

Plasticity in adult cat visual cortex (area 17) following circumscribed monocular lesions of all retinal layers

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1. In eight adult cats intense, sharply circumscribed, monocular laser lesions were used to remove all cellular layers of the retina. The extents of the retinal lesions were subsequently confirmed with counts of α -ganglion cells in retinal whole mounts; in some cases these revealed radial segmental degeneration of ganglion cells distal to the lesion.
2. Two to 24 weeks later, area 17 (striate cortex; V1) was studied electrophysiologically in a standard anaesthetized, paralysed (artificially respired) preparation. Recording single- or multineurone activity revealed extensive topographical reorganization within the lesion projection zone (LPZ).
3. Thus, with stimulation of the lesioned eye, about 75% of single neurones in the LPZ had 'ectopic' visual discharge fields which were displaced to normal retina in the immediate vicinity of the lesion.
4. The sizes of the ectopic discharge fields were not significantly different from the sizes of the normal discharge fields. Furthermore, binocular cells recorded from the LPZ, when stimulated via their ectopic receptive fields, exhibited orientation tuning and preferred stimulus velocities which were indistinguishable from those found when the cells were stimulated via the normal eye.
5. However, the responses to stimuli presented via ectopic discharge fields were generally weaker (lower peak discharge rates) than those to presentations via normal discharge fields, and were characterized by a lower-than-normal upper velocity limit.
6. Overall, the properties of the ectopic receptive fields indicate that cortical mechanisms rather than a retinal 'periphery' effect underlie the topographic reorganization of area 17 following monocular retinal lesions.

It has been shown in a number of previous studies that in adult cats discrete retinal lesions induce a reorganization of visuotopic maps in that part of striate cortex (area 17; V1) in which the lesioned part of the retina was represented (Kaas *et al.* 1990; Chino *et al.* 1992, 1995; Gilbert & Wiesel, 1992; Darian-Smith & Gilbert, 1995; Schmid *et al.* 1995, 1996; Calford *et al.* 1999). Projected onto area 17, these lesions represented an area (lesion projection zone; LPZ) typically 3 to 5 mm in diameter, within which the visual receptive fields of many neurones were displaced to normal retina immediately adjacent to the lesioned retina. So far the studies of this issue have covered three experimental protocols: (1) matched homonymous retinal lesions have been made in the two eyes (Gilbert & Wiesel, 1992; Chino *et*

al. 1995; Darian-Smith & Gilbert, 1995); (2) a retinal lesion has been placed in one eye while the other has been enucleated (Chino *et al.* 1992; Schmid *et al.* 1996); and (3) a retinal lesion has been made monocularly while the retina in the other eye remained intact (Chino, 1992; Schmid *et al.* 1996). The topographical extent of the retinal lesion-induced plasticity in the dorsal lateral geniculate nucleus (LGNd) is very small and therefore presumably incapable of providing a substrate for the extensive reorganization of the visuotopic map in the cortex (Eysel *et al.* 1981; Darian-Smith & Gilbert, 1995). It is therefore generally agreed that the apparent topographic reorganization observed in studies with the 1st and 2nd experimental protocols, is based on plasticity at the cortical level and that the most likely source

of inputs to a locus in area 17, which allows neurones to encode new receptive fields, are corticocortical afferents from area 17 interneurons (Darian-Smith & Gilbert, 1994; Das & Gilbert, 1995a). These neurones are thought to provide the capacity for an initial 'unmasking' of large receptive fields shortly after placement of a retinal lesion (Gilbert & Wiesel, 1992; Calford *et al.* 1999) or of a visual mask (artificial scotoma; Das & Gilbert, 1995b). At a later stage, with some terminal sprouting (Darian-Smith & Gilbert, 1994), these afferents are thought to be involved in refinement of the initial response (increased response reliability, decreased receptive field size).

There is, however, a substantial disagreement concerning plasticity of the visuotopic map in area 17 of adult cats after monocular retinal lesions (3rd experimental protocol listed above). Both Chino and his colleagues (1992) and Schmid and her colleagues (1996) tested the responsiveness to photic stimuli of area 17 neurones of adult cats, several weeks to several months after making a discrete laser lesion in one retina. Chino and his colleagues (1992) reported that as long as the eye in which the retina had not been lesioned was not removed, no area 17 neurones within the cortical LPZ responded to stimulation via the eye with the retinal lesion. However, there was an immediate 'unmasking' of such responsiveness after removal (by enucleation) of the unlesioned eye. By contrast, Schmid and her colleagues (1996) reported that despite the presence of the intact eye, when area 17 cells were stimulated via the lesioned eye, reorganized receptive fields were apparent at 50 to 60% of recording sites within the LPZ. Furthermore, acute removal (by laser coagulation of the optic-nerve head) of the visual input from the other eye had no effect on the proportion of recording sites with neurones having reorganized receptive fields.

Whereas the basis of the discrepancy between the results of the two groups remains unknown, some testable hypotheses have been formulated. These include the suggestion that the responsiveness of neurones within a monocular LPZ to stimulation of ectopic receptive fields via the lesioned eye does not necessarily indicate true visuotopic reorganization of area 17 neurones but may reflect retinal events. One interpretation (Chino *et al.* 1995) is that the responsiveness of cortical neurones to photic stimulation of the lesioned retina before the removal of the unlesioned eye might reflect a well known retinal integration phenomenon, the so-called 'periphery' or 'shift' effect, based upon intraretinal connections (McIlwain, 1964, 1966; Ikeda & Wright, 1972; Krüger & Fischer, 1973). Similarly, Horton & Hocking (1998) have suggested that with laser lesions restricted to the outer retinal layers, as used by Schmid and her colleagues (1995, 1996), there was a possibility that the same cross-retinal connections which give rise to the periphery effect may allow for plasticity of ganglion cell receptive field properties.

The present study was designed as a direct test of the competing interpretations regarding the site of the

reorganization sampled in area 17, following monocular retinal lesions. We present results from eight cats in which we recorded single-unit activity from area 17 several weeks to several months after intense laser lesions were used to remove all cells (including the retinal ganglion cells) from a discrete retinal region of one eye. Despite the absence of ganglion cells in the lesioned region of the retina, an extensive topographical reorganization in area 17 of these animals was clearly apparent when area 17 cells were photically stimulated via the lesioned eye. In addition, we present a quantitative comparison of the response properties of binocular area 17 neurones that were photically stimulated via topographically displaced (ectopic) receptive fields induced by the retinal lesions with those stimulated via the normal eye. A preliminary report has been presented (Calford *et al.* 1998).

METHODS

Retinal lesions

As indicated in Table 1, the results were obtained from eight adult cats. Under ketamine (40 mg kg⁻¹ i.m., Ketalar) and xylazine (4 mg kg⁻¹ i.m., Rompun) anaesthesia, discrete retinal lesions of approximately 5 to 9 deg radius, were placed in the near-upper nasal retina of the left eye. With the animals held lightly in a stereotaxic frame, lesions were produced with an argon-green laser (see Schmid *et al.* 1996 for details of delivery system) focused to approximately 300 µm, at an intensity of 450 to 650 mW. Lesions of all neural retinal layers were achieved by continuous delivery of the laser while the spot of light was slowly swept across the chosen region; total delivery time being around 3 min. A few minutes after completion, lesions appeared uniformly white and no damage to retinal blood vessels was evident. Lesions were placed in near superior-nasal retina and did not encroach within 3 deg of the area centralis (Figs 1, 2 and 3). In total, the lesioning procedure took about 20 min and the animals recovered fully from the anaesthesia within a few hours. Thereafter they were returned to the animal holding facility for up to 24 weeks. No visual or other disturbances were apparent in the behaviour of the animals. After perfusion with 4% paraformaldehyde (see 'Localization of recording sites') retinæ were flat-mounted onto gelatinized slides (Robinson *et al.* 1989), and stained with cresyl violet.

The extents of the lesions were confirmed by: (a) back projections during the acute experiments onto a tangent screen using a fibre optic light source and (b) postmortem counts of ganglion cells in retinal whole mounts. For the latter analysis, retinæ were viewed at a total magnification of ×400. Cell densities were determined within 0.40 mm² areas at a 500 µm grid separation (250 µm in areas of rapid change in density), following the method of Robinson and his colleagues (1989). To avoid the problem of distinguishing macrophages or other glia from smaller ganglion cells and other neurones we examined the density distribution of only the large, that is, α-ganglion cells.

Animal preparation

Two to 24 weeks after placement of the lesions (Table 1), extracellular recordings were made from the part of area 17 corresponding to and surrounding the projection zone of the lesion. The animals were initially anaesthetized with ketamine (20 mg kg⁻¹ i.m., Ketalar) and xylazine (4 mg kg⁻¹ i.m., Rompun) and given dexamethasone (0.3 mg kg⁻¹ i.m.) and atropine sulphate

Table 1. Summary of experimental conditions for eight cats

	Age when retinal lesions were made (months)	Interval between the lesions and recording (days)	Extent of retinal lesions	
			Visual projection equivalent radius (deg)	Cortical projection area (mm ²)
VL4	5.5	27	9.0	45
VL5	5.5	34	6.6	34
VL9	> 8.0	14	5.4	18
VL10	> 8.0	24	5.6	12
CRS2	> 8.0	21	6.6	58
CRS5	> 8.0	53	6.2	37
CRS6	> 8.0	80	6.3	32
CRS7	> 8.0	168	7.2	49

The cortical projections of the lesions (given as direct; not including radial degeneration projections) were determined by reference to topographic maps of the visual representation in area 17 (Tusa *et al.* 1978).

