Heterogeneity Increases Information Transmission in Neuronal Populations

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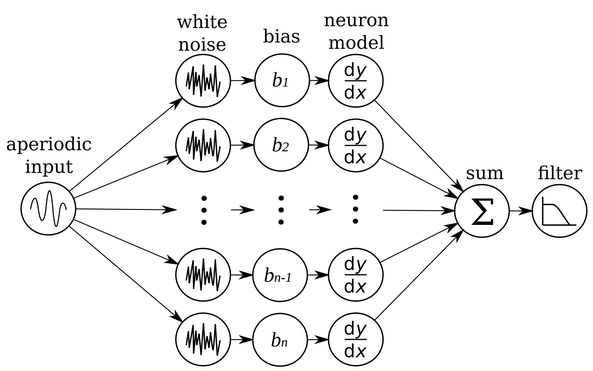
Abstract

Noise [1] and heterogeneity [2] are known to allow neuronal populations to encode more information about an input signal. We examined these two phenomena in the context of information encoding by a population of simulated neurons, and found that noise and heterogeneity use similar mechanisms to offer similar benefits to neural representation. Specifically, both phenomena increase neuronal population information encoding by 1) desynchronizing neuronal firing, and 2) linearizing neuronal responses. Furthermore, noise and heterogeneity both exhibit resonance effects: there is a non-zero, and non-infinite, optimal level for both phenomena.

Experiment

Input: An aperiodic random signal
(amplitude = 0.1, max. frequency = 5 Hz)
Neurons: 64 Fitzhugh-Nagumo (FHN)
or leaky integrate-and-fire (LIF) model neurons
Noise: Gaussian white noise added to neuron membrane
Heterogeneity: Introduced by choosing neuron bias currents from uniform distributions (larger distribution radius corresponds to increased heterogeneity)
Output: Summed and filtered spikes from all neurons
Performance metric: Mutual information calculated between input and output signals



References

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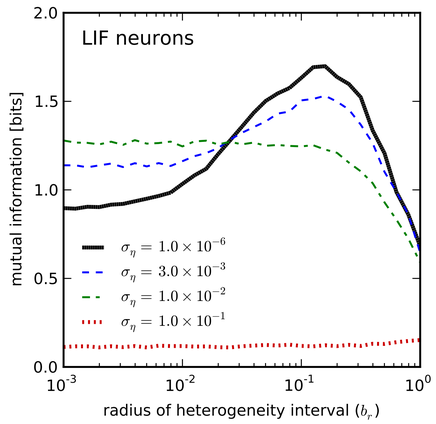
[2] C. Eliasmith and C. H. Anderson, *Neural Engineering: Computation, Representation, and Dynamics in Neurobiological Systems*. Cambridge, MA: MIT Press, 2003.

[3] N. G. Stocks, "Information transmission in parallel threshold arrays: Suprathreshold stochastic resonance," *Phys. Rev. E*, vol. 63, pp. 1–9, Mar. 2001.

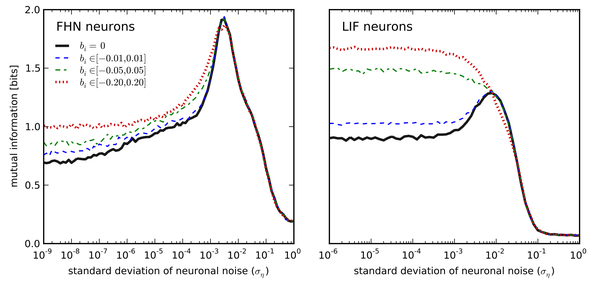
[4] S. D. Burton, G. B. Ermentrout, and N. N. Urban, "Intrinsic heterogeneity in oscillatory dynamics limits correlation-induced neural synchronization.," *J. neurophysiology*, vol. 108, pp. 2115–33, Oct. 2012.

[5] F. S. Chance, L. F. Abbott, and A. D. Reyes, "Gain modulation from background synaptic input.," *Neuron*, vol. 35, pp. 773–82, Aug. 2002.

