A Computational Study of the Role of Synchrony in Neural Input/Output Relationship

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Introduction

For all neurons, the output, in the form of an action potential, depends on the spatiotemporal patterns of input stimuli. However, it is experimentally expensive to blindly stimulate at different sites in order to characterize the output.

The goal of this project is to computationally generate inputs with known spatiotemporal statistics and analyze the output produced by a regular spiking Izhikevich neuron model. Two statistical populations of inputs have been studied. These two populations have the same pairwise correlations, but differ in the higher-ordered statistics within the population. By jittering the inputs into predictable spatiotemporal patterns, we have studied how those patterns affect the output of the model. For instance, we found that an increase in jitter decreases output firing rate exponentially. The result of these simulations can help guide a similar experiment and provide an expectation of the outcome.

Inputs

Poisson Input Spike Trains

The input trains were two kinds of Poisson processes, introduced by Kuhn et al.:

- Single Interaction Process (SIP) and,
- Multiple Interaction Process (MIP).

Let w_u be a Poisson process with rate *a*. Then each spike train x_i of in a set of N SIP processes is defined by

$$x_i = w_u + w_i, \quad 1 \le i \le N,$$

where each w_i is a Poisson process with rate b. Then the rate of x_i is *a+b,* and the pairwise correlation coefficient is *a/(a+b).*

Each spike train y_i of in a set of N MIP processes is defined by random thinning of w_u, where ε is the probability of that a spike in w_u will also be in y_i. The rate of y_i is thus $a\varepsilon$ and the pairwise correlation coefficient ε.

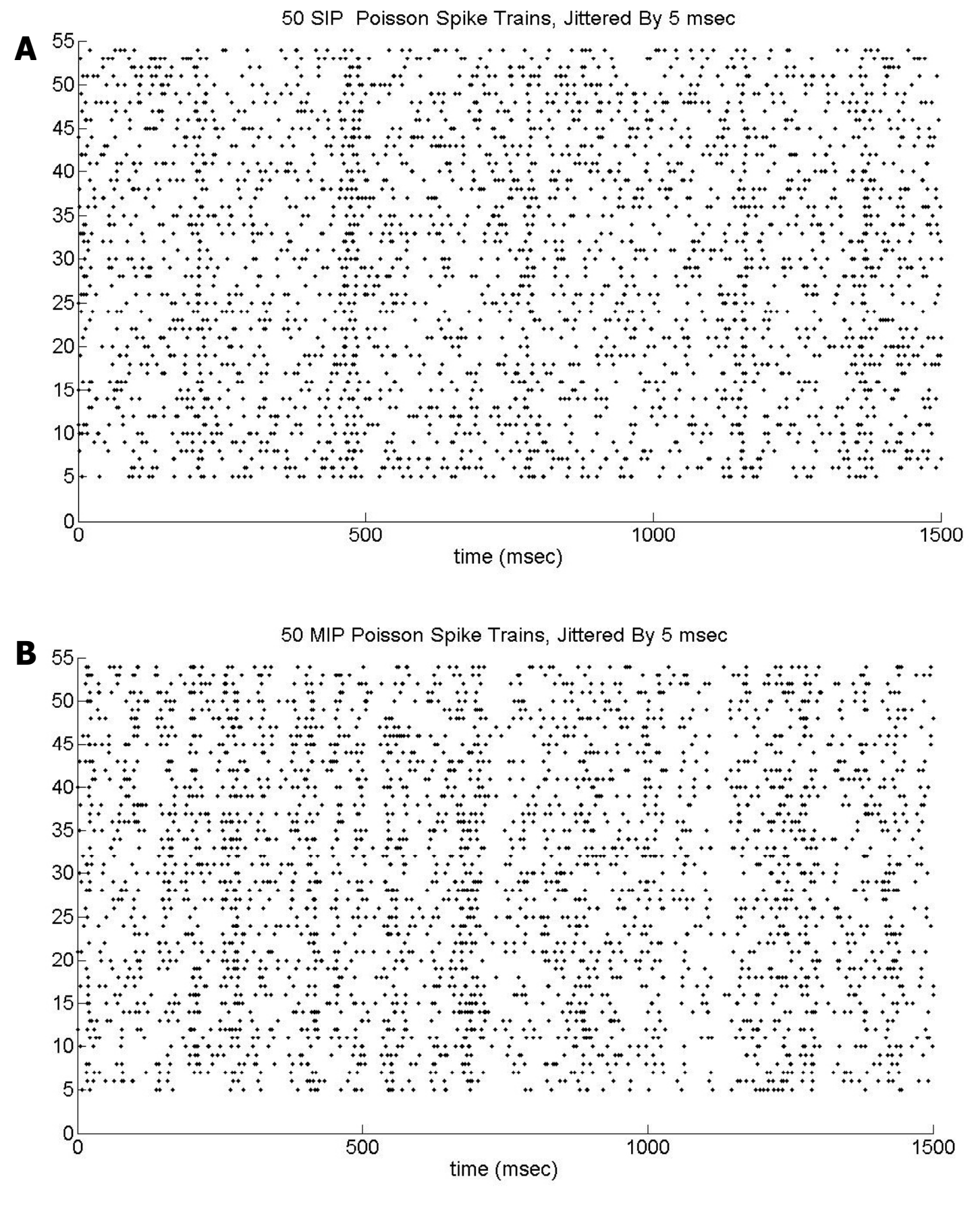
We will use interspike interval (ISI) instead of rate, with the relationship being: ISI=1/rate.

