Neurobiology

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Lecture 5.5: Insect olfactory system

Hi everyone, welcome back to Neurobiology. In the last video we started looking at the sense of smell, olfaction. And we saw that this sense is present not only in humans but in even very simple organisms such as sea elegance which has only about 300 neurons in its brain. And one class of organisms in which olfaction has been studied quite well are insects which have about 100,000 neurons or a million neurons in their brains. We started looking at the insect olfactory system a little bit in the last video and in this video we will take a more detailed look and see how smell functions in the insect brain. Here is a schematic of the insect olfactory system.

The odors are detected by the olfactory receptors and there are about 100 types of olfactory receptor proteins. That exact number varies depending on the exact insect species that we are looking at. And each of the receptor proteins is expressed in multiple receptor neurons. So these are known as olfactory receptor neurons or olfactory sensory neurons that are present on the antenna in which the olfactory receptors are expressed.

In this diagram different colors indicate different types of receptors. So the same receptor may be present on multiple neurons. And all the neurons that are expressing the same receptors converge in the same region within the antenna lobe. And these regions are basically about 50 or 100 spherical zones known as glomerulus or plural is glomeruli. Now within the antenna lobe there are two types of neurons that are present.

The neurons that are present only within the antenna lobe are known as local neurons. So these neurons provide lateral connections between different glomeruli. And the other major type are known as the projection neurons. So these neurons take information from the antenna lobe to higher brain areas. These higher brain areas are mushroom body and lateral horn.

In the last video we discussed that at the level of olfactory receptors the odors are encoded by a combinatorial code. So each odor activates a specific subset of the olfactory receptors. Now we can try to understand how this information is communicated to neurons in the antenna lobe. All the information that the higher areas will contain about the odor can only come from the

projection neurons. So it is important for us to understand how the odors are encoded in the population of the projection neurons.

There are interactions between projection neurons and local neurons within the antenna lobe such that projection neurons can excite local neurons and local neurons can inhibit back projection neurons. So there are feedback loops. And now we also know that there are some excitatory local neurons so they can also excite projection neurons. We can measure the responses of projection neurons using intracellular recordings. This can be done using the technique of whole-cell patch recording that we have seen earlier or another technique of the sharp intracellular recording in which a very sharp electrode is put in the cell body or in the dendrite of the neuron.

And if we do that we get a measurement something like this. So when odor is delivered to the antenna and this blue bar here shows the timing of the odor we can see that this particular neuron is showing an increase in the firing rate of action potentials. We can also measure the average activity of multiple neurons using blunt electrodes. And this kind of recording is known as the local field potential. The projection neurons have their branches distributed widely in the mushroom body.

So basically a blunt electrode like this will reflect the average activity from many many projection neurons coming into the mushroom body. And in locusts and some other insects it has been reported that when odors are presented we see these kind of oscillations in the local field potential. So once we are able to get the intracellular recordings from a projection neuron we can deliver different odors to the antenna and see how that projection neuron is responding to different odors. And this is what we see. So in these images the top trace represents the projection neuron's activity and the bottom trace here shows the local field potential which we can interpret as the average activity in the whole PN population.

And this bar here represents the timing of the odor and the kind of odor that was delivered is shown here. So when cherry odor was delivered for about half a second we see that there is activity in the local field potential. This oscillatory activity tells us that many projection neurons are active during this time and the particular projection neuron that we are recording from shows an increase in action potentials. So we can say that this projection neuron was responding to the cherry odor. Now later when floral odor was given we see that the same projection neuron was not responding to this odor.

There are no action potentials here now. But there is still local field potential activity which means that there is some activity in the overall PN population even if this particular PN is not responding. So there must be other PNs that are responding to this odor. Similarly for apple odor here we see that there is no activity in this PN but there is local field potential activity which

means that some other PNs must be active. And interestingly when a mixture of cherry and apple odor is given then also we see no activity in that particular PN even though there was activity in the local field potential.

