Ascending Projections of Simple and Complex Cells in Layer 6 of the Cat Striate Cortex

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Receptive field properties vary systematically across the different layers of the cat striate cortex. Understanding how these functional differences emerge requires a precise description of the interlaminar connections and the quality of information that they transmit. This study examines the contribution of the two physiological types of neuron in layer 6, simple and complex, to the cortical microcircuit. The approach was to make whole-cell recordings with dye-filled electrodes *in vivo* to correlate visual response property with intracortical projection pattern. The two simple cells we stained projected to layer 4, as previously reported (Gilbert and Wiesel, 1979; Martin and Whitteridge, 1984). Six of the eight complex cells that we labeled projected to the superficial layers, a pathway not previously described in the cat. The remaining two cells targeted the infragranular layers. Layer 4 is dominated by simple cells, whereas layers 5 and 2+3 are mainly composed of complex cells (Hubel and Wiesel, 1962; Gilbert, 1977). Hence, our results indicate that the ascending projections of simple cells in layer 6 target other simple cells. In parallel, the ascending projections of a population of complex cells in layer 6 favor other complex cells. Anatomical experiments in several species (Lund and Boothe, 1975; Burkhalter, 1989; Usrey and Fitzpatrick, 1996; Wiser and Callaway, 1996) had also demonstrated that layer 6 gives rise to two separate intracortical pathways. Pooling the results of these anatomical studies with our own suggests a common feature of the laminar organization: cells that project to different intracortical targets have distinct functional characteristics.

Key words: visual cortex; patch recording in vivo*; simple cell; complex cell; layer 6; pyramidal cell*

We are interested in how visual information is coded by the different elements of the cortical microcircuit. With the striking exception of layer 6, each layer in the cat striate cortex is mainly composed of one physiological cell type, simple or complex (Hubel and Wiesel, 1962; Gilbert, 1977; Gilbert and Wiesel, 1981; Grieve and Sillito, 1995; see Fig. 6). Simple cells dominate layer 4, the principal target of the lateral geniculate nucleus; their receptive fields are built of adjacent subregions arranged so that neighbors prefer stimuli of the opposite contrast (Hubel and Wiesel, 1962; Gilbert, 1977). The laminae that receive little input from the thalamus, layer 2+3, and layer 5, are largely composed of complex cells, neurons whose receptive fields lack spatially separate subregions (Hubel and Wiesel, 1962; Gilbert, 1977). Layer 6 is divided into two tiers, as distinguished by the pattern of thalamic innervation (LeVay and Gilbert, 1976). The upper stratum receives appreciable contact from the geniculate and contains a mix of simple and complex cells. The lower aspect derives its chief input from intracortical sources and is populated by complex cells (Hubel and Wiesel, 1962; Gilbert, 1977; Grieve and Sillito, 1995).

In keeping with their physiological uniformity, layers 2+3, 4, and 5 each have one principal laminar target. Layer 4 projects to 2+3, which directs its output to layer 5; layer 5, in turn, projects to layer 6 (Gilbert and Kelly, 1975; Gilbert and Wiesel, 1979; Lin et al., 1979; Martin and Whitteridge, 1984; McGuire et al., 1984). Based on the projection patterns of just a handful of labeled cells in layer 6 *in vivo*, it was thought that the entire interlaminar output was directed to layer 4. We have characterized the receptive field structure and projection pattern of simple and complex cells throughout the depth of layer 6. The approach was to combine whole-cell recording with intracellular staining *in vivo*. The simple cells we labeled targeted layer 4, as previously reported (Gilbert and Wiesel, 1979; Martin and Whitteridge, 1984). By contrast, the complex cells we stained had a different projection pattern. These directed the bulk of their output to the laminae composed of complex cells, layers 5 and 2+3, rather than to layer 4. Thus, a population of complex cells in layer 6 provides an ascending projection to the superficial layers distinct from the path that leads from layer 6 to layer 4.

MATERIALS AND METHODS

Anesthesia. Nine adult cats, 2.5–3.5 kg, were anesthetized with ketamine (10 mg/kg, i.m.) followed by thiopental sodium (20 mg/kg, i.v.), supplemented as needed. Lidocaine was applied topically at all incisions or points of pressure. Temperature (37°-38°C), EKG, EEG, and expired CO_2 (27–33 mmHg) were monitored throughout the experiment. Anesthesia was maintained by continuous infusion of thiopental sodium (2–4 mg · kg · hr, i.v.) adjusted as indicated by the EEG and EKG. After the completion of surgery, animals were paralyzed [vecuronium bromide (Norcuron) 0.2 mg · kg · hr, i.v.] and respired artificially.

Surgery. An endotracheal tube was introduced through a tracheotomy before the animal was placed in a stereotaxic apparatus. Then, a cortical craniotomy centered on Horsley–Clark coordinates P3-L2 was made to expose the longitudinal gyrus. After dilating the pupils (1% atropine sulfate) and retracting the nictitating membranes (10% phenylephrine),

the eyes were refracted and fitted with contact lenses to focus on a tangent screen. The position of the area centralis and the optic disk of each eye was determined with a fundus camera. Before recording, the dura was reflected, and the cortex was covered with agarose.

Acquisition of visually evoked responses. Intracellular and extracellular records were collected by a computer running the Discovery software package (Datawave Systems, Longmont, CO); intracellular records were normally sampled at 3–4 kHz. An AT-vista board (Truevision, Indianapolis, IN), controlled by the same computer that received the data, generated visual stimuli that were presented on a computer monitor (frame rate, 100, 105, 128, or 140 Hz). Each cycle of the stimulus protocol consisted of light or dark squares at various contrasts (range, 30–70%) flashed singly for 29–39 msec in pseudorandom order, 16 times on a 16 × 16 grid (sparse noise; Jones and Palmer, 1987). Grid spacing ranged from 0.4 to 0.85° and square size from 0.4 to 1.7°.

Determination of receptive fields. Depolarizations evoked by bright stimuli were termed "*on*" responses and those to dark stimuli, "*off*" responses. Receptive fields with separate and adjacent *on* and *off* subregions were classified as simple; those that lacked segregated *on* and *off* responses were considered complex (Hubel and Wiesel, 1962; for review, see Skottun et al., 1991). To generate maps of the simple receptive fields, responses to dark stimuli were subtracted from bright ones. For complex cells, separate maps of bright and dark responses were made. All fields shown were smoothed by one half pixel.

