# Dynamics of neuronal processing in rat somatosensory cortex

Christopher I. Moore, Sacha B. Nelson and Mriganka Sur

**Recently, the study of sensory cortex has focused on the context-dependent evolution of receptive fields and cortical maps over millisecond to second timescales. This article reviews advances in our understanding of these processes in the rat primary somatosensory cortex (SI). Subthreshold input to individual rat SI neurons is extensive, spanning several vibrissae from the center of the receptive field, and arrives within 25 ms of vibrissa deflection. These large subthreshold receptive fields provide a broad substrate for rapid excitatory and inhibitory multi-vibrissa interactions. The 'whisking' behavior, an ~8 Hz ellipsoid movement of the vibrissae, introduces a context-dependent change in the pattern of vibrissa movement during tactile exploration. Stimulation of vibrissae over this frequency range modulates the pattern of activity in thalamic and cortical neurons, and, at the level of the cortical map, focuses the extent of the vibrissa representation relative to lower frequency stimulation (1 Hz). These findings suggest that one function of whisking is to reset cortical organization to improve tactile discrimination. Recent discoveries in primary visual cortex (VI) demonstrate parallel non-linearities in center-surround interactions in rat SI and VI, and provide a model for the rapid integration of multi-vibrissa input. The studies discussed in this article suggest that, despite its original conception as a uniquely segregated cortex, rat SI has a wide array of dynamic interactions, and that the study of this region will provide insight into the general mechanisms of cortical dynamics engaged by sensory systems.**

*Trends Neurosci.* (1999) 22, 513–520

AS FIRST OBSERVED by Woolsey and Van der Loos, the rodent primary somatosensory cortex (SI) vibrissa representation contains a map of discrete layer-IV-cell clusters ('barrels') that correlate on a one-to-one basis with the facial vibrissae[1] (Fig. 1). Subsequent studies demonstrated that afferents from the primary thalamic somatosensory nucleus [the ventral posterior medial (VPm) nucleus] to layer IV typically terminate within a barrel[3–5], and dendrites of layer-IV neurons tend to respect barrel boundaries[6,7], further reinforcing the discrete nature of the vibrissa representation. In correspondence with these anatomical features, the initial electrophysiological studies of the rat SI vibrissa representation emphasized the pointillistic nature of its receptive fields. For example, in the barbiturate anesthetized rat, neurons in a given layer-IV barrel responded to input from only the somatotopically appropriate vibrissa[8,9].

In contrast to this conception of the projection from a vibrissa to its cortical barrel as a labeled line, more-recent studies have demonstrated extensive spatial and temporal integration of sensory input throughout the depth of rat SI. Over longer timescales (hours to days), the adult rat SI representation is plastic following

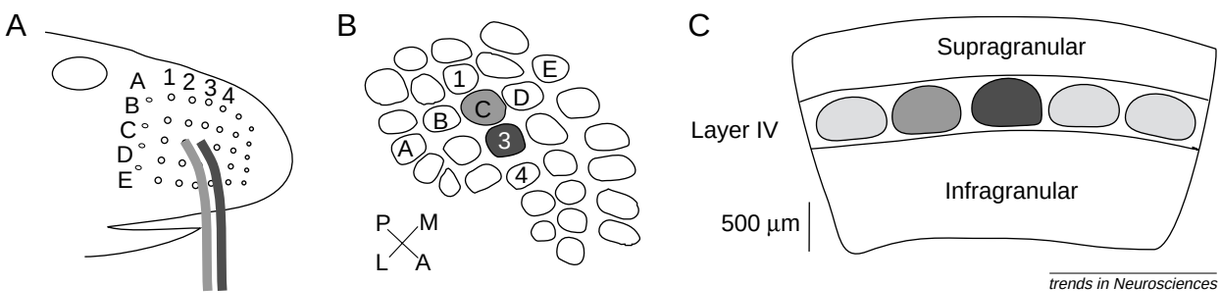


**Fig. 1.** ***The correlation between the vibrissae and the rat primary somatosensory cortex (SI) barrels.*** **(A)** *The lateral surface of the rat's face is covered with vibrissae aligned in regularly spaced rows and arcs. These are conventionally labeled by letters (rows) and numbers (arcs).* **(B)** *The barrels, which are clusters of cells in layer IV, form a map of the vibrissae on the rat's face when viewed in the tangential plane. This diagram is a reconstruction of the barrels in the rat SI vibrissa representation from a cytochrome-oxidase stained cortex in tangential section. The light- and dark-gray vibrissae in* (A) *correspond to the light- and dark-gray barrels in* (B). **(C)** *A schematic of a coronal section through the barrel cortex with corresponding light- and dark-gray barrels. Abbreviations: A, anterior; L, lateral; M, medial; P, posterior.* (B) Adapted, with permission, from Ref. 2.

*Christopher I. Moore and Mriganka Sur are at the Dept of Brain and Cognitive Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA, and Sacha B. Nelson is at the Dept of Biology, Brandeis University, Waltham, MA 02254-9110, USA.*

 PII: S0166-2236(99)01452-6

## Box 1. New techniques for investigating rat SI cortex:

Two relatively new techniques, whole-cell *in vivo* recording and intrinsic-signal optical imaging, have improved our understanding of the the organization and reorganization of rat somatosensory cortex (SI).

**Whole-cell *in vivo* recording**

Whole-cell *in vivo* recording techniques follow in a long tradition of *in vivo* intracellular recording in the mammalian somatosensory cortex using 'sharp' intracellular electrodes[a–f]. Using whole-cell recording *in vivo*, it is possible to achieve the tight recording relationship that characterizes the whole-cell recording approach *in vitro*[g] (Fig. IA). This configuration between electrode and neuron has several advantages for *in vivo* recording. First, it permits superior control of the voltage of the cell membrane. Second, the whole-cell recording relationship adds stability to the electrode–neuron connection. Stability of the recording is a major concern for *in vivo* intracellular recording, as several factors, including cortical pulsations with the heart rate and respiration, present mechanical noise that is not present *in vitro*. Using this technique, neurons can be held for more than 3 h, which permits relatively extensive receptive-field mapping of the vibrissa field[h,j]. Third, agents placed in the whole-cell electrode can be diffused discretely into the cell, allowing for cell-specific block of specific currents, a powerful tool for investigating aspects of local circuit versus aspects of single-neuron sensory integration[k].

