# Analysis of Neural Encoding in Primate Motor Cortex using Raster Plots, Peri-Event Time Histograms, and Tuning Curves

Jacey L. Davies, *University of Florida*

***Abstract*—Neuronal encoding is the study of how neurons represent information through action potentials. In the primary motor cortex, some neurons are tuned to a particular movement direction and thus will fire more when the subject moves in that direction. Two neurons from the motor cortex of a macaque monkey performing a motor task were analyzed to determine the direction, if any, they were tuned to. The analysis was done by creating raster plots, peri-event time histograms (PETHs), and tuning curves in MATLAB for each neuron. The plots pointed to neuron 1 being tuned to a certain direction and neuron 2 being untuned. There are limitations to this analysis such as using a parabola for the tuning curve rather than a sinusoidal curve.**

***Index Terms*—Neural encoding, neural tuning, tuning curve, raster plot, primary motor cortex**

## I. Introduction

THE action potential of a neuron is an ‘all or nothing’ signal and thus no attributes of the stimulus are included in this signal. Instead, these attributes are often encoded in the frequency of neuronal spikes. The frequencies can be visualized in raster plot, where the spikes of all the trials for a neuron are plotted in rows against time. This helps see what time the neuron fired the most. Thus, raster plots for the neurons analyzed here were created to visualize the neural spikes. Similar to the raster plot is the peri-event time histogram (PETH), which is a histogram of the neural spike times. PETHs are created in this paper as well. Neuronal encoding is the study of how neurons represent information through action potentials. One way that neurons do this is by being ‘tuned’ to a certain orientation or direction and thus firing more when encountering that stimulus. This neural tuning is important in facial recognition. The neurons in the associated brain area will be tuned to specific facial structures/patterns and will thus fire more upon seeing a face [1]. Similarly, neurons in the motor cortex will fire differently based on the force exerted, the direction of the movement, or the velocity of the movement, or a combination of these [2]. This dependence of the neuronal response on movement-related parameters is often represented in a tuning curve, which should be bell-shaped or sinusoidal [2,3]. The tuning curve created in this paper plots the firing rates of a neuron against the direction of the movement. Theoretically, the firing rates should increase as the stimulus approaches the direction the neuron is tuned to. This analysis of the tuning of motor neurons is important for developing neural interfaces that can intuitively control devices such as robotic prostheses [4].

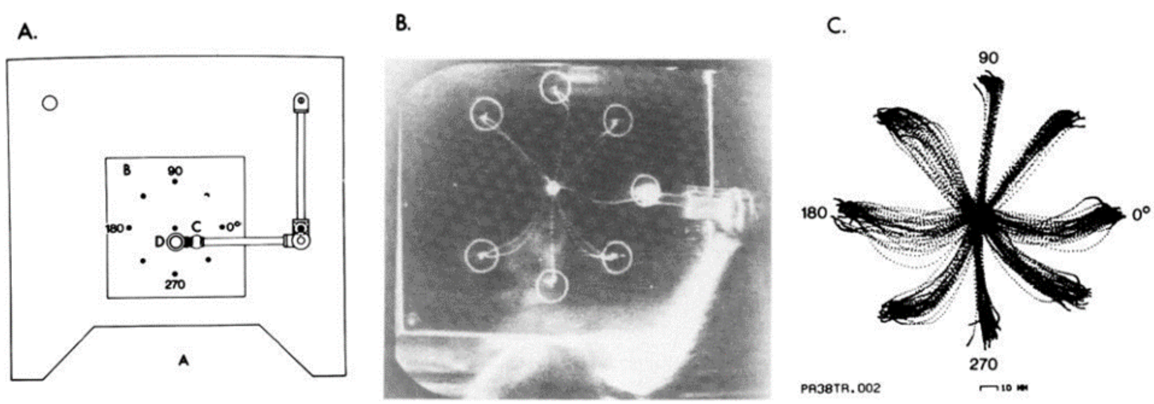


Fig. 1. A, The overall set up for the task. The monkey sits at position A and the working surface (B) has one LED at the center and eight on a circle labeled 0-315° counterclockwise; the monkey grabs the articulated manipulandum (C) and moves the clear plastic circle (D) over the illuminated LED. B, overhead view of a monkey performing the task and moving the arm over the 0° LED. C, trajectories of 30 movements from one monkey. Each dot represents the position of the center of the plastic circle taken at 10ms intervals. From [2].

