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Lateral Geniculate Projections to the Superficial Layers of Visual Cortex in the Tree Shrew

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ABSTRACT

Our recent studies of tree shrew striate cortex have focused on the organization of lateral geniculate projections to layer IV and the projections from IV to layer III. Although these pathways play an important role in determining the response properties of layer III neurons, there are additional pathways from the lateral geniculate nucleus (LGN) that terminate directly in layer III. Previous studies provided evidence that these projections originate from layers 6 and 3 of the LGN and terminate in different subdivisions of layer III. In this study we used injections of biocytin to examine the projections of layers 6 and 3 to the cortex in more detail.

Consistent with earlier work, we found that LGN layer 6 projects heavily to lower IIIc, while LGN layer 3 terminates densely in layer IIIb and sparsely throughout layers IIIa–I. In addition, we found that neurons in layers 6 and 3 have collateral projections: neurons in LGN layer 6 project to the bottom of layer IVb and sparsely to I–IIIb; neurons in LGN layer 3 project sparsely to layers V and VI and to the middle of IV.

These patterns of projections are significant in the light of our studies of the connections from cortical layer IV to layer III. LGN projections to the superficial layers are organized into parallel pathways that exert selective influence over different populations of neurons in layers I–III and on the layer IV neurons that supply them.

Key words: W-cells, striate cortex, geniculocortical, parallel pathways, biocytin

The neurons in layer IV of striate cortex are the primary target of axons from the lateral geniculate nucleus (LGN), and serve as the major route by which visual activity reaches neurons in the superficial layers (layers I–III) (Hubel and Weisel, '72; Harting et al., '73; Lund, '73; Fitzpatrick et al., '85). However, LGN axon terminals are not restricted to layer IV; indeed, a significant number of LGN fibers pass through layer IV to terminate directly in the superficial layers (LeVay and Gilbert, '76; Carey et al., '79; Fitzpatrick et al., '83). An important clue to the significance of these two routes to the superficial layers lies in the types of LGN neurons that supply them. Axons that terminate directly in the superficial layers arise from small pale staining neurons that are the targets of the finest caliber retinal axons; in contrast, LGN axons that supply layer IV arise from larger neurons that are targets of correspondingly larger retinal fibers (Guillery, '70; Carey et al., '79; Itoh et al., '82; Fitzpatrick et al., '83; Conley et al., '84; Diamond et al., '85). These anatomical differences correspond with differences in the response properties of the two groups: LGN neurons projecting to the superficial layers are characterized as "W-cells" and are distinguished in several ways from the "X" and "Y" cells that provide the input to layer IV (Cleland et al., '76; Wilson et al., '76; Sherman, '85; Norton and Casagrande, '82; Irvin et al., '86). For example, W-cells are sluggish in their responsiveness to visual stimulation and, in the cat at least, they lack the fine spatial and temporal resolution that characterize the X- and Y-cell pathways. Thus the direct projections from the LGN and those that are channeled through layer IV convey different types of information to the superficial layers.

The goal of this study was to provide a better understanding of the anatomical relationship between these two routes to the superficial layers. Our interest in this issue grew out of a recent study of the organization of efferent projections of layer IV in the tree shrew striate cortex (Muly and Fitzpatrick, '91, '92). We found that the superficial layers consist of three distinct laminar subdivisions that receive projections from different tiers of layer IV. This raises the question: What is the relationship, if any, between the

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highly ordered pattern of projections from layer IV to the superficial layers and the direct projections from the LGN?

Previous studies using bulk injections of wheatgerm agglutinin conjugated to horseradish peroxidase (WGA-HRP) into the superficial layers of the cortex or into different combinations of LGN layers provided evidence for two distinct sources of projections to the superficial layers in the tree shrew, LGN layers 3 and 6 (Carey et al., '79; Conley et al., '84). In addition, the study by Conley et al. ('84), concluded that these two small-celled layers terminate in different parts of layer III. It was argued that LGN layer 3 projects to the upper part of layer III (IIIa and IIIb) and to a lesser extent layer I, while layer 6 projects to the lowest part of layer III (layer IIIc), near its border with layer IV. Since these subdivisions of layer III are targets of neurons that lie in different tiers of layer IV (Muly and Fitzpatrick, '91, '92), the results suggest a specific relationship between the direct projections to the superficial layers and those conveyed by layer IV.

In this report, we describe experiments in which we made small extracellular injections of biocytin into LGN layers 3 and 6 to examine the morphology and the laminar distribution of LGN axons that supply the superficial layers of tree shrew striate cortex. The results presented here confirm the earlier work, and in addition they show that individual neurons that project to the superficial layers give rise to collaterals that arborize in deeper cortical layers, including specific subdivisions of layer IV. We argue that LGN projections to the superficial layers are organized into parallel pathways that exert selective influence over different populations of neurons in layers I–III and on the layer IV neurons that supply them. Some of these results have appeared in abstract form (Usrey et al., '91).

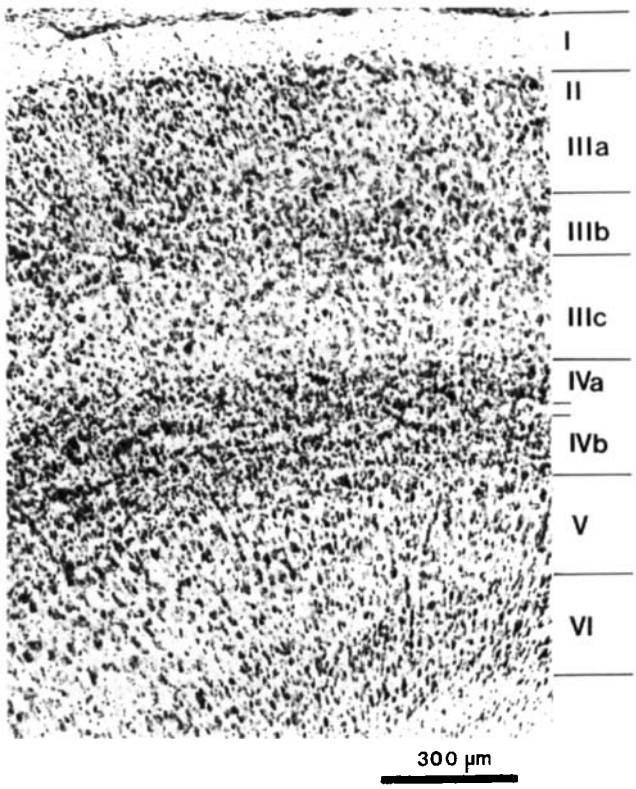

Fig. 1. Photomicrograph of a Nissl-stained section of tree shrew striate cortex. Layer IV is subdivided by a cell-sparse cleft into IVa and IVb. Layer III is subdivided on the basis of cell density into IIIa, IIIb, and IIIc.

MATERIALS AND METHODS

Injections of biocytin

A total of five tree shrews were used in this study. Surgical anesthesia was induced with a mixture of ketamine and xylazine (180 mg/kg:5.75 mg/kg, i.m.), and maintained with supplements of sodium pentobarbital (0.1–0.2 ml of 10 mg/ml i.p.). Tree shrews were placed in a stereotaxic apparatus; an incision was made in the scalp and a small hole was drilled in the cranium over the temporal cortex. A micropipette was angled at 30° from vertical and inserted into the brain. Layers within the LGN were selected for injection by recording through the injection pipette the responses of neurons to flashes of light to the left or right eye. The pipette contained a mixture of biocytin (Sigma; 5% in saline) and was broken to achieve a tip diameter of 10–15 μm. After the appropriate site for injection was located, 3–4 μA of pulsed current (7 seconds on, 7 seconds off) was passed through the tip for 15–20 minutes. After a 2-day survival, the animal was sacrificed with an overdose of sodium pentobarbital. It was then perfused with a saline rinse followed by 4% paraformaldehyde in 0.1 M phosphate buffer, pH 7.4. Following fixation, the brain was rinsed in 10% sucrose (0.1 M phosphate buffer) and immersed overnight in a 20% sucrose solution.

