ABERRANT VISUAL PROJECTIONS IN THE SIAMESE CAT

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SUMMARY

1. Guillery has recently shown that the Siamese cat has a grossly abnormal lateral geniculate body. His anatomical study suggested that certain fibres originating in the temporal retina of each eye cross in the chiasm instead of remaining uncrossed. They thus reach the wrong hemispheres, but in the geniculate they terminate in the regions that the missing fibres from the ipsilateral eye would normally have occupied. The result is that each hemisphere receives an input from parts of the ipsilateral field of vision, this input being entirely from the opposite eye. The purpose of the present work was to study the physiological consequences of this aberrant projection, in the lateral geniculate body and visual cortex.

2. Single-cell recordings from the lateral geniculate body confirmed the presence of projections from the ipsilateral visual field of the contralateral eye. The part of layer A1 receiving these projections was arranged so that the receptive fields of the cells were situated at about the same horizontal level and at the same distance from the vertical meridian as the fields of cells in the layers above and below (layers A and B), but were in the ipsilateral visual field instead of the contralateral. They thus occupied a region directly across the midline from their normal position.

3. In the cortex of all animals studied, we found a systematic representation of part of the ipsilateral visual field, inserted between the usual contralateral representations in areas 17 and 18. When the visual cortex was crossed from medial to lateral the corresponding region of visual field moved from the contralateral periphery to the midline, and then into the ipsilateral field for 20°. The movement then reversed, with a return to the mid line and a steady progression out into the contralateral field. The entire double representation was, with some possible exceptions, a continuous one. The point of reversal occurred at or near the 17–18 boundary, as judged histologically, and this boundary was in about the same position as in ordinary cats.

4. Cells in the part of the cortex representing the ipsilateral fields had
normal receptive fields, simple, complex, or hypercomplex. These fields tended to be larger than those in corresponding parts of the contralateral visual fields. Receptive-field size varied with distance from the area centralis, just as it does in the normal cat, so that cells with the smallest fields, in the area centralis projection, were situated some distance from the 17–18 border.

5. Projections originating from the first 20° from the midvertical in both visual half-fields had their origin entirely in the contralateral eye, as would be expected from the abnormal crossing at the chiasm. Beyond this visual-field region, and out as far as the temporal crescents, there were projections from both eyes, but we found no individual cells with input from the two eyes. The cells were aggregated, with some groups of cells driven by one eye and some by the other.

6. From previous work it is known that ordinary cats raised with squint show a decline in the proportion of cells that can be driven binaurally, whereas animals raised with both eyes closed show little or no decline. A Siamese cat raised with both eyes closed had binocular cells in the regions of 17 and 18 subserving the peripheral visual fields, suggesting that the absence of binocular cells seen in the other Siamese cats was indeed secondary to the squint.

7. In two Siamese cats there were suggestions of an entirely different projection pattern, superimposed upon that described above. In the parts of 17 and 18 otherwise entirely devoted to the contralateral visual field, we observed groups of cells with receptive fields in the ipsilateral field of vision. The electrode would pass from a region where cells were driven from some part of the contralateral visual field, to regions in which they were driven from a part of the ipsilateral field directly opposite, across the vertical mid line. The borders of these groups were not necessarily sharp, for in places there was mixing of the two groups of cells, and a few cells had input from two discrete regions located opposite one another on either side of the vertical mid line. The two receptive-field components of such cells were identical, in terms of orientation, optimum direction of movement, and complexity. Stimulation of the two regions gave a better response than was produced from either one alone, and the relative effectiveness of the two varied from cell to cell. These cells thus behaved in a way strikingly reminiscent of binocular cells in common cats.

8. The apparent existence of two competing mechanisms for determining the projection of visual afferents to the cortex suggests that a number of factors may cooperate in guiding development. There seems, furthermore, not to be a detailed cell-to-cell specificity of geniculocortical connexions, but rather a tendency to topographic order and continuity, with one part of a given area such as 17 able to substitute for another.
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Whether or not these tentative interpretations are ultimately proved correct, it seems clear that this type of genetic anomaly has potential usefulness for understanding mechanisms of development of the nervous system.

INTRODUCTION

Among animal breeders it is common knowledge that Siamese cats are frequently cross-eyed. A few years ago we showed that ordinary cats raised with squint from an early age develop marked abnormalities in the connexions subserving binocular interaction in the cortex (Hubel & Wiesel, 1965b), and we wondered whether Siamese cats would develop similar abnormalities, or if they might possibly show them at birth.

Recently Guillery (1969) has observed that Siamese cats possess a strikingly abnormal lateral geniculate body. Patterns of fibre degeneration following removal of one eye revealed that in each geniculate body parts of the layers that in the normal cat connect to the ipsilateral eye, in the Siamese received their input from the contralateral eye. Guillery suggested that some fibres from the temporal retina, which are normally uncrossed, become misdirected and cross to the opposite hemisphere during development.

If optic fibres that normally are uncrossed at the chiasm instead become crossed, there should be cells in the geniculate with receptive fields in the ipsilateral half-field of vision. One may then ask how these cells project to the cortex, whether, for example, there is in each hemisphere an added systematic topographic representation of part of the ipsilateral field of vision, or whether the aberrant projections become scrambled with the normal ones. What happens when the cortex is presented with an abnormal input could obviously be of interest for an understanding of normal development. Because of this, and our interest in the squint, we decided to investigate the central pathway of Siamese cats and kittens, particularly the topographic projections of the retinas to areas 17 and 18 of the visual cortex, and the receptive-field properties and binocular interaction of cells in these areas.

METHODS

Seven purebred Siamese cats were used: a litter of five kittens whose parents both had overt strabismus, and one additional adult cat and a 4-month-old kitten. The adult cat had no obvious squint. In the two kittens that were observed from birth to age 5 months, one developed a clear squint by about 2 months, though it was not nearly as marked as in some adult Siamese cats. The other kitten had only a suggestion of a squint by 5 months (as described below, however, both had a readily demonstrable convergent strabismus when the eyes were paralysed).

