Fast-spike Interneurons and Feedforward Inhibition in Awake Sensory Neocortex

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Introduction

GABAergic inhibition shapes the responses of cortical neurons and constrains runaway excitation (Dykes et al., 1984; Sillito, 1984; Nelson et al., 1994; Vidyasagar et al., 1996; Ferster and Miller, 2000). This inhibitory control is mediated by heterogeneous subpopulations of interneurons that are both morphologically and neurochemically distinct, and which exhibit their influence through both feedforward and feedback circuitry (Fairen et al., 1984; Houser et al., 1984; DeFelipe, 1993; Cauì et al., 1997; Gupta et al., 2000). Feedforward inhibition is the faster of these two mechanisms, being disynaptic, and mediated by direct thalamocortical input to intracortical interneurons (White and Rock, 1981; Agmon and Connors, 1992; Swadlow, 1995; Porter et al., 2001). It is, therefore, very well suited to constrain cortical target neurons, and even to prevent them from ever reaching threshold when stimuli are weak or non-optimal. In contrast, feedback inhibition is slower (trisynaptic), and, unlike feedforward inhibition, requires spike activity in some excitatory cortical neurons before inhibitory neurons can be engaged.

Although GABAergic interneurons are relatively abundant within the cortex [they comprise 15–25% of the neurons in many cortical areas (Hendry et al., 1987; Meinecke and Peters, 1987; Prieto et al., 1994)], these neurons have received little attention in studies of receptive field and other response properties of cortical neurons in intact subjects. This may, in part, be due to the difficulty in identifying these neurons in the extracellular record. Whereas cortical efferent neurons may be unambiguously identified by antidromic activation, the identification of interneurons is more problematic. This chapter will review evidence indicating that one class of inhibitory interneurons can be identified in the extracellular record. The receptive fields and other response properties of these neurons will be described, and the relationship of these receptive fields to a highly divergent/convergent functional network that links these neurons to their thalamocortical afferents will be explored.

The Identification of GABAergic Interneurons in the Extracellular Record

In order to identify a GABAergic interneuron definitively, it is necessary to record intracellularly, label the neuron, and examine its morphological and/or cytochemical properties. This is now readily achieved in slice preparation. However, in sensory cortices of intact subjects, only a small number of such identified interneurons have been subject to detailed receptive field analysis, and these have provided important insights into the properties of these elements (Martin et al., 1983; Azouz et al., 1997; Hirsch et al., 2000). This elegant and difficult strategy, however, limits the range of observations that can be made and the conditions under which these neurons can be studied. If some degree of error can be tolerated in the identification of these neurons, there is considerable evidence that one class of GABAergic interneurons [the ‘fast-spike’ variety (Connors and Gutnick, 1990; Amitai and Connors, 1995)] can be identified with some confidence using extracellular methods.

It has been recognized for some time that some interneurons have distinctive response properties. A high-frequency burst of spikes elicited by electrical stimulation of convergent inputs was described in ‘Renshaw’ cells of the spinal cord (Eccles, 1957) and in many other central interneurons (Andersen et al., 1964a,b). In sensory neocortex, Mountcastle et al. (Mountcastle et al., 1969) speculated that cells in somatosensory cortex with ‘thin spikes’ may be interneurons, but added the caveat that such cells could actually be thalamic afferents. Similarly, Simons (Simons, 1978) identified such ‘fast-spike’ neurons in rat somatosensory barrel cortex, and showed that they have receptive field properties that differ from those of ‘regular spike’ neurons. The suggestion that these fast-spike cortical elements may be interneurons gained considerable support from intracellular studies showing that a class of cortical neurons with short-duration action potentials had an aspinous or sparsely spiny non-pyramidal morphology (McCormick et al., 1985; Connors and Kriegstein, 1986). In addition, these cells were shown to respond to a depolarizing intracellular current pulse with a very high-frequency, non-adapting discharge of action potentials and, subsequently, to stain positively for GAD. It was soon shown, however, that ‘fast-spike’ interneurons comprise only a subset of the population of cortical inhibitory interneurons. Other
identified GABAergic interneurons were shown to lack the physiological signature of the fast-spike population. Moreover, this latter class of inhibitory interneurons did not stain for parvalbumin, a calcium-binding protein that is associated with fast-spike interneurons (Kawaguchi, 1993; Kawaguchi and Kubota, 1993).

