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Dynamic changes in receptive-field size in cat primary visual cortex

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ABSTRACT **Immediately after focal retinal lesions, receptive fields (RFs) in primary visual cortex expand considerably, even when the retinal damage is limited to the photoreceptor layer. The time course of these changes suggests that mere lack of stimulation in the vicinity of the RF accompanied by stimulation in the surrounding region causes the RF expansion. While recording from single cells in cat area 17, we simulated this pattern of stimulation with a pattern of moving lines in the visual field, masking out an area covering the RF of the recorded cell, thereby producing an "artificial scotoma." Over ≈10 min this masking resulted in a 5-fold average expansion in RF area. Stimulating the RF center caused the field to collapse in size, returning to near its original extent; reconditioning with the masked stimulus led to RF reexpansion. Stimulation in the surrounding region was required for the RF expansion to occur—little expansion was seen during exposure to a blank screen. We propose that the expansion may account for visual illusions, such as perceptual fill-in of stabilized images and illusory contours and may constitute the prodrome of altered cortical topography after retinal lesions. These findings support the idea that even in adult animals RFs are dynamic, capable of being altered by the sensory context.**

The extent of a receptive field (RF) is usually defined by the visual-field area over which a cell can be activated by a simple stimulus, such as an oriented line segment or edge. It is now evident, however, that the response of a cell can be modulated by stimuli lying outside of the RF (1–7). This principle at the cellular level is accompanied by a corresponding set of observations at the psychophysical level, whereby one's percept of a local attribute is influenced by the context within which a feature is presented (8–10). The basis for transmission of visual information from one part of the visual field to another is seen in the pattern of connections within the visual cortex. Long-range horizontal connections formed by cortical pyramidal cells enable the recipient neurons to integrate information over a large region of cortex and, hence, a larger part of the visual field than that covered by their RFs, as classically defined (11–15).

Although the contextual influences on the firing of a cell under ordinary circumstances are subthreshold, certain manipulations of input to visual cortex may elevate these influences to an activating level: focal destruction of the retina causes the cortical area that receives input from the affected retina, over a few months, to reorganize its topography so that cells shift their RFs to the perilesion retina (16–18). Even in the short term, within minutes after retinal lesions, single-unit RF size in area V1 expands (19). Because effects were observed over such a short time and could be induced by as minor an intervention as destruction of the photoreceptor layer, it was logical to ask whether the effect could be simulated simply by occluding the RF, restricting stimuli to the area surrounding the RF. The masked part of the visual field would represent an "artificial scotoma" analogous to the scotoma induced by the laser lesion. We show that this manipulation leads to a dramatic increase in RF size, providing further evidence that RF properties, even in adult visual cortex, are dynamic, changing in response to changes in context.

MATERIALS AND METHODS

We recorded from 53 cells in area 17 of 15 adult cats. Recordings were made in anesthetized, paralyzed animals (20) with insulated tungsten microelectrodes (cf. ref. 21) and were restricted to the superficial layers of the cortex.

The RF was originally mapped by using the minimum-response-field technique—i.e., the edges were determined by shifting a moving bar from the periphery toward the RF center until a response was elicited. Using a hand-held stimulus projector, the RF properties of the cell (orientation selectivity, end inhibition, ocular dominance) were determined by monitoring audio output from the recording electrode. The borders of the RF were established quantitatively by presenting mapping stimuli on a computer-generated display while collecting the output of the recording electrode into the memory of a second computer (Fig. 1 *Lower*). Mapping stimuli were small, optimally oriented bars that passed through the RF in a direction orthogonal to its axis of orientation. Length of the bars was approximately one-third to one-fourth the length of the RF. The bars were positioned at 11 loci evenly spaced along the orientation axis to test the responsiveness over an area several times the original RF diameter, and each trial consisted of one sweep each in the null and preferred direction. All 11 trials together covered the entire extent of the RF as well as a significant area of the surrounding visual field. Thus, peristimulus–time histograms (PSTHs) recorded during the trials represent a quantitative map of RF size. Fig. 1 shows that spike counts from the PSTHs could be accumulated into a second histogram to statistically compare RF profiles along the orientation axis.

