Guest lecture: David Bjanes

[00:00:02.58] Hi there. My name is David Bjanes. I'm a PhD candidate in electrical engineering at the University of Washington. Today, we're going to talk about Brain Computer Interfaces, or BCIs, and specifically talk about restoring touch and proprioception, how we can understand how the brain interprets sensory information.

[00:00:26.07] Just a brief outline of the things we're going to talk about today, we're going to talk about why somebody should study neuroscience. We're going to talk a little bit about my career path and how I ended up doing research on brain computer interfaces. We're going to talk about what is a brain computer interface and some of the basics of how do we talk to and how do we listen to our brains. And at the end, I'm going to talk about the specific details of my research. I hope you enjoy.

[00:00:57.66] So why study neuroscience? There's many different reasons that people go into neuroscience. For me, the primary motivating factor as an engineer was to build something really cool. I got interested in Iron Man as a kid, as many engineers out there, who wanted to build something that could fly, something they could do really amazing things. And as many of you have seen the movies, Iron Man talks to this computer that can interface with him and do a lot of really interesting things.

[00:01:33.90] This led me to sort of what are impossible problems here today. Some of the most interesting and complex things in our science world are the brain and the human body. We don't understand a lot about how the brain works, or how it's connected together, or how it does mean basic things.

[00:01:55.05] And when our brains or our bodies break, we don't understand many things about how to put them together or how to fix them. One of the specific problems we're going to talk about today is when someone has a spinal cord injury and how we enable them to have feeling again, to have an idea of where their limbs are in space, or to feel things such as touch, pressure, pain, or temperature.

[00:02:20.76] And, of course, maybe the most obvious one is just to help people. People that study neuroscience can have a large impact on a number of diseases, a number of debilitating conditions. Some of the specific ones we'll be talking about are people who have suffered a stroke; people who have been paralyzed, either through a car accident, a skiing accident, or some other traumatic event; or amputation, someone who has had a disease or an injury that causes them to lose a limb.

[00:02:55.15] Specifically, there are many, many people in the US that deal with these very difficult debilitating conditions. And for stroke, we have almost 7 million people that have suffered a stroke. Many of them need a primary caregiver. They need somebody to help them do daily tasks. This makes it very difficult for them to have a sense of individualism or autonomy.

[00:03:23.40] There are about a quarter million people with paralysis or spinal cord injuries. And these patients need either a physical therapist to help them walk or move their hands again. They need somebody to help them transport themselves from place to place. They may have a wheelchair or an exoskeleton or some other robotic device that try to help them move around and interact with their world.

[00:03:50.04] For amputees, there's about 2 million amputees in the US. And many of them use a prosthesis, either on their list upper extremities, their arms, or their legs. But many of them choose not to, because they're clumsy, difficult to use, they're painful to wear, or they figured out another way to get around without them. There are many opportunities for people who study neuroscience to help patients with each one of these conditions-- to improve their quality of life; to help them day to day perform tasks, easier, more reliably; and to have them have a sense of greater autonomy, be able to do things by themselves to have a greater sense of being able to make an impact in the world.

[00:04:40.18] So let's talk a little bit about how I got here. I began my journey as an engineer and neuroscientist playing with LEGO. I was involved in middle school in the FIRST LEGO League, which is a international competition to solve different challenges using a programmable brick based off of the LEGO Mindstorms.

[00:05:05.01] Teams develop a bunch of different robots and solve different challenges on a playing field under like time conditions. You have to program the robot. You have to build the robot. You have to present it to judges. You have to plan a business model around your device, incorporating many aspects that you see today in different companies and engineering aspects.

[00:05:33.60] The next thing I began working on was active prosthetics. Out of FLL and building things with LEGO, I wanted to be able to build things that could help people and everyday have somebody be able to use my device to be able to get around better, to be able to do things on their own. I worked with Hugh Herr at the Media Lab at MIT, building knee and active ankle prostheses.

[00:06:01.29] This was my first sort of foray into understanding what does it take to build a device that interfaces with somebody's body. There's a socket for the knee and the ankle, which needs to attach to their arm or leg. This needs to be comfortable. It can't pinch them. Typically, there are damaged nerves around the end of their amputated appendage. It can be very painful to wear some of these for many hours at a time.

