

# Frequency-Dependent Processing in the Vibrissa Sensory System

**Christopher I. Moore**

*Massachusetts Institute of Technology, McGovern Institute for Brain Research and Department of Brain and Cognitive Sciences, Cambridge, Massachusetts 02139*

Submitted 23 September 2003; accepted in final form 7 January 2004

**Moore, Christopher I.** Frequency-dependent processing in the vibrissa sensory system. *J Neurophysiol* 91: 2390–2399, 2004; 10.1152/jn.00925.2003. The vibrissa sensory system is a key model for investigating principles of sensory processing. Specific frequency ranges of vibrissa motion, generated by rodent sensory behaviors (e.g., active exploration or resting) and by stimulus features, characterize perception by this system. During active exploration, rats typically sweep their vibrissae at ~4–12 Hz against and over tactual surfaces, and during rest or quiescence, their vibrissae are typically still (<1 Hz). When a vibrissa is swept over an object, microgeometric surface features (e.g., grains on sandpaper) likely create higher frequency vibrissa vibrations that are greater than or equal to several hundred Hertz. In this article, I first review thalamic and cortical neural responses to vibrissa stimulation at 1–40 Hz. I then propose that neural dynamics optimize the detection of stimuli in low-frequency contexts (e.g., 1 Hz) and the discrimination of stimuli in the whisking frequency range. In the third section, I describe how the intrinsic biomechanical properties of vibrissae, their ability to resonate when stimulated at specific frequencies, may promote detection and discrimination of high-frequency inputs, including textured surfaces. In the final section, I hypothesize that distinct low- and high-frequency processing modes may exist in the somatosensory cortex (SI), such that neural responses to stimuli at 1–40 Hz do not necessarily predict responses to higher frequency inputs. In total, these studies show that several frequency-specific mechanisms impact information transmission in the vibrissa sensory system and suggest that these properties play a crucial role in perception.

## INTRODUCTION

Mice and rats are two of the most widely employed “model” systems of mammalian neural function, and the vibrissae (whiskers) on the face are an essential and high-resolution sensory input for these animals (Woolsey and Van der Loos 1970). Rats can use their vibrissae for activities as diverse as judging subtle differences in surface texture (e.g., the roughness of sandpaper or of a fine-milled grating; Carvell and Simons 1990, 1995, 1996; Guic-Robles et al. 1989, 1992), object recognition (Brecht et al. 1997; Harvey et al. 2001), estimating the distance of a gap prior to jumping across it (Hutson and Masterton 1986), and searching for food in opaque underwater environments (Dehnhardt et al. 1999; seals also use their vibrissae for underwater navigation and exploration: Dehnhardt et al. 2001).

Vibrissa-based perception is characterized by vibrissa motion in specific frequency ranges. When in a resting or quiescent state, rats typically do not move their vibrissae, and novel contact by an external stimulus occurs in the context of a low frequency of vibrissa motion (e.g., <1 Hz). In contrast, when actively exploring their environment, rats

sweep their vibrissae at frequencies of ~4–12 Hz in a rhythmic, primarily posterior-anterior motion (known as “whisking,” Fig. 1A) (Carvell and Simons 1990; Harvey et al. 2001; Welker 1964). Whisking is observed in a wide variety of perceptual contexts, and there is evidence that the precise frequency of whisking impacts the accuracy of perceptual judgments (Carvell and Simons 1995; Harvey et al. 2001). As rats whisk over objects, features on the sensory surface in turn likely vibrate the vibrissae at much higher frequencies, at least up to several hundred Hertz (Figs. 1A and 2) (Fend et al., 2003; Neimark et al. 2003). In this review, I describe how the frequency-dependent processing of vibrissa sensory signals, instantiated in the filter characteristics of the thalamus and cortex and in the vibrissae themselves, may play a crucial role in perception. This paper is organized in four sections. In the first section, I provide an overview of thalamic and cortical responses to vibrissa stimulation at 1–40 Hz. In the second section, I propose that these neural response characteristics serve to optimize detection during low-frequency contexts (e.g., resting) and discrimination during whisking. In the third section, I describe vibrissa resonance and propose that it may be crucial for the representation of high-frequency stimuli. In the fourth section, I hypothesize that distinct low- and high-frequency processing modes may exist within somatosensory cortex (SI).

## FREQUENCY-DEPENDENT FILTERING OF VIBRISSA-EVOKED ACTIVITY IN THE THALAMUS AND CORTEX

Theories of neural coding of sensory input commonly focus on variation in either the rate of action potential activity (number of spikes evoked; e.g., Romo et al. 2002) or the fine timing of spiking activity (e.g., Mountcastle et al. 1969; Rieke et al. 1997). Recent studies have described frequency-dependent modulation of both metrics in the ventral posterior medial nucleus of the thalamus (VPM), the principal thalamic relay nucleus for vibrissa signals, and in SI. Depending on the type of measure applied, VPM and SI neurons show a wide variety of frequency-dependent filter characteristics, including “low-pass” (i.e., greater relative values for lower frequency stimuli), “high-pass” (i.e., greater relative values for higher frequency stimuli), and “band-pass” (i.e., throughput of signals in an intermediate frequency range).

Address for reprint requests and other correspondence: C. I. Moore (E-mail: cim@ai.mit.edu).

The costs of publication of this article were defrayed in part by the payment of page charges. The article must therefore be hereby marked “advertisement” in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

### VPM

**PHASIC SPIKE RATE: LOW-PASS.** When the effect of vibrissa stimulation frequency on spike rate is measured as the number of spikes evoked in a brief window after vibrissa deflection [e.g., 0–15 ms; “phasic spike rate” (PSR)], VPM neurons demonstrate significant adaptation at higher stimulus frequencies (Fig. 1*B*, *left*) (Ahissar et al. 2000; Castro-Alamancos 2002a,b; Chung et al. 2002; Deschenes et al. 2003; Diamond et al. 1992; Fanselow and Nicolelis 1999; Hartings et al. 2003; Sosnik et al. 2001). The lowest frequency at which this VPM adaptation is observed, and its relative strength, varies across studies. Values from 2 to 5 Hz (Ahissar et al. 2000; Castro-Alamancos 2002a,b; Diamond et al. 1992; Sosnik et al. 2001) to  $\geq 30$  Hz (Castro-Alamancos 2002a,b) have been reported. This adaptation profile can be modulated by several factors, including brain stem reticular formation (RF) stimulation, the direct application of neuromodulators, the relative depolarization of VPM neurons, and the vibrissa deflection pulse width (Castro-Alamancos 2002a,b; Deschenes et al. 2003; Sosnik et al. 2001).

Perhaps the most important factor known to influence VPM adaptation is the behaving state of the awake, freely behaving rat (Fanselow and Nicolelis 1999). Fanselow and Nicolelis (1999) found that electrical stimulation of the infraorbital nerve evoked a smaller response in the VPM while a rat was whisking compared with when it was in a quiescent state. One explanation for this effect is that whisking generates sensory feedback at the frequency of vibrissa motion, even when rats whisk in air and the vibrissae do not contact a surface (Fee et al. 1997). As a result, VPM neurons are likely already in an adapted state during whisking, leading to a smaller initial evoked response. These authors also observed that paired-pulse stimulation caused greater relative suppression of the second stimulus in the quiescent but not the whisking state (Fanselow and Nicolelis 1999): given that the first pulse in the nonwhisking state (the putatively nonadapted state) is much larger, this finding is consistent with the idea that the VPM is already adapted to “floor” levels by whisking, diminishing the relative capacity for further adaptation.

