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Visual Activity in Area V2 During Reversible Inactivation of Area 17 in the Macaque Monkey

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SUMMARY AND CONCLUSIONS

1. The presence of a direct lateral geniculate nucleus (LGN) input to area V2 raises the possibility that some neurons in this area remain active when area 17 is inactivated. It is also known that many neurons in area MT are visually responsive in the absence of input from area 17. Because MT sends a strong projection to V2, it appears likely that visual activity could be transferred to V2 through this feedback connection when the V1 afferents are disabled. For these reasons, we decided to reexamine the residual visual activity of neurons in V2 during inactivation of area 17. A circular region 16 mm in diameter on the opercular part of area 17 was cooled by a thermoelectric Peltier device, and single- and multiunit activity was recorded in the retinotopically corresponding region of area V2.

2. Because of the proximity of areas V1 and V2, it was necessary to make sure that neurons in V2 could not be directly blocked by cooling applied to V1. Temperature gradients within cortex were measured with a specially designed thermocouple at different heat flows imposed by the Peltier device. Gradients ranged between 2.3 and 5.5°C/mm. Knowing the temperature gradients and the temperature of the cooling plate, it was possible to deduce the temperature at a given depth within cortex. With this method we measured the blocking temperatures of neurons in area 17, i.e., the temperature at which neurons completely ceased to respond to optimal visual stimulation. Blocking temperatures ranged between 4 and 18°C, values that are substantially lower than those reported in previous papers. Knowing the blocking temperatures, it was possible to determine the cooling-plate temperature necessary to entirely block the region of V1 under the cooling plate. Using the temperature gradients, we then calculated the depth of recording for which V2 neurons could not be directly blocked by the cold. For this reason, all our recordings were made in or near the fundus of the lunate sulcus.

3. During cryoblocking of V1, we recorded 154 sites in penetrations normal to area V2. All these sites had receptive fields included within the visual-field region coded in the cooled zone. In addition, we recorded 55 sites in tangential penetrations aimed at traveling in V2 for long distances. Among these 209 sites, only 3 could be considered as unambiguously active when V1 was blocked. Two of these sites were located at or close to the V2-V3 border.

4. After staining sections containing the tangential penetrations for cytochrome oxidase, it was clear that neurons in all types of stripes (thick, thin, and pale) were inactivated for similar temperatures applied to V1. Similarly, all major cell types in area V2 were inactivated by cryoblocking V1.

5. These results suggest that, for most neurons in V2, the direct geniculate input and the feedback projection from MT to V2 do not constitute an efficient drive in the absence of an input from V1 and that the functional role of these connections is not to transfer convergent visual information to neurons in V2 but, more likely, to modulate the information relayed through area 17.

INTRODUCTION

The visual cortex of mammals is composed of many functional areas, which are located within the cytoarchitectonic areas 17, 18, and 19. The discovery of a mosaic of areas beyond area 17 led several authors to question the traditional model of organization of visual-information processing (Merzenich and Kaas 1980; Stone et al. 1979). This model assumes that visual information is conveyed from the lateral geniculate nucleus (LGN) to area 17, where it is processed and transferred in a serial fashion through areas 18 and 19.

This type of organization was first questioned in cat, in which the presence of a direct input from the LGN to area 18 had been shown by anatomic and electrophysiological methods (Doty 1958; Maciewicz 1975; Rosenquist et al. 1974; Tretter et al. 1975). In keeping with the presence of such a route bypassing area 17, it was demonstrated that neurons in area 18 remain visually responsive when area 17 is inactivated or lesioned (Donaldson and Nash 1975; Dreher and Cottee 1975; Sherk 1978).

For a long time, it was believed that the organization of the primate visual system is different from that of other species. Thus it was thought that in primates the LGN projects only to area 17 and that this area constitutes the unique distributing center of visual information to extrastriate visual areas. This view was given support by the results of Schiller and Malpeli (1977), who showed that, when neural activity in area 17 is blocked by the cold, neurons in area V2 are no longer responsive to visual stimulation.

More recently, it has been demonstrated that, in the monkey as in the cat, the LGN sends projections to extrastriate visual areas (Benevento and Yoshida 1981; Bullier and Kennedy 1983; Yukie and Iwai 1981). In particular, direct projections exist from the interlaminar regions and the S layers of the LGN to area V2 (Bullier and Kennedy 1983). The presence of this direct geniculate input to area V2 raises the possibility that some neurons in this area may remain active when V1 is inactivated. Furthermore, it is known that different functional types of neurons are not evenly distributed within area V2 (De Yoe and Van Essen 1985; Hubel and Livingstone 1987). It is therefore possible that active regions may have been missed in the study of Schiller and Malpeli, who reported results from an unspecified number of sites tested in two animals only.

The presence of a direct LGN input to V2 would be a sufficient reason to reexamine the question of visual activity in this area in the absence of a V1 input. We were

further encouraged in this direction by the results of Rodman and her collaborators (Rodman et al. 1985, 1989), who showed that many neurons in area MT remain active when V1 is lesioned or blocked by cooling. Similar data have been obtained by Blakemore and his collaborators (personal communication). These results, which we recently confirmed (Bullier and Girard 1988), demonstrate that at least some extrastriate visual areas do not depend entirely on the visual activity relayed by V1 for their function. Because area MT receives a strong input from the thick cytochrome oxidase bands within V2 (De Yoe and Van Essen 1985; Shipp and Zeki 1985), it appears likely that some of the residual activity in MT may be relayed by V2 neurons belonging to these functional subdivisions.

Finally, a strong projection exists from MT to V2 (Kennedy and Bullier 1985; Maunsell and Van Essen 1983). This projection originates in the infragranular layers (Kennedy and Bullier 1985; Maunsell and Van Essen 1983; Rockland and Pandya 1979) and terminates mostly outside layer 4 (Maunsell and Van Essen 1983), two main characteristics of a caudally directed or feedback connection (Maunsell and Van Essen 1983; Rockland and Pandya 1979). Because the majority of neurons in MT remain active in the absence of a V1 input (Bullier and Girard 1988; Rodman et al. 1985, 1989), this raises the possibility that some visual activity may be transferred back to V2 through this pathway. In other words, studying the visual responses of V2 neurons in the absence of area 17 input is one way of probing the functional contribution of feedback connections.

All these reasons, therefore, prompted us to reexamine the visual activity of neurons in V2 when V1 is inactivated. In the present study, we examined the visual responses of a large number of neurons in V2, and we specifically addressed the question of a residual activity within the thick cytochrome oxidase bands. Because of the close proximity of areas V1 and V2, it is difficult to lesion completely V1 without affecting V2 or its afferent fibers. We therefore decided to use a reversible method for blocking V1, and we chose the cooling method because it makes possible the complete inactivation of a relatively large region of V1. Because of the proximity of areas V1 and V2, it was necessary to exclude the possibility of a direct inactivation of V2 neurons by the cold applied to V1. For this reason, we measured the blocking temperatures of neurons in V1 and the temperature gradients under the cooling plate. This, in turn, enabled us to record neurons in V2 at a sufficient distance from the cooling plate that units would be minimally affected by the cold applied to area 17.

METHODS

Implantation

Male adult cynomolgus monkeys (*Macaca cynomolgus*) were premedicated with corticosteroids (Soludecadron, 0.4 mg/kg im) to avoid cerebral edema, atropine sulphate (0.02 mg/kg im) to lessen mucus secretion, and chlorpromazine (Largactil, 0.4 mg/kg im). Anesthesia was induced with ketamine hydrochloride (Imalgene, 16 mg/kg im) and maintained by small repeated intravenous injections of alphadolone/alphaxalone (Saffan, 0.1–0.3 ml iv). A circular trephine hole 2 cm in diameter was made in the bone overlying 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 stainless steel well was implanted around the bone defect with dental cement and surgical screws. A stainless steel plate was also attached to the frontal part of the skull to hold the head of the animal during recording sessions.

Cooling

Cooling was achieved with a thermoelectric Peltier device (Melcor model No. CP 14 71 06 L). The cooling power of the Peltier device was adjusted with the use of a current regulator to change the electric current running through it. The Peltier device was too large to be applied directly on the cortical surface. We therefore built a gold-plated copper extension plate that was shaped to fit into the circular well and the bone defect while covering a surface of ~ 2 cm^2. To increase thermal conductivity between the dura and the extension plate, we used a thin layer of aquasonic gel. During the initial experiments, five holes were made through the plate for thermocouple penetrations; a similar extension plate with only one central hole was used during microelectrode penetrations. Figure 1 shows a sagittal view of the experimental set-up with the cortex underneath the cooling plate.

The temperature was monitored with a specially designed thermocouple that has a negligible inertia and does not interfere with the temperature gradients within the cortex. This was achieved by the use of 50-μm thick wires, thus minimizing the possibility of artifactual heat loss within these wires. The wires were encased in a small (<1 mm thick) glass tube, the thermocouple being protected by a thin ball of araldite protruding from the tube. This thermocouple gives a perfectly linear calibration curve and a precision better than 0.25°C. The temperature of the plate was measured with another thermocouple (plate thermometer on Fig. 1) placed at the angle between the extension plate and the copper bridge linking the Peltier device and the extension plate (Fig. 1). The precision of this thermometer is better than 0.5°C.

The temporal response of cortex to cooling was measured in one monkey. When cooling is applied through the Peltier device, the temperature within cortex reaches 90% of its final value in 5 min and stabilizes at the final value within 10 min. During active rewarming, the control temperature is reached in 7 min. In the recording sessions, therefore, we waited 7–10 min after onset of cooling or rewarming before recording the visual responses of neurons.

The spatial extent of the region of area 17 where neurons were blocked by the cold was measured in one monkey by recording the temperature near the edge of the cooling plate. These measurements show that, for a cooling-plate temperature of −12°C, neurons 1 mm deep in cortex reach 6°C at 3.5 mm from the edge of the plate. For a cooling plate of 0°C, this value is 1 mm. If we assume that cortex is totally blocked at 6°C (see RESULTS), depending on the plate temperature, the extent of blocked cortex is therefore between 2 and 7 mm wider than the diameter of the cooling plate.

