Receptive Field Properties of Single Neurons in Rat Primary Visual Cortex

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Girman, Sergej V., Yves Sauvé, and Raymond D. Lund. Receptive field properties of single neurons in the rat primary visual cortex. J. Neurophysiol. 82: 301–311, 1999. The rat is used widely to study various aspects of vision including developmental events and numerous pathologies, but surprisingly little is known about the functional properties of single neurons in the rat primary visual cortex (V1). These were investigated in the anesthetized (Hypnorm-Hypnovel), paralyzed animal by presenting gratings of different orientations, spatial and temporal frequencies, dimensions, and contrasts. Stimulus presentation and data collection were automated. Most neurons (190/6%) showed sharply tuned (<30° bandwidth at half height) orientation selectivity and a bias for horizontal stimuli (31%). Analysis of response modulation of oriented cells showed a bimodal distribution consistent with the distinction between single and complex cell types. Orientation specific interactions occurred between the center and the periphery of receptive fields, usually resulting in strong inhibition to center stimulation when both stimuli had the same orientation. There was no evidence for orientation columns nor for orderly change in optimal orientation with tangential tracks through V1. Responses were elicited by spatial frequencies ranging from zero (no grating) to 1.2 cycle/degree (c/°), peaking at 0.1 c/°, and with a modal cutoff of 0.6 c/°. Half of the neurons responded optimally to drifting gratings rather than flashing uniform field stimuli. Directional preference was seen for 39% of oriented units at all depths in the cortex. Optimal stimuli velocities varied from 10 to 250°/s. Some units, mainly confined to layer 4, responded to velocities as high as 700°/s. Response versus contrast curves (best fit with Naka-Rushton) varied from nearly linear to extremely steep (mean contrast semisaturation 50% and threshold 6%). There was a trend for cells from superficial layers to be more selective to different stimulus parameters than deeper layers cells. We conclude that neurons in rat V1 have complex and diverse visual properties, necessary for precise visual form perception with low spatial resolution.

INTRODUCTION

The primary visual cortex, area 17 of several species shows adaptive responses both during development and at maturity to modification of visual inputs or manipulation of the primary optic pathway. Such adaptations are manifested by changes in visual field representation (Gilbert and Wiesel 1992), patterns of ocular dominance (Hubel et al. 1977), anatomic indices (Darian-Smith and Gilbert 1994), immediate early gene expression (Rosen et al. 1992), and growth factor levels (Castren et al. 1992; Schous et al. 1995) among others. Although most studies of plasticity in the visual system have used larger animals (cats, ferrets, primates), rodents have been particularly important when performing exploratory experimental procedures such as when examining factors affecting development (for a review, see Lund 1978) or strategies for promoting regeneration of the primary optic pathway (Berry et al. 1996; Harvey and Tan 1992; So and Yip 1998; Vidal-Sanz et al. 1987) or when using genetic mutants or transgenics that serve as models for human disease states.

There are a number of rodent diseases in which photoreceptor degeneration mimics human conditions such as retinitis pigmentosa and age-related macular degeneration (Dowling and Sidman 1962; LaVail 1981). A range of potential therapies, including transplantation (Gouras et al. 1989; Li and Turner 1988; Little et al. 1996), growth factor injections (Faktorovich et al. 1992), and gene therapy (Bennett et al. 1996) are being developed in the rodent models. Most attention has been given to examining how such therapies affect retinal integrity, but equally important is how they modify the visual cortical response properties that underlie the conscious experience of vision. To achieve this, a more complete description than is presently available of unit properties in the normal cortex (Burne et al. 1984; Girman 1985; Mangini and Pearlman 1980; Parnavelas et al. 1981; Shaw et al. 1975; Tiao and Blakemore 1976; Wiesendahl and Kornel 1975) is needed. This study has provided such data for the rat.

METHODS

Animals, preparation, and maintenance

The results presented here are based on recordings done in the primary visual cortex (V1) of 25 female adult (Lister Hooded) rats, weighing between 150 and 250 g. This excludes animals, mostly from pilot experiments, in which recordings were considered less than optimal due to the condition of the animal, the cortex, or recording electrodes. Animals were housed and handled in conformity with the policy of the American Physiological Society. They were anesthetized with an intraperitoneal injection of 2.7 ml/kg of a solution of fentanyl citrate and fluanisone (Hypnorm: 0.315 mg/ml, fluanisone: 10 mg/ml; Janssen-Cilag) and midazolam (Hynov: 5 mg/ml; Roche), one part of each in two parts of distilled water. Preliminary studies using a range of anesthetics showed that some depressed cortical activity (urethane, chloral hydrate), others caused spontaneous spiking that confounded data collection (barbiturates); these anesthetics also gave unstable baseline conditions or were not suitable for long recording sessions. In contrast, Hypnorm-Hynov gave stable and tightly tuned responses over many hours.

