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Visual Activity in Areas V3a and V3 During Reversible Inactivation of Area V1 in the Macaque Monkey

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SUMMARY AND CONCLUSIONS

1. Behavioral studies in the monkey and clinical studies in humans show that some visuomotor functions are spared in case of a V1 lesion. This residual vision appears to be subserved at least partially by visual activity in extrastriate cortex. Earlier studies have demonstrated that neurons in area V2 lose their visual responses when V1 is reversibly inactivated. On the other hand, Rodman and collaborators have recently shown that neurons in the middle temporal area (area MT) remain visually responsive when V1 is lesioned or inactivated. The purpose of the present study was to determine whether area MT is unique among extrastriate cortical areas in containing visually responsive neurons in the absence of input from area 17.

2. A circular part of the opercular region of area V1 was reversibly inactivated by cooling with a Peltier device. In that condition, 149 sites were recorded in the retinotopically corresponding regions of areas V3 and V3a.

3. About 30% of sites in area V3a still responded to visual stimulation when V1 was inactivated. On the contrary, nearly all sites in area V3 ceased to fire to visual stimulation. Receptive-field properties were assessed with qualitative measures; for most single cells or multiunit sites that responded during V1 inactivation, these properties did not change during cooling.

4. These results suggest that area V3a could take part in spared visuomotor abilities in case of a lesion of V1. Areas V3a and MT are both part of the occipitoparietal pathway, which suggests that the residual vision observed after a lesion of area 17 may depend mostly on this pathway.

INTRODUCTION

It is generally accepted that area V1 constitutes the first cortical relay in the processing of visual information in the monkey. Available data about the subcortical afferent connections to extrastriate visual cortex suggest, however, that some visual information may bypass area V1 to reach directly extrastriate visual areas. Thus it is known that the lateral geniculate nucleus (LGN) sends a direct projection to extrastriate cortex (Benevento and Yoshida 1981; Bullier and Kennedy 1983; Fries 1981; Yukie and Iwai 1981). Visual information may also reach extrastriate cortex through a tectopulvinar pathway (Benevento and Rezak 1976; Rezak and Benevento 1979; Standage and Benevento 1983).

The pivotal role of area V1 as the sole distributing center of visual information in primate cortex has also been challenged by functional studies. For example, visually responsive cells can still be recorded in the middle temporal area (area MT) after total ablation or reversible inactivation of area V1 (Bullier and Girard 1988; Rodman et al. 1989; Blakemore, personal communication). On the other hand, areas V2 and V4 have been shown to be totally silenced by inactivation of area V1 (Girard and Bullier 1989; Girard et al. 1991; Schiller and Malpeli 1977). This raises the question of whether area MT is unique in containing visually responsive neurons in the absence of a V1 input. This is an important question, because behavioral studies in the monkey and clinical studies in humans both suggest that the observed residual visuomotor abilities might be subserved by visual cortex in case of lesion of area 17 (Segraves et al. 1987; Weiskrantz et al. 1974).

We have, therefore, investigated the visual responses of cells in two other extrastriate areas, V3 and V3a, when area V1 was blocked by cooling. Like area MT, both areas receive subcortical connections that bypass area V1.

Our study reveals a major difference between the two areas. Some cells in V3a could be visually driven independently from V1. On the contrary, V3, similarly to area V2 and V4, appears to depend totally on its input from striate cortex.

METHODS

Implantation

Methodological details concerning anesthesia and animal care during surgery have been given in an earlier publication (Girard and Bullier 1989). Three young adult male macaque monkeys (*Macaca fascicularis*) received a circular craniotomy (2-cm diam) above the operculum. The approximate position of the hole center was 1 cm in front of the occipital crest and 1.5 cm lateral to the midline. A circular well was placed around the bone defect and was closed by a plastic lid.

A metal plate was also attached to the rostral part of the skull. This plate was used to hold the head during the recording sessions, thus avoiding the use of potentially painful earbars.

It is known that receptive fields of neurons in extrastriate cortex can cross the vertical meridian (Van Essen and Zeki 1978); to suppress a potential drive from the opposite hemisphere, the splenium of the corpus callosum was sectioned during the implantation surgery. At least 1 wk separated the implantation and the first recording session.

Cooling

The cooling technique (Peltier device) and the relevant parameters have been described in detail in a previous paper (Girard and Bullier 1989). During the first recording session for each monkey,

we determined electrophysiologically the receptive fields of V1 cells located at the inner border of the circular craniotomy. An imaginary line linking the centers of these receptive fields delimits what we call the "cooling perimeter." This region corresponds broadly to the region of the visual field represented by neurons situated under the cooling plate. (Because of the nonzero dimensions and scatter of receptive fields in V1, the regions of visual field represented by neurons under and outside the cooling plate are not strictly separated by the limits of the cooling perimeter but by an annular region a few tenths of a degree wide containing receptive fields of neurons below or outside the cooling plate). In addition to our previous study, we attempted to evaluate possible perturbations of the temperature gradients by blood vessels under the cooling plate. We recorded the temperature of the cooling plate for which the response to visual stimulation stopped in the lower layers of V1 (100–200 μm above the white matter). We found that this temperature was lowest when the penetration was near the lunate sulcus, but the difference with the blocking temperatures recorded for other penetrations at the same depth did not exceed 2°.

During cooling sessions, one microelectrode advanced through a central hole in the cooling plate was left in the lower part of layer 6 in V1 and recorded a reference group of cells. Another microelectrode was recording in areas V3 and/or V3a. In all cases, cells were tested in V3 and V3a only after the visual responses of the reference group of cells were blocked by the cold. We occasionally had to push down the reference electrode in V1, because the thickening of the dura mater during the experiment displaced the lower layers further away from the tip of the electrode. Because of the inertia of the cooling system, cells in V3a and V3 were generally tested when the temperature in the deep layers of V1 was more than 2° below that needed to inactivate cells recorded by the microelectrode placed in V1. The receptive fields of the reference cells in V1 were plotted before and after each recording in V3-V3a to correct the position of the cooling perimeter in case of eye movements and to check the convergence of the visual axes.

Even when the receptive field of a given cell or group of cells was completely included within the cooling perimeter, we were careful to stimulate only the region of the cooling perimeter by placing a mask on the surrounding regions. Such a consideration applies to every site we have studied. When the receptive field extended beyond the cooling perimeter, it was also studied with the mask, but if, at the end of cooling, the activity was blocked, we then sought to determine whether the outer part of the receptive field was responsive by removing the mask.

Recording

Two monkeys were used for semichronic experiments lasting 10–12 h, except for the terminal session, which lasted several days. Recording sessions were separated by ≥2 days. The third monkey was used during an acute session of 5 days.