(0.1 mg kg⁻¹ i.m.). The trachea was cannulated to allow for artificial ventilation. During the recording sessions anaesthesia was maintained with a gaseous mixture of N₂O/O₂ (67/33%) and halothane (0.5–1.0%). In order to minimize eye movements, animals were paralysed with either pancuronium bromide (Pavulon, 0.15 mg kg⁻¹ h⁻¹ i.v.) or bilateral sympathectomy was performed and paralysis induced with gallamine triethiodide (7.5 mg kg⁻¹ h⁻¹ i.v.) in a mixture of equal parts of 5% dextrose solution and sodium lactate (Hartmann's) solution. Animals were artificially ventilated; peak expired CO₂ was continuously monitored and kept in the range 3.7 to 4% by adjustment of respiration rate or volume of the pulmonary pump. Body temperature was maintained at about 37.5 °C by an electric heating blanket. Heart rate and brain activity (electroencephalogram, EEG) were also monitored continuously. By adjusting the concentration of halothane in the gaseous mixture the EEG maintained a slow wave record while heart rate was kept below 160 beats per minute. An antibiotic (amoxycycline trihydrate, 75 mg), dexamethasone phosphate (4 mg) and atropine sulphate (0.3 mg) were injected (i.m.) daily. Atropine sulphate (1–2 drops, 1%) was applied to dilate the pupils and block accommodation while phenylephrine hydrochloride (1–2 drops, 0.128%) was applied to retract the nictitating membranes. Experimental procedures and husbandry follow the guidelines of the Australian Code of Practice for the Care and Use of Animals for Scientific Purposes and were approved by animal ethics committees at the University of Queensland, the University of Sydney and the Australian National University.

The eyes were focused at either 57 or 114 cm by means of air-permeable contact lenses of appropriate curvature and supplementary corrective lenses. In the experiments with quantitative stimulation (CRS series – Table 1), artificial pupils (3 mm in diameter) were placed in front of the contact lenses. To monitor occasional eye movements the optic discs, the retinal lesions and major retinal blood vessels were projected routinely every few hours onto a tangent screen using a fibre optic light source (Pettigrew *et al.* 1979). In some cases the area centralis could be directly imaged, in others it was plotted by reference to the optic disc (Pettigrew *et al.* 1979). Relative alignment of the two eyes was achieved by aligning the projections of the areae centrales. All lesions were made in the upper retina which, in the cat, contains highly reflective tapetum lucidum. Laser destruction of the outer

retinal layers at the lesion site resulted in an absence of tapetal reflection from this region, allowing the lesion boundaries to be easily plotted after direct projection onto the tangent screen.

Recording and visual stimulation

A craniotomy was made above the marginal gyrus of the occipital cortex (Horsley-Clarke co-ordinates anterior 3 to posterior 5, lateral –2 to 6) and a Perspex cylinder about 10 mm high was mounted around the opening and glued to the skull with dental acrylic to form a well. Recordings were made with either tungsten-in-glass or platinum–iridium glass-coated microelectrodes. In the VL series experiments the dura was retracted and the well was filled with silicone oil. In the CRS series of experiments a smaller opening in the dura was made above each recording site, and when the tip of the electrode was positioned just above the cortical surface, the well was filled with 4% agar gel and sealed with wax to reduce brain pulsations. The microelectrode was advanced along the medial aspect of the marginal gyrus with a hydraulic micromanipulator. Action potentials were conventionally amplified, displayed on an oscilloscope and transduced through a loudspeaker. Triggered standard pulses were then fed to a microprocessor. They were also digitized for the recording of time of occurrence with respect to presentation of visual stimuli (see Rosa *et al.* 1995 and Dreher *et al.* 1993 for further details). Two recording strategies were employed: in four cases (VL series) emphasis was placed on mapping the extent of topographical plasticity by recording at fixed intervals of 500 μm or 1 mm in multiple penetrations of the medial bank of the marginal gyrus to a depth of about 6 mm, e.g. insets in Fig. 3A and B. Evaluations were made of the response properties of identifiable multiunit activity or of isolated single-unit responses to stimulation with hand-operated stimuli (Rosa *et al.* 1995; Schmid *et al.* 1995). The excitatory receptive fields (discharge fields) of cortical cells were defined as the area of visual space within which the visual stimuli elicited an increase in a cell's firing rate. The sizes of the discharge fields were determined using hand-operated elongated bars that were lighter or darker than the background (cf. Barlow *et al.* 1967; Burke *et al.* 1992; Dreher *et al.* 1992, 1993). In four animals (CRS series) responses of isolated single units were evaluated both qualitatively and quantitatively. For quantitative analysis stimuli were projected from a slide projector onto the tangent screen via computer-controlled galvanic motors operating a dual mirror arrangement (Dreher *et al.* 1992, 1993). For both

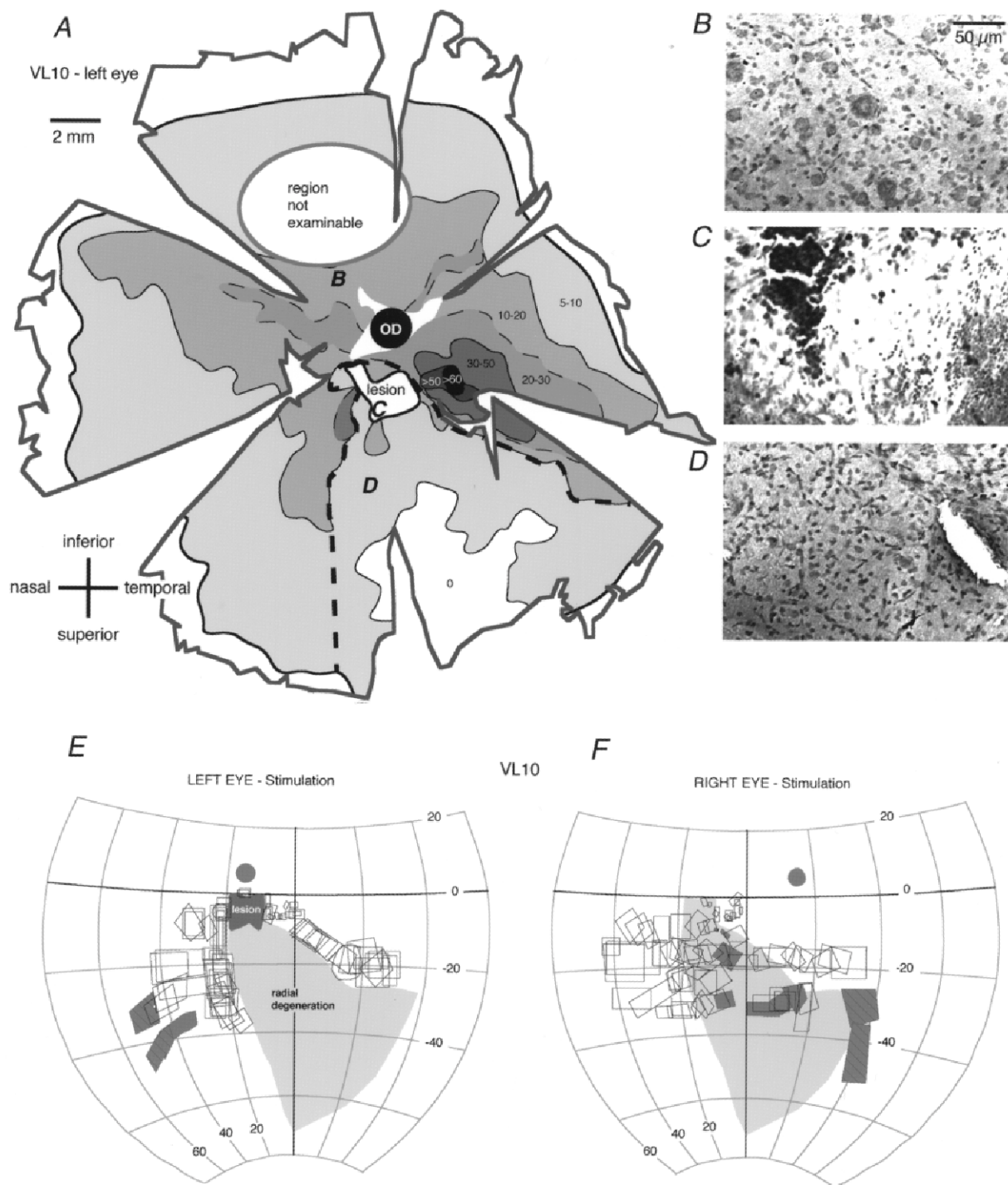


Figure 1. Anatomy of retinal lesions and displacement of cortical receptive fields

A, density contours of α -ganglion cells (mm^{-2}) as determined by extrapolating from the density at 410 sampled sites, each of 0.40 mm^2 , on the whole mounted left retina of cat VL10. The retinal lesion produced a degeneration of ganglion cells in a radial segment (inside dashed contour) due to damage to the nerve fibre layer at the lesion site. Positions marked B, C and D indicate the centres of the photomicrographs shown at the right. Micrograph C is from the edge of the lesion and reveals no surviving neurones. Micrographs B and D are of the ganglion cell layer from regions that would normally have similar densities of ganglion cells. Note that micrograph D from the area distal to the lesion shows clear indications of microglia activation and contains no α -ganglion cells. This retina was removed 15 days after production of the lesion. E and F, projection of all the receptive fields of single units and multiunit clusters recorded bilaterally from area 17 of cat VL10 for stimuli presented separately through each eye (Lambert projection, 20 deg grid, optic discs are indicated as shaded circles). Monocular receptive fields are shaded – those with a hatch pattern are probably beyond the area of binocular overlap. A laser lesion was made in the left eye, as indicated. In addition to

recording strategies stimulation was with high contrast elongated bars which usually had a luminance of 15 cd m^{-2} against a background luminance of 0.9 cd m^{-2} . Peristimulus time histograms were constructed by summing the responses to a number of consecutive stimulus sweeps at each test condition. The responses were then smoothed using a Gaussian-weighted average over five neighbouring bins. The direction and orientation selectivities were tested with moving elongated (at least three times longer than the length of the plotted receptive field) light slits. The direction selectivity index (DI; %) was calculated by the following formula:

$$\text{DI} = [(R_p - R_{np})/R_p]100,$$

where R_p and R_{np} are the peak discharge rates at the preferred and non-preferred direction, respectively (cf. Burke *et al.* 1992; Dreher *et al.* 1992, 1993).

