PSYC 5270 - Computational Neuroscience
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Data Exploration Project

Introduction

The data set used for this project comes from a study entitled "*Sound representation methods for spectro-temporal receptive field estimation*", conducted by Theunissen et al. (2009). In this study, the authors focused on how auditory stimuli are processed by adult male zebra finches by studying their auditory cortex and more precisely, two brain regions: the Mesencephalicus Lateralis Dorsalis (MLD), located in the upstream auditory midbrain nucleus and the downstream Auditory Pallial region (FLD). The male zebra finches were presented two types of stimuli: 20 authentic stimuli, called conspecific, corresponding to songs from other zebra finches, and 10 synthetic stimuli, called flatrip. In vivo single-unit extracellular recordings were obtained for 10 trials of the natural and synthetic stimuli for different neurons in each region. The data was stored in binary files (.txt files), containing spike times between two seconds before the onset of the stimulus up to four seconds after the stimulus was presented. All the data was left unmodified.

The primary interest of this project was to better understand encoding in two different brain areas at two different levels in the auditory pathway. The MLD, being located upstream in the pathway and hence closer to the auditory canal, should demonstrate a distinct firing rate as opposed to the FLD, which is downstream. This is due to the current audition paradigm in which neurons closer to the auditory canal encode simple features and neurons further downstream are involved in higher level processing. In fact, it is known that, when receiving an auditory stimulus, the neurons close to the auditory canal encode simple features about its frequency as well as time-related aspects. On the other hand, it also acknowledged that neurons further down the processing stream are involved in higher-level processing such as the categorization of auditory stimuli. However, there is less information about the selectivity process that is conducted by intermediate areas. In other words, there remain some questions regarding how non-significant stimuli are filtered out while relevant stimuli are more strongly encoded.

Based on what has been mentioned above, we had several research questions that we attempted to answer throughout this project. First of all, we wanted to see if there were any differences in spiking rates between synthetic and authentic stimuli for the same neuron. Then, we checked if the spiking rates differed across regions, for the same type of stimulus. Indeed, for synthetic stimuli, we would expect more spiking rates in the FLD cells than in the MLD neurons since such stimuli should have been filtered out during the auditory processing due to their non-relevant nature. Finally, we tried to see if we could predict whether a stimulus was synthetic or authentic based on the spiking rates.

Results

In order to answer our research questions, we first had to choose which neuron we would study, one for each brain region. We selected the neurons based on how much results we could get from their raster plots and their distance matrices, described later on in this section. The neurons were

studied were neuron yg0616_8_B in the Auditory Pallial region (FLD), and neuron pipu0617_6_A in the Mesencephalicus Lateralis Dorsalis brain region (MLD).

We plotted some raster plots to visually detect any differences in responses across brain regions and for different types of stimuli. We had to equalize the length of the spike trains. Each synthetic stimulus was two seconds in duration, whereas the authentic stimuli had more variance in length. In order to avoid any bias or artifacting from varying spike train lengths and counts, we took responses from 2 seconds before the onset of the stimulus up to 4000 ms after that, in order to avoid any artifacts. In Figure 1, we see that the spike times are quite sparse for both synthetic and authentic stimuli. It does not appear to be much differences in responses across the different types of stimuli. The difference we can note, however, is that, despite all the stimuli being of the same duration, the responses vary length-wise when the stimuli are authentic (about 1,800 ms for stimulus 9 vs. 2,400 ms for stimulus 10) compared to when they are synthetic. Indeed, the responses have roughly the same length for synthetic stimuli (about 2,000 ms). Looking now at Figure 2, we first notice that the neuron in the Auditory Pallial region produce a lot more spikes than the one from the MLD region, which is contrary to what we expected. Interestingly, we see the same variations in length of responses, based on the type of the stimuli: same lengths for the synthetic stimuli, very different lengths for the authentic stimuli. Also, we see more variations in spike rates for authentic stimuli, i.e. responses are more sparse and fluctuate more (e.g. no spikes between 800 and 1,000 ms for authentic stimulus 9), while the responses are quite homogenous for synthetic stimuli.

