Stochastic and Coherence Resonance in Hippocampal Neurons

D.M. Durand and W.C. Stacey
Neural Engineering Center, Department of Biomedical Engineering and Neurosciences
Case Western Reserve University, Cleveland, OH

Abstract-**Stochastic Resonance (SR) is a phenomenon observed in nonlinear systems whereby the introduction of noise enhances the detection of subthreshold signals. Both computer simulations and experimental recordings in the hippocampal brain slice have shown that stochastic resonance could play a significant role to enhance the detection of synaptic potentials generated in distal synapses. The noise variance required to improve synaptic detection in CA1 neurons is well within the physiological range of the noise generated by endogenous sources. Intracellular recordings in CA1 pyramidal cells confirmed that subthreshold signals could be detected with the generation of small amplitude endogenous noise in single cells. Computer simulations have been applied to test the hypothesis that the effect of stochastic resonance is enhanced when the noise and subthreshold signals are applied to several neurons at the same time. Computer simulation of the coupled network of hippocampal neurons did reveal a marked improvement in signal detection when independent noise sources were applied to multiple neurons. However, the addition of noise to a coupled neuronal network also revealed the appearance of synchronized neural activity similar to epilepsy. This recently observed phenomenon, known as coherence resonance, is responsible for the appearance of spontaneous neuronal activity and decreases the signal to noise ratio of subthreshold synaptic inputs**.

***Keywords* - Hippocampus, neurons, stochastic resonance**

I. INTRODUCTION

Stochastic resonance (SR) is known to enhance signal detection of subthreshold signals in many non-linear systems. Both a threshold and noise are required to generate this effect. Since neurons do have a threshold and are known to operate in the presence of significant amount of noise, stochastic resonance should play a significant role in the detection of subthreshold synaptic inputs. Both computer simulations and experimental evidence show that noise can enhance the detection of synaptic inputs located in distal locations in the dendritic tree [1].]. This phenomenon was observed intracellularly and the noise required to generate this effect is well within the physiological noise amplitude know to be present within neurons [2]. However, neurons are arranged in arrays and the effect of SR could be enhanced significantly when both noise and signals are applied to many neurons. This phenomenon (Array enhanced SR) has been previously analyzed [3] and coupling between elements is known to affect the signal detected. In this paper, we have analyzed the effect of SR on synaptic signal detection in a model of hippocampal neural network. The effect of noise and coupling on detection was measured using computational models. We also investigated the effect of noise on the synchronization of the neuronal population. As noise is added to a coupled array of oscillators, spontaneous synchronization is generated in the absence of any input [4]. This phenomenon known as coherence resonance was observed in the hippocampal array. The amount of synchronization and its effect on stochastic resonance was studied as a function of noise amplitude and coupling between neurons.

II. METHODOLOGY

All simulations were carried out using the NEURON Software [5]. The hippocampal CA1 models have been previously described [1] and contained a soma with sodium calcium and four potassium channels as well as passive dendrites. The neurons were connected using AMPA type, *en-passant* synaptic connections between neurons. The input (2.5Hz) was applied either globally or to single cells. The noise was generated by random events (Poisson distributed) at each synapse and the noise variance was modulated by the maximum synaptic conductance (g_{max} = 0.2nS or 1nS) and by the mean firing frequency of the synapse. Noise synapses were either independent or located on en passant axons. The number, location and firing time of each synapse was random. Coupling between each cell was implemented by adding a coupling current ($I_{coupling}$) term shown below:

$$I^{i}_{coupling} = \sum_{j=0}^{N-1} a \bullet c_{ij}(V_j - E_{leak}) \quad (j \neq i) \qquad (1)$$

$$f_C\ (c_{ij}) = \frac{1}{C_{\max} - 0} \qquad all\ c_{ij} = c_{ji} \qquad (2)$$

where a is an arbitrary constant, c_{ij}, the coupling strength drawn for a uniform probability density function (f_c). The response of the network was assessed by summing the voltage from all the neurons. The signal was processed to detect action potential. The signal to noise ratio was calculated by calculating the power at 2.5Hz and dividing by the baseband power near 2.5 Hz.

III. RESULTS

Effect of multiple detecting neurons: The addition of noise to the network clearly allowed the detection of subthreshold signals for a single cell and could be modeled by the typical SR curve [2]. As the number of cells involved was increased, the signal to noise ratio (SNR) improved further and the peak value of the SNR increased as shown in Table 1. As the maximum amplitude of the noise was increased (1nS), the detection of the signal dropped significantly. This effect could be attributed not only to the increase in the variance of the noise but also to spontaneous oscillatory behavior of the network.