Recording. Patch-pipette resistance was ≥12 MΩ when filled with internal solution, in mM: K gluconate, 120; NaCl, 5; CaCl$_2$, 1; MgCl$_2$, 1; EGTA, 11; GTP, 0.2; ATP, 2; HEPES, 40; and biocytin 1%, pH 7.3, 290 mOsm (Malinow and Tsien, 1990). Initial seal resistances were 0.5–1.0 GΩ. Recordings were made with an Axopatch 200A amplifier (Axon Instruments, Foster City, CA) and stored as described above; neither capacitance nor access resistance was compensated, so fast spikes were filtered. Because the access resistance often increased after rupture of the membrane (Edwards and Konnerth, 1992), the voltages recorded were sometimes divided (Stühmer et al., 1983).

Histology. After histological processing (Horikawa and Armstrong, 1988; Hirsch, 1995), labeled neurons were drawn using a camera lucida, or a computerized three-dimensional reconstruction system, (Micro-Brightfield, Colchester, VT).

RESULTS

Physiological differences between simple and complex cells in layer 6

The response patterns of simple cells and complex cells are illustrated in Figure 1. Simple receptive fields comprise adjacent *on* and *off* subregions; within each subregion stimuli of reverse contrast evoke responses of the opposite sign (Hubel and Wiesel, 1962; Jones and Palmer, 1987; Ferster, 1988, Hirsch et al., 1995). Postsynaptic responses to stimuli flashed within the *on* subregion of a layer 6 simple cell are shown in Figure 1*A*; the receptive field map above the traces indicates stimulus position. Each presentation of a bright square evoked a strong depolarization; a slight hyperpolarization and excitatory rebound followed the withdrawal of the stimulus. Dark squares elicited a hyperpolarization followed by an excitatory rebound. Responses from the *off* subregion were similar except that dark stimuli were excitatory, and the bright ones were inhibitory (data not shown). This "push–pull" pattern of response is also common to simple cells in layer 4 and its borders (Hirsch et al., 1995).

Although complex receptive fields are far more varied than those of simple cells (Hubel and Wiesel, 1962; Gilbert, 1977; Movshon et al., 1978; Palmer and Davis, 1981; Ohzawa and Freeman, 1986), they share a common characteristic: their receptive fields are not divided into subregions. The map at the top of Figure 1*B* shows the field of a complex cell that responded to dark stimuli; these evoked a brief depolarization (Fig. 1*B*, *bottom right*). Bright spots were essentially ineffective, with only a faint response to withdrawal of the stimulus (Fig. 1*B*, *bottom left*). This sort of response pattern was the most common in our sample (see Figs. 3*A,B*, 5*B*). Variations among cells included responses dom-

inated by inhibition rather than excitation (see Fig. 4*A*), insensitivity to the flashed stimuli (see Figs. 4*B*, 5*A*; fields were mapped with moving bars) or overlapping *on* and *off* responses (data not shown). As yet, we have not detected physiological trends that correlate with the different projection patterns of the complex cells that we describe below.
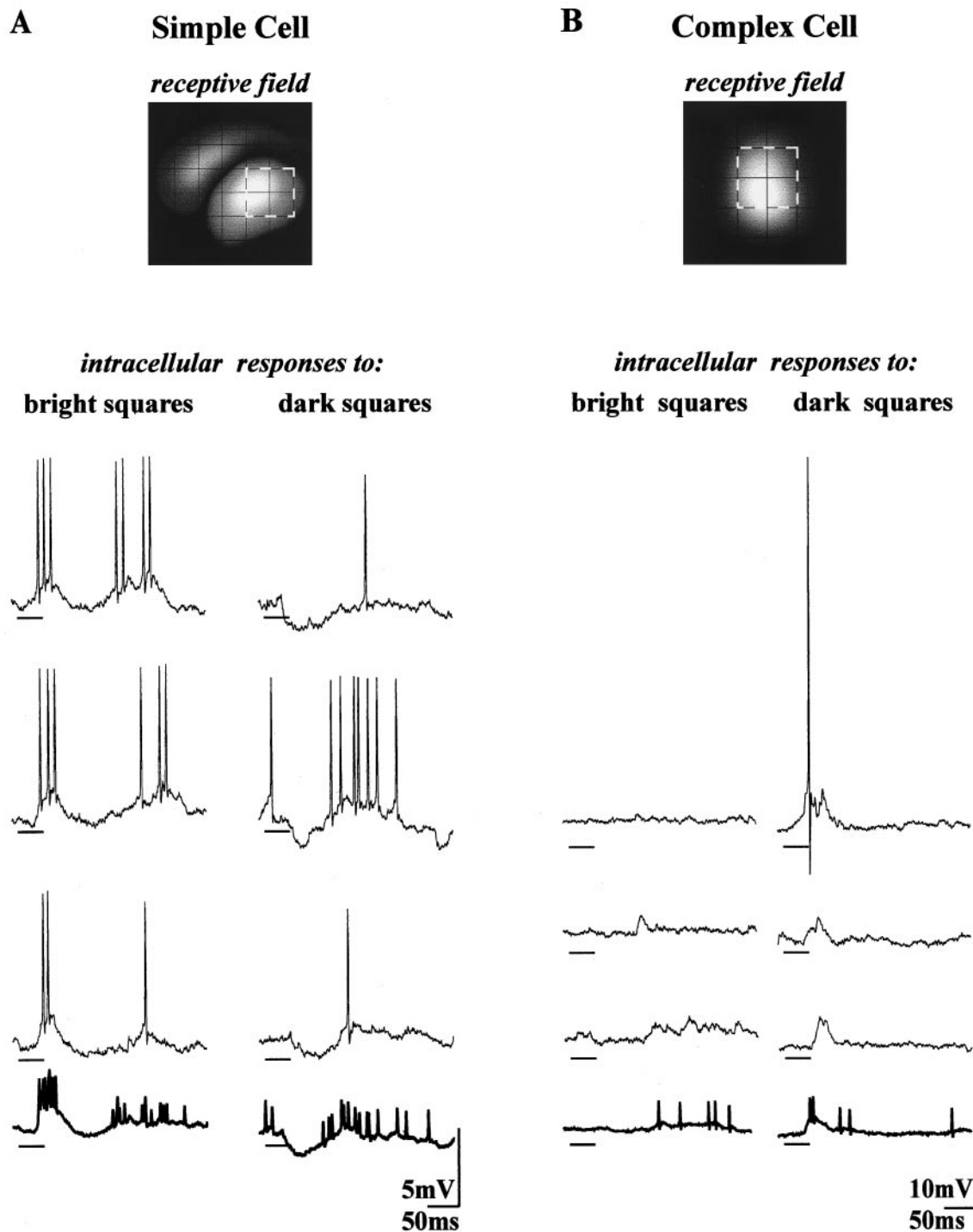
Projections of simple cells

