

## Chapter 5

### Conclusions and Future Directions

#### 5.1 Conclusions

This thesis has explored the idea that the short-term reductions in neural activity that are commonly observed following repeated exposure to a stimulus (termed *repetition suppression*) are due primarily to the short-term plasticity mechanisms of firing-rate adaptation and synaptic depression that are present in individual cortical cells and at individual synapses. These mechanisms can simultaneously serve to facilitate perception and improve processing efficiency by helping to coordinate spike times over large populations of cortical cells. However, adaptation and synaptic depression can also impair perception if neuromodulatory levels are too low, attenuating nearly completely the flow of sensory signals. Global cholinergic and noradrenergic neuromodulatory processes that are sensitive to behavioral state/performance can potentially serve to strike an effective balance between performance and metabolic cost by dynamically reducing the impact of adaptation and synaptic depression when performance begins to suffer.

The eight simulations presented above demonstrate the central aspects of this proposal. *Simulation 1* showed that a number of the detailed empirical characteristics of short-term repetition suppression that have been observed in neural recording and neuroimaging experiments are nicely addressed by adaptation and synaptic depression when incorporated in a large interconnected network of spiking neurons. Since the parameters of the model that dictated the time course and magnitude of these short-term plasticity mechanisms were first fit to independent sources of neurophysiological data, this demonstration is a strong one. *Simulations 2* and *3* provided the critical demonstration that adaptation and synaptic depression synchronize neural spike times while they reduce activity. This was partly due to the lowering of firing rates which made excitatory interactions relatively fast and partly due to the ways in which these mechanisms altered the shape of the response function (PRC) of the excitatory neurons. Inhibition also played a more limited role in promoting synchrony by reducing firing rates. Repetition-related increases in spike synchrony were found to be reasonably tolerant of input heterogeneity and local synaptic delays, and they survived interactions with other populations of cells separated by longer synaptic delays, provided that the degree of positive feedback between the populations was not too strong. These simulations also suggested that reductions in firing-rate variance due to synaptic depression might contribute to increased spike synchrony beyond those effects due simply to reductions in the mean firing rate.

*Simulation 4* explored one potential way in which simultaneous decreases in firing rate and increases in spike synchrony throughout a perceptual processing pathway could drive motor responses more effectively, thus facilitating reaction times. When

excitatory and inhibitory synaptic influences on a single output cell were relatively balanced, it tended to reach a critical threshold number of spikes earlier when its inputs were more synchronized, even when the overall firing rates of the inputs were decreasing. When this simple single-neuron output was taken as a proxy for the latency of motor responses, reaction times estimated for *Simulation 2* were shown to be facilitated by stimulus repetition over a wide range of input heterogeneity values (0-60%). However, if rates dropped too low or if changes in coherence were too small, reaction times could also be slowed by repetition. Based on the reaction time results, *Simulation 5* provided a simple demonstration that processing efficiency in terms of the changes in reaction time and the number of input spikes per response did indeed increase with stimulus repetition.

*Simulations 6-8* showed that repetition-related performance decreases rather than increases can occur when levels of neuromodulators such as acetylcholine and norepinephrine are too low. This occurs because neuromodulation alters the responsiveness of cells and the magnitude of short-term plasticity effects; under low levels of neuromodulation, short-term plasticity effects are strong and cellular responsiveness to excitatory input is decreased, permitting stimulus repetition to reduce firing rates to the point that small changes in coherence were not effective. *Simulation 6* utilized these ideas in accounting for the contrasting pattern of performance observed in two different populations of brain-damaged patients with acquired semantic impairments. Patients referred to as *access/refractory* are strongly influenced by presentation rate, semantic relatedness of distractors, and repetition, yet they seem relatively unaffected by lexical frequency. *Degraded-store* patients, on the other hand, are strongly affected by lexical frequency but less affected by presentation rate, semantic relatedness, or

