Neurobiology

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Lecture 5.2: Tuning Curves, Receptive Fields, Sensory threshold

Hi everyone, welcome back to Neurobiology. From the last video we started looking at sensory systems. We discussed that there is a variety of physical stimuli present in the world and our brain is capable of detecting only a small portion of those. And from those it creates a virtual perceptual world inside. We discussed various senses, what kind of stimuli underlies those senses and what kinds of receptors are required to detect those stimuli. In this video we will look at some general properties of the sensory receptors.

So are the receptors very specific to certain features of stimuli or are they more broadly responsive? How do we quantify that? Are the receptors able to detect stimuli only in a narrow region of space around us or from a wide space? And how do the receptors convey information about the strength of the sensory stimuli? Within a sensory modality, the physical stimuli that generate sensory perception can vary in terms of various physical parameters. For example, in the case of sound, the pressure waves that generate sound can vary in terms of their frequencies. And not all receptors are equally sensitive to these different frequencies. So we can study how sensitive a particular receptor is to various frequencies by doing an experiment in which we measure the response of that receptor by giving stimuli of different frequencies.

And if we do that, we can check that for different frequencies which are shown on the X axis here, we can see what intensity of sound is needed to activate that receptor. So the minimum intensity of sound needed to activate the receptor is shown on the Y axis here. And for this particular receptor, we find that it is most easily activated at 2 kHz frequency at which it requires about 20 decibel of sound. And then for higher frequencies, it requires more intensity. At 5 hertz, it requires almost 100 dB of sound.

And similarly on the left side, as we go farther away from 2 kHz, we need more and more intensity of sound. So we can say that this particular receptor is specialized or tuned to 2 kHz frequency of sound. And the shape of this curve tells us how narrowly or how widely tuned the receptor is. So if this tuning curve was even narrower, let's say like this, then that would tell us that the receptor is very, very specifically tuned to 2 kHz and is unlikely to respond to any other frequency. Whereas if it were more broadly tuned, something like this, then we could say that it is somewhat likely to respond to other frequencies also, even though it is best tuned at 2 kHz.

And different receptors in our brains may be tuned to different frequencies. So there may be other receptors whose peak occurs at 3 kHz or 5 kHz or 1 kHz. And that's how we are able to detect different frequencies. Now let's look at the photoreceptors. Light is detected by opsins that are present on two types of cells in the retina, rods and cones.

Cones themselves are of three kinds, which are called blue cones, green cones, and red cones. And these cones are basically sensitive to different wavelengths of light. So they have different tuning curves. The tuning curves are shown here. On the x-axis, we have different wavelengths of light, ranging from about 400 to 700 nanometers.

And on the y-axis, we are plotting how much of that wavelength of light is absorbed by the photoreceptor. So the y-axis here is plotted in a different manner compared to the previous slide, in which we were looking at the minimum intensity required to activate the receptor. And here we are directly looking at how much of that wavelength is absorbed by the receptor. So a higher value means that more of this wavelength is absorbed by this photoreceptor. So this photoreceptor is more sensitive to this wavelength.

Therefore the tuning curves are shaped like mountains instead of tuning curves that were shaped like valleys in the previous slide. The blue cone here is most sensitive to 437 nanometers of light, and then it has a relatively broad distribution around it. The green cones have their peak at 533 nanometers, which is around green, and then a wide distribution around it. And the red cones, although they are called red cones, but their peak actually happens at 564 nanometers, which is yellow. But they are called red cones because these are the ones that are most sensitive to red colors.

Rods also have a tuning curve, and rods are very sensitive to light, so they are the ones that enable us to see even in dim light during late night when the cones are not activated at all. And one of the ways in which rods can become more sensitive to light compared to cones is that they have larger time constants, and that allows them to integrate the signal over longer period of time. So the signal in this case comes from the photons that are striking the photoreceptors and result in opening of some ion channels. And because rods have longer time constants, the input that comes from one photon does not decay quickly before the input from the second photon comes. Now let's think about how we are able to see different colors.

In the case of auditory system, the coding of different frequencies of sound is somewhat easy, because we have different receptors for different frequencies of sound. But in the visual system where we can see millions of colors, we do not have millions of types of cones. We only have these three cones that are tuned to 437 nanometers, 533 nanometers, and 564 nanometers of light. So how are we able to see many many colors in that case? We are able to see many colors because each color would activate these three types of receptors in different ratios. The brain can look at these ratios and figure out the color.

So if we look at 600 nanometers of light, it would activate red cones with high efficiency. Let's say there is 70% activity in them. And it would activate green cones with low efficiency, let's say 25%. And the blue cones will be activated very very minimally.

