INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
34100 TRIESTE (ITALY) - P.O.B. 586 - MIRAMARE - STRADA COSTIERA 11 - TELEPHONE: 2240-1
CABLE: CENTRATOM - TELEX 460392 - 1

SMR/302-32

COLLEGE ON NEUROPHYSICS:
"DEVELOPMENT AND ORGANIZATION OF THE BRAIN"
7 November - 2 December 1988

"Development and Plasticity of Retinal X and Y Axon Terminations in the Cat's Lateral Geniculate Nucleus"

Mriganka SUR
M.I.T.
Department of Brain and Cognitive Sciences
Cambridge, MA
USA

Brain, Behavior and Evolution
Editor-in-Chief: R. Glenn Northcutt, La Jolla, Calif.

Reprint
Publisher: S. Karger AG, Basel
Printed in Switzerland

Brain Behav. Evol. *31*: 243–251 (1988)

Development and Plasticity of Retinal X and Y Axon Terminations in the Cat's Lateral Geniculate Nucleus

Mriganka Sur

Department of Brain and Cognitive Sciences, Massachusetts Institute of Technology, Cambridge, Mass., USA

Key Words. Retinogeniculate axons · X cell · Y cell · Terminal arbors · Developmental interactions

Abstract. The technique of injecting single retinogeniculate fibers with horseradish peroxidase enables the terminal arbors of physiologically identified axons to be fully characterized morphologically. We have used this technique to study the postnatal development of retinal X and Y cell arbors within the cat's lateral geniculate nucleus, and the plasticity of these arbors following a variety of manipulations that perturb normal development. These experiments suggest quite specific sequences and mechanisms for the development of individual X and Y retinogeniculate axons. Retinal X axons appear to innervate the lateral geniculate nucleus before Y axons do, and are probably specified innately to their appropriate target lamina A or A1. By 3–4 weeks postnatally, X axons from each eye develop exuberant terminal arbors within the A laminae that by 12 weeks get pruned to the narrow adult form by later developing Y axon arbors from the same eye. The Y arbors progressively expand to form their characteristic broad terminal zones during this period. The laminar location of Y arbors depends on interactions between axons from the two eyes, and their transverse extent on the presence of normal afferent activity in retinogeniculate fibers.

Introduction

The cat's retina contains at least three physiologically and anatomically distinct cell classes: X, Y and W cells [Rodieck, 1979; Lennie, 1980; Sherman and Spear, 1982]. X cells and Y cells each constitute relatively homogeneous populations that can be distinguished from each other along a number of parameters. Retinal X cells have medium-sized somata with small dendritic arbors and medium-caliber axons, and small receptive fields that sum luminance linearly. Y cells have large somata with large dendritic arbors and thick axons, and larger receptive fields that sum luminance nonlinearly. In contrast to X and Y cells, retinal W cells are a rather diverse population. Most W cells have small somata with fine axons, large dendritic arbors and large receptive fields. W cells can be subdivided according to differences in physiological [Rodieck, 1979] or anatomical [Leventhal et al., 1985] features, and different subclasses of these cells may project to different termination zones in the thalamus and midbrain.

X and Y retinal ganglion cells give rise to two pathways that convey information in parallel through the lateral geniculate nucleus to the visual cortex [Hoffmann et al., 1972; So and Shapley, 1979]. Individual X and Y retinal axons have characteristic terminations within the lateral geniculate nucleus (fig. 1, 2), as shown by the method of injecting horseradish peroxidase (HRP) into single, physiologically identified, retinogeniculate axons in the optic tract of adult cats [Bowling and Michael, 1980, 1984; Sur and Sherman, 1982; Sur et al., 1987]. Contralaterally projecting X axons terminate in lamina A, and ipsilaterally projecting axons in lamina A1. X axons have narrow terminal arbors that are about 100 μm wide and contain 500–1,000 terminal boutons (fig. 1). Y axons projecting contralaterally branch to innervate laminae C and A, and those projecting ipsilaterally terminate in lamina A1, in broad, fairly extensive termination zones. Y axon arbors are often 300 μm or so wide and contain 800–2,000 terminal boutons (fig. 2).

Once the normal, adult morphologies of single retinogeniculate arbors are characterized, it is possible