We found that simple cells in layer 6 had dendrites and axons that arborized densely in layer 4, as previously described (Gilbert and Wiesel, 1979; Martin and Whitteridge, 1984). Maps of the receptive fields are shown above the reconstructions. The cell pictured in Figure 2*A* was located in middle of layer 6. Its basal dendritic arbor spread densely within ~100 μm of the soma; the apical dendrite fanned into long branches that traversed the depth of layer 4. Axonal projections were sparse near layer 6; they became more elaborate as they entered layer 4 to innervate its upper half. A second simple cell sat at the border between layers 5 and 6 (Fig. 2*B*). Its basal dendrites were rooted in layer 6; its apical dendrite and its apical arbor split into a few vertical branches in layer 4. Unlike the neuron in Figure 2*A*, this cell directed horizontal connections in layer 6. In sum, for simple cells, the dendrites and axons tended to ramify in the vicinity of other simple cells, that is, in regions where the afferents from the dorsal layers (A, A1) of the lateral geniculate terminate (see Fig. 6).

Projections of complex cells

For the complex cells we labeled, the projection pattern was distinctly different from that for simple cells and demonstrates a novel component of the cortical microcircuit. Instead of ending in layer 4, the complex cells directed the majority of their output to layer 2+3 or layer 5. That is, they targeted regions that are populated by other complex cells and that receive input from the ventral (C) layers of the geniculate and extrageniculate nuclei (see Fig. 6). The projection patterns we have observed so far cluster into three groups: cells that favor the lower aspect of layer 2+3, those preferring the upper tier of layer 2+3, and those that send stronger projections to the infragranular (layers 5 and 6) than to the supragranular (layer 2+3) layers.

Cells favoring the lower aspect of layers 2+3

Two complex cells that directed their output to the lower tier of layer 2+3 are drawn in Figure 3. The soma of one cell lay at base of the layer (Fig. 3*A*); its basal dendrites spread near the soma, with a few reaching into the white matter. The apical dendrite approached layer 1 but did not branch after leaving layer 5. Axonal arbors remained fairly sparse until reaching the border between layers 4 and 2+3. There they divided frequently, with most shoots innervating lower layer 2+3. A second cell with a similar projection pattern is pictured in Figure 3*B*. Its soma also occupied the lower part of the layer. With the exception of a shorter apical process, the dendritic arbor was much like that seen in Figure 3*A*; it avoided regions supplied by the primary afferents. The axon gave off short collaterals in layers 6 and 5 before traveling through layer 4. As for the cell in Figure 3*A*, axonal branching was densest at the upper border of layer 4 and lower layer 2+3. A collateral that left the home column formed a separate cluster in the superficial layers. Last, the axons of both of these cells seemed to end in the white matter rather than exiting area 17.
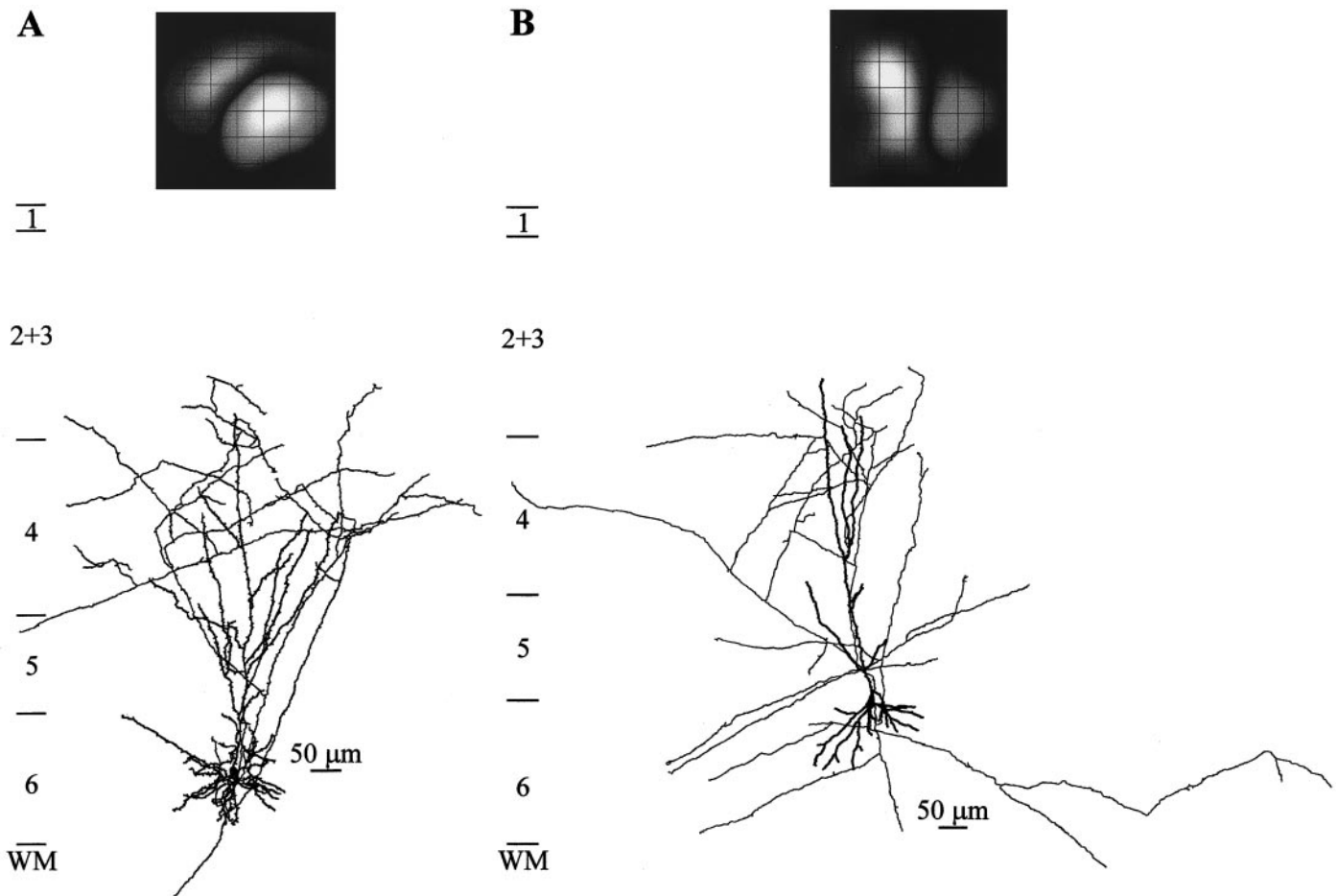
A   Simple Cell

