How mathematicians are unlocking the secrets of the human brain

Dr. Jérémie Lefebvre combines computer and brain power to discover how our minds work

David Israelson

The mysteries of the mind may challenge philosophers, but to Dr. Jérémie Lefebvre the challenge is different – the brain is the ultimate computer math puzzle.

"Think of the brain itself as a computer – a biological computer. Instead of using software or hardware, it uses wetware," says Dr. Lefebvre, a neuroscientist and mathematician at the Krembil Research Institute in Toronto.

Dr. Lefebvre's lab at Krembil studies computational neuroscience and non-linear dynamics.

It's called the SYNC lab – it synchronizes studies and stimulates corroborative work around the world among researchers working in a variety of disciplines. Dr. Lefebvre and his team develop and analyze models of neural circuits to better understand the brain and how it is affected by neurodegenerative diseases.

"This is where mathematics and physics come in," he explains. "The neurons in the brain are actually doing computations and calculations, and we're trying to crack the code."

Using [data from] all the most up-to-date information-gathering techniques, such EEGs, scanners and fMRIs that are used by his colleagues and collaborators, Dr. Lefebvre and members of his SYNC lab team assemble data about what's actually going on in the brains they examine.

That's only the beginning of the research. He says it's "interesting" to see a part of the brain light up when, say, a patient raises an arm, but the SYNC lab is looking for more.

"This is where my work starts: we look at what the brain is doing and how it's doing it, as opposed to where in the brain it's going on," Dr. Lefebvre explains.

The goal of the one-year-old lab's clinical research is to develop mathematical and computational descriptions of neural systems. The SYNC team wants its work to continue to stimulate interdisciplinary work and collaboration among experimental, clinical and theoretical scholars in neuroscience and medicine.

"In particular, what I'm working on is brain stimulation. Right now, there's a resurgence of interest in the use of electrical fields to shape the activity of neurons in the brain," says Dr. Lefebvre. He's been interested in brain research since childhood, wondering why the brain patterns of his sister, who has cerebral palsy, caused her severe disability.

"I combined my curiosity with my interest in math," he says. He cautions that research takes a long time to yield answers.

In July 2016, Dr. Lefebvre and the SYNC lab announced what their computational model is revealing so far. It shows that in addition to sustained and recurring stimulation, exposure to intense, high-frequency brain stimulation can cause brain waves to accelerate – a sign of improved information processing and awareness.

"These results open new perspectives. Information gleaned from our model lays the groundwork for future studies investigating how temporary treatment with brain stimulation can cause lasting effects in neuropsychiatric diseases with unbalanced brain activity, including major depression, Parkinson's disease and schizophrenia," he says.

"Neurons are using electricity to communicate, so the idea is to use electricity to manipulate or control those neurons, [to] tell them what to do. Maybe we'll be able to tell those neurons to do things differently, to restore healthy function."

While deep brain stimulation is already a form of treatment for Parkinson's, SYNC's research hopes to yield more comprehensive understanding, to improve its precision and effectiveness.

"We actually don't know how it works yet. We don't know how the electrical stimulation patterns interact with the different networks of the brain."

Another aspect of the computational science at the SYNC lab is to analyze neural data gathered from patients, to find the "signature" elements common to particular brain diseases. This information is shared with researchers around the world.

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"We're developing models of diseases and how they work, to go beyond just applying some form of drug. If we understand the mechanics of the disease, we can be more efficient," Dr. Lefebvre says.

As part of their groundbreaking study, Dr. Lefebvre and his team build computer models of neural networks, which they can mix and manipulate on screen.

"We can see what happens if we take one component of a model out – is it similar to what we see in human data?" It's a less risky and potentially more accurate way of pinpointing what parts of the brain are linked to neural disorders.

The SYNC lab has the ability to tap into the most high-powered supercomputers and the latest state-of-the-art software.

"And we use the most sophisticated tool – mathematics," Dr. Lefebvre says.

"We devise equations by hand, and we use the computer to see if we can't solve them analytically. We collect the data that's gathered throughout various clinical labs and try to compress it and chunk it into something that makes sense."

Unlike research that relies on ultra-expensive technology, "here we can do a lot with little resources. We can go quite far with moderate investments, because math does not require expensive equipment. Most of the funding we require goes into recruiting the best people," he says.

"The brain is the most complicated object in the known universe. Being able to crack that device is most satisfactory and using mathematics to do it is something that I find profoundly elegant." ■