**PROFESSOR:** All right. So today then we are going to talk about eye movement control. This is a fact-laden set of topics. We're going to talk about the basics of eye movements, and then we're going to talk about the various neural structures that are involved in eye movement control.

The interesting thing about studying eye movement control here, which is very closely, obviously related to vision. It's also very closely related to the ocular motor system because it involves moving the eyes. Now the basic fact is that we move our eyes practically endlessly every day.

We make about three saccades a second. And we make more than 150,000 saccades every day. And it's not something you ever think about. Yet every time you look at something, you have to decide as to where you're going to look next. You're not even aware of it. It just happens automatically.

It's a remarkable system, works with incredible rapidity, and it involves recognizing objects out there, recognizing the visual scenes, making a selection, moving your eye there, and you keep doing it, as I said, three times a second. So this is, obviously, the eye movements that you make like that, jumping from one location to another.

And with each of those eye movements, as I've said, you need to decide where are you going to look next. So that's quite an amazing feat. And it's not just something that we do as humans, but it's also done regularly by animals. And most of the work I will tell you about has been conducted actually on monkeys whose eye movements are remarkably similar to those of our eye movements.

Now let's first of all go over what I'm going to cover in the next two sessions. First of all, before I do that, I just thought I'll show you an amusing cartoon from *The New Yorker*, which was made in 2001 which sort of puts in a nutshell what the nature of all this is.

Here's a cat. He's going to try to jump up there to get the thing. And so it has to make a decision where that thing is in space, has to make the calculations, as to how to generate the motor activities to jump up there. Now when it comes to the eye movements, you don't have to jump up there, but you have to decide how to jump your eye from one location to the next.

So what we are going to try to understand is what are these calculations that we perform to be able to make accurate eye movements from one location to another. And what neural structures are involved in this, and what are the various rules these neural structures are involved in to generate those eye movements.

Now here are the topics. First of all, we're going to look at just the basics of eye movements. Then we are going to look at the so-called eye plant and the brain stem nuclei, which are involved in moving your eye muscles. Then, we are going to look at an important structure in eye movement generation which is called the superior colliculus that we hadn't talked about yet.

And then we are going to look at the visual input for saccade generation. We're going to examine what the various types of retinal ganglion cells do to be involved in eye movement generation. In particular, we are going to look at the midget and the parasol cells.

Then perhaps a little bit today, but most of the next time, we can look at the cortical structures involved in movement control. Then we're going to look at the effects of paired electrical and visual stimulation because that would give us additional insights about the nature of eye movements.

And then we're going to look at what happens when you have various deficits in motor control as a result of having lesions in various parts of the visual and ocular motor systems. And then we're going to look at some pharmacological studies to try to understand what the pharmacology is of eye movement control. And I should only say visually guided eye movement control.

All right. So let's first start then with the basics of eye movements. We can ask a question, why do we move our eyes. Now you already have the answer to the first reason we do that, which is that in the retina, we have a highly specialized system in higher mammals and humans where there's only a very small area where you have a very high density of photoreceptors. And so to see fine detail, you need to move your eye to the location to be able to analyze it at a high level acuity.

So that then involves the directive to acquire objects for central viewing. Because it's the central viewing that allows you to have high acuity. Now those are accomplished predominantly by saccadic eye movements, just like the ones I had mimicked at the very beginning. You make these very rapid eye movements fro one location to another.

Another important part of eye movement control is that when either your are in motion, or whatever you're looking at, like a bird flying in the sky, to be able to analyze it, you track that object. You make what is called smooth pursuit eye movements. So that is another important mechanism that enables you to analyze things accurately in the world.

Now yet another factor is that when we move about, it's important for us to be able for our eyes to be stable with respect to the world out there. And one of the mechanisms involved in that, as we shall see, is the accessory optic system-- and that's what you're going to be writing a paper about-- that is involved in controlling the eyes involving both visual stimuli and the vestibular system.

So that is what we're going to talk about. Actually that part we're probably going to talk about when we-- in the next to last lecture, not next time, but the time after. We're going to talk about the accessory optic system a bit. All right. So now then, just to reiterate then, we're talking about the vestibular ocular reflex and the accessory optic system.

So now then, people have classified eye movements into some very basic types. We have so-called conjugate eye movements when the two eyes move in unison, and then vergence eye movements of an object comes close to you, it goes away from you, then the two eyes converge or diverge.

And that still has to be done to make sure that the images you see in the world fall upon corresponding regions of the two eyes. Now the conjugate eye movements fall into two basic categories. They're called saccadic eye movements, the ones we have talked about already a bit, and smooth pursuit eye movements that causes us to be able to track object so that we can keep that object on the fovea.

Now vergence eye movement-- you go back to that picture I'd shown you before in which you have the horopter or the Vieth-Muller circle, if you remember. If any object is along the Vieth-Muller circle, like going from 1 to 2, say an object jumps from here to here, then when the eyes track it, they follow in corresponding points into two retinae.