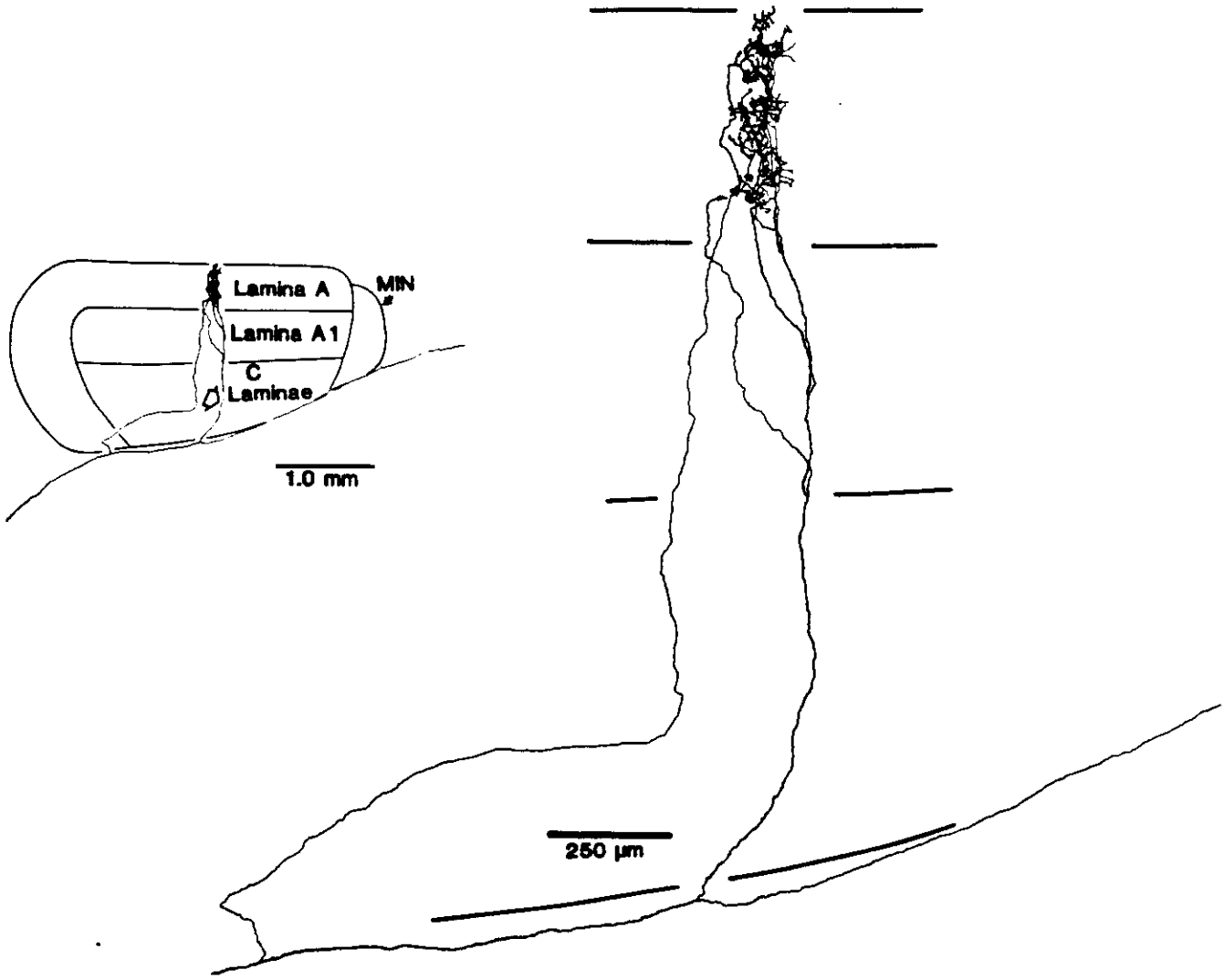

Fig. 1. A retinogeniculate X axon from the right eye of a normal adult cat innervating lamina A of the left lateral geniculate nucleus. The axon had an ON center receptive field that was 0.9° in diameter and was located 9° from the vertical meridian and 2° below the horizontal zero in the right visual field. It was characterized physiologically and injected intracellularly with HRP. The inset to the left shows the injection site (marked with open arrow) on a coronal view of the left lateral geniculate nucleus. The axon was reconstructed from 21 consecutive 100-µm thick serial sections, and the terminal zone in lamina A (containing 793 boutons) from 3 consecutive sections. Apart from the number of terminal boutons, we routinely measured the width and volume of the terminal arbor of all X axons we recovered. MIN: Medial interlaminar nucleus.

to ask how these arbors develop. We have used the intracellular HRP technique to describe: (1) the postnatal development of X and Y axon arbors in kittens, and (2) the plasticity in single axon arbors following a variety of manipulations that perturb normal development. We have compared qualitatively and quantitatively the terminal arbors of X and Y axons in normal adult cats, developing kittens, and adult cats reared with the manipulations described below. These studies then help us to propose specific sequences and mechanisms for the postnatal development of retinal X and Y axon arbors within the lateral geniculate nucleus.

Prenatal Development

It is useful to first review the prenatal development of the cat's retinogeniculate projection, to place the present results on postnatal development in context