Histology

The brains were sectioned at 50 μm on a freezing microtome, rinsed three times in 0.01 M phosphate-buffered saline (PBS), and incubated in the avidin biotin complex solution (Vector Laboratories) diluted in PBS and 0.75% Triton for 2 hours on a shaker table. Following three rinses in PBS, the sections were placed in 0.1% glutaraldehyde for 4 minutes, rinsed in PBS, and then reacted for peroxidase histochemistry by using diaminobenzidine (DAB) intensified with nickel and cobalt (Adams, '81). They were then mounted and allowed to dry on gel-coated slides before being stained with thionin, dehydrated, cleared, and coverslipped in permount.

Data analysis

In order to document the complete pattern of projections from LGN layers 3 and 6, a single section through the center of the terminal field in the striate cortex was selected and all of the labeled fibers were drawn. The contribution of individual fibers to the total pattern was assessed by reconstructing single-labelled fibers through multiple sections. These drawings were made with the aid of a camera lucida and 63× oil objective.

Comparisons of bouton size and axon caliber were made with the aid of a camera lucida and 100× oil objective. Biocytin-filled fibers served as the source of data on layers 3 and 6; HRP-filled fibers from a previous study (Raczkowski and Fitzpatrick, '90) served as the source of data on the other LGN layers. All measurements of fiber diameter were made in the subcortical white matter. Three different groups were compared: axons from LGN layer 6, axons from LGN layer 3, and axons from LGN layers 1, 2, 4, and 5. In each group, five axons were measured; each axon was measured at five different points along its length. Mean

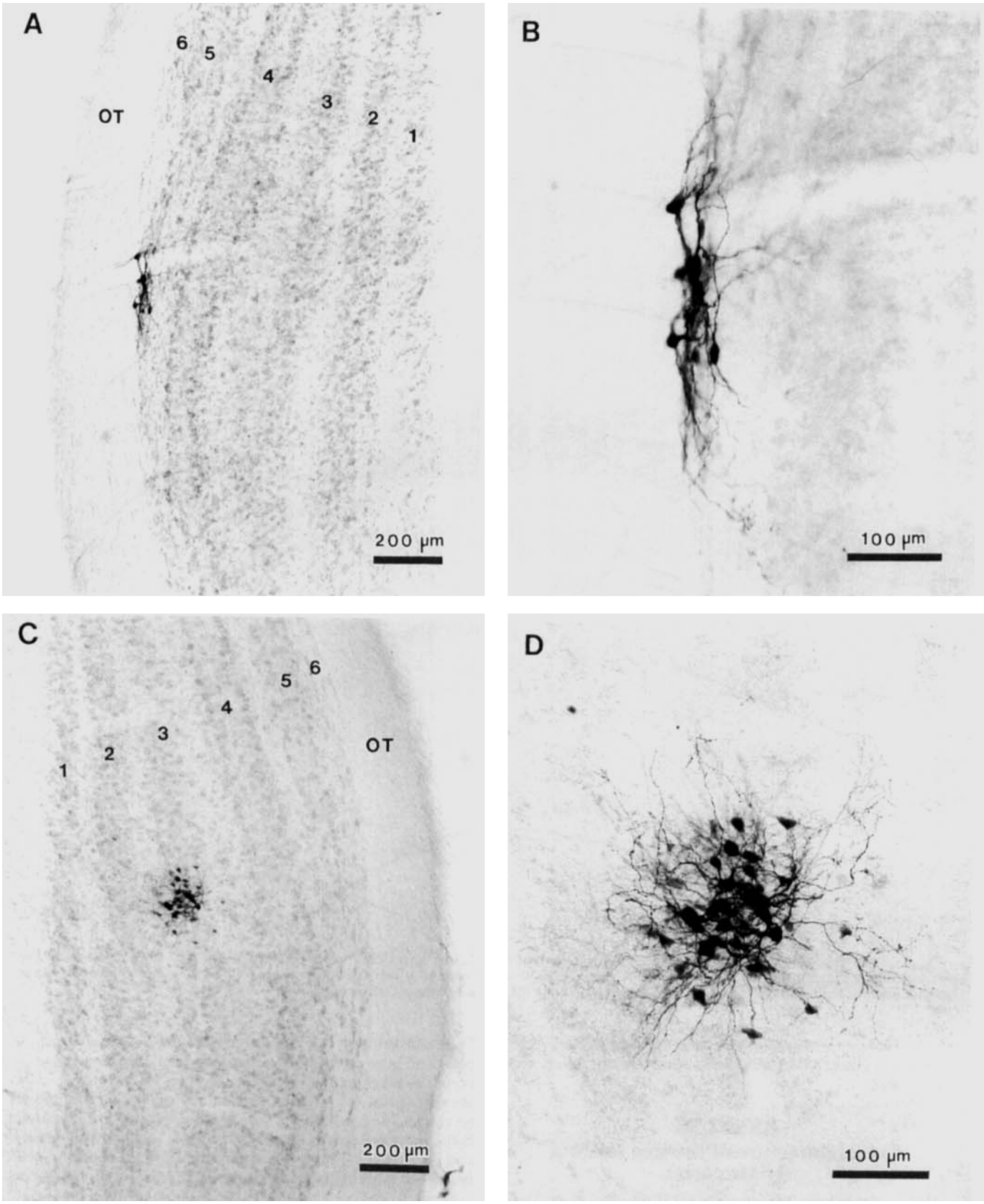

Fig. 2. Examples of biocytin injection sites in lateral geniculate nucleus (LGN) layers 6 and 3. **A:** Photomicrograph of a Nissl-stained section of the LGN with an injection of biocytin limited to layer 6. **B:** High-power view of the injection site shown in A. **C:** Photomicrograph of a Nissl-stained section of the LGN with an injection of biocytin limited to layer 3. **D:** High-power view of the injection site shown in C. OT, optic tract.

