Mapping electric fields with fish and robots: How weakly electric fish may perceive their environment

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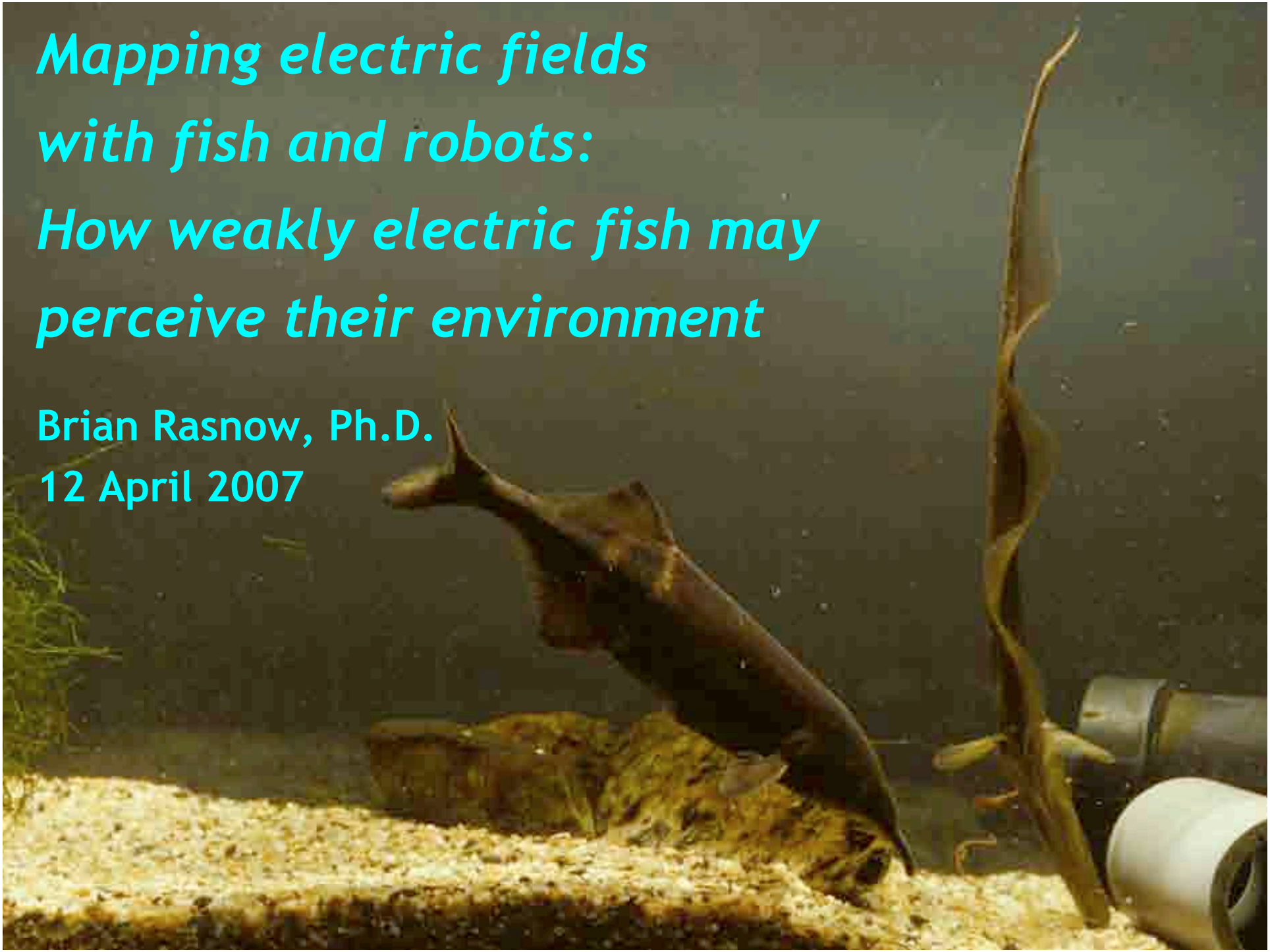


Outline

- Why study electric fish?
- How does electric sense work?
  - Superficially and quantitatively
- Can we generalize these lessons?
  - Understand how other sensory and motor systems work
  - Engineer useful systems on these principles

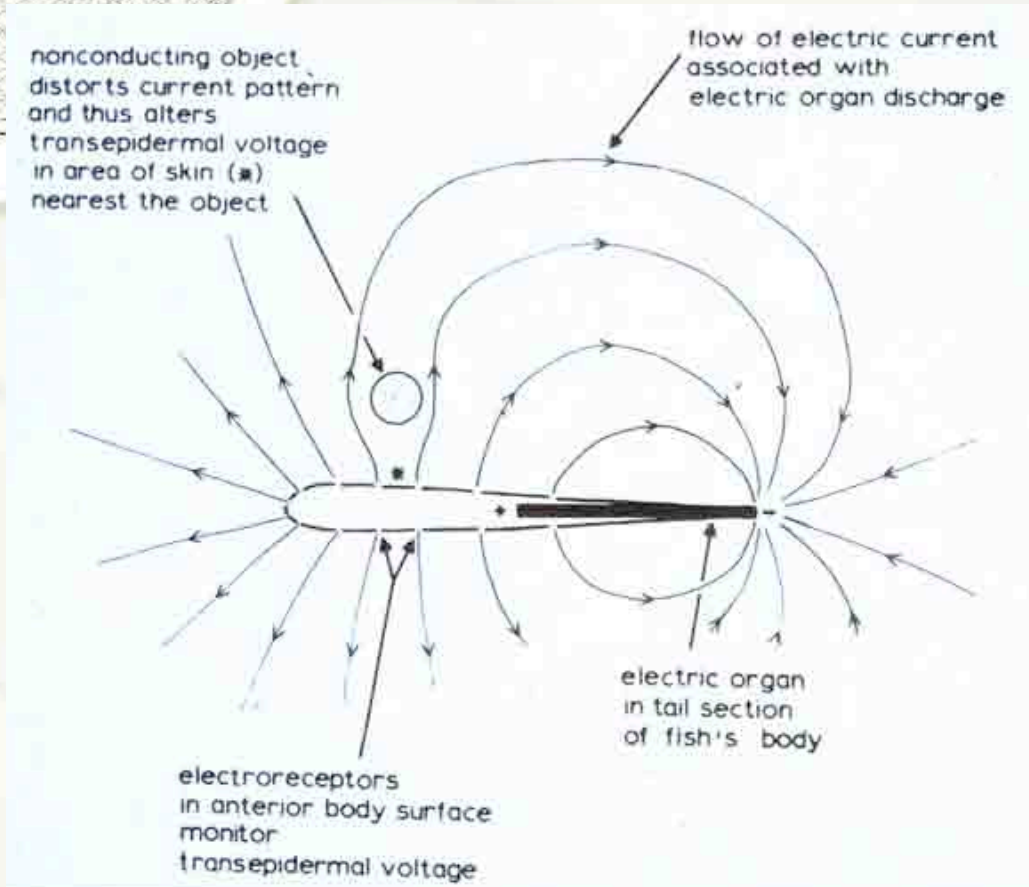
How do our brains work?