Introducing Jitter to the Spike Trains to Produce Statistically Quantifiable Spatiotemporal Patterns

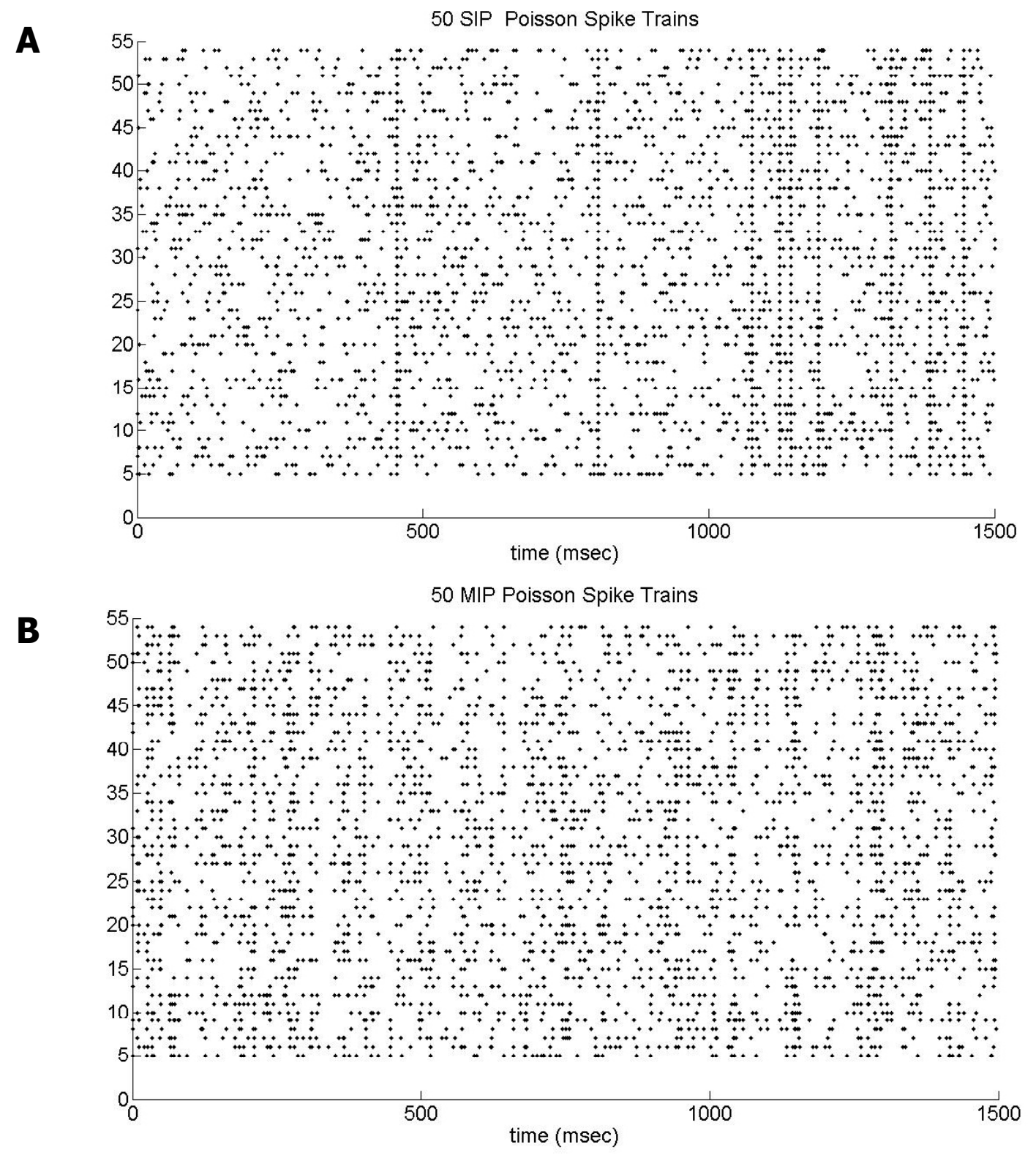
We jitter the SIP and MIP processes to disrupt synchrony to a predetermined degree. The algorithm for jitter is as follows:

For each spike at time *t* in a spike train, pick a random number *r* from a normal distribution with standard deviation j. Shift that spike from time *t* to time *t+r*.

Notation: when we say jitter by *j* we mean jitter with a normal distribution of standard deviation *j*.

