[40] Response Properties of Hodgkin's Three Classes of Neurons

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Introduction

The ability of neurons to encode and decode the characteristics of presynaptic stimuli enables the flow of information within our brains. For decades, many influential coding schemes were proposed, such as rate coding, temporal coding, and population coding. What kinds of coding schemes used in nervous systems is a topic of intense debate within the neuroscience community. It is also believe different neurons play different roles in information processing and transmission. While the precise coding recipe in the nervous system is uncertain, the responses of various classes of neurons to different stimuli are fundamental to understand information transfer in the nervous system. Here, we studied the firing rate and first spike latency responses of Hodgkin's three classes of Morris-Lecar neurons.

Model

We utilize a modified Morri-Lecar (ML) model, which can exhibit all the three excitabilities by only varying one parameter. This ML neuron is described by

$$C\frac{dV}{dt} = -g_f m_\infty(V)(V-E_{Na}) - g_s W(V-E_K) - g_l(V-E_l) + I_{ext}, \quad (1)$$

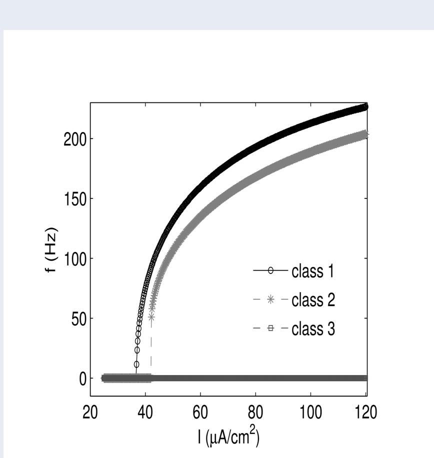
$$\frac{dW}{dt} = \Phi\frac{W_\infty(V)-W}{\tau(V)}, \quad (2)$$

$$m_\infty(V) = 0.5\left[1+\tanh\left(\frac{V-\beta_m}{\gamma_m}\right)\right], \quad (3)$$

$$W_\infty(V) = 0.5\left[1+\tanh\left(\frac{V-\beta_W}{\gamma_W}\right)\right], \quad (4)$$

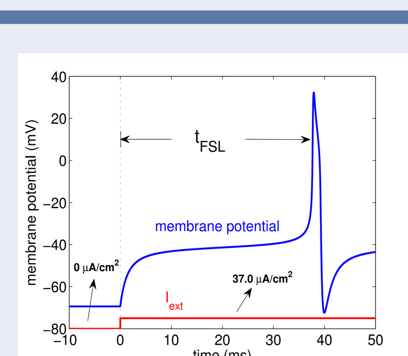
$$\tau(V) = 1/\cosh\left(\frac{V-\beta_W}{2\gamma_W}\right). \quad (5)$$

Here, V is the membrane potential and W is a slower recovery variable. The parameters are $E_{Na} = 50$ mV, $E_K = -100$ mV, $E_l = -70$ mV, $g_f = 20$ mS/cm^2, $g_s = 20$ mS/cm^2, $g_l = 2$ mS/cm^2, $\Phi = 0.15$, $C = 2\ \mu$F/cm^2, $\beta_m = -1.2$ mV, $\gamma_m = 18$ mV, $\gamma_W = 10$ mV. And β_W is identified as a tunable parameter. I_{ext} is the external input current.



