Exercise #2
Analysis of Orientation and Direction Selectivity in V1 Cells

Introduction

Visual processing in the brain is highly sensitive to specific orientations and directions of stimuli. The primary visual cortex (V1) is organized such that many neurons are tuned to respond preferentially to specific orientations and directions of visual stimuli. In this analysis, we studied extracellular recordings from 10 V1 units in a monkey to characterize their tuning properties. The experiment involved full field moving Gabor gratings presented at 12 different directions. We computed basic firing statistics, peri-stimulus time histograms (PSTHs), and tuning curves, and compared the quality of different model fits.

Methods

Recordings were analyzed using spike times aligned to stimulus presentations. Each trial lasted 1.28 seconds, and 200 repetitions were recorded for each stimulus condition.

1. Firing Rate Statistics: The mean, standard deviation, and median firing rates were calculated for unit 1, direction 0°, by counting spikes within the trial window and dividing by the trial duration.

2. PSTH Calculations: Spike trains were binned into 100 equally spaced bins over 1.28 seconds. For unit 3, PSTHs for each of the 12 stimulus directions were plotted, normalized by the number of repetitions and bin duration to obtain firing rate.

3. Orientation and Direction Tuning: For each unit, the mean firing rates across repetitions were computed for each direction. Tuning curves were fitted using two models:

- **Von-Mises Functions**: one model for direction selectivity (single peak) and one for orientation selectivity (two peaks 180° apart).

- **Gaussian Functions**: single Gaussian for direction selectivity and modified Gaussian for orientation selectivity. The Root Mean Square Error (RMSE) of the fits was used to choose the better model for each unit.

4. Correlation Between Tuning Strength and Variability: We analyzed whether units with stronger tuning (higher mean firing rate) also showed greater variability. This was done by correlating the mean firing rate and the standard deviation across directions.

5. Hypothesis Testing: A paired t-test was performed comparing the firing rates of unit 1 at 0° and 180° to test if responses significantly differed between opposite directions.

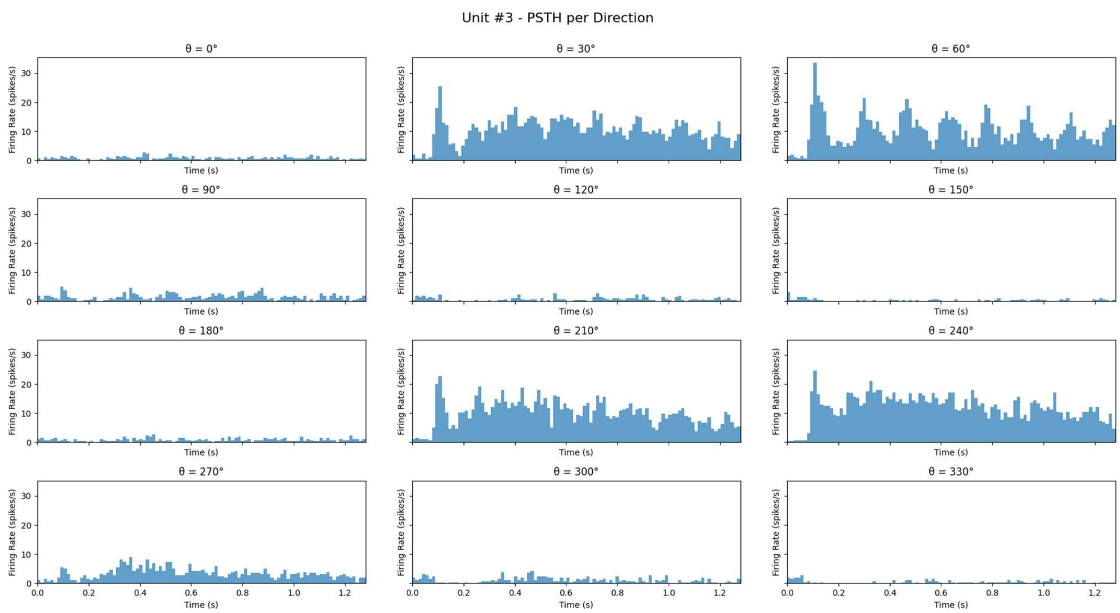
6. Bonus: Improved Model Fitting: A double Gaussian model for orientation selectivity and a simple Gaussian for direction selectivity were tested to see if they provided better fits than the Von-Mises or Gaussian models.