As recently reported by Castro-Alamancos and colleagues, PSR adaptation in the VPM is dependent on synaptic depression of the feedforward excitatory postsynaptic potentials (EPSPs) from the brain stem (Castro-Alamancos 2002a,b; see also Deschenes et al. 2003). Many somatosensory brain stem neurons follow high-frequency vibrissa stimulation (Ahissar et al. 2000; Deschenes et al. 2003; Hartings et al. 2003; Sosnik et al. 2001), in turn generating large sensory-evoked EPSPs in VPM neurons at frequencies up to several hundred Hertz (Castro-Alamancos 2002a,b; Deschenes et al. 2003). Synaptic depression can prevent these EPSPs from initiating suprathreshold spiking activity during repeated stimulation (Castro-Alamancos 2002a,b; Deschenes et al. 2003). Increased thalamic depolarization can overcome synaptic depression at this synapse (Castro-Alamancos 2002b), suggesting that the different PSR adaptation profiles reported by different studies reflect, in part, the degree of postsynaptic depolarization under different recording conditions. Depolarization level of the VPM can be modulated by acetylcholine and norepinephrine and by inhibitory input from the neighboring reticular nucleus (Castro-Alamancos 2002a; Lee et al. 1994).

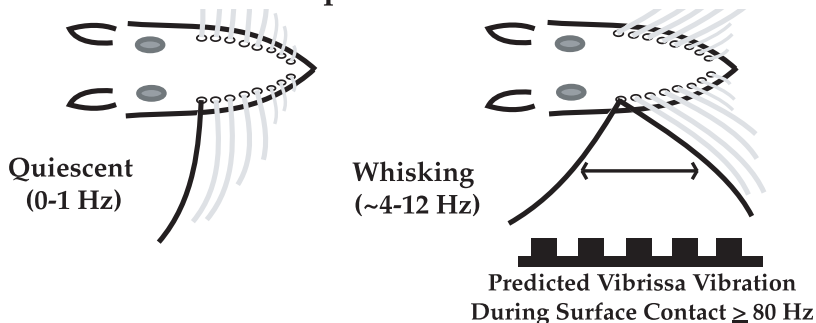
**TOTAL SPIKE RATE: HIGH-PASS.** In contrast to this low-pass PSR adaptation, when firing rate is calculated instead as the total number of spikes evoked over an extended stimulation period [total spike rate (TSR)], high-pass filter characteristics are observed for the range from 1 to 40 Hz. Specifically, Hartings et al. (2003) found that the number of spikes occurring over the duration of a 1 to 4-s train of pulses increased slightly with each increase in the frequency of stimulation (Fig. 1*B*, *middle*). The intuition behind this finding is relatively straightforward: although responses to a single vibrissa deflection may evoke fewer action potentials at higher frequencies (PSR) over a longer time window, the TSR increases (or stays constant) with increasing frequency because the number of vibrissa deflections in that time window has increased. This kind of TSR integration over multiple stimuli is believed to be crucial for primate frequency discrimination (for a review, see Romo et al. 2002).

**SPIKE TIMING: HIGH-PASS.** The entrainment of spike firing to the stimulation frequency is also influenced in the VPM by stimulation frequency, and like TSR, acts like a high-pass filter in the range of 1–40 Hz. The relative modulation (RM) of spike firing in the VPM, the power of the Fourier component at the stimulation frequency normalized by the total number of spikes evoked by the train, increases rapidly from 1 to 12 Hz and demonstrates more modest increases at higher stimulation frequencies (Hartings et al. 2003). A key implication of this finding is that, as stimulation frequency is increased, feedforward input from the thalamus will maintain high synchrony in the arrival time of action potentials to SI. Other studies by Simons and colleagues and Swadlow and colleagues have demonstrated that the onset synchrony of thalamic input to SI is crucial in driving excitatory evoked activity (Pinto et al. 2000; Swadlow 2003; Swadlow et al. 1998; Temereanca and Simons 2003). The high temporal fidelity observed in VPM should preserve the efficacy of feedforward input to SI at higher frequencies (up to  $\geq 40$  Hz).

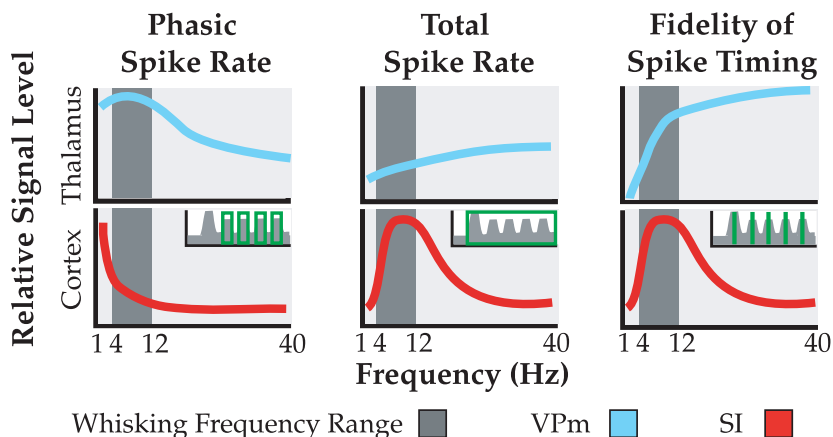
### SI cortex

**PHASIC SPIKE RATE: LOW-PASS.** One important role of thalamic activity is transmission of signals to the cortex, and recent studies have observed substantial frequency-dependent modulation of SI vibrissa-evoked activity. Excitatory neurons in the layer IV barrels in SI (a primary recipient of feedforward VPM input) show low-pass PSR adaptation in anesthetized animals (Fig. 1*B*, *left*) (Ahissar et al. 2000, 2001; Chung et al. 2002; Garabedian et al. 2003a; Simons 1978). Several studies suggest that low-pass PSR adaptation is also present in awake rat SI. As in the VPM, in the awake and freely behaving animal, SI shows reduced evoked activity to an initial stimulus in the whisking state and greater paired pulse suppression in the quiescent state (Fanselow and Nicolelis 1999). Further, in the nonwhisking, head-posted rat, low-pass adaptation is observed for the peak initial firing rate of SI neurons (Kleinfeld et al. 2002). Stimulation of the brain stem RF in the anesthetized rat, a paradigm believed to emulate “awake” neural activity in the anesthetized animal, also leads to suppression of sensory evoked responses in SI that is similar to suppression observed during higher-frequency stimulation (Castro-Alamancos and Oldford 2002). The amount of SI PSR adaptation is significantly greater than that observed in the VPM, in large part

**A Behavioral State & Frequencies of Vibrissa Motion**



**B Frequency-Dependent Response Properties of VPM & SI**



**C Frequency-Dependent Modulation of SI Activity Extent**



FIG. 1. Vibrissa stimulation frequency influences thalamic and cortical response properties. *A: (left)* when rats are in a quiescent or resting state, their vibrissae are typically still. *Right:* in contrast, when actively exploring their environment, vibrissae are “whisked” at a rate between ~4 and 12 Hz. When whisked over a surface, multiple stimulus features on the surface (e.g., ridges in a grating) should create vibrissa vibrations at multiples of the whisking rate. As shown for this idealized surface, sweeping over 5 ridges at a rate of 8 Hz should create oscillations of  $\geq 80$  Hz. *B:* frequency dependence of 3 response metrics is shown for evoked activity in the ventral posterior medial nucleus of the thalamus (VPM) and the primary somatosensory cortex (SI). *Left:* in the VPM and SI, the number of spikes evoked during an initial period following a deflection (phasic spike rate) shows a low-pass adaptation profile, with fewer spikes at higher frequencies. *Center and right:* when the total spike rate (all spikes evoked over a sustained steady-state period) or when the fidelity of spike timing to the stimulation frequency are considered, VPM neurons have high-pass filter characteristics (Hartings et al. 2003). In contrast, in the SI barrel cortex, band-pass filter characteristics are observed for frequencies of stimulation that overlap with the whisking range (gray background behind graphs) (Garabedian et al. 2003a). *Insets:* cartoons of poststimulus time histograms of spike count in gray, with green markings indicating the type of analysis applied for each metric. *C:* stimulation of vibrissae in the whisking frequency range also leads to a relative contraction of the extent of cortical activation. *Left:* as demonstrated with intrinsic signal optical imaging, there is a steeper fall off in the strength of cortical activation with distance from the center of the activated region during higher frequency stimulation (Sheth et al. 1998). This finding suggests that, when a vibrissa deflection occurs during a resting state, a broader cortical region will be activated leading to greater overlap in the activation regions of two spatially adjacent vibrissae (*center*), while repeated whisking against an object will recruit a more discrete representation in SI (*right*). Filtering properties of thalamic and cortical neurons, along with the modulation of spatial extent of SI activation, suggest that processing in the vibrissa sensory system is optimized for detection of contact in the low-frequency quiescent state and for discrimination of detailed stimulus features in the ~4- to 12-Hz whisking frequency range (Moore et al. 1999).