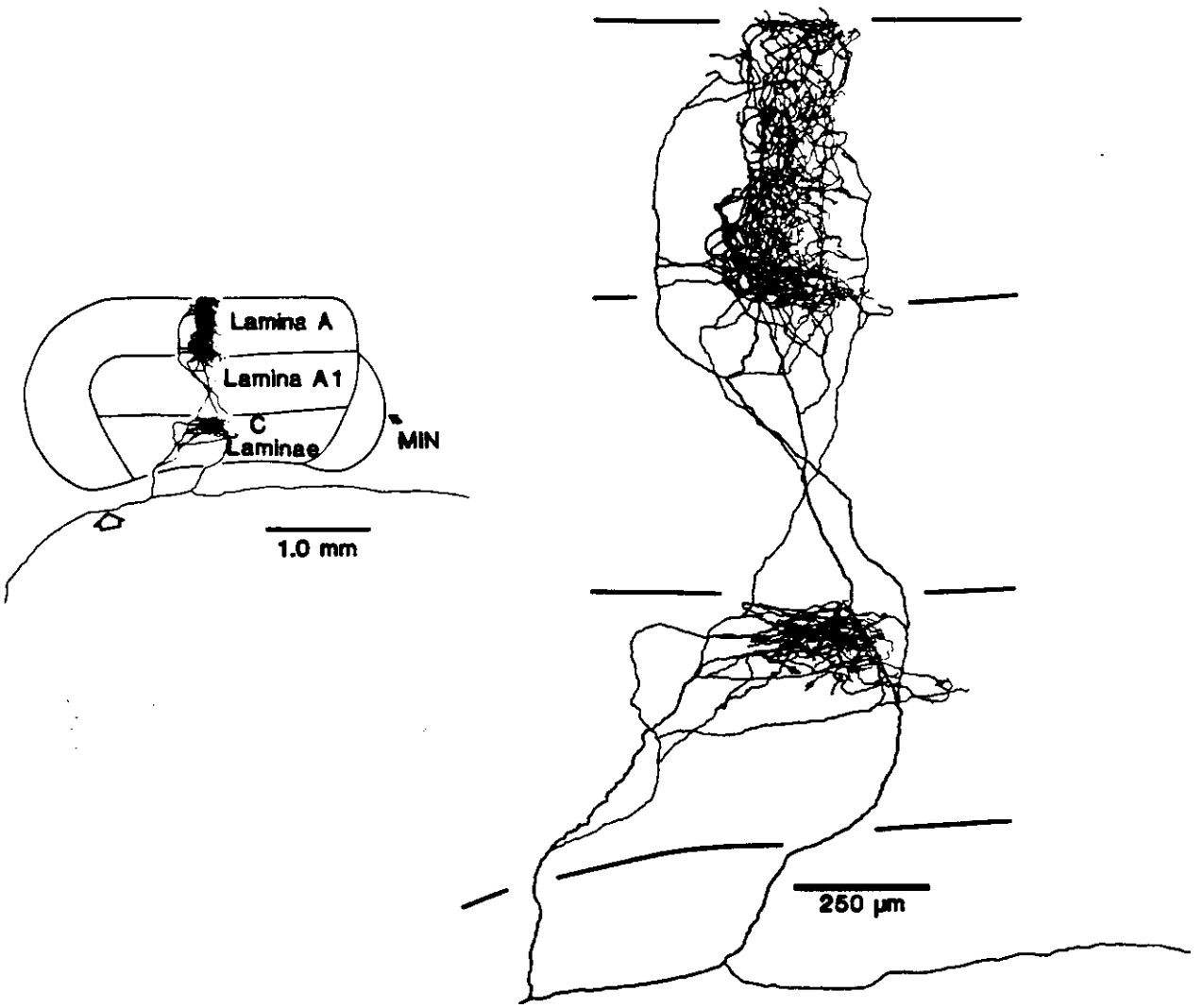

Fig. 2. A retinogeniculate Y axon from the right eye of a normal adult cat innervating laminae C and A of the left lateral geniculate nucleus. The axon had an OFF center receptive field that was 1.2° in diameter and was located 11.5° from the vertical midline and 3.5° below the horizontal zero in the right visual field. The inset to the left shows the injection site (marked with open arrow) on a coronal view of the left lateral geniculate nucleus. The axon was reconstructed from 27 consecutive 100-µm thick serial sections, and the terminal zone in lamina A (containing 1,405 boutons) from 6 consecutive sections. We routinely counted the number of boutons and measured the widths and volumes of terminal arbors for our recovered Y axons. MIN: Medial interlaminar nucleus.

[see also Shatz and Sretavan, 1986]. Three major events can be identified in prenatal retinogeniculate development.

(1) In the retina, medium-sized cells (presumably X cells) are generated first, starting in the central retina at embryonic day 23 (E23; kittens are born at approximately E63), followed by large cells (presumably Y cells). Small cells (presumably W cells) are generated throughout the period of cell division, and many of these cells are the last ganglion cells born in the retina [Walsh et al., 1983; Walsh and Polley, 1985]. Fiber ingrowth into the optic nerve and tract follows a similar pattern [Guillery et al., 1982; Walsh et al., 1983]. The oldest, medium-caliber axons lie farthest from the pia, large fibers lie nearer the pia, and many of the smallest fibers are nearest the pia.

(2) Numbers of retinal ganglion cells and their axons in the optic nerve increase rapidly until E39 [Williams et al., 1982; this may extend to E45, Ng and Stone, 1982] and then decline, first rapidly and then