**Intrinsic-signal optical imaging**

Intrinsic-signal optical imaging has recently been applied to the investigation of several cortical systems, including the cat and monkey visual cortex[l–o], rat auditory cortex[p], human SI (Refs q,r) and rat SI (Refs s–gg). The basic approach of

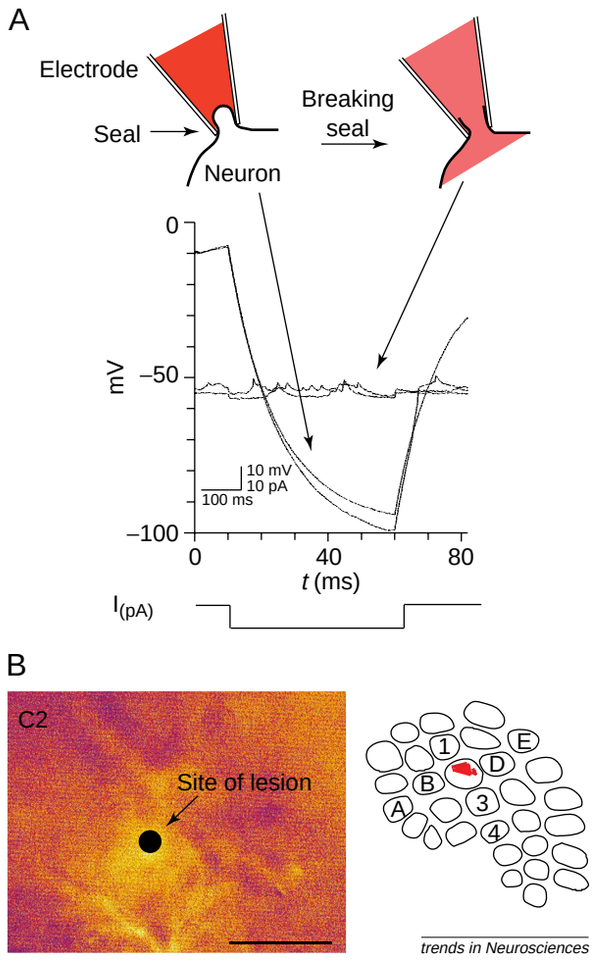


**Fig. I.** ***Whole-cell* in vivo *recording and intrinsic-signal optical imaging in rat somatosensory cortex.*** **(A)** *The whole-cell recording relationship is achieved by removing back pressure on the tip of the electrode when it is resting against the neuronal membrane, forming a seal of several GΩ in magnitude (top left). When the membrane is ruptured (top right), the tight connection between electrode and membrane is preserved, which provides superior control over the electrical properties of the neural membrane and lends mechanical stability to the connection. Traces are shown for an* in vivo *recording prior to rupturing the seal (below, large amplitude voltage changes resulting from current steps in the presence of the high-resistance seal) and after rupturing the neuronal membrane (recording of resting membrane potential at ~−55 mV; arrows identify the responses elicited pre- and post-break-in).* **(B)** *The correlation between the location of the peak intrinsic optical signal and the center of the barrels is robust. As shown in the pseudocolor image, stimulation of the C2 vibrissa causes a localized increase in the intrinsic signal (yellow pseudocolor indicates maximal optical signal; scale bar, 1 mm). The peak of optical signal was centered over the histologically defined C2 barrel, which was marked with an electrolytic lesion. The letters mark the position of the barrel rows, the numbers mark the position of barrel arcs and the red indicates the site of the lesion. Scale bar, 1 mm.* (A) adapted, with permission, from Ref. h, and (B) adapted, with permission, from Ref. i.

non-invasive changes in the pattern of vibrissa input[10–14]. Over more rapid timescales (milliseconds to seconds) rat SI neurons are also influenced by a broad spatial range of vibrissa input. Recent studies have observed multi-vibrissa suprathreshold (action potential) receptive fields in all layers of rat SI (Refs 15–18). Furthermore, as observed in other sensory cortices[19,20], rat SI neurons reveal significant shifts in receptive-field structure that are dependent on the spatial and temporal pattern in which the neuron is stimulated, and on the time post-stimulus at which the receptive field is assessed[21–25].

### Spatial integration and inhibition in rat SI neurons

The cortical substrate for rapid temporal and spatial integration is the subthreshold receptive field: the EPSPs and IPSPs that converge on a single SI neuron. Using intracellular recording techniques *in vivo* (whole-cell recording[24,26] and sharp electrode recording[22]; see Box 1), the extent and timecourse of these inputs in the rat vibrissa representation have been mapped. Subthreshold receptive fields throughout the depth of the cortex are large, and incorporate stimuli from two rows and arcs of vibrissae away from the vibrissae at the center of the receptive field (Fig. 2)[24,26]. The neurons in the C3 vibrissa column, for example, should receive subthreshold input from 25 or more vibrissae on the rat face[24]. These inputs converge on a given neuron within the first 25 ms of vibrissa deflection[24,26]. Extensive subthreshold receptive fields, which have been identified under different anesthetic regimens (urethane[24] and sodium pentobarbitol[26]; Fig. 2), are present throughout the depth of the cortex, including layer IV (Refs 24,26), in the three major intrinsic cell firing types [regular-spiking (RS), fast-spiking (FS) and intrinsically bursting cells][26], and in different regions

## whole-cell *in vivo* recording and intrinsic-signal optical imaging

intrinsic-signal optical imaging is to measure changes in the reflectance of light at specific wavelengths as a result of neural activity[x,hh]. Many studies of rat SI vibrissa cortex representation have employed changes in the reflectance of 600 nm to 630 nm wavelength light to obtain functional signal[l,s,y,z,c–ee,gg]: in this range, deoxyhemoglobin absorbs light more effectively than oxyhemoglobin[ff,hh]. The prevailing view is that when the cortex is activated, oxygen use increases and the deoxyhemoglobin concentration proximal to active neurons also increases, resulting in a local darkening of the cortex[hh]. This signal is initiated 300–500 ms after the onset of neural activity and is prominent for approximately 1500 ms (Refs l,x,hh). The primary advantage of intrinsic-signal optical imaging is that it permits imaging of several square millimeters of rat SI simultaneously, with a spatial resolution of between 50 μm and 100 μm, making it an ideal tool to study spatial changes in map or single-vibrissa representations. A second advantage of the intrinsic signal is that one can image for relatively long periods of time, with an interim of days between imaging sessions[ee]. These extended imaging sessions are possible because the intrinsic signal does not require toxic voltage-sensitive dyes and because the images can be taken while leaving a thinned (~100 μm) skull intact[i,z].

A series of studies has investigated the relationship between intrinsic optical signal and the underlying anatomy and physiology of the rat SI vibrissa representation. Frostig and colleagues were among the first to apply this technique to the vibrissa representation[z,cc–ee,gg], and demonstrated a precise correlation between the location of the center of the optically derived vibrissa representation and the anatomical center of the barrels[z] (for a similar example, see Fig. IB). There is also a strong correlation between the level of neural activity in rat SI and the amplitude of the hemodynamic intrinsic optical signal. Petersen *et al*. varied the amplitude of vibrissa deflection and observed a linear relationship between the mean level of action potential firing and changes in the strength of the optical signal[bb]. This group also observed decreased signal following multi-vibrissa stimulation, in agreement with the inhibition that predominates in electrical recording studies[w]. The underlying electrophysiological correlate of the spatial extent of the intrinsic optical signal is believed to include a significant contribution from subthreshold neural activity. In the cat visual cortex, the point-spread of intrinsic signal is significantly broader than that of suprathreshold activity, suggesting that subthreshold activity alone can drive the intrinsic optical response[m,n]. Within rat SI, a similar subthreshold spread has been derived by comparing the relative amplitude of optical signal in a cortical location with the relative amplitude of subthreshold input[s] (cf. Ref. bb with Ref. gg).

