HW1 Report - 20190829 박준

Matlab Version:	2023a
Files for HW Problems:	Files are divided according to part name (a~h) : HW1_a, HW1_b, …, HW1_h
Function Files used for Simulation:	spike_generator_stochastic.m, raster_plot.m, plot_conv.m, avg_fire_rate_conv.m

Neuron Modeling:

The leaky integrated-fire model was used to simulate a single neuron. As the problem pertains to simulating the response of a single neuron without any input from other nearby neurons, the effect of synapses on conductance was ignored.

Neuron variability was incorporated into the model using a random reset voltage and a random threshold voltage. Both were varied according to a normal distribution due to the ubiquity of the central limit theorem: if a large enough sample of neuron populations are gathered, it is most likely by the central limit theorem that the distribution is gaussian.

A minimal degree of neuron variability was considered for the purpose of simulation. While the variability is not eliminated altogether, the standard deviation of the normal distribution was taken to be 1 percent of the equilibrium and threshold values. Thus, the standard deviation for the stochastic threshold voltage is 0.65 mV while the standard deviation for the stochastic reset voltage is 0.55 mV. While neurons vary considerably in terms of their threshold voltage and equilibrium voltage, this simulation will limit itself to considering neuron variability within the same region of the brain. In this case, a minimal amount of threshold voltage variation can be considered as the ion channel properties of the neurons are most likely similar. Similarly, a minimal amount of temperature fluctuation and ion concentration fluctuation is considered; hence, the equilibrium voltage variability is minimal.

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Firing Rate Estimation:

A common firing rate estimation method was used for the entire simulation. For a given input current, the firing rate was estimated by finding 10 trial spike trains over an interval of 1000 ms, or 1 second. A gaussian filter normalized to have an area of one was convolved with each spike train, which returns the firing rate at each time. Then, the mean of the resulting rates over the 1000 ms interval was used to determine the average firing rate. In the matlab code, the function defined in plot_conv.m shows the visual result of convolving the filter with the spike train. A visual demonstration of this approach is given in the answer for a).

A gaussian filter was used in order to create a smooth, continuously varying spiking rate estimation at each time. The variance of the gaussian was set to a low value of 5 ms in order to accommodate cases where spikes occur very close to each other. The firing rate was determined at each time since the random variability of the neuron may lead to irregular spiking. As such, it is best to determine the rate for each time step and then average the rates to more accurately determine the average firing rate.

The time window was set at 1000 ms mainly as a compromise between computational tractability and accurate firing rate. With a 1000 ms time window, the lowest firing rate which can be measured accurately becomes 1 Hz; this is the case when a single spike occurs within the time window. While ideally a larger time window could be used so that a lower rate can be determined, this makes estimation of the response function for a large range of current inputs computationally expensive. For cases where a more precise measurement of rate is necessary (later in part c)), the time window is increased.

a)

Find the value of constant current injected to this neuron, I_inj(t) = Ic mA, that induces an average firing of 20Hz. Make a sample raster plot of output spikes for 1sec and explain how you estimated Ic for this condition.

Since it is known that the neuron firing rate increases abruptly above a certain threshold, the input was increased from zero with a resolution of 0.1 mA to first find the threshold current at which the neuron begins firing. Zero was used as the starting input current since no firing occurs at this current. After finding this threshold input current and determining the average firing rate at that current, the input current was then increased using a finer increment of 0.01 mA until the average firing rate was within 0.1 Hz of the target 20 Hz.

It is worth noting that the difference between the threshold current and the current which leads to a 20 Hz firing rate is very small - lower than 0.2 mA.

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Table 1 - Threshold Current and Current for 20 Hz Fire Rate

Threshold Current which initiates Firing (mA)	Rate at Threshold Current (Hz)	Current for 20 Hz Firing Rate (mA)	Average Firing Rate closest to 20 Hz (Hz)
0.8000	2.0160	0.9550	19.7438