As mentioned above, two recording microelectrodes were used, one in V1 and another in V3-V3a. Microelectrodes were of the tungsten-in-glass type (4- to 6-MΩ impedance before plating; Merrill and Ainsworth 1972). We recorded from one to three units (multiunit activity) for qualitative recording and from single units for quantitative measurement of activity. The signals were amplified and filtered (100 Hz–10 kHz and notch filtered at 50 Hz, Neurolog system) and passed through a nonlinear amplification device (slice) that removed most of the low-amplitude background noise.

The recording procedure was the same as that employed in the previous study, with a few changes in animal maintenance. Pancuronium bromide (Pavulon) was used with an initial dose of 0.1 mg/kg iv and a continuous infusion of 0.08 $mg \cdot kg^{-1} \cdot h^{-1}$ in Ringer lactate with 5% sucrose. A continuous infusion of an opiate (Fentanyl 0.14 mg/h iv) was made to improve analgesia and stabilize the preparation. At the end of the recording session (semichronic cases), 1 h after the paralyzing agent had been stopped, 0.1–0.4 mg of neostigmine methylsulfate (prostigmine) was injected intravenously to reverse paralysis. The monkey was then replaced in its home cage and monitored until it had fully recovered.

The blood vessel above the lunate sulcus could be seen through the dura. To reach the fundus of the lunate sulcus, where V3-V3a is situated, we drilled a small aperture 8 mm in front of this vessel and 14–16 mm lateral to the midline. The electrode was lowered in this hole with an angle of 30° with respect to the vertical in the parasagittal plane.

Visual stimulation was presented in the form of light or dark bars of optimum size, orientation, direction, and speed. Binocular fusion was achieved by means of a Risley prism while recording from a binocular cell in area V1. During recording in V3 and V3a, monocular or binocular stimulation was used, depending on which situation produced the best response. In practically all the cases, binocular stimulation was used. Before or after each recording in areas V3 and V3a, we checked that the receptive fields of the V1 cell corresponding to each eye were superimposed; if an eye movement had occurred during the previous recording, we discarded that recording. We sampled groups of cells every 50–150 μm, almost every site being sufficiently responsive in V3-V3a to be properly tested. Quantitative analysis of the response was done on isolated single units with the use of a visual stimulator described in an earlier publication (Girard and Bullier 1989). Peristimulus time histograms (PSTHs) were computed from the response after all activity ceased in area 17, usually 5–10 min after the cooling procedure began. This time period has been shown to be sufficient for the cortex to reach equilibrium temperature (Girard and Bullier 1989). When PSTHs were computed after rewarming, this was done ~15 min after cortex had reached normal temperature. The extent of inactivation was estimated for a number of single units by use of the blocking index defined by Maunsell et al. (1990). The blocking index is computed as 1 − (response during cooling/response before cooling); it equals 1 when the unit is totally blocked and 0 when cooling has no effect on the response. The index is >1 when the response is below spontaneous activity during cooling and negative when the response is higher during cooling than before. For moving stimuli, the value of the response was computed as the number of spikes per presentation above spontaneous activity.

Histological procedure

Electrolytic lesions were placed during electrode penetrations (electrode negative: 10 μA during 10 s) to reconstruct the tracks. Neurons were placed in area V3 or V3a on the basis of myeloarchitectonic criteria given at the beginning of RESULTS. The borders between V2, V3, V3a, and V4 could be clearly identified in the two animals in which the most neurons (137/149) were found. At the end of the recording session, the animal was deeply anesthetized and perfused with normal saline followed by 10% Formalin and ascending concentrations of sucrose. The brain was cut on a freezing microtome (60-μm-thick sections) in the parasagittal plane, and alternate sections were stained for myelin (Gallyas 1979) and with thionin to reveal areal boundaries.

RESULTS

In three monkeys, we recorded 149 sites (34 single units) in the fundus of the lunate sulcus or in the region anterior to it that forms the annectant gyrus. Physiological criteria, such as differences between sizes of the receptive fields in each area, are not marked enough to indicate whether recording was from V3 or V3a. Thus we relied only on the

histology to assign neurons to specific cortical areas. In myelin-stained parasagittal sections, area V3 appears to be limited to a relatively small portion of the fundus of the lunate sulcus. As described earlier (Colby et al. 1988; Morel and Bullier 1990; Van Essen et al. 1986), the staining in V3 is dense and rather uniform, the outer band of Baillarger is faint or absent, and the inner band of Baillarger is not separated from the white matter by a clear band, as it is in V2 (Fig. 1). Anterior to V3 in parasagittal sections is found V3a in the annectant gyrus. Although difficult to identify in sections stained with the Heidenhain-Woelcke method (Gattass et al. 1988), the border between V3 and V3a can be recognized in sections stained with the method of Gallyas (1979). It is characterized by the appearance in V3a of two distinct bands of Baillarger, the inner one being separated from the white matter by a clear band (Fig. 1). These characteristic features correspond to those mentioned by Colby et al. (1988) and Morel and Bullier (1990) and to those apparent in cortex labeled as V3a by Van Essen and collaborators (Burkhalter et al. 1986; Van Essen et al. 1986). The anterior limit of V3a with V4 is often more difficult to identify, although it can be obvious in some sections (for example, Fig. 2 in Morel and Bullier 1990). The bands of Baillarger are more sharply defined in V4 than in V3a, and V4 shows stronger radial fibers than V3a. Further support for our belief that our recordings were confined to V3 and V3a is provided by the similarity of the sulcal pattern in the cortical region of our recording sites to that of the cortical regions identified as V3 and V3a by electrophysiological mapping (Gattass et al. 1988). Because of the uncertainty in recognizing the border between areas in one monkey, some sites could not be placed unambiguously in V3 or V3a but clearly belonged to either one. We placed these sites in a V3-V3a category. Because we did not place electrolytic lesions in all tracks, there were doubts about the precise recording depth of some other units that we also placed in the V3-V3a category. Using the criteria described above, we assigned 76 sites to V3a (13 single units), 37 to V3 (13 single units), and 36 to V3-V3a (8 single units).

The photomicrograph on Fig. 1 shows a parasagittal section of the occipital part of the brain of one monkey (*PG17*). The borders between cortical areas are marked by large arrows. One electrolytic lesion can be recognized in V3a near the V3-V3a border. This lesion was placed within the electrode track that is reconstructed in the schema below. The positions of sites that have been recorded along the track and the occurrence of inactivation of their responses during cooling of V1 are also indicated. The silence corresponding to the crossing of the sulcus by the electrode could be detected during the recording. Above the sulcus, recording was in area V3a; below, it was in area V3. Figure 1 illustrates the major point of the paper; during recording in V3a (above the sulcus), a number of sites (black squares) remained active when V1 was blocked, whereas in V3 (below the sulcus) all cells were inactivated (open squares).