After isolation and RF mapping of single units in area V1, the cat was presented with a 14 × 11° array of small bars oriented parallel to the orientation axis of the RF and moving back and forth in a direction orthogonal to their orientation (Fig. 1 *Upper*). The RF was occluded by a large "artificial scotoma" that matched the luminance of the background without the bars and encompassed the RF and the surrounding visual field so that the cell remained unstimulated. The size of the artificial scotoma was initially set at approximately three times the diameter of the original RF, so that the surrounding bars did not activate the cell. Fig. 1 schematically illustrates the relative position of the RF (heavy lines) within the artificial scotoma (dotted lines). In the actual stimulus, the scotoma borders were invisible; the bars simply disappeared as they passed through the scotoma region.

Manual- and automated-mapping trials were interspersed with variable periods of exposure to conditioning stimuli, consisting either of the artificial scotoma configuration or of

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Abbreviations: RF, receptive field; PSTH, peristimulus–time histogram.

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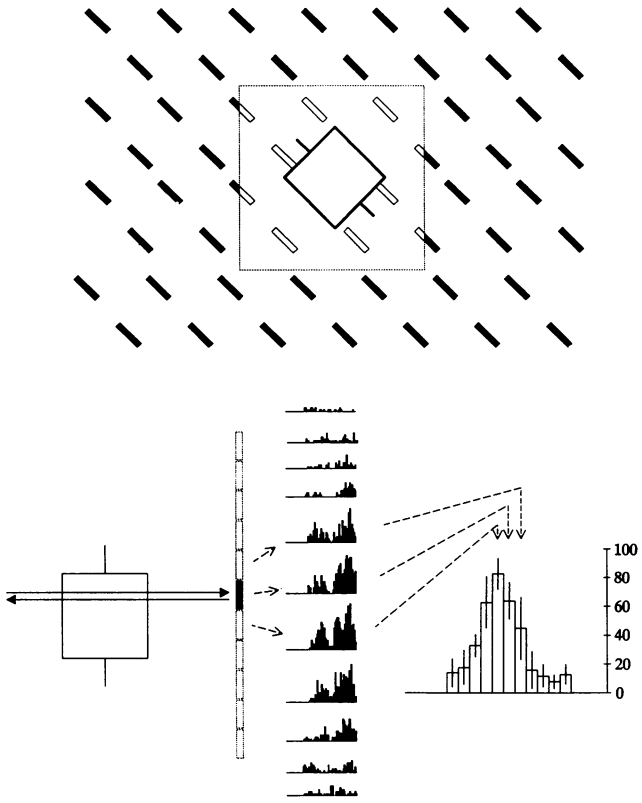

FIG. 1. Visual stimuli and data-collection techniques. (*Upper*) Cartoon of artificial scotoma conditioning stimulus. Bars, 0.1 × 0.5°, were arrayed in a hexagonal pattern with centers 1.0° apart and moved back and forth in a direction orthogonal to their orientation; their excursion was described by a triangular wave with amplitude of 4–10° and period of 2 sec. The artificial scotoma was typically three times the diameter of the RF, as determined by initial hand mapping. (*Lower*) Automated mapping procedure: (*Left*) typical RF outline is shown flanked on the right by an array of mapping bars arranged to illustrate their approximate position with respect to the RF. The bars were approximately the same size and brightness as those used in the conditioning stimulus. Solid arrows through the RF show the path taken by the central bar (represented by black bar) during its mapping trial. One bar at a time was swept across the field, and in consecutive trials the bar was placed at different positions along the orientation axis, as indicated by the dotted bars. Dashed arrows show how data from the mapping trials was accumulated into the RF profile at right. For example, as the central mapping bar passed through the RF, spike counts from the resulting PSTH were collected into the central bin of the RF profile. The bars directly adjacent to the central mapping bar were collected into adjacent bins of the profile (each bin representing the mean and SD of five trials), and thus the profile only showed changes in RF size along the orientation axis.

an optimally oriented bright bar presented in the center of the RF. Thus, the manual- and automated-mapping procedures could differentiate the responsiveness and RF size of cortical units under a variety of visual conditions.