because of additional synaptic depression of the incoming signal at the thalamocortical synapse (Chung et al. 2002; see also Peterson and Sakmann 2001), and at frequencies above ~8–10 Hz, is likely enhanced by intracortical GABAergic inputs (Garabedian et al. 2003a; Kyriazi et al. 1996, 1998; Moore and Nelson 1998; Zhu and Connors 1999).

**TOTAL SPIKE RATE AND SPIKE TIMING: BAND-PASS.** Whereas the VPM shows high-pass filtering of spike rate (TSR) and spike timing, SI demonstrates band-pass properties for these measures centered on the whisking frequency range (Fig. 1B). Garabedian et al. (2003a) stimulated vibrissae at frequencies from 1 to 40 Hz and observed that TSR in SI, measured during the steady-state period after adaptation has reached a plateau (1–5 s after stimulus onset), showed the highest firing rate in a range from 5 to 12 Hz (Fig. 1B, *middle*). Similarly, the fidelity of spike timing, measured as vector strength, also showed a peak in this range (Fig. 1B, *right*). While differences in the experimental preparation may contribute to the differences between the VPM and SI response characteristics observed thus far, the SI band-pass behavior for spike rate and spike timing and its contrast to VPM high-pass behavior for these metrics imply that cortical mechanisms are essential for these transformations. A computational model of SI layer IV circuitry driven by VPM input suggests that the band-pass behavior of TSR is dependent on the strength of thalamocortical depression. In contrast, this model suggests that the band-pass behavior of fine spike timing does not vary as a function of thalamocortical depression, but is instead dependent on longer-lasting intracortical inhibition, with a time course similar to that evoked by GABA<sub>B</sub> recruitment. This longer-lasting inhibition establishes a periodicity that matches the whisking frequency range: at frequencies below ~8 Hz, this inhibition suppresses “noisy” spikes that are not tightly stimulus locked, increasing the overall consistency of the spikes within the analysis period, whereas at frequencies above ~8 Hz, this inhibition lasts long enough to impact the subsequent evoked response, decreasing response fidelity (Garabedian et al. 2003a).

### *Paralemniscal system*

In addition to lemniscal foci such as VPM and the SI barrels, vibrissa stimulation also drives activity in the paralemniscal pathway, a parallel network of brain stem, thalamic, and cortical regions that may play a crucial role in frequency-dependent processing of vibrissa stimuli (Ahissar et al. 2000; Diamond et al. 1992). Paralemniscal neurons of the posterior medial nucleus of the thalamus (POM) are typically reported to have more diffuse receptive fields and more sluggish temporal response properties than those of the VPM (Diamond et al. 1992; Sosnik et al. 2001). Consistent with these receptive field properties, POM neurons show low-pass PSR adaptation with a lower frequency cut-off and more complete adaptation of responses than VPM neurons (Ahissar et al. 2000; Diamond et al. 1992; Sosnik et al. 2001). This more robust adaptation is correlated with an increased latency to the onset of POM firing that occurs without a similar increase in the latency to response offset, affording a smaller window for generating action potentials (Ahissar et al. 2000, 2001; Sosnik et al. 2001). In layer V of SI, which provides feedback to the POM, similar adaptation and latency-delay properties are observed (Ahissar et al.

2000, 2001). The TSR and fidelity of spike timing have not, to our knowledge, been analyzed for paralemniscal responses.

### *Frequency-dependent transformations of spatial activation patterns in SI*

The frequency of vibrissa stimulation not only modulates the spiking behavior of SI neurons, but also the horizontal extent of the cortex activated by stimulation of a vibrissa (the cortical “point spread” function). In the anesthetized rat, stimulation of a vibrissa at 1 Hz evokes a significantly broader point spread than stimulation at 5 or 10 Hz (Fig. 1C) (Sheth et al. 1998). A parallel effect is also observed in awake animals, where infraorbital nerve stimulation recruits a significantly smaller area of SI during whisking than during nonwhisking states (Fanselow et al. 2001), and in anesthetized rats during RF stimulation, where the point spread of activation is similarly restricted (Castro-Alamancos 2002c). Several mechanisms likely contribute to this frequency-dependent spatial restriction of activation (Moore et al. 1999). Feedforward mechanisms include differential adaptation of paralemniscal and lemniscal SI inputs: in SI layer IV, POM neurons project to septal regions that surround the barrel, whereas VPM neurons project to the barrels, suggesting that the lower-frequency adaptation of POM neurons may selectively remove surround activation at higher frequencies. Another potential feedforward mechanism is the synaptic depression of surround thalamocortical projections (Castro-Alamancos 2002c). Intracortical mechanisms that could suppress the lateral spread of activity include intracortical synaptic depression (Markram and Tsodyks 1996; Petersen 2002; Thompson et al. 1993; Varela et al. 1997) and more efficacious recruitment of inhibitory neurons with increasing stimulation frequency (Simons 1978). In general, the finding that spatial restriction occurs with increasing frequency is consistent with the greater susceptibility of relatively weaker surround receptive field synaptic inputs to a variety of kinds of suppression (Moore et al. 1999; Mountcastle and Powell 1959; Simons 1996).

### IMPORTANCE OF FREQUENCY-DEPENDENT NEURAL PROCESSING IN THE VIBRISSA SENSORY SYSTEM

Why are these myriad “filtering” properties of the thalamus and cortex important? One hypothesis is that this pattern of frequency-specific signal transmission optimizes the vibrissa sensory system for either the detection or discrimination of sensory information as a function of the statistics of sensory input (Moore et al. 1999). Specifically, in the 4- to 12-Hz whisking frequency range, the vibrissa sensory system should be optimized for the discrimination of spatial and temporal aspects of sensory stimuli, whereas at lower frequencies of vibrissa motion observed while the rat is in a resting/quiescent state, the system should be optimized for detection of vibrissa contact. As described above (Fig. 1B), during ~4- to 12-Hz stimulation, VPM and SI neurons show more precise spike timing (Garabedian et al. 2003a; Hartings et al. 2003a), and in SI, a more focal extent of activation (Fanselow and Nicolelis 2001; Sheth et al. 1998). When a rat is repetitively whisking against an object (e.g., an edge or corner), this greater fidelity of spike timing and more focal SI cortical point spread should

place the system in an optimal state to make fine temporal and spatial discriminations, respectively. In contrast, during the “resting” and nonwhisking state, where this ~4- to 12-Hz activity context is not present, novel contact on the vibrissae should generate a robust and nonadapted spike transient (equivalent to the greater PSR at low frequencies) and a wider lateral extent of cortical activation. While this larger transient signal and extended cortical point spread are probably not optimal for fine discrimination (however, see Pouget et al. 1999), they would appear to be ideal for the detection of sensory stimuli, a broad and loud “alerting” signal that unanticipated contact has occurred.