For our next research question, we compared spiking rates of different stimuli (10 trials for each of the 10 authentic stimuli and 10 synthetic stimuli, hence 200 responses) through a pairwise distance matrix analysis. We created the distance matrices using the SPIKE-profile in the *PySpyke* Python package. The package required us to precise what timeframe we should use for computing the distances between stimuli. We decided to take into account responses between the onset of the stimulus and 4,000 ms so that the values were not impacted by random noise. Figure 3 presents the distance matrix for the neuron in the MLD and Figure 4 presents the distance matrix for the neuron in the FLD. In Figure 3, the first thing we notice is that there are a few obvious yellow lines throughout the matrix, suggesting that there were trials where the responses were very different to all the other responses. We can also see the top-left square containing the 100 first responses (the 10 trials for each of the 10 synthetic stimuli) to be darker, suggesting that the responses are more similar to one another, compared to the responses to the 10 authentic stimuli. Regarding the top-right and bottom-left squares, the colors are lighter, representing the higher differences between responses for authentic vs. synthetic stimuli. Finally, it is interesting to see that in the bottom-right square (authentic stimuli), we notice a lot of 10 by 10 small squares. That shows that 10 successives responses (potentially 10 trials to the same stimulus) have very similar spiking rates.
If we now look at Figure 4, the distance matrix for the responses of the neuron in the FLD region to the 20 same stimuli (10 trials for each of the stimuli), we observe clear quadrants, compared to Figure 3. The top-left 100-by-100 square (responses to the 10 synthetic stimuli) is much darker than the three other squares, suggesting very similar responses for the synthetic stimuli, but very different from the responses to the conspecific stimuli. For the bottom-right square (responses to the 10 authentic stimuli), we notice that there is a lot of variability. That is representative of very

different responses to one authentic stimulus compared to another authentic one. However, it is important to note that we notice the same patterns, seen in the previous figure, of 10-by-10 squares within the bottom-right 100-by-100 square. Similarly to the previous figure, that suggest that 10 successives responses (potentially 10 trials to the same stimulus) have very similar spiking rates, and even more so for the downstream Auditory Pallial region.

To compute the difference in means of spike times between authentic and synthetic stimuli for the two regions, we had to plot the spiking rates for the different stimulus within each category. In order to do so, we first concatenated the spike times for each one of the trials for each stimulus. With the summed up spike times for each stimulus, we used the gaussian kernel on each of the series of spikes so that we could get the probability density functions that we could plot. In Figure 5 and 6, we see the spiking rates of each stimulus for each category (synthetic vs authentic) for the neuron in the upstream MLD brain region. When comparing those two graphs, we observe that there seems to be much more variability in spiking rates for authentic stimuli. Indeed, the curves seem to have very different patterns. Conversely, in Figure 6, it appears that the synthetic stimuli tend to elicit very similar responses, though they can differ in intensity as well as in speed: there seems to be a peak in activity, then a decrease and then another peak. In Figure 7 and 8, we plotted the probability density functions in a similar fashion, except that this time, the spike rates of the neuron in the downstream Auditory Pallial region are featured. Interestingly, we do not notice similar patterns for both synthetic and authentic stimuli, despite the previous findings from the distance matrices. That may be explained by the large number of stimuli, which makes it hard to read.

Finally, we wanted to see if we could obtain interesting findings for overall spiking rates for authentic and synthetic stimuli in the two brain regions studied. After concatenating the spiking rates for all stimuli based on their type (synthetic vs. authentic), we used the gaussian kernel similarly to what we did earlier. In Figure 9, we can look at the global spike rates for the two types of stimuli for the neuron in the upstream MLD brain region. We notice that the distributions are not the same. In fact, as the spiking rate is higher for the synthetic stimuli, that suggests that synthetic stimuli tend to have similar distributions, hence the higher peak compared to authentic stimuli. For the latter, as they have very different patterns, there is no apparent peak. In Figure 10, we did the same thing as for the previous figure, except that the spike rates belong to the neuron in the downstream Auditory Pallial region (FLD). Compared to the previous figure, we observe that the distributions are relatively the same for authentic and synthetic stimuli. This contradicts the previous finding from the distance matrix, stating that the spike rates for the two types of stimuli differed.

As stated previously, we wanted to computed the difference in means of spike times between authentic and synthetic stimuli for the two regions. The difference between the mean spike times of the neuron from the Auditory Pallial region when presented stimuli synthetic vs. authentic is equal to 0.1076 ms. The difference between the mean spike times of the neuron from the Mesencephalicus Lateralis Dorsalis region when presented stimuli synthetic vs. authentic is equal to -0.033 ms. As none of the global distributions are normally distributed, those values cannot be interpreted as is.

