

High Responsiveness and Direction Sensitivity of Neurons in the Rat Thalamic Reticular Nucleus to Vibrissa Deflections

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Hartings, Jed A., Simona Temereanca, and Daniel J. Simons. High responsiveness and direction sensitivity of neurons in the rat thalamic reticular nucleus to vibrissa deflections. *J. Neurophysiol.* 83: 2791–2801, 2000. The thalamic reticular nucleus (Rt) is strategically positioned to integrate descending and ascending signals in the control of sensorimotor and other thalamocortical activity. Its prominent role in the generation of sleep spindles notwithstanding, relatively little is known of Rt function in regulating interactions with the sensory environment. We recorded and compared the responses of individual Rt and thalamocortical neurons in the ventroposterior medial (VPM) nucleus of the rat to controlled deflections of mystacial vibrissae. Transient Rt responses to the onset (ON) and offset (OFF) of vibrissa deflection are larger and longer in duration than those of VPM and of all other populations studied in the whisker/barrel pathway. Magnitudes of ON and OFF responses in Rt were negatively correlated with immediately preceding activities, suggesting a contribution of low-threshold T-type Ca^{2+} channels. Rt neurons also respond with high tonic firing rates during sustained vibrissa deflections. By comparison, VPM neurons are less likely to respond tonically and are more likely to exhibit tonic suppression. Rt and VPM populations are similar to each other, however, in that they retain properties of directional sensitivity established in primary afferent neurons. In both populations neurons are selective for deflection angle and exhibit directional consistency, responding best to a particular direction of movement regardless of the starting position of the vibrissal hair. These findings suggest a role for Rt in the processing of detailed sensory information. Temporally, Rt may function to limit the duration of stimulus-evoked VPM responses and to focus them on rapid vibrissa perturbations. Moreover, by regulating the baseline activity of VPM neurons, Rt may indirectly enhance the response selectivity of layer IV barrel neurons to synchronous VPM firing.

INTRODUCTION

The thalamic reticular (Rt) nucleus, comprised of inhibitory projection neurons, is an integrative center for control over sensory and other signals en route to the cerebral cortex (Scheibel and Scheibel 1966; for review see Guillery et al. 1998). Combining both ascending thalamocortical and descending corticothalamic inputs with intrinsic nonlinearities, Rt neurons can modulate and gate the activity of thalamocortical neurons in a state- and behavior-dependent fashion. During slow-wave sleep, Rt generates “spindle” oscillations which are widely synchronous throughout thalamocortical circuits and presumably disrupt refined spatiotemporal processing of sensory signals (Steriade et al. 1987; for review see Steriade et al. 1993). During wakefulness, Rt activity varies according to an ani-

mal’s level of vigilance (Steriade et al. 1986) and has been suggested to be involved in high-level functions such as attention (Crick 1984; Yingling and Skinner 1976). Indeed, lesions of Rt disrupt orienting responses to sensory stimulation (Friedberg and Ross 1993) and abolish attentional effects of cueing on reaction times (Weese et al. 1999).

Anatomic and physiological findings suggest that Rt may also play a more specific role in processing ascending sensory signals. Rt is subdivided into sectors according to physiological modality and anatomic connectivity with specific relay nuclei (Jones 1975; see also Jones 1985), and within each sector there are topographic maps of sensory space (Montero et al. 1977; Shosaku et al. 1984; see Guillery et al. 1998). In behaving animals the visual and somatosensory sectors showed selective increases in *c-fos* expression depending on the modality of sensory exploration (Montero 1997, 1999). In anesthetized preparations, Rt neurons exhibit peripherally drivable responses which resemble, but differ from, those of their afferent thalamocortical neurons (visual: Dubin and Cleland 1977; Ulrich et al. 1991; Wrobel and Tarnecki 1984; somatosensory: Shosaku 1985; Sumitomo and Iwama 1987). Characterizing the different sensory-evoked responses of Rt versus relay neurons is a critical step in determining how Rt affects sensory processing during different behavioral or attentional states.

Most *in vivo* single-unit studies of the somatosensory sector of Rt have been conducted in the rat vibrissa system. In the ventroposterior medial (VPM) nucleus neuronal aggregates, called “barreloids,” correspond in a one-to-one fashion with individual vibrissae on the contralateral face. Feedback inhibition from Rt is the only source of inhibition onto barreloid neurons, as the rodent VPM is virtually devoid of inhibitory interneurons (Barbaresi et al. 1986; Harris and Hendrickson 1987), and ablation of Rt alters the response properties of VPM neurons in a fashion similar to direct application of GABA receptor antagonists (Lee et al. 1994a,b). Like their afferents from VPM, Rt neurons have spatially focused receptive fields that are typically dominated by a single vibrissa (Shosaku 1985; Sumitomo and Iwama 1987). Accordingly, anatomic studies have demonstrated that axons of VPM neurons can have restricted collateral branching in Rt (Harris 1987) and that, conversely, individual Rt neurons project mainly to specific subnuclear or single barreloid domains (Pinault et al. 1995; see also Pinault and Deschenes 1998). These reciprocal connections likely exist between neuronal modules corresponding to the same vibrissa, as physiological studies employing cross-correlation techniques have provided evidence for functional

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connectivity between VPM and Rt neurons only when they have the same vibrissa receptive field center (Shosaku 1986).

To study the role of Rt in processing low-threshold tactile information, we recorded the responses of Rt neurons to the same controlled vibrissa deflections used to characterize other populations in the ascending lemniscal system. In previous studies we found that approximately 75% of primary afferent (N. V.) neurons respond tonically to sustained vibrissa deflections in a preferred direction and are directionally well-tuned; the remainder respond only phasically and are less direction selective (Lichtenstein et al. 1990). In VPM a large percentage of neurons also exhibit high direction selectivity. However, unlike N. V. neurons, only 37% of VPM cells are tonically responsive, and many exhibit tonic suppression at particular directions (Shosaku 1985; Simons and Carvell 1989). Here, we report that Rt neurons discharge at high firing rates during both transient and maintained vibrissa deflections, and they do so in a manner that is dependent on stimulus direction. These findings are consistent with the view that Rt contributes to the processing of specific aspects of tactile stimuli.

METHODS

Surgical procedures and recordings

Adult Sprague-Dawley rats weighing 250–300 g were prepared for electrophysiological study using methods described previously in detail (Simons and Carvell 1989). Halothane anesthesia was used during surgical procedures. A steel post was fixed to the skull with dental acrylic to hold the animal's head, and a craniectomy was made at stereotaxic coordinates overlying the recording location in the thalamus (VPM: 2.0–4.5 posterior, 1.5–4.0 lateral to bregma; Rt: 1.5–3.5 posterior, 2.5–4.5 lateral to bregma; Paxinos and Watson 1982; Shosaku et al. 1984). After surgery halothane was discontinued, the animal was immobilized by pancuronium bromide, artificially respired through a tracheal cannula, warmed by a servo-controlled heating blanket, and maintained in a lightly narcotized state by a steady infusion of fentanyl (Sublimaze, Jansen Pharmaceuticals; $\sim 10 \mu\text{g} \cdot \text{kg}^{-1} \cdot \text{h}^{-1}$). The animal's condition was assessed by continuously monitoring electroencephalogram, femoral arterial blood pressure, tracheal airway pressure, and pupillary reflexes.

