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: 9240-1
CABLE: CENTRATOM - TELEX 460392 - 1

SMR/302-31

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

"Interaction Between Retinal Axons During Development of Their Terminal Arbors in the Cat's Lateral Geniculate Nucleus"

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

Cellular thalamic mechanisms
M. Bentivoglio and R. Spreafico, editors

Interactions between retinal axons during development of their terminal arbors in the cat's lateral geniculate nucleus

PRESTON E. GARRAGHTY* AND MRIGANKA SUR

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

Introduction

It is now well-established that the cat visual system is made up of no less than three distinct parallel channels, the W, X and Y cell pathways (see Refs. 36, 39 and 51 for reviews). These cell classes can be readily distinguished physiologically and morphologically (e.g., see Ref. 39 for review), and they have characteristic, partially overlapping, sets of central targets (e.g., Refs. 26 and 27). These various cell classes also differ in their developmental schedules [57,59,60] and in their responsivity to early postnatal environmental manipulations such as visual deprivation (Refs. 12, 28, 42, 54 and 58; and see Ref. 41 for review). These observations, together with the fact that very little cross-talk exists between channels (e.g., Refs. 10, 14, 25, 44 and 62) have tended to reinforce the notion that these various cell classes are indeed independent.

While the physiological processing of sensory input within these afferent streams may be largely independent under normal circumstances, recent evidence suggests that competitive interactions between X and Y retinogeniculate axons from the same eye may well occur during development [18,40,52,54,57]. In addition, interactions between axons from the two eyes also shape the structure of their arbors [16,17,45]. We have used the technique of injecting single, physiologically identified retinogeniculate axons with horseradish peroxidase (HRP) to visualize the morphology of their terminal arbors. In the present review, we shall summarize some of the evidence which provides support for these hypothesized interactions between retinogeniculate afferents during development.

*Present address: See list of contributors.

The retinogeniculate projection in normal cats

In normal adult cats, the retinal projections from the two eyes form alternating eye-specific bands within the lateral geniculate nucleus (LGN) [19,24]. These eye-specific bands of retinal afferents, in turn, correspond to cellular laminae within the LGN. The cat LGN consists of six layers termed A, A1, C, C1, C2 and C3 by Hickey and Guillery [24] with layer A being farthest from the optic tract and layer C3 nearest. Laminae A, C and C2 are innervated by the contralateral eye, whereas laminae A1 and C1 are ipsilaterally innervated. Lamina C3 does not receive direct retinal input. In addition to the ocular segregation characterizing these various layers, the functional subclasses of retinogeniculate axons also display preferences in the location of their terminal arbors. X axons terminate in lamina A (and rarely also in lamina C) if from the contralateral retina, or in lamina A1 if from the ipsilateral retina [2,53,55]. Y axons terminate in laminae A and C if from the contralateral retina and in lamina A1 if from the ipsilateral retina [1,2,53,55]. Since W cells are recorded in laminae C, C1 and C2 [49,50,56,62], it is probable that retinogeniculate W axons terminate in these layers, a possibility which has received indirect support from bulk-filling experiments which have demonstrated fine caliber optic tract fibers (i.e., presumably W axons; see Ref. 13) terminating on these layers [29].

Retinogeniculate development

During prenatal development, retinogeniculate axons from the two eyes overlap extensively in the LGN [37]. The axons are characterized by very simple morphology consisting of a main axon with a few short side branches. As maturation continues, axons elaborate terminal arbors in regions of the LGN appropriate for their eye of origin, while side branches are eliminated in geniculate zones where axons from the opposite eye elaborate their arbors. This segregation of individual axons correlates spatially and temporally with the overall formation of eye-specific laminae [37,46,47] with little or no overlap between afferents from the two eyes remaining at birth [38,46,47]. Because this sequence of events can be disrupted by the early removal of one eye, it has been widely presumed that competitive interactions between the sets of afferents from the two eyes are responsible for their segregation (e.g., Ref. 32; and see below).

