

Relationship between field potentials and spike activity in rat S1: multi-site cortical recordings and analysis.

Stephen D. Van Hooser^{a,c} Ulrich G. Hofmann^{b,c}
David T. Kewley^c James M. Bower^c

^a*Brandeis University, Department of Biology, 415 South St., Waltham, MA 02454*

^b*Medical University of Lübeck, Inst. f. Signal Processing,
Seelandstr. 1a) Geb. 5, 23569 Lübeck, Germany*

^c*California Institute of Technology, Div. of Biology,
MS 216-76, Pasadena, CA 91125*

Abstract

We present field potential and multiple single unit data simultaneously recorded from somatosensory cortex of the anesthetized rat using a multi-site silicon electrode. We find that although single units fire spontaneously only during troughs of the low frequency field potential, there is high variability in the timing of their firing. Viewing our results in the context of previous anatomical, physiological, and modeling studies of cerebral cortex, we suggest that local field potentials are better characterized as a recording of local synaptic currents rather than a recording of the superposition of spike activity in populations of neurons. If true, then our data show that similar circuit-level synaptic inputs do not predict the timing of spiking output by the neurons receiving those inputs. These results have important implications for theories of cerebral cortical network function and information coding based on the interpretation of coherence in recorded field potentials.

Key words: Field Potential; Multi-unit recording; Somatosensory Cortex; Neural Coding; Spike Timing

1 Introduction

Over the last several years considerable theoretical interest has been generated in the idea that the nervous system uses the synchronous firing of many neurons to code, or specifically bind, higher order features of peripheral stimuli (14). Such a mechanism was first proposed on theoretical grounds (15) and

then obtained support by observations made using field potential recordings in the monkey visual system (2; 3). In the ensuing years, synchronous spike firing theory has been extended to include the physiological basis of visual attention as well as consciousness itself (1).

A fundamental assumption of many physiological and modeling studies of synchronized cortical oscillations is that the temporal structure of field potential recordings directly reflects the temporal structure of the spiking output of nearby cortical neurons (14). This has been assumed despite the general understanding that cortical evoked potentials and scalp EEGs are more directly related to slow synaptic currents rather than spiking currents (9; 12; 16). However, to our knowledge to date no one has attempted to qualitatively access the relationship between the temporal structure of field potentials and neuronal spike timing for localized regions of the cerebral cortex.

In this study we have used multi-site silicon recording electrodes to examine this relationship. Using silicon electrodes of our own design (7), we have been able to record both local field potentials and individual spiking neurons from a single electrode inserted perpendicular to the surface of the somatosensory cortex of the rat. The results indicate that while local field potentials do predict the general occurrence of spiking activity, there is considerable trial to trial variation in the detailed timing of that activity. These results suggest that it is not possible to infer relationships in spike timing from field potential recordings.

2 Cortical Data Analysis

Using a silicon electrode (7) with eight vertically-spaced recording sites ($40\ \mu\text{m}$ site-to-site), we recorded spontaneous extracellular activity in the somatosensory cortex of ketamine-anesthetized rats. Ketamine was chosen as an anesthetic because this drug is known to produce oscillatory behavior that is similar to the behavior seen in awake preparations (4). We examined this data in two frequency bands: the low frequency field potential ($<300\text{Hz}$) and the high frequency spike activity ($>500\text{Hz}$). Cluster cutting techniques (13) were used to separate the action potentials of individual neurons.

3 Results

Figure 1A shows representative field potentials recorded in this study which demonstrate the typical slow waves of activity at $\sim 0.5\text{Hz}$ seen under ketamine anesthesia. The lower section of Figure 1A demonstrates that 12 neurons