These frequency-dependent increases in the apparent specificity of spatial and temporal representation of vibrissa input likely also apply to other sensory features. Preliminary data, for example, suggest that SI receptive field tuning for the angle of vibrissa deflection is more precise at 8 than at 1 Hz (Garabedian et al. 2002). Further, the adaptation observed for a given feature of stimulation (e.g., the direction of vibrissa motion) may not generalize to other stimuli. As such, sudden changes in the pattern of stimulation (e.g., in the angle of vibrissa deflection) likely evoke nonadapted responses that can enhance detection of a novel stimulus feature (Abbott et al. 1997; see Petersen 2002 for a model of this prediction in rat SI and Garabedian et al. 2003b for preliminary evidence for it).

The hypothesis that frequency context optimizes the vibrissa sensory system for detection or discrimination also predicts transitions in optimal perceptual representation within an epoch of object exploration. During a bout of whisking, the first whisk of the vibrissae into a stimulus, like the first deflection in a train of stimuli, will typically have the least refined representation. This initial neural state could allow the rat to optimize object detection. Over the course of multiple whisks and contacts, as during a train of vibrissa deflections, frequency-dependent tuning should refine the stimulus representation, permitting more precise discrimination. As such, the dynamics of the system may facilitate the initial generation of a less-specific representation of the perceived object and subsequent confirmation and improvement of that representation over repeated vibrissa contacts.

#### *Role of thalamic firing states and feedback loops in frequency-dependent processing*

Recent studies have emphasized the potential importance of thalamic firing states and feedback loops in the processing of vibrissa input. Because these ideas have been reviewed extensively (see Ahissar 1998; Ahissar and Kleinfeld 2003; Kleinfeld et al. 1999; Nicolelis and Fanselow 2002), I will discuss them as they relate to the hypothesis presented here, that the statistics of sensory input are crucial for vibrissa sensory processing. As reported by many laboratories, two firing states characterize thalamic sensory relay neuron activity, a bursting and tonic mode (see Sherman 2001 for a review). In the bursting mode, novel stimuli evoke multiple action potentials in a high-frequency onset “burst” followed by a sustained epoch of suppressed firing. In contrast, in the tonic mode, firing activity follows repeated stimulus input more closely, without the postburst suppressive period. Models proposed in the visual system (Sherman 2001) and vibrissa sensory system (Nicolelis and Fanselow 2002) have argued that the burst mode is optimal

for the detection of stimuli because the burst provides a strong onset transient. In contrast, while bursting activity does not closely follow stimulus input, tonic firing is better suited for the “linear” representation of more complex stimulus features. This concept is similar to the proposal (Moore et al. 1999) that low-frequency stimuli are likely to promote detection because of their robust transient activation and that the greater precision in spiking activity (spatial and temporal) observed during ~4- to 12-Hz stimulation facilitates discrimination. Further, a transient stimulus presented to a quiescent rat in a low-frequency context (i.e., not whisking) is likely to drive an onset burst and to trigger whisking (a high-frequency context) and a tonic response firing state (Hartings et al. 2003; Moore et al. 1999; Nicolelis and Fanselow 2002). Thus while quantitative studies of the interaction between the filtering properties recruited by the statistics of sensory input and those dependent on thalamic firing states in the awake rat remain to be conducted, it is consistent to suggest that both features of the system act in concert to optimize perception.

The proposed feedback model of the vibrissa sensory system that has received the greatest theoretical and empirical examination is a phase-locked loop (PLL), a circuit optimal for temporal decoding that relies on the comparison of an input signal with a frequency maintained by a central oscillator. Ahissar, Kleinfeld and colleagues have hypothesized that, at the level of thalamocortical interaction within the vibrissa sensory system, the POM provides a gated input signal that is controlled by SI neural oscillatory activity through layer Va feedback projections (Ahissar and Kleinfeld 2003; Ahissar et al. 2000, 2001; Sosnik et al. 2001). These authors suggest that the latency and PSR adaptation of POM activity provide ideal signals for temporal decoding in the whisking frequency range (Ahissar and Kleinfeld 2003). In support of the suggestion that the vibrissa sensory system implements a PLL, several phenomena predicted by this model have been observed, including frequency-dependent latency shifts in paralemniscal foci and the invariance of POM PSR across stimulus conditions (Sosnik et al. 2001). Further, the spectral components of SI activity evoked by sensory stimulation during ongoing cortical oscillations are consistent with the instantiation of a “mixer” that compares the sums and differences of external and internal frequencies, a key feature of a PLL (Ahrens et al. 2002). The PLL model, and more generally, the view that feedback plays a key role in adaptively transforming sensory input (Sherman and Guillery 1996), is compatible with the concept that frequency-dependent dynamics of VPm and SI impact and potentially optimize information processing in the whisking-frequency range of stimuli. These properties may in fact depend on feedback projections in several ways, including modulation of thalamic postsynaptic depolarization and firing state. Further, SI neural response behavior may promote the frequency-specific processing of information that is essential to the function of a PLL. For example, band-pass behavior in SI (e.g., of vector strength; Garabedian et al. 2003a) may contribute to the band-pass nature of evoked responses in rat primary motor cortex (M1), where responses to sensory stimuli in the whisking frequency range (5–15 Hz) show power only at the stimulation frequency (Kleinfeld et al. 2002).

BEYOND THE WHISKING FREQUENCY RANGE:  
VIBRISSA RESONANCE AND FREQUENCY-  
SPECIFIC AMPLIFICATION OF HIGH-FREQUENCY  
INFORMATION

The studies discussed thus far suggest that, for stimuli occurring in the whisking frequency range (e.g., <20 Hz), information processing by the rat is informed by neural dynamics in VPM and SI neurons. Stimulus contact conditions like the repeated striking of an edge with subsequent whisk cycles would generate this kind of perceptual context. However, when a whisking rodent sweeps its vibrissae over an extended surface, contact with microgeometric features on that surface likely generate frequencies much higher than the whisking frequency rate. As diagrammed in Fig. 1A (*right*), the sweep of a vibrissa over five surface ridges during a whisk cycle should, if whisking is occurring at 8 Hz, create a  $\geq 80$  Hz oscillatory vibration of the vibrissa. This example describes a low estimate of the frequencies generated during surface perception: Naturally encountered textures should drive much higher frequencies of vibration, because vibrissa contact with sandpaper at realistic velocities generates microvibrations in the hundreds of Hertz (Fend et al. 2003; Neimark et al. 2003). Under these conditions, whisking may be better understood as a carrier frequency on which higher-frequency vibrations occur.

A key step in the processing of these high-frequency signals may occur in the initial transduction of sensory information, because the vibrissae may amplify high-frequency inputs and act as frequency-specific band-pass filters due to their resonance properties (Fig. 2). When vibrissae are presented with stimuli that simulate contact over a surface (using either controlled piezoelectric stimulation or a "natural" surface rolled across the vibrissae, such as sandpaper or a grating) they resonate, showing significantly greater amplitude of motion when stimulated at their fundamental resonance frequency (Fig. 2) (Neimark et al. 2003). Resonance-dependent amplification for texture-like stimuli can be significant, because many vibrissae demonstrate greater than a 10-fold increase in motion amplitude at their fundamental resonance frequency, and the frequency tuning precise, because many vibrissae have band-pass filter characteristics that are as well-tuned as band-pass elements of the auditory system (Fig. 2C) (Neimark et al. 2003). Not only are individual vibrissae tuned for specific frequencies, but this frequency tuning is organized in a systematic map across the rat face. Because the fundamental resonance frequency varies inversely with the length of a beam or of a vibrissa (Hartmann et al. 2003; Landau and Lifshitz 1975; Neimark 2001; Neimark et al. 2003), the long vibrissae at the back of the face are more responsive to lower tip-stimulation frequencies and those on the front of the face to higher frequencies, providing an anterior-posterior frequency amplification map (Fig. 2). Recent studies suggest that these peripheral transduction properties are translated into neural frequency tuning and a somatotopic SI frequency map (Andermann et al., 2004).