### References


a **Albe-Fessard, D. and Buser, P.** (1955) *J. Physiol.* 47, 67–69
b **Innocenti, G.M. and Manzoni, T.** (1972) *Arch. Ital. Biol.* 110, 322–347
c **Hellweg, F.C., Schultz, W. and Creutzfeldt, O.D.** (1977) *J. Neurophysiol.* 40, 463–479
d **Carvell, G.E. and Simons, D.J.** (1988) *Brain Res.* 448, 186–191
e **Zarzecki, P. *et al.*** (1993) *J. Neurophysiol.* 69, 1422–1432
f **Svoboda, K. *et al.*** (1999) *Nat. Neurosci.* 2, 65–73
g **Hamill, O.P. *et al.*** (1981) *Pflügers Arch.* 391, 85–100
h **Moore, C.I. and Nelson, S.B.** (1998) *J. Neurophysiol.* 80, 2882–2892
i **Sheth, B.R., Moore, C.I. and Sur, M.** (1998) *J. Neurophysiol.* 79, 464–470
j **Zhu, J.J. and Connors, B.W.** (1999) *J. Neurophysiol.* 81, 1171–1183
k **Nelson, S. *et al.*** (1994) *Science* 265, 774–777
l **Grinvald, A. *et al.*** (1991) *Proc. Natl. Acad. Sci. U. S. A.* 88, 11559–11563
m **Das, A. and Gilbert, C.D.** (1995) *Nature* 375, 780–784
n **Toth, L.J. *et al.*** (1996) *Proc. Natl. Acad. Sci. U. S. A.* 93, 9869–9874
o **Sheth, B.R. *et al.*** (1997) *Science* 247, 2110–2115
p **Bakin, J.S. *et al.*** (1996) *Cereb. Cortex* 6, 120–130
q **Cannestra, A.F. *et al.*** (1996) *Neuroimage* 3, 202–208
r **Toga, A.W., Cannestra, A.F. and Black, K.L.** (1995) *Cereb. Cortex* 5, 561–565
s **Moore, C.I. *et al.*** (1996) *Soc. Neurosci. Abstr.* 22, 1058
t **Blood, A.J., Narayan, S.M. and Toga, A.W.** (1995) *J. Cereb. Blood Flow Metab.* 15, 1109–1121
u **Dowling, J.L. *et al.*** (1996) *J. Neurosci. Methods* 66, 113–122
v **Godde, B. *et al.*** (1995) *NeuroReport* 7, 24–28
w **Goldreich, D., Peterson, B.E. and Merzenich, M.M.** (1998) *Cereb. Cortex* 8, 184–192
x **Grinvald, A. *et al.*** (1986) *Nature* 324, 361–364
y **Hodge, C.J., Jr *et al.*** (1997) *Neurosurgery* 41, 1137–1145
z **Masino, S.A. *et al.*** (1993) *Proc. Natl. Acad. Sci. U. S. A.* 90, 9998–10002
aa **Narayan, S.M., Santori, E.M. and Toga, A.W.** (1994) *Cereb. Cortex* 4, 195–204
bb **Peterson, B.E., Goldreich, D. and Merzenich, M.M.** (1998) *Cereb. Cortex* 8, 173–183
cc **Chen-Bee, C.H. *et al.*** (1996) *J. Neurosci. Methods* 68, 27–37
dd **Chen-Bee, C.H. and Frostig, R.D.** (1996) *J. Neurophysiol.* 76, 884–894
ee **Masino, S.A. and Frostig, R.D.** (1996) *Proc. Natl. Acad. Sci. U. S. A.* 93, 4942–4947
ff **Frostig, R.D. *et al.*** (1990) *Proc. Natl. Acad. Sci. U. S. A.* 87, 6082–6086
gg **Masino, S.A. and Frostig, R.D.** (1999) *Somatosens. Mot. Res.* 16, 184
hh **Malonek, D. and Grinvald, A.** (1996) *Science* 272, 551–554


of the rat SI map (for example, the forepaw representation[27]). Recent intracellular studies of cat primary visual cortex (VI) have also observed large subthreshold receptive fields, with a similar decrease in the strength of input as a function of distance from the center of the response[28].

Simons and colleagues have studied spatial and temporal integration in rat SI neurons during multi-vibrissa stimulation, and have found that inter-vibrissa suppression predominates[21,22,25,29,30]. Comparable results have also been reported at the level of the cortical map, using optical imaging techniques that integrate information over several square millimeters of cortex [intrinsic-signal optical imaging[31] (see Box 1) and voltage-sensitive dyes[32]; see also Ref. 33 for similar findings using electrical-potential recordings following stimulation of the thalamus]. By stimulating two vibrissae simultaneously or in rapid succession, Simons[25] observed significant inter-vibrissa suppression of the action-potential response over the initial 200 ms post-deflection, with a peak suppression observed between 10 and 20 ms (Refs 25,29; Fig. 3). These interactions possess the following five characteristics. First, the strongest suppression is mediated by the vibrissa with the largest excitatory component[25]. Second, the strength of sensory-induced suppression of the central vibrissa increases with the number of surround vibrissae stimulated[21]. Third, the relative effect of suppression is greatest on smaller amplitude inputs: disinhibition of the cortex with GABA-receptor antagonists leads to a relatively greater increase in the amplitude of non-central vibrissa inputs[34]. Fourth, VPm neurons show multi-vibrissa suppression less frequently, suggesting that this phenomenon is largely mediated intracortically[29]. Fifth, there is spatial