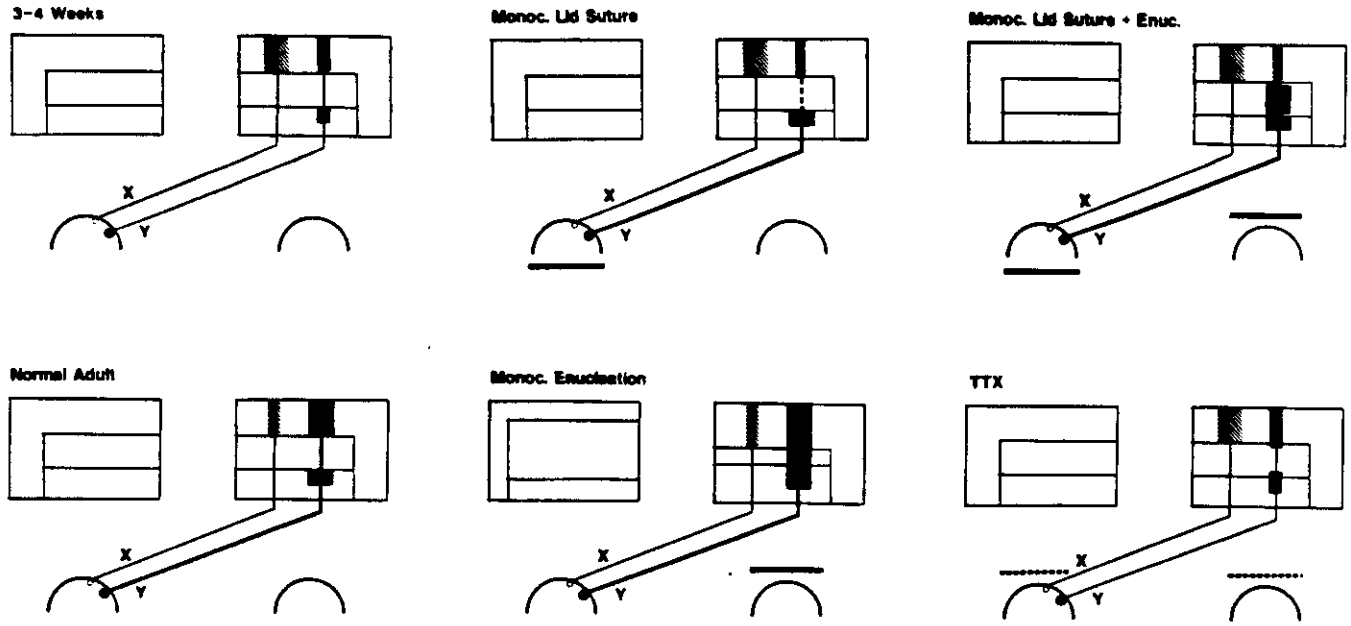

Fig. 3. Summary of retinogeniculate terminations in normal 3- to 4-week-old kittens and normal adult cats, as well as in cats reared with monocular lid suture, monocular enucleation, monocular lid suture of one eye plus enucleation of the other, and binocular retinal impulse blockade with tetrodotoxin (TTX). Each schematic shows the two eyes and two lateral geniculate nuclei, with retinogeniculate X and Y axons from the left eye projecting contralaterally to the right lateral geniculate nucleus. Each lateral geniculate nucleus contains laminae A, A1 and C, as shown also in figure 1 and 2. The normal postnatal development of X and Y axon arbors within the A laminae, and the inter- and intralaminar plasticity of arbors following manipulations that perturb development, are indicated in the figure and described further in the text.

more gradually to reach adult numbers by the 4th to 6th postnatal week.

(3) In the lateral geniculate nucleus, projections from the two eyes initially overlap, with maximum overlap seen around E45 [Shatz, 1983; Chalupa and Williams, 1984b]. Axons from the two eyes then start to segregate into eye-specific laminae, so that by birth the adult pattern of laminar organization is seen in the nucleus. During the prenatal overlap period, retinogeniculate fibers have simple morphologies and are relatively restricted in extent [Sretavan and Shatz, 1984, 1986]. Reduction in overlap occurs by loss of a limited number of minor branches that lie in inappropriate laminae, and laminar development by selective growth within appropriate eye-specific regions of the lateral geniculate nucleus. Reduction in overlap may also occur by loss of retinogeniculate axons that project to inappropriate regions of the nucleus [Sherman, 1985]; however, the bulk of axonal loss occurs before laminar segregation begins [Williams et al., 1982]. At birth, retinogeniculate axons have narrow terminal arbors that are approximately 80–100 μm in width [Sretavan and Shatz, 1986], but it is not possible to physiologically separate them into X or Y axons at this stage.

Postnatal Development of X and Y Retinogeniculate Axons

Postnatally, the earliest age at which retinal ganglion cells and retinogeniculate axons can be physiologically classified as X or Y cell is 3–4 weeks after birth [Hamasaki and Flynn, 1977; Hamasaki and Sutija, 1979; Sur et al., 1984; Friedlander et al., 1985]. At this age, many retinogeniculate axonal branches terminate in growth cones or filopodia [Mason, 1982; Sur et al., 1984], but the laminar location and extent of terminal arbors is still quite clear. X axons at 3–4 weeks of age have fairly extensive terminal zones in lamina A or A1 that are *wider* or more extensive than in the adult (fig. 3) [Sur et al., 1984]. These terminal

zones progressively narrow over the next 8 weeks, so that by 12 weeks the adult extent of terminal arbors is achieved [Sur et al., 1984]. By 12 weeks, the terminal boutons on X axon arbors are also well formed and have the clumped appearance characteristic of adult X axon terminals.

In contrast to the progressive *reduction* in X axon arbors from 3–4 to 12 weeks, Y axon arbors *expand* during this period [Friedlander et al., 1985; Sur et al., 1984]. Thus Y axons in 3- to 4-week-old kittens are much narrower than in adults (fig. 3), and these arbors progressively grow larger in extent through 12 weeks and even beyond. The complementary development of X and Y axon terminations suggested to us that these arbors are shaped by interactions between X and Y axons from the same eye during development. We hypothesized that X axons from one eye invade the lateral geniculate nucleus before Y axons do and develop exuberant terminal arbors in the A laminae that get pruned as the later-developing Y axons from the same eye expand their terminal arbors in the A laminae. Some of the experiments on plasticity of retinogeniculate terminations described below are designed to test this hypothesis of interactions between X and Y axons from the *same* eye during development. Other experiments are designed to *study* the interactions between axons from the *two* eyes during development. The experiments together enable us to propose specific mechanisms for the development of the laminar locations and sizes of retinogeniculate X and Y axon arbors.

