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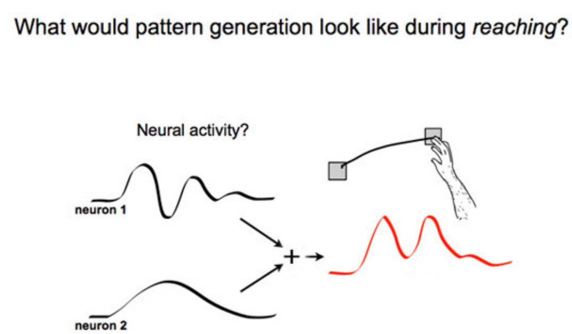
Stanford engineers discover neural rhythms drive physical movement

Neuroscientists had once believed that the neurons that control movement send specific external information such as distance, direction and velocity to the muscles of the body. In a surprising new finding, however, researchers at Stanford University have proposed a new model that says motor neurons instead send basic rhythmic patterns down the spine to drive movement.

By Andrew Myers

Illustration courtesy of Stanford School of Engineering



The 19th-century mathematician Joseph Fourier showed that two rhythms could be summed to produce a third rhythm. Stanford researchers have shown that such mathematics are at play in the brain activity that produces arm movements. (Click image to enlarge)

The neurons that control movement are not a predictable bunch. Scientists working to decode how such neurons convey information to muscles have been stymied when trying to establish a one-to-one relationship between a neuron's behavior and factors such as muscle activity or movement velocity.

In an article published online June 3 by the journal *Nature*, a team of electrical engineers and neuroscientists working at Stanford University propose a new theory of the brain activity behind arm movements. Their theory is a significant departure from existing understanding and helps to explain, in relatively simple and elegant terms, some of the more perplexing aspects of the activity of neurons in the motor cortex.

In their paper, electrical engineering Associate Professor Krishna Shenoy and post-doctoral researchers Mark Churchland, now a professor at Columbia, and John Cunningham of Cambridge University, now a professor at Washington University in St. Louis, have shown that the brain activity controlling arm movement does not encode external spatial information – such as direction, distance, and speed – but is instead rhythmic in nature.

Understanding the brain

Neuroscientists have long known that the neurons responsible for vision encode specific, external-world information – the parameters of sight. It had been theorized and widely suggested that motor cortex neurons function similarly, conveying specifics of movement such as direction, distance and speed, in the same way the visual cortex records color, intensity and form.

"Visual neurons encode things in the world. They are a map, a representation," said Churchland, who is first author of the paper. "It's not a leap to imagine that neurons in the motor cortex should behave like neurons in the visual cortex, relating in a faithful way to external parameters, but things aren't so concrete for movement."

Scientists have disagreed about which movement parameters are being represented by individual neurons. They could not look at a particular neuron firing in the motor cortex and determine with confidence what information it was encoding.

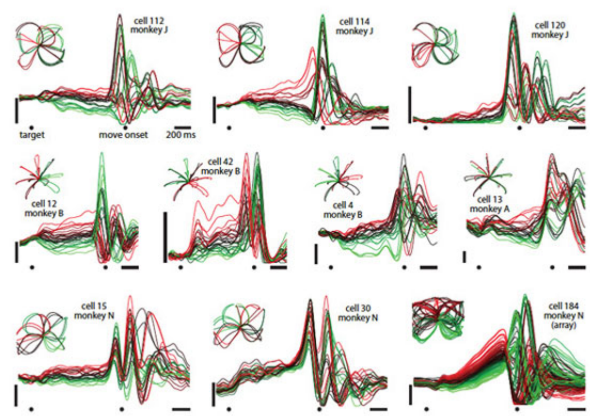
"Many experiments have sought such lawfulness and yet none have found it. Our findings indicate an alternative principle is at play," said co-first author Cunningham.

"Our main finding is that the motor cortex is a flexible pattern generator, and sends rhythmic signals down the spinal cord," said Churchland.

Engine of movement

To employ an automotive analogy, the motor cortex is not the steering wheel, odometer or speedometer representing external-world information. It is more like an engine, comprised of parts whose activities appear complicated in isolation, but which cooperate in a lawful way as a whole to generate motion.