- In our heads is an internal reality that models the external world
- The internal reality is built from genetics and our senses (“nature and nurture”)
- Our brains do a great job of this, but they reveal little about the underlying biophysics and neural computation to our consciousness

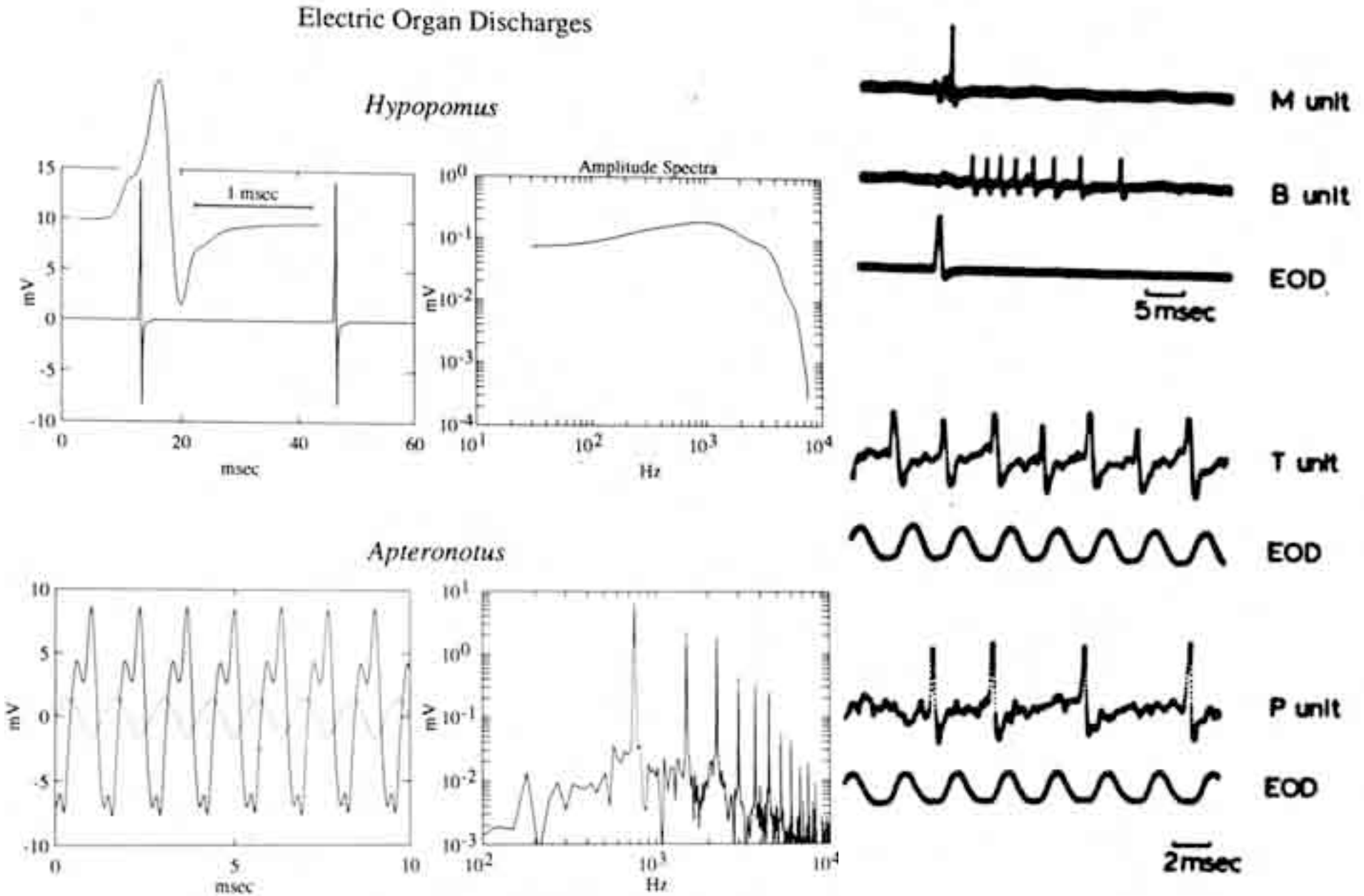
How do brains process sensory information?

- We don't know.
- Around 1960 a graduate student was given a video camera and computer and a thesis goal to connect them and program the computer to see
- About a year ago an autonomous vehicle drove ~150 miles through the desert
  - The winning car didn't rely primarily on vision
- Our best computers and robots don't come close to the sensorimotor capabilities of a cockroach
  - We don't understand the biological paradigm

Electrolocation and electrocommunication



Time and frequency domains



Evolution of brains

- Most neural structures and circuits are highly conserved throughout evolution
- Species mainly differ in relative size and elaboration of the same basic structures
- Attractors?

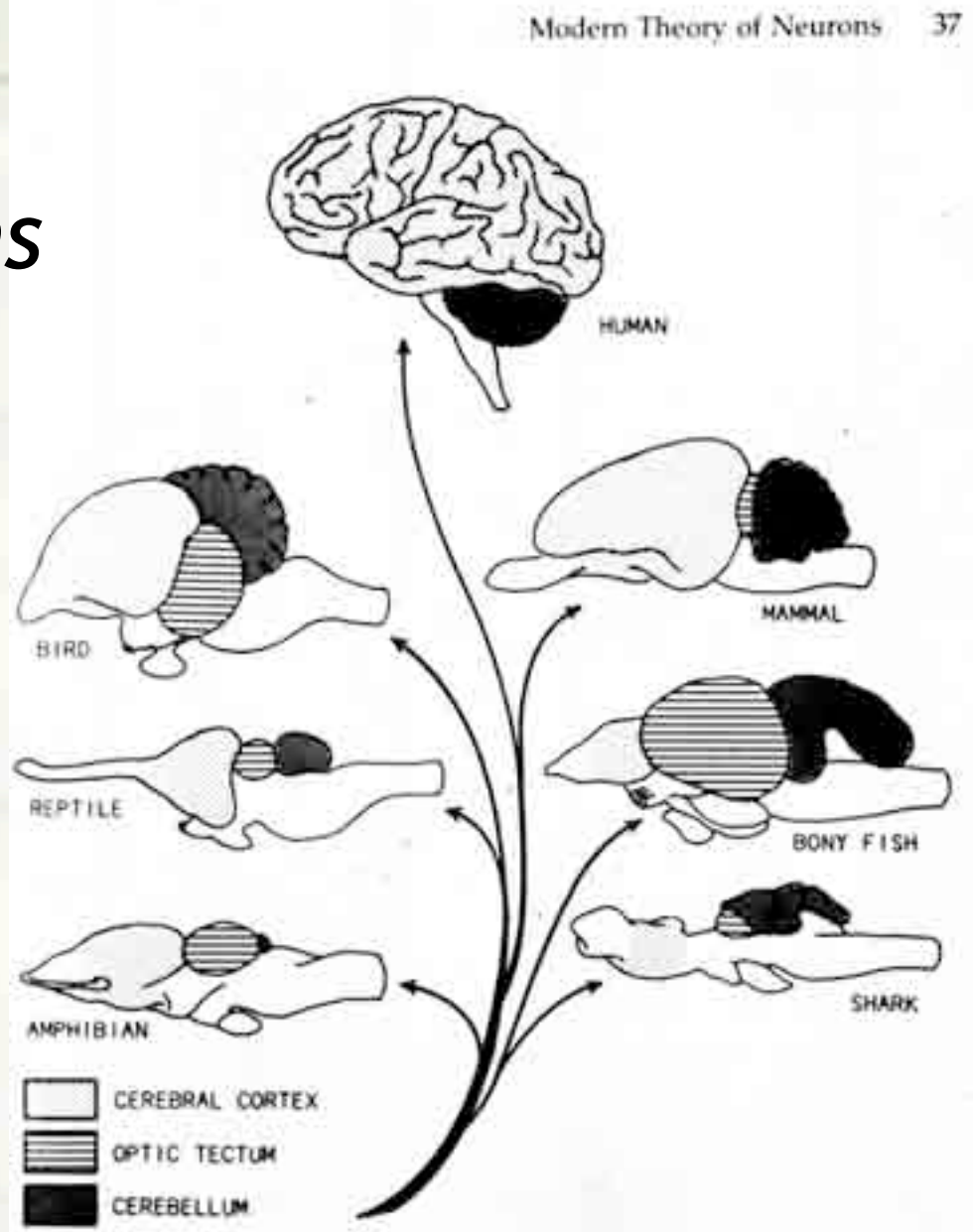
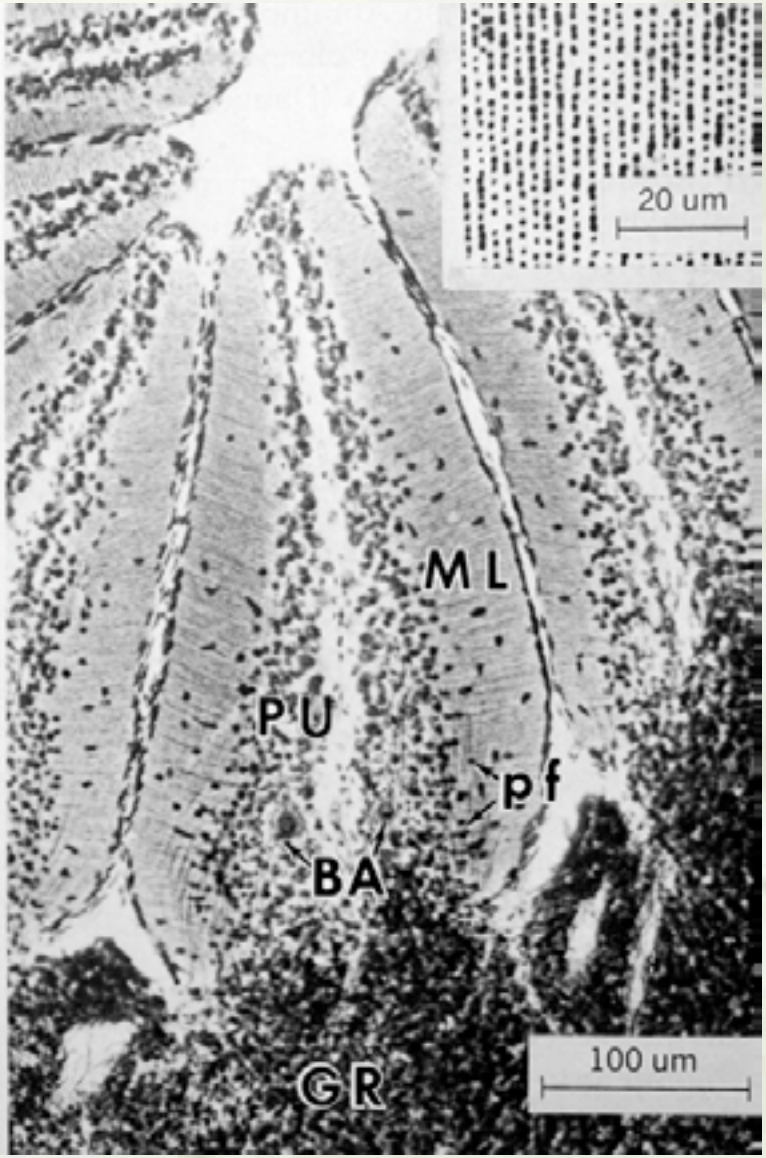