Figure 1 - Raster Plot for 20 Hz Firing Rate

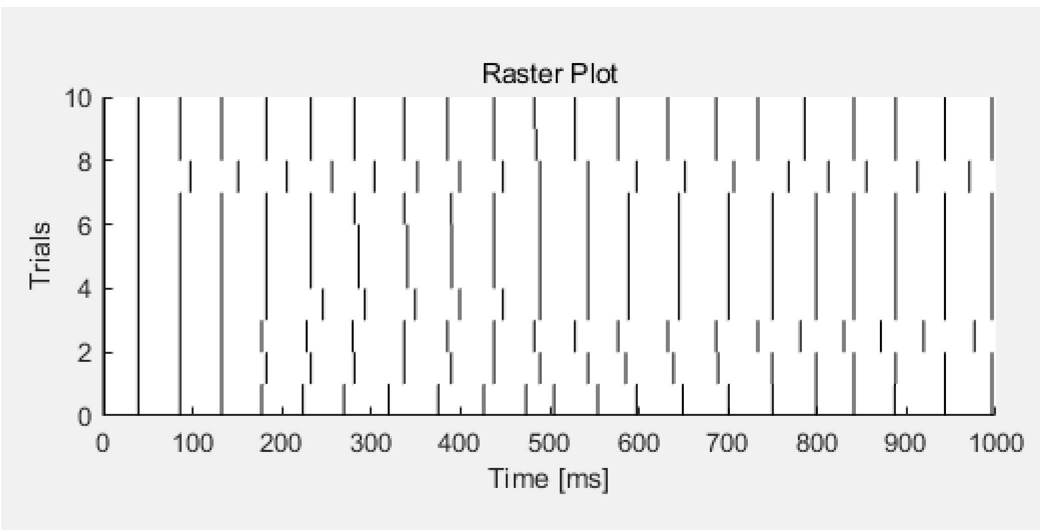

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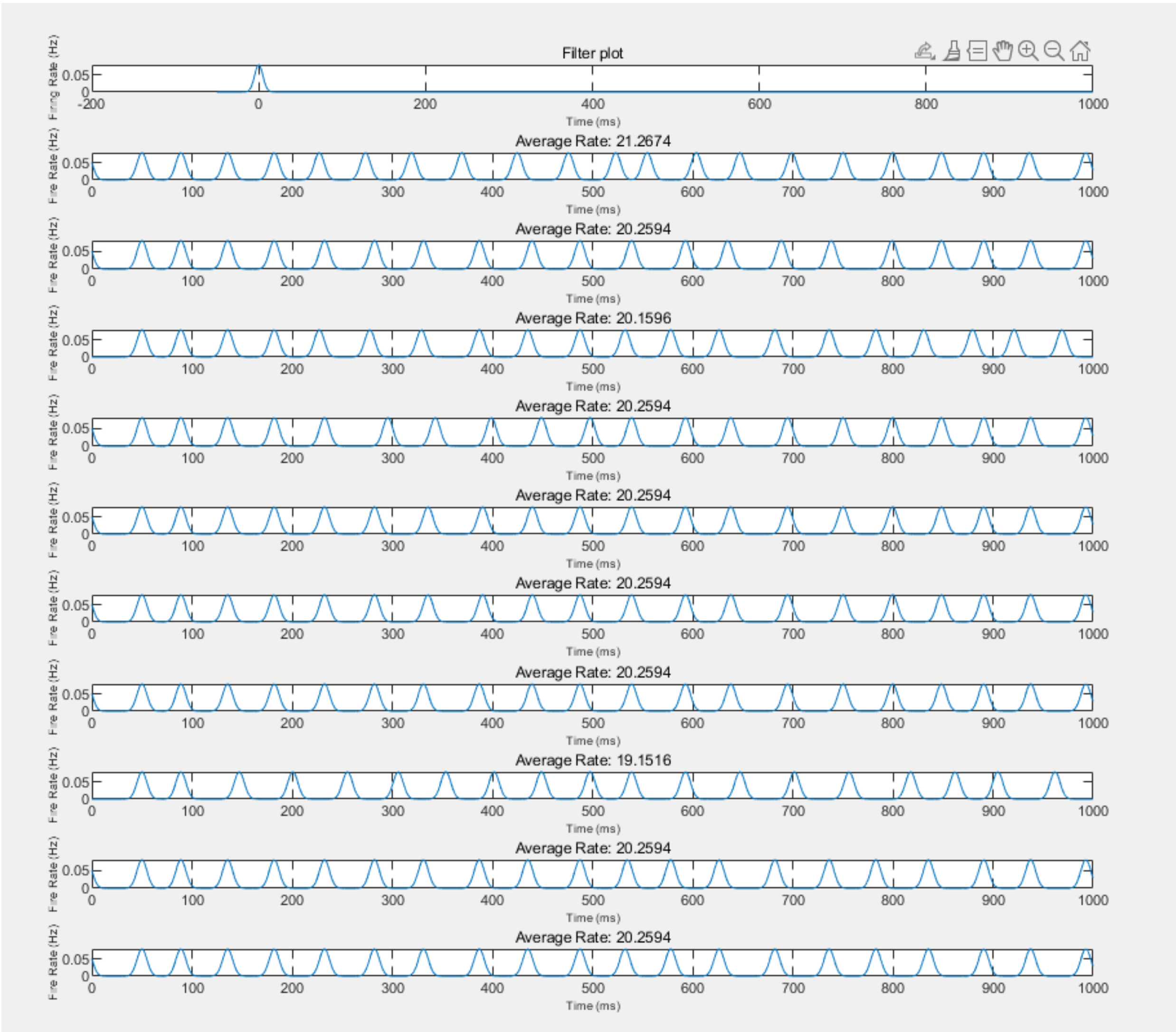
Figure 3 - Time against Firing Rate for 10 Trials



