Aniruddh Patel

Nobel Conference 47

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Well, welcome everyone. And I want to thank Chuck and Esther for this invitation and everybody else at Gustavus that has made this possible in this, this is a very exciting conference and it's an honor to be here with you and with all of these other distinguished neuroscientists.

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My question tonight is really about the connection between biology and music. What is the connection between biology and music? This is a question I've been grappling with for my entire career. Now when I started graduate school, this question was definitely outside the box. But I was fortunate to work with Edward L. Wilson and even though ants rank pretty low on music appreciation, Wilson was intimately engaged in finding answers to larger questions in science and with his support, he supported my work and I was able to get started during the infancy of this field.

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And in the past 15 years since my PhD, I'm been fortunate to work at the Neurosciences Institute, a private basic research institute in San Diego directed by Nobel Laureate, Gerald Edelman. Dr. Adelman is driven by fundamental questions about the brain and also has a deep passion for music. So thanks to Wilson and Edelman, I've been able to explore this question about the relationship between biology and music and be part of a young branch of cognitive neuroscience that's devoted to the study of music and the brain.

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So historically this question of the connection between biology and music has been approached as an evolutionary question. Why do we make music? And Darwin himself was very puzzled by this. In his book on human evolution, *The Descent of Man*, he wrote, 'As neither the enjoyment nor the capacity of producing musical notes are faculties of the least direct use to man in reference to his ordinary habits of life, they must be ranked among the most mysterious with which he is endowed.' So he's really mystified by music.

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Now you might ask why did Darwin care? I mean, here he is writing one of the most important books in the intellectual history of our species, *The Descent of Man*, arguing that we, like every other lifeform on this planet, descended from lower organisms. We're not a product of special creation. Why is he bothering to talk about music? Well, Darwin had some beliefs about music. He believed it was universal in human culture. He believed it was ancient and he believe it was powerful, emotionally very powerful, partly based on his own experiences and partly from what he observed. And in all of these things, he has been proved amply right. It is genuinely a human universal. There is no culture that does not have music. It is present in every single human culture no matter how small and esoteric. It's very ancient.

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This was really brought home recently by a discovery in a cave in Southern Germany. Now probably many of you are aware of the earliest cave paintings in Southern France. Werner Herzog recently made a movie about them, *Cave of Forgotten Dreams.* Those cave paintings are about 30,000 years old. This flute is about 5,000 years older than those cave paintings so the history of music is indeed very ancient. And it's emotionally powerful. And it's spiritually powerful and esthetically powerful. I think we can all attest to that from our personal experience. Brain science can confirm this. This is a couple of images from colleagues in Montreal who've imaged people listening to music that gives them pleasure. Now the music that gives you pleasure may not give me pleasure so they allowed people to bring in their own CDs and know, and choose music that gave them pleasure. And they found activations in some of these reward areas of the brain that we've been hearing about earlier in the lecture, nucleus accumbens, the ventral tegmental area.

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So music is activating these deep and ancient reward centers and this is purely instrumental music, a very abstract sort of stimulus. And music seems to activate and access all of the brain’s many emotion systems. So what was Darwin’s theory? He felt music required an evolutionary theory because of these properties of being ancient, universal and powerful. History was that we used it originally as a kind of mating signal. He wrote, ‘Musical notes and rhythm were first acquired by the male or female progenitors of mankind for the sake of charming the opposite sex.’

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So Darwin was a comparative biologist and he was thinking about other organisms that sang and make music-like sounds and he thought of course of birds. Now birds sing to attract mates. They don't have language but they sing and Darwin thought perhaps where music came from in our own species. Perhaps we have some pre-linguistic song-like communication system that we used as a courtship display. This is part of what his theory of sexual selection, which is a actually a major component of the book *The Descent of Man.* And it’s a useful theory for explaining many puzzling features in nature like the peacock’s tail. Now if you’re a peacock, a male peacock, having this enormous, colorful tail behind you is a pretty bad idea in terms of escaping from predators or flying up in trees or hunting for food. You have to drag this really big thing around all the time. But it’s very useful for one thing. And that’s attracting a mate. So it can survive and persist in the population because of that utility, even though it has no utility in your day-to-day survival.

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Now this is a somewhat problematic theory with respect to human music. One of the traits we see over and over again with sexually-selected traits is sexual dimorphism. They’re different in the male and the female. So typically male birds sing. It’s the male peacock that has the tail. And sexual selection, you know, applies to our own species as well. We have sexually-selected traits but biologists believe that the facial hair of men and our deeper voice are part of sexual selection, characteristics that make us look bigger or seem bigger, which may have been important in competition with each other.

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But music doesn’t really fit that bill. There’s no evidence at all, zero, that men and women differ in musical ability in any important respect. However, Darwin’s theory was important because it gave rise to a number of other adaptationist theories. And there’s a number of them now trying to explain music and our existence of music in our species by some survival-based mechanism.

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One that’s really popular these days has to do with social cohesion. Now this is a wood cut from Captain Cook’s first voyage to Tahiti. And one of the things that Westerners noticed when they started to explore the world was that music was present in every culture but it was often a very social activity. So instead of a performer up there and then everybody else in the audience, it was often a group, kind of group activity. It involved synchronizing with each other, dancing, moving together. And so theorists have suggested maybe this is a way that promotes bonds because it brings everybody together in a positive way. It puts them on the same emotional page. And, in fact, one thing I think that’s interesting about this theory, it’s gone beyond speculation and inspired some experimental studies having to do with whether or not moving in time, in synchrony with another person as you do in music actually changes the way you feel about them, increases your sense of social affiliation.

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And one nice study that’s been published recently in a journal called *Social Neuroscience*, or *Social Cognition*, is a study where they experimentally manipulated this. They had subjects come into a lab and they told them, you’re going to be doing an experiment where you tap with a metronome. And the metronome is just a visual bar that goes up and down and you have to tap along with it. Well, on some conditions, there was an experimenter sitting next to the, well, there’s an experimenter sitting next to the subject in all of the conditions, but in some cases, the experimenters said, I’m going to do my own experiment here and they tapped to a metronome, too. On half the trials, that experimenter was synchronized with the experimental subject. And in another condition, they were not synchronized. They were tapping to the beat of their own drummer, so to speak. And then in the third condition they weren’t tapping at all, they were just sitting there. And at the end of the experiment, they just gave the people an exit survey, the subjects. And it said, one of the questions they asked was, how much did you like the experimenter? And it turns out that people that had synchronized with the experimenters said they like the experimenter more, even though they didn't really have, they weren't in essence doing any obvious cooperative behavior. So something about moving in sync seems to promote this feeling of connectedness, which was not seen when you were just tapping along with somebody who was tapping at a different rate or not tapping at all. And there's the data from that study showing increased liking with synchrony.

