3.5 Mental Imagery and the Brain

[00:00] In the previous few discussions, we've talked about vision as a computational problem. We've looked at phenomena like recognizing objects in the world, at distinguishing the edges, the boundaries of objects, at depth perception. There's much more to say about vision per se. We're only touching on a few subjects in vision. But we've looked at some of the ways in which what we think of as the automatic processes of vision can be illuminated, and we can gain more understanding of them by looking at them as computational problems, as things that we can try to write programs to do in a computer. We may not get all the answers about how human beings accomplish vision, but the computational approach division is very rich in that it enables us to gain more insight into how hard or easy certain elements of what we think of as an automatic task might be.

[01:26] We have to do vision virtually every second of the day, at least about our waking day, and by trying to reinterpret the vision problem computationally we can learn a great deal. Today we're going to talk about something kind of related to vision, but not exactly the same. This is the issue of mental imagery, and mental imagery is not only a fascinating topic in its own right, but historically it represents a tremendously important source of early controversies in the field of cognitive science. And I don't know how much detail I'll be able to go into about that, but suffice it to say that in the early days of cognitive science, there wasn't a whole lot of attention paid to trying to make computational models of mental imagery because it sort of ran against the grain of the kind of programming that people did in those early years of cognitive science. Again, I'm not sure how much detail to go into about this, but the kinds of programs that cognitive scientists were most comfortable doing in those early years matched up much better with our discussions of problem solving and search then they do with mental imagery.

[03:13] So what is mental imagery? We have a colloquial or intuitive understanding of what mental imagery is. As far as we're concerned, we think of it as the ability to conjure up pictures in our heads: images of things that we are not in fact perceiving. So for example, I could ask you to form an image of a unicorn. You're not looking at a unicorn, you've never seen a unicorn, but you should most likely be able to form a mental image of one, a picture of one in your mind. And then you could even answer questions about it. You could answer questions like is the unicorn's horn longer than its leg or something like that. I could pose questions to you about your mental image, which you could then give consistent answers to. So mental imagery is a very interesting phenomenon. It seems to be this cognitive ability to form pictures that we can look at in our heads, inspect, and then answer questions about. That talent has proven to be an extremely challenging subject for the cognitive sciences and for the computational representation of mind in general.

[05:07] Let's just talk about some of the historical ways in which people have thought about mental imagery. The subject of mental imagery has been a venerable subject in the philosophy of mind. So people who've talked about the philosophy of mind have often appealed to this ability that we seem to have of forming pictures in our heads, and in fact, for some of the philosophers of mind, mental imagery is at least one major foundation of human thinking. So here's Aristotle: “The nature of memory and its process has now been explained as the persistent possession of an image, in the sense of a copy of the thing to which the image refers…” Before we go on, note that Aristotle was saying that the image is a copy. We see something, and then we form a kind of copy of it in our heads, and then we're able to inspect that copy.

[06:18] There's a little bit of a difference here with the views of [Thomas Hobbes](). Thomas Hobbes is a 17th century philosopher, and what he was writing is: “...after the object is removed or the eye shut, we still retain an image of the thing seen, though more obscure than when we see it.” This is from his famous book *Leviathan*. Now notice that he's adding something to Aristotle's description of mental imagery. He's saying that we have a mental image of something, though it's a little more obscure than when we actually saw it. That's an interesting point, and we'll elaborate on that as we go along.

[07:04] And finally here's [John Locke](), a later British philosopher, who's saying “The ideas of the nurse and mother are well framed in their [children's] minds; and, like pictures of them, represent only those individuals.” So throughout the history of philosophy of mind, people have appealed to mental imagery as a recurring aspect and often a fundamental aspect of human thinking. I'm particularly interested in mental imagery in my own research because I'm interested in mathematics and science education. And there are repeated references from working scientists and mathematicians essentially testifying to the fact that they make heavy use of mental imagery in their own work. That is, often they will say things like they think in images or they mix images and words or images and symbols as they're thinking.

[08:22] [Jacques Hadamard](), French psychologist and mathematician, wrote a quite interesting book in the middle of the 20th century. It's been translated and sometimes the title is a little different, but in my translation it's called *The Psychology of Invention in the Mathematical Field*. He talked to a number of mathematicians and physicists in that book, one of them being Albert Einstein. So here is a quote from Albert Einstein writing to Jacques Hadamard about the nature of his thinking. It's written in this rather formal style, but we’ll elaborate on what he's getting at here.

> “The psychical entities which seem to serve as elements in thought are certain signs and more or less clear images which can be ‘voluntarily’ reproduced and combined... The above mentioned elements are, in my case, of visual and some of muscular type. Conventional words or other signs have to be sought for laboriously only in a secondary stage, when the mentioned associative play is sufficiently established and can be reproduced at will.”

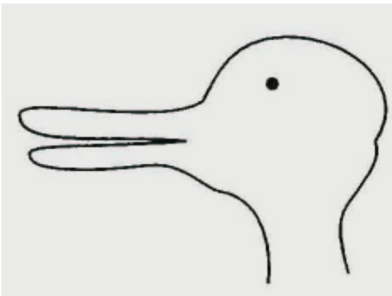
The paraphrasing of this, and it’s consistent with what quite a number of mathematicians and physical scientists report, is that their initial ideas emerge from a play of images in their mind. The symbolic, linguistic, or algebraic representation of those ideas comes as a second step. As Einstein says, often they come laboriously. It's effortful to translate these intuitive mental images of some mathematical idea or some physical phenomenon. It's difficult to translate those intuitions into symbols or algebraic equations, and that takes place in a second step. This seems to be the case as reported by many scientists, and if that's true, it's extremely interesting. It suggests that if we want to understand how scientific thinking proceeds, how creative science and mathematics is done, then one of the things we should understand is the nature of mental imagery.

[11:12] So naturally as someone interested in education in those fields, I'm also interested in how people make use of mental imagery. In a book by Eugene Ferguson called *Engineering and the Mind's Eye*, he makes a case for actually teaching and sharpening students' mental imagery if they're interested in engineering. But I think he would agree that the same idea applies to other natural sciences as well. Despite the low academic status of visual thought, it is an intrinsic and inseparable part of engineering.

[12:01] So what have we got so far? We've got this phenomenon that is a little bit puzzling. We're able to form pictures or images in our heads, and answer questions about them. Throughout the centuries, people have made a variety of explanations of this, often very loose or intuitive. There are other people like Einstein who say "this is important in my thinking". So we're not talking about some kind of phenomenon that is some interesting little trick of the mind that may be only of interest to scholars. This seems to be a very fundamental issue. One of the recurring questions about mental imagery is what exactly is its relation to normal vision, the kind of visual tasks that we've been talking about in the past few discussions. We've talked about things like binocular vision for depth perception, object recognition, edge recognition, recognizing motion, color or texture; all kinds of interesting tasks in vision. What do those tests in vision tell us or fail to tell us about the activity of mental imagery? How are they similar, if at all, and how are they different?