Using plot_conv.m, the real-time firing rate for each trial can be visualized. The topmost subplot shows the unit gaussian filter convolved with the spikes to find the rates.

b)

Try to find the value of Ic that induces an average firing of 1Hz. Explain why it is not easy.

The current which leads to an approximate firing rate of 1 Hz is 0.7857 mA. This current is difficult to determine since the firing rate increases abruptly above the threshold current. As mentioned in a), the difference between the threshold current which first causes non-zero firing and the current which causes a 20 Hz firing rate is lower than 0.2 mA.

In order to determine this current, a similar strategy to a) was used. The current was first increased from 0 mA with an increment of 0.01 mA to find the threshold current. Then, the current was reduced with a finer increment of 0.0001 mA in order to find the current which caused the neuron to fire at around 1 Hz. By first increasing the current with a large increment and then decreasing the current using a finer increment, the current can be found with higher precision.

Table 2 - Threshold Current and Current for 1 Hz Fire Rate

Threshold Current which initiates Firing (mA)	Rate at Threshold Current (Hz)	Current for 1Hz Firing Rate (mA)	Average Firing Rate closest to 1Hz (Hz)
0.7900	3.1197	0.7857	1.0084

c)

Estimate the lowest firing rate of the neuron you can achieve reliably. Estimate the threshold value of input current Ic at this point. Explain your idea to measure it as precisely as possible.

Given a time interval of 1000 ms, the lowest firing rate which can be measured reliably is 1 Hz - this lowest firing rate can be achieved when a single spike occurs within the time interval. It can be seen that the time interval on which spikes are collected presents a lower bound to the lowest spike rate which can be measured, since at least one spike must occur within the interval for a non-zero firing rate to be measured.

In order to measure the lowest firing rate and the threshold current most accurately, it is best to use the same strategy for measuring the threshold as in a) using a larger time interval for rate measurement. The time interval was increased to 10000 ms (10 s). Starting from a minimum current which was heuristically determined to not cause firing, the firing rate was increased with an increment of 0.01 mA until a non-zero firing rate occurred.