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But there's a different view of music in terms of evolution and that's that music is a human invention. It really has nothing to do with adaptation at all. It's not something that we evolved to do. And a prominent proponent of this view has been psychologist Steven Pinker, author of, *The Language Instinct*, a book that many of you probably know. And in that book, or in a subsequent book, *How the Mind Works,* Pinker argued that, 'music appears to be a pure pleasure technology. A cocktail of recreational drugs that we ingest through the ear.' So what he's arguing is that music tickles pleasure circuits that exist for other reasons. For example, pleasure circuits that evolved to reinforce our linguistic behaviors, or our emotional calls or motor control and so forth. And music has found a way to stimulate all those things and that's why we have it and we're attracted to it. But it didn't serve any biological and evolutionary significance.

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Well, this debate's been going on for a while. One question we can ask with the new tools that we have in neuroscience is, well, what can neuroscience contribute to this? Because we have now the ability to look inside the brain with some of the techniques you've been hearing about, magnetoencephology, MRI, EEG and so forth. And importantly, in terms of music in the brain, we have a history now of growing cognitive research. Just having a brain-imaging machine is not going to get you very far in studying music and the brain unless you have some psychological theories to base your research on. And luckily in the past decade there's been a real explosion in research on music cognition.

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This is a little figure that was published in *Nature* by Dan Levitin, showing the number of papers published in the field of music cognition by decade. And it starts in the 1930s, I believe, and then goes on and the final, the big blue bar is the 2000s and you can see there's been a lot of growth in this area. So the combination of good psychological experiments and cognitive theory and MRI and other brain-imaging tools has allowed us to really grow the field of music and the brain.

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But what can neuroscience contribute? I mean, MRI machines are great but they're not time machines. So how can we understand evolution using those kinds of techniques. What questions can music neuroscience really answer? Well, it can answer questions about what brain mechanisms support our musical abilities. So we can look at the relationship between the brain and music with the arrow going in that direction. But importantly, you can also answer questions about how musical behaviors shape our brains.

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As we've heard today, the brain is an enormously plastic organ. It changes its structure and function throughout life as a product of experience. And music turns out to be a very strong driver of neuroplasticity, so we can ask how do musical behaviors shape our brains, and the things that our brains do both within and without the domain of music.

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So tonight I want to talk about what brain mechanisms support our musical abilities. Because these questions will actually go back and have some implications for the evolutionary debates. And I want to talk about rhythm, in particular perceiving a beat and moving to it. And pitch, in particular perceiving how pitches are related to each other. And then I'll turn to how musical behaviors shape our brain and in particular how musical training impacts language abilities.

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Well, let's start with the beat. Now you probably all intuitively have some sense of what the beat is in music. It's an underlying periodic pulse that organizes musical patterns. A much less formal way of saying that is it's what you would tap your foot to when you hear music. And the beat has a kind of dual nature, which is why I put this picture of Janus, the Two-Faced God, up on this slide. We think of the beat as being in the music. Well, the beat is in the bass or the beat is in the drums. But actually the beat is in our head and we use the cues in music to get that beat in our head. But, you know, just to make sure we're all on the same page here, I'll play a little clip of music and [music playing] Are we on? OK. Can you hear that? [snapping fingers] So there's a beat, right? It's just what you would tap your foot to.

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Now beat perception has several key aspects. First of all and really importantly, it's predictive. And you can see this in a very simplified and reduced setting if you just have somebody tap with a metronome. This is a very easy thing for people to do. You don't need any musical training. Little kids can do it. Bring them into the lab, say, can you tap along with the metronome, and what everybody does without exception is that they tap in synchrony with the metronome. In fact, their taps typically anticipate the timing of the metronome. So if these little bars here are schematically the ticks of the metronome, the little red circles are examples of actual date of a subject tapping along. And you can see they're actually a little bit ahead of the metronome. So they're predicting the timing of the beats, they're not reacting to the beats.

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It's flexible. It adapts to different tempi. So you can make the metronome or the music slower or faster and people have no problem synchronizing to that. It's precocious. It's present in infants. Now how would you know that? Because infants, even though they wriggle very excitedly when you play music, they don't synchronize to the beat of music. But we've devised some novel ways of testing whether or not somebody perceives a beat independent of whether or not they can synchronize with it. And I thought I would play you a couple of examples because this is a recently designed test that we think is a lot of fun. We call it The Beat Alignment Test. And I'll give you a couple of examples right now.

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In this test, all you do is listen. You're going to hear some music and superimposed on top of that music will be some beeps, a sequence of metronome-like beeps. And all you have to do is decide, are the beeps on the beat or not? OK, let’s take a couple of examples. Let’s try this one. [music playing with beeping in the background] OK. There’s one example. All right. And let’s try another one. [Audience member: Louder.] Louder somebody said? Can you turn it up a little bit? [music playing with beeping in the background] Don’t like that so much?

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Well, it turns out babies don’t like that either. So that’s one way of telling whether babies perceive a beat because it’s equally bizarre to have a metronome going, a beeping metronome going in both conditions but they’re distinguishing those conditions, they prefer the ones where they’re on the beat. So babies seem to get this very early in life, even though they haven’t yet learned to move to the beat, which is sort of interesting.

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And this beat perception is intimately related to action. It’s an example of perception-action coupling because what do we typically do when we hear a beat? We tap our foot, we nod our head, or if we’re dancing, we dance to the beat. So there’s this close coupling between perception and action in this particular phenomenon.

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Well, what do we know about beat processing in the brain? Well, you might think, well, this is just an example of kind of a timing ability that we have and it would be related to any other timing ability that we have in the brain. But that’s now how it looks when we look at the brain. It looks like the beat processing network is distinct from other brain processing networks. It’s distinct anatomically, as suggested by neuroimaging research. It’s distinct clinically as suggested by patient studies. And it’s distinct evolutionarily, as suggested by cross-species studies, and I’ll go through all of those now.