[13:47] To begin with, let's look at some immediate questions. Just things that maybe could pique your interest about mental imagery so you start thinking about this question. First of all, let's take Aristotle's idea that the mental image is a copy of the things seen. We could begin by taking a potshot at that statement, by saying lots of times we form mental images of things that are not copies, that we've never seen like unicorns. Let's try something. Form a mental image in your mind right now of a tiger. Try to form a good strong mental image of a tiger. Now, how many stripes are on the tiger? If you had a photograph in front of you of a tiger, you could answer that question by simply counting the stripes. You could count them and give back an answer. With mental imagery, most people report that they can't do anything like that. They can say there are stripes, and maybe more than three or four, but they can't hold the image strongly enough to count the stripes and give a distinct answer to that question. This already resonates with the quote from Hobbes, who said that the image is there, but a little more indistinct than it was when we actually saw the object. So the tiger image is there, and we might even report that it's pretty vivid, but it's not like looking at a photograph.

[15:55] A particularly interesting experiment about mental imagery was done in the 1980s, and it involved forming images of ambiguous figures. The one that is most discussed is the duck rabbit ambiguous figure. So I'm showing that here. This is just a teeny little sketch. Actually, the original duck rabbit ambiguous figure is much more detailed, but this sketch, for our purposes, is a better example. So you look at that sketch. You can see, depending on how you interpret it, that you could view this as a very crude sketch of a duck with the things on the left being the beak or as a rabbit with the things on the left being the ears. Now, here's the experiment. People were shown this sketch relatively briefly. Briefly enough so that they could



just get one a quick impression of it, but enough to form a mental image. So they were shown this particular picture briefly, and then they were asked to form a mental image of it. I'm gonna go back to the previous slide. Then they were asked what was in the image that they had in their minds. People would either answer duck or rabbit. Then you could ask them if they can reinterpret the image in their mind to see a rabbit. In general, they would say no. Interestingly, people were then asked to draw out on a piece of paper the image that they had in their mind. Once they drew that image out on a piece of paper and looked at it visually, then they could see how that could be a rabbit. They could reinterpret the image once it was drawn out, but not when it was just in their heads.

[19:17] This is counter evidence to the idea that mental imagery is just like staring at a photograph. If it were like staring at a photograph, then it should be very easy to say I thought this was an image of a duck, but now that I look at the photograph-like image in my head, I can see that it could also be a rabbit. That doesn't happen so something different is going on with mental images than with just plain vision. A number of similar experiments have been done with ambiguous figures. So you can briefly show people something like the Star of David, and ask them to form a mental image of it. Once they form a mental image of it, you can then ask them “Is this element a portion of your image?”. Typically people will report yes - that's a part of my image. You could then also ask them “Is this a part of your image?”. People will have a much more difficult time saying whether that's a portion of their image. They may well say no - that's not a portion of the image. When the full picture is placed in front of them, they can see that the parallelogram is indeed part of the Star of David image, but that only becomes apparent when they're looking at the picture right there in front of them. So this is another case in which having an image doesn't seem to be quite the same thing as looking at an actual perceived object. There's something different about them.

[21:50] Finally, there's a philosophical objection that people would often make in this case to the classic theory about mental images. Something a little bit like Aristotle and also Hobbes and Locke. This is that if you think of this kind of scenario as having a picture in your head that you're looking at, then your model is like a little person inside your head looking at a movie screen. Then the question comes up of what's that little person looking with - their own eyes? If they're looking with their own eyes, does that little person also have mental images? And does that person have a little person inside them and so forth? You get into these questions of infinite regress. It's sometimes called the homunculus objection. This is to say that sitting in our minds is a little guy, a homunculus, who's looking at pictures. But then what's inside the mind of that little guy? Yet another little guy? So there's something very philosophically unsatisfying about the Aristotelian portrait of imagery.

[23:21] Before getting to some of the debates around the nature of mental imagery, what I'd like to do is give you some of the landmark experiments which are part of the shared culture around the understanding of mental imagery, and which informed and sometimes inflamed those debates. So this is one of the most famous cognitive psychology experiments, and was done by Shephard and Metzler in the 1970s. It was a mental rotation experiment. Here's the idea. It's worth taking a little bit to understand this. What you're looking at here are three pairs of drawn 3d objects. In each of these little frames, there are two sketches of three-dimensional objects. In two of those cases, you could view those two objects as being the same object, but rotated so that they look different. For example in that case on the upper left, you could see that if you take the object on the left and rotate it clockwise, you get the object on the right in that first panel. You could view those two sketches as pictures of the very same object, but with a rotation difference between them. The pair of objects at the bottom is similarly the same object, but you would have to take the object on the left and rotate it around an axis. The axis is in the paper, but you're rotating it around that axis so that it goes out of the plane of the screen. Then you would find that those two objects are the same. The two objects in the middle frame, the frame towards the right, cannot be rotated into each other. They are distinct objects.

[25:50] In the experiment, subjects were told to look at these pairs of objects and press a button that indicated whether one object could be rotated to coincide with the other object. So they were given pairs of objects like this. They were told to look at them, and as quickly as possible, press a button to say whether one object could be rotated into the other so that they would be the same thing. Or, if not, to press a button to say that they're not the same object. There are a number of interesting things here, but here's what happened. I'm going to show you one results graph from this experiment. When two paired objects were the same, but they were distinct by a rotation, the time taken to answer whether the two objects were the same was linearly related to the angular distance between the two objects. In other words, the time taken to answer that those two objects are the same was a linear function of the angular discrepancy between those two objects. If you had to rotate the left object 90 degrees to get it to coincide with the right object, people took not quite twice as long, but they took longer than they did if you had to rotate the left object 45 degrees. And that in turn took longer than if you had to rotate the object 30 degrees. And that in turn took longer than if you had to rotate the object 15 degrees.

[28:29] The time taken to answer that these two are the same object falls on a straight line. I'm not a cognitive psychologist by trade, but I had a very memorable conversation with a colleague in the psychology department who told me that when a graph comes out that close to linear in a psychology experiment, it's a shocker. People don't expect graphs to come out that perfect. The experiment has been replicated, and there are many variations of this experiment. These are the results that you get from the experiment, but the linearity of this graph is really striking. What would be the colloquial interpretation of this? It seems as though when people see two objects like those at the upper left here, they're taking one object and rotating it at a certain angular velocity. They're rotating it from the left view to the right view. Naturally, if you're doing that, it takes longer to rotate the object by 90 degrees than it would to rotate the object by 45 degrees - just as it would in the physical world.

[30:13] Now consider this though. For those computer programmers who may be watching this at the moment, there are ways of rotating three-dimensional objects in computational representations. In computer graphics, you can take a polyhedron and rotate it by applying a matrix to it. If it's a three-dimensional object, you apply a three by three matrix to the object. Applying a three by three matrix to the object takes every bit as long as whether you're applying a 90 degree rotation or a 45 degree rotation or a 30 degree rotation. Applying a matrix multiplication for computer graphics folks takes the same amount of time regardless of how much you're rotating the object. So if you were, as a computer scientist, to say look at those top two objects there at the left. I see that I could take the left object and rotate it into the right object by applying a 90 degree rotation matrix. Then you should not get a graph like this because applying a 90 degree rotation matrix should take exactly the same amount of time as applying a 45 degree rotation matrix. You wouldn't get a phenomenon where it appears that there's a smooth rotation from one form to another that takes longer if there's a greater discrepancy. To be colloquial about this, it seems like there's a 3d representation of the object in our head, and we're taking it and rotating it with a certain consistent velocity. Once we've rotated it to coincide with the other object, we stop and say, yes, that's a little odd. It certainly is not the easiest thing to reconcile with a computer scientist’s standard ideas about how to rotate one object into another.