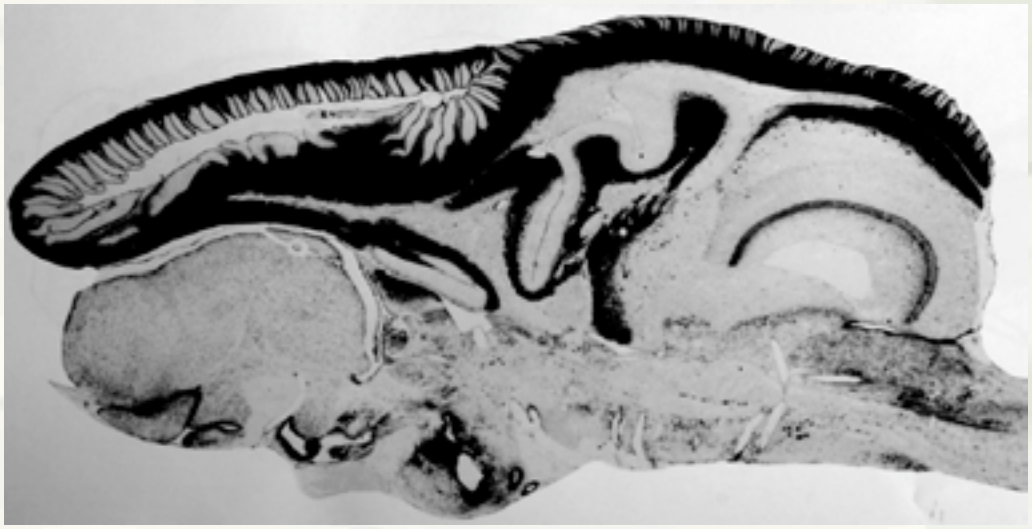
Figure 2.1
Lateral view of several vertebrate brains showing relative development of major brain divisions. Brains not drawn to scale. (Modified from Northcutt (1977). In *McGraw-Hill Encyclopedia of Science and Technology*. New York: McGraw-Hill.)

What does the cerebellum do?

- An ancient neural circuit
  - Simpler than cortex, few cell types
  - Highly conserved over time
  - “crystalline” structure
- The cerebellum inputs, outputs, and computation (transfer function) are *all* poorly understood



Electric fish have huge cerebellums!



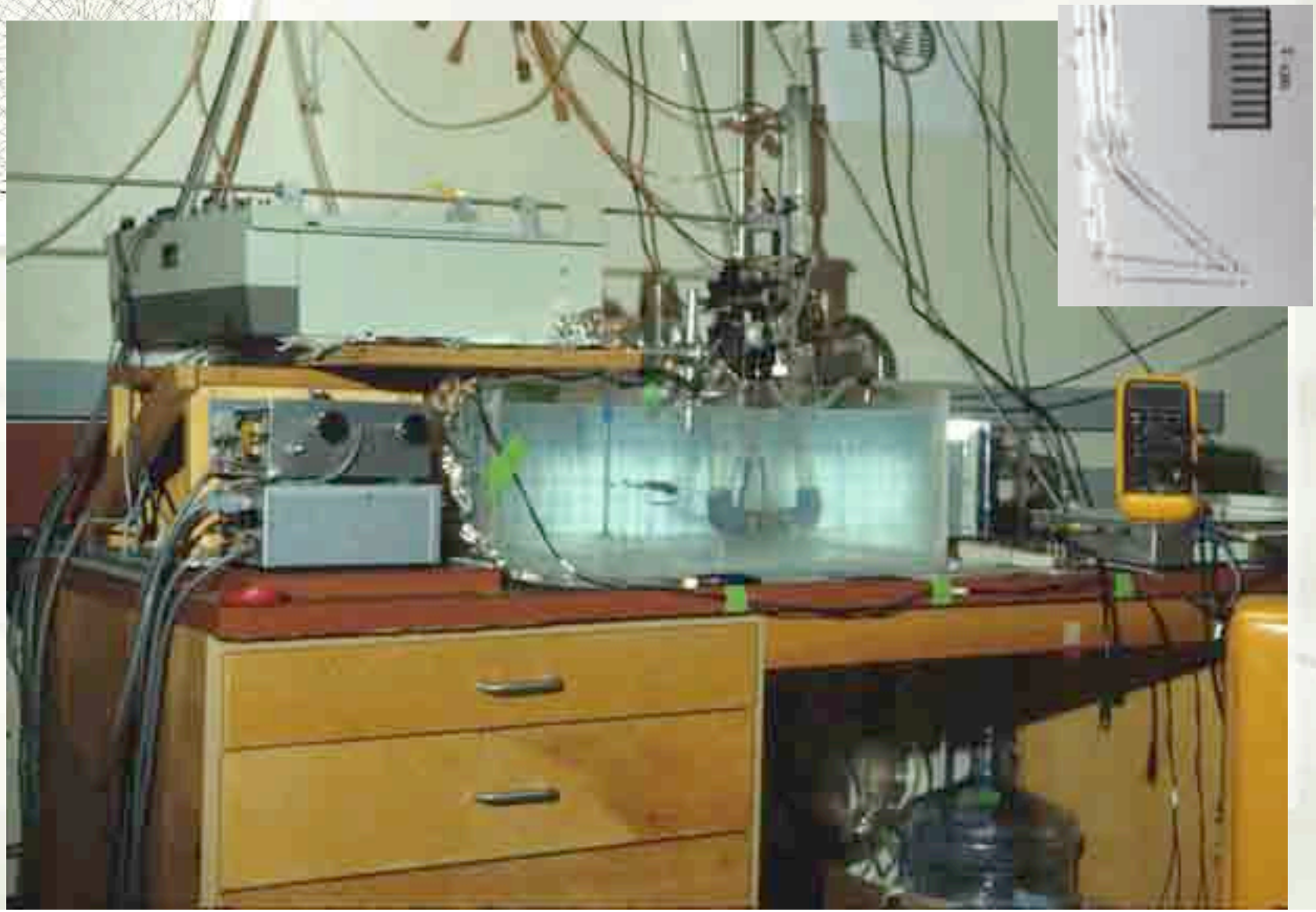
- Electroreceptors in the fish's skin detect local transdermal electric fields and transmit the sensory information to the electrosensory lateral line lobe (ELL)
- The ELL (and DCN) have many similarities to cerebellum