Recording

Data were obtained from five young adult male macaque monkeys ranging between 2.5 and 5 kg in weight. A semichronic preparation was used, the animals being used once or twice a week for 1–2 mo. On the day of recording, animals were premedicated with atropine sulphate (0.02 mg/kg im) and diazepam (Valium, 0.6 mg/kg im) and initially anesthetized with ketamine (16 mg/kg im). After intubation, the animal was placed in front of the tangent screen, its head being held by the implanted plate. To suppress ocular movements, the animal was paralyzed by gallamine triethiodide (Flaxedil, 10 mg·kg^{-1}·h^{-1} iv) in a solution

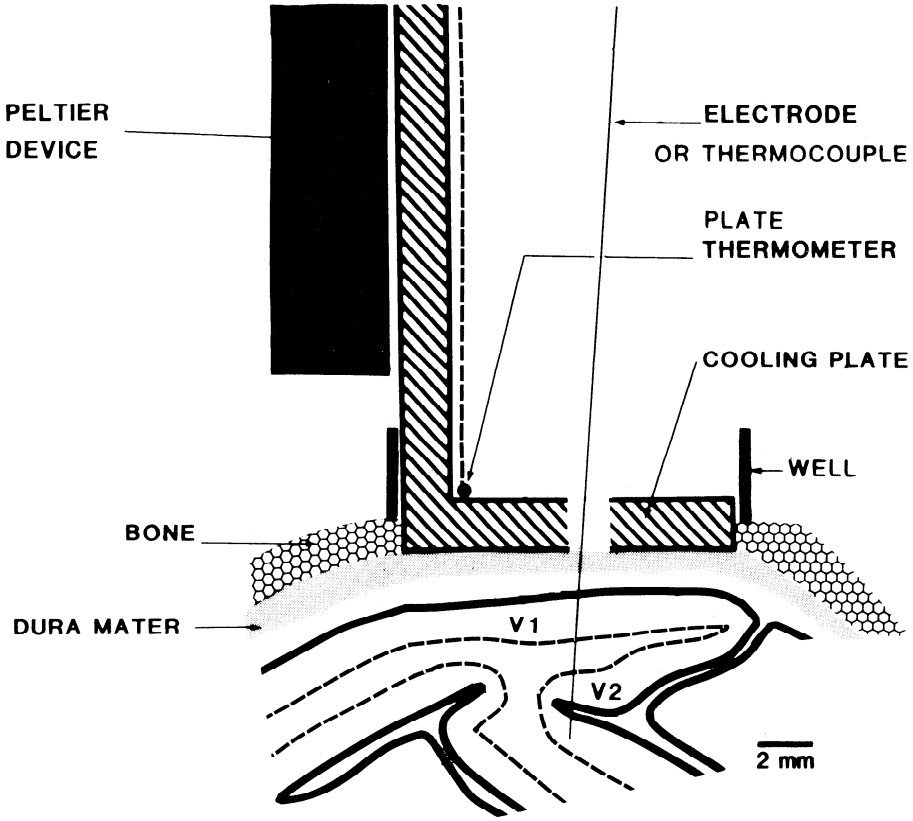


FIG. 1. Schematic view of the experimental set-up shown on a parasagittal section of the brain (see text for description). Rostral is down, dorsal to the right. See Fig. 6 for further orientation.

containing 5% glucose in saline. The animal was artificially respired with a mixture of 70% N_2O-30% O_2 and the respiration volume adjusted to maintain the end-tidal CO_2 between 4.5 and 5%. Pulmonary pressure was recorded on a manometer, and accumulation of mucus was removed when a rise in pressure occurred. Physiological temperature (37.5°C) was continuously maintained by a heating blanket. The electrocardiogram (ECG) and electroencephalogram (EEG) were recorded and proper level of anesthesia maintained by supplementing the N_2O-O_2 mixture with low doses of halothane to maintain a steady heart rate and the presence of slow waves in the EEG.

The pupils were dilated (ophthalmic atropine 0.5%) and corneal lenses used to prevent the cornea from drying. Refraction errors were measured by retinoscopy and corrected by appropriate spectacle lenses. At the end of each recording session, ophthalmic ointment (Terramycine) was applied on the eyes.

Each fovea was identified with a reversible ophthalmoscope and its position visualized on a screen placed at 1.14 m from the animal. The precision of this procedure is ~0.5°. Visual axes were brought together by placing a Risley prism in front of one eye while recording from a binocular cell with a small receptive field in area V1.

At the end of each recording session, the well was filled with an antibiotic solution (Soframycine) and closed. In the intervals between the later experiments, a thin layer of silastic or the bone defect was placed on the dura to reduce the growth of the dura mater, which was between 1 and 2 mm thick at the time of perfusion.

After a number of recording sessions—which spanned a period of 1–2 mo—electrolytic lesions were placed along electrode tracks (electrode negative: 10 μA during 10 s). The animal was then deeply anesthetized and perfused with normal saline, followed by 10% Formalin and ascending concentrations of sucrose. The brain was cut in a freezing microtome (40 or 60 μm) and sections stained with the use of thionin or myelin stain (Gallyas 1979) to reveal electrode tracks and areal boundaries. The V2-V3 boundary was estimated from myelin-stained sections by the use of previously described criteria (Gattass et al. 1981; Ungerleider and Desimone 1986) and was also apparent on adjacent thionin-stained sections by the disappearance of large darkly stained pyramidal cells at the base of layer 3 when passing from V3 to V2 (Von Bonin and Bailey 1947) (Fig. 6). Two monkeys with penetrations parallel to the surface of V2 were perfused with 1% paraformaldehyde-1.25% glutaraldehyde and the sections stained for cytochrome oxidase (Carroll and Wong-Riley 1984).

Single units were recorded with glass-coated tungsten microelectrodes (Merrill and Ainsworth 1972) with impedances between 0.5 and 6 MΩ before plating with platinum black. The minimum response field of each cell was first hand-plotted on the screen; and color, ocular dominance, orientation, end-stopping, direction, or speed selectivity were determined by the use of qualitative assessment of the response through an audio monitor. Color selectivity was assessed with Wratten Kodack filters compensated for equiluminance with neutral-density filters. A cell was considered color-selective when the response to moving or flashing light was clearly different for different colors as judged from the audio monitor. A neuron was considered as end-stopped when the response to a moving bar of light was totally abolished by lengthening the bar. Finally, binocular interaction was tested by comparing the response to monocular or binocular stimulation after having made the visual axes converge with the use of a binocular neuron within V1. A cell was considered as showing binocular interaction when the response was strongly facilitated or strongly diminished by binocular stimulation.

For quantitative analysis, we used an optic bench driven by a MINC 11/23 computer (Digital Equipment). This system produces a moving light bar of adjustable width, length, orientation, and speed. This bar can be used to stimulate the receptive field of the cell under study while recording poststimulus time histograms (PSTHs) for 10 or 20 presentations while the bar moves alterna-

tively in two opposite directions with a 1-s pause between each sweep. The luminance of the light bar is 5 Cd/m^2 and that of the background 0.8 Cd/m^2. The quantitative index measuring the cell response is the peak firing rate of the unit as computed from 10-, 20-, 30-, or 40-ms bins.

RESULTS

The results are presented in two sections. In the first, we present data concerning temperature gradients and effects of cooling on the neural activity of neurons in area V1. In the second section, we examine the consequences of cryoblocking V1 neurons on the visual responses of neurons in area V2.

Temperature gradients and effects of cooling on area V1 neurons

Because the regions of areas V1 and V2 representing the same part of the visual field are separated only by a thin layer of white matter (Figs. 1 and 6), V2 neurons could be directly affected by the cold applied to the surface of area V1. To assess the direct effects of the cold on the responses of neurons in V2, it was first necessary to determine the temperature reached by these neurons when cooling was applied to the surface of V1 by measuring the temperature gradients below the cooling plate.

TEMPERATURE GRADIENTS. Despite the small size of the thermocouple, it was impossible to record simultaneously the temperature and the visual responses of single neurons. We therefore deduced the temperature of a given neuron from its depth below the cooling plate and the temperature gradients within cortex.

Temperature gradients were measured in the depth of area V1 with the use of a specially designed thermocouple (see METHODS) that was lowered through the central hole in the plate (Fig. 1). Temperature measurements were made after allowing sufficient time for thermal equilibrium to take place. The data are presented on Fig. 2 for different temperatures of the cooling plate. The first 2 mm on the abscissa of Fig. 2 correspond to the thickness of the cooling plate, thus the approximately constant temperature within this region. For each curve, the temperature within these first 2 mm is slightly higher than the cooling-plate temperature, because the latter is measured at a point of the plate that is closer to the Peltier device than the point of penetration of the thermocouple (Fig. 1).

Beyond the region of approximately constant temperature corresponding to the depth of the cooling plate, the first 2 mm correspond to the dura mater and the subarachnoid space, whereas deeper regions correspond to cortex and white matter. Temperature-gradient curves have a monotonous shape and tend towards an asymptote value, which is the physiological temperature (37°C). The slopes of these curves, computed from the linear regions, depend on the heat flow imposed by the Peltier device, which itself is related to the temperature of the cooling plate. The curves are steeper for lower plate temperatures, and the values of the gradients range between 2.3 and 5.5°C/mm. We did not see any major irregularities in the shapes of the temperature-gradient curves, suggesting that these curves are not influenced by the presence of the dura, by cerebrospinal fluid, or by neighboring blood vessels. We did, however, observe such an effect of blood flow during a pilot study on a cat. When the thermocouple was lowered near the venous sinus, the temperature gradients were markedly increased (4.2°C/mm for a cooling-plate temperature of 1°C).