[32:44] Here's a similar mental imagery experiment that was done. This is a famous experiment by Kosslyn, Ball, and Reiser. The idea here is that people were shown this sketch of an island, the sketch that you see at the top there. On the island, there are a number of objects. There's a tree and a hut and a well and a patch of grass and a little pond. So people were asked to look at this picture long enough so that they could form a good strong mental image of it. And then the original picture was taken away. Then people were asked to do something like focus your attention on the tree on the island. Now shift your focus to the hut, and signal when your focus has been shifted from the tree to the hut. They would do that. Then they were asked to focus your attention on the tree and shift your attention to the grassy patch, toward the upper part of the island. Then people would focus their image attention on the tree, and then in their image, shift their focus to the grassy patch. They would report how long it took them to shift focus. The results, as seen at the bottom here, indicated that the amount of time it took people to shift their focus from object A to object B was again linearly related. Not quite as perfect as the Shepard Metzler graph, but still pretty good. The amount of time needed to shift focus from one object to the other was linearly related to the Euclidean distance on the island map itself between the two objects. So if the distance between the tree and the grassy patch is five centimeters, and the distance between the tree and the hut is 2 centimeters, then it would take longer to shift from the tree to the grassy patch than it would from the tree to the hut. Intuitively, it seems like your explanation of this would be something like, well, it's almost like there's a little dot of attention that's sitting there on the island in our minds. When we move that dot of attention from one place to another, it moves at a certain rate. It takes longer to shift that dot of attention over a long distance than it does over a short distance.

[36:18] There's some things about this that should be a little troubling. We could get back to them. When I first read about these experiments, I totally believed the results. That's not the question. But I was sort of thinking that from the computational standpoint, there's some hidden questions here. Let's mention one of them before we go on. Let's look at this example again. You are told in your mental image to focus on the tree and then shift your focus to the grassy patch. In our colloquial interpretation of the experiment, that little dot of attention starts at the tree and then it travels upward to the grassy patch. You are then told to refocus your attention on the tree and shift your attention to the hut. And then your little dot of attention moves to the hut. It takes longer to go the longer distance than it does to go the shorter distance. All well and good. From the computational standpoint, how do you know when you're shifting the focus of attention? How do you know which direction to move? A naive computer program might start doing a search of the island. In other words, you've got your computational attention on the tree, and you're told to now find the grassy patch. A naive computer program might start scanning the island back and forth, looking for the grassy patch, and then finally when it gets up to this part of the island, says okay I found it. That's not the same as just moving straight like an arrow from the tree to the grassy patch. It's more like doing a search. Maybe you might spiral outward from the tree in ever-increasing circles until you find the grassy patch. In other words, if you were writing a computer program to answer these questions, you might again answer it along very different lines and get very different results than the experimenters did. Why is it that for people, whatever is in this image is enough to tell them which direction to go? It's enough to tell them which direction to go, but they still have to take more time in going from the tree to an object at a fair distance up this way than from the tree to an object at a modest distance this way. That's a little puzzling.

[39:33] The body of experiments that started coming out about mental imagery along these lines prompted tremendous debate in the cognitive science community. One camp within the cognitive science community, which as a shorthand I'll call the symbol camp, said that - and I'm making a strong version of their argument. It's the most extreme version, but it's not a totally implausible caricature of this view. What they would say is there is no visual element of mental imagery. It is not like looking at a picture, and it's not like turning an object in our heads. What we have are symbolic representations of things like the 3d objects and the island here. When you are told to do tasks like move your attention from one object to another, you do that by a manipulation of symbols - not by scanning anything like a pictorial image in the mind.

[41:03] There were a number of arguments made for that view. One being that we already know that we do have symbols in the mind. At least that symbols are a reasonable representation for many kinds of language or puzzle type situations. We can represent search in many cases reliably. We can represent it symbolically. We can represent many linguistic tasks symbolically. So one of the arguments for the symbol camp was why postulate another pictorial representation if we don't need one. If we don't need a pictorial representation, and we can show how we can answer questions like this through a purely symbolic representation, why not just stick with that? It's a kind of economy - it's a little bit like an Occam's razor type of argument. We're saying we have one representation that gives us a kind of simple portrait of the basis of the mind. If that's all we need, why postulate more complication than we need?

[42:36] Another group, which I could call the visualists, argued that no, in fact, experiments like these show that there is a strong visual component of mental imagery and that the tasks involved in vision and mental imagery strongly interact. This debate raged for a number of years, and there were a number of relevant experiments that pushed the debate one way or another. I won't quite get to what is acknowledged to be more or less the resolution of this debate just now, but I will in the next discussion.

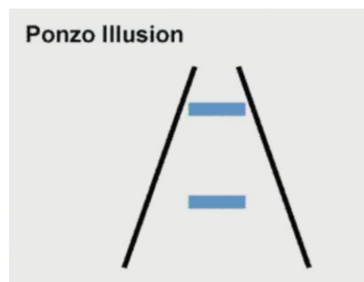
[43:29] Here's an interesting experiment that was done by a psychologist named Ronald Fink. His experiment was the following. He showed people a variety of grids. So you have a coarse-grained grid. Look at the picture on the left of this trio in the top graph. Look at those three little circles in the bottom there. Imagine superposing those three little circles at the center of that target just above them. So, in other words, you could be looking at that target and at the center of that target is one of those three grid pictures that you're seeing below. The grid picture at left is coarse-grained. The one in the center is medium grained. The one at the right is fine-grained. Now let's just stick with this question visually for a moment. So no imagery involved. Let's imagine that you take that coarse-grained grid, you place it at the center of the target, and again, this is all vision - you're actually staring at this thing. Now you're asked to shift your attention along one of the spokes of this wheel, along one of the radii of this target until you move out toward the edge. Then you're asked to report at what point along that radius does the central image blur. At what point are you no longer able to really tell the vertical from the horizontal stripes? At what point does the central image become a blur to you? So you mark the distance along each radius where the central image becomes a blur. As you might imagine, those distances are longer for the coarse-grained grid than they are for the fine-grained grid. That is, if you put the fine-grained grid at the center of that wheel and then move your attention along one of the radii, it doesn't take very long before the image starts to blur.

[46:11] Now, instead of doing this with the grid there, what we will do is have somebody look at the grid and form a mental image of the grid at the center of the target. So in the second condition, instead of actually looking at the grid at the center of the target, they have a mental image of one of those grids at the center of the target. Again, they are asked to move along the radius and report in their image when the lines start to blur. A couple of very interesting things that are represented in the center and right graph in the upper picture here. First, what you're looking at in the second picture is that as the frequency increases, in other words, as the grid goes from coarse to medium to fine (that's the x-axis), then the distance that you have to go to blur an image along some particular radius goes down. So on the x-axis, think of it as coarse, medium, fine - it’s the spatial frequency of the grating. And on the y-axis is how far you have to go along a particular radius for the image to blur. Naturally, the image blurs at a higher radius for the coarser grain.