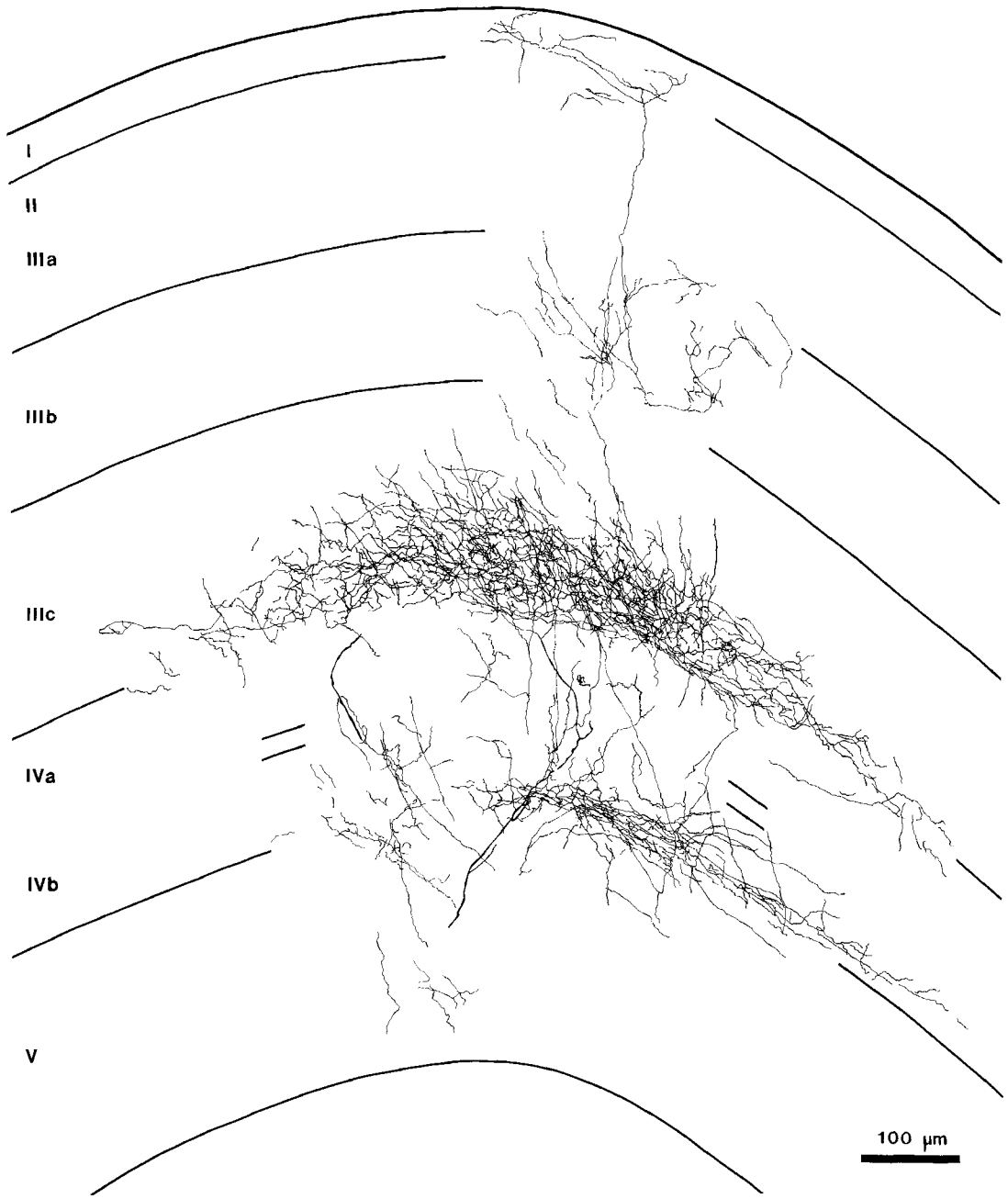

Fig. 3. Camera lucida drawing of labeled axonal arbors present in two adjacent 50 μm sections of striate cortex following an injection of biocytin that was limited to LGN layer 6 and is illustrated in Figure 2A. Lower layer IIIc receives a dense projection, while lower layer IVb receives a moderate projection. A few fibers extend above IIIc and arborize sparsely across IIIb–I.

width and standard error were determined and the Scheffe F-test was used to determine the statistical significance of differences.

RESULTS

Cytoarchitecture of the tree shrew's striate cortex

Before describing the experimental results, it is worth reviewing the laminar organization of tree shrew striate cortex as revealed in a Nissl-stained section (Fig. 1). Layer IV is a prominent cell-rich layer composed of small granule cells and separated by a cell-sparse cleft into two roughly equal sublayers, IVa and IVb. Layer III is quite wide, occupying almost half the cortical depth. It can be divided on the basis of cell density into three parts: layer IIIb which is the most cell dense, layer IIIc which is the least cell dense, and layer IIIa, which is intermediate. Layer II is a thin, cell dense layer lying just beneath layer I. The II–IIIa border is difficult to discern, and since LGN axons have no special relation with layer II, we have not defined this border in our figures.

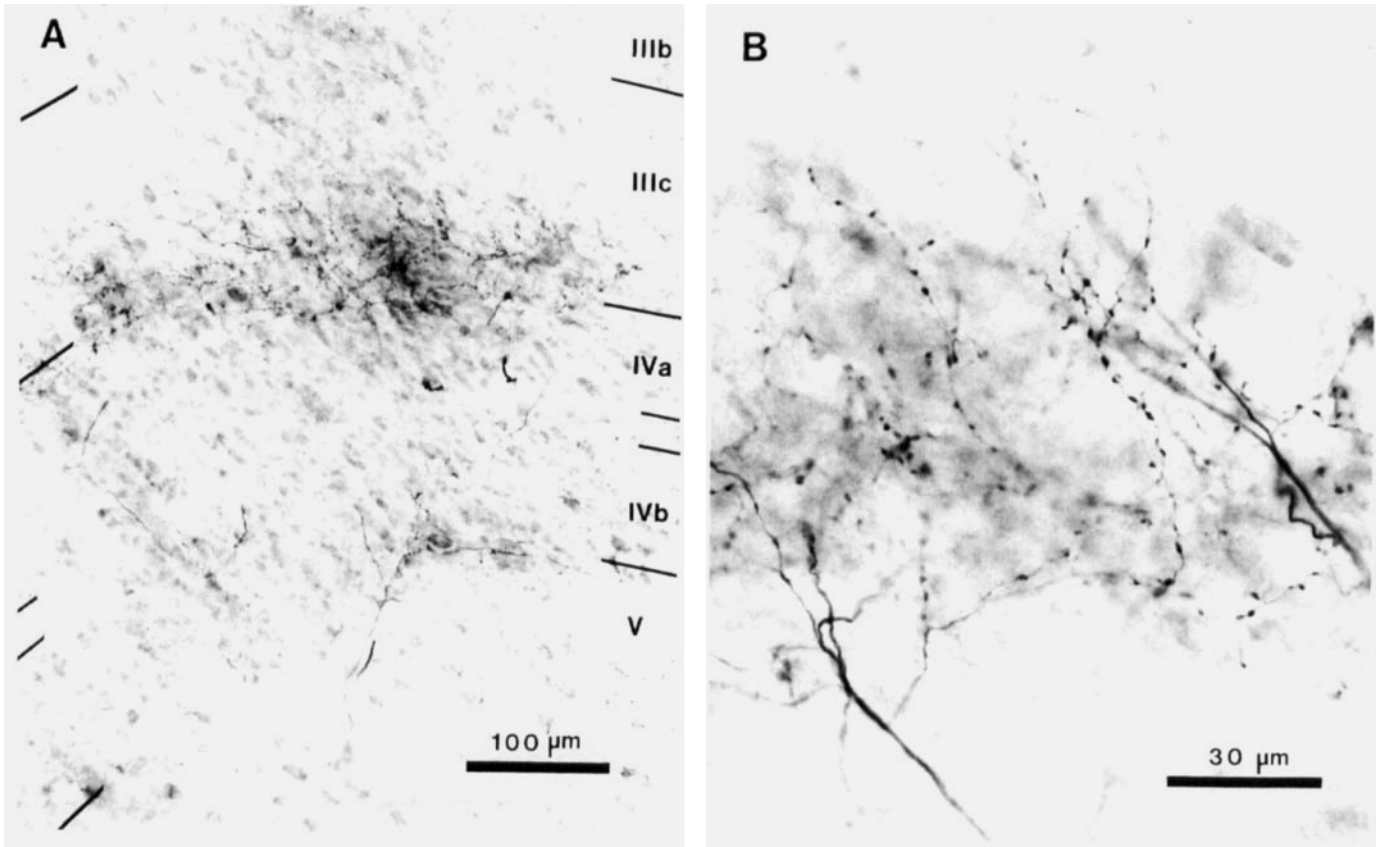

Fig. 4. Photomicrographs of labeled axons in a Nissl-stained section of striate cortex after a biocytin injection in LGN layer 6. **A:** Low-power photomicrograph showing a dense projection to lower layer IIIc and a moderate projection to lower layer IVb. **B:** High-power photomicrograph of lower layer IIIc revealing the fine nature of the axons and boutons.

Projections of layer 6 of the lateral geniculate nucleus

Two animals received injections of biocytin that were limited to LGN layer 6; photomicrographs of one of these injections are shown in Figure 2 (A and B). A significant advantage of the biocytin technique is that the injection site is defined by the location of labeled cells—there is no halo of reaction product or diffuse label to complicate the interpretation of the injection site. In addition, the cells at the injection site are filled with reaction product such that the finest details of their dendritic processes are revealed. As described in previous Golgi studies, layer 6 neurons have narrow dendritic fields elongated parallel to, and largely restricted within, the borders of the layer (Brauer et al., '81).