Now it is interesting that although this projection neuron was responding to cherry odor alone but when cherry odor and apple odor are given together then it is not responding. These kind of changes are possible when mixtures are given because the projection neurons are also receiving inhibitory input from local neurons. So it would still be getting the excitatory input that it was getting for the cherry odor but it may also receive some additional inhibitory input because of the inclusion of the apple odor and that inhibitory input might result in the loss of the spikes that were present only for the cherry odor. And this points to the importance of the lateral interactions that are made possible by the presence of local neurons in the antennal lobe. Another important property of the responses of projection neurons is that these responses are temporally patterned.

So here we are looking at the response of a projection neuron to a particular odor given for one second and the timing of the odor is indicated by this pink bar here. And we see that there are some spikes in the background before the odor is given but these spikes seem to be present at random times. But once the odor is given then we see a particular pattern of spikes. So there is a short burst of spikes here then there is some silent period. Then there is another burst of spikes then a small silent or inhibitory period.

Then another burst of spikes and then some silent period again. And after that it seems to return to the baseline spiking. And this pattern is not random. If the same experiment is done multiple times in the scientific language we call these trials. So if multiple trials are done with the same odor we see essentially a similar temporal pattern of spikes.

Here we are looking at four trials. We can summarize this data in a simplified format by only showing the time of the spikes. So it can look something like this. Here each dot indicates where the spike is and instead of showing the whole membrane potential and the shape of the spike we are just showing a dot at the time when the spike occurred. So each row here indicates one trial.

So we have four trials here and these are the timings of spikes in these four trials. So this kind of representation is known as the raster format. It's a concise summary of the spike timing information that is present in this whole data set. Are these temporal patterns the same for all the odors or do they depend on the identity of the odor? We can find that out by comparing the response of this neuron to many different odors. So here is the response to the first odor in the raster format.

We are looking at the data from ten trials and this gray region here shows the timing of the odor. So we can see that for this particular odor there is a reduction in spiking after the odor pulse.

Then there is an increase in spiking and then there is a long inhibitory period after which it comes back to baseline. Now I am going to show you the data for other odors from the same neuron.

So here it is. Now we are looking at the responses of this projection neuron to eight different odors. And it is clear that the temporal patterns are quite different for different odor ends. So for the second odor we see mainly an inhibitory period but for some odor ends such as odor five here we see a long excitatory period and then a long inhibitory period after that. And for odor seven and odor eight we see somewhat shorter excitatory periods and then inhibitory periods after that. So it is clear that the exact temporal pattern of spikes depends on the identity of the odor even within the same neuron.

But the patterns are more or less conserved across different trials of the same odor which means that these patterns are not random but are informative about the identity of the odor. And although not shown here these patterns can also change with the identity of the projection neuron. So it is not the case that the odor one will always generate this type of temporal pattern in any neuron that responds to it. Another neuron that is responding to odor one may have a different temporal pattern. So in summary we can say that the odors are encoded in the antenna lobe in the population of projection neurons by three features.

The first one is the identities of the projection neurons that are responding to a given odor. The antenna lobe may contain a few hundred projection neurons and of those a subset would respond to any given odor. And the identity of these neurons is informative about which odor was present. The second feature is the temporal patterns of spikes that are produced in these neurons. As we saw that each odor generates a specific temporal pattern in the corresponding projection neuron and it is possible that two different odors activate the same neuron but they do so in different temporal patterns.

And the third feature is that when odors are delivered activities of projection neurons become synchronized and a result of that is the oscillation that is observed in the LFP signal as has been observed in locusts and some other insects. Now because this code involves both the identity of neurons so there is a spatial aspect to it. If we consider the fact that these neurons are present at different locations within the antenna lobe then certain parts of the antenna lobe are responding to any given odor. So that is a spatial aspect and then there is a temporal aspect that the neurons are responding in specific temporal patterns. Therefore it is sometimes described as a spatiotemporal code of odors in the antenna lobe.