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First of all, it’s sort of anatomically distinct. You can take brain images of people as they listen to tone sequences, either do or do not give a sense of a beat. So some sequences would be rhythmic sequences more complex than a metronome but they convey a sense of a beat, and other don't because you scrambled up the timing and it sounds more like just Morse code. And what you find is that beat-based rhythms activate a distinct network in the brain that connects the cortex with subcortical structures.

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Here's one image from a colleague's work, Jessica Grahn that she published and she's mapping out a number of areas. These are some of the auditory areas here and there, but there are motor areas. Now this is just beat perception. The subjects aren't moving at all. They're just listening. But when they feel a beat in the music, you're getting activation of motor centers in the brain. Supplementary motor area, premotor cortex, deep structures like the Putamen. So this circuit seems to involve both auditory and motor centers, simply for the analysis of sound when it has a beat.

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Beat perception also seems to have a special auditory motor relationship. Now we got interested in this because, of course, you can get timing information through multiple modalities. You can get information through vision, you can get it through touch. Is there anything distinctive about the auditory system in terms of beat? Well, we did an experiment to test this. We took tone patterns that invoked a sense of a beat and we had people tap along with them, tap the beat. And people found this pretty easy. So let me give you an example. So these were not musically trained individuals. [beeping sound pattern][snapping fingers] Like that. That's all you had to do. In fact, we made it even easier than that. We started off with a metronome that essentially gave you the beat. And then we turned on this more complicated pattern and all you had to do with stick with the beat.

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So people find it very easy. Now we repeat the whole experiment but instead of tones we use light flashes. So every time there was a tone, now there's a light flash. So you're getting exactly the same temporal information coming into your brain. But it's through your eyes instead of through your ears. Do exactly the same task. Tap along with a metronome at the beginning, a visual metronome now, and then continue to tap in a way that's on the beat. People thought this was very easy, too.

They would tap along with the visual metronome, the flashes would start in a more complex pattern and they would continue tapping. At the end of the experiment, we go back and look at the data and their taps have absolutely no relationship to the structure of the stimulus. They're just tapping along at their own preferred tempo. They're not feeling a beat at all. They're not able to extract that sense of a beat from the visual flashing temporal pattern. So it does seem like there's something special about the fact that it's an auditory motor phenomenon.

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So what we're doing now is we're combining MRI and MEG to ask the following question, what is the motor system doing when you're just sitting there perceiving beat and you're not moving? Is it perhaps actually helping you analyze sound? We think perhaps it is. We think perhaps the motor system is helping you make the temporal predictions that are involved in beat perception. We know that motor system is very good at generating periodic events like walking and gait. And we think perhaps the auditory system and beat perceptions recruiting the motor system and turning its normal function around and saying, instead of making movements, help me predict time. Help me predict internal and maybe essentially doing kind of covert movement for prediction. So we're testing that by combining MEG and MRI now.

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This beat processing network is also clinically distinct from other networks. What do I mean by that? Well, there are patients that have some serious and obvious problems with their normal timing brain networks. For example, the networks that control gait. Parkinson's disease patients. Now this has been observed clinically for a while but music with a regular beat can sometimes help these patients in terms of their walking. And I'll show you a movie that illustrates that. I'm going to play this for you now. And this is from Connie Tomaino at the Beth-Abraham in New York, her Institute for Music and Neurologic Function. And what you'll see is, the movie will start. The patient is sort of frozen and she'll ask for help. And then the music will come on and I want you to pay attention to her movements, and in particular, the relationship between her steps and the rhythm of the music. [plays video]

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Well, it’s interesting. It’s sort of like one of Dr. Ramachandran’s interesting clinical observations but it’s gone beyond that. It’s actually been used to develop a therapy based on music with rhythm for these patients and there have been randomized-control trails comparing that to gait therapy that doesn’t use music and showing that this kind of therapy has measurable outcomes and improvements in terms of gait, velocity, and stride length that are superior to traditional therapy. It’s a young area but it’s growing. But it also raises some very interesting basic questions. So what, how is the auditory system connecting up to the motor system in a way that can bypass the problematic timing networks in the brain and use the beat-based network to help drive moment. That’s a very interesting basic question that I think deserves to be studied.

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OK. Now what about this question of evolution and the network, the beat network in an evolutionary framework. It’s also an evolutionary distinct network. Why do we know that? Well, many species are good at timing single intervals. Rabbits can do it. Monkeys can do it. You just get them to learn a particular temporal interval and judge whether it’s longer or shorter than the one that they’re supposed to have learned. They find that you can do that with lots of animals. But what about periodic intervals? That’s the essence of beat, it’s an interval that repeat regularly in time. Well, how would you test that? Well, one way to test that is see if you can get an animal to tap to a beat, something that humans find really easy. This had not been done ever in the history of psychology or neuroscience until recently when a laboratory in Mexico that is a very experienced monkey neurophysiology laboratory decided they wanted to try and do this in order to study the underlying brain mechanisms. They used rhesus monkeys and they started with one monkey and they trained the monkey on this task for 5 hours a day, 5 days a week, for 5, 6 months, 7 months, 8 months, a year. The monkey was not able to learn the task.

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They realized, you know, these labs know that every once in a while you get a dud, so they tried again and with a second monkey, 5 months, 6 months, a year, no luck. Third monkey, 5 hours a day, 5 days a week, a year, no luck. This is not a trivial thing for a monkey to be able to do. And you would think, gosh, how easy is that. You know, we’re not asking the monkey to paly the Goldberg variations. We’re just asking it to tap to a beat and it’s not able to do it. I think that’s an important finding. Of course it needs to be replicated. Maybe they just didn't have the right training. But these guys were pros.

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But it does raise the question of why we would have basic auditory motor abilities that tmonkeys don't have. You know, it seems like tapping to a beat is pretty basic. Well, one idea is that there’s something about our brains that’s just different from other primates. And that’s true. Humans, well, it’s true in many ways, but there’s one way. Humans are vocal learners. We are, in fact, we’re the only vocal learning primate. Vocal learning is the ability to imitate novel complex sounds and we do that when we learn language. A child growing up in France learns to speak French sounds. A child growing up in America learns to speak English sounds and so forth. But we’re the only species that do that. Other primates have innate calls that they can control when they give but they don't seem to learn these calls or modify them very much.