However, if there is an object that falls outside or inside the Vieth-Muller circle, as shown here, then the object, the second object follows an non-corresponding point. And so therefore you have to bring about eye movements that involved vergence-- either divergence or convergence.

For the most part, we get, today especially and the next time as well, we're going to be talking about saccadic eye movements. And then as I said, after we have covered movement, we're going to look at the movements that involve pursuit and vergence. Let's now take a look at a human subject and see the eye movements the subject makes. I mean, you're perfectly aware of it, but I thought it would be fun for you to look at it.

So here's a subject, and he's looking at something, right? And all these eye movements obvious there's nothing moving out there, so these are all saccadic eye movements. The head is fixed. And so now once you've seen this, there are a number of questions that comes into one's mind.

The first one, on the not too scientific end, is well was that a male or female. Or secondly, what was a person looking at? And then thirdly, way down the list you say, but how does the brain do this. So let's see if you can answer these three questions.

The third one will take the two lectures. But the first and second one can be answers fairly quickly. Was it a male or female? Anybody want commit themselves?

**AUDIENCE:** Male, male, male.

**PROFESSOR:** Male, male, male. Anybody think it was a female? You guys are good. It was a male. Very good. All right. Now the second thing, of course, is what on earth was this person looking at.

Now there's no way you could glean that until I tell you. So let me tell you what this person is looking at. And what this person looking at is up picture which is created by Rene Magritte. And actually resides in at the National Gallery of Art in Washington DC.

That's quite an interesting painting, and that's what I'm showing it to you. And it relates closely to perception-- the curious aspects of it. And you can see this doesn't make sense quite right. But it's because of that, because of the puzzling nature of this picture that it is in the fabulous museum. Because it is so unusual and different that it makes you think.

So anyway, what happens then suppose you started here when picture came on, then you're going to have to make a decision where you're going to look next. So what would you look at next? Most, commonly, would look at the eyes Of the rider. Then you would look at the eyes of the horse. And so I look at various outstanding features.

Now the way this looks, more or less-- looks like in real time, looks like this. So that's what this person was looking at. And that makes you aware of the fact that whenever you look at the pictures, you look at anything, you make all these eye movements in this very short time for you to comprehend the scene and to understand it in some detail.

When this kind of eye movement series is made, you wonder is this something that animals also do. And the answer is yes. Monkeys certainly do. Most mammals do, and even birds do this kind of stuff.

So what I want to show you next is, first of all, what the pattern of eye movements is in humans and the initial person who did beautiful work on this who's name is Yarbus. Now this is a famous sculpture. This sculpture the so-called Bust of Nefertiti. And what Yarbus did is he looked at the kinds of eye movements a person makes when they look at this figure to be to comprehend it.

And you can see what is interesting about this is there is a lot of saccades along the edges, and there's a lot of detail, and not too many saccades made to regions where there's smooth areas. So what Yarbus did, he actually published a book on this analyzing the nature of our eye movements just looking at its behavior like this.

Now if you do the same thing with monkeys, they are going to show you that monkey, a bunch of monkeys, they also move their eyes just like we do. They also have foveas, of course, as we discussed. And so as they move around and look around in the world, they make even more eye movements than we do.

They're a little bit more quick about it, and so they make many, many eye movements and make about maybe almost four saccades a second. Now to see whether they also actually select objects in a sensible way, what you can do is you can present a bunch of displays. Here is a bunch of round ones-- in round locations, I should say-- different objects.

And here we have a bunch of them arranged in a rectangular fashion. Then on the right, with the [INAUDIBLE] fixed again, you see the kinds of eye movements the monkey makes. And what you can readily do, even if you didn't see these here, you can tell that there must be a whole bunch of objects at these locations, including one in the center, and here, that the objects must be-- are aligned the way they are there.

So clearly the monkeys do the same thing we do. They tend to look at particular objects in the scene, and make accurate saccades to them to be able to analyze them. So because of that, it is natural to take monkeys and to study their eye movements and to study the underlying neural mechanisms in these animals, which would then make us more capable of understanding just how the brain moves your eyes about.

So now, let us becoming more concerned with the neural mechanisms and the machinery involved in eye movement generation. And so we are going to refer to this as eye plant and the brain stem nuclei, which are in the mid and lower portions of the brain, not in the cortex.

We'll talk about the cortical factors later on. So let's start first of all, with the muscles. Each eye have six extraocular muscles, as they are delineated here. They're called the superior and inferior recti, the medial and lateral recti, and the obliques, the superior and inferior oblique muscles.

Now the remarkable feature about these muscles that renders them different from the muscles that you have in the rest of your body is that the fibers of each muscle run the entire length of the muscle itself. It's not segmented. Most muscles in the body are segmented.

Because of that, they're often difficult to understand the nature of the operation. But here we have a situation that since all the fibers on the entire length, it is a relatively easy to comprehend the basic mechanisms that generate the eye movements at this low level.

The next thing that's important to know is that the eye is a balanced structure. It doesn't have any weights anywhere. And so when you move the eyes, it's not like when you have to pick up an object.

