2 Adaptation in spiking behaviour

2.1 Spike-Rate Adaptation

(Video 2.1) We are going to add a new current to the model neuron that is responsible for a phenomenon called Spike Rate Adaptation (SRA), also known as spike frequency adaptation. This potassium-mediated current causes a neuron to decrease its output spikes over time, during constant current input. We can think of this as a fast homeostatic plasticity mechanism that prevents a neuron from becoming overly active. The SRA current is also hyperpolarizing, like inhibition. However, its dynamics are slower. The SRA is added to the LIF neuron equation in the following way:

$$\tau_{\text{mem}} \frac{dV}{dt} = E_{\text{leak}} - V + g_{\text{e}}(E_{\text{e}} - V) + g_{\text{i}}(E_{\text{i}} - V) + g_{\text{SRA}}(E_{\text{k}} - V), \tag{1}$$

and the conductance of SRA

$$\frac{dg_{\text{SRA}}}{dt} = -\frac{g_{\text{SRA}}}{\tau_{\text{SRA}}} + \sum_{k=1}^{K} \delta(t_{\text{post},k} - t)\Delta g_{\text{SRA}}. \tag{2}$$

which indicates that after each postsynaptic spike $t_{\text{post},k}$, with a total of K postsynaptic spikes, g_{SRA} is increased by a fixed amount Δg_{SRA}. In that way, g_{SRA} builds up when output spiking is frequent, contributing to hyperpolarizing the neuron.

Let us remove the synaptic inputs temporarily, and replace them by a current step input, as in our very first exercise in Sec. 1.1.:

$$\tau_{\text{mem}} \frac{dV}{dt} = E_{\text{leak}} - V + R_{\text{m}} I_{\text{ext}} + g_{\text{SRA}}(E_{\text{k}} - V), \tag{3}$$

In this current step input, the membrane resistance R_{m} is set to 10 MΩ, and the external current I_{ext} to 1.45 nA. Furthermore, set $\Delta g_{\text{SRA}} = 0.06$, $\tau_{\text{SRA}} = 100$ ms, and E_{k} = -70 mV. Also ensure in your program that g_{SRA} is always non-negative. Now plot the membrane potential and the Δg_{SRA} over time. Also show the frequency of output spikes, by taking each inter-spike interval in seconds and taking the inverse. Compare these results to the case where SRA is deactivated in the same model. To do this, simply set Δg_{SRA} to zero. Is the frequency of output spikes decreased compared to when SRA is deactivated?

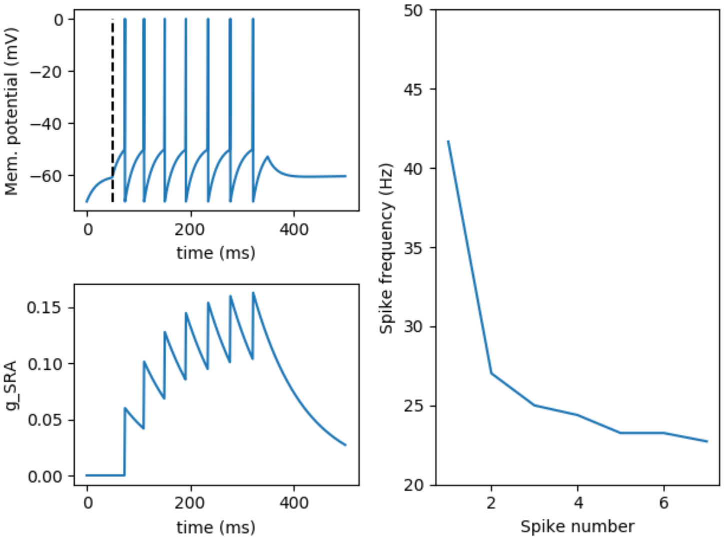

Figure 1: A LIF neuron with spike-rate adaptation (SRA) and current step input applied in the interval 50 to 350 ms. Top left: The membrane potential and spikes are shown. The dotted line indicates the moment the step current has started. The spikes can be seen to be delayed more and more over time. Bottom left: The SRA conductance g_{SRA} builds up over time with each output spike due to potassium-mediated hyperpolarisation, and this conductance decays back to zero when spiking ceases. Right: The frequency of the spikes, inversely proportional to the spike delay, is shown one by one for each output spike. In the presence of SRA, spikes are delayed as SRA conductance builds up, leading to a decrease in output frequency.

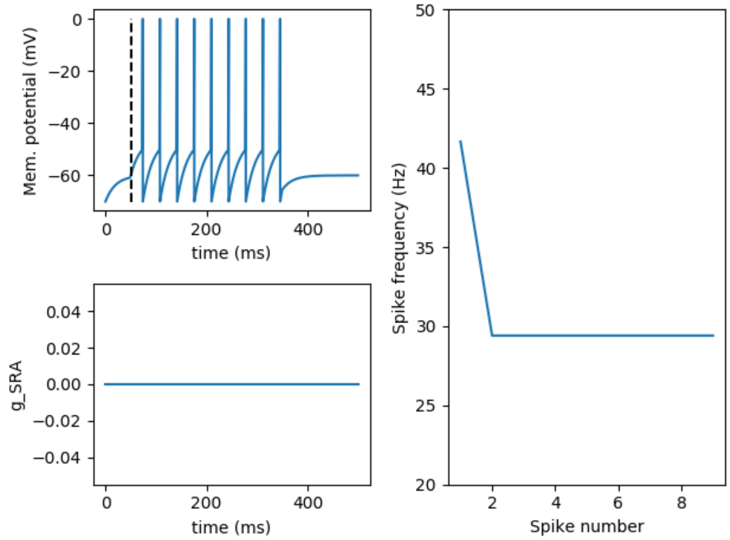

Figure 2: A LIF neuron with current step input applied in the interval 50 to 350 ms but without spike-rate adaptation (SRA). Top left: The membrane potential and spikes are shown. The dotted line indicates the moment the step current has started. The output spikes do not bcome more delayed over time. Bottom left: The SRA conductance g_{SRA} is zero because the SRA has been disabled in this neuron. Right: The frequency of the spikes, inversely proportional to the spike delay, is shown one by one for each output spike. In the absence of SRA, the neuron continues to fire regular ouput spikes in response to the step current input. Output frequency is higher than in the neuron with SRA, and this equilibrium frequency is reached directly after the first spike.