These latter results showed that not all cortical GABAergic interneurons have action potentials of very short duration. Conversely, it has also become clear that not all short-duration action potentials are generated by fast-spine, parvalbumin-expressing interneurons. Intracellular studies have documented short-duration action potentials in a number of neurons that were subsequently labeled and shown to be of pyramidal morphology (Dykes et al., 1988; Gray and McCormick, 1996) [also see (Takahashi, 1965)], and the spikes of a small but significant number of cortical efferent neurons, recorded extracellularly and identified by antidromic activation, are of very short duration (Swadlow, 1988, 1989, 1990). We can conclude, then, that although a majority of cortical neurons with short-duration spikes are fast-spike GABAergic interneurons, other cortical populations may also have short-duration action potentials.

To reduce this ambiguity, criteria other than spike-duration can be added to the procedure for identifying fast-spike interneurons in the extracellular record. As noted above, these cells can emit very high-frequency bursts of action potentials, and this characteristic has been useful in identifying putative inhibitory interneurons (Swadlow, 1988, 1989, 1990, 1991, 1994). Thus, suspected inhibitory interneurons (SINs) in visual and somatosensory cortices were identified by a burst of three or more spikes elicited by electrical stimulation of afferent pathways, where peak frequencies were required to exceed 600 Hz. As expected, SINs identified by the above criteria also had action potentials that were much briefer (approximately half the duration) than those of efferent populations. In addition, SINs in these cortical regions respond vigorously at short latencies to electrical stimulation of multiple cortical sites, which alleviates concerns that they may be thalamic afferents (above). Figure 1A1, A2 shows the extracellular spikes elicited by ventrobasal (VB) thalamic stimulation in one such neuron in rabbit barrel cortex. Intracellular recordings were obtained from a small number of such neurons (live) in S1 barrel cortex that met the above extracellular criteria for classification as a SIN. Each of these cells, recorded in fully awake rabbits, responded to a depolarizing current pulse with the high-frequency, non-adapting discharge of action potentials that is characteristic of fast-spine, GABAergic interneurons. Figure 1B shows results from one of these neurons.

It is significant that, in a wide range of cortical regions (Swadlow, 1988, 1989, 1990, 1991). only ~0.5% of antidromically identified efferent neurons have responded to electrical stimulation of afferent pathways with a burst of three or more high-frequency (>600 Hz) synaptic spikes (three neurons of >700 corticocortical and corticofugal neurons studied in rabbit sensory and motor cortex). Thus, had antidromic identification of these efferent neurons not been employed in these experiments, <0.5% of these efferent neurons would have been falsely categorized as a SIN using the above identification procedure. The use of spike duration as the sole criterion in these studies would have led to incorrect classification of many more of these neurons (see Figs 15, 7 and 5 of Swadlow, 1988, 1989, and 1990, respectively). It should be noted, however, that at present there is no documented method for identifying spiny stellate neurons using extracellular criteria, so these neurons were not included in the above extracellular analyses of spike duration. However, intracellular observations indicate that these neurons are ‘regular spiking’ (i.e. they do not have short-duration action potentials (Feldmeyer et al., 1999), as are some classes of GABAergic interneurons (Kawaguchi, 1993, Kawaguchi and Kubota, 1993). The nature of these neurons’ responses to electrical stimulation of afferent pathways has not been characterized in any detail.

Response Properties of Fast-spike Interneurons in Sensory Cortex

In awake rabbits, SINs of V1, S1 and S2 (Swadlow, 1988, 1989, 1990, 1991) are highly excitable. All of the SINs studied in layers 2–6 of each of these regions were clearly driven by peripheral sensory stimulation. This universal responsivity contrasts markedly with the properties of efferent populations, where 25–50% of corticocortical neurons (found primarily in layers 2–3, but also in deeper layers) and corticothalamic neurons of layer 6 lacked a demonstrable (suprathreshold) receptive field. SINs in the above sensory cortical areas also had much higher levels of spontaneous activity than did efferent populations. SINs had spontaneous firing rates of 10.6–19 spikes/s (mean or median values in these areas). In contrast, most corticocortical neurons and corticothalamic neurons of layer 6 were nearly silent, with spontaneous rates of considerably less than 1 spike/s (many of these neurons were never observed to fire in the
neurons, showed little or no selectivity for the direction of whisker displacement. This is surprising, because most SINs receive strong thalamocortical input, much of which originates in thalamocortical neurons that show strong directional selectivity. I will argue (below) that this results from a non-selective convergence of thalamocortical input onto SINs of layer 4. Similar results are seen in rabbit visual cortex, where most corticocortical and corticofugal (corticotectal and corticothalamic) efferent neurons show both orientation and directional selectivity, but SINs are very widely tuned for both orientation and direction of motion (Swadlow, 1988).

