



Retinogeniculate Terminations in Cats: Morphological Differences between X and Y Cell Axons

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sensory” on the basis of both corticocortical connectivity and neuronal responses to more than one modality of sensory stimulation (13) also showed relatively high levels of [³H]naloxone binding. These fields included the superior temporal polysensory cortex (Fig. 2a), the ventral temporal polysensory cortex (14), part of the inferior parietal lobule (15), and the orbital frontal cortex (Fig. 3a) (14). The ventral temporal and orbital frontal fields had among the highest levels of binding in the cortex.

If increased opiate receptor density indicates greater functional importance, then the laminar and areal patterns of opiate receptors shown by the present investigation indicate that opiates are important in the modulation of specific cortical elements. It appears that opiates may predominantly influence the outflow of cortical fields and those fields involved in polymodal information processing and limbic functions.

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16. We thank E. V. Evarits, E. G. Jones, M. Mishkin, W. T. Newsome, and W. Stewart for their comments on the manuscript.

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Retinogeniculate Terminations in Cats: Morphological Differences Between X and Y Cell Axons

Abstract. We injected horseradish peroxidase into single, physiologically identified, optic tract axons of X and Y cells in cats and studied their termination patterns in the lateral geniculate nucleus. All X cell axons innervate lamina A or A1 in narrow zones, and some sparsely innervate the medial interlaminar nucleus. All Y cell axons have broad terminal zones in laminae A and C (from the contralateral retina) or lamina A1 (if ipsilateral), and most innervate the medial interlaminar nucleus densely.

The cat's retinogeniculocortical pathways are represented by W, X, and Y cells in the retina and in the lateral geniculate nucleus. These form three parallel, largely independent neural systems that appear to analyze different

features of the visual scene (1). We know a great deal about physiological differences among these cell classes but little about morphological differences that underlie the physiology. This is because of the difficulty of directly identifying W,