[00:06:29.20] So in the lab, we worked on something that was comfortable for somebody to be able to wear all day long, something that mimicked actual ankles and actual knees and the same motion, such that, if somebody had one, fully complete leg and a robotic leg, that the two did not cause the person to walk off balance. These are just some of the challenges that I started being aware of by working in this area.

[00:06:58.18] The next thing, after working on appendages on the arm or leg, I wanted to work more in the brain. So I began doing research with brain signals that we had recorded from individual neurons in different animals and also humans. One of the challenges is to identify what is a signal-- what is actual brain activity-- and what is noise-- what is background activity.

[00:07:26.55] And many of the signals in the brain are very, very small. And so I developed some algorithms to try to identify which of the signals was interesting for the particular task or things that we were looking at and which were background information and how to extract those important signals, even if they were very small, from very large background noises.

[00:07:52.19] After I had worked on brain signals, I wanted to understand more about rehabilitation-- people who undergo a stroke or spinal cord injury and what are the actual therapies out there for helping them regain function and more autonomy in their daily life. This is a robot called Bones. And it is a zero-G gravity upper extremity rehabilitation robot, which provides the user mobility by putting their arm essentially in a zero-G environment.

[00:08:25.25] This enables somebody who doesn't have the strength to pick up their arm under gravity, put them in a zero-G environment, so that they can use whatever little muscles activity that they have left in order to move their arm. The hope is they can use this robot over time and slowly add more and more gravity until they can move their arm on their own outside of the sling.

[00:08:48.77] I did research here with normal humans that don't have a spinal cord injury, understanding what are the best ways to help somebody learn use this robot. When somebody is using an assistive robot, that can use it as a crutch. And they can not go through their therapy correctly by using the robot to cheat essentially and help them do it, rather than them learning on their own. So I investigated some ways to prevent people from cheating when they're using this robot in order to effectively do their therapy.

[00:09:21.66] After college, I decided to go to graduate school, because no companies were working on the specific brain type problems that I wanted to work on. There weren't any companies building devices or ones that could make money off of some of the fundamental science questions that I wanted to ask. So I went to the University of Pittsburgh to look more about how to understand brain signals and how we could use them to control a prosthetic device.

[00:09:51.11] I'm going to use the analogy of a stadium. So we can imagine that our brain is a giant stadium, watching a football or a soccer game. And there is a lot of spectators. There's a lot of people cheering or screaming in relation to this game.

[00:10:05.39] In the brain, we have trillions and trillions of neurons that are each doing tasks. They're communicating with one another. They're connected in very complex networks. And this is roughly analogous to a whole bunch of people in a stadium all talking, conversing with each other, ultimately having some goal.

[00:10:28.76] When we want to listen to the brain, what we can do is insert tiny little electric wires into the brain, either on the surface or inside of the brain itself, to listen to the activity of these neurons. And this is sort of roughly the same as sticking a bunch of microphones in our stadium and listening on the other end with a pair of headphones.

[00:10:50.06] When we want to talk to the brain, we can, of course, use a loudspeaker in our stadium analogy to have a bunch of people hear and understand what we're trying to say. For their brains, we can use those same little wires. And we can stimulate with tiny bits of electricity in order to activate those different neurons.

[00:11:14.37] When we're thinking about accessing different amounts of neurons, we can start from the macroscopic, the very large, ECoG, electrocorticography And these are very large diameter metal disks that we can place on the surface of the brain. And they can communicate with a very large number of neurons.

[00:11:35.09] If we record from these disks, we can record several thousands of neurons. And we get the average response of a large number of them. And this is roughly the equivalent of listening to a microphone perhaps hanging from the ceiling above our stadium. We can listen to a whole section either cheering or screaming or booing.

[00:11:55.41] We can go smaller by looking at microelectrocorticography grids. These are much smaller but still record the activity of thousands of neurons in the brain. And because we're on the surface of the brain, we're a little removed from these neurons. So again, we're getting an average. Maybe we're listening to a single section or a smaller section.