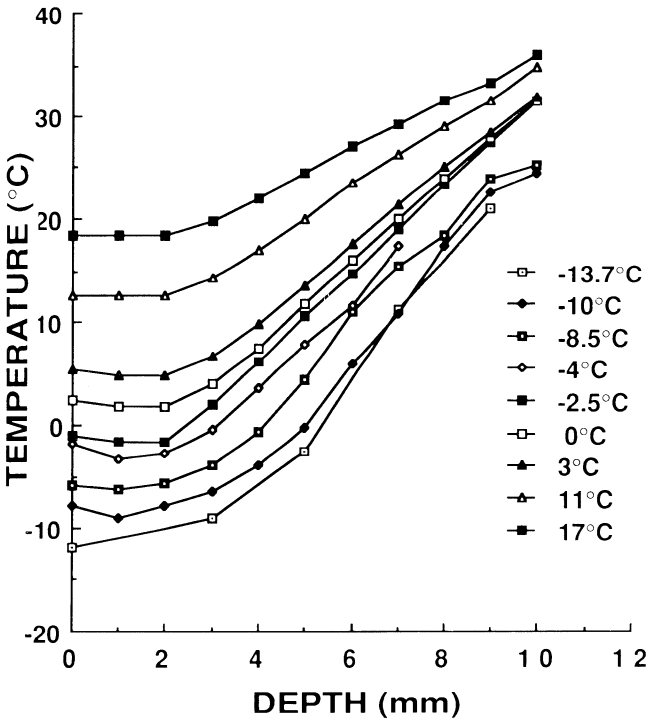


FIG. 2. Temperature gradients measured within the cortex of area 17. Each curve corresponds to a given temperature of the cooling plate (temperature given in the *inset*). Depth refers to that below the upper surface of the cooling plate. Thus the 1st 2 mm on the abscissa correspond to the thickness of the cooling plate.

The temperature recordings were remarkably reproducible for a given animal. On several occasions we had to replicate the measurements for a curve, and the temperatures found were always within 1°C of the original measurements. Several curves were measured on two animals, and the results were also very similar: the curve at −8.5°C was measured in two additional animals (*PG10* and *PG11*) and the measured temperatures found to be within 1° of each other. Similarly, the curve at 3°C was measured in two animals (*PG3* and *PG10*), and the resulting values were within 1°, except for four measurements that were within 2° of each other. These observations, and the fact that the curves have a smooth appearance and do not cross each other despite small differences of the plate temperatures, convinced us that it is possible to deduce the temperature of a cell from the depth of its recording with a precision of 1–2°.

Using a cooling plate with several holes, we measured the temperature gradients at several points below the plate and found that they were similar. The isotherm surfaces below the cooling plate were found to be flat.

EFFECT OF COOLING ON THE VISUAL RESPONSES OF NEURONS IN AREA V1. Because the region of V2 situated below the cooling plate is mostly innervated by the region

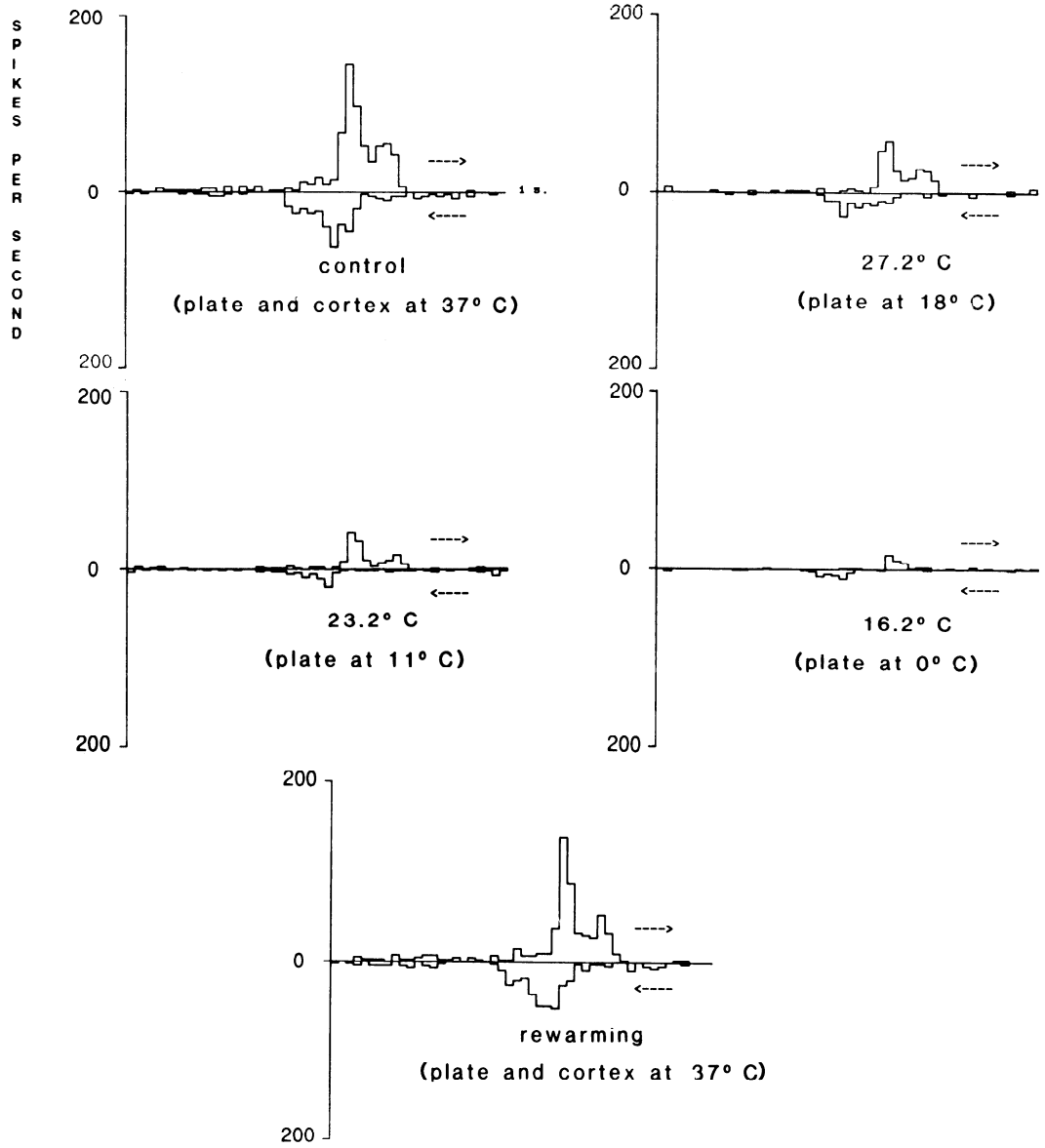


FIG. 3. Effect of cooling on the visual response of cell 24-4 recorded in area V1 at 6 mm below the upper surface of the plate. Poststimulus time histograms (PSTHs) of the response evoked by a moving bar traveling back and forth through the receptive field are shown for different temperatures of the cell and of the cooling plate. The temperature placed above the plate temperature represents that of the neuron, calculated as explained in the text. Complete block of visual response occurred at 15.2°C (plate at −1°C). For each temperature, the *top histogram* (→) gives the response of the cell to the stimulus moving in one direction. The *bottom* one, drawn upside down and read from *right* to *left*, illustrates the response of the cell to the opposite direction. Speed of the stimulus was 5 deg/s. Response was recorded over 20–40 sweeps of the stimulus and the PSTHs computed with a binwidth of 20 ms.

of V1 situated immediately below the plate (Figs. 1 and 6), it is impossible to study the effects of the cold on the visual responses of V2 neurons without inactivating—at least partially—their V1 input. Because of this, we studied the effects of the temperature on the responses of V1 neurons situated immediately below the cooling plate, or in the region of the calcarine fissure situated below the plate, and later assumed that the neurons in V2 would behave similarly when subjected to cooling. The second aim of these experiments was to determine the temperatures at which cells in area V1 cease to respond to visual stimulation. Thus we determined the proper temperature of the cooling plate to inactivate the entire depth of the region of V1 situated immediately below the cooling plate.

In a first series of experiments, we studied quantitatively the effects of temperature on the visual responses of 27 neurons in V1. In all cases, the temperature of the recorded neuron was deduced from knowledge of the depth at which recording took place, of the temperature gradients presented on Fig. 2, and of the cooling-plate temperature. Most of the quantitative data (19 units) come from neurons in the cortex of the calcarine sulcus situated below the operculum, in which V1 neurons have receptive fields situated in the periphery of the visual field.

Identical procedures were followed for each recording site. First, we determined the minimum response field and the optimal parameters of the visual stimulation. Next, we recorded a control PSTH in response to an optimal stimulus at physiological temperature (37°C). Then cooling was applied and the visual response measured again by a PSTH for a given cooling-plate temperature once the temperature in cortex had reached equilibrium. Cortex was then rewarmed to 37°C and another control response measured before beginning a new cooling cycle.

Figure 3 shows several PSTHs obtained from one V1 cell at different temperatures. For the temperature of 27.2°C, the firing of this unit is already severely reduced (by 60%). For lower temperatures, the visual response decreases more gradually. All visual response and spontaneous activity stopped at 15.2°C. The visual response measured on rewarming after each cooling cycle was very similar to that of the first control. This was generally the case for most recorded units; in some cases, the response after rewarming was lower or higher than in the control. Even when cells had been kept under very low temperatures (0–6°C), a strong visual activity was found after rewarming, even after cooling for 20 minutes. For some units, however, we had to wait for >15 min before recovering a response similar to the control response.

Figure 4 presents the visual responses at different temperatures for several cells of V1 recorded in the same penetration as the neuron illustrated in Fig. 3 (the curve concerning the neuron illustrated in Fig. 3 is shown by crosses). All the neurons show a similar steep decrease of activity as the temperature is lowered. The response is strongly decreased at 20°C, and a complete block of visual activity occurs only below 20°C.

We did not observe any major modification of the receptive-field properties (orientation or direction selectivity) during cooling. We did not, however, test for minor effects by quantitatively comparing orientation or direction tuning curves before and during cooling.