Responses of neurons during cryoblocking of V1

During inactivation of V1, for most units we assessed the presence of a residual visual response by listening to the audiomonitor. Sites were considered inactivated when no response to visual stimulation could be elicited, whether or not spontaneous activity was suppressed. Except in four cases for which only weak visual responses were heard, the neurons classified as remaining active gave unequivocal visual responses (see below), and it was possible to plot a receptive field with the residual response. The responses of 11 single units were analyzed with quantitative methods. This was particularly necessary for some neurons that had a bursting spontaneous activity during the blocking of V1. Comparison between the decision reached with qualitative methods (blocked or not blocked) and the value of the blocking index computed from the quantitative records was used to validate the qualitative methods: among the six units judged not to be blocked, the blocking index ranged between −0.2 and 0.75 (mean 0.35), whereas it ranged between 0.91 and 1.5 (mean 1.11) for the five blocked units. Furthermore, for the one blocked unit with a blocking index <1, the "residual response" consisted of an elevation of burstiness during visual stimulation instead of a well-defined increase of activity, as recorded for units that were judged not to be blocked.

When area V1 was inactivated by cooling, we observed several different effects on the visual responses of cells in V3a or V3, depending on the position of the receptive field with respect to the cooling perimeter. When a site had its receptive field completely included in the cooling perimeter, it was considered blocked if its visual response disappeared completely when V1 was silenced. If a visual response remained, we considered it not blocked. For sites with receptive fields partially overlapping the cooling perimeter, we used a mask to study only the region of the receptive field that was included in the cooling perimeter. If no visual response could be evoked in that region but a response was still present in the outer part (when the mask was removed), we called this observation "selective block." When visual responses remained in the region of the receptive field inside the cooling perimeter, we considered the unit not blocked.

Figure 2 presents a case of selective block of a single cell (*44-2*) in V3a, the receptive field of which overlapped only partially with the cooling perimeter. After removal of the mask, a light bar was flashed at several positions along one axis of the receptive field. The sequence of presentation of the flash was randomized. The curve illustrates the value of the blocking index for the ON response as a function of the position of the bar. For the two positions inside the cooling perimeter (1 and 2), the response was completely blocked (index >1), whereas for the positions outside the cooling perimeter, the response was diminished but not blocked (index between 0 and 1).

The decrease of the response outside the cooling perimeter can be explained by the lateral spread of the cold within the cortex of area V1. Visual response is strongly decreased for stimulation 2.5° away from the cooling perimeter. Assuming an inverse magnification factor of 0.6°/mm in the corresponding region of area 17 (Hubel and Wiesel 1974), 2.5° of visual angle correspond to a lateral distance over the cortical surface of 4.1 mm. During control experiments, we found that the cortical temperature 4 mm lateral to the cooling plate reaches 18°C, a temperature that strongly reduces the activity of neurons in area 17 and inactivates some (Girard and Bullier 1989). Thus the cooling perimeter corresponds to the region of V1, where all neurons are

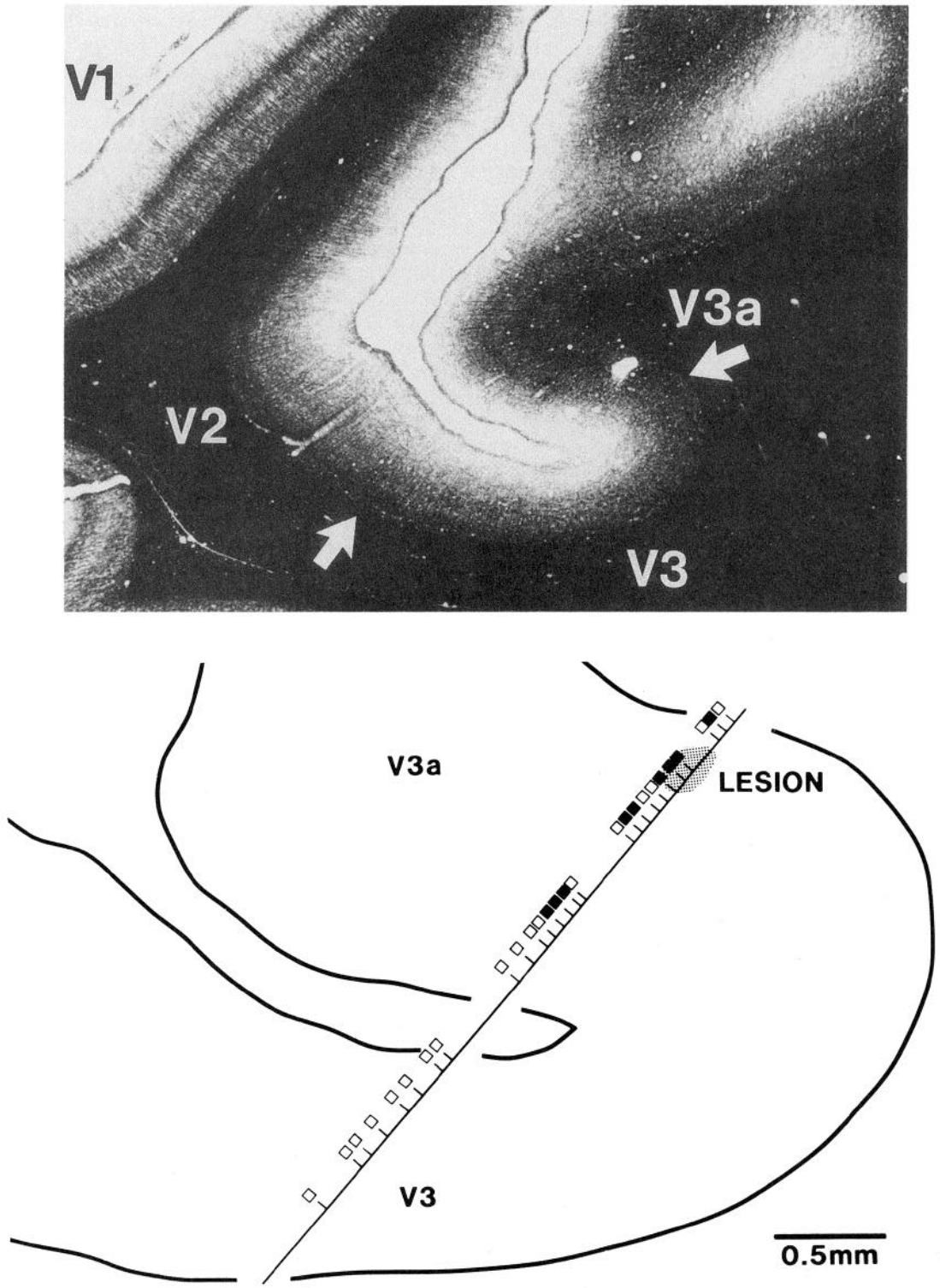

FIG. 1. Myelin-stained parasagittal section of cortex of 1 monkey (*PG17*). Arrows show areal boundaries. An electrolytic lesion can be seen in V3a near V3-V3a border. A small part of cortex of V1 that was blocked by cooling is shown. Notice the good histological appearance of this region. *Bottom*: reconstructed electrode track is shown with lesion. Each open square represents a cell (or a small group of cells) that was inactivated when V1 was blocked. Black squares represent those sites that were not inactivated.

blocked, whereas the surrounding region corresponds to a region of decreased activity. In all cases, the border between the active and the silent parts of a receptive field was within 1° of the cooling perimeter. The same precise correspondence between the cooling perimeter and the inactivated region in case of selective block was found in V3a and in V3. In two cases of large receptive fields containing one region inside the cooling perimeter between two parts outside of it, these two outer regions were visually responsive, whereas the central was inactive.