Extracellular single-unit recordings were made in VPM or Rt with 10 M Ω stainless steel microelectrodes (Frederick Haer, Brunswick, ME). VPM and Rt were reliably distinguished during recording sessions on the basis of their medial and lateral locations, respectively, relative to the ventroposterior lateral nucleus, and by different burst patterns during spontaneous firing (Domich et al. 1986); Rt neurons display longer bursts characterized by more spikes and an accelerate-decelerate pattern. At the end of recording sessions animals were deeply anesthetized with sodium pentobarbital (Nembutal) and perfused transcardially. Brains were sectioned in the coronal plane and stained with thionin to confirm the location of electrode tracks through the appropriate nucleus.

Vibrissa stimulation and data analysis

Hand-held probes were used to identify the vibrissa evoking the strongest response from an isolated unit, i.e., the principal whisker. A piezoelectric mechanical stimulator was then attached to this whisker 10 mm from the face (Simons 1983). We did not record responses to movements of adjacent whiskers or attempt any systematic study of receptive field size. The stimulation protocol, which we have used in previous studies, consisted of a ramp-and-hold deflection of the vibrissa from its resting position. Deflections were 1 mm in amplitude ($\sim 5.7^\circ$), with onset and offset velocities of 125 mm/s and a plateau

duration of 200 ms. Deflections were applied in eight randomly interleaved directions spanning 360° in 45° increments and were repeated for 10 trials, for a total of 80 stimuli. Peristimulus time histograms (PSTHs) for each of the eight directions were computed and displayed on-line. All units which exhibited even minimal responsiveness to vibrissa deflections were included in our analyses.

A time/amplitude window discriminator (BAK Electronics) and a digital storage oscilloscope were used to isolate single units. Sequential spike event times were recorded with 100- μs resolution and analyzed with custom-designed programs on a DEC LSI 11/73. Responses to the onset and offset of vibrissa deflections in each direction were computed as the mean number of spikes recorded for all 10 trials during 20-ms epochs after the onset and offset of vibrissa deflections (ON and OFF responses, respectively). This time period was chosen on the basis of the duration of evoked responses of VPM neurons (see PSTHs in Fig. 7). For purposes of direct comparison, 20-ms periods were also used for Rt data unless noted otherwise. Responses to the stimulus plateau, when the vibrissa was maintained in a deflected state, were measured during a 100-ms period beginning 75 ms after stimulus onset (see Fig. 1). Spontaneous activity was measured during a 100-ms period preceding the deflection. Maximally effective directions for ON, OFF, and plateau responses were defined as those which evoked the most activity during the corresponding time epochs.

Data analyses and statistical tests were performed on an IBM PC using Microsoft Excel/Visual Basic and the statistics package from SPSS, Inc. Mann-Whitney *U* tests were used to compare distributions. The slowly or rapidly adapting nature of each unit's response was assessed by using a procedure employed previously in a study of N. V. neurons (Lichtenstein et al. 1990). Two-tailed *t*-tests with 95% confidence limits were used to compare spontaneous firing rates with those evoked during the stimulus plateau. A cell was classified as tonically responding if the plateau response at the maximally effective direction was significantly greater than spontaneous firing ($P <$

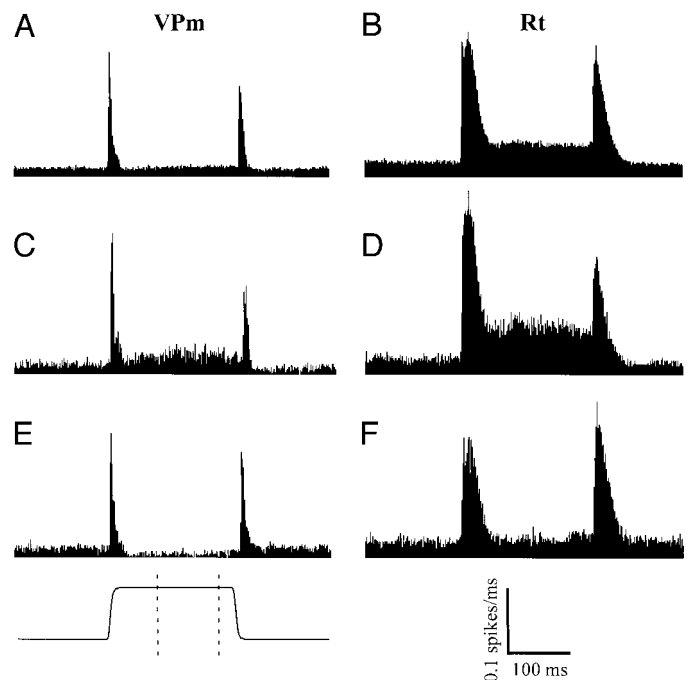


FIG. 1. Population peristimulus time histograms (PSTHs) of ventroposterior medial (VPM) and thalamic reticular nucleus (Rt) responses. *A* and *B*: PSTHs computed for all neurons included in the analysis and for all 8 deflection angles ($\times 10$ trials per direction). *C* and *D*: PSTHs computed for all neurons at the direction evoking the most activity during the period of the stimulus plateau. *E* and *F*: PSTHs for the directions selected for the least activity during the plateau period. Bin width, 1 ms. Stimulus waveform, lower left. Dashed lines, period for which plateau activity was calculated.

0.025). Units with significantly less activity at the minimally effective direction were characterized as “inhibited.”

We assessed each unit’s sensitivity to vibrissa movements in different directions using three measures. Tuning ratios were computed as the response magnitude evoked at the maximally effective direction divided by the response averaged over all eight directions (Kyriazi et al. 1996); a higher value denotes greater selectivity. In a second analysis each unit was classified into one of eight tuning categories based on the number of deflection angles (0–7) that evoked responses statistically smaller than those of the maximally effective direction ($P < 0.05$, one-tail; see Simons and Carvell 1989); category 7 represents the most selective responses. Tuning ratios and tuning categories were calculated separately for ON, OFF, and plateau responses, because neurons in the trigeminal ganglion and in central populations often have different preferred directions for the different response phases.

A third measure, used previously to analyze responses of N. V. neurons (Lichtenstein et al. 1990), assessed the degree to which a unit responded to a particular stimulus direction regardless of the vibrissa’s initial position relative to rest. This property, termed directional consistency, was quantified by computing a linear correlation coefficient for mean ON and OFF response magnitudes evoked at each stimulus angle. Cells that fire most vigorously to stimulus onset in one direction and to stimulus offset after initial movements in the opposite direction exhibit negatively correlated ON and OFF responses. A unit was classified as “directionally consistent” if the correlation coefficient was significantly negative ($P < 0.05$, one-tail).

Each of the three measures captures related but different aspects of a neuron’s directional properties. It is not clear which, if any of these measures, represents the most salient aspect of directional processing in the vibrissa system. Here, we use these measures as quantitatively descriptive probes for comparing response specificity between VPM and Rt neurons.

RESULTS

We recorded and analyzed the responses of 62 VPM and 85 Rt neurons discharging to vibrissa deflections in a total of 13 animals. These neurons constituted the majority of neurons encountered in vibrissa-responsive regions in our recordings; no attempts were made to activate unresponsive units by other modalities of stimulation. The response characteristics of VPM neurons reported here are comparable to populations previously studied under the same physiological and stimulus conditions (Kyriazi et al. 1994; Simons and Carvell 1989).