Discussion

Throughout this study, we attempted to answer several research questions. The first one was comparing spike times between authentic and synthetic stimuli of neurons in the MLD and the FLD brain region. Contrary to our hypothesis, there was an observed lack of variability in spike activity between natural and synthetic stimuli based on the raster plots. We also hypothesized that there would be a significant difference between the neural responses for the two types of stimuli between regions of the auditory cortex based on their position in the auditory processing stream. However, there was a difference in response activity between brain regions. We observed a greater magnitude of spiking in the FLD, the downstream region. than in the MLD, the upstream region. Within these regions, there was a difference in their variability response. Unlike what was expected, we observed a greater degree of variability in the responses of the downstream region as opposed to the upstream region. Due to being higher in the auditory processing pathway, the upstream region was expected to be noisier, and to contain a higher spike count. However, the opposite pattern was observed from the data.

The findings that there seemed to be a noisier signal in the downstream region as compared to the upstream region was not what we had expected to see, but is in line with what some theories of the functioning of the auditory processing pathway. The FLD is located close to the thalamus, the region which performs higher level computation and integration of various sensory systems in the auditory pathway. The location of the FLD, upstream of the thalamus, makes it a prime candidate as a preprocessing center for auditory information. A study by Yoonseob Lim demonstrated that this was indeed the case. Primarily studying the processing of temporally patterned stimuli, the results of their inquiry suggest that the FLD serves as an area of temporal sequence transformation (Lim et al, 2016). This seems to be corroborated by the results of our project as the raster plots for MLD recordings are sparser than those for the FLD. What we had initially interpreted as a noisier signal in the FLD may rather be a more involved signal. One point of interest was that there was a more readily recognizable difference in the synthetic and authentic stimuli plots for the FLD than for the MLD. This may further provide support to the claim that the FLD is involved in preprocessing, as the signals are more distinguished.

As we discovered later on through the distances matrix, the differences of spike responses between synthetic and authentic stimuli are greater for the downstream FLD region, compared to the responses in the upstream MLD region. Furthermore, we saw that the responses to the same stimuli were very similar across trials if the stimulus was authentic, suggesting that it would be encoded in a similar fashion across trials. If the stimulus was synthetic, the responses elicited were quite similar compared to the responses to other synthetic stimuli. This finding was even more obvious for the FLD region. We could not find any studies supporting this finding but we can say that, based on our results, neurons in the downstream region are very likely to produce the same spikes when the stimuli are authentic. Regarding the yellow lines that we found on the distance matrix, we can assume that something unexpected impacted the environment of the experiment, thus affecting the results.

After this finding, we compared the spike rates between the types of stimuli and across regions. We saw that in the upstream region, authentic stimuli elicited very different responses while synthetic stimuli produced similar patterns of responses. The distinction seen may be due to this function of discriminating between natural and synthetic stimuli. The MLD comparatively functions more to compute time and frequency data with a great degree of precession as suggested by a study by Woolley and Casseday (Woolley and Casseday, 2004). The rasters plots we made concur with this finding, as the plots are indeed more refined than those for the FLD. As previously said, the difference in spike rates between authentic and synthetic stimuli in the downstream region (FLD) was not as obvious for the downstream region. In their study (Boumans et al., 2008), Boumans et al. used functional MRI to study the impact of different kinds of songs (synthetic vs. authentic) on different brain structures in the auditory cortex, including the auditory pallial region (FLD). After performing fMRIs, they also found no particular differences between responses to authentic and synthetic songs in the FLD region. Their explanation to that nonsignificant difference is that artificial stimuli contain a higher number of frequencies, which can activate a lot of neurons, similarly to authentic sounds. There is a clear distinction between the curves for the upstream region, suggesting that there is a greater sensitivity between natural and synthetic stimuli. This further suggests that there is a high degree of functional specification in the auditory processing pathway, the further understanding of which can lead to a more comprehensive understanding of stimulus processing.

To conclude, we have seen throughout this analysis how different brain areas encode auditory stimuli. Upstream brain regions in the auditory cortex seem to encode stimuli in a similar fashion through basic processes, while downstream brain regions appear to perform higher-level processes, thus producing more neuronal activity. Differences in responses for authentic stimuli suggested that each stimulus conveys certain information while similar responses for the synthetic stimuli showed that they do not convey as much meaning to the birds. Therefore, we can expect that based on some neuronal response, we can predict what stimulus was presented to a zebra finch. However, it is worth mentioning that our results are based on specific neurons and due to time constraints and to simplify the results, we did not generalize those findings on other neurons which may have yielded different results (e.g. more noise in raster plots, less significant distance matrices).

