# An Electrosensory Virtual Reality to Study Spatial-Temporal Processing in Mormyrid Fish

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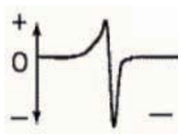
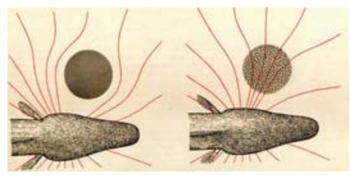
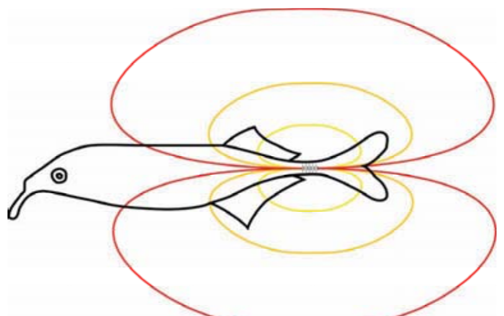
## 1 Introduction: Electrosensory Processing in Mormyrid Fish

The mormyrid senses its environment by emitting an electric organ discharge (EOD) and detecting the perturbations that nearby objects cause in the electric field. Specialized mormyromast receptors on the skin sense the self-generated EOD field.







The experimental preparation disables (by curare) the fish's EOD, and the experimenter substitutes an artificial EOD triggered by the fish's command signal.

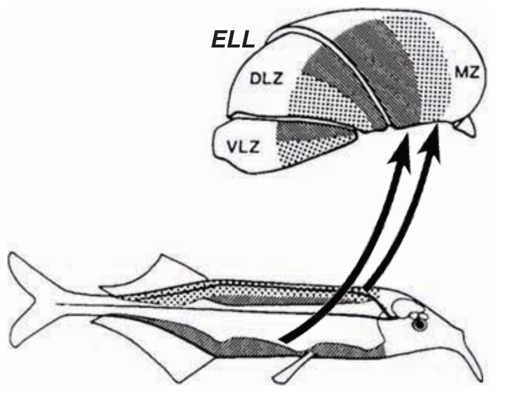
Unlike the visual system, the weak link in electrosensory neuroscience is the absence of precisely-controlled, repeatable experimental stimuli. Previous research used simple dipole sources.

Our new stimulus system presents controlled, tailored spatial-temporal electric field patterns to the fish's skin.

## 2 The First Central Processing Site: Electrosensory Lateral Line Lobe (ELL)

Electrosensory responses are conveyed with somatotpic precision to ELL. Corollary discharge inputs --- with precise time relation to the EOD command signal --- and proprioceptive (e.g. tail bend) information converge in ELL.

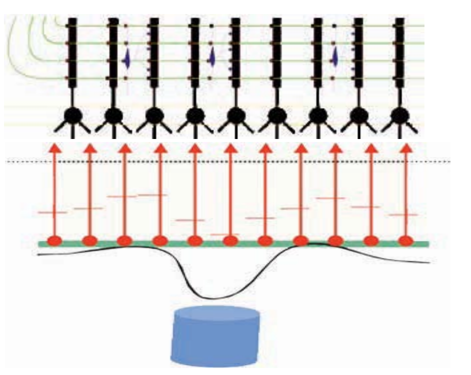
Spatial coding of the electric field




(Bell and Szabo, 1986)