Resonance and Heterogeneity



Resonance and Noise

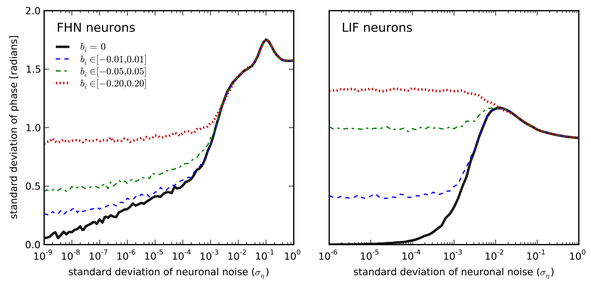


- LIF neurons exhibit resonance only at low levels of heterogeneity
- FHN neurons exhibit resonance at all levels of heterogeneity, since heterogeneity cannot fully desynchronize neurons

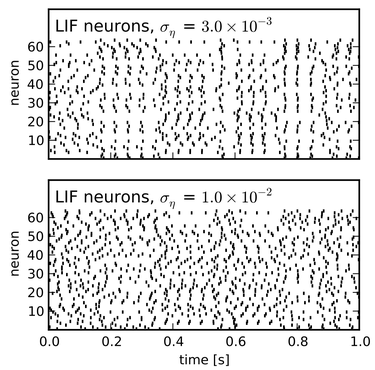
Desynchronization

Noise [3] and heterogeneity [4] desynchronize neuronal spiking.

- FHN neurons have about the same firing rate for all stimuli above the firing threshold, so heterogeneity in the biases is not able to fully desynchronize them
- In LIF neurons, heterogeneity is slightly better than noise at desynchronizing neuronal firing

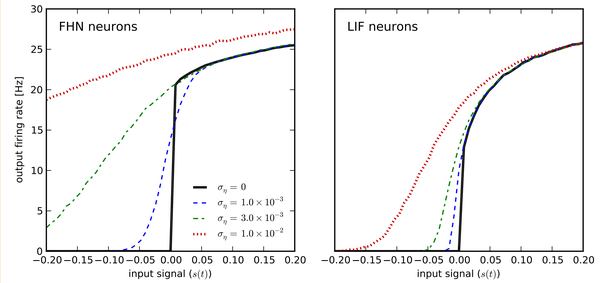


Spike rasters for LIF neurons with low noise (top) and high noise (bottom) demonstrate that noise reduces synchrony.

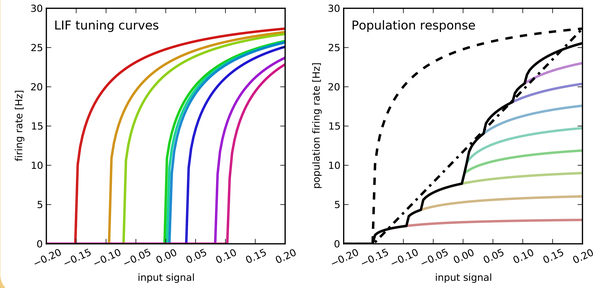


Linearization

Noise can improve population encoding by linearizing neuron stimulus-response curves [5]:



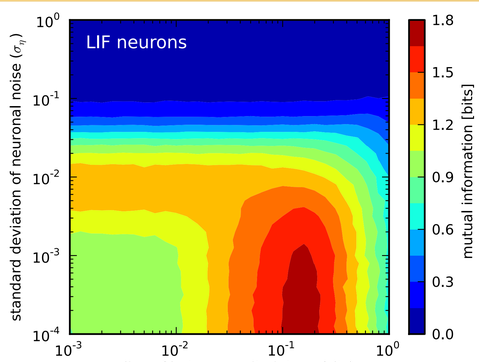
Heterogeneity linearizes the *population* stimulus-response:



Redundant Benefits

Since heterogeneity and noise operate through similar mechanisms, their benefits are not additive.

- For LIF neurons (right), overall information encoding is optimized for biases chosen from the range $b_i \in [-0.15, 0.15]$ and no noise
- Given optimal heterogeneity, adding noise ($\sigma_\eta = 10^{-2}$) reduces encoded information
- But in the absence of heterogeneity, a moderate amount of noise ($\sigma_\eta = 10^{-2}$) optimizes encoded information (see Resonance and Noise)



Conclusions

- Noise and heterogeneity both provide a neuronal population with a better basis for encoding signals
- This is done by desynchronizing neuronal firing and linearizing neuron tuning curves
- Both noise and heterogeneity show resonance effects, offering increases in information encoding only across finite ranges
- The benefits of noise and heterogeneity are not additive; only one or the other is required

Future work

- Examine more sophisticated neuron models and other decoding methods
- Extend heterogeneity to other neuron parameters (*e.g.*, maximum firing rate) to determine if this increases the benefits of heterogeneity in FHN neurons
- Quantify these effects in the context of a functional multi-layer model of the visual system