Methods of stimulating and recording from kittens and adult cats have already been described in detail (Hubel & Wiesel, 1962, 1963). The 5-month-old kittens were anaesthetized with thiopentone, but in two 2-week-old kittens xylocaine was used.
both as a general anaesthetic and for local infiltration of the skin wounds. The anaesthetized animal was placed in a stereotaxic head holder and the corneas protected with contact lenses, which also focused the eyes on a projection screen 1.5 metres away. The eye muscles were paralysed with succinylcholine, making it necessary to use artificial respiration. Tungsten electrodes were positioned in a closed-chamber system. Receptive fields were mapped with spots, slits, dark bars and edges, produced by a hand-held slide projector. Our main concern was to compare the responses of cells driven from the two eyes and to localize the receptive fields in the visual fields for as many cells and over as wide a region of visual cortex as possible, examining area 18 as well as 17. In each electrode track one or more electrolytic lesions were made, and the tracks were later reconstructed in the usual manner from serial Nissl-stained sections.

RESULTS

Recordings from the lateral geniculate body

In the lateral geniculate body of the normal cat (Text-fig. 1) the nasal half-retina of the contralateral eye projects to the most dorsal layer (A) and to the most ventral (B), while the temporal half-retina of the ipsilateral eye projects to the intermediate layer, A1. (Guillery, 1970, has shown in the normal cat that there is a sublamina of layer B which also receives ipsilateral projections.) The contralateral half-field of vision is mapped on to each layer systematically, with the three maps in precise register, so that in any vertical penetration one first records cells driven from the contralateral eye, then cells driven from the ipsilateral, and then the contralateral, all with their receptive fields in the same part of the contralateral field of vision (Hubel & Wiesel, 1961; Bishop, Kozak, Levick & Vakkur, 1962). The further medial the penetrations, the closer the receptive fields are to the vertical meridian of the visual fields.

If, in the Siamese cat, part of layer A1 is supplied by the temporal retina of the contralateral eye, rather than the ipsilateral, the sequence of events during a vertical penetration should be very different from the normal. To study this we made four penetrations in the lateral geniculate bodies of two Siamese kittens, one 5 months old (No. 3), and the other 4 months old (No. 7). In three of the penetrations some of the cells had their receptive fields clearly in the ipsilateral field of vision, several degrees from the vertical meridian. Two of the three penetrations, however, were far forward in the geniculate, where the anatomy is not easily interpreted. The third, shown in Text-fig. 2, was near the middle of the left geniculate’s antero-posterior extent.

The first group of cells in penetration 3, recorded from layer A, had fields some 5–6° from the mid line in the right (contralateral) field of the right eye. The next cells, from what we interpret to be A1, instead of being in the right field of the left eye, were in the left field of the right eye, in a roughly
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mirror-symmetric position across the vertical mid line. The last cells, from layer B, were driven from the right eye and right field, as would be expected in the dorsal part of this layer. The final electrode position was marked by a lesion (Text-fig. 2, Pl. 1). Except for their positions in the wrong visual field of the wrong eye, all of the cells recorded from layer A1 behaved normally. These findings agree with Guillery's results concerning contralateral-eye input to A1, and support his interpretation that the input originated from the temporal half of the contralateral retina.

Text-fig. 1. Diagram to illustrate visual-field topography for areas 17 and 18 of normal cat cortex. The right-hand diagram shows a view of the cortex from above. The continuous line shows the level of the coronal section illustrated to the left. Geniculate and cortex are shown in coronal section, since for both structures a medio-lateral movement at a given coronal level corresponds roughly, in the visual field, to a movement to or away from the vertical mid line. (An anterior or posterior movement in geniculate or cortex corresponds to movement down or up in the visual fields.) For simplicity, connexions from geniculate to area 18, and from 17 to 18, are omitted.

Cortical recordings

Normal cats. The general topographic arrangement of the normal cat visual cortex is shown in Text-fig. 1 (Talbot & Marshall, 1941; Hubel & Wiesel, 1965a). The lateral geniculate body projects to the primary visual cortex in a systematic manner. There is also a direct projection from the main part of the lateral geniculate body to area 18 (Garey & Powell, 1967;
Glickstein, King, Miller & Bailey, 1967). From Nauta-degeneration experiments in a series of normal cats, with small lesions confined to layers A or A₁ of the geniculate, we have shown that this projection to area 18 is a systematic one, consistent with the topographic representations as determined physiologically, and with the known anatomical projection from 17 to 18.

A given location in either 17 or 18 receives projections from a region in each of the three geniculate layers, one lying directly above or below the

Text-fig. 2. Penetration through the left lateral geniculate body of a Siamese kitten (No. 7); Horsley–Clarke lateral 9-0, anterior 4-0. Each receptive field is shown relative to the area centralis, which is indicated, for each cell, by a short horizontal cross bar intersecting the long vertical line. The first cells, 23–25, were recorded from layer A, and had receptive fields in the right eye, 5–6° to the right of the mid-vertical and 1.5° above the horizontal meridian. Cells 26–28, recorded from layer A₁, and again driven from the right eye only, had fields 4–5° to the left of the mid line, 1° below the horizontal. Finally a cell recorded in the uppermost part of B had fields in the right eye in the same position as the fields of cells 23–25. The area centralis was not well defined, and no attempt was made to correct for eye rotation in the equatorial plane. OT = optic tract.
other, as would be expected from the fact that the three topographic maps are in register. As one explores the cortex from medial to lateral, at a given coronal level, there is a displacement in the corresponding positions in the visual fields, beginning in the contralateral visual field and moving inwards to the vertical mid line, and then out again to the contralateral periphery (Talbot & Marshall, 1941). The point of reversal at the vertical meridian is represented by the anatomical 17–18 border (Otsuka & Hassler, 1962; Hubel & Wiesel, 1965a). The ipsilateral field of vision, of course, projects to the other hemisphere. A forward movement along the cortex corresponds to a downward movement in the visual field. Within 50–60° of the vertical mid line, the projection to the cortex is from both eyes. The visual field beyond this (the temporal crescent) is represented by the contralateral eye only.