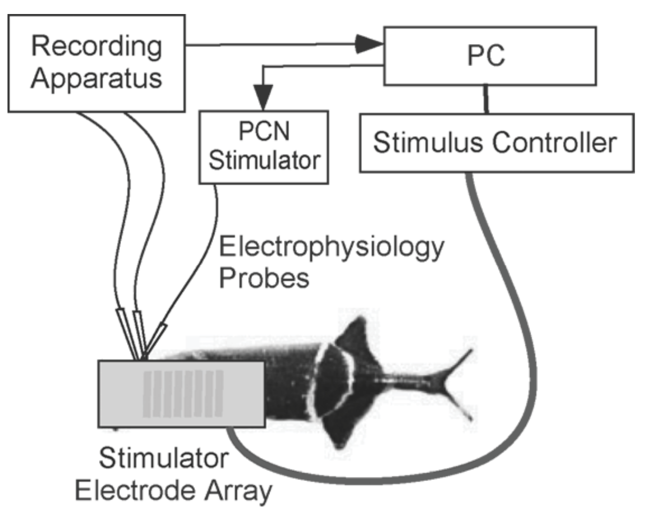
Temporal coding of electric field strength

The latency from EOD to the first spike of the afferent response is inversely proportional to the field strength. (Szabo and Hagiwara, 1967)

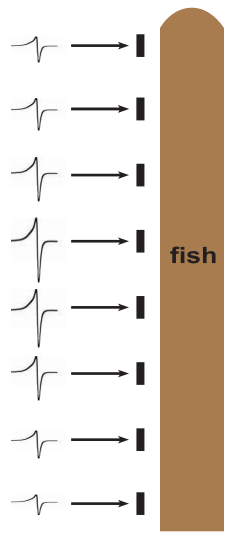


## 3 Innovation --- Put Precise Spatial Voltage Patterns on the Skin

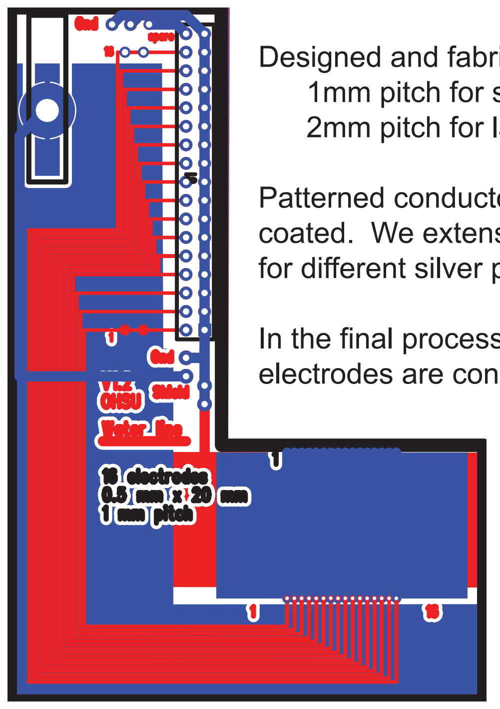
By presenting precisely-tailored spatial patterns while recording from neurons in ELL, we can characterize ELL responses and test hypotheses about electrosensory processing.