[47:55] There are two graphs here: black and red. I'd have to look carefully at the caption to this, but as I recall the red graph is the imagery graph and the black graph is the vision graph. It doesn't matter really for the purposes of this discussion. The point is those two graphs look pretty similar. The red and black lines look pretty similar. So people will respond to this purely psychophysical question of how an image blurs. They respond to that question pretty much identically whether they're dealing with an actual perceived picture or a mental image. That's kind of interesting. The graph at the right is even more interesting. It's showing how the blur distance changes all around the target. Because it’s a little squashed, and it's longer on the left and right then it is at the top and bottom, one of the things you can say about this is that the blurring distance as we move horizontally tends to be greater than the blurring distance as we move vertically. This is for one particular choice of grating frequency. So, in other words, you take a particular choice of grating frequency and then see along each radius how far you have to go to blur the frequency at the center. One thing you find is that it's simply true that you have to go further along the left and right distances to blur the image,we seem to have sharper vision that way, than if you go up and down. Again, there's a red and a black graph here, and the red line is the visual imagery condition and the black line is the true picture condition. They look virtually the same.

[50:24] Now, one of the questions that was asked about this is if the Symbolists are right, if it's really true that you don't need to postulate a visual component of mental imagery, how do they explain this experiment? It's a very tricky experiment to explain for the Symbolists. The question would be why would such a purely visual phenomenon be replicated with a representation that was purely symbolic? The subjects going into the experiment have no idea that they should take longer to blur the grading if they move left and right than if they move up and down. The subjects going into the experiment have no idea about the nature of the sharpness of vision that way. It's not as though they're expecting to give some kind of answer from common sense knowledge. This is not part of our common sense knowledge. So the fact that people would give very similar answers when they were forming a mental image as when they were looking at the picture itself strongly suggests, at least to a reader like me, that there's a visual component of mental imagery, and it can't be reduced entirely to symbols.

[52:10] A simpler kind of experiment involved something called the Ponzo illusion. In the Ponzo illusion, you take two lines of equal length. These blue lines are of equal length, and you have two diagonal lines surrounding them. People reliably see, it may not be the strongest illusion, but they generally see the upper line as being longer than the lower line even though they are the same length. The explanation of this is usually that the diagonal lines conjure up some of the response that you would have from looking at a road or railroad track in front of you. If you were thinking of those two lines as parallel lines of a railroad track going off into the distance, then the line toward the back corresponds to a larger object because it's more distant than the line toward the front. They have the same length on your retina, but you interpret the upper line as being more distant, and, hence, longer. Naturally though, this is still an illusion as written on the paper. These are just two diagonal black lines and two horizontal blue lines. When you look at them, even though the blue lines are of equal length, you see them as being of unequal length.



[54:24] Now here's the experiment that was done. You could show people these two blue lines purely without anything else, and then ask them to form a mental image of the two black diagonal lines around them. Once people formed the mental image of the black lines around them, they could induce the Ponzo illusion. They would then say that the upper blue line looks longer than the bottom blue line. In this case, they are not actually looking at the full Ponzo illusion, they're just looking at two blue lines of equal length, and they're imagining the surrounding sort of railroad tracks. The mental image was enough for them to get the optical illusion. Again, as with the Fink experiment, the question arises how would you explain that purely symbolically? The Ponzo illusion has a visual explanation. If it has an explanation in terms of vision, and it's replicated by mental imagery, it seems suggestive that there is a visual component to mental imagery. It's replicating a visual optical illusion. The people coming into the experiment don't know about the Ponzo illusion so it's not like they're expecting the lines to change lanes. As with most optical illusions, despite their better efforts, they see the upper line as longer when they form the mental image of the two black diagonal lines.

[56:29] Maybe the most striking experiment along these lines had to do with something called the McCollough effect. I should warn you if you're looking at this slide, please don't stare too long at the picture on the right of the screen here. I actually mean this. The McCollough effect is a color related visual afterimage effect that is orientation specific. Here's how it works. Again, unless you're really into this kind of thing, I would suggest not doing this. If you stare for a long time at the green patch on the left and the red patch on the right and the green patch on the left and the red patch on the right, then when you are shown plain grids, plain striped patterns of black stripes, you get a color afterimage. Because the vertical stripes were associated with green, when you look at the plain vertical stripes afterward, you can see a kind of pink background behind them. And with the horizontal stripes you see a kind of green background behind them. This is not a retinal effect. It seems to have to do with the primary visual cortex. I am told, I've never really gone wholeheartedly into becoming a subject of the McCollough effect, but I'm told that this color after effect can last days, maybe even longer, before it finally wears off. So I don't really want to get myself into this, where every time I'm looking at a series of black vertical stripes I see pink behind them. It takes a long time to go away so it's not a matter of the fatigue of the cones in the retina. It seems to have to do with the primary visual cortex.

[58:59] This is a visual effect that you can replicate if you stare at these two patches long enough. When people are shown just a block of green without stripes and a block of red without stripes and are asked to form mental images of black vertical stripes on the green patch and black horizontal stripes on the red patch, they still get the McCollough effect. I'm told it is weaker than in the original case, but they still report getting the McCollough effect after doing that. Think about that. Nobody who is a subject comes into this experiment knowing about the McCullough effect. If I came into this experiment, I wouldn't even want this effect to happen to me so if I could, I'd resist it. The idea is you're shown these two plain color patches and then asked to form images of black stripes in different orientations on the two of them. Then later you report seeing these color after images. No subject would expect that to happen. It again seems a purely visual effect, but it's one that's induced by mental imagery.

[1:00:55] So all of these experiments that we've been talking about, lend themselves to some really interesting questions about the relationship between vision and imagery. We'll sum up for now and talk about this some more in the next discussion. Certain types of operations may be performed on mental images. Seems that we can rotate mental images as in the Shepard and Metzler experiment with 3d blocks, or we can scan mental images as in the Kosslyn, Ball, and Reiser experiment with the island. There are some visual effects that mental imagery does seem to recreate. An optical illusion like the Ponzo illusion, the McCollough effect, this blurring of grids as in the experiment by Fink, but mental imagery is not like vision in other respects. We find it difficult to reinterpret ambiguous figures like the duck rabbit experiment. So to sum up for now, it seems that we've got a bit of a puzzle. We have this phenomenon of mental imagery that seems to overlap in many important respects with vision, but it isn't quite the same as vision. It also seems to be really important to human thinking. We've got something very interesting for the person interested in both machines and minds. How does the mind work that it produces a phenomenon like this, and what can we say about this phenomenon computationally that would help us understand it better? That's where we're headed in the next discussion.

3.6 Mental Imagery and the “Turn Towards Neuroscience”

[00:00] In the previous discussion, we talked about the phenomenon of mental imagery, and a whole lot of different experiments that added to both the interest and the sense of puzzlement around the phenomenon of mental imagery. We also argued that this is an extremely important topic for people interested like me in science, math and engineering education. The professionals in these fields routinely report the extensive use of mental imagery in their creative thought. And yet there are all these questions about what mental imagery is, how it relates to vision, if at all. And then there are separate questions which go still further like “can it be taught?”. Can we get better at it? Can we become more expert at forming mental images? We'll touch a little bit on questions like that here.

[01:34] Moreover, what I want to talk about in this discussion is not just mental imagery, but what the discussion of this subject meant for the cognitive sciences. And so the title of this talk includes the phrase “the turn towards neuroscience” with the idea being that the study of mental imagery led cognitive scientists and those interested in machine models of mind to move much closer to a study of the brain, both human and animal brains, as the sources of not just inspiration but important information. People were led much more toward the study of the brain as a basis for understanding the mind than they hitherto thought was necessary.