The above results for SINs in rabbit S1, S2 and V1 are very similar to those reported for ‘fast-spike’ neurons in layer 4 of rat barrel cortex (Simons, 1978). These neurons also demonstrate very high levels of spontaneous activity, and are very responsive to peripheral stimulation, yet they lack the directional selectivity seen in most VB neurons and in ‘regular-spike’ neurons (presumed pyramidal or spiny stellate neurons) of this cortical region.

It is not yet clear whether the above results in rabbit and rat, showing a high sensitivity, but low degree of specificity in the responses of SINs (or fast-spike neurons), hold for these elements in sensory cortex of other species. A small number of GABAergic interneurons have been identified in in vivo intracellular studies of cat visual cortex. Both Martin et al. (Martin et al., 1983) and Azouz et al. (Azouz et al., 1997) report that these neurons are orientation selective, and these results are consistent with results showing orientation selectivity in the IPSPs onto pyramidal neurons of cat V1 (Ferster, 1986). However, recent intracellular studies (Hirsch et al., 2000) have revealed inhibitory interneurons that lack orientation selectivity in layer 4 of cat V1. It would be useful to know whether these latter cells receive significant monosynaptic input from LGNd and could, thereby, mediate a broadly tuned feedforward inhibition onto spiny stellate neurons (Troyer et al., 1998; Ferster and Miller, 2000). Surprisingly, putative fast-spike inhibitory interneurons have not been identified with any regularity in extracellular analyses of feline visual cortex. This is curious, given the great number of studies and intense interest in this cortical region. It may be that these neurons are more difficult to isolate in cat or simply that they have not been sought with sufficient effort.

Thalamocortical Connectivity of Fast-spike Interneurons

VB thalamocortical axons of mouse and rat form synapses with aspinous and sparsely spinous non-pyramidal neurons of S1 layer 4 (White, 1986, 1989). Moreover, some of the synapses onto these neurons occur directly on their somata. This fact may account for the powerful thalamocortical physiological responses observed in these neurons (below). Electrical stimulation of VB thalamus in rat and rabbit elicits short-latency responses in fast-spike interneurons and in SINs, respectively (Agmon and Connors, 1992; Swadlow, 1995). In the intact somatosensory thalamocortical system, latencies to peripheral sensory stimulation are sufficiently short and robust to allow detection of a single synaptic delay (Armstrong-James et al., 1992; Swadlow, 1995). In the rabbit, the median latency of VB thalamocortical neurons to potent air-puff stimulation is ∼5 ms (Fig. 3A). Based on the conduction time along thalamocortical axons (∼1 ms, filled histograms in Fig. 3A), these impulses arrive in the cortex at a latencies of ∼6 ms following the peripheral stimulus (Fig. 3B), and a large population of S1 SINs respond at latencies of 6–7 ms (Fig. 3C). Thus, there is little time for more than one synaptic delay between the arrival of VB impulses in S1 and the initial spike elicited in most SINs. Moreover, SINs that responded

**Figure 2.** (A) Angular threshold for the detection of vibrissa movements of efferent neurons of different classes and SINs located in S1 barrel cortex. Efferent neurons studied included descending corticofugal neurons of layer 6 (CF-6 neurons) and layer-5 (CF-5 neurons) and ipsilateral cortico-cortical neurons projecting to S2 (C-IC neurons). (B) The highest frequencies of vibrissa deflections that could be followed by SINs and by efferent neurons of different classes. (C) Directionality ratios of efferent neurons of different classes and of SINs. The ratio of the number of spikes elicited in the preferred versus the null direction is shown. Source: (Swadlow, 1989).

absence of antidromic activation). Most descending projection neurons of layer 5 had spontaneous rates of 4–8 spikes/s.