Spatial array of controlled-amplitude EOD signals tailors skin surface potential



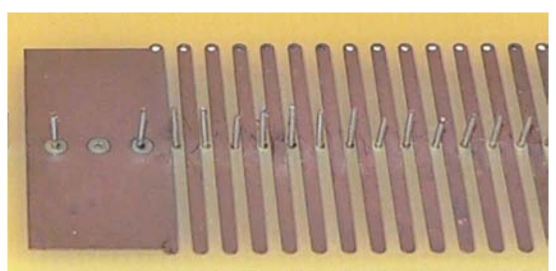

## 4 Stimulator Array



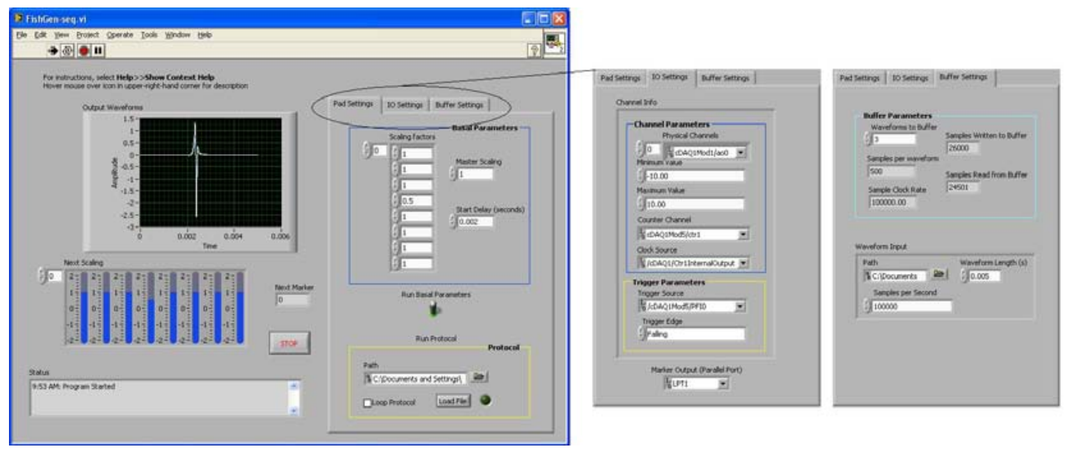
Designed and fabricated two arrays:
- 1mm pitch for small features
- 2mm pitch for large areas

Patterned conductors are silver-plated, and Ag-AgCl electro-coated. We extensively tested performance of Ag-AgCl coatings for different silver processes and chloride plating doses.

In the final process, voltage offset relative to commercial AG-AgCL electrodes are consistently 5mV.



## 5 Pattern Control User Interface



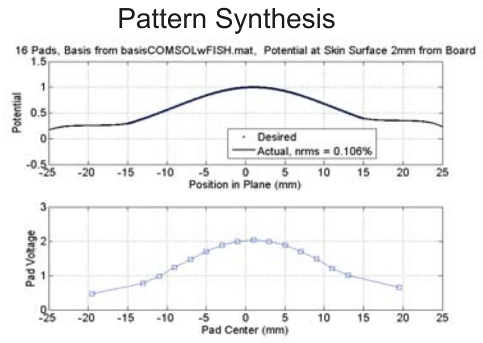
We developed two (LabVIEW) programs to present spatial voltage patterns.

The first changes the spatial pattern with each new EOD.The second changes the spatial pattern with timing pre-determined --- like the frames of a movie.

For each, the artificial EOD carrying the spatial pattern is slaved to the fish's EOD command signal, and neural responses are recorded for each pattern.

## 6 Synthesizing Desired Electric Potential Pattern

Pattern Synthesis




The potential at point $x$ on the skin is the sum of contributions from each pad

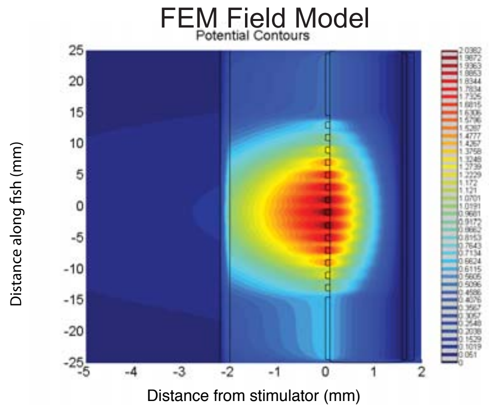
$$\phi(x; V_{pads}) = \sum_{i=1}^{N_{pads}} V_{pads}^{i}\, \phi_i(x) = V_{pads} \bullet \Phi(x)$$

with $V_{pads}^{i}$ the impressed pattern voltage on pad $i$; $\phi_i(x)$ the potential at $x$ --- pad $i$ at 1.0V, others grounded.