J. L. Davies is with the Biomedical Engineering Department, University of Florida, Gainesville, FL 32611 USA.

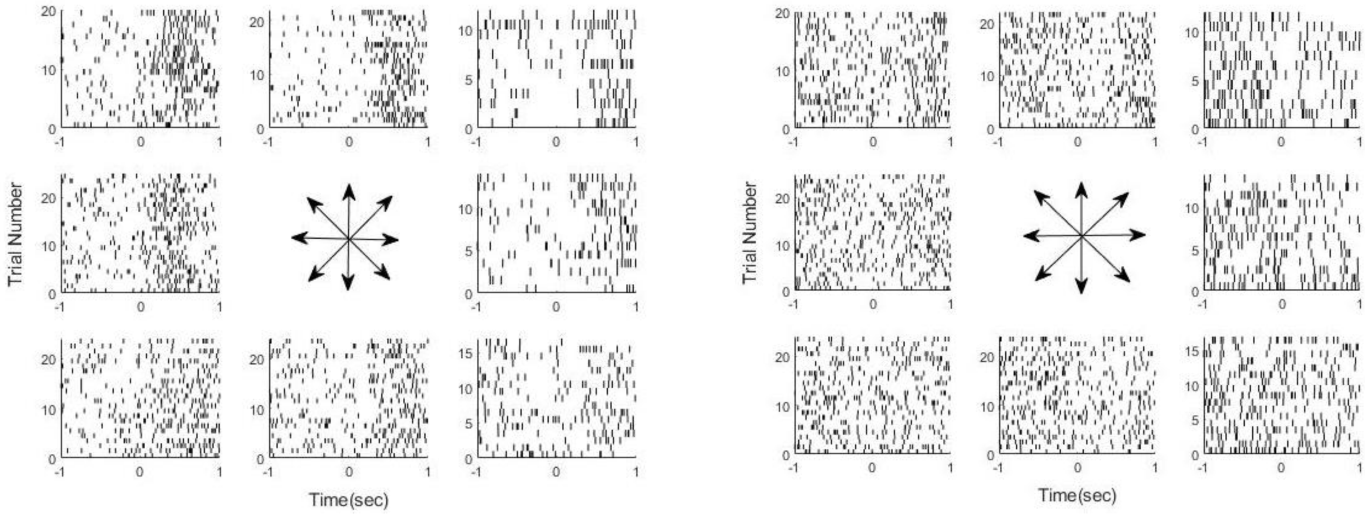


Fig. 2. The raster plots for neuron 1 (left) and neuron 2 (right). The arrows in the center correspond to the directions of the LEDs in Fig. 1. The raster plot that an arrow points to is the plot for the trials in that direction. For example, the plot in the second row, third column shows the spikes in the 0° direction. The go cue is at 0s. A cluster of lines/spikes indicates a heightened response to the stimulus and thus a preference for that direction.

## II. Materials And Methods

The software utilized to create the raster plots, PETHs, and tuning curves was MATLAB 2020.

### *A. Data Source*

The data were provided by the Hatsopoulos Laboratory. There, a macaque monkey performed a task seen in Fig. 1 based on the task used in the experiment by A.P. Georgopoulos [2]. The monkey sat in front of a set of LEDs with one in the center and eight arranged in a circle labeled from 0° to 315° counterclockwise. The subject would hold the articulated manipulandum/arm so that the ring was over the center LED for 500ms. Then one of the LEDs in the circle would light up. After 1000-1500ms, the subject would be given a go cue and would move the arm to the target and hold it there for 500ms. The response of two neurons in the primary motor cortex was recorded and spike sorted. The times of the spikes were given for each neuron, along with the times for the go cues and the corresponding LED/direction for each cue. The directions were labeled as 1 through 8, corresponding to 0° through 315° in 45° intervals.