Figure 3 shows the distribution of biocytin-labeled fibers in the striate cortex resulting from the injection site shown in Figure 2 (A and B). This figure was generated by drawing all of the labeled fibers and terminals in two adjacent 50 μm thick sections and superimposing them using blood vessels as landmarks. Labeled fibers and terminals were concentrated in two distinct zones of striate cortex. The densest zone of terminations was in the lower half of layer IIIc, just above layer IV; a second zone of terminals was concentrated within layer IVb near its border with layer V. In addition to these regions of dense terminations, a few labeled fibers extended through layer IIIb to I. Photomicrographs illustrating the distribution and morphology of biocytin-labeled layer 6 axons are shown in Figure 4.

In order to determine whether the projections to layer IIIc and layer IV originate from the same or different populations of neurons, we reconstructed five individual layer 6 axons. Two of these are illustrated in Figure 5. As shown in these drawings, the projections to layer IIIc and layer IV originate as collaterals from the same layer 6 axons. Each of the axons we examined was found to give rise to collaterals in both layers and the terminations in layer IIIc were always more numerous than those in layer IV. None of the axons that we reconstructed was found to have a terminal arbor extending above layer IIIc. Thus, the small number of fibers seen in layers I–IIIb of Figure 3 could represent a sparse collateral projection from axons that target layer IIIc or the axon terminals of a small but distinct class of layer 6 neurons.

Projections of layer 3 of the lateral geniculate nucleus

Injections of biocytin were confined to LGN layer 3 in three animals. Photomicrographs of one of these injection sites are shown in Figure 2 (C and D) and the total pattern of labeled fibers and terminals in the striate cortex resulting from this injection is illustrated in Figures 6 and 7A. Following injections into LGN layer 3, labeled fibers and terminals are distributed across the depth of the cortex, with the main terminal field in layer IIIb (see also Fig. 7B). This terminal field extended into layers I–IIIa, where, in layer I, fibers turn and run horizontally for short distances.

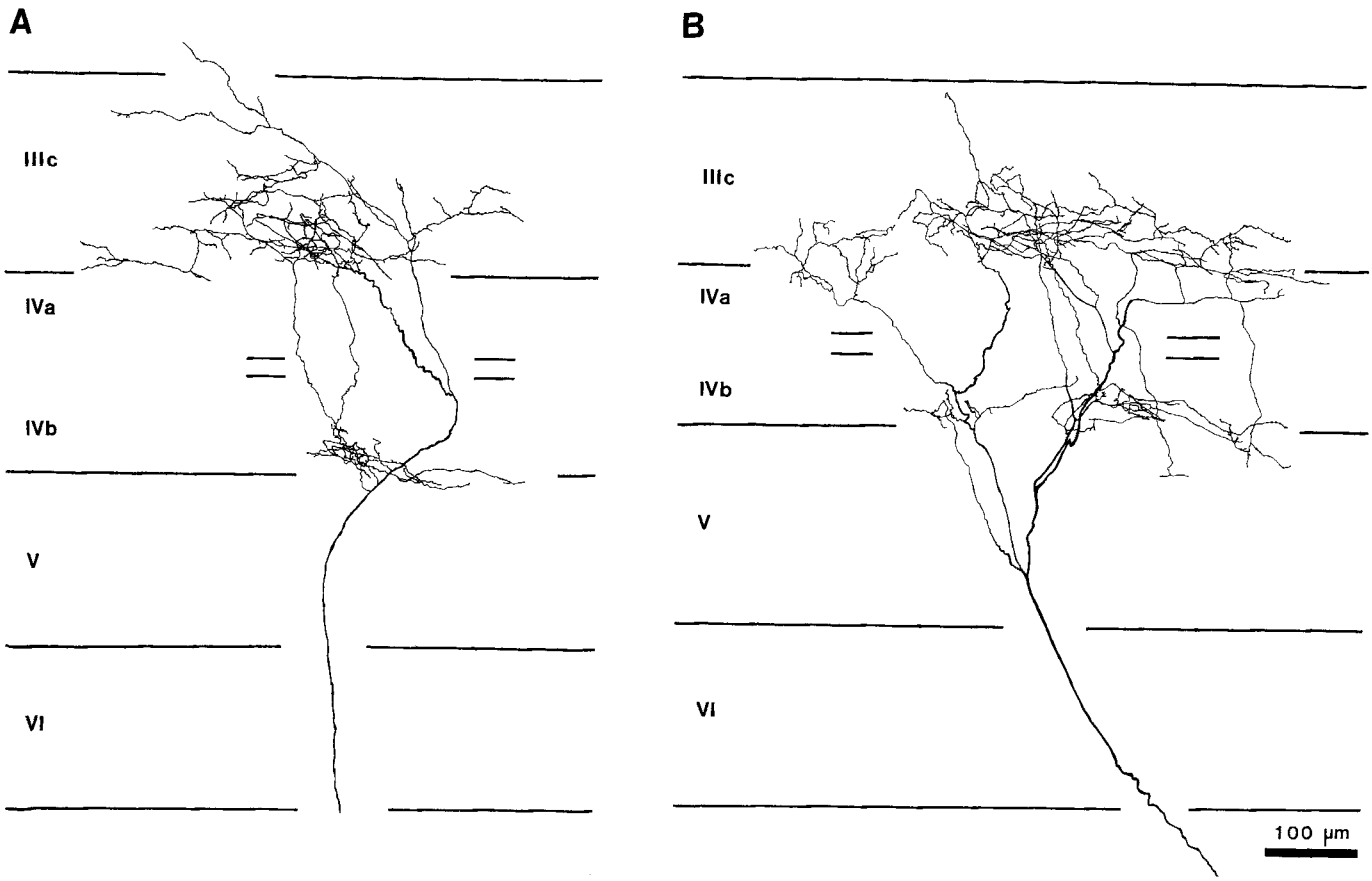

Fig. 5. Camera lucida drawings of two axon arbors (**A** and **B**) in striate cortex labeled by an injection of biocytin that was limited to LGN layer 6. Both axons have a dense terminal field in lower layer IIIc and give rise to collateral projections to the lower part of layer IVb.

Layer 3 axons also contribute terminals to cortical layer IV. These terminals are clustered in the middle of layer IV, in the region of the cell-sparse cleft and the immediately adjacent parts of IVa and IVb (Fig. 7C). Finally, a sparse distribution of labeled terminals is also present in layers V and VI (Fig. 7D).

Five individual LGN layer 3 fibers were reconstructed from serial sections and three examples are shown in Figures 8 and 9. All of the fibers had vertically oriented axon arbors that spread from layer IIIb to I. Some of the axons, like that illustrated in Figure 8A, had terminal arbors restricted to the superficial layers. Others, like those in Figures 8B and 9 gave rise to collaterals in layers V and VI and in the middle of layer IV. Since none of the reconstructed fibers had terminal fields restricted to the deep layers, it seems likely that the terminals in layers IV, V, and VI originate only from collaterals of axons that target the superficial layers.

Comparison of layer 3 and 6 axons with those that terminate in layer IV

The axons of LGN layers 3 and 6 were compared with those of LGN layers 1, 2, 4, and 5 that had been labeled by intracellular injections of HRP in a previous study (Raczkowski and Fitzpatrick, '90). In addition to their laminar distribution, we noted two obvious differences between the groups. First, axonal diameters of cells in LGN layers 6 and 3 were significantly smaller than their counterparts in the other LGN layers (Scheffe F-test, 95% confidence) but they were not statistically different from each other (layer 6, $\overline{\chi}$ = 1.2 μm, ±0.1; layer 3, $\overline{\chi}$ = 1.2 μm, ±0.1; other layers, $\overline{\chi}$ = 2.0 μm, ±0.1). Second, terminal boutons from LGN layers 3 and 6 were smaller than those from other LGN layers. As illustrated in Figure 10, this was found to be true for the layer 3 and 6 axons that terminated in cortical layer III as well as for those that terminated in layer IV. The boutons of layer 3 axons in cortical layer IV appeared to be slightly larger than the terminals in layer III but no attempt was made to test this quantitatively.

