Computational Neuroscience

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Week – 01

Lecture - 04

Welcome to the fourth lecture in our lecture. We will be discussing computational neuroscience course in the first week where we are continuing our discussion on introduction to neurons. And so we have discussed the basic structures of the brain marking out the different sensory areas and the prefrontal regions and the motor areas in the cortex. And we have alluded to the various subcortical structures as well and we have mentioned that there is a certain way in which the arrangement is present in these different sensory pathways. And let us discuss that in our lectures about the system of neural processing that is the way the different systems are organized in order to achieve neural processing. So to begin with if you are given the task that you have to interact with the physical world.

Let us say you have to design an artificial system that will have to design, that will have to interact with the external world, the entire environment, other people and so on. So in order for this artificial system to interact with everything else around it, it must first be able to detect the various kinds of inputs from the different regions, from the different aspects in the environment. And for that you probably will first start off by designing sensors, sensors that will pick up the signals of the environment, signals as in if we want to, if the artificial system has to understand the sounds that are produced around it or to understand the speech that people are making, it first needs something like a microphone which is a sensor that picks up those auditory physical signals. Similarly if this artificial system has to walk around and feel its way around let us say in a robot that is artificially going around this room in this class and opening the door and going out, it also has to have an interaction like that we see in the somatosensory system that is the percept of touch or it is broadly touch but there are many, many different minute nuances in the term touch and the way that touch is perceived and the way that touch is transduced.

It is not simply just touch as in the feeling of a pressure but there are many other aspects to it. Further as we said if the artificial system has to move around based on these touching and feeling its way around, it must have a motor system that also has to talk with its sensory systems that is the somatosensory system which is providing the artificial system with information about the somatosensory world around it and it may also use the visual world around it. So basically then you need something like a camera in order to get the images all around the room or the artificial system needs to process that visual input coming in from the entire world. So the brain is no different in that sense or rather the human body with its nervous system does something exactly like what we were discussing and that it interacts with the external world first through multiple different sensors where this information is transduced into the nervous system. So if we think of our artificial system, the first stage, so if we think about our artificial system, then the first stage in the periphery which is also true for the central, for the nervous system that we have are a set of sensors.

These sensors will take up, so if we have an environment, external environment, the signals are picked up by the peripheral sensors or set of sensors that transduce this information into something that is readable by neurons and that is electrical signals. So this is where sensory transduction takes place and here we convert it into some form of electrical signals. So the various different sensory systems have various different ways in which this transduction happens through biological sensors that are present. For example, the photoreceptors in the eye transduce visual information that is photons are converted into some form of electrical signal that is conveyed into the central nervous system with action potentials. So we have talked about the three sensory systems that is the visual system, the auditory system and the somatosensory system so far.

These three are somewhat different from the other two sensory systems that we have which is the olfactory system and the gustatory system. So the sense of smell and the sense of taste, these are very different from these first three systems that is because the visual, auditory and somatosensory systems are physical systems in the sense that the stimuli or the external environment has parameterizable forms of stimuli. That is in the visual system we can physically parameterize what the intensity is at a particular location in front of us in the field of view and what color it is based on the wavelength of light that is coming in and so on. Similarly, in the auditory system we have sound pressure wave forms that are coming and impinging on our ear drum and finally getting converted into action potentials in the auditory pathway. Similarly in the somatosensory system we have said that it is, it feels the pressure on the skin or vibrations on the skin and so on.

So all these are parameterizable whereas the olfactory and the gustatory system these are chemical senses that is they are more special or different in the sense that here the stimuli are not parameterizable that is we cannot assign numbers to the different kind of olfactory stimuli such that they can be put in an ordered space that is one olfactory stimulus or molecule is greater than another olfactory molecule. We simply cannot say that. Similarly, the gustatory system also is a chemical sense where the test sense just like the odorants are molecules and they are individually converted into the electrical signals in the to be conveyed into the central nervous system. So they are a set of stimuli that are present in the olfactory and gustatory system is simply that this is a very discrete set and not complete. And similarly the visual auditory and somatosensory system more easily can be represented as a continuous, it can be represented in continuous space over variety of number of dimensions.

And so our treatment of the visual auditory and somatosensory system in this course would be of a particular kind where we convert stimulus parameters and then try to understand how series of action potentials are generated from those set of parameters. What happens if we vary the parameters of the visual or auditory system and how the neuron responses change or the spike trends change. On the other hand, that kind of modeling will not be possible for the olfactory and gustatory system here because the stimuli are discrete in nature and so we will have to use other kinds of tools like those of information theory where each entity is treated as a different or each molecule is treated as a different thing and we study the system based on how we discriminate to differentiate and so on. So in as we were discussing, so this is the first stage in the information processing pathway where at the periphery the physical world or the chemical world outside is transduced, the events outside are transduced into electrical signals and converted into those action potentials in some way which are taken forward into the central nervous system. And what we will see in our further discussions is that even beyond the periphery, a common principle is present in terms of how things are organized as we have been saying.