If you were to pick up a heavy object and you thought it was a feather then you would practically hit yourself in the face. But if you know what the object is, you can correct for the way you're going to lift it, which adds another huge dimension on how you move your body about, and how you operate your muscles.

Luckily when it comes to the eyes, that is not a factor. And because of that, it's easier to understand the way it operates. So now that you have this, the next question one can ask is how are these muscles innervated. I mean obviously, you have to have some nerves that connect to it that's cause the muscles to contract or to let go.

The way that works is that the nerves that connect to the muscles of the eye release acetylcholine that causes the muscle to contract. OK so that's a basic-- that happens everywhere in the body. So that's very basic. You already know all that.

But what you probably don't know yet is what are the nuerons-- where do they come from, in other words, to innervate these muscles. Well it turns out that there are three cranial nerves-- how many cranial nerves are there in the brain?

**AUDIENCE:** 12. 12?

**PROFESSOR:** 12. 3 of those, believe it or not, are involved in the control of eye movement. And so we can designate that. We can tell you that the lateral rectus is innervated by the abducens nerve. The abducens nerve comes from the abducens nucleus.

The superior oblique muscle is innervated by trochlear nerve, which is the fourth cranial nerve. And the rest of them are innervated by sub-nuclei of the third nerve, which is called the oculomotor nerve. So we have these three oculomotor is a third, trochlear is the fourth, and abducens is the sixth.

So it's these three nuclei which-- note again that the oculomotor has sub-nuclei-- that innervate these muscles. So now that we know that, the next question is how do these neurons from these three nuclei act to do this.

But before I tell you that, I want to make sure that you learn what the 12 cranial nuclei are. What you can do here-- and I'm using a so-called clean mnemonic device. On old Olympus towering tops a fat armed girl vends snowy hops. That's easy enough to remember.

The first letter of each designates each of the 12 cranial nerves. So if we then look at that, here they are. The first one is the olfactory one, the second is the optic. Then we have the ones in blue here, which innervate the eye muscles-- oculomotor, trochlear, abducens.

And then one important ones that you're going to hear a lot about is the auditory one-- that's number eight. So those are 12 cranial nerves. And then, you don't have to remember this, it might help to know that, of course, you have a whole bunch of spinal nerves as well.

You have 31 of them. And those 31, of course, each doubles-- one on the left side, one on the right side. You have 8 cervical, 12 thoracic, 5 lumbar, 5 sacral, and 1 coccygeal. Now you don't-- as I say, you don't have to remember this. And I'm not even tell you have to remember these.

But it's good to know that. It's something that you can commit to memory, so that when you go to a party and talk to somebody, you can say, hey, you know about the 12 cranial nerves. And they go, [YAWNS], see you later. All right. So anyway, we can move on now and see how these neurons that innervate the muscles, that are so often referred to as a final common path-- how they operate.

Actually that underwent quite a bit of debate for a long, long time. We're not going to go into the debate itself, but I'm just going to tell you how it works. But the fact is that these neurons are involved in generating all sorts of eye-- all the eye movements we talk about, meaning smooth pursuit, meaning maintained eye position, and saccade.

And so here's an example. This show vertical eye movements, just vertical eye movements. And what you can see here is that the more they eye looks down, like here, the more sustained activity to keep the muscle contracted, to keep the eye down.

Now but you also have to remember that while this is happening here, the opposite muscle on top, the superior rectus, has to let go. So there would be no activity to contract the muscle in the superior rectus-- no muscle fibers in the superior rectus.

Secondly, the important thing to notice here is that whenever there's a saccade-- saccade, saccade, saccade, saccade, and so on, when there's a little saccade, there's a high frequency burst. And the high frequency is short. When you have a big saccade, there's a much longer high frequency burst. And when there's a saccade in the opposite direction, there is a pause.

So what do you think happens when there's a pause? In that case, the superior rectus would get a burst and would contract rapidly to get an upward eye movement. So this muscle will cause your downward eye movement, and the superior rectus records an upward movement, of course.

So that is the basic layout. Now this is schematic, but to show you that this is real, I'm going to show you some data here of a monkey doing the actual eye movements, recording from the ocular motor nucleus. And in this case again, invading the inferior rectus.

And what you can see here are a bunch of saccades. And here the monkey is tracking an apple as it moved down. And what you can see-- let's look first at this at the bottom. What you can see here is that somewhere along the line here is what the monkey's tracking. This particular neuron begins to cut in, and then gradually it increases the rate of its activity as a result of which, you get smooth pursuit eye movements.

Now if you look at the upper part, once again as I've shown you, the frequency of activity is proportional to the angular deviation of the eye, this case because you're talking about the inferior rectus, in the vertical dimension. And whenever there's a saccade downward, there's a high frequency burst. And whenever there's a saccade upward, there's a pause.

So that is the basic nature of this. And what is so lovely about this, is it's like a machine. This is so lovely that if you then collect data from several cells, and here's an example of it, and you look at the number of spikes per second and the angular deviation of the eye, it shows you that each of these four neurons acts in a linear fashion.