Localization of recording sites

At the end of the recording session (lasting 2–6 days) the animals were deeply anaesthetized with an intravenous injection of 120 mg of sodium pentobarbitone and perfused transcardially (with descending aorta clamped) with 500 ml of warm (37°C) saline or Hartmann's solution followed by 1500 ml of a 4% solution of paraformaldehyde in 0.1 M phosphate buffer (pH 7.4). The caudal halves of cerebral hemispheres were stereotaxically blocked and sectioned coronally at $50 \mu\text{m}$ on a freezing microtome, mounted on gelatinized slides, and counterstained with cresyl violet.

Statistical analysis of the data

Two non-parametric statistical tests were used: the χ^2 test and the Wilcoxon matched-pairs signed-ranks test. Statistical significance of the differences between sets of data was accepted if the associated (always two-tailed) probability (P) was < 0.05 . Means are presented with standard errors and correlations were examined with the Pearson statistic (r). Calculations were made with the GB-STAT package for Macintosh from Dynamic Microsystems.

RESULTS

Examination of retinal whole mounts confirmed that the laser lesions affected all neural layers and that within the lesioned areas all neural elements were absent (Fig. 1C). The density distribution of the distinctively large α -ganglion cells was determined for the entire retina. The density maps revealed that in four of these cases (VL4, 5 and 10 and CRS7) the lesions also destroyed the innermost nerve fibre layer of the retina, resulting in retrograde degeneration of ganglion cells distal to the lesion. Thus, in these animals the effective extent of the lesion was far larger than that produced physically and encompassed a large radially defined segment of the retina (Figs 1A and 2B). The innermost retinal layer throughout this segment was fasciculated in appearance and was heavily populated with small densely stained cells, which have the appearance of macrophages (Fig. 1D).

The large extent of these lesions was also apparent from the cortical recordings. Thus, Fig. 1E and F presents for cat VL10 all the receptive fields determined for multiple-unit (66%) and single-unit (34%) recordings from area 17 of either hemisphere in response to photic stimulation through the lesioned left eye and the unlesioned right eye. The receptive fields revealed by photic stimulation of the normal eye were in the expected position. However, photic stimulation of the eye with the retinal lesion did not reveal any receptive fields within a large segment of visual space corresponding to the visual projection of the lesion and the region of radial degeneration of ganglion cells in the retina (Fig. 1A). Nevertheless, the vast majority of units or multiunit clusters (79%; 30/38 recording sites) within the lesion projection zone plus the degeneration-segment projection zone were binocular. Only 21% (8/38) of recording sites sampled neurones that could be activated exclusively via the unlesioned right eye. In other words, the cortical receptive fields revealed by photic stimulation via the lesioned left eye at 30 sites were displaced from the usual position represented at these sites (close to the fields obtained through the other eye) to just beyond the boundary of the projection of the inactivated region of the retina.

Physiological data from another case in which emphasis was placed on recording from many sites within the LPZ are shown in Fig. 2A, with the corresponding α -ganglion cell density map in Fig. 2B; arrows extend from the position of the centre of the receptive field determined by photic stimulation through the unlesioned right eye to the receptive field determined by photic stimulation through the lesioned left eye. These indicate that neuronal receptive fields sampled throughout this extensive LPZ were, for the lesioned eye, displaced from the expected position of their original fields to the edge of the lesion. Indeed, binocular disparities of the receptive fields located outside the LPZ were far smaller than those within it. The proportion of sampled sites within the LPZ found to generate a neuronal response only when photic stimuli were presented via the unlesioned right eye was, at 29%, typical of the other experiments.

Properties of neuronal responses within displaced (ectopic) receptive fields

The positions of recording sites were determined as being outside the LPZ, within the LPZ or within the fringe projection zone (FPZ; that is, the part of area 17 in which receptive fields plotted via the normal eyes were located in the region corresponding to a zone inside the border of the lesion). The latter distinction was made to allow for the

the direct affected area this produced a large segment of visual space within which neurones were unresponsive to photic stimulation (radial degeneration). This segment of visual space corresponds with the segmental degeneration of ganglion cells shown in A. The projection of the lesion plus degeneration segment is reproduced in F to indicate that many recordings were made from single units and multiunit clusters which had a normally positioned right-eye receptive field and a displaced (ectopic) left-eye receptive field.

possibility that neural response properties may differ between this region and the central LPZ. Following from the definition used previously (Schmid *et al.* 1996: the radius of the point-spread function, after Albus, 1975), the FPZ was specified as the region within 1.4 mm, in cortical projection terms, inside the border of the lesion projection. This distinction also allows for a stronger statement of unequivocal reorganization from the central LPZ, in that intervening variables are less likely to contribute to a misidentification of an ectopic receptive field. Over the region of our recordings in the CRS series cases, the 1.4 mm criterion was applied where the cortical magnification factor averaged 2.1 deg mm^{-1} (lower limit 1.53 deg mm^{-1}); in the VL series, where more eccentric locations were examined, the magnification was greater than 4 deg mm^{-1} . We recorded from 122 well-isolated single units (neurones) in the LPZ/FPZ. This sample comprised 45 single units from

the four 'mapping' experiments (VL series) and 77 single units from the four experiments in which quantitative stimulus presentation and single-unit recording techniques were combined (CRS series).

Since, in visual projection coordinates, the lesions were located temporal and inferior to the area centralis (Figs 1, 2 and 3), in order to record from the LPZ we had to advance our electrodes along the medial aspect of the marginal gyrus. Reconstruction of electrode tracks revealed that as the electrodes advanced they wandered from supragranular layers to the infragranular layers and occasionally back into the supragranular layers (insets in Fig. 3A and B).

Initial procedures for studying single units in both types of experiments were the same. Thus, after an initial rough estimate of the preferred stimulus characteristics (bar-length and -width, orientation and velocity) careful delineation of

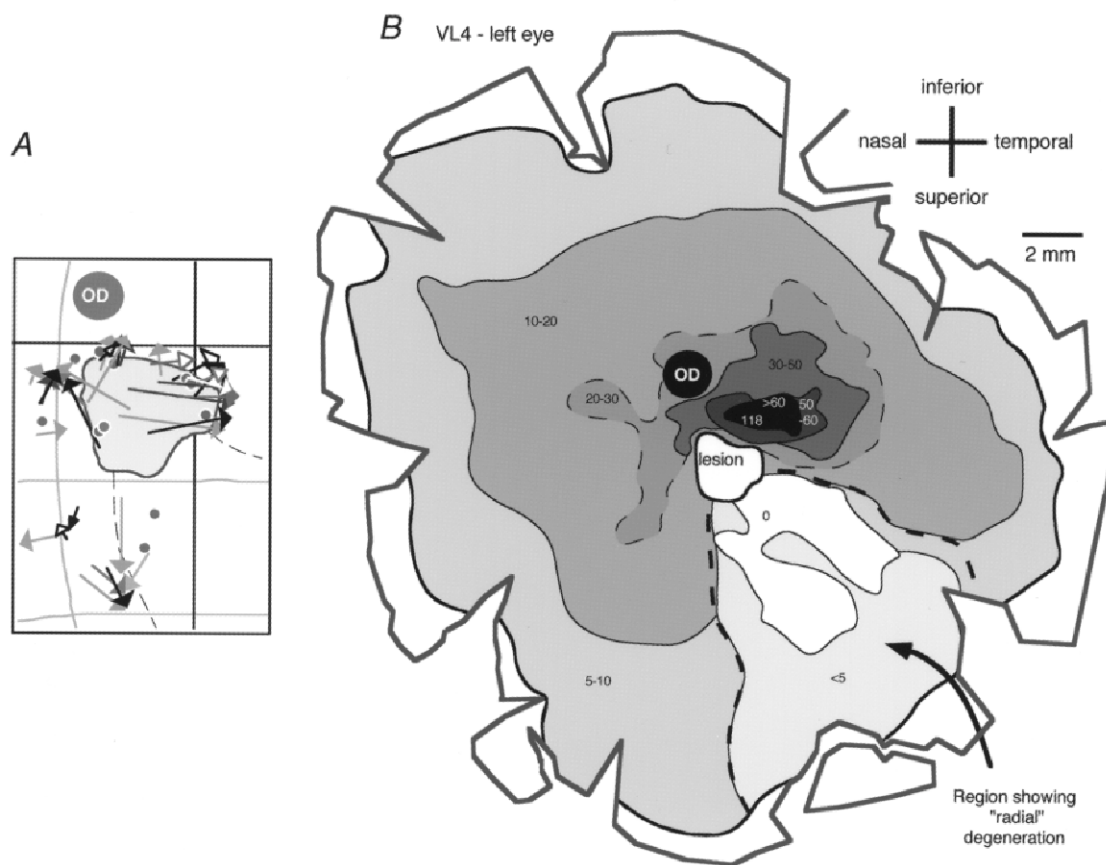


Figure 2. Receptive field displacement and topography of retinal lesion

A, projections of the laser lesion (shaded) in the left eye and of the receptive fields of single units and multiunit clusters recorded in area 17 of cat VL4 (Lambert projection, 20 deg grid). Arrows extend from the position of the receptive field centres plotted with stimulation of the right eye (normal field positions), to those determined with stimulation of the left eye; indicating ectopic field displacements for neurones in the lesion projection zone (LPZ) and retinal degeneration segment projection (dashed lines indicate limits). Grey circles show the position of the centre of a receptive field determined through the right eye when stimulation through the left eye yielded no responses at the cortical site. OD, projection of left optic disc. B, density contours of α -ganglion cells (mm^{-2}) determined for the left retina of cat VL4. This retina was removed 28 days after the lesion and there was a clear degeneration segment, extending radially from the lesion, within which the density of α -ganglion cells was very low. OD, optic disc.