DISCUSSION

The present results, showing that layers 3 and 6 of the lateral geniculate nucleus project to different subdivisions within layer III, are consistent with previous studies that used bulk injections of HRP or WGA-HRP to study geniculocortical pathways in the tree shrew (Carey et al., '79; Conley et al., '84). What could not be deduced from the earlier work is that these layers of the LGN also project to the deeper cortical layers. While these deep projections are much less robust than the projections to layer III, they are no less specific: LGN layer 6 axons project to the lower part of IVb, while some LGN layer 3 axons terminate in the middle of layer IV and in layers V and VI (Fig. 11C). In the

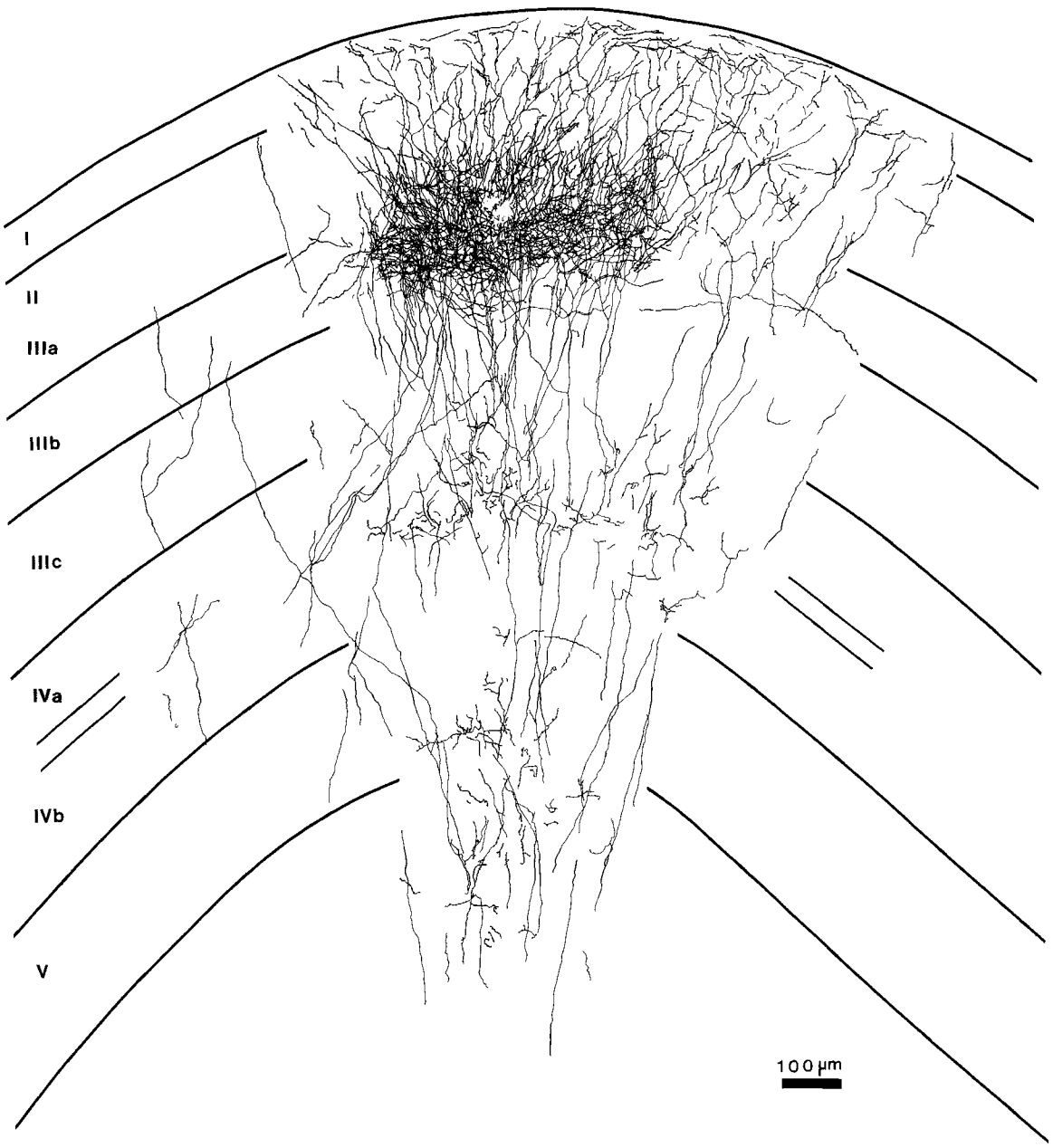

Fig. 6. Camera lucida drawing of labeled axonal arbors in a 50 μm section of striate cortex following a biocytin injection that was limited to LGN layer 3 and is illustrated in Figure 2C. Labeled fibers and terminals are distributed across the depth of the cortex, with the greatest density in layers IIIb–I. Sparser terminal fields are present in the middle of layer IV and in layers V and VI.

sections below we consider the relationship of these projections to the intrinsic circuitry of tree shrew striate cortex. We also relate our findings to results in other species and speculate on the functional significance of LGN pathways to the superficial layers of striate cortex.

Relation of layer III pathways to the pathways relayed through layer IV

The significance of the projections of LGN layers 3 and 6 to different subdivisions of layer III must rest, at least in part, on the fact that these LGN layers convey different types of visual information to the cortex. Although they both receive fine caliber retinal fibers, neurons in layers 3 and 6 differ in their responses to visual stimulation: individual neurons in layer 6 have both ON and OFF responses and respond transiently to retinal stimulation, while those in layer 3 are strictly ON or OFF (mainly OFF) and have sustained responses (Conway and Schiller, '83; Norton, '82; Holdefer and Norton, '86). Furthermore, the projections from another source that layers 3 and 6 share in common, the superficial layers of the superior colliculus, also arise from different populations of neurons (Fitzpatrick et al., '80; Diamond et al., '91). Thus it would appear that LGN pathways that target the superficial layers are