receptive field

B   Complex Cell

receptive field

intracellular responses to:

bright squares   **dark squares**

intracellular responses to:

bright squares   **dark squares**

5mV
50ms

10mV
50ms

Figure 1. Synaptic responses of simple and complex cells in layer 6. The receptive field of a layer 6 simple cell had a small *off* subregion left of a stronger *on* subregion (*A, top*). The *dotted square* indicates the peak of the *on* subregion. The left and right panels beneath the map each show three individual trials of a bright or dark stimulus that fell over the peak of the *on* subregion; the averaged response of all sixteen trials of each stimulus is shown in *bold*. The *thick bar* under every trace marks stimulus duration. The essential features of the response pattern are that the bright stimuli initiated a strong depolarization (*A, bottom left*), whereas dark stimuli flashed at the same spot elicited hyperpolarizations (*A, bottom right*). *B* illustrates responses of a typical complex cell in layer 6. Its receptive field (*B, top*) was constructed from responses to dark stimuli because bright squares had limited action. The responses evoked by dark squares falling in the peak of the field (*dotted square*) were small, brief depolarizations (*B, bottom right*). There was no response to the introduction of bright squares, although a weak depolarization occasionally followed stimulus withdrawal (*B, bottom left*).

Cells favoring the upper aspect of layer 2+3

Figure 4*A* shows a striking example of a cell that favored the upper tier of the superficial layers; its soma was near the top of layer 6. The basal dendrites formed a radial array that extended well into layer 5, and the apical dendrite ended in a compact tuft in layer 1. A dense axonal plexus wove around the basal dendrites,

Figure 2. Projections of simple cells in layer 6. The receptive fields of two simple cells are shown above the anatomical reconstructions. The receptive field in panel A is the same as in Figure 1*A*. The cell was located in the middle of layer 6 and projected densely to layer 4. A second cell had a receptive field comprising a strong *off* subregion flanked by a weaker *on* subregion. This cell also projected to layer 4; in addition, it made horizontal connections within layer 6 itself. Both neurons had descending collaterals that appeared to leave area 17. Grid spacing was 0.4° for *A* and 0.85° for *B*.

with several collaterals ascending to layer 2+3 (one ascending trunk rose only so far as layer 4). Once in the upper half of the superficial layers, these axons split into many short processes that ended within ~100 μm of the apical dendrite. The cell also directed a prominent collateral outside of the home column, as in Figure 3*B*. A second cell, located in the middle of the layer, sent local dendrites throughout the laminar depth and into the white matter; its apical dendrite reached the middle of layer 2+3. Ascending axons loosely spiraled the apical dendrite, sending numerous twigs in layers 6 and 5 and few in lower layer 4. The main collaterals continued on a path to the superficial aspect of layer 2+3 where they forked into long branches that reached the pia. Two additional cells (data not shown) were located at the bottom of layer 6 and had dendrites that reached layer 1. One sent a sparse projection that reached layer 1; the axon of the other terminated in a thick spray within the upper aspect of layer 2+3. Three of the four cells had axons that appeared to exit area 17.

Cells favoring infragranular layers

The remaining two complex cells were somewhat different from those previously shown. The cell drawn in Figure 5*A* was located near the bottom of layer 6. It gave off small basal and apical dendritic branches in layers 6 and 5, then the apical dendrite took a straight course to layer 2+3, where it bifurcated, with each limb nearing the pia. The axon ramified thickly through layers 5 and 6

while a rare process entered layer 4. Only one collateral traversed the depth of the granular layer to end at the upper border. An unusual pyramidal cell was located in lower layer 6, Figure 5*B*. Its basal dendrites (some too pale to trace) were directed horizontally, and its apical dendrite reached layer 5. The axons rambled for nearly a millimeter at each side of the soma. The majority of the collaterals took a horizontal course after leaving one of the principal trunks. The many short branches that fringed the main processes indicated a high degree of connectivity throughout the arbor. The thickest bundle of fibers ran along the top of layer 5; a substantial meshwork spread though layer 6 as well. Additional projections included a central spray of terminals shot from layer 4 to layer 2+3 and sparser collaterals in the middle of layer 4 and its upper border. Neither of the cells drawn in Figure 5 seemed to have axons that exited area 17.