The anesthetized animal was placed in a stereotaxic apparatus. EEG electrodes were installed to monitor anesthetic depth by the presence of EEG sleep spindles; supplementary injections of anesthetic were...
given as necessary. The animal was paralyzed with d-tubocurarine chloride (Sigma, 3 mg/kg im) to minimize eye movements and artificially ventilated through the nose. Body temperature was maintained at 37°C with a thermostatically controlled heating pad. The heart rate was monitored continuously. The cornea was protected with a non-refractive contact lens. Pupil dilation and accommodation paralysis with atropine were not used. The pupil diameter remained between 0.5 and 1 mm throughout the experiment.

**Recording and visual stimulation**

Most recordings were from the region of V1 receiving input from the frontal third of the horizontal meridian (coordinates: 1 mm nasal from lambda, 3.5 mm lateral from the midline). In experiments requiring tangential microelectrode penetrations, a horizontal channel was drilled along the skull. At the end of the channel, a small opening was made (approximate coordinates: 3.0 mm nasal from lambda, 6.0 mm lateral). Tungsten-in-glass microelectrodes (Levick 1972) were used for recording single units extracellularly. The recording micro-electrode was introduced into the tiny craniotomy made over V1. As the microelectrode was advanced slowly, various stimuli were displayed across the animal’s visual field to activate cells, many of which had very low or no spontaneous activity. When a single unit was isolated, we first mapped the location and size of the corresponding visual receptive field (RF). The RF was centered on a BARCO ICD 451B monitor (stimuli driven by an AT Truetime Vista Graphic board). The distance between the eye and monitor was set at 57 cm. At this viewing distance, the screen subtended 20 x 20° of visual angle. Preliminary tests showed that spatial resolution was not improved by varying the distance or by placing corrective lenses in front of the eye to correct for the previously reported hypermetropia (up to +9D: Hughes 1977; +4.5 to +8.5D: Mutti et al. 1997) or myopia (−2 to −2.8: Brown and Roja 1965; −3D: Montero et al. 1968) of the rat eye. Only black-and-white display mode was used in the experiments; the average screen luminance was 30 cd/m². Quantitative experiments proceeded under computer control. Each experiment consisted of several blocks of trials in which stimuli with particular parameter values were presented in a random order to minimize the possible effects of response variability. Results of several repeated trials (typically 5, but not less than 3) were averaged. Responses to a uniform field of averaged luminance also were recorded to measure the neuron’s spontaneous firing rate. Responses were compiled into average histograms synchronized with respective temporal cycles of the stimulus. On-line Fourier analysis was performed to calculate the mean firing rate and the response at the fundamental stimulus spatial frequency (SF). The experimental protocol and software for stimulus presentation and analysis followed exactly those used in studies of monkey visual cortex used by Gegenfurtner et al. (1997).

At the end of some recording sessions, electrolytic lesions (2 µA for 3 s) were made at three levels along the recording track: at the ventral limit of the cortex, at an intermediate depth of 100 µm below the brain surface. Precise readings of the depth indicator on the hydraulic micromanipulator were noted at each lesion site. The rat then was killed with an overdose of tribromoethanol (1,000 mg/kg ip) and perfused intracardially with buffered 4% paraformaldehyde. The brain was removed and the tissue block containing V1 cortex was taken and put in 30% sucrose. Frozen sections then were cut at 40-µm thickness in coronal planes and stained with cresyl violet, for reconstruction of the electrode track.

**RESULTS**

We recorded from 205 visually responsive cells in the rat V1 cortex, from within the area of maximum visual acuity in the rat (corresponding to the temporal retinal representation) (Dreher et al. 1985; Fukuda 1977). As many as 20 units could be isolated in a single vertical penetration, but for full analysis, 9 units on average (range 4–13) per penetration were studied. In a single vertical track, receptive fields (RF) were roughly in the same position in the animal’s visual field.

In healthy animals, nearly all cells in V1 were visually responsive. Nonresponding cells usually were observed in animals with deteriorating conditions, i.e., bradycardia, corneal clouding and mydriasis, and decay of electroencephalographic amplitude. We were able to hold single cells for as much as 3 h; axonal units were excluded from the analysis. Sometimes discharges of two cells were recorded simultaneously. In such cases, the single units were isolated using a window discriminator, permitting analysis of response properties of neighboring cells.