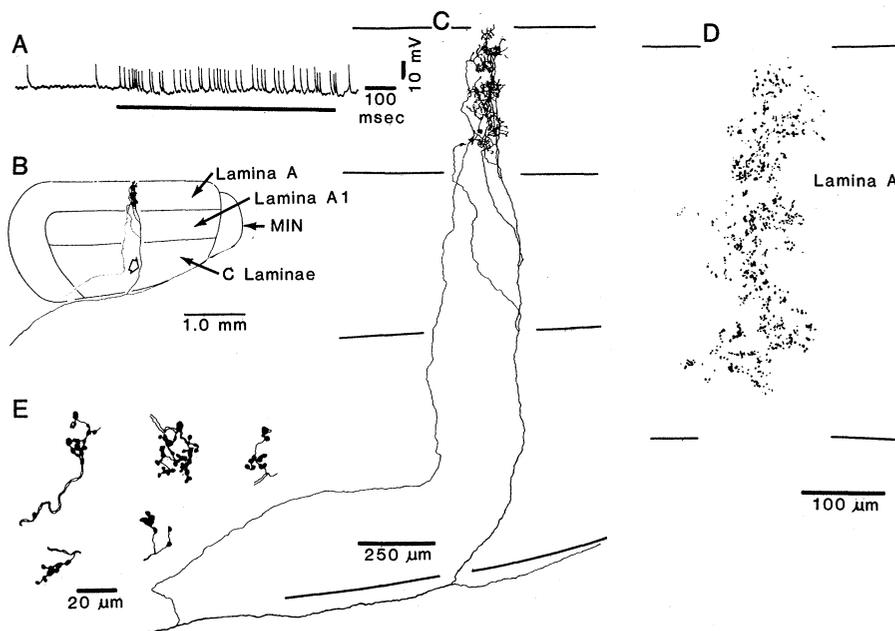


Fig. 1. Data from an X cell axon driven by the right eye (contralateral to the recording site). The axon's receptive field had an ON center of 0.5° diameter located 9° from the vertical meridian and 2° below the horizontal zero parallel of the visual field. The conduction latency from the optic chiasm to the recording and injection site [open arrow in (B)] was 0.9 msec. (A) Intracellular recording. The bar below part of the trace indicates the presence of a small spot of light placed in the receptive field center. Note the sustained response to this stimulus. (B) Drawing of the left lateral geniculate nucleus in the coronal plane with the axon shown. Compressed in this view are 21 consecutive, 100- μ m-thick coronal sections. The parent trunk of the axon is 2 μ m thick, and its geniculate termination is limited to lamina A. The thin medialward branch continues posteriorly (see text). MIN, medial interlaminar nucleus. (C) More detailed drawing of the terminal zone in lamina A. (D) Location and shape of the 793 terminal boutons in lamina A, reconstructed from three consecutive, 100- μ m-thick coronal sections. For clarity, the preterminal axon branches are not shown. (E) Morphology of typical terminal bouton arrangements in lamina A. Note both the clustering of the boutons and the relatively homogeneous composition of the medium-sized, spherical type (see text, and compare with Fig. 2E).

X, or Y cells for morphological analysis. Such morphological knowledge is essential for our understanding of how these different neural systems are functionally organized. The different morphological features of geniculate W, X, and Y cells in cats (2) have been examined by the technique of intracellular injection of horseradish peroxidase (HRP) into physiologically identified neurons (3). We now describe our use of the same techniques to study the functional organization and morphology of X and Y cell retinogeniculate terminals. We found a number of morphological differences between these two physiological pathways, and these differences are important to the way retinal X and Y cells transmit visual information centrally.

Our general experimental methods have been described (2, 4). Optic tract axons were recorded first extracellularly within or ventral to the lateral geniculate nucleus (see Figs. 1, A and B, and 2, A and B), and they were identified as X cell or Y cell by standard criteria (5). They were then impaled. Identification was verified intracellularly, and then HRP was injected into the axon by iontophoresis with depolarizing pulses of up to 20 nA at 4 to 8 Hz for several minutes. After

a 2- to 20-hour survival for each injected axon, the cat was killed for histological examination.

We have thus obtained structure-function correlates for 16 X cell and 12 Y cell axons. In this report, we describe the appearance of terminal zones within the main geniculate laminae [that is, the A and C laminae (6)]. The morphology correlates well with the X cell or Y cell physiological classification, but we found no obvious morphological correlate to ON and OFF center responses. Figure 1, B to D, shows the morphology of a typical X cell terminal zone, and Fig. 2, B to D, does likewise for a typical Y cell terminal zone. Our data for Y cells confirm and extend those of Bowling and Michael (7). Five major morphological differences can be described between retinogeniculate X cell and Y cell axons. These include differences in axon diameter, axon location within the optic tract, regions of termination, geometry of terminal fields, and the structure and arrangement of individual boutons.

1) Within the optic tract, X cell axons are thinner than Y cell axons. We measured axon diameters to the nearest 0.5 μm (2). The mean diameter for 13 X cell axons that we could trace through the

optic tract was 2 μm , and the range was 1.5 to 2.5 μm . The corresponding values for the 12 Y cells were 3 μm and 2 to 4 μm . Within the lateral geniculate nucleus, however, X cell and Y cell axons branch repeatedly before terminating. Since the preterminal branches of X cell and Y cell axons are equally fine, fiber diameter within the lateral geniculate nucleus should not be used to infer cell type.

2) Within the optic tract, X cell axons tend to lie dorsal to Y cell axons, with little or no overlap. All of the 13 X cell axons lie in the dorsal third of the optic tract. All of the 12 Y cell axons lie ventral to the X cell axons. These observations are consistent with prior reports that thicker axons are more ventrally located than thinner ones in the optic tract (8).