*Role of vibrissa resonance in detection and discrimination*

Rats show high acuity for the perception of textures (Carvell and Simons 1990, 1995; Guic-Robles et al. 1989, 1992), and vibrissa resonance may facilitate the detection and discrimination of these surfaces (Neimark et al. 2003). The propensity of

vibrissae to resonate should allow greater overall amplification of signals that have higher-frequency components (e.g., rougher surfaces), facilitating the detection of increased spatial frequency. Further, the map of frequency tuning across the face should allow the animal to discriminate between different spatial frequencies by the pattern of somatotopic frequency amplification, with greater activity more posterior on the face indicating lower spatial frequency surfaces and vice versa. Similarly, vibrissa resonance could also facilitate the discrimination of frequency-specific stimuli transmitted in the air, such as sound pressure waves that are beneath the audible range of rodents ( $\sim 250$  Hz is the low-frequency boundary of rat hearing; Kelly and Masterton 1977) or air currents generated by wind or by other animals (e.g., which may have different laminar or turbulent air flow properties and frequency "signatures" as a function of stimulus origin; Rinberg and Davidowitz 2000). These vibrissa biomechanical properties may also contribute to other aspects of sensory perception. Hartmann et al. (2003) demonstrated resonance following vibration of the vibrissa at the base and have provided evidence in the behaving rat that vibrissae resonate when they spring forward after contact with a bar. In this context, these vibrissa oscillations could provide an "end stop" signal for vibrissa motion past an edge.

DISTINCT HIGH- AND LOW-FREQUENCY  
PROCESSING MODES IN SI?

The apparent importance of high-frequency vibrissa vibration raises an important question. Area SI is essential for texture perception by rats (Guic-Robles et al. 1992; as it also is for frequency discrimination in monkeys, LaMotte and Mountcastle 1979), suggesting that a frequency-specific representation is present in SI. However, as shown in Fig. 1B, SI shows substantial spike rate adaptation to frequencies  $\geq 20$  Hz. This adaptation would appear to prevent the effective representation in SI of the higher frequencies ( $\geq 80$  Hz) that are generated by textured stimuli, even if these stimuli are differentially amplified by vibrissa resonance. A resolution to this apparent conflict is that SI, and more generally the vibrissa sensory system, may have distinct low- and high-frequency processing modes. While direct investigation of this hypothesis is lacking, several lines of evidence support it. First, recent studies in which sinusoidal stimuli were applied show that SI neurons are responsive to stimuli  $\geq 100$  Hz (Andermann et al.; 2004; Arabzadeh et al. 2003; Detsch et al. 2002). Second, when behaving rats sweep their vibrissae over textured surfaces, sustained increases in SI neural firing are observed, suggesting that these responses are at least in part driven by the high-frequency components in textured stimuli (Kelly et al. 1999; Prigg et al. 2002). Third, task-specific control of thalamic gating could permit the transmission of high-frequency information to SI in the behaving animal: if VPM neurons in the awake, whisking animal are sufficiently depolarized, synaptic depression could be overcome and the high-frequency EPSPs that are transmitted to the VPM translated to spiking activity (Castro-Alamancos 2002a,b; Deschenes et al. 2003). In this case, the high-pass fidelity in spike timing of the VPM should enhance the reliable transmission of high-frequency information to SI, presuming these findings extend to frequencies above 40 Hz (Hartings et al. 2003). Fourth, Barth and colleagues have identified intrinsic