The receptive field size in 54 of the cells tested failed within the limits imposed by the stimulus presentation screen (<20°). However, the other cells responded to stimuli larger than the screen dimension, making it impossible to define the actual field size using this experimental set up.

For each neuron, a battery of tests was performed to study its tuning for orientation and direction, spatial and temporal frequency, size of receptive field, orientation tuning of surround modulation, and contrast sensitivity. Figure 1 illustrates typical experimental data obtained from a single cell, recorded at a depth of 420 µm (within layers II–III).

Figure 1A shows the responses of the cell to sinusoidal gratings of different orientation. This cell responded to gratings with an optimal orientation of 210°. It responded slightly more weakly to gratings of the same orientation but moving in the opposite direction (30°). No response could be recorded for any other orientation or direction of movement. Other examples of properties studied are: spatial tuning (Fig. 1B), temporal tuning (Fig. 1C), response versus contrast (Fig. 1D), and dependence on stimulus dimension (Fig. 1E). For cells strongly inhibited by stimuli presented outside their classical RF (as shown in Fig. 1E), we studied how this inhibition was influenced by the orientation of the surround stimuli (Fig. 1F). As with all units tested, stimulation of the surround on its own (right on the x axis), regardless of orientation, did not elicit a response. In this particular case, presentation of surround at any orientations (left) had an inhibitory effect on the response to center stimulation. This inhibition tended to be strongest when the surround orientation corresponded to that of the center.

**Cell reactivity and selectivity to stimulus orientation and direction of movement**

A summary of the reaction index of all recorded cells is presented in Fig. 2A. The majority of cells (140/205, ~70%) had a reaction index (RI) that exceeded 0.7; no cells had RI = 0. A cell is considered as orientation selective if its orientation index (ORI) is ≥0.7 and as directional selective if its direction index (DI) is ≥0.7. For the cell shown in Fig. 1, the value of ORI is close to 1.0 and DI is nearly 0.1.

Figure 2B illustrates the orientation preference for all oriented cells encountered. Of all cells recorded, 77% (158/205) fulfilled the criterion for being categorized as orientation selective (ORI > 0.7), whereas an additional 16% (32/205) showed an orientation bias (0.5 < ORI < 0.7). Therefore the
majority (93%) of the 205 visual units recorded were tuned at some level for orientation, whereas 7% (15/205) had no orientation bias (ORI = 0.5); about half of these (7/15) had no modulation to any orientation (ORI = 0). There was a significant bias of orientation preference for horizontal grating stimuli. Table 1 also shows that 35% (55/158) of all oriented cells responded optimally to stimuli oriented at 90 or 270°. As can be seen in Fig. 2C, the majority of orientation-selective cells

![Graph showing orientation preference](image)

**Fig. 1.** Data obtained on-line from a single cell at 420-μm depth (layer 2–3). In all graphs, the y axis shows the response as impulse per second (imp/s). Spontaneous activity (SA; discharge rate with uniform field of average luminance) is presented to the right of each x axis as 2 horizontal lines: SA + SE and SA − SE, respectively; SE is the standard error of the mean. In this cell, SA approximates 0. Solid line in all graphs links the average responses (AR) of individual experimental points. Dashed lines correspond to AR + SE and AR − SE, respectively. Orientation index (ORI) = (max resp − orth resp)/max resp, where max resp and orth resp are responses to optimal and orthogonal to optimal orientation respectively. Direction index (DI) = (optim resp − oppos resp)/optim resp, where optim resp and oppos resp are responses to optimal and opposite to optimal direction respectively. A: responses to sinusoidal gratings of different orientations. As a convention, the orientation noted as 0° corresponds to vertically oriented bars moving from temporal to nasal visual field; 90° corresponds to horizontally oriented bars moving downward in the field. B: responses to gratings of different spatial frequencies. C: responses to different temporal frequencies. D: responses to gratings of different contrast. E: responses to grating patches of different sizes. F: responses for testing center-surround interactions. This particular cell was strongly end-stopped.