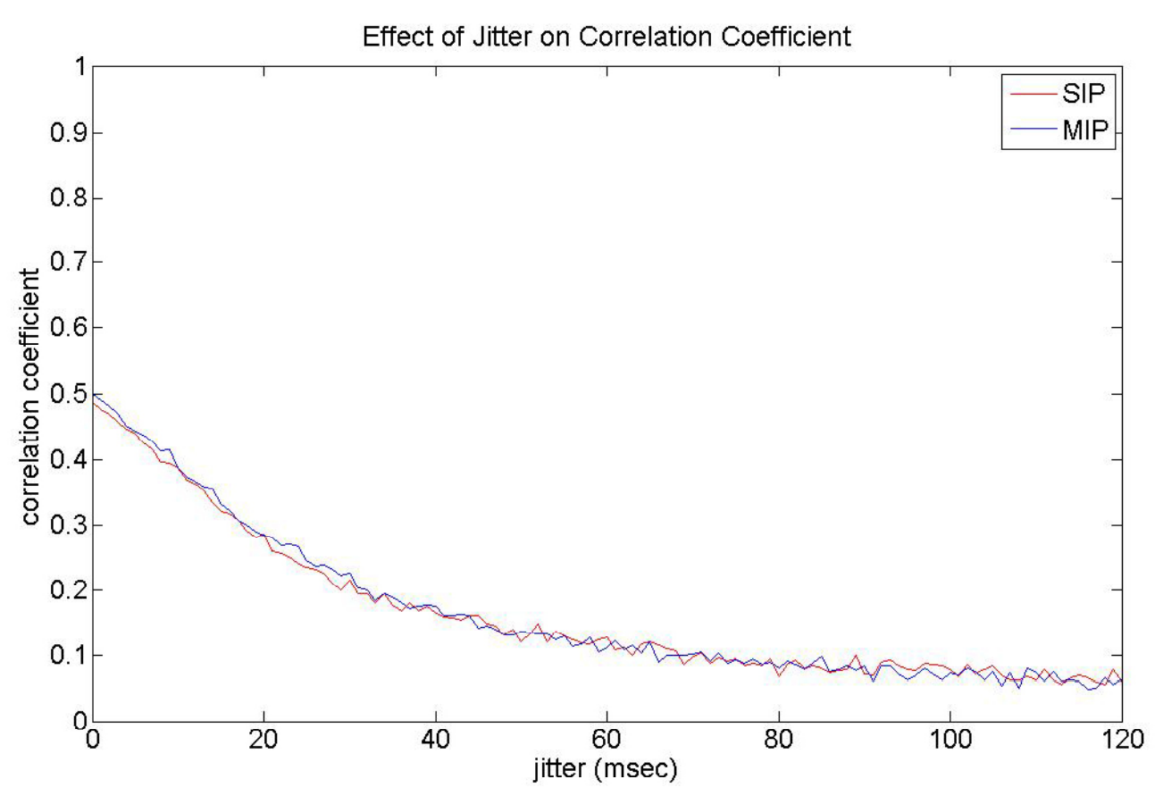


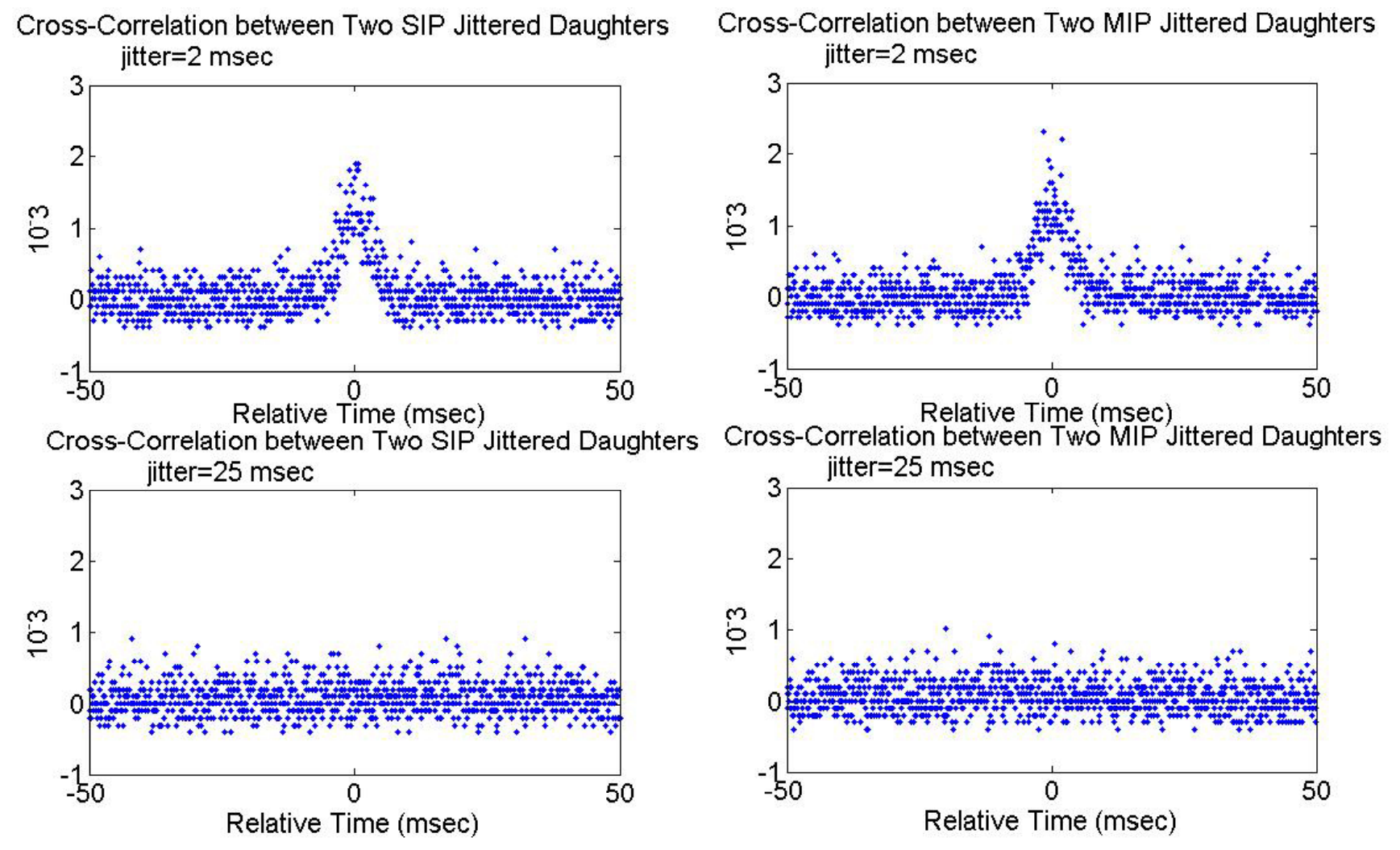
Fifty SIP (A) and MIP (B) spike train populations jittered by 5 msec. ISI = 25 msec, time step = 0.02 msec, unjittered correlation coefficient = 0.15.



(above) Fifty SIP (A) and MIP (B) spike train populations with identical rates (.04Hz) and pairwise correlations (.15) but different higher-order statistics.

(below) Effect of jitter on pairwise correlation coefficient between two SIP (red) or MIP (blue) spike trains. In both cases, correlation coefficient