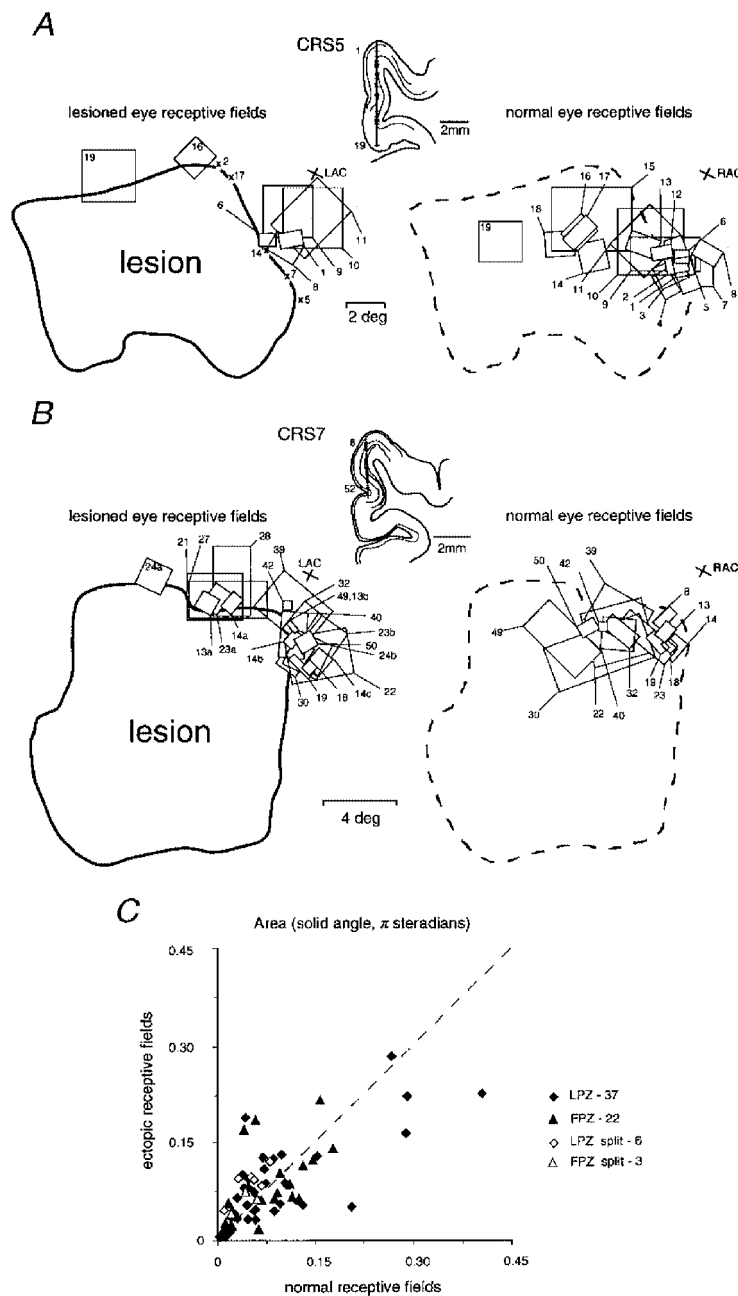


Figure 3. Ectopic and normal receptive field positions and areas

A and *B*, tangential projection of the receptive fields of single neurones recorded in two cases in which controlled stimulus presentation and quantitative recording methods were used. Insets show outline drawings of frontal sections through occipital cortex and the reconstructed positions at which recordings were made. On the left are shown the outlines of the lesion, the position of the area centralis (LAC) and the boundaries of neural receptive fields plotted in response to stimulation of the lesioned left eye. The receptive fields revealed by stimulation of the normal right eye, referenced to the projection of the lesion and the right area centralis (RAC), are shown on the right panel. For case CRS7, to improve clarity, the receptive fields for only about 1/3 of the neurones recorded in the illustrated electrode track are presented. Where responses were evident but weak, only the approximate receptive field centre is indicated (x). *C*, pairwise comparison of the receptive field area (presented as solid angles) for 62 single neurones from the LPZ and FPZ for stimulation of either eye. Some neurones had multiple ectopic receptive fields to stimulation of the lesioned eye; the combined area of these multiple fields was significantly larger than for the single field obtained to stimulation of the normal eye (Wilcoxon matched-pairs signed-ranks test, $P < 0.02$). For neurones with a single receptive field to stimulation of the lesioned eye, the areas of the ectopic and normal receptive fields were not significantly different and were significantly correlated, for locations both in the centre of the LPZ ($r^2 = 0.53$, $P < 0.001$) and in the FPZ (within 1.4 mm of the LPZ boundary; $r^2 = 0.32$, $P < 0.007$).

the discharge field for stimuli presented via each eye was made with hand-controlled moving bars. This was followed by estimates of other response properties such as receptive field class (simple or complex), ocular dominance class (5 categories), velocity tuning and orientation tuning. About a third of the units was further examined quantitatively which involved, firstly, setting the bar at the determined optimal orientation and varying velocity (typically 3 to 1900 deg s⁻¹). Units that were still reliably isolated at this stage were studied by setting optimal velocity and varying orientation (10–20 deg steps). In all the above procedures the stimuli were presented via each eye separately, while the other eye was optically masked.

Size of the discharge fields

The boundary of the lesion as determined from the absence of tapetal reflection was found to represent a clear limit to photic stimulation of evoked activity in cortex. In a number of test cases, using single-unit recording, the boundary of the lesion as defined by the lack of reflection was found to align precisely with the boundaries of visually responsive retina (as previously described for outer-layer lesions; Schmid *et al.* 1996). However, the method of defining receptive field boundaries using the classic technique of determining the limits of responsiveness by a moving bar at a preferred orientation orthogonally, can sometimes give the impression of responsiveness from the lesioned area. This is because the method produces a rectangularly shaped receptive field – filling-out the corners of a truncated field (Fig. 3*A* and *B*). In addition there were 23 neurones with quantitatively demonstrated responsiveness to stimulation through the normal eye at an ectopic location but for which it was difficult to define precise receptive field boundaries (e.g. cells 2, 5, 7, 14 and 17 in Fig. 3*A*; see ‘Ocular dominance’ section below). With these provisions, the extent of the ectopic receptive fields is comparable with that of their counterparts determined through stimulation of the normal eye. In Fig. 3*C* we have plotted for VL and CRS cats the excitatory receptive field (discharge field) areas of 43 single binocular neurones recorded from the LPZs as well as discharge areas of 25 cells recorded from the FPZs. It is apparent from the plot that, although the areas of the discharge fields of individual units revealed by photic stimulation of the normal eyes are often different from those of the ectopic receptive fields revealed by stimulation of the lesioned eyes, overall the areas of the ectopic fields and their normal counterparts are similar. There were no significant differences in the size of discharge fields revealed by stimulation through either eye. Indeed, the sizes of receptive fields revealed by photic stimulation via each eye were significantly correlated for both the LPZ ($r^2 = 0.53$, $P < 0.001$) and FPZ samples ($r^2 = 0.32$, $P < 0.007$). However, there was a distinct subpopulation of units in which the discharge fields revealed by photic stimulation via the lesioned eyes were quite different from their normal counterparts in having two or three spatially distinct subunits. Six of these neurones were recorded from the

LPZs, while three were recorded from the FPZs; the combined areas of the multiple discharge fields were significantly larger than single discharge fields revealed by stimulation via the normal eyes ($P < 0.02$; Wilcoxon matched-pairs signed-ranks test).

Response class

For 47 neurones recorded from the LPZ we tested the responses to stationary flashing slits of light and determined the discharge fields to elongated moving stimuli, lighter and darker than the background. When tested via the unlesioned eye, the clear majority (63.8%; 30 cells) were identified as C-type cells (see C cells and B cells of Henry, 1977; cf. complex cells of Hubel & Wiesel, 1962; see also Gilbert, 1983); the ‘on’ and ‘off’ discharge regions in their receptive fields overlapped and/or their discharge regions revealed by moving stimuli brighter than the background spatially overlapped with discharge regions revealed by moving stimuli darker than the background. Only about a third of cells (36.2%; 17 cells), when tested via the unlesioned eye, were identified as S cells (see S and A cells of Henry, 1977; cf. simple cells of Hubel & Wiesel, 1962; see also Gilbert, 1983); these had spatially separated ‘on’ and ‘off’ discharge regions and largely non-overlapping discharge regions to moving stimuli brighter or darker than the background. All S cells were recorded either from layer 4 or from the supragranular layers 2 and 3. By contrast, all but five C cells were recorded from the infragranular layers (mainly layer 5).

A small number (18) of binocular neurones recorded from the LPZs were identified as S or C cells by photic stimuli presented through either eye; six cells were identified as S cells and 12 cells were identified as C cells. Each of these was categorized as belonging to the same response class irrespective of the eye of stimulation.