![Graph showing reaction index](image)

**Fig. 2.** Cell reactivity and orientation selectivity. A: histogram showing the reaction index of all recorded cells. Reaction index (RI) = |(max dev − SA)/(max dev + SA)|; 0 > RI < 1, where max dev is the neuronal response, to a specific stimulus, with maximal deviation from its SA. For example, max dev = SA and RI = 0 in the case where there is no neuronal response to any pattern of stimulus presentation. B: histogram showing the preferred orientation in the overall population of recorded cells. C: histogram of tuning for all orientation selective cells.
about orientation columns in the rat visual cortex

Cells with very different preferred orientations often could be encountered in a single vertical penetration through the cortex (Fig. 4B). The regular shift of orientation preference with progressive depth that is seen in cat or monkey for example with a slightly oblique penetration was never encountered. Furthermore when recording from two cells simultaneously, their preferred orientations often could be quite different (29/38, 76%) and in 18% of cases were even tuned for orthogonal orientations. This surprising observation has also been made in the cat V1 (Shelev et al. 1995). We recorded these cells for a long enough (from 1 to 3 h in several cases) to document this fact and show that it was repeatable over time. The optimal stimulus parameters for each cell were identical for the two preferred orientations.

About orientation columns in the rat visual cortex

We observed a few individual cells (n = 6) with the very unusual characteristic of responding to two stimulus orientations which were nearly orthogonal to one another. This surprising observation has also been made in the cat V1 (Shelev et al. 1995). We recorded these cells for a long enough (from 1 to 3 h in several cases) to document this fact and show that it was repeatable over time. The optimal stimulus parameters for each cell were identical for the two preferred orientations.

Orientation index = DI/0.7.

(99/158) have an orientation tuning (bandwidth at half height) of 60° or sharper (30°).

Of all oriented cells, 37% (59/158) were directionally selective (DIR = 0.7), whereas a further 22% (35/158) showed a directional bias (0.5 ≤ DIR < 0.7). Thus more than half of the oriented cells (59%) responded differentially to directional stimuli. No preferred direction was evident.

Using criteria based on the nonlinear versus linear properties of V1 neurons (Skottun et al. 1991), we found that oriented cells could be divided in two populations: complex-like (43%; F1/F0 < 1), responding mainly with unmodulated elevation in discharge, and simple-like (57%; F1/F0 > 1), having their frequency of discharges mainly modulated at the fundamental stimulus frequency. This distribution of cells according to their F1/F0 ratio is presented in Fig. 3.

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Table 1. Distribution of oriented cells by preferred orientation

<table>
<thead>
<tr>
<th>Angle</th>
<th>n</th>
<th>Percent</th>
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<tbody>
<tr>
<td>0°, 180°</td>
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<td>13</td>
</tr>
<tr>
<td>30°, 210°</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>60°, 240°</td>
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<td>55</td>
<td>35</td>
</tr>
<tr>
<td>120°, 300°</td>
<td>26</td>
<td>16</td>
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<tr>
<td>150°, 330°</td>
<td>19</td>
<td>12</td>
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Spatial tuning

The spatial tuning of 189 cells was examined using gratings in which the SF was varied and other parameters kept optimal. Rat V1 neurons are sensitive to spatial frequencies of ≤ 1.2 c/° (Fig. 5A). Approximately half of the cells (94/189) had low band-pass higher than zero (Fig. 5C); that is, they had no or very weak responses to uniform stationary ON-OFF stimuli and responded optimally to moving gratings. Most cells had optimal responses at ≤ 0.08 c/° (Fig. 5B). Twenty-one cells (11%) responded optimally to flashing uniform field stimuli (0 c/°). In general, neurons were tuned to relatively low SF. The majority had sharp SF tuning. The mode of band-pass width distribution was 2 octaves. Approximately 64% of the cells had band-pass widths less than two octaves (Fig. 5D).

The spatial frequency properties of cells tuned to horizontally oriented gratings (90° and 270°) were compared with those of cells tuned to other orientations. The distribution of the peak SF and cutoffs for these two cell populations did not differ significantly (P > 0.60; χ²). These findings indicate that the bias for horizontal orientations is unlikely to be due to astigmatism.

Temporal tuning

As can be seen from Fig. 6, cells in the rat V1 cortex responded best to high temporal frequencies. The distribution of the highest temporal frequency giving a response (high cutoff) peaked at 27.5 Hz (Fig. 6A, top). The temporal frequencies associated with maximal responses were distributed almost regularly from 0.43 to 6.88 Hz (Fig. 6B, top). Cells responding optimally to SF > 0 could be characterized further by stimulus velocity parameters. The distribution of high cutoff for stimulus velocities peaked at 500°/s (Fig. 6A, bottom).