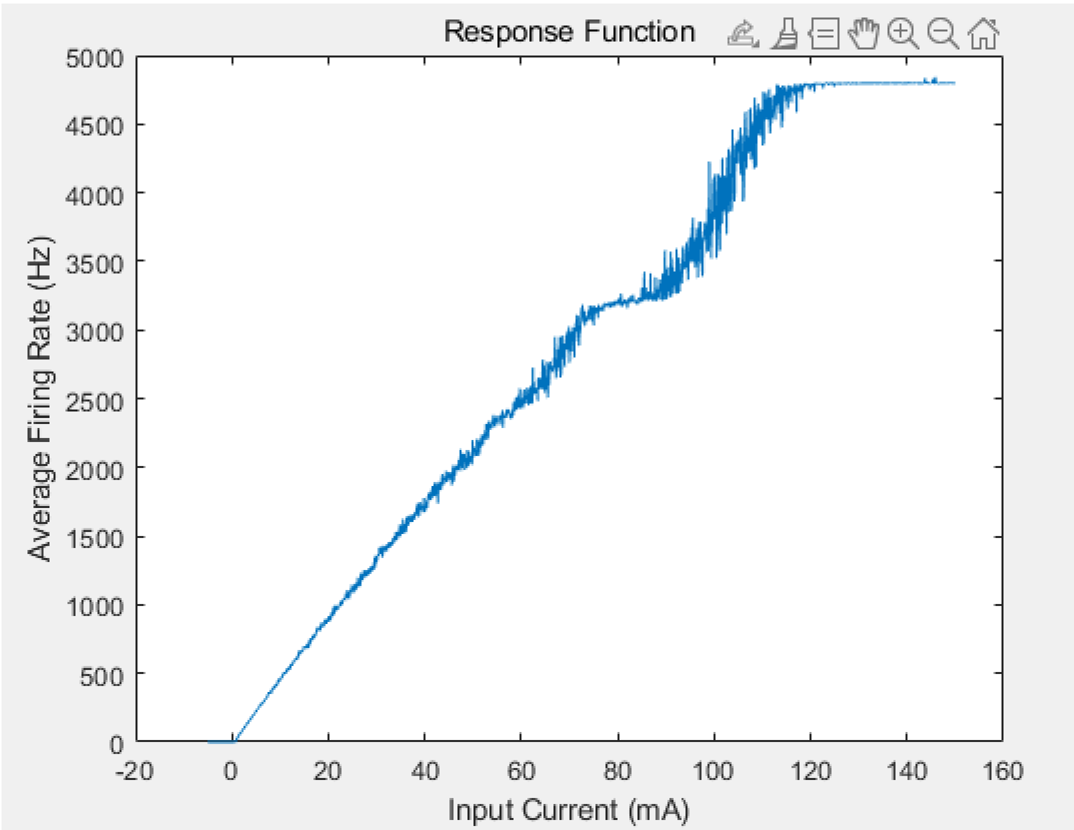
Table 3 - Lowest Threshold Current

Threshold Current which initiates Firing (mA)	Rate at Threshold Current (Hz)
0.7370	0.2016

d)

Now vary the injected current Ic from 0 to Imax. Properly choose Imax and the interval of Ic to achieve the complete response function of the neuron. Plot the response function and present two nonlinear characteristics of the curve. Discuss how you can utilize this neuron regarding the nonlinear filtering of inputs.

Figure 4 - Response Function without Noise



The two non-linear characteristics are the firing of the neuron after a given threshold value and the saturation of the firing rate at high input currents.

It can be seen that there is a quick onset of firing rate after the input current reaches a certain threshold value. The average firing rate asymptotically approximates a linear function after the input current exceeds the threshold. Finally, the average firing rate then saturates at a high value.

This form of neuron firing can be used as a filter which transmits information within a certain band of input currents. Information from the neuron can be considered as the change in firing rate in response to a change in input current. Any input current below the threshold current leads to zero firing rate, which encodes no information. Similarly, in the saturation region, there is no change in firing rate in response to an increase in input current: thus, no information is transmitted in this region either. On the other hand, in the linear regime, a change in input current leads to a proportional change in firing rate. As such, information can be transmitted as changes in rate within a certain band of inputs. Overall, the neuron behaves as an “on-off” filter in which information is only transmitted for inputs above a threshold current and below a saturation current.

e)

A background noise can be implemented as a random current added to input current, which is a constant value randomly sampled from a uniform distribution [-Inoise, Inoise] at each time t. Turn off the injected current as Ic = 0. Tune your background noise value Inoise so that the neuron fires spontaneously at 5Hz. Plot sample spike trains of 5 repeated trials. Explain your strategy to measure the firing rate precisely

A strategy similar to that in a) was utilized. Unlike in a), the input current was set to zero while the noise current was varied. The noise current was initially increased from zero to determine the first current which causes the neuron to fire. After this threshold noise current is determined, the noise current was increased in a finer increment of 0.01 mA to find a current at which the rate is within 0.5 Hz of the target 5 Hz firing rate. The 0.5 Hz resolution was the best rate resolution which could be determined heuristically: a resolution greater than 0.5 Hz, such as 0.1 Hz, could not be achieved even when the current was increased in finer increments.

Table 4 - Threshold Noise Current and Noise Current for 1 Hz Fire Rate

Threshold Noise Current which initiates Firing (mA)	Current for 5Hz Firing Rate (mA)	Average Firing Rate closest to 5 Hz (Hz)
1.5000	1.6200	5.2034

The spike train for 5 trials is displayed below in the form of a raster plot.