A vertical penetration entering the cortex near the medial border of the lateral gyrus (see Text-fig. 1) should thus record cells in 17 or 18 with fields close to the vertical meridian. If the penetration extends far down the medial bank of the gyrus the receptive fields should gradually move out further and further into the contralateral visual field. On the other hand a series of vertical penetrations beginning at successively more lateral positions along the lateral gyrus should record cells in area 18 with fields that again occupy progressively more peripheral positions in the contralateral field of vision.

**Siamese cats: topography and binocular interaction.** In seven Siamese cats, sixteen penetrations were made, and 303 cells were adequately studied. The first cat (No. 3) was examined at an age of 5 months. When awake and alert the animal was obviously strabismic. When it was anaesthetized and paralysed, the eyes took up a rest position with their axes converged by 12°, instead of the usual divergent separation of about 5° (Hubel & Wiesel, 1962; Bishop, Kozak & Vakkur, 1962). By this method of measurement there was thus about 17° of convergent squint.

Two cortical penetrations were made in this kitten, one in each hemisphere. Both penetrations were abnormal, in that all cells responded only to the contralateral eye and had abnormal receptive-field positions. Otherwise the cells responded normally, showing typical simple, complex, and hypercomplex properties. The first penetration (Text-fig. 3) entered the right post-lateral gyrus at a point that normally is well within area 17, and corresponds to a visual-field region 1–2° or less from the area centralis (Talbot & Marshall, 1941; Hubel & Wiesel, 1965a). In this cat, however, the fields began 15–20° in the ipsilateral field of vision, some 5–10° below the horizontal meridian. As the electrode descended along the medial bank there was a clear systematic trend first towards the vertical mid line, which was crossed at about cell 36, and then out into the contralateral field of
Text-fig. 3. First penetration in the right hemisphere of a 5-month-old Siamese cat (No. 3). The diagram at left shows a dorsal view of the brain surface, indicating the points of entry of two micro-electrode tracks. Right part of the Figure shows a reconstruction of the micro-electrode track in the right hemisphere. The plane of section (Horsley-Clarke 0-0) is indicated on the brain surface map by a dotted line. Positions of units are indicated by numbered cross bars to the right of the electrode track. L₁, L₂, and L₃ refer to three electrolytic lesions made in the course of the penetration. Numbers just outside the cortical tracing refer to approximate azimuth positions of receptive fields, positive numbers standing for regions of visual field contralateral to the hemisphere recorded from; negative standing for ipsilateral.

In the diagram on p. 41 the position of each receptive field is shown relative to the area centralis, which is indicated for each cell or set of cells by a horizontal cross bar intersecting the long vertical line. Ipsilateral visual field is to the right, contralateral to the left, of each vertical line. All cells in this penetration were influenced only from the left (contralateral) eye. Orientations, for most receptive fields, are indicated by two short lines. Thus unit 1 had a 10 o’clock–4 o’clock orientation.

Note (1) the gradual drift of receptive-field positions from ipsilateral to contralateral as the electrode descended along the medial bank; (2) the decrease in field size with decreasing distance from the area centralis, for both ipsilateral and contralateral fields, and (3) the larger average size of ipsilateral fields, compared with contralateral ones.
vision, ending about 15° from the mid line. A second penetration down the medial aspect of the left hemisphere gave very similar results.

The ipsilateral-to-contralateral progression of receptive fields shown in Text-fig. 3 is what is normally seen with a lateral-to-medial movement of an electrode across area 17; what was most unprecedented was the inclusion of 15–20° of ipsilateral visual field in this progression. Clearly in this animal part of the cortex was devoted to a systematic representation of the medial part of the ipsilateral visual fields. The extent of the representation was not established, and the lateral parts of the lateral gyrus were not explored. In neither penetration was there any sign of responses from the ipsilateral eye in either field of vision; this was expected, given that the optic nerve fibres representing the central 30–40° of visual field were, in the Siamese cat, presumably virtually all crossed. From the morphological normality of the lateral parts of the lateral geniculate
bodies in these animals one would predict a normal binocular input to parts of the cortex representing the contralateral visual fields beyond 20° or so. Obviously, what was needed next was an exploration of both 17 and 18, including parts representing the more peripheral contralateral visual fields.

Cat No. 4, a litter-mate of the previous cat, was also studied at 5 months of age. In this animal there was only a faint suggestion of a strabismus on simple inspection, but the convergent strabismus estimated from the rest position with muscles paralysed was 16°.

Text-fig. 4. Five penetrations in the right visual cortex of a 5-month-old Siamese cat (cat. No. 4, a litter-mate of Nos. 1, 2, 3, and 5). Horsley–Clarke anterior 5-0. Receptive fields drawn with continuous lines indicate that cells were driven from contralateral eye only; dashed lines, ipsilateral eye only. Penetration 1 (P1), from unit 10 on, shows a steady drift of receptive fields out into the contralateral field of vision; this is typical of area 17. Comparing field positions in the upper part of penetration 1 and penetrations 2–5, the movement from ipsilateral to contralateral in the visual field suggests that these recordings were all in area 18; this is supported by the large size of the fields and their wide scatter, in contrast to the smaller and better ordered fields in area 17. Up to cell 23 all responses were from the contralateral eye only. Beyond about 15°, in both 17 and 18, occasional cells were driven from the ipsilateral eye only. No cells were binocularly driven. Arrow shows the approximate position of the 17–18 border, as estimated from Nissl and myelin-stained sections.
Text-fig. 4 (cont.)
The entire lateral gyrus was explored at coronal level +5 by making five penetrations, as shown in Text-fig. 4. In the first, most medial penetration (P1) the first fields were 10–20° ipsilateral to the vertical meridian, and later ones, in the medial bank, showed a steady trend outwards beginning at the mid line and ending 30° in the contralateral visual field. Up to a point halfway down the medial bank, near lesion 2 (unit 23), all cells responded only to the contralateral eye; here, however, we came upon a group of cells driven only from the ipsilateral eye. Receptive fields were about 15° from the mid line, in about the same place as the fields of the contralateral-eye cells recorded just before. It can be seen in Text-fig. 4 that these cells occurred in groups (the fields are drawn in dashed lines): first units 23–26, later unit 32, and finally units 34–40. It seemed that we were going from regions where all cells were driven by one eye to regions where they were all driven by the other, an impression that was reinforced on noting that the background activity was influenced by one or the other eye, but not by both, except very briefly at the transition points.