Response profiles

The most prominent features of Rt neuronal activity are the large magnitude and long duration of stimulus-evoked responses, compared with those of VPM neurons. This is illus-

trated in the population PSTHs of Fig. 1, *A* and *B*, which show the accumulated responses of all neurons to all deflection angles. Both VPM and Rt responses to the onset and offset of vibrissa deflection (ON and OFF responses, respectively) peak within a few milliseconds, the rise of the Rt response being delayed relative to VPM by approximately 1.3 ms. VPM activity, however, begins to decay within 5 ms, whereas Rt neurons continue to respond for approximately 20 ms before decaying more slowly to a steady firing rate (see also Fig. 7). To quantify these differences in the temporal dispersion of the response, we calculated the time in the 20-ms response period of the 50th percentile spike for each cell. The population means and standard deviations for VPM and Rt were 7.2 ± 6.6 and 14.3 ± 4.2 ms, respectively, for the ON response ($P < 0.001$), and 10.0 ± 4.9 and 12.9 ± 4.2 ms for the OFF response ($P < 0.001$).

The greater responsiveness of the Rt population is evident in all measures of unit activity. Table 1 lists the mean responses of VPM and Rt neurons averaged over all deflection angles as well as mean responses to each neuron’s maximally effective angle. For each response measure, and for spontaneous activity, Rt activity is greater than VPM; in each case the difference is highly significant, even after correcting response magnitudes for differences in spontaneous activities ($P < 0.001$). Figure 2 shows the distributions of these measures for the two populations, illustrating that differences in mean values reflect trends throughout the populations, rather than outlying responses of a few cells. As shown in Fig. 3, the differences in response profiles are readily observable even in the responses of individual VPM and Rt neurons. The mean ON and OFF responses of the VPM neuron consist of 1.19 and 1.35 spikes, respectively, which are precisely time-locked to the stimulus, yielding narrow peaks in PSTHs. The Rt neuron, on the other hand, responds to stimulus onsets and offsets with 4.49 and 2.25 spikes, respectively, which in both cases are more broadly distributed over tens of milliseconds.

Tonic versus phasic response characteristics

A particularly striking difference between VPM and Rt responses occurs during the stimulus plateau (i.e., maintained vibrissa deflection). In Rt mean plateau activity averaged over all deflection angles (49.7 spikes/s) is more than twice the mean spontaneous activity (22.4 spikes/s), whereas VPM activity is nearly equivalent during these periods (plateau: 14.9 spikes/s; spontaneous: 13.2 spikes/s; see Fig. 1, *A* and *B*). A

TABLE 1. Stimulus-evoked responses and spontaneous activities of VPM and Rt populations

	Mean Responses (All Angles)			Maximal Responses (One Angle)		
	VPM*	Rt*	Rt†	VPM*	Rt*	Rt†
ON‡	1.27 ± 0.68	3.46 ± 1.54	5.69 ± 2.35	2.14 ± 0.95	5.00 ± 1.85	7.65 ± 2.69
OFF‡	1.17 ± 0.71	2.68 ± 1.26	4.07 ± 1.73	2.06 ± 0.98	3.90 ± 1.56	5.95 ± 2.48
OFF/ON	1.10 ± 0.75	0.83 ± 0.37	0.78 ± 0.41	1.09 ± 0.58	0.84 ± 0.46	0.83 ± 0.42
Spontaneous	13.2 ± 7.1	22.4 ± 16.2				
Plateau	14.9 ± 10.6	49.7 ± 29.8		29.2 ± 19.8	74.0 ± 38.8	

Values are means ± SD. VPM, ventroposterior medial; Rt, reticular nucleus; ON, onset; OFF, offset. * 20 ms windows were used to compute ON and OFF response magnitudes for both populations, based on the duration of the VPM response. † Rt responses were also computed for a window (38 ms) appropriate for their duration. ‡ Mean spike count per window. Because all values are expressed as the means ± SD of individual cell values, the OFF/ON ratios may differ slightly from the ratio that can be calculated from the mean OFF and ON responses. Spontaneous and plateau activities are expressed as spikes/s.

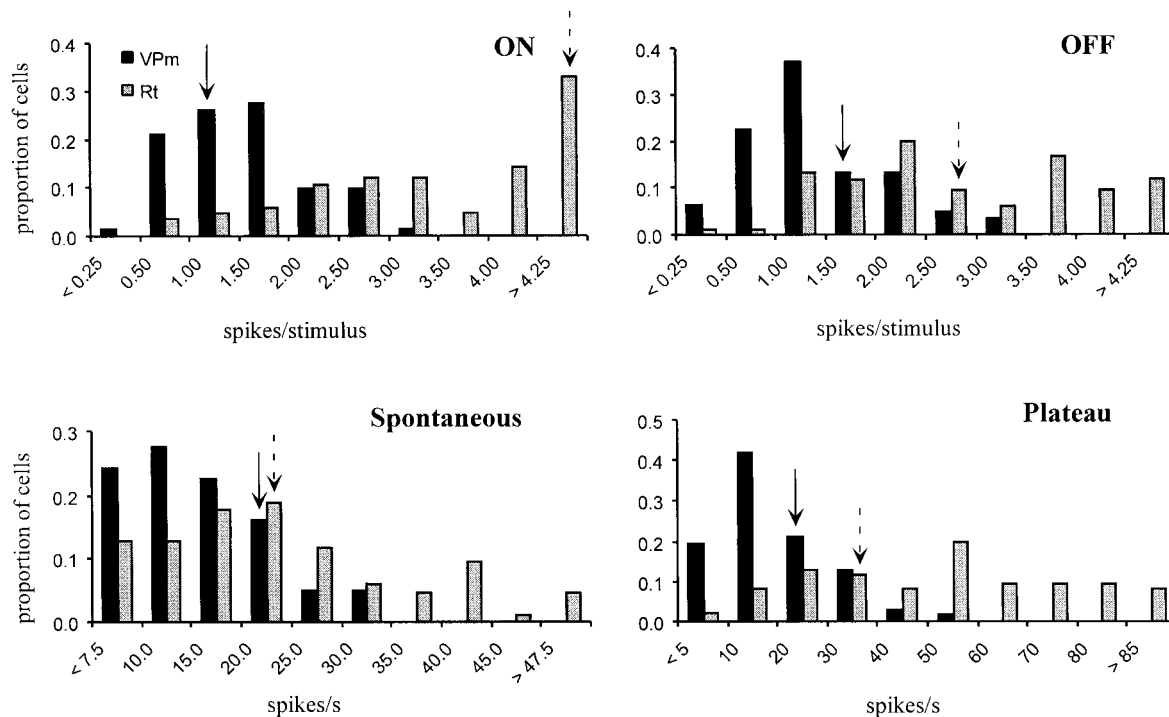


FIG. 2. Frequency distributions of VPM and Rt response magnitudes averaged over all deflection directions. Onset (ON) and offset (OFF) response magnitudes were computed for 20-ms windows after the onset and offset of vibrissa deflection. Note that these values are underestimates for Rt responses, which are longer in duration. Spontaneous and plateau activities were both calculated for 80×100 -ms periods. Solid and dashed arrows indicate the values corresponding to the VPM and Rt cells, whose responses are shown in Fig. 3.

