An Introduction to Cognitive Neuroscine

Amirali Soltani Tehrani
aa.soltanitehrani@gmail.com
Instructor: Dr. Abdol-Hossein Vahabie
Deadline: 21 Tir

1) The Hodgkin-Huxley model is a mathematical model that describes the generation and propagation of action potentials (electrical signals) in neurons. It was developed by Alan Hodgkin and Andrew Huxley in the 1950s and is considered one of the landmark achievements in neuroscience.

A. Theoretical Questions

a) What is the minimal current leading to repetitive spiking?
b) If you increase the sodium conductance further, you can observe repetitive firing even in the absence of input, why? Is this phenomenon naturally plausible?

محسن

B. Simulation Questions

Consider following formulation for Hodgkin-Huxley model

$$\begin{cases} C\dot{V} &= I - \underbrace{\bar{g}_K n^4 (V - E_K)}_{I_K} - \underbrace{\bar{g}_{Na} m^3 h (V - E_{Na})}_{I_{Na}} - \underbrace{g_L (V - E_L)}_{I_L} \\ \dot{n} &= \alpha_n(V)(1-n) - \beta_n(V)n \\ \dot{m} &= \alpha_m(V)(1-m) - \beta_m(V)m \\ \dot{h} &= \alpha_h(V)(1-h) - \beta_h(V)h \end{cases}$$

in which:

$$\alpha_n(V) = 0.02\frac{V-25}{1-\exp\left(\frac{-(V-25)}{9}\right)}, \beta_n(V) = -0.002\frac{V-25}{1-\exp\left(\frac{V-25}{9}\right)}$$

$$\alpha_m(V) = 0.182\frac{V+35}{1-\exp\left(\frac{-(V+35)}{9}\right)}, \beta_m(V) = -0.124\frac{V+35}{1-\exp\left(\frac{V+35}{9}\right)}$$

$$\alpha_h(V) = 0.25\exp\left(\frac{-(V+90)}{12}\right), \beta_h(V) = 0.25\frac{\exp\left(\frac{V+62}{6}\right)}{\exp\left(\frac{V+90}{12}\right)}$$

with these parameters given as below:

$$\begin{cases} V(0) = -65\ mV, \quad n(0) = 0.32 \quad m(0) = 0.05, \quad h(0) = 0.6 \\ g_{NA} = 120, \quad g_K = 36, \quad g_L = 0.3 \\ E_{Na} = 50, \quad E_K = -77, \quad E_L = -54.4 \\ C = 1\ \mu F \end{cases}$$

1) Action Potential Generation:

[illegible]

a) Simulate the Hodgkin-Huxley model using the given parameters. What is the threshold current required to elicit an action potential?
b) Investigate the effects of varying the amplitude and duration of the applied current on the action potential waveform and firing rate.
c) Compare the action potential waveforms generated by the Hodgkin-Huxley model with different initial conditions. How do these variations affect the shape and duration of the action potential?

2) More Computational Problems:

[illegible]

a) Using the formula of model, draw the action potential over time. Consider the amplitude of the excitation equal to $20\,\mu A/cm^2$ lasting $0.2\,ms$. Compute the minimum amplitude of excitation for this model to spike for fixed excitation time width.
After it, compute the minimum excitation current for at least 5 different excitation widths.
b) Draw g_{Na} and g_K over time. Also draw the time change of m, n and h and interpret them comparing to previous plots.
c) Draw the current for Na and K channels.
d) In single excitation state, what is the effect of increasing the capacitance of membrane on the shape of action potential.
e) Now change the program. After 15 ms, apply the second excitation with amplitude $40\,\mu A/cm^2$.

2) In this exercise, we will delve into the fascinating world of computational neuroscience by simulating the dynamical systems presented in the seminal paper "Synaptic Mechanisms and Network Dynamics Underlying Spatial Working Memory in a Cortical Network Model" (Cell, 2002). Utilizing the Brian Simulator, a powerful Python library designed for spiking neural networks, we will recreate the neural dynamics outlined in the paper. The Brian Simulator is renowned for its user-friendly syntax and flexibility, allowing us to define and simulate complex neural models with relative ease.
Your task is to implement the model described in the paper, paying close attention to the equations governing the dynamics of the neural network. You will need to translate these equations into Python code, using the Brian Simulator's framework to define neuron models, synapses, and the network architecture. As you work through the simulation, observe how altering parameters affects the behavior of the network, and compare your results with the findings reported in the paper. This hands-on experience will not only enhance your understanding of spiking neural networks but also provide you with practical skills in using computational tools to explore brain function and dynamics.

I. Submission

For the programming section, each student is required to submit a well-structured, typed PDF report that presents a concise summary of their analysis. The report should include the figures mentioned in the problem description and offer a detailed discussion of each. Please avoid uploading theoritical problem in .jpg format and upload them in a single .pdf file. For each section of the report, a separate script is expected, which can be written in MATLAB (.m), Python 3 (.py or .py3), or R (.r). Avoid submitting scripts in formats like MATLAB live scripts, Python notebooks, or R Markdown. It is crucial that the submitted code is compatible with the grader's system. Be sure to include all relevant functions and any non-standard libraries used in your code. The report should be treated as an academic piece of writing, and it should not contain any code snippets or expla- nations of coding logic. Instead, it should provide the author's insights about the results and demonstrate a strong grasp of the reference article. Academic reports typically maintain a concise and highly formal tone. Each section of the report should briefly outline the hypoth- esis being tested. The responsibility for designing and imple- menting the tests lies with the students, as does explaining the results. Interpretations should be comprehensive without unnecessary verbosity. The report can be written in either Persian or English, with no preference for either. In Persian reports, use B Nazanin with a font size of 14 for the text body and B Titr with a font size of 18 for titles. English reports should use Times New Roman 12 for the body text and Times New Roman 16 for titles. Sentences should be written in the passive tense. In Persian reports, the correct usage of the zero-width non- joiner is mandatory. In all reports, equations, figures, and tables must be labeled with unique numbers and referenced accordingly. Referring to figures as ”the following figure,” ”the figure above,” and similar expressions is considered incorrect. Every figure in the report should be accompanied by a descriptive caption below it, while tables should have captions above them. Feel free to use footnotes and citations as necessary for clarity and proper attribution.