Functional Organization of Input from Areas 17 and 18 to an Extrastriate Area in the Cat

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In the cat, areas 17 and 18 have 2 main cortical targets: area 19 and a large region of suprasylvian cortex, referred to here as the Clare-Bishop area (Hubel and Wiesel, 1969). The functional organization of the latter area is not well understood. It seems likely that its organization reflects, in part, the organization of its inputs from areas 17 and 18, and I therefore studied the functional organization of these inputs. Responses were recorded directly from afferents terminating in the Clare-Bishop area after silencing its cells by local injections of kainic acid.

Afferents were precisely ordered according to preferred orientation in a fashion resembling the columnar organization of area 17. Preferred direction was also an important organizing parameter. Within sizable regions of cortex, directional preference changed gradually or not at all, while at these regions' boundaries, preferred direction reversed by 180°. Except for a loose grouping according to eye dominance, afferents were not ordered according to other response properties.

It is possible that the afferent array is also compartmentalized according to the area of origin of each afferent. Inputs from areas 17 and 18, for example, might end in separate territories in the Clare-Bishop area. However, physiological recording, as well as anatomical experiments, failed to show a clear segregation.

This study provides the first direct demonstration that a cortico-cortical pathway can be organized according to particular response properties. While the existence of an organization according to preferred orientation was not surprising, the high degree of order was unexpected. It is also interesting that afferents were well ordered according to 1 parameter, directional preference, that is weakly organized, at best, in area 17.

One of the hallmarks of primary visual cortex is its precise organization into functional domains, the best known of which are orientation columns and ocular dominance columns (Hubel and Wiesel, 1962, 1968; Shatz et al., 1977). In the cat, both areas 17 and 18 contain such columns (Hubel and Wiesel, 1965; Shatz et al., 1977). However, much less is known about the functional organization of the extrastriate cortex beyond area 18. In the cat, 2 extrastriate areas besides 18 receive input from area 17: area 19 and the Clare-Bishop area [defined here as the

region of suprasylvian cortex that receives input from area 17; while it cuts across several of the areas delineated by Palmer et al. (1978), it appears to be functionally (Spear and Baumann, 1975) and connectionally (Sherk, 1986a) homogeneous] (Fig. 1). Both area 19 and the Clare-Bishop area reportedly contain orientation columns (Hubel and Wiesel, 1965, 1969; Blakemore and Zumbroich, 1987), but what other kinds of functional organization are present is not certain. It is not easy to address this question directly, particularly in the Clare-Bishop area, because cells there are often poorly responsive in anesthetized animals. Therefore, in the present study, a different approach was taken: the functional organization of the afferent input from areas 17 and 18 to the Clare-Bishop area was investigated. If this afferent array is functionally organized, its organization presumably will reflect that of cells in the Clare-Bishop area itself.

If both the source (area 17) and target (Clare-Bishop area) are organized into orientation columns, it seems likely that afferents from area 17 terminate in an array that is ordered according to preferred orientation. But this need not be the case; orientation selectivity is apparently generated independently in 2 other extrastriate areas (18 and 19) and survives the loss of input from area 17 (Donaldson and Nash, 1975; Dreher and Cottee, 1975; Sherk, 1978; Kimura et al., 1980). Whether this occurs in the Clare-Bishop area is controversial (Spear and Baumann, 1979; Guedes et al., 1983). What other kinds of functional organization exist in this area is uncertain. Therefore, the first aim was to discover what response properties, if any, are organized in the pathway from area 17 to the Clare-Bishop area. Assuming some kind of organization was found, the next question was whether afferents are arranged in as orderly a fashion as are cells in area 17. A third and particularly interesting question was whether afferents are organized in a manner not found in area 17.

Cortical afferents to an extrastriate area could be organized not just according to their response properties, but also on the basis of their origin. Area 17, the largest source of input to the Clare-Bishop area (Sherk, 1986a), might have its own exclusive target zones within the Clare-Bishop area, with axons from area 18 or other sources ending in separate zones. When injections of anterograde tracer are made in area 17, they always produce multiple patches of label in suprasylvian cortex (Montero, 1981), and it is possible that input from area 18 terminates in the gaps between patches of input from area 17. Evidence for segregation of inputs has been reported by Malpeli and his colleagues (Lee et al., 1985, 1986). They showed that inactivation of area 18 cells providing input to the Clare-Bishop area drastically reduces cell responses in restricted zones within the Clare-Bishop area. Furthermore, their anatomical data suggested that the intervening, unsuppressed zones in the Clare-Bishop area

Received Dec. 20, 1989; revised Mar. 20, 1990; accepted Mar. 29, 1990.