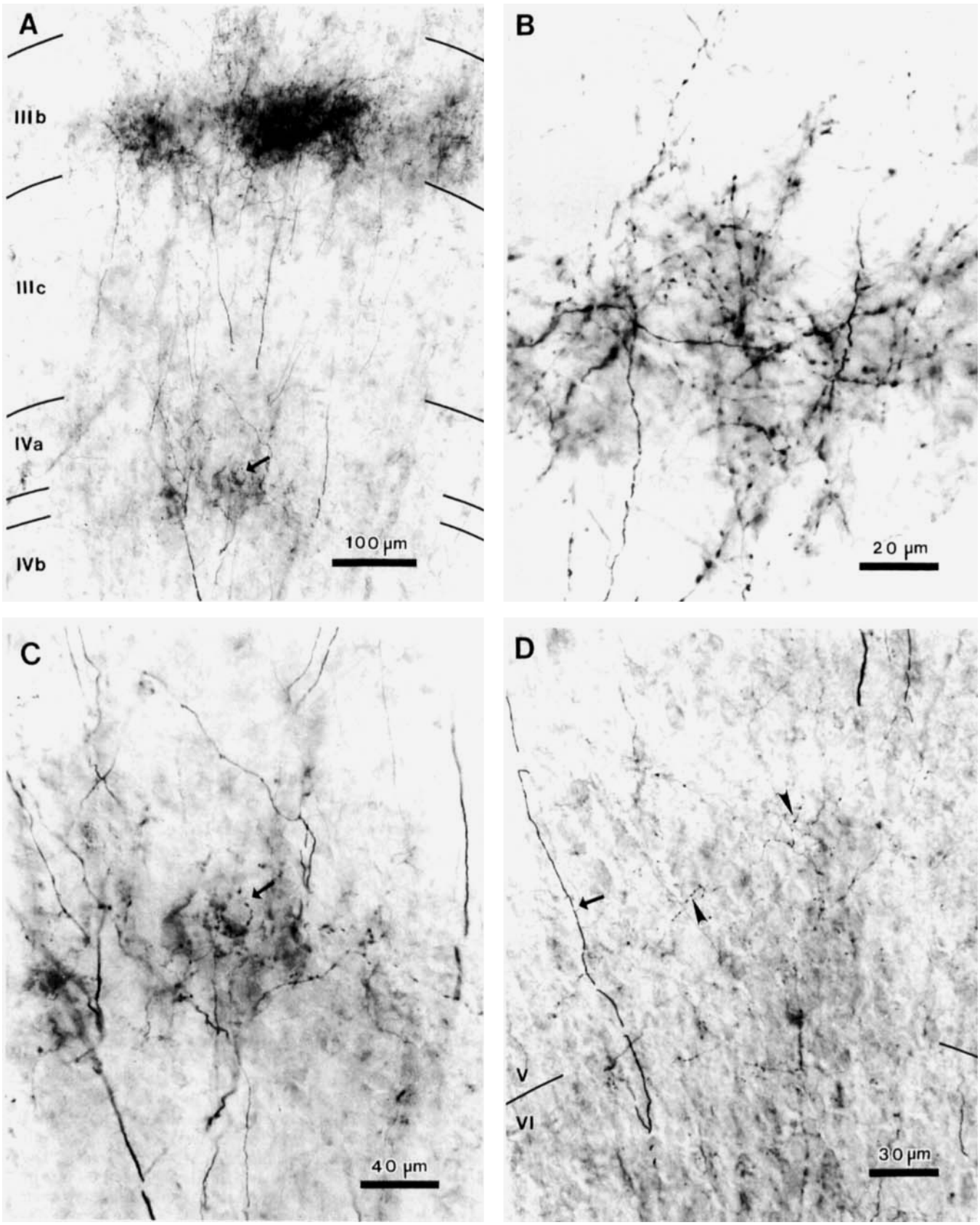

Figure 7

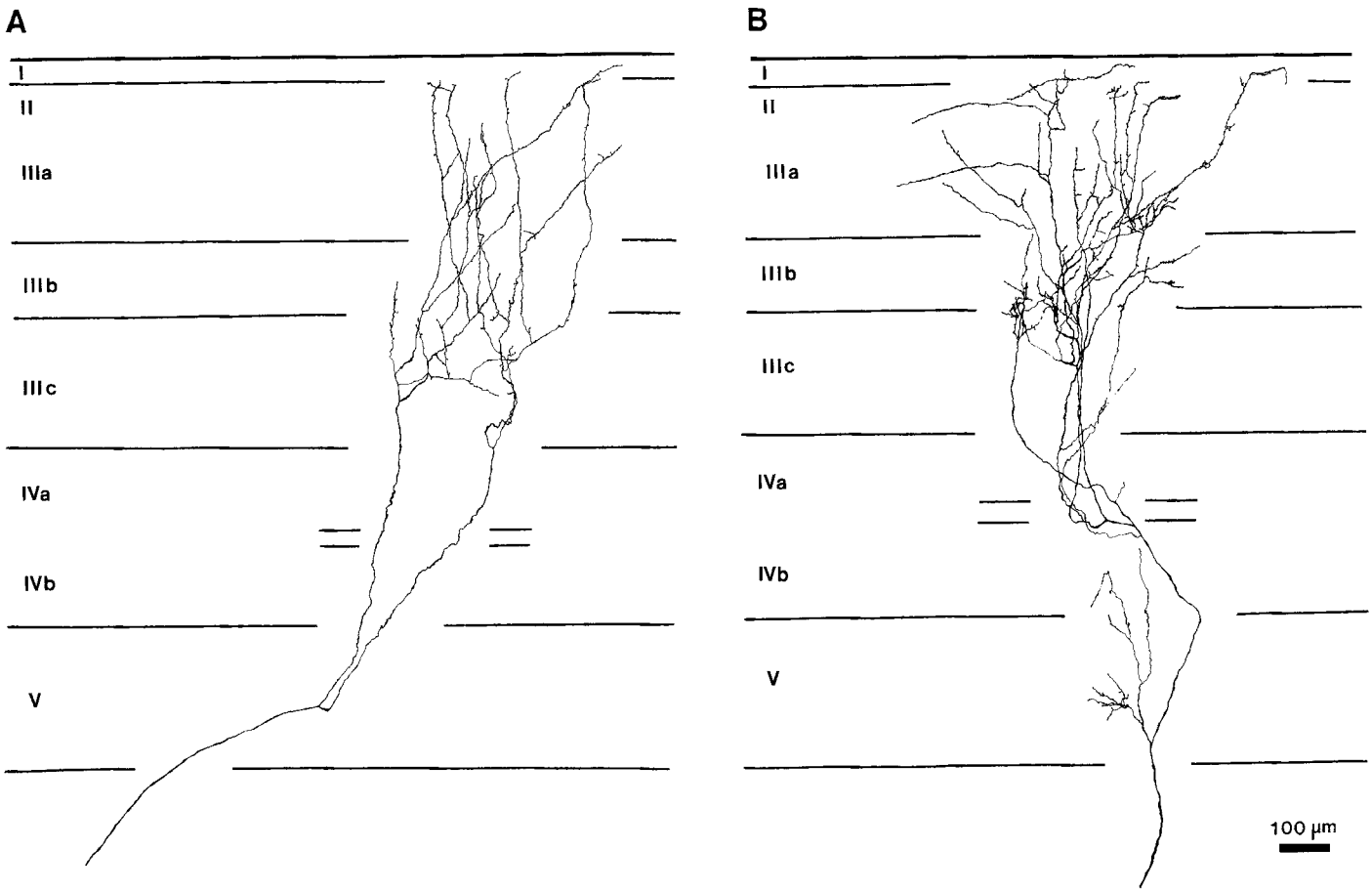

Fig. 8. Camera lucida drawings of axonal arbors in striate cortex labeled by an injection of biocytin limited to LGN layer 3. **A:** An LGN layer 3 axon with an arbor extending from the IIIb/IIIc border superficially to layer I. **B:** An axon that, in addition to having an arbor in IIIb-I, has a collateral in layer V.

themselves composed of parallel systems that transmit different types of visual information to different cortical neurons.

Another clue to the significance of the segregated patterns of LGN projections to layer III is provided by the fact that the cortical targets of layers 3 and 6, layers I–IIIb and IIIc, respectively, also differ in their connections with cortical layer IV (see Fig. 11B). Neurons in layers I–IIIb receive inputs from neurons that lie near the cleft in both IVa and IVb, while those in the lower part of IIIc receive their inputs from neurons that lie at the edges of layer IV, the upper part of layer IVa, and the lower part of layer IVb (Muly and Fitzpatrick, '91, '92). These parts of layer IV, in turn, differ in the pattern of projections they receive from the principal layers of the LGN. As shown in Figure 11, layer IVa is the target of ON-center LGN neurons while layer IVb is the target of OFF-center LGN neurons. Both IVa and IVb can be further subdivided according to the pattern of inputs from the two eyes. The upper part of IVa and the lower part of IVb receive overlapping inputs from the two eyes while the region surrounding the cleft receives input only from the contralateral eye (Casagrande and Harting, '75; Hubel, '75; Conway and Schiller, '83; Conley et al., '84; Kretz et al., '86; Raczkowski and Fitzpatrick, '90).