decreases exponentially with jitter. ISI = 25 msec, time step = 0.1 msec, unjittered correlation coefficient = 0.5, window radius = 50 msec.





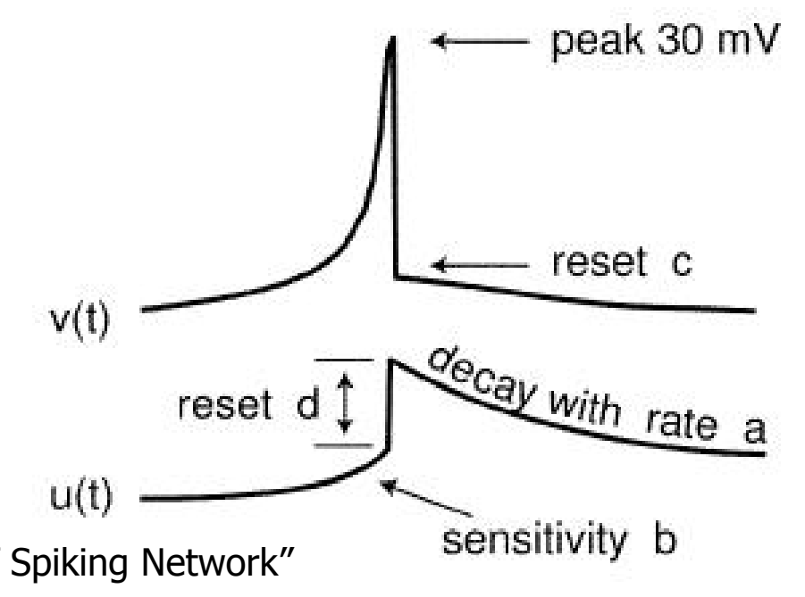
Cross correlation between two trains from the SIP population jittered by 2 msec (A) and 25 msec (C), and the MIP population jittered by 2 msec (B) and 25 msec (D). Pairwise cross-correlation is the same between SIP and MIP. Increasing jitter flattens the cross correlation function. Although flattened, the functions in (C) and (D) are still gaussians.