SINs have very low thresholds to sensory stimulation. Figure 2A shows that SINs of S1 barrel cortex had much lower angular thresholds for detecting a whisker displacement than did any of the efferent populations of this region (Swadlow, 1989). More than 70% of SINs responded to a deflection of 0.8° in their ‘principle vibrissa’. In contrast, most efferent neurons of all classes required a deflection of >2°. Similarly, SINs in the vibrissae and forepaw representations of S1, as well as in S2 and in motor cortex (Swadlow, 1989, 1990, 1991, 1994) responded much more faithfully to high-frequency peripheral stimulation (Fig. 2B) than did the efferent populations. Another remarkable difference between SINs and the efferent populations of S1 barrel cortex was in their responses to different directions of whisker deflections. Most efferent neurons of all classes responded selectively to a narrow range of displacement angles (Fig. 2C). This is, perhaps, not surprising since most VB thalamocortical neurons also display strong directional selectivity (Simons and Carvell, 1989). However, the great majority of SINs, found in the same microelectrode penetrations as the efferent
at short latencies to the air puff (<7 ms) were largely located in the vicinity of layer 4, and these cells also responded at short latencies (<1.8 ms) to electrical stimulation of VB. Together, these data indicate a powerful monosynaptic input to fast-spike interneurons of layer 4.

Cross-correlation analysis has provided further evidence for strong functional connectivity between VB thalamocortical neurons and S1 SINs (Swadlow, 1995). These studies require precise topographic alignment between thalamic and cortical recording sites. When this was achieved, most SINs within and near to layer 4 showed a sharp increase in spike frequency following a thalamic spike, which is consistent with monosynaptic activation. This response is brief (often <1 ms in duration), and the peak increase in spike rate generally occurs at latencies of 1.2–2.2 ms following VB action potentials. The ‘efficacy’ of the functional connectivity between most VB neurons and S1 SINs was 1–2% (Swadlow, 1995). This value reflects the strength of the functional connectivity between the thalamic and cortical neuron, and is given by the ratio of presynaptic (thalamic) spikes to the number of spikes in the peak of the cross-correlogram (minus the number of spikes expected by chance during the period of the peak). In some cases, the efficacy of the thalamocortical input to SINs can be quite high.

Figure 4 shows cross-correlograms indicating very strong functional connectivity between a single VB thalamocortical neuron and two SINs that were simultaneously studied (on separate cortical microelectrodes) in the aligned S1 barrel. Thalamocortical efficacies were 0.21 and 0.13 in Figure 4B and Figure 4C, respectively, and peak latencies were 1.5 and 1.6 ms.

**Convergence and Divergence of Thalamocortical Input to S1 SINs**

In an earlier study of this system (Swadlow, 1995), single thalamocortical neurons were studied simultaneously with only a single cortical SIN. One surprising result of that analysis was that most of the S1 SINs under study showed evidence of functional connectivity with most of the thalamocortical neurons that were identified within the aligned VB barrels. Unlike the high degree of specificity seen in the functional connections between geniculocortical neurons and simple cells of V1 (Reid and Alonso, 1995), and between auditory thalamocortical neurons and their cortical recipients (Miller et al., 2001), the thalamocortical input to S1 SINs showed little evidence of specificity, other than the requirement for precise topographic alignment. VB thalamocortical neurons show a wide variation in receptive field properties [sustained vs. transient responses to maintained whisker deflection, directionally selective responses (which can be sharply tuned) versus multi-directional responses]. However, correspondence in these characteristics was not required for thalamocortical connectivity with S1 SINs. These results imply a very high degree of convergence and divergence in the thalamocortical connectivity of this feedforward inhibitory system (Swadlow, 1995).

Recently, we provided a more direct demonstration of this high degree of functional convergent and divergent connectivity by obtaining simultaneous recordings of multiple VB neurons and multiple, topographically aligned S1 SINs (Swadlow and Gusev, 2002). This strategy allowed us to compare the impact of several different VB neurons on the same SIN and, conversely, to examine the influence of a single thalamocortical neuron on multiple post-synaptic targets. Our results confirmed the highly convergent/divergent functional thalamocortical input to S1 SINs. SINs that lacked any directionality were shown to receive a strong convergent functional input from multiple VB neurons that each showed a strong directional selectivity, but in widely
diverging cause of the near-simultaneous EPSPs generated by the common, reasoning, Sears and Stagg (Sears and Stagg, 1976) predicted and. This would be expected to demonstrate another property: The recipient neurons of such a highly divergent/convergent directional preferences. A large number of thalamocortical neurons with widely differing their multidirectional receptive fields by pooling the input from. In this view, SINs obtain the target neuron. SINs have sacrificed ‘complexity of task’, however, in that they lack the directional selectivity that is seen in most of their thalamocortical inputs. In this view, SINs obtain their multidirectional receptive fields by pooling the input from a large number of thalamocortical neurons with widely differing directional preferences.