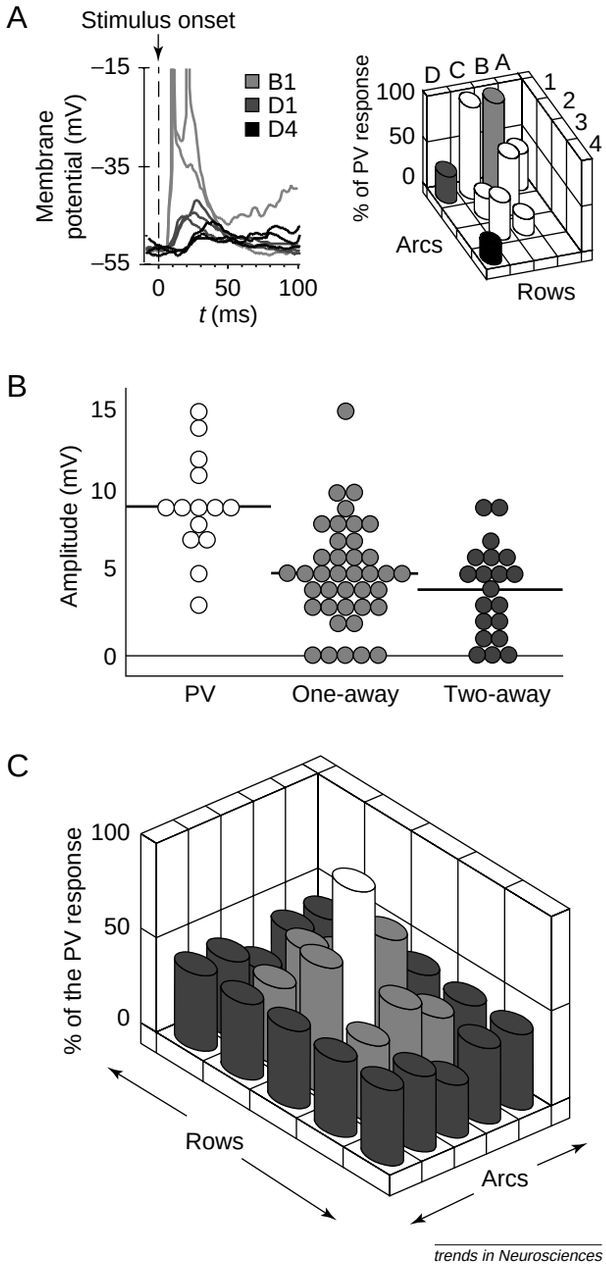


**Fig. 2.** ***Intracellular recordings demonstrating convergence of subthreshold input from a large number and a wide spatial extent of vibrissae in rat somatosensory cortex (SI) neurons.*** **(A)** *Stimulation of the B1 (light-gray trace), D1 (dark-gray trace) or D4 (black trace) vibrissae elicited consistent responses in a layer-IV neuron (645 μm deep to the cortical surface; left). The receptive field for this neuron is shown normalized to the peak subthreshold amplitude of the largest input [produced by the primary vibrissa (PV); right]. In this neuron, all ten vibrissae tested elicited suprathreshold and subthreshold (two vibrissae) responses, or exclusively subthreshold (eight vibrissae) responses.* **(B)** *The amplitudes of responses elicited by the PV (white circles), the vibrissae adjacent to the PV (one-away, gray circles), or vibrissae two-away from the PV (black circles) are shown (*n *= 14 neurons and 74 vibrissae). Black bars show the mean amplitude.* **(C)** *The average of the normalized amplitude of rat SI receptive fields (*n *= 14 neurons) is shown as percentage of the PV response.* Adapted, with permission, from Ref. 24.

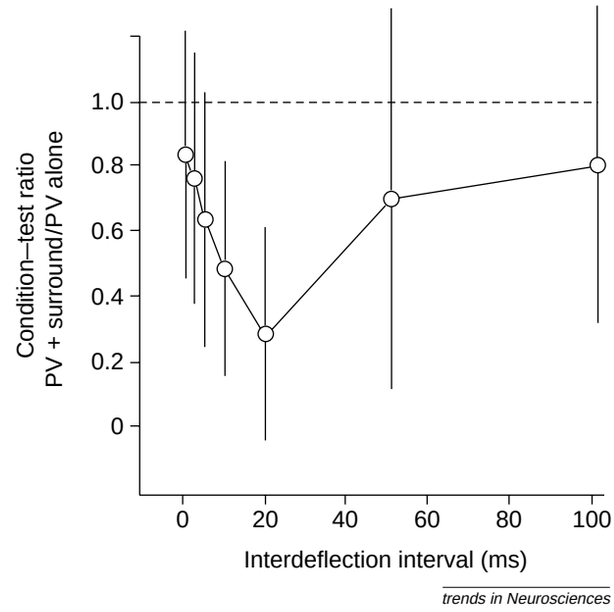


**Fig. 3.** ***Suprathreshold activity suppression following deflection of an adjacent vibrissa.*** *The amplitude of the suprathreshold stimulus-evoked response following deflection of the principal vibrissa (PV) and a surround vibrissa, calculated as a percentage of the response elicited by deflection of the PV alone (broken line), is plotted against the inter-deflection interval. At intervals from 0 to 100 ms, there is a significant decrement in the amplitude of the response, with a peak at ~20 ms. Responses were measured from regular-spiking neurons (*n *= 33 cells) and error bars are ± 1 SD.* Adapted, with permission, from Ref. 29.

asymmetry in the organization of inhibitory inputs, with less inhibitory input from the dorsal vibrissae[21,29].

Intracellular recordings from SI neurons illustrate IPSPs that can account for the key attributes of sensory-induced suprathreshold-response suppression[22,24]. As shown in Fig. 4, inputs from two vibrissae elicit robust IPSPs that predominate within 10 ms of the onset of the excitatory response, corresponding to the peak of inter-vibrissa suppression. Mapping the spatial distribution of inhibitory potentials over the spatio–temporal receptive field reveals that the strongest IPSPs are consistently elicited by the primary vibrissa, predicting the centered suppression observed in the suprathreshold receptive field. Furthermore, several vibrissae in any given neuron elicit inhibitory potentials, which provide the substrate for the summation of inhibition across multiple vibrissae[22,24]. The greater efficacy of inhibition on less-robust excitatory inputs probably results from a convergence of factors. Smaller depolarizations are closer to the threshold for action-potential firing and, therefore, more sensitive to concurrent inhibition. This susceptibility is exacerbated by the timing of these inputs: smaller depolarizations arrive at longer latency and have a slower rise time[24], which aligns their peak with the latency of di-synaptic intracortical inhibition[29,35]. Bias in the spatial orientation of inhibitory potentials has not been investigated systematically using intracellular techniques, although individual neurons have been observed with asymmetric inhibitory organization[22,24] (see, for example, Fig. 4C).

Studies in the rabbit somatosensory cortex by Swadlow and colleagues[36,37] suggest that at the lowest amplitudes of thalamocortical input, the inhibitory circuitry within a barrel filters the throughput of information from the thalamus to the cortex. Suspected inhibitory interneurons (SINs) in the layer-IV barrels are rapidly and synchronously activated at lower amplitudes of thalamocortical stimulation than non-SINs (Ref. 37). These findings suggest that feed-forward inhibition will predominate at lower amplitude input and set a threshold for the effective spread of signal within a cortical column.

### Frequency-dependent dynamics in the rat SI

During active exploration and discrimination, rats initiate a change in the dynamic context in which perception occurs: the whisking behavior[38,39]. When rats rest, their vibrissae are typically still, but when they explore their environment, they move their posterior vibrissae at a dominant frequency of ~8 Hz in an ellipsoid fashion[40,41]. This behavior has several benefits for perception, as it increases the temporal sampling rate of contact with a given object and permits the vibrissae to contact multiple locations on that object in rapid succession[41,42].

Stimulation of individual vibrissae in the frequency range encompassed by whisking has context-dependent effects on both individual neurons[36,43] and the cortical map[2]. In individual layer-IV neurons, increasing the frequency of vibrissa stimulation leads to the adaptation of RS neurons and, at higher frequencies, FS neurons (Refs 36,43). At the level of the vibrissa representation, increasing the frequency of stimulation (5 and 10 Hz) focuses the projection area of an individual vibrissa relative to a broader divergence of signal at low frequencies of stimulation (1 Hz; Fig. 5)[2]. This finding is predicted by single-unit studies in the monkey SI by Mountcastle and Powell[44], who observed that responses from the edge of a suprathreshold receptive field could not follow the high-frequency trains of sensory stimuli that responses in the center of the receptive field were able to follow.