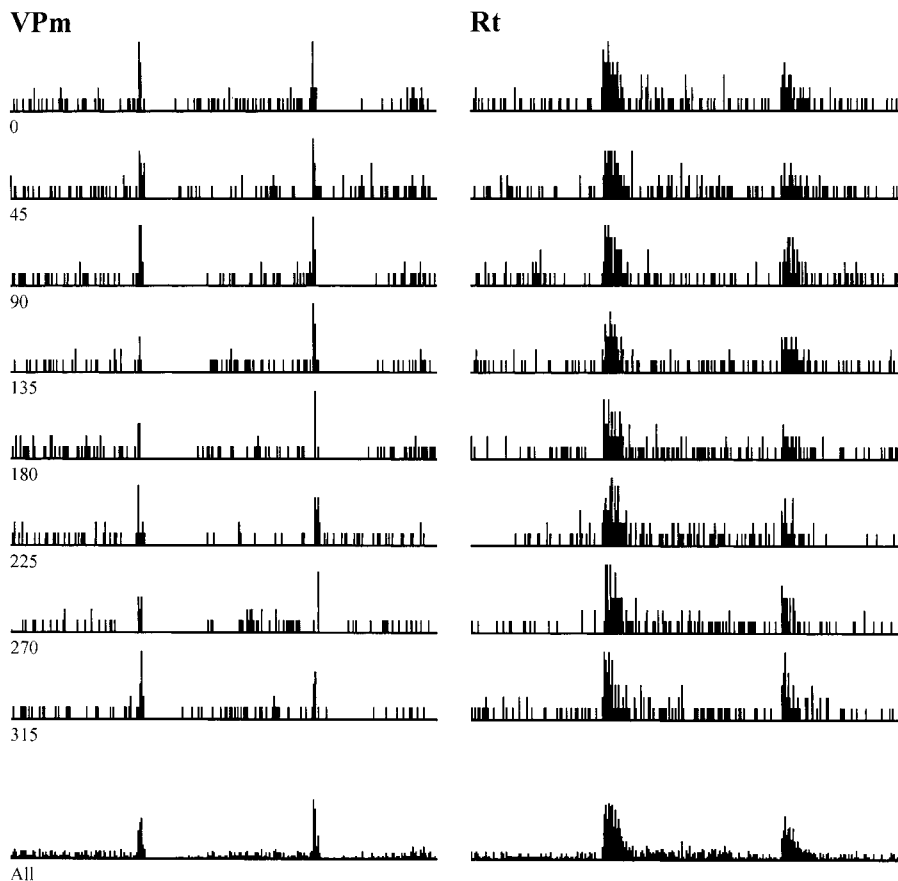


FIG. 3. Responses of single VPM and Rt neurons to different angles of vibrissa deflection. The upper 8 PSTHs show accumulated responses to 10 trials at each of 8 deflection angles indicated at left. 0° represents an initially caudal deflection, 90° , an initially dorsal deflection. Lower PSTHs show responses accumulated over all angles. Duration of PSTH is 500 ms and individual ticks represent 1 spike/ms bin. These cells are representative of their respective populations in their temporal response profiles and were intentionally selected for their lack of direction selectivity.

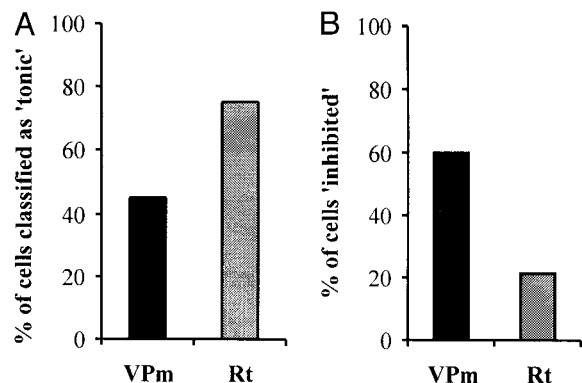


FIG. 4. Comparison of VPm and Rt plateau activity. See METHODS for classification criteria.

similar relationship holds for VPm and Rt responses to directions evoking the greatest plateau activity (Fig. 1, C and D).

We quantified differences in Rt and VPm plateau activity by classifying individual neurons as tonically or phasically responsive. Units were considered "tonic" if their plateau activity at the maximally effective plateau direction was significantly elevated above spontaneous levels; all others were categorized as "phasic." Within Rt, 75.3% of the units responded tonically compared with only 45.1% of VPm units (χ^2 test, $P < 0.001$, Fig. 4A). Even among the subpopulations of tonic Rt and VPm neurons, the former displayed greater plateau activity in terms of both absolute spike counts and relative to spontaneous levels (Table 2).

At the least effective angle for evoking plateau responses, many neurons fire at lower than spontaneous rates (see Fig. 1E). We classified units as putatively inhibited if their plateau activity at the minimally effective direction was significantly less than spontaneous firing. Figure 4B shows that a greater proportion of VPm neurons are inhibited during vibrissa deflections than Rt neurons (59.7 versus 21.2%, χ^2 test, $P < 0.001$).

Data were examined to determine whether neurons classified as phasic were more likely to be inhibited in at least one direction than neurons classified as tonic. In VPm, 71% (24/34) of phasic units were inhibited compared with 46% (13/28) of tonic cells (χ^2 , $P = 0.054$). The same relationship was observed in Rt (phasic: 48% inhibited; tonic: 13% inhibited; $P < 0.001$). Similarly, in both VPm and Rt, tonic cells fire more spikes at the least effective plateau direction than phasic cells; conversely, inhibited cells have smaller maximum plateau responses than noninhibited cells (Table 2). Together, these analyses indicate that inhibition, if present, influences a neuron's plateau responses in all directions, rather than in nonpreferred directions only. As such, tonic responsiveness in the

thalamus is not simply determined by a neuron's excitatory inputs, but is also influenced by inhibitory mechanisms.

Direction sensitivity

As demonstrated previously, many VPm neurons, like N. V. neurons, respond differently depending on the direction of vibrissa movement (Simons and Carvell 1989). Polar plots of single neuron responses, such as those shown in Fig. 5, reveal that Rt neurons also exhibit directionally sensitive firing for the ON, OFF, and plateau response periods. Note, however, as in Fig. 5, that the maximally effective directions for evoking ON, OFF, and plateau responses often differ for the same neuron. This is true for primary afferent neurons as well (Lichtenstein et al. 1990), especially in the case of ON and OFF responses (see below). To compare directional tuning in VPm and Rt, tuning ratios were computed separately for ON, OFF, and plateau responses by dividing each neuron's maximal angle response by its mean response to all deflection angles. By these measures, ON, OFF, and plateau responses of the VPm population are significantly better tuned than those of Rt neurons ($P < 0.001$). The ON response tuning of the sampled VPm and Rt populations is directly compared in the normalized polar plots of Fig. 6. Population data from 83 N. V. neurons are also presented for comparison (Shoykhet and Simons, unpublished data). At each sequential stage of processing directional tuning becomes broader.