Ocular dominance

Ocular dominance classification of the excitatory response was determined as a 5-point categorization using standard techniques (cf. Burke *et al.* 1992). Figure 4*A* displays the ocular dominance distribution histogram for 122 single neurones recorded from LPZs or FPZs and the ocular dominance distribution histogram for the sample of 247 cells recorded from the visuotopically corresponding regions of area 17 of normal cats (our own unpublished data, cf. Burke *et al.* 1992). Compared to the sample from normal area 17 there is a clear shift in the ocular dominance distribution of LPZ towards dominance of the normal eye. It is apparent from Fig. 4*A* that most neurones recorded from the LPZs (82.7%) and the majority of neurones recorded from the FPZs (63.8%) were either dominated by the normal ipsilateral eye (class 4 cells) or could be activated exclusively via the normal ipsilateral eye (class 5 cells). The ocular dominance distribution of cells recorded from the LPZs is not significantly different from that of the cells recorded from the FPZs ($0.1 < P < 0.2$; χ^2 test).

For the combined sample of cells recorded from the LPZs or FPZs, the ocular dominance distribution was clearly shifted towards the normal eye. Indeed, whereas in normal cats class 4 binocular cells (dominated by the ipsilateral eye) constituted about 26.5% of the sample (65/247), among the cells recorded from the LPZs or FPZs, class 4 cells (dominated by the normal unlesioned, ipsilateral eye) constituted 50% of the sample (61/122). The shift in the ocular dominance distribution in the sample of area 17 cells recorded from the LPZs or FPZs towards dominance by the ipsilateral (normal) eye is highly significant ($P < 0.001$; χ^2 test). The majority of class 4 cells recorded from the LPZ responded sufficiently strongly to photic stimuli presented via the lesioned contralateral eye, that we could plot the extents of their ectopic receptive fields. Note, however, that 23 of 61 class 4 cells (37.5%) recorded from the LPZs or FPZs responded so weakly to stimuli presented via the lesioned contralateral eye that we could only estimate a position of the presumed centre of the receptive field (by relying on the peristimulus time histograms to a large number of stimulus presentations) but not the entire extent of the receptive fields (e.g. cells 2, 5, 7, 14 and 17 in

Fig. 3A). These cells were so strongly dominated by the ipsilateral, normal eye they would be classified as class 6 cells in the Hubel & Wiesel (1962) categorization scheme which encompasses seven ocular dominance categories. It is noteworthy that such responses tended to characterize neurones recorded from the granular or supragranular layers. Furthermore, such neurones constituted the majority of class 4 cells recorded from these layers.

With reference to Fig. 4A, it is worth pointing out that: (1) a small number of area 17 cells (5/122; 4.1% of the sample) recorded from the LPZ or FPZ, could be activated only via their ectopic receptive field in the lesioned contralateral eye (class 1 cells); (2) some area 17 cells (9.8%; 12/122) recorded from the LPZ or FPZ, were dominated by the input from the lesioned contralateral eye (class 2 cells) rather than by the input from the ipsilateral, unlesioned retina; and (3) the proportion of area 17 cells, recorded from the LPZ or FPZ, which responded equally well to photic stimuli presented through the unlesioned eye and those presented via the lesioned eye (class 3 cells; 10.7%; 13/122) was very similar to that obtained from normal cats (12.15%; 30/247). Additionally, it is worth noting that the great majority

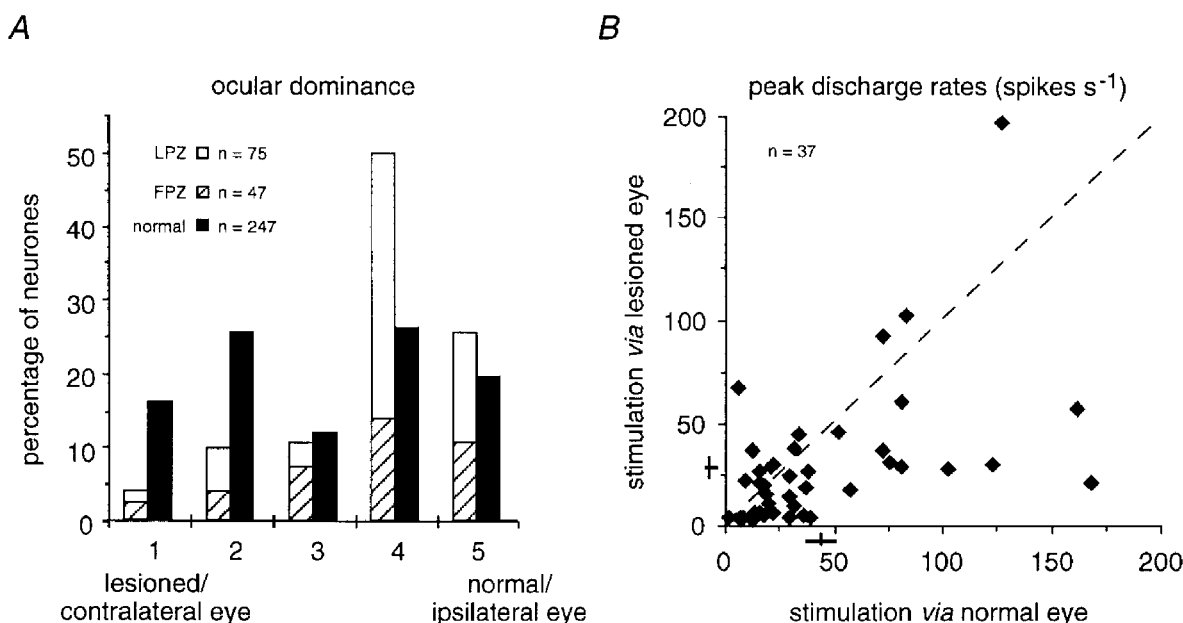


Figure 4. Comparison of ocular dominance and peak discharge rates

A, ocular dominance distribution for 122 single neurones located in the LPZ (open areas of columns) and FPZ (hatched areas of columns). For categorization each eye was stimulated separately. Neurones in categories 1 and 5 were judged monocular for the indicated eye; those in categories 2 and 4 were judged binocular with a stronger excitatory response to stimulation of one eye; and those in category 3 were judged to have approximately equivalent excitatory responses to stimulation of each eye. For comparison, the shaded bars display the ocular dominance distribution of 247 neurones from normal cats (unpublished data added to that of Burke *et al.* 1992), classified using the same criteria as in the present study, with category 1 indicating contralateral eye dominance; the LPZ/FPZ distribution and the normal cortex distribution are significantly different ($\chi^2 = 447$; $P < 0.001$). *B*, pairwise comparison of peak discharge rates at optimal stimulus conditions to stimulation of each eye for 37 binocular single units located within the LPZ. Lines outside the axes indicate means and standard errors. While there is considerable variation in peak discharge rates for stimulation of either eye, peak discharge rates to stimulation of the lesioned eye are generally lower than those for stimulation of the normal eye (Wilcoxon matched-pairs signed-ranks test, $P < 0.05$).

(20/25) of class 2 and 3 cells in our sample of cells recorded from the LPZ or FPZ were recorded from the infragranular layer 5.

Peak discharge rates

The responses of binocular neurones to photic stimuli presented via the lesioned eye tended to be weaker than those to stimuli presented via the normal eye. In particular, the peak discharge rates of responses to stimuli presented via the lesioned eye were lower (mean 28.7 ± 5.3 spikes s^{-1}) than those of the responses to stimuli presented via the normal eye (mean 44.0 ± 6.4 spikes s^{-1}). In Fig. 4*B*, for our sample of quantitatively tested binocular area 17 cells recorded from the LPZ, we have plotted the peak discharge rates of the responses to optimally oriented stimuli moving at preferred velocities presented via the lesioned eye (the ordinate) against the peak discharge rates of responses to stimuli presented via the unlesioned eye (the abscissa). Consistent with the shift in the ocular dominance

distribution, the difference in the peak discharge rates of responses to stimuli presented via the lesioned eye and those of the responses to stimuli presented via the unlesioned eye is statistically significant ($P < 0.05$; Wilcoxon matched-pairs signed-ranks test).

Velocity sensitivity

Figure 5*A* and *B* presents a fairly typical example of the response profiles of a binocular, class 4, neurone recorded from the LPZ as a function of stimulus velocity. Thus, at lower velocities (3.8 and 9.5 deg s^{-1}) there are clear excitatory responses to an optimally oriented bar moving in both directions. However, faster moving (38 and 380 deg s^{-1}) stimuli evoked responses only when presented via the normal eye. Thus, for stimuli presented via the lesioned (contralateral) eye the cut-off velocity was substantially lower than that for stimuli presented via the unlesioned (ipsilateral) eye. On the other hand, for a small proportion of area 17 cells recorded from the LPZ the cut-off velocities for