I am grateful to Bill Gardner for technical help and to Christine Curcio, Dennis Dacey, and Kate Mulligan for their perceptive comments on the manuscript. This work was supported by Grant EY 04847.

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do not receive input from area 18, though whether these zones receive afferents from area 17 is not known.

In the present study, the organization of cortical inputs to the Clare-Bishop area was investigated by recording directly from afferent terminals. Several lines of evidence indicated that these afferents originated largely, or perhaps entirely, from areas 17 and 18. This evidence has been presented in detail in an earlier paper describing the response properties of these afferents (Sherk, 1989) and is summarized here. (1) All afferents were selective for orientation and/or direction, and most were binocular, ruling out an origin in the lateral geniculate nucleus. (2) The afferents' receptive fields were modest in size and generally much too small to belong to axons from the lateral posterior nucleus (Godfraind et al., 1969; Chalupa and Fish, 1978; Mason, 1978, 1981; Chalupa et al., 1983; Chalupa and Abramson, 1989). Also, afferent responses were vigorous, while cells in this nucleus have poor or no visual responses under barbiturate anesthesia (Mason, 1978, 1981; Sherk, unpublished observations). (3) This same argument would tend to exclude an origin from area 19, where cell responses are depressed by barbiturate anesthesia (Saito et al., 1988; Sherk, unpublished observations). Furthermore, direction selectivity was very common among afferents, and end-stopping was very rare, while cells in area 19 show the opposite pattern (Duysens et al., 1982; Tanaka et al., 1987; Saito et al., 1988). (4) An origin from the contralateral Clare-Bishop area seems unlikely for several reasons. This area has large receptive fields, and its neuronal responses are quite vulnerable to barbiturate anesthesia (Hubel and Wiesel, 1969; Spear and Baumann, 1975; Camarda and Rizzolatti, 1976; Zumbroich et al., 1986; von Grunau et al., 1987). Moreover, the population of cells in the contralateral Clare-Bishop area with receptive fields in the appropriate visual hemifield is small (Palmer et al., 1978). Finally, these terminate in a superficial band in the Clare-Bishop area, while many afferents were encountered deeper in the gray matter (Sherk, 1989). (5) The most compelling finding was that the afferents' receptive field sizes and response properties closely resembled those found in areas 17 and 18; a quantitative comparison suggested that they arose from a subset of the population in these 2 areas (Sherk, 1989).

The issue of possible segregation of inputs from areas 17 and 18 was assessed both physiologically and in anatomical experiments. In the latter, one tracer was injected into area 17 and a different tracer into area 18 at a retinotopically corresponding point. The outcomes of the 2 approaches both indicated that there is considerable overlap between afferents from areas 17 and 18.

Materials and Methods

Electrophysiological data were collected from 10 cats using procedures described in a previous paper (Sherk, 1989). General anesthesia was initiated by the intramuscular injection of ketamine and was maintained throughout both surgery and recording with sodium pentobarbital given intravenously. Pancuronium bromide was used for paralysis, and standard methods of life support and monitoring were employed.

Electrode penetrations and recording. Spikes from afferent terminals were recorded with electrodes made of glass-insulated tungsten after neurons in the Clare-Bishop area had been silenced by the injection of kainic acid (Sherk, 1989). In the first 4 experiments, kainic acid injections were made before recording was begun. In the other 6 experiments, kainic acid was injected in small increments (usually 0.02 μ l) while recording. In these cases, the injection pipette was glued to the electrode so that the tips were 800 μ m apart.

Most penetrations were intended to be tangential to the cortical surface. Most commonly, the electrode was in a coronal plane and was angled medially about 45° from vertical so that it traveled down the

Figure 1. Approximate location of the Clare-Bishop area in the right hemisphere. The medial and posterior banks of the suprasylvian sulcus have been exposed by cutting away the lateral gyri. The area's boundary (dashed line) varies from one animal to another and should therefore be considered schematic. Recordings were concentrated near the "corner" where the medial and posterior suprasylvian banks adjoin, with most penetrations traveling down the medial bank.

medial bank of the suprasylvian sulcus. Penetrations made into the posterior bank of the posterior suprasylvian sulcus were in a parasagittal plane and were angled from anterior to posterior.