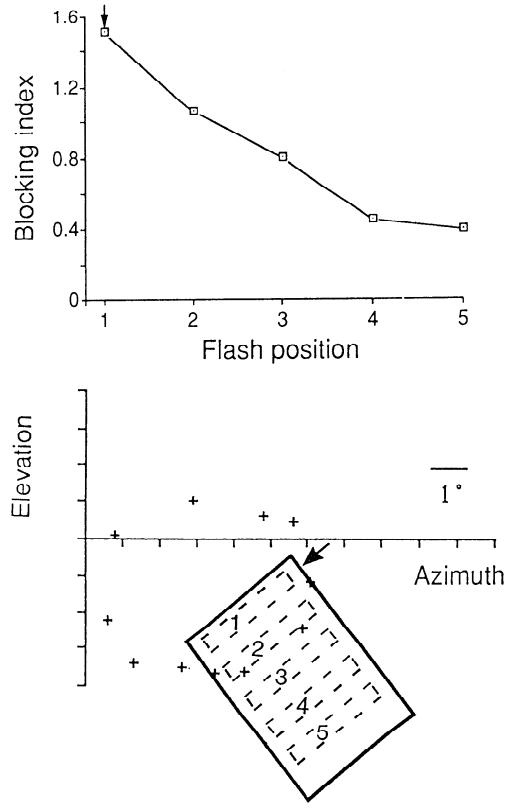

FIG. 2. Value of blocking index computed from responses of a cell in V3a (*44-2*) to stimulation by a flashing bar at different positions (1–5) within its receptive field before and during cooling of V1. *Bottom*: position in the visual field of the receptive field of the cell (□), the flashing light inside the receptive field (▭), and the cooling perimeter (circled by crosses). Arrows point to the same flash position in the diagram of the visual field and on the curve. Ten presentations of the flash, 1 s ON, 1 s OFF. Blocking index computed from response to ON stimulation (peak firing rate with a 20-ms binwidth minus spontaneous activity). Temperature of cooling plate, −8°C.

In three cases (1 in V3a and 2 in V3-V3a), the receptive field became larger by up to 2° during cooling. This was the case for one cell with a receptive field that was completely inside the cooling perimeter before cooling V1. During cooling, a responsive region adjacent to the receptive field but situated outside the cooling perimeter was unveiled. This cell is placed in the selective block category in Table 1 (see below), even though its receptive field was completely inside the cooling perimeter. The two remaining units had receptive fields that crossed the cooling perimeter, and the outer responsive part of the field grew during cooling V1.

Unlike the neuron illustrated in Fig. 2, other neurons in V3a were still responsive when V1 was blocked. Figure 3 shows the PSTHs of another cell recorded in V3a, the receptive field of which overlapped only partially the cooling perimeter. Figure 3*A* shows the responses before (control) and during blocking of V1 by the cold when visual stimulation was restricted to the part of the receptive field situated outside the cooling perimeter by placement of a mask in the cooling perimeter. During the cooling of V1, the visual response hardly changed, thus providing a control for the possible direct or indirect effect of the cold on the activity of cells in V3a. When stimulation was restricted to the cooling perimeter (Fig. 3*B*), the response was only slightly diminished (blocking index 0.1 in the upward direction).

Other neurons in V3a had their receptive fields completely included in the cooling perimeter. Figure 4 presents an example of a neuron with receptive field close to the receptive fields of the control units recorded in V1. When V1 was inactivated by cooling, it gave a clear although strongly reduced response to visual stimulation (blocking index 0.7).

When the microelectrode entered V3, practically all sites ceased to respond to visual stimulation when V1 was inactivated. Figure 5 illustrates such a case. As shown by the PSTHs recorded during visual stimulation by a moving bar before (control), during, and after blocking of V1, the response of the neuron clearly disappeared, but the spontaneous activity remained close to its control level. The visual response after recovery was smaller than before cooling, a common observation in this type of experiment unless we had waited 0.5 h to record the responses after the rewarming.

The histograms of Fig. 6 show the proportions of sites recorded in V3a or V3 that still responded to visual stimulation when V1 was blocked. The most striking fact illustrated in this figure is that 30% of sites in area V3a gave unequivocal visual responses when V1 was blocked. By contrast, all but 1 site in area V3, out of 37 tested, stopped firing to visual stimulation when V1 was blocked. Furthermore, the remaining response of that multiunit was classified as "weak residual activity," and a receptive field could not be plotted during inactivation of V1. In the sample of V3-V3a sites, 14% of sites were still active during the blocking of V1.

Table 1 shows details of the results presented in Fig. 6. For each area, sites were subdivided in two categories, depending on the positions of their receptive fields with respect to the cooling perimeter. In V3a, many (12/38) receptive fields that were partially included within the cooling perimeter underwent selective blocks. The occurrence of selective block was also frequent (4/5) for cells in V3 with receptive fields partially included in the cooling perimeter.

It must be stressed that the high proportion of cells that were not blocked in V3A is not due to a higher proportion of cells with receptive fields only partially included in the cooling perimeter. In fact, 13/38 cells for which the receptive field was completely included in the cooling perimeter were still firing to visual stimulation.

Cortical neurons that possess the same receptive field properties are likely to be gathered in patches, and one may wonder whether neurons that remain responsive are also

TABLE 1. *Numbers of inactivated and responsive cells*

	V3a		V3-V3a		V3	
	In	Partially in	In	Partially in	In	Partially in
No block	13	10	2	3	1	0
Selective block	0	12	1	9	0	4
Block	25	16	15	6	31	1

In, neurons with receptive fields inside the cooling perimeter. Partially in, neurons for which 25–75% of the receptive field was included in the perimeter. Selective block refers to the situation in which only the part of the receptive field inside the cooling perimeter became silent during inactivation of V1 (Fig. 2).