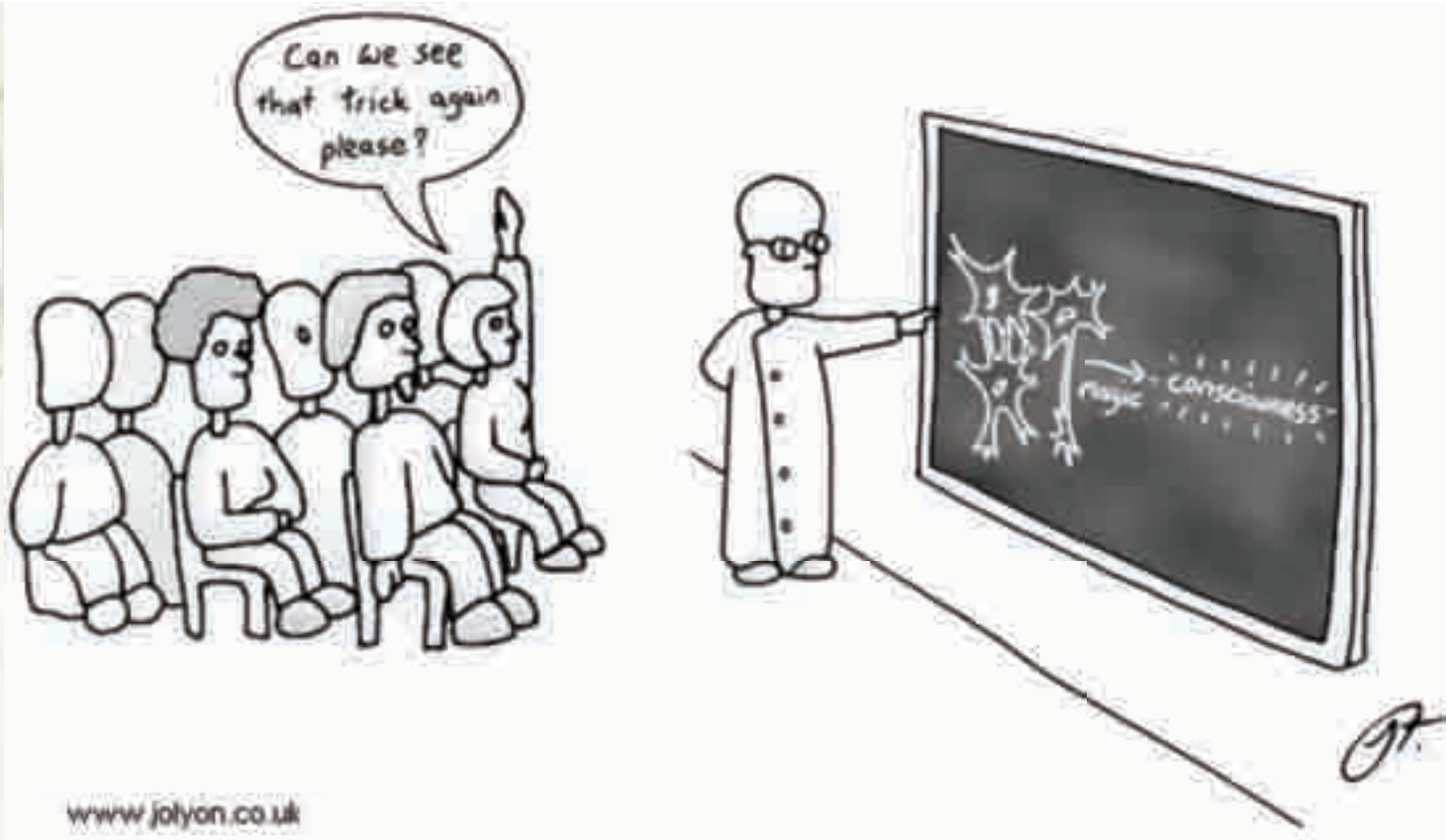
Model systems

- Electric fish are model systems for sensorimotor integration
  - Sensory receptors are relatively accessible on the skin
  - Their electric organ discharge (EOD) is both an output and an input that is easily and noninvasively monitored
  - Many other practical reasons make these fish easier to study
- Simpler organisms highlight principles of biology, chemistry, physics, and computation that *generally* are conserved in higher organisms

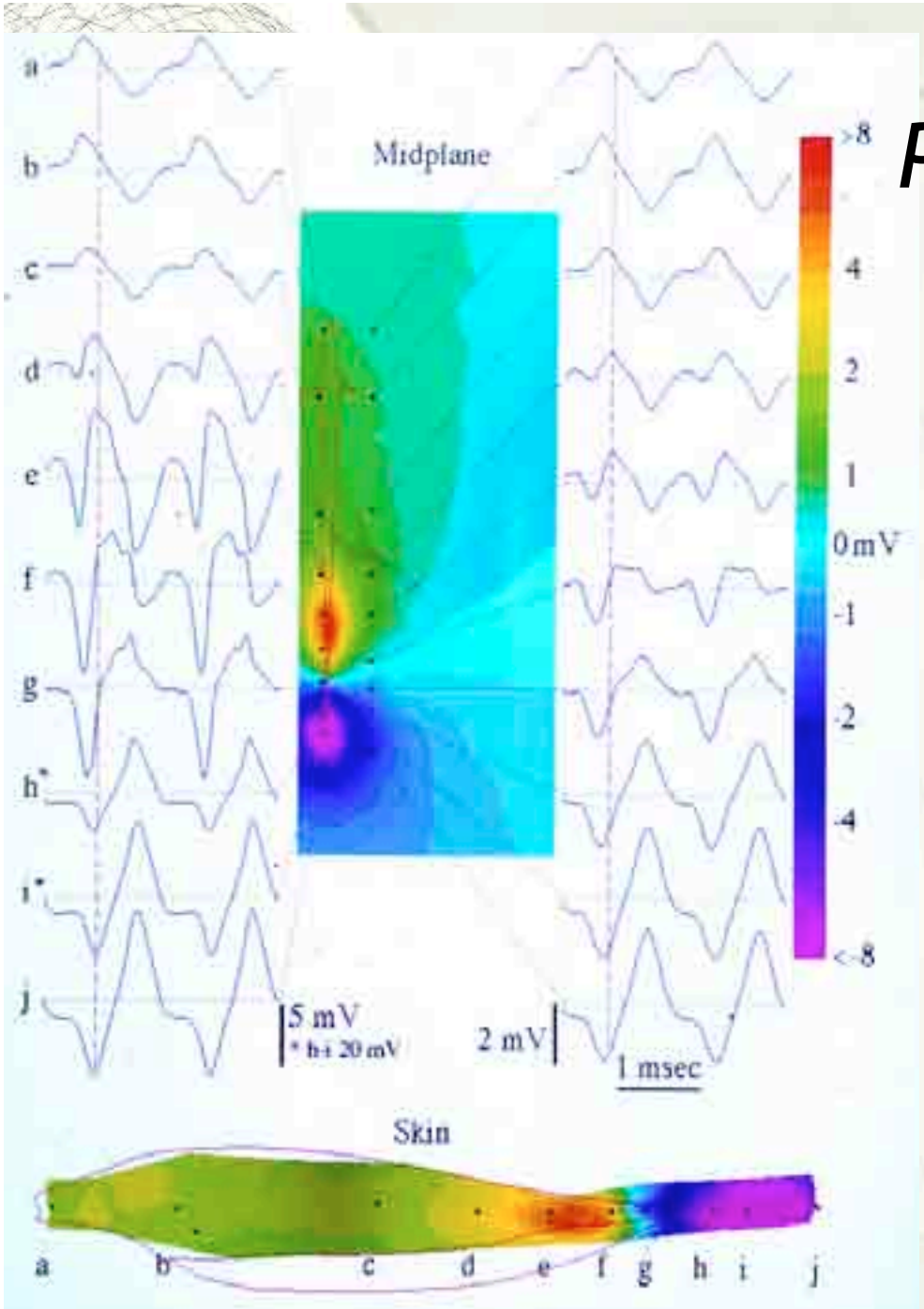
Measuring electrosensory input

Robotic electric field mapper





- After extensive electronic and software engineering and development of protocols and methods, I achieved ~200 nV resolution, <1 μsec phase jitter, electrode position uncertainty <20 μm, and the ability to record millions of voltages from thousands of positions around a fish in a few hours