DISCUSSION

Layer 6 of the cat visual cortex includes two physiological classes of neuron, simple and complex. Simple cells are restricted to the upper tier of the layer, whereas complex cells populate its full thickness (Gilbert, 1977). It had previously been thought that layer 4 was the common target of all the pyramidal cells in the layer 6 (Gilbert and Wiesel, 1979; Martin and Whitteridge, 1984; McGuire et al., 1984). We have found a novel projection from
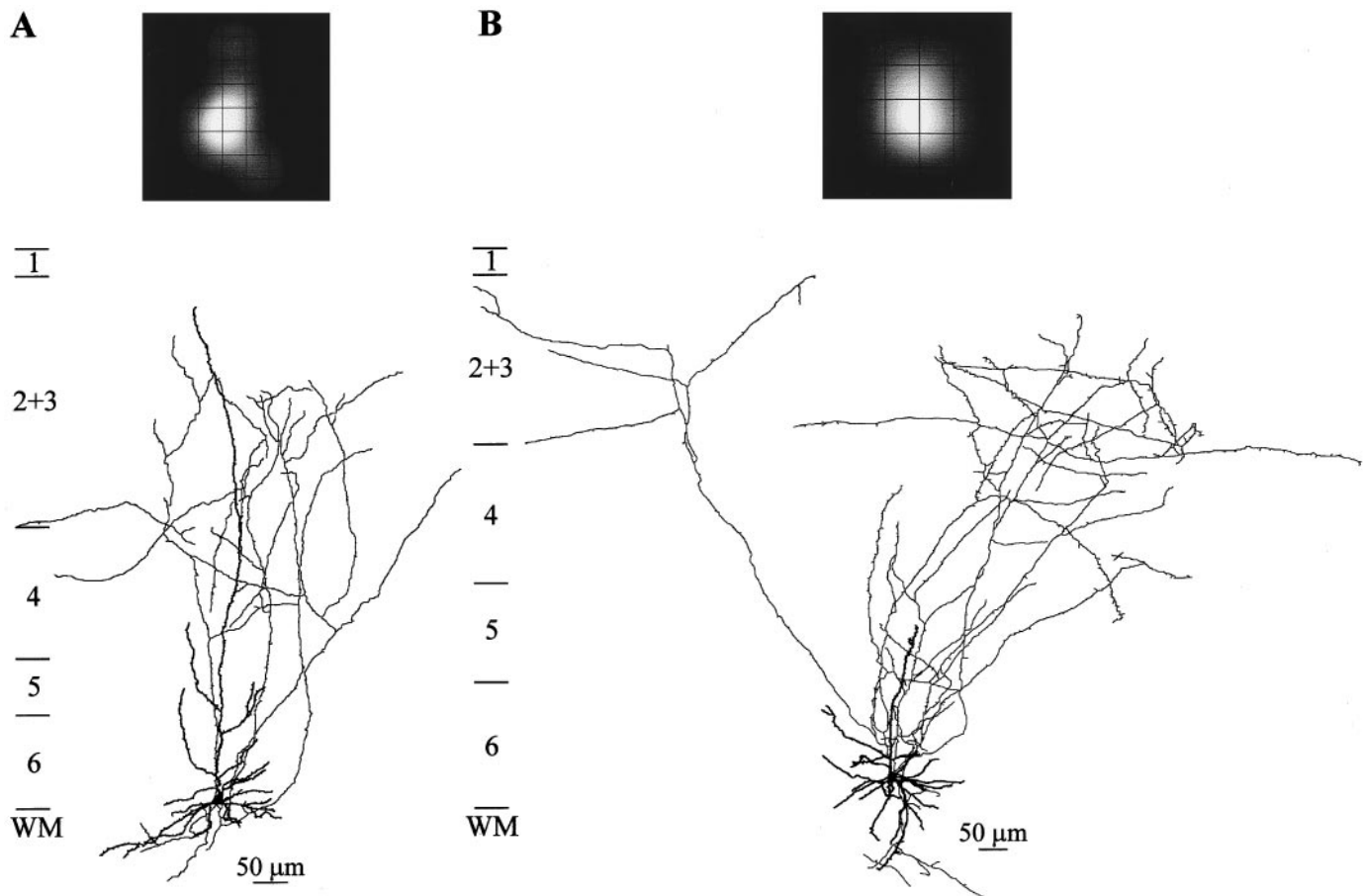
Figure 3. Complex cells in layer 6 that direct their densest output to the lower aspect of the superficial layers. Both cells were located in lower layer 6 and sent much of their output to the border between layers 4 and 2+3, and lower layer 2+3. The cell drawn in *B* gave off prominent collaterals that traveled outside the home column to synapse in the superficial layers. Neither cell seemed to project beyond the white matter. Grid spacing was 0.85°; both maps were constructed from responses to dark stimuli because those alone were effective. Intracellular records from the cell pictured in *B* are seen in Figure 1*B*.

layer 6 by which some complex cells direct their output to the superficial layers. Hence, the functional diversity of layer 6 is reflected in distinct interlaminar patterns of connectivity.

## Intracortical connectivity

Intracolumnar connections

Our principal finding is that complex cells in layer 6 send much of their output to regions populated by other complex cells, that is, to layers 2+3 and 5. Moreover, this complex cell pathway is distinct from the one made by simple cells, which supplies dense input to layer 4 (Gilbert and Wiesel, 1979; Martin and Whitteridge, 1984; Fig. 2 this study). Six of the eight complex cells studied projected to the superficial layers. Of these, four preferred the upper aspect of layer 2+3, and two preferred the lower tier. The remaining cells shared a preference for the infragranular layers. It seems reasonable to conclude that the superficial layers receive strong input from layer 6, although our sample remains too small to permit an exact estimation of the relative weight of ascending input that each layer or sublamina receives.

It is important to mention that not every complex cell in layer 6 favors layers containing other complex cells. McGuire et al. (1984) illustrate two complex cells whose projection patterns resemble those made by simple cells. Complex cells fall into two groups, based on their station in the cortical microcircuit: first order cells receive substantial direct input from the thalamus and

second order cells do not (Hoffman and Stone, 1971; Bullier and Henry, 1979; Ferster and Lindström, 1983). In a study of the superficial layers, we recently reported that first and second order complex cells have distinct synaptic physiologies (Hirsch et al., 1997). That is, the visual responses of first order complex cells, like those of simple cells, reliably capture the pattern of thalamic input. By contrast, the behavior of second order cells is variable and unpredictable. The response patterns of the layer 6 complex cells included in the current study resemble the records made from second order cells. Perhaps McGuire et al. (1984) recorded from a different physiological population of layer 6 complex cells, one that receives substantial direct input from the thalamus. In keeping with this idea, the complex cells illustrated in McGuire et al. (1984), like all layer 6 simple cells labeled *in vivo* (Gilbert and Wiesel, 1979; Martin et al., 1984; Fig. 2), had basal and apical dendritic branches that ramified within upper layer 6 and layer 4, where the fibers from the dorsal layers of the lateral geniculate terminate. The complex cells that we labeled branched less frequently in these regions.