Two classes of neural mechanisms that could, alone or in combination, account for the decrease in peripheral signal at higher frequencies of vibrissa stimulation are the loss of subcortical input, and differential engagement of excitatory and inhibitory circuitry in the cortex. A subcortical origin for this effect is supported by differences in the thalamocortical input channels to rat SI. The two principal somatosensory thalamic nuclei, the VPm and the posterior medial nucleus (POm) of the thalamus, have different projection patterns and adaptation-response properties. At the cortical depth at which these rapid frequency-dependent effects were observed (upper layer IV to lower layer III), VPm neurons project to the barrels[3–5] and adapt only mildly, if at all, at peripheral stimulation frequencies of 5 Hz and 10 Hz (Refs 45,46). In contrast, at this cortical depth, POm neurons project to the septae surrounding the barrels, and adapt substantially at 5 Hz and 10 Hz (Refs 45,47). The selective sensory adaptation of the POm system could, therefore, uncouple the center and surround of the vibrissa representation.

There are three important differences between the circuits subserving intracortical excitation and inhibition that favor selective engagement of the inhibitory circuitry of the barrels at higher frequencies. First, as described above, RS neurons (which have lower peak firing rates and are predominantly excitatory neurons) demonstrate sensory adaptation at lower frequencies of vibrissa stimulation than FS neurons[36,43] (which have higher peak firing rates and are inhibitory interneurons[36,48]). Second, excitatory inputs to many putative inhibitory interneurons show enhancement of transmission at these inter-stimulus intervals[49–51], while excitatory inputs to pyramidal neurons in the neocortex exhibit prominent frequency-dependent depression[52–56]. Finally, although inhibitory synapses on pyramidal neurons exhibit synaptic depression, the frequency-dependent reduction in the strength of inhibitory input is less prominent

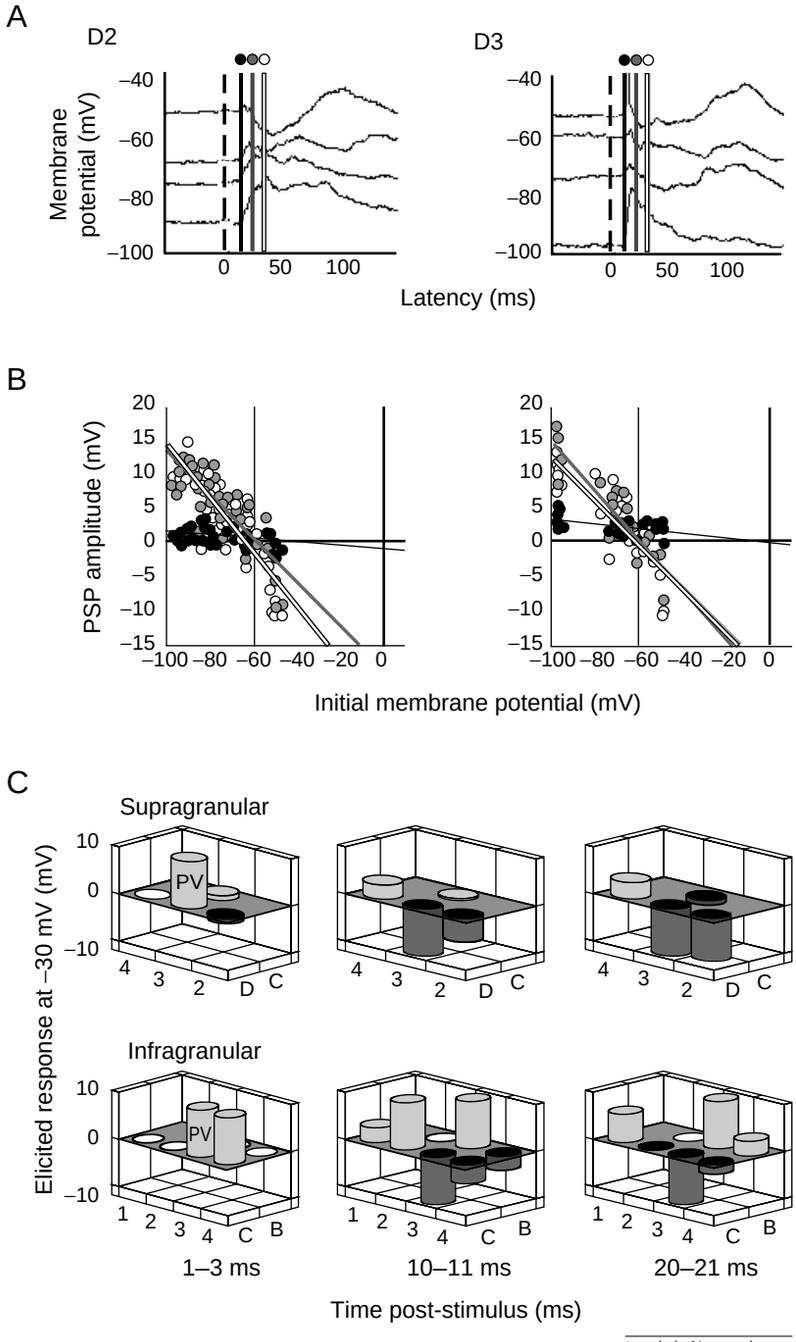


**Fig. 4.** ***The pattern of vibrissa-elicited excitatory and inhibitory subthreshold potentials mapped over space and time.*** **(A)** *Depolarizing and hyperpolarizing currents were injected through the recording electrode into the neuron during deflection of individual vibrissae (the D2 and D3 vibrissa). Depolarizing current injection reveals prominent IPSPs, caused by deflection of either vibrissa, that are robust within 10 ms post-response onset.* **(B)** *Mapping vibrissa responses during current injection reveals the reversal potentials resulting from vibrissa deflection. The left and right graphs plot the amplitude of the elicited response (y-axis) as a function of the membrane potential prior to vibrissa stimulation (x-axis) for the D2 (left) and D3 (right) vibrissae. For elicited responses from both vibrissae, EPSPs occurring 1–3 ms after the onset of the response (for example, the ~0 mV reversal potential observed following D3 deflection [black circles and lines in* (A) *and* (B)*] are followed at 10–11 ms and 20–21 ms by prominent IPSPs (the ~−60 mV reversal potentials observed by deflection of both vibrissae [gray and white circles and lines in* (A) *and* (B)*].* **(C)** *The amplitude of elicited responses, at a projected membrane potential of −30 mV, is plotted for a supragranular and an infragranular neuron. Because −30 mV lies halfway between a purely excitatory (0 mV) and inhibitory (−60 mV) reversal potential, the amplitude and direction (positive, upward gray columns; negative, downward black columns) of the evoked response provide an estimate of the balance of excitatory and inhibitory current flow. In both neurons, the primary vibrissa (PV) elicits the greatest excitatory potentials between 1 and 3 ms, and the largest inhibitory potentials between 10 and 11 ms, and between 20 and 21 ms. Inhibition is present, but more variable, in responses elicited by the surrounding vibrissae.* Adapted, with permission, from Ref. 24.

