Electric And Near-Field Acoustic Detection, A Monograph

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LONG-TERM GOALS

After a 40-year long career of exploring unfamiliar waters, after discovering the electric sense of sharks and rays and charting the low-frequency acoustic sense of fish in general, my ambitious long-term goal for the remaining years of wisdom is to clear my scientific storehouse of ideas, data, and new insights by publishing the results in the world-wide scientific literature, in the form of peer-reviewed journal articles, prestigious, readily available handbook chapters, and—deo volente—in textbook format.

OBJECTIVES

To provide prospective scientists with a vantage point from where to continue my pioneering efforts. In particular, to give the more daring biologists a clear view of the theoretical physics needed for a thorough study of the animals' senses and to give the more inquisitive physicists and engineers a greater insight into the sensory systems on which our perception of the physical world is founded.

APPROACH

I would prefer to write just one text, not only describing my work on the electromagnetic and near-field acoustic senses of fish, but also introducing the necessary physics and biology. In my experience, very few scientists have the background needed in both disciplines. The only means of giving biologists the necessary appreciation of physics, and physicists the necessary appreciation of biology, is to introduce the unfamiliar disciplines from their familiar biological or physics points of views, respectively.

Although this approach will on the long run be most effective, I have been advised to reach my goals in a two-step process: firstly, to document the data in refereed journal articles to give those that can not judge the validity of my work at least the confidence that others have approved of it, and secondly, to make the same information available with the necessary biology and physics introductions, so as give the reader the knowledge needed to judge for himself about the far-reaching implications of my work.

The present project formally comprises only the first step, the publication of the refereed journal articles. I myself, though, will not be satisfied until I have achieved my long-term goal of completing the planned comprehensive monograph that I have barely started. Unfortunately, one is supposed to write a book in one's own free time, which for an active scientist is very little. Ideally, this ambitious, follow-up project should have a sponsor convinced of its great importance to make it all realistic.

WORK COMPLETED

The work on which the articles are being based falls in four categories:

1. Detection of underwater objects, (a) by the electric sense and (b) by the acoustic sense, 2. Detection of magnetic compass directions, by the electric sense, 3. Detection of weak-electric fields, by the

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ampullae of Lorenzini, 4. Detection of low-frequency acoustic fields, by the inertial sensors of the fish inner ear.

Aquatic animals produce bioelectric and fluid-accelerations fields, both of which are predominantly ruled by Laplace's equation. Hence, in zeroing in on their target, ocean predators may use the same approach algorithm, whether relying on the electric sense or the inertial organs of the inner ear. Interestingly, in the acoustic case, the inertial sense organs are stimulated not only by the familiar local or temporal derivative of the fluid velocity, but also by the less familiar vective or spatial derivative of the prey's velocity field.

The magnetic sense of sharks and rays is based on the principle of motional-electric induction, a physical process that had not been fully elucidated until Einstein in 1905 developed the special theory of relativity, which actually was conceived to solve this very problem. It simply is a misconception among biologists and physicists alike that the theory of relativity applies only to bodies moving at great speed. Einstein's magnets and conductors move at the speeds of his pedestrians and trains, and I add, of our sharks.

The nearly incredible electrical sensitivity of sharks and rays has been subjected to a biophysical analysis showing the feasibility of ordinary excitable ion channels providing graded amplification by the receptor epithelium based on the principle of positive feedback. By maintaining the feedback factor close to, but slightly less than one, it appears possible to achieve any gain desired. Hence, not sensitivity, but noise and stability are the limiting factors. Our ampullary model deals efficiently with those issues.

Our behavioral findings of predatory fish orienting in the fluid acceleration fields of moving prey and our interpretation in terms of the inertial sensors of the inner ear called for electrophysiological verification. Indeed, we found many nerve fibers in the acoustic nerve to be sensitive to accelerations less than 10 Hz, or even less than 1 Hz. Interestingly, those fibers did not respond to the acceleration as such, but to more than a full derivative of the acceleration, that is, to the change in acceleration.

RESULTS

The approach algorithm has been applied to the electric as well as the acceleration field, in the latter case, to both the local and the vective derivative of the prey's velocity field. The results signify a close relationship between the electric and acoustic sense and suggest that the original inertial function of hearing was based on two types of accelerations: the local derivative of the velocity which led to far field hearing, and the vective derivative which enabled predators to detect prey even when gliding at a constant velocity.

By applying the principle of relativity to the problem of the shark's magnetic sense, we have arrived at a powerful means of testing the theory of electromagnetic orientation in behavioral experiments. For these tests, we have received an NSF grant. At long last, our quiet Electromagnetic Research Facility, to which ONR has contributed, will serve the function for which it was designed: to prove that, when sharks and rays orient magnetically, they do so by use of their acute electric sense.

Our electroreceptor model, based on the principle of graded positive feedback, has provided a powerful means of analyzing the high electrical sensitivity of sharks and rays and also given us a new insight into the properties of electrically excitable ion channels and the operation of nerve cells in general. In brief, it is a fundamental property of electrically excitable ion channels that they behave as voltage-to-current converters featuring negative conductance, in electroreceptors as well as in the nerve system.

For recording the inner-ear responses to low-frequency acceleration fields, we designed and built a setup capable of moving a fully enclosed body of water with any desired acceleration stimulus in the range of zero to one hundred hertz. We applied both sine-wave accelerations fields and the acceleration fields previously recorded in the vicinity of an approaching and passing prey fish. The most interesting result is that the nerve responses to a higher fractional derivative then merely the acceleration of the field.

IMPACT

The project is highly relevant to several Navy issues: (1) the electric and low-frequency acoustic detectability of submarines and other underwater equipment, (2) the method to be utilized for guided missiles seeking sources of galvanic and fluid velocity fields, (3) shark bite, at underwater cables, towed arrays, and other critical equipment and gear, (4) the environmental impact of naval oceanic activities.

TRANSITIONS

Because of our physics and engineering oriented approaches, all the results are expressed in a language rendering them directly available for naval and industrial implementation.

RELATED PROJECTS

By its very nature, the present project takes into consideration all concurrent and earlier scientific studies conducted in my own laboratory and elsewhere. We are also negotiating investigations to be carried out for the Navy and the oil-exploration industry to prevent sophisticated towed hydrophone arrays and other sensitive underwater equipment from being bitten by large ocean predators.

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