In many regions, afferent spikes could be recorded continuously as the electrode advanced, often commencing within a few hundred microns of the surface. Response properties were tested at 10- μ m intervals in early experiments, and in later experiments, at 20- μ m intervals. It was often impossible to tell, on the basis of waveform, whether the afferent under study was different from that at the previous recording site, a problem arising from the small size and stereotyped shape of the afferents' spikes. However, different afferents could be readily distinguished on the basis of receptive field location and other response properties. Receptive fields recorded at sites only 10 or 20 μ m apart were frequently clearly different. Sometimes, however, what appeared to be the same afferent was recorded over many tens of microns, suggesting that the electrode recorded from a series of terminals belonging to the same arbor. It appeared that, at any particular site, the electrode generally recorded spikes from just 1 terminal or from several terminals that belonged to just 1 arbor. This conclusion was based on 2 observations. First, receptive fields had sharply defined borders and were usually small, while if terminals from several afferents were recorded simultaneously, the aggregate receptive field would be large and probably somewhat diffuse. Second, there were often discrete jumps in receptive field location and clear-cut changes in response properties when the electrode advanced, suggesting that 2 different afferents were recorded at successive sites.

There were also regions in some penetrations within which no afferent spikes could be recorded. In some cases, the electrode was probably deeper than the layers in which inputs from areas 17 and 18 end, but in other instances, there was no obvious explanation for the missing spikes.

Visual stimuli were presented manually and consisted of moving light bars or either light or dark edges. After plotting an afferent's receptive field, the following response properties were tested: (1) orientation selectivity, (2) direction selectivity, (3) end-stopping, (4) summation to increasing stimulus length, (5) ocular dominance, (6) range of velocities that elicited responses, (7) edge preferences, and (8) vigor of response. In the later experiments, the eyes were aligned so that it was possible to compare binocular and monocular responses; about half of the data were collected in these experiments.

Small electrolytic lesions were made at the end of each penetration and at 1-mm intervals during electrode withdrawal. These were used to reconstruct electrode tracks in sections stained with cresyl violet. For most experiments, a series of sections were also stained to reveal fibers using Gallyas's method (1979).

Anatomical experiments. Two cats were used for anatomical tracing experiments. In both, wheat germ agglutinin conjugated to HRP (WGA-HRP, 1–2% in saline) was injected into area 18, and 3 H-proline mixed with 3 H-leucine was injected into area 17. Injection sites were located by recording. The object was to find sites that had matching receptive field locations but that were sufficiently far apart that neither tracer

DISTANCE ALONG ELECTRODE PENETRATION (um)

Figure 2. Four electrode penetrations and the preferred orientations of afferents recorded along them. Electrode tracks are shown at *left*; all were made in the medial bank of the suprasylvian sulcus (the midline of each section is at *left*). Dots represent electrolytic lesions. Afferents whose data are plotted at *right* were recorded in the final stretch of each penetration except in *B*; here, afferents were recorded in the stretch preceding the upper lesion. In the graphs, squares indicate preferred orientations of individual afferents. S.I. = scatter index, computed as discussed in Materials and Methods.

would spread into the adjacent cortical area. Responses were recorded through the injection pipette, and the tracer was ejected slowly using air pressure. In the first cat, 0.2 μ l was injected in area 17 over a period of 77 min, and 0.3 μ l was injected in area 18 over a period of 44 min. In the second cat, 0.9 μ l was delivered in area 17 over a period of 94 min, and in area 18, 0.95 μ l was delivered over a period of 89 min.

After a survival time of about 36 hr, the cat was perfused and the tissue processed as described previously (Sherk, 1986a). Tetramethylbenzidine was used as the chromagen for reacting the HRP, in one case following the protocol of Mesulam (1976), and in the other, that of Olucha et al. (1985).

Data analysis. Most response properties were plotted as a function of distance in the cortex to see whether they changed in a systematic fashion with cortical location. In the case of preferred orientation, which showed a clearly systematic progression as the electrode moved through the cortex, the scatter along this progression was also calculated. A problem in this calculation is that, even if there is no scatter, in a columnar organization such as that in area 17, preferred orientation will change from 1 recording site to the next because adjacent columns have slightly different best orientations (Hubel and Wiesel, 1974). Therefore, a unit's preferred orientation should be compared with the best orientation of the columnar system at its own recording site, not with that of its neighbors. In order to estimate these presumptive best orientations, a best-fit line was drawn through the data points (see Fig. 4D) using a smoothing function (a moving boxcar average). The difference (D) was found between a unit's preferred orientation and the value of the best-fit line at the corresponding cortical location. A scatter index (SI) was then calculated for the whole penetration using the following equation:

$$SI = \sqrt{\frac{\sum D^2}{n-1}}, \quad (1)$$

where n is the number of units in the penetration. When there was a gap of 200 μ m or more between units (see, e.g., Fig. 2A), scatter was calculated separately for the segments of the penetration on either side of the gap. Scatter in preferred orientation was also calculated for 25 tangential penetrations made in area 17 in an earlier study (Sherk and LeVay, 1983). This measure appeared to be unaffected by spacing between cortical recording sites, which was an important consideration because the afferents' recording sites were generally closer together than recording sites in area 17 (on average, cells in area 17 were separated by 87 μ m, compared to 28 μ m for afferents). Penetrations in area 17 in which recording sites were closely spaced had scatter indices that were just as high as ones in which recording sites were far apart.

When directional preference was analyzed, the question was whether neighboring afferents (or cells) had the same preferred direction. In this analysis, only 2 preferred directions needed to be considered (e.g., if the afferents were selective for orientations near vertical, preferred direction could be either leftward or rightward). Three simple statistical tests were performed (Sokal and Rohlf, 1969). A runs test was used to see whether there was a significant grouping of afferents or cells according to preferred direction. A binomial test was used to see whether a penetration as a whole was strongly biased toward 1 direction. Finally, pairs of sequentially recorded afferents or cells that were within 70 μ m of each other were classed as having the same or opposite directional preferences to see whether nearby recording sites tended to have similar directional preferences.

Results

Orientation

It may be helpful to begin by reviewing how preferred orientation is organized in the cat's area 17 before considering the organization among afferents to the Clare-Bishop area. In area 17, orientation preference is organized both perpendicular to the cortical surface, in columnar fashion, and parallel to the cortical surface, in tangential fashion (Hubel and Wiesel, 1962, 1974). Cells in an orientation column all have the same preferred orientation. Viewed tangentially, cells having the same preferred orientation generally form long stripes (Singer, 1981; Albus and Sieber, 1984; Lowel et al., 1987), and adjacent stripes have very similar preferred orientations. Therefore, when a tangential pen-

Figure 3. Preferred orientation of afferents recorded along a penetration nearly parallel to cell columns in the Clare-Bishop area. The location of the penetration is shown in the 2 upper drawings. The track was terminated with an electrolytic lesion, indicated by the open circle in the enlarged view (upper right). Bundles of radial fibers visualized with a silver stain are also shown. The graph shows that preferred orientation changed only slightly throughout the penetration.

etration is made, preferred orientation changes gradually as the electrode travels through the cortex (Hubel and Wiesel, 1974).

In the present experiments, most penetrations (11 of 14) were oriented tangentially in the Clare-Bishop area. These all showed evidence of a systematic progression in preferred orientation as the electrode moved through the cortex. Figure 2 presents data from the 4 longest tangential penetrations. Note that the recording sites were more closely spaced than if the electrode had been recording from cell bodies; this was due to the small size of the afferents' spikes, which were quickly lost and replaced by new ones as the electrode advanced. As a result, these penetrations yielded quite detailed pictures of the progression of preferred orientation across the cortex.

It was more difficult to tell whether there was a columnar-orientation organization. Cell columns (which were visualized by staining radial fiber bundles) tended to be curved, so it was not possible to make a penetration that remained within 1 cell column. Two penetrations were approximately parallel to cell columns, and one of these is illustrated in Figure 3. In both cases, preferred orientation was fairly constant throughout, as one would expect if all afferents to 1 cell column had the same preferred orientation.

Regarding the tangential organization of preferred orientation, one might ask whether these penetrations were as orderly as penetrations in area 17. Penetrations in the Clare-Bishop area were compared with a series of tangential penetrations made in area 17 in an earlier study (Sherk and LeVay, 1983). Four of the latter are shown in Figure 4. The scatter in these penetrations was typical of area 17. At first glance, these data looked similar to those recorded from afferents to the Clare-Bishop area. To see whether the 2 sets of data differed quantitatively, a smooth

Figure 4. Preferred orientations of cells recorded along 4 penetrations in area 17. In *D*, the best-fit line used for computing the scatter index for this penetration is shown. S.I. = scatter index.