To illustrate more clearly how changes in responsiveness translated into RF size, we converted the PSTHs collected during the automated-mapping procedure into the two-dimensional RF maps of Figs. 5 and 6. Each PSTH is depicted as a band of individual bins where bin width and height represent the extent of visual space traversed by the mapping stimulus. The density of each bin corresponds to spike frequency at that point in the RF during the mapping procedure. The PSTHs were taken from bars matching the preferred orientation and direction of motion of the cell, and these data were smoothed by boxcar averaging across nine bins.

RESULTS

The effect of conditioning with an artificial scotoma is exemplified by the hand-drawn maps shown in Fig. 2. The original RF outline is indicated by box 1. When the conditioning stimulus with scotoma was presented for 15 min, the field expanded to the size of box 2. After the conditioning stimulus was presented without the scotoma, the RF shrank down to box 3. Subsequent conditioning stimuli with and without the scotoma, respectively, reexpanded (box 4) and recompressed (box 5) the RF. In this example the scotoma region was slightly larger than box 2. Of 53 cells studied, 39 showed similar expansions, with a mean area expansion factor of 5.2. All cells studied were located in the superficial cortical layers.

The stimulus-dependent reversibility of the RF expansion made quantification of RF size difficult. The manual and automated versions of the minimum-response-field technique enabled us to locate the RF borders as well as define the response characteristics of individual subregions of the RF. By interdigitating the test with the conditioning stimuli, the changes in RF properties were maintained. To induce robust expansion and contraction of RF size, the conditioning stimuli were usually presented for several minutes. Because quantitative mapping also took several minutes, the exact time course of the observed changes was impossible to determine.

Results from this approach are illustrated by the RF profiles in Fig. 3. After initial conditioning with the artificial scotoma for 15 min, the conditioning stimuli were interspersed with the mapping trials so that changes in RF size could be observed. Fig. 3 reveals changes in RF size along the orientation axis. For the cell shown, the length of the RF before conditioning was 2°, and during conditioning the length increased to 4.5°. The dimensions obtained with the quantitative mapping technique corresponded closely to those measured by hand mapping. Of our cell sample, the field expansion was confirmed by the quantitative-mapping technique for 10 cells; the hand mapped and quantitative maps yielded equivalent results. Quantitative mapping had

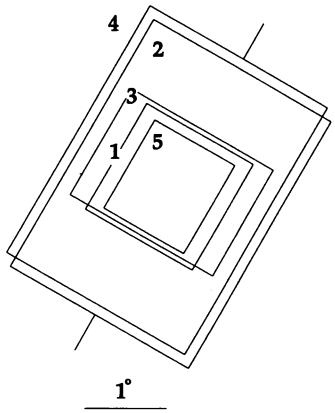

FIG. 2. RF maps of a single cell taken before, during, and after conditioning with the artificial scotoma. The cell was located in the superficial layers of cat area 17; its field was located ≈5° below the area centralis, near the vertical meridian. Maps were obtained by hand with the minimum-response-field technique. The original RF outline, taken after a period of random stimulation within and outside the field, is indicated by box 1. After a conditioning with the artificial scotoma for 15 min, the field expanded, as indicated by box 2. When the occluder was removed—i.e., with the lines passing through the RF—the field collapsed to the boundaries shown by box 3. By replacing and removing the occluder, the field could, respectively, be reexpanded (box 4) or collapsed (box 5). The scotoma used for this example was slightly larger than box 2.