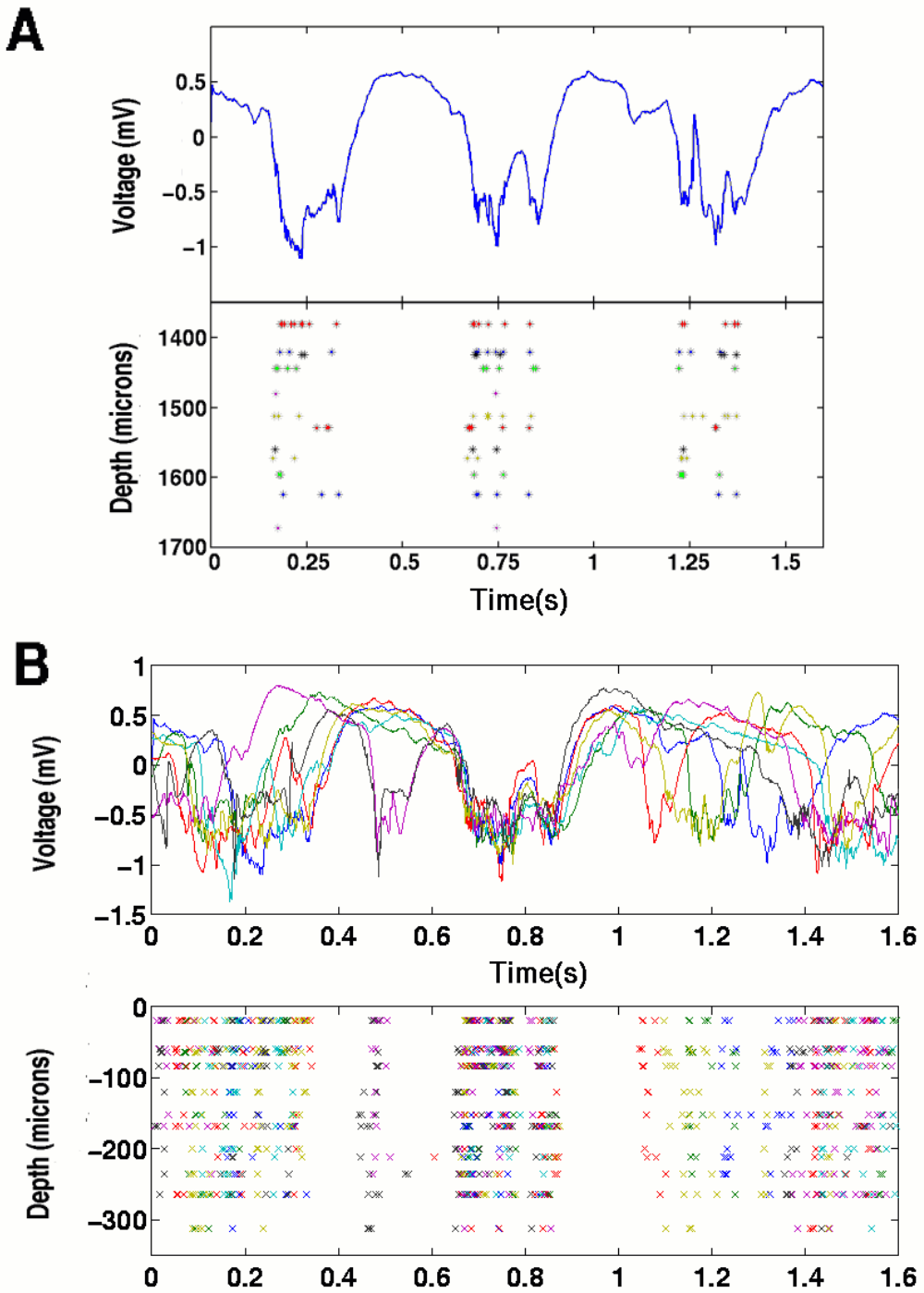


Fig. 1. A) shows three typical field potential troughs (top) and the associated single unit activity of 12 individual neurons (bottom). Each isolated neuron is represented by a different color, and each '*' represents one spike. The depth of each neuron is indicated at the left. B) shows 7 similar field potential waveforms (top) and the corresponding single unit activity of the same 12 neurons (bottom). In this plot, each color represents the activity during one of the 7 waveforms. The depth of each cell relative to the top of the electrode is again indicated at the left. The unit activity is highly variable from trough to trough.