We subsequently determined the blocking temperature of neurons in V1 (i.e., the temperature at which a neuron completely ceases to respond to visual stimulation). This was done by assessing the responses through the audio monitor on an additional set of 57 neurons in V1. In a

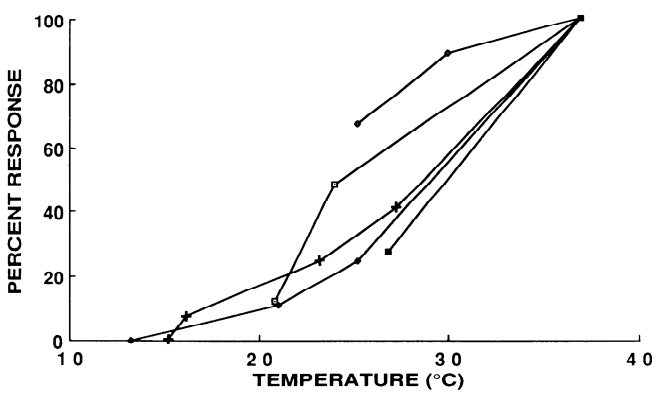


FIG. 4. Effect of cooling on the visual responses of 5 cells in area V1 recorded within the same penetration as the neuron illustrated in Fig. 3. Responses of the cell presented in Fig. 3 are shown by crosses. Temperatures are computed from the temperature gradient curves.

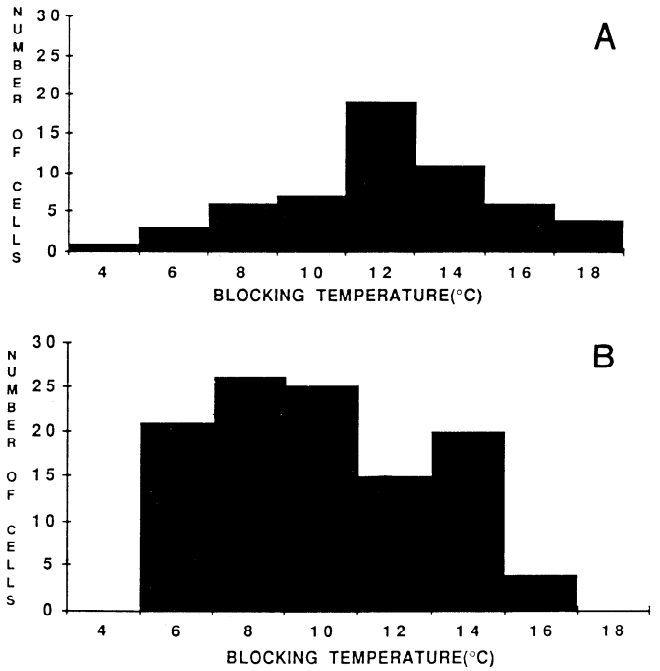
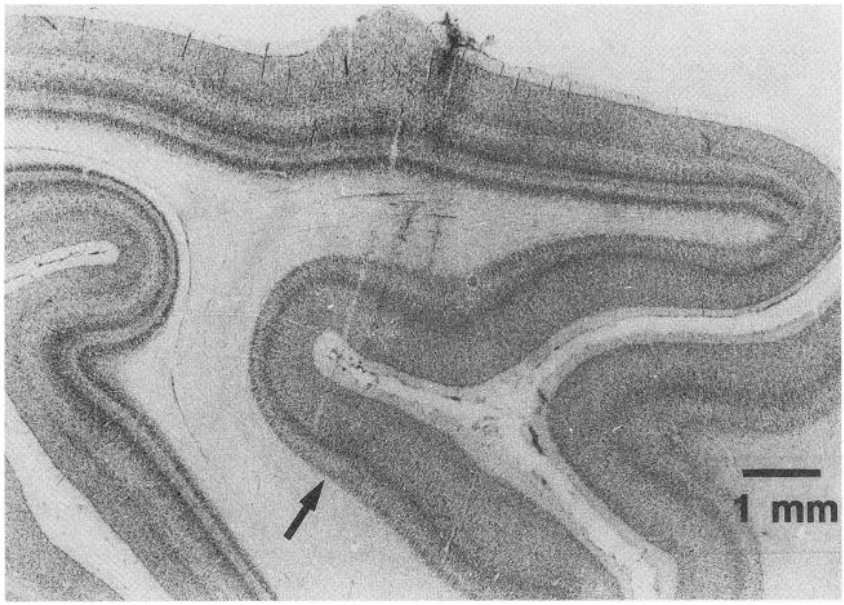


FIG. 5. Histograms of the blocking temperatures of the cells in V1. *A*: results of direct measurements in 57 recording sites in V1. Blocking temperature was deduced from the cooling-plate temperature that led to a complete silence of the cell when optimally stimulated. *B*: histogram of the temperatures reached 1 mm deep within area V1 when cells in V2 were inactivated.

small number of neurons, there was a residual spontaneous activity that persisted during cooling, despite the fact that no more visual response could be elicited. The histogram of blocking temperatures for neurons in V1 is presented in Fig. 5*A*. Blocking temperatures are distributed around a peak at 12°C, the lowest temperature being 4°C. When activity subsisted in units at temperatures below 12°C, it was always very reduced (<1 spike per stimulus presentation). It is also important to mention that the interneuron variability observed on Fig. 5*A* is not simply a consequence of measurement inaccuracy but corresponds to actual differences between neurons. Thus, when several units were recorded together, it was a common observation that one neuron was blocked for a temperature several degrees higher than the blocking temperature for the remaining cells.

Further confirmation of the range of blocking temperatures in area V1 is provided by measuring the temperature reached by neurons situated 1 mm deep within area V1 when neurons in area V2 were inactivated. This measurement was made by the use of the temperature gradients, the cooling-plate temperature necessary to inactivate the visual responses of neurons in V2, and the depth below the plate of a site 1 mm deep in V1. This depth was known from recording in area V1 before penetrating in V2. Figure 5*B* presents the histogram of the temperatures reached by neurons 1 mm deep in V1 during inactivation of the V2 neurons. We omitted from this analysis the V2 cells whose receptive fields were not included in the visual-field region represented by the cooled zone in area V1 and those that were not inactivated by cooling V1. The range of values shown in Fig. 5*B* is similar to that found by the direct



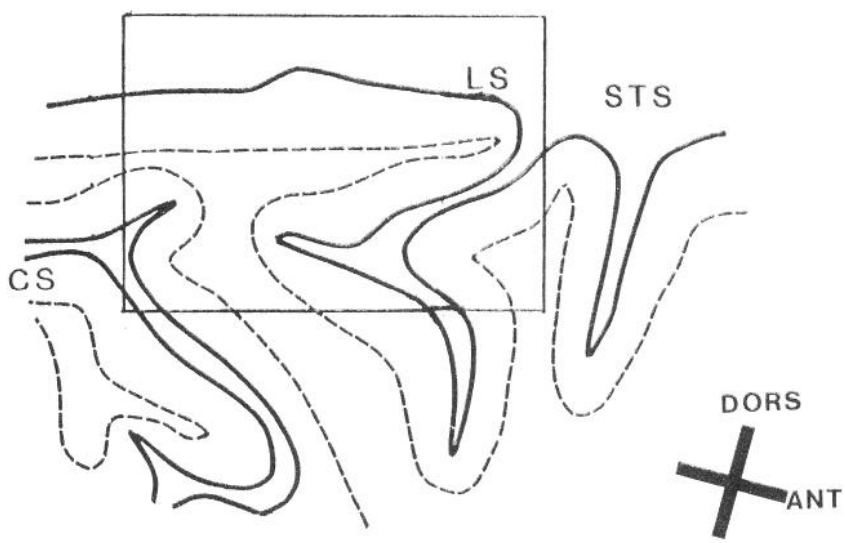


FIG. 6. Parasagittal view of the cortex stained with thionin. Notice several electrode tracks reaching area V2. Boundary between areas V2 and V3 is shown by an arrow. *Inset*: a rectangle illustrates the region represented on the photograph. Extent of cortex covered by the extension plate corresponds to the entire region shown on the photomicrograph (cf. Fig. 1). Note that, apart from a small edema at the site of entrance of electrode penetrations, the histological appearance of cortex below the cooling plate is normal, despite having been subjected to >100 cooling cycles at temperatures < 10°C. LS, lunate sulcus; STS, superior temporal sulcus; CS, calcarine sulcus.

measurement of Fig. 5*A* and confirms that visual activity ceases in V1 neurons for temperatures between 4 and 18°C, with the majority of units being blocked between 6 and 14°C.

Knowing the blocking temperatures of area V1 neurons and the temperature gradients below the cooling plate, it is possible to determine a minimal recording depth in area V2 for which V1 can be completely blocked, whereas neurons in V2 are not directly silenced by the cold. Because the border between white matter and V1 was generally placed 5 mm below the upper surface of the cooling plate, to maintain the whole depth of area V1 at a temperature below 6°C, it is necessary to use a cooling-plate temperature of −8°C. In fact, during our recording sessions in area V2, we routinely inactivated neurons with plate temperatures ranging between 0 and −8°C. With a plate temperature of −8°C, to record neurons in V2 that are above 20°C, it is necessary to record deeper than 8 mm below the upper surface of the cooling plate (Fig. 2). To achieve this, we aimed our penetrations toward the fundus of the lunate sulcus (Figs. 1 and 6). This enabled us to record cells in V2 with receptive fields contained within the scotoma (the visual-field zone represented in the cooled region of V1), these cells being minimally affected by direct influence of the cooling plate. Figure 6 shows a sagittal view of the cortex stained with thionin, with electrode tracks in the recording sites in V2. The maximal depth below the cortical surface of the recording sites in V2 in this case is 5 mm (end of the longest track). When the widths of the dura mater and the subarachnoid space (2 mm) are added to that of the cooling plate (2 mm), this corresponds to a depth of 9 mm below the top of the plate.

Recording in V2 when V1 is cryo-blocked

We recorded 272 sites in area V2, of which 106 were multiunit activities and 166 single units, during 31 penetrations in five monkeys. Two hundred seventeen sites were recorded during penetrations normal to the surface (3 monkeys); the remaining 55 sites (51 single units) were recorded in the other two monkeys within tangential penetrations aimed at recording from different types of cytochrome oxidase bands within V2.