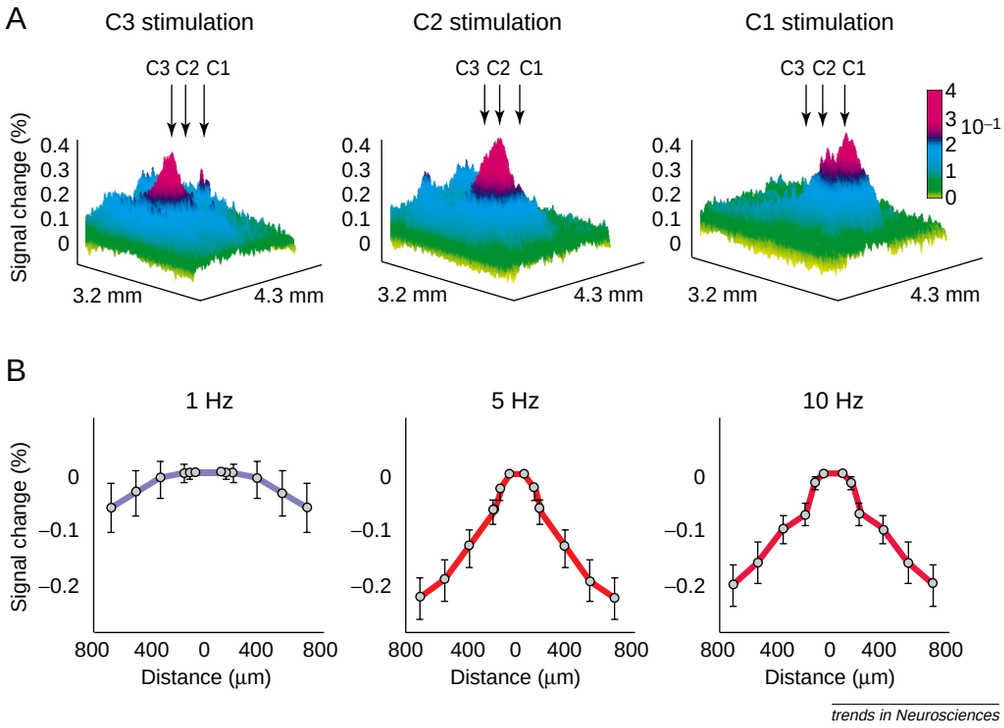


**Fig. 5.** ***Somatotopic mapping of the rat somatosensory cortex (SI) vibrissa map and frequency-dependent focusing of the vibrissa representation measured with intrinsic-signal optical imaging.*** **(A)** *A cortical map of activation following stimulation of three individual vibrissae (the C3, C2 and C1) is shown. Height and pseudo-color indicate increased optical signal change, measured as a percentage of the baseline condition. Responses represent the mean percent signal change, as compared with a no-stimulation condition, averaged over 30 trials of stimulation. Signal was sampled during the period 500–2000 ms post-onset of a 5 Hz, 2 s train of single-vibrissa stimulation.* **(B)** *Stimulation at 5 and 10 Hz results in a more-restricted spread of cortical optical signal than stimulation at 1 Hz. Activity was calculated by centering a series of concentric rings on the peak activation region within a cortical map and summing activity under each ring. In both* (A) *and* (B)*, distance refers to distance within the cortex.* (B) was adapted, with permission, from Ref. 2.

than the frequency-dependent reduction in excitatory input[57,58] (see Ref. 59 for a review).

## Perceptual implications of context-dependent dynamics for whisking

Given the importance of whisking in active discrimination, how do the cortical dynamics described above contribute to perception? This article proposes that whisking versus non-whisking represents a specificity versus sensitivity trade-off in the processing of perceptual input. During whisking, there is an increase in the frequency of vibrissa movement and in the contact of multiple vibrissae with an object at rapid (<200 ms) inter-contact intervals. As described above, contact with multiple vibrissae at rapid inter-stimulus intervals will effectively summate inhibition within the cortex[21], which will differentially suppress smaller surrounding inputs and amplify the relative signal strength from the center of the barrel[24,34]. As Simons and colleagues have proposed, one important purpose of the predominantly inhibitory barrel circuitry might be to increase the spatial contrast of central versus adjacent vibrissa input in the barrel[29,30,60,61]. Similarly, high-frequency vibrissa stimulation narrows the spread of cortical signal beyond the center of the barrel[2]. When the whisking rat is palpating objects, these lateral spatial and frequency-dependent interactions should combine to produce a more-focused vibrissa representation. This more-focal representation might, in turn, correspond to a decreased sensitivity to less-robust non-primary inputs and a greater relative signal from the primary vibrissa, which would improve the contrast between neighboring inputs. Conversely, in the resting, non-whisking state, there is a broader spatial divergence of activity in the cortex. This divergence of information might compromise the ability to segregate inputs (decrease specificity), but would increase sensitivity to input from throughout the vibrissa field. This state would be optimal for alerting and orienting the animal to objects that would then require more-detailed examination.

## Non-linear spatial cortical dynamics in rat SI: predictions from VI

This view of the sensitivity versus specificity trade-off in rat SI has a mechanistic correlate within the visual system. In the cat and monkey visual cortices, several recent lines of evidence demonstrate that stimulation of the region surrounding the suprathreshold receptive field modifies the response of the center stimulus as a function of the contrast of the central input, and also as a function of the similarity between center and surround inputs[62–66]. When the stimulus presented to the center of the suprathreshold receptive field is nil or of low contrast, then high-contrast stimuli presented to the surround enhance the response in the center of the receptive field; conversely, when the central input is of high contrast, then stimulation of the surround will effectively inhibit the central response[67,68]. If the surround stimulus (typically a grating) has the same orientation as the center stimulus, there is relatively greater facilitation and suppression of the center response, whereas other orientations are less effective[64,67,69].

The contrast-dependent relationships between center and surround described for the visual cortex provide a set of hypotheses for multi-vibrissa integration in rat SI cortex. The primary prediction is shown in Fig. 6; specifically, when large-amplitude stimuli are presented to the primary vibrissa, there should be a net inhibitory effect produced by surround-vibrissa stimulation on this response. Conversely, when large-amplitude stimuli are presented to only the surround vibrissae, there should be a net excitatory effect in a given neuron. These most-extreme predictions are met in rat SI. As described in a previous section, when simultaneous drive for both the center and surround vibrissae is high, multi-vibrissa inhibition results[21,22,25,29,30]. In contrast, when the drive in the center of a vibrissa receptive field is nil, stimulation of adjacent surround vibrissae typically elicits a smaller, consistent response[14–17]. Recent work by Ghazanfar and Nicolelis[23] has demonstrated summation of these surround excitatory effects. Stimulation of three surround vibrissae in a row or arc leads to a significant increase in the spread of input over a population of neurons, while stimulation of individual vibrissae elicits a lesser response.

The parallels in rapid integration demonstrated by SI and VI neurons suggest that this type of control over the relative level of enhancement or suppression of the neural response is a general feature of cortical dynamics. During conditions of absent or impoverished central input, the cortex acts to amplify surround signals; during conditions of more-robust input, cortical circuitry acts to improve discrimination. Such segregation is likely to characterize the early perceptual events associated with object detection and discrimination (see Ref. 66 for a computational model of these principles as applied to VI). Within the visual cortex, these center-surround interactions have primarily been documented in the supragranular layers and are believed to be maintained by horizontal intracortical connectivity[66]: the predominance of inhibitory circuitry in the barrels suggests that the proposed dynamics might also occur in SI through integration in non-granular layers. It is not currently known whether differences in the similarity of center and surround inputs influence the responses of SI neurons differentially, as they do in area VI. Two stimulus dimensions along which similarity could influence the effect of surround stimulation are: (1) the frequency of the stimulus and (2) the angle of simultaneous vibrissa deflection across several vibrissae. Differences in frequency or direction of vibrissa deflection would imply the presence of change within a stimulus space, such as transition to a surface of different roughness (frequency difference), or a non-uniform region along a stimulus edge (angle-of-deflection difference).