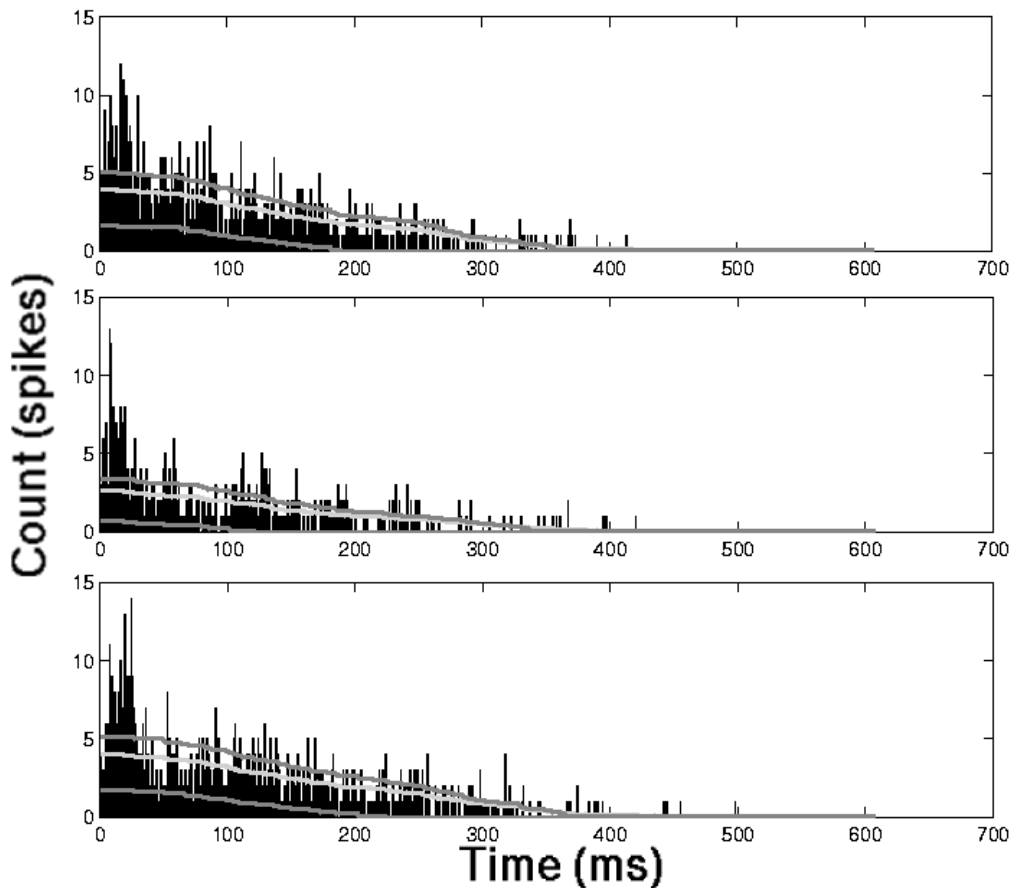


Fig. 2. This figure shows histograms of three representative neurons, triggered on trough onset. The light gray line shows the expected counts if spikes were randomly dropped into 1ms bins, and the dark gray lines show the 20 and 80% confidence lines.

recorded from the same silicon electrode have a strong tendency to fire action potentials during the troughs of the cortical field potentials. In our data, 19,429 of the 22,408 spikes recorded (87%) occurred during the troughs. A movie showing an entire 33s recording of both field potential and single unit activity is available at <http://www.bbb.caltech.edu/USERS/vanhoosr/probe3.mov>. Figure 2 examines in more detail the pattern of neuronal firing for three characteristic neurons within each trough in the field potential. In this figure, histograms were constructed by aligning spiking activity to trough onset (troughs were defined as a crossing from positive voltage to negative and back to positive). The three lines in the figure show the expected bin counts and 20 and 80% confidence limits if the spikes occurred randomly within each trough. Except for a slightly elevated firing frequency at the beginning, neurons appear to fire in a random fashion within the troughs. Figure 1B examines the relationship between similar appearing field potentials and neuronal spiking. Similar field potentials were identified by sliding a template trough waveform across the entire data set and then computing the mean squared error. Fig-

ure 1B reproduces a set of 7 similar waveforms and the spikes generated by the recorded neurons during these trials. There is no clear pattern in the single unit recorded single unit behavior. Further, no peaks were found in the cross-correlogram among all pairs of neurons (data not shown).

4 Discussion

We have reported that single unit activity is only observed during the troughs of the low frequency field potential, and that, during spontaneous activity, neurons do not fire at characteristic times from trough to trough. In addition, similar field potential waveforms do not necessarily imply similar single unit firing patterns, and we have observed clear oscillatory activity without peaks in single unit cross-correlograms. While the oscillations studied here were produced by ketamine, we have evidence that the general pattern of ketamine induced oscillations is similar to that seen in awake behaving rats (4).