FIG. 3. Distribution of F1/F0 ratio, where F1 is the fundamental harmonic of a neuron’s response to sinusoidal gratings and F0 is the 0 frequency or d.c. of the response.
About 25% of the cells responded to higher stimulus velocities, at least \( \leq 700°/s \) (limit of display by BARCO monitor). Response peak velocities had a more or less flat distribution, ranging from 10 to 250°/s (Fig. 6, bottom).

**Contrast sensitivity**

A wide range of shapes was observed for response versus contrast curves. Some curves showed a linear increase in the firing rate with increasing contrast (Fig. 7A), whereas others showed nonlinear responses that saturated at various contrast levels (Fig. 7, B and C). To characterize quantitatively the response versus contrast relationship, the contrast sensitivity of a given cell was calculated as the inverse of the threshold contrast. The latter was defined as the minimal contrast level where the respective standard errors for the cell’s response and for the spontaneous activity did not intersect. In cases where
there was no spontaneous activity, the minimal contrast corresponded to the point at which the response minus the standard error exceeded zero. Moreover, the nonlinear regression using the Naka-Rushton equation,

$$R = y_0 + a/[1 + (Cs/C)^b]$$

enabled us to find the best fit for the experimental data ($R$, response; $C$, contrast; $Cs$, contrast level at the point of midsaturation; and $y_0$, $a$, $b$: mathematical constants giving the best fit). Regression lines are shown in the figures as - - -. Fig. 7, D–F, shows the distributions of the midsaturation contrasts, the contrast response exponent and the contrast sensitivity of all cells. Half of the cells analyzed (64/128) had a sensitivity that exceeded 10. Approximately 20% of the cells had almost linear response increments with increasing contrasts ($Cs$ exceeding 100%). Approximately half of the cells (57/128) had nonlinear curves ($b > 8$). There was no correlation between the three parameters: the cross-correlation coefficients were 0.15 ($P < 0.01$), 0.15 ($P < 0.01$), and 0.02 ($P = 0.08$) for the pairs $Cs$-$b$, $Cs$-sensitivity, $b$-sensitivity, respectively. Therefore any combinations of these three contrast response properties can be encountered in rat V1 cells.

## Center-surround interactions

For many cells, mainly recorded in the upper third of the cortex, increasing the stimulus diameter decreased the response. The RF center size of these cells varied from 3 to 13° in diameter. Of the 158 cells with strong orientation selectivity (ORI $> 0.7$), 54 had clear inhibition when presented with stimuli extending beyond their RF center. The response to the largest stimuli was often $< 20\%$ of the response to center illumination alone. For 18 of these cells, the center-surround interactions were studied in detail. The following stimuli were used: optimal center size (size producing the maximal response) with other parameters adjusted for highest reaction index (marked as 0 in Fig. 8); peripheral ring of different orientations, adjusted to be immediately outside the area of optimal stimulus (right on x axis); and stimuli 1 and 2 presented simultaneously (left on x axis). All stimuli were presented in a random order. In all cases, peripheral stimulation alone did not elicit any significant reactions (note the flat curve on the right part of all graphs in Fig. 8). However, when presented in combination with stimulation of the center, it could modulate the size of the response to center stimulation dramatically.

Three types of center-surround interactions were found: peripheral stimuli, regardless of their orientation, produced a strong inhibition of the response to RF center stimulation ($n = 4$, Fig. 8A); the level of inhibition on RF center responsiveness depended on the orientation of the peripheral stimulus (this inhibition was usually maximal for matching orientations of central and peripheral stimuli) ($n = 10$, Fig. 8B); and peripheral stimuli had strong orientation-specific excitatory and inhibitory effects on the response to RF center stimulation ($n = 4$, Fig. 8C). Twelve of the 18 units were simple-like ($F_1/F_0 > 1$), 4 were complex-like ($F_1/F_0 < 1$), and the remaining 2 were undetermined ($F_1/F_0 \sim 1$). The majority (16/18) of the units had sharp SF tuning. There was no apparent relation between the type of center-surround interactions and the type of response versus contrast curve. However, in comparison with all the neurons studied, these units had relatively lower contrast sensitivity.

## Depth distribution of cell properties

On reconstructing recording tracks, following electrolytic lesions made at different depths, a good correspondence was found between the values read on the depth indicator of the micromanipulator and the distance between the brain surface and the lesion sites as seen on coronal sections. The most superficial units that could be isolated successfully were lo-
FIG. 7. Representative examples of response vs. contrast curves for V1 cells. Experimental points (●) have been fitted using Naka-Rushton equation (- - -). Spontaneous activity (response to 0 contrast) is presented as in Fig. 1. A: nearly linear contrast response (the midsaturation is out of the contrast range). B: nonlinear contrast response from a highly sensitive neuron. C: highly nonlinear response with a steep threshold at ~25% contrast. Histograms of contrast response parameters are presented in D–F: midsaturation contrast (D), exponent (E), and sensitivity (F).