The tuning ratio used here, like those commonly employed in other systems (e.g., width at half-height of tuning curve), employs normalization and hence is a relative measure of neuronal activity at different directions. In terms of absolute spike counts, however, we find that the difference between the maximum angle response and the response averaged over all eight angles is greater in Rt (1.54 ± 0.85 spikes) than VPm (0.87 ± 0.50 spikes; $P < 0.001$). The same relationship holds for the OFF and plateau responses (Table 1). The smaller tuning ratios (Fig. 6 polar plot) for Rt neurons thus reflect their greater mean responsiveness (denominator of tuning ratio) rather than more reliable discrimination between directions. For example, a difference of 2.0 spikes/stimulus between the response at the preferred angle and the average for all eight angles yields a higher tuning ratio for a neuron whose average response is 2.0 ($4.0/2.0 = 2.0$) than for a neuron whose average response is 6.0 ($8.0/6.0 = 1.33$). We therefore also assessed directional tuning by using a measure based on the mean and variance of the spike counts. Each unit was classified into one of eight tuning categories based on the number of deflection angles (0–7) that evoked responses statistically smaller than those of the maximally effective direction ($P < 0.05$, one-tail t -test; see Simons and Carvell 1989); category 7 represents the most selective

TABLE 2. Plateau activities in subpopulations of VPm and Rt neurons

	VPm			Rt		
	Maximum	Minimum	Mean	Maximum	Minimum	Mean
Tonic	43.3 \pm 19.4	6.5 \pm 6.9	21.9 \pm 10.9	84.8 \pm 36.9	31.5 \pm 21.5	57.6 \pm 28.9
Phasic	17.6 \pm 10.4	3.2 \pm 3.2	9.2 \pm 6.1	41.3 \pm 23.5	14.1 \pm 15.3	25.7 \pm 17.4
Noninhibited	33.2 \pm 20.2	8.7 \pm 6.2	19.8 \pm 11.9	78.7 \pm 36.4	32.6 \pm 20.2	55.1 \pm 27.7
Inhibited	26.5 \pm 19.2	2.0 \pm 2.2	11.6 \pm 8.3	56.7 \pm 43.6	7.4 \pm 12.9	29.5 \pm 29.4

Values are means \pm SD and are expressed in spikes/s. Data are based on responses evoked by the maximally and minimally effective plateau directions, as well as mean responses computed over all directions.

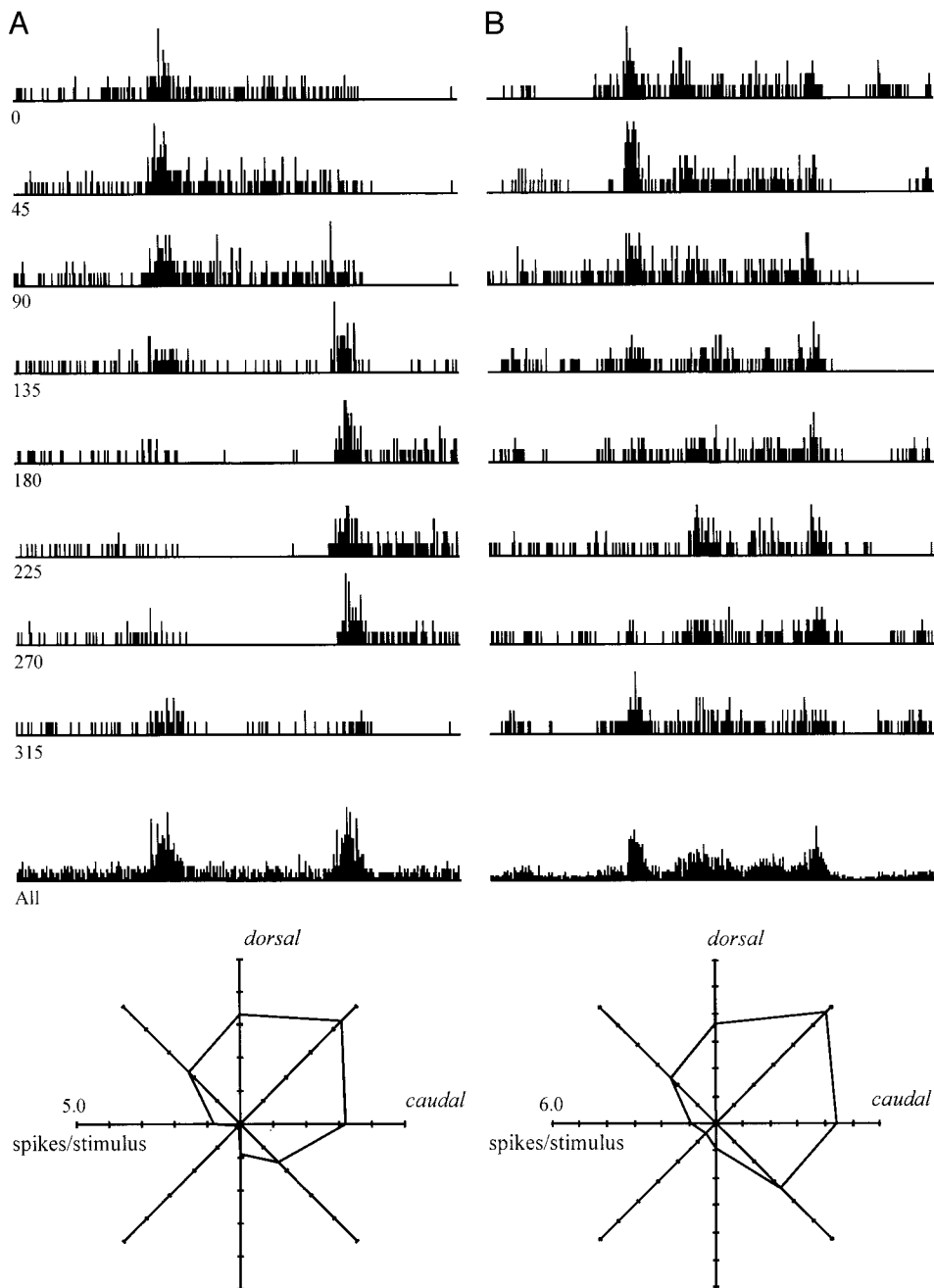


FIG. 5. Directional response properties of two Rt neurons. PSTH conventions are the same as in Fig. 3. *Bottom*: plots of ON response magnitudes at each of the 8 directions shown in polar coordinates. Rightward is 0° and represents an initially caudal deflection; upward is 90° and represents a dorsal deflection. Distance from the origin (radial axis) is labeled in spikes/stimulus onset (20-ms window). Tuning categories of these cells are A: ON: 7, OFF: 5, plateau: 6; and B: ON: 6, OFF: 2, Plateau: 1. Correlations between ON and OFF responses at each angle are A: -0.86 and B: -0.87 .

responses. Figure 6 shows that the distribution of cells across the eight categories is similar for VPM and Rt populations (χ^2 , P 's > 0.1). For example, 37 and 46% of VPM and Rt neurons, respectively, have significantly greater ON responses in the maximally effective direction than in five or more other directions.

A third measure of a unit's directional properties is directional consistency. Directionally consistent cells discharge most vigorously to the onset of vibrissa deflection in one direction and to stimulus offset after initial movements in the opposite direction (Fig. 5A). The proportions of directionally consistent cells in VPM and Rt are similar (25.8% versus 30.6%; χ^2 , $P = 0.53$). Moreover, in both populations directionally consistent cells have higher ON and OFF tuning indices than cells that are not directionally consistent ($P < 0.05$); the

same relationship is observed in primary afferent neurons (Lichtenstein et al. 1990; see DISCUSSION). However, unlike the primary afferent population tonic and phasic neurons in VPM are equally likely to display directional consistency [tonic: 50.0% (8/16); phasic: 43.5% (20/46), $P = 0.65$]. The same is true for Rt [tonic: 71.2% (42/59); phasic: 84.6% (22/26), $P = 0.18$].