In addition to the interocular competitive interactions alluded to above, competition between axons from the same eye has also been implicated in the refinement of retinogeniculate connectivity [17,18,52,54,57]. Early in postnatal life (i.e., 3–4 weeks of age), retinogeniculate X axons have terminal arbors which are much broader than those of X axons in adult cats (Ref. 57; and see Figs. 1 and 2). On the other hand, Y axons are much narrower than in adults [11,57]. As development proceeds, the X axon arbors become smaller while the Y axon arbors expand so that they have achieved their adult form by the end of the third postnatal month (Ref. 57 and see Figs. 1 and 2). X axons, therefore, exhibit an initial exuberance followed by retraction or pruning, a sequence which apparently exists in other developing systems (e.g., Refs. 5–7, 30 and 31). Y axons, in contrast, apparently grow

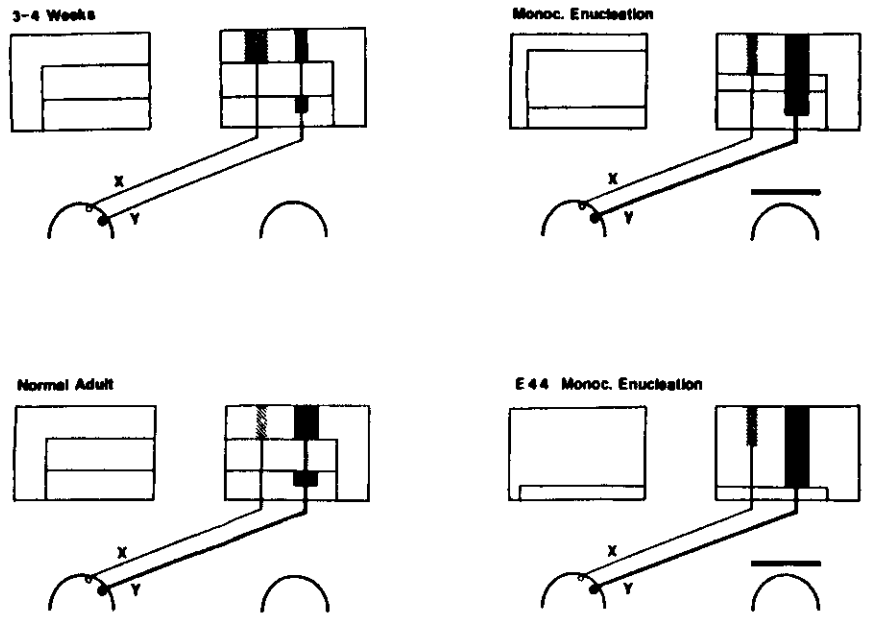

FIG. 1 Schematic representations of retinogeniculate X and Y axons in the cat's lateral geniculate nucleus (LGN) during normal development, and after monocular enucleation. In all cases, contralaterally projecting axons are illustrated. At 3–4 weeks postnatal age (upper left), X axons are broader than in the adult (lower left). Y axons, on the other hand, are narrower at 3–4 weeks of age than in the adult. Arbors of both classes of axon are restricted to LGN lamina(e) appropriate for their eye of origin. Neonatal monocular enucleation (upper right) produces some distortion in geniculate lamination, but X axon arbors are restricted to appropriate laminae, while many Y axons form sprouts in geniculate territory denervated by the enucleation. After monocular enucleation at embryonic day 44 (E44; gestation period is about 65 days), the pattern of lamination in the LGN is severely disrupted (lower right), but X axons remain segregated to what appear to be their appropriate zones of termination (i.e., in this instance, contralaterally projecting axons terminate in the outer part of the nucleus where lamina A normally would have formed). Y axons, however, are again found to terminate heavily in denervated portions of the nucleus. Therefore, interocular interactions appear to be of importance for Y, but not X, axons in the normal process of segregation of retinal afferents. See text for additional details.

monotonically to their adult form without undergoing a process of retraction. Obviously, these complementary parallel changes in X and Y retinogeniculate axons arbors could reflect independent development processes. Alternatively, competitive interactions could occur such that the later-growing Y axons actually displace the exuberant portions of the earlier-growing X axons. Interestingly, the terminations of contralaterally projecting Y axons in layer C, which is largely devoid of X input, mature more quickly than do Y axon terminations in the A-laminae [11],