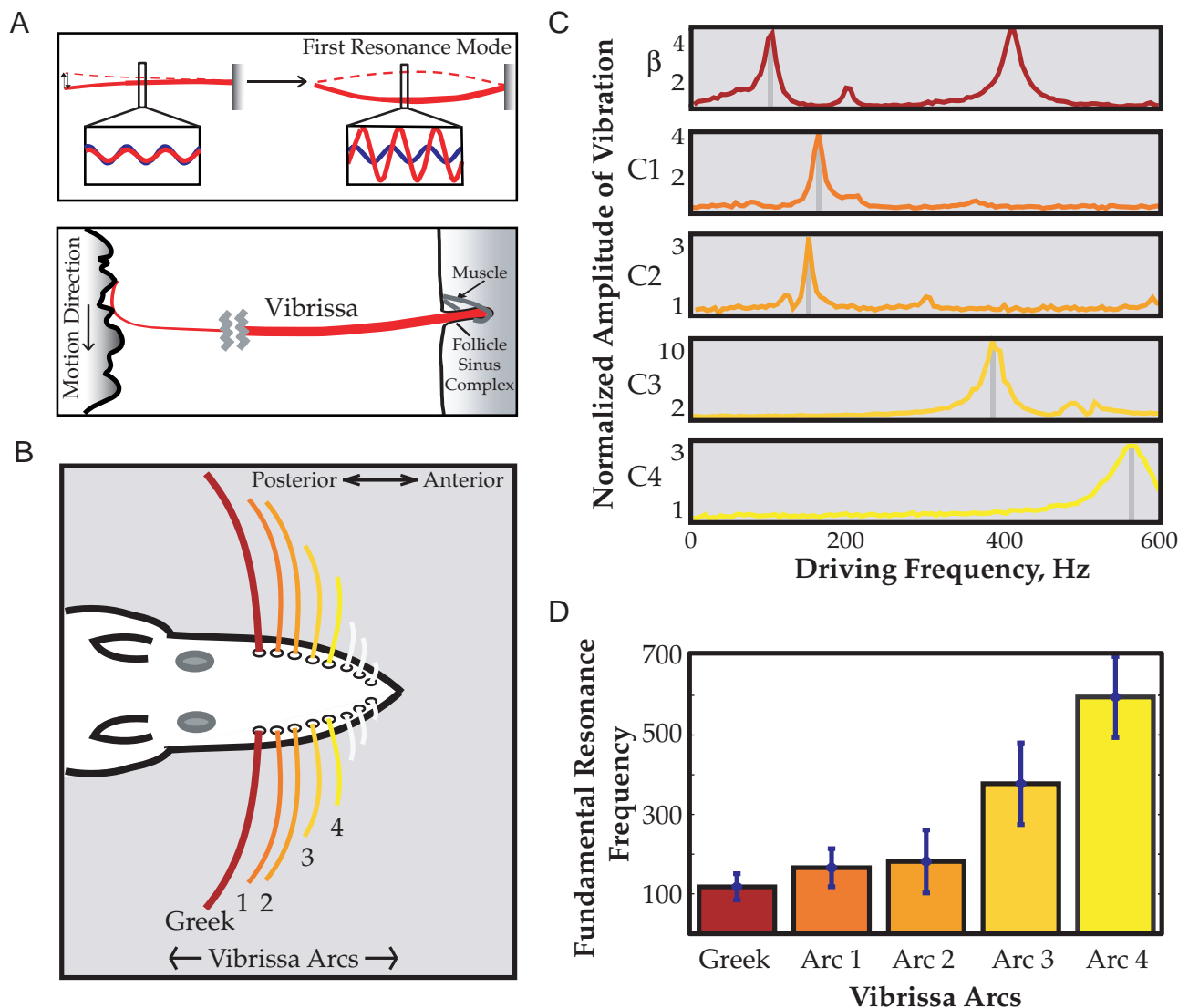


FIG. 2. Vibrissa resonance may contribute to the encoding of high-frequency stimuli. *A: (top)* when a thin elastic beam is vibrated, it will demonstrate resonance modes, frequencies at which the motion of the beam is selectively amplified. *Bottom:* a vibrissa can be modeled as a thin elastic beam (Hartmann et al. 2003; Neimark 2001; Neimark et al. 2003), leading to the prediction that the high-frequency microvibrations generated when a vibrissa is swept over a texture will induce resonance amplification. Furthermore, the behavior of a thin elastic beam suggests that longer vibrissae should demonstrate lower fundamental resonance frequencies, such that more posterior vibrissae should show lower frequency tuning. *B:* vibrissae on the rat face are organized into distinct anterior-posterior rows and dorsal-ventral arcs. As shown in this top-down view, more posterior vibrissa arcs have longer vibrissae than more anterior arcs. *C:* examples of the motion amplitude of a set of C-row vibrissae, driven across a range of frequencies by stimulation at the vibrissa tip. At the fundamental resonance frequency (gray vertical bars), each vibrissa shows several-fold amplification of its range of motion and relatively sharp frequency tuning around that peak. *D:* systematic increase in the vibrissa fundamental resonance frequency is demonstrated in measurements across multiple vibrissae from the Greek to the 4-arc. This pattern of frequency tuning creates a spatial anterior-posterior map of frequency across the rat face that may facilitate high-frequency perception by the vibrissae, including the detection and discrimination of textured stimuli (figure adapted with permission from Neimark et al. 2003).

high-frequency rhythms in the SI vibrissa representation at >200 Hz (e.g., Barth 2003; Staba et al. 2003): how these rhythms impact information processing remains an open question, but they provide evidence that the circuitry of rat SI vibrissa cortex can maintain these high-frequency signals. Fifth, in the cat SI vibrissa representation, inhibitory postsynaptic potentials adapt significantly to stimulation  $\geq 40$  Hz, and in at least a subset of cases, this decreased inhibition is coincident with a higher action potential firing rate in SI at 100 than at 20 Hz (Hellweg et al. 1977). Sixth, Keller and colleagues

have shown, using voltage-sensitive dyes in rat SI thalamocortical slices, that 100-Hz bursts evoke a greater lateral spread of signal in SI than <1-Hz stimuli, an effect blocked by *N*-methyl-D-aspartate (NMDA) receptor blockade (Laaris et al. 2000; see also Swadlow and Gusev 2002). These latter two studies suggest that both disinhibition and summing excitation provide neural mechanisms in SI for greater response to high-frequency, as opposed to lower-frequency, stimuli. Seventh, neurons throughout the lemniscal pathway, including SI, are acutely sensitive to high-velocity/acceleration vibrissa

stimulation (e.g., Hartings et al. 2003; Minnery and Simons 2003; Pinto et al. 2000; Temereanca and Simons 2003). As recently emphasized by Arabzadeh et al. (2003), velocity sensitivity predicts activation in SI to high-frequency sinusoidal inputs: for sinusoidal stimuli, as frequency increases, velocity and acceleration increase as frequency  $\times$  amplitude and as frequency squared  $\times$  amplitude, respectively. This sensitivity may allow high-frequency increases in velocity and acceleration to overcome suppressive mechanisms and drive responses in SI that are not observed for lower frequency (e.g., lower velocity) stimuli. While speculative, these several considerations suggest that there may be distinct high- and low-frequency processing modes in SI, permitting the system to overcome lower frequency adaptation.

## CONCLUSION

The studies reviewed here indicate that low-frequency stimulus processing in the vibrissa sensory system is modulated by the neural filtering properties of the thalamus and cortex, and high-frequency processing is modulated by the frequency tuning of the vibrissae themselves. In several respects, these observations are potentially important beyond their application to the vibrissa sensory system. The primary auditory and somatosensory cortices of the cat share at least a subset of the frequency-specific neural response characteristics observed in the 1- to 40-Hz range in rat SI (Eggermont 1991, 1999; Hellweg et al. 1977), meaning that the results obtained in the model vibrissa sensory system may apply directly to other systems. Further, similar findings in primate association cortices have led to the hypothesis that adaptation plays a key role in cognitive tasks, including verbal working memory and object recognition (for a review, see Ranganath and Rainer 2003). The discovery of vibrissa resonance suggests several parallels to encoding by the cochlea, because both transduction mechanisms use resonance to establish a spatial frequency map. This correspondence implies that touch and audition have realized convergent evolutionary solutions to the problem of frequency encoding. The suggestion that distinct low- and high-frequency processing modes exist in SI is similar to the proposal that distinct flutter and vibratory processing channels exist in primate perception (Bolanowski et al. 1988; Mountcastle et al. 1972). The flutter-vibration distinction in large part derives from differences in the intrinsic transduction properties of peripheral receptors: an important future direction in study of the vibrissa sensory system will be the relation of anatomically identified specific receptor endings (Ebara et al. 2002) with firing properties.

Alternatively, the frequency-specific aspects of the vibrissa sensory system described here could be epiphenomenal and may not impact (or could even impair) optimal perception by the awake and behaving animal. Determination of the importance of these observations will require targeted studies examining the relevance of frequency-specific neural dynamics and of vibrissa resonance in the context of varying neuromodulatory, EEG, and behavioral states. Given the utility of the rodent vibrissa sensory system for a wide variety of approaches, ranging from genetic manipulation (e.g., knockout mice, Tonegawa et al. 1995) to behavioral models (Skinner 1974), this preparation is ideally positioned for the pursuit of these important questions.

## ACKNOWLEDGMENTS

The author thanks M. Andermann, C. Cheney, C. Garabedian, S. Jones, A. Nelson, J. Ritt, G. Stanley, and a reviewer for helpful comments on the manuscript.

