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REVERSAL OF THE MORPHOLOGICAL EFFECTS OF MONOCULAR DEPRIVATION IN THE KITTEN'S LATERAL GENICULATE NUCLEUS

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SUMMARY

1. Eleven kittens were deprived of vision in one eye until the age of between 5 and 14 weeks. Their eyes were then reverse-sutured, they were allowed to survive for a further 3–63 days, and their brains were then examined histologically.

2. Measurement of the cross-sectional area of cells in the lateral geniculate nucleus (LGN) showed that when the reversal of lid suture was performed at the age of 8 or 14 weeks, the mean cell size was smaller in laminae connected to the initially closed right eye than it was in other laminae.

3. When the reversal of lid suture took place at 5 or 6 weeks of age there was a reversal of interlaminar size differences: the initially deprived eye was then connected to laminae containing larger cells. Even within 3 days after the reversal of lid suture, most of the morphological effects of the initial suture had been abolished, and they were fully reversed within 12 days.

4. These results are compared with physiological changes in the visual cortex of these and similarly reared animals.

INTRODUCTION

Monocular deprivation of form vision in young kittens causes profound and long-lasting changes in the central visual pathways. The physiological and behavioural effects of early monocular deprivation, and the extent to which they may be reversed by later forced usage of the deprived eye, have been discussed in the preceding papers (Movshon, 1976*a*, *b*). In this

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paper we examine the reversibility of the morphological effects of monocular deprivation in the lateral geniculate nucleus (LGN).

Following closure of one eye shortly after birth, a difference in the average size of LGN neurones innervated by the two eyes has been widely reported. The cross-sectional area of cells in laminae driven by the deprived eye is, on average, between 25 and 40% smaller than that of cells connected to the experienced eye (Wiesel & Hubel, 1963; Kupfer & Palmer, 1964; Guillery & Stelzner, 1970; Guillery, 1972; Garey, Fisken & Powell, 1973*b*). These effects, like the physiological and behavioural effects of monocular deprivation, may only be produced during the 'sensitive period' in visual development, between the second week and the fourth month of life. Very brief periods of deprivation during the fourth and fifth weeks of life can produce substantial effects (Hubel & Wiesel, 1970; Garey *et al.* 1973*b*; J. A. Movshon & M. R. Dürsteler, in preparation).

In view of the severity of the changes consequent to early monocular deprivation, there has been considerable interest in examining the extent to which they may be reversed by visual experience. Wiesel & Hubel (1965) and Hubel & Wiesel (1970) found no change in the interlaminar cell size differences in the LGNs of cats permitted as much as 5 years of normal visual experience after a period of monocular deprivation extending throughout the sensitive period. Closing the previously experienced eye and opening the previously deprived eye (reverse-suturing) produced little physiological or morphological recovery. Chow & Stewart (1972) observed some morphological recovery in some experimental animals reverse-sutured for a year or more following prolonged early deprivation; the reason for the difference between their results and those of Wiesel & Hubel is obscure.

It is possible to obtain partial or total recovery of physiological function in the deprived eye if kittens are reverse-sutured *within* the sensitive period (Blakemore & Van Sluyters, 1974; Movshon & Blakemore, 1974; Movshon, 1976*a*). We have examined the brains of some of the animals used in these studies, and of kittens reared in an identical manner, to determine the extent to which the physiological recovery seen in the visual cortex is matched by morphological recovery in the LGN. Some of these results have been briefly reported elsewhere (Dürsteler, Movshon & Garey 1975; Garey & Dürsteler, 1975).

METHODS

Eleven kittens were used in these experiments. At or near the time of natural eye opening the lids of one eye were sutured shut by the method of Wiesel & Hubel (1963) as described in a preceding paper (Movshon, 1976*a*). The left eye of one kitten was closed until the age of 8 weeks, and the animal was then sacrificed as a control.

The remaining ten kittens initially underwent suture of the right eye. At the age

of 5, 6, 8 or 14 weeks they were reverse-sutured: the lids of the right eye were parted while those of the left eye were sutured shut. Four kittens, initially deprived for 5, 6, 8 and 14 weeks, were allowed to survive for a further 9 weeks. Six kittens were reverse-sutured at the age of 5 weeks, and allowed to survive for 3 days (two kittens), 6 days, 9 days, 12 days and 18 days. Four of the kittens were used for physiological recording experiments before perfusion (Blakemore & Van Sluyters, 1974; Movshon & Blakemore, 1974; Movshon, 1976*a*).

At the end of the survival period or the recording session, the kittens were anaesthetized with Nembutal (50–75 mg.kg^{-1}, I.P.) and perfused through the heart with Ringer solution, followed by 10% buffered formalin. In those animals that had been used for physiological recording, blocks of the visual cortex were removed for examination of the electrode tracks. The brains were post-fixed in formalin, embedded in paraffin and sectioned coronally at either 10 or 25 μm. Every fifth or tenth section over the LGNs was mounted and stained with cresyl violet. The sections from each kitten were coded to conceal their origin from the experimenter who was to analyse them.

Cells were sampled from the LGN by a technique modified from that of Guillery & Stelzner (1970). Two levels were chosen for sampling: one near the junction of the rostral and middle thirds of the nucleus, and one between the middle and caudal thirds. Thus, measurements were made from those parts of the LGN representing the visual field within about 10° of the horizontal meridian (Bishop, Kozak, Levick & Vakkur, 1962; Sanderson, 1971).

The whole nucleus was traced at a magnification of either 60 or 100 through a microscope drawing tube, and the outlines of laminae A and A1 defined. Lamina A1, receiving axons from the ipsilateral retina, was treated as a whole; lamina A, however, was divided into a binocular segment, receiving fibres from the portion of the contralateral retina serving the binocular portion of the visual field, and a monocular segment, receiving axons only from the temporal monocular crescent of the contralateral retina. These segments will be referred to hereafter as Ab (binocular) and Am (monocular). Ab was taken as that part of lamina A that had cells in lamina A1 adjacent to it; Am was the remaining, lateral portion of the lamina.

Each segment (Ab, Am and A1) was divided by a line midway between its dorsal and ventral borders; the lines were themselves divided into four equal lengths, and cells sampled from a single high-power field at the middle of each. This ensured that the sample excluded cells from the medial interlaminar nucleus, and large cells near the borders of the laminae that may receive binocular input (Hayhow, 1958; Garey & Powell, 1968; Guillery, 1971).

The central twelve or thirteen somata in each field were drawn in outline at a magnification of 1000 with the aid of the drawing tube; cells were only drawn if the nucleus and nucleolus were clearly visible. In this way a total of 600 cells was sampled from each brain. The cross-sectional area of each outline was determined with a Quantimet 720 special purpose computer.

RESULTS

Table 1 summarizes the results of measurements of 6600 cell outlines from the eleven experimental kittens. The mean and standard error of the cell areas in each segment of each LGN are given, along with the left-right differences (expressed as a percentage of the greater mean) and their significance on Student's t test. In view of the fact that any given sample of outlines tended to be more homogeneous in size than the population of

outlines from one layer, each outline may not constitute an independent sample, and the lower significance values should be interpreted with caution.

In the kitten monocularly deprived of vision until the age of 8 weeks, our observations are in agreement with previous reports on the effect of such deprivation. Photomicrographs of the LGNs of this kitten are shown in Pl. 1 (*A* and *B*), and show that cells in the laminae innervated by the deprived left eye (right Ab and left A1) are, on average, rather smaller than cells in the experienced laminae. Pl. 2*A* shows a higher power detail of laminae Ab and A1 of the right LGN of this kitten. Histograms showing the distributions of cell sizes in the laminae representing the binocular portion of the visual field are shown in Text-fig. 1*A*. Cells in the deprived laminae are, on average, 31 % smaller than those innervated by the deprived eye. There is a marked absence of very large cells from the deprived laminae. In agreement with previous reports, we found no significant differences in cell size between the monocular segments of laminae A (Table 1; Guillery & Stelzner, 1970).