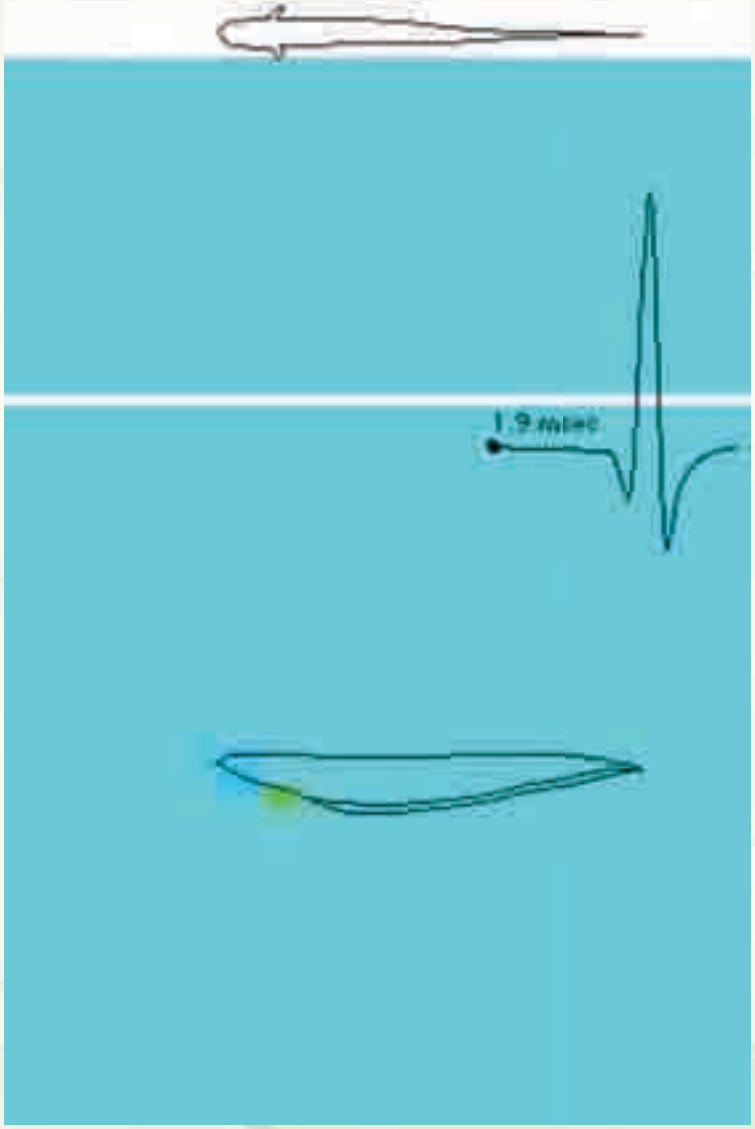


Pseudocolor midplane maps of a wave EOD

- At the time (phase) indicated by the vertical line, voltages are interpolated between measurement points and displayed in pseudocolor
- Multiple

Mapping and visualizing the EOD

- These pseudocolor potential maps result from millions of automated measurements of the fish's electric organ discharge (EOD)
- The maps enable modeling electrosensory input to ELL
- Correlating the input with known neuroanatomy and physiology enabled me to propose a neurocomputational model of electrolocation



Note: the actual EOD is 10,000 times faster than this movie

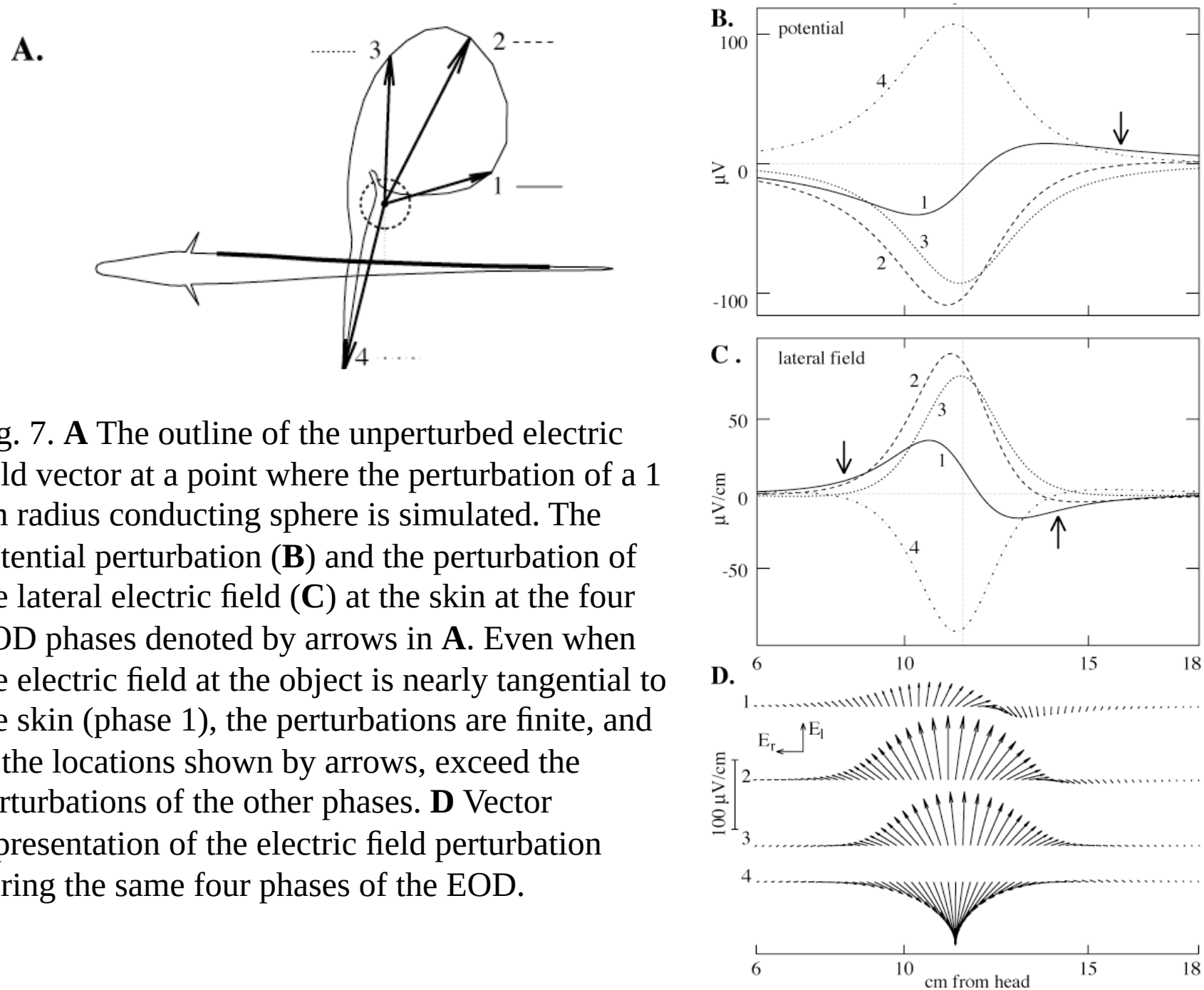
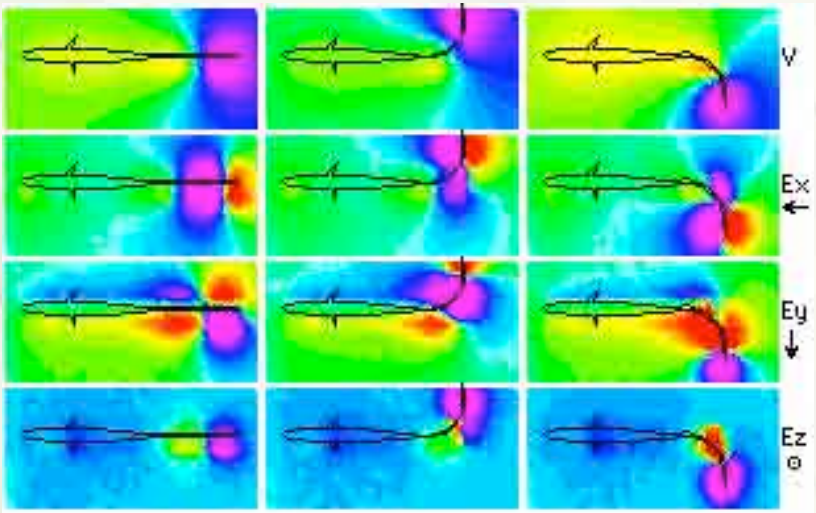
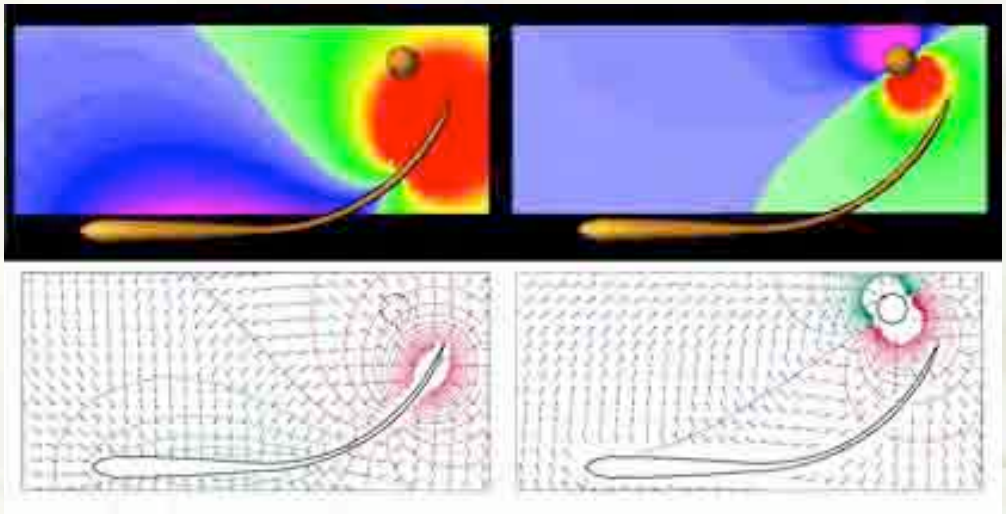