3) Y cell axons have more extensive and more widely branching terminal fields than do X cell axons. Every X and Y cell axon in our material exhibits a terminal zone in lamina A or A1, although terminal zones elsewhere are more variable (see below). From the contralateral retina, Y cell axons branch extensively to provide large terminal fields in laminae A and C and in the superior colliculus. Those from the ipsilateral retina branch to innervate lamina A1 and the superior colliculus. Most of the Y cell axons also densely innervate the medial interlaminar nucleus (a subdivision of the lateral geniculate nucleus), but a minority (5 of 12 in our sample) do not (Fig. 2B). In the earlier description (7), each of the nine recovered Y cells innervated the medial interlaminar nucleus. To date, we have not seen obvious physiological differences between Y cells that innervate the medial interlaminar nucleus and those that do not, nor do these groups of Y cells obviously differ with regard to their terminal zones within the A laminae. In contrast to the Y cell terminal zones, those of X cells lie only in lamina A or A1. However, 2 of the 12 X cell axons from the contralateral eye branch to yield a few terminals in lamina C. Eleven X cell axons continue posteriorly into the brachium of the superior colliculus (Fig. 1B). Of these, four issue sparse terminals into the medial interlaminar nucleus.

4) Perhaps the clearest difference between X cell and Y cell terminal zones lies in their geometry within the A laminae (see Figs. 1 and 2). The terminal zones of X cells are small and typically cylindrical, with the long axis perpendicular to the geniculate laminae. Y cell terminal zones are more variable in

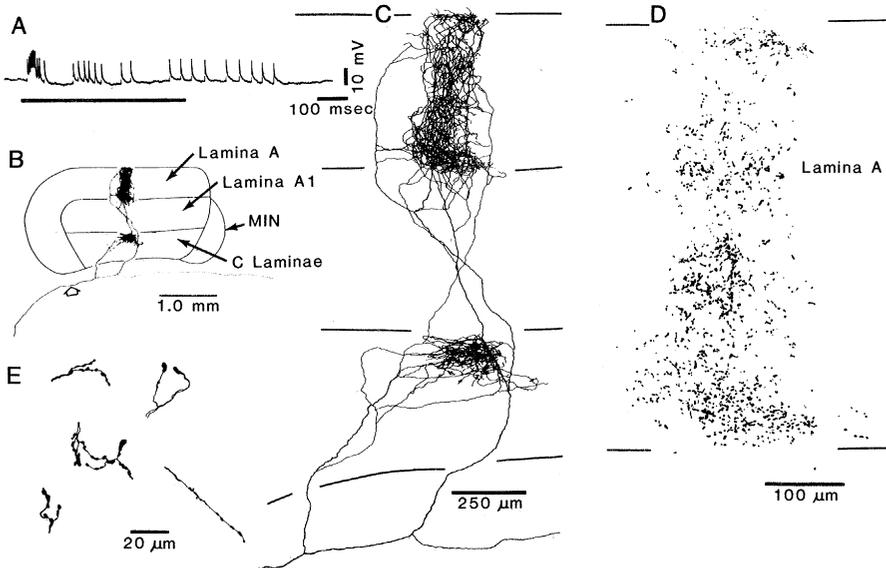


Fig. 2. Data from a Y cell axon driven by the right eye (contralateral to the recording site). Most conventions are as in Fig. 1. The axon's receptive field had an OFF center of 1.2° diameter located 11.5° from the vertical meridian and 3.5° below the horizontal zero parallel of the visual field. The conduction latency from the optic chiasm to the recording and injection site [open arrow in (B)] was 0.5 msec. (A) Intracellular recording. The bar below part of the trace indicates the presence of a small black spot placed in the receptive field center. Note the transient response to this stimulus. (B) Drawing of the left lateral geniculate nucleus and axon from 27 consecutive, 100- μm -thick coronal sections. The parent trunk of the axon is 4 μm thick, and the medialward branch passes posteriorly beyond the medial interlaminar nucleus (MIN), with no terminals there. Geniculate terminals are limited to laminae A and C. (C) More detailed drawing of the terminal zones in laminae A and C. (D) Location and shape of the 1405 terminal boutons in lamina A, reconstructed from six consecutive, 100- μm -thick coronal sections. (E) Morphology of typical terminal bouton arrangements in lamina A. Note both the lack of bouton clustering and their relatively heterogeneous composition (see text and compare with Fig. 1E).

shape and much larger (roughly two to three times wider and almost an order of magnitude larger in volume than those of X cells). The mean width and range of terminal zones for X cell axons are 140 μm and 100 to 170 μm , and for Y cell axons are 293 μm and 220 to 410 μm . On average, more of the terminal zone of Y cell axons is distributed in the bottom half of lamina A or A1, whereas no such division is seen for the X cell axons. Within the medial interlaminar nucleus, Y cell terminations spread predominantly dorsoventrally.