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And we know that vocal learning is rare among animals in general. There’s just a few groups of birds that do this, the song birds, the parrots, and the hummingbirds. And a few groups of mammals, including our species, dolphins, elephants, bats, and seals. And importantly it’s associated with special connections in the brain between the auditory and the motor regions on the brain. And this has been shown very nicely and in the best kind of way by bird neurobiologists, including Eric Jarvis at Duke University and this is one of his figures showing auditory regions of the brain and motor regions of the brain and showing that in vocal learners you have special connections between these areas that do not exist in non-vocal learners. So there’s, there’s a different neuroanatomy in terms of connectivity and in terms of the sizes of some of these brain areas that comes along with vocal learning.

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And this ability has evolved in other social mammals besides us. For example, I mentioned dolphins. And so it’s quite possible in our own lineage we evolve vocal learning as a social signal, because that’s what a lot of these other mammals use it for that live in stable social groups like dolphins and seals. It’s a kind of way of learning the acoustic label that identifies you as a member of a group.

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Well, this led to a particular hypothesis, this idea that maybe auditory and motor connections in the brain because of vocal learning were the key foundation for moving to a musical beat. That’s what I call the vocal learning and rhythmic synchronization hypothesis. Now how would this work because vocal learning involves connections between auditory centers and vocal centers. But when you move to a beat, you definitely don't vocalize. You typically move your limbs or your trunk or your legs. Well, it could be that developmentally the auditory system sends projections to the motor system to try and target the vocal regions but there’s, for whatever reasons, some more projections get carried along for the ride. They go to limb-control regions, or trunk-control regions. Maybe it’s kind of a byproduct, we don't know yet. But I suspect that those special connections between the human auditory regions and the human motor regions are the ones that support beat perception.

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Now this hypothesis makes some testable and somewhat risky predictions because it makes a categorical distinction between animals that do and don't have vocal learning and says, those that don't have it will never be able to learn to move to musical beats. I mean, that one lab in Mexico, that’s just one study. But this hypothesis says, you’ll never get there if you try and train a monkey, no matter how good you are as a neurophysiologist and a trainer, you’ll never get there with a dog. And note that dogs can do all kinds of complicated things that they did not evolve to do, like catch Frisbees. And so it’s not that they don't have complex motor control. It’s just you’re saying they don't have the right kinds of brains to be able to move to a beat. And neither with bonobos or chimps, these animals that share 98 percent of our DNA because they don't have the right kind of brain organization. So it makes kind of a negative prediction, a very strong, categorical negative prediction, which should be tested further than that one monkey study.

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But it also makes a positive prediction that if we are going to see other vocal learners, other animals that can move to a beat, it will only be vocal learners. Now I thought, this is something I'm never going to get to test. And that's, right around that time by a complete wonderful coincidence, I got an e-mail from a colleague with a link to a video if this bird, Snowball, that you saw in the introduction, dancing to human music. This was a YouTube video. The Backstreet Boys' song was playing, Snowball was dancing. It seemed like it might be synchronized to the beat. This was the first case of another species having this capacity. And I was amazed. But of course I was also a bit skeptical. After all, this is a YouTube video and one wonders, is this for real? Could he just be getting timing cues from humans who are dancing off camera. And critically can he adjust to different tempi if you change the temperature of the song.

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So I sent an e-mail to the owner of the bird, Irena Shultz, who owns Bird Lovers Only Rescue Shelter in Indiana where Snowball lives. And she agreed, thankfully, to do a controlled experiment with us. So we collaborated with her. We did kind of the simple and obvious thing. We took the song we saw him dancing to. We slowed it down and sped it up to 11 different speeds ranging from about 20 percent slower to 20 percent faster than the original song. And we just videotaped him to see what he would do. We made sure nobody was dancing off camera. That was very important. And then we sent the videos back to the lab and we did quantitative blinded analyses because it's really important. You can't just watch videos and decide is he synchronized or not because it's very easy to be fooled.

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So we turned the sound off. We had coders who were unaware of what he was listening to code every head bob of his and make a timeline and then we extracted the musical beats using computer software and that made another timeline and we used mathematical and statistical techniques to see how well those timelines lined up.

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And the result was it really was true synchronization to a musical beat and we could show it using statistics that it was more than chance. Now he synchronized in what we call bouts. That is he would be on for a while and then he would sort of dance, go off and dance to sort of a different beat and, but he would come back and lock on again. Sort of what we think like perhaps a human child would do. This paper caught a lot of interest. The editors of *Current Biology* love this [inaudible] story, they put Snowball on the cover. They changed the color of the masthead to match his yellow mohawk. [laughter] They do really like this.

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But I want to show you a couple of videos from this study. Now these are not YouTube videos. These are from our experiments, so nobody's dancing off camera. And I want to show you a couple of these bouts. Now this one comes from a condition that's a little bit slower than the original song. [video plays] OK. And this one I selected on purpose. This is the fasted condition he's ever, this 20 percent faster. Now he didn't have any rehearsals. You know, it wasn't like we took him backstage and said, you gotta get this down. [laughter] You know, this is the first time he's hearing this. So look what happens. Now I picked this video for a reason. This is a little bit too fast for him and you'll see that, but you'll see he also figures out a solution towards the end of the video. [plays video][laughter]

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So he figures out essentially meter. He figures out multiple levels of periodicity and that's what humans do when we dance. We don't just go like this. We're kind of doing a lot of movements at the same time. Sometimes some of the movements are at half the rate of the other movements . We do nested hierarchical periodic movements. And that's what he's doing. And nobody showed him that. So it's amazing to us.

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Now of course whenever you have a remarkable animal and you show something with it, a big question comes out in science. Is this some unusual freak of nature? Well, we were very fortunate in this regard. There was a group at Harvard led by a graduate student, Adena Schachner in the psychology department who got interested in this problem just around the same time we did and she took a slightly different approach. Instead of working experimentally with one parrot, she said I'm going to do a big survey. Again, this was YouTube to the rescue. She called this her summer of YouTube. And she said I’m going to look for any examples of animals moving to music and I’m going to see if there’s any distributional biases, whether it tends to be vocal learners more than non-vocal learners, so things like birds and dolphins and so forth, song birds, or dolphins, or parrots as opposed to dogs and cats and horses and things like that.