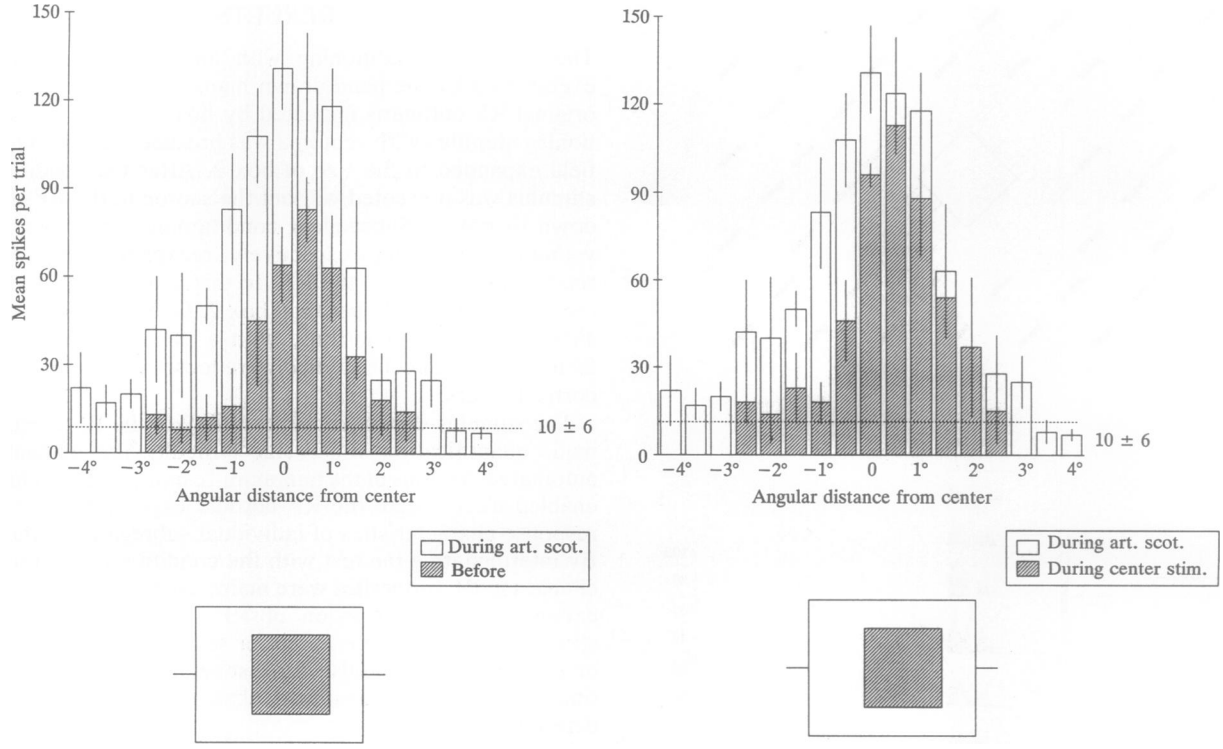

FIG. 3. Quantitative demonstration of RF expansion with an artificial scotoma. The position of the cell and its RF location were similar to that of the cell illustrated in Fig. 2; the RF orientation was vertical. The procedure was as described in the legend for Fig. 1. (*Left*) Initial cellular response is indicated by hatched bars; the response during conditioning with the artificial scotoma (art. scot.) is indicated by open bars at *Left* and *Right*. (*Right*) Responses after stimulating the RF center are indicated by hatched bars. Distance from RF center to the locus of each mapping stimulus is shown on the abscissa. Extent of the RF according to hand mapping is shown schematically below each histogram; data from hand- and quantitative-mapping techniques agreed well. The maps have been placed so that the abscissa of each pair of profiles accurately reflects the scale of the map below. Dashed horizontal line at 10 spikes per trial represents spontaneous firing of the cell in the absence of visual stimuli. Response of the cell during conditioning with the scotoma increased for stimuli positioned within, as well as outside, the original RF boundaries. This expansion was reversible: once the occluder was removed, the responses were nearly equivalent to those seen before conditioning.

the additional benefit of showing changes in field substructure and responsiveness within different parts of the field.

PSTHs from stimuli to the expanded portions of the field revealed clear activity peaks as the stimulus moved across the orientation axis, as distinct from the preconditioned state, in which the same stimulus only elicited spontaneous activity. Furthermore, we observed not only newly responsive parts of the RF but also an increased responsiveness from the area of the original RF. The spontaneous activity did not change. As shown with hand mapping, the observed expansion was reversed by vigorous stimulation of the RF center (Fig. 3 *Right*).

