A-Currents Reduce Spike Synchrony Driven by Input Transients

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Abstract

Neural populations can be driven to spike synchronously by sudden increases in external input. The degree of synchrony depends on a number of factors. For leaky integrate-and-fire (LIF) neurons firing in the regular spiking regime, the rate of depolarization decreases as threshold is approached. The increased likelihood of being near threshold translates into an increased likelihood of spiking (synchrony) just after an input transient. A-type potassium channels (a hyperpolarizing current activated near threshold) can counteract this effect, reducing population synchrony in a simple LIF model.

1. Introduction

Neural populations can be driven to spike synchronously by sudden increases in external input. However, the presence and degree of synchrony depends on a number of factors, including the intrinsic properties of the neurons in the population, in which regime the neurons are operating (regular or random firing), and the statistics of the input. To begin to understand the relative importance of these factors, we compared input-driven synchrony in simple leaky integrate-and-fire (LIF) neurons and a comparable model that included an A-type potassium channel (LIF-A).

For LIF neurons firing in the regular spiking regime, the rate of depolarization decreases as threshold is approached. Thus, a random sample of voltage during ongoing activity in this regime will reveal an increased likelihood of being near threshold. Thus, just after inputs are increased further, there will be an increased likelihood of spiking. This increased probability of spiking at the neuron level will result in an increase of spike synchrony at the population level. A-type potassium channels carry a hyperpolarizing current that is activated near threshold. We reasoned that such a current might counteract the effect of voltage "bunching" near threshold and hence reduce the degree of spike synchrony induced by a sudden increase in synaptic input.

2. The Model

We constructed a current-based LIF neuron model with time varying stochastic (Poisson) input. Additionally, we created a second model where we added an A-type potassium channel to the LIF. Modeling was performed in MATLAB (Mathworks, Natick, MA). In both models, threshold voltage V_{thresh}= -54 mV, resting membrane potential V_{rest} = -74 mV, and reset voltage V_{reset} = -67 mV [2]. Leak conductance for the LIF-A model was set to g_L = 0.3125 nS. The A-channel conductance followed the Hodgkin-Huxley formalism and was matched to the model of Connor and Stevens (1977)[1]. The A-channel conductance

$g_A = \bar{g}_A a^3 b(V - E_A)$, with $\bar{g}_A$ = 7.8125 nS and E_A = -77 mV. Gating dynamics took the form

$\tau_z(V)\dfrac{dz}{dt} = z_\infty(V) - z$, with

$$a_{\infty}(V) = \left(\frac{0.0761 \exp(0.0314(\mathrm{V} + 94.22))}{1 + \exp(0.0346(\mathrm{V} + 1.17))} \right)^{1/3}$$

$$\tau_a(V) = 0.3632 + \frac{1.158}{(1 + \exp(0.0497(\mathrm{V} + 55.96))}$$

$$b_{\infty}(V) = \left(\frac{1}{1 + \exp(0.0688(\mathrm{V} + 53.3))} \right)^{4}$$

$$\tau_b(V) = 1.24 + \frac{2.678}{(1 + \exp(0.0634(\mathrm{V} + 50)))}$$

For comparison, we constructed a LIF model where the leak conductance was matched to the average total conductance (leak + A-channel) during the simulations of the LIF-A model, g_L = 0.5362 nS.

Synaptic inputs had Poisson statistics and took the form of short current pulses with an instantaneous rise and exponential decay. For simplicity, excitatory and inhibitory inputs had the same magnitude (peak = 0.041 mV) and time constants (τ_{syn} = 2.5 msec).

3. Results

We wanted to investigate the synchrony of spiking induced by sudden changes of input. We chose excitatory and inhibitory input rates to ensure that our neuron model began in the regular spiking regime (mean input is supra-threshold) and then increased the net excitation to achieve a higher firing rate. We ran a simulation of the LIF-A model 100,000 times, each for 600 msec total. Initially, the mean excitatory and inhibitory inputs were 48.3333 kHz and 11.6667 kHz, respectively, resulting in a steady-state output-firing rate of 73.9130 Hz. After 300 msec, the mean excitatory and inhibitory inputs were altered to increase firing rate. The increase in excitation was matched with a decrease in inhibition. Since the amplitude of excitatory and inhibitory inputs was the same, the variance of the synaptic current remained fixed. Resulting input rates were 58.3333 kHz and 1.6667 kHz, resulting in output-firing rates of 167.3913 Hz. Before running the LIF simulations, input rates were altered to match the mean output firing rates of the LIF model to the mean firing rates of the LIF-A model. The rates for the first 300 msec were 47.8333 kHz and 12.1667 kHz. For the second 300 msec, they were 57.6667 kHz and 2.3333 kHz. Using the data from the 100,000 trials, we created a histogram (PSTH) of spike frequencies for both models (Fig 1).

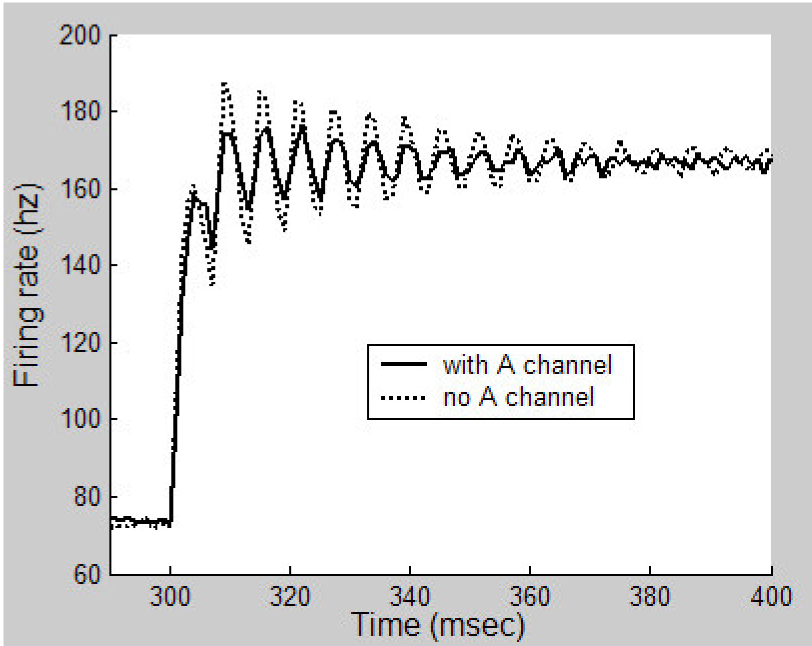

Fig 1: PSTH of spike frequencies collected from 100,000 trials.

We wanted to compare the modulation in firing rate to the mean rate in the two models. First, we expressed the modulation in rate as a percentage of the mean firing rate. The mean rate function should follow a step change in inputs rates with an exponential decay whose time course matches the synaptic time constant (2.5 msec). Therefore, we computed the ratio of the observed PSTH to a mean rate function of this form. We then looked at the first five peaks for the LIF and LIF-A models and computed the ratio of the peaks for LIF-A to LIF. For the five above mean rate peaks, the average ratio was 0.4710. For the five below mean rate peaks, the average ratio was 0.5959. Therefore, the total average ratio of LIF-A peak to LIF peak was 0.5334.

4. Conclusion

From these preliminary simulations, we conclude that A-currents do indeed reduce the degree of spike synchrony induced by transient changes in input. Further simulations will be necessary to fully quantify this effect. To gain a more general understanding, future work will investigate the relationship between the phenomenon of input-driven synchrony and the phase response curve.

References

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