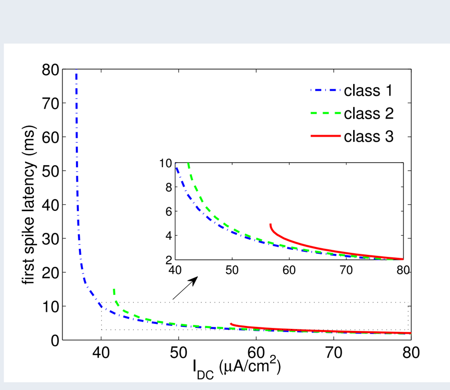
- Frequency-current (f-I) curves of three classes of excitabilities.
- Class 1 neurons ($\beta_{W=0\ mV}$) have a continuous f-I curve, occuring through saddle node bifurcation.
- Class 2 neurons ($\beta_{W=-13\ mV}$) have a discontinuous f-I curve, occuring through Hopf bifurcation.
- Class 3 neurons ($\beta_{W=-21\ mV}$) fail to spike repetitively, typically spiking only once at the onset of stimulation, occuring through a quasi-separatrix crossing.

- Firing rate is defined as the average number of spikes appearing during the simulation time.
- First spike latency in our simulations is the time of the first crossing of the detection boundary at 10 mV by the membrane potential V, as right figure shown.