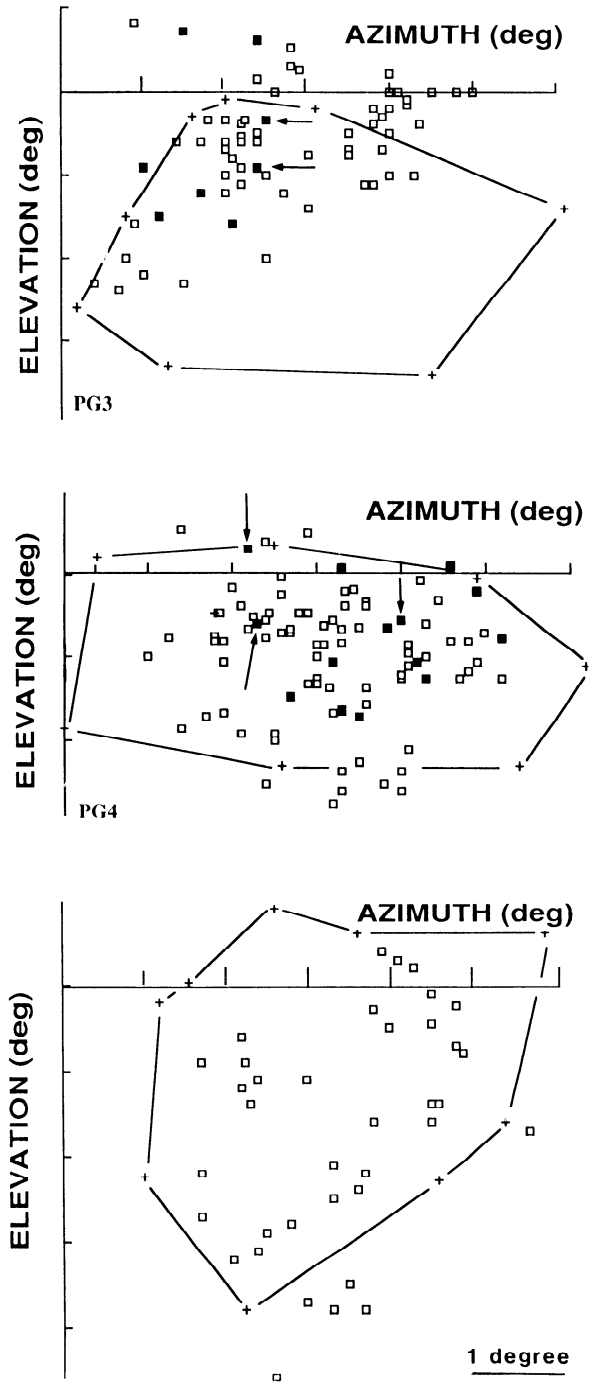


FIG. 7. Position in the right visual hemifield of the receptive-field centers of cells recorded in V2 for 3 monkeys. Scotomas that correspond to the visual-field regions represented in the cooled regions in area V1 are illustrated by straight lines joining crosses. Each cross corresponds to the position of the receptive-field center of a V1 neuron recorded at the edge of the cooled region. Empty squares represent the receptive-field centers of inactivated cells in V2, full squares those of cells giving responses when stimulated in a part of (partial inactivation) or in the totality of their original receptive field. Five neurons that remained active when V1 was at a sufficiently low temperature to be entirely blocked and that have their receptive-field centers in the scotoma are indicated by arrows.

TABLE 1. *Number of single units and multiunits recorded in V2 in penetrations normal to the cortical surface during cryoblocking of V1*

	Inactivated Neurons		No or Partial Inactivation		
	Single units	Multiunits	Single units	Multiunits	Total
RF center outside cooling perimeter	22	17	3	3	45
Possible direct block by cold (V2 below 20°C)	5	3			8
V1 possibly not blocked (deep layers of V1 above 15°C)			5	5	10
RF center inside cooling perimeter (V1 below 12°C)	78	66	2	8	154
Total	105	86	10	16	217

RF, receptive-field.

PENETRATIONS NORMAL TO THE SURFACE. At the beginning of each penetration normal to the V2 surface, we systematically made several control coolings of neurons in V1 to determine the plate temperature for which neurons were blocked in layer 6; this value was generally between −6 and +2°C. During subsequent cooling of V1 while recording in V2, we used temperatures which were equal to or below this temperature.

Because it is likely that interconnected regions in areas V1 and V2 approximately represent the same part of the visual field, it was important to check that the receptive fields of neurons recorded in V2 were included within the visual-field region represented in the part of V1 that was cooled (the scotoma). The extent of the scotoma was estimated by recording at seven to nine sites around the zone of cooling in V1 and joining the receptive-field centers of neurons recorded in these penetrations. The extents of the scotomas determined in this fashion for three monkeys are shown by the areas enclosed by lines joining crosses in Fig. 7. In this figure are also illustrated the positions of the receptive-field centers of the neurons recorded in V2 in these animals. The number of points in the figure is inferior to the number of recorded cells because several units may have the same receptive-field center location.

Most of the receptive-field centers of V2 cells are located inside the scotoma. However, for 45 neurons (25 single units), the receptive-field centers were outside the zone of cooling (Table 1). Thirty-nine of them (22 single units) were inactivated by cooling V1. For five other recording sites (3 single units), the receptive-field centers were outside the cooling perimeter, and the visual activity was not inactivated by cooling V1. Finally, on one occasion, we observed a partial inactivation of a multiunit site, which had a

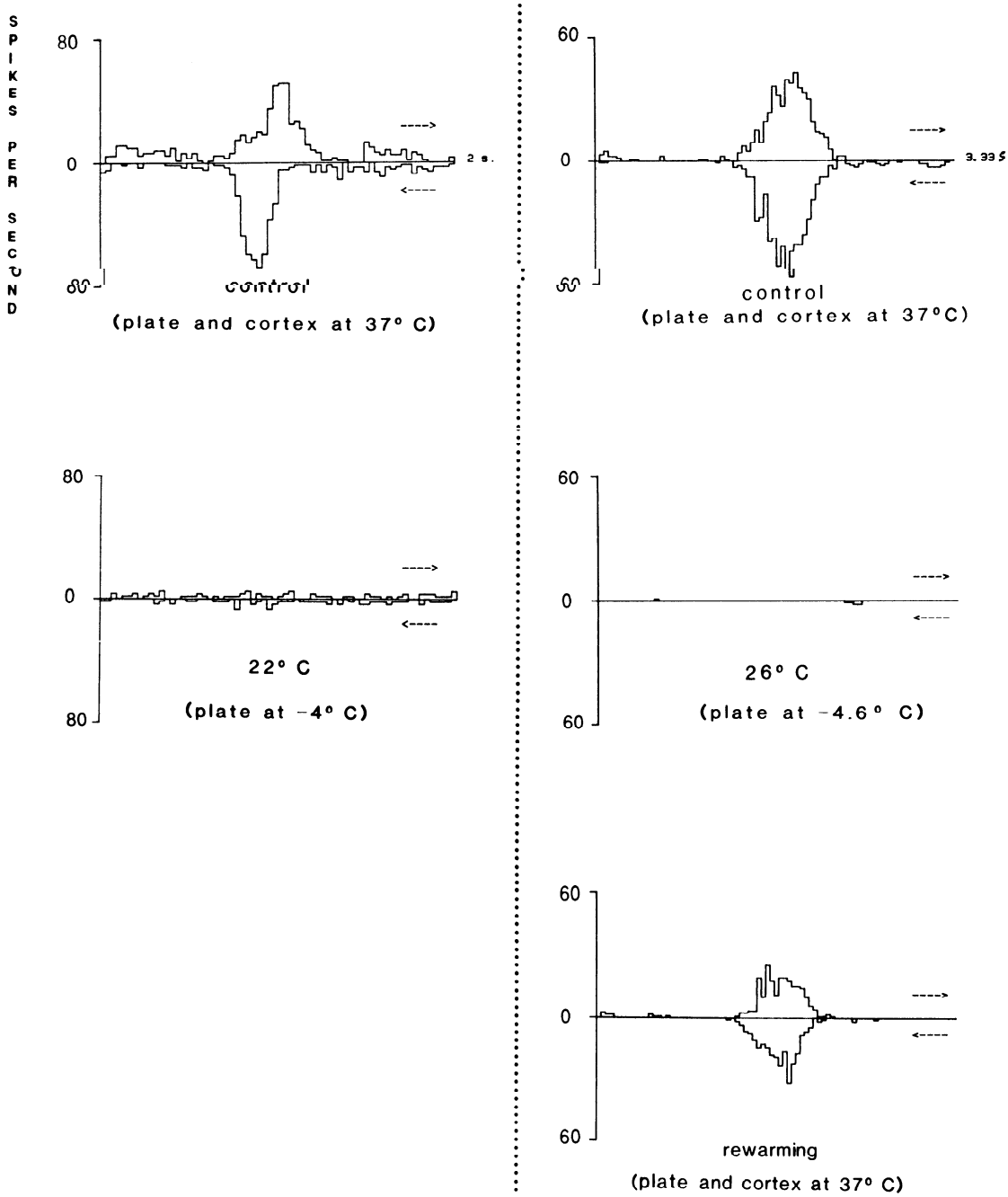


FIG. 8. Effect of cooling area V1 on the visual responses of 2 cells in area V2. Same presentation as Fig. 3. In the case shown on the *left* side of the figure, the spontaneous activity was not blocked. *Cell on the left side*: speed of the stimulus, 5 deg/s; binwidth, 30 ms. Cell was strongly responsive after rewarming, but a PSTH could not be recorded for technical reasons. *Cell on the right side*: speed of the stimulus, 3 deg/s; binwidth, 40 ms.

composite receptive field overlapping only partially with the scotoma. For this neuron, during cooling of V1, the visual response disappeared only within the region of the receptive field included in the scotoma.