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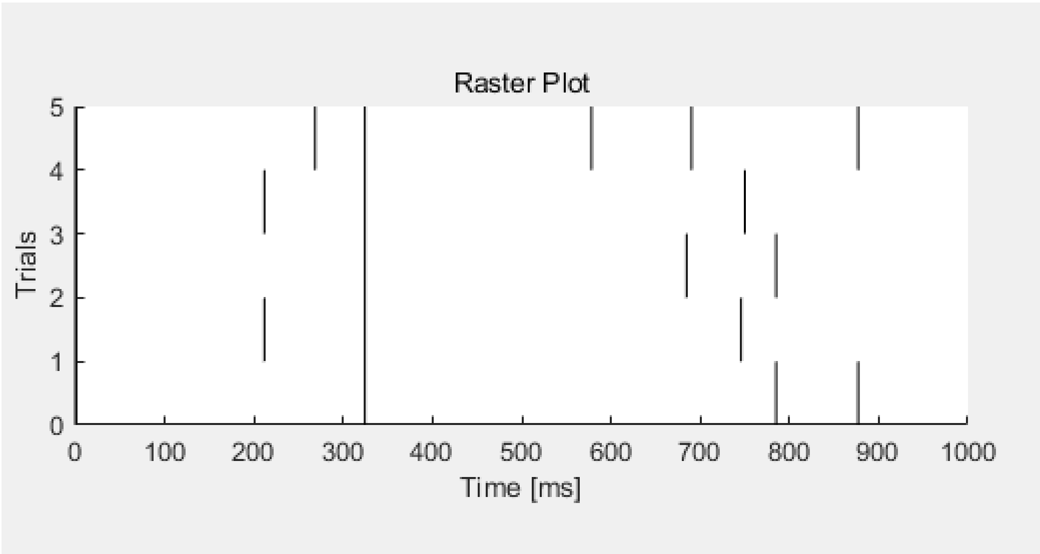
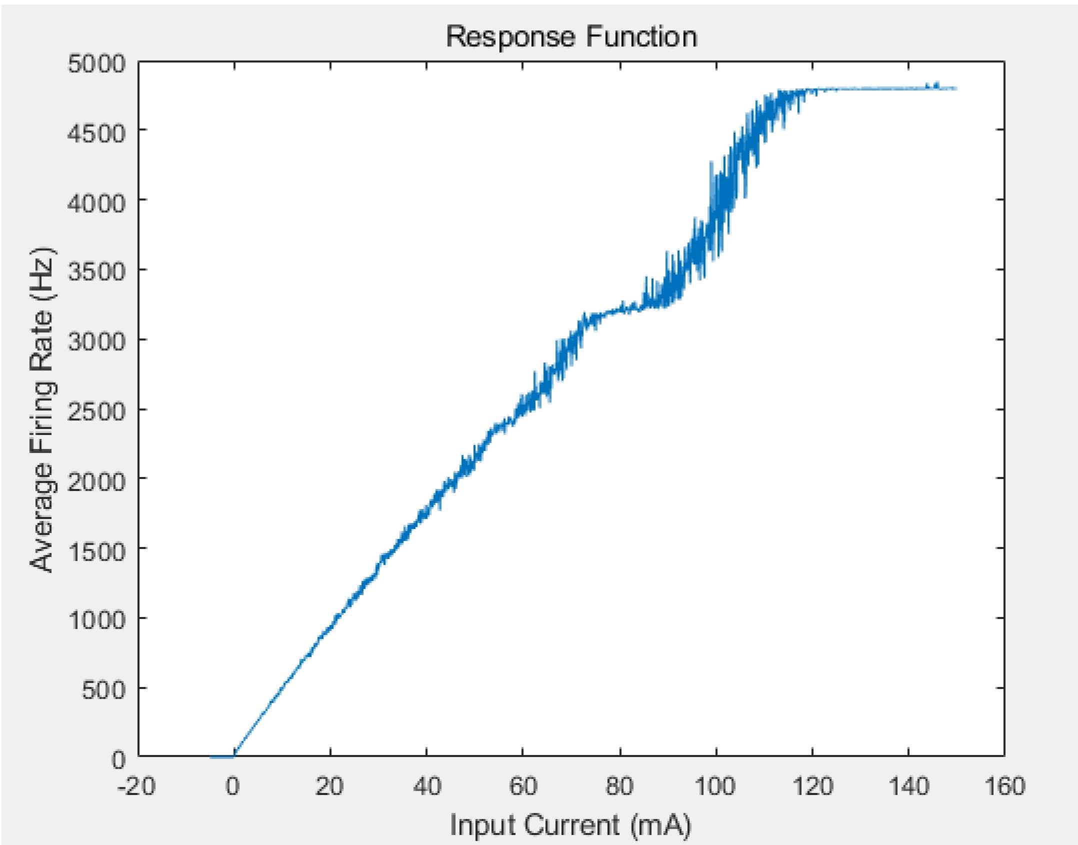
Figure 5 - Raster Plot for 5 Hz Firing Rate with Noise



f)