Let's say 1%. So this pattern of activity 70%, 25%, 1% corresponds to 600 nanometers of wavelength or say orange color. And similarly each color would correspond to one particular vector in this three dimensional space of the red cones activity, green cones activity, and blue cones activity. By looking at these different combinations, the brain can figure out what color it must have been. Now you can imagine what would happen if one of the cones were missing or dysfunctional. So let's say red or green cones were missing.

The colors in this region are not activating the blue cones as much. So the discrimination between these colors is possible mostly based on the ratios of red and green cones. And if one of those are missing, then our ability to discriminate colors in this region will go down. And we will not be able to differentiate between various shades of red or green. And this is one of the common types of color blindness.

Similarly if other cones are missing, there would be deficits in other types of color discrimination. Now you might be wondering why I am ignoring the rods here. Rods also have a tuning curve and they respond to different wavelengths in different ways. So why don't they contribute to color sensing in the same way as red and green cones? Before I show you the answer, do you want to pause your video here and think about this for a minute? Well if the rods were activated at the same time as the other three cones, then they should have also contributed to the color sensing. But in reality, as we have discussed, the rods are much more sensitive to light than the cones.

So during daytime when the cones are activated, blue, green and red cones are active, the rods are oversaturated with light. And so they do not contribute to visual sensing as much because they are not providing any information. And during night when the rods are being useful, at that time the cones are not getting enough light and so they are not active. So basically rods and cones are getting activated at different times during the day. And that's why rods are not able to help cones in better discrimination of colors.

When we detect stimuli, we not only know their physical characteristics such as wavelength or frequency, we also get some spatial information about them. For example, we know the location of the stimulus. So if I am looking at an animal, I immediately know whether the animal is towards my right side or towards my left side and so on. I also immediately know the size and shape of the animal. So whether the animal is a small animal like a rabbit or whether it's a large animal like a tiger.

And I also know the fine details within that broader shape. So I can know whether the animal has stripes or has a plain body or has dots in it. And that can help me in differentiating whether it's tiger or a lion or a leopard and so on. So how do I get all this information? If the activity of the photoreceptors is only dependent on receiving the photons of certain wavelengths, how do they get to know all this spatial information about the stimuli? This becomes possible because neurons, at least in some sensory modalities, respond preferentially to inputs in certain parts of the space. So these regions of space where stimulation or presence of stimuli excites the neuron, these regions can be called the receptive field of that sensory neuron.

To take an example from the visual system, so this is the eye and at the back side of the eye is the retina and in front is the lens here. So if there is an object in front, an image of that object is formed on the retina and this image is inverted. So a photoreceptor that is at the bottom of the retina will get input from objects that are relatively high up in the visual space. And a neuron towards the top of the retina will get inputs from objects that are towards the bottom part of the visual space. Similarly a neuron towards the right will get input from things that are on the left side of the visual space.

So each photoreceptor in the retina gets input from only a narrow region of the visual space. A neuron here will not be activated if the objects are in the top part of the visual field. Such an object will only activate neurons towards the bottom side of the retina. So this preferred spatial location of these neurons can be called their receptive fields. And although we are defining receptive fields for sensory neurons here, the same idea can also be applied for other neurons in the sensory systems.

So even deeper neurons in the visual system have preferred spatial locations to which they respond. So we can define the receptive fields of those neurons as well. In one of the introductory videos, we had looked at the idea of homunculus. So just to refresh your memory, sensory homunculus tells us how the various regions of the somatosensory cortex respond to touch in different parts of the body. So if we apply touch to certain part of the body then there is activity in a certain part of the somatosensory cortex.

For example, if you touch on neck, then neurons here are activated. And if touch is applied to nose or face, then neurons here are activated. So for a neuron that is located here, we can say that the receptive field of this neuron is neck because that's where it responds to the sensory stimuli. And similarly for a neuron that is located here, we can say that the receptive field of this neuron is nose because it responds when contact is applied to the nose. So the homunculus is an example of the receptive field although these are not sensory neurons.

The sensory neurons are located on the respective body parts. These neurons are receiving information indirectly from them. The receptive fields are not used by all the sensory systems. They are most common in the visual system and the somatosensory system, that is touch. And using the receptive fields, it's easy to understand how the brain can figure out the location of the stimulus and the approximate shape and size of the stimulus.

But how do we get to know the fine details within those shapes? That also becomes possible by the receptive fields. They just have to be fine enough. So let's consider the example of somatosensory system. Our whole skin is lined up with touch receptors and the receptive field of each receptor is basically the area of the skin above it. So if we touch our hand with a rectangular object like this, our brain can easily figure out where the touch was made and how big the object was depending on which touch receptors were activated.