As the eye deviates more and more, the frequency, the activity, gradually increases. This is not saccades, obviously. This is maintained activity-- let me go back again-- like here, like here, like here, and like here. So you get this beautiful linear function, which again as I've said, makes it relatively easy to understand quantitatively the process of moving the eyes.

So that is the basic mechanism that you see in the oculomotor nuclei. And the important thing to understand then is that the activity of these neurons is involved both in the making saccades and in maintaining various eye positions. The reason I emphasize this is because maybe about 30 years ago, there was a big debate.

Some people argued, and they initially began to record from these oculomotor nuclei that we have two different sets of neurons in the final common path, one of which controls saccades, and one of which controls maintained position, or smooth pursuit.

But that's not the case. The case is that these neurons do both. Now why did this confusion arise?

Well, it arose because it was found that if you looked at the so-called supranuclear complex, which are neurons which are sort of above, if you will, the oculomotor, trochlear, and abducens nuclei, there are a whole bunch of subnuclei there-- we're not going to go into details about them. You don't have to know that.

But at any rate, in those nuclei there are neurons that are indeed separately coding different attributes. I'm going to show this, but before I do I want to make one more important point. If you take a microelectrode, and you put it in one of these nuclei that controls a final common path, if you stimulate there at a high frequency, in this case 500 Hertz, if you increase the duration of the stimulation, you get progressively bigger saccades, Which proves, with stimulation that it's indeed the duration of the high frequency burst that defines the size of the saccade that you elicit.

So now we can move on. And in this case as I say, you don't have to know this, but I want to just mention it briefly. We have a [INAUDIBLE] the eye-- the eye muscle. And then we have, in addition to the final common path, we have a supranuclear complex, which have various neuron, some which pause, in other words, that don't cause saccades, and some which fire only to saccades.

I think that's the only ones I need to point out. But at that level, they're separate. But once they come together in the oculomotor complex, then they impinge on these neurons of the final common path that carry both of these signals. So that then is the essence of the oculomotor complex that I want to cover.

And so we can a quick, summary diagram here. We're going to make a diagram that's going to grow over in this session and the next one, and that's going to be very complex in the end, unfortunately. But here we have the brain stem oculomotor complex.

And the way to put this-- because you talk about what kinds of coding operations are involved-- this carries what you're going to call a rate code. The higher the rate, the greater the angular deviation of the eye. And of course, the longer the high frequency burst, the bigger the saccade. So that is the so-called rate code.

So this is the basic layout then. And of course, if there's a lot of activity here, this muscle is going to contract, the eye is going to deviate downward. At the same time, you're going to get a signal to the upper part that's going to let go. In other words, the signal is going to be terminated so that you have no activity in the upper part, so that that muscle can expand.

So that's basically it at this point. And as I say, this will grow, and grow, and grow, and grow, until by the end of next time, it's going to be really complicated. But that's how the brain works. It's complicated.

So with that then, we are next going to move to the so-called superior colliculus. Now the first thing I want to say about this structure is that this region of the brain-- I'll show you a picture of it in just a minute-- is one that has undergone tremendous changes in the course of evolution.

In more primitive animals, like in fish and in amphibia, what you find is that this structure is the prime structure for analyzing vision. So it does vision and then generates commands of various sorts, including commands to make eye movements, or generate other kinds of movements in different animals.

And this is the case because in these animals, there is very little cortex. But with the process of encephalization more and more of the analytical undertakings the brain was involved in had been relegated to the cortex. And that also meant that more and more of the way we analyze vision became more central, as we have discussed already, with cortical mechanisms.

Now to make this clear, let me show you three drawings of a so-called toad, a rabbit, and a monkey. And what you see here, the toad-- here is the superior colliculus. This structure is quite large relative to the rest of the brain. Then when you come to the rabbit, there's some degree of encephalization. So this structure is much smaller relative to the rest of the brain.

And then when it comes to the monkey, it looks like the superior colliculus is actually quite tiny. And in monkeys and humans, the superior colliculus is very small. It's maybe about five or six millimeters in diameter. And yet, it's an extremely important structure and we're going to examine just what the structure does. And later on, we're going to examine what happens if you lose that structure.

So now here is a sagittal midline section of the monkey. So you can see this real. And here we have the lunate again. This is what part of the brain here? This is a cephalic area.

**AUDIENCE:** [INAUDIBLE].

**PROFESSOR:** OK, good. This is area V1 here. Then if you look down here, you see this little bubble looking thing here? That's the superior colliculus. So that is a structure that we are going to look at in some detail.

Now if one enlarges this-- this in a cat actually-- and one takes a coronal cross section of the superior colliculus, they can see it's a fairly complicated structure. It has several layers. People have distinguished at least seven clear layers. And you can see the upper part here is often referred to as superficial gray. There are two layers of that.

The very top layer gets an input directly from the retina. The one little further down, I'll elaborate on that in the minute. It gets input from the visual cortex. And then we have a whole bunch of other layers that we are going to examine in some detail in just a minute.