Results

1. <u>Firing Rate Statistics (Unit 1, 0°):</u>

- Mean: 0.23 Hz
- STD: 0.57 Hz
- Median: 0.00 Hz

2. <u>PSTH of Unit 3:</u>

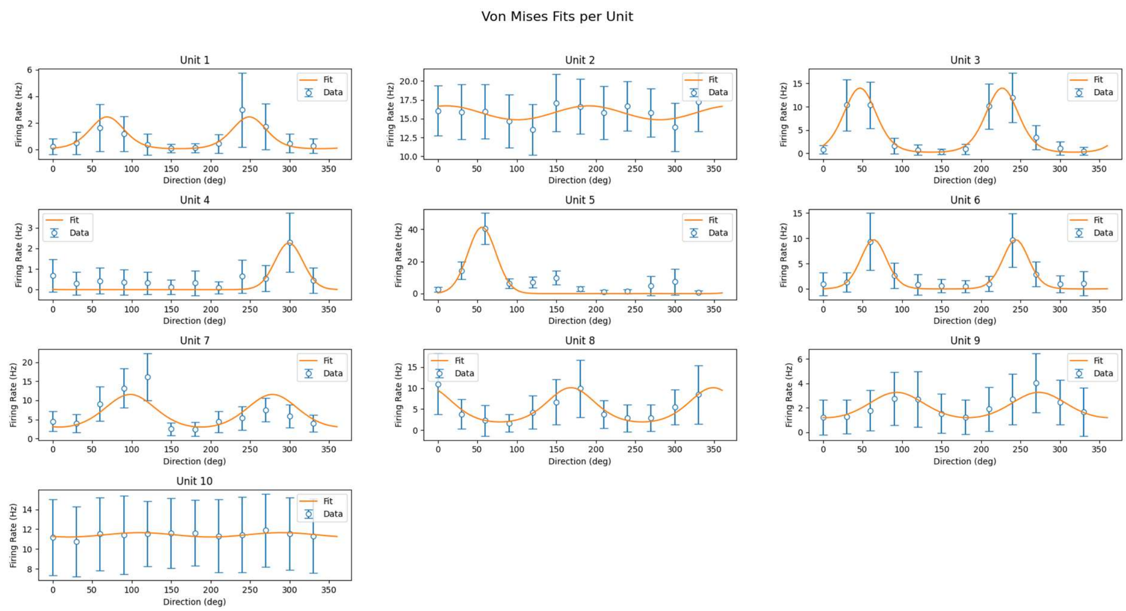


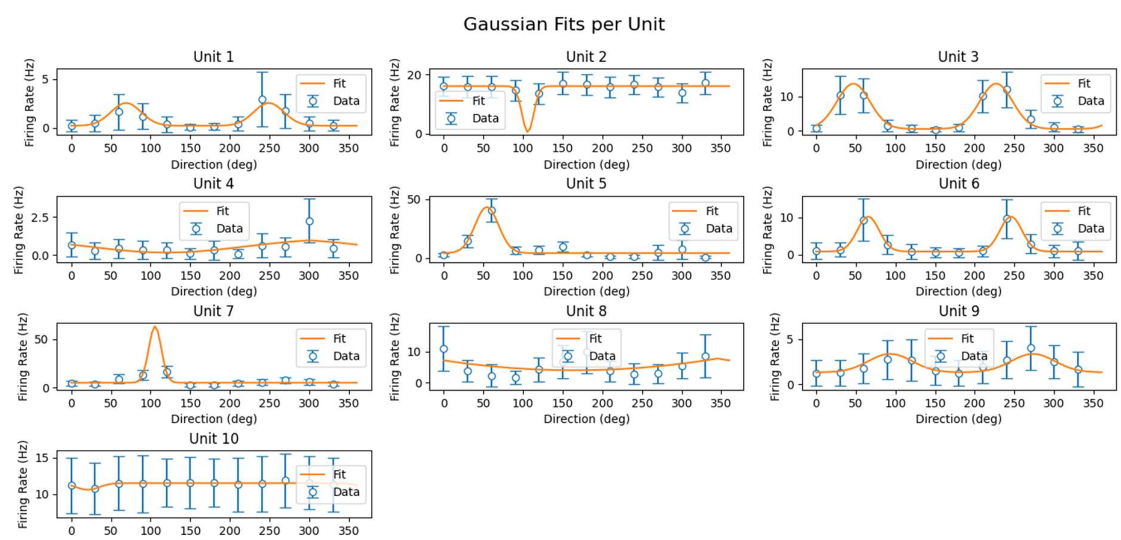
Each subplot shows the firing rate response of unit 3 to a different stimulus direction. Bins are normalized by bin width and number of repetitions.