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She said watching videos of animals moving to music was fun for about a half an hour and then it became a summer of real work because she had to do all of the kind of mathematical analyses I told you about before. But what she did find at the end of the day was synchronization to be in 14 more species of animals. And all were vocal learners, every single one without exception, so no dogs, no cats, nothing else. And here’s the kicker, 13 out of 14 were parrots. And then there was an Asian elephant which is also a vocal learner. [laughter]

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Now this raised some interesting questions. And, by the way, it was both male and female parrots that did this. Now why parrots and no songbirds? Songbirds are vocal learners like mockingbirds and so forth. Well, parrots are really interesting socially and we’ve heard a lot about sociology and the brain today. Well, parrots will often pair bond for life. And they do visual imitation, which is unusual for an animal so they can actually imitate the movements of a human. And this is actually an interesting aspect of Snowball’s story. So I met the previous owner of Snowball, the one that dropped him off at the bird shelter. And he told me that he bought Snowball at a bird show, brought him home, and even though his favorite, it was like, his favorite music was barbershop quartet but for some reason he had a passion for the Backstreet Boys. So one day he put on the Backstreet Boys album and he noticed Snowball kind of bobbing. And he got excited. And he and his daughter started dancing with Snowball. And when they danced with him, they would do these big arm gestures like this, and that possibly is the source of Snowball’s foot lifting behavior when he dances. So there’s some visual imitation that goes on in parrots that songbirds don't have.

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And parrots also have motivation for coordinated movement with a partner. So I mentioned, they bond in the wild for very long periods. They have these ritual displays that they do together with coordinated movement. And I think that’s a very important ingredient because in the setting where snowball is a pet, you’re taking this animal out of the wild, putting it in a human setting where you are essentially its partner that it wants to bond with. And so it wants to do coordinated movement displays with you, wants to imitate you and it has vocal learning and I think those three things are the three things you need to move to a beat. And that’s why I think he can do it.

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So to further test this social side of movement to music, we did an experiment we call The Dancing with Myself Experiment, because we wanted to see just how important is it, this kind of social side of this for Snowball. So we had his owner turn on the music and just leave the video camera rolling and leave the room. Or stay in the room and give him verbal encouragement like, you know, good boy. Or actually dance with him. And then we just measured how much of the time he spent dancing while the music was on. And you can see from the data, it’s an enormous effect. And it’s very clear. He dances the least when he’s alone. More when he’s encouraged verbally. And the most when he’s with a human partner. So I think for him, like for us, dancing is very often a, is a social kind of bonding experience for the most part. Although because of the vocal learning brain, he can synchronize and he can do that when there are no other people dancing as we showed in our experiment.

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So what are the evolutionary implications of this? Well, it seems that important components of music cognition can exist without natural selection for music. Parrots don’t dance to music in the wild. This is not something they evolved to do. They don't synchronize to an auditory beat in the wild, and yet they can do it because they have the kind of brain that can do that. And I think that’s consistent within certain invention view of music, that important components of music cognition. We’re not necessarily selected for it but they arose for other reasons and then we built things out of them in a musical sense.

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Now if I want to make [sounds like] a key distinction between evolutionary significance and biological significance. Now maybe synchronization to a musical beat is a byproduct of other brain systems, like the brain system for vocal learning. But it's still valuable for studying how brain systems interact, which is a very fundamental problem in neuroscience. You know, we all tend to focus on one brain system, but we also all know that for a complex behavior to occur, brain systems have to interact and how that works in the brain dynamically is a big important question for neuroscience. And here's a nice, simple model system, where you have the auditory system and the motor system interacting and the primary dimension along which they're interacting is time. So using techniques that help give you information about timing in the brain, like magnetoencephalography combined with techniques that give you information on brain localization, you can actually begin to understand the mechanisms of how brain systems interact to produce a complex behavior in real time. And as we've discussed with Parkinson's disease, movement to a beat has significant practical applications.

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All right. Let me move on to musical pitch. And what I want to talk about in musical pitch is perceiving relationships between pitches because that's what music is, it's about perceiving sounds in terms of their relationships, not just in terms of isolated events. Now pitch we all know from speech and we perceive certain relationships between pitches and speech. You can hear a voice going up or a voice going down. Or you can, and that's all part of what we do in normal speech. Our voices all go up and down as we speak to accent certain words or mark certain sentences as questions and so forth. But in music, so in other words, in speech, pitch has this perceptual quality of being higher or lower. And we're all sensitive to that.

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But the perceived relationships in music go beyond that. And let me illustrate that for you in a few examples. I want you to listen to a couple of melodies. They were composed by my colleague, Jason Rosenberg, in the Music Department at University of California, San Diego, for the purposes of illustration. Just listen to them and pay attention to the last note in particular and ask yourself, is it a stable ending point, a good ending point for the melody, or does it feel sort of incomplete, like the melody should go on in order to sound finished? OK. We may need to bring the volume up a bit on these. Here's the first one. [melody plays] OK. Let's listen to the second one. [melody plays] Sound done? Most people want this. [musical note plays] They want a final note to make that second one sound done. So what, but what is the pitch that ended the first melody? [note plays] It's a B. And what's the pitch that ended the second melody? [note plays] It's a B. It's exactly the same physical tone. For many people it sounds complete at the end of the first melody, and that same physical stimulus sounds incomplete at the end of the second melody because of the way it's functioning in music in what's called the musical key.