Figure 5. Convergent input from three VB neurons to a single SIN. (A) Schematic illustration of the functional connectivity between the three thalamocortical (TC) neurons and the SIN. Arrows indicate the very different directional preferences (range = 135°) of the TC neurons and the multidirectional responses of the SIN. (B) Cross-correlograms of each of these TC neurons and the SIN under study, TC functional connectivity was assessed in the absence of peripheral stimulation (following the receptive field analysis). Under conditions of ‘spontaneous’ activity. Values on the y-axis are given in spikes/s. Cross-correlograms were not filtered or smoothed and bin-widths were 0.1 ms. Source: (Swadlow and Gusev, 2002).

Remarkable divergence from single VB neurons to multiple SINs of a barrel was also demonstrated (Swadlow and Gusev, 2002). One VB neuron (dubbed ‘Hercules’ because of potent functional contacts with many SINs) was shown to make a functional contact with each of nine SINs that were studied over a 4 day period in the aligned S1 barrel. The VB–SIN pairs shown in Figure 4 show two of the contacts made by Hercules on one of these days.

Figure 6. Cross-correlogram of the spike trains of two SINs recorded within the same S1 barrel. Data were obtained in the absence of peripheral stimulation, under conditions of ‘spontaneous’ activity. Source: (Swadlow et al., 1998).

Sharp Synchrony Among Fast-spike Interneurons of S1
The recipient neurons of such a highly divergent/convergent network would be expected to demonstrate another property: sharply synchronous activity. This would be expected because of the near-simultaneous EPSPs generated by the common, diverging presynaptic input (Moore et al., 1970). Based on such reasoning, Sears and Stagg (Sears and Stagg, 1976) predicted and documented a ‘short-term’ synchrony between homonymous motoneurons [which receive a highly divergent input from muscle spindle 1a afferents (Mendell and Henneman, 1971)]. Similarly, potent coincident input from diverging optic tract fibers is believed responsible for the observed sharp synchrony between LGNd neurons with overlapping receptive fields and common response properties (Alonso et al., 1996). If SINs of an S1 barrel are, indeed, the recipients of a highly divergent input from many thalamocortical neurons, then they should also demonstrate such sharply synchronous activity. Moreover, because the VB thalamocortical terminal arborization is largely limited to a single barrel (Jensen and Killackey, 1987), the synchrony should also be so limited.

These predictions were tested by recording from pairs of SINs within an S1 barrel (Swadlow et al., 1998). The cross-correlogram presented in Figure 6 shows results generated by two SINs of the same barrel, each of which gave strong evidence of receiving monosynaptic thalamic input (latencies of <1.7 ms to electrical stimulation of VB and <7.5 ms to air-puff stimulation, above). Here, and in nearly all pairs of such thalamocortically driven SINs that were found within the same barrel, a sharp increase in spike frequency occurred in each SIN nearly simultaneously (~1 ms) with a spike in the other SIN. This effect did not depend upon peripheral stimulation, as it occurred whether action potentials were ‘spontaneous’ or stimulus driven. Moreover, it was seen at horizontal inter-electrode distances of up to 350 µm, as long as the two SINs were found within the same barrel. For pairs of SINs recorded within a single barrel, ~4% of the spikes of each SIN were sharply synchronous with the spikes of the other. As expected, sharp synchrony between SINs of neighboring barrels was minimal or absent, even when inter-electrode distances were <300 µm. We found that sharply synchronous activity in layer-4 SINs was not oscillatory. Autocorrelograms generated by the action potentials of individual SINs and by the synchronous events occurring between two SINs showed no signs of ‘side-bands’ that are indicative of oscillatory activity. Moreover, sharp synchrony between SINs was present in both fully awake and anesthetized states. Sharp synchrony was not seen between SINs and other populations of the same barrel that showed no evidence of monosynaptic thalamic input. Recent preliminary evidence based on recordings of triads of SINs within a barrel (unpublished) indicate that sharply synchronous activity between two SINs does not reflect a communal synchrony among all SINs of the barrel. Instead, synchronous events among the SINs of a barrel are roughly independent.

One consequence that can be inferred from the above findings is that fast-spike interneurons of layer 4 rarely discharge in isolation, even in the absence of peripheral stimulation. Instead, when a thalamocortical impulse generates an action potential in...
one SIN, a significant population of the SINs in the same barrel discharge in sharp synchrony (~4% according to the above results). This coincident discharge of GABAergic interneurons will generate a synchronous feedforward release of GABA onto post-synaptic targets. We have recently argued that the compound IPSPs generated by this synchronous release of GABA can be detected in the extracellular record (using methods of spike-triggered averaging) as a positive field potential within layer 4 that follows action potentials of individual thalamocortical neurons (Swadlow and Gusev, 2000).