Qualitative examination of the LGNs of the kitten reverse-sutured for 9 weeks at the age of 14 weeks shows a clear difference in relative cell sizes between the two sides: on the left side, A1 contains obviously larger cells, while on the right side, the situation is reversed, and Ab contains larger cells. On first sight the most striking feature is the obvious difference between laminae Ab and A1 in the left LGN, while that in the right LGN is slightly less marked. A few very large neurones are present throughout the large-celled laminae, and absent from the small-celled laminae. Cell sizes in Am on both sides vary, but there is no difference distinguishable in either case between them and the adjacent lamina Ab. The distributions of cell sizes in the binocular laminae of this animal are shown in Text-fig. 1*B*, and are rather similar to those shown for the monocularly deprived kitten in Text-fig. 1*A*. The mean cell area in right A1 is 32 % smaller than that in left A1. The mean area in left Ab, however, is only 15 % smaller than that in right Ab; this difference is rather smaller than might be expected in a monocularly deprived animal.

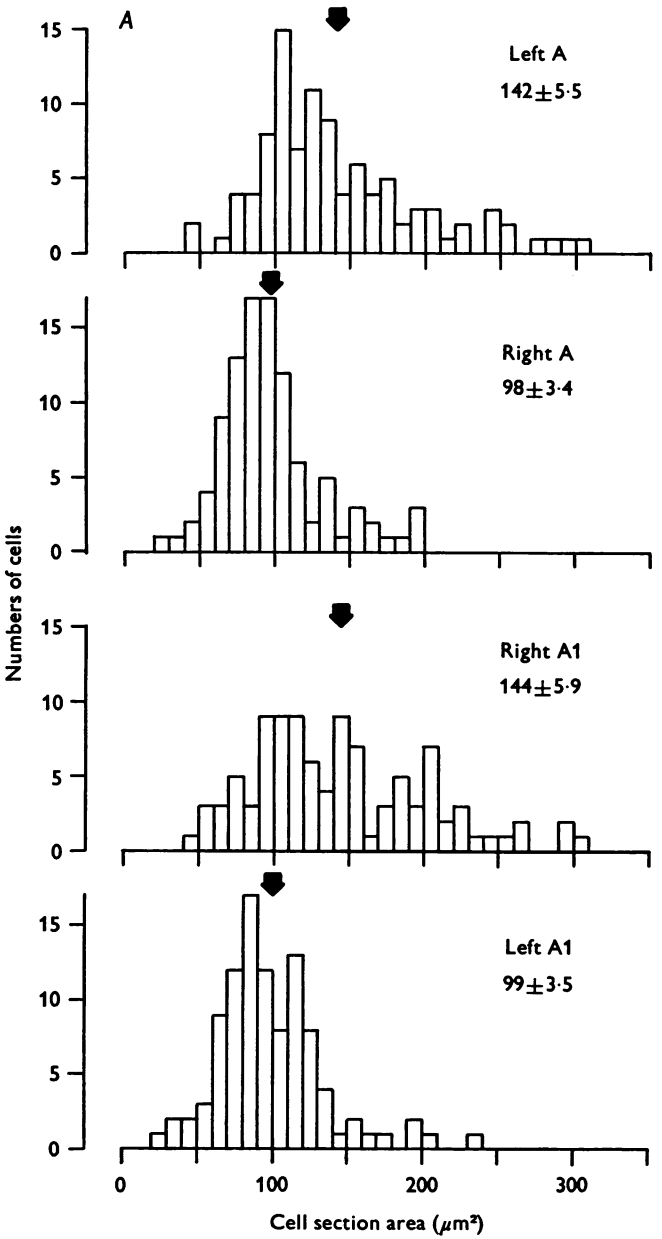
In the kitten reverse-sutured for 9 weeks at the age of 8 weeks, the appearance of the LGNs again suggests a pattern appropriate to a right-eye monocular deprivation: cells in left Ab and right A1 are noticeably smaller than the others. Measurement shows that neurones in left Ab are on average 24 % smaller than those of the right, while those in right A1 are 15 % smaller than those on the left. There is a 9 % difference between the two monocular segments of this kitten.

Thus, reversed monocular eyelid suture late in the sensitive period has little effect on the morphology of the LGN. Reverse-suturing performed

TABLE 1. Mean cell section areas (μm^2), plus and minus 1 S.E. of the mean, in the different segments of the LGNs of the eleven experimental kittens. The description of each animal under the heading 'experiment' indicates its age in weeks at the time of reverse-suturing, plus the duration in days of the reversed suture. The animals marked with an asterisk underwent physiological recording immediately before perfusion

	Right LGN			Left LGN			% difference and significance		
Experiment	Am	Ab	A1	Am	Ab	A1	Am	Ab	A1
8+0	118 ± 3·6	98 ± 2·6	144 ± 5·9	122 ± 4·3	142 ± 5·5	99 ± 3·5	3−	31+++	31+++
14+63	149 ± 5·3	163 ± 6·4	126 ± 3·8	140 ± 4·9	139 ± 3·9	185 ± 7·1	6−	15+++	32+++
8+63*	104 ± 4·0	106 ± 3·8	85 ± 3·0	95 ± 2·5	80 ± 2·4	100 ± 3·8	9−	24+++	15+++
6+63*	123 ± 3·4	111 ± 5·1	156 ± 6·4	109 ± 3·7	128 ± 4·1	116 ± 4·1	11++	13++	26+++
5+63*	116 ± 3·7	127 ± 4·2	165 ± 5·1	132 ± 5·4	136 ± 4·6	124 ± 3·9	12+	6−	25+++
5+3A	167 ± 4·5	162 ± 4·8	154 ± 4·5	164 ± 3·5	148 ± 3·5	167 ± 4·6	2−	9+	9−
5+3B*	171 ± 6·2	177 ± 5·2	176 ± 5·5	187 ± 5·7	175 ± 5·0	199 ± 5·9	9−	1−	11++
5+6	138 ± 3·7	153 ± 4·2	164 ± 4·8	147 ± 4·5	141 ± 4·1	150 ± 4·7	6−	8−	8−
5+9	127 ± 3·6	132 ± 4·0	140 ± 4·3	146 ± 3·9	145 ± 3·9	148 ± 4·2	13+++	9−	9−
5+12	136 ± 4·7	139 ± 5·3	170 ± 6·1	129 ± 4·4	149 ± 5·5	133 ± 5·5	5−	7−	22+++
5+18	116 ± 3·4	128 ± 5·2	143 ± 4·8	119 ± 4·8	147 ± 4·6	153 ± 5·9	3−	13++	6−

Significances: − = $P > 0.01$; + = $P < 0.01$; ++ = $P < 0.005$; +++ = $P < 0.001$.



Text-fig. 1. Histograms showing the distribution of cell section areas in the binocular laminae (Ab and A1) of the LGNs of two kittens. *A*, cell size histograms from a kitten monocularly deprived until the age of 8 weeks. *B*, cell size histograms from a kitten monocularly deprived for 14 weeks and then reverse-sutured for a further 9 weeks. In these and all similar

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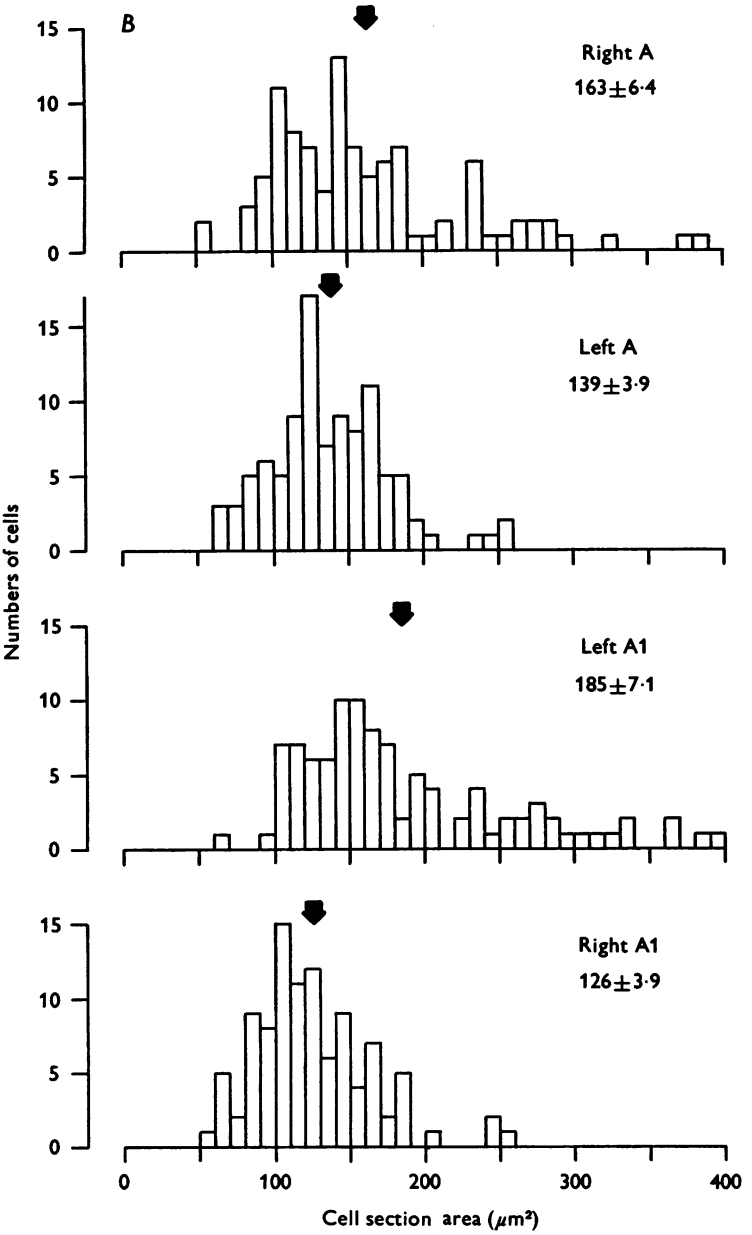