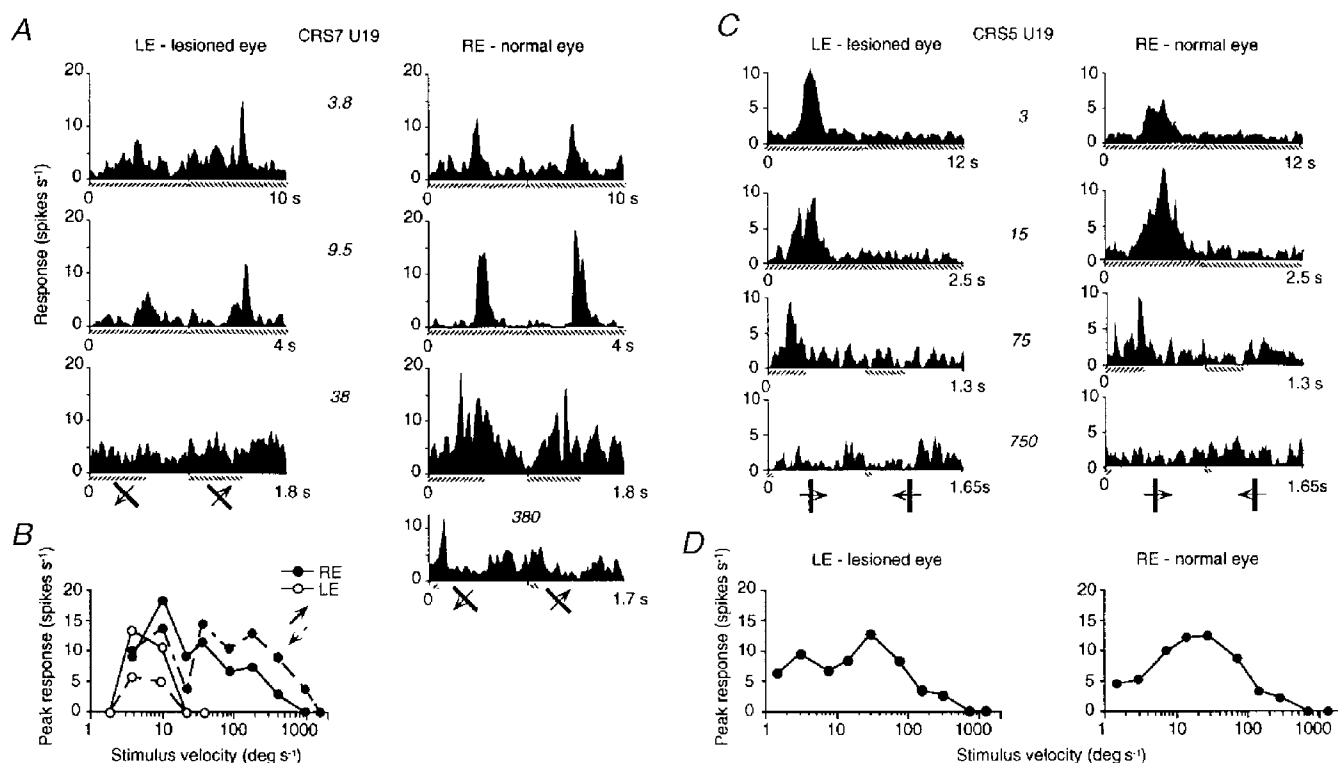


Figure 5. Velocity tuning for ectopic and normal receptive fields

A and *C*, peristimulus response-time histograms to a horizontal light bar (5.5×0.6 deg) moving at the indicated velocities (italicized values in spikes s^{-1}) and presented via the right (normal, ipsilateral) or the left (lesioned, contralateral) eye, for two neurones. In each case (see Fig. 3) the receptive field revealed by photic stimulation to the right (normal) eye was located in the region corresponding to the projection of the retinal lesion in the left eye; the receptive field revealed by photic stimulation via the left (lesioned) eye was located just outside the lesion projection. *B* and *D*, velocity selectivity curves for the peak responses (average of five bins centred at the time with highest number of spikes, minus spontaneous discharge rate), for the same neurones considered in *A* and *C*, respectively. Note the direction selectivity of the responses in *C* which are apparent only for movements to the right. The response profiles shown in *A* and *B* are typical in revealing that the evoked response persists at higher stimulus velocities for stimulation of the normal eye than for stimulation of the lesioned eye. Each peristimulus response-time histogram is compiled from 30 stimulus sweeps. Hatched lines under the timebase indicate the duration of photic stimuli applied.

stimuli presented through lesioned or unlesioned eyes were either equivalent (Fig. 5*C* and *D*) or were higher for stimuli presented via the lesioned eyes. All neurones with such a relationship responded equally well to stimulation of either eye or more strongly to the lesioned eye (binocular class 3 or 2).

Overall, it is apparent from Fig. 6*A* that for binocular neurones recorded from the LPZ, the cut-off velocities for photic stimuli presented via the lesioned (contralateral) eye (ordinate) tend to be substantially lower than those for stimuli presented via the unlesioned (ipsilateral) eye (abscissa). Only for a minority of cells was the cut-off velocity higher for stimuli presented via the lesioned eye. Overall the median cut-off velocity for stimuli presented via the lesioned eye was 38 deg s^{-1} ; considerably lower than the median of 190 deg s^{-1} for normal eye stimulation. A pairwise comparison reveals the difference to be highly significant ($P < 0.004$; Wilcoxon matched-pairs signed-ranks test).

Figure 6*B* shows preferred velocities for the same binocular neurones whose cut-off velocities were plotted in Fig. 6*A*. Two points are apparent from this graph. First, the preferred velocities, irrespective of the eye through which the stimuli were presented, tended to be low and in our sample never exceeded 100 deg s^{-1} . Second, for most cells there is little difference in the preferred velocities for stimuli presented through the normal and lesioned eyes. Overall, the medians of the preferred velocity distributions for stimuli presented via either eye were the same, at 9.8 deg s^{-1} ; a pairwise comparison reveals the difference between the distributions to be insignificant ($P > 0.322$; Wilcoxon matched-pairs signed-ranks test).

Orientation selectivity

The sample of neurones recorded from the LPZ (and those from the FPZ for which a large displacement or multiple ectopic fields indicates a clear reorganization) for which confident statements can be made of the orientation tuning to stimulation of each eye is relatively small ($n = 25$). Figure 7*A* presents examples of orientation tuning for two such cells. In Fig. 7*B*, for our sample of orientation-selective or orientation-biased area 17 cells recorded from the LPZ, we have plotted the preferred orientation for stimuli presented via the lesioned eye (the ordinate) against the preferred orientation for stimuli presented via the unlesioned eye (the abscissa). It is apparent from Fig. 7*A* and *B* that preferred orientations for moving light bars presented through either eye tend to be very similar. Figure 7*C* represents separately, for the lesioned and unlesioned eyes, the frequency histograms of orientation-tuned cells (orientation tuning range not exceeding 90 deg), orientation-biased cells (orientation tuning range not exceeding 150 deg) and cells without clear orientation tuning. It is apparent that, while over 90% (23/25) of binocular neurones recorded from the LPZ and tested for orientation selectivity were orientation tuned when stimuli were presented via the unlesioned eye, the proportion of such

cells was substantially lower (68%; 17/25) when the stimuli were presented via the lesioned eye. A few cells (3/25) did not show clear orientation tuning when the stimuli were presented via the lesioned eyes. Such cells were not, however, apparent when the stimuli were presented via the normal eyes. Nevertheless, the difference in the categorization of orientation selectivity between the two groups is not statistically significant ($P > 0.1$; χ^2 test).

Direction selectivity

Consistent with numerous previous reports, the directional selectivity of neurones in the primary visual cortices (areas 17 and 18; cf. Baker, 1988; Burke *et al.* 1992; Dreher *et al.* 1992) often vary with stimulus velocity. An example can be

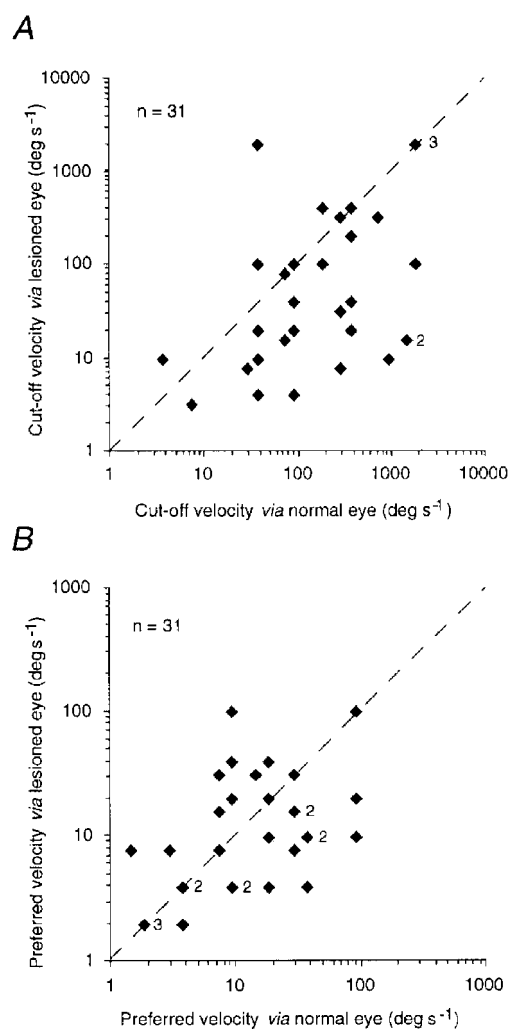


Figure 6. Pairwise comparisons of the velocity sensitivity of 31 LPZ neurones for stimulation of either eye

A, the upper velocity limit of excitatory responsiveness to stimulation of each eye (cut-off velocity) and, *B*, the velocity giving the maximal response for stimulation of each eye (preferred velocity). Stimuli were at the optimal orientation for each receptive field. The velocity cut-off for normal eye stimulation was significantly higher than that for lesioned eye stimulation (see text), but there was no significant difference between the preferred velocities.

seen in the neural response presented in Fig. 5A (normal, right eye). In the majority of cells in our sample the directional selectivity index (DI) was maximal at the same velocities at which the peak discharge rate was maximal. Therefore, for our sample of cells recorded from the LPZ (plus those from the FPZ where there is clear indication of reorganization) the DI is presented at the velocity and orientation at which a neurone gave the maximal response.