The data we report is consistent with analyses performed for both EEGs and evoked potentials that suggest that these signals are more related to the timing of summed synaptic events than synchronized action potential generation. The current source density analysis performed by Haberly and colleagues in the piriform cortex (12) clearly demonstrates the association between the spatial and temporal patterns of synaptic input on the apical dendrites of pyramidal cells and the evoked potential generated by shock activation of the afferent pathway from the olfactory bulb. Similarly, our analysis of a realistic network simulation of the olfactory cortex (16) as well as a cortical model replicating the original experiments of Gray and Singer (17) are consistent with this interpretation.

What the data here suggests is that visually similar field potentials, which imply similar local patterns of synaptic input, do not necessarily result in similar spiking output. While this might at first appear to be counterintuitive, it must be kept in mind that evoked potentials represent electrical activity summed over a large volume of cortex. Further, modern physiological and modeling studies of pyramidal cells clearly demonstrate that many parameters influence action potential generation beyond afferent synaptic input (6; 10). Neuromodulators, for example (11), can significantly affect the integrative properties of single cells. In addition, evidence suggests that inhibitory synaptic inputs are often difficult to detect in evoked potentials but clearly can have a substantial influence on somatic spiking (5).

The major conclusion of this study is that field potential recordings do not predict the detailed firing patterns of nearby neurons. For this reason, caution must be exercised in using field potential data to infer temporal patterns of

neuronal spike coding (3; 8). In particular, synchronous field potentials do not imply synchronous firing in pairs or groups of nearby neurons.

References

- [1] F. Crick, C. Koch, *Seminars Neurosc* **2** (1990) 263.
- [2] R. Eckhorn, R. Bauer, W. Jordan, M. Brosch, W. Kruse, M. Munk, H.J. Reitboeck, *Biol. Cybern.* **60** (1988) 121.
- [3] C.M. Gray, W. Singer, *Proc. Natl. Acad. Sci., USA* **86** (1989) 1698.
- [4] M.J. Hartmann, J.M. Bower, *J. Neurophys.* **80** (1998) 1598.
- [5] A. Kapur, W.W. Lytton, K.L. Ketchum, and L.B. Haberly, *J. Neurophys.* **78** (1997) 2546.
- [6] D. Johnston, J.C. Magee, C.M. Colbert, B.R. Christie, *Annu. Rev. Neurosci.* **19** (1996) 165.
- [7] D.T. Kewley, M.D. Hills, D.A. Borkholder, I.E. Opris, N.I. Maluf, C.W. Stormont, J.M. Bower, G.T.A. Kovacs, *Sens. and Actuat. A (Phys)* **58** (1997) 27.
- [8] G. Laurent, M. Wehr, and H. Davidowitz, *J. Neurosci.*, **16** (1996) 3837.
- [9] J.H. Martin in *Principles of Neural Science*, E.R. Kandel, J.H. Schwartz, T.M. Jessel, Eds., Appleton & Lange, Norwalk, CT, 1991, p. 777.
- [10] Z.F. Mainen, J. Jeorges, J.R. Huguenard, T.J. Sejnowski, *Neuron* **15** (1995) 1427.
- [11] A. Protopapas, *Caltech Ph.D. Thesis* (1998) California Institute of Technology.
- [12] R. Rodriguez, L.B. Haberly, *J. Neurophys.* **61** (1989) 702.
- [13] M. Sahani, J.S. Sejnowski, *Neuron* **15** (1995) 1427. Pezaris, R.A. Andersen, in *Adv. in Neural Inf. Proc. Sys.* **10**, M. I. Jordan, M. J. Kearns, S. A. Solla, Eds., MIT Press, Cambridge, 1992.
- [14] W. Singer, *Neuron* **24** (1999) 49.
- [15] C. von der Malsburg, *MPI Biophysical Chem, Internal Report* (1981) 81.
- [16] M. Wilson, J.M. Bower, *J. Neurophys.* **67** (1992) 981.
- [17] M. Wilson, J.M. Bower, *Neur. Comp.* **3** (1991) 498.