Fig. 7. **A** The outline of the unperturbed electric field vector at a point where the perturbation of a 1 cm radius conducting sphere is simulated. The potential perturbation (**B**) and the perturbation of the lateral electric field (**C**) at the skin at the four EOD phases denoted by arrows in **A**. Even when the electric field at the object is nearly tangential to the skin (phase 1), the perturbations are finite, and in the locations shown by arrows, exceed the perturbations of the other phases. **D** Vector representation of the electric field perturbation during the same four phases of the EOD.

The fish's electrosensory world

- The tedious path of self-education with a new model system ultimately revealed a complex electrosensory world, rich in spatiotemporal structure, that others had largely overlooked



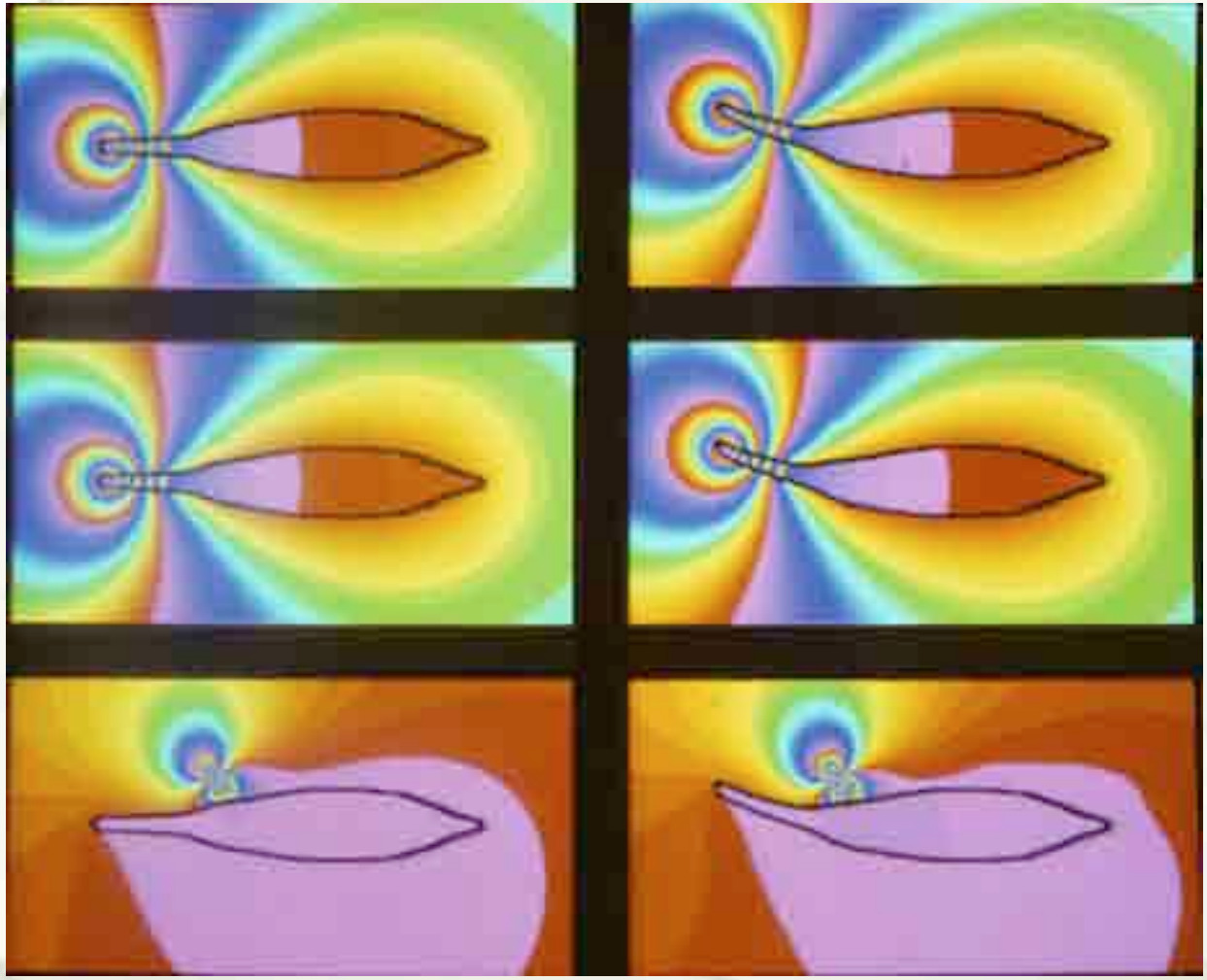


- Electric fish have also provided a much better understanding of what cerebellum does