repetition. A firing-rate connectionist neural network incorporating synaptic depression and some basic properties of cholinergic and noradrenergic neuromodulation exhibited an access/refractory pattern under a severe neuromodulatory deficit with little or no damage to neural connections between groups of neurons representing semantic information. This resulted from the lack of suppression of transmitter release and heightened synaptic depression. A degraded-store pattern, on the other hand, was produced by damage to connections between semantic regions with normal levels of neuromodulation. *Simulation 7* demonstrated that this relatively simple proposal was also capable of accounting for the main patterns of exception to the basic contrasting patterns (e.g. frequency effects without consistency, consistent responding with little or no frequency effects, and access/refractory performance lacking serial position effects). *Simulation 8* demonstrated in a spiking model similar to those in *Simulations 1-5* that both short-term repetition priming and habituation effects could be produced within the same model if several of the main cellular actions of acetylcholine and norepinephrine are taken into account (e.g. suppression of transmitter release, synaptic depression, and firing-rate adaptation; increased input resistance and depolarized resting potential for excitatory cells; decreased input resistance for inhibitory cells). Repetition-related decreases in rate and increases in synchrony leading to priming occurred under moderate to high levels of neuromodulation, whereas lower levels of neuromodulation led to rate decreases without marked changes in synchrony, producing habituation effects.

While the models used in these simulations are highly simplified approximations of the neural processes that are believed to underlie these various phenomena, the current proposal provides a principled explanation as to why neural activity decreases might

accompany improved performance in many circumstances: It is easier to observe efficient coordinated spiking activity in networks of excitatory and inhibitory neurons when they spike at lower rather than higher rates. Metabolic efficiency in neural processing is critical for biological organisms because neural activity is particularly costly as far as biological processes go (Laughlin, 2001). The importance and utility of mechanisms that promote neural processing efficiency over short time scales should also be clear, given the wide variety of behavioral circumstances in which individual stimuli (objects, images, sounds, etc.) are repeatedly encountered or manipulated over a relatively short period of time. Aside from any arguments about the importance of efficiency, the current set of models address data acquired in a wide variety of experimental contexts, ranging from neurophysiological and pharmacological to neuropsychological and behavioral. The models do this with relatively few free parameters, as the equations and parameters of most of the processes have been constrained by and fit to independent sources of anatomical and physiological data. The benefit of this approach over purely psychological theorizing is that it improves the falsifiability of the proposal by making novel predictions in neuroscience, as well as psychological experiments. Along these lines, the models afford the following predictions:

- The magnitude of short-term repetition suppression effects in neural recording experiments should be positively correlated with the firing rate to the first stimulus presentation (i.e. larger firing rate decreases for larger initial rates).

- The magnitudes of repetition suppression effects in neural recording and neuroimaging experiments (measured proportionately to the initial response) should be reduced under cholinergic (muscarinic) or noradrenergic agonists.
- Short-term repetition suppression effects should be correlated with enhanced spike synchrony in extracellular neural recording experiments (measured either through the use of multi-neuron recording techniques or simultaneous single-unit and local-field potential recordings); both short-term repetition suppression and increases in spike synchrony should be correlated with reductions in reaction time.
- Short-term repetition suppression and behavioral priming effects should not be eliminated under an NMDA block, whereas long-term effects should be.
- Cholinergic agonists should increase activity and synchrony overall due to actions on input resistance that speed up excitation and slow down inhibition, along with actions that increase the impact of interneuron networks that are dominated by gap junctions.
- Patients suffering from neuromodulatory deficits of acetylcholine and/or norepinephrine should be more likely to exhibit repetition-related decreases in performance, and they may show improved performance when administered pharmacological treatments that include agonists of acetylcholine/norepinephrine.

The current proposal bears some similarity to previous theories about the role of spike synchrony in neural processing, although it provides a number of unique contributions, as well. Hopfield and Brody (2001) have recently proposed a role for

synchrony in identifying particular spatio-temporal patterns. They showed that when a population of excitatory and inhibitory spiking neurons received inputs with a range of values and different rates of decay, neurons transiently synchronized at points in time when inputs were relatively homogeneous. Transient synchrony was then able to generate a spiking response in an output neuron that was sensitive to synchrony due to its relatively short membrane time constant. They also showed that the synaptic connections in their model could be configured easily to distinguish between different spatio-temporal patterns in a way that was invariant to a uniform time warp of the patterns or uniform changes in input intensity. While the spiking models presented in this thesis did not represent multiple stimuli, synchronous spiking was similarly influenced by the relative homogeneity of input values (*Simulation 2*, **Section 3.3**). The response of the models to stimuli did also depend on the ability of an output neuron to be driven more effectively by synchronous inputs, although this was achieved by relatively balanced excitation and inhibition rather than by a short membrane time constant (*Simulation 4*, **Section 3.5**). The current proposal is more similar to those of Salinas and Sejnowski (2000, 2001) and Fries et al. (2001), in which synchrony primarily plays a role of gain enhancement rather than altering the content of what is being processed. In other words, information coding in networks of neurons is thought to rely specifically on which cells are active by virtue of their patterns of synaptic connectivity - similar to existing firing-rate neural network proposals (e.g. Grossberg, 1976, 1980; Rumelhart & McClelland, 1986). The relative weighting of the information encoded by subpopulations of cells at any one time is conveyed by firing-rate magnitude and degree of synchrony. These proposals differ notably from those focused more on spike synchrony as a mechanism for resolving