Results

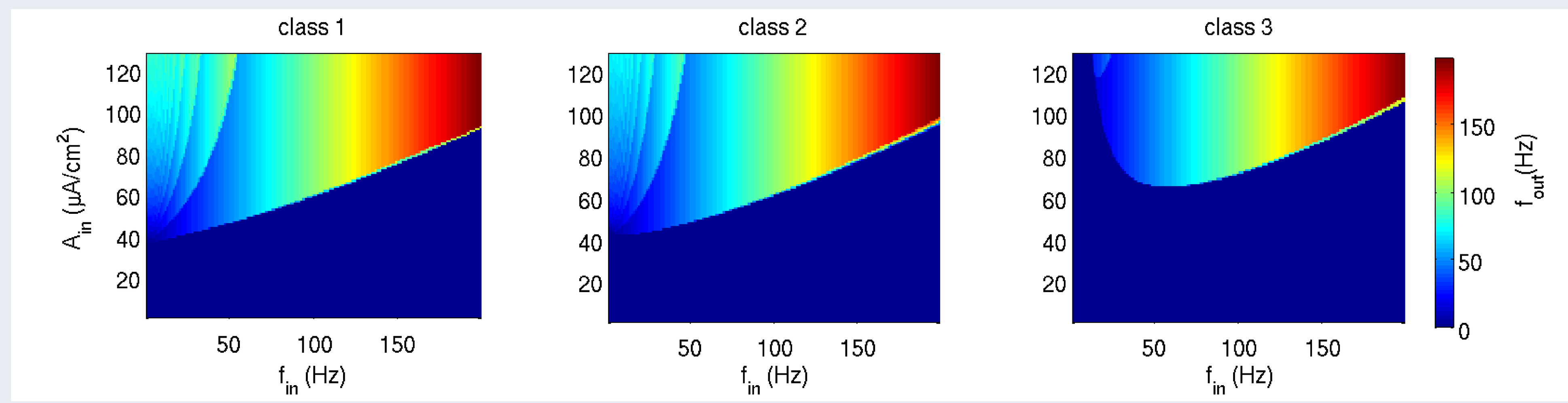
1. DC current input



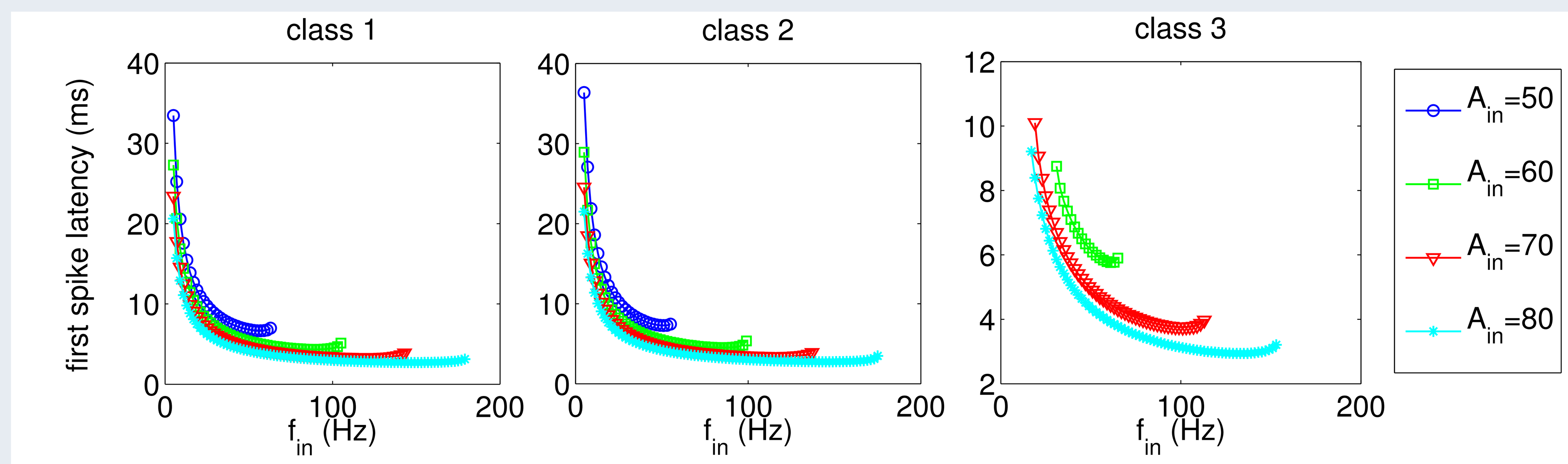
- Fist spike latencies of three classes of neurons as functions of DC current input shown in left figure.
- Fist spike latencies of all neurons decrease with the input intensity.

2. Sinusoidal input

$$I_{ext} = A_{in}\sin(2\pi f_{in} t) \quad (6)$$



The average output frequency f_{out} of the three classes of neurons as a function of the sinusoidal input frequency f_{in} and amplitude A_{in}.

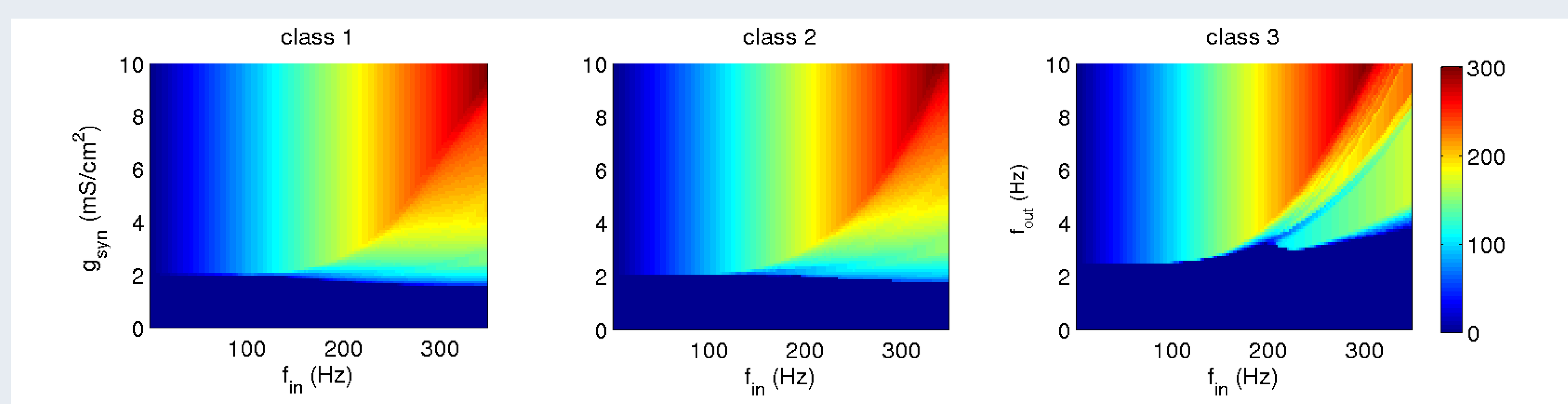


The FSLs of (a) class 1, (b) class 2, and (c) class 3 neurons as a function of the frequency of sinusoidal current input with different amplitudes.