References

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Dataset: https://crcns.org/data-sets/aa/aa-1/about

Acknowledgements

We thank Patrick Gill, Junli Zhang, Sarah M. N. Woolley, Thane Fremouw, Frédéric E. Theunissen for providing the data for this study.

Appendix

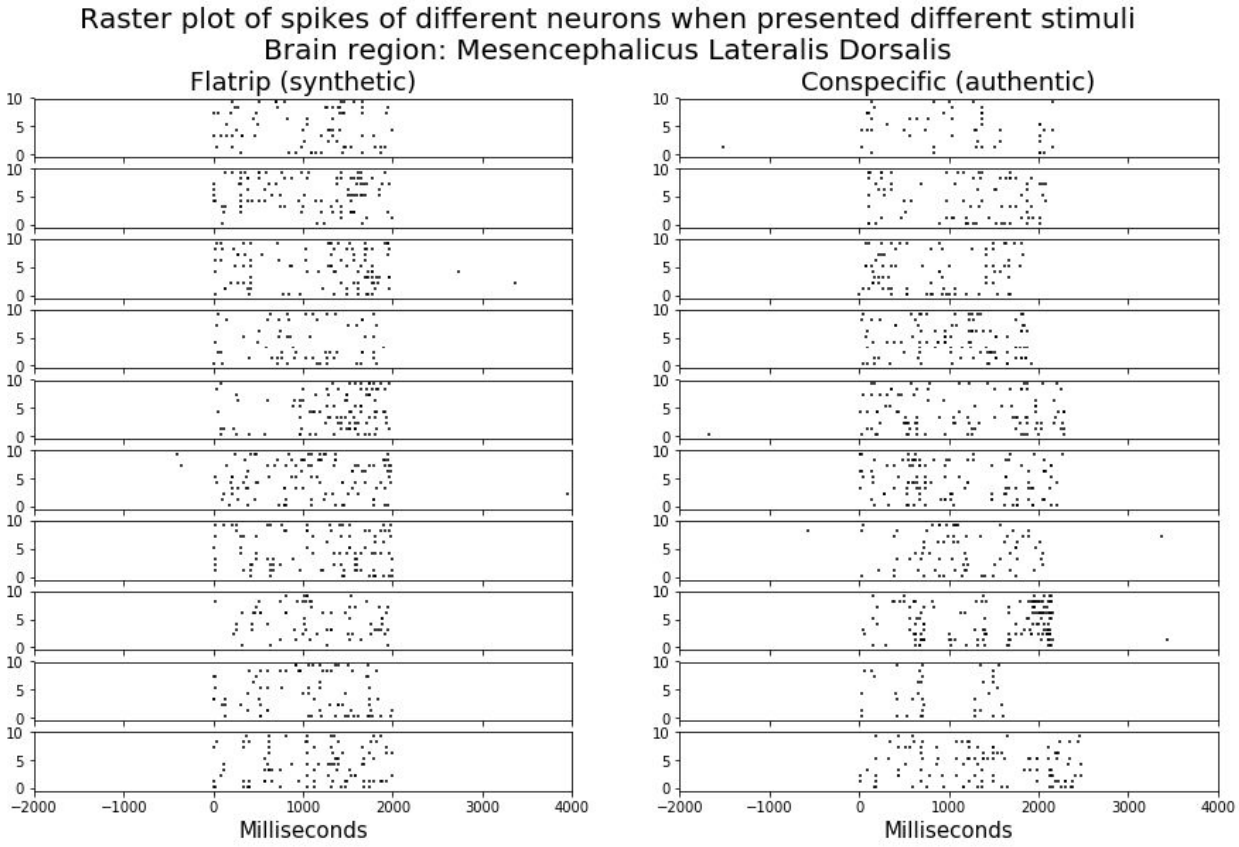

Figure 1: Raster Plot of spikes of different neurons in
the Mesencephalicus Lateralis Dorsalis when presented different stimuli