perceptual ambiguities through feature binding (e.g. Gray et al., 1989; Singer & Gray, 1995). The current proposal adds to the previous ones mainly by forging a link to previous theoretical work on the mechanisms that generate phase-locked states in coupled neural oscillators and by using these insights to articulate how it is that mechanisms such as synaptic depression, firing-rate adaptation, and enhanced concentrations of neuromodulators can lead to synchrony (e.g. Chow, 1998; Ermentrout et al., 2001; Gerstner et al., 1996; Hansel et al., 1995; van Vreeswijk et al., 1994). The simulations demonstrate that factors that lead the exact synchronous solution to break down (e.g. input heterogeneity) do not necessarily disrupt near-synchrony completely. Indeed, the degree of synchronous spiking appears to degrade rather gradually over increases in such factors. The proposal also places a stronger emphasis on the role that synchrony may play in processing efficiency.

While spike synchronization may play an important role in a variety of perceptual and cognitive phenomena, it is unlikely to be the only important functional mode in the nervous system. Asynchronous neural spiking can also be very useful for certain functions. For example, some researchers have suggested that noisy, asynchronous spiking may be important for improved sensitivity to weak perceptual inputs (e.g. van Rossum, Turrigiano, & Nelson, 2002; Destexhe, Rudolph, Fellous, & Sejnowski, 2001). If some fraction of neurons is always close to spiking threshold due to randomly distributed spike times, then weak inputs will always be able to evoke some degree of response. Asynchronous spiking activity has also been proposed to be important for the existence of the sustained "delay period" activity that has been observed in prefrontal cortex (PFC) in working memory contexts (e.g. Gutkin, Laing, Colby, Chow, &

Ermentrout, 2001). Since synaptic currents can be relatively transient, activity may terminate prematurely if cells fire too synchronously at slow rates. Sustained activity can be made more stable by spreading around the times of spikes, insuring that there is always some degree of synaptic input to keep the activity going. Others have similarly emphasized the importance of slow excitatory (NMDA) synaptic currents for sustained neural activity, currents that de-synchronize activity through slow excitatory kinetics (e.g. Compte, Brunel, Goldman-Rakic, & Wang, 2000; Wang, 1999, 2001). Under these circumstances, reduced firing-rate descriptions may be reasonable approximations of population firing rate activity because the conditions required for accurate spatio-temporal averaging are better met (e.g. Amit & Tsodyks, 1991; Gerstner, 1995; Wilson & Cowan, 1972). Firing-rate descriptions of neural activity are poorer approximations when activity is relatively synchronous because they fail to capture the transient peaks and troughs that occur within and between coordinated volleys of spikes, as well as the transient changes in synaptic gain that may occur (e.g. Salinas & Sejnowski, 2000; see also *Simulation 4*, **Section 3.5**). On these points, it is interesting to note that stimulus repetition does not lead to neural activity decreases in all brain regions and in all tasks. Some regions, such as frontal and insular cortices have been shown to exhibit either no activity decreases or even increases across short-term stimulus repetitions in tasks such as delay match-to-sample and silent naming (e.g. Jiang et al., 2000; van Turennout et al., 2000). Repetition-related activity increases have also been observed in medial temporal and anterior prefrontal cortical regions during the performance of cued recall and recognition memory tasks (e.g. Schacter & Buckner, 1998). It is also possible to observe activity increases in more posterior regions (e.g. fusiform) for repeated novel stimuli in

perceptual identification (e.g. Henson et al., 2000), as well as activity increases prior to recognition of primed objects presented in a gradual unmasking paradigm (James, Humphrey, Gati, Menon, & Goodale, 2000). Whether or not the lack of short-term activity decreases in these brain regions under these task circumstances is due to dynamic changes in neuromodulation, enhanced top-down activity, or differences in cellular properties in different brain regions remains to be explored.