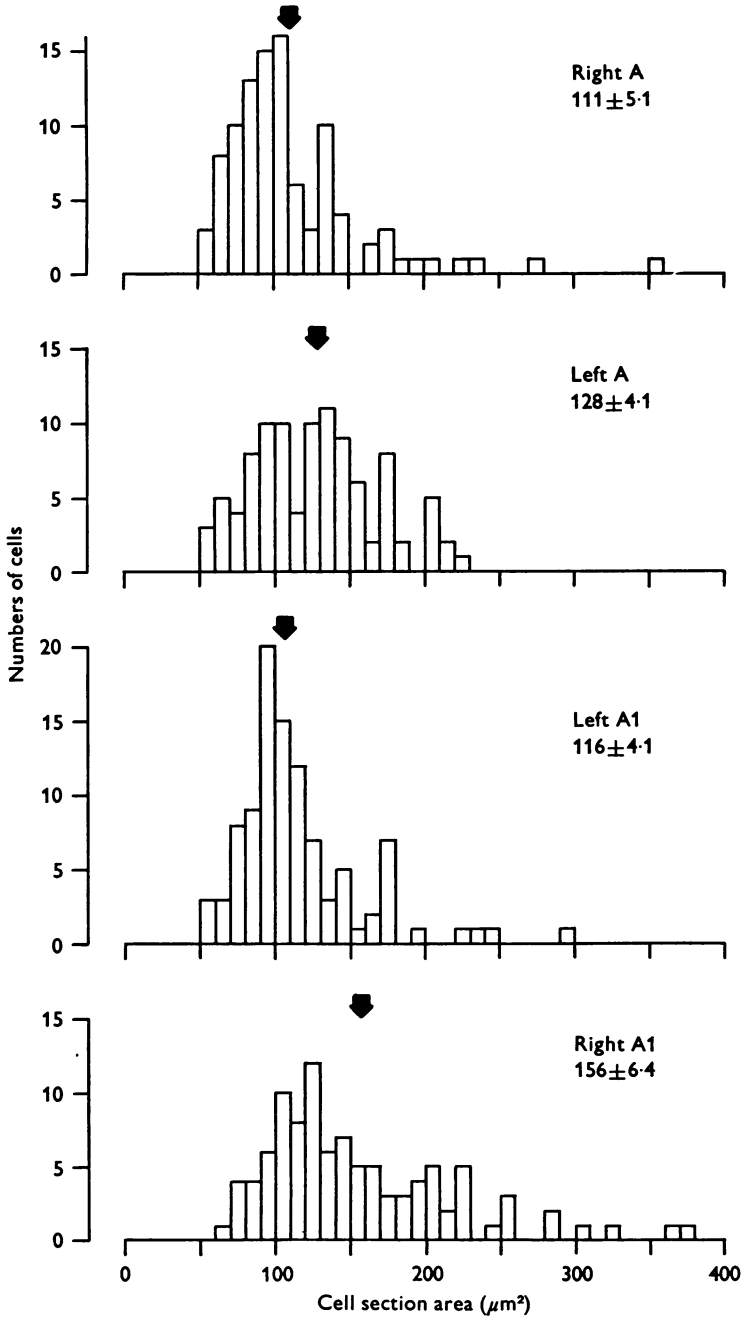
Figures, the histograms are arranged in the following order from the top to the bottom of the Figure: lamina A contralateral to the initially experienced eye; lamina A contralateral to the initially deprived eye; lamina A1 ipsilateral to the initially experienced eye; lamina A1 ipsilateral to the initially deprived eye.

earlier, however, has marked effects. Inspection of the LGNs of the kitten reverse-sutured for 9 weeks at the age of 6 weeks shows, in contrast to the animals discussed above, a pattern more appropriate to a *left*-eye monocular deprivation: cells in right A1 and left Ab are noticeably larger than those in the other segments. A noticeable difference between this brain and the two discussed above is that, even in the small-celled laminae, there are several very large cells, and all the laminae have a rather heterogeneous appearance with aggregations of medium and large cells among the small. Text-fig. 2 shows cell-size histograms for the binocular segments of the LGNs of this animal, revealing a difference of 26% between the A1 segments and of 13% between the Ab segments. Such a pattern is inconsistent with the unmodified effects of the initial closure of the right eye, and rather resembles the expected effects of a *left* monocular suture, particularly in the A1 laminae.

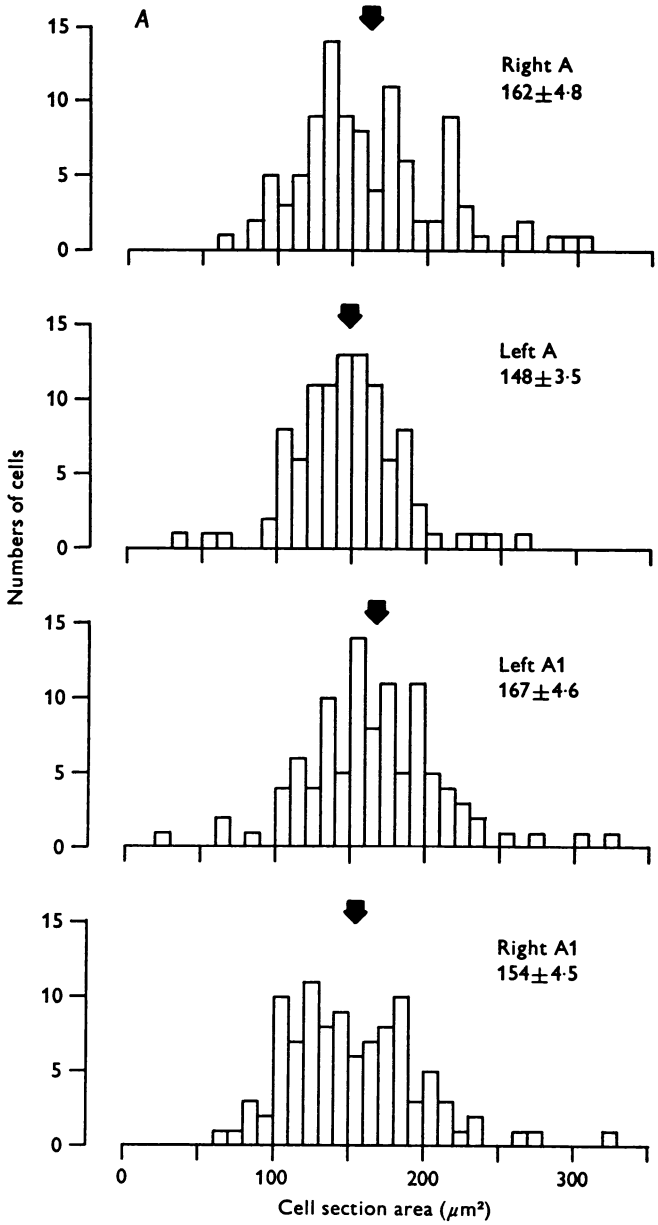
The results obtained from the kitten reverse-sutured for 9 weeks at the age of 5 weeks are similar to those obtained from the kitten reverse-sutured at the age of 6 weeks: cells in left A1 are 25% smaller than those on the right, but the difference between the Ab segments is only 6%. Scattered large cells are visible throughout the small-celled laminae of this kitten, but they are relatively scarce in the left A1 segment, a newly deprived lamina innervated by the initially open right eye. Thus, in the experiments in which the initial deprivation lasted only 5 or 6 weeks, the distribution of cell sizes in the LGNs have, after 9 weeks of reversed lid suture, reversed completely in the A1 laminae and partially in the Ab laminae, compared with the results of an unmodified monocular deprivation.