We also examined whether inhibited and noninhibited neurons differ with respect to directional tuning ratios. VPM cells with inhibited plateau responses are better tuned for the plateau response than cells that are not inhibited ($P < 0.001$). Although the mean plateau activity is significantly lower for inhibited cells, the preferred angle response is also smaller (Table 2; $P < 0.01$). The difference in absolute spike count between maximum and mean plateau activities is therefore the same for

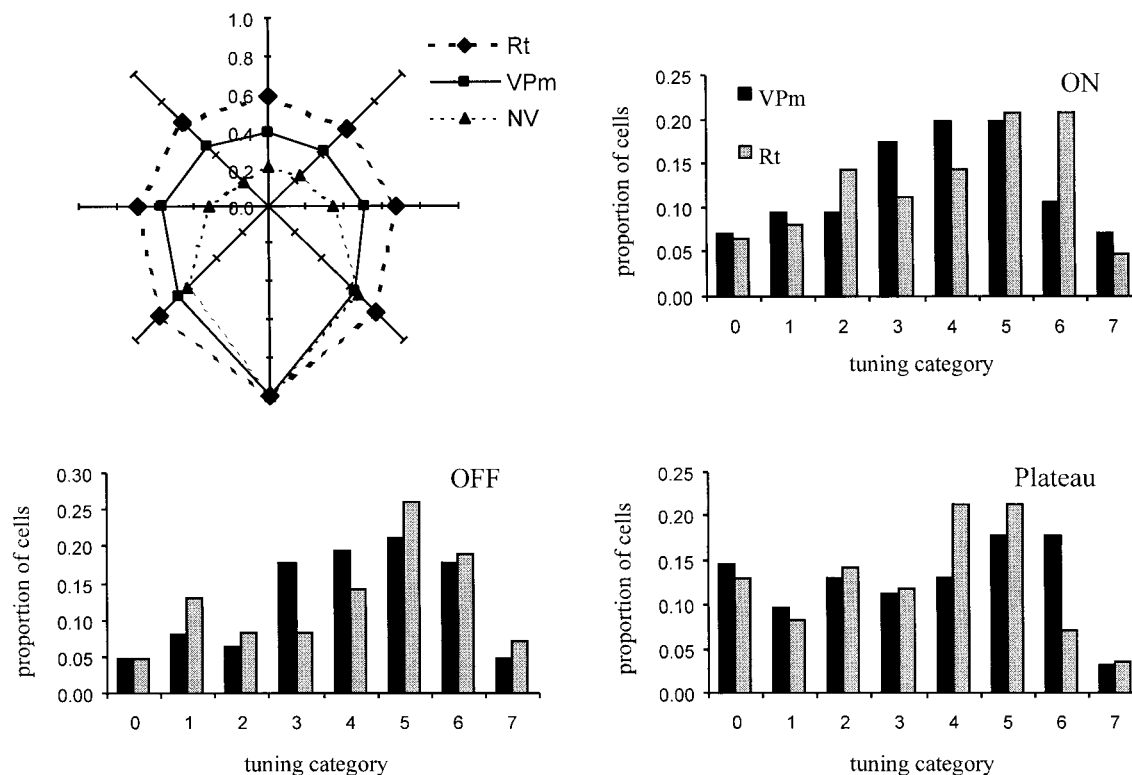


FIG. 6. Directional tuning of VPM and Rt populations. *Top left*, polar plot of ON response magnitudes of the N. V., VPM, and Rt populations at different directions. For each population, each cell's maximum response was normalized to 1.0 and, for purposes of comparison, rotated to a common (ventral, 270°) direction. Responses of all cells within a population were then averaged. Histograms compare the distributions of VPM and Rt neurons across the 8 directional tuning categories, computed separately for ON, OFF, and plateau time windows. Category 7 represents the most direction selective responses during the respective period of the stimulus. 20-ms windows were used for ON and OFF responses for both populations.

inhibited (14.9 ± 12.0 spikes/s) and noninhibited (13.4 ± 9.5 spikes/s) cells ($P = 0.60$). As explained above, the higher tuning ratios of inhibited versus noninhibited cells thus reflect their lower overall (mean) discharge rates at all directions. There are no significant differences in ON or OFF tuning ratios between inhibited and noninhibited VPM neurons, and their response magnitudes are equivalent. In Rt, on the other hand, inhibited cells are better tuned for ON, OFF, and plateau responses ($P < 0.05$). Again, the higher tuning ratios are due to a significantly lower mean responsiveness of inhibited cells ($P < 0.05$), rather than a greater difference in the maximum and mean number of evoked spikes. Inhibited and noninhibited cells did not differ with respect to tuning categories in either VPM or Rt.

ON and OFF response transformations

VPM and Rt neurons differ substantially with respect to the relative magnitudes and temporal profiles of their ON and OFF responses. We computed OFF:ON response ratios for VPM and Rt neurons (Table 1) and found that Rt neurons, like cortical and N. V. populations (Kyriazi et al. 1994), have significantly smaller ratios (i.e., relatively smaller OFF responses) than VPM neurons ($P = 0.007$ for 20-ms Rt window, $P < 0.001$ for 38-ms window).

Figure 7 shows ON and OFF PSTHs at high-temporal resolution. The Rt ON response has a rapidly rising early peak, similar to the VPM ON response, followed by a second phase of large

magnitude, which develops and decays more slowly. In contrast, the Rt OFF response consists of a single peak which begins to decay earlier than its ON response counterpart. These profiles suggest that there are two components of Rt responses, and that their differential engagement might account for the smaller OFF:ON ratios of Rt neurons relative to those in VPM. This is indeed the case. We computed OFF:ON ratios separately for early and late portions (see bars in Fig. 7) of the responses. Ratios for the early components of the Rt responses are comparable to those in VPM ($P = 0.81$, M-W U test), but are larger than ratios for the late Rt components (early: 0.925; late: 0.646; $P < 0.001$).

Based on a previous study of VPM neurons (Kyriazi et al. 1994), we hypothesized that the early component of the Rt ON and OFF responses is mediated by fast, ion-gated glutamate receptors, whereas the late component reflects activation of voltage-gated T-type Ca^{2+} (I_T) channels (Huguenard and Prince 1992). I_T channels require hyperpolarization to deactivate (i.e., open inactivation gates) and hence to conduct regenerative depolarizing current on subsequent suprathreshold depolarization. If the early response is mediated by voltage-independent ion-gated channels and the late component by I_T , the magnitude of the early response should be directly proportional to the level of immediately preceding activity, and that of the late response should be inversely related. We therefore examined how the magnitudes of the early and late components of Rt responses correlate with the presence or absence of a spike in each 1-ms bin preceding the evoked

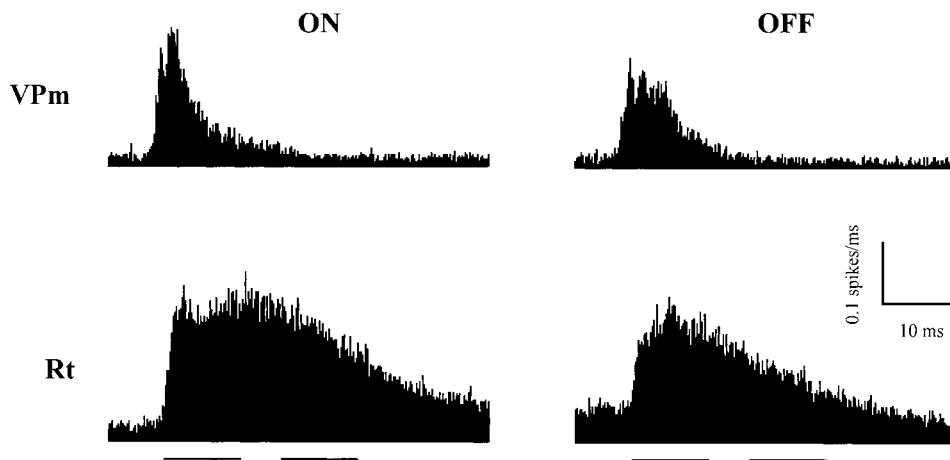


FIG. 7. Population PSTHs of ON and OFF responses to all deflection angles. These are the same responses as in Fig. 1, *A* and *B*, shown here with 100- μ s bins. Bars below the Rt responses indicate the 10-ms windows used for computing response magnitudes of the early and late components.

