Controlling oscillations in Parkinson's disease

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NOTE: This project cannot be solved in a group; only a single student's solutions will be accepted.

1 Introduction

The goal of the final project is to learn to construct a more complex network inspired by state-of-the-art research, analyze the results, and present them in a written form. Our motivation will be the publication *The role of inhibition in generating and controlling Parkinson's disease oscillations in the basal ganglia* [1]. In this paper, Kumar et al. explore the origin of beta oscillations involved in Parkinson's disease and how to suppress them with deep brain stimulation (DBS). We will build a smaller network with adjusted parameters that exhibits similar behaviour.

2 Let's dive in!

2.1 What model are we going to work with?

Using the NEST simulator, create 2 populations of neurons:

- 300 neurons (analogue to STN, excitatory),
- 500 neurons (analogue to GPe, inhibitory).

Neurons in both populations have the same parameters:

- *Membrane capacity*: 30 pF
- *Leak reversal potential*: -70 mV
- *Reset potential*: -70 mV
- *Spike threshold*: -60 mV
- *Refractory period*: 2 ms
- *Membrane time constant*: 20 ms
- *Time constant of an excitatory synapse*: 1 ms
- *Time constant of an inhibitory synapse*: 10 ms

Connect neurons in both populations (both within and across populations) with the connection rule *fixed indegree*. Set the parameters of the connections as follows:

	indegree	synaptic weight (pA)	synaptic delay (ms)
GPe -> STN	30	-15	5
STN -> GPe	50	30	5
GPe -> GPe	30	-5	2
STN -> STN	50	50	2

Next, create one Poisson generator with a rate of 800 Hz and connect it to the GPe with a weight 40 pA and to the STN with a weight 65 pA. Create a spike recorder a connect each population to it. If you wish, you can also create and connect a voltmeter to observe the membrane potential. Now you are ready to simulate the network and observe the activity.

- What is the role of the Poisson generator in this model? What biological phenomenon is it equivalent to? Why do we use a Poisson random process to model this input? Is the input excitatory or inhibitory?

2.2 Increased input to the GPe

Create a Poisson generator with a mean firing rate of 800 Hz and connect it to all neurons in the GPe with a weight -5 pA. Pick a start and stop time such that you can observe both the activity with and without this additional input.

- Plot a raster plot of spikes and the total spiking activity in each of the two populations to see how activity changes when you switch on and off the additional external input. Is this step equivalent to increasing the excitation or inhibition to the network? Why? What biological phenomenon is this step modelling?

2.3 Deep brain stimulation

Create a direct current generator with a current amplitude of -180 pA and connect it to all neurons in the STN.

- Pick start and stop time so that you see activity in all three conditions (no additional input, additional inhibitory Poisson input to GPe, additional Poisson input to GPe and DBS to STN). Again, plot the raster plot and the total spiking activity per population. What phenomenon is modelled here? How do activities in these conditions differ?

3 Expected outcomes

Write up a report with the analysis report answering all the questions posed above, and in addition to that, address the following points:

- Plot the spectrogram and a power spectral density of the binned population firing rate in all three conditions. In what conditions does the oscillation appear? What is the frequency of the oscillation? Do we see the *1/f* spectral component? Why? Which size of the window (*nperseg*) parameter did you use to plot the results and how does that influence them?

- Plot the auto-correlation function of the population firing rate for each population and each condition. Do you see any interesting features? How does the autocorrelogram reflect the amplitude and frequency of oscillations? Does it bring us any additional information that could not be read from the spectral analysis performed in the previous step?

- *Bonus No. 1*: Test different amplitudes of the DBS. How sensitive is the effect to changes in the DBS amplitude? Address both positive and negative values. Create figures to demonstrate your results. What is the biological interpretation of the results?

- *Bonus No. 2*: Let us experiment with other network regimes a bit more. How can we manipulate the parameters of the DBS simulation to achieve even faster oscillations? On the other hand, consider the network in the state when the oscillations are attenuated, as achieved by DBS as tuned previously. Is this state the same as the network state at the beginning? If not, create and test an idea how to achieve the regime more similar to the initial network state. Explain what your idea means in biological terms. Report if the strategy was succesful or not, and explain possible reasons for this outcome.

- Compare the results achieved in your model with the paper. Are they coherent? Did you observe anything interesting not captured by the authors of the paper? What are the limitations of their study? Review shortly how the field has addressed these limitations since the year 2011 up to today.

Write down a PDF file where you answer all the questions and describe methods that you used in your analysis. The method part should be written clearly and formally, similar to the style of the section on the method as presented in neuroscience papers. Based on this, your analysis should be fully reproducible. Please ensure all the figures are correctly named, and the axes and units are well-described. All the additional code used for the analysis should be submitted alongside of the report in the form of a Jupyter notebook. In the report, also provide a screenshot of the final version of your model. Have this model ready and running on your PC for further inspection by the lecturer.

Completing only the exercises not labeled as Bonus will result in a grade of 3. By correctly addressing Bonus No. 1, you can get to grade 2. By addressing both Bonus questions, you can get to grade 1. At the beginning of the report PDF, clarify to what extent you used the AI tools.

Send all the files to *studenicova.k@gmail.com* until 09th January 2026.

References

[1] A. Kumar. The role of inhibition in generating and controlling Parkinson's disease oscillations in the basal ganglia. *Frontiers in Systems Neuroscience*, 2011. URL: https://doi.org/10.3389/fnsys.2011.00086.