FIG. 8. Examples of several types of end-stopping effects. Orientation of gratings presented in the periphery of the RF are indicated at the left and right of the x axis. Central 0 corresponds to center RF stimulus alone. All center RF stimulation (central 0 and left of curve) consisted of the same stimulus, with optimal orientation. A: any grating orientation in RF periphery inhibits the cell’s response to RF center stimulation (orientation 270°). B: inhibitory effect of peripheral stimuli on response to optimal central stimulus (60°) is quite orientation selective. C: response to central stimulus (120°) is excited or inhibited by stimuli presented in the RF periphery depending on their orientation. Note, x axis represents the orientation of the surround (deg); the value 0 in the middle of the x axis corresponds to the stimulation of the center of the RF alone, using optimal orientation.
cated at a depth of \(\sim 200 \mu m\) below the cortical surface (upper border of layer II). From this depth down to 500–600 \(\mu m\) (encompassing layers II and III), cells had mainly no or very low spontaneous activity, with high reaction index, orientation index, and sharpness of orientation. Layers II–III cells responded to stimuli of relatively high spatial frequencies and low temporal frequencies. Cells with center-surround interactions were found mostly in these superficial layers. The highest temporal resolution was attributed mainly to cells confined to layer IV (\(\sim 900 \mu m\)). Cells from layer IV as well as from layers V–VI had the highest spontaneous activity. Many of these cells responded optimally to uniform ON- OFF stimuli or to gratings of low SF. However, these cells also were intermixed with other cells having characteristics resembling those of cells in layers II–III. The changes in response properties with recording depth are summarized in Fig. 9. Statistical analysis (Student’s \(t\)-test) confirmed the differences between several properties of neurons recorded at 200–600 \(\mu m\) and of those recorded deeper. These properties include: spontaneous activity level: mean 0.66 and 1.67 imp/s, respectively, \(P < 0.01\); reaction index: mean 0.87 and 0.72, \(P < 0.001\); orientation index: mean 0.90 and 0.80, \(P = 0.015\); bandwidth of orientation tuning: mean 58 and 73\(^\circ\), \(P < 0.001\); peak SF: mean 0.11 and 0.07 c/\(\circ\), \(P < 0.01\) (the bandwidth of SF tuning shows a trend that however does not reach statistical significance: mean 1.94 and 2.12 octaves, \(P = 0.08\); SF cutoff did not show any depth differences at all); peak temporal frequency: mean 2.4 and 4.8 Hz, \(P < 0.001\); bandwidth of temporal frequency tuning: mean 3.0 and 3.6 octaves, \(P < 0.001\); and cutoff of temporal frequency: mean 16.5 and 25.4, \(P < 0.001\).

**DISCUSSION**

The present study has focused on the quantitative assessment of receptive field properties in the primary visual cortex of the rat. The results show that the response properties of rat V1 neurons are surprisingly well tuned. Cells respond to a highly specific set of stimulus parameters and many have receptive field organization characterized by complex interactions between center and surround components. Such findings indicate that the responses of these rodent V1 neurons are as specialized, in many ways, as those of highly visual animals (cat, primate). The conclusion reached by some of the earlier studies that cells in the rat visual cortex only responded to relatively large, nondescript stimuli and therefore that the rat had very poor visual capabilities is not supported by the present studies.

**Technical considerations**

Differences between the present and previous studies of rat visual cortical physiology largely stem from technical advances in animal preparation and data analysis. The use of computer-generated stimuli and associated data analysis permits objective, quantitative assessment of response properties. Several investigators have relied on urethan or barbiturate anesthesia. In our hands, although urethan does not seem to interfere with visual responsiveness in the superior colliculus, it depresses neuronal activity in the primary visual cortex. ON/OFF characteristics rather than tuning to orientation, spatial or temporal frequencies can be emphasized; a high proportion of ON/OFF units in a study suggests that the anesthetic is depressing responsiveness. The use of barbiturates also causes spontaneous or bursting activity that can contaminate the results. Paralysis has not been used routinely in rodents as in cats or monkeys, leaving the possibility for eye movements to interfere with the interpretation of the results. Recordings usually were done with large craniotomies; this can result in spreading depression and in restriction of the blood supply to the cortex. Such conditions affect predominantly units from superficial layers (where the proportion of orientation tuned units is highest), while preserving units from deeper layers, which are generally less tightly tuned. We have found that very small craniotomies (in the order of 150 \(\mu m\)) permit much better recordings, especially from the superficial layers, and ensure that more units can be characterized per penetration. The condition of the preparation clearly has a major bearing on the variability encountered in previous results, for example in the proportion of oriented units, which varies among studies from...
Orientation encoding