In penetrations 2–5, as the recording site moved laterally, the fields shifted from the ipsilateral visual field (penetration 2) into the contralateral (penetration 3), moving further and further out, as far as 30° in penetration 4, and 50° in penetration 5. All cells were driven from the contralateral eye except for two in penetration 4 which were influenced only from the ipsilateral eye and whose receptive fields were about 15–20° out from the mid line in the contralateral visual field.

We interpret these experiments as indicating that the extra 20° or so of ipsilateral visual field, in 17 and 18, had been, as it were, inserted into the cortex at the 17–18 boundary. It seemed that the extra piece was organized so that in a medio-lateral exploration of the cortex the visual-field representation proceeded not from the contralateral periphery to the vertical mid line and back out again, as it normally does (Text-fig. 9, left half), but instead progressed from the contralateral periphery to the mid line and beyond, into the ipsilateral field for some 20°. Then, in the region of cortex where the 17–18 border normally comes, there was a reversal in direction and, on traversing 18, a return to the mid line and a progression into the contralateral visual field (Text-fig. 9, right half). The prediction was confirmed that in the peripheral part of the visual fields, beyond about 20°, there should be input from both eyes. Even here, however, there was no evidence for binocular convergence upon single cells.

Effects of strabismus on Siamese cat cortex. In ordinary cats reared with artificial strabismus, there is a striking decline in the number of cells driven by both eyes. One sees instead a mixture of cells, some driven by one eye, others driven by the other (Hubel & Wiesel, 1965b). We naturally
wondered if in Siamese cats the lack of binocular convergence in the periphery was secondary to the strabismus. The most direct way of settling this is to record from kittens at a very early age, before a critical period of susceptibility to deprivation begins. For eye closure the onset of this period is about 4 weeks of age (Hubel & Wiesel, 1970) and it seems reasonable to assume that for squint it is probably the same, though this has not been studied extensively. Two kittens (Nos. 1 and 2) were accordingly studied at 15 and 16 days of age, but neither survived long enough for examination of the outlying parts of the visual-field representations. We recorded from a total of fifty cells in the apex of the lateral gyrus, and, as expected from recordings in the older animals, all cells were driven exclusively from the contralateral eye. The responses seemed normal for animals at this age, but difficulties in seeing the retinal landmarks because of the cloudy ocular media prevented our localizing the receptive fields in relation to the area centralis and optic disk.

To circumvent the difficulties in working with very young animals, we brought up one of the kittens (No. 5) to an age of 5 months with both eyelids sutured. This procedure does not lead to any obvious change in binocular interaction in the cortex (Wiesel & Hubel, 1965), and with both eyes closed the proportion of binocularly driven cells should obviously not be influenced by the presence of a squint. When the eyelids were separated and the muscles paralysed there was a convergence of 2° and a vertical disparity of about 8°. Deviations as large as this are occasionally seen in normal cats and in cats with binocular closures, after paralysis with succinylcholine. Clearly this cat differed from its littermates of the same age in having no marked convergent squint. Both this difference and the fact that the squint in the other animals developed only after several months of vision suggest that the squint is secondary to the neural abnormality.

A single penetration was made down the medial bank of the lateral gyrus at coronal level +3 (Text-fig. 5). Thirty-nine cells were recorded from, their fields localized, and responses to stimulation of the two eyes compared. As usual in binocularly deprived animals, about half the cells failed to respond, responded sluggishly, or showed other abnormalities such as a decline in orientation selectivity. Once more the initial fields were about 20° out from the vertical in the ipsilateral field of vision and the cells were driven only by the contralateral eye; subsequent fields progressed steadily inwards to the vertical meridian. Following a gap between units 20 and 21, during which the electrode crossed layer I, the trend continued, with the first fields 15° contralateral and the final ones 30° contralateral. Ipsilateral fields in the first part of the penetration were several times larger than the contralateral fields recorded in the latter part, even though the two groups were about the same distance from the vertical meridian. This
tendency was also seen, though not quite so compellingly, in the penetration of Text-fig. 3.

All cells were driven only by the contralateral (left) eye until unit 32, whose field was 20° contralateral; that cell was driven from both eyes, the left eye slightly dominating (group 3). We then observed a series of cells driven from both eyes, after which the cells, with one exception, again became monopolized by the contralateral eye. Thus this cat, unlike the

Text-fig. 5. Five-month-old Siamese cat (No. 5) whose eyelids had both been sutured shut from birth. Thirty-nine cells were recorded from apex and medial aspect of lateral gyrus; all of these except possibly the very first were in area 17, to judge from the steady ipsilateral-to-contralateral progression in field position. Cells were influenced from the contralateral eye only, up to unit 32, whose field was 20° contralateral to the midvertical; from this point on there was a mixture of cells driven from both eyes (represented by dashed and continuous rectangles superimposed) and cells driven only from the contralateral eye. Numbers in parentheses following unit numbers refer to ocular-dominance groupings; e.g. '2' means that contralateral eye gave much stronger responses than ipsilateral, etc. (see Hubel & Wiesel, 1962). Note the relatively large size of ipsilateral receptive fields, and the very much smaller contralateral ones. Receptive fields represented by circles were not clearly oriented, a frequent finding in cats reared with both eyes closed from birth (cells 29–33 are out of sequence because electrode was withdrawn and then readvanced).
previous two, showed clear convergence of input from both eyes on single cells. It is not possible to say whether the actual distribution of cells according to ocular dominance is normal, given such a small sampling of cells, but it seems clear that binocular convergence on to single cells is present at

birth, and subsequently disappears because of strabismus, just as it does in ordinary cats or monkeys when a squint develops early in life.