[02:40] Let's go back and just review a discussion of some of the debates that raged even once that body of experimentation was established. There were folks who argued, yes, the experiments seem to show that there is some kind of visual component to mental imagery, but there are problems with that interpretation. First of all, let's just get this out of the way. Even if we think in our own minds that what we're doing is pictorial, in other words, a lot of times people will say I'm forming an image of a tiger or a unicorn or Santa Claus and that feels like I'm looking at it. It certainly doesn't feel like a purely linguistic or symbolic enterprise to me. It feels like I'm making some sort of picture in my mind and looking at it.The first counter-argument to that is that what you feel is not necessarily dispositive. It doesn't really tell you necessarily what's going on psychologically. The fact that you believe something is true of the way you're thinking doesn't mean that it actually is true. And there's a long history in cognitive psychology of memory of people being in one sense or another unaware of what they're thinking or unaware of how they're thinking. There are lots of phenomena and experiments in which introspection can be fooled, so the fact that something is plausible to you by introspection is not terribly meaningful. It’s maybe a little something to take into consideration, but the fact that you feel that what you're doing is pictorial is hardly proof that the symbolic camp is wrong.

[05:10] Another argument made by the symbolic camp was touched on in the discussion last time. If these experiments are purely visual, that is, if mental imagery is purely visual, then it doesn't explain how we have certain kinds of hidden knowledge, which could be called symbolic or representational knowledge, about the images that we’re examining. The island example was one. If you remember the island example, people were told to focus their attention on one landmark and then move their attention toward another landmark. I raised the question of how do you know in which direction to move. That seems to be something that people just sort of implicitly know in responding to this island experiment. But it's not necessarily apparent in the mental image itself. Again, if you were doing a computational search of an image, if you had to do a computer search of an image, you might search the image in a systematic way looking for some other landmark. Unless you have some additional knowledge, then you wouldn't know in which direction to start moving your focus of attention. That additional knowledge seems to be something extra visual beyond the visual.

[07:02] Similarly, if you think about the rotating blocks experiment with Shepard and Metzler, a crucial question to begin with is “Around what axis should you rotate the left image to make it coincide with the right image?”. How do you pick that axis? Again, a computer program might do a lot of searching to choose an axis around which to rotate. People don't seem to have that issue. We could go into more detail, but the bottom line is that it seems like there's extra visual knowledge involved in the blocks rotation task.

[07:47] There are other questions that come up around some of these experiments. One of the more eloquent of the cognitive psychologists named Zenon Pylyshyn, and it might not be unfair to call him a kind of spokesperson for the symbolist camp, but certainly a brilliant expositor of the symbolist point of view in interpreting mental imagery, mentioned the blocks rotation experiment. He said that if the phenomenon were purely visual, if there was no symbolic information included in the response to the blocks experiment, then the results shouldn't be affected by background or outside knowledge. What do I mean by that? I'm actually not sure about all the variants of this experiment that have been run. If you tell people that these blocks in the Sheppard Metzler experiment are huge heavy cement blocks, then the timing of the rotation experiments is different than if you tell people that these blocks are just made of light plastic and are very easy to move. This background knowledge can impact the results of mental imagery experiments. If that's the case, then mental imagery can't be purely visual because if it were, as Pylyshyn points out, it should be cognitively impenetrable by all of this background knowledge. What difference does the substance of the blocks make in whether the two objects can be rotated to coincide with each other? The only difference it could make is if we somehow know as background knowledge that in certain conditions it’s actually physically very hard to rotate the blocks.

[10:35] I mentioned last time this “parsimony” argument, which is a sort of Occam's razor argument. This is that if we can make an explanation for these phenomena using symbols alone, why bother with an additional visual representation? So this is a philosophy of science argument, where if one explanation suffices, why throw in a second?

[11:09] There were arguments that the whole process of mental imagery seemed to be oddly powerful and oddly lacking in powers. So for example, people could report things in mental imagery much like the kinds of special effects you see in the movies where you cut from one scene to another or you zoom in or you zoom out or suddenly highlight one portion of a scene. There is an awful lot that mental imagery seems to be able to do. There were some questions about where the limits are on this. If mental imagery is so powerful, what kind of phenomena could it not explain? If people can do X, Y and Z, this proves that mental imagery is not visual because mental imagery seems to be able to do just about anything. How would you show that an effect can't be purely visual? Roughly speaking, the argument is that mental imagery seems to be weirdly powerful. It's capable of all kinds of effects that seem to go beyond those that we usually have as human beings like zooming up for aerial shots, zooming in, or cutting from one scene to another.

[12:52] Finally, there are interesting cases where mental imagery doesn't seem to be able to do even relatively simple things. I know that seems a bit contradictory from the past point. There's some questions like if mental imagery is a visual task, it should be up to certain kinds of things that we can do with visual perception, but that we can't do otherwise. This is an example from [Geoffrey Hinton](), and I'll have you imagine it. So you're gonna use mental imagery as you're watching me right here, and I'm gonna do the experiment with you. You could try it with a friend. Here's the suggestion. Imagine coming up, and there's a cube. I'm holding the diagonally opposite corners of the cube so I'm holding this corner and this corner back here. I'm holding the opposite corners of the cube. I want you to look at the cube in your mental image. See where the corners are. Now, I'm just gonna move my two fingers so that they're vertical. And again, if you were standing in front of me, what I would want you to do is point to the other corners of the cube. I'm holding two of them. Point to the other corners of the cube. Turns out that what many people do in answering this question is they point to four corners, like that, around these two. That's not true, and you can tell it's not true. Let's go back to the regular perception of the cube. Here's our cube - imagine it. How many corners are there? There are eight. There are eight vertices in a cube. If I move it this way, there should still be eight vertices in a cube. So there should be six vertices unaccounted for if I'm holding these two. If I ask you to point to the remaining vertices of the cube, you should be looking for six vertices to point to. Naturally this is not a hard task, if you're actually looking at somebody holding a cube. This seems to be a very hard task for mental imagery.

[15:26] So there remains some weird things that need to be explained regardless of which camp one would find oneself in at the end of the 1980s. For the symbolists or the visualists, for both those camps there's some difficult phenomena to explain. In the early 1990s, the cognitive scientist [Stephen Kosslyn]() wrote a highly influential book called *Image and Brain.* Maybe with a teeny bit of optimism, the subtitle was *The Resolution of the Imagery Debate*. This came out in the 1990s. It's still worth reading. It's a tremendous book. I don't know if it's still in print. Of course, many of the debates and experiments described in the book have been updated a great deal since the book came out, which is now something like 25 years ago. Nonetheless, it's a terrific book and - to some extent - a good first approximation. It did, in fact, resolve the imagery debate.