Izhikevich Single Cell Model

Dr. Eugene Izhikevich reduced biophysically accurate neural models like the Hodgkin-Huxley type through bifurcation methods down to a two-dimensional set of ordinary differential equations:

$$v' = 0.04v^2 + 5v + 140 - u + I$$
$$u' = a(bv - u)$$

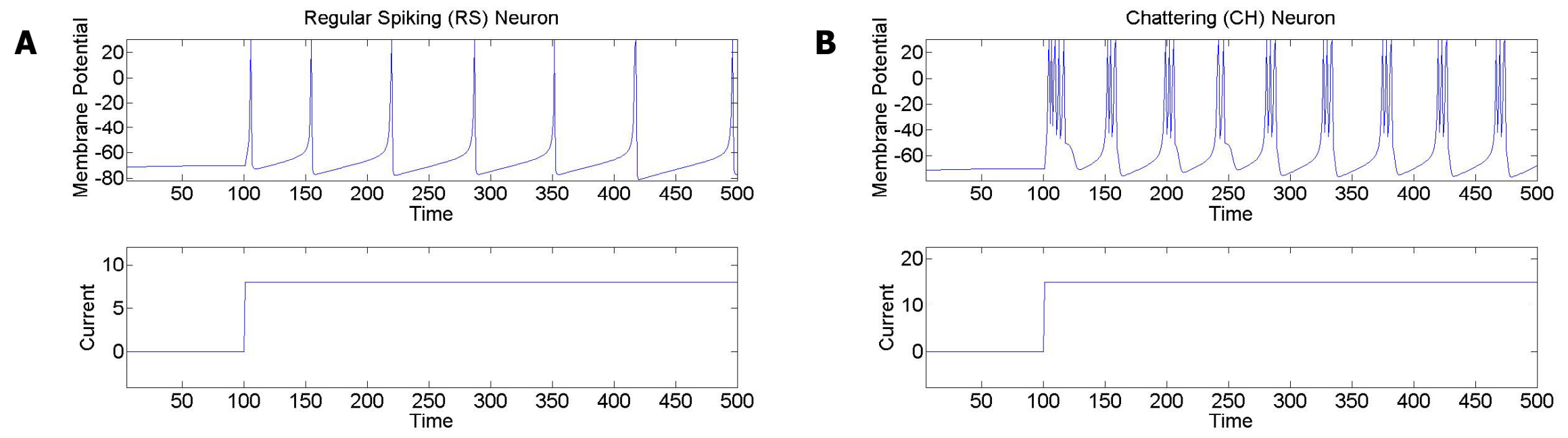
if v = 30 mV,
then $v \leftarrow c, \quad u \leftarrow u + d$



Taken from E. M. Izhikevich, "Simple Model of Spiking Network"

This model is computationally simple and capable of producing rich firing patterns exhibited by real biological neurons. The model fails, however, at capturing sub-threshold dynamics.

Since we are interested in output firing patterns, the advantages of this model clearly outweighs the disadvantage.



In this project, we studied the output of **RS** neurons, which are presented in later sections.

Different firing patterns correspond to different values of the parameters *a*, *b*, *c*, and *d* in the model. (A) Regular spiking neurons. In this model, a=0.02, b=0.2, c=-65 mV, d=8. (B) Chattering neurons, a=0.02, b=0.2, c=-50 mV, d=2. The values for c and d means that RS neurons have a deeper voltage reset and larger after-spike jump of *u* than CH neurons.

Outputs

Adaptation Made to the Model

We changed the Izhikevich model to model synapses with transient membrane conductance changes:

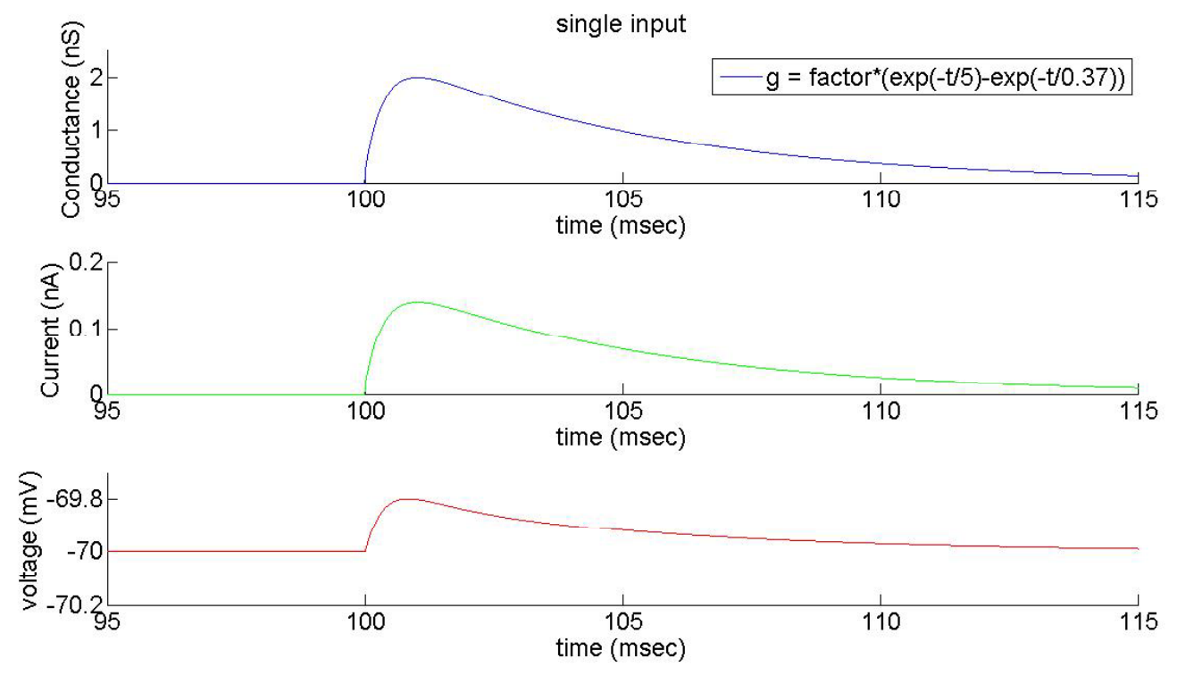
- A single stimulus changes the membrane conductance, *g*, in an alpha-like function:

$$g = g_0(e^{t/\tau_2} - e^{t/\tau_1})$$

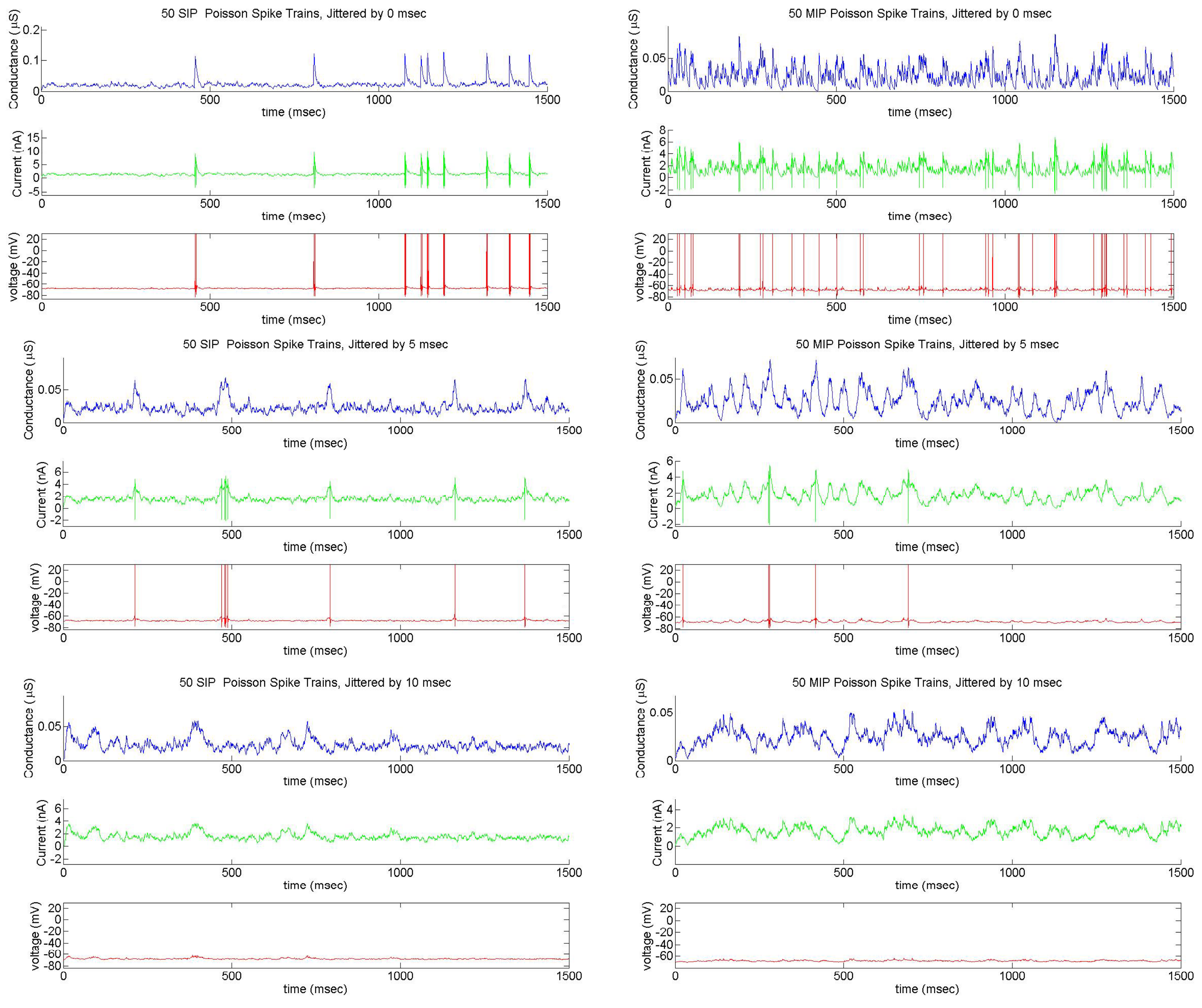
where τ_1 is the rise time τ_2 is the decay time.