So all the touch receptors that are under that object will get activated. Now if all these receptors were activated equally, then we could figure out that the object was perhaps smooth. And if all the receptors were activated equally but one receptor in the middle was activated very strongly, then the brain can understand that maybe this object had a sharp point in the middle. And if we had a pattern where say two receptors were activated weakly, then two receptors were activated strongly, then two weakly, then two strongly and so on, then that would tell us that the object had a certain texture. Maybe it had horizontal lines of a certain thickness.

And how much detail we can get will depend on how many sensory neurons there are and how small their receptive fields are. So if we have smaller receptive fields, we can get more detailed information. In summary, a sensory system can have higher resolution if it has a dense population of receptors with small receptive fields. And this is not very different from what happens in the case of camera images. So an image with a smaller number of pixels would appear grainy, whereas as you increase the number of pixels, you get more and more quality in the image, even if the overall size of the image remains the same.

And that's because when you have a smaller number of pixels, then each pixel contains information from a relatively large area. But as you increase the number of pixels, then within that same area, you have more number of pixels, so you can resolve more details. The same thing happens in the case of sensory systems. If you have more receptors with smaller receptive fields, you are able to resolve more detail. So we have talked about how the features of stimuli are encoded and how the spatial information is encoded.

Now let's talk about stimulus intensity. So how do we know the light that we are seeing is bright or dim? One of the ways in which the intensity is encoded is in the frequency of action potentials. So either the sensory neurons or neurons in the subsequent layers can fire more action potentials if the stimulus is stronger. This is not always true and there are exceptions. There may be other ways in which the intensity is encoded, but this is one of the simplest and more common mechanisms. If we look at the frequency of action potentials as a function of the stimulus intensity, so frequency is on the y-axis, intensity is on the x-axis, each of these curves indicate one receptor neuron.

We usually see an S-curve-like shape, that there is some minimum intensity required to activate the neuron and that minimum intensity is known as the sensory threshold of that neuron or that receptor. And once the intensity is more than that, then the neuron can respond. Its firing rate increases as a function of the stimulus intensity and as the intensity increases then eventually the firing of the neuron saturates. So beyond a certain range it would not increase further. And this range between the minimum value and the maximum value can be called the dynamic range of one receptor.

Similarly, another receptor may have a different dynamic range and the range of the whole system will be the combined range of the individual receptors. So even if an individual receptor is informative only in a certain range of intensities, the brain can extract information for a wider range. In the modern cameras we often hear this term HDR, that refers to high dynamic range. So such a camera typically takes multiple images with different settings, each of which mimics say a high sensitivity neuron and a low sensitivity neuron. And those images are later combined in software to increase the overall range of the image.

Here is an example of a sensory neuron from the somatosensory system. So if we apply a touch and this touch is basically some kind of a mechanical stimulus with different penetration depths and we are seeing the number of action potentials generated in the sensory neuron. So when a weaker touch is applied, we see smaller number of action potentials and as the intensity of the touch increases, we see more action potentials. The trace here shows the timing of the stimulus. So it's a step pulse, the stimulus was applied here and stopped here.

If we look at these firing patterns carefully, we also notice an interesting pattern. So for example here, there is a high density of action potentials in the beginning and then it begins to slow down over time, even though the stimulus is maintained at the same level throughout. This gradual reduction in the spiking rate is known as adaptation and this is often seen if the stimulus persists unchanged for several seconds or minutes. We can see the behavioral manifestation of this adaptation in our perception. So for example, if you enter a room where a new bottle of perfume was opened, you can smell the perfume quite strongly in the beginning.

But if you stay in that room for some time, you notice that the intensity of the perfume starts to decay over time. But if you go out of the room and come back, then you can again feel the strong perception of the smell, which means that it's not that the odor molecules had moved away. It's just that the neurons in our brain were firing at a lower rate. But you might be wondering that why it doesn't seem to happen in the case of visual system. So if you are looking at a tree and if you keep staring at it, it's not that the tree starts to fade away over time.

So what's different there? Do the visual neurons not adapt? Well, there is adaptation in the visual system also, but there is one more thing that is happening there. Our eyes are actually constantly moving and when the eyes move, the lens of the eye moves and that shifts the image that is formed on the retina slightly. These small movements are happening all the time without us noticing them actively and these are known as microsaccades. And because of this process, the image on the retina is shifting and therefore the photoreceptors on the retina are getting slightly different input over time, which prevents adaptation. And our brain keeps track of these movements and therefore adjusts the image that is formed.

So we do not see the image moving because our brain already takes care of that and provides us a stable image. But if the microsaccades were prevented, then we would observe the adaptation happening and the image over time fading away as well. Thank you.