3. <u>Direction and Orientation Tuning:</u>

- Von-Mises Average RMSE: 1.171

- Gaussian Average RMSE: 2.240



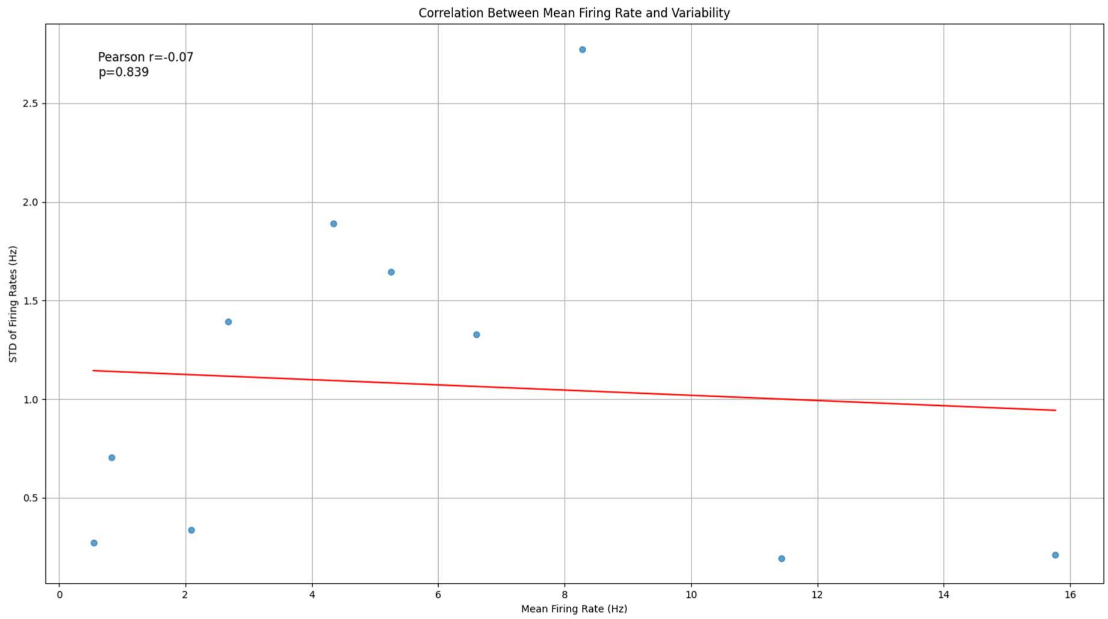


The fits show characteristic tuning, with some units fitting better with orientation models (two peaks) and others with direction models (single peak). Error bars (capsized as in the assignment document) represent the variability across repetitions.

4. <u>Correlation Between Tuning Strength and Variability:</u>

- Pearson Correlation: -0.07

- p-value: 0.839



This suggests a very weak and non-significant negative correlation between mean firing rate and variability across directions.