So we have seen the spatiotemporal code of odors at the level of projection neurons. Now let us take a look at what happens at the next layer of processing in the olfactory system. The projection neurons send their output to an area called the mushroom body and in the mushroom

body there is a large population of neurons called cannon cells. Each of the cannon cells receives information from many different projection neurons. And just as we studied the responses of projection neurons by doing recordings we can also put electrodes in the cannon cells and we can see how each cannon cell is responding to different odors.

Now one naive expectation might be that because cannon cells are getting information from many projection neurons so they might respond to many odors and they may have strong activity. But when the experiments were done it turned out that the responses of cannon cells were very sparse. So here are the responses of a cannon cell to different odors and one thing that immediately jumps out is that there is very little activity in all of these cases. There are very few background spikes and the cell is responding only to some of the odors and even when it is responding the number of spikes in any given trial is very small compared to the responses in the projection neurons. So the responses of projection neurons can be called dense responses because there is lot of activity whereas in the cannon cells there are very few spikes and the cell is responding to very few odors and such kind of responses can be described as sparse responses.

Now there is some evidence that cannon cells are involved in formation of olfactory memories. So insects have the ability of learning the behavioral implications of odors. If you give an odor and then give a reward immediately after it and if that pairing is done a few times then the insect can learn that that odor is good, it predicts reward and if just odor is presented later the insect will move towards it. And these kinds of associative memories are thought to be formed in the mushroom body and cannon cells are involved in it. Researchers in the field believe that these sparse responses may be helpful in formation of these associative memories.

These memories probably involve changes in the synaptic strength between cannon cells and their output neurons and because the cannon cells are responding very specifically to only some of the odors it might be easier to change these connections and affect the responses for only some of the odors at the level of cannon cells whereas at the level of projection neurons if you change the connections of one neuron you might affect the responses of many odors. So the sparse responses of cannon cells make intuitive sense but let's think about what mechanisms result in these sparse responses given that the cannon cells are receiving input from many projection neurons that have dense responses. Now based on what we have seen in this course so far one possible reason could be that the synaptic strengths between the projection neurons and cannon cells may be weak. So even though there are lots of spikes in projection neurons that are resulting in synaptic input to cannon cells but the EPSPs that are produced may be small in magnitude so you need a lot of EPSPs to reach the threshold and also the thresholds in cannon cells may be relatively high. So these are the intrinsic properties of cannon cells but another possible factor is that maybe cannon cells also receive inhibition from other neurons that keeps their activity in check.

Can we do something to figure out whether inhibition actually plays a role? Maybe you can pause your video here and think about it for a minute. As we have seen earlier in this course the most common inhibitory neurotransmitter is GABA. So if there is indeed inhibition that is mediated by GABA in the system then we can check that by using some chemical that can block GABA receptors and picrotoxin is one such chemical that blocks GABA A receptors. So we can do the same experiments in which we measure the responses of cannon cells to different orders after applying picrotoxin and blocking GABA A receptors and when researchers did that they found that the activity of the cannon cells increased significantly. So that clearly shows that GABA mediated inhibition was playing a role in keeping the activity of cannon cells under control and when that inhibition is removed by blocking GABA then the activity of cannon cells increases.

So both the intrinsic properties of cannon cells such as their high thresholds and the network properties that is getting inhibition from other neurons helps in maintaining their sparse firing rates. And now we know where this inhibition to the cannon cells comes from. So in the insect brain there is one neuron called the giant GABAergic neuron that receives input from all of the cannon cells and then it gives inhibitory output back to the cannon cells. So this is a feedback loop. It's getting positive input from cannon cells and then summing up that input and then it gives inhibitory output back to the cannon cells in the form of neurotransmitter GABA.

So this feedback loop will basically result in a normalizing function. If the total activity of the cannon cell population is weak, so if the overall input coming from the projection neurons is low then the overall activity in this inhibitory neuron would also be weak and therefore it would give overall less inhibition. But if the overall activity in cannon cells happens to be high then it will also give more inhibition to bring that activity down. So this feedback loop will help in maintaining the overall activity of the cannon cells and prevent it from becoming too high. Thank you.