9.49 / 9.490 Neural Circuits for Cognition
Project/final homework
Due: Tuesday December 10, by 4pm;
interim data due on Wednesday December 4 by midnight.

In this project, you will explore switching dynamics during perceptual bistability. We will build models, analyze data from the models, and perform psychophysics experiments to compare behavior with models. Team up with one classmate so you can do the project in groups of two. If you wish to do a different project related to themes and topics covered in class, that is possible. **Please meet with me by Tuesday, November 26 if so.**

Perceptual bistability and switching. Consider a pair of neurons in a circuit:

$$\tau \frac{d\mathbf{s}}{dt} = -\mathbf{s}(t) + f(\mathbf{W}\mathbf{s}(t) - g\mathbf{a}(t) + b_0(1 + \mathbf{n}(t))) \equiv \mathbf{r} \tag{1}$$

where W is a 2×2 matrix of synaptic weights, $\mathbf{s}$ is the time-varying synaptic activation variable, τ is the synaptic time-constant, and b is the strength of the feedforward input. Let the $f - I$ (transfer) function be the sigmoid $f(x) = e^x/(1 + e^x)$.

The 2×1 variable $\mathbf{a}$, used to model *neural adaptation*, is a running average of recent activity in each neuron:

$$\tau_a \frac{d\mathbf{a}}{dt} = -\mathbf{a}(t) + \mathbf{r} \tag{2}$$

where $\tau_a >> \tau$ is a slow adaptation time-constant (i.e., slower than τ), and $\mathbf{r}$ is the 2×1 vector of firing rates of the neurons, as given in Equation (1). This adaptation variable feeds back into the dynamics of Equation (1), in the form of a negative feedback. The more a neuron fires, the more adapted it becomes (a_i increases), and the greater the negative drive to the neuron. The strength of adaptation is controlled by the parameter g.

The term $\mathbf{n}(t)$ reflects internal circuit noise, with independent components n_1, n_2, which we will assume are simply linearly low-pass filtered versions of random Gaussian noise:

$$\tau_n \frac{d\mathbf{n}}{dt} = -\mathbf{n}(t) + \sigma \sqrt{\frac{2}{\tau_n}} \xi \tag{3}$$

where $\tau_n << \tau$ and ξ is a 2×1 vector of two independent zero-mean Gaussian random variables of unit variance (`randn` in Matlab). Let the two neurons symmetrically inhibit each other, so that

$$W = \begin{bmatrix} 0 & -w \\ -w & 0 \end{bmatrix}.$$

We will use these dynamics to model the psychophysical phenomenon of perceptual bistability, to investigate potential mechanisms of perceptual switching. In what follows, use parameters for w that ensure the system is a bistable switch (when $g = 0$), and set $b_0 = w/2$. Use $\tau = 20$ ms, $\tau_n = 4$ ms, $dt = 0.2$ ms. A reasonable value to begin with for $\tau_a = 200$ ms.

a. **Psychophysics.** In a quiet, dark room without distractions, view the Necker cube stimulus (enclosed file) and log the times of your perceptual switches. (If you use Matlab, you could use the enclosed code: `switch_time_recording.m`; and if you use Python, you could use `switch_time_recording.py` to record the times of a button click.) Do the experiment under 2 conditions: eyes fixed on the dot, versus eyes free to move. Collect as much data as possible with both members of your team as subjects (but at least 100 switches per subject; run multiple sessions with breaks between sessions as needed if this is tiring)! Record the data in a simple tab-deliniated 2-column text file with column 1 being switch number and column 2 being the ISI (Inter-Switch time Interval). In the end, you will have four data files; please name these four files Dij, where $i = 1, 2$ for subject number, and $j = 1, 2$ for fixed, free eye positions. **Please send me and Su these data files by Wednesday, Dec 4**. We will share (anonymized) across-subject files with you for your data analysis.

b. **Modeling I.** Switching driven by adaptation only (zero noise, $\sigma = 0$): Code your simulations and plot r_1, r_2 versus time. Activation of one of the two neurons indicates activation of one of the two possible percepts. What are the statistics of the model ISI's (plot a histogram)? How does the time-scale of switching vary with g? Plot. For a fixed g, how does the switching period depend on b, the strength of the ff input? Does period go up or down as the strength of the input drive (the contrast of the stimulus) is increased?

c. **Modeling II.** Switching driven by noise only (zero adaptation, $g = 0$): Fix the noise standard deviation σ to some appropriately large value to drive noise-induced switching, and plot r_1, r_2 versus time. For different values of the noise standard deviation σ, plot ISI distributions: How does the ISI mean (average switching time) vary with σ?

d. **Model analsysis I.** For the purely noise-driven model in d., compute the *switch-triggered average* (STA) of the input ($b_i(t)$, which includes the constant and noise components of the input) for switches from neuron 1 active to neuron 2 active, per neuron. The STA measures the average time-course of the input that preceded switching: $\mathrm{STA}_i(t) = \sum_\alpha b_i(t_\alpha - t)$ where t_α is the time of the α'th switch from neuron 1 to neuron 2, and i is the index of the neuron whose STA is being computed. If switches are defined by thresholding the vector r, and recorded as a binary switch vector of 0's and 1's, with a 0 at each discrete timestep of the simulation if no switch or a switch from neuron 2 to 1 occurred at that time, and 1 means a switch from neuron 2 to neuron 1 occurred at that time, then the STA is simply the cross-correlation between the stimulus and the binary switch vector (show/verify this with pen and paper, as part of your report methods!). (Actually, writing the switch vector as a $\{0, 1, -1\}$ vector with -1 referring to switches in the opposite direction, and computing the croscorrelation between the switch vector and the inputs will produce the sum of the STA for positive switches and the negative of the STA for negative switches; since these should be equal and opposite versions of each other, you will be computing the average STA across both switch conditions; try this.)

e. **Model analsysis II.** Model with both adaptation and noise: Fix an adaptation strength g, then plot normalized ISI histograms (we'll call these ISI distributions) for a few (4-5) different but well-spaced values of noise variance. Get all ISI distributions on same plot, including the zero-adaptation case. Interpret.

f. **Data analysis and models.** Plot a single across-subject ISI distribution for switches (ignoring the sign of the switch). Which version of the models qualitatively best fits the ISIs in your data: pure adaptation-based switching, pure noise, or a mixture? Try to find good values of the model parameters to fit the experimental ISI distribution. Also plot the individual-subject ISI distributions (ignoring the sign of the switch), as separate curves in a single plot, to give a sense of inter-subject variability. Finally, is there a significant difference between the eyes fixed and eyes free conditions?

g. **Report.** Each group: Write and submit a $\approx$ 3-page summary/report of your work (1 page: introduction to problem and setup of your model and experiments; 1 page: results and analysis; 1 page: comparison with literature and discussion). Please read, briefly describe, and relate your work to the following paper, as part of your report: R. Moreno-Bote, J. Rinzel, and N. Rubin. Noise-induced alternations in an attractor network model of perceptual bistability. *J. Neurophysiol* 98: 1125-1139. All results and figures generated in response to parts a-f above should be part of this report, and this report should be in the form of a brief research article, with introduction, results, methods, and discussion sections, as well as embedded figures with captions. **Graduate students: your report should include 1 additional page of context, background, and literature review.**