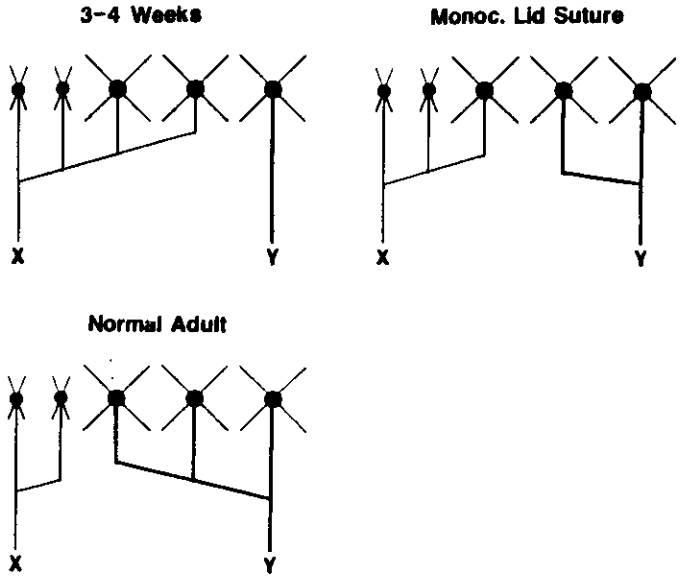

FIG. 2 Schematic representation of hypothesis of X axon retraction and Y axon growth during development. At 3–4 weeks of age, X axon arbors are larger than in adults and may transiently contact geniculate neurons which eventually receive Y axon innervation as Y axon arbors expand (compare upper and lower left). It is plausible that these complementary changes involve competitive interactions between X and Y axons from the same eye within geniculate lamina A or A1. When Y axons are placed at a competitive disadvantage by monocular lid suture (upper right), some neurons with morphological features normally associated with Y cells are classified physiologically as X, presumably because the normally transient X input has been retained. See text for further details.

possibly because the C-layer terminations of Y axons are relatively free of the competitive interactions with X axons that are hypothesized to occur in the A-laminae [18,52].

Experimental evidence for interactions between X and Y axons from the same eye

Data from animals which have undergone alterations of visual inputs during development support the hypothesis that X and Y axons from the same eye interact competitively during early postnatal life. The effects of monocular lid suture from birth have been widely studied (see Ref. 41 for review). The suggestion that retinogeniculate terminations may be altered by monocular lid suture was provided first by Friedlander et al. [12] who studied the morphology of physiologically identified LGN neurons. They noted that some deprived geniculate X cells had morphologies which had earlier been shown to be associated only with Y cells (Refs. 9 and 10 and

see Fig. 2). This finding implied that deprived retinogeniculate X axons had either retained or acquired connections with geniculate neurons which would have been Y cells under normal circumstances. Sur et al. [54] studied the effects of monocular

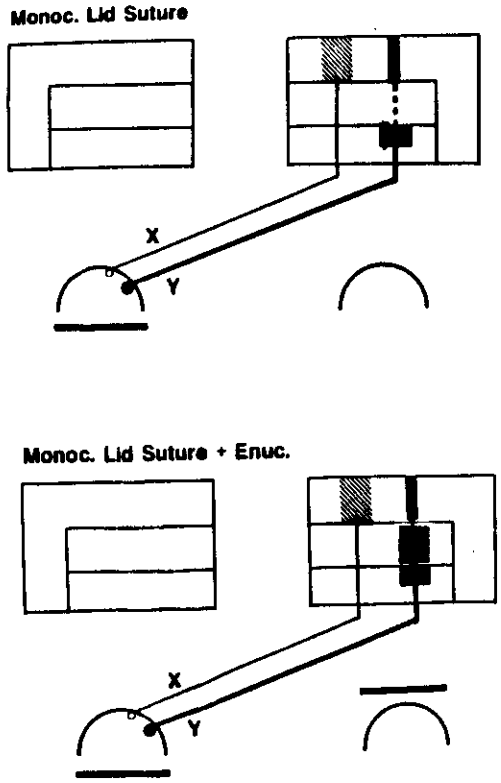

FIG. 3 Schematic representation of the lateral geniculate nucleus of cats reared with monocular lid suture either alone (top) or paired with enucleation of the open eye (bottom). After monocular lid suture, deprived X axons are broader than normal, much like X axons in normal 3–4 week old kittens (cf. Fig. 1). In contrast, deprived Y axons in these same cats are smaller than normal, but only in laminae with extensive X axon terminations (in this case lamina A but not lamina C). The line connecting the A and C arbors of this Y axon is dashed to indicate that some Y axons lose their lamina A arbors completely. When enucleation at birth is paired with lid suture, axon arbors suggest a simple confirmation of the results of enucleation (Fig. 1) and monocular lid suture (Fig. 3A). First, the effects of deprivation are not mitigated by concurrent enucleation of the non-deprived eye. X axons again retain their immature exuberance, while Y terminations in zones receiving extensive X inputs are smaller than normal or completely absent. Second, the effects of monocular enucleation are not altered by the imposition of visual deprivation. X axon arbors are still confined to appropriate zones of termination, and Y axons still sprout freely into denervated areas of the nucleus. See text for further details.