The effect of blocking V1 was dramatic on the visual activity of V2 cells: the great majority completely ceased firing to visual stimulation. Examples of two V2 cells that were completely inactivated are illustrated in Fig. 8. During the cooling session, the temperature of the first cell (illustrated on the *left* of Fig. 9) was 22°C and that of the second one was 26°C, so they could not have been directly blocked by the cold (Fig. 5). In the neuron illustrated on the *left* of Fig. 8, some spontaneous activity remained after the visual response had disappeared. This was the case on a number of occasions. In other cases, the spontaneous activity of V2 cells was inactivated or enhanced. When cooling was stopped, the response returned to values close to its control level. The response after cooling was sometimes reduced, as illustrated in Fig. 8. In other cases, it was similar to the control response or enhanced. In every case, we

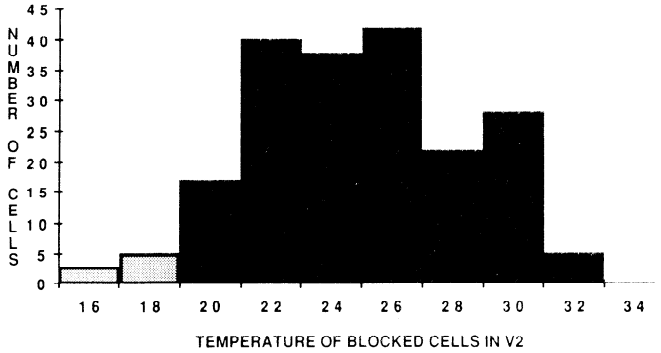


FIG. 9. Histogram of the temperatures of inactivated neurons in V2. Neurons with temperatures < 20°C are likely to be directly inactivated by the cold. Only those neurons with receptive-field centers inside the scotoma are included in this histogram.

were able to record a visual response from the cell when the temperature returned to normal.

Only rarely did we observe changes of receptive-field properties of the cells in V2 before the disappearance of the response during the cooling of V1. There were some occasional changes in orientation or direction selectivity. In a few instances of color-selective cells, we checked that the selectivity was not affected during cooling by assessing the excitatory ON response given by stimulation by one color and the silence and OFF response produced by another color.

Table 1 gives a summary of the fate of 217 cells recorded in V2 during normal penetrations when V1 was cooled. Inactivation occured for 191 sites (86 multiunits and 105 single units), including the 39 units having their receptive-field centers outside the scotoma.

The histogram of the temperatures of inactivated neurons in V2 is presented in Fig. 9. Direct blocking by the cold appears unlikely because practically all V2 units (183 sites) were above 20°C, with an appreciable proportion (>50%) above 25°C, a temperature which has a limited effect on the response (Fig. 4). At eight sites (5 single units and 3 multiunits), visual responses could have been directly blocked by the cold, because the temperature fell below 20°C.

We recorded 20 sites (8 single units) with receptive-field centers inside the scotoma and at which visual responses could still be recorded when V1 was cooled. For 10 sites (5 single units; Table 1), the temperature at a site 1 mm deep in V1 was above 12°C, and the deep layers of V1 were above 15°C. If we refer to the histograms of blocking temperatures in V1 (Fig. 5), it is impossible to be sure that the residual visual response was not because of an incomplete block of V1. Five other sites (all multiunits) were cases of partial inactivations, the only responsive region during cooling being outside the scotoma. Among the five remaining units (marked by arrows in Fig. 7), two had their receptive fields inside the scotoma but very close to its edge. Several reasons lead one to suspect that residual ac-

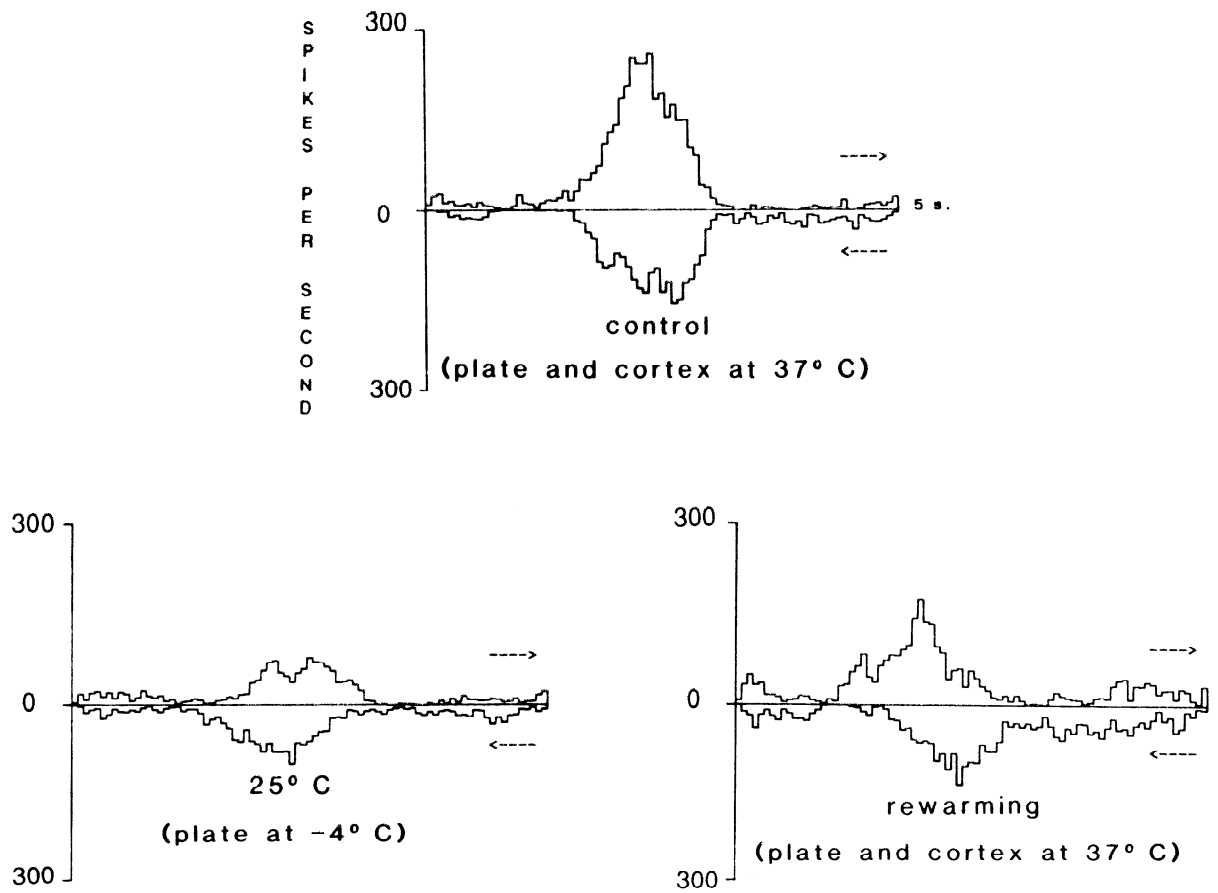
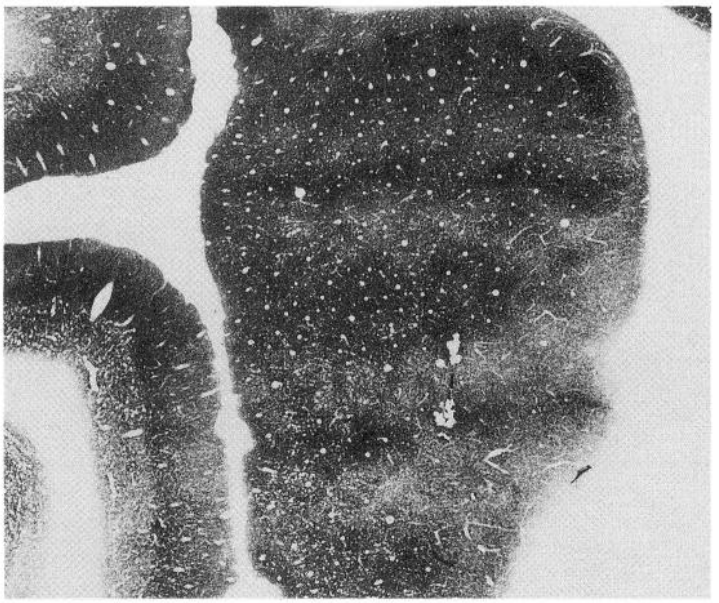


FIG. 10. Effect of cooling of area V1 on the visual responses of the multiunit activity 32-11 in area V2. Same presentation as Figs. 3 and 9. Speed of the stimulus, 1 deg/s; binwidth, 60 ms.



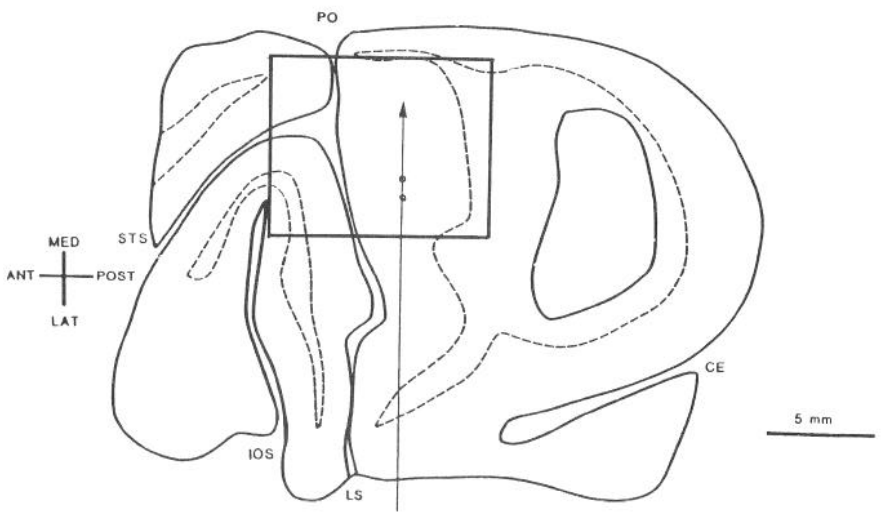


FIG. 11. Section cut parallel to the surface of V2 and stained for cytochrome oxidase. Two lesions can be seen, 1 in a thin band and 1 at the border of a thick band. *Inset*: position of the photographed region with respect to the sulci. Arrow shows the path of the microelectrode penetration. PO, parieto-occipital sulcus; IOS, inferior occipital sulcus; STS, superior temporal sulcus; CE, external calcarine sulcus.

tivity in these units may be because of an incomplete block of their drive in V1: first, because of the limited precision in the plotting of the fovea (in the range of 0.5°), part of the receptive fields of both cells may actually have been outside the scotoma: this is particularly likely to be the case for one of them (a multiunit) whose composite receptive field was partly inactivated and for which the region of the receptive field remaining active was close to the edge of the cooling perimeter. Also, because of the curved surface of the brain, it is likely that cooling was less efficient close to the edge of the cooling plate, where the part of V1 corresponding to these receptive fields must have been located. It is therefore possible that the temperature reached by V1 in this region may not be as low as below the central part of the plate.