*Aberrant input.* At this stage it appeared to us that the project of surveying the Siamese cat was reasonably complete, but since all the

Text-fig. 5 (cont.)
Text-fig. 6. First three penetrations in cat No. 6, an adult Siamese unrelated to cats 1-5. Horsley-Clarke 0-0. Upper part of penetration 1 and penetrations 2 and 3 were all in area 18, as judged by the histology and the ipsilateral-to-contralateral progression in receptive-field positions accompanying medio-lateral movement across the cortex. In the deeper half of penetration, and in penetration 3 there were occasions in which cells and background activity could be driven by stimuli in the ipsilateral visual field, roughly across the mid line from the part of the visual field from which the prevailing responses were obtained. In area 17, cells 14, 15, and 19 had dual fields, with components roughly symmetrically placed in each visual field. (Fig. 7 illustrates a recording from cell 14.) For these fields, the orientations of the two components, as well as the field sizes and directional preferences, were identical. (Fields 11-18 are numbered in the order in which they were recorded, but are illustrated in their anatomical order.) In area 18, background activity recorded simultaneously with unit 46 was again driven from the mirror-symmetric position in the ipsilateral field (46a). All cells were driven only from the contralateral eye, except for Nos. 32 and 33, which were driven also by the ipsilateral eye (group 2).
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animals had been from the same litter we thought it wise to repeat the experiments in one or two unrelated Siamese cats. Accordingly the next experiment consisted of four penetrations made in an adult cat (No. 6). The results, in terms of topographic representation and binocular interaction, were entirely consistent with the previous ones, with one interesting addition.

The first three penetrations were made at Horsley–Clarke coronal level 0·0 (Text-fig. 6). In the most medial penetration, P1, units 1–10 had fields in the vertical mid line area about 10° below the centre of gaze. This upper part of the penetration was slightly inclined so that there was a component of movement relative to the surface in a lateral-to-medial direction. The drift in receptive-field positions from contralateral to ipsilateral suggested that this region of cortex was area 18. After crossing white matter, the electrode, as expected, entered a region in which the first cells (Nos. 11 and 12) had fields in the contralateral visual field, in this case about 15° out; these cells were driven from the contralateral eye. Advancing the electrode rather rapidly, we suddenly entered a region in which the background activity was still driven by the contralateral eye, but now from the ipsilateral visual field, about the same distance out, and at about the same horizontal level. There was no trace of a response from the contralateral
visual field. A well isolated cell, No. 13, had its field in this ipsilateral area. We withdrew the electrode slowly, to see if there was any overlap between these two mirror-symmetric cortical representations. A short distance back there was indeed a region in which activity was driven from both areas of visual field, with no response from the vertical mid line region between. Here we came upon a well isolated cell (No. 14) which was driven from both areas, a finding so unprecedented that we went to great pains to be sure that the recording was not from two different cells. We finally convinced ourselves that it was a single cell by adjusting the electrode position back and forth, watching the spikes from the unit wax and wane, nevertheless remaining identical in size at any electrode position regardless of the region of visual field stimulated.

A recording from this cell is illustrated in Text-fig. 7. The two components of the field were exactly the same size, and both showed identical preferred stimulus orientations, with a moderate directional preference for downward movement. The situation was thus reminiscent of the usual cortical cell with a receptive field in each eye; all this time, however, the right eye was absolutely silent, and the fields, far from being in corresponding positions, were in virtual mirror-symmetry. What reinforced the analogy to the usual system of binocular interaction in cat cortex was the existence of clear summation when the two areas were stimulated together, and especially the fact that while the regions had similar properties in most respects, the responses were not equally brisk, the contralateral region giving slightly stronger bursts than the ipsilateral (the difference is not apparent in Text-fig. 7). In the normal cat it will be recalled that cortical cells are not necessarily driven with equal vigour from the two eyes (Hubel & Wiesel, 1962).

Advancing the electrode, we recorded another unit with a double field (No. 15), whose components had the same positions and orientations as unit 14. Again the contralateral region dominated slightly. Cells 16–18 had fields only in the ipsilateral area, with no background activity evoked from the contralateral region. Cell 19 had a double field with the ipsilateral region now strongly dominant, while No. 20, recorded simultaneously, was driven only from the ipsilateral area. The next cell, No. 21, again responded only in the ipsilateral region. From that point on all activity disappeared from the ipsilateral area, and as cell after cell was mapped the receptive fields as usual moved gradually further into the contralateral visual field. Late in the penetration two more cells, Nos. 31 and 35, had receptive fields confined to the ipsilateral side. These fields were not as far out on that side as were the fields of their neighbours on the contralateral side. All this time the ipsilateral (right) eye gave no hint of activity until cells 32 and 33, both of which were, however, strongly dominated by
the contralateral eye (group 2), and were influenced only from the contra-
lateral field of vision.

Cells recorded in penetration 2, lateral to 1 (Text-fig. 6), again had fields
that were virtually in the mid line. In penetration 3 the fields of the initial
cells were, as expected, further out in the contralateral field. A careful
scrutiny of the ipsilateral visual field during the entire penetration again
showed one small patch of cortex, containing cell 46, in which background
activity was influenced both from the region of that cell's field and from
the same eye in an area of ipsilateral field roughly opposite (No. 46a);

Text-fig. 7. Responses of cell 14 of Text-fig. 6 (cat No. 6, penetration 1).
The cell was driven from two regions, each 4° × 4° in size, one 9° to the left
of the vertical mid line and 124° below the horizontal (left records), the
other 8° to the right of the vertical mid line and 13° below the horizontal
(right records). Between these regions (middle set of records) no responses
were evoked. Since this cat had a poorly defined area centralis, estimates of
the vertical mid line could have been off by 2–3° in either direction. In each
area the best responses were to a 2:30–8:30 slit moving downwards. Re-
sponses from the contralateral region were slightly brisker than those
from the ipsilateral (though this does not show in the illustration). Dur-
ation of each trace, 4 sec.

cell 46 itself was driven only from the contralateral region. The two mirror
regions were too close together for us to be absolutely certain that they did
not merge across the mid line, but it was clear that in this part of area 18
there were patches in which there was input from the ipsilateral field.
In a final penetration made 6 mm further forward, a long traverse of the medial segment gave results very similar to those of Fig. 4, penetration 1. There were no patches of mirror representation.