lid suture on the development of retinogeniculate X and Y axons. They discovered that the development of retinogeniculate Y axons from the deprived eye was severely disrupted by visual deprivation. Many contralaterally projecting Y axons, which normally terminate in both laminae A and C [1,2,53,55] were found to have severely reduced arbors or even no arbors at all in lamina A, whereas their arbors in lamina C were apparently normal (see Fig. 3). Similarly, ipsilaterally projecting Y axons had reduced terminations in lamina A1. In these same animals, on the other hand, deprived X axons were found to have arbors in the A-laminae which were more extensive than normal [54]. In fact, the deprived X axons seemed very similar to those which are seen in normal 3–4-week-old kittens (Refs. 54 and 57; and see Figs. 1 and 3), suggesting that the exuberant portions of their arbors which would normally have been lost were now retained in the deprived geniculate laminae. The failure of the deprived Y axons to develop normal-sized arbors in the A-laminae is consistent with the hypothesis that they were unable to displace the earlier-growing X axons, perhaps because normal visual stimulation is a requisite for their development [15]. Since X axon inputs to layer C are very sparse [53], the fact that deprived Y axons developed normally in this part of the LGN provided additional support for the conclusion that their failure to develop in the A-laminae was in fact due to the competitive superiority of deprived X axons in these laminae.

Experimental evidence for interactions between axons from the two eyes

The most obvious way to study the role of binocular interactions during development is to eliminate the inputs from one eye and assess the consequences of this manipulation on the development of inputs from the remaining eye. When cats are monocularly enucleated at birth, after axons from the two eyes are almost completely segregated into eye-specific laminae [37], intraocular injections of anatomical tracers reveal that inputs from the remaining eye expand into territory normally reserved for inputs from the enucleated eye [20,23]. When individual retinogeniculate axons are bulk-filled with HRP, many individual axons are found to have portions of their arbors extending into geniculate zones denervated by the enucleation [34,35]. Injecting single physiologically identified retinogeniculate axons with HRP demonstrates that the sprouting observed with the earlier methods is not a general phenomenon. Rather, only the Y class of retinal axons form these aberrant sprouts, whereas X axons and a small percentage of the Y axons are appropriately restricted (Ref. 17 and see Fig. 1). Moreover, the arbors of the X axons are larger and contain more boutons than normal, suggesting that they may have retained their immature exuberant form [57]. The alternative explanation, that the X axons go through a normal phase of retraction followed by a secondary phase of expansion caused by factors related to the enucleation, seems overly complex. This possibility, however, cannot be ruled out without data from a range of early postnatal ages. The fact that X axons retain (or re-acquire) their youthful exuberance suggests that portions of their arbors which would normally have been eliminated by the later-growing Y axons are spared this fate after enucleation. As with X axons, Y axons have larger terminal field volumes than normal, but, in contrast, have normal numbers of boutons [17]. Y axons may find that the denervated laminae offer an avenue for growth that offers less resistance than that involving the competitive displacement of the exuberant portion of X axon arbors already present in their normal target layer. There are at least three possible explanations for the observation that only Y axons exhibit translaminar sprouts after early postnatal enucleation. Thus, Y axons may sprout in these animals because: (1) they have some sort of advantage (such as greater light-evoked activity than X axons) in innervating denervated layers; (2) they develop later, and hence sprout into territory made available; or (3) they may be the only axons capable of sprouting, and X axons are not. Our experiments, described below, eliminate the first possibility, and while we cannot completely exclude the second, the third possibility seems more likely to us at present.

Do Y axons enjoy a competitive advantage in denervated layers?

In monocularly sutured cats, it seems likely that lid suture places the later growing Y axons from the deprived eye at a competitive disadvantage compared to X axons within deprived LGN laminae. In contrast, in monocularly enucleated cats, it is possible that the later growing Y axons have a competitive advantage when denervated territory is made available by removing the inputs from one eye neonatally. Thus, putting them at a possible disadvantage by lid suture might prevent their sprouting. In an attempt to test this possibility, monocular enucleation was combined with visual deprivation; that is, one eye was removed on the first day of postnatal life and the remaining eye was deprived of patterned vision by lid suture. In these cats, X axons were still found to be confined to their appropriate target laminae, while Y axons were again found to sprout heavily into the denervated layers (Ref. 18 and see Fig. 3). Therefore, even when X axons are placed at a competitive advantage by means of lid suture, they still fail to invade denervated territory. Y axons, even though competitively disadvantaged, still form sprouts. Furthermore, the arbors of Y axons in the normally innervated, deprived geniculate laminae, where X axons also terminate, are small or absent. In contrast, Y axon terminations in the C-laminae or in denervated layers, where X axons do not terminate, are as extensive as in normal cats or in monocularly enucleated cats without lid suture. This again suggests that interactions between X and Y axons normally determine the extent of their terminal arbors in the A-laminae.

