Wet neural nets in lamprey locomotion

With gaping, round mouths ringed by sharp, horny teeth, lampreys are among the most primitive of aquatic vertebrates. Lacking bones, they slip through water with a rapid, undulating motion created by flexing their muscles to generate waves that travel from head to tail down their eel-like bodies.

A novel mathematical model of how nerve cells along a lamprey's spinal cord may generate the rhythmic waves of electrical signals that trigger muscle contractions has now provided surprising insights into lamprey locomotion. In particular, the model predicts – and laboratory experiments confirm – that the passage of signals from one segment to another along the spinal cord occurs more readily from tail to head than from head to tail.

This finding runs counter to the notion intuitively held by biologists that because the wave travels from head to tail, head-to-tail neural connections would likely be stronger than tail-to-head connections. It also prompts a variety of previously unasked questions, which require further investigation in the laboratory, concerning the precise characteristics of the signal-carrying fibers that run along the lamprey's spinal cord.

"One wants to understand where these [locomotion] patterns come from," says mathematician Nancy Kopell of Boston University, who, along with G. Bard Ermentrout of the University of Pittsburgh, developed a mathematical model of the neural network responsible for lamprey locomotion. "Mathematics allows one to take a mountain of possibly relevant detail and sort out what's really important."

Kopell described the lamprey work and related research at a joint meeting of the American Mathematical Society and the Mathematical Association of America, held last week in Baltimore.

To help solve the puzzle of how lampreys generate a smoothly coordinated swimming motion, Kopell and Ermentrout started with a set of equations representing a chain of oscillators. Each mathematical oscillator corresponds roughly to a group of cells along the lamprey's spinal cord, which collectively generate periodic electrical bursts. "We used as few assumptions and restrictions [in the model] as possible," Kopell says.

The researchers found equations that reproduce the chief characteristics of the electrical signals required to generate the lamprey's distinctive swimming motion. One can picture that motion by imagining the passage of an S-shaped wave along a lamprey's body. As the wave slips off the tail, it simultaneously starts up again at the head so that one full wavelength always spans the length of the lamprey's body.

To make their model work, Kopell and Ermentrout had to assume that adjacent oscillators continue influencing each other even when both are in the same electrical state. To get a traveling wave, they also needed to assume that this special kind of coupling was stronger in one direction along the spinal cord than in the other.

The researchers then studied what happens to the natural frequency of the waves in a chain of coupled oscillators when they feed a periodic signal of a different frequency into one end, thereby forcing a new motion. They discovered that how the natural frequency changes depends on which end of the chain has been forced.

"The mathematical results were compelling enough to make [biologists] look anew at the physiology," Kopell says.

To test the prediction, experimental biologists Karen A. Sigvardt of the University of California, Davis, and Thelma L. Williams of St. George's Hospital Medical School in London, England, looked for a similar effect in spinal cords extracted from lampreys. Stripped of the brain and all muscle, then immersed in a saline solution spiked with an appropriate amino acid, the lamprey spinal cord generated the same traveling waves of electrical activity seen in the intact animal.

With one end free to move and the other end periodically wiggled by a small motor, the cord's electrical activity showed the same asymmetry present in the mathematical model. "To everybody's astonishment, it worked," Kopell says.

She and Ermentrout have since refined their model and taken a closer look at some of their assumptions. For example, they found that their system behaves quite differently when they make the coupling between oscillators stronger than initially assumed.

This type of mathematical research may prove useful for elucidating the mechanisms that govern rhythmic behaviors such as walking, chewing and breathing – not only for understanding living systems but also for designing robots (SN: 11/30/91, p.361). Conversely, applications of mathematics to biology suggest new mathematical phenomena worthy of investigation. Kopell's recent work on neural networks in the stomachs of lobsters, for example, generated a number of interesting mathematical questions.

"We learn not only about lobsters and lampreys but also about mathematics," she says. *– I. Peterson*

Cooperation evolves in computer tourney

Evolutionary theorists often point out that natural selection – the perpetuation of genetically based traits that increase an individual's chances of surviving and producing offspring – favors selfish behavior. However, computer tournaments that pit a variety of strategies for obtaining payoffs in social encounters against one another provide clues to how natural selection also promotes cooperation among genetically unrelated individuals, scientists report in the Jan. 16 Nature.

This brand of cooperation, known as reciprocal altruism, prevails when some individuals forgo constant selfishness for a "tit-for-tat" tactic, in which they cooperate with a colleague on a first encounter, and on subsequent occasions do whatever their cohort did on the previous encounter. In computer simulations, programs that eschew cooperation nearly wipe out their tit-for-tat compatriots, which then stage a comeback and give way to a "generous" version of tit-for-tat that forgives a few selfish deceptions by others, report zoologist Martin A. Nowak of the University of Oxford, England, and mathematician Karl Sigmund of the University of Wien, Austria.

Nowak and Sigmund tested tactics derived from the "prisoner's dilemma," in which two players score varying amounts of points by either cooperating or acting selfishly. An individual receives the most points by acting selfishly when the other cooperates; if both cooperate, each obtains a moderate payoff; and both score poorly in cases of dual selfishness. Prior computer tourneys suggested that, in repeated encounters, the tit-for-tat strategy outscores all others.

To better simulate encounters between biological organisms, Nowak and Sigmund programmed occasional random errors into each of 100 different prisoner's dilemma strategies. When the sample excluded the tit-for-tat approach, a strategy of consistent selfishness gained dominion, because competing strategies did not immediately retaliate against exploiters. Although tit-for-tat initially performs poorly against selfish programs, "the tide turns when 'suckers' are so decimated that exploiters can no longer feed on them," the researchers assert. Reciprocators then eliminate exploiters and "generous" tit-for-tat takes over.

The computer results suggest that evolution favors simple, probabilistic rules of conduct, writes biologist H.C.J. Godfray of Imperial College in Berkshire, England, in an accompanying editorial. Cooperative strategies may succeed more easily in nature than in computers, Godfray adds, since most animals interact with relatives more often than with strangers.

– B. Bower