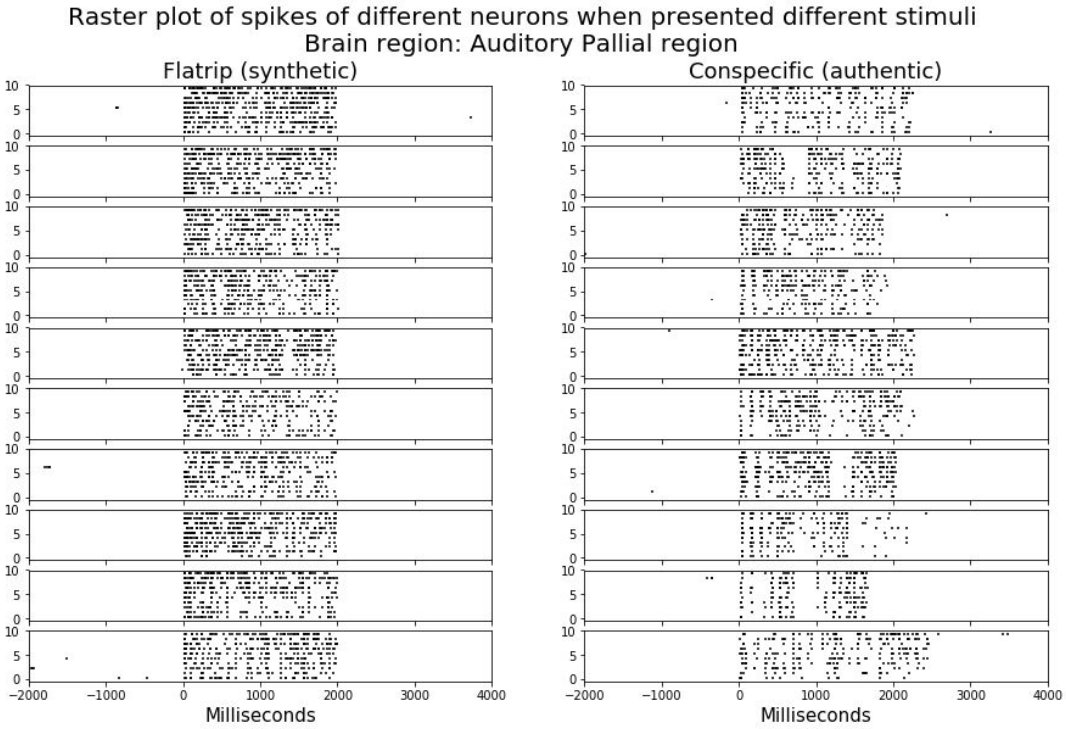

Figure 2: Raster Plot of spikes of different neurons in the Auditory Pallial when presented different stimuli

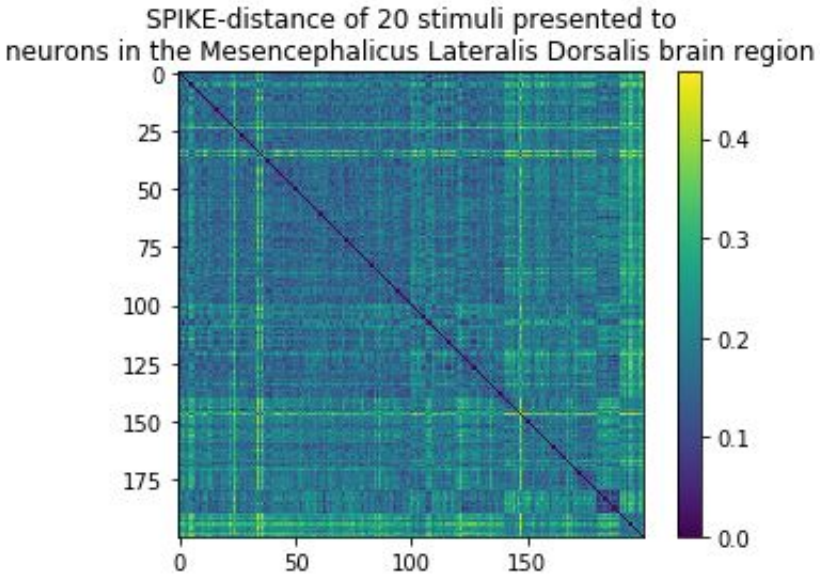

Figure 3: SPIKE-distance of 20 stimuli presented to neurons in the Mesencephalicus Lateralis Dorsalis