Interestingly, even though X axons can apparently retain the exuberant portion of their terminal arbors after visual deprivation or monocular enucleation, they have no more boutons when these manipulations are combined. Therefore, it seems likely that numbers of boutons found for X axons after lid suture, monocular enucleation, or a combination of the two, reflects the maximum number that can be sustained in adulthood. The fact that X axons are capable of retaining more boutons than normal following such manipulations demonstrates that the normal process of retraction of their arbors or terminal boutons is not caused by the action of an intrinsic program (e.g., Ref. 3), but rather depends upon extrinsic factors. The extrinsic factor which seems most likely is competitive interactions with later-growing Y axons.

Do Y axons sprout because they develop later?

As mentioned previously, the development of the Y pathway lags somewhat behind that of the X pathway. The fact that Y axons sprout after early postnatal enucleation whereas X axons do not could be a simple reflection of the fact that the two classes of axons share a common developmental program which is implemented at different times. If monocular enucleation was performed even earlier in development, would X axons also form sprouts? To investigate this possibility, cats were studied in which monocular enucleation was performed on embryonic day 44 (E44), a time when axons from the two eyes overlap extensively in the LGN [37]. It is more problematic to define sprouting in such animals, because the formation of geniculate laminae is profoundly disrupted. Rather than the usual multilayered structure with alternating eye-specific laminae described earlier, only two layers form, a large dorsal layer and a considerably smaller ventral layer [4,16,43]. The terminations of the individual X and Y axons which have been recovered in these cats have been confined to all or some portion of the dorsal lamina. This, together with LGN soma size data [16], suggests that the smaller ventral layer probably corresponds to the ventral sublamina of layer C and laminae C1 and C2, while the dorsal layer probably corresponds to laminae A and A1 and the dorsal sublamina of layer C [8,16,21,22,24,33,36,39]. Even though normal lamination fails to develop in cats enucleated at E44, X axons still have arbors restricted to what would appear to be their appropriate regions of the LGN (Refs. 16 and 45, and see Fig. 1). That is, contralaterally projecting X axons terminate in the upper third of the dorsal layer, an area consistent with the location of lamina A, while ipsilaterally projecting X axons arborize in the middle of the dorsal layer, a region consistent with the location of lamina A1. On the other hand, many Y axons have arbors which extend throughout the dorsal–ventral extent of the dorsal layer; that is, they arborize in portions of the LGN avoided by the X axons which are apparently the regions which would have been innervated by the enucleated eye (Refs. 16 and 45 and see Fig. 1). Therefore, even when enucleation is performed as early as E44, the pattern of results is similar to that found with early postnatal enucleation in that X axons arbors are apparently appropriately restricted, whereas Y axons terminate freely in regions inappropriate for their eye of origin.

Are X axons incapable of sprouting?

This difference in the response of X and Y axons to neonatal or prenatal monocular enucleation raises the possibility that these two cell classes differ fundamentally in their response to the removal of binocular interactions, particularly since the prenatal enucleation at E44 was performed about 3 weeks earlier than in the neonatal experiments while the development of putative X and Y cells in the retina is offset by only about 4 days [59]. Therefore, X axons may be intrinsically capable of making normal arbors in the appropriate parts of the LGN, while Y axons may lack this ability.

It remains possible that the binocular interactions necessary for X axons to remain restricted in arbor size have occurred by E44, and that, if binocular interactions were eliminated even earlier, then X axons might also innervate inappropriate regions of the LGN. Sretavan and Shatz [48] studied fetuses in which enucleation was performed at E23 and axons were bulk-filled at E59. Surprisingly, they found that all axons were restricted in dorsal–ventral extent, arborizing either in the middle or outer one-third of the nucleus (i.e., lamina A1 or A, respectively). Since these axons cannot be physiologically classified at E59, it could not be determined whether the appropriately targeted axons (i.e., those terminating in the outer third if from the contralateral retina, or middle third if from the ipsilateral retina) were X or Y or a combination of both. In either event, however, these results demonstrate that X axons do not sprout even when enucleation is performed very near the beginning of retinal neurogenesis [59,60].

Mechanisms of development of retinogeniculate X and Y axons

It is clear that cells located in the same structure, the retina, with axons projecting to the same target, the LGN, are influenced in their development by different sets of factors. Our experiments suggest interactions between axons from the two eyes as well as between different functional cell classes from the same eye in development. These data in turn point to important differences between retinogeniculate X and Y axons, both in the development of their laminar locations and in development of their arboreal extents within the A-laminae of the LGN.