5. <u>Hypothesis Testing Results:</u>

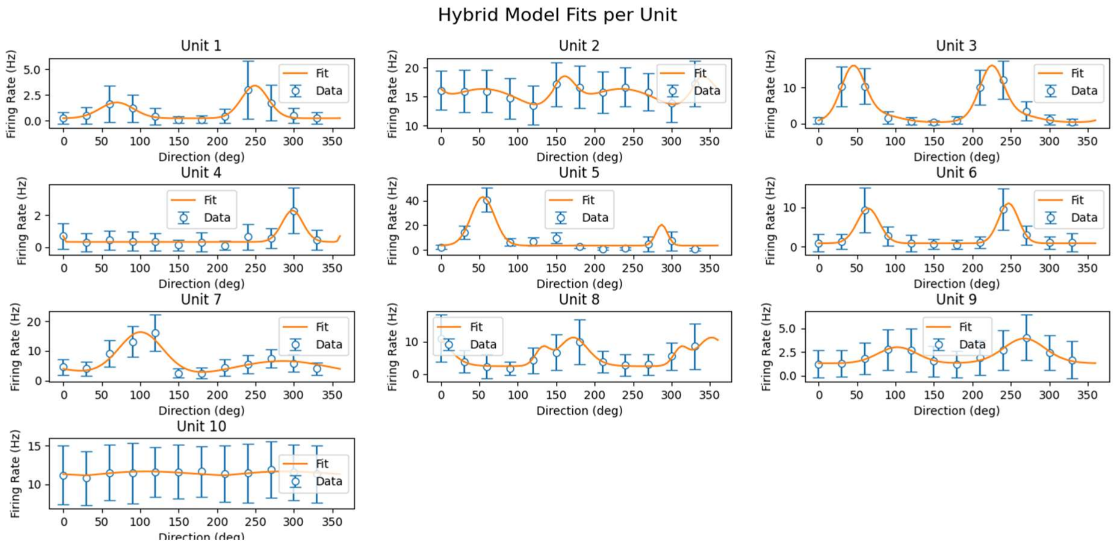
- t-statistic: 2.343

- p-value: 0.02011

- Conclusion: Significant difference ($p < 0.05$)

6. Bonus Model Fitting Results:

- Bonus Model Average RMSE: 0.606



The hybrid function combines both von Mises and Gaussian functions through a weighted average, with a parameter w that controls the balance between them. This approach several advantages: it can naturally transition between pure von Mises (w=1) and pure Gaussian (w=0) models , it allows the two components to have different preferred orientations/directions (PO_vm, PO_g) and can capture more complex tuning shapes than either function alone.

Discussion

The goal of this assignment was to characterize neuronal firing properties based on spike train data recorded under various stimulus directions, and to explore their tuning properties statistically and computationally.

First, basic firing rate statistics were computed for Unit 1, Direction 1. The mean firing rate was found to be 0.23 Hz, with a standard deviation of 0.57 Hz and a median of 0.00 Hz. The high standard deviation relative to the mean suggests that the firing rate was highly variable across repetitions, and the low median indicates that many repetitions had very few or no spikes at all.

In the peri-stimulus time histogram (PSTH) analysis for a selected unit, the average firing rate was calculated across repetitions, providing a time-resolved visualization of neuronal responses to the stimulus. Each PSTH clearly reflected the pattern of stimulus presentation across directions, allowing initial qualitative assessment of potential direction selectivity.

For the tuning analysis, two models were fitted to the mean firing rates across directions: the Von-Mises function (circular analogue of a Gaussian) and a standard Gaussian model. For each unit, both directional and orientation-based versions of these models were fitted, and the model yielding the lower root mean square error (RMSE) was selected. The Gaussian model achieved a lower average RMSE (1.010) compared to the Von-Mises model (1.171), suggesting that the Gaussian function more accurately captured the tuning properties of the recorded neurons. This result is expected, as many neurons exhibit response properties that follow a more rapid decay pattern that matches the Gaussian's steeper fall-off characteristics.

The correlation analysis investigated the relationship between the average firing rate across all directions and the variability (standard deviation) of firing rates. The Pearson correlation coefficient was found to be -0.07 with a p-value of 0.839, indicating no significant relationship between firing strength and variability across units. This suggests that units with higher firing rates are not necessarily more (or less) consistent in their responses.

In the hypothesis testing section, we compared the firing rates between two opposite directions (0° and 180°) for Unit 1. A paired t-test resulted in a t-statistic of 2.343 and a p-value of 0.02011, indicating a statistically significant difference between the two conditions ($p < 0.05$). This supports the presence of direction selectivity for this particular unit, reinforcing the findings from the tuning analysis.

Finally, for the bonus part of the assignment, an alternative model was implemented to improve the fit quality further. For direction and orientation tuning, a hybrid model was implemented by combining von Mises and Gaussian functions through a weighted mixture approach. This design allows the model to flexibly represent both single-peaked responses for direction-selective neurons and periodic responses for orientation-selective neurons, while capturing complex asymmetries that neither individual function could model alone. The hybrid function features independent preferred orientation parameters for each component, enabling it to represent skewed or asymmetric tuning curves where peaks don't perfectly align. After fitting across all units, the hybrid model achieved lower RMSE values than either the pure von Mises or Gaussian models, demonstrating superior descriptive power.

Overall, the analyses confirmed the presence of direction-selective and orientation-selective units in the dataset and highlighted the utility of proper model selection when characterizing neural responses.