The initial RF expansion required stimulation of the area surrounding the RF: for five cells we measured the RF with the test stimuli twice, separated by a 20-min exposure to a blank screen. We then stimulated with the artificial scotoma-conditioning stimulus for 10 min and determined RF size again. We found that exposure to a blank screen had little effect on the RF size, whereas subsequent stimulation with the artificial scotoma produced a large increase in size (Fig. 4).

Precise determination of the shrinkage extent in the expanded RF after removal of the artificial scotoma-conditioning stimulus is difficult. Clearly, though, visual stimulation of the cell shrinks the field more quickly than exposure of the expanded field to a blank screen over time. Although some fields showed a degree of shrinkage when exposed to a blank screen, the test stimuli themselves may have caused the RFs to contract. Thus, because stimulation causes shrinkage, measurement of the time course of shrinkage is difficult. In this version of a neuronal "Heisenberg uncertainty," testing a RF changes it.

The two-dimensional maps in Fig. 5 represent an RF of the same cell under the same conditions shown in the profiles of Fig. 3—before conditioning, during conditioning with artificial scotoma, and during center stimulation. The changes in responsiveness demonstrated with the RF profiles translate

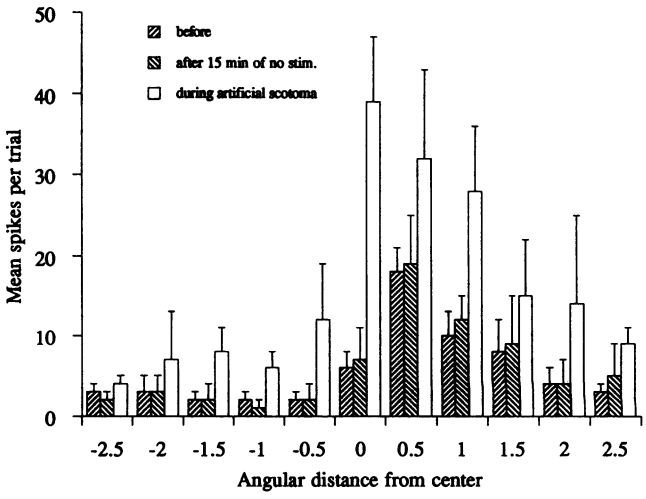

FIG. 4. Comparison of effects of conditioning with a blank screen to effects of stimulation in the area surrounding the RF. In the example shown, no significant difference in RF size or in the responsiveness of the cell was seen after exposure to a blank screen for 15 min (second hatched bar in set). The same cell, when conditioned with the artificial scotoma for 10 min, expanded its RF length and its peak response at the RF center (open bars).

