Mathematical keys to a sixth sense -- the lateral-line system

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Biophysicists at the Technische Universitaet Muenchen are leading an effort to develop and apply models of the so-called lateral-line system found in fish and some amphibians. This sensory organ enables an animal, even in murky water, to map its surroundings and recognize other animals. In *Physical Review Letters*, the researchers report mathematical models that capture essential elements of the system, agree with experimental data, and could be easy to implement technically, as in robots.

Fish and some amphibians possess a unique sensory capability in the so-called lateral-line system. It allows them, in effect, to "touch" objects in their surroundings without direct physical contact or to "see" in the dark. Professor Leo van Hermmen and his team in the physics department of the Technische Universitaet Muenchen are exploring the fundamental basis for this sensory system. What they discover might one day, through biomimetic engineering, better equip robots to orient themselves in their environments.

With our senses we take in only a small fraction of the information that surrounds us. Infrared light, electromagnetic waves, and ultrasound are just a few examples of the external influences that we humans can grasp only with the help of technological measuring devices - whereas some other animals use special sense organs, their own biological equipment, for the purpose. One such system found in fish and some amphibians is under investigation by the research team of Professor Leo van Hemmen, chair of theoretical biophysics at TUM, the Technische Universitaet

Muenchen.

Even in murky waters hardly penetrated by light, pike and pickerel can feel out their prey before making contact. The blind Mexican cave fish can perceive structures in its surroundings and can effortlessly avoid obstacles. Catfish on the hunt follow invisible tracks that lead directly to their prey. The organ that makes this possible is the lateral-line system, which registers changes in currents and even smaller disturbances, providing backup support for the sense of sight particularly in dark or muddy waters.

This remote sensing system, at first glance mysterious, rests on measurement of the pressure distribution and velocity field in the surrounding water. The lateral-line organs responsible for this are aligned along the left and right sides of the fish's body and also surround the eyes and mouth. They consist of gelatinous, flexible, flag-like units about a tenth of a millimeter long. These so-called neuromasts - which sit either directly on the animal's skin or just underneath, in channels that water can permeate through pores - are sensitive to the slightest motion of the water. Coupled to them are hair cells similar to the acoustic pressure sensors in the human inner ear. Nerves deliver signals from the hair cells for processing in the brain, which localizes and identifies possible sources of the changes detected in the water's motion.

These changes can arise from various sources: A fish swimming by produces vibrations or waves that are directly conveyed to the lateral-line organ. Schooling fishes can recognize a nearby attacker and synchronize their swimming motion so that they resemble a single large animal. The Mexican cave fish pushes a bow wave ahead of itself, which is reflected from obstacles. The catfish takes advantage of the fact that a swimming fish that beats its tail fin leaves a trail of eddies behind. This so-called "vortex street" persists for more than a minute and can betray the prey.

For the past five years, Leo van Hemmen and his team have been investigating the capabilities of the lateral-line system and assessing the potential to translate it into technology. How broad is the operating range of such a sense organ, and what details can it reveal about moving objects? Which stimuli does the lateral-line system receive from the eddy trail of another fish, and how are these stimuli processed? To get to the bottom of these questions, the scientists develop mathematical models and compare these with experimentally observed electrical nerve signals called action potentials. The biophysicists acquire the experimental data - measurements of lateral-line organ activity in clawed frogs and cave fish - through collaboration with biologists. "Biological systems follow their own laws," van Hemmen says, "but laws that are universally valid within biology and can be described mathematically - once you find the right biophysical or biological concepts, and the right formula."

The models yield surprisingly intuitive-sounding conclusions: Fish can reliably fix the positions of other fish in terms of a distance corresponding to their own body length. Each fish broadcasts definite and distinguishing information about itself into the field of currents. So if, for example, a prey fish discloses its size and form to a possible predator within the radius of its body length, the latter can decide if a pursuit is worth the effort. This is a key finding of van Hemmen's research team.

The TUM researchers have discovered another interesting formula. With this one, the angle between a fish's axis and a vortex street can be computed from the signals that a lateral-line system acquires. The peak capability of this computation matches the best that a fish's nervous system can do. The computed values for nerve signals from an animal's sensory organ agree astonishingly well with the actual measured electrical impulses from the discharge of nerve cells. "The lateral-line sense fascinated me from the start because it's fundamentally different from other senses such as vision or hearing, not just at first glance but also the second," van Hemmen says. "It's not just that it describes a different quality of reality, but also that in place of just two eyes or ears this sense is fed by many discrete lateral-line organs - from 180 in the clawed frog to several thousand in a fish, each of which in turn is composed of several neuromasts. The integration behind it is a tour de force."

The neuronal processing and integration of diverse sense impressions into a unified mapping of reality is a major focus for van Hemmen's group. They are pursuing this same fundamental investation through the study of desert snakes' infrared perception, vibration sensors in scorpions' feet, and barn owls' hearing.

"Technology has overtaken nature in some domains," van Hemmen says, "but lags far behind in the cognitive processing of received sense impressions. My dream is to endow robots with multiple sensory modalities. Instead of always building in more cameras, we should also along the way give them additional sensors for sound and touch." With a sense modeled on the lateral-line system, but which would function as well in air as under water, robots might for example move safely among crowds of people. But such a system also offers many promising applications in the water. Underwater robots could use it to orient themselves during the exploration of inaccessible cave systems and deep-sea volcanoes. Autonomous submarines could also locate obstacles in turbid water. Such an underwater vehicle is currently being developed within the framework of the EU project CILIA, in collaboration with the TUM chair for guidance and control technology.

More information:

"Hydrodynamic Object Recognition: When Multipoles Count," Andreas B. Sichert, Robert Bamler, and J. Leo van Hemmen, Physical Review

Letters, 102, 058104 (2009) Link: dx.doi.org/10.1103/PhysRevLett.102.058104

"Wake Tracking and the Detection of Vortex Rings by the Canal Lateral Line of Fish," Jan-Moritz P. Franosch, Hendrik J. A. Hagedorn, Julie Goulet, Jacob Engelmann, and J. Leo van Hemmen, *Physical Review Letters* 103, 078102 (2009) Link: dx.doi.org/10.1103/PhysRevLett.103.078102

See also: "Following in the wake," *Nature* 460, 1061 (27 August 2009) dx.doi.org/10.1038/4601061a

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