In the second series of experiments, reverse-suturing was always performed at the age of 5 weeks, but the duration of the survival period following reverse-suturing was varied in order to examine the time course of the morphological changes.

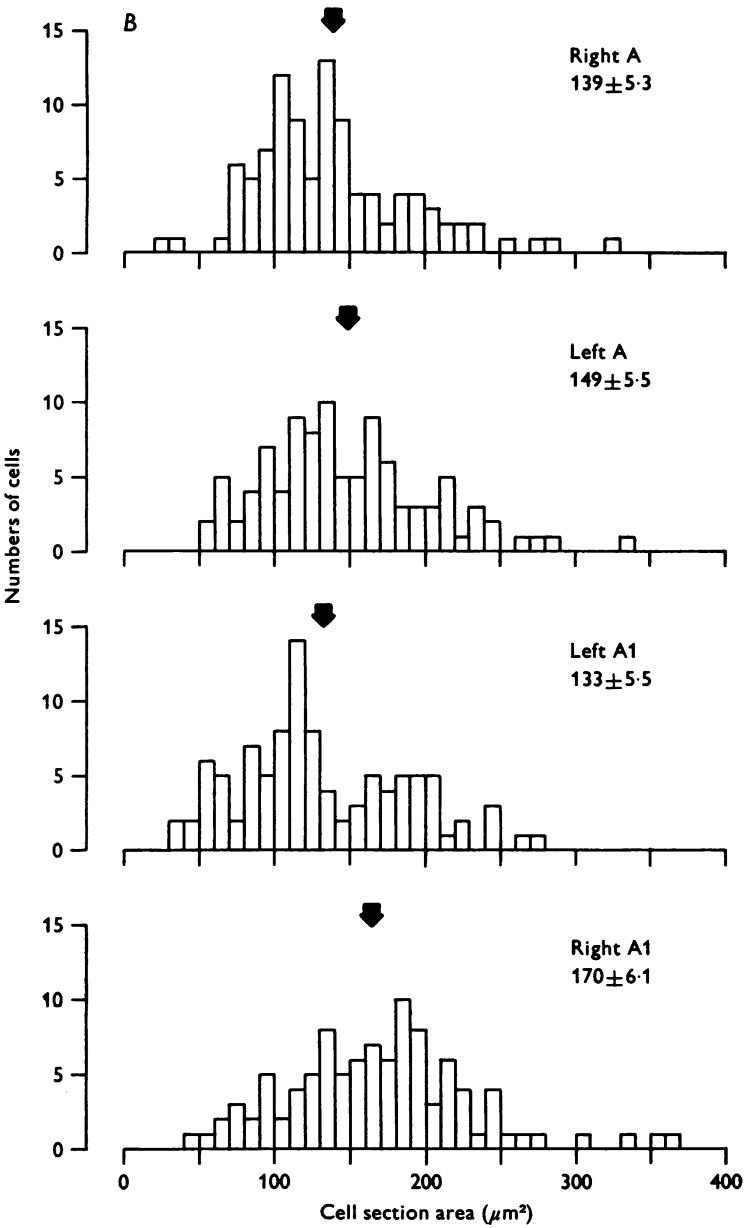
Pl. 1 (*C* and *D*) shows the LGNs of a kitten reverse-sutured at 5 weeks for 3 days. It is apparent that the morphological appearance of the nuclei of this kitten has been greatly altered by the brief period of reversed deprivation: it is difficult to detect any differences among the laminae, and large neurones are present throughout the nuclei. It is worth noting that prior to the reversal of lid suture, the LGNs of this kitten presumably resembled those of the control kitten shown in Pl. 1 *A* and *B*. Pl. 2 *B* shows a high-power detail of laminae Ab and A1 of the left LGN of this kitten. Inspection of the histograms of cell sizes from the binocular laminae of one of the two kittens reverse-sutured for 3 days (Text-fig. 3 *A*) confirms the impression obtained from Pl. 2: the differences between the laminae are much less than would be expected to result from the initial period of monocular deprivation, although the direction of the differences is still



Text-fig. 2. Histograms showing the distributions of cell section areas in the binocular laminae of the LGNs of a kitten monocularly deprived until the age of 6 weeks, and then reverse-sutured and allowed to survive for a further 9 weeks.



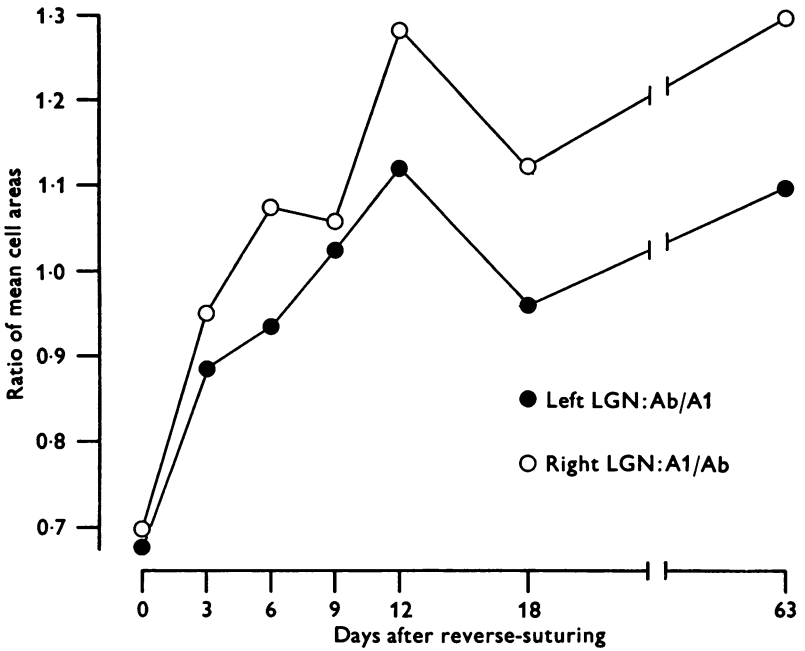
Text-fig. 3A. For legend see facing page.



Text-fig. 3. Histograms showing the distributions of cell section areas in the binocular laminae of the LGNs of two kittens reverse-sutured at the age of 5 weeks. *A*, reverse-sutured for 3 days. *B*, reverse-sutured for 12 days.

appropriate to that deprivation. The differences between the Ab laminae in the two kittens reared in this way are 9 and 1 %, those between the A1 laminae are 9 and 11 %. There are no significant differences between the Am laminae.

After reversed lid-suture for 6 or 9 days, little interlaminar difference is detectable qualitatively. Large cells are present throughout the LGNs of both kittens. None of the differences between the binocular laminae in

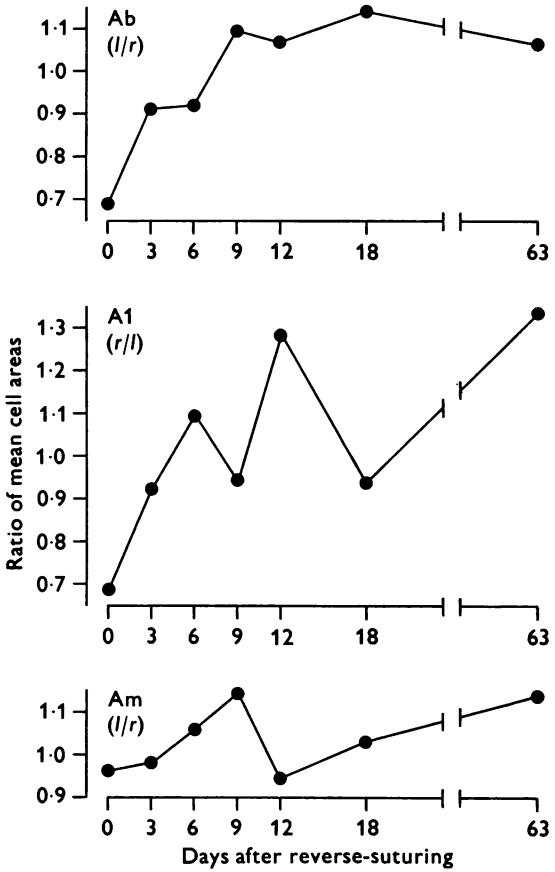


Text-fig. 4. A comparison of the effects of reversed monocular deprivation at the age of 5 weeks on the LGNs contralateral and ipsilateral to the initially deprived eye. The ratios of the means of the cell areas in the laminae of each LGN innervated by either eye are plotted, with the mean of the lamina driven from the initially deprived eye always set as the numerator.

these kittens are significant but, surprisingly, there is a 13 % difference between the Am segments of the kitten reverse-sutured for 9 days. Examination of sections other than those chosen for measurement suggested that this result is, however, not consistent at all rostro-caudal levels, and that wider sampling might produce a smaller difference.