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Let me give you one other example. You're going to hear a couple of chord sequences. The first one just pay attention to the last chord and ask yourself does it sound consonant or dissonant? So here's the first one [music plays]. What about this one? [music plays] OK. [laughter] Yeah, for most people that second one's a little unusual. But if I played you that last chord in isolation, it's a perfectly well-tuned major chord. It's nothing inherently dissonant about it. It's just the way it's used in the context that it makes it sound dissonant. It comes from a distance key compared to the original. And I'll end up with one, in case some of you haven't been hearing these and you're getting a little worried, I want to play you one that hopefully you will all hear. Listen to this melody, it will be quite familiar to you and just try and ask yourself is there anything odd here. [The Star Spangled Banner plays] OK. Could you all hear that? Yeah, if you didn't hear anything weird, please see me after the lecture. [laughter]

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There's some seriously weird notes in there. Some of them are just too low but they're still in the key. Others are too low and they go out of the key and they have that distant, psychologically distant quality, that kind of sour note quality to them, which can be nice depending on how you use them. But they're perfectly well, they're all perfectly well-tuned pitches on a piano. It's just some of them pop out in that context. So we have things in musical pitch that have to do with contextual stability, with contextual dissonance, contextual distance that we don't see in speech at all. These are special aspects of musical pitch. And we see them in many cultures, not just western culture. I just put up a image of a Thai xylophone to point that these having stable and unstable pitches and contextual qualities to pitches is not just an aspect of Western music, because this is in many musical traditions around the world, even though they may have different scale structures.

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So in music, pitch takes on these abstract perceptual qualities. Now this is due to the use of stable musical scales, emphasis on certain pitches at any given time. There's a whole cognitive psychology of this having to do with musical pitch. You might ask then what kinds of brain mechanisms are involved in processing these pitch relationships in music. Now one kind of almost intuitive idea is it just cannot be that complicated. I mean, we are just talking about tones, right? This is not, there's no propositions, there's no semantics. This is not higher math. How hard can this be for the brain to do? And I think that kind of thinking underlies the use of music, this growing use of music for animals, and here's one C.D. that's now available on Amazon called, *Through a Dog's Ear, Music for the Canine Household* and music for dogs and their people. And I think, you know, it's kind of, it's nice to think that maybe music has some appeal to dogs and maybe calm sounding music sounds sort of calm to them. But I'm not sure they're getting all the same kind of abstract qualities out of music as we are when we listen to music.

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So maybe the processing is actually quite complex. And it's just, maybe it, and one reason I believe that is that musical pitch processing involves discrete elements in principles of combination. So you have discrete notes on a piano or on a xylophone and principles by which you combine them. You don't just strike the keyboard randomly in any culture. They're hierarchically organized sequences of sound. And sounds start to belong to abstract structural categories. You get tones that either sound stable or unstable, in key or out of key, consonant or dissonant purely by their context and the way they're used, not because of their inherent physical features.

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And I wondered if this could actually share mechanisms with the processing of language in my early work. In particular, our linguistic grammatical relationships, those relationships that help us understand the structural relations between words and a sentence. And this was an exciting question to study when I was in graduate school because linguistic grammatical processing in the brain, there were some new findings in the mid-1990s from neuroimaging suggesting that there were some specific signatures of grammatical processing in terms of brain waves and in terms of brain areas that one could sort of use to identify when the brain was doing language grammar processing.

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So what I decided to do was a comparative study, a direct comparative study using a single group of participants and comparing their brain responses to tonal and harmonic structure in music to linguistic grammatical structure in language. And I used ERPs or brain waves for that study. This was the first study to do this kind of direct comparison. And what we found was a surprising degree of overlap, similarity in the brain responses to these tonal events in music, these abstract tonal events, and to language grammar processing.

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Later on this was extended, in many ways by other colleagues using other techniques including magnetoencephalography, MRI, implanted electrodes or a variety of techniques. One interesting finding was the activation of Broca's region, which is known to be involved in the processing of linguistic grammatical structure, also being activated by the processing of tonal harmonic structure.

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So this led to a hypothesis. Why would you get this similarity between language and music since we're talking about tones, not words. Well, the idea that I proposed in a 2003 paper was that perhaps this is a case of distinct knowledge but shared computations on that knowledge. Now what do I mean that? Let me try and illustrate that with an analogy. If you know the came of chess, and I show you this image, you immediately know, you have a lot of knowledge that's very specific to chess that is sort of activated by looking at that picture. You know that's a king, that's a queen, that's a bishop. You know what kinds of moves they make, you know what checkmate is and so on. That's all just very chess specific knowledge. It really doesn't apply to anything else in your life. But when you play the game of chess, are you using mechanisms in your brain that are only designed for playing chess?

That’s very unlikely. You’re probably using mechanism that do other things, like your ability to strategize, to recognize complex spatial patterns, to think about what somebody else is thinking, what’s called theory of mind. So there’s computations that act on that specialized knowledge but those computations are not unique to that knowledge. And that’s the intuition behind this hypothesis.

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I go into much more detail in my book and in this paper because I relate specific theories of linguistic grammatical structure processing to specific theories of musical tonality processing. And the important thing is, though, that the hypothesis makes some testable and novel predictions. And I, these are kind of predictions about what we might call walk and chew gum experiments. They’re about whether things interfere with each other. You can walk and chew gum at the same time because doing those two things typically doesn’t interfere with each other in terms of the brain mechanisms that you need to do those two things. But if you're processing complex tonal relationships and complex grammatical relationships at the same time in language, maybe that will interfere with each other if they’re using similar brain mechanisms. That was the prediction. And that’s exactly what’s been found in now five published studies across four labs using a range of methods. Only two of these papers have I been involved with. So it’s looking like this might actually hold up.

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The broader picture, though, is that a perceptually unique feature of musical pitch, these abstract qualities, may be related to language processing, even though it doesn’t seem to be related at all in an obvious, kind of intuitive way. And it’s, again, consistent with this sort of music as invention view. That we didn't have to have evolution specialized our brain to do these abstract things with music. Perhaps evolution specialized our brain for language processing and then we can use those computational abilities in this other domain.

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Now again let’s make a distinction between evolutionary and biological significance. The fact that perhaps our evolaution hasn’t specialized our brain for complex processing in music, doesn’t mean it’s not significant biologically. In fact, I think that music may provide a simpler system for understanding certain functional computations in language, in particular, ones that have to do with this kind of grammatical abstract structural relationships, because music lacks semantics. Tones are pure structure. You can study structural relationships without having to get into the complexities of referential meaning, and maybe some of the things we discover in that simpler system will apply to what we understand about language.

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So let's get back to our bigger question of what can neuroscience answer? I've talked about what brain mechanisms support our musical abilities and how those brain mechanisms can have connections to other things that the brain does. But how do musical behaviors in turn shape our brain? This is taking the arrow in the other direction and is very much concerned with the issue of neuroplasticity. I want to just give you a couple of examples from this tonight.