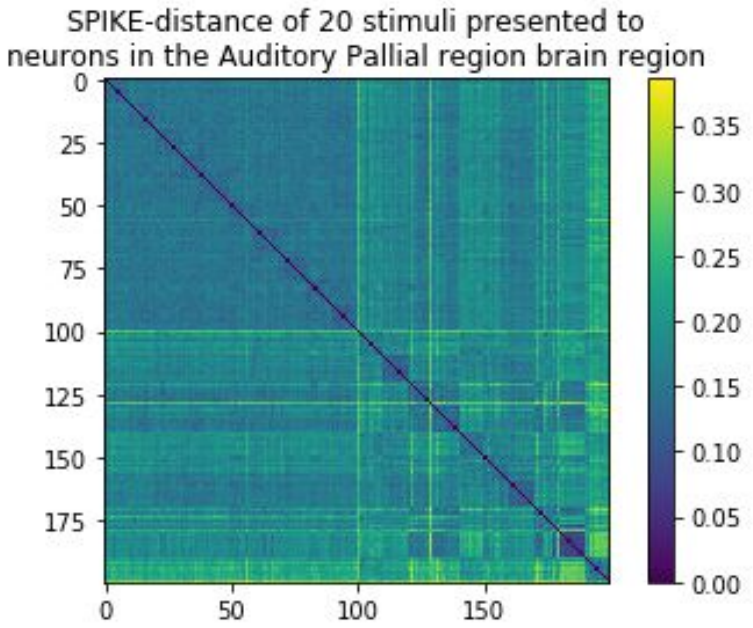

Figure 4: SPIKE-distance of 20 stimuli presented to neurons in the Auditory Pallial region

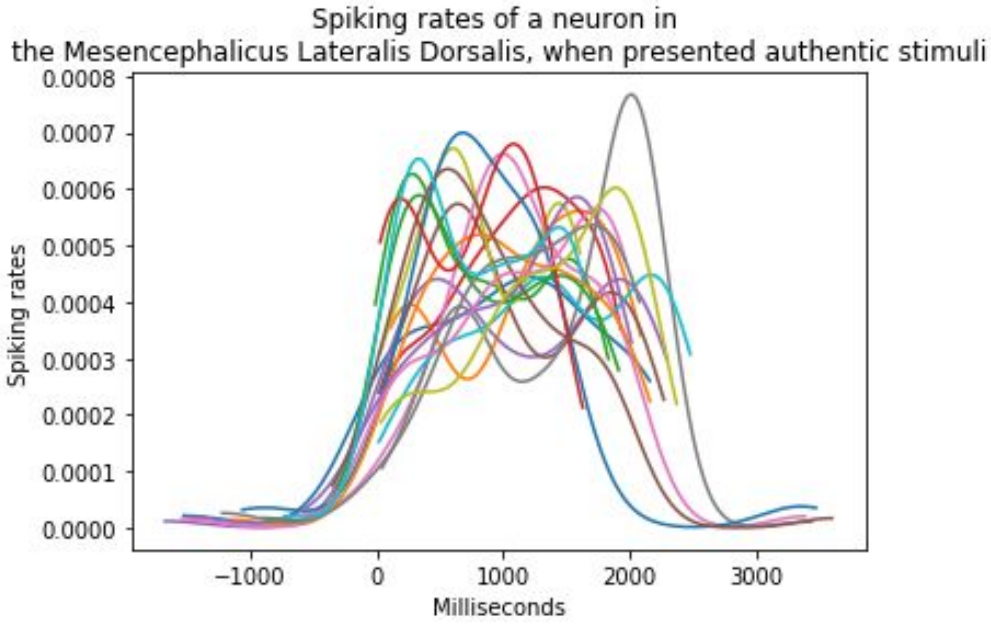

Figure 5: Spiking rate curves for neuron pipu0617_6_A in response to authentic stimuli