Plasticity of X and Y Axon Arbors

Monocular Lid Suture

Suturing the lids of one eye from birth to adulthood has profound consequences on the physiology and morphology of cells in the lateral geniculate nucleus. Y cells are recorded in significantly fewer numbers in deprived laminae [Sherman et al., 1972; see for review Sherman and Spear, 1982], and cells in these laminae have smaller somata in the binocular segment [Guillery, 1972a; Wiesel and Hubel, 1963]. Many Y cells have abnormal morphologies, and some X cells have morphology typical of Y cells [Friedlander et al., 1982], suggesting that some cells that would normally receive Y cell input now accept and retain X cell input. At least some of these effects may be due to the fact that Y cells are generated later in the retina than X cells, the development of the Y cell pathway may lag the X cell pathway, and the Y cell pathway may thus be much more susceptible to postnatal manipulations such as lid suture (see below).

When we examined the retinogeniculate arbors of X and Y axons in adult cats raised with monocular lid suture from birth, we found that Y axon terminations in the A laminae were severely reduced compared to normal adult arbors (fig. 3) [Sur et al., 1982]. Many contralaterally projecting Y axons, that in normal adult cats innervate both laminae C and A, now innervated only lamina C and did not innervate lamina A at all. Y axon terminations in lamina C were normal. At the same time, many X axon arbors (in the A laminae) were larger than those in normal adult cats. The widths of both the expanded X axon arbors and reduced Y axon arbors in the A laminae were statistically different from those in normal adult cats, and the arbors in monocularly sutured cats appeared similar to X and Y axon arbors in 3- to 4-week-old kittens. These results suggest that X and Y axons from the same eye indeed interact with each other during development, perhaps for synaptic space on cells in the A laminae of the lateral geniculate nucleus. Thus, the expanding Y arbors, which would normally prune the exuberant X arbors in the A laminae, are now placed at a disadvantage due to the lid suture and fail to prune the X arbors which then remain exuberant. In regions where X arbors are not present, such as the C lamina, Y arbors develop normally. Consistent with this hypothesis is the result that in the deprived A laminae of monocularly sutured cats, X axon arbors contact cells that they may not normally contact (that is, cells with morphology typical of Y cells), and many Y cells in the deprived A laminae have abnormal morphologies [Friedlander et al., 1982; see, however, Weller and Humphrey, 1985].

We next asked how axons from the two eyes interact in shaping terminal arbors within the lateral geniculate nucleus.

Neonatal Monocular Enucleation

We examined retinogeniculate axon morphologies in cats that were raised with one eye enucleated within 1 day after birth [Garraghty et al., 1986b]. Neonatal monocular enucleation leads to sprouting of some retinogeniculate fibers from the remaining eye into the denervated lamina(e) [Guillery, 1972b; Hickey, 1975; Robson et al., 1978]. We wondered whether both X and Y axons from the remaining eye gave rise to

translaminar sprouts or whether sprouting by some axons had any effect on the morphology of axons that did *not* sprout. We found that X axons from the remaining eye were always restricted to lamina A or A1 appropriate to their eye of origin whereas Y axons sprouted into the denervated lamina(e). For example, contralaterally projecting X axons always projected to, and remained confined to, lamina A, while contralaterally projecting Y axons projected not only to laminae C and A but also sprouted into lamina A1 (fig. 3). Furthermore, X axon arbors had more terminal boutons than in normal adult cats and were larger in terminal volume than normal, suggesting that they retained their immature exuberance into adulthood, perhaps as a result of the Y arbors preferring to sprout into denervated territory and thus failing to prune the X arbors.

The sprouting of Y axons, for example the sprouting of contralaterally projecting Y axons through denervated lamina A1, created another lamina in addition to lamina C where there were only Y axon terminations and no X axon terminations. If now monocular lid suture were added to the enucleation (that is, if one eye were removed at birth and the other eye sutured), we could test further the hypothesis that development of X and Y axon arbors involved pruning of X arbors by Y arbors. If contralaterally projecting Y axon arbors, for example, were reduced in all laminae including the sprouted lamina A1, it would suggest that Y axon arbors developed independently of X arbors. If, on the other hand, (1) contralaterally projecting Y arbors were reduced only in lamina A innervated normally by the remaining eye (to which X axons also projected), but remained extensive in the sprouted lamina A1 as well as in normally innervated lamina C (to both of which X axons did not project), and (2) a reduction in Y arbor extent and bouton number in lamina A compared to normal would be paralleled by an increase in X arbor extent and bouton number, as observed in deprived lamina A or A1 in monocularly sutured cats, (see above), it would provide further evidence that the development of X and Y arbors involved interactions between the two cell classes. The latter, indeed, is what our results clearly indicate [Garraghty et al., 1986a]. Considering contralaterally projecting axons, for example, Y axon arbors in lamina A are much smaller than in normal cats or in monocularly enucleated cats without lid suture of the remaining eye, but their terminations in lamina C as well as their sprouted terminations in lamina A1 are extensive in terminal size and bouton number (fig. 3). At the same time, X axon arbors in lamina A (or in lamina A1) are larger in terminal volume and bouton number compared to normal. The results in lamina A for contralaterally projecting axons, or in lamina A1 for ipsilaterally projecting axons, are thus very similar to those in monocularly sutured cats where the other eye is open.