[16:56] Let me tell you a little bit about Kosslyn’s notion of mental imagery. Kosslyn identified mental imagery as a subset of the general task of vision. His argument is that imagery is highly visual in nature. When we are doing mental imagery, we are performing part of the full task that we perform when we actually interpret an object in front of us. Mental imagery, in cognitive terms,represents a subset of the resources that we bring to bear on the vision problem in general. The structure of his book was built around a series of diagrams of the vision process. Those diagrams get more and more elaborate as the book goes on, more and more filled out. It’s the same basic structural diagram that gets more detail and more arrows and so forth as the book goes on. I've chosen a diagram from a little past the center of the book. The main point here is that for Kosslyn, mental imagery is represented by the arrow. You can see the back part of the arrow right beyond where my finger is pointing. There are two things here labeled Category Pattern Activation and Exemplar Pattern Activation, and between those there's an arrow that leads back to the Visual Buffer and the Attention Window. That arrow is the essence of what Kosslyn would call mental imagery. Think of it as the part of the visual process that is top down rather than bottom up. When we were talking about vision as a computational problem, we primarily, maybe exclusively, thought of it as a bottom-up problem. You get these pixels, you get these intensity numbers into the retina, and you use those intensity numbers and you process them to find a portrait of an object out in space. That's a bottom-up portrait of vision. It sort of takes the data and moves upstream until you get an object recognition.

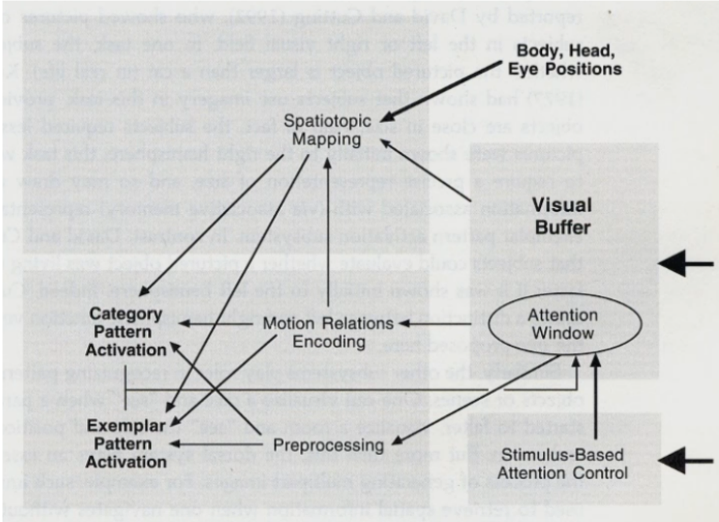


Figure 6.10 The division of the pattern activation subsystem into two more specialized subsystems, one that encodes categories (perhaps represented as prototypes) and one that encodes specific exemplars. The subsystems are illustrated in the context of the subsystems discussed previously.

[20:00] Vision is not exclusively bottom-up. It's both bottom-up and top-down. The top-down portion of it involves taking things from visual memory and matching them to a visual scene. That's part of what goes on when we identify objects, people or other things in the world. When we see an elephant, for example, part of the process of identifying it as an elephant is to use remembered visual images of an elephant. Remembered visual images of an elephant and to superpose or at least use those as guides for interpreting the perception that we're actually seeing, that top-down process is what Kosslyn refers to as mental imagery. That top-down process, in the absence of incoming perception, is kind of pure mental imagery. So we can form a mental image of a unicorn without seeing one because we can activate that arrow in this diagram. We can take elements from visual memory, combine them, and use them to activate our visual buffer in such a way that it's as though we were looking at a unicorn, even though we don't actually see one.

[21:45] One of the crucial pieces of evidence that Kosslyn used in discussing this theory involved fMRI scans. This was relatively new at the time that he was writing this book. The idea here is we want to see whether mental imagery and actual vision involve similar brain structures. Notice that this is a new kind of question. We're not just seeing whether we can make a computational model of mental imagery using symbols or pictures or whatever. In this case we're trying to answer an empirical question about how human brains operate. So people would go into an fMRI machine, and I'm not going to go into the details of how an fMRI machine works. I'll suggest some additional readings about this so you can look into the question of how fMRI works. At a first approximation what it's doing is measuring blood flow in different parts of the brain as a task is performed. So you are asked to perform a task and the fMRI image being produced is one that indicates where in the brain oxygenated blood is flowing to accomplish that task. That is generally interpreted as what areas of the brain are most active or need the most caloric energy to accomplish this task. So if you put someone in an fMRI machine and ask them to do some cognitive task and measure where the blood flow in the brain is going, you get an indirect but informative measure of what areas of the brain seem to be involved in solving this task. Informally, the way that people describe it is that we see what areas of the brain light up on the fMRI image when they're asked to perform a particular task.

[24:20] Now for Kosslyn's mental imagery experiment, the contrast was pretty straightforward. He showed people some pictures, like a picture of a tree, and then in one group he would have them close their eyes. When they were given some sort of cue, like tree, they would form a mental image of the tree in their minds. They would do this while in the fMRI machine. In the other condition, they were given the auditory cue of "tree", but then they were actually shown a faint picture of the tree. What the experimenters wanted to see was how different is the brain response to these two situations. If the Symbolists are correct, if there's really no visual element to visual imagery, you would expect to see very different fMRI images from these two conditions. If the pictorial lists are correct and mental imagery involves a heavy element of visual processing, you would expect to see a great deal of overlap. In fact, you saw a great deal of overlap. Not perfect overlap, and if you study the details of the differences between the two, you can get into more nuance about the distinction between mental imagery and vision. But the overlap was significant to the point where it was now essentially undeniable that mental imagery and visual perception had a great deal in common. Crucially, this was accomplished by the use of brain research, not by computational modeling purely.

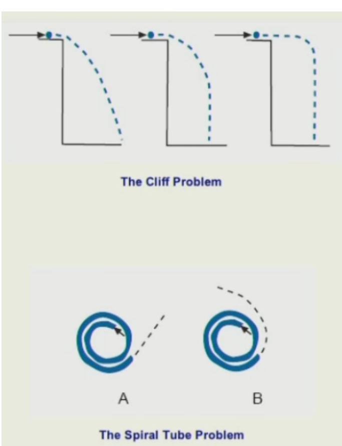
[26:22] There's some reasonable things that Kosslyn's model accounts for, some of the things we've already talked about in the experimental literature. Imagery is effortful because the top-down connections to the visual cortex are weaker than the bottom-up connections from the visual cortex to other areas in the brain. That is, the top-down connections from this exemplar activation, category activation are weaker and one has to exert more effort to keep those connections refreshed, strong or active than in a sort of general resting mode of the brain. So imagery is effortful. You have to do some work to do imagery. It's therefore not surprising that since it's part of the top-down process of vision, it would be associated with semantics. Think again of the duck rabbit experiment where people formed an image of a duck or a rabbit and then had difficulty reinterpreting it while it was an image. There's at least a plausible explanation for that, which is that the mental image is accompanied by a kind of semantic labeling that's saying "I think this is a duck". So reinterpreting the mental image is difficult because the mental image is formed for the purpose of making some semantic judgment. The mental image is formed with semantic content kind of bundled into it. So sure if you form a mental image and your mental image has inside it something to the effect that this is an image of a duck, then it's difficult to reinterpret it as an image of a rabbit. It also gives some indication of why there might be differences in imagery effects for things like color, motion, texture, shape. The different aspects of vision might lend themselves in different ways, in sort of pure or more indirect ways to the phenomena of mental imagery.

[29:00] Finally, there's a fair amount of clinical evidence that supports Kosslyn's view.