Incomplete block of V1, however, does not appear to be the explanation of residual activity for the three remaining sites (1 single unit). All these had their receptive fields completely inside the scotoma and, in each case, sites in the close neighborhood (100 μm above and below) were completely inactivated by cooling V1. The top of V1 was brought to 1.4°C for the first multiunit, 4°C for the second one, and 3°C for the single unit. It is, therefore, clear that the superficial layers of V1, which provide the major input to V2, were completely silenced. It is known that a thin stripe of neurons at the border between layers 5 and 6 in V1 also provide an input to area V2 (Kennedy and Bullier 1985). Temperatures of neurons at this depth reached 8.9°C for the first, 11°C for the second, and 9.2 for the third site. Although some of the infragranular-layer neurons projecting to V2 may not have been totally blocked in these cases, they were brought to temperatures at which <1 spike/presentation can be recorded. In view of the strong responses recorded at these active sites (example on Fig. 10), it appears unlikely that they were driven by

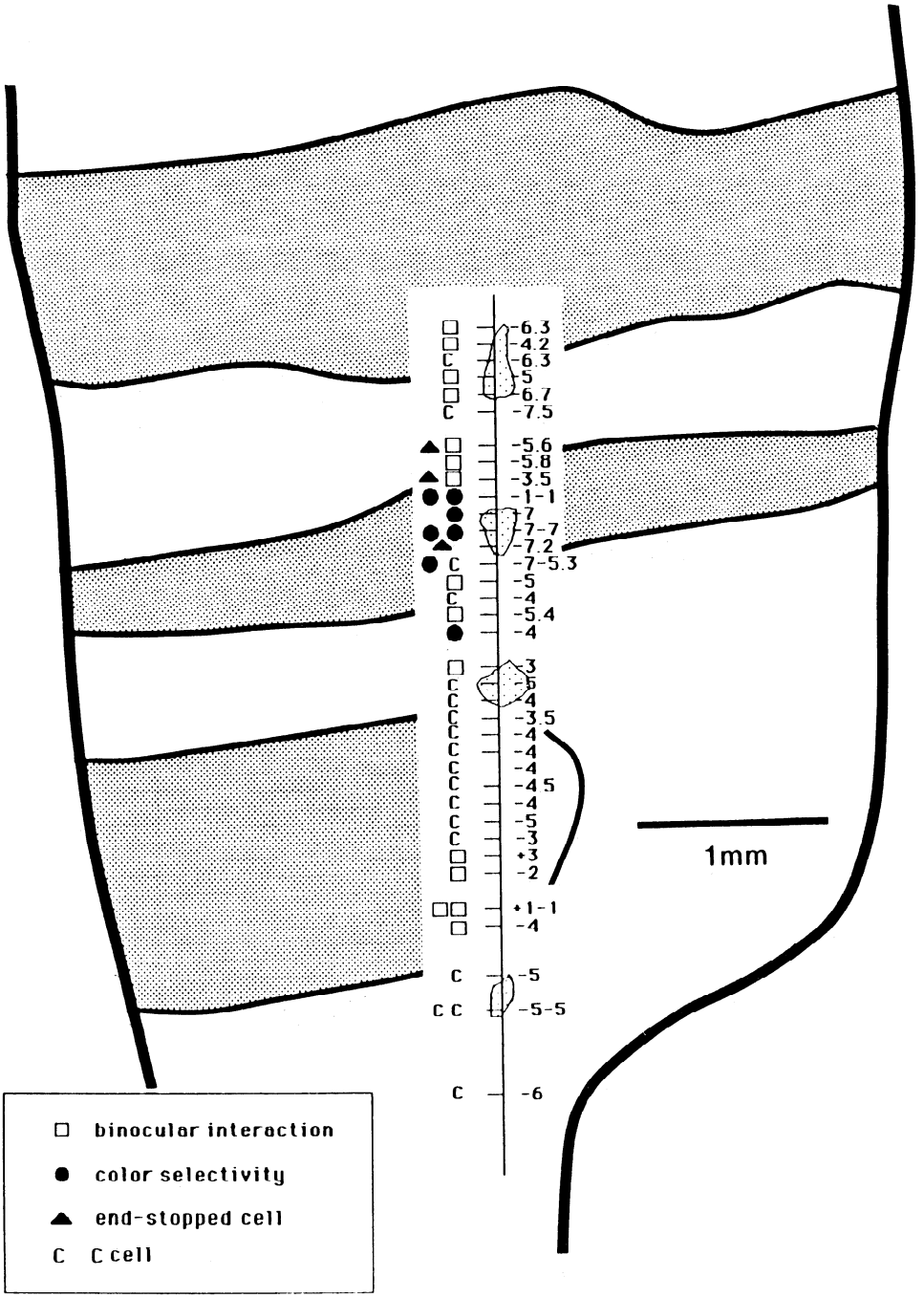


FIG. 12. Reconstruction of the penetration illustrated in Fig. 11. Two lower lesions were placed by examination of sections adjacent to that shown in Fig. 11. Cells were sampled approximately every 100 μm. Their receptive-field properties are indicated by symbols on the *left* of the track. Figures on the *right* of the track refer to the cooling-plate temperature measured when these neurons stopped responding to optimal visual stimulation. Note that cells in all cytochrome oxidase bands and of all functional types are inactivated for similar temperatures.

incompletely blocked infragranular neurons in V1. A PSTH of the remaining activity is given in Fig. 10 for one of the multiunits: although diminished, its response was still very clear. This strong response is even more striking because the temperature of this multiunit was 25°C, so that part of the decrease of the response could be because of a direct effect of the cold. The other multiunit was at a lower temperature (21.5°C). The visual response of the single unit could not be studied quantitatively. As can be judged by ear, it was direction selective and still gave strong responses to large dark contours moving ~30°/s when V1 was cooled. According to the histological reconstructions of electrode tracks, two of the sites remaining active were close to the V2-V3 boundary.

TANGENTIAL PENETRATIONS. To determine whether neurons in all subdivisions of V2 (thick, thin, and pale bands of cytochrome oxidase) were similarly inactivated by blocking V1, we made long penetrations angled to remain for a long distance within V2. In these tangential penetrations, 55 sites (51 single units) were studied, the sampling rate being ~1 site every 100 μm. All these sites had receptive fields that were completely included within the scotoma (not represented). All 55 units recorded in tangential penetrations were inactivated by blocking V1. Although we did not study quantitatively the response selectivity to different parameters of the visual stimuli, in most instances response selectivities could be clearly identified with qualitative methods.

TABLE 2. *Positions of the 55 cells recorded within tangential penetrations with respect to different types of cytochrome oxidase band*

	Cytochrome Oxidase Bands			
	Thick	Pale	Thin	Undetermined
No. of cells	16	17	10	12

In the case of tangential penetrations, it is impossible to precisely assess the depth of recording in V2 with respect to the cooling plate. Therefore the temperature of the recorded cells could not be determined. We can nonetheless assume that our penetrations were placed near the fundus of the lunate sulcus because the receptive fields were close to the horizontal meridian, approximately in the same part of the visual field as the receptive fields of cells recorded within penetrations normal to the surface of V2. It is, therefore, unlikely that the inactivation of V2 cells in tangential penetrations was because of a direct effect of the cold. This is also suggested by the fact that spontaneous activity was retained during cooling in some units and that we did not observe the characteristic widening of the spikes at temperatures below 20°C (Gahwiler et al. 1972; Sherk 1978).

Lesions were made every millimeter or two along the electrode tracks to position every cell within the penetrations with respect to the nearest cytochrome oxidase band. The photomicrograph of Fig. 11 shows two lesions in a section cut parallel to the surface of V2 and stained for cytochrome oxidase. The penetration crosses a thick band, then a thin one, and finally enters a thick band. Figure 12 presents a reconstruction of the electrode track. The two lesions at the end of the track correspond to those shown on Fig. 11; the other two were positioned from examination of adjacent sections.

In the penetration illustrated in Figs. 11 and 12, the position of 41 sites could be assigned to different types of cytochrome oxidase band, with the restriction that some of them were at the frontier between two bands (Fig. 12). In a second penetration (not shown), seven cells were placed either in pale bands or in a dark band which we could not determine as thick or thin. In three other penetrations, seven units were recorded but could not be assigned to a given band. Table 2 summarizes the position of all the cells recorded in tangential penetrations with respect to the cytochrome oxidase bands.

There was no sharp segregation of receptive-field properties in different cytochrome oxidase bands except for the color-selective neurons. In Fig. 12, for example, we note a gathering of color-selective cells in the thin band. Six out of the seven color-selective cells were recorded in the thin band. In the other penetration, in which we could not identify the type of dark bands, six color-selective cells were recorded in or very close to the dark band. Cells with strong binocular interaction (strong facilitation or inhibition) were most commonly encountered in the thick bands (9 out of 15) but were also recorded in pale bands or at the edge of thin bands. Because we did not test binocular interactions with continuous variation of disparity, a number of other cells labeled C in Fig. 12 may have shown some degree of binocular interaction if properly tested.

End-stopped cells were not common in our recordings but seemed to avoid thick bands. Some of these end-stopped cells also showed strong binocular interaction or directional properties. Eighteen cells did not show specific color selectivity, binocular interaction, or end-stopping; they were only selective to the orientation of the stimulus (and to its direction for 6 of them). We refer to those as C cells in Fig. 12. We usually found C cells in the thick or the pale bands. For example, on Fig. 12, a group of C cells is found in a thick band, just above a cluster of binocular-only cells. Direction selectivity occured in 11 units, of which 7 were C cells and 4 were cells with strong binocular interaction. They seemed evenly distributed in pale or thick bands (1 was at the edge of a thin band).