The general principle is that at the very beginning at the periphery where these sensors are present, the first thing is breaking down the external world into very small discrete elements or rather the very simple elements. We break down the entire sensory stimulus into some very, very small elements. For example, the visual system, if we talk of the visual system, this breaking down is into spots of light in the spots in the visual space in front of us. So the retina has as we will see has photoreceptors that correspond to one particular spot in the visual space. And so the entire field of view at the first stage is broken down into these tiny little pixels very much like in an artificial system you would have in a camera where you have pixels if you have a digital camera where we have pixels that are correspond to each different location in front of the pathway.

So here the visual system is converted into pixels and pixels meaning the stimuli in that pixel is encoded in some particular way through the retina. And the whole field of view is broken down into these parallel channels of information of these very tiny elements. Similarly in the auditory system what we will see is that in this case it is broken down into something akin to frequencies. It is not exactly breaking down into frequencies but more like narrow band filters breaking down into energy narrow filters that is very close to frequencies. So the sound pressure waveform that we have that in general when we are listening the sound pressure waveform that is impinging on our eardrums contains many different frequencies simultaneously with different energies of the different frequencies at different times.

And that is constantly varying over time. And the first stage in the auditory pathway which is at the basilar membrane in the cochlea this information is broken down into individual frequency components or rather into elements that are outputs of filters which are quite narrow depending on the energy in the sound. So which is akin to what we call frequency. So it is almost like something like a Fourier transform although it is not exactly so but something akin to it. Similarly in the somatosensory system what we have is again similar to pixels but on positions on the skin.

So the entire skin region is the kind of pressure waveform that is present or the vibrations that are present and so on all kinds of somatosensory stimulus parameters are broken down into the different spots on the skin that is very tiny little elements throughout the entire skin. So if we could flatten out the entire skin then each little point on the skin will has a corresponding input going into the central nervous system. So that is also like the visual systems pixels. So and that also is changing dynamically the visual system is also changing dynamically although much less than how the auditory system changes or the somatosensory system changes in the time scales in which these parameters change. So in terms of the chemical senses also it is broken down into the basic some of the basic odorant receptor based action and it is not entirely clear what is the basis of the breaking down in the very beginning.

So beyond this point for the discussions we will be referring primarily to the visual and auditory and somatosensory system when we are talking about how we model from parameter space in the sensory world to neural responses or how we go back from neural responses to what the stimulus was which is decoding. So in the first stage as we said it is breaking down into small elements and then gradually there is integration of these elements that is at and yet it is hierarchically organized from one stage to the next stage and to the next stage and then into the cortex and then secondary regions and so on. What happens in this integration is basically depending on the requirement depending on what the system is trying to achieve based on the external world the system has evolved in such a way that it integrates information from these little elements this broken down sensory world it takes up different parts of it together binds them together and gradually this in hierarchy this kind of integration keeps on happening until we form a person. So that is the basic principle behind the organization and the processing in these neural systems. So we start with small elements then gradually start integrating some of them then more of them and more of them and then form the percept of let us face or let us say a sentence or a word in the auditory system or let us say the percept of this table based on the somatosensory inputs.

So now let us go into a little bit more detail in of the different systems that we have just so that we have an idea when we talk about neuronal encoding and decoding. So in the visual system as we have said so the hierarchy is like this that it starts with the retina. So on the left hand side is the retina where light is falling on the retina from the bottom side and there are photoreceptors that are rods and cones we do not need to go into the details but these are the regions where the photons are absorbed and through that absorption and subsequent secondary steps happening within the rods and cones that these rods and cones produce a change in its electrical signal on the next stage cells which are the bipolar cells as drawn in blue or even the horizontal cells which are there for another purpose and then subsequently the bipolar cells provide inputs into the ganglion cells inputs in the sense that the membrane potentials changes from the rods or cones to the bipolar cell and produces further changes in the membrane potential of the bipolar cells and then those membrane potential changes finally get transmitted onto the ganglion cells or the retinal ganglion cells and the retinal ganglion cells are the first neurons that produce action potentials in the visual pathway and their axons transmit that information through the optic nerve into the central nervous system. So if we think of this particular cone or this rod or this particular region in the retina this receives photons from a very small spot in the visual field in front of us and all the light information that is coming in is transduced in this region of in this particular region of the retina and that information through some processing with the bipolar cells and the horizontal cells and the amacrine cells is converted into the action potentials of the ganglion cells and these action potentials are transmitted via the optic nerve into the central nervous system and so various different spots in our visual field have corresponding spots with the rods and cones providing that information and this entire optic nerve is carrying this information like the entire video so to speak in terms of action potentials into the central nervous system the first stage being the lateral geniculate nucleus and in the visual system this lateral geniculate nucleus which is shown here has different elements in it and different layers in it and there is an arrangement in terms of how inputs are coming in into the LGN based on the inputs from the two different eyes and these action potentials are further processed and sent on into the primary visual cortex as shown here and in the primary visual cortex there are multiple different layers that are present which we have discussed so if we look at the primary visual cortical layer there are as we have discussed layer 1, 2, 3, 4, 5 and 6 and depending on the species there are various sub layers within the layers and it is really in layer 4 that the thalamic inputs are coming in. So the lateral geniculate nucleus is the thalamus of the visual system and the retinal ganglion cells that bring the information to the thalamus or the LGN are then conveyed into the primary visual cortex in its layer 4 and this is the input layer in the cortex.