So that's the nature of the structure-- the superior colliculus. And the fact is that in more primitive animals, actually, it is a structure with many more layers. Some of these more primitive animals have as many as 14 layers in this structure because it is heavily involved in eye movement control, as well as in the analysis of vision.

Now the interesting fact about the way this is laid out in the cat, and in higher animals, and in humans, that most of the cells in the various layers reside in those layers. They don't talk to each other that much. But they get a lot of input from many other structures that control those layers. And I'll go into that in some detail in a minute.

Now the next important fact about the superior colliculus, which makes it similar to lateral geniculate nucleus in the cortex, is that the visual field is laid out in a topographic manner in the superior colliculus. This is a top view of the colliculus. This is the visual field.

And once again, the rule, if you remember, is that the contralateral half of the visual field is it projects to the superior colliculus. And of course, the opposite then is the case for the other side. And then if you look at the nature of the connections, you find that everything that's close to the fovea, the foveal representation, projects to the anterior level of the superior colliculus.

So this is sort of the foveal region. Then the upper visual field projects to the medial portion of the colliculus. The horizontal meridian area projects to the horizontal meridian of the colliculus in the back. And the lower part of the visual field projects to the lateral portion of the colliculus.

Now why do I emphasize this? You will see in just a minute why that is important. It's very important for us understand that there's a lovely topographic layout of the visual field on to the superior colliculus.

So now we are going to move on and examine the question of what is the nature of the responses of neurons in the superior colliculus. Now I can tell you right off that in the monkey colliculus, in the cat colliculus, the nature of the responses of these neurons is not particularly interesting. They're small receptive fields, and they tend to respond both to the onset and the termination of a visual stimulus, meaning that they seem to get an input from both on and off.

And then if you make the a stimulus progressively larger. You get an increase in responses, but then once you make it quite large, in this case 10 degrees and 20 degrees, the response greatly declines, which says that just like in the retina, these neurons have centers around antagonism. And they respond vigorously to small spots and very little to large spots.

Now that's a basic layout. But then if you ask the question, well, are these cells in the colliculus orientation and direction specific? Are these cells color selective? For the most part, that answer is no, not entirely, but mostly no, meaning that these cells are not that really interesting. They are very, very, very basic.

So that is the nature of the responses of these neurons in the superior colliculus in the superficial layers. I've told you that the superficial gray, which consists of two layers, the one that that's a direct input from the retina, and the other that gets an input from the cortex, gives you vigorous visual responses.

But now, when you get into the deeper layers of the colliculus, you find something very exciting an extremely interesting. And that is sort of diagrammed here. What you have is a bunch of eye movements. And then look at this cell.

This cell responds-- it's the same cell throughout-- responds vigorously to a small saccade. And this responds well before the saccade is made. That's what happens here. But then if the monkey makes bigger saccades, and some even in the same direction, like these here, you don't get a response.

So what does that mean? That's curious. So what that means is that these cells, some have something to do with eye movements. This fires vigorously, and then eye movement ensues-- fires vigorously and eye movement ensues. Now there's an eye movement that ensues here as well, but there's no saccade.

So how do we explain this? Well, what you're do in these kinds of experiments then is that you collect extensive data to see when a cell like this fires, and when it doesn't fire. And you can generate a response curve, if you will, or a response diagram to see when it fires and when it doesn't fire.

So now to look at that, here's an example of that. In this case, all the white spots are saccadic eye movements generated from a central point that were not preceded by eye move-- saccadic-- by neural responses. And the red ones show the times when the neurons you're recording from, the single cell, responded vigorously.

So that meant that whatever mark you made a saccade in this direction, there was vigorous activity in this neuron, meaning the neuron had an important role in generating an eye movement, whereas all the other saccades did not generate a responds in this particular neuron.

But to make this clear, there are many different neurons in many different parts of the colliculus. And so when you generated other eye movements, other neurons fired. So how can we analyze this in more detail? Well, the way we can-- let me just add one more point here.

This green circle here is what we're going to call the motor field of this particular neuron. So that's a new concept for you-- motor field. These neurons in the intermediate and deep layers of the colliculus have motor field that define the size of the saccade. Now let me say one more thing in anticipation-- that if you then study where the cells' visual receptive field is, it's right there relative to the central fixation point.

So it means that this particular cell fires when a saccade is made into the receptive field of that neuron. So how can we verify this interesting, clever arrangement in the superior colliculus? Well, the way we can do this is to instead of recording, or actually I shouldn't say instead, really. But we can do two things. We can record and see what happens in different parts of the colliculus. Or we can electrically stimulate there.

Well, so here is a schematic. Here is a colliculus-- this is anterior, this is posterior. So this, obviously, if you remember, this is close to the fovea. And here is medial and here is lateral.

And what we can do then, we can see where the receptive fields are of these neurons. And we can plot them out. Here are the receptive fields. Here is number 1, close to the fovea, number 2 is medial is up, and lateral is down. Now that one has done this, you can switch over and you can electrically stimulate.