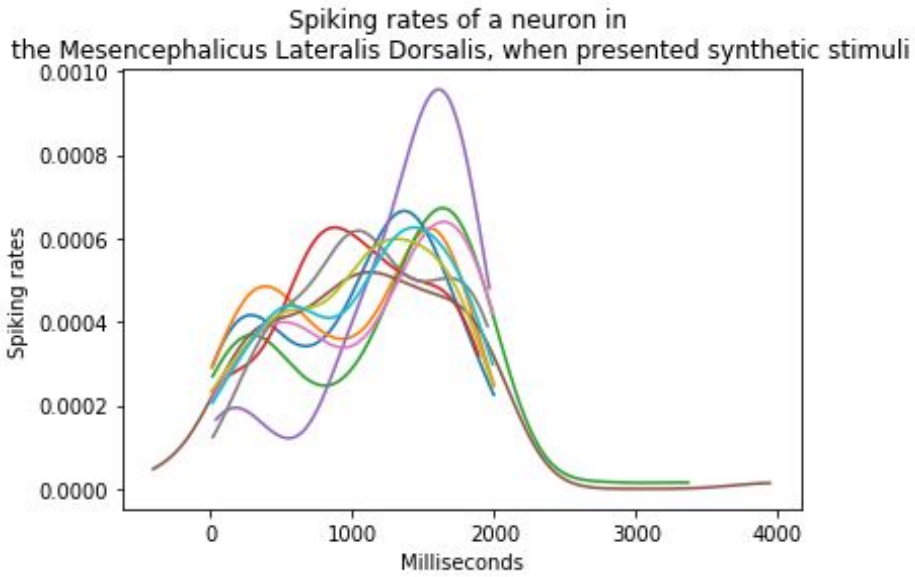

Figure 6:
Spiking rate curves for neuron pipu0617_6_A
in response to synthetic stimuli

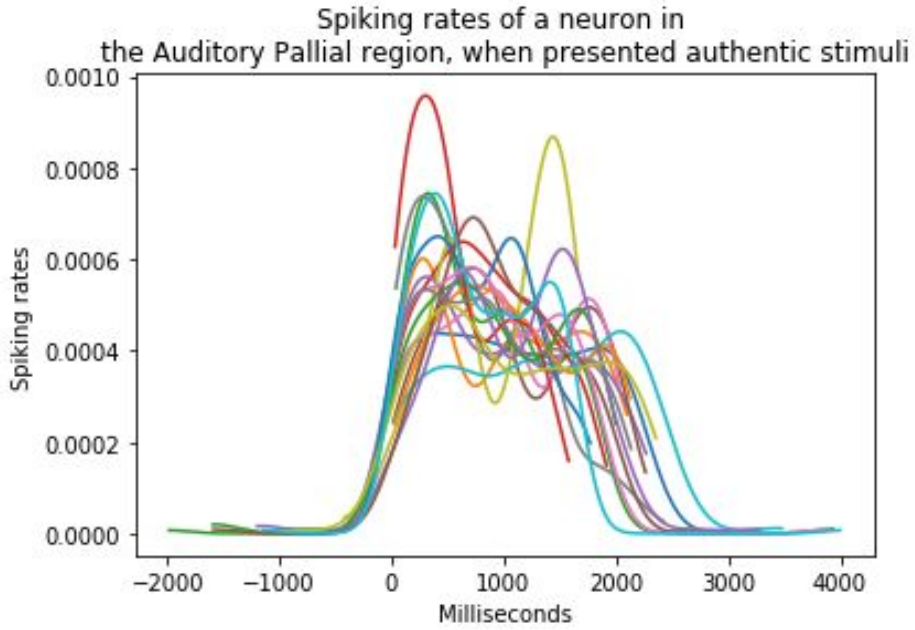

Figure 7: Spiking rate curves for neuron yg0616_8_B
in response to authentic stimuli

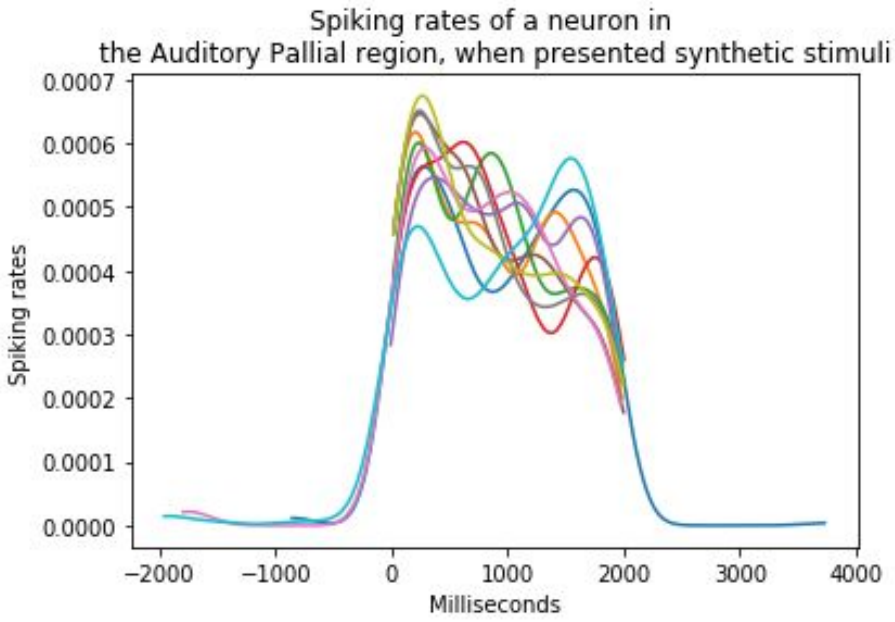

Figure 8:
Spiking rate curves for neuron yg0616_8_B
in response to synthetic stimuli