Blocking V1 inactivated the visual response of cells of all functional types and in all kinds of cytochrome oxidase bands (Fig. 12 and Table 2). Different cell types were inactivated for similar temperatures of the cooling plate. In Fig. 12, a group of cells with strong binocular interaction appears to be inactivated at relatively high temperatures, but this was not a consistent finding for all cells of this type within this penetration, and it was also not observed in penetrations normal to the surface. Neurons belonging to all cell types were also inactivated during normal penetrations.

DISCUSSION

The present results show that cortical neurons cease to respond to visual stimulation when they are placed at temperatures between 4 and 18°C. They also demonstrate that the vast majority of neurons in V2 are inactivated when the corresponding region in V1 is blocked by cooling. The results concerning the cooling technique are discussed first. The physiological significance of inactivation of V2 neurons is examined in a second section.

Cooling method

It was impossible to measure directly the temperature at the site of electrophysiological recording because of the thermocouple size. We therefore had to rely on the temperature gradients within cortex to compute the temperature reached by neurons at a given depth. Because depth can be measured with a precision of the order of a few hundred microns, the validity of the temperature values depends mainly on that of temperature gradients. We made these measurements with the use of a specially designed thermocouple that provides a reliable estimate of the temperature at a given point, whereas standard thermistors or thermocouples give erroneous temperature gradients because of heat loss in the wires. To minimize errors because of changes in the thermal characteristics of cortex over time, gradients were measured at the site of electrode penetration and immediately after recording. Because the width of the dura mater varied substantially after repeated coolings, it was important to confirm the earlier observation (Baker and Malpeli 1977) that the gradients are not different in this tissue and in cortex.

The temperature gradients measured in the present study are within the range of reported values, which vary between 2.5 and 3.5°C/mm (Schiller and Malpeli 1977), 3 and 4°C/mm (Kalil and Chase 1970), 5°C/mm (Jasper et al. 1970; Schmielau and Singer 1977), and 7°C/mm (Baker and Malpeli 1977). It is clear that temperature gradients vary with the heat flow imposed by the cooling device (Fig. 2) and the geometry of the cooling plate as well as that of the underlying cortical surface and its vascular pattern. There is, therefore, not a unique temperature gradient for all cooling experiments, and it is necessary to measure a set of curves for different heat flows in each experimental situation.

In the present study, we determined the temperature at which neurons in area 17 cease to respond to visual stimulation. Most previous reports on neural inactivation by the cold used the EEG (Schiller et al. 1974) or the evoked potentials elicited by sensory (Jasper et al. 1970; Kalil and Chase 1970) or electrical stimulation (Benita and Condé 1972; Schmielau and Singer 1977) to detect the abolition of neural activity. All these studies are in agreement that the EEG and evoked potentials disappear around 10°C. This is in keeping with our finding that most visual neurons cease to respond at temperatures higher than 10°C and that the residual activity below 10°C is always extremely weak. It is clear, however, that EEG and evoked potentials are not sensitive enough to detect the presence of a small number of units that remain active below 10°C. Because it was essential for our study to determine the temperature below which *all* visually evoked neural activity was blocked, we measured this temperature in a relatively large sample of neurons. Our results show that extremely weak visual responses can still be evoked in a small number of neurons at temperatures as low as 4°C. These low values are not the consequences of errors in temperature gradients or depth measurements in some penetrations, because units that still responded at temperatures below 10°C were found intermixed within the same penetrations with units for which activity was blocked between 10 and 18°C.

Few studies have determined directly the temperature at which neurons cease to be active. Most measurements made in cortex found values above 20°C (Moseley et al. 1972; Sherk 1978; Sosenkov and Chirkov 1970). The validity of these findings appears questionable because considerable EEG and evoked activity can still be recorded from cortex at 20°C (Jasper et al. 1970). This is also in clear contradiction with our results, because none of the neurons in our study were blocked above 20°C, although activity in some units was substantially reduced (Fig. 4). This discrepancy may result from nonoptimal stimulation of neurons in some of the studies mentioned above, because a given neuron could appear inactivated when stimulated with nonoptimal stimuli, whereas responses could be evoked at lower temperatures under conditions of optimal stimulation. Another potential source of error is the use of thermistors with relatively thick wires as temperature monitoring devices, which may change the local distribution of isotherms, because these wires act as thermal short circuits, thus leading to erroneously high temperature values. This appears especially likely in the study of Moseley et al. (1972) in which the thermistor was embedded in a syringe needle. Both sources of error were avoided in our study by optimal stimulation of neurons and the use of a thermocouple with extremely thin wires.

The low values of blocking temperature recorded in the present study for some neurons are in keeping with the results of Gahwiler et al. (1972) on the spontaneous activity of cultured neurons at different temperatures. In this study in which the temperature was measured with good precision, it was clear that all neurons are still active at 20°C and that activity remained in a number of neurons for temperatures between 5 and 10°C.

Blocking V1 inactivates V2 cells

Our results show that the vast majority of V2 neurons cease to respond to visual stimulation when V1 is cooled. It is unlikely that this inactivation is because of a direct effect of the cold for the following reasons. First, except for eight units, the temperatures of recorded neurons in V2 were above 20°C (Fig. 9), at which direct blocking does not occur (Fig. 5). This is confirmed by the fact that, with the exception of two cases, we did not notice any widening of the action potential in V2 neurons under cooling. This widening becomes particularly noticeable below 20°C (Gahwiler et al. 1972) and is readily detected when the action potentials are heard on the audio monitor (Sherk 1978; Girard and Bullier, unpublished observations). Second, if the inactivation of V2 cells directly resulted from the cold, one would expect that the histogram of blocking temperatures for V2 neurons would be similar to that for neurons in V1. Because these histograms (Figs. 9 and 5) practically do not overlap, it appears impossible that V2 neurons were blocked by direct action of the cold. Finally, of the 19 V1 neurons recorded in the calcarine fissure and which were therefore at similar depths as most neurons recorded in V2 in later penetrations, none were directly blocked by the cold applied to the opercular region of V1.

One could argue that the inactivation of neurons in V1 and V2 were the consequence of a general depression of neural activity created by the effect of the cold on vascular supply. This possibility appears unlikely because we observed partial blocking of multiunits in several cases. In these instances, visual responses were blocked when the part of the receptive field inside the scotoma was stimulated, whereas activity could still be elicited by stimulation of a part of the receptive field outside the scotoma. Also, the total reversibility of the responses of cells in V1 and V2 and the normal aspect of the cortex under the cooling plate (Fig. 6) argue against the possibility of general or local damage to the vascular supply.

The inactivation of V2 neurons could also result from blocking in the white matter of afferent axons en route toward V1 and V2. This would be particularly unfortunate if the axons carrying visual activity from the LGN or extrastriate areas to V2 were blocked, because these possible bypasses of the V1-V2 connection would thus be disabled. However, this appears unlikely, because the temperature of the white matter between V1 and V2 was higher than that of the gray matter in V1 and thus was above 10°C and because it is known that conduction in fiber tracts is blocked only for temperature lower than 10°C (Bénita and Condé 1972; Franz and Iggo 1968).

In penetrations normal to the cortical surface, we recorded 154 units with receptive fields inside the scotoma and which were studied when V1 was cooled to temperatures sufficiently low to ensure its complete inactivation. In penetrations tangential to the surface of V2, we recorded 55 such units. When pooled together, these two samples make a total of 209 sites, among which 5 still gave a response when V1 was cooled. As argued in RESULTS, only three of these sites had receptive fields sufficiently well centered within the scotoma to ensure that no experimental artifact could explain their residual visual responses.

The small proportion (1.5%) of V2 neurons active during blocking of V1 raises the possibility that our sampling was not uniform across all the layers or cytochrome oxidase bands. Undersampling of some cortical layers appears unlikely because we made repeated normal penetrations, and histological reconstructions showed that all layers were equally sampled. Our recordings made tangential to the surface and running through different cytochrome oxidase stripes also rule out the possibility that we missed a given population within one of these divisions. Histological reconstructions provided the interesting observation that two of the three active sites during V1 cooling were located close to the V2-V3 border. It may be that some neurons in V3 do not depend entirely on input from V1 for their visual responses and that this may also be true near the V2-V3 border.

The conclusion that very few neurons remain active during inactivation of V1 is in keeping with the results of Schiller and Malpeli (1977), who concluded from a presumably smaller sample that "every time area 17 was cooled sufficiently to inactivate single cells there, the units in area 18 stopped responding to visual stimuli." Our results show that this is true for all functional types of cells in all subdivisions of V2. The fact that cells within thick cytochrome oxidase stripes are inactivated when V1 is blocked is particularly interesting in view of the fact that these regions of V2 provide a major input to area MT (De Yoe and Van Essen 1985; Shipp and Zeki 1985), where numerous neurons remain active when V1 is removed or cryoblocked (Bullier and Girard 1988; Rodman et al. 1985, 1989). Thus the residual activity in MT neurons in the absence of a V1 input does not appear to be transferred through V2.

The small number of neurons in V2 that remain active when V1 is blocked is surprising considering the numerous pathways which bypass area V1 (see INTRODUCTION). For a number of V2 cells, one could argue that the neural activity potentially relayed by such pathways could be quenched by the direct effect of the cold. This, however, is unlikely to be the case for more than 30 neurons that were above 30°C and thus were little affected when V1 was cooled (Fig. 9). Despite this, all these units were completely inactivated when V1 was blocked. It appears, therefore, that the direct geniculate input and the strong projection from MT are not able to drive V2 neurons in the absence of an input from V1. This domination of the V1 input over all others may be related to the fact that it terminates mainly in layer 4, whereas the MT projection avoids it (Maunsell and Van Essen 1983; Ungerleider and Desimone 1986). This suggests that the input that terminates in lamina 4 dominates the response of most neurons in this area, whereas afferents terminating in other laminae provide a modulatory role that can only be observed when the layer-4 input is active. Direct test of this hypothesis in other corticocortical connections would give some functional meaning to the anatomic distinction between ascending or feedforward (which terminate in layer 4) and descending or feedback (which avoid layer 4) pathways in cortical connections of the visual system (Maunsell and Van Essen 1983; Rockland and Pandya 1979).

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