line was fitted to the data points in each penetration, as illustrated in Figure 4*D*. This line was used to compute a scatter index for each penetration (see Materials and Methods), which was a measure of the disorder in the progression of preferred orientations. Measures of scatter for penetrations made in area 17 varied from 6.6° to 22°, with a mean value for 25 penetrations of 14.4°. For 11 penetrations in the Clare-Bishop area, the mean

scatter index was surprisingly low, only 8.4° (the range was 2.1°–16.3°). Taken at face value, these numbers would suggest that afferents are more highly ordered according to preferred orientation than are cells in area 17. Technical differences between the 2 methods of recording (from afferent terminals as opposed to cell bodies) may explain the difference (see the Discussion). Still, it seems safe to conclude that afferent terminals in the Clare-Bishop area are no less precisely ordered according to preferred orientation than are cells in area 17.

Direction selectivity

Direction-selective cells in areas 17 and 18 prefer directions orthogonal to their optimal orientation, so a cell can favor 1 of 2 possible directions. If there is no systematic organization of preferred direction, one would expect to see frequent and randomly occurring 180° reversals in preferred direction as the electrode moves through the cortex. However, in the present experiments, the electrode often traversed regions of 400 μm or more in which such reversals were rare or absent. Figure 5 shows the preferred directions of afferents from 3 of the penetrations shown in Figure 2. In Figure 5*A*, throughout the entire penetration only 1 afferent (at a depth of 3,730 μm) had a preferred direction opposite to that of its neighbors. In Figure 5, *B* and *C*, there were more 180° reversals, but, with 1 exception, these occurred at boundaries between zones of relatively constant direction preference. Statistical tests (see Materials and Methods) confirmed that this clustering was significant ($p < 0.05$) in 9 of 10 long penetrations.

Although only 2 penetrations were made approximately parallel to cell columns, in both of these, preferred direction remained the same throughout the penetration, with few or no exceptions. In Figure 3, for example, all but 3 afferents preferred leftward movement. It therefore seems likely that there is a columnar organization of preferred direction among afferents to the Clare-Bishop area.

Was this grouping of similar preferred directions a reflection of an organization intrinsic to area 17? Despite a report of direction-selective columns (Payne et al., 1980), a consistent pattern in directional preference is seldom obvious in area 17. The penetrations in Figure 6 show data typical of area 17: preferred direction appeared to reverse frequently and at random intervals as the electrode moved through the cortex.

One could argue that domains in which preferred direction remained constant (or at least did not show reversals) might be difficult to detect in area 17 because direction-selective cells were recorded too far apart. The main reason for the wide spacing was that many cells in area 17 lack direction selectivity. A technical factor also contributed to wide spacing: an electrode recording somatic action potentials will pick up a spike from the same cell over a relatively long distance (in contrast, action potentials generated by afferent terminals usually were recorded for much shorter distances). Generally, 50–100 μm of area 17 were traversed before one well-isolated spike was replaced by another. To deal with the problem of widely spaced sampling sites, one can consider only direction-selective cells that are close together and ask whether these cells have the same preferred direction. This question was tested for successively recorded cells (or afferents) that were spaced 70 μm or less apart. (This was the smallest interval that yielded a sample from area 17 equivalent in size to that recorded in the Clare-Bishop area.) There were 258 such pairs of cells in area 17 and 250 such pairs of afferents. Each pair was classified as preferring the “same”

Figure 5. Preferred directions of afferents recorded in 3 penetrations. Preferred direction was plotted as a function of distance along the electrode track. In *B* and *C*, arrows point to 180° reversals in the progression of preferred direction.

direction (directions within 90° of each other) or “opposite” directions (ones more than 90° apart). If there was no continuity in preferred direction, 50% of the pairs should have had the same preferred direction, and 50%, the opposite direction. There was a modest tendency towards clustering in area 17, with 66% of the neighboring cells sharing the same preferred direction (see Fig. 7, left side). However, this trend was much stronger among the afferents, where 86% of the neighboring afferents had the same preferred direction (Fig. 7, right side). I would conclude that there is a weak tendency toward clustering according to preferred direction in area 17. Among afferents to the Clare-Bishop area, however, there appear to be distinct domains within which preferred direction changes only gradually, without 180° reversals.