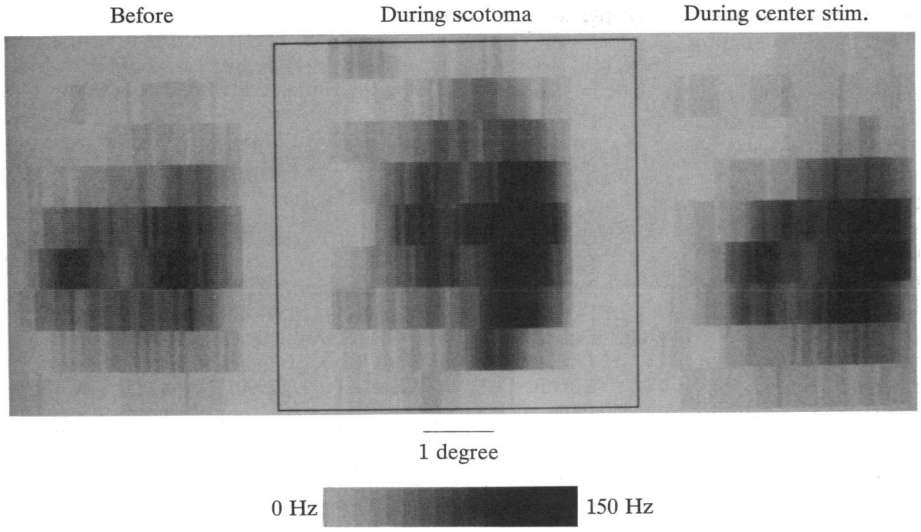

FIG. 5. Two-dimensional maps of the RFs of the cell illustrated in Fig. 3 before conditioning, during conditioning with artificial scotoma, and during center stimulation (stim.). The box at center shows size and position of the occluder. Each PSTH is depicted as a band of individual bins where width and height represent the extent of visual space traversed by the mapping stimulus. PSTHs were taken from bars moving in the preferred direction of motion of the cell, and these data were smoothed by boxcar averaging across nine bins. Level of responsiveness at each visual-field position is indicated by level of shading (key at bottom). This result shows expansion along the dimension of RF width as well as length, although greater expansion in this and other cells tended to be along the orientation axis.

into striking changes in field area, and one can see expansion in width as well as in length. Furthermore, the expansion elicited by the artificial scotoma never exceeded the boundaries of the scotoma.

Although the mechanism of the RF expansion is unknown, the source of visual input to the parts of the expanded RF outside the original RF might well be the long-range horizontal connections that run parallel to the cortical surface. These connections have been shown to link cortical columns of similar orientation specificity (20, 22), and if these connections cause the RF expansion, one might expect the expansion to depend on the relative orientation of the conditioning stimuli and the RF. To test this hypothesis we first conditioned the cell by presenting the artificial scotoma against a background of moving bars oriented orthogonally to the RF. If this cross-orientation (ortho) stimulus did not significantly increase the RF size, we repeated the conditioning procedure with a conditioning stimulus oriented the same as the RF of the cell (iso-orientation).

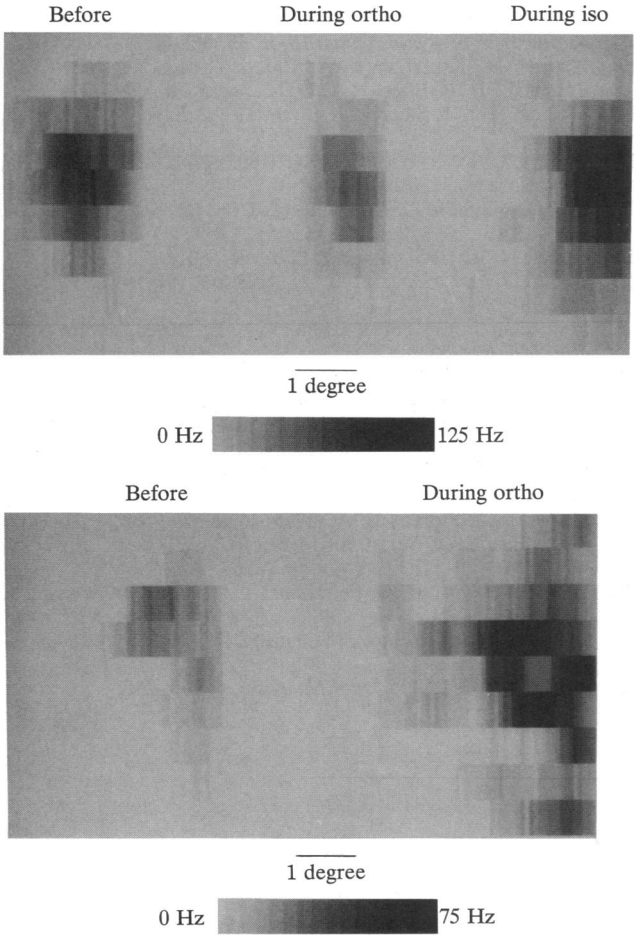

FIG. 6. Maps of RFs of cells before and during conditioning stimuli containing a central scotoma and surrounding bars of the same orientation (iso) and orientations perpendicular to (ortho) the RFs of the cells. (*Upper*) Cell in which RF shrank with the ortho-conditioning stimulus and expanded with the iso-conditioning stimulus. (*Lower*) Cell in which RF expanded with the ortho-conditioning stimulus.