Differences in mechanisms of laminar specificity

The experiments involving monocular enucleation either at birth or at E44 indicate clearly that the laminar location of X arbors is not altered by this manipulation. Thus, binocular interactions are either not required by X axons to develop arbors of appropriate laminar specificity, or else the binocular interactions required occur very early in development, prior to E44. However, even when enucleations are performed at E23, well before retinal axons have reached the optic chiasm and hence can interact, retinogeniculate arbors are only as tall as the height of a single lamina [48]. Therefore, X axons certainly do not require binocular interactions to develop arbors with heights restricted to approximately that of a single LGN lamina (A or A1). This feature of X axon arbors thus must be determined innately or by factors intrinsic to one eye.

Y axons, on the other hand, sprout significantly into denervated zones following removal of one eye. Y axons thus require binocular interactions to develop arbors that are restricted to laminae appropriate to their eye of origin.

Differences in postnatal arbor development and stabilization within LGN laminae

Within lamina A or A1, X and Y axons arising from the same eye follow distinctly different modes of development. X axons are characterized by an initial period of exuberance followed by pruning or retraction [57]. It is likely that the X axon arbors are actively pruned, because a number of experimental manipulations permit

them to retain the exuberant portions of their arbors [17,18,54], and we have suggested that the most likely agent for this process is the later-growing Y axons. This sort of overgrowth–retraction strategy is generally thought to be a common developmental program [5–7,30,31]. Y axon arbors, on the other hand, appear to develop their adult form through a process of monotonic growth, eschewing a phase of retraction, a seemingly less common mode of development, and clearly very different from that employed by X axons.

If the exuberant portions of X cell axonal arbors in the LGN are dislodged during development by later-growing Y axons, it is possible that the connections which are eliminated are onto cells destined to be Y cells (see Fig. 2). That is, X axons may not be overly specific for their target cells within the A-laminae, at least early in development. Thus, monocular lid suture, which causes X axons to retain exuberant arbors in deprived lamina A or A1, leads also to cells in these laminae that have physiological properties typical of X cells but morphologies more characteristic of adult Y cells (Ref. 12; and cf. Ref. 61).

Finally, our experiments suggest a delicate combination of intrinsic and extrinsic factors that shape retinogeniculate projections in cats. X axons, innervating the LGN earlier, probably have their laminar specificity determined by cues intrinsic to these axons or to their target locations in the LGN. Thus, X axons might play a unique role in defining ocular territory within the LGN during development. The transverse extent of X axons within the A-laminae, on the other hand, is apparently determined by extrinsic factors such as interactions with Y axons from the same eye. Y axons, in contrast, depend on extrinsic factors such as binocular interactions for appropriate laminar restriction, but must in turn display a high degree of specificity for their target neurons to be able to dislodge X axons from these same cells.

Acknowledgements

We gratefully acknowledge the invaluable contributions of our many collaborators, in particular M. Esguerra, D.O. Frost, A.L. Humphrey, M.F. Kritzer, C.J. Shatz, S.M. Sherman, D.W. Sretavan and R.E. Weller. Supported by NIH grant EY07023.

References

1 Bowling DB, Michael CR. *Projection patterns of single physiologically characterized optic tract fibres in cat.* Nature 1980;286:899–902.
2 Bowling DB, Michael CR. *Terminal patterns of single physiologically characterized optic tract fibers in the cat's lateral geniculate nucleus.* J Neurosci 1984;4:198–216.
3 Brown MC, Jansen JKS, Van Essen D. *Polyneuronal innervation of skeletal muscle in new-born rats and its elimination during maturation.* J Physiol (Lond) 1976;261:387–422.
4 Chalupa LM, Williams RW. *Organization of the cat's lateral geniculate nucleus following interruption of prenatal binocular competition.* Hum Neurobiol 1984;3:103–107.
5 Changeux J-P, Danchin A. *Selective stabilisation of developing synapses as a mechanism for the specification of neuronal networks.* Nature 1976;264:705–712.
6 Cowan WM, Fawcett JW, O'Leary DDM, Stanfield BB. *Regressive events in neurogenesis.* Science 1984;225:1258–1265.