### Specific patterns of spatio–temporal interactions: moving stimuli

When similarity is distributed in time, that is, when a discrete stimulus is moving through the vibrissa field, the angle of vibrissae deflection forms a relevant stimulus feature. Simons has provided evidence that the coherence of direction of movement modulates evoked responses differentially[25]. Sets of vibrissae deflected as if receiving a movement (that is, deflected in sequential order and at the same angle of vibrissa deflection) were more likely to demonstrate suprathreshold-response facilitation or disinhibition than other multi-vibrissa combinations, which typically cause inhibition. There are two components to this type of motion: the order of vibrissa deflection and the angle of deflection. The spatial orientation of subthreshold excitatory and inhibitory regions within the spatio–temporal receptive field described above (Fig. 4C) provides insight into tuning for the order of deflection: asymmetry in the structure of inhibitory subfields should lead to a relative enhancement of directions of movement originating in vibrissae that demonstrate minimal inhibition, while producing an inhibition of directions of movement that engage inhibitory subregions of the receptive field initially. Furthermore, the temporal organization of subthreshold subfields implies velocity tuning for the movement of a stimulus through the receptive field. A deflection order and rate that produces temporal convergence of excitatory and inhibitory inputs should suppress moving input maximally, while rates that align excitatory inputs, or stagger the peak of excitation and inhibition, will be facilitated or suppressed less effectively.

The second component of multi-vibrissa movement selectivity, the correlated orientation of angular tuning across multiple vibrissae, has not been examined with intracellular mapping techniques, though Carvell and Simons[22] have demonstrated that different angles of deflection of the same vibrissa elicit distinct patterns of EPSPs and IPSPs.

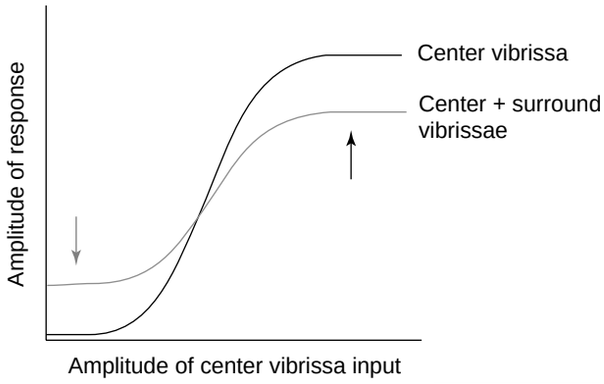


**Fig. 6.** ***A general model of the influence of surround-vibrissa input on the response elicited by the central vibrissa in rat somatosensory cortex (SI), based on findings in the primary visual cortex (VI).*** *Center–surround interactions in the visual system[66] predict the following general model of center–surround interactions in rat SI. When the surround vibrissae are deflected without the center vibrissa (gray arrow, gray line), the net effect should be excitatory and a small suprathreshold response will be generated. Conversely, when surround vibrissae are deflected in the presence of strong central input (black arrow, gray line), the response to the central vibrissa should be inhibited relative to the signal generated by deflection of the central vibrissa in isolation (black line). These predictions have been substantiated in rat SI (Refs 14–17,23,25).*

### Motor activity and context-dependent interactions

Motor activity might also have an important role in the context-dependent processing of somatosensory input, especially given the importance of the whisking behavior to active tactile perception. In support of this connection, Shin and Chapin[70] have shown the suppression of somatosensory responses in rat SI and VP during movement. Similarly, Castro-Alamancos and Connors[71] have demonstrated the diminution of the 'augmenting response', a form of paired-pulse facilitation observed in rat sensorimotor cortex following electrical stimulation of the ventrolateral nucleus of the thalamus, during active exploration. An important question in this area of research is whether motor activity modulates SI activity as a function of the sensory input generated or as an internally generated 'efference copy'. Fee *et al.*[72] have correlated the firing of rat SI neurons with the phase and amplitude of whisking movements. These authors observed that during unilateral blockade of the facial motor nerve, the phase-related activity of SI neurons was absent, suggesting that it is mediated by sensory input, but that amplitude-related modulation of the signal was maintained, suggesting that it results from a central mechanism. Nicolelis *et al.*[73] have also observed correlated 7–12 Hz oscillations within SI immediately prior to whisker twitching, a finding that provides further evidence for internally generated, motor-related signals in the SI vibrissa representation.

### Concluding remarks

Rat SI cortex is often considered a 'model' system for the study of cortical organization because of the anatomical labels of somatotopic position: the barrels. The research reviewed in this article suggests that the study

of rat SI will also provide insight into general mechanisms of cortical dynamics. Rapid spatial and temporal integration is prominent in rat SI neurons, and is potentially important for the processes of tactile perception. Furthermore, the regulation of context-dependent enhancement and suppression as a function of the strength of input to the center and surround, might be a general feature of cortical processing.

An important set of questions with respect to cortical dynamics in rat SI is what stimulus features (for example, direction of motion) can be encoded as more-complex functions of space and time. Addressing these questions will require the use of stimuli that engage multiple vibrissae in complex patterns, such as the reverse correlation approaches that have yielded important insights in other species and cortical areas recently[17,18,74]. Additionally, establishing the broader significance of context will require studies in different behavioral states, using awake behaving models[71–73] and using techniques that examine sensory integration at several levels of organization, including the intracellular and multi-columnar (see Box 1).

**Acknowledgements**
*The authors thank Bhavin Sheth for many helpful conversations, and Dan Simons, Josh Brumberg and Susan Masino for their beneficial comments on the manuscript.*