And look what happens. If you electrically stimulate at 1, you get a saccade that moves the eye into the receptive field of that neuron-- that set of neurons, I should say. Then if you stimulate in 2, you get saccades that move it to 2. And when you simulate in 3, it moves to location 3.

Now what more do we need to verify given this situation? How can one believe this hypothesis, if you will, at this stage? What did I tell you about when you electrically stimulate the neurons in the final common paths, back in abducens, in the oculomotor nucleus, for example? What did I tell you? That this duration of the simulation define the size of the saccade elicited, right?

Now if that's the case, if that's were the case, then this would not mean a damn thing, would it? Because you could take that same location and stimulated longer, and you would get a bigger saccade. So what you need to do? You need to systematically vary the duration of the high frequency burst in the colliculus to compare it with what happens when you stimulate in the abducens or oculomotor nuclei.

OK so let's look at that. Here is a picture I've shown you before. As we increase the duration of the high frequency burst, you get progressively biggest saccades. So now we do the same thing in the colliculus. And lo and behold, you get something totally different because you have a totally different code in the colliculus.

What you get here is that you get after you exceed a very short time-- just 10 milliseconds-- when you don't get a saccade. From 25 to about 120 milliseconds, you get saccades, but they're all the same size, so meaning it's where you stimulate in the colliculus, not how long you stimulate.

And then to prove this even further, when you make the stimulation much longer than that, you get a staircase of saccades, each reaches the same size. Now yet another proof here is that if you stimulate an anterior tip of the colliculus, remember where the receptive fields are very close to the foveola, then they get a hold array of, I think there's something like 14 saccadic eye movements-- bang, bang, bang bang, bang, bang-- because the simulation goes on for a long time.

So each little saccade is the same size, you just get a staircase of them. So that proves that the coding operation in the colliculus is one that defines the location of a receptive field, and when you stimulate it, it generates a saccade that moves the eye into that receptive field.

So that then in a nutshell tells you what the basic principle is off the functioning of the colliculus when it comes to eye movement. Namely it says, a saccade is generated by computing the size and direction of the saccadic vector needed to null the retinal error between the present and intended eye positions.

That's just putting it in a slightly different way, saying that, OK, I decide I'm going to make a saccade to here-- bang, like that. Just a saccade line. And but you did that you had an intended location. And by making an eye movement, you know the error.

Now the colliculus is really quite accurate. You can make saccades with very small error. Usually the error is roughly, at most around 10%, meaning that when you make very small saccades, is almost negligible. When you make a large saccade, then maybe there is an error. And when that happens, sometimes what you have to do is to make what is called the corrective saccade.

So suppose you're looking here and an object appears here. And so you say, I intend to go here, and the colliculus fires in that region of the colliculus to generate an eye movement. And say the eye movement goes to here. Then what you have to do is to make a second saccade, like that, to correct for that little error.

So sometimes when you make large eye movements, indeed, you make a secondary saccade for the correction because your accuracy is roughly around 90% correct. Does everybody so far follow the basic principle? It's very important to understand the basic principle of the operational characteristics of the superior colliculus.

So again to repeat, a saccade is generated by computing the size and direction of the saccadic vector needed to know the retinal error between the present and intended eye position. And what you have in the colliculus is a cell that is being activated because a target falls into it. And that activation then generates a signal to the lower parts of the colliculus-- we'll talk about that, how that is done-- which then results in a saccadic eye movement that nulls that error signal.

Very clever, very basic, very beautiful-- and almost computer-like at this level. So what we can do now, we are adding the superior colliculus, the very basics of it so far, to this diagram. And that says that the colliculus then sends a signal to the brain stem. Some of it initially to the supranuclear complex, and then from there it sends a signal to the abducens, or oculomotor, or trochlear nuclei to generate the appropriate eye movements.

So that then is the very basics of the operational characteristics of the superior colliculus. Now what we're going to do next is we are going to examine what the nature of the visual input is, predominantly the superior colliculus-- not entirely, but heavily-- to generate a saccadic eye movement.

So if you remember, I told you that in the retina, we make a major distinction between two classes of retinal ganglion cells-- the midget and the parasol. The midget project to the parvocellular layers of the colliculus. And the parasol cells project to the magnocellular layers.

However, it's also been found that-- I mentioned that only briefly, that in the retina there is yet another class of cells it is called-- some people have called it the W cells in the cat. Other people have called it the corneal cellular cells that reside in the relatively small numbers compared to the other two throughout the retina, and project, in part, to interlaminar layers of the lateral geniculate nucleus. But it's been found that they also project heavily to the superior colliculus.

Now how do we know this? Well let me tell you, it's important always is to understand the experimental procedures. So let me skip that here. Just to remind you again are the connections. This I've shown you several times before.

So it says here the interlaminar layers project to the upper portions of the visual cortex. But I didn't tell you before that these corneal cellular cells also project to the superior colliculus. So here's the superior colliculus. And here, initially, we can ask the question, what projects look to the colliculus. So how do we find out?