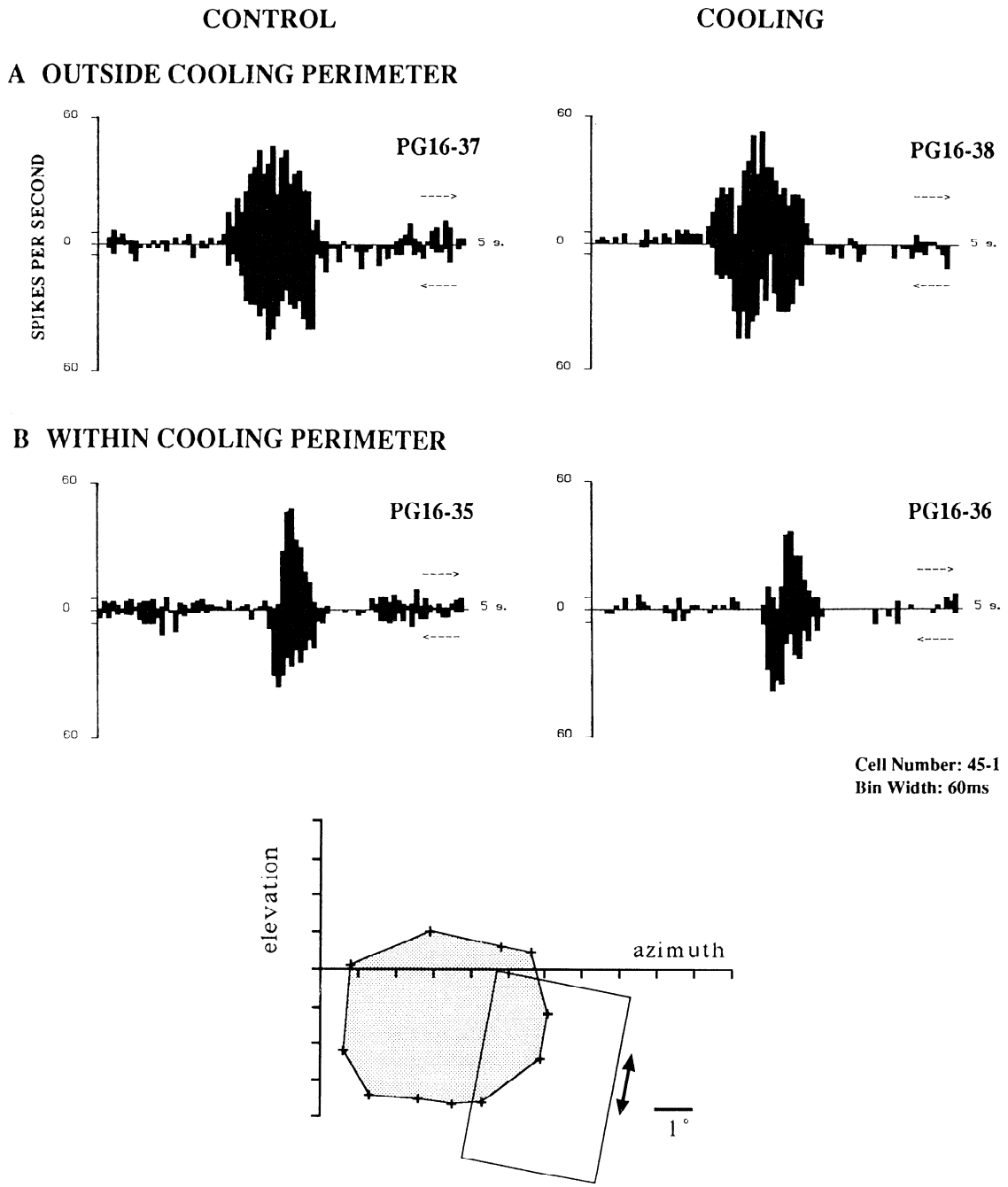

FIG. 3. Effect of cooling V1 on visual responses of a cell in V3a (*16-45-1*). Visual responses are presented in the form of poststimulus time histograms (PSTHs) of the activity evoked by a moving bar, traveling back and forth through the receptive field. In each case the *top* histogram shows the response to the bar moving in the upward direction, and the *bottom* one (upside down and read from *right* to *left*) illustrates the response of the cell to the opposite direction. *A*: response to stimulation of the part of the receptive field situated outside the cooling perimeter. *B*: response of the cell to stimulation of the part of the receptive field included in the cooling perimeter. *Inset*: position of the receptive field (□) with respect to the cooling perimeter (shaded area circled by crosses). Binwidth 60 ms. Temperature of cooling plate, −8°C.

organized in this way. Although Fig. 1 suggests some evidence for clustering in V3a, this was not always the case. Visually responsive sites during cooling could be found in supra- as well as infragranular layers (cf. Fig. 1).

The receptive-field properties of sites that remained active were assessed with qualitative measures before and during blocking of area V1. All sites that were orientation selective remained so during V1 inactivation, and the optimal orientation did not change. There were no major changes in direction selectivity, except for one cell that clearly became direction selective when V1 was blocked. Ocular dominance remained unchanged except in one instance when it changed from group 4 to 1 (binocular to contralateral dominance). Most cells were driven by both eyes equally but a few groups of neurons that remained active were classified as ocular dominant 1 or 2. These neurons remained in the