For a few cells in which we tested the dependency of expansion on orientation of the conditioning stimulus (3 out of 15), we did see an expansion with the iso-orientation conditioning stimulus and did not see an expansion with the orthogonal pattern (Fig. 6 *Upper*). In the example shown, the orthogonal pattern actually reduced the RF size and responsiveness of the cell. More commonly, however, we found expansion for both iso-orientation and orthogonal-orientation conditioning stimuli (Fig. 6, *Lower*, 12 out of 15 cells), although no cells expanded exclusively to conditioning with ortho-orientation stimuli.

We attempted to correlate the ability to expand RF by the artificial scotomata with other RF properties. There was no obvious dependence of the effect on end-inhibition or the sharpness of orientation tuning of the RF.

DISCUSSION

Our results indicate that the size of RFs in adult cats shows a surprising degree of mutability and depends on the context within which the RF lies. The tendency for RF expansion has been shown for cells with fields located at the boundaries of retinal scotomata (19). Our findings suggest that the operative influence is the presence of stimuli outside the RF and the absence of stimuli within it.

We believe that these changes may help to explain how perception of local attributes is influenced by contextual stimuli. In particular, these results may explain the perceptual filling-in of visual scotomata by stimulus patterns (23) in surrounding regions and the filling-in of homogeneous colors (23–27). As the borders of the RFs contained within the unstimulated regions approach the scotoma edges, the cells may be driven by stimuli outside the scotoma, falsely signaling the presence of stimuli located close to the RF center. In this way the scotoma appears to fill-in with whatever visual stimuli surround it. From the viewpoint of cortical topogra-

phy, there is effectively an increased representation of the part of the visual field into which the RFs expand. A small stimulus activates a larger cortical area during the conditioning with the artificial scotoma, falsely signaling the presence of the stimulus over more of the visual field than actually subtended by this stimulus.

Stimuli in the surround have been shown to facilitate the response of a cell to stimuli placed concurrently within the RF center (1–3, 5–7, 28). Moreover, in area 18, cells can be driven by complex stimuli in the regions surrounding their classical RFs, effecting responses to illusory contours (29, 30). Our results demonstrate that the influence of surround stimulation on RF size changes the responsiveness of a cell even to the simple single-bar stimulus; one can thus activate the cell at stimulus positions outside the original bounds of the RF, requiring neither the complex pattern in the surround nor the concurrent stimulation of the center.

A number of mechanisms could account for this RF expansion. Adaptation of inhibition could allow the long-range excitatory influences to tip the balance toward activation. If this surround inhibition is continuous through the center, one could explain the higher response levels seen with centrally placed stimuli. Alternatively, potentiation of the excitatory horizontal inputs could lead to an expansion. The influence of center stimulation may be related to the contrast-gain control reported elsewhere (31, 32), although these studies show that gain changes are maximized when the center alone is stimulated, and adding stimuli in the surround has no additional effect. The salient feature of our findings is an increase in responsiveness with stimulation (opposite to the effect seen in the contrast-gain studies) and evidence that this increase is an "action at a distance," occurring only when the stimulation covers the surround with the center excluded. Reversal of the expansion by center stimulation could be viewed, however, as analogous to the earlier studies. One may speculate that contrast gain could reflect a balance of excitation and inhibition modulated by input from *both* the center and surrounding regions of the RF. We emphasize, however, that one cannot explain the expansion in terms of adaptation to a blank field with an increase in sensitivity in unstimulated parts of the visual field, because stimulation of the surround is required for the full effect.

Our results taken together show how contextual information, possibly carried by long-range horizontal connections, can influence RF size and responsiveness of single units in cat primary visual cortex. We believe that the observed changes mimic the short-term changes in RF size seen after retinal lesions. Our findings may reflect the dynamic nature of single-unit behavior during the processing of information normally present in the visual scene.

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