Cat No. 7, a 4-month-old Siamese unrelated to the others (Text-fig. 8), was examined to confirm the existence of these ipsilateral patches of input. The animal already had a clear convergent squint. As in cat No. 6, the areae centrales were unusually poorly defined, and our estimate of their positions could have been off by several degrees in any direction. A penetration down the medial cortical bank revealed a topography virtually identical to that of previous experiments – an ipsilateral progression, a jump to the mid line after crossing white matter, and a subsequent progression into the contralateral field. Careful monitoring of the ipsilateral field during these recordings showed two portions of the penetration (cells 47–50; 54–56) in which responses were obtained from two separate regions of visual field, one on each side of the vertical meridian. On the first of these occasions

Text-fig. 8. Siamese kitten (No. 7) 4 months of age. A single penetration in the right visual cortex at coronal level 0·0. The first cells were recorded from area 18, as judged by the large size of receptive fields and progression out into the ipsilateral visual field. In the medial segment, presumably area 17, there was the usual regular contralateral drift of relatively small fields, broken only by two brief episodes of activity from the ipsilateral field of vision. No cells were seen with dual fields, but there were three examples in which the two simultaneously recorded cells were driven from regions to either side of the midvertical (47 and 48; 49 and 50; 54 and 55). All cells were driven from the contralateral eye only.

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two cells (47 and 48) were recorded together, one with a field about $12^\circ$ in the contralateral visual field, the other with a field of slightly different orientation, about $7^\circ$ in the ipsilateral visual field and slightly lower in position. There was abundant background activity influenced from both areas. Cells 49 and 50 were likewise simultaneously recorded. Two other cells, Nos. 54 and 56, had fields ipsilateral to the midvertical; in both recordings there was simultaneous activity driven from the contralateral field. At no point in the penetration were responses evoked from the ipsilateral eye.

This experiment, then, confirmed the presence of patches of input from the ipsilateral visual field superimposed on what was predominantly a representation of the contralateral field of vision. The lack of a strict mirror symmetry in the positioning of these receptive fields, and the relatively large scatter in their field positions, agrees with a similar finding in the previous experiment (Text-fig. 6, cells 31 and 35), but contrasts with the regularity suggested earlier in the same penetration (Text-fig. 6, cells
13–21). On the whole we had the impression that the ipsilateral-field input was less well organized than the input from the contralateral field, which is as orderly as in the normal cat.

**DISCUSSION**

These experiments confirm Guilley's observation that the central visual pathway of the Siamese cat is highly abnormal, and they support his idea that the abnormality consists primarily of a mistake at the chiasm, with some optic fibres from the temporal retina crossing instead of remaining uncrossed. In this paper we have tried with the help of physiological tools to learn how the brain deals with the aberrant fibres, with the ultimate hope of gaining more insight into normal developmental processes.

At the geniculate level the problem of aberrant fibres is solved, it would seem, in the simplest and most obvious way. A medial segment of layer A₁ on one side should normally receive the innermost 15–20° of temporal fibres from the ipsilateral eye; these fail to reach the geniculate, which instead must deal with the innermost 15–20° of temporal fibres from the contralateral eye. Not surprisingly, the aberrant fibres project to just the gap in the geniculate that the absent optic fibres would have filled. Text-fig. 2 suggests that they do so in a systematic manner, since as the electrode crosses from layer A to A₁ the fields of cells jump from a region in the contralateral visual field to a region roughly in the corresponding part of the ipsilateral field, with mirror-like symmetry. Normally the site of termination of a retinal fibre relative to the medial border of the geniculate depends on the distance of its origin in the retina from the retinal vertical mid line, and the mirror-symmetry suggests that this is true even for aberrant fibres from the ipsilateral field. This ability of optic fibres to grow to precisely the right location in the geniculate, but on the wrong side with mirror symmetry, implying an absence of strict left-right specificity, is reminiscent of experiments in which Sperry (1945) obtained restoration of vision in frogs after crossing the optic nerves; his behavioural result seems to imply that the fibres had succeeded in growing back to the appropriate parts of the tectum, but on the wrong side.

The next question is how the cortex deals with such a complex input. In trying to predict the answer one may imagine several possibilities. The projections from layer A₁ of the geniculate might be organized very much as they are in the normal visual pathway, with groups of cells in A₁ connected to the same region of cortex as cells directly above, in layer A of the geniculate, and below, in the ventral set of layers (B). Or an entirely separate region of cortex might be set aside for the projections from the additional 15–20° of ipsilateral visual field, in which case neighbouring cells from A and A₁ would project to very different places. Finally, fibres from the
abnormal part of A₁ could be mixed in with, and superimposed upon, the normal projection from the contralateral field in more or less random fashion.