7 Easter SS Jr, Purves D, Rakic P, Spitzer NC. *The changing view of neural specificity.* Science 1985;230:507–511.
8 Famiglietti EV Jr. *Another look at lateral geniculate lamination in the cat.* Soc Neurosci Abstr 1975;1:41.
9 Friedlander MJ, Lin C-S, Sherman SM. *Structure of physiologically identified X- and Y-cells in the cat's lateral geniculate nucleus.* Science 1979;204:1114–1117.
10 Friedlander MJ, Lin C-S, Stanford LR, Sherman SM. *Morphology of functionally identified neurons in lateral geniculate nucleus of the cat.* J Neurophysiol 1981;46:80–129.
11 Friedlander MJ, Martin KAC, Vahle-Hinz C. *The structure of the terminal arborizations of physiologically identified retinal ganglion cell Y axons in the kitten.* J Physiol (Lond) 1985;359:293–313.
12 Friedlander MJ, Stanford LR, Sherman SM. *Effects of monocular deprivation on the structure/function relationship of individual neurons in the cat's lateral geniculate nucleus.* J Neurosci 1982;2:321–330.
13 Fukuda Y, Hsiao C-F, Watanabe M, Ito H. *Morphological correlates of physiologically identified Y-, X- and W-cells in cat retina.* J Neurophysiol 1984;52:999–1013.
14 Garraghty PE. *Mixed cells in the cat lateral geniculate nucleus: functional convergence or error in development?* Brain Behav Evol 1985;26:58–64.
15 Garraghty PE, Frost DO, Sur M. *The morphology of retinogeniculate X- and Y-cell axonal arbors in dark-reared cats.* Exp Brain Res 1987;66:115–127.
16 Garraghty PE, Shatz CJ, Sretavan DW, Sur M. *Prenatal monocular enucleation in the cat: effects on the morphology of retinogeniculate axons and formation of laminae in the lateral geniculate nucleus.* Invest Ophthal Vis Sci Suppl 1987;28:335.
17 Garraghty PE, Sur M, Weller RE, Sherman SM. *The morphology of retinogeniculate X and Y axon arbors in monocularly enucleated cats.* J Comp Neurol 1986;251:198–215.
18 Garraghty PE, Sur M, Sherman SM. *The role of competitive interactions in the postnatal development of X and Y retinogeniculate axons.* J Comp Neurol 1986;251:216–239.
19 Guillery RW. *The laminar distribution of retinal fibers in the dorsal lateral geniculate nucleus of the cat: a new interpretation.* J Comp Neurol 1970;138:339–368.
20 Guillery RW. *Experiments to determine whether retinogeniculate axons can form translaminar collateral sprouts in the dorsal lateral geniculate nucleus of the cat.* J Comp Neurol 1972;146:407–420.
21 Guillery RW. *A speculative essay on geniculate lamination and its development.* Progr Brain Res 1979;51:403–418.
22 Guillery RW, Oberdorfer MD. *A study of fine and coarse retinofugal axons terminating in the geniculate C laminae and in the medial interlaminar nucleus of the mink.* J Comp Neurol 1977;176:515–526.
23 Hickey TL. *Translaminar growth of axons in the kitten dorsal lateral geniculate nucleus following removal of one eye.* J Comp Neurol 1975;161:359–382.
24 Hickey TL, Guillery RW. *An autoradiographic study of retinogeniculate pathways in the cat and the fox.* J Comp Neurol 1974;156:239–254.
25 Hoffmann K-P, Stone J, Sherman SM. *Relay of receptive-field properties in dorsal lateral geniculate nucleus of the cat.* J Neurophysiol 1972;35:518–531.
26 Leventhal AG. *Morphology and distribution of retinal ganglion cells projecting to different layers of the dorsal lateral geniculate nucleus in normal and Siamese cats.* J Neurosci 1982;2:1024–1042.
27 Leventhal AG, Rodieck RW, Dreher B. *Central projections of the cat retinal ganglion cells.* J Comp Neurol 1985;237:216–226.
28 Mangel SC, Wilson JR, Sherman SM. *Development of neuronal response properties in the cat dorsal lateral geniculate nucleus during monocular deprivation.* J Neurophysiol 1983;50:240–264.