**Selected references**

1 **Woolsey, T.A. and Van der Loos, H.** (1970) *Brain Res.* 17, 205–242
2 **Sheth, B.R., Moore, C.I. and Sur, M.** (1998) *J. Neurophysiol.* 79, 464–470
3 **Killackey, H.P.** (1973) *Brain Res.* 51, 326–331
4 **Jensen, K.F. and Killackey, H.P.** (1987) *J. Neurosci.* 7, 3529–3543
5 **Koralek, K.A., Jensen, K.F. and Killackey, H.P.** (1988) *Brain Res.* 463, 346–351
6 **Harris, R.M. and Woolsey, T.A.** (1983) *J. Comp. Neurol.* 220, 63–79
7 **Simons, D.J. and Woolsey, T.A.** (1984) *J. Comp. Neurol.* 230, 119–132
8 **Welker, C.** (1971) *Brain Res.* 26, 259–275
9 **Welker, C.** (1976) *J. Comp. Neurol.* 166, 173–190
10 **Armstrong-James, M., Diamond, M.E. and Ebner, F.F.** (1994) *J. Neurosci.* 14, 6978–6991
11 **Delacour, J., Houcine, O. and Talbi, B.** (1987) *Neuroscience* 23, 63–71
12 **Diamond, M.E., Armstrong-James, M. and Ebner, F.F.** (1993) *Proc. Natl. Acad. Sci. U. S. A.* 90, 2482–2085
13 **Diamond, M.E., Huang, W. and Ebner, F.F.** (1994) *Science* 265, 1885–1888
14 **Welker, E., Soriano, E. and Van der Loos, H.** (1989) *Exp. Brain Res.* 74, 441–452
15 **Armstrong-James, M. and Fox, K.** (1987) *J. Comp. Neurol.* 263, 265–281
16 **Armstrong-James, M., Fox, K. and Das-Gupta, A.** (1992) *J. Neurophysiol.* 68, 1345–1358
17 **Chapin, J.K.** (1986) *Exp. Brain Res.* 62, 549–559
18 **Ito, M.** (1985) *J. Neurophysiol.* 54, 479–490
19 **DeAngelis, G.C., Ohzawa, I. and Freeman, R.D.** (1993) *J. Neurophysiol.* 69, 1091–1117
20 **DeCharms, R.C., Blake, D.T. and Merzenich, M.M.** (1998) *Science* 280, 1402–1403
21 **Brumberg, J.C., Pinto, D.J. and Simons, D.J.** (1996) *J. Neurophysiol.* 76, 130–140
22 **Carvell, G.E. and Simons, D.J.** (1988) *Brain Res.* 448, 186–191
23 **Ghazanfar, A.A. and Nicolelis, M.A.L.** (1997) *J. Neurophysiol.* 79, 506–510
24 **Moore, C.I. and Nelson, S.B.** (1998) *J. Neurophysiol.* 80, 2882–2892
25 **Simons, D.J.** (1985) *J. Neurophysiol.* 54, 615–635
26 **Zhu, J.J. and Connors, B.W.** (1999) *J. Neurophysiol.* 81, 1171–1183
27 **Li, C.X. and Waters, R.S.** (1996) *NeuroReport* 7, 2261–2272
28 **Bringuier, V. *et al.*** (1999) *Science* 283, 695–699
29 **Simons, D.J. and Carvell, G.E.** (1989) *J. Neurophysiol.* 61, 311–330
30 **Simons, D.J.** (1995) in *Cerebral Cortex* (Jones, E.G. and Diamond, I.T., eds), pp. 263–297, Plenum Press
31 **Goldreich, D., Peterson, B.E. and Merzenich, M.M.** (1998) *Cereb. Cortex* 8, 184–192
32 **Kleinfeld, D. and Delaney, K.R.** (1996) *J. Comp. Neurol.* 375, 89–108
33 **Castro-Alamancos, M.A. and Connors, B.W.** (1996) *J. Neurosci.* 16, 2767–2779
34 **Kryazi, H.T. *et al.*** (1996) *J. Neurophysiol.* 75, 547–560
35 **Agmon, A. and Connors, B.W.** (1992) *J. Neurosci.* 12, 319–330
36 **Swadlow, H.A.** (1989) *J. Neurophysiol.* 62, 288–308
37 **Swadlow, H.A., Beloozerova, I.N. and Sirota, M.G.** (1998) *J. Neurophysiol.* 79, 567–582
38 **Welker, W.I.** (1964) *Behaviour* 22, 223–244
39 **Wineski, L.E.** (1983) *J. Zool.* 200, 261–280
40 **Brecht, M., Preilowski, B. and Merzenich, M.M.** (1997) *Behav. Brain Res.* 84, 81–97
41 **Carvell, G.E. and Simons, D.J.** (1990) *J. Neurosci.* 10, 2638–2648
42 **Carvell, G.E. and Simons, D.J.** (1995) *Somatosens. Mot. Res.* 12, 1–9
43 **Simons, D.J.** (1978) *J. Neurophysiol.* 41, 798–820
44 **Mountcastle, V.B. and Powell, T.P.S.** (1959) *Bull. Johns Hopkins Hosp.* 105, 173–200
45 **Diamond, M.E., Armstrong-James, M. and Ebner, F.F.** (1992) *J. Comp. Neurol.* 318, 462–476
46 **Hartings, J.A. and Simons, D.J.** (1998) *J. Neurophysiol.* 80, 1016–1019
47 **Diamond, M.E.** (1995) in *Cerebral Cortex* (Jones, E.G. and Diamond, I.T., eds), pp. 189–220, Plenum Press
48 **McCormick, D.A. *et al.*** (1985) *J. Neurophysiol.* 54, 782–806
49 **Thomson A.M.** (1997) *J. Physiol* 502, 131–147
50 **Reyes, A. *et al.*** (1998) *Nat. Neurosci.* 1, 279–285
51 **Markram, H., Wang, Y. and Tsodyks, M.** (1998) *Proc. Natl. Acad. Sci. U. S. A.* 95, 5323–5328
52 **Thomson, A.M., Deuchars, J. and West, D.C.** (1993) *J. Neurophysiol.* 70, 2354–2369
53 **Abbott, L.F. *et al.*** (1997) *Science* 275, 220–222
54 **Varela, J.A. *et al.*** (1997) *J. Neurosci.* 17, 7926–7940
55 **Markram, H. and Tsodyks, M.V.** (1996) *Nature* 382, 807
56 **Tsodyks, M.V. and Markram, H.** (1997) *Proc. Natl. Acad. Sci. U. S. A.* 94, 719–723
57 **Song, S. *et al.*** (1997) *Soc. Neurosci. Abstr.* 27, 2362
58 **Galaretta, M. and Hestrin, S.** (1998) *Nat. Neurosci.* 1, 587–594
59 **Nelson, S.B. and Turrigiano, G.G.** (1998) *Nat. Neurosci.* 1, 539–541
60 **Simons, D.J. *et al.*** (1992) *Exp. Brain Res.* 91, 259–272
61 **Kyriazi, H.T. and Simons, D.J.** (1993) *J. Neurosci.* 13, 1601–1615
62 **Toth, L.J. *et al.*** (1996) *Proc. Natl. Acad. Sci. U. S. A.* 93, 9869–9874
63 **Levitt, J.B. and Lund, J.S.** (1997) *Nature* 387, 73–76
64 **Sengpiel, F. *et al.*** (1998) *Vis. Res.* 38, 2067–2080
65 **Polat, U. *et al.*** (1998) *Nature* 391, 580–584
66 **Somers, D.C. *et al.*** (1998) *Cereb. Cortex* 8, 204–217
67 **Knerim, J.J. and Van Essen, D.C.** (1992) *J. Neurophysiol.* 67, 961–980
68 **Grinvald, A. *et al.*** (1994) *J. Neurosci.* 14, 2545–2568
69 **Sillito, A.M. *et al.*** (1995) *Nature* 378, 492–496
70 **Shin, H-C. and Chapin, J.K.** (1990) *Exp. Brain Res.* 81, 515–522
71 **Castro-Alamancos, M.A. and Connors, B.W.** (1996) *Science* 272, 274–277
72 **Fee, M.S., Mitra, P.P. and Kleinfeld, D.** (1997) *J. Neurophysiol.* 78, 1144–1148
73 **Nicolelis, M.A. *et al.*** (1995) *Science* 268, 1353–1358
74 **DiCarlo, J.J. and Johnson, K.O.** (1999) *J. Neurosci.* 19, 401–419