response. For each millisecond, a correlation coefficient was computed based on 10 trials \times 8 directions \times 85 neurons. Figure 8*B* shows that the late component of the OFF response is negatively correlated with activity in each of the 24 consecutive bins preceding the beginning of the OFF response. By contrast, the early component is positively correlated with the same preceding activity (Fig. 8*C*). To determine more precisely the time course of these relationships, the total spike count over the 25 ms preceding the OFF response was correlated with the presence or absence of a spike in each 1-ms bin of the response (Fig. 8*D*). Consistent with the preceding analyses, correlations are positive during the first 10 ms of the OFF response but become negative after \sim 15 ms. The same analyses were applied to the ON response, and similar results were obtained (data not shown). Specifically, the early component of the ON response was positively correlated with preceding (spontaneous) activity, whereas the late component was negatively correlated.

DISCUSSION

In this study we employed the same ramp-and-hold vibrissa deflections to study the response characteristics of Rt neurons as were used previously to characterize neuronal signaling in N. V., thalamocortical, and cortical neurons. There are three main results presented here as follows: 1) Transient responses of Rt neurons are larger in magnitude and longer in duration than those of thalamocortical and other populations previously studied, 2) High firing rates emerge in Rt neurons during sustained vibrissa deflection, in the absence of proportionately high activity in the VPM population, and 3) Rt neurons exhibit directional sensitivities consistent with their receiving specific afferent inputs. These results demonstrate a modification/transformation of response characteristics in Rt neurons relative to those at other stages of the sensory pathway and implicate Rt functionally in the processing of sensory information.

ON and OFF responses

The magnitudes of transient responses in Rt are by far the largest of any vibrissa-responsive population studied thus far under the same conditions (compare mean ON response for all angles: Rt = 5.69 spikes, N. V. neurons = 2.15, cortical layer IV regular-spike units = 0.92, layer IV fast-spike units = 1.70), including those of the VPM neurons which are the principal source of Rt afferent drive (mean ON = 1.27) (Kyriazi

et al. 1994). The peak firing rates of VPM and Rt populations are similar; rather, it is the long duration of the Rt response which accounts for its larger magnitude (Fig. 7). The analyses presented in Fig. 8, demonstrating a negative correlation between this later component of Rt responses and activity preceding the response, strongly suggest that it is partially mediated by I_T (see Bal and McCormick 1993; Contreras et al. 1992, 1993; Sumitomo et al. 1989). This interpretation is based on the presumption that extracellularly recorded spike activity reflects the extent of a unit's membrane polarization. When a cell is relatively hyperpolarized (e.g., in the absence of a stimulus), I_T channels become deactivated and can conduct large, regenerative currents on subsequent stimulus-evoked depolarization (e.g., ON response). When relatively depolarized (e.g., during the stimulus plateau), a greater proportion of I_T channels are inactivated and less depolarizing current can be elicited by a subsequent depolarization of equal amplitude (e.g., OFF response). If the stimulus plateau is hyperpolarizing, as for VPM neurons, the OFF response is enhanced (Kyriazi et al. 1994). The long, late component of Rt responses may also be mediated in part by *N*-methyl-D-aspartate (NMDA) receptors, which have been identified histochemically in Rt neurons (Liu 1997). Although NMDA receptors are also found on VPM neurons, the expression of their currents may be masked by the greater levels of Rt inhibition onto these neurons than onto other Rt neurons.

Functionally, high stimulus-evoked activity of Rt neurons may be necessary for adequate summation of IPSPs to terminate VPM responses and limit them to a small number of precisely timed spikes. Kim and McCormick (1998) have shown that there is increasing facilitation of IPSPs in thalamocortical neurons for at least three consecutive spikes at 100–500 Hz and that the peak amplitude of compound IPSPs increases linearly with the frequency of presynaptic spikes. Thus \sim 6 Rt spikes over 30 ms (200 Hz) would powerfully inhibit VPM responses and prevent subsequent spikes that are not as closely time-locked to stimulus onset. This feedback inhibition would enhance the temporal specificity of thalamocortical signaling and, therefore the information carried by individual spikes. Indeed, Lee et al. (1994a,b) found that eliminating Rt influences on VPM resulted in an increase in VPM response magnitude and duration. Even if, under the influence of Rt, individual VPM neurons fire only single spikes per stimulus, synchronous firing within the population can serve as

an efficient, rapidly transmitted signal to which cortical circuits are particularly sensitive (Pinto et al. 2000).

We found that the mean OFF:ON ratio is smaller for Rt than for VPM and that this transformation can be accounted for in part by a diminished late component in the Rt OFF response. This diminution is likely due to the inactivation of I_T channels during periods of elevated activity preceding stimulus offset. Previously, Kyriazi et al. (1994) used the same correlation analysis presented here to suggest the involvement of I_T in

enhancing VPM OFF responses. Decreased VPM activity during the stimulus plateau (i.e., greater hyperpolarization due to Rt-mediated inhibition) *deinactivates* I_T channels, rendering them available to enhance VPM responses to stimulus offset. The converse influences of I_T on Rt and VPM OFF responses depend on the balance of activity in the thalamic circuit during stimulus plateaus.

Tonic responses

The mean plateau activity averaged over all deflection angles for Rt is elevated 27.3 spikes/s (122%) above its spontaneous levels. By contrast, VPM activity is only 1.7 spikes/s (13%) greater than spontaneous activity. How can such elevated firing rates emerge in Rt in the absence of significant drive from VPM? One explanation, consistent with the larger ON and OFF responses in Rt, is that there is high gain at VPM–Rt synapses. This could be due to the presence of amplifying ion- and voltage-gated currents (e.g., NMDA and I_T) and also to the high-input resistances of Rt neurons (McCormick and Prince 1986). In addition, Ca^{2+} influx through I_T channels during the ON response may activate Ca^{2+} -dependent cation currents, which contribute to tonic activity after burst discharges (Bal and McCormick 1993). A second factor may be a high degree of convergence of VPM synapses onto single Rt neurons. Although there are an estimated 250–300 VPM neurons with the same receptive field center (i.e., within a barreloid; Land et al. 1995), there are only 10–30 corresponding Rt neurons (Shosaku 1986). Because ~76% of VPM neurons collateralize within Rt (Harris 1987) and 80% of VPM neurons show physiological connections with Rt neurons in cross-correlation studies (Shosaku 1986), there is likely to be a many-to-one relation in connections from VPM to Rt cells. A third mechanism underlying large tonic Rt responses may be a disproportionately large number of inputs to Rt from tonic versus phasic VPM neurons. Finally, Rt neurons are less likely to inhibit each other than they are to inhibit VPM neurons (Fig. 4B); this allows Rt neurons to be tonically active and thereby inhibit the plateau activity of VPM neurons.