The result, in fact, is a mixture of the first and second possibilities. Of these the second plan, in which part of the cortex of each hemisphere is devoted specifically to the 0–20° region of ipsilateral field, seems the dominant one, for it occurred in all of the Siamese cats in which topographic mappings were made. One of the most surprising findings in these experiments was the high degree of order shown by the new ipsilateral representations. Far from the scrambled topographic picture that one might have expected, the arrangement was almost as systematic as in the normal animal. In response to the problem of where in the cortex to represent an additional 20° of ipsilateral visual field, the answer has been to wedge it in neatly along the 17–18 boundary, which normally receives projections from the vertical meridian of the visual field. This is illustrated for the right hemisphere in Text-fig. 9: as the visual cortex is crossed from medial to lateral the visual-field representation begins as usual in the far left periphery and moves to the mid line. Instead of reversing here, it proceeds for another 20° into the right field. With further progression laterally across the cortex the movement reverses itself, going from 20° in the right field back to the mid line, and then advancing again across the left visual field. Presumably medial cortex, up to the reversal point, is area 17, and cortex lateral to this is area 18. Unfortunately, in none of the experiments was the point of reversal in the cortex precisely established, chiefly because the extreme curvature of cortex in this region makes it difficult to do so in a small number of electrode penetrations. Our estimates of it, however, coincided well with the anatomical 17–18 borders in Nissl and myelin sections, which are marked by arrows in Text-figs. 4, 5, 6 and 8. These anatomical transition points were as usual not sharply defined, but they can be estimated with reasonable confidence to within a millimetre or so. The anatomical borders and reversal points were roughly the same in position as the 17–18 border in the common cat (Otsuka & Hassler, 1962; Hubel & Wiesel, 1965a).

The presence of an added 20° of course distorts the normal topography, so that in any coronal section a point in area 17 representing a given region of visual field is shifted medially by up to 4–5 mm, and similarly the representation in 18 is shifted laterally (see Text-fig. 9). There may also be some distortion in the anteroposterior direction, since all of our receptive-field positions seemed slightly low; a survey of much more of the striate cortex and area 18 would probably be necessary to learn whether such a distortion exists.

There are several hints that in the Siamese cat the topography is in
places more complex and less regular than what we have described. Guillery's paper shows that, at least at some anteroposterior levels, there may be two segments of layer A1 that receive aberrant contralateral-eye input, separated by a normal segment. In terms of topography a move-

Text-fig. 9. Diagrams for normal and Siamese cats showing pathways from retina to cortex. Left diagram is the same as in Text-fig. 1. In the Siamese cat, abnormal projections are shown by dashed lines; note that the connexions from peripheral retina, beyond 15–20°, are normal. Shaded cortex represents areas receiving input from both eyes; unshaded regions receive input from contralateral eye only; black region in Siamese cat indicates the additional 20° of ipsilateral-field representation in 17 and 18 in the contralateral eye. The dashed pathway to the black region supplies this additional representation, whereas the dashed pathway to the unshaded area supplies the patches of ipsilateral field to the cortical region that otherwise mainly represents 0–20° in the contralateral field.
ment medially along A or A₁ corresponds to a visual-field displacement inward towards the vertical meridian. One would therefore expect that the part of temporal retina yielding crossed aberrant fibres would not necessarily extend uninterrupted to the mid line of the visual field, but might form several islands or strips in the ipsilateral field. In that case one would also expect in the cortex a corresponding discontinuity in the ipsilateral-field representation. This seemed not to be so in some of our cortical penetrations, such as that of Text-fig. 3, for in that experiment there was a continuous progression extending from 15° ipsilateral across the mid line to 15° contralateral. Text-fig. 5 likewise shows no gap. Moreover, there was no hint of any ipsilateral-eye input to the contralateral fields in their most medial parts, though Guillery's result might predict such an input. But the inner 10–20° of visual field, contralateral or ipsilateral, were in most experiments not thoroughly enough explored to rule out minor discontinuities, and it may be that the part of the temporal retina giving rise to crossed fibres extends uninterrupted to the mid line at some horizontal levels but not at others, or that all Siamese cats may not have the same number and distribution of aberrant fibres. It would be interesting to know the exact shape and extent of the retinal region or regions giving rise to the aberrant crossed fibres, and the variability in this from animal to animal.

The functional architecture of the Siamese cat's visual cortex may be of some value for understanding mechanisms of normal development. It is important, for example, to learn whether each geniculate cell is specifically connected to particular cortical cells. Our results seem to suggest that this is not so, but that the geniculate axons instead arrive at the cortex in a topographically ordered fashion and simply fill out the available space, connecting to certain classes of cells in highly specific groupings that produce simple-field and complex-field characteristics and so forth, but without absolute specificity for receptive-field position. In other words, a cortex that would normally receive fibres representing only the contralateral field of vision finds itself confronted with input from an additional 20° of ipsilateral field. The solution is to place the fibres with the furthest ipsilateral representation where the innermost ones would normally go, at the 17–18 border, and pack in the rest, as usual, in an ordered double representation. Even if the size of the visual field representation is larger for each hemisphere, the total number of incoming fibres is presumably not increased, since over the anomalous 20° there is input from the contralateral eye only.

This apparent lack of rigid specificity in geniculo-cortical connexions is reminiscent of the findings of Gaze, Jacobson & Székely (1963), in Xenopus embryos with compound eyes (double nasal or double temporal), that optic
fibres which would normally have projected to only half of the contralateral tectum regenerate so as to fill the whole tectum. The analogy is of course a tenuous one since our results do not involve regeneration after surgical intervention, and furthermore the process is one of compression of a topographical representation after an addition of visual-field input rather than an expansion after a field deletion.

In the common cat, cortical receptive fields in or near the area centralis tend to be very much smaller than those in the periphery. The same is true in the Siamese cat, to judge from experiments like that of Text-fig. 3, even though the region of area 17 representing the area centralis is displaced. This suggests that the detailed interconnexions and transformations in the cortex are not very different from region to region of a given subdivision such as 17 or 18. In parts of cortex subserving the area centralis there is more cortex per degree of visual field than in peripheral parts (i.e. the magnification factor is larger), but there are also more entering geniculate fibres, whose receptive fields are smaller. If differences in precision of representation that occur in various parts of the visual field, in 17 and 18, are not reflected in differences in architecture, then any part of area 17 may substitute for any other, as the present results in the Siamese cat seem to imply. This idea is also supported by the relative histological uniformity of these regions.