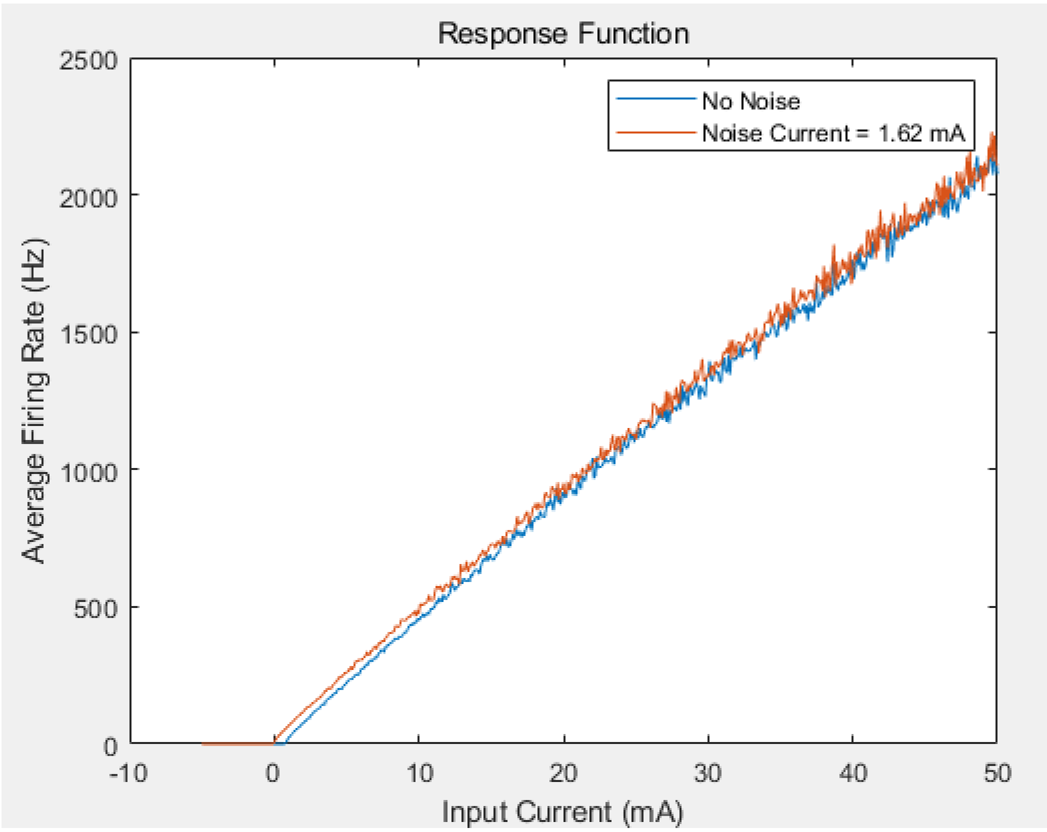
Now estimate the response function again with the background noise you set in e. Discuss whether you need to try anything differently compared with doing it in d.

Figure 6 - Response Function with Noise



The response function seen in Figure 6 has the same form as that of Figure 4 in d), where no noise input was given. However, a difference can be observed near the threshold current.

Figure 7 - Comparison of Response Functions with and without Noise



It can be seen in Figure 7 that the noise causes a leftward shift in the threshold current. At the same time, the overall shape of the response function is maintained - above the threshold, the response functions are asymptotically linear both with and without noise. Moreover, the linear curves are not entirely parallel - the output firing rates of both response functions approach similar values at higher input currents. Overall, it is likely that an increase in noise decreases the threshold current but does not affect the firing rate at higher input values.

g)

Estimate the new threshold value of input current that initializes neural spiking in f. Explain your idea to measure it as precisely as possible.