The results of measurements made on the LGNs of the kitten reverse-sutured for 12 days are shown in Text-fig. 3*B*, and it is clear that there are marked cell-size differences among the binocular layers (Pl. 2*C*). Further-

more, the direction of those differences is appropriate to the *second* period of lid-suture: cells in left Ab are, on average, 7% larger than those in right Ab, and the difference between the A1 laminae is 22%. Thus, within 12 days after reversal of lid suture at the age of 5 weeks, deprivation effects in the LGN may be reversed.



Text-fig. 5. A comparison of the effects of reversed monocular deprivation at the age of 5 weeks on the different laminae of the LGN. Each graph plots the ratio of the mean cell areas in the two laminae of each kind, with the mean of the lamina driven by the initially deprived eye always set as the numerator.

The interlaminar differences in the LGNs of the kitten reverse-sutured for 18 days are smaller than those seen in the kitten reverse-sutured for 12 days – 13% between the Ab segments and 6% between the A1 segments – but they are also in a direction appropriate to the second lid suture.

When considering the time scale of the morphological changes in the LGN that follow reverse-suturing, it is of interest to examine separately the changes in relative cell-size between the two nuclei, and between the layers of the same nuclei. Text-fig. 4 plots the ratios of the mean cell section areas for cells in the left and right LGNs of the kittens reverse-sutured at the age of 5 weeks. The LGN segment innervated by the initially deprived eye is the numerator in both cases. It is clear that changes in the ratio of cell sizes take place in both LGNs over a similar time following reverse-suturing, but there is a consistent difference between the ratios on the two sides: cell sizes in the right LGN appear to be biased in favour of the initially deprived eye to a greater degree than those in the left LGN in all animals, suggesting that the LGN changes may proceed more rapidly in the nucleus contralateral to the second eye to be open. It is worth bearing in mind, however, that Guillery (1973) reported that the mean cell size in layer A1 of normal cats tends to be approximately 10 % greater than the mean in Ab, which could account for some, if not all, of the differences observed.

Text-fig. 5 shows a similar analysis of the ratios of cell areas between the different segments of the LGNs of the kittens reverse-sutured at the age of 5 weeks. The upper graph plots the ratios between the Ab segments and the middle graph plots the ratios between the A1 segments: it is clear that both segments undergo a similar change, with the ratio favouring cells in the segments innervated by the initially deprived right eye, although the variance of the measurements in A1 appears to be greater than that of those in Ab. There is also some variation in the calculated ratios between the Am segments, but there is no over-all correlation between the ratio and the duration of the reversed suture ($r = 0{\cdot}55$, $n = 7$, $P > 0{\cdot}05$).

DISCUSSION

The nature of the cellular changes in the LGN

The changes in relative cell size between LGN laminae innervated by the two eyes could be due to a rapid growth of cells in initially deprived layers or to a shrinkage of cells in initially experienced layers, or to some combination of the two. Animal-to-animal comparisons of cell size are perilous due to the large variation among animals (Cook, Walker & Barr, 1951; Wiesel & Hubel, 1963; Guillery & Stelzner, 1970; Guillery, 1973). It may be significant, however, that the data in Table 1 reveal that most of the cell populations are rather small compared with previously published results using similar histological methods (Garey, Fisken & Powell, 1973*a*; Guillery, 1973), and that there is no tendency for the mean area of cells in the initially deprived layers to increase with increased periods of reversed

deprivation. Rather, there is an apparent decrease in the size of cells innervated by the initially open eye. Since the period of normal LGN cell growth is all but finished by the age of 5 weeks (Garey *et al.* 1973*a*), one interpretation of these results is that cells in laminae driven from the initially open eye shrink following reverse-suturing, with the result that cells in all laminae are reduced in size after a period of reversed deprivation.

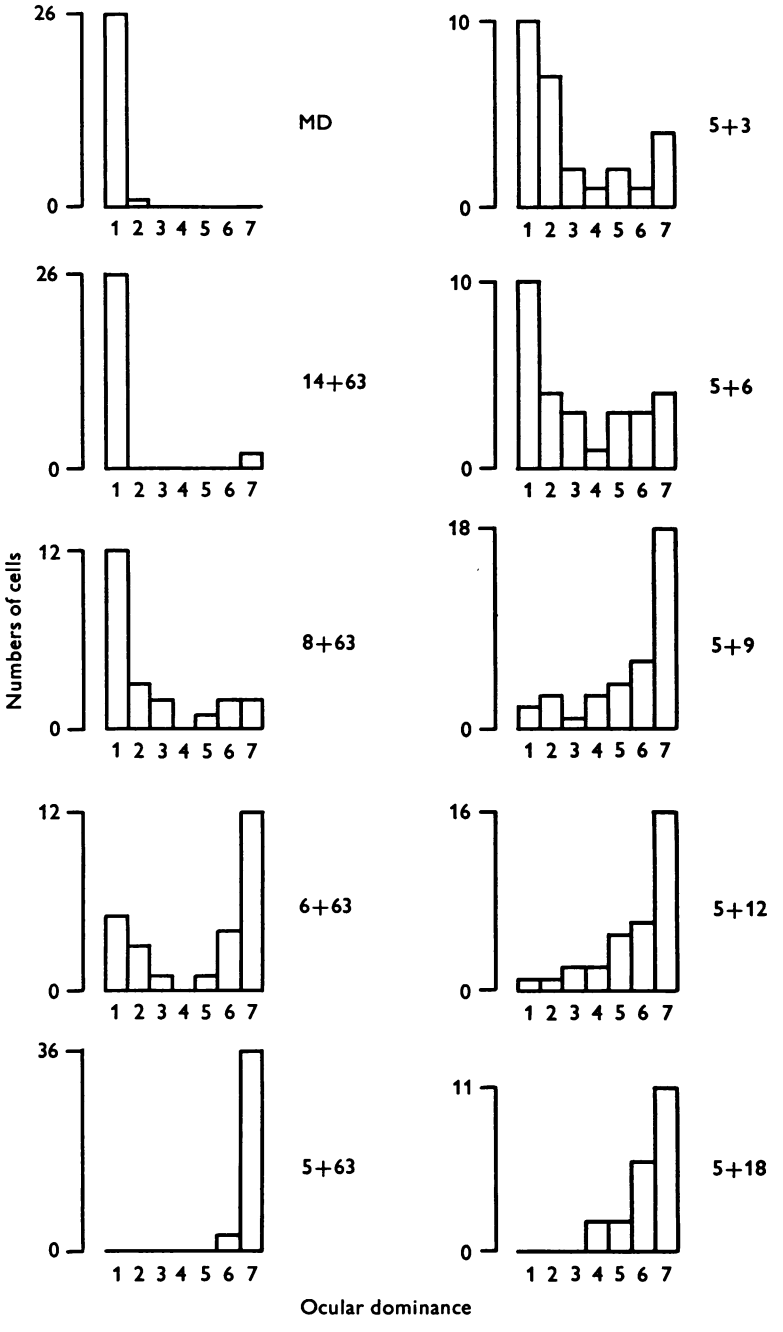
It may, however, be argued that, if cells in the monocular portions of layer A are unaffected by either the initial period of deprivation or by the subsequent period of reversed deprivation, their final size should be independent of both manoeuvres. If reverse-suturing causes an overall shrinkage in the binocularly innervated laminae, then cells in Am, which are normally similar in size to those in Ab (Guillery & Stelzner, 1970), should be larger than those in Ab or A1. There is no such tendency in our results, and we thus infer that there has been at least partial regrowth of cells in the layers driven by the initially deprived eye, though they may not have attained their normal size. Some regrowth is suggested by the presence of some very large cells in laminae driven by that eye: these cells are similar in size to the large cells seen in normal adults, and are absent from the deprived laminae of monocularly deprived cats (see, for example, Text-fig. 1*A* and Pl. 1).