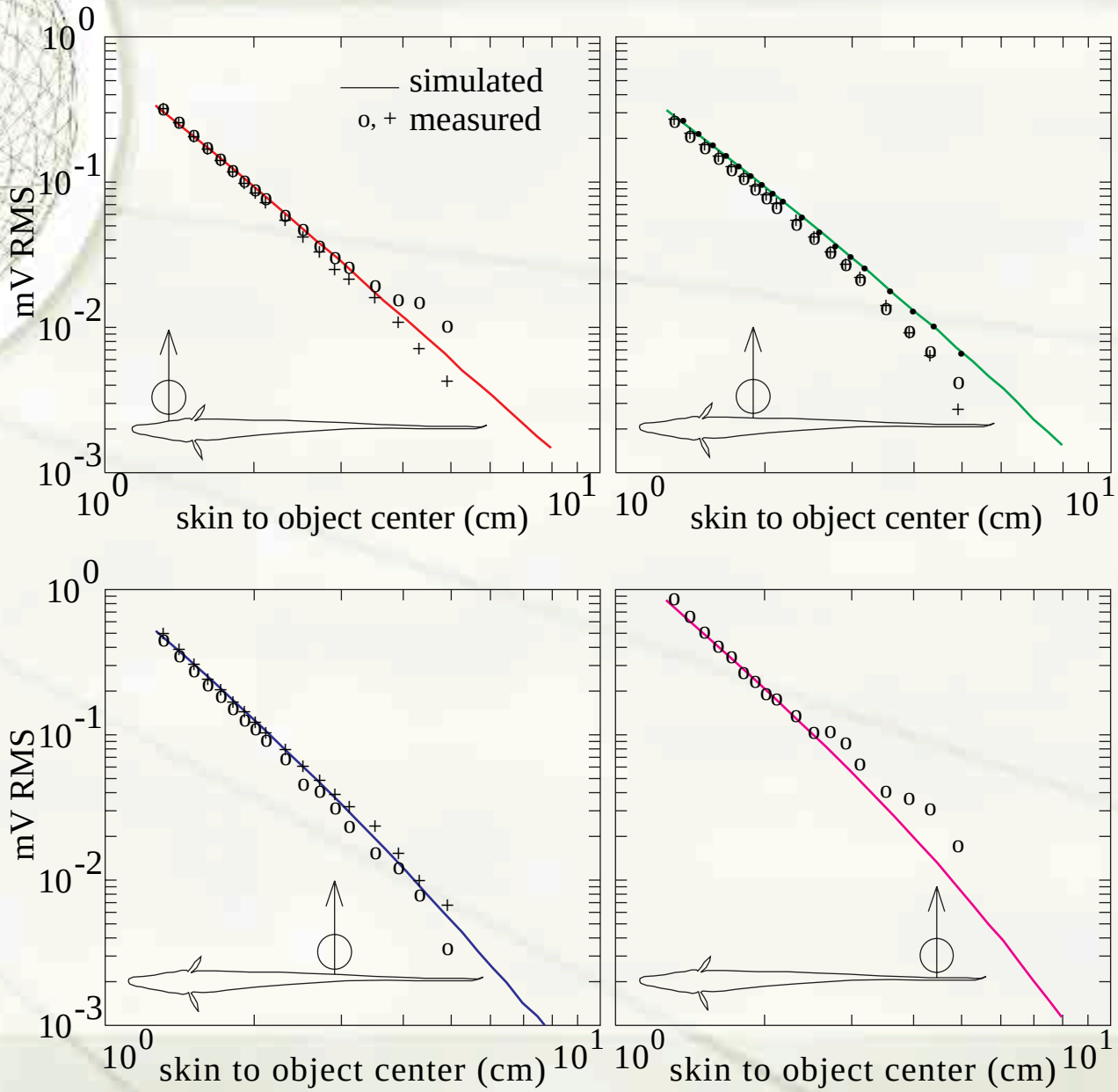
Of brains and robots

- Autonomous dynamic systems include complex hierarchies and loops of components
- Components communicate using diverse protocols, symbols, and semantics
  - Abstraction at successive levels simplify the signals but the representations become more complex to parse (e.g., a toral neuron may respond unambiguously to object distance)
- Biological systems …
  - Rely more on feedback and feedforward than hierarchies
  - Mix computation and communication
- As lab automation matures and increases robustness and adaptability, it becomes more dimensionally complex
- Machines, neural networks, and genetic networks likely exhibit universality at some scale