[00:12:16.26] The smallest that we can go, according to our current technology, would be intracortical microwires. And these tiny microwaves are about 1/10 to 1/100 the diameter of a human hair. And we stick a whole bunch of these on a grid, maybe a millimeter by millimeter. And that's that square rectangle that you see in a picture. And these can access hundreds to tens to individual neurons.

[00:12:41.95] And this is like having a microphone sitting right next to a person in that stadium. We can dial in and listen to only a few neurons. Or we can listen to tens of neurons. All these different approaches allow us to talk to different groups of neurons. And depending on our application, whether we want to drive a prosthetic limb or that we want to listen to a whole brain area, can help us make decisions about which ones would be appropriate to use.

[00:13:13.92] Now, each one of these, being on the surface of the brain, which mean ECoG or the penetrating wires, they can also access different layers of the brain. Without going into specifics, you can see here the large diameter dipoles around the circular disk. That would be the ECoG laying on the surface of the brain. Or we can embed those wires deep into the brain and listen at deeper structures depending on our application.

[00:13:45.03] My research in the University of Pittsburgh was trying to understand how many different neurons are we listening to under different conditions, different record types of recordings. So for the microwire, we can see here in the top left corner, you can see a long spike. That long spike is a tiny little wire. And these little black dots in that panel are different individual neurons. And depending on the distance from our wire to the individual neurons would determine how large or how small our signal will be.

[00:14:20.79] You can see the raw output of what we'd record on that wire. This is the essentially audio file or the signal that we get listening to those neurons. And every time you see a large spike or the cyan-colored snips is when an action potential has fired. We can record that as electrical activity.

[00:14:41.16] My software developed a way to extract those individual times when the action potential has fired, what you can think about is somebody talking or saying a sentence. We can aggregate those down at the bottom under the box called Snippets. Or we can use a different type of extraction procedure, which enables us to look at all of it, all of our data in a different way. And this is under the Snippets PCA. So here, we can see each different one as a different cluster.

[00:15:11.49] Here, I've highlighted where actually each of the neurons came from. Each of the different shapes correspond to a different neuron. Looking at it when everything is the same color, it can be really difficult to tell how many different neurons are actually present. But using some mathematical and statistical tools, we can identify how many clusters there are, how many neurons there are, and get an idea of who is talking when.

[00:15:39.86] And finally, I'm here at the University of Washington, doing my PhD in electrical engineering. And once I had a little information of how we can listen to the brain, I wanted to be able to talk back to the brain. I wanted to be able to communicate it and give it information, specifically sensory information.

[00:16:00.01] A sensory motor cortex in humans divided into a couple of different areas. There's something called the homunculus, which is this curve that you see down underneath the brain. And that divides the region of brain which receives sensory information from the rest of your body into a bunch of different sections. So depending on where the sensation is coming from-- say your throat, your tongue, or your teeth-- that's going to go to a specific region of the brain. And that's shown in red here.

[00:16:29.47] Specific information coming from your neck or your head of your shoulder is going to go to a different part of that region. And using scientific experiments, doctors have experimented and been able to map out pretty reliably between different human's specific sections of your brain which correlate to different parts of your body.

[00:16:49.55] We can stick one of our microwire arrays in a specific section-- say, the hand or the arm for somebody who has been paralyzed and can no longer feel touch in their hands or feel somebody gripping them or somebody touching them on the arm. And what we'd like to do is talk back to that area. And when our robotic sensors understand somebody has touched you or gripped your hand, we can communicate back to the brain and tell them this is going on.

[00:17:21.49] In the brain, we have an area called M1, which is where the brain communicates to your arm or your hand, for example, and tells it to wiggle your fingers, to grab a cup, to type on a keyboard, or play the piano. You have another area of your brain, which we were just talking about, the sensory motor cortex, or called S1. And this is the part of the brain that receives all that sensory information that comes. When you type on the keyboard and your fingers feel you press the button down, that information goes up your spinal cord into your S1.

[00:17:57.84] You also have another way of telling that you've pressed the key or gripped a coffee cup, and that's your eyes. We have visual feedback. You can see that you've pressed the key. You can see that you've grabbed a cup.

[00:18:10.53] That also goes back to here, the visual cortex, or V1. It gets processed by your brain. And that's another way for your brain to confirm, OK, when I told my hand to press a key, that actually happened.