A strategy similar to that in c) was used to measure the threshold current to greater precision. The time interval was increased from 1000 ms to 5000 ms so that the lowest possible rate which can be measured is 0.2 Hz. Starting from a minimum current which is heuristically determined to not cause firing, the input current is increased with a resolution of 0.001 mA until the neuron begins to fire at a non-zero rate.

Table 5 - Threshold Noise Current and Noise Current for 1 Hz Fire Rate

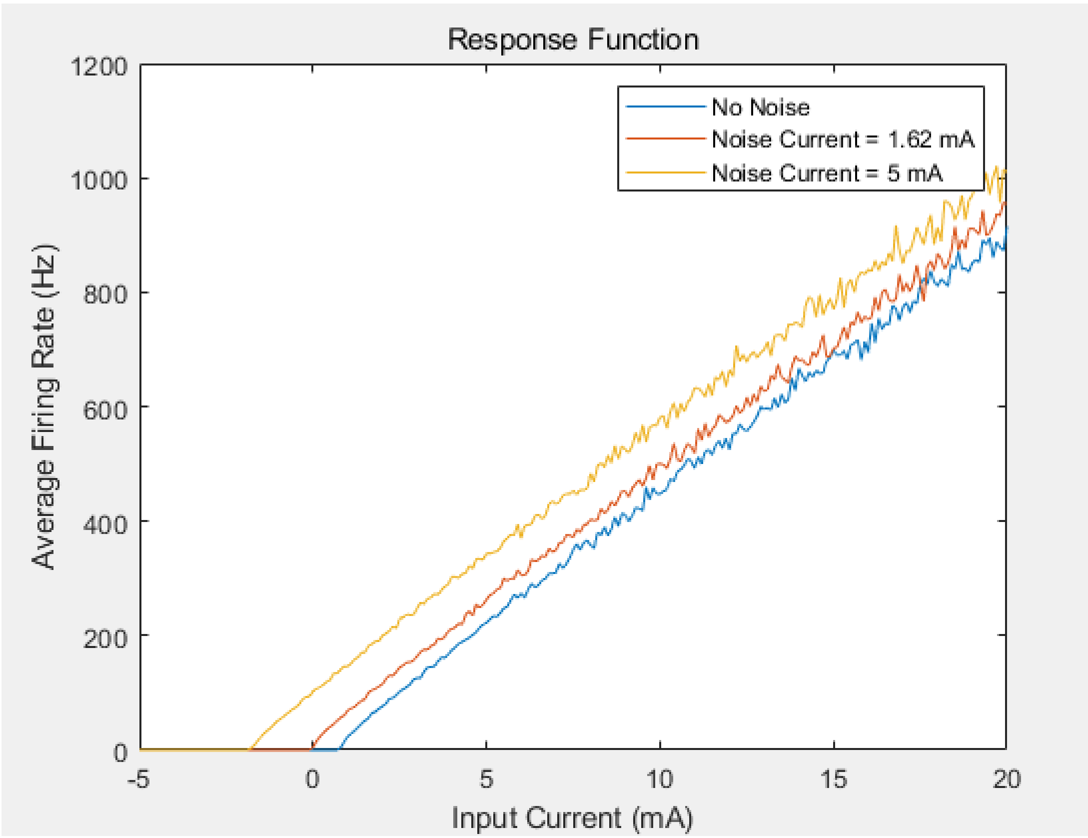
Threshold Current which initiates Firing (mA)	Average Firing Rate at Threshold Current (Hz)
-0.0950	0.0403

h)

Discuss how you can utilize the distinct characteristics of response functions, with and without background noise.

Background noise can shift the response function to the left. It can be seen in Figure 8 below that a greater amount of noise shifts the response function's threshold current to the left while leaving the overall shape unchanged.

Figure 8 - Comparison of Response Functions with and without Noise



Previously, in d), it was mentioned that the threshold current determines the value of the input at which information can be transmitted. Changing the noise can change the input at which the neuron “turns on”.

When neurons activate at different thresholds, this may signify that certain neurons may remain dormant for a given input while other neurons activate. The variability in threshold may allow for the selective activation of different neurons, which may be useful in situations when it is not necessary to activate all neurons within a region in response to certain stimuli. For example, in response to light input, it is likely not necessary to increase the activity of other neurons other than the visual cortex neurons. By adjusting the level of noise, it may be possible to keep certain neurons relevant for a stimulus “on” while keeping neurons related to other, extraneous functions “off”.