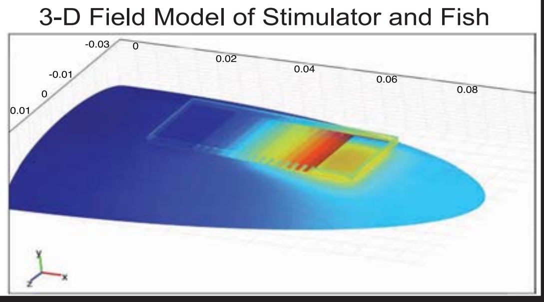
Given desired skin voltage $V_{desired}(x)$, required pad voltages $V_{pads}$ follow from least squares regression.

Basis fields $\Phi(x)$ vary with board-fish distance, skin, flesh, and water resistance. They are computed by FEM and stored in databases (decoupling FEM modeling from experimental protocol).

FEM Field Model



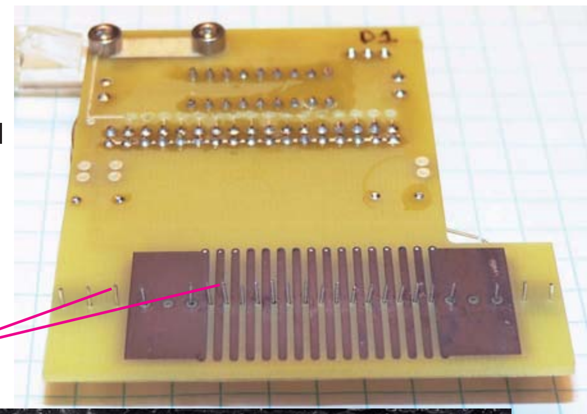

3-D Field Model of Stimulator and Fish

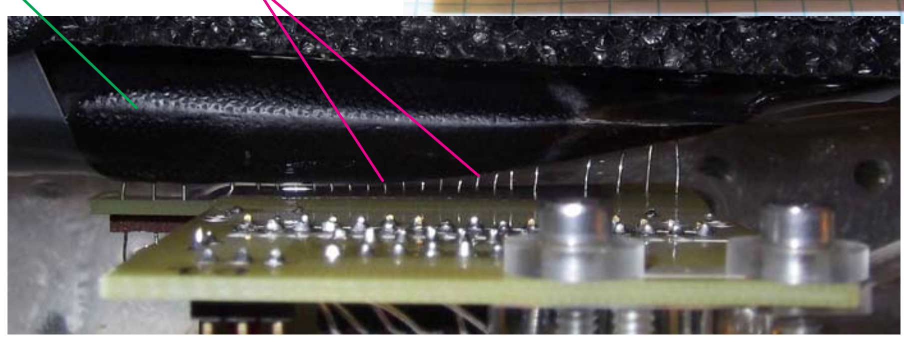


## 7 Model Verification and Calibration

Silver probe wires (insulated to tip, chloride coated at end) measure potential at skin.

Model parameters (skin and flesh effective conductivities) are fit to match measurements.



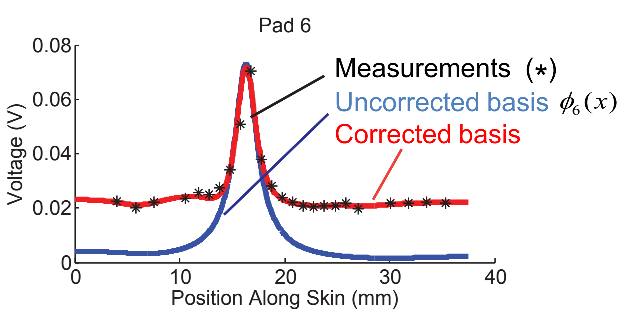



## 8 Model Adjustment by Data Assimilation

After calibration, residual model errors (e.g. from boundary conditions, as here) are corrected by data assimilation. The errors at the probe locations $x_i$