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The first has to do with the recovery of verbal fluency after stroke. After left hemisphere damage, many people develop problems communicating with language, what's called aphasia. And if the lesion is large enough, these can be very persistent problems. And you can imagine, you know how important language is for the way we interact with each other as a species. If you have a long-lasting and persistent and debilitating problem with language, this is very, very severely limiting to you. Especially because it doesn't involve a general loss of intelligence. You're quire aware that you're having this problem.

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So what can we do to help these people? Well, there's no, currently there's no pill you can give them that will make them better. There is no surgery that can you do that will make them better. There's some experimental techniques involving electrical stimulation with implanted electrodes but currently they're still very experimental and there's nothing, it's not a useful technique in a clinical sense right now.

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So what can we do to help them? Well, there’s an interesting observation from the clinic, and it’s over 100 years old, that sometimes these patients can sing songs, very fluently. Songs that they’ve learned from their past. And it’s very striking in the clinic when you see a patient that just doesn’t seem to have any words suddenly produce them fluently when they’re singing.

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This suggest that maybe something about the right hemisphere is involved because that’s the intact hemisphere. And in fact neuroimaging supports the idea that song recruits regions of the right hemisphere that are not recruited for ordinary speech. There are a number of, there have been a number of published studies on this. This is just some from a study that I analyzed with Dan Callan in Japan. And we see a couple of areas in the right hemisphere, including the insula, the superior temporal gyrus, and then the cerebellum that are only activated when somebody sings the lyrics of a song as opposed to speaks them. But the point is that there are these right hemisphere circuits that seem to be more involved in song than speech.

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Well, the idea that the right hemisphere is kind of more biased towards singing than speech led to the idea of a therapy for these patients, these non-fluent aphasic patients, called melodic intonation therapy. And the idea was to use these right hemisphere circuits to help get the words out. And you would start with simple phrases instead of elaborate songs. You’d start with simple real-world phrases, I love you, I love my children, I love my daughter and my sons. These little phrases depicted and the up and down arrows represent the voice going up and down just between two pitches, low and high. But you, instead of just speaking them, you kind of semi-sing them, or melodically intone them. You practice this, the patient practices this with a therapist rather intensively and the goal is to get to longer and longer phrases and ultimately to generalized and novel phrases that the patient actually wants to say.

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The technique has both melodic and rhythmic components because the patient taps with the other hand to each syllable in a metronome like way. And now this is not a cure for aphasia but it does often help.

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But does it work? And if it does work, how does it work? It has been shown and it’s used, but the number of actual randomized clinical trials to study its efficaciousness is still relatively low. There’s one that’s going on now in Boston at the Harvard Medical School that’s particularly interesting because it includes both behavioral and neural components being connected by Dr. Gottfried Schlaug. And he’s doing a randomized control trial looking at melodic intonation therapy what he calls speech repetition therapy which is exactly the same as melodic intonation therapy except you don't have the patient actually melodically intone the sentences. They just speak them back. So it’s like a repeat-after-me kind of therapy.

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And he’s done this now with several patients. These are 40 sessions of therapy, so one and a half hours each session, so this is a fairly intensive therapy. And I want to show you a little data from just two subjects because he’s published some pilot data. Apparently this is now holding up in the larger sample, but this is what’s published. And these are data concerning how much improvement you see. Now these patients were both a year post-stroke. And the conventional wisdom is a year out from a stroke you’ve seen all the improvement you’re going to see in language recovery if you’ve got a big aphasia. But that’s not what they find.

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In both the conditions, the melodic intonation therapy and the other one, they see substantial improvement after this therapy, to the tune of 200 percent improvement in things [sounds like] about the number the phrases they’re able to get out per minute, the number of syllables per phrase and so forth. But the melodically-based therapy is looking better than the other therapy in this pilot data and subsequently in the larger sample.

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And interestingly, Dr. Schlaug, after therapy, had the patients go into the FMRI scanner and he scanned them while they were speaking. Not sing, but actually trying to utter words in a spoken way. And what he found was the patients that had been through this therapy showed greater right hemisphere activations, here, this is the patient that had melodic intonation therapy, shows greater right hemisphere activations when they speak than does the patient who went through the traditional therapy, suggesting that somehow this therapy has perhaps recruited right hemisphere circuits to take over for processes of word articulation that are damaged in the left hemisphere and through neuroplasticity has retrained those circuits to be able to do that.

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He's also observed something very interesting in terms of the structure of the brain. There's many fiber tracks that connect distant regions of your brain. There's one that connects the frontal and temporal lobes called the arcuate fasciculus. It's actually a conglomeration of many fiber tracks but for the purposes of this talk, let's think of it as one big super-highway, information super-highway in your brain. It's important for auditory motor integration. Well, Dr. Schlaug imaged this structure using diffusion tensor imaging, a technique that gives you information about the structure of the brain rather than the functional activation in patients before and after the therapy. And in this image, which I hope you can see on the bottom left, this is kind of a glass brain view. The nose is up here and the back of the head is here and you're looking in and what he's done is, he's used a color to trace the kind of structure of this fiber bundle before and after therapy. And it may be a little hard to see but it's actually measurably different. And the structure seems a bit thicker after therapy, though we're not quite sure what that is, if it's more fibers or more myelin. That remains to be determined. But the structure seems to be changing as a function of this therapy, and the degree of change actually seems to predict how well the patients do in terms of their verbal recovery.

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Now you don't even need to look at patients to see these kinds of effects of music on the structure of the brain. Dr. Schlaug has also published some very interesting data looking at these long-range fiber bundles in musicians versus non-musicians. This is from a paper, a couple of recent papers, and what you're seeing here is another view of the brain. Just to orient you, the nose would now be here and the back of the head here and you're getting kind of a top-down cut-through view. And these are the long fiber bundles on the left and the right, the same arcuate fasciculus. And this is in a 63-year-old non-musician. And this is in a similar-aged musician. And just I think hopefully you can see the difference in the volume of those bundles. And what's particularly intriguing to me is that it's not just the right side that's bigger. These are intact, healthy brains now. You see actually the biggest differences are on the left side of the brain, where we think the fasciculus is involved in language functions. This to me is a very provocative and interesting finding. In fact, one wonders, if these two people had a stroke that damaged a large portion of their left hemisphere, which one do you think would recover better in terms of language functions? I would put my money on this guy. Because of this larger amount of tissue that's devoted to connecting, fibers that are devoted to connecting distant brain regions in the language areas. And this seems to be potentially a function of musical training, though of course you need to do actual experiments to see if this is a causal relationship than just a genetic difference.