5) The terminal boutons of X cell and Y cell axons generally differ (Figs. 1, D and E, and 2, D and E). Both have small spherical ($< 2 \mu\text{m}$ in diameter), medium-sized spherical (2 to 5 μm), and large ($> 5 \mu\text{m}$) crenulated boutons (9). The X cell terminals more homogeneously consist of the medium-sized boutons, whereas the Y cell terminals are more heterogeneous. Furthermore, X cell boutons tend to cluster together, whereas those of Y cells tend to occur singly or on short, fine stalks (Figs. 1E and 2E). Consequently, X cell axons tend to have fewer boutons that occur in higher density than do those of Y cells.

Several of these morphological features can be related to those described for geniculate neurons (2, 10). (i) The narrower and more vertically arranged terminal zones of X cell axons closely match the dendritic geometry of geniculate X cells, whereas the wider terminal zones of Y cell axons are more closely related to the radial arrangement of geniculate Y cell dendrites. (ii) The observation that Y cell terminal zones are larger and more widely distributed than X cell terminal zones is consistent with the suggestion that more divergence occurs in the retinogeniculate Y cell pathway than in the X cell pathway, so that more geniculate Y cells than X cells are innervated by each optic tract axon. (iii) The clustering of X cell terminal boutons might be related to the clustered dendritic appendages that are a much more common feature of geniculate X cells than of Y cells.

The clear morphological differences between X and Y cell axons indicate that the X and Y cell pathways differ markedly in their retinogeniculate projections. Previously, morphological differences have been described between geniculate X and Y cells (2) and their cortical terminations (11). These data, then, reinforce the significance of the organization of the central visual pathways into cell types that can be physiologically distinguished. The anatomical differences in

the X and Y cell pathways show that these indeed represent distinctly different neural circuits.

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Hemispheric Asymmetries in the Behavioral and Hormonal Effects of Sexually Differentiating Mammalian Brain

Abstract. *Estrogen pellets were placed in either the right or left hypothalamus of newborn female rats so that only one side of this brain area was exposed to the postnatal masculinizing and defeminizing effects of the hormone. The effects of estrogen on gonadotropin secretion and reproductive behavior depended on both the region and the side of implantation. Exposure of the left hypothalamus to estrogen resulted in defeminized development. Exposure of the right hypothalamus to estrogen resulted in masculinized development. Thus the response of the developing hypothalamus to gonadal steroids may be asymmetric.*

During a restricted period of perinatal development, gonadal steroids act on the mammalian hypothalamus to masculinize or defeminize reproductive functions, including behavior (1). Masculinization increases male sexual behavior in adult males or females exposed to testosterone or its metabolite, estradiol (E_2); defeminization decreases female sexual behavior and eliminates positive-feedback effects on the secretion of luteinizing hormone (LH) in adults exposed to E_2 . These two aspects of sexual differentiation are independent processes involving separate regions of the hypothalamus (2). We suggest here that the hypothalamus develops asymmetrically with re-

spect to sexual differentiation. When we exposed only the left side of the hypothalamus of neonatal rats to gonadal steroid, development was defeminized. When we exposed only the right side of the hypothalamus to gonadal steroid, development was masculinized.

Between 24 and 48 hours after birth, 91 female rat pups received bilateral intrahypothalamic implants of steroid (3). Thirty control pups received implants of cholesterol. Experimental females received E_2 on one side (31 right, 30 left) and cholesterol on the other. We used E_2 as the hormonal stimulus for sexual differentiation because it is the active metabolite of testosterone for this process