

# Coupled Oscillations in Nervous Systems

Linear Waves in Mammalian Motor Cortex During Planning

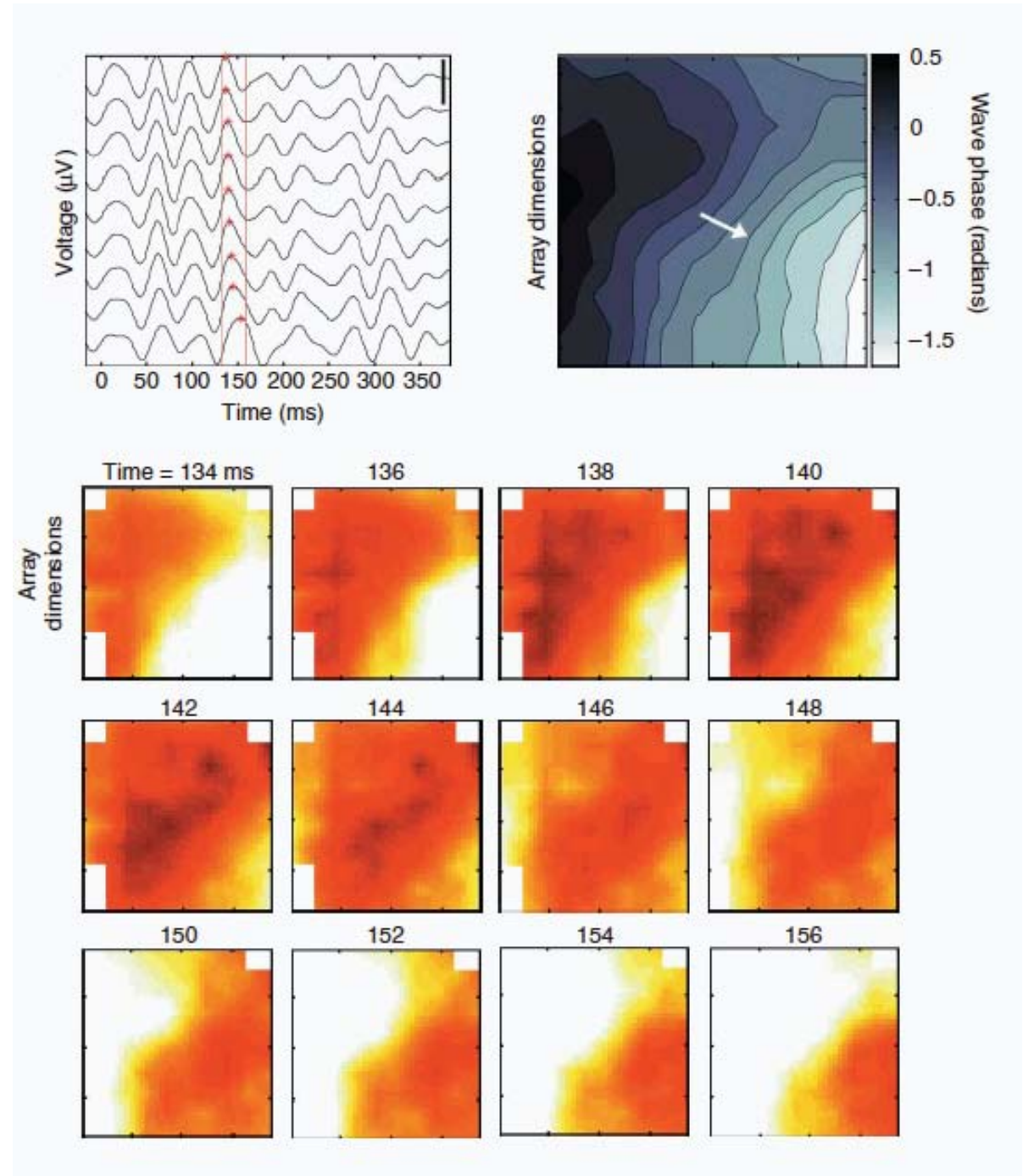
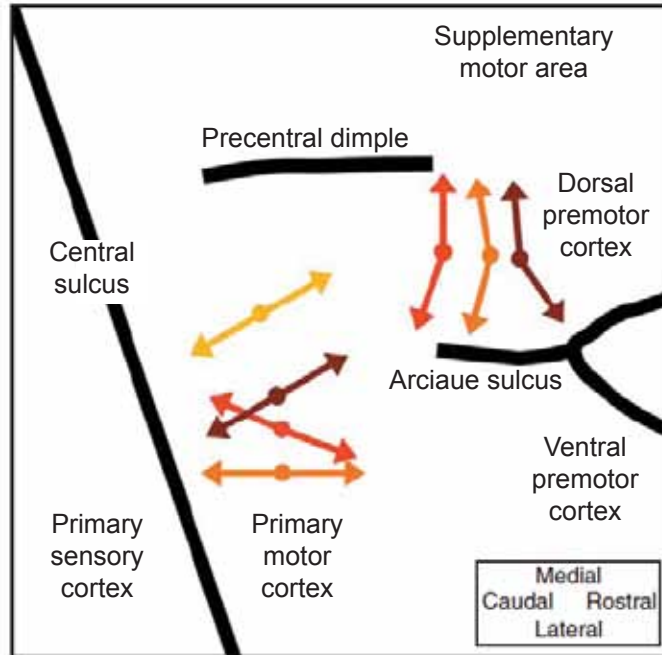
Linear Waves in an Invertebrate Central Olfactory Organ  
(Wave consequence of an intrinsic frequency gradient)

Linear and Rotating Waves in Lower Vertebrate Visual System  
(Linear part consistent with biased connectivity)