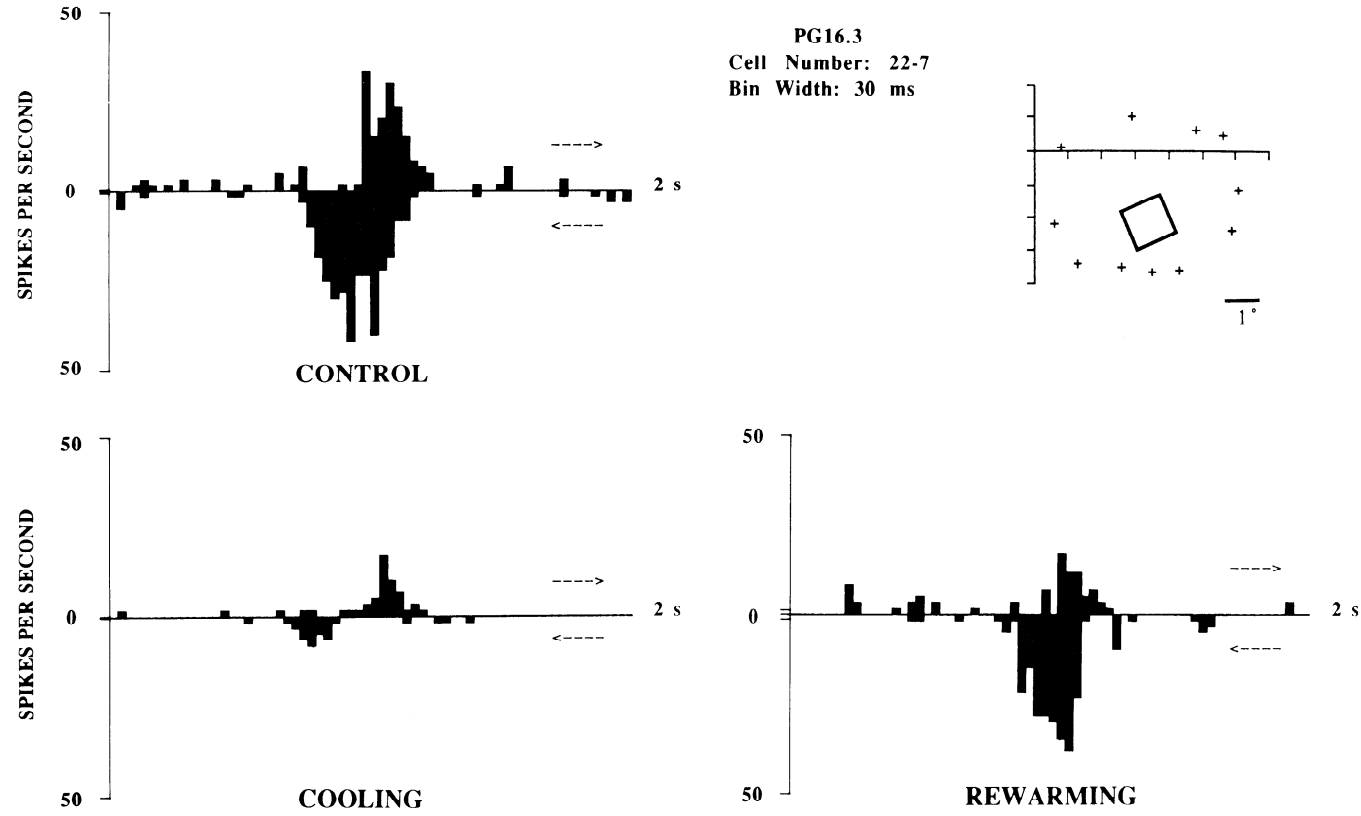

FIG. 4. Response of another V3a neuron (*16-22-7*), the receptive field of which was completely included in the cooling perimeter. Although diminished, the response remains clear when V1 is inactivated. Response was recorded over 20 sweeps of the stimulus; PSTHs were computed with a binwidth of 30 ms. Temperature of cooling plate, −7°C. Same conventions as in Fig. 3.

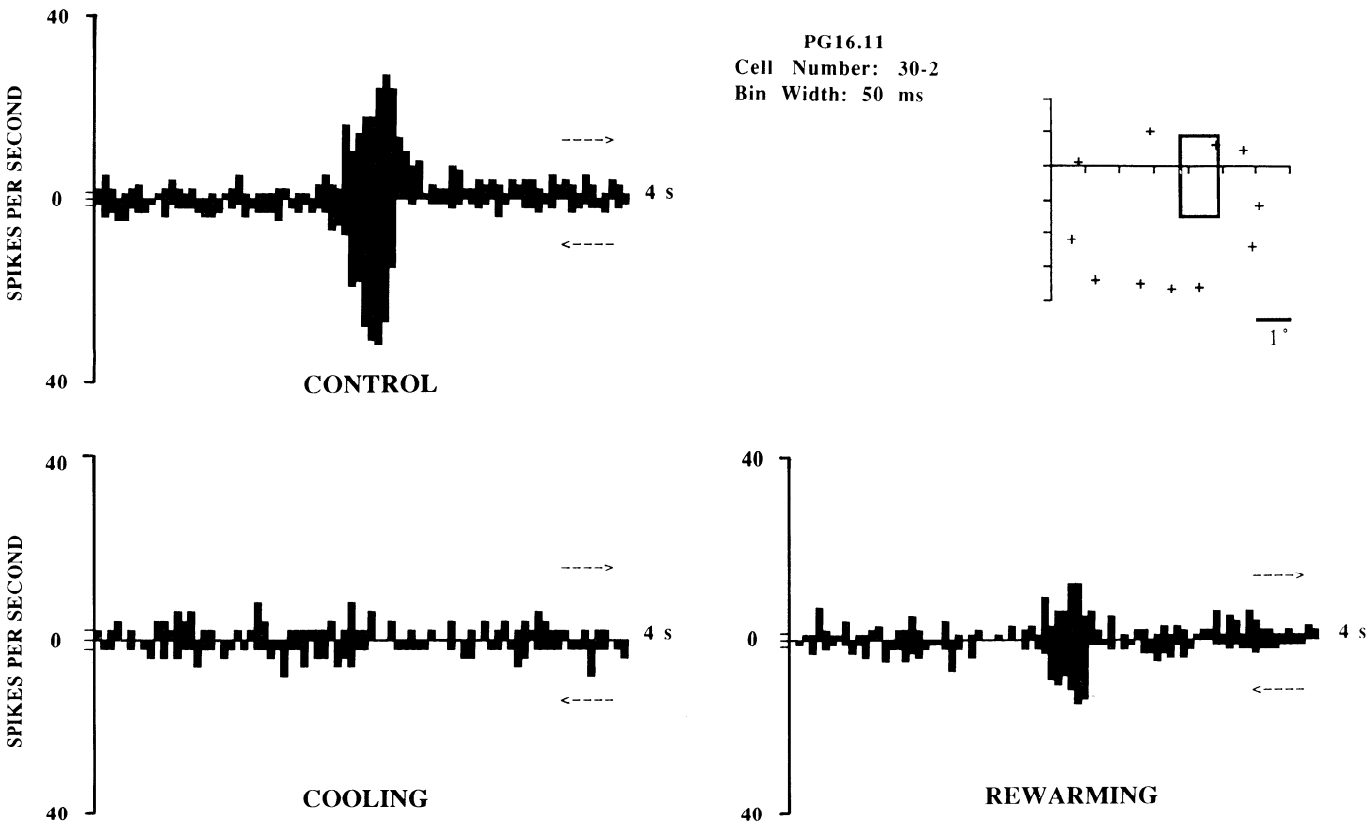

FIG. 5. Effect of cooling V1 on visual responses of a cell in V3 (*16-30-2*). Same presentation as in Fig. 3. Twenty sweeps; binwidth is 50 ms. Temperature of cooling plate, −8°C.