Despite the successes of the current simulations, there is plenty of room left for improvement. *Simulation 2* showed that moderately strong positive feedback between cortical regions across longer synaptic delays could disrupt repetition-related changes in synchrony. It will be important to explore whether allowing inhibitory interneurons to fire multiple spikes, doublets in particular, alleviates this disruption (e.g. Ermentrout & Kopell, 1998; Karbowski & Kopell, 2000; Kopell et al., 2000). Ideally, this would involve constraining the balance of excitation and inhibition in the feedforward and feedback directions with neurophysiological data, as choices for the current simulations have not been guided by much other than a desire to achieve firing rates in a 10-60 Hz range (see also discussion in **Section 3.3.2**). Repetition-related changes in coherence in the models also decayed somewhat faster over delays than do short-term repetition priming effects (e.g. McKone, 1995; 1998). This may be due to the current lack of inclusion of firing-rate adaptation at somewhat slower time scales (e.g. 1-10 seconds: Sanchez-Vives et al., 2000; Schwindt et al., 1988). However, it could also be due to the lack of inclusion of longer-lasting plasticity mechanisms (e.g. LTP, LTD, synaptic scaling, etc.: Turrigiano & Nelson, 2000; van Rossum et al., 2000) that may be operating to some degree in the short-term priming experiments. Future work will need to explore

both of these possibilities. A further problem was that the integrate-and-fire excitatory (inhibitory) neurons used in the simulations fired more synchronously (asynchronously) than other Type I model neurons. This was likely due to the lack of currents responsible for action potential kinetics ( $I_{Na}$  and  $I_{Kdr}$ ) that by decreasing input resistance near the time of each spike would make excitation and inhibition relatively slow (Golomb & Hansel, 2000; Neltner et al., 2000; see also discussion in **Section 2.2.1** and **Appendix D**). While results are not expected to differ qualitatively if more realistic Hodgkin-Huxley style neurons are used, it will be important to verify that similar quantitative changes in synchrony are possible over a similar range of firing rates. These issues indicate that the current work is perhaps best viewed as a fruitful starting point for a more full account of the relationship between practice-related changes in neural activity and behavioral performance. The current models involve many simplifications and do not incorporate all of the neural processes that are potentially relevant for synchronous spiking. For example, a number of researchers have emphasized the importance of electrical synapses ("gap junctions") in networks of inhibitory interneurons for spike synchrony in cortical cells (e.g. Beierlein et al., 2000; Galarreta & Hestrin, 2001). Neuromodulators such as acetylcholine have been shown to have a different impact on different groups of interneurons, elevating activity among interneurons that are connected exclusively by gap junctions and suppressing activity in other types of interneurons (e.g. Xiang, Huguenard, & Prince, 1998). While these potential contributions to neural synchrony are not obviously expected to interact with stimulus repetition, they underscore the possibility that there are mechanistic pathways that lead to neural synchrony other than those involved in mediating short-term plasticity. A variety of mechanisms might aid

synchrony by altering the electrical coupling of interneurons, by making excitatory synaptic interactions fast relative to firing rates and membrane time constants, or by making inhibitory synaptic interactions relatively slow.

## 5.2 Future Directions

Future work will be aimed at addressing some of the shortcomings of the current simulations and extending the ideas explored here to address several other relevant neural and behavioral phenomena. As mentioned above, it will be important to explore the impact on spike synchrony of the balance of excitation/inhibition in bottom-up versus top-down synaptic interactions between cortical regions, slower short-term and longer-term plasticity mechanisms, and the use of neurons with more detailed biophysical characteristics. It would also be nice to extend the current simulations to address some well-known behavioral slowing phenomena in neurologically intact human participants, in addition to facilitatory phenomena. For example, the models in their current form might be able to account nicely for *semantic satiation*, a phenomenon in which strong initial semantic priming effects attenuate markedly over multiple rapid stimulus repetitions (e.g. Balota & Black, 1997; Smith, 1984; Smith & Klein, 1990). This is potentially very similar to the trend observed in *Simulations 4* and *8* for strong priming after a small number of stimulus repetitions that attenuates after a larger number (e.g. see Figures 3.31 and 4.12). *Verbal transformation* effects for syllables and words presented auditorially may be a more extreme instance of the same phenomenon; 1-2 minutes of