Relationships between physiological and morphological effects

In these experiments we have attempted to relate the physiological 'recapture' of cortical neurones by an initially deprived eye in reverse-sutured kittens with morphological changes in the LGN. Text-fig. 6 shows ocular dominance histograms of 286 visual cortical neurones from ten kittens raised in a manner identical to the experimental kittens in this series; some of them are in fact the same animals (from Blakemore & Van Sluyters, 1974; Movshon, 1976*a*).

These authors devised a simple mathematical representation of the extent to which the physiological dominance of the visual cortex had been altered by the period of reversed deprivation, which they termed the 'reversal index'. The physiological reversal index is simply the proportion of visually responsive cortical neurones dominated by the initially deprived eye. In the case of the data shown in Text-fig. 6, the initially deprived eye was the right one in all cases, and all the recordings were obtained from the right hemisphere, so the physiological reversal index is the number of cells in ocular dominance groups 5, 6 and 7 divided by the total number of visually responsive neurones.

In order to facilitate comparisons between these physiological data and our own morphological results, we have devised an analogous measure of the extent to which relative cell size has changed in the binocular laminae



Text-fig. 6. For legend see facing page.

of the LGN, which we term the 'morphological reversal index'. The morphological reversal index is designed to cancel out any differences between different layers and different sides in cell-size changes. It is the grand mean of all possible pair-comparisons between the mean cell sizes in the deprived and experienced laminae of the LGN. For animals initially deprived in the right eye, the formula is:

$$\frac{\frac{\text{left Ab}}{\text{right Ab}}+\frac{\text{right A1}}{\text{left A1}}+\frac{\text{left Ab}}{\text{left A1}}+\frac{\text{right A1}}{\text{right Ab}}}{4}.$$

An animal without interlaminar differences in cell size would have a morphological reversal index of 1·0; an index of less than 1 indicates that cells in laminae driven by the initially deprived eye are smaller than those in laminae driven by the initially experienced eye (no reversal); an index greater than 1 indicates that reversal has been effective.

Text-fig. 7 compares the morphological and physiological reversal indices obtained from the two series of animals. Text-fig. 7*A* presents the results obtained from the first series of animals, reverse-sutured for 9 weeks at different ages (Blakemore & Van Sluyters, 1974); the abscissa is the age at which the kitten was reverse-sutured. Text-fig. 7*B* shows similar graphs for the second series of animals, reverse-sutured at 5 weeks of age for different periods of time (Movshon & Blakemore, 1974; Movshon, 1976*a*); the abscissa is the duration of the reversed lid suture.

Text-fig. 7*A* shows clearly that the extent of the morphological changes seen after different periods of initial deprivation is well correlated with the physiological changes following similar rearing. After 8 or 14 weeks of monocular deprivation, reversal of lid suture is ineffective in producing either physiological recapture of cortical neurones (Text-fig. 6) or significant alteration of cell size in the LGNs (Text-fig. 1*B*). Reverse-suturing at the age of 5 or 6 weeks, however, is effective both in altering the cortical pattern of ocular dominance (Text-fig. 6) and the balance of cell sizes in the LGN (Text-fig. 2). The physiological reversal index rises to near 1, indicating that most or all cortical neurones have come to be dominated by the initially

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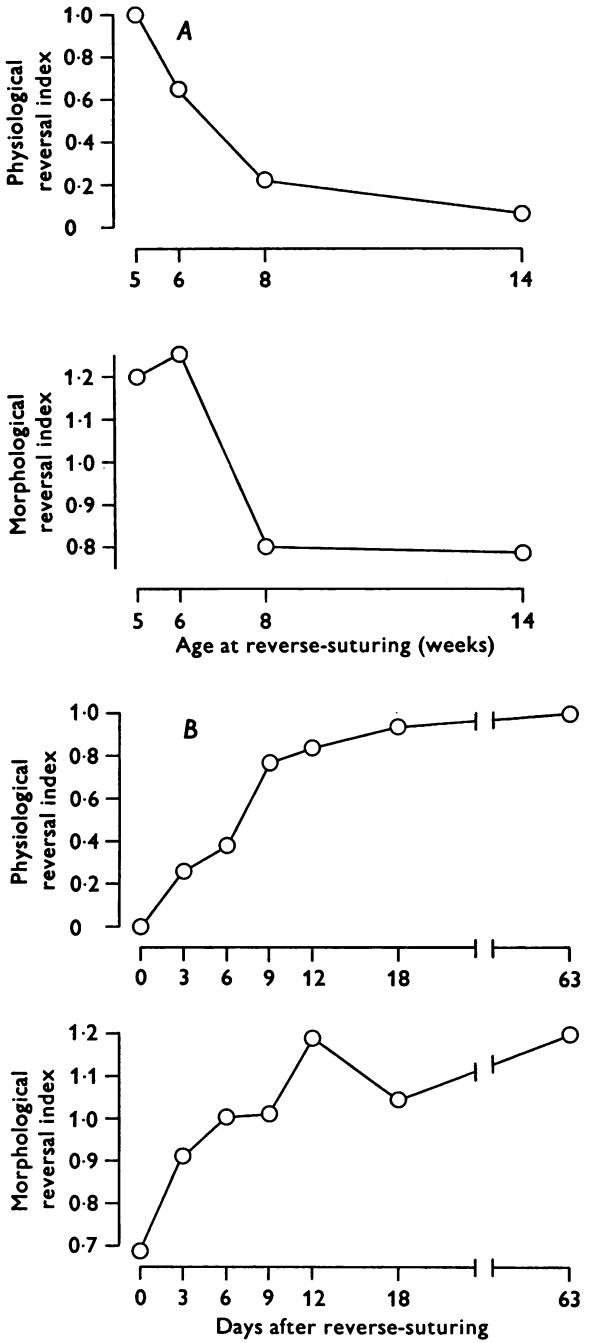
Text-fig. 6. Ocular dominance histograms of 286 visually responsive neurones from ten kittens reared in a manner identical to the experimental kittens in this study. The age (in weeks) at reverse-suturing and the duration (in days) of the reversed suture are indicated beside each histogram. All recordings were made from the right hemisphere, so cells on the left-hand side of each histogram were driven primarily or totally from the initially experienced left eye, while cells on the right-hand side of each histogram were driven primarily or totally from the initially deprived right eye. The ocular dominance classification is that of Hubel & Wiesel. From Blakemore & Van Sluyters (1974) and Movshon (1976*a*).



Text-fig. 7*A* and *B*. For legend see facing page.

deprived eye, and the morphological index reaches approximately 1·2, indicating that analogous changes have taken place in the LGN.

Text-fig. 7*B* shows that the correlation between cortical physiology and geniculate morphology seen after extended periods of reversed deprivation is also present after shorter periods. The changes in physiological and morphological reversal index appear to go hand in hand. After only 3 days of reversed deprivation, changes toward an even ocular dominance distribution and an even cell-size distribution are apparent, and between 6 and 9 days after reverse-suturing, the physiological reversal index passes 0·5 while the morphological reversal index passes 1·0. More than 12 days after reverse-suturing, the reversal of deprivation effects in both cortex and LGN is obvious. There is a clear and close parallel between the changes in the LGN and those in the visual cortex.

In view of the suggestion that the size of a cell in the LGN is partly determined by the effectiveness of the connexions it makes in the visual cortex (Guillery, 1972; Sherman, Guillery, Kaas & Sanderson, 1974), it is interesting to note the very close temporal relationship between the changes seen in the two structures that is shown by Text-fig. 7*B*. This resemblance, and the rapidity with which changes may be seen in both the cortex and the LGN, lend weight to the idea that some kind of binocular competition taking place at a single site may underlie both effects.

The most likely candidate for that site is the geniculocortical synapse, where competition may either take the form of competition for space on the post-synaptic membrane of cortical neurones (Hubel & Wiesel, 1965), or of the selection of a subset of possible synaptic contacts by those cortical neurones (Stent, 1973). The changes in the LGN would then be secondary to those in the cortex, and mediated either by the retrograde transport of some factor down the axons of geniculate relay cells (LaVail & LaVail, 1972; Stoeckel & Thoenen, 1975), or by the action of cortico-geniculate fibres (Guillery, 1967; Garey, Jones & Powell, 1968). Whatever pathway mediates these effects it must act extremely rapidly in order to explain the close relationship between changes in the two structures shown in Text-fig. 7*B*.