So now what we have reached here is in the cerebrum the grey matter region that we had in the gyri and the white matter region contains these fibers that are bringing in that information and now as we have discussed earlier the nature of the network and synapses these LGN axons form synapses with neurons in layer 4 and as you can see on the right hand side there is a canonical structure or canonical way in which information is processed wherein input is coming into layer 4 from the LGN which is conveyed further into layer 2, 3. Layer 2, 3 then talks to other regions of the cortex other cortical regions and also it connects to layer 5 and layer 5 is the region that connects to the lower cortical subcortical areas and layer 5 connects to layer 6 and layer 6 projects to the thalamus that is it contains the reciprocal connections from the cortex to the thalamus. So this is simply a canonical structure it is not entirely exact there are many differences in the flow of information in the different systems even in the visual system this is how we like to broadly think of information flow but there are many details in there that we will not look into here. So similarly if we look at the beyond the primary visual cortex that as we said that output from the primary visual cortex goes into the secondary regions in this case we are now looking at the primate primary visual cortex which is much larger than in the human the primary visual region which then projects on to secondary regions V2 as we said from the layer 2, 3 there are connections going into the non-primary areas then beyond that to V4 and then further along the temporal infra-temporal region which is the posterior IT the central IT and the AIT where finally percept of faces and so on different objects form. So, I would like you to look at the diagram on the right hand side which essentially shows us the nature of the organization in the neural system that we have talked about.

So, in the very beginning it is the retina which has probably a million different retinal ganglion cells and it is almost a one to one correspondence into the lateral geniculate nucleus in the thalamus. So, we have these little broken down pieces of information from the retina to the LGN which suddenly expands into the visual cortex into I mean 100 times in magnitude. So, that is now the at each different pixel all the different kinds of information possible is being made up in primary visual cortex or is being extracted in the primary visual cortex. This is where the most elemental description of the visual world is present that or rather in terms of what we need in order to process information in the visual system. So, the spots of light get converted into many other features in the primary visual cortex.

Similarly, it is similar in nature although the receptive fields become larger in size in the first secondary region in the visual part which is V2. And then gradually the integration starts as we said that different parts of information are integrated together.

And so as you can see from 1 million we have come down to 37 million then to 29 million then the output is 15 million from V4 and then order of 10 million outputs in the infra temporal cortex. And so that is the sort of the number of representations of different objects that are approximately present in the final stage of the visual pathway which is the anterior IT in the infra temporal cortex in the primary. Now these information is this information then is carried on into the executive regions to do perform decision making.

So this similar kind of arrangement is present in the auditory system and also in the somatosensory system on the left hand side is the description of the auditory pathway where as you can see in the cochlea using the frequency information that is carried by the different auditory nerve fibers goes in into the brain stem. The first stage in the auditory pathway which is the cochlear nucleus where there are parallel pathways that begin and there is breakdown of information of different kinds for each different frequency just like for different spots different kinds of features of information got broken down into in V1. Now from these parallel information channels created in the cochlear nucleus gradually in the midbrain in the inferior colliculus there is further convergence of information and integration starts to happen from the inferior colliculus in the midbrain the inputs go into the medial geniculate body which is the thalamus of the auditory system which then projects into the primary auditory cortex in the cortical regions in the superior temporal gyrus in the human. And from there we have secondary regions, association regions as we have discussed and then finally information goes into the executive regions. In a very similar manner again the somatosensory system is organized and there are two different parallel pathways that carry information one is shown on the left and the other is shown on the right and essentially the spinal cord is heavily involved in carrying the information from the entire body up to the central nervous system in the somatosensory cortex.

So again as you see these mechanosensory receptors of the different parts of the body bring that information into the central nervous system and information passes on through different tracks of information to finally reach the primary somatosensory cortex via the thalamic regions in the somatosensory pathway. In this case is the ventral posterior lateral nucleus of the thalamus of the somatosensory system and the ventral posterior medial nucleus of the thalamus in the for the other tract information which is the trigeminal thalamic tract. So here also at these different nerve inputs parallel channels of information from the different parts of the skin are coming in which are gradually getting integrated as we go up and finally in the somatosensory system we have a whole breakup of the entire skin and if we look at the representation of different points in the somatosensory system we have an arrangement that is reflect that reflects the overall skin and different regions depending on the amount or the sensitivity of the somatosensory system in those regions there is more space in the cortical regions allocated. And so this brings us to the end of our discussions of the system of neural processing and we will follow this up with a more integrative approach in the next lecture and then go on to our actual lectures after we complete the introduction.

Thank you.