### *B. Raster Plot Creation*

Raster plots were created for both neurons, one neuron at a time. For each direction, 1-8, the trials using that direction were found. Then the spike times during the time period 1s before the go cue to 1s after the cue were found for each trial in said direction. The spikes from 1s before were used to provide a baseline. The times were centered around zero by subtracting the go cue time from each time. These spike times were plotted as vertical lines. One for loop was used to cycle through the directions so a raster plot for each direction could be put in a subplot. Another loop was placed inside this loop and was used to plot the spikes for each trial so each trial would be a row of lines in the raster plot. This was repeated for the second neuron. The arrows were added using the MATLAB figure editor.

### *C. PETH Creation*

When making the PETHs for the two neurons, 20ms bins and 1s windows were used. This means that the spikes were sorted into 20ms intervals ranging from -1s to 1s. Similar to the raster plots, the trials for each direction were found. The spike times were found and centered around the go cue time in the same way as before. Using the histc() function, the spike times were sorted into the bins. One for loop was used to cycle through the directions so a PETH for each direction could be put together in a subplot. Another for loop was placed inside this loop to sort the spike times of each trial. The histograms were normalized by dividing the neuron spike counts by the number of trials for each direction and the bin size. This process was repeated for the second neuron. The arrows were added using the MATLAB figure editor.

### *D. Tuning Curve Creation*

To create the tuning curve, the average firing rates for each direction had to be found. Like before, the trials for each direction were found. All of the spike times for the neuron were centered by subtracting the go cue time. Then the number of spikes for each direction for 1s after the go cue was found. This number was normalized by dividing by the number of trials for the direction and the bin size (1s). The average number of spikes were plotted against their corresponding directions from 0° to 315° in a scatterplot. A parabolic line of best fit was added to visualize the tuning curve. The line of best fit was calculated by using the polyfit() and polyval() functions in MATLAB. The line had the following formula:

$$p(x) = p_1 x^2 + p_2 x + p_3. \tag{1}$$

Where p(x) was the line of best fit and $p_1$, $p_2$, and $p_3$ are coefficients generated by MATLAB. This process was repeated for the second neuron.