Why do X axons from the remaining eye not sprout through the denervated laminae? There are two possibilities here: either the enucleation is not done early enough and by birth X axons are already past their 'critical period' for dramatic arbor growth, or there are intrinsic differences between X and Y axons such that only Y axons possess the capacity to sprout and X axons always remain confined to their appropriate target lamina. To distinguish between these possibilities, we have studied cats that were monocularly enucleated prenatally.

Prenatal Monocular Enucleation

The first group of cats we have studied has been adult cats that had one eye removed at E44. At this age, overlap of fibers from the two eyes is maximal in the lateral geniculate nucleus [Shatz, 1983], and we reasoned that, if indeed the shaping of retinogeniculate arbors involved significant interactions between afferents from the two eyes, the effect of eye removal on terminal arbors should be pronounced at this age.

Following monocular enucleation at E44, eye-specific laminae do not develop in the lateral geniculate nucleus. The nucleus has only two histologically demarcable zones, a broad 'magnocellular' zone in the dorsal part separated by an interlaminar plexus from a narrow ventral 'parvocellular' zone. The magnocellular zone probably represents laminae A, A1 and dorsal C collapsed together, and the parvocellular zone probably represents the ventral C laminae [Garraghty et al., 1987b; cf. Chalupa and Williams, 1984a]. We find a striking difference between the terminal arbors of X and Y axons in these cats [Sretavan et al., 1985; Garraghty et al., 1987b]. X axons from the remaining eye appear to always terminate in territory appropriate to their eye of origin, as if laminae A or A1 were present. That is, X axons projecting contralaterally terminate in the dorsal third of the nucleus, where lamina A would have been, and X axons projecting ipsilaterally terminate in the middle third, where lamina A1 would have been. In contrast, most Y axons from the remaining eye (projecting either

contralaterally or ipsilaterally) show extensive terminations throughout the magnocellular portion of the nucleus, as if they sprouted through laminae A, A1 and dorsal C. We have also recovered one contralaterally projecting Y axon that has its terminal arbor restricted to the middle tier only, where lamina A1 would have been, and one ipsilaterally projecting Y axon that is restricted to the outer tier, where lamina A would have been. These axons possibly represent axons that would have either retracted or died if the other eye were present but survive now.

While these experiments do not conclusively demonstrate that X axons never sprout into inappropriate territory (cats with even earlier ages of enucleation would be needed here), our results do suggest that there are indeed intrinsic differences between retinogeniculate X and Y axons that determine the laminar location of their arbors. X axons from each eye appear to be innately specified to their appropriate target lamina A or A1 independent of the other eye. Y axons from one eye need the laminar specificity established by the other eye (presumably by the earlier born X axons) to know when to stop growing, and in the absence of such preestablished laminar specificity sprout into regions normally inappropriate for their eye of origin.

Blockade of Retinal Impulse Activity

In the final experiment in this series, we asked what features of axons from one eye indicate to Y axons from the other eye when to stop growing across their appropriate lamina. Furthermore, we wished to study the role of afferent impulse activity in development, and distinguish this from physical removal of an eye or even disruption of light through monocular lid suture, binocular lid suture [Uhlrich et al., 1986] or dark-rearing [Garraghty et al., 1987a]. As described above, the effects of monocular lid suture on retinogeniculate arbors differ from those of monocular enucleation: monocular lid suture from birth does not cause Y axons from the nondeprived eye to sprout into deprived laminae, whereas monocular enucleation at birth causes Y axons from the remaining eye to sprout into deafferented laminae. However, Y arbors in deprived lamina A or A1 in monocularly sutured cats are much reduced compared to normal, and X arbors are correspondingly larger.

We examined retinogeniculate X and Y axon arbors in cats reared with binocular blockade of retinal impulse activity from 2 to 10 weeks after birth, and in cats reared with monocular blockade from birth to 8–10 weeks [Sur et al., 1985]. The blockade was produced by regular, repeated intraocular injections of tetrodotoxin in doses known to block impulse activity but not cause systemic toxicity [Stryker and Harris, 1986]. In monocularly blocked animals, we found that contralaterally projecting Y axons from the normal eye sprouted terminations into blocked lamina A1, just as contralaterally projecting Y axons from the remaining eye do in monocularly enucleated cats. X axons from the normal eye appeared qualitatively normal in these cats. We have not yet recovered significant numbers of axons from the blocked eye in monocularly blocked animals.

In binocularly blocked animals, we found that Y axons (from either, blocked, eye) sprouted slightly into adjacent laminae (fig. 3). At the same time, the normal development of both X and Y arbor *within* lamina A or A1 seemed to be arrested, and the arbors seemed similar to those in very young normal kittens or in deprived lamina A or A1 in monocularly sutured cats reared to adulthood. Thus, Y arbors in the A laminae of binocularly blocked animals were much smaller than in normal animals at the same age but comparable to Y arbors in normal 3- to 4-week-old kittens, while X arbors in the binocularly blocked animals were broader than in normal animals at the same age but similar to X arbors in 3- to 4-week-old kittens (fig. 3). Furthermore, the size and density of terminal boutons on both X and Y axons were very immature in binocularly blocked animals. These results suggest that a necessary prerequisite for the normal development of retinogeniculate arbors (both the interlaminar restriction as well as the intralaminar shaping of X and Y axons) is electrical activity in the two eyes.

Mechanisms of Retinogeniculate Development

What mechanisms do these experiments suggest for the normal development of retinogeniculate X and Y axons, and how do these mechanisms in turn explain the plasticity that we observe in X and Y arbors after manipulations that perturb normal development?