Ocular dominance

Most cells in the Clare-Bishop area are reported to be strongly binocular, with the population as a whole being dominated by

Figure 6. Preferred directions of cells from 3 penetrations in area 17.

the contralateral eye (Hubel and Wiesel, 1969; Spear and Baumann, 1975). No segregation according to ocular dominance has ever been noted. It was therefore somewhat surprising to find that, in some penetrations, there was a tendency for afferents to be grouped by eye preference. Three examples are shown in Figure 8. In Figure 8, *A* and *B*, in the initial part of each penetration, afferents tended to be dominated by the contralateral eye (groups 1–3), but as the electrode advanced, the ipsilateral eye became dominant. The third penetration (Fig. 8*C*) is particularly interesting because, in addition to a region dominated by the contralateral eye and a region dominated by the ipsilateral eye, there were short stretches in which afferents required binocular stimulation (group 8). The clustering of these “obligate binocular” afferents was more striking in 2 other penetrations (not shown); in one case $\frac{2}{3}$ of the afferents belonged to group 8, while in the other, all afferents belonged to group 8.

One might suspect that ocular dominance grouping among afferents was merely a somewhat jumbled reflection of the highly ordered ocular dominance columns found in area 17. But ocular dominance is not well segregated in layers superficial to layer 4 in area 17, and these are the layers that project to the Clare-

Figure 7. Pairs of neighboring units that had "same" or "opposite" preferred directions. Only successively recorded units separated by 70 μ m or less were considered. Those with preferred directions within 90° of each other were classed as "same"; those with preferred directions differing by more than 90° were classed as "opposite." In practice, because neighboring units usually had similar preferred orientations, "same" preferred directions often were nearly the same, and "opposite" ones generally differed by about 180°.

Bishop area (Gilbert and Kelly, 1975). In penetrations in area 17 that were restricted to layers 2 and 3, the ocular dominance grouping was relatively weak, as illustrated in Figure 9. Therefore, for both afferents to the Clare-Bishop area and cells in area 17's supragranular layers, it appeared that there was a tendency toward ocular dominance grouping but not a segregation into distinct ocular dominance domains.

End-stopping

End-stopped afferents were rare, making up only 7% of the sample (Sherk, 1989). However, they were not uniformly distributed: almost all were encountered in just 3 penetrations, in groups of 2 to 4. This pattern suggested that there were occasional small islands of end-stopped afferents embedded in a large population of afferents lacking end-stopping. In area 17's layers 2 and 3, on the other hand, there was no evidence that end-stopped cells were clustered.

Origin of afferents: area 17 versus area 18

The last kind of functional grouping that was investigated was a segregation of afferents according to origin. Most (and possibly all) afferents recorded appeared to come from areas 17 and 18 (Sherk, 1989). There are 2 response properties that might serve to indicate whether afferents are segregated into origin-specific domains. The first is receptive field size, because cells in area 18 generally have larger fields than those in area 17 (Hubel and Wiesel, 1965; Movshon et al., 1978; Ferster, 1981). However, there was no tendency within a given penetration in the Clare-Bishop area for afferents with large receptive fields to be grouped separately from those with small receptive fields. The only suggestion of segregation was the finding that, in some penetrations, no afferents had large receptive fields.

The second parameter tested was velocity preference. Many

Figure 8. Ocular dominance of afferents plotted as function of distance along the electrode penetration. Numbers on the ordinate refer to the 7 ocular dominance groups of Hubel and Wiesel (1962). Units in group 1 responded only through the contralateral eye; units in group 2 responded well through the contralateral eye and slightly through the ipsilateral eye; units in group 3 responded through either eye, but somewhat better through the contralateral one; units in group 4 responded equally well through either eye. Groups 5–7 were dominated by the ipsilateral eye, with the balance of domination reversed relative to groups 3–1. Units in group 8 required binocular stimulation for their response. In these 3 penetrations, there was a weak tendency for nearby afferents to be dominated by the same eye or to fall in group 8.

cells in area 18 respond well to fast movement, in contrast to the situation in area 17 (Movshon, 1975; Orban and Callens, 1977; Orban et al., 1978). Therefore, one might ask whether there was a tendency for those afferents that responded well to fast-moving stimuli to occur in clusters. Again, the outcome was negative; many such afferents were encountered, but they were randomly intermixed with afferents that responded poorly to fast movement.

An alternative way of testing whether inputs from areas 17 and 18 tend to remain segregated from each other is to label them anatomically. In 2 cats, one tracer (WGA-HRP) was injected into area 18, and another (3 H-amino acid) was injected into area 17. The retinotopic locations at the 2 injection sites were matched. Each injection yielded multiple patches of label in the Clare-Bishop area; 3 examples are shown in Figure 10. In some sections, such as that shown in in Figure 10A, it looked as though the 2 different inputs tended to avoid each other. But in other sections, there was considerable overlap (Fig. 10, B, C). There was neither a consistent pattern of avoidance nor evidence of any kind of systematic relationship between afferents from area 17 and afferents from area 18.