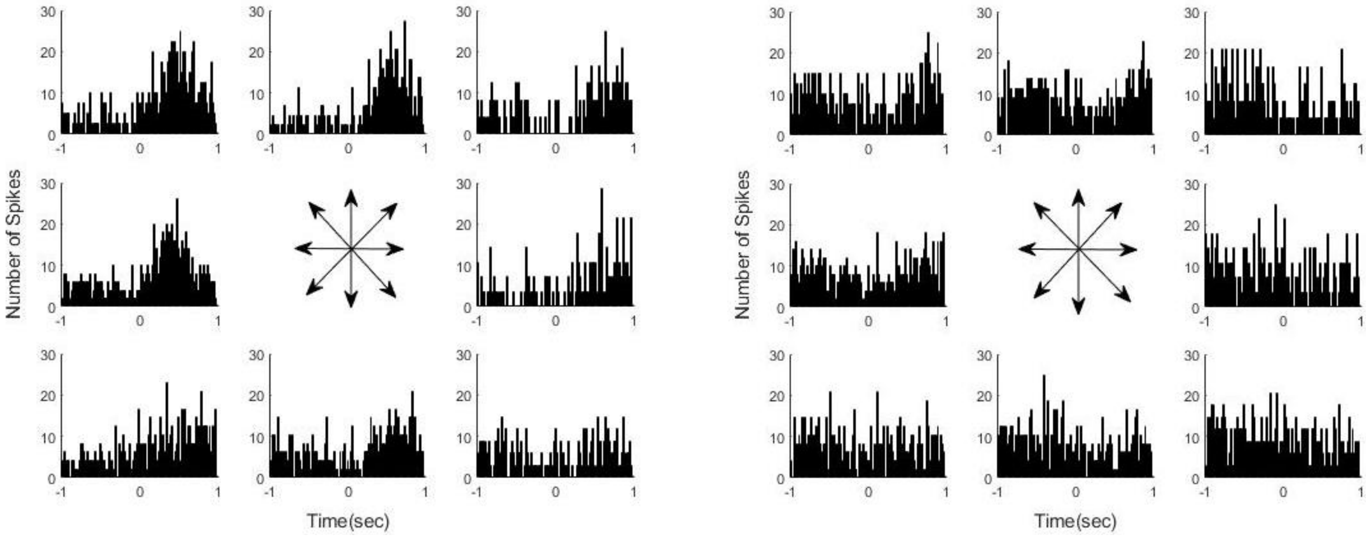


Fig. 3. The PETHs for neuron 1 (left) and neuron 2 (right). The arrows in the center correspond to the directions of the LEDs in Fig. 1. The PETH that an arrow points to is the plot for the trials in that direction. For example, the plot in the second row, third column shows the spike counts in the 0° direction. The go cue is at 0s. A larger bar indicates more spikes during that time period. A cluster of large bars indicates a heightened response to the stimulus and thus a preference for that direction.

## III. Results

### A. Raster Plots

The raster plots for the two neurons for each direction are shown in Fig. 2. The spikes are shown as vertical lines and the go cue is placed at 0s. The arrows in the center point to the raster plot for that particular direction. A cluster of spikes indicates an increased response from the neuron to the stimulus and thus a preference to that direction. For the first neuron, clusters can be seen for the 90°, 135°, and 180° directions (Fig. 2.). This implies that this neuron is tuned to a direction in that range. In contrast, the second neuron does not seem to have any discernible clusters as the spikes are evenly spaced out. This implies that the second neuron is not tuned to any particular direction. Also, of note is that the clusters occur after the go cue. Although the monkey is planning the movement before the cue, the neuronal response does not occur until the movement is being executed.

### B. PETHs

The PETHs for both neurons are shown in Fig. 3. The plots are arranged in the same way as the raster plots. A cluster of larger bars compared to before the go cue indicates an increased response to the stimulus and thus a preference for that direction. As before, the largest and most defined clusters are for neuron 1 and in the 90°, 135°, and 180° directions (Fig. 3.). Neuron 1 seems to be tuned to a direction in this range. The histograms for neuron 2 show a pretty even number of spikes across the board, implying that the neuron is not tuned to a direction.

### C. Tuning Curves

The average firing rates for each direction for each neuron are plotted in Fig. 4. The lines of best fit are also included in the plots. The formulas for the lines of best fit are