We can propose, at the level of testable hypotheses, both the sequel of normal development and the factors that shape X and Y axon arbors in the A laminae. The sequel of prenatal and postnatal events in reti-

nogeniculate development suggested by our data (in conjunction with other data reviewed earlier) is the following. X cells are born earlier in the retina than Y cells, and X axons innervate the lateral geniculate nucleus earlier. Their axons develop arbors that are, at least for the most part, confined to the appropriate location for lamina A or A1 within the nucleus. Between birth and 3–4 weeks postnatally, X axons develop exuberant arbors within lamina A or A1 that get pruned by Y axon arbors in these laminae.

The factors that shape X and Y axon arbors in the A laminae are the following. The laminar location or dorsoventral height of X arbors appears to be specified innately, perhaps through axon-target interactions or target-mediated substrates in the lateral geniculate nucleus. No manipulation we have done has changed the laminar specificity of X axons. The transverse extent or width of X axons in the A laminae is determined by interactions with Y axon arbors from the same eye. Manipulations that cause Y arbors in lamina A or A1 to remain small (monocular lid suture with or without enucleation of the other eye, and retinal impulse blockade) lead to expanded X axon arbors (that is, X arbors with retained immature exuberance) in the same lamina. The laminar location or dorsoventral height of Y axon arbors from one eye seems to depend most critically on interactions with axons from the other eye. When one eye is enucleated or its electrical activity blocked, Y axons from the other eye sprout into the deafferented or blocked lamina. The transverse extent or width of Y arbors in the A laminae perhaps depends simply on normal afferent activity in the retinogeniculate fibers. Manipulations that impede normal activity such as monocular lid suture (with the other eye open or enucleated), and total impulse blockade, all lead to abnormally small Y axon arbors in deprived or blocked lamina A or A1. It should be emphasized that these remain hypotheses about the mechanisms of retinogeniculate development at the level of single fibers from physiologically distinct retinal cell classes, and these hypotheses may have to be modified or altered as future experiments dictate.

Acknowledgments

I thank Anna Roe and Preston Garraghty for their comments on the manuscript. Supported by NIH grant EY 07023, the Sloan Foundation and the Whitaker Health Sciences Fund.

References

Bowling, D.B.; Michael, C.R.: Projection patterns of single physiologically characterized optic tract fibers in cat. Nature *286:* 899–902 (1980).

Bowling, D.B.; Michael, C.R.: Terminal patterns of single, physiologically characterized optic tract fibers in the cat's lateral geniculate nucleus. J. Neurosci. *4:* 198–216 (1984).

Chalupa, L.; Williams, R.W.: Organization of the cat's lateral geniculate nucleus following interruption of prenatal binocular competition. Hum. Neurobiol. *3:* 103–107 (1984a).

Chalupa, L.; Williams, R.W.: Prenatal development and reorganization in the visual system of the cat; in Stone, Dreher, Rapaport, Development of visual pathways in mammals, pp. 89–102 (Liss, New York 1984b).

Friedlander, M.J.; Martin, K.A.C.; Vahle-Hinz, C.: The structure of the terminal arborizations of physiologically identified retinal ganglion cell Y axons in the kitten. J. Physiol. *359:* 293–313 (1985).

Friedlander, M.J.; Stanford, L.R.; Sherman, S.M.: Effects of monocular deprivation on the structure/function relationship of individual neurons in the cat's lateral geniculate nucleus. J. Neurosci. *2:* 321–330 (1982).

Garraghty, P.E.; Frost, D.O.; Sur, M.: The morphology of retinogeniculate X- and Y-cell axons in dark-reared cats. Exp. Brain Res. *66:* 115–127 (1987a).

Garraghty, P.E.; Shatz, C.J.; Sretavan, D.; Sur, M.: Prenatal monocular enucleation in the cat: effects on the morphology of retinogeniculate axons and formation of laminae in the lateral geniculate nucleus. Investve Ophthal. vis. Sci., suppl. *28:* 335 (1987b).

Garraghty, P.E.; Sur, M.; Sherman, S.M.: The role of competitive interactions in the postnatal development of X and Y retinogeniculate axons. J. comp. Neurol. *251:* 216–239 (1986a).

Garraghty, P.E.; Sur, M.; Weller, R.E.; Sherman, S.M.: The morphology of retinogeniculate X and Y axon arbors in monocularly enucleated cats. J. comp. Neurol. *251:* 198–215 (1986b).

Guillery, R.W.: Binocular competition in the control of geniculate cell growth. J. comp. Neurol. *144:* 117–130 (1972a).

Guillery, R.W.: Experiments to determine whether retinogeniculate axons can form translaminar collateral sprouts in the dorsal geniculate nucleus of the cat. J. comp. Neurol. *146:* 407–420 (1972b).

Guillery, R.W.; Polley, E.H.; Torrealba, F.: The arrangement of axons according to fiber diameter in the optic tract of the cat. J. Neurosci. *2:* 714–721 (1982).

Hamasaki, D.I.; Flynn, J.T.: Physiological properties of retinal ganglion cells of 3-week-old kittens. Vision Res. *17:* 275–284 (1977).

Hamasaki, D.I.; Sutija, V.G.: Development of X- and Y-cells in kittens. Exp. Brain Res. *35:* 6–23 (1979).

Hickey, T.L.: Translaminar growth of axons in the kitten dorsal lateral geniculate nucleus following removal of one eye. J. comp. Neurol. *161:* 359–382 (1975).