Extracolumnar projections

In addition to their role in local processing, projections from layer 6 appear to convey information across visual space. Four of the complex cells we filled sent collaterals outside of their own column to form superficial clusters in adjacent zones. These
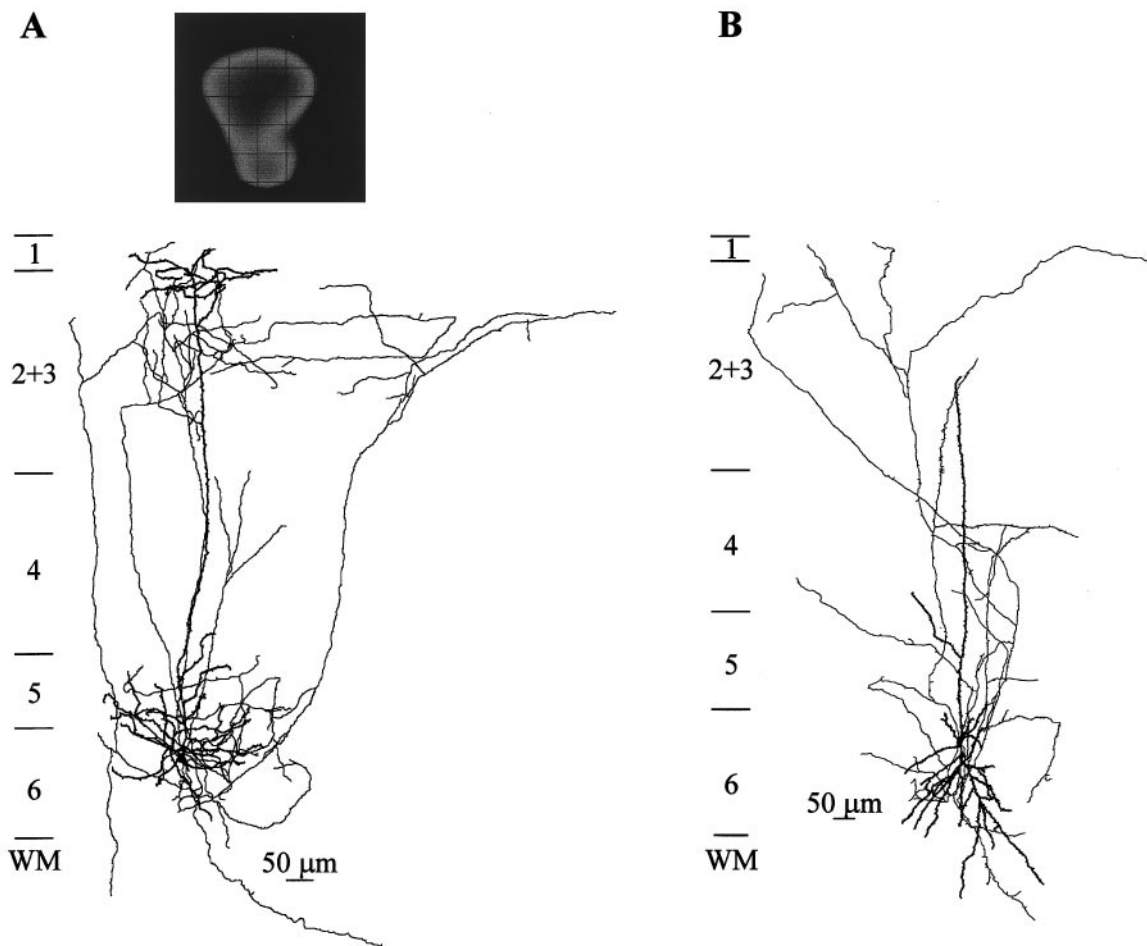
Figure 4. Complex cells in layer 6 whose projections target the upper tier of the superficial layers. The cell drawn in *A* projected densely to the top half of the superficial layers. The projection included a dense axonal arborization in vertical register with the apical dendrite and a prominent secondary cluster that lay outside the home column. The receptive field map shows responses to dark stimuli; it has an inverse shading pattern to indicate that the net response was inhibitory rather than excitatory (responses to bright stimuli were weak and are not shown); grid spacing was 0.85°. The cell drawn in *B* also had axon collaterals that reached the pia. This neuron failed to respond to the flashed squares and was mapped by hand with moving light bars. Each of these cells appeared to leave area 17.

clusters were comparable in size and spacing to those made by the horizontal connections that course within layers 5 and 2+3 (Gilbert and Wiesel, 1979, 1983; Martin and Whitteridge, 1984; Gilbert and Wiesel, 1989); albeit the intralaminar collaterals span larger distances (Gilbert and Wiesel, 1983).

Simple cells in layer 6 are also known to direct collaterals that terminate in layer 4, at a distance from the home column (Martin and Whitteridge, 1984; Katz, 1987). We have found evidence of another extracolumnar path, a simple cell that sent lateral connections to layer 6 itself (Katz, 1987). This finding complements the previous observation of a layer 4 simple cell that sent horizontal collaterals in layer 6 (Hirsch et al., 1995). Hence, there appears to be an interlaminar feedback circuit by which simple cells integrate information across cortical columns. This circuit may help to build the long, simple receptive fields occasionally encountered in layer 4 (Jagadeesh and Ferster, 1990) and layer 6 (Gilbert, 1977; Grieve and Sillito, 1991, 1995).

Lamination in cat cortex

In the primate and tree shrew, fine-grained laminar subdivisions are obvious even from the distribution of cell bodies. This is not the case for the cat. The sublaminar preferences in axonal pro-

jection seen in this study, together with illustrations provided by others (Gilbert and Wiesel, 1979, 1983; Lin et al., 1979; Martin and Whitteridge, 1984), indicate that the cat has a higher degree of laminar organization than is evident from the cytoarchitecture alone. As yet, however, it is not clear that the position of a given cell in the depth of layer 6 predicts the sublaminar preference of its output.

Subcortical connectivity

Claustral targets

Cells in layer 6 are known to project to the visual claustrum (LeVay and Sherk, 1981; Katz, 1987); many of these have long apical dendrites that reach layer 1. Physiological studies show that corticoclaustal cells have simple receptive fields (Grieve and Sillito, 1995). Given that the only cells we labeled that had long dendrites were complex, it is unlikely that we recorded from claustral projecting cells, which make up 3–5% of the layer 6 population.