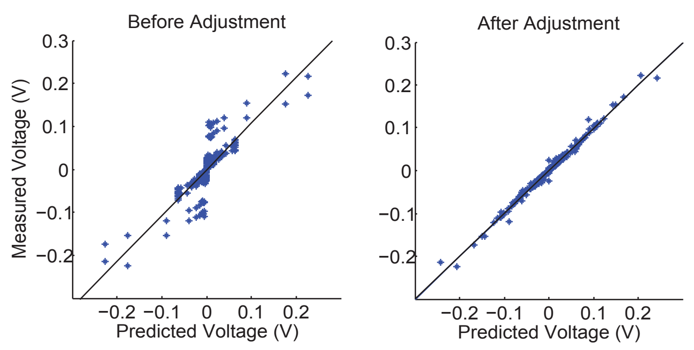
$$\delta(x_i) = V_{measured}(x_i) - V_{pads} \bullet \Phi(x_i)$$

are interpolated by smoothing splines, and the error field $\delta(x)$ used to adjust the basis set $\Phi(x)$.

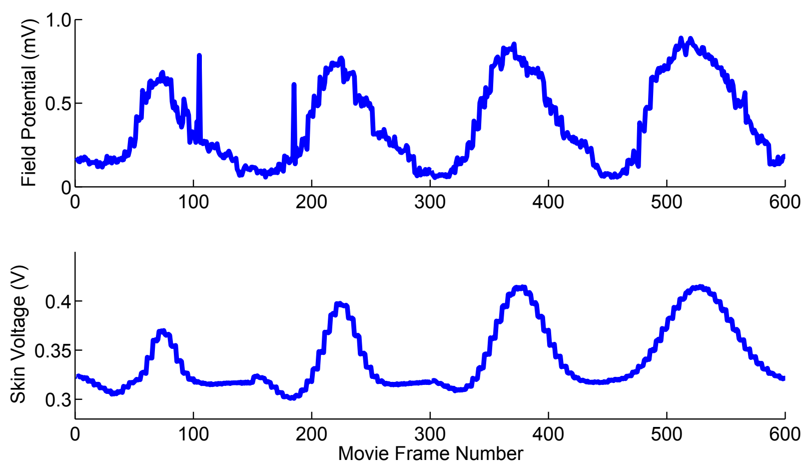



Plots show predicted vs measured skin voltage before and after basis adjustment.

Data for scatter plots are at probe positions not used to correct basis set $\Phi(x)$ (hold-out data).



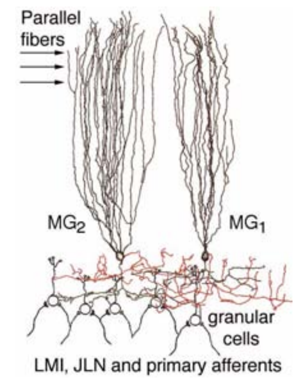

## 9 System Test: Central Response to Moving Stimuli

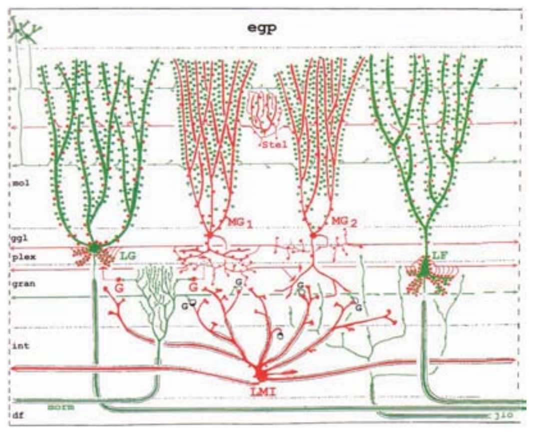



Gaussian bumps (bottom) of widths 2, 4, 8, and 12 mm were loaded into a movie (each pattern repeated 5 times, hence the staircase) and played over the surface of the skin. Concurrently, field potentials (top) were measured in the granular cell layer of ELL.