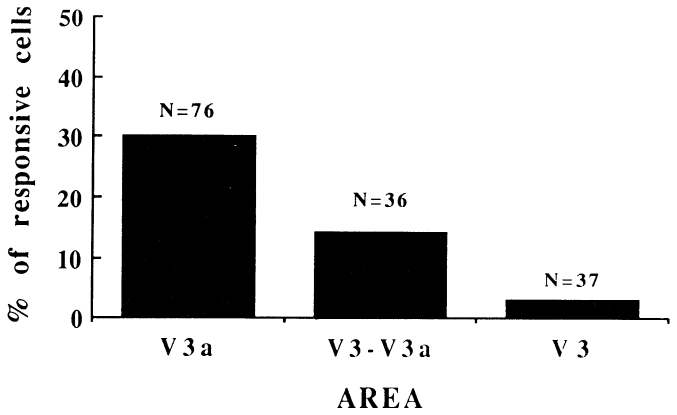

FIG. 6. Histograms of percentage of cells in V3 and V3a that still responded to visual stimulation during blocking of V1.

same ocular dominance class when V1 was blocked. Complete block of spontaneous activity during cooling was extremely rare, but it was impossible to properly estimate variations of spontaneous activity by listening to the audiomonitor. Quantitative records showed that cooling of V1 gave an increase in some neurons and a decrease in others.

DISCUSSION

We found that neurons in areas V3a and V3 do not depend in a similar fashion on the input coming from V1. In regions of these areas encoding central visual field, nearly all sites in area V3 ceased to fire to visual stimulation when V1 was blocked. By contrast, 30% of sites in V3a were still visually responsive in the absence of their V1 drive, with a mean blocking index of 0.35. These values are lower than those measured in area MT (80% of sites remaining active and 0.53 mean blocking index; unpublished results). Thus, although area MT is not the sole area remaining visually responsive after V1 inactivation, it appears to be the most responsive of the areas so far tested. In the first part of the DISCUSSION we examined the validity of our results; in the second part we discuss their functional significance.

Methodological considerations

It is important to check that the remaining visual activity of neurons in V3a during cryoblocking of V1 does not result from experimental artifacts. It is unlikely that the part of V1 under the cooling plate was not entirely inactivated by our cooling device, because we always checked that the visual responses of cells in the lower layers of V1 were blocked. Because the isothermal curves below the plate are flat (Girard and Bullier 1989), it is likely that the entire region of V1 under the cooling plate was blocked. Moreover, we often recorded the activity of neurons in V3 or V3a when area V1 was at several degrees below the temperature necessary to block neurons in the lower layers of V1. Incomplete blocking of area V1 was also unlikely because we usually recorded within the same penetration some neurons that were blocked and others that were not (cf. Fig. 1). Finally, practically all the cells in V3 were blocked, and in all cases we recorded inactivated neurons in area V3 in the same penetrations as those in which we recorded neurons that remained active in V3a.

One could argue that the neurons that remained responsive were driven by V1 cells with receptive fields on the border of the cooling perimeter, a region that might be difficult to cool properly because of the brain curvature. The data presented in Table 1 show that this is not the case. More than one-half the sites that remained responsive had their receptive fields completely included in the cooling perimeter. We found numerous examples of sites with receptive fields in the very middle of the perimeter that still responded to visual stimulation during blocking of V1. In 10 cases of sites that still responded during cooling, their receptive fields overlapped those of the control neurons in the lower layers of V1 that were inactivated. Therefore, for nearly one-half the sites with neurons remaining responsive, it is absolutely certain that their visual drive from V1 was completely silenced.

It is important to be sure that the visual responses of some neurons were not artifactually blocked. It is unlikely that some sites in V3-V3a were blocked directly by the cold. The recording sites in both areas were ~12 mm below the upper surface of the cooling plate. This was measured on histological sections, such as the one presented in Fig. 1, by use of a shrinkage coefficient of 10% and a distance of 6 mm between the upper surface of the cooling plate and the bottom of layer 6 in V1 (these parameters were routinely measured in each animal). With the aid of the temperature-gradient curves that we reported earlier (Girard and Bullier 1989), we can deduce that cells in V3-V3a were above 30°C in all cases and were thus unlikely to be directly affected by the cold (Girard and Bullier 1989).

The observation that stimulation outside the cooling perimeter elicited a visual response that was unchanged during cooling of V1 (Fig. 3) provides an excellent control for the possibility of nonspecific inactivation of neurons in V3 and V3a. Sources of such inactivation could be alteration of the blood supply or the spreading depression that is known to be triggered by cooling (Marshall et al. 1951; Zacharova and Zachar 1961) and could travel from V1 to V3 within the time span of a cooling session (Lauritzen 1987; Marshall et al. 1951).

The residual activity was assessed on the audiomonitor for most units, and one may wonder whether this method is appropriate. Experiments were performed to test this point on 11 single units and showed a good agreement between the decision reached by use of qualitative estimates of residual activity and the blocking index. The proper filtering of background noise and the use of a slice device (see METHODS) gave a very clear signal of multiunit neural activity on the loud speaker, and it is very unlikely that we overestimated the number of inactivated units. The residual response, although reduced, was usually clear and could be elicited from the same region of the receptive field as before cooling. In only four cases of sites that were not blocked (1 in V3 and 3 in V3a) did we record a weak residual response with which it proved impossible to plot a receptive field.

It is possible that we underestimated the proportion of sites remaining responsive within the population of units with receptive fields partially overlapping the cooling perimeter. This results from the fact that we used visual stimulation that was limited to the cooling perimeter (cf. METHODS). For neurons that need elongated stimuli, this may constitute a nonoptimal stimulus. However, in agreement with previous studies (Galletti and Battaglini 1989; Gaska

et al. 1987), we did not find that length summation was a common feature of V3a and V3 cells.

Significance of the presence of responsive neurons in V3a

ANATOMIC CONSIDERATIONS. It is obvious that the neurons that remain visually active must receive another drive than the one from V1. It has been shown that V3a and V3 receive projections from the contralateral hemisphere through the splenium of the corpus callosum (Pandya et al. 1971; Van Essen and Zeki 1978; Van Essen et al. 1982). Because in all monkeys the splenium of the corpus callosum was sectioned, it is clear that interhemispheric connections cannot be involved in the remaining responses in V3a when V1 is inactivated.

The connections that are involved in driving visually active neurons in V3a when V1 is blocked are likely to travel through the superior colliculus and the pulvinar (Benevento and Rezak 1976; Harting et al. 1980) or the regions of the LGN that are known to project to extrastriate cortex (Benevento and Yoshida 1981; Bullier and Kennedy 1983; Fries 1981; Yukie and Iwai 1981).

It seems unlikely, however, that the LGN alone could provide a direct functional input to extrastriate areas: Mohler and Wurtz (1977) have shown that ablation of both striate cortex and superior colliculus is sufficient to definitively impair visuomotor behavior in the visual field corresponding to the lesion. Moreover, Rodman et al. (1990) have shown that similar lesions abolished all visual responses in neurons of area MT. It is likely, therefore, that for V3a also, the major residual drive comes through the superior colliculus–pulvinar route.