These results raise the possibility that the segregated projections of LGN layers 3 and 6 are related to functional differences in the pathways from layer IV to layer III. One likely functional difference between the projections from layer IV to layer IIIc and those to I–IIIb relates to their inputs from the two eyes: neurons in layer IIIc are likely to receive binocular information from layer IV while those in layers I–IIIb are likely to receive information largely from the contralateral eye (Fig. 11A,B). Why LGN layer 6 should

Fig. 7. Photomicrographs of labeled axons in a Nissl-stained section of striate cortex after a biocytin injection in LGN layer 3. **A:** Low-power photomicrograph showing a dense projection to layer IIIb with a moderate projection to the middle of layer IV. The arrow points to a ring of boutons that are identified by a similar arrow in C. **B:** High-power photomicrograph of the terminal field in layer IIIb, revealing the fine nature of the axons and boutons. **C:** High-power photomicrograph of the terminal field in the cleft of layer IV. The arrow points to the same ring of boutons that are identified in A. **D:** High-power photomicrograph of the terminal field in layers V and VI. The arrow points to an axon while the arrowheads point to boutons.

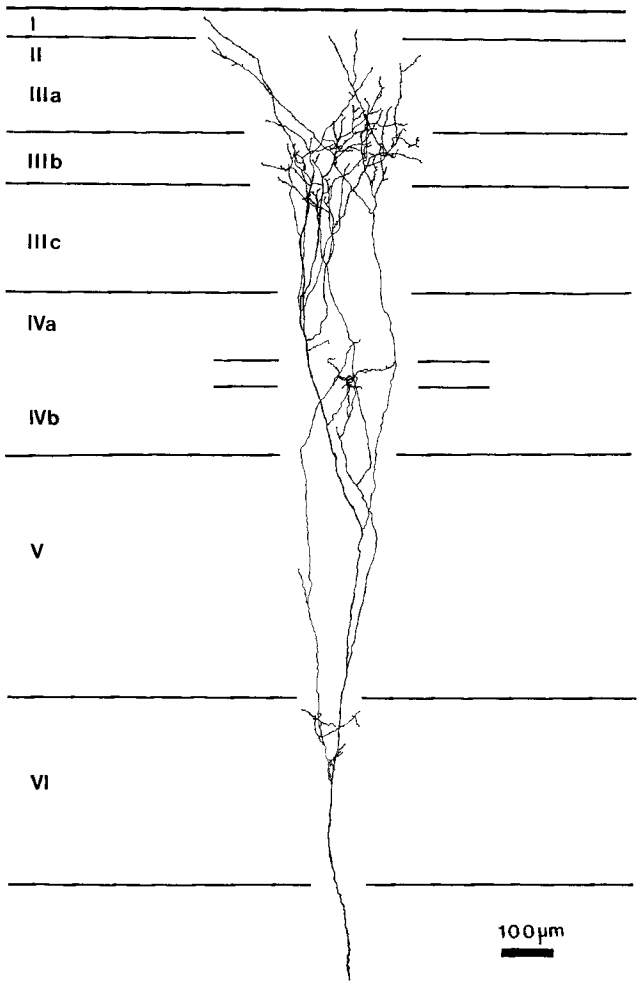

Fig. 9. Camera lucida drawing of the terminal arbor in striate cortex labeled by an injection of biocytin limited to LGN layer 3. The axon terminates primarily in layer IIIb with projections continuing superficially to layer I. The axon also gives rise to collateral terminals in the middle of layer IV and in layer VI.

be associated with a binocular pathway and layer 3 a monocular pathway is unclear since both layers of the LGN receive inputs only from the contralateral eye. We can only assume that there are other functional differences across the depth of layer IV and between IIIc and IIIa,b that have not yet been recognized.

Nevertheless, the relationship between LGN layers 3 and 6 and the pathways coming out of layer IV seems to be substantial since LGN layers 3 and 6 also selectively target the regions of layer IV that supply layers IIIb and IIIc. For example, the axons of some LGN layer 3 cells send off collaterals in the center of layer IV—the region of layer IV that projects to layer IIIb–I (see Fig. 11). In the same way, neurons in LGN layer 6 give rise to collaterals in the lower part of layer IVb and this region is a source of projections to the lower part of layer IIIc. Thus both LGN layers 3 and 6 appear to have multiple sites at which to influence their distinct cortical circuits.

Comparison with other species

The LGN projections that terminate in layer III of tree shrew share a number of features in common with pathways that have been identified in the cat and primate. In all of these species, cells projecting to the superficial layers of the cortex are small and pale staining, and they receive fine caliber retinal fibers (LeVay and Gilbert, '76; Fitzpatrick et al., '83; Weber et al., '83; Diamond et al., '85). In addition, the LGN layers that contribute axons to the superficial layers of the cortex are the principal target of projections from the superficial layers of the superior colliculus (Graham, '77; Fitzpatrick et al., '80; Harting et al., '91). Given these similarities, it is worth considering whether any of the other features of the layer III projections described in this paper are present in other species. First, is there evidence for multiple pathways to the superficial layers in other species? Second, is there evidence that the neurons that project to the superficial layers give rise to terminals in deeper layers and, in particular, layer IV?

The projections to the superficial layers of cat striate cortex originate from the parvicellular C layers of the LGN. Evidence from anterograde and retrograde tracing studies suggest that these projections terminate in a laminar pattern that is quite similar to the pattern we have described in the tree shrew. For example, following injections of anterograde tracers into the parvicellular C layers, labeled terminals are present in layer I, at the III–IV border, and at the IV–V border (LeVay and Gilbert, '76). Restricted injections of HRP into different layers of the striate cortex also support the view that all of these regions are targets of small neurons in the parvicellular C layers (Leventhal, '79). Whether there are separate classes of neurons within the parvicellular C layers that make different contributions to this terminal pattern remains unknown. Individual W-cells within the parvicellular C layers differ considerably in their responses to visual stimulation (Cleland et al., '76; Wilson et al., '76; Sur and Sherman, '82; Stanford et al., '83; Sherman, '85). Given the results in the tree shrew, one would predict that different types of W-cells give rise to different laminar axonal distributions within the striate cortex.

The small pale staining cells that project to layer III in New World monkeys (and probably Old World monkeys as well) are gathered into groups that are intercalated in and around the magno- and parvicellular layers of the LGN (Fitzpatrick et al., '83; Weber et al., '83). In the squirrel monkey these layers give rise to terminals in layer I, in the cytochrome oxidase-rich blobs of layer III and in layer IVA, a thin strip of cells that lies below the cytochrome-rich blobs and above the main target of LGN axons, layer IVC (using the Brodmann terminology) (Fitzpatrick et al., '83). Evidence has been presented for the existence of subpopulations of cells with different patterns of projections to this target region. For example, the intercalated cells near the parvicellular layers in the squirrel monkey LGN project to the cytochrome oxidase-rich blobs in layer III and to IVA. In contrast, the intercalated cells ventral to layer 1 project to the blobs but not to lamina IVA (Fitzpatrick et al., '83). Whether any of the cells in the intercalated layers have projections to layer IVC remains unknown. Recent studies of the small cell layers in the prosimian Galago suggest that these projections terminate exclusively in the superficial cortical layers (Lachica and Casagrande, '89).