Suppose you are in a laboratory where the big question is what kinds of cells project from the retina to the superior colliculus. Think about this for a minute. What kind of experiment would you do? How would you find out? Well, that's quite an interesting question.

And so to understand that, I'm going to tell you about a couple of techniques. One technique would be that you could inject-- anatomical technique-- you would inject a substance in the colliculus that would be then retrogradely transported to the retina, and would light up the cells there. That's would be one approach.

Another approach is that you could actually record from the retina itself with microelectrodes. And you could electrically stimulate the colliculus. That way we would be backdriving cells. And when you find the cell in the retina that is backdriven from the colliculus, you know that particular cell does project to the colliculus.

So that's a very strong technique because that enables you then to identify the cell type and also you could, if you do intercellular recording, to label it. So they can do the same thing also-- because I'm going to talk about that as well-- is to see what happens in terms of inputs to the colliculus from the cortex. So let's talk about each of those, and that'll give us a better sense of what the projections are from the retina and from the cortex to the colliculus.

So here's an example of how you do it again. So we are recording from the retina here, or in a different experiment, you can record from the cortex. You can then electrically stimulate here. You can backdrive the cells in the retina, or we can backdrive the cells in the visual cortex.

And then once we do so, and record it from a single cell, you can study to see what it is like. So that is the approach. And if you do that, you come up with some very nice answers. First of all, these cells are W-like, which means that they're like the corneal cellular cells that we have seen the retina.

These are these small cells that are not particularly rapidly conducting, obviously and are not color selective. And then if we look at the cells up here, we find that all those cells are complex cells, and they all reside in layer five. That's already known anatomically that the cells in layer five are the ones that project-- many of them project to the superior colliculus. So that then is the basic procedure.

So now we can expand on this basic procedure. What we can do here is we can record from the superior colliculus. And then we can eliminate the inputs from the cortex by cooling it. That's one approach.

So if you do that, you record from a cell here, you drive it by electric stimulation-- by visual stimulation. We identify that cell in V1 by backdriving it. And then once you cool it, cool the visual cortex, you see what happens to that cell in the various layers of the superior colliculus.

Well when you do that, you get a very dramatic and, luckily, clear cut result. The result is the following. If you look at the superficial layers of the colliculus, and look at what happens before you cool, when you cool, and after you cool, the cells keep firing.

So in these upper layers in superficial gray, those cells keep firing. They're not interested in anything that comes down from the cortex. That's because the inputs from the retina goes to these upper layers of the superior colliculus, and goes predominantly to the superficial gray.

However, once you get down to the intermediate layers, and the lower layers as well, every time you cool, the cell stops firing, as you can see here. Which means that these cells in the intermediate and lower layers of the colliculus are driven by the cortical down flow. They're not driven by the direct input from the retina.

So now that we have seen this, one can say, OK, that's fine. But is this really something that happens over time, or is this just something peculiar to the particular experiment that's been run? So what do you do to see if this is really something-- a permanent effect?

Well, what you can do here is you can take a monkey, and you can remove the visual cortex on one side, so the monkey can see fine in half the visual field. And then you can record on either side-- the intact side or the affected side-- in the superior colliculus. Everybody follow that? All right.

So if you do that, what you find is this is the intact side, and this is the side where there's no V1. And this was taken months after the area V1 was removed. And here you see these red spots here, and the red spots here? That spot is the location after which you no longer could drive any cells visually.

So in the intact side, you can drive it to very deep layers of the colliculus. They had responded very well to visual stimuli. But on this side, they stopped responding here. So none of these deeper layers could be activated by visual stimuli because those deep layer, indeed, are driven by visual inputs from the downflow from the cortex.

So that then is the basic rule of what has happened in the superior colliculus. All right. Now let's see-- the next big question we can ask is this downflow from the cortex that drives these important intermediate layers, which are involved in eye movement generation, to what degree are those cortical tactile cells driven by either the parvocellular or the magnocellular layer of cells, meaning by the midget cells, or the parasol cells.

Well how do you do that? I've already told you about experiments in which what you can do is you can put a recording electrode, in this case in the colliculus. And then you can inactivate either the parvocellular or the magnocellular of the lateral geniculate nucleus, while you record in the superior colliculus.

So what happens is that these cells then, obviously as shown here, project to V1, and then layer five cells project down. So what we are going to identify then is what is the nature of these cells in layer five that drive down there. So first of all, what this shows is that if you record from-- in this case, from two cells in the geniculate shown-- sorry, two cells in the colliculus shown, this is under normal conditions, and this is when the parvocell layers are blocked.

Here's another cell-- normal condition, and then magnocellular layers are blocked. So this clearly shows-- and this was done with dozens, and dozens, and dozens of cells-- that blocking the parvocellular layers, meaning blocking the midget system, had no effect on the cortical tactile driving of cells, whereas magnocellular block eliminated it.

So that meant that these cells in layer five that project to the superior colliculus are driven exclusively by the parasol system. And indeed then, that was also done-- now let me go back to that-- that was also done in another set of experiments showing that those cells in the cortex in layer five, that you could drive from the geniculate by backdriving it if you then block the midget or parasol cells, those cells would stop firing. So those were indeed cells that were driven exclusively by the parasol system.