## REFERENCES

- Abbott LF, Varela JA, Sen K, and Nelson SB.** Synaptic depression and cortical gain control. *Science* 275: 220–224, 1997.
- Ahissar E.** Temporal-code to rate-code conversion by neuronal phase-locked loops. *Neural Comput* 10: 597–650, 1998.
- Ahissar E and Kleinfeld D.** Closed-loop neuronal computations: focus on vibrissa somatosensation in rat. *Cereb Cortex* 13: 53–62, 2003.
- Ahissar E, Sosnik R, Bagdasarian K, and Haidarliu S.** Temporal frequency of whisker movement. II. Laminar organization of cortical representations. *J Neurophysiol* 86: 354–367, 2001.
- Ahissar E, Sosnik R, and Haidarliu S.** Transformation from temporal to rate coding in a somatosensory thalamocortical pathway. *Nature* 406: 302–306, 2000.
- Ahrens KF, Levine H, Suhl H, and Kleinfeld D.** Spectral mixing of rhythmic neuronal signals in sensory cortex. *Proc Natl Acad Sci USA* 99: 15176–15181, 2002.
- Andermann ML, Ritt J, Neimark MA, and Moore CI.** Neural correlates of vibrissa resonance: band-pass & somatotopic representation of high frequency stimuli. *Neuron* In press.
- Arabzadeh E, Petersen RS, and Diamond ME.** Encoding of whisker vibration by rat barrel cortex neurons: Implications for texture discrimination. *J Neurosci* 23: 9146–9154, 2003.
- Barth DS.** Submillisecond synchronization of fast electrical oscillations in neocortex. *J Neurosci* 23: 2502–2510, 2003.
- Bolanowski SJ Jr, Gescheider GA, Verillo RT, and Checkosky CM.** Four channels mediate the mechanical aspects of touch. *J Acoust Soc Am* 84: 1680–1694, 1988.
- Brecht M, Preilowski B, and Merzenich MM.** Functional architecture of the mystacial vibrissae. *Behav Brain Res* 84: 81–97, 1997.
- Carvell GE and Simons DJ.** Biometric analyses of vibrissal tactile discrimination in the rat. *J Neurosci* 10: 2638–2648, 1990.
- Carvell GE and Simons DJ.** Task- and subject-related differences in sensorimotor behavior during active touch. *Somat Mot Res* 12: 1–9, 1995.
- Carvell GE and Simons DJ.** Abnormal tactile experience early in life disrupts active touch. *J Neurosci* 16: 2750–2757, 1996.
- Castro-Alamancos MA.** Different temporal processing of sensory inputs in the rat thalamus during quiescent and information processing states in vivo. *J Physiol* 539: 567–578, 2002a.
- Castro-Alamancos MA.** Properties of primary sensory (lemniscal) synapses in the ventrobasal thalamus and the relay of high-frequency sensory inputs. *J Neurophysiol* 87: 946–953, 2002b.
- Castro-Alamancos MA.** Role of thalamocortical sensory suppression during arousal: Focusing sensory inputs in neocortex. *J Neurosci* 22: 9651–9655, 2002c.
- Castro-Alamancos MA and Oldford E.** Cortical sensory suppression during arousal is due to the activity-dependent depression of thalamocortical synapses. *J Physiol* 541: 319–331, 2002.
- Chung S, Li X, and Nelson SB.** Short-term depression at thalamocortical synapses contributes to rapid adaptation of cortical sensory responses in vivo. *Neuron* 34: 437–446, 2002.
- Dehnhardt G, Hyvarinen H, Palviainen A, and Klauer G.** Structure and innervation of the vibrissal follicle-sinus complex in the Australian water rat, *Hydromys chrysogaster*. *J Comp Neurol* 11: 550–562, 1999.
- Dehnhardt G, Mauck B, Hanke W, and Bleckmann H.** Hydrodynamic trail-following in harbor seals (*Phoca vitulina*). *Science* 293: 102–104, 2001.
- Deschenes M, Timofeeva E, and Lavallee P.** The relay of high-frequency sensory signals in the Whisker-to-barreloid pathway. *J Neurosci* 23: 6778–6787, 2003.
- Detsch O, Kochs E, Siemers M, Bromm B, and Vahel-Hinz C.** Increased responsiveness of cortical neurons in contrast to thalamic neurons during isoflurane-induced EEG bursts in rats. *Neurosci Lett* 317: 9–12, 2002.
- Diamond ME, Armstrong-James M, and Ebner FF.** Somatic sensory responses in the rostral sector of the posterior group (POM) and in the ventral posterior medial nucleus (VPM) of the rat thalamus. *J Comp Neurol* 318: 462–476, 1992.
- Ebara S, Kumamoto K, Matsuura T, Mazurkiewicz JE, and Rice FL.** Similarities and differences in the innervation of mystacial vibrissal follicle-