- The current, *I*, is then, $I = g(V - E)$,

where E is the reversal potential at the synapse and set to 0 mV for our simulations.

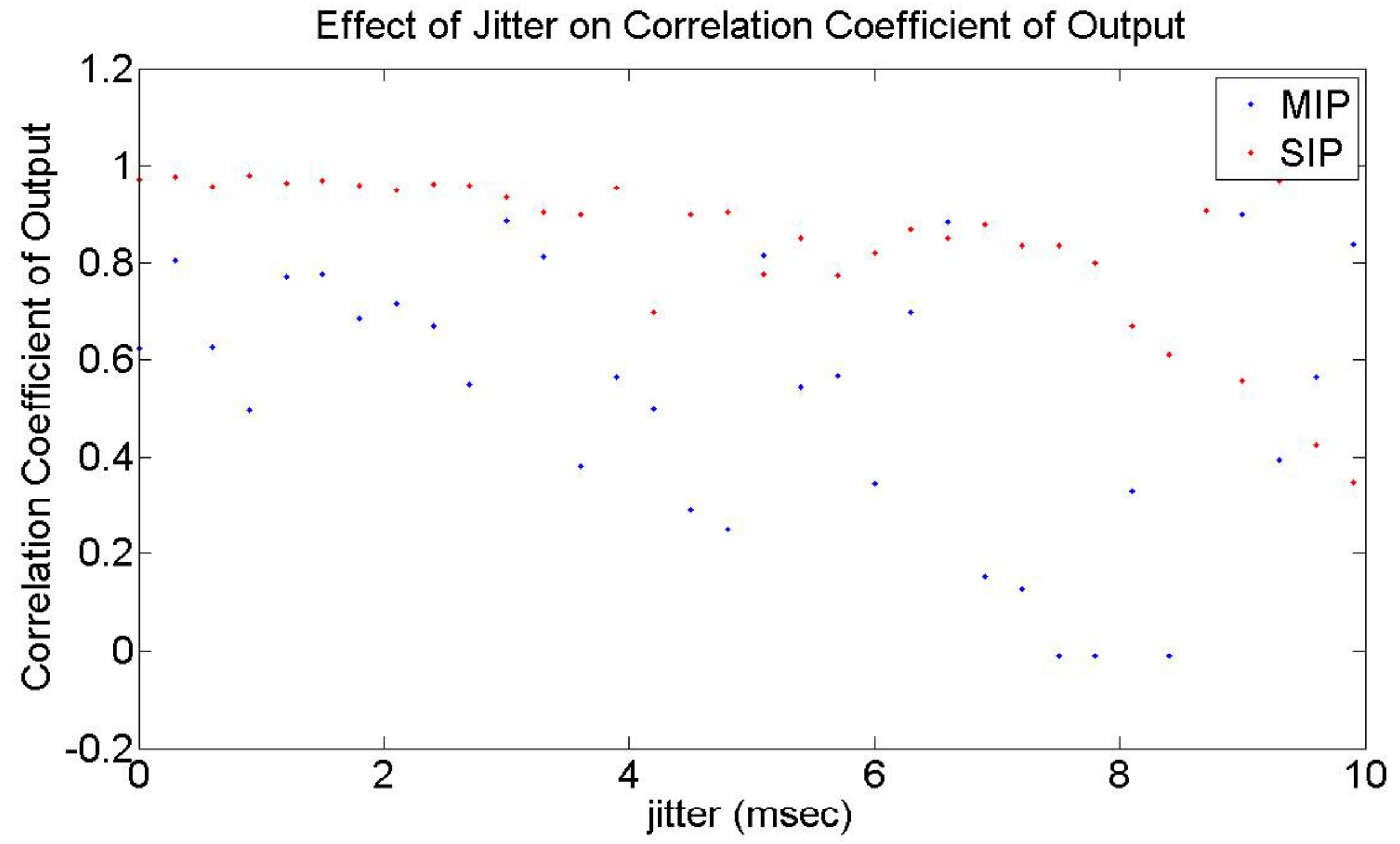


Response of a regular spiking Izhikevich model to a single input. The factor is the number necessary to make the conductance peak at 2 μS.