When people have certain kinds of visual injuries to the visual cortex, that affects their imagery. A famous example involves hemispheric inattention. So hemispheric inattention is what happens when people have an injury to one part of the visual cortex. An injury to the right part of the visual cortex means that they do not pay attention to the left part of their visual field. What does that mean? It means that in actual patients who have this condition, they may do things like if they're a man shaving, they may only shave one half of their face and leave the other half unshaven because they simply don't register the other half of their face in the mirror. If you give them a plate with a meal on it, they'll eat the portion of the meal on the right half of the plate, and they won't eat the portion of the meal on the left half of the plate. Then if you take the plate and turn it around, they will say there's more food here, and they'll eat the food that has now appeared to their right visual field.

[30:36] Hemispheric inattention is a phenomenon that results from an injury to the visual cortex, but it also seems to impact mental imagery. So people who have hemispheric inattention are also unable to form images with detail on the left side of their mental image. One man with hemispheric inattention, who knew the city of Venice very well, was asked to form a mental image standing at one point of this famous square in Venice. He was asked to form a mental image of what he saw in front of him in this square. He described only those things in his image that were on the right side of the visual field. Then he was asked in his mind - he's not actually in Venice - to walk to the other side of the square and turn around. Now all of a sudden in his mental image, he could see all the stuff that was on the new right side of the image that he had ignored before. From this vantage point, he's missing all the things on this side of the square. He walks in his mind to the other side of the square, turns around, and now he picks up this side of the square and leaves out this part. That's a really interesting phenomenon, and it's consistent with Kosslyn's portrait. Since mental imagery is a top-down element of visual processing, and it involves these top-down connections to the primary visual cortex, if a part of the primary visual cortex is injured that will affect the mental imagery that we can do that would otherwise use that portion of the cortex.

[32:51] I mentioned that I am interested in the relation of mental imagery to science and math education. I'll mention a few cases that are of interest to me where people seem to have scientific misconceptions or difficulties in imagining certain scientific notions or concepts that I believe are related to limitations of imagery. Let me mention a few of these. Some of these are kind of classic physics experiments. Take that cliff problem at the upper right here in this picture. You ask somebody to draw what the path of a projectile will look like if it's rolling off a cliff and then continues to roll off the cliff and continues downward. This is maybe not the sort of event that people see each and every day, but it's not the least common kind of physical phenomenon either. What you're asking students to do is form a mental image of a ball rolling off a cliff and report what you see in that image. As it turns out, the leftmost of these three images is the correct one, and that stems from, at least according to Newtonian mechanics, a very good approximation in real life. The



The Cliff Problem

The Spiral Tube Problem

horizontal velocity of the ball doesn't change as it drops. There is no point at which the ball is really dropping straight vertically down. That seems to be the case in the second and third representations here. Similarly, people are told a ball is rolling along in a spiral tube, and it emerges from the end of the spiral tube, and then asked how it will proceed after that. Some people argue or will predict that the ball will follow the path in path B here. It'll continue on in a spiral, when that's not true at all. Again, at the time that the ball emerges from the spiral, it has a certain velocity, and it's just going to continue on with that velocity in the absence of any other forces so it'll go in a straight line as it emerges from the spiral.

[35:31] So these are classic physics problems. People could answer them by knowing physics theory, but the fact that many people answer them wrong suggests that there are limitations to our mental imagery. If we were answering according to the things that we had seen, we should give correct answers. But we don't seem to do that.

[36:03] The picture at the bottom right there has to do with seasons of the earth. If people are asked why there are seasons on earth, then most people answer that the earth is further from the Sun in wintertime than it is in summertime. That's not true. First of all, they have this image of the orbit of the earth around the Sun as an ellipse, which it is, but it's an ellipse that looks very close to a circle. So in mathematical terms, the Earth's orbit is an ellipse, but an ellipse with a very low eccentricity. The main reason for seasons, as the course of the year progresses, is that as the Earth rotates around the Sun, it's at a tilt. So the portion of this year that we in the northern hemisphere experience as summer is the portion when the northern hemisphere is tilted toward the Sun. The portion of the year which we experience as winter is the portion of the year when the northern hemisphere is tilted away from the Sun. You could explain this to people. They still find it rather difficult to visualize, which again suggests that there's a mental imagery issue here.

[37:50] Finally, there's yet another classic physics problem that people can be asked about, which is why there are phases of the Moon. You look up at the moon over the course of a month's time, and you see the moon looks different over the course of a month from one week to another. The moon changes shape. Why does that happen? Again, that's taxing people's mental imagery to answer a question like that. Many people answer the question by saying when you don't see a full moon that's because the earth is blocking part of the sunlight that gets to the moon. Not true - when the earth blocks sunlight that gets to the moon, we've experienced that phenomenon as a lunar eclipse. It occurs when there would ordinarily be a full moon and the earth is between the Sun and the moon, and the shadow of the earth is cast on the moon. We see that as a lunar eclipse. The reason that we see phases of the Moon is because as the moon is rotating about the earth, the angle of the Sun hitting the moon only reveals part of the moon's surface to us as we see it from the earth. The diagram toward the bottom there gives you a somewhat better view of why that should be the case. It's not the easiest thing to visualize. All of these are physics questions that tax mental imagery in one way or another.

[39:24] I'm interested in questions of mental imagery because the difficulties of certain kinds of mental imagery seem to lead to difficulties with certain kinds of scientific content. Back in undergraduate, I was a chemistry major, and I discovered that the students who were the very best chemistry students seemed to be the people who had the greatest facility at visualizing 3d structures. Visualizing 3d structures is a non-trivial task. Some people seem to do it better than others. I believe that people can learn to perform better at tests like 3d visual imagery. We can get better at it, but regardless of that question, the people who do better at 3d visual imagery seem to be able to understand chemical ideas and chemical reactions with greater ease than people who struggle with that kind of 3d imagery. It's one of the reasons I'm interested in it.

[41:05] Historically, this chapter in cognitive science led to a close examination of what we described earlier as the computational metaphor of mind. You remember that earlier we talked about the computational metaphor of mind as suggesting that if software is to hardware as the mind is to the brain, then you can be a cognitive scientist who studies the mind and not worry too much about the brain. Much like computer programmers can study programs and algorithms without worrying too much about the fine points of computer architecture. If that original computational metaphor mind is to be taken seriously, if it's true, then you don't have to be a brain scientist to be a cognitive scientist. I don't know if there's anything wrong with that idea, it just doesn't seem to have been borne out historically and empirically. The mental imagery debate is a case in point. Until people were able to look at the actual behavior of human brains, they weren't able to resolve this question of to what extent visual processing was involved in mental imagery.

[42:42] Let me give you a very whirlwind beginning to the neuroscientific perspective on cognitive science. We'll talk in a little bit more detail as the course goes on. When I was growing up and people were describing the brain, they described it in only the coarsest terms like there were a few major areas of the brain and it's basically a kind of homogeneous mass. Totally incorrect. There's a great deal of structure in the brain, and people have learned a great deal about it. For our purposes, we'll just focus on the main divisions in the brain. The first level of division to know about is that there are four lobes in the cerebral cortex, the outer portion of the brain. There's the front portion which is called the frontal lobe. There's the parietal lobe. The portion toward the back of the brain is called the occipital lobe, and there's a portion toward the side called the temporal lobe. So frontal, parietal, occipital, and temporal - that's a first order of knowledge of brain structure. We'll get to more detail as we need it, but if you've never encountered brain science before, that's the first level of division that you ought to know.