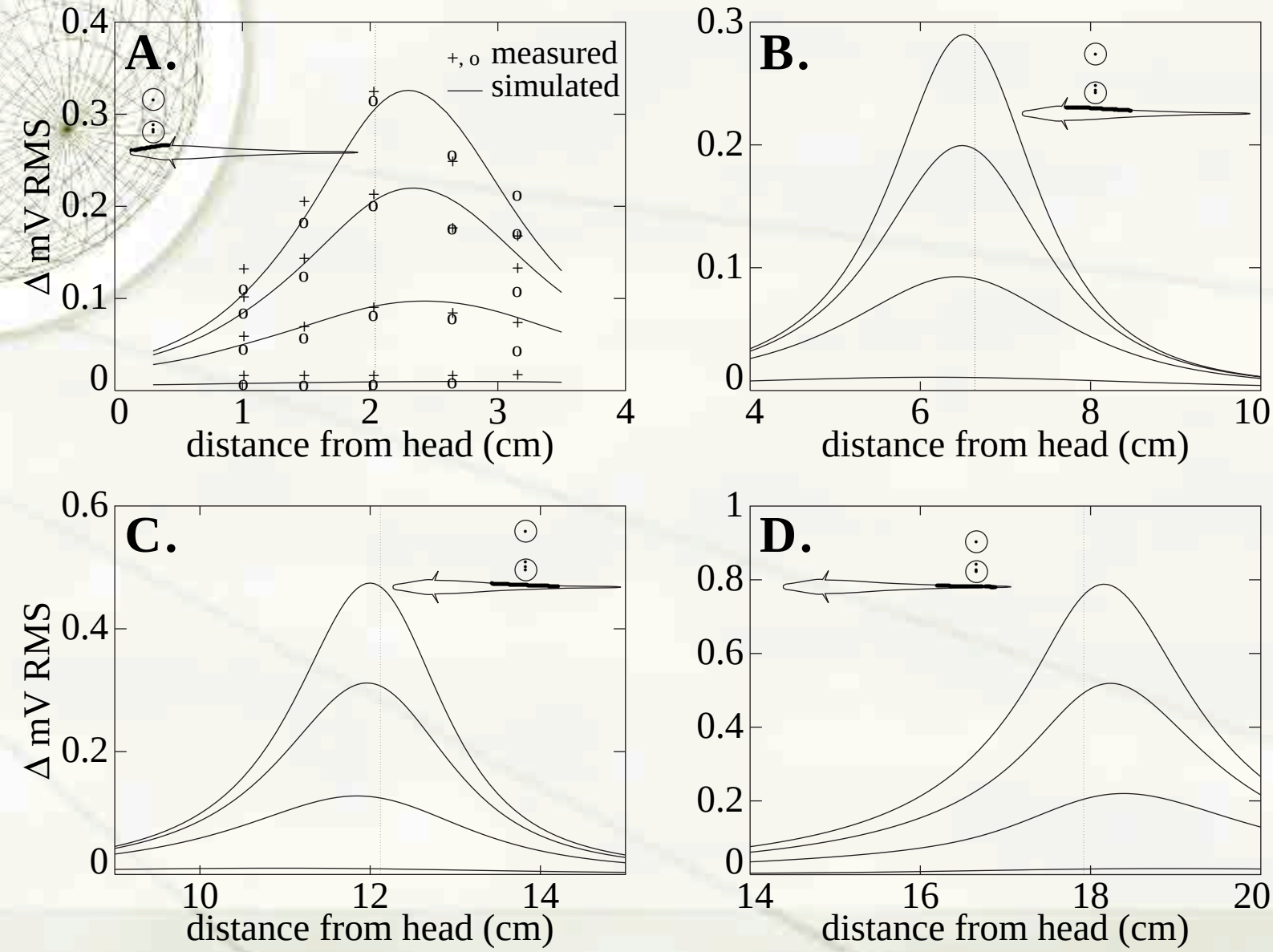
FEM simulations of objects



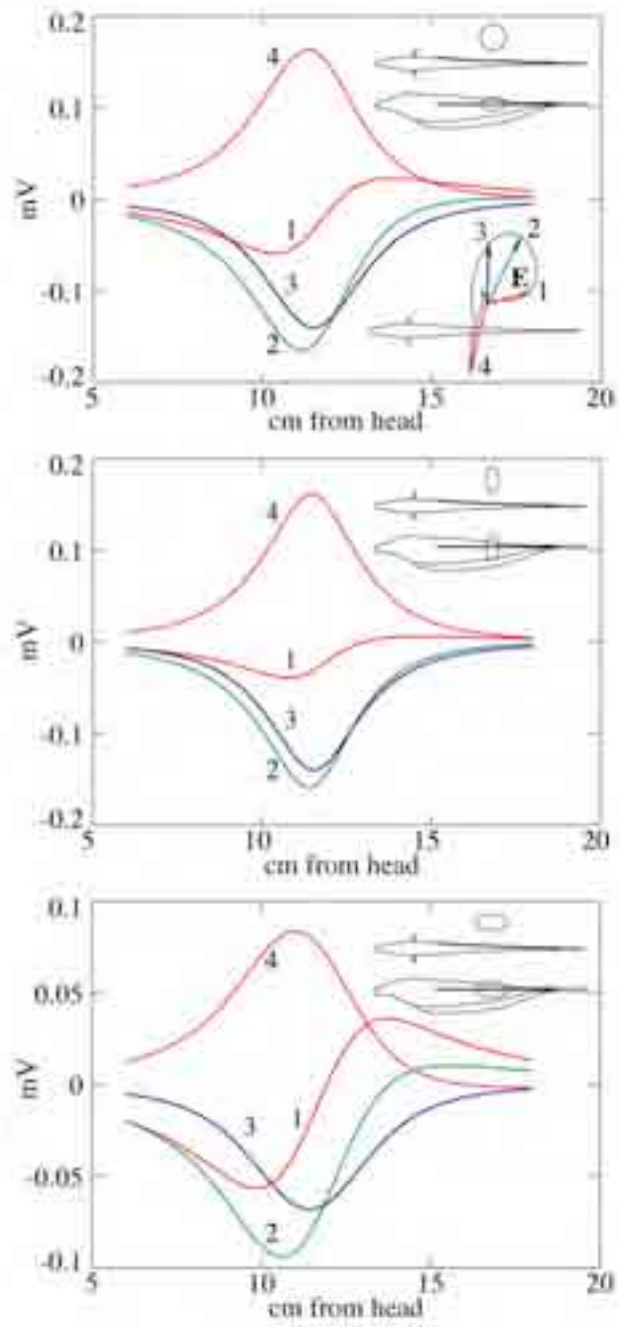
Perturbation Amplitudes



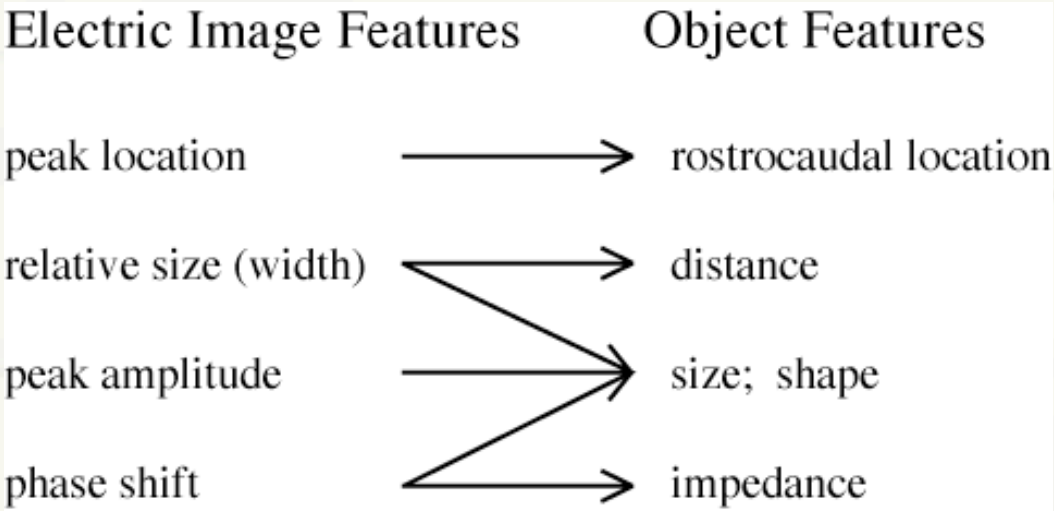
Midline Electric Images



Different Phases Reveal Different Cross Sections



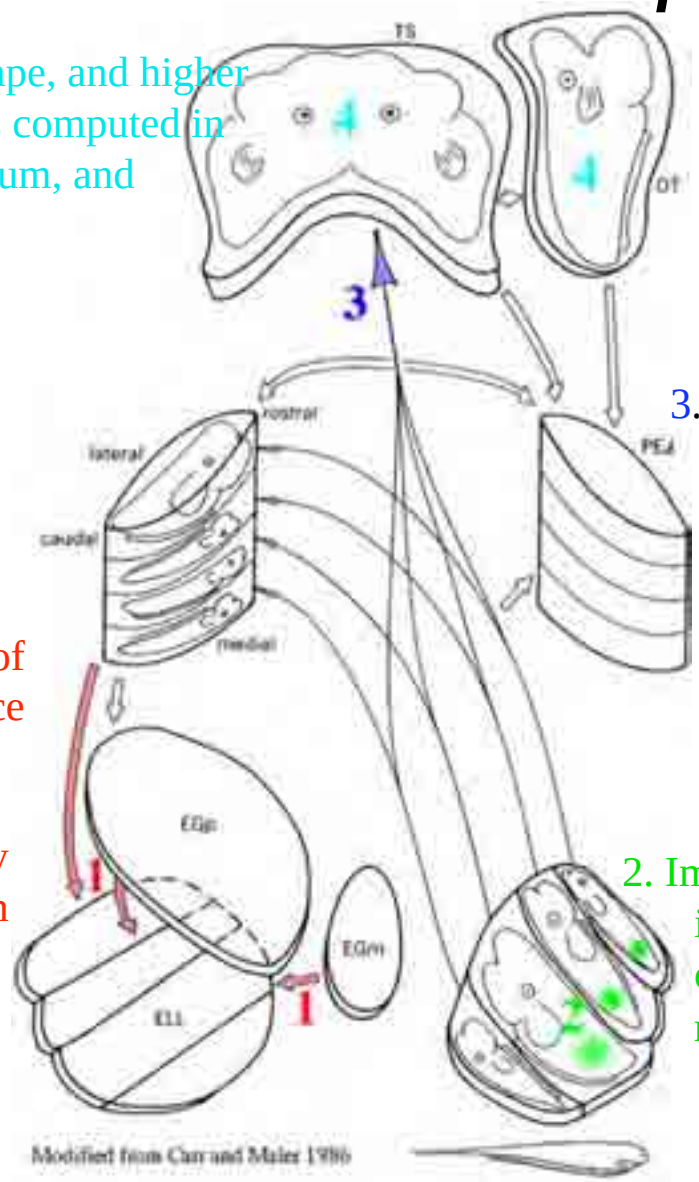
Electrosensory architecture



- Summary of the proposed mapping between sets of electric image (sensory) features and object (physical) attributes.
- Where and how in the fish's brain might these computations take place?

Proposed Neural implementation

4. Object size, shape, and higher order features computed in the torus, tectum, and higher areas



3. Object distance (and image size) ∝∫ELL activity, computed in the convergent projections to the TS

Expectation of sensory reafference

1. Object image = sensory input minus expectation

2. Image size = Object image convolved with center-surround receptive fields

Rasnow B, Bower JM (1997) Imaging with Electricity: How Weakly Electric Fish Might Perceive Objects. Computational Neuroscience: Trends in Research. Bower JM (ed) Plenum, New York, pp 795-800.

Summary

- The engineering and math underlying biological paradigms for perception are largely unknown
- Electroreception is a powerful model system for studying and elucidating sensory-motor algorithms
  - The neural inputs and outputs are electric fields in water, and are *relatively* easy to noninvasively measure and simulate
  - The physics and math underlying bioelectric fields are fully understood (Maxwell's Equations, electrostatics)
  - Our lack of innate intuition may actually help rather than hinder our ability to discover and understand the neurocomputational algorithms

Summary

- Mapping and modeling electric images has led to testable predictions of neurophysiological responses in various electrosensory areas of the fish's brain
  - Future measurements of these responses should lead to construction of more accurate models, thus bootstrapping a better understanding of the electrosensory system, and general principles of neural computation.