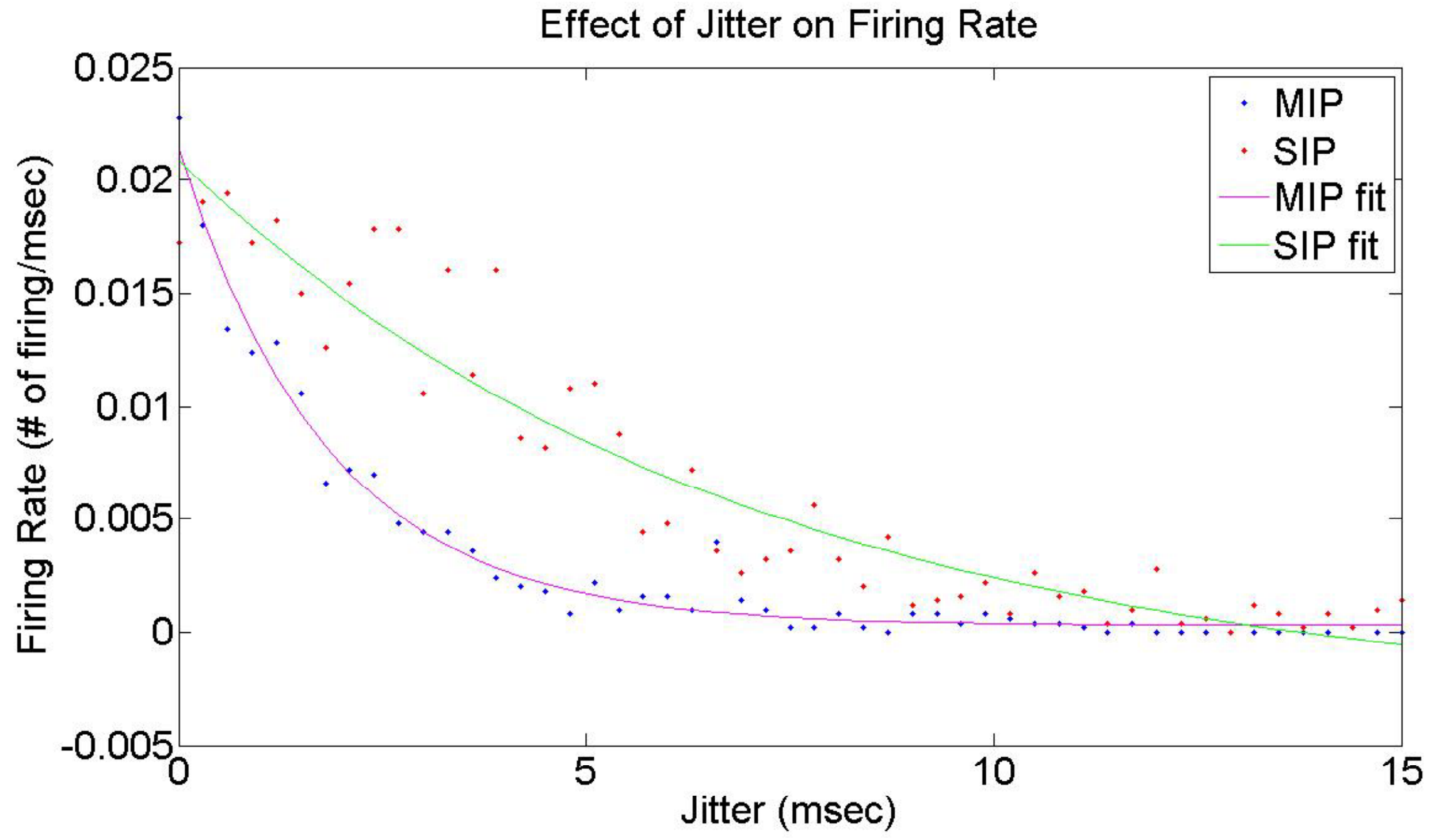


Response of a regular spiking Izhikevich model to 50 input spike trains, jittered by various times. In both the SIP and MIP, as jitter increased from 0 to 5 to 10 msec, the number of action potentials decreased. Total time = 15000 msec, time step = 0.02 msec, unjittered pairwise correlation coefficient = 0.15, for both the SIP and MIP models.

Analysis



Effect of jittering SIP and MIP populations on correlation coefficient of output. One hundred input spike trains (SIP and MIP) of the same jitter were divided in half: fifty of them produced an output, and the other fifty produced another output. Correlation coefficient between those two outputs is computed for each jitter. Total time = 5000 msec, time step = 0.02 msec, unjittered pairwise correlation coefficient = 0.15, regular spiking Izhikevich neuron model.



Effect of jittering SIP and MIP populations on firing rate. Fifty spike trains, total time = 5000 msec, time step = 0.02 msec, unjittered pairwise correlation coefficient = 0.15, regular spiking Izhikevich neuron model.

Summary

- We generated two types of neural inputs with well-defined temporal patterns, which have the same pairwise correlation but different higher-ordered correlations
- We changed a diverse, yet computationally simple, single-compartment current-based neuron model to a conductance based model for more biophysical accuracy.
- SIP inputs had a higher output correlation than MIP inputs across all jitter.
- As jitter increased, the output firing rate decreased exponentially. The firing rate of the MIP process decreased faster than that of the SIP.
- To further study the role of jitter in input/output relationship, we will mathematically link the SIP and MIP output patterns with the spatiotemporal patterns of the inputs.

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