In Fig. 8 we have plotted the DI for responses to photic stimuli presented via the lesioned (contralateral) eyes (ordinate) against the DI for the responses to stimuli presented via the normal (ipsilateral) eyes (abscissa). It is apparent that for our sample of cells the DI indices for stimuli presented via the normal eye and those for stimuli presented via the lesioned eye can be very different (e.g. Fig. 5A) or very similar. Secondly, irrespective of the eye through which the stimuli were presented, only a minority of cells exhibited a high DI of 60% or more.

However, in our sample the proportion of such cells was substantially higher (44.4%; 12/27) when the cells were stimulated via the lesioned eye than when the cells were stimulated via the normal eye (25.9%; 7/27). Overall, for the binocular cells recorded from the LPZ/FPZ, the mean DI for stimuli presented via the lesioned eye was 49.3% ($\pm 5.5\%$) while that for stimuli presented via the normal eye was 40% ($\pm 5.2\%$). Whereas this difference is small, a pairwise comparison confirms that the DIs for stimuli presented via the lesioned eyes exceed those for stimuli presented via the normal eyes to a statistically significant extent ($P < 0.05$; Wilcoxon matched-pairs signed-ranks test).

DISCUSSION

The present results indicate that reorganization of the representation of a retina in area 17 takes place even when the input to the affected neurones from the other retina is intact. Over 70% of single neurones recorded from the

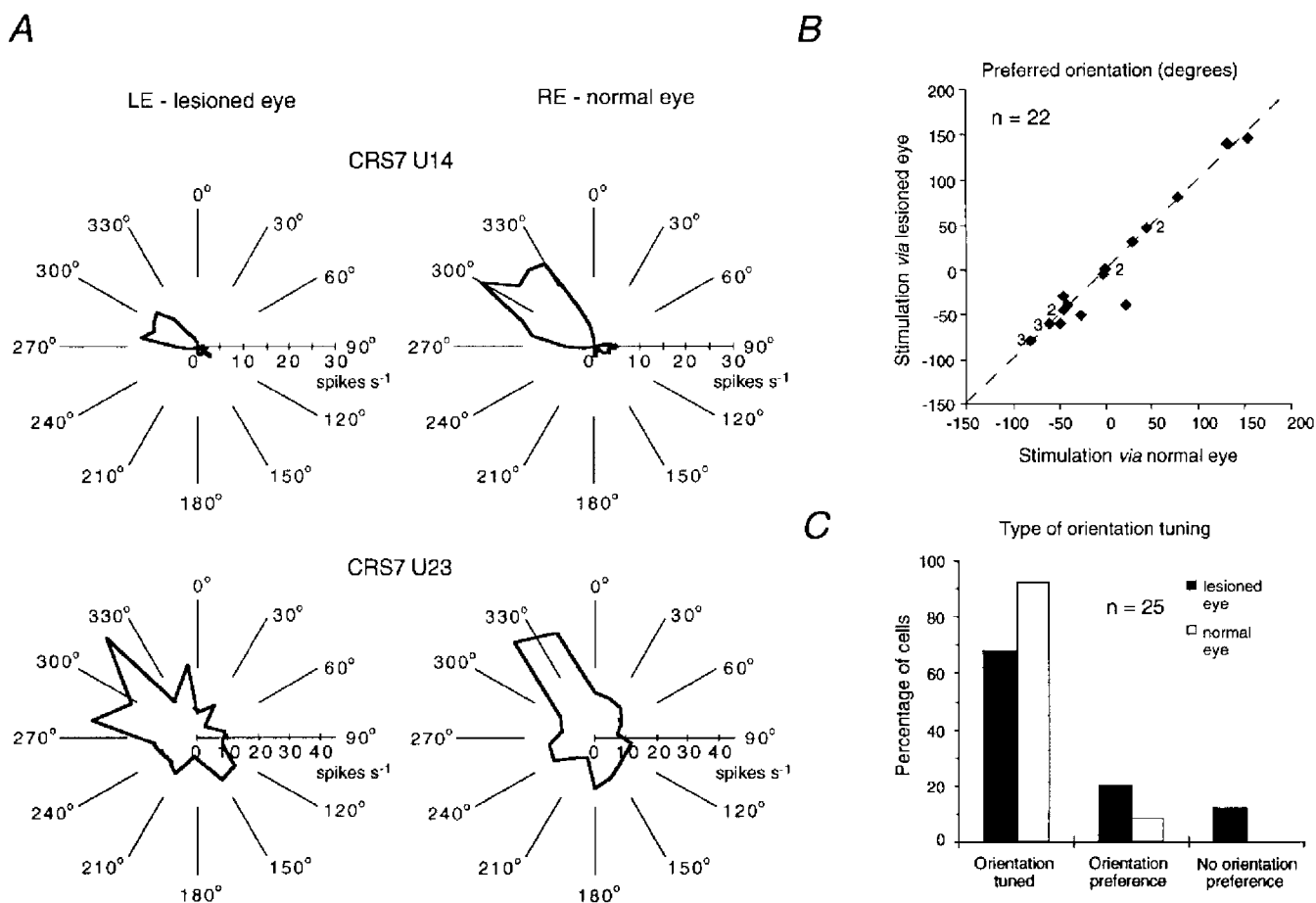


Figure 7. Orientation tuning for ectopic and normal receptive fields

A, polar plots of the orientation tuning of the peak excitatory response of two neurones to stimulation of each eye with moving bars of optimal size and at preferred velocity. Neurone CRS7 14 was located in the FPZ, but showed clear evidence of reorganization in that three distinct ectopic receptive fields were found (Fig. 3B); neurone CRS7 23 (LPZ) had two distinct ectopic receptive fields. As is evident in *B*, where the preferred orientation is compared for stimulation of the two eyes for 22 neurones, the orientation giving the maximal response is similar for normal and ectopic receptive fields. *C*, a qualitative comparison of the degree of orientation tuning for single neurones for stimulation of each eye. Orientation tuned: range not exceeding 90 deg; Orientation biased: range not exceeding 150 deg.

cortical area directly affected by the lesions (LPZ) could be activated through either eye, but the receptive fields revealed by photic stimulation through the lesioned eye were ectopic, that is, displaced beyond the boundary of the lesion (Figs 1, 2 and 3). In common with the studies involving monocular outer-layer lesions (Schmid *et al.* 1996; Calford *et al.* 1999) and monocular retinal detachments (Schmid *et al.* 1995), this conclusion conflicts with that of Chino and his colleagues (1992) who reported that topographic reorganization could be revealed only after removal of the non-lesioned eye. Furthermore, the suggestion that the plasticity apparent following monocular lesions with the unlesioned eye remaining intact might have resulted from normal retinal mechanisms, such as periphery or shift effects (Chino *et al.* 1995; Horton & Hocking, 1998), is not supported by the present study in which large-scale reorganization was apparent following lesions that removed all neural layers of the retina.

For most binocular neurones recorded by us from the LPZs, the responses to photic stimulation of the ectopic receptive field were substantially weaker (lower peak discharge rates) than those resulting from the photic stimulation via the unlesioned eye. Thus, in our sample, the proportion of cells dominated by the unlesioned ipsilateral eye (class 4 cells) was substantially higher than the proportion of area 17 cells dominated by the ipsilateral eye in normal cats (50% of class 4 cells among the cells recorded from the LPZs compared with 26.5% of such cells in area 17 of normal cats). Furthermore, over a third (37.5%) of class 4 cells recorded from the LPZs responded to photic stimulation of the lesioned eye so weakly that we were unable to outline the extent of their ectopic receptive fields. The majority of cells located in granular/supragranular layers fell into this category. Additionally, the majority of binocular cells recorded from the LPZs, when stimulated via the lesioned eye, exhibited substantially lower cut-off velocities than those for stimulation via the normal unlesioned eye.

Chino and his colleagues (1995) reported that in animals in which a retinal lesion in one eye was accompanied by enucleation of the normal eye, the response properties of area 17 neurones recorded from the LPZs (with receptive fields displaced to the normal retinae immediately adjacent to the lesioned retinae) to high-contrast drifting gratings were 'strikingly normal' in terms of orientation tuning, direction selectivity and spatial frequency tuning. At the same time, Chino and his colleagues (1995) reported for cells recorded from the LPZs an elevation of contrast thresholds. In the present study, most area 17 cells recorded from the LPZ of cats with monocular retinal lesions responded to moving high-contrast stimuli presented via the lesioned eyes and had ectopic receptive fields displaced to the normal retinae immediately adjacent to the lesioned retinae. Although we did not investigate the contrast sensitivity function of the cells recorded from the LPZs, significantly weaker responses (lower peak discharge rates) to stimuli presented via the lesioned eyes are consistent with the

elevation of contrast thresholds reported by Chino and his colleagues (1995). Furthermore, consistent with results of Chino and his colleagues (1995), most of the neurones in our sample that were examined for orientation selectivities using moving high-contrast bars exhibited orientation selectivities very similar to those exhibited by the same cells when they were stimulated via the unlesioned eye. Apart from the relative weakness of the responses to stimuli presented via the lesioned eyes (Fig. 4A and B), cells recorded from the LPZs exhibited significantly lower cut-off velocities to stimuli presented via the lesioned eye (Figs 5 and 6) and somewhat greater direction selectivity (higher direction selectivity indices to optimally oriented stimuli moving at optimal velocities; Fig. 8). Overall, however, the stimulus-tuning properties of neural responses to stimulation of ectopic receptive fields were within the limits of those found in normal cortex and are separable, on the three measures of response strength, upper-velocity limit, and directional selectivity, only by direct comparison with their counterparts in response to stimulation of the normal eye.