[00:18:26.70] Visual feedback is much slower than touch. This is why you can throw a baseball without having to watch your hands curl around that ball and throw it. And you can do several other tasks, such as tie a tie and do your buttons, things that require that you don't have to actually look for.

[00:18:49.20] When you have a spinal cord injury, your communication between your brain and your body, it gets cut or it gets broken. And your M1 is still telling your body, hey, I want you to wiggle your thumb. But the connection between your brain and your thumb, it's been broken.

[00:19:07.35] And similarly, the sensation of your thumb moving, of your thumb squeezing a coffee cup, or touching a keyboard, your thumb is telling your brain, oh, something has touched me, oh, I'm pushing down, oh, I've squeezed something. But it doesn't get back to your brain. And so you don't know that it's happening, because that has been cut. Your eyes still work. You can still see, so that pathway still remains open.

[00:19:34.71] This lady's name is Jan at the University of Pittsburgh. And she has been implanted with those same wires in her motor cortex and her sensory cortex. And she is controlling the arm by reading those brain signals.

[00:19:50.43] There's a computer, which is reading out. When she's telling the robot to move, she's thinking the same things that you would think when you make your arm move. The computer is translating those brain signals, which are being captured into a control to tell the robot to move. In this case, she is picking up a piece of chocolate. She can bring it to her mouth, and she can eat it.

[00:20:13.50] Even though this is incredible and amazing that she can do this, she still doesn't have any sensory feedback, which you can see. She misses a little bit. She hits her chin.

[00:20:23.68] It's still a little difficult for her to move that around. It doesn't look as fluid or dexterous as if you were to pick up a piece of chocolate and move it to your mouth. What we want to do is add sensation to that, so that when she squeezes that chocolate with the robot hand, she can feel it just like you feel a piece of chocolate in your hand when you're moving it to your mouth.

[00:20:43.39] Another thing is probably reception. So if you close your eyes and move your hand around, you know exactly where your hand is. You can tell whether it's open or whether it's closed.

[00:20:51.39] She doesn't have any feeling of that robot hand. So she has to watch it continually with her eyes. We would like to stimulate the sensory motor cortex and will give somebody an idea of whether that hand is open or closed or where that robot is in space, so that they can have the same type of feeling that you would for a normal arm.

[00:21:13.21] So this is how the computer is going to come in. So in our spinal cord injury patient, the motor pathway-- so the command is coming from the motor cortex down to your arm, those are broken. The sensory information coming from your hand back to your brain, that's also disconnected. So we're going to stick a computer to be able to record those signals from your brain in order to tell your robotic arm or maybe your actual arm through reanimation what to do.

[00:21:44.62] What my research is focused on is we want to go also the other way-- we want to talk back to the brain. This is a Bidirectional Brain Computer Interface, or BBCI. And what we want to do is identify what is the signal that we want to send back to the brain. The brain is looking for some code, which used to come up the spinal cord, to tell it, hey, my hand is opening, or, hey, my hand is closing. We want to have this happen at the same kind of speed as a normal person when you touch or when they feel something on the order of about 20 milliseconds.

[00:22:19.25] A question for us is, what is that signal supposed to be, and what does it look like? The primary way that we are going to talk back to the brain is through electrical stimulation. We're going to use a tiny little bits of electricity. And we're going to activate those neurons in the same way that neurons would activate each other through those electrical and chemical reactions.

[00:22:40.83] The basic building block of these patterns-- the electrical patterns that we're going to present to the brain-- is this biphasic pulse, so you can see as a square pulse, starts with a high pulse followed by an identical low pulse. And what we can do is we can change that amplitude. So we can make it bigger. Or we can change the width of it, and we can make it wider.

[00:23:01.55] It's important that they're balanced, so that we don't leave any leftover electricity in the brain. That could cause the tissue to start heating up or to get damaged. Imagine, it would be like electrocuting your brain. But by having the same size pulses with a high and low, we can make sure that all the electricity we inject also comes right back out.