Functional Thalamocortical Connectivity, Sharp Synchrony and Electrical Coupling Among Fast-spke, GABAergic Interneurons

The brief and powerful peaks in spike probability occurring in SINs at intervals of 1.2–2 ms following thalamocortical impulses (Fig. 4) are strongly suggestive of monosynaptic excitatory input, and the sharply synchronous activity seen between pairs of SINs within an S1 barrel (Fig. 6) are consistent with this idea. However, recent findings of electrical coupling among fast-spke interneurons in rat and mouse (Galarreta and Hestrin, 1999; Gibson et al., 1999) suggest that SINs may be functionally linked by both divergent thalamocortical axons and electrically coupled dendrites. Although electrical coupling has been studied primarily in immature tissue, such coupling has also been seen in slices taken from 26-day-old pups (Gibson et al., 1999). Moreover, connexin-36, which is believed to underlie this electrical coupling, is present in the cortex of mature brains (Deans et al., 2001). If electrical coupling is, indeed, present among fast-spke interneurons in adult brains, then it could contribute to the observed sharply synchronous activity among these elements and, to some extent, to the observed functional divergent/convergent thalamocortical connectivity. Divergent thalamocortical synaptic input and electrical dendritic coupling both could serve to couple the behavior of GABAergic interneurons, and these two mechanisms of could act together, in a cooperative, synergistic manner, to facilitate widespread, synchronous discharge of fast-spke interneurons following thalamocortical impulses. Indeed, it is possible that some SINs with little or no direct (synaptic) thalamocortical connectivity could show an increase in spike probability following thalamic spikes due to electrical coupling with other SINs that do receive direct thalamocortical input.

It is important to note that we do not yet know the extent to which fast-spke interneurons are electrically coupled in intact adults, and how general this phenomenon is among various mammalian lines. Given outstanding questions concerning the orientation tuning of GABAergic interneurons in layer 4 of cat (Azuol et al., 1997; Hirsch et al., 2000) and the putative role of such neurons in controlling the receptive fields of excitatory neurons (Troyer et al., 1998), it would be very useful to know whether these elements are electrically coupled in adult cats, the spatial extent of any such coupling, and the relationship of this coupling to orientation tuning and other receptive field properties of these neurons. If fast-spke GABAergic interneurons of feline visual cortex are electrically coupled over distances similar to those seen in rodents (±200 μm (Amitai et al., 2001)), one would expect this to broaden any orientation preference in these neurons that was directly generated by feedforward (thalamocortical) connectivity. This effect could be especially prominent near ‘pinwheel’ centers, where the distance between orientation columns is reduced (Maldonado et al., 1997). Clearly, further experimental work and computational studies are required to unravel the relative contributions of diverging/converging thalamocortical synaptic input and electrical dendritic coupling to (i) the observed sharp synchrony among these interneurons, (ii) their highly divergent/convergent functional thalamocortical connectivity and (iii) their receptive field properties.

Fast-spke Interneurons of Layer 4: a Substrate for Fast, Potent Feedforward Inhibition

Figure 7 schematically illustrates many of the above results. Thalamocortical impulses functionally diverge and converge to generate a rapid, widespread and synchronous activation of layer-4 fast-spke interneurons of the topographically aligned S1 barrel (Swadlow, 1995; Swadlow and Gusev, 2002). One result of this convergent circuitry is a receptive field transformation: VB thalamocortical neurons with widely differing directional preferences converge non-selectively onto fast-spke interneurons of layer 4, generating highly sensitive but broadly tuned receptive fields. A result of the divergent thalamocortical circuitry is a sharp synchrony among these interneurons following thalamocortical impulses (Swadlow et al., 1998). This will, in turn, generate a sharply synchronous release of GABA, and a consequent compound IPSP in recipient cortical spiny neurons that limits the duration of the excitation generated by the thalamocortical EPSPs (Swadlow and Gusev, 2000). Thus, single thalamocortical impulses will generate only a brief ‘window of excitability’ during which cortical spikes can occur and contribute to feedforward and recurrent excitatory processes. This fast, synchronous, highly sensitive and broadly tuned
feedforward inhibitory network [cf. (Troyer et al., 1998)] is well suited to suppress spike generation in spiny target neurons following all but the most optimal feedforward excitatory inputs.

**Notes**

Supported by grants from NSF (IBN-0077694) and NIMH (MH-64024).

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