Text-fig. 7. A comparison of the physiological and morphological effects of reversed monocular deprivation. *A*, the series of animals reverse-sutured for 9 weeks; the abscissa is the age at reverse-suturing. *B*, the series of animals reverse-sutured at the age of 5 weeks; the abscissa is the duration of the reversed lid suture. The physiological reversal index is the proportion of visually responsive cortical neurones dominated by the initially deprived right eye, and is derived from the ocular dominance histograms shown in Text-fig. 6. The morphological reversal index is related to the sizes of cells driven through the two eyes, and is defined in the text.

An interesting comparison can be made between the results of the present series of animals reverse-sutured at 5 weeks of age and those of an earlier study (Garey *et al.* 1973*b*) in which two cats, monocularly deprived until the age of 5 weeks, subsequently had both eyes opened for a further 6–7 weeks. In these experiments there was still a considerable size difference (respectively 13 and 23 %) between the deprived and experienced Ab laminae (A1 was not measured). Thus it is concluded that merely *opening* the closed eye is not an effective stimulus for recovery of cell size; the lid-suture must be *reversed*. This is in agreement with physiological observations of cortical ocular dominance changes in similar kittens (Hubel & Wiesel, 1970).

The results of this study indicate once again the remarkable plasticity of the kitten's central visual pathways at the height of the sensitive period in the fifth week of life. A very few days of visual deprivation at this time are sufficient to cause gross morphological and physiological changes at a time when in the normal animal cellular and synaptic development is approaching mature levels (Garey *et al.* 1973*a*; Cragg 1975). In the third month, maturation continues, as exemplified by the development of normal visual acuity (Freeman & Marg, 1975; Mitchell, Giffin, Wilkinson, Anderson & Smith, 1976), but plasticity, and the reversibility of prior developmental effects, declines. Nevertheless, the fact that morphological and physiological changes in the visual pathway *can* be reversed suggests that there are no irremediable changes in the visual cortex or LGN after monocular deprivation for the first few weeks of life.

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REFERENCES

BISHOP, P. O., KOZAK, W., LEVICK, W. R. & VAKKUR, G. J. (1962). The determination of the projection of the visual field on the lateral geniculate nucleus in the cat. *J. Physiol.* **163**, 503–539.

BLAKEMORE, C. & VAN SLUYTERS, R. C. (1974). Reversal of the physiological effects of monocular deprivation in kittens: further evidence for a sensitive period. *J. Physiol.* **237**, 195–216.

CHOW, K. L. & STEWART, D. L. (1972). Reversal of structural and functional effects of long-term visual deprivation in cats. *Expl Neurol.* **34**, 409–433.

COOK, W. H., WALKER, J. H. & BARR, M. L. (1951). A cytological study of transneuronal atrophy in the cat and rabbit. *J. comp. Neurol.* **94**, 267–292.

CRAGG, B. G. (1975). The development of synapses in the visual system of the cat. *J. comp. Neurol.* **160**, 147–166.

DÜRSTELER, M. R., MOVSHON, J. A. & GAREY, L. J. (1975). Reversal of the effects of visual deprivation in the lateral geniculate nucleus. *Expl Brain Res.* **23** (suppl.), 63.

FREEMAN, D. N. & MARG, E. (1975). Visual acuity development coincides with the sensitive period in kittens. *Nature, Lond.* **254**, 614–615.

GAREY, L. J. & DÜRSTELER, M. R. (1975). Reversal of deprivation effects in the lateral geniculate nucleus of the cat. *Neuroscience Letters* **1**, 19–23.

GAREY, L. J., FISKEN, R. A. & POWELL, T. P. S. (1973*a*). Observations on the growth of cells in the lateral geniculate nucleus of the cat. *Brain Res.* **52**, 359–362.

GAREY, L. J., FISKEN, R. A. & POWELL, T. P. S. (1973*b*). Effects of experimental deafferentation on cells in the lateral geniculate nucleus of the cat. *Brain Res.* **52**, 363–369.

GAREY, L. J., JONES, E. G. & POWELL, T. P. S. (1968). Interrelationships of striate and extrastriate cortex with the primary relay sites of the visual pathway. *J. Neurol. Neurosurg. Psychiat.* **31**, 135–157.

GAREY, L. J. & POWELL, T. P. S. (1968). The projection of the retina in the cat. *J. Anat.* **102**, 189–222.

GUILLERY, R. W. (1967). Patterns of fiber degeneration in the dorsal lateral geniculate nucleus of the cat following lesions in the visual cortex. *J. comp. Neurol.* **130**, 197–213.

GUILLERY, R. W. (1971). Survival of large cells in the dorsal lateral geniculate laminae after interruption of retinogeniculate afferents. *Brain Res.* **28**, 541–544.

GUILLERY, R. W. (1972). Binocular competition in the control of geniculate cell growth. *J. comp. Neurol.* **144**, 117–127.

GUILLERY, R. W. (1973). The effect of lid suture upon the growth of cells in the dorsal lateral geniculate nucleus of kittens. *J. comp. Neurol.* **148**, 417–422.

GUILLERY, R. W. & STELZNER, D. J. (1970). The differential effects of unilateral lid closure upon the monocular and binocular segments of the dorsal lateral geniculate nucleus in the cat. *J. comp. Neurol.* **139**, 413–422.

HAYHOW, W. R. (1958). The cytoarchitecture of the lateral geniculate body in the cat in relation to the distribution of crossed and uncrossed optic fibers. *J. comp. Neurol.* **110**, 1–64.

HUBEL, D. H. & WIESEL, T. N. (1965). Binocular interaction in striate cortex of kittens with artificial squint. *J. Neurophysiol.* **28**, 1041–1059.

HUBEL, D. H. & WIESEL, T. N. (1970). The period of susceptibility to the physiological effects of unilateral eye closure in kittens. *J. Physiol.* **206**, 419–436.

KUPFER, C. & PALMER, P. (1964). Lateral geniculate nucleus: histological and cytochemical changes following afferent denervation and visual deprivation. *Expl Neurol.* **9**, 400–409.

LAVAIL, J. H. & LAVAIL, M. M. (1972). Retrograd eaxonal transport in the central nervous system. *Science, N.Y.* **176**, 1416–1417.

MITCHELL, D. E., GIFFIN, F., WILKINSON, F., ANDERSON, P. & SMITH, M. L. (1976). Visual resolution in young kittens. *Vision Res.* **16**, 363–366.

MOVSHON, J. A. (1976*a*). Reversal of the physiological effects of monocular deprivation in the kitten's visual cortex. *J. Physiol.* **261**, 125–174.

MOVSHON, J. A. (1976*b*). Reversal of the behavioural effects of monocular deprivation in the kitten. *J. Physiol.* **261**, 175–187.

MOVSHON, J. A. & BLAKEMORE, C. (1974). Functional reinnervation in kitten visual cortex. *Nature, Lond.* **251**, 504–505.

SANDERSON, K. J. (1971). The projection of the visual field to the lateral geniculate and medial interlaminar nuclei in the cat. *J. comp. Neurol.* **143**, 101–118.

SHERMAN, S. M., GUILLERY, R. W., KAAS, J. H. & SANDERSON, K. J. (1974). Behavioral, electrophysiological and morphological studies of binocular competition in the development of the geniculo-cortical pathways of cats. *J. comp. Neurol.* **158**, 1–18.

STENT, G. S. (1973). A physiological mechanism for Hebb's postulate of learning. *Proc. natn. Acad. Sci. U.S.A.* **70**, 997–1001.

STOECKEL, K. & THOENEN, H. (1975). Retrograde axonal transport of nerve growth factor: specificity and biological importance. *Brain Res.* **85**, 337–341.

WIESEL, T. N. & HUBEL, D. H. (1963). Effects of visual deprivation on morphology and physiology of cells in the cats's lateral geniculate body. *J. Neurophysiol.* **26**, 978–993.

WIESEL, T. N. & HUBEL, D. H. (1965). Extent of recovery from the effects of visual deprivation in kittens. *J. Neurophysiol.* **28**, 1060–1072.