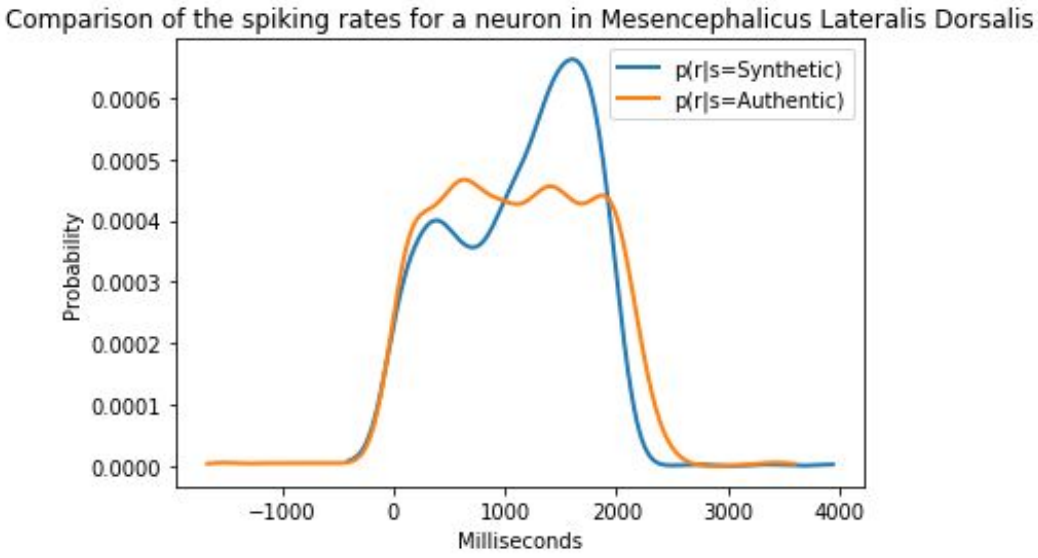

Figure 9:
Comparison of global spiking rates for neuron pipu0617_6_A in response
to authentic and synthetic stimuli

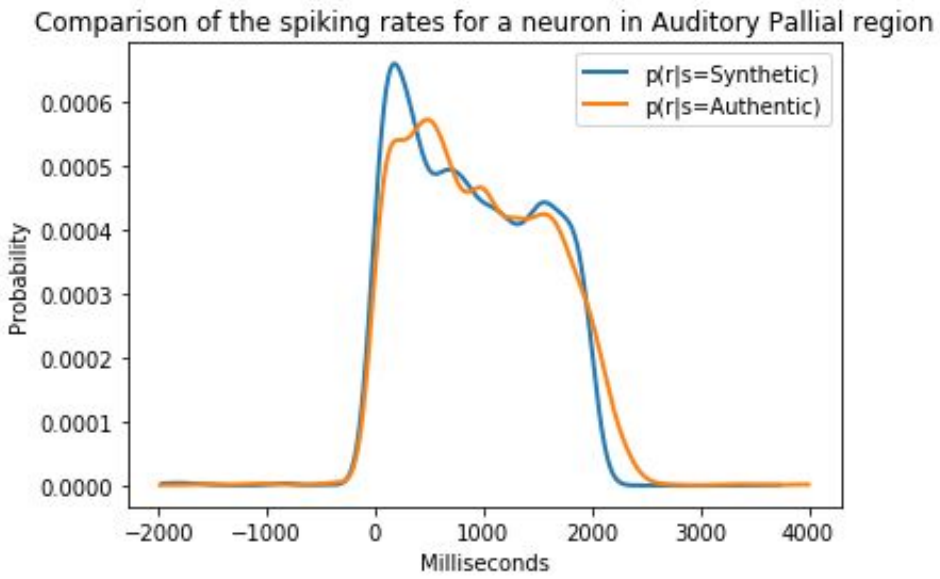

Figure 10:
Comparison of global spiking rates for neuronyg0616_8_B in response to authentic and synthetic stimuli