[00:23:28.18] And we can assemble this building block into a series of trains. So we can set several of these places altogether, and we'll call that a train. Now, we have a couple of different variables we can play with. We can play with the stimulation frequency, so we can deliver those individual pulses very rapidly, like gzz, gzz, gzz, gzz. We can deliver them really long, gzzz, gzzz, gzzz, gzzz. So we can change that.

[00:23:52.80] We can also change the number of pulses. We can deliver a group of 5, a group of 10. We can deliver them one at a time. And we can also change how often do we send these trains. So that's called are interchangeable. So we send them really close together? Do we spread them far apart?

[00:24:08.67] All of these variables give us different ways to change the pattern. And they might impact the sensation that the person has. So we can imagine, if you change the amplitude, we might change the intensity of the feeling. If we change the width, it might change the duration of the feeling. These are questions you want to look at.

[00:24:27.78] So we have our pattern. We have a set number pulses. We a frequency of those pulses being delivered. We've established some frame to deliver each one of those trains. And what we want to do is we want to map that to intensity.

[00:24:41.49] We're going to be working with animals. So we can't ask them, what do you feel? But we can train them to identify for us more intense or less intense feelings.

[00:24:52.44] So for example, for frequency, a group of researchers took a rat. And they had the rat look around for some apple juice. So here in the circular arena, you can see three different little targets.

[00:25:07.80] What happened was, for the target that they wanted the rat to find-- in this case, port number 3-- the closer the rat was playing to that, the higher the frequency. So when the rat was pointing directly at the correct target, you knew the frequency was at the highest value possible. And when the rat looked away, you could see the frequency would decrease. And so in this way, the rat could use the frequency to identify which target to go to.

[00:25:34.64] This is a way that we could train intensity. So perhaps, if you grip your coffee cup really, really hard, we could tell you tell your brain that by stimulating in a very high frequency. Versus if you weren't touching your coffee cup at all, it might be at a very low. Frequency

[00:25:54.19] I developed a series of tasks to enable rats to be able to communicate what they were feeling. We had the rats play a little game called finding the invisible ball. They grip a little Xbox joystick that is attached to a 3D printed handle. So it's their size, so they can use it. And they move it around to different targets in a half semicircle.

[00:26:17.78] So this is kind of like when you're at the carnival and you're sticking your hand in a cardboard box. And you feel something. And you're trying to feel where is the squishy thing.

[00:26:28.76] In our case, the animal wasn't sticking their hand and feeling the squishy things. But in every target that it goes to, we can deliver a different stimulation pattern. So initially, we can just have it find where is this stimulation. So in all the targets except for one, we don't deliver any stimulation. No electrical patterns are given to the brain.

[00:26:49.79] But on the target that we want it to do identify, we can give a specific pattern. And then the animal can go in search. And it'll find the stimulation. This is the way we know the animal can feel the electrical power we're giving it.

[00:27:05.75] But beyond this, we want to ask, OK, can you tell us which is a more intense one? So if I make my pulses larger, can you feel that I'm making it larger? This is a way for us to understand how many different combinations can we give to the brain. We want to see a large number of patterns, because we want to communicate many different things, many different sensations. If by changing the amplitude a lot and the animal cannot tell the difference between two different amplitudes, this would tell us we need to change something else.

[00:27:43.87] Here, you can see a picture of the device. So the animal will grip the little joystick and can move it all around. We have a series of lights around the outside. And that tells it all the different targets that it is going to.

[00:27:59.59] So after they learn how to use that joystick, we can stick those wires into their brain. So we do a small surgery, which is just a small cut on the side of their head. And we can stick these wires into the different layers of the brain that correspond to where the animal would feel some sensation on their hand or on their arm.

[00:28:28.52] And to make sure that we got in the right spot, what we can do is we can stick a little electrical pad on their arm and give it a little burst of electricity that makes their bicep twitch. This doesn't hurt at all. You can do this on yourself.

[00:28:43.57] And what we can do is we can record from those specific areas, those wires that we implanted, and we can see if some sensory information comes back. And here, I've shown a heat map on a couple of different rats. So the more red each box is, the more sensory information came on that site, so that we can identify a certain part of the brain that's responding to that sensory information.

[00:29:11.08] So now, as a main part, what do we want to really find out? So we're trying to understand, what is a just noticeable difference. So in human psychophysical studies, what we'd like to do is understand how many different states there are between, say, two actions, such as closing your fist to open your hand the whole way.