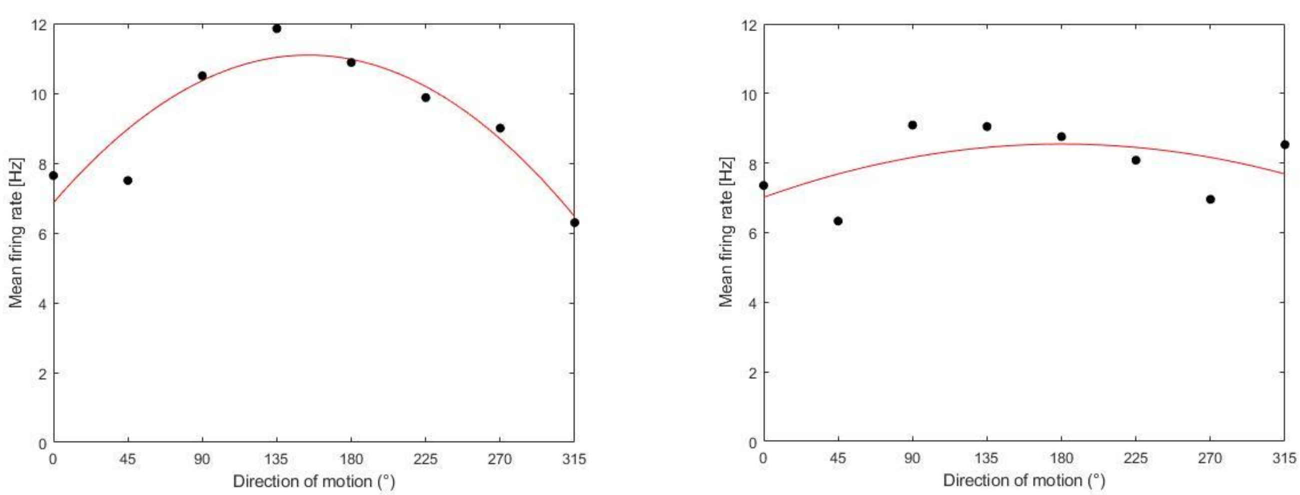


Fig. 4. The tuning curves for neuron 1 (left) and neuron 2 (right). The points are the mean firing rate for each direction. The red line is the parabolic line of best fit. A more pronounced curve indicates a tuned neuron as some directions are much more preferred over others.

$$p_1(x) = -1.7847 \cdot 10^{-4} \cdot x^2 + 0.0550x + 6.8623, \quad (2)$$

for neuron 1 and

$$p_2(x) = -4.7252 \cdot 10^{-5} \cdot x^2 + 0.0170x + 7.0164, \quad (3)$$

for neuron 2. These follow the format of (1) and the coefficients were generated by MATLAB. As seen in both in the equations and in the figure, there is more variation in the mean firing rates in neuron 1 than in neuron 2. Neuron 1 better fits the expected bell curve shape. The highest firing rates are at 90°, 135°, and 180°, which agrees with the raster plot and PETH (Fig. 4). With the curve, it can be seen that the highest response is for a direction around 135° where the curve peaks. This shows that neuron 1 is tuned for movements that are about 135° in direction. On the other hand, neuron 2 has a less pronounced curve and the firing rates are relatively close in value. This means that neuron 2 is most likely not tuned to a direction.

## IV. Discussion

The raster plots, the PETHs, and the tuning curves all point to neuron 1 being tuned to a direction around 135° and neuron 2 being untuned. This sort of information is important to know when creating robotic prostheses. If one would want the user to move the robotic arm laterally in the 135° direction, the robotic arm would have to detect activity from neurons like neuron 1. However, there are several limitations to this analysis. For one, interpreting neural activity during arm movements is difficult because there are simultaneous changes in motor and sensory activity as well as limb biomechanical variables. This makes it very difficult to isolate a specific stimulus for each neuron. An alternative is to study arm posture control, which is a natural behavior that does not have the complexity of the time-varying movements that the monkey did for this [3]. Additionally, only a two-dimensional plane of movement is considered. These neurons could be tuned to a three-dimensional movement vector. There are also multiple coordinate systems that could be considered. The direction of movement can be represented as spatial direction (Cartesian spatial coordinates), a combination of joint angle rotations (joint angle coordinates), or a collection of muscle length changes (muscle-space coordinates). It is important to differentiate between coordinate systems because they can change the interpretation of the neuron's role in the overall motor circuit [5]. Plus, neuronal responses always involve some irregularity, even when they are averaged across trials [3]. This can be seen in the imperfection of the tuning curve for neuron 1 (Fig. 4). There are complex nonlinear components that are important for decoding the neuronal response of the motor cortex which are not considered here [3]. Finally, the line of best fit used to analyze the mean spike firing rates was a parabola, not a sinusoidal curve as used in previous studies [2]. A first-degree sinusoidal regression could provide a more accurate tuning curve than the parabola used.

## References


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