Linear and Rotating Waves in Epileptic Mammalian Cortical Slice  
(Rotating part consistent with random connectivity)



# Propagating waves mediate information transfer in the motor cortex



(Rubino, Robbins & Hatsopoulos, Nature Neuroscience 2006)

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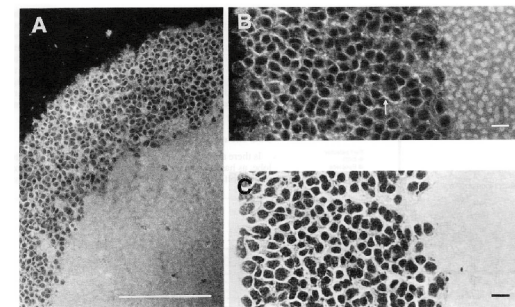
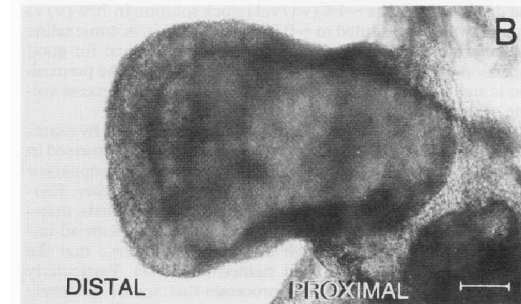
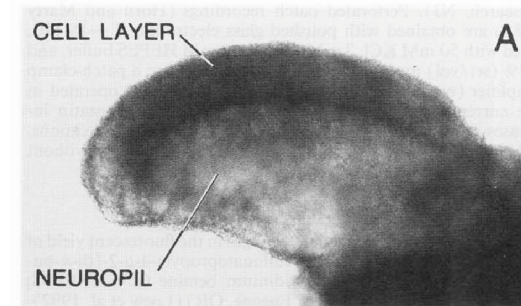
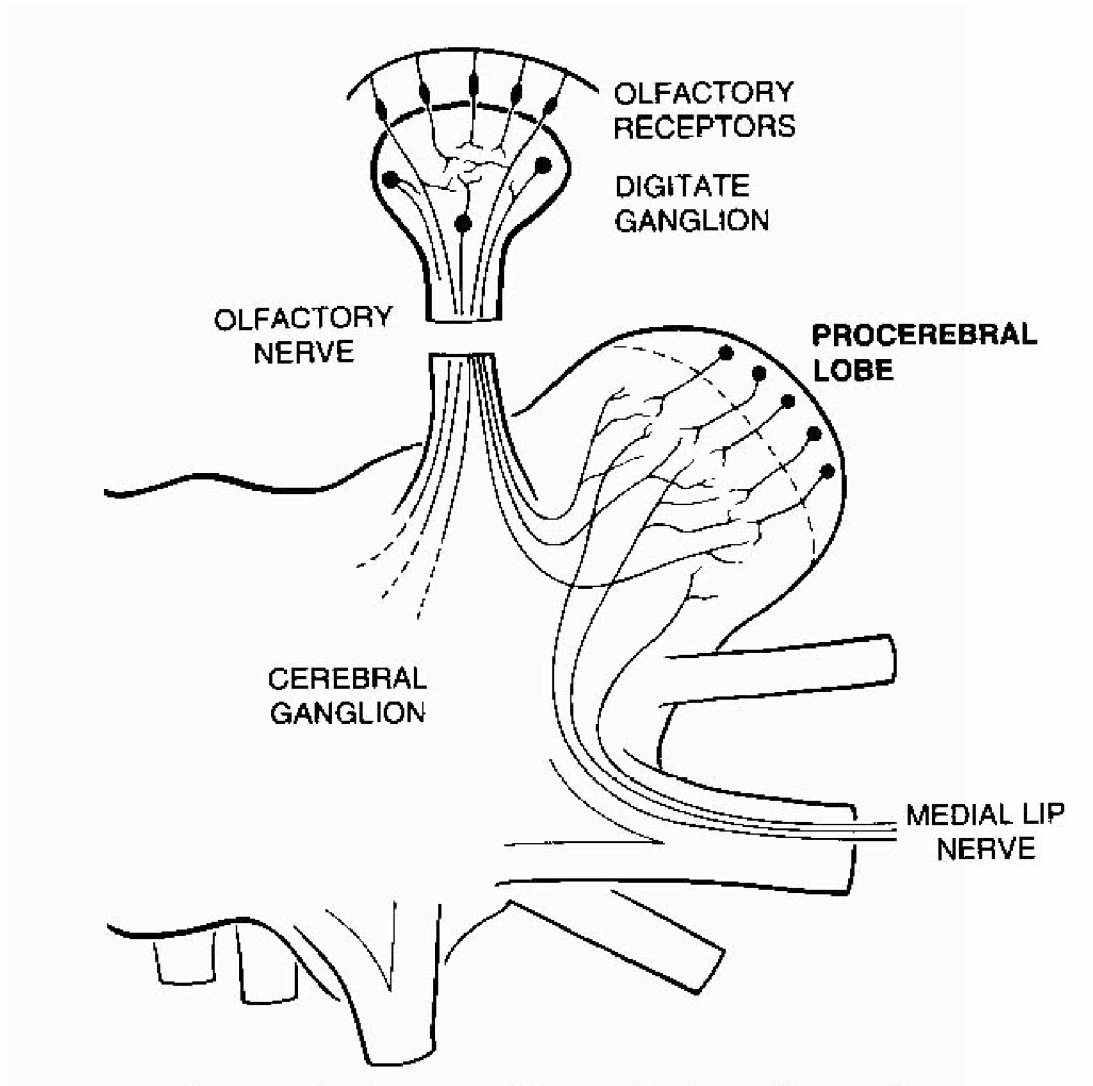
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