Report Documentation Page

Report Date	Report Type	Dates Covered (from... to)
25OCT2001	N/A	-

Title and Subtitle Stochastic and Coherence Resonance in Hippocampal Neurons	**Contract Number**
	Grant Number
	Program Element Number
Author(s)	**Project Number**
	Task Number
	Work Unit Number
Performing Organization Name(s) and Address(es) Neural Engineering Center, Department of Biomedical Engineering and Neurosciences Case Western Reserve University, Cleveland, OH	**Performing Organization Report Number**
Sponsoring/Monitoring Agency Name(s) and Address(es) US Army Research, Development & Standardization Group (UK) PSC 802 Box 15 FPO AE 09499-1500	**Sponsor/Monitor's Acronym(s)**
	Sponsor/Monitor's Report Number(s)
Distribution/Availability Statement Approved for public release, distribution unlimited	
Supplementary Notes Papers from the 23rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society, October 25-28, 2001, held in Istanbul, Turkey. See also ADM001351 for entire conference on cd-rom.	
Abstract	
Subject Terms	
Report Classification unclassified	**Classification of this page** unclassified
Classification of Abstract unclassified	**Limitation of Abstract** UU
Number of Pages 2	

Table 1. Signal to noise ratio (SNR) for multiple cells involved in the detection of the subthreshold input signal in the presence of low (0.2nS) and high (1nS) noise variance.

# Cells	1	5	10
Peak SNR (0.2nS)	174	467	467
Peak SNR (1nS)	13	79	85

Effect of coupling: As coupling between the neurons was increased (Cmax = 0.5), the ability of the network to detect the signal increased significantly with SNR values as high as 1100. However, as the noise amplitude increase (1nS), the SNR dropped since the combination of high noise amplitude and coupling repetitive firing and oscillations.

Coherence resonance: From the previous analysis of the stochastic resonance it is clear that the combination of noise and signal could generate spontaneous oscillations in the network. Since the signal was subthreshold, we then tested the hypothesis that noise alone applied to the CA1 hippocampal neural network could cause synchronized oscillations. The degree of synchronization was estimated by calculating the power at the frequency of oscillations divided by the width of the spectrum peak at half the amplitude. With no coupling, all 10 cells fired asynchronously in the presence of noise. As coupling increased, the neurons fired synchronously and generated spontaneous oscillations (coherence resonance) at frequencies between 4 and 10Hz. The frequency increased at low noise amplitude and decreased for noise variances greater that $100pA^2$. The degree of synchronization was a function of both noise and coupling. The network did show significant amount of synchronization at low level of noise provided that the coupling was increased. Under these conditions, a single cell by itself would not fire but the network would generate spontaneous oscillations at low frequency. Similarly, a neural network with low coupling and high noise can also produce spontaneous oscillatory activity when noise variance is increased.

IV. CONCLUSION

The results of the simulation clearly indicate that the signal detection of subthreshold signals is improved when more than one neurons is involved in the detection. Therefore, stochastic resonance is amplified in the hippocampal neuronal network by both the number of neurons involved and the coupling between them. However, noise applied to neural networks can generate synchronized oscillations that significantly decrease the SNR. These oscillations occur at physiological frequencies and the waveforms are similar to epileptiform activity observed in hippocampal slices. Therefore, this noise-induced synchronization could underlie the abnormal neural epileptifo rm activity in the hippocampus.

ACKNOWLEDGMENT

The work was supported by a grant from the Whitaker Foundation and the National Institutes of Health Medical Science Training Program.

REFERENCES

[1] W.C. Stacey and D.M. Durand, "Stochastic resonance can enhance synaptic transmission," *J. of Neurophysiology*, vol. 83, pp. 1394-1402, 2000.

[2] W.C. Stacey and D.M. Durand, "Synaptic noise improves the detection of subthreshold signals in the hippocampus," *J. Neurophysiology*, in press.

[3] J. Collins C.C. Chow and T.T. Imboff, "Stochastic resonance without tuning," *Nature* vol. 376: pp. 2236-2238, 1995.

[4] J.J. Woutter and A. Karma, *Physical review letter*, vol. 77: pp. 3256-3259, 1996.

[5] M.L. Hines, "NEURON, a program for simulation of nerve equations," in: *Neural systems: analysis and modeling*. Edited by F. Eeckman. Norwell, MA, Kluwer Academia Pub, 1993, pp. 127-137.