- sinus complexes in the rat and cat: A confocal microscopic study. *J Comp Neurol* 449: 103–119, 2002.
- Eggermont JJ.** Rate and synchronization measures of periodicity coding in cat primary auditory cortex. *Hearing Res* 56: 153–167, 1991.
- Eggermont JJ.** The magnitude and phase of temporal modulation transfer functions in cat auditory cortex. *J Neurosci* 19: 2780–2788, 1999.
- Fanselow E and Nicolelis M.** Behavioral modulation of tactile responses in the rat somatosensory system. *J Neurosci* 19: 7603–7619, 1999.
- Fanselow EE, Sameshima K, Baccala LA, and Nicolelis MA.** Thalamic bursting in rats during different awake behavioral states. *Proc Natl Acad Sci USA* 98: 15330–15335, 2001.
- Fee MS, Mitra PP, and Kleinfeld D.** Central versus peripheral determinants of patterned spike activity in rat vibrissa cortex during whisking. *J Neurophysiol* 78: 1144–1149, 1997.
- Fend M, Bovet S, Yokoi H, and Pfeifer R.** An active artificial whisker array for texture discrimination. Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, Las Vegas, NV, 2003.
- Garabedian CE, Andermann ML, Merzenich MM, and Moore CI.** Direction-specific adaptation of rat SI neurons. *Soc Neurosci Abstr* 24, 2003a.
- Garabedian CE, Jones SR, Merzenich MM, Dale A, and Moore CI.** Band-pass response properties of rat SI neurons. *J Neurophysiol* 90: 1379–1391, 2003b.
- Garabedian CE, Merzenich MM, and Moore CI.** Frequency dependent sharpening of direction tuning in rat SI. *Soc Neurosci Abstr* 814.12, 2002.
- Geisler C.** *From Sound to Synapse*. New York: Oxford, 1998.
- Guic-Robles E, Jenkins WM, and Bravo H.** Vibrissal roughness discrimination is barrel cortex-dependent. *Behav Brain Res* 48: 145–152, 1992.
- Guic-Robles E, Valdivieso C, and Guajardo G.** Rats can learn a roughness discrimination using only their vibrissal system. *Behav Brain Res* 31: 285–289, 1989.
- Hartings JA, Temereanca S, and Simons DJ.** Processing of periodic whisker deflections by neurons in the ventroposterior medial and thalamic reticular nuclei. *J Neurophysiol* 90: 3087–3094, 2003.
- Hartmann MJ, Johnson NJ, Towal RB, and Assad C.** Mechanical characteristics of rat vibrissae: resonant frequencies and damping in isolated whiskers and in the awake behaving animal. *J Neurosci* 23: 6510–6519, 2003.
- Harvey MA, Bermejo R, and Zeigler HP.** Discriminative whisking in the head-fixed rat: optoelectronic monitoring during tactile detection and discrimination tasks. *Somat Mot Res* 18: 211–222, 2001.
- Hellweg FC, Schultz W, and Creutzfeldt OD.** Extracellular and intracellular recordings from cat's cortical whisker projection area: thalamocortical response transformation. *J Neurophysiol* 40: 463–479, 1977.
- Hutson KA and Masterton RB.** The sensory contribution of a single vibrissa's cortical barrel. *J Neurophysiol* 56: 1196–1223, 1986.
- Kelly JB and Masterton B.** Auditory sensitivity of the albino rat. *J Comp Physiol Psychol* 91: 930–936, 1977.
- Kelly MK, Carvell GE, Kodger JM, and Simons DJ.** Sensory loss by selected whisker removal produces immediate disinhibition in the somatosensory cortex of behaving rats. *J Neurosci* 19: 9117–9125, 1999.
- Kiang NY, Pfeiffer RR, Warr WB, and Backus AS.** Stimulus coding in the cochlear nucleus. *Trans Am Otol Soc* 53: 35–58, 1965.
- Kleinfeld D, Berg RW, and O'Connor SM.** Anatomical loops and their electrical dynamics in relation to whisking by rat. *Somat Mot Res* 16: 69–88, 1999.
- Kleinfeld D, Sachdev RN, Merchant LM, Jarvis MR, and Ebner FF.** Adaptive filtering of vibrissa input in motor cortex of rat. *Neuron* 34: 1021–1034, 2002.
- Kyriazi HT, Carvell GE, Brumberg JC, and Simons DJ.** Effects of baclofen and phaclofen on receptive field properties of rat whisker barrel neurons. *Brain Res* 712: 325–328, 1996.
- Kyriazi HT, Carvell GE, Brumberg JC, and Simons DJ.** Quantitative effects of GABA and bicuculline methiodide on receptive field properties of neurons in real and simulated whisker barrels. *J Neurophysiol* 75: 547–560, 1996.
- Laaris N, Carlson GC, and Keller A.** Thalamic-evoked synaptic interactions in barrel cortex revealed by optical imaging. *J Neurosci* 20: 1529–1537, 2000.
- LaMotte RH and Mountcastle VB.** Disorders in somesthesia following lesions of parietal lobe. *J Neurophysiol* 42: 400–419, 1979.
- Landau L and Lifshitz E.** *Theory of Elasticity*. Oxford, UK: Pergamon Press, 1975.
- Lee SM, Friedberg MH, and Ebner FF.** The role of GABA-mediated inhibition in the rat ventral posterior medial thalamus. I. Assessment of receptive field changes following thalamic reticular nucleus lesions. *J Neurophysiol* 71: 1702–1715, 1994.
- Markram H and Tsodyks MV.** Redistribution of synaptic efficacy between neocortical pyramidal neurons. *Nature* 382: 807, 1996.
- Merzenich MM and Brugge JF.** Representation of the cochlear partition of the superior temporal plane of the macaque monkey. *Brain Res* 50: 275–296, 1973.
- Minnery BS and Simons DJ.** Response properties of whisker-associated trigeminothalamic neurons in rat nucleus principalis. *J Neurophysiol* 89: 40–56, 2003.
- Moore CI and Nelson SB.** Spatio-temporal subthreshold receptive fields in the vibrissa representation of rat primary somatosensory cortex. *J Neurophysiol* 80: 2882–2892, 1998.
- Moore CI, Nelson SB, and Sur M.** Dynamics of neuronal processing in rat somatosensory cortex. *Trends Neurosci* 22: 513–520, 1999.
- Mountcastle VB, LaMotte RH, and Carli G.** Detection thresholds for stimuli in humans and monkeys: comparison with threshold events in mechanoreceptive afferent nerve fibers innervating the monkey hand. *J Neurophysiol* 35: 122–136, 1972.
- Mountcastle VB and Powell TPS.** Neural mechanisms subserving cutaneous sensibility, with special reference to the role of afferent inhibition in sensory perception and discrimination. *Bull Johns Hopkins Hosp* 105: 173–200, 1959.
- Mountcastle VB, Talbot WH, Sakata H, and Hyvarinen J.** Cortical neuronal mechanisms in flutter-vibration studied in unanesthetized monkeys: neuronal periodicity and frequency discrimination. *J Neurophysiol* 32: 453–484, 1969.
- Neimark M.** *The mechanics of whisking: the first stage of transduction of surface textures into neural signals*. (Thesis). Princeton, NJ: Princeton University, 2001.
- Neimark M, Andermann M, Hopfield J, and Moore CI.** Vibrissa resonance as a transduction mechanism for tactile encoding. *J Neurosci* 23: 6499–6509, 2003.
- Nicolelis MA and Fanselow EE.** Thalamocortical optimization of tactile processing according to behavioral state. *Nat Neurosci* 5: 517–523, 2002.
- Petersen CC.** Short-term dynamics of synaptic transmission within the excitatory neuronal network of rat layer 4 of barrel cortex. *J Neurophysiol* 87: 2904–2914, 2002.
- Petersen CC and Sakmann B.** Functionally independent columns of rat somatosensory barrel cortex revealed with voltage-sensitive dye imaging. *J Neurosci* 21: 8435–8446, 2001.
- Pinto DJ, Brumberg JC, and Simons DJ.** Circuit dynamics and coding strategies in rodent somatosensory cortex. *J Neurophysiol* 83: 1158–1166, 2000.
- Pouget A, Deneve S, Ducom JC, and Latham PE.** Narrow versus wide tuning curves: what's best for a population code? *Neural Comput* 11: 85–90, 1999.
- Prigg T, Goldreich D, Carvell GE, and Simons DJ.** Texture discrimination and unit recordings in the rat whisker/barrel system. *Physiol Behav* 77: 671–675, 2002.
- Ranganath C and Rainer G.** Neural mechanisms for detecting and remembering novel events. *Nat Rev Neurosci* 4: 193–202, 2003.
- Rieke F, Warland, D, de Ruyter van Steveninck R, and Bialek W.** *Spikes: Exploring the Neural Code*. Cambridge, MA: MIT Press, 1997.
- Rinberg D and Davidowitz H.** Do cockroaches 'know' fluid dynamics? *Nature* 405: 756, 2000.
- Romo R, Hernandez A, Salinas E, Brody CD, Zainos A, Lemus L, de Lafuente V, and Luna R.** From sensation to action. *Behav Brain Res* 135: 105–118, 2002.
- Sherman SM and Guillery, RW.** Functional organization of thalamocortical relays. *J Neurophysiol* 76: 1367–1395, 1996.
- Sheth BR, Moore CI, and Sur M.** Temporal modulation of spatial borders in rat barrel cortex. *J Neurophysiol* 79: 464–470, 1998.
- Simons DJ.** Response properties of vibrissa units in rat SI somatosensory neocortex. *J Neurophysiol* 41: 798–820, 1978.
- Simons DJ.** Neuronal integration in the somatosensory whisker/barrel cortex. In: *Cerebral Cortex*, edited by Jones EG and Diamond IT. New York: Plenum Press, 1995, p. 263–298.
- Skinner BF.** *About Behaviorism*. New York: Knopf, 1974.
- Sosnik R, Haidarliu S, and Ahissar E.** Temporal frequency of whisker movement. I. Representations in brain stem and thalamus. *J Neurophysiol* 86: 339–353, 2001.
- Staba RJ, Brett-Green B, Paulsen M, and Barth DS.** Effects of ventrobasal lesion and cortical cooling on fast oscillations (>200 Hz) in rat somatosensory cortex. *J Neurophysiol* 89: 2380–2388, 2003.

- Swadlow HA.** Fast-spike interneurons and feedforward inhibition in awake sensory neocortex. *Cereb Cortex* 13: 25–32, 2003.
- Swadlow HA, Beloozerova IN, and Sirota MG.** Sharp, local synchrony among putative feedforward inhibitory interneurons of rabbit somatosensory cortex. *J Neurophysiol* 79: 567–582, 1998.
- Swadlow HA and Gusev AG.** Receptive-field construction in cortical inhibitory interneurons. *Nat Neurosci* 5: 403–404, 2002.
- Temereanca S and Simons DJ.** Local field potentials and the encoding of whisker deflections by population firing synchrony in thalamic barreloids. *J Neurophysiol* 89: 2137–2145, 2003.
- Thomson AM, Deuchars J, and West DC.** Large, deep layer pyramid-pyramid single axon EPSPs in slices of rat motor cortex display paired pulse and frequency-dependent depression, mediated presynaptically and self-facilitation, mediated postsynaptically. *J Neurophysiol* 70: 2354–2369, 1993.
- Tonegawa S, Li Y, Erzurumlu RS, Jhaveri S, Chen C, Goda Y, Paylor R, Silva AJ, Kim JJ, Wehner JM, Stevens CF, and Abeliovich A.** The gene knockout technology for the analysis of learning and memory, and neural development. *Prog Brain Res* 105: 3–14, 1995.
- Varela JA, Sen K, Gibson J, Fost J, Abbott LF, and Nelson SB.** A quantitative description of short-term plasticity at excitatory synapses in layer 2/3 of rat primary visual cortex. *J Neurosci* 17: 7926–7940, 1997.
- Welker WI.** Analysis of sniffing of the albino rat. *Behavior* 12: 223–244, 1964.
- Woolsey TA and Van der Loos H.** The structural organization of layer IV in the somatosensory region (SI) of mouse cerebral cortex. The description of a cortical field composed of discrete cytoarchitectonic units. *Brain Res* 17: 205–242, 1970.
- Zhu JJ and Connors BW.** Intrinsic firing patterns and whisker-evoked synaptic responses of neurons in the rat barrel cortex. *J Neurophysiol* 81: 1171–1183, 1999.