Thalamic targets

In cat, ~50% of the cells in layer 6 project to the geniculate; these are scattered through the full depth of the layer (Gilbert and
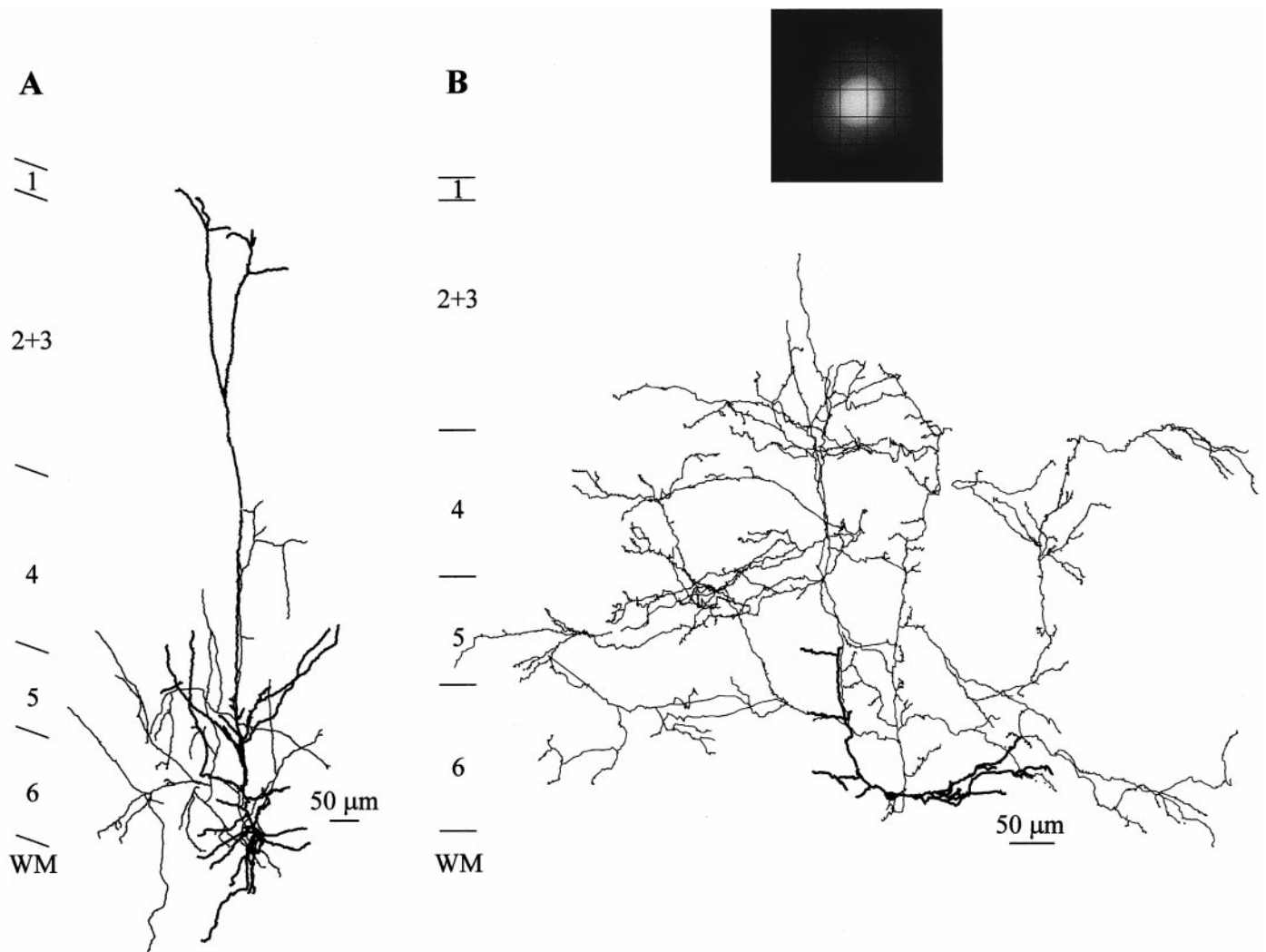
Figure 5. Layer 6 complex cells that terminate most heavily in the infragranular layers. Although these two cells were different in many regards, they shared a preference for layers 5 and 6. Neither seemed to project beyond area 17. The cell seen in *A* did not respond to flashed stimuli and was mapped by hand with moving light bars. The map in *B* was constructed from off responses because bright stimuli were not effective; grid spacing was 0.85°.

Kelly, 1975; McCourt et al., 1986; Katz, 1987), and most of these have simple receptive fields (Grieve and Sillito, 1995). Katz (1987) characterized two types of geniculate projecting cells *in vitro*. The most common type had dendrites that extended long branches in layer 4 and resembled the simple cells that we and others have filled (Gilbert and Wiesel, 1979; Martin and Whitteridge, 1984; Fig. 2). The other class of corticothalamic cell had sparse apical dendrites that rose no further than layer 3 (presumably the superficial axonal arbors were severed when the slices were cut); these recall one of the complex cells we stained (Fig. 4*B*). Thus, it appears that our sample included both simple and complex geniculocortical cells.

Comparative anatomy

Results of anatomical studies in other species give the sense that parallel ascending and descending projections from layer 6 are phylogenetically preserved features of the mammalian visual pathway. Moreover, there is a certain reciprocity in the flow of information between the cortex and thalamus. In one circuit, cells in upper layer 6 direct some axonal collaterals up to layer 4 and others down to the dorsal layers of the geniculate: there, relay

