Minimal Model of Prey Localization through the Lateral-Line System

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The clawed frog *Xenopus* is a predator catching prey at night by detecting water movements. We present a general method, a 'minimal model' based on a minimum-variance estimator, to explain prey detection through the frog's lateral-line organs. Waveform reconstruction allows *Xenopus* to determine both direction and character of the prey and even to distinguish two simultaneous wave sources.

Figure 1: The clawed frog's lateral-line organs can be seen as white "stitches".

In the present case water can be taken as a linear system[1] where the deflection y_i of cupula i is linear in the stimulus $x^{\mathbf{p}}$ at position $\mathbf{p}$ on the water surface,

$$y_i(t) = (h_i^{\mathbf{p}} \star x^{\mathbf{p}})(t) = \int_{-\infty}^{\infty} h_i^{\mathbf{p}}(\tau)\, x^{\mathbf{p}}(t-\tau)\, \mathrm{d}\tau\,. \quad (1)$$

Here $h_i^{\mathbf{p}}$ is the so-called impulse response at cupula i. An approximation of the transfer function is given by

$$H(\omega) = \sqrt{\frac{r_0}{r}}\, D_{\Delta\varphi}\, \exp\left[\frac{4\nu k^3}{\omega}(r_0 - r) + ik(r_0 - r)\right]. \quad (2)$$

We minimize the expectation value of the least-squares error

$$||x^{\mathbf{p}} - \hat{x}^{\mathbf{p}}||^2 = \int_0^{T_I} [x^{\mathbf{p}}(t) - \hat{x}^{\mathbf{p}}(t)]^2\, \mathrm{d}t\,. \quad (3)$$

The solution minimizing the error in (3) can be shown to be

$$\hat{x}^{\mathbf{p}} = \sum_j s_j^{\mathbf{p}} \star y_j\,, \quad S_j^{\mathbf{p}}(\omega) = \frac{H_j^{\mathbf{p}*}(\omega)}{\sum_i |H_i^{\mathbf{p}}(\omega)|^2 + \sigma^2} \quad (4)$$

The functions $S_j^{\mathbf{p}}$ are the Fourier transforms of the *reverse* transfer functions $s_j^{\mathbf{p}}$.

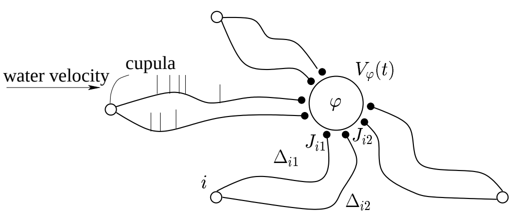

Figure 2: Connections of a neuron, sensitive for direction φ, to the lateral-line organs.

Membrane potential $V^{\mathbf{p}} \approx \hat{x}^{\mathbf{p}}$ of the spike-response[2] neuron

$$V^{\mathbf{p}}(t) = \sum_{i,k,f} J_{ik}^{\mathbf{p}} \varepsilon(t - t_i^f - \Delta_{ik}^{\mathbf{p}}) + \sum_{i,k,f'} J_{ik}^{\mathbf{p}'} \varepsilon(t - t_i^{f'} - \Delta_{ik}^{\mathbf{p}'}) \quad (5)$$

where the t_i^f are the firing times of the nerve from lateral-line organ i and $\Delta_{ik}^{\mathbf{p}}$ is the delay time of synapse k with synaptic strength $J_{ik}^{\mathbf{p}}$.

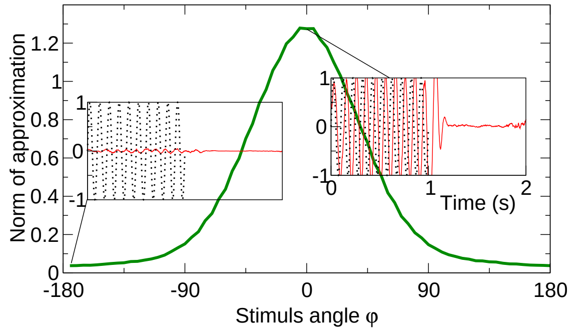

Figure 3: Neurons responding strongest ($\varphi \approx 0$) tell *Xenopus* the direction of the wave source. The membrane potential of these neurons gives *Xenopus* an approximation to the actual wave form and allows the animal to distinguish different kinds of prey.

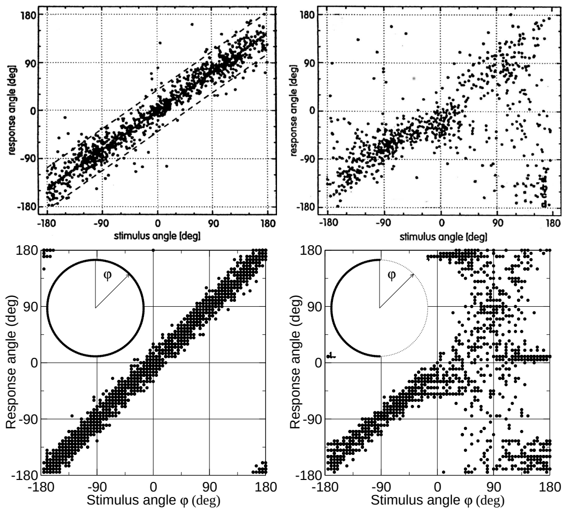

Figure 4: Top: *Xenopus*' experimental response angle[3] versus stimulus angle. Left: intact *Xenopus*. Right: lateral-line organs at the right-hand side have been deactivated. Bottom: Response of our neuronal model.

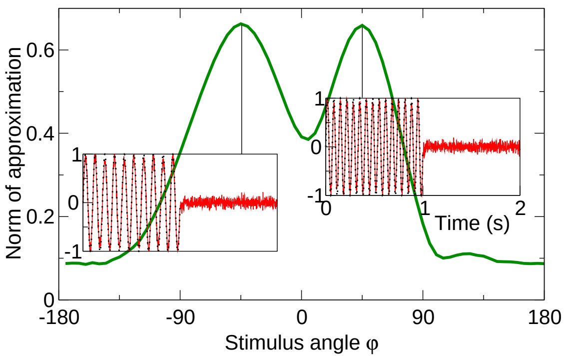

Figure 5: 'Map' like that of Fig. 3 for *two* wave sources, positioned at $\varphi = -45°$ and $45°$. With the help of its evaluations, *Xenopus* could easily distinguish position and waveform of the sources, as in experiment[4].

[1] Lamb, H. (1932) *Hydrodynamics* (Cambridge University Press) 6th edn. §§226ff, 246, 331, 332.
[2] Gerstner, W. & van Hemmen, J. L. (1994) in *Models of Neural Networks II*, eds. Domany, E., van Hemmen, J. L. & Schulten, K. (Springer, New York) chap. 1 pp. 39–47.
[3] Claas, B. & Münz, H. (1996) *J. Comp. Physiol.* **178**, 253–268.
[4] Elepfandt, A. (1986) *Neurosci. Lett. (Suppl.)* **26**, 380.