Hoffmann, K.-P.; Stone, J.; Sherman, S.M.: Relay of receptive-field properties in dorsal lateral geniculate nucleus of the cat. J. Neurophysiol. *35:* 518–531 (1972).

Lennie, P.: Parallel visual pathways. Vision Res. *20:* 561–594 (1980).

Leventhal, A.G.; Rodieck, R.W.; Dreher, B.: Central projections of cat retinal ganglion cells. J. comp. Neurol. *237:* 216–226 (1985).

Mason, C.A.: Development of terminal arbors of retino-geniculate axons in the kitten. I. Light microscopical observations. Neuroscience *7:* 541–559 (1982).

Ng, A.Y.K.; Stone, J.: The optic nerve of the cat: appearance and loss of axons during normal development. Devl Brain Res. *5:* 263–271 (1982).

Robson, J.A.; Mason, C.A.; Guillery, R.W.: Terminal arbors of axons that have formed abnormal connections. Science *201:* 635–637 (1987).

Rodieck, R.W.: Visual pathways. Annu. Rev. Neurosci. *2:* 193–225 (1979).

Shatz, C.J.: The prenatal development of the cat's retinogeniculate pathway. J. Neurosci. *3:* 482–499 (1983).

Shatz, C.J.; Sretavan, D.W.: Interactions between retinal ganglion cells during the development of the mammalian visual system. Annu. Rev. Neurosci. *9:* 171–207 (1986).

Sherman, S.M.: Development of retinal projections to the cat's lateral geniculate nucleus. Trends Neurosci. *8:* 350–355 (1985).

Sherman, S.M.; Hoffmann, K.P.; Stone, J.: Loss of a specific cell type from the dorsal lateral geniculate nucleus in visually deprived cats. J. Neurophysiol. *35:* 532–541 (1972).

Sherman, S.M.; Spear, P.D.: Organization of visual pathways in normal and visually deprived cats. Physiol. Rev. *62:* 738–855 (1982).

So, Y.T.; Shapley, R.: Spatial properties of X and Y cells in the lateral geniculate nucleus of the cat and conduction velocities of their inputs. Exp. Brain Res. *36:* 533–550 (1979).

Sretavan, D.W.; Garraghty, P.E.; Sur, M.; Shatz, C.J.: Development of retinogeniculate axon arbors following prenatal unilateral enucleation. Soc. Neurosci. Abstr. *11:* 805 (1985).

Sretavan, D.W.; Shatz, C.: Prenatal development of retinal ganglion cell axons: segregation *into eye-specific layers within the* cat's lateral geniculate nucleus. J. Neurosci. 6: 234–251 (1986).

Sretavan, D.W.; Shatz, C.: Prenatal development of individual retinogeniculate axons during the period of segregation. Nature *308:* 845–848 (1984).

Stryker, M.P.; Harris, W.A.: Binocular impulse blockade prevents the formation of ocular dominance columns in cat visual cortex. J. Neurosci. *6:* 2117–2133 (1986).

Sur, M.; Esguerra, M.; Garraghty, P.E.; Kritzer, M.F.; Sherman, S.M.: Morphology of physiologically identified retinal X- and Y-cell axons in the cat lateral geniculate nucleus. J. Neurophysiol. *58:* 1–32 (1987).

Sur, M.; Garraghty, P.E.; Stryker, M.P.: Morphology of physiologically identified retinogeniculate axons in cats following blockade of retinal impulse activity. Soc. Neurosci. Abstr. *11:* 805 (1985).

Sur, M.; Humphrey, A.L.; Sherman, S.M.: Monocular deprivation affects X- and Y-cell retinogeniculate terminations in cats. Nature *300:* 183–185 (1982).

Sur, M.; Sherman, S.M.: Retinogeniculate terminations in cats: morphological differences between X- and Y-cell axons. Science *218:* 389–391 (1982).

Sur, M.; Weller, R.E.; Sherman, S.M.: Development of retinogeniculate X- and Y-cell terminations in kittens. Nature *310:* 246–249 (1984).

Uhlrich, D.J.; Raczkowski, D.; Sherman, S.M.: Axonal termination patterns in the lateral geniculate nucleus of retinal X- and Y-cells in cats raised with binocular lid suture. Soc. Neurosci. Abstr. *12:* 439 (1986).

Walsh, C.; Polley, E.H.: The topography of ganglion cell production in the cat's retina. J. Neurosci. *5:* 741–750 (1985).

Walsh, C.; Polley, E.H.; Hickey, T.L.; Guillery, R.G.: Generation of cat retinal ganglion cells in relation to central pathways. Nature *302:* 611–614 (1983).

Weller, R.E.; Humphrey, A.L.: Structural correlates of functional subgroups among X-cells in the cat LGN. Soc. Neurosci. Abstr. *11:* 318 (1985).

Wiesel, T.N.; Hubel, D.H.: Effects of visual deprivation on morphology and physiology of cells in the cat's lateral geniculate body. J. Neurophyisol. *26:* 978–993 (1963).

Williams, R.W.; Bastiani, M.J.; Lia, B.; Chalupa, L.M.: Growth cones, dying axons, and developmental fluctuations in the fiber population of the cat's optic nerve. J. comp. Neurol. *246:* 32–69 (1982).

Dr. Mriganka Sur
Department of Brain and Cognitive Sciences
MIT, E25–618
Cambridge, MA 02139 (USA)