cells project back to the upper subtier of layer 6 and to layer 4 (rat, Burkhalter, 1989; galago, Conley and Raczkowski, 1990; macaque, Lund et al., 1975, 1979; Fitzpatrick et al., 1985, 1994; Wiser and Callaway, 1996). A second group of cells, at the base of layer 6 (rat, Burkhalter, 1989; Boursassa and Deschenes, 1995; galago, Conley and Raczkowski, 1990) or distributed throughout its depth (macaque, Fitzpatrick et al., 1985; Wiser and Callaway, 1996) provides ascending input to the supragranular layers and descending axons to the ventral and koniocellular layers of the geniculate and extrageniculate nuclei (for review, see Lund, 1988; Casagrande, 1994; Fitzpatrick, 1996; Callaway, 1998). These thalamic divisions project back to the supragranular layers in turn (rat, Bourassa and Deschenes, 1995; galago, Conley and Raczkowski, 1990; macaque, Fitzpatrick et al., 1994). The divergence in the input and output of layer 6 is best appreciated in the tree shrew. There, upper layer 6 targets the granular layers and the specific subset of geniculate laminae that supply them. A correspondent feedback circuit links lower layer 6 with the supragranular layers and with the remaining geniculate laminae and pulvinar (Usrey and Fitzpatrick, 1996).
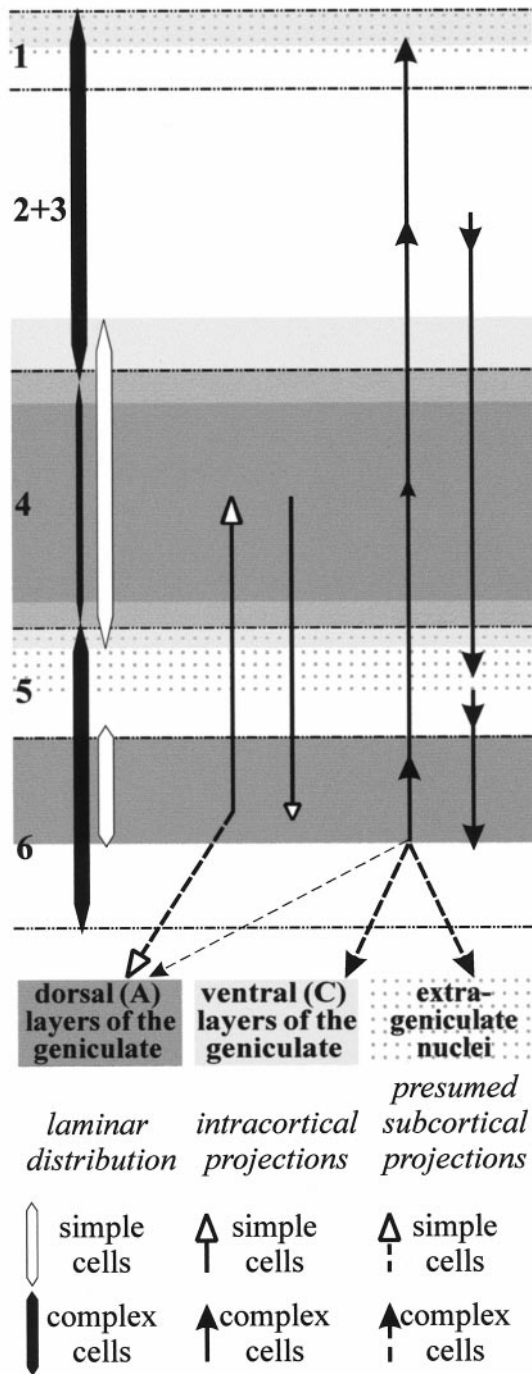
Figure 6. Thalamocortical feedback circuits involving the simple or the complex cells of layer 6. The extent and weight of the simple (*white*) and complex (*black*) cell populations in each cortical layer are indicated by the length and width of the *pointed bars* at the left of the diagram. The major intracortical pathways are denoted by *arrows* with *solid shafts* and presumed descending projections are represented by *arrows* with *dotted shafts*. *Open arrowheads* indicate projections by simple cells, and *filled arrows* depict projections by complex cells. Thalamorecipient cortical zones are *shaded*. *Dark gray* codes regions contacted by the A layers of the lateral geniculate nucleus, *light gray* shows the projection from the C laminae, and *stippling* denotes input from extrageniculate nuclei such as the pulvinar and medial interlaminar nucleus.

Information flow in the projections to and from layer 6 in cat

Taking the earlier studies (Lund and Boothe, 1975; Lund et al., 1975; Gilbert and Wiesel, 1979; McGuire et al., 1984; Martin and Whitteridge, 1984; Fitzpatrick et al., 1985, 1994; Burkhalter, 1989; Conley and Raczkowski, 1990; Casagrande, 1994; Bourassa and Deschennes, 1995; Sawatari and Callaway, 1996; Usrey and Fitzpatrick, 1996; Wiser and Callaway, 1996) together with our own suggests a pattern of ascending and descending projections from layer 6 that is outlined in a summary diagram (Fig. 6). The projections are divided into two, loosely parallel feedback circuits. One involves the layer 6 complex cells that project to laminae 5 and 2+3 (Fig. 6, *filled arrows*). These cells receive input from the ventral layers of the lateral geniculate and the extrageniculate nuclei; subcortical information arrives directly via the apical dendrites or is relayed by overlying complex cells (LeVay and Gilbert, 1976; Miller et al., 1980; Bullier et al., 1984). The path is closed by the descending projections from the layer 6 complex cells to the same thalamic sources. A second loop (*open arrows*) interconnects the dorsal layers of the geniculate and their principal cortical targets (simple cells and, perhaps, a subgroup of complex cells) (Gilbert and Wiesel, 1979; Robson, 1983; Boyapati and Henry, 1984; McGuire et al., 1984; Humphrey et al., 1985; Ferster, 1990; Ahmed et al., 1994; Grieve and Sillito, 1995; Murphy and Sillito, 1996). The two pathways overlap to an extent; one clear example is that the complex cells that project to the superficial layers provide some input to layer 4. A larger sample of layer 6 cells is required to understand exactly the pattern of information that these two circuits exchange.

The effect of the projection from layer 6 complex cells to the superficial layers remains to be explored. The axons that ascend from layer 6 to layer 4 synapse selectively with dendritic shafts (McGuire et al., 1984; Somogyi, 1989; Ahmed et al., 1994) and appear to contact a higher proportion of smooth cells (McGuire et al., 1984; cf. Ahmed et al., 1994) than do other cortical pathways; these, by and large, favor dendritic spines (McGuire et al., 1991; Johnson and Burkhalter, 1996). Hence, although the synapses made by the layer 6 pyramids are themselves excitatory (Ferster and Lindström, 1985), they have the potential to exert strong inhibitory influence in layer 4 via smooth interneurons (McGuire et al., 1984; Bolz and Gilbert, 1986; Hirsch, 1995). We hope to learn if the projection from layer 6 to the superficial laminae shares the same target preferences as the counterpart path to layer 4.

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