Specificity of connections within VPM–Rt circuit

In a study employing cross-correlation analyses of VPM and Rt neuronal activity, Shosaku (1986) found that cells exhibited functional interactions only if they responded best to the same vibrissa. Extending this finding of connectional specificity, we report that a substantial proportion of Rt neurons exhibit directionally selective responses (Figs. 5 and 6). This result demonstrates precision in connectivity from VPM to Rt, inasmuch as nonspecific convergence of VPM cells having different, or no, directional preferences onto individual Rt neurons would render them nondirectional. Like N. V. and VPM neurons, many Rt neurons respond selectively to vibrissa move-

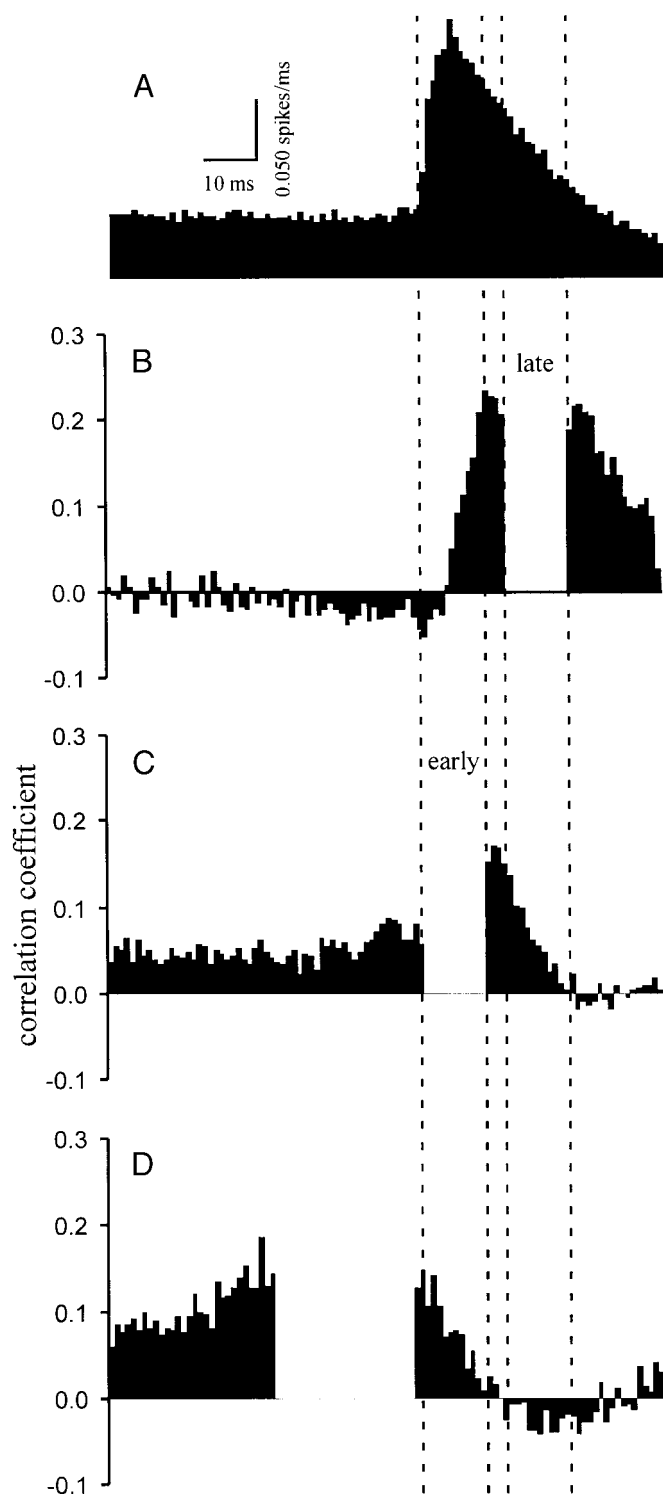


FIG. 8. Relationship of transient Rt OFF response with preceding activity. *A*: mean OFF response of Rt population averaged over all deflection angles and preceding plateau activity (as in Fig. 7). *B*: correlation coefficients computed between spike counts over the late 10-ms window of the response (denoted by dashed lines and zero values) and activity in each 1-ms bin. *C*: same as *B*, but using a 10-ms window capturing the earliest component of the response. *D*: correlation coefficients computed between spike counts over a 25-ms period preceding the evoked response and activity in each 1-ms bin. Time-scale bar applies to all panels.

ment in a particular direction regardless of the starting point of the movement, a property termed directional consistency. This property, too, would require specific inputs to Rt neurons from directionally consistent VPM cells having the same directional preference. These results demonstrate that VPM axons synapse onto Rt cells in a manner that is defined by specific parameters of sensory activation.

Our findings contrast with results of Shosaku (1985), who, relying principally on manual vibrissa stimulation, reported that Rt neurons are not directionally selective. According to his model, nondirectional Rt cells mediate both cross- and isodirectional inhibition in VPM (Shosaku et al. 1989). Indeed, the present findings suggest that nondirectional inhibition from Rt could enhance tuning of plateau activity in VPM by simply raising the threshold for responses. On the other hand, Lee et al. (1994a,b) reported that directional tuning of VPM responses was unaffected by eliminating Rt-mediated inhibition. Interpretation of those findings is complicated somewhat by the use of a response measure that combined discharges to deflection onsets and offsets, which, as described, often have opposite directional tuning. Although Rt may not play an active role in imparting directional tuning to VPM neurons, our finding that many Rt cells are directionally well-tuned nevertheless raises the possibility that Rt-mediated inhibition could affect the firing of VPM neurons during sequential whisker movements in opposite directions, as occur, for example, during transitions between whisker retraction and protraction. These influences may be better revealed experimentally by sequentially deflecting the same whisker in different directions.

Rt control of thalamocortical circuit activity

Strong feedforward engagement of cortical inhibitory neurons by thalamocortical afferents sets a brief "window of opportunity" for temporally synchronous thalamic inputs to elicit a response in excitatory neurons (Pinto et al. 1996). Because of the circuit's nonlinear properties, the layer IV "barrel" acts to increase response differentials between preferred (synchronous) and nonpreferred (temporally dispersed) thalamic input signals. Importantly, the strength of this tuning effect (i.e., the size of the window) is modulated by thalamic background activity, which tonically activates inhibitory barrel neurons more so than excitatory ones (Brumberg et al. 1996; Swadlow 1995, 1998). Thus by regulating ongoing activity in VPM, Rt neurons could control the balance of excitation and inhibition, and hence response tuning, in the cortex.

High evoked firing rates emerge in Rt neurons during maintained deflections despite minimal increases in VPM activity. Because slowly adapting N. V. units, which comprise 75% of the population, fire at a mean rate of 70 spikes/s above their spontaneous activity during stimulus plateaus (Lichtenstein et al. 1990), it is likely that Rt acts to suppress corresponding increases in the VPM population. This is supported by our finding that phasic VPM cells were more likely to be inhibited at nonpreferred directions than tonic cells. Through amplification mechanisms, Rt neurons are able to respond to small changes in baseline VPM firing and to subsequently counteract these changes by increasing or decreasing their own activity. The high spontaneous and stimulus-evoked firing rates of Rt neurons would permit them to do this over a broad range of stimulus conditions without encountering floor or ceiling ef-

fects. Thus by controlling the maintained activity of VPM cells on a long time scale (10s or 100s of milliseconds), Rt may act as a gain control that keeps thalamocortical activity in a range optimal for signal processing and transmission in the cortical barrel. Depending on the state of the animal (see Crick 1984), this indirect influence of Rt inhibition could act in concert with its enhancement of transient thalamocortical spiking on a shorter time scale by means of deinactivation of I_T channels. Efficient signaling of rapid changes in vibrissa position is likely to be important in enabling the fine vibrissae-based texture discriminations of which rodents are capable (Carvell and Simons 1990, 1995).

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