Illustration courtesy of Stanford School of Engineering



In a series of striking graphs, the Stanford team plotted the signals from individual neurons in the motor cortex as monkeys completed a series of reaches. The reaching motions are shown by the starburst patterns at the top left of each graph. The neuronal patterns are then plotted atop one another for the entire series of reaches, clearly establishing the rhythmic nature of the brain activity. (Click image to enlarge)

"If you saw a piston or a spark plug by itself, would you be able to explain how it makes a car move?" asked Cunningham rhetorically. "Motor-cortex neurons are like that, too, understandable only in the context of the whole."

In monitoring electrical brain activity of motor-cortex neurons, researchers found that they typically exhibit a brief oscillatory response. These responses are not independent from neuron to neuron. Instead, the entire neural population oscillates as one in a beautiful and lawfully coordinated way.

The electrical signal that drives a given movement is therefore an amalgam – a summation – of the rhythms of all the motor neurons firing at a given moment.

"Under this new way of looking at things, the inscrutable becomes predictable," said Churchland. "Each neuron behaves like a player in a band. When the rhythms of all the players are summed over the whole band, a cascade of fluid and accurate motion results."

Precedents in nature

In the new model, a few relatively simple rhythms explain neural features that had confounded science earlier.

"Many of the most baffling aspects of motor-cortex neurons seem natural and straightforward in light of this model," said Cunningham.

The team studied non-rhythmic reaching movements, which made the presence of rhythmic neural activity a surprise even though, the team notes, rhythmic neural activity has a long precedence in nature. Such rhythms are present in the swimming motion of leeches and the gait of a walking monkey, for instance.

"The brain has had an evolutionary goal to drive movements that help us survive. The primary motor cortex is key to these functions. The patterns of activity it displays presumably derive from evolutionarily older rhythmic motions such as swimming and walking. Rhythm is a basic building block of movement," explained Churchland.

Reaching for the grail

To test their hypothesis, the engineers studied the brain activity of monkeys reaching to touch a target. According to the researchers, experiments show this "underlying rhythm" strategy works very well to explain both brain and muscle activity. In their reaching studies, the pattern of shoulder-muscle behavior could always be described by the sum of two underlying rhythms.

"Say you're throwing a ball. Beneath it all is a pattern. Maybe your shoulder muscle contracts, relaxes slightly, contracts again, and then relaxes completely, all in short order," explained Churchland.

The researchers say that although the activity may not be exactly rhythmic, it can be created by adding together two or three other rhythms. The team asserts that this may be how the brain solves the problem of creating patterns of movement.

"This surprised us a bit. In decidedly arrhythmic movements, there were these unmistakable patterns," said Churchland.

"This research builds on a strong theoretical framework and adds to growing evidence that rhythmic activity is important for many fundamental brain functions," said Yuan Liu of the National Institute of Neurological Disorders and Stroke, National Institutes of Health (NIH). "Further research in this area may help us devise more effective technology for controlling prosthetic limbs." Liu is the co-lead of the NIH-NSF (National Science Foundation) Collaborative Research in Computational Neuroscience program.

"In trying to find the basic response properties of the motor cortex, Dr. Shenoy and his colleagues are searching for the holy grail of neuroscience," said Dr. Daofen Chen, program director, Systems and Cognitive Neuroscience at the National Institute of Neurological Disorders and Stroke at NIH. "They consistently tackle important but tough questions in thought-provoking ways and in ambitious proposals. NIH is proud to support this kind of pioneering and transformative research."

Accordingly, the seemingly complex system that is the motor cortex can now be at least partially understood in more straightforward terms.

"The motor cortex is an engine of movement that obeys lawful dynamics," said Shenoy.

Also authors on the paper are: Stanford post-doctoral fellow Matthew Kaufman, bioengineering PhD student and medical science training program student Paul Nuyujukian, electrical engineering graduate student Justin Foster, and electrical engineering consulting assistant professor and Palo Alto Medical Foundation neurosurgeon Stephen Ryu.

Andrew Myers is associate director of communications for the Stanford University School of Engineering.

Media Contact

Andrew Myers, School of Engineering: (650) 736-2245, admyers@stanford.edu