The superficial layers of the superior colliculus that receive a direct retinal input (Cowey and Perry 1980; Hubel et al. 1975) are known to project to the inferior and lateral pulvinar nuclei (Benevento and Standage 1983; Harting et al. 1980). Neurons in the superficial layers of the superior colliculus are still visually responsive (Schiller et al. 1974), whereas the firing of inferior pulvinar neurons is stopped immediately after a V1 lesion (Bender 1983). Some units in the lateral pulvinar remain visually active after striate cortex ablation (Burman et al. 1982), so that this subdivision of the pulvinar might also be responsible for transferring the residual visual activity to extrastriate cortex.

Because practically all neurons in V3 are inactivated, whereas numerous cells remain active in V3a, it would be interesting to examine whether this difference may be related to different organizations of subcortical afferents to these two areas. As far as we know, no published study attempted to compare the organization of subcortical afferents with V3 and V3a.

It is also possible that area MT, which is the only other prestriate area known to contain visually responsive cells in the absence of its V1 input (Bullier and Girard 1988; Rodman et al. 1989), could provide the input to responsive neurons in V3a by means of feedback connections (Ungerleider and Desimone 1986). This would mean that the feedback projections to V3a plays a different functional role from those projecting to areas V2–V4, which are completely inactivated.

PHYSIOLOGICAL CONSIDERATIONS. Studies of humans or monkeys with lesions of the primary visual cortex show that patients or lesioned monkeys still possess some kind of residual vision, a phenomenon called blindsight (Weiskrantz et al. 1974). Subjects can make saccades or point to a target that, however, could not be consciously seen (at least in humans) (Pöppel et al. 1973; Weiskrantz et al. 1974).

Lesion studies in the monkey and clinical studies in humans suggest that blindsight or other residual visuomotor abilities that are spared by a lesion in V1 are observed only after a period of functional recuperation. For example, Mohler and Wurtz (1977) found that, after V1 lesions, monkeys could not make visually guided saccades for ~3 wk.

Our experimental paradigm is different from lesion studies because the time course of the experiment is such that there is no possibility of recuperation. Therefore the presence of a residual visual response in this condition is the sign of a functional visual input other than that coming from V1.

Because visual responses occur immediately under inactivation of V1, whereas residual vision takes weeks to develop, one could argue that residual visual activity in area V3a may not play a major role in blindsight. One should remember, however, that lesions and cold inactivation are very different ways of suppressing the influence of a given neural structure. Cortical lesions could produce a stress reaction of cortical tissue, known as diaschisis (e.g., Finger and Stein 1982). The destruction of a cortical zone could drive to silence its target regions or even suppress other afferents. For example, prestriate cortex could become insensitive to subcortical afferents as a result of destruction of area V1. Subcortical structures themselves may also be subject to diaschisis, as suggested for the inferior pulvinar by the return of visual responses in this structure 3 wk after a V1 lesion (Bender 1983). This period of 3 wk is strikingly similar to the recovery period of oculomotor behavior after a lesion of V1 (Mohler and Wurtz 1977). It is possible, therefore, that visual activity in area V3a plays a role in residual vision, but that, because of diaschisis, it appears only progressively during the course of recovery after a lesion of area V1.

Although we did not use quantitative methods to measure tuning curves, it was clear from qualitative assessment that cells in V3a that are selective for orientation and direction retained their selectivity during inactivation of V1. Similar results have been observed in area 18 of the cat after reversible inactivation or lesions of area 17 (Donaldson and Nash 1975; Dreher and Cottee 1975; Sherk 1978). Assuming that the functional input to cells in V3a in the absence of V1 input is provided by the superior colliculus and the pulvinar, these selectivities are surprising because tectal cells are broadly tuned to orientation and are not direction selective (Schiller and Koerner 1971), as are pulvinar neurons in the absence of V1 (Bender 1983). As we recorded visual responses in cells of V3a as soon as the beginning of the blocking of V1, it appears very unlikely that any kind of plastic reorganization may have occurred. A more plausible interpretation of this observation is that the prestriate network is able to generate orientation selectivity, seemingly as precise as in the normal condition, when the sole visual input is from the tectopulvinar pathway. This interpretation echoes that of Rodman et al. (1989), who suggested that direction selectivity is recreated de novo in area MT in

the absence of area 17. The input from the tectal pathway also seems to match precisely that from V1 because the receptive-field positions before and during cooling were precisely aligned, and, apart from one case, neurons in V3a kept the same ocular dominance after V1 had been inactivated.

As stated above, visuomotor behavior is not totally disrupted by lesions of primary visual cortex. Segraves et al. (1987) report that monkeys without primary visual cortex can make saccades with good precision toward a stationary target appearing in the blind part of the visual field. This implies that neurons can, in the situation of altered visual inputs, code the stimulus position in egocentric coordinates.

One physiological study (Galletti and Battaglini 1989) has shown that ~50% of V3a neurons display a strong selectivity to the gaze position. It is tempting to speculate that visually responsive cells in V3a during V1 inactivation are the same as those selective for gaze position. These cells could participate in residual visuomotor behavior by receiving eye position as well as visual information from the superior colliculus through the pulvinar. This would fit the presence of a corollary discharge signal in some collicular cells (Guthrie et al. 1983; Richmond and Wurtz 1980). It would be interesting to test this hypothesis directly by recording neurons in V3a in the absence of V1 in a behaving monkey. Our hypothesis would predict that visually responsive neurons should be related to eye movements.

The presence of gaze-position selectivity in V3a neurons is in keeping with the fact that this area is strongly connected with the parietal cortex (Baizer et al. 1991; Cavada and Goldman-Rakic 1989; Morel and Bullier 1990), which is known to contain cells with visual responses that are influenced by the position of gaze (Andersen et al. 1985). By extension, it is possible that cortical visual areas in the occipitoparietal pathway, which plays a role in visuomotor behavior, contain neurons that remain active in absence of area 17. This is indeed the case for areas V3a and MT, which are connected with parietal cortex and have cells with responses that are influenced by eye movements. Although there are no published data on the effect of a V1 lesion on the activity of cells in parietal cortex, we would predict that visually responsive cells would be found there after a V1 lesion.

It is also interesting to note that V3a (but not V3) is strongly connected with the medial superior temporal area (Boussaoud et al. 1990). This area also contains eye-movement–related cells (Komatsu and Wurtz 1988) and sends heavy projections to the superior temporal polysensory area in the upper bank of the superior temporal sulcus, in which numerous neurons still respond to visual stimulation in the absence of V1 (Bruce et al. 1986). It is likely, therefore, that cortical areas in the superior temporal sulcus, which are connected with the medial superior temporal and superior temporal polysensory areas, remain active in the absence of a V1 input.

In contrast with the likely involvement of the occipitoparietal pathway in residual vision, it appears that the occipitotemporal pathway is inactive after inactivation or lesion of V1, because this is the case for neurons in area V4 (Girard et al. 1991) and in inferior temporal cortex (Rocha-Miranda et al. 1975).

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