continual repetition of the same word can eventually lead to impaired perception of component sounds (phonemes) and auditory distortions/hallucinations (e.g. Pilotti, Balota, Sommers, & Khurshid, 2000; Tuller, Ding, & Kelso, 1997; Warren, 1961, 1968). When short-term plasticity mechanisms such as synaptic depression and firing-rate adaptation play more of an habituating role in neural models (see *Simulation 8*), they can also be shown to account nicely for a number of the empirical characteristics of binocular rivalry phenomena in visual perception (e.g. Laing & Chow, 2002; Logothetis, Leopold, & Sheinberg, 1996). It may therefore be possible to provide a unified neural theory of short-term repetition priming, habituation, and perceptual rivalry that is testable behaviorally, physiologically and pharmacologically. Such an account would involve the representation of multiple stimuli in different competing and/or cooperating populations of neural cells. This should afford a deeper understanding of how the dynamic changes in synchrony explored in this thesis are altered by stronger competitive interactions. It should also allow the exploration of mechanisms proposed to underlie selective attention abilities by incorporating top-down inputs representing prefrontal cortical activity to the competing groups - referred to as "biased competition" (Desimone & Duncan, 1995).

One of the more important future extensions of the work will involve the inclusion of long-lasting synaptic plasticity mechanisms. Most of the studies using neuroimaging techniques to relate changes in neural activity to changes in reaction time have involved stimulus repetitions spaced by minutes or longer (e.g. Henson et al., 2000; van Turennout et al., 2000; Wagner et al., 2000). The longer time scales involved in these cases have implicated slower cortical learning mechanisms, and proposals have centered around ideas such as representational sharpening in service of improved

behavioral performance (e.g. Desimone, 1996). The models are currently unable to address repetition suppression or priming effects that last longer than a few seconds, and the incorporation of longer-lasting plasticity mechanisms may help to address effects at these longer time scales. Some recent simulation work exploring spike-timing dependent LTP/LTD and synaptic scaling mechanisms suggests that stimulus repetition may lead to increased neural selectivity, potentially mediating representational sharpening and reduced firing rates (e.g. Song, Miller, & Abbott, 2000; van Rossum, Bi, & Turrigiano, 2000). These mechanisms might have an additional impact on spike synchronization by compressing the variability in firing rates across stimulus repetitions and/or selecting out subgroups of neurons with reliable and predictable spike times, although these issues have yet to be explored in much detail either theoretically or empirically (see Schieber, 2002, and Vazquez et al., 2001, for preliminary evidence of learning-related increases in spike synchrony).

It will be difficult to explore slower learning-related changes in neural activity and behavioral performance without developing a clearer view of the role that neuromodulators may play in learning and in dynamic changes in processing state. *Simulation 8* demonstrated that the cellular actions of neuromodulators such as acetylcholine and norepinephrine may be synchronizing (see also Beierlein et al., 2000; Rodriguez, Kallenbach, Singer, & Munk, 2001). Given the importance of spike-timing for long-lasting plasticity and demonstrations that cholinergic/noradrenergic agonists and antagonists can enhance or block synaptic plasticity and practice-related changes in neural receptive fields, neuromodulation is likely to play a central role in long-term neural and behavioral changes, as well as the short-term changes explored here (e.g.

Boroojerdi, Battaglia, Muellbacher, & Cohen, 2001; Brocher, Artola, & Singer, 1992; Kilgard & Merzenich, 1998; Markram, Lubke, Frotscher, & Sakmann, 1997). The current simulations have dealt only with changes in tonic levels of neuromodulation, although changes in the neurologically intact brain are far more likely to be dynamic in response to environmental and task contingencies. Changes that are dependent on behavioral context and the level of task performance may help to improve efficiency by permitting lower spiking activity when possible. Much about the mechanisms that might permit this type of flexibility and control is unknown. Future work will be focused on understanding how mean levels of firing rate and synchrony in cortical cells might themselves serve as cues for local adjustments in neuromodulatory concentrations. For example, if heightened firing rates and/or synchrony indicate a well-known stimulus and good performance, a simple opponent relationship of cortical activity feeding back to neuromodulatory centers might help to explain the relative lack of cholinergic activity under these circumstances, as well as the more vigorous cholinergic activity observed during the processing of novel stimuli (e.g. Acquas, Wilson, & Fibiger, 1996; Miranda, Ramirez-Lugo, & Bermudez-Rattoni, 2000; see Sohal & Hasselmo, 2000, for a similar proposal). Future work will also explore the ability of such ideas to address the behavioral performance patterns of brain-damaged patients who are believed to suffer from neuromodulatory deficits. For example, Sandson and Albert (1987) have suggested that certain types of performance errors in patients reflect distinct types of neuromodulatory deficits. Visual and verbal *perseverations*, incorrect repetitions of previous responses, are often produced by patients with acquired language impairments resulting from left-hemisphere damage (e.g. Allison & Hurwitz, 1967; Albert & Sandson,