3. Synaptic input

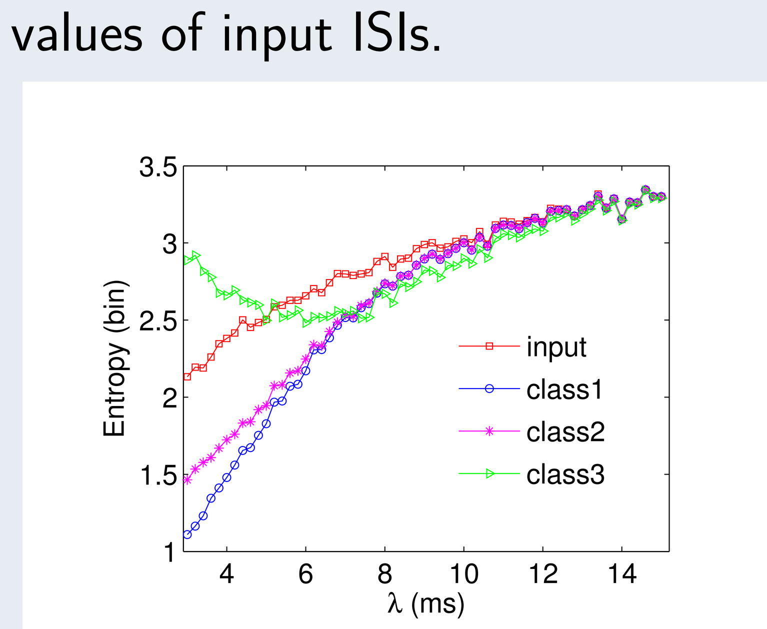
$$I_{ext} = g_{syn}\Sigma_n \alpha(t-t_{i,n})(V_a - E_s). \quad (7)$$

- here, $\alpha(t) = (t/\tau)\,e^{-t/\tau}\theta(t)$, $t_{i,n+1} = t_{i,n} + T_i$, g_{syn} is synaptic conductance controlling the input amplitude, $t_{i,n}$ represents the start time of the nth presynaptic input pulse. θ is the Heaviside step function. T_i is the ith ISI of synaptic input.



The average output frequency f_{out} of three classes of neurons driven by synaptic stimuli with dependent ISI inputs ($T_i = T_{const}$) and the input frequency is calculated by $f_{in} = 1/T_{const}$.

- Here T_i is assumed to be a Poisson distribution,
$$P_p(x) = e^{-\lambda}\lambda^x/x! \qquad (x = 0, 1, \ldots). \quad (8)$$
x is the random variables and mean ISIs is controlled by λ.
- It is helpful to use the information entropy to make clear the output ISI distribution property
$$H = -\sum_{observe\Delta t} P_{ISI}(\Delta t)\ln\left(P_{ISI}(\Delta t)\right). \quad (9)$$
- Following figure shows information entropy of three classes of neurons against with the mean values of input ISIs.



Summary and discussion

- Varying the input frequency and amplitude, that the output frequency responses of class 1 and 2 neurons show similar properties, whereas class 3 neurons display more complicated response behaviors.
- Neurons can code information of external input, such as intensity, frequency and initial phase, into different FSLs.
- Neurons can encode external stimulus into different FSLs independently of the rate coding scheme.

1. E. M. Izhikevich, Dynamical Systems in Neuroscience: The Geometry of Excitability and Bursting (MIT Press, Cambridge, MA, 2006). 2. S. A. Prescott, Y. De Koninck, and T. J. Sejnowski, PLoS Comput. Biol. 4, e1000198 (2008). 3. H. Wang, L. Wang, L. Yu, and Y. Chen, Phys. Rev. E 83, 021915 (2011).