The majority of neurons in the rat V1 cortex showed clear orientation bias with tuning (defined as the bandwidth at half height) $\sim$60° or even sharper and in this respect compares with cat (Murphy and Berman 1979) and monkey (Celezini et al. 1993; DeValois et al. 1982b). More than half the cells were directionally selective, again placing the rat within the range achieved in other mammals (DeValois et al. 1982b; Gizzi et al. 1990; Hammond and Pomfrett 1989).

We observed a bias for orientation-selective cells toward horizontal gratings. This observation was confirmed repeatedly for all neuron types recorded in either vertical or horizontal penetrations. Orientation preference for horizontal bars, and less frequently for vertical bars, has been reported in several other species (mouse: Drager 1975; hamster: Tiao and Blakemore 1976; rabbit: Bousfield 1977; Murphy and Berman 1979; cat: Bauer and Jordan 1993; Murphy and Berman 1979; monkey: DeValois et al. 1982b; human: Campbell et al. 1966;Leehey et al. 1975) but has not been noticed previously in rats. Although behavioral tests indicated that acuity did not vary with differently oriented gratings (Dean 1981), rats nevertheless learned to detect low spatial frequency gratings with fewer errors for horizontal or vertical orientations compared with obliques. It has been suggested that this orientation preference might rely on anisotropy intrinsic to the physiological processing of visual information (Bauer and Jordan 1993;Leehey et al. 1975), but our finding that spatial-, temporal-, or contrast-related parameters were similar for cells irrespective of orientation tuning argues against this.

Relation of classification to classical terminology

In the present study, we avoided using the classification of V1 neurons as simple, complex, and hypercomplex (Hubel and Wiesel 1962, 1968) in the primary analysis. However, quantitative analysis shows that simple cells tend to be modulated while complex cells are unmodulated: this is expressed using the ratio F1/F0 (Skottun et al. 1991). Our findings show that the distribution of rat V1 cells according to the F1/F0 ratio is clearly bimodal, as in the cat or monkey V1 (Skottun et al. 1991).

Orientation columns

The previous literature in rats is unclear with respect to the presence or absence of orientation columns. Although not examined systematically, orientation columns were not described in mice (Metin et al. 1988), hamsters (Tiao and Blakemore 1976), and rabbits (Bousfield 1977; Murphy and Berman 1979). Nearly all of these authors assumed the existence of clusters of cells with similar functional properties, however. None attempted horizontal penetrations to see whether there was any indication of progressive change across the cortex. We found evidence neither for the existence of iso-orientation clusters nor for progressive change in orientation preference in horizontal penetrations. When units were recorded simultaneously, they were more likely to respond to different orientations than to the same. The commonality of this finding, coupled with the lack of regular change in horizontal penetrations, argued against recordings being from “break points” (Braitenberg and Braitenberg 1979) or “pin wheels” (Maldonado et al. 1997) in an otherwise regular array of orientation representations as has been shown in cats and monkeys. Although unlikely, it is still plausible that orientation columns do exist in the rat but on such a small scale that they cannot be detected using microelectrode recordings. It should be noted, however, using a more accurate discrimination between neighboring units in cat V1 (using the tetrode technique) that orientation appears more heterogeneously represented locally than was previously thought (Maldonado and Gray 1996).

An interesting corollary of the absence of orientation columns is the pattern of horizontal connections in the upper layers of the cortex. In a number of animals, in which orientation columns have been identified, punctate horizontal projections connect points responding to similar orientations (ferret: Weliky et al. 1995; cat: Kisvarday et al. 1997; tree shrew: Bosking et al. 1997; monkey: Malach et al. 1993; Yoshioka et al. 1996). Such lattice connections intrinsic to V1 appear to be absent in the rat (Tyler et al. 1998). This might be expected given the absence of regular iso-orientation zones.