Discussion

Orientation and direction selectivity

The main finding of this study was that the pathway from areas 17 and 18 to the Clare-Bishop area is highly ordered according to 2 parameters: preferred orientation and preferred direction. The organization of preferred orientation resembled that in area 17; tangential electrode penetrations in the Clare-Bishop area and in area 17 both yielded orderly progressions of preferred orientation. The organization of preferred direction, however, was much more pronounced among afferents than in area 17. While preferred direction reversed frequently and at unpredictable intervals along electrode penetrations in area 17, there were distinct domains among afferents in which preferred direction changed only gradually, without 180° reversals.

Was the organization of preferred orientation among afferents really the same as in area 17? One might first ask whether there were orientation columns running orthogonal to the surface. It proved surprisingly difficult to give a conclusive answer, both because cell "columns" are actually curved and because afferents from areas 17 and 18 terminate only in the upper half of the cortex (Sherk, 1989). The available data were thus limited, but they did suggest that afferents end in iso-orientation columns. Next, one might ask whether there were tangential iso-orientation domains. These clearly did exist, and, as in area 17, adjacent domains had similar preferred orientations. Whether these domains formed long stripes, like those in area 17, or formed some other shape was left unresolved.

One of the most unexpected findings was that preferred orientation appeared to be more precisely organized in the afferent array than in area 17. But the difference might be more apparent than real: spikes recorded from cell bodies are large, and an electrode in area 17 can probably pick up spikes from cells located some distance away. This would increase the scatter in preferred orientations found along a given track. However, an electrode recording from afferents presumably samples from nearby terminals because of the small size of terminal spikes (Zahs and Stryker, 1988; Sherk, 1989). A more faithful and less noisy picture of preferred orientation along the electrode's path should result.

Whether or not there is any real difference in how well ordered orientation preference is in area 17 compared to its outputs to the Clare-Bishop area, there is no doubt that the afferent array is quite well organized. This outcome was surprising. Only one other kind of organization—retinotopic—has been previously identified in the pathway from area 17 to the suprasylvian visual cortex, and most reports comment on the disorderly nature of this pathway (Hubel and Wiesel, 1969; Spear and Baumann, 1975; Palmer et al., 1978; Zumbroich et al., 1986). Thus, a somewhat puzzling picture of the pathway from areas 17 and 18 emerges: it maintains a high degree of order for orientation preference but is relatively jumbled in its retinotopy.

The existence of directional domains in the afferent array was obvious in all but 1 tangential penetration. In one sense, such an organization was not surprising: numerous investigators have stressed the large number of direction-selective cells in the Clare-Bishop area (Hubel and Wiesel, 1969; Spear and Baumann, 1975; Camarda and Rizzolatti, 1976; Blakemore and Zumbroich, 1987; Hamada, 1987; von Grunau et al., 1987). However, from another point of view, this organization was unexpected because domains of consistent preferred direction are not an obvious feature of area 17's organization. Statistically,

Figure 9. Ocular dominance of cells in 3 penetrations recorded in layers 2 and 3 of area 17. Conventions are as for Figure 8. As for afferents to the Clare-Bishop area, there was a modest tendency for nearby cells to be dominated by the same eye.

it was possible to demonstrate a weak tendency toward clustering of cells with like preferred directions in area 17, but this grouping was far from clear from simply looking at the data. Indeed, Tolhurst et al. (1981) found a grouping that was even weaker than that observed here. On the other hand, Payne et al. (1980) reported a considerably stronger tendency for neighboring cells to have similar preferred directions. The discrepancy might be due to the use of tangential penetrations in the present experiments, in contrast to the variety of penetration angles employed by Payne et al. (1980). Suppose that columns normal to the surface in area 17 contain cells that all have the same preferred direction, but suppose that these hypothetical columns are not grouped together in any systematic way. In such a case, data collected from surface-normal penetrations would reveal a high degree of organization, while data collected from tangential penetrations would reveal very little organization at all. Indeed, Tolhurst et al. (1981) reported that there was no clustering according to preferred direction in penetrations that were oblique or tangential. Whether or not this is the correct explanation, one can conclude from the present experiments that the tangential organization of preferred direction in area 17 is weak at best.