29 Mason CA, Robson JA. *Morphology of retino-geniculate axons in the cat.* Neuroscience 1979;4:79–97.
30 Purves D, Lichtman JW. *Elimination of synapses in the developing nervous system.* Science 1980;210:153–157.
31 Purves D, Lichtman JW. *Specific connections between nerve cells.* Annu Rev Physiol 1983;45:553–565.
32 Rakic P. *Development of visual centers in the primate brain depends on binocular competition before birth.* Science 1981;214:928–931.
33 Rioch DM. *Studies on the diencephalon of carnivora. I. The nuclear configuration of the thalamus, epithalamus and hypothalamus of the dog and cat.* J Comp Neurol 1929;49:1–119.
34 Robson JA. *Abnormal axonal growth in the dorsal lateral geniculate nucleus of the cat.* J Comp Neurol 1981;195:453–476.
35 Robson JA, Mason CA, Guillery RW. *Terminal arbors of axons that have formed abnormal connections.* Science 1978;201:635–637.
36 Rodieck RW. *Visual pathways.* Annu Rev Neurosci 1979;2:193–225.
37 Shatz CJ. *The prenatal development of the cat's retinogeniculate pathway.* J Neurosci 1983;3:482–499.
38 Shatz CJ, Kirkwood P. *Prenatal development of functional connections in the cat's retinogeniculate pathway.* J Neurosci 1984;4:1378–1397.
39 Sherman SM. *Functional organization of the W-, X- and Y-cell pathways in the cat: a review and hypothesis.* In: Sprague JM, Epstein AN, eds. *Progress in psychobiology and physiological psychology, vol. 11.* Orlando, FL: Academic, Press 1985;233–314.
40 Sherman SM. *Development of retinal projections to the cat's lateral geniculate nucleus.* Trends Neurosci 1985;8:350–355.
41 Sherman SM, Spear PD. *Organization of visual pathways in normal and visually deprived cats.* Physiol Rev 1982;62:738–855.
42 Sherman SM, Hoffmann K-P, Stone J. *Loss of a specific cell type from the dorsal lateral geniculate nucleus in visually deprived cats.* J Neurophysiol 1972;35:532–541.
43 Shook BL, Chalupa LM. *Organization of geniculocortical connections following prenatal interruption of binocular interactions.* Dev Brain Res 1986;28:47–62.
44 So YT, 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 1979;36:533–550.
45 Sretavan DW, Garraghty PE, Sur M, Shatz CJ. *Development of retinogeniculate axon arbors following prenatal unilateral enucleation.* Soc Neurosci Abstr 1985;11:805.
46 Sretavan DW, Shatz CJ. *Prenatal development of individual retinogeniculate axons during the period of segregation.* Nature 1984;308:845–848.
47 Sretavan DW, Shatz CJ. *Prenatal development of retinal ganglion cell axons: segregation into eye-specific layers within the cat's lateral geniculate nucleus.* J Neurosci 1986;6:234–251.
48 Sretavan DW. Shatz CJ. *Prenatal development of cat retinogeniculate axon arbors in the absence of binocular interactions.* J Neurosci 1986;6:990–1003.
49 Stanford LR, Friedlander MJ, Sherman SM. *Morphology of physiologically identified W-cells in the C laminae of the cat's lateral geniculate nucleus.* J Neurosci 1981;1:578–584.
50 Stanford LR, Friedlander MJ, Sherman SM. *Morphological and physiological properties of geniculate W-cells: a comparison with X- and Y-cells.* J Neurophysiol 1983;50:582–608.
51 Stone J, Dreher B, Leventhal A. *Hierarchical and parallel mechanisms in the organization of visual cortex.* Brain Res Rev 1979;1:345–394.
52 Sur M. *Development and plasticity of retinal X and Y axon terminations in the cat's lateral geniculate nucleus.* Brain Behav Evol 1988; in press.
53 Sur M, Esguerra M, Garraghty PE, Kritzer MF, Sherman SM. *Morphology of physiologically identified retinogeniculate X and Y axons in the cat.* J Neurophysiol 1987;58:1–32.

54 Sur M, Humphrey AL, Sherman SM. *Monocular deprivation affects X- and Y-cell retinogeniculate terminations in cats.* Nature 1982;300:183–185.
55 Sur M, Sherman SM. *Retinogeniculate terminations in cats: morphological differences between X and Y cell axons.* Science 1982;218:389–391.
56 Sur M, Sherman SM. *Linear and nonlinear W-cells in the C-laminae of the cat's lateral geniculate nucleus.* J Neurophysiol 1982;47:869–884.
57 Sur M, Weller RE, Sherman SM. *Development of X- and Y-cell retinogeniculate terminations in kittens.* Nature 1984;310:246–249.
58 Tumosa N, McCall MA, Spear PD. *Effects of monocular deprivation on W cells in the C laminae of the cat's lateral geniculate nucleus.* Invest Ophthal Vis Sci Suppl 1987;28:405.
59 Walsh C, Polley EH. *The topography of ganglion cell production in the cat's retina.* J Neurosci 1985;5:741–750.
60 Walsh C, Polley EH, Hickey TL, Guillery RW. *Generation of cat retinal ganglion cells in relation to central pathways.* Nature 1983;302:611–614.
61 Weller RE, Humphrey AL. *Structural correlates of functional subgroups among X-cells in the cat LGN.* Soc Neurosci Abstr 1985;11:318.
62 Wilson PD, Rowe MH, Stone J. *Properties of relay cells in the cat's lateral geniculate nucleus: a comparison of W-cells with X- and Y-cells.* J Neurophysiol 1976;39:1193–1209.