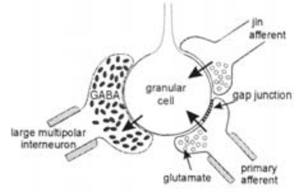
## 10 Circuitry of Electrosensory Processing in the ELL

Afferent input to the granular cells in the deep layers of the ELL are combined with a corollary discharge signal from the juxtalobar nucleus (JLN) to detect the strength of the electric field via coincidence detection. The granular cells transmit the electric field strength information to the principal cells of ELL.



Field strength is coded in the afferent as latency from the EOD. The granular cells convert the latency into a burst duration code.




## 11 Network Model Predicts ELL Activity Patterns

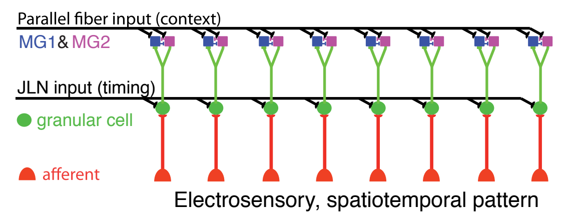
The neural models for afferents and granular cells are connected in a network. An external electric field pattern is simulated by depolarizing the afferents. Afferents make electrical synapses onto granular cells and combine with excitatory chemical inputs from JLN to determine the timing and duration of granular cells bursts. Granular cells make GABA-ergic synapses onto MG1 cells and electrical synapses onto MG2 cells. Excitatory inputs from parallel fibers onto MG cells combine with granular cell inputs and mutual inhibition between MG cell types to generate bursts of spikes.

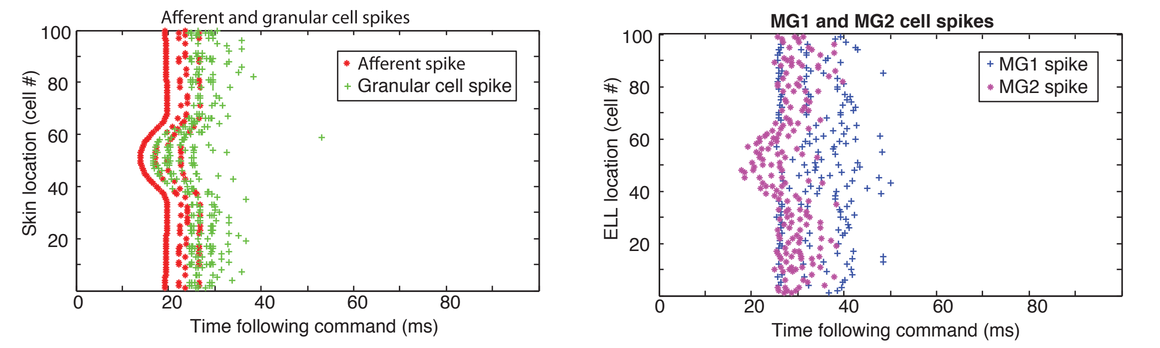
**Membrane voltage equations:**

$$C\dot{v} = k(v_r - v)(v_t - v) - u + I$$
$$\dot{u} = a(bv - u)$$

if $v > \theta$, then reset $v \to c$ and $u \to u + d$

(Izhikevich, 2003)




## 12 Conclusions and Directions

**Technology Developments:**

1. Simulations: 2-D & 3-D FEM electric field model for design and database of field simulations to decouple experimental workflow from FEM calculations.
2. Software: User interface for experimental protocol. Estimation of stimulus pad voltages required to generate desired field at skin, maximum likelihood receptive field estimation, model calibration and correction (data assimilation) using measured skin potentials.
3. Hardware: Electrode arrays with probe wires for model calibration and correction, control hardware and software.
4. Biophysical model of ELL network to predict MG cells from afferent stimulation.
7. System test in physiology lab. Measured field potentials in ELL cells resulting from swept stimuli.

**Future Work:**

1. Compare spatial and temporal receptive fields in electroreceptor afferents, and granular, MG, and efferent cells.
2. Characterize adaptive properties of MG and efferent cells, and test network model predictions.