It is possible that preferred direction is more highly organized in area 18. A recent study of this area by Cynader, Swindale, and Matsubara (Cynader et al., 1987; Swindale et al., 1987) concluded that there are regions in which preferred direction either remains constant or varies gradually. However, this con-

Figure 10. Coronal sections from 2 experiments in which one anterograde tracer (WGA-HRP) was injected into area 18, and another (^3H -amino acid) into area 17 at a retinotopically corresponding location. The *top* 2 sections (*A*, *B*) contain the injection sites. In the *middle* row are 2 sections from the first experiment and 1 from the second that contained patches of anterograde label in the Clare-Bishop area. In the *bottom* row are enlarged drawings of these patches. In the *left-hand* example, there was little overlap between the different tracers, but in the *middle* and *right-hand* sections, the overlap was more substantial.

clusion is open to some question. The procedure used, in which many vertical penetrations are made and preferred direction is assessed at just 1 site in each, is valid only if all cells in a column have the same preferred direction. It is not known whether there is a columnar organization of preferred direction in area 18. Furthermore, preferred direction was judged for a cluster of units; if some cells prefer one direction and others the opposite, an assessment of the whole cluster's preferred direction has little meaning. Finally, one must be cautious in concluding that preferred direction shifts in an orderly way across the cortex, because preferred direction is confounded with preferred orientation, a parameter that clearly is well ordered in area 18.

An interesting question that was first addressed by Spear and Baumann (1979) is whether cells in the Clare-Bishop area depend upon input from area 17 for their direction or orientation

selectivity. While Spear and Baumann (1979) reported that most cells do depend upon areas 17 and/or 18, Guedes et al. (1983) have reported the opposite result. The present results do not resolve this controversy, but they do show that the connectivity between other cortical areas and the Clare-Bishop area is sufficiently ordered to give rise to orientational and directional preferences in target cells. The degree of order in the input array is critical because a target cell has dendrites extending over tens of microns and thus can, in theory, receive input from an appreciable cross-section of the afferent array. Consider direction selectivity: if nearby afferents have a range of preferred directions and all have access to the dendrites of a target cell, the cell should respond to this range of directions. Only if nearby afferents have the same or similar preferred directions can they confer direction selectivity on the target cell.

Other response properties

Response properties other than orientation and direction selectivity showed at best a marginal tendency toward organization. A weak trend toward grouping according to ocular dominance was evident. End-stopped afferents likewise appeared to be clustered, but they were so rare that end-stopping could hardly be considered a major organizing parameter of the afferent array. No other response property showed any systematic organization.

Segregation of afferents from areas 17 and 18

Neither physiological nor anatomical data supported the idea that afferents from areas 17 and 18 are segregated in the Clare-Bishop area. Yet, the elegant experiments of Malpeli and colleagues (Lee et al., 1985, 1986; see introductory remarks) have suggested that there are regions dominated by input from area 18, with intervening zones that depend primarily upon some other, unidentified source of input. One possibility is a partial segregation of inputs from areas 17 and 18. There could be zones that receive input only from area 17, zones that receive input only from area 18, and zones that receive a mixed input. This scheme would be consistent with the anatomical results shown in Figure 10. Furthermore, in the present experiments, there were some penetrations in which the electrode encountered only afferents with small receptive fields; these might have traversed zones that had input only from area 17. Other penetrations yielded both large and small fields, and these presumably traversed zones that had input from both areas 17 and 18. However, regions were not found where all afferents had large fields, as one would expect to find in zones receiving input only from area 18. Therefore, while the present results are consistent with a partial segregation between afferents from areas 17 and 18, they do not provide strong support for such a scheme.

The puzzle of patchy labeling of inputs from area 17 in tracer experiments could be explained by an entirely different mechanism. Whenever a small tracer injection is made in area 17 or 18, it preferentially labels cells with similar preferred orientations because the tracer is most concentrated in a few adjacent orientation columns. Perhaps the afferents from one orientation column in area 17 go to several columns in the Clare-Bishop area, all having the same preferred orientation. Because the afferents to the Clare-Bishop area are ordered according to preferred orientation, one would then see several patches of labeled afferents corresponding to these target orientation columns. The unlabeled gaps would represent different preferred orientations. This mechanism seems plausible when patches of labeling are close together, but it seems less likely when they are far apart. However, other evidence suggests that widely separated patches belong to duplicate retinotopic maps within the Clare-Bishop area (Sherk, 1986b; Sherk and Ombrellaro, 1988).

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