Functional significance of direct geniculate projections to layer III

What contribution do the two routes, those that are direct, and those that are channeled through layer IV, make

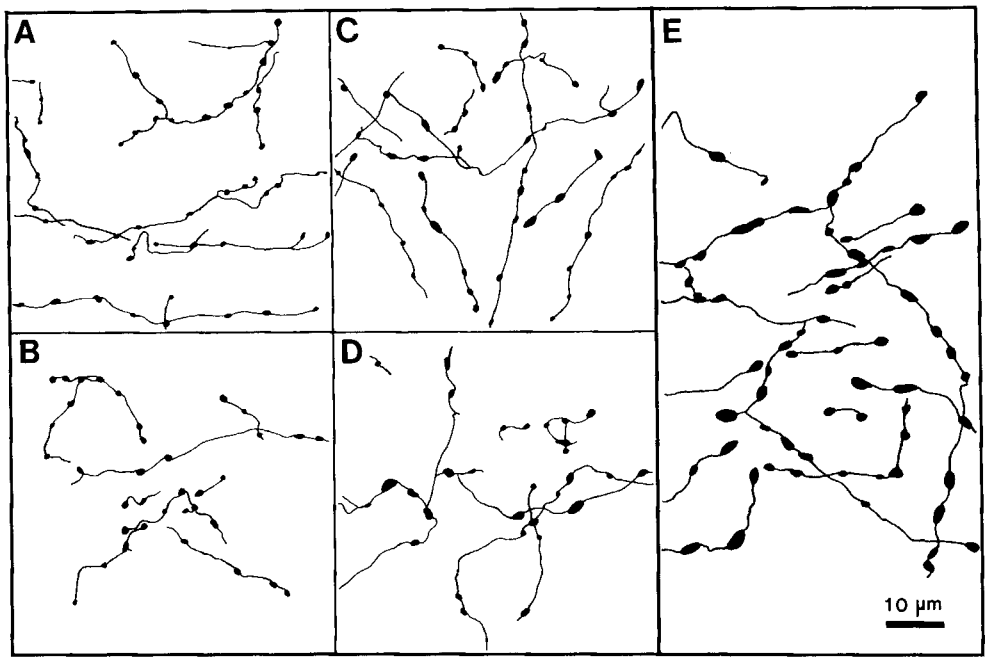

Fig. 10. Camera lucida drawings comparing the morphology of axons and boutons in striate cortex from neurons in different layers of the LGN. **A:** Terminal field of LGN layer 6 neurons in cortical layer IIIc. **B:** Terminal field of LGN layer 6 neurons in cortical layer IVb. **C:** Terminal field of LGN layer 3 neurons in cortical layer IIIb. **D:** Terminal field of LGN layer 3 neurons in the middle of cortical layer IV. **E:** Terminal field of a layer 2 LGN neuron that is typical of those projecting only to layer IV.

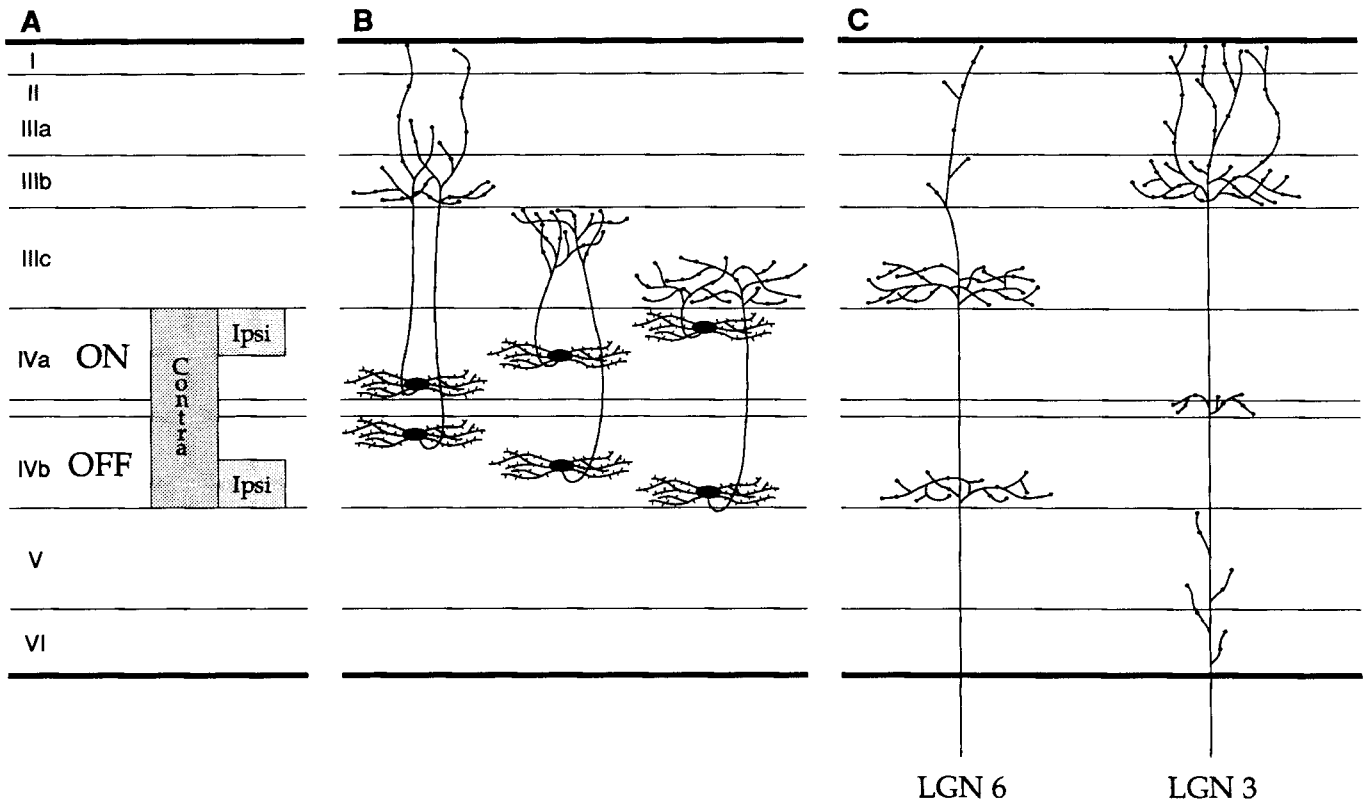

Fig. 11. Summary diagram showing the organization of LGN projections and their relation to the intrinsic circuitry within striate cortex. **A:** Pattern of LGN projections to layer IV. ON and OFF axons terminate within IVa and IVb, respectively. LGN fibers driven by the contralateral eye terminate throughout the depth of IVa or IVb; those driven by the ipsilateral eye terminate at the edges of IVa or IVb. **B:** Projections from layer IV to layer III. Projections from IVa and IVb overlap throughout layers III–I, but do so in a highly ordered fashion. Neurons near the middle of layer IV (lower IVa and upper IVb) project to layers IIIb–I; those at the edges of layer IV (upper IVa and lower IVb) project to the lower part of IIIc; neurons in the middle of IVa and IVb project to the upper part of IIIc. **C:** Pattern of termination of LGN layer 3 and 6 axons described in this study. Layers 3 and 6 project to distinct sets of cortical layers that are themselves interconnected by the spiny stellate neurons of layer IV.

to the responses of neurons in the superficial cortical layers? The available physiological evidence indicates that the small cells, which are the source of the direct pathway, lack the brisk responsiveness and the fine spatial and temporal resolution that characterize the pathways that are channeled through layer IV and that would seem to be required to generate the specific responses of layer III neurons (Sherman, '85). In support of this contention, recent experiments by Mignard and Malpeli ('91) show that the direct projection from the parvicellular C layers of the cat LGN is unable to sustain the responses of neurons in the superficial layers of area 17 in the absence of the other geniculocortical pathways. Thus, it seems likely that the main excitatory drive for neurons in the superficial layers is provided by the pathways that are channeled through layer IV and that the direct LGN pathways serve some other function. Perhaps, instead of contributing directly to the receptive field properties of layer III neurons, the small cell layers act to modulate the responsiveness of layer III neurons to pathways that emanate from layer IV.

Whatever the role of LGN projections to layer III, the present results emphasize their close and specific relationship with pathways that emanate from layer IV. While the selective nature of this relationship is well illustrated by our results in the tree shrew, there is also evidence for a similar arrangement in primates. The cytochrome oxidase-rich blobs of layer III, which are the principle targets of the intercalated layers (Fitzpatrick et al., '83; Weber et al., '83; Diamond et al., '85), receive a specific pattern of projections from layer IV: the blobs receive inputs from IVCα and IVCβ, whereas the interblob regions receive their inputs only from IVCβ (Casagrande et al., '89, '90). Further insight into the function of LGN projections to layer III will require a closer examination of this relationship to determine whether the projections from the LGN and those from layer IV contact the same or different neurons in the superficial layers.

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