1986; Gotts, Incisa della Rocchetta, & Cipolotti, 2002; Hirsh, 1998; Martin, Roach, Brecher, & Lowery, 1998; Santo Pietro & Rigrodsky, 1982). These errors have been shown to correlate with low cortical levels of acetylcholine (Fuld, Katzman, Davies, & Terry, 1982), and accordingly Sandson and Albert (1987) have proposed that verbal perseverations result from cholinergic deficits. At the same time, verbal perseverations often occur after a number of intervening stimuli/responses and have been argued to result from learning mechanisms that mediate priming effects in neurologically intact human participants (e.g. Cohen & Dehaene, 1998; Martin et al., 1998; Vitkovitch & Humphreys, 1991). These errors may therefore provide some relatively unique insight into the interaction of neuromodulatory systems and cortical learning mechanisms (e.g. Gotts et al., 2002). Whether neuromodulatory deficits will be capable of explaining the characteristics of verbal perseverations, as well as the pattern of errors exhibited by access/refractory patients (see *Simulations 6* and *7*, **Sections 4.3** and **4.4**), remains to be seen. The relatively strong changes in coherence observed at moderate neuromodulatory levels in *Simulation 8* compared to those observed at lower neuromodulatory levels may ultimately provide a possible resolution (see Figures 4.11 and 4.12).

The highly simplistic nature of the response mechanisms employed in this thesis will also need to be revisited in future work. While the amount of time taken to reach a critical threshold number of spikes in a single output motor cortex neuron should be correlated with the time taken to reach a critical firing rate (assuming a relatively smooth approach to that rate), it would be nice to address the dynamical changes in firing rate that ultimately determine at what point the critical firing rate is reached to initiate a motor response (e.g. Hanes & Schall, 1996; Schall, 2001). One promising approach to the

generation of simple decisions and responses has been taken by Usher and McClelland (2001) in which individual firing-rate style neurons that represent individual choices or responses dynamically compete through lateral inhibition. One of the units is taken to have generated a response once a criterion of activity is reached, and the ultimate winner of the competition is the neuron that over time receives the strongest input from sensory systems or other internal sources. Although relatively simple, the model is capable of addressing a range of behavioral results observed in humans performing alternative-forced-choice psychophysical tasks, and its implementation through standard neural computational mechanisms may also allow it to address the neural phenomena associated with response generation and response times (e.g. Hanes & Schall, 1996). As discussed above, the firing-rate style neurons used by Usher and McClelland (2001) may provide a reasonable approximation to average population activity when the spiking neurons in the population are firing relatively asynchronously (e.g. Amit & Tsodyks, 1991; Gerstner, 1995; Wilson & Cowan, 1972). A spiking neural network capable of asynchronous firing similar to those used by Gutkin et al. (2001) and Wang (1999) to simulate prefrontal cortical activity in working memory contexts may therefore be capable of addressing the same range of behavioral phenomena as the Usher and McClelland (2001) model. Whether or not this model would be capable of effectively integrating partially synchronous inputs such that faster rates of buildup could be observed for higher degrees of input synchrony as the input rates are decreasing is a crucial open question in need of further work. The use of spiking models will be important for this exploration because too much synchrony in the inputs may disrupt the asynchronous spiking and terminate the temporal integration prematurely (Compte et al., 2000; Gutkin et al., 2001). The

threshold property of spiking cells is also a critical aspect of what allows them to be more sensitive to changes in synchrony as rates decrease (see *Simulation 4*, **Section 3.5**). Examining these issues simultaneously in firing-rate style connectionist neural networks and spiking models should provide additional insight into the relationship between connectionist models and real neural activity.