Heterogeneity increases information transmission of neuronal populations

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Abstract

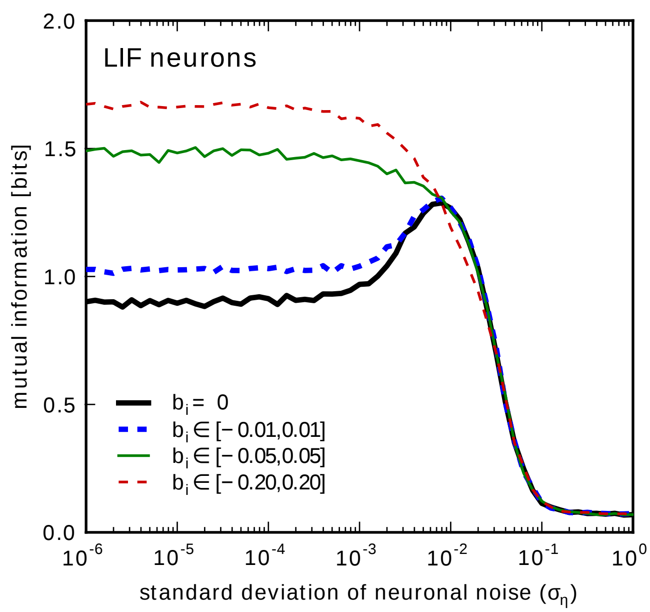
Noise, in the form of stochastic fluctuations added to the membrane voltages of neurons in a population, can have a beneficial effect on the information encoding ability of the population; this phenomenon is one type of stochastic resonance. We have found that heterogeneity, in the form of randomly varying firing thresholds among neurons in a population, can also improve the ability of the population to encode an input signal. Specifically, we performed numerical experiments using populations of FitzHugh-Nagumo neurons and leaky integrate-and-fire neurons, and measured the mutual information between the input signal and the decoded output signal. We found that heterogeneity exhibits a similar resonance effect to noise, where a non-zero amount of heterogeneity maximizes the mutual information between the input and output signals, for both neuron models. We also performed numerical experiments examining three common mechanisms that allow both noise and heterogeneity to increase information transmission in neuronal populations: 1) both temporally desynchronize neurons in the population, 2) both decrease the response time of a population to a sudden change in input signal, and 3) both linearize the response of the population to a stimulus. The main contribution of this research is that it demonstrates that heterogeneity can play an important role in neuronal population coding, and examines the mechanisms it uses to fill this role. Heterogeneity has frequently been overlooked in neuroscience; our study explains why it is an important feature of neural systems, and why it should not be overlooked when modeling such systems.

Additional Detail

The phenomenon of stochastic resonance (SR)—where a non-zero level of noise optimizes some performance measure of a system—has been examined in both simulated and real neurons in numerous studies. The original work on SR in neuroscience examined what is now known as *subthreshold* SR, where noise is added to a signal which would otherwise be entirely below a neuron's firing threshold, thereby allowing the signal to cross the threshold and cause the neuron to fire [1]. *Suprathreshold* SR, on the other hand, examines how noise can improve the ability of *populations* of neurons to encode signals which are already able, without noise, to cross the neurons' thresholds and elicit firing events [2]. Our study focuses on suprathreshold SR, and how heterogeneity can achieve similar effects to noise for suprathreshold input signals.

We performed numerical experiments examining the effects of noise and heterogeneity on information transmission in populations of FitzHugh-Nagumo neurons (a type II neuron model) and leaky integrate-and-fire neurons (a type I neuron model). We presented these populations with aperiodic random signals with amplitude $\sigma_s = 0.1$ and a frequency cutoff of 5 Hz (with equal power at all frequencies below the cutoff, and no power at frequencies above the cutoff). The output signal was decoded by linearly summing and filtering the outputs of all neurons in the population, and this signal was compared with the input signal using mutual information. Experiments were performed across many levels of noise σ_η (i.i.d. Gaussian noise added to the neurons' membrane voltages), and many levels of heterogeneity (by varying the intervals of the uniform distribution randomly generating the firing thresholds b_i).

The figure below illustrates the effect of noise (x-axis) and heterogeneity (individual traces) on the transmitted information (y-axis). The stochastic resonance effect of noise is clearly visible at $\sigma_\eta = 10^{-2}$, and moderate to high levels of heterogeneity ($b_i \in [-0.05, 0.05]$ and $b_i \in [-0.20, 0.20]$) have clear benefits for information transmission across a range of noise levels.



References

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