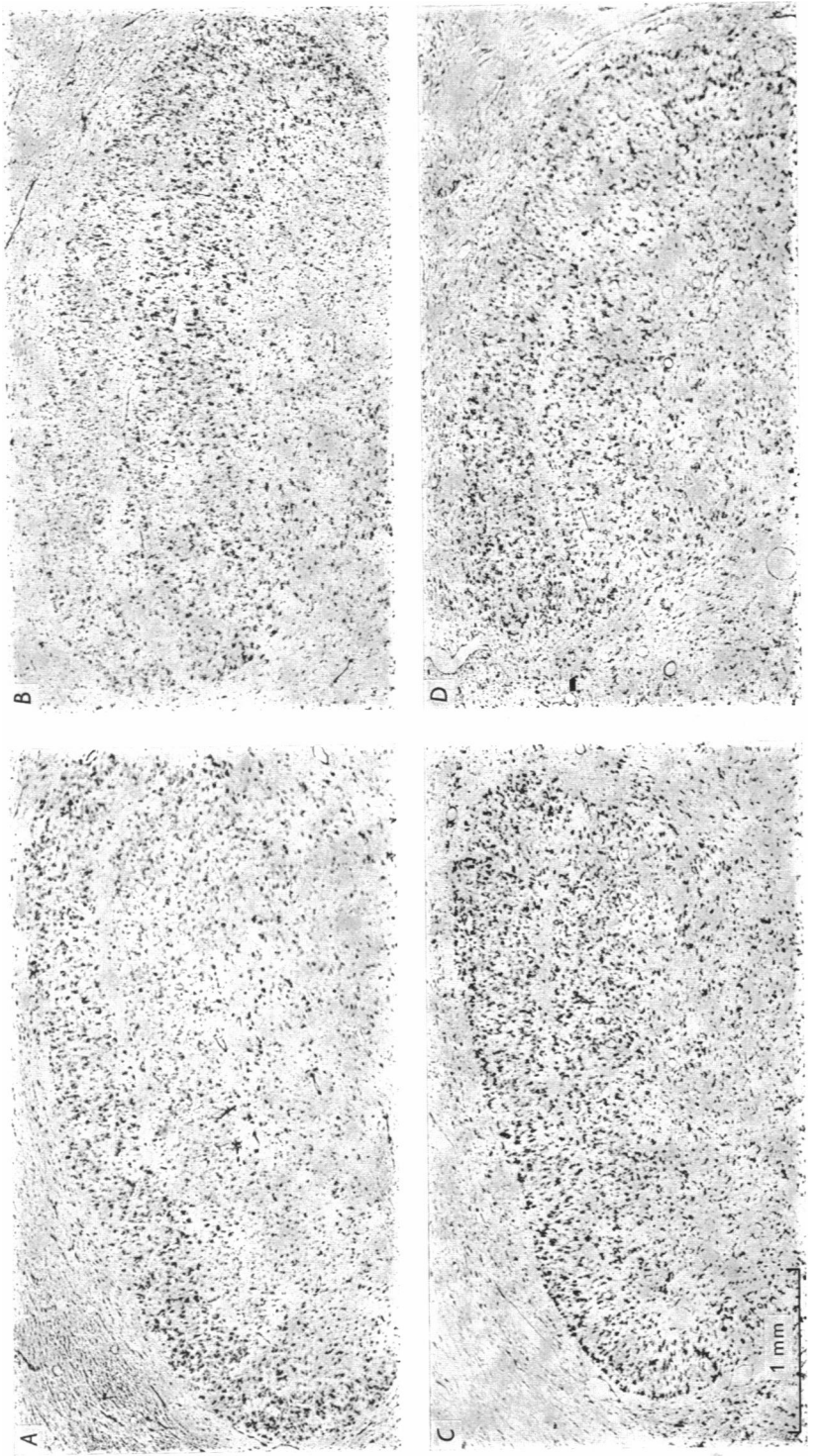
EXPLANATION OF PLATES

PLATE 1

Photomicrographs of the LGNs of two kittens. *A* and *B*: the left and right LGNs, respectively, of the kitten monocularly deprived until the age of 8 weeks. *C* and *D*: the left and right LGNs, respectively, of one of the kittens reverse-sutured for 3 days at the age of 5 weeks (kitten 5 + 3A in Table 1).

PLATE 2

Photomicrographs of selected regions of laminae Ab and A1 from the LGNs of the two kittens whose LGNs are shown in Pl. 1. *A*, the right LGN of the kitten monocularly deprived until the age of 8 weeks. *B*, the left LGN of the kitten monocularly deprived until the age of 5 weeks, and then reverse-sutured for 3 days. *C*, the left LGN of the kitten monocularly deprived until the age of 5 weeks, and then reverse-sutured for 12 days.



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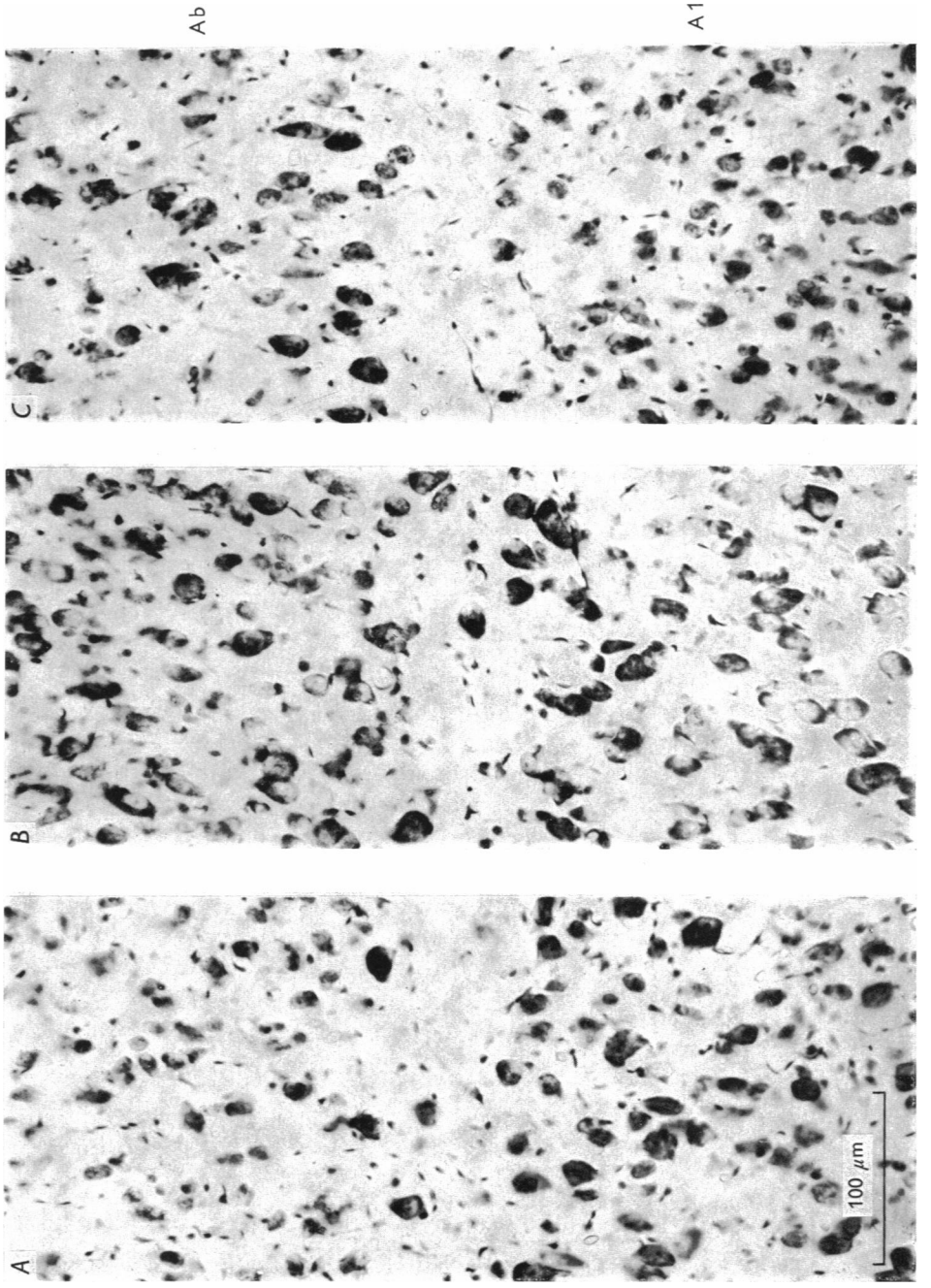
Ab
A1
C
B
A
100 μm