[44:28] Through the years, there’s been a variety of clinical evidence to the effect that brain injuries of one form or another can have rather specific and interesting cognitive effects. So here are a few classic cases. The upper left picture there shows what are called Broca's and Wernicke's areas of the brain. Broca's area is up here toward the junction between the temporal and frontal lobes. The Wernicke's area is further back towards the back of the temporal lobe. These were among the earliest brain areas identified as having cognitive functions. Paul Broca was a French surgeon in the 19th century, and he examined patients who had difficulty in speaking. They had a certain kind of aphasia, which has now come to be called Broca's aphasia. Broca's aphasia is characterized by difficulty in forming sentences and speaking in response to questions. It's very effortful for people who have Broca's aphasia to respond to questions. Often they seem to be at a loss for words. They do seem to understand the questions well. So it's not a problem of their understanding the questions, they have difficulty in actually speaking and formulating an answer. Broca found consistent evidence that people who had an injury in this area, called Broca's area, in the brain exhibited Broca's aphasia. People who had injuries in other areas of the brain did not show Broca's aphasia. People who had injuries in that area of the brain did show it.

[46:43] Wernicke was a slightly later brain scientist who identified a different area of the brain called Wernicke's area. When that is injured, there's a different kind of aphasia. People with Wernicke's aphasia have problems understanding questions, and when they respond to questions, they often respond with non grammatical or nonsense type sentences. They do not have problems in the physical act of speaking so they don't have Broca's aphasia. They do have a different kind of cognitive deficit, which seems to be related to word understanding, the understanding of sentences and questions. Those are two specific brain areas that are linked to two specific kinds of deficits.

[47:47] The picture on the right shows a very famous case from American history. A rail worker named Phineas Gage was injured by having a rail spike that was actually blown up through his head. It was blown up through part of his brain, and it destroyed a portion of his brain in the frontal lobe. He miraculously survived this accident and went on to live for a while, and even posed here with the spikes that caused his accident. This was before there was really a time when people would have systematic study of what was going on. But it's very clear from the descriptions of Gage's life before and after that his personality did change after the injury. People with injuries to this area of frontal lobes are known to have changes, for example, in their ability to make judgments, to make plans, and to interpret things like their own emotions as part of their plans. You would expect that there would be some change in Phineas Gage after this accident. There are many other respects in which he didn't seem to be impaired. He was still able to speak, for example. He was still able to dress himself. But his ability to manage planning and social situations seems to have been greatly impaired.

[49:43] At the bottom left there, there's a highlighting in green of areas in the brain that are sort of toward the left and right back called the fusiform gyrus. People with a stroke in that area will often exhibit the symptoms of what's called prosopagnosia, which is a clinical inability to recognize faces. Somebody who's had a stroke in that area of the brain and has prosopagnosia will not be able to recognize faces of people. If they see someone, they'll recognize that this is a person and that person has a face, but they won't recognize whose face that is. That even applies to looking at themselves in the mirror. They don't recognize themselves in a mirror. You remember that this topic briefly came up when we were talking about the geon theory of object recognition. A person who has prosopagnosia is able to look at a face and recognize that a category. They'll say that is a face. However, the actual recognition of human faces, individuals from one to the next, seems to involve much more than merely the machinery involved in geon based object recognition. When somebody looks at another person's face, a great deal more brain machinery comes into play to notice the fine details of facial structure. People with this kind of injury are still often able to get by reasonably well. That is, a person with prosopagnosia might look in the mirror and say I don't know that face. I do, however, know that I'm looking in a mirror so that must be me. They could reason that way. So people with at least some degree of prosopagnosia can still get by reasonably well. But it too reflects a specific cognitive deficit that results from injury to a specific brain region.

[52:19] This kind of clinical evidence is one of the bodies of evidence behind cognitive neuroscience. There are other threads of evidence. Some of them involve animal experiments. Some of the classic early experiments in vision took place by placing electrodes in contact with specific neurons in the visual cortex of a cat, and then showing the cat particular simple images and registering how the neuron in the cat's visual cortex responded to certain kinds of visual stimuli. This work won the Nobel Prize for Hubel and Wiesel, who did the original experiments. The cells in the cat's visual cortex were responsive to certain kinds of lines in certain orientations, but not others - motion along one direction, but not in others. In the diagram that you're seeing here, this particular cell in the cat neuron was highly responsive to a bar that would move up and down in this diagonal fashion. So you see the stimulus involves a bar moving up and down along this way. When the bar was vertical, there would be less response from the neuron. When the bar was perpendicular to its original direction, there would be very little response from the neuron.

[54:33] So one of the results of these animal experiments was to investigate some of the crucial steps of vision that have informed the computational modeling of vision. And these experiments could only be done with live animals in the process of actually looking at particular stimuli. You couldn't do them with human beings because they required actually placing an electrode in long-term contact with particular neurons. So animal experiments have been a venerable thread in cognitive neuroscience.

[55:26] fMRI, which we mentioned before is a different branch of cognitive neuroscience, involves trying to measure or in some cases affect externally brain activity without actually opening up the brain. So fMRI is one such example where people are given cognitive tasks to do and the experimenter looks at where the blood is flowing in the brain. EEG is yet another example where a mesh of electrodes is placed around the head to record electrical activity in the brain. Neurons operate by electrochemical activity so when neurons are operating as in the brain, there's mild changes in the electric fields around the neurons. You can study them, and there are certain patterns in those electric fields that you can register using recording devices like EEG, which allow you to study rapid responses to things like word or image presentation.

[56:42] There are other more recent techniques. One is called transcranial magnetic stimulation, where instead of just measuring electrochemical activity in the neurons, you can actually use a magnetic pulse to affect electrical activity in the neurons. So you can, for example, briefly stimulate or suppress certain neurons in the brain. That too can be very interesting. For example, you could ask people questions, stimulate a certain portion of the brain or suppress activity in a certain portion of the brain, and see if they have more difficulty than usual in answering those questions. So that's a more recent method where the idea is not just to measure neural activity, but to tweak it a little bit from the outside.

[57:39] There are still other threads in cognitive neuroscience. We discussed some of them in the previous lecture when we were talking about mental imagery. Cognitive psychology experiments in the lab, like the ones involving mental rotation and so forth, can be very telling and part of the body of evidence that goes into reasoning about the nature of brain structures. For example, we could say that those experiments involving the visual correlates of mental imagery that we talked about last time, certainly suggest that you might well expect to see neural connections between the primary visual cortex and higher-order visual processing in the brain. You would expect to see the kind of connections that Kosslyn talks about. those top-down connections. The reason you would expect to see them is because the experimental evidence from the cognitive laboratories is consistent with them. You do these experiments, you see that the experiments suggest that this is what we're gonna see if we look at brain structures.

[59:02] Finally, and this is a topic that we'll get to shortly, is that we can do computer simulations of collections of neurons in the brain. That is, we can actually create models of what are called neural networks in the brain, neural structures in the brain. We can study the behavior and properties of those simulations, and we can use those to inform ourselves or make predictions about what we're going to see in actual brain structure. Similarly, we can use experiments with people in cognitive psychology labs to direct the sorts of computer simulations that we make. So we'll start talking about that shortly in the next session or two.