Given that the response properties of area 17 neurones reflect the influence of the properties of the parallel streams of the ascending visual pathway and integration of these at the cortical level (see for recent review Burke *et al.* 1998), low cut-off velocities of LPZ cells for stimuli presented via the lesioned eyes may be related to the fact that encoding of higher stimulus velocities is known to be a property of the large fibre Y-cell pathway (Burke *et al.* 1992; Dreher *et al.* 1992). It is possible that there is little contribution of Y-cell pathway inputs to the generation of the ectopic receptive fields of the LPZ cells and that the response properties reflect mainly X-cell pathway inputs. Such an interpretation may

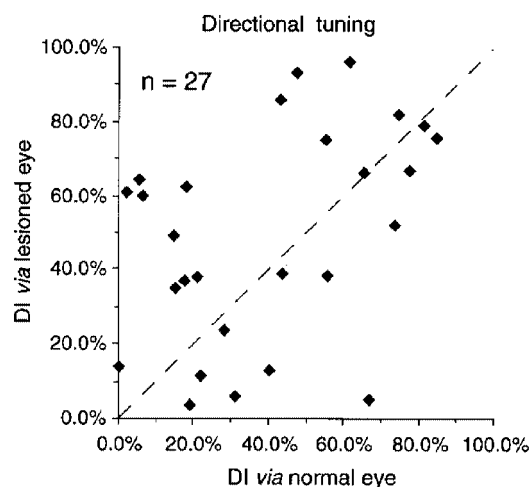


Figure 8. Pairwise comparison of the directional selectivity of the response at the preferred orientation

Percentage response obtained for the reverse compared to the obverse presentation (DI) for a combined LPZ/FPZ sample, indicating a wide variation in distributions of selectivity for stimulation of either eye and a bias towards higher directional selectivity for stimulation of the lesioned eye (Wilcoxon matched-pairs signed-ranks test, $P < 0.05$).

also be consistent with the reported higher contrast threshold of neurones with ectopic receptive fields after binocular lesions (Chino *et al.* 1995), as elements of the Y-cell pathway tend to have lower contrast thresholds than those of the X-cell pathway at lower spatial frequencies (Lee *et al.* 1992; Troy, 1983, 1987).

Another putative explanation comes from considering the intrinsic corticocortical connections of area 17 (Gilbert, 1983; Matsubara *et al.* 1985) which are the most likely source of inputs allowing neurones in the LPZ to express ectopic receptive fields (Darian-Smith & Gilbert, 1994; Das & Gilbert, 1995*a, b*). In normal animals, these inputs from regions of area 17 representing different parts of visual space, are thought to modulate the response of area 17 neurones during presentation of large and complex stimuli (Gilbert, 1983; Nelson & Frost, 1985; Kitano *et al.* 1995; Das & Gilbert, 1995*a*). It is possible that these connections do not convey sensitivity to higher velocities. Interestingly, since area 18 neurones are 'dominated' by the Y-cell pathway and, thus, have a tendency to respond optimally to higher stimulus velocities and exhibit higher cut-off velocities than those of area 17 cells (see for review Dreher *et al.* 1992), our findings are inconsistent with an idea that the corticocortical 'feedback' projections from area 18 constitute the principal source of input to loci in area 17 allowing for the expression of ectopic receptive fields (cf. Darian-Smith & Gilbert, 1995).

Independent plasticity of the area 17 representation of the two eyes

In the normal cat, the majority of area 17 neurones are binocular (cf. Fig. 4A; Burke *et al.* 1992). This is also the case for the neurones sampled in the LPZ/FPZ after monocular retinal lesions, both in the present study (Fig. 4A) and in previously published work where outer-layer lesions were used (Schmid *et al.* 1995, 1996; Calford *et al.* 1999). Indeed, the proportion of cells which could be activated via stimulation of an ectopic receptive field through the lesioned eye in the samples of cells recorded from the LPZ, 3–11 h after creation of retinal lesions at 73.4% (Calford *et al.* 1999) is almost identical to that in the present sample of cells (74.6%), recorded from the LPZ 2 weeks to several months after creation of retinal lesions.

Comparing short- and long-term effects of monocular lesions reveals that the initially unmasked responses undergo substantial refinement. Thus, 1–11 h after creation of the monocular lesions restricted to the outer retinal layers, the ectopic discharge fields revealed by stimulation of the lesioned eye were significantly larger (up to five times linearly) than the corresponding discharge fields revealed by stimulation of the unlesioned eye (Calford *et al.* 1999). Similarly, there are reports of dramatic expansion (2- to 10-fold) of the receptive fields of cells recorded within a few hours following topographically matched binocular retinal lesions, in area 17 of macaque monkeys and cats (Gilbert &

Wiesel, 1992; Darian-Smith & Gilbert, 1995). By contrast, in the present series of experiments in which the ectopic receptive fields were studied several weeks to several months after the creation of retinal lesions, the sizes of ectopic discharge fields were not significantly different from those of the corresponding discharge fields revealed by the stimulation of the unlesioned eye. It is rather unlikely that the enlarged ectopic receptive fields observed shortly after the lesions restricted to the outer retinal layers reflect the 'periphery effect' operating in the lesioned retina (see Calford *et al.* 1999). If surviving ganglion cells, deprived of their photoreceptor input conveyed via bipolar cells, would have remained functional after the retinal lesion their apparent receptive fields would be very diffuse, probably covering most of the visual fields. Indeed, strong periphery effects can be evoked by stimuli located as far as 30–40 deg from the classical receptive fields of retinal ganglion cells and in the case of the LGNd neurones the periphery effect could be evoked from the visual field ipsilateral to the LGNd under examination (McIlwain, 1964). By contrast, in cats with monocular retinal lesions restricted to the outer retinal layers, the new ectopic receptive fields of cortical cells stimulated via the lesioned eye, although enlarged, were clearly circumscribed (Schmid *et al.* 1995, 1996). Thus it would appear that short- and long-term topographic plasticity in area 17 after discrete monocular retinal lesions result from cortical mechanisms and that the large receptive fields unmasked in the short term are refined to become smaller in the long term.

Our observations, that several weeks or months following the monocular retinal lesions the ectopic receptive fields revealed by stimulation of the lesioned eye were not significantly larger than the corresponding receptive fields revealed by stimulation of the unlesioned eye, seem to be in conflict with reports that in both cats (Gilbert & Wiesel, 1992; Chino *et al.* 1995; Darian-Smith & Gilbert, 1995) and macaques (Gilbert & Wiesel, 1992; Darian-Smith & Gilbert, 1995), with topographically matched binocular retinal lesions receptive fields are slightly, but significantly, larger than normal. However, these studies also report that several months after placing the lesions the receptive fields of neurones recorded from the LPZ of area 17 of cats and macaques were substantially smaller than those sampled shortly after the lesions were placed. Thus the trend towards the gradual reduction of the areas of ectopic receptive fields in area 17 with time, is apparent not only in animals with monocular retinal lesions but also in animals with the topographically matched binocular retinal lesions.

At the moment very little is known concerning the orientation and direction selectivities of LPZ cells, to stimuli presented via the lesioned eyes several hours after creation of retinal lesions. It is possible that direction and orientation selectivities of ectopic receptive fields matching those of their normal counterparts develop only gradually.

Given that after monocular retinal lesions area 17 neurones recorded from the LPZ have normally active input from the unaffected eye, it is quite remarkable that there is sufficient presence of appropriately correlated inputs for the refinement of the response properties of the ectopic receptive fields to take place. While it may be seen as counterintuitive when considered in the framework of Hebbian-type plasticity which is thought to enable refinement of feature detection during development (e.g. Rauschecker, 1991), the independent plasticity of two topographical representations within the same array of neurones has a direct parallel in studies of auditory cortex (Rajan *et al.* 1993). Alternatively, it may be the case that intracortical connections which contribute to orientation coding have a predisposition to achieving a particular solution, for there is evidence indicating that in binocular neurones of cat area 17, the precise orientation match for two eyes can be achieved without common visual experience (Gödecke & Bonhoeffer, 1996).

Following partial lesions of one cochlea, effectively monaurally deafferenting for a limited range of frequencies, it has been shown that the representation of the affected cochlea undergoes topographic plasticity while the representation of the intact cochlea in the same population of neurones appears unaffected (Rajan *et al.* 1993). There is very strong experimental support for the idea that the neural encoding of interocular positional disparity (Barlow *et al.* 1967; Nikara *et al.* 1968; Pettigrew *et al.* 1968; Pettigrew & Dreher, 1987; see for review Bishop & Pettigrew, 1986; LeVay & Voigt, 1988) and/or interocular phase disparity (Ohzawa & Freeman, 1986*a,b*) observed in the visual cortices of the cat provides the basis for stereopsis; but not all area 17 neurones need be involved in this processing. It is not so clear whether an interaural disparity in tuning for sound frequency is required for any specific feature-detection process in audition. However, manipulation of this disparity produces auditory illusions consistent with a role in spatial localization (Dougherty *et al.* 1998). Nevertheless, neurones in auditory cortex are involved in bilateral processing of interaural level differences, as the major cue to sound localization at higher frequencies, which would normally require sensitivity to the same range of frequencies. Thus, in both auditory and visual cortices of the cat, neurones which normally have a specific relationship between encoding of a bilateral stimulus property can be made to undergo plasticity in their encoding of one laterality by a restricted peripheral lesion, while appearing to retain the encoding of the other laterality in the normal manner. In the present work stimulation of each eye was undertaken separately, but qualitative observations have previously been reported indicating masking of the response to the lesioned eye by stimulation of the normal eye (Schmid *et al.* 1996). Clearly, there is a need to study neuronal responses from the LPZ with dichoptic manipulation of the stimuli.

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