If a new topographic order is the chief principle used to deal with the anomalous cortical input, there seems to be a second competing process in which cells of the anomalous segment of geniculate layer A1 connect to the same regions as their immediate neighbours in layers A and B, above and below. In a normal animal, of course, these two tendencies need not compete, since the topographic maps of the visual fields in the three layers A, A1 and B are in precise register. In the Siamese cat cortex, the second tendency results in alternating regions or patches (possibly columns) of two types: not left eye–right eye regions, as is found in common cats, but areas with contralateral-field input, mixed with occasional patches representing more or less mirror-symmetric ipsilateral-field regions. Here the two mirror-symmetric inputs are from the contralateral eye only. At boundaries between the two kinds of region, or where the two overlap, cells with receptive fields on one side of the vertical mid line may be intermixed with cells having fields on the opposite side, and an occasional cell may even be driven by one eye from two separate regions, one in the left and one in the right visual field. In the three cells of this type that were seen the orientations of the two regions were identical, showing that in some respects there was a high degree of specificity of connexions. Moreover, the responses from the two regions were not necessarily equal. This system thus strikingly resembles the system for binocular convergence in
the cat, as would be expected if both systems depend on the same connexions.

The mirror-like patches of ipsilateral-field representation resemble even more closely the pattern of binocular convergence in ordinary cats brought up with strabismus, for here one sees especially sharp separation of left-eye and right-eye patches, with only a small proportion of cells receiving input from both eyes (Hubel & Wiesel, 1965b). In ordinary cats raised with strabismus the separation is the result of the long-term absence of correlated stimulation of corresponding regions in the two retinas. The same could well be true in the Siamese, for only by chance would identical stimuli ever fall upon points symmetrically disposed on either side of the vertical meridian of the visual field. In the present study we used an animal with eyes bilaterally occluded from birth to show that there is initially binocular convergence on cortical cells in the peripheral fields, from 20° to the temporal crescents, and that this convergence breaks down in the presence of squint early in life. A similar strategy might be used to test whether in Siamese cats cells with double fields in one eye are more common in very young animals. Indeed, the question might have been asked in cat No. 5, but at that time we were not aware that such cells existed, and even if they had been more frequent in that cat, we may simply have missed them. In any case, the relative scarcity of ipsilateral patches seems to indicate that the main ipsilateral projections go to the topographically organized regions near the 17–18 border.

Patches of mirror-symmetric ipsilateral field representation were found in the predominantly contralateral-field region (in Text-fig. 9, the unshaded parts of the cortex), both in 17 and 18. We look upon this as a process reflecting a tendency for axons from adjacent parts of A, A₁ and B to travel to a common destination, namely the cortical region where contralateral fields are represented. There would be no reason to expect patches of contralateral-field input (from layers A and B) to be engrafted on the cortical ipsilateral-field representation (the black region in Text-fig. 9) and in fact no such mirror patches were found.

If all of the ipsilateral visual field input went to the new topographically ordered region (black, in Text-fig. 9), one might expect this projection to be just as detailed as its counterpart in the contralateral field. The ipsilateral input is divided, however, some going to the topographically ordered area, some to the patches in the otherwise purely contralateral region. The prediction from this would be that the ipsilateral projection should be cruder than the contralateral. The relatively larger size of receptive fields in the ipsilateral field representation in area 17 (see Text-fig. 3 and Text-fig. 6) may be one reflexion of a coarser representation.

All of these results indicate that the Siamese cat lacks any of the
cortical mechanisms for binocular vision in the central 40° or so of its visual field. If these mechanisms play any part in binocular fixation it may not be surprising that a marked squint develops. The notion that the squint is secondary to the neural abnormality is supported by the absence of squint during the first few months in our animals, and the failure of a convergent squint to develop after 5 months when the eyes are kept closed. That the squint is convergent seems to make sense, since that would lead to a favouring of the nasal half retinas over the temporal halves. It is, of course, the temporal half retinas that give rise to the aberrant projections, producing from the contralateral eye the crude ipsilateral-field representation in the cortex. With a marked convergent squint these projections may not receive much use. The fact that cat breeders have virtually eliminated squint in Siamese cats suggests that the extent of the neural abnormality may vary from one pedigree to the next.

Though as far as we know the visual capabilities of Siamese cats have never been tested behaviourally, the anatomical and physiological results suggest that this breed may be very defective. Surely even in the absence of squint there should be no stereoscopic depth perception for the first 20° of the visual fields in either direction out from the vertical mid line. Mirror-like patches of cortex, and cells such as the doublets of Text-figs. 6 and 8, are also hardly likely to enhance an animal’s visual capacity.

In all of this discussion it has been assumed that the primary visual defect in the Siamese cat is an error occurring at the optic chiasm. At present, however, one has no idea what it is that causes such mistakes to occur in cat after cat. The real difficulty is that one does not know what guides the fibres in deciding whether or not to cross at the chiasm; if it is some kind of chemical attractant in the lateral geniculate, then the error in the Siamese cat may arise either from a misreading of the directions by a certain set of optic fibres, or a faulty specification of the geniculate cells. It would be of great interest to know why only certain fibres go astray. It hardly seems likely that one gene looks after a special set of temporal retinal fibres and another looks after a different set. Perhaps instead the error is one of programming, in which the timing of events is faulty. Thus the fibres that cross by mistake may do so because they arrive at the chiasm earlier or later than the others, before or after the normal signalling mechanism is in force.

It is of course surprising to find such anomalies in an animal that has been on the doorstep for so many centuries. Such a visual mutation in a species with a highly evolved visual system seems experimentally very useful, especially since the effects are mild enough not to destroy the visual system but severe enough to be interesting. Finally, one is
encouraged to look for other mutants in higher mammals, and also to study the genetics of this one more thoroughly.

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REFERENCES


EXPLANATION OF PLATE

Coronal section through left lateral geniculate body of a Siamese kitten (No. 7); compare Text-fig. 2. Electrolytic lesion made at the final position of the micro-electrode is indicated by the arrow, which shows the direction of the track. Nissl stain.