So the parasol system plays a very important role in getting-- in driving the colliculus. But doing it so only through the cortex, not directly. so to then put this in an easy to remember the diagram, is to say that when you come to these high level animals, what happened is that due to encephalization, the cortex gained control over the superior colliculus, except the superficial gray.

Everything else in the colliculus is controlled by the cortical downflow. And that, of course, became very important because when you make a decision as to where you're going to look next, where you're going to identify an object, you have to have information from the cortex itself, which then has to be transferred, in this case, to the colliculus to generate the desired eye movement, so that you can analyze in detail what you want to analyze.

So that then is the basic layout. And so now what we can do is we can expand some more on this diagram, namely-- once again, let's go through all this. We have the brain stem here, which is a rate code. And then we have a superior colliculus. And that code that we're going talk about there, that I've already described, you can refer to that as the vector code.

And then what we can see here-- some of this work I've shown you before-- is that we have these three systems from the retina that we talked about now. The midget, the parasol, and the W system, or the corneal cellular system, that goes up the cortex. And then the downflow from V1, we now know, is driven exclusively, it seems, by the parasol system.

However, remember also that when we go to higher cortical areas-- V2, MT, and V4, and so on-- these areas, some of them get a mixed input from two systems, like V4 and the temporal lobe. And MT, on the other hand, is dominated by inputs from the parasol system, but it's not exclusive. So in the end, the colliculus also gets an input from the midget system. But the heaviest input to it is indeed from the parasol system.

So that then is what the diagram looks like at this point. And so what we are going to do next time, we're going to expand on this connection in which we are going to look at some other cortical structures-- namely I've already referred to that a few times-- the frontal eye fields and the medial eye fields, which are regions in the cortex that control eye movements. And that's what we're going to look at in much more detail.

So now I'm ready to summarize what I told you so far. First of all, there are several classes of eye movements one can distinguish. Those are vergence eye movements and conjugate eye movements. And the conjugate eye movements come in two major types, which we call the smooth pursuit type and the saccadic type.

Then we're going to talk about eye movements as a result of the 6 extraocular muscles that we have. And important to note that these extraocular muscles are such that the fibers in the muscle run the entire length of the muscles. They're not segmented, and that they are innervated by the third, fourth, and sixth cranial nerves.

Then we say that the discharge rate in neurons of the final common path is proportional to the angular deviation of the eye. Saccade size is a function of the duration of the high frequency burst in these neurons. And if you look it up and down eye movements, as I've shown you, if the more the muscles contract that are the inferior recti, the more the idea deviates downwards.

And because it's reciprocal, as the eye deviates more and more, the superior rectus is activated less and less. So we have this proportional arrangements. It's as beautiful as I've shown you-- a linear system that defines very accurately the degree of deviation of the eye as a function of the frequency of the neuronal activity.

Then the superior colliculus codes saccadic vectors whose amplitude and direction is laid out in an orderly fashion and is in register with the visual receptive fields. I told you that in the anterior colliculus, the receptive fields are very close to the fovea. And then you go to the back of the colliculus, the progressively further peripheral, and medial is up, lateral is down.

It's a nice orderly arrangement. And you have an arrangement where the visual receptive fields and the motor fields are in register with each other. And every time there's activity, there's a particular receptive field location, the result is that a saccade will move the eye into the receptive field, thereby nulling the retinal error signal.

And then the retinal input to the superior colliculus comes predominantly from w-like cells. But the cortical downflow from V1, which comes from layer 5, is driven by the parasol system. But we should not neglect the fact-- I'm not sure if you're-- neglect the fact that they are other pathways to which the midget system can also make maybe a more limited contribution in generating eye movements.

And as a diagram I had shown you, I demonstrated that the superior colliculus is on the cortical control in higher primates. So that then is the essence of what I wanted to cover today.

And then next time, we are going to talk about-- let me see, do I have a-- we're going to talk about the cortical areas involved in saccadic eye movements control, which we will then highlight the fact that this incessant activity of us moving the eyes is incredibly elaborate and complicated. There are millions of neurons involved in doing it. And yet, it's such an incredible system that it's something we never even think about.

Luckily, it's a kind of system-- partly because of the fact that there's no wait involved in the muscles, and that the fibers run the entire length of each of the extraocular muscles-- it is a system that one has been fortunate enough to understand reasonably well in how it works in the brain. So that, in essence, is what I wanted to cover today.

If any of you have any questions, anything that-- I know this is kind of complicated, but I hope that you will understand this reasonably well. And if it's not clear to you, I will be very happy to answer any questions that you might have. Well, I was reasonably clear then.

So next time-- here's my to-do-- the cortex, heavily. I will also show you some interesting movies about that. And I think you're going to find that it's a really fascinating story of how the cortex has evolved to generate more and more areas that are involved in an incredible number of functions in the generation of eye movements, as well, of course, as in processing visual information. OK. Well, thank you very much.