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But those sorts of experiments are beginning to happen. Let me just give you an example from a study of healthy children to give you some idea, because this is a really interesting new direction in the neuroscience of music. It's looking at how musical training impacts other cognitive domains. In particular, there's a lot of interest in how it impacts language abilities. So this was a paper published a couple of years ago by Silvan Mirano [SP] and colleagues and he looked at 8-year-old kids and he had them divided into two groups, one that was assigned music lessons, and one that was assigned painting lessons. And the kids found the lessons equally enjoyable. They were equally kind of stimulated by this. And these lessons lasted for 6 months. They met once or twice a week with teachers and they did cognitive tests before and after training. And what was interesting is that both groups showed improvement in cognitive tests but only the music group showed improvement in reading of complex words. Now this was interesting because they weren't practicing reading of complex words. They were practicing xylophones. They were practicing drums. And yet somehow this training was having an impact on their linguistic abilities.

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Moreno and colleagues also showed through EEG that showed enhanced auditory processing of speech. So perhaps something about sharper processing of speech was somehow feeding into their language system and ultimate influencing their reading skills.

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So there’s this now growing body of research on musical training and language abilities in normal young individuals. And I think this is very important research because it has educational implications about the effects that music is having on young minds in school. This research is interesting because there are many auditory features that are shared by music and speech such as pitch and amplitude and duration. And there’s growing evidence that musical training actually sharpens the way the brain encodes some of these features. And this is work being done by Dr. Nina Kraus and colleagues at Northwestern, and she’s actually looking at how the brain stem encodes speech sounds. So in the auditory system, there’s a lot of processing that happens between the cochlea, where sound is transduced into neural activity, and the cortex. There’s many, many neural centers on the way up. These are the subcortical structures. And that’s what she’s measuring using EEG in human subjects. And she’s finding people with musical training show sharper neural encoding of speech sounds and the degree of improvement, their degree of enhancement correlates with the number of years in musical training suggesting it’s a neural plasticity effect, perhaps driven by connections between the cortex that go back down to these centers. There’s actually more connections in the auditory system from the cortex going down than there are from the peripheral centers going up. So there’s a lot of potential for the brain to influence these lower cortical processing centers through experience.

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Now many of these studies are correlational, but as I mentioned, they’re starting to do randomized studies where you assign people to training and then look at changes in the brain as a function of training. And I think this is going to hold up that music is actually causing these changes in the brain.

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And what’s exciting is that these encoding accuracy differences between musicians and non-musicians are associated with important real-world language abilities like reading, hearing and noise, and interestingly, these enhancements that you see in musicians that seem to confer benefits in these language abilities are exactly mirrored by people who have certain types of language deficits, like dyslexia or hearing and noise problems where you see poorer than normal encoding in the brain stem, which raises the interesting possibility that music could actually be useful as a therapy for some of these people.

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Well, this work is all really intriguing but it raises kind of a basic question for neuroscience which is why, why would musical training benefit the neural encoding of speech? It's interesting that it does but if we really want to understand the mechanisms, we have to have a therapy about why it happens. And this is what I've been trying to think about recently and I published a paper in a journal called *Frontiers in Psychology* where I lay out a specific hypothesis for why this would occur. I'm just going to give you the briefest kind of overview of this. But the idea is that music training enhances speed encoding when five essential conditions are met. There's overlap in the brain networks that process some shared feature of music and speech like pitch or amplitude envelope or duration. There's higher precision demands in music than in speech in terms of how well you have to process that feature in order to do what you need to do adequately, for example, play a melody if you're playing a musical instrument.

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There's emotion associated with that encoding. So in music you often get positive emotion when doing musical activities, either because the music is just beautiful or because you're having a good time with your friends or because doing well gives you a positive emotional response. Doing well on a difficult task, like playing a musical instrument. There's extensive repetition, which is what we do when we practice music. We don't just get a piece of music, look at it and then go to the recital, we practice and practice and practice and practice. And we pay a lot of attention when we practice. And when you put all those things together, emotion, repetition, attention, high precision encoding, and overlap with other brain systems, that's a recipe for neuroplasticity, I believe, adaptive neuroplasticity that can drive speech networks to higher levels of performance than they normally would have to have.

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Well this hypothesis makes some novel predictions, which is what I always try and do when I come up with a hypothesis concerning how musical rhythmic training would actually relate to improvements in linguistic reading skills, and this is all laid out in this paper that was just published. But I just wanted to give you a flavor of this. But the idea here is that going back to our big picture about music and evolution, you know, it's possible that music is not something that evolved by natural selection. It's something we evented because we had a complex brain that could do other things and we could put together processing components in novel ways and create this wonderful artistic, aesthetically valuable domain called music.

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If you believe that, which I do, I think you have to make a key distinction between the cultural value of music and its biological significance. I think the cultural value of music is its emotional, aesthetic, social, and spiritual qualities. And this is independent of any biological impact that music has on the brain. Whether or not music influenced our brains is an orthogonal, it's a separate question. I think music is deeply valuable for humanistic regions, even if it isn't something we evolved to do.

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However, I think there is biological significance to music that is different from a culture significance and I think this has to do with neural plasticity and the benefits that accrue from learning a musical instrument, not just listening to music, but actually actively learning music. And this has, this is a consequence of how the brain works, having to do with neural plasticity. And in this process, emotion, which we think of as the first thing that's the biological significance of music is not the biological significance of music. Emotion is the fuel for changing the brain through neural plasticity with music. And that ultimately to me is the biological significance of music.

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So in other words, when T.S. Eliot said, 'You are the music while the music lasts,' I think he was capturing something very important about music in the moment, the fact that music transports us to places, aesthetically, spiritually, emotionally, that we might not be able to go otherwise. And that's why we love it and that's why it means so much to us. But in the area of neuroscience, I think the message is you are the music long after the music has been turned off because of what it does to our brains. And I think that’s the exciting area that you’ll be seeing a lot more of in the coming years. And I think I’ll close with that. I want to thank you very much for your attention.