[00:29:30.75] So when we are conveying a sensation to somebody, we don't want to just tell them, your hand is totally open or your hand is totally closed. We'd like to tell them anywhere in between where their hand is-- so all the way from my hand is totally closed, to it's opened a little bit, to it's opened a little bit, to it's halfway open, to it's open some more, to it's almost all the way opened, to it's completely opened. Anywhere the hand is, we want to be able to tell the brain, this is the position of the hand.

[00:29:58.11] What we would like to do is use our stimulation patterns to tell us, which one has the most resolution, which one can we convey the most amount of states? And the way we're going to measure that is we're going to pick the highest state-- so the one that corresponds to my hand is totally open, say this is a large pulse. And we're going to ask the rat to find that pattern.

[00:30:20.34] Then we can present in the wrong targets smaller distractor patterns. So the amplitudes there will be much smaller. And then we can ask the animal, can you feel the difference, can you find that high one? And when the distractor ones are really tiny and the difference is really large, it's really easy. They get it right every time.

[00:30:39.61] And as the amplitude gets bigger and bigger, it gets harder to tell the difference. And then we can identify, OK, this is how much amplitude we need to change in order for the animal to tell that something changed. Hence, we call it the just noticeable difference.

[00:30:55.80] We could plot this on a graph. Here at the very end, we've said, the amplitudes are almost the same, and the animal is right at chance. And as the distractor amplitude gets smaller and smaller, i.e. the difference gets greater, it becomes easier and easier for the animal to detect a difference. And then their performance goes up to 80% to 90%.

[00:31:24.25] We've done this with two different ways of changing that stimulation. So we've done this with amplitude and pulse width. And you can see these really nice curves, which tell us when we change the amplitude, when we make it smaller and smaller, it becomes easier and easier for the animal to tell the difference between two amplitudes.

[00:31:45.12] When we compare two different pulse widths, similarly the smaller the difference, the harder it is for them to tell, and the larger difference, the easier it is for them to tell. And this give us a measure to say, oh, we need to change pulse width and amplitude about 30% for the animal to reliably tell the difference. This tells us that, when we're stimulating on a range of, say, 20 microamps to 100 microamps, we maybe have five to six different states in there that we can tell the animal, your hand is totally open to your hand is totally closed.

[00:32:18.76] At the very end here, I want to talk a little bit about failure. In science, many experiments happen. And we don't exactly know what's going to happen before we start our experiments. A lot of science is trying to understand something that nobody understands or nobody has figured out before. And this is why we do experiments.

[00:32:40.66] Because we don't know what we're doing, we don't know exactly what we're going to find. A lot of the times, we do not get the results that we respect, or we don't get any results at all. We have to try things by trial and error. We need to try the same things multiple different times.

[00:32:58.91] And rather than, I'm going to plan my experiment, I'm going to figure this out, I have a nice linear path to figuring out how to deliver sensory information, most often our paths look something like this. It can be disheartening and difficult to try many, many things many times and not be able to understand it. But that's a part of science. It's also a way to keep our eyes open when we're doing experiments and to see things that we were not looking for or to see things that we didn't expect and to try new experiments based off of those things.

[00:33:40.12] In life, life is also rarely a straight A to B or A to Z line. Often, there's many backtracks and many missteps. And rather than seeing those as failures, we need to see them as opportunities to try to learn more and understand the world about us.

[00:33:59.07] So in conclusion, I talked a little bit about how engineering is really about problem solving, trying to figure out the different things in the world that we don't understand, and trying to build some tools, trying to build some math to try to make people's lives better, and to build them things that help them in their everyday life. In engineering, we can learn how to solve many different types of problems. We talked a lot about neuroscience and how to help people who have had either strokes, spinal cord injuries, or amputees, and some of the different ways that we can do research to help them overcome the many challenges that they face.

[00:34:40.08] Engineering is really broad. There are so many different ways to apply the tools that we learn to so many different areas. And at the end of the day, we want you to have fun. Engineering is about helping people. It's about understanding the world around us. And it's about enjoying ourselves and being able to solve these problems.