Spatial frequency

The SF tuning of V1 neurons covers a range of 0–1.2 c/° with an optimal response at 0.08 c/°. Very similar figures were found when recording visually evoked cortical potentials (Silveira et al. 1987): the maximal response was observed at 0.1 c/° with a cutoff at 1.2 c/°. The upper limit of the spatial resolution corresponds particularly well with that found in behavioral experiments using rats (1.0–1.6 c/°; Seymour and Juraska 1997; 1.0 c/°: Dean 1978, 1981; Lashley 1938; 0.9 c/°: Wiesenfeld and Branchek 1976; 1.6 c/°: Yagi et al. 1995) and is near to the limit of 1.8 c/° estimated from the maximal density of ganglion cells in the rat retina (6,500 cells/mm²) (Fukuda 1977). Brain lesion studies (Dean 1981) showed that the striate cortex is responsible for discrimination of spatial frequencies of up to $\sim$1 c/°. From this, Dean concluded that the rat cortex is responsible for the analysis of fine details. This is in agreement with the present study where V1 neurons were shown to have a high-frequency cutoff of $\leq$1.2 c/°. As in cats (Maffei and Fiorentini 1977), the highest SF to which a cell responded appeared to be related to the receptive field width: units with maximal cutoff tended to have the smallest RFs. In addition, rat cells had similar band-pass widths as in cats (1–2 octaves bandwidth for a large population of neurons in cat V1) (De Valois et al. 1982a). However, the lowest SF and highest cutoff were much less in rats (0–1.2 c/°, respectively) than in cats (0.5–15 c/°) (De Valois et al. 1982a). In fact, half of the rat V1 neurons responded to flashing uniform field stimuli (0 SF), which is in agreement with the absence of low SF cutoff found in behavioral studies in rats (Dean 1978).

Temporal frequency

With respect to temporal frequency tuning, our results show that, as in mouse (Mangini and Pearlman 1980), rat V1 neurons can respond at much higher stimulus velocities ($\sim$700°/s) than cat V1 neurons (Orban et al. 1981). Such high cutoffs are found more often for cells in the vicinity of layer IV and resemble...
more closely those of cat geniculate afferents to V1 (700°/s) (Orban et al. 1981). Perhaps those units that respond to the highest velocities in rats correspond to V1 neurons receiving direct geniculate inputs.

Response versus contrast

An important point that needs to be addressed is the influence of the background illumination on the response properties of rat V1 neurons. Although we did not examine directly the level of rod saturation at the background illumination used in the present study (30 cd/m²), it is a reasonable assumption that the rod system has not reached full saturation. Previous behavioral measurements based on rod activation failed to detect any signs of saturation up to the maximal level tested of 20 cd/m² (Jacobs and Birch 1975). Furthermore analysis of the pupillary light reflex under different levels of background illumination have shown a linear response for a range encompassing 6 log units (Trejo and Cicerone 1982), where the pupil reached a minimal diameter of 0.2 mm. In our study, the smallest pupil diameter was in the region of 0.5 mm.

The wide range of response versus contrast curves we obtained for rat V1 units is in agreement with findings in cats and monkeys where there is a ‘‘great deal of variation, from cell to cell, in the shape and location of the contrast response function’’ (Albrecht and Hamilton 1982).

Differential distribution of response properties with depth

The present distribution of functional properties with depth is consistent with most of the previous observations in mouse (Drager 1975; Mangini and Pearlman 1980; Metin et al. 1988) and rabbit (Murphy and Berman 1979); there is a trend for cells in the superficial layers to be more selective to different stimulus parameters than deeper layer cells. Orientation-selective neurons are more tightly tuned in the upper rather than lower half of the visual cortex while nonoriented cells are distributed preferentially in the lower layers. Cells with the smallest receptive fields, having low or no spontaneous activity, and responding most selectively to different stimulus parameters, are typical for layers II–III. As in the cat (Bullier and Henry 1979; Mustari et al. 1981), cells in rat with the highest temporal frequency cutoff tended to be confined around lamina IV.

Conclusions

In summary, our findings suggest that the functional organization of area V1 in the rat is designed to extract cues from the visual image that are necessary for precise visual form perception with low spatial resolution. Where parallels can be made, the physiological properties of rat V1 neurons correlate with the findings from rat psychophysical experiments. In addition to providing information about the substrates of visual information processing in V1 of the rat, the present results provide essential insights for understanding the impact of inherited retinal degeneration on visual function. In addition, it provides the background for evaluating the possible effects of potential treatments including retinal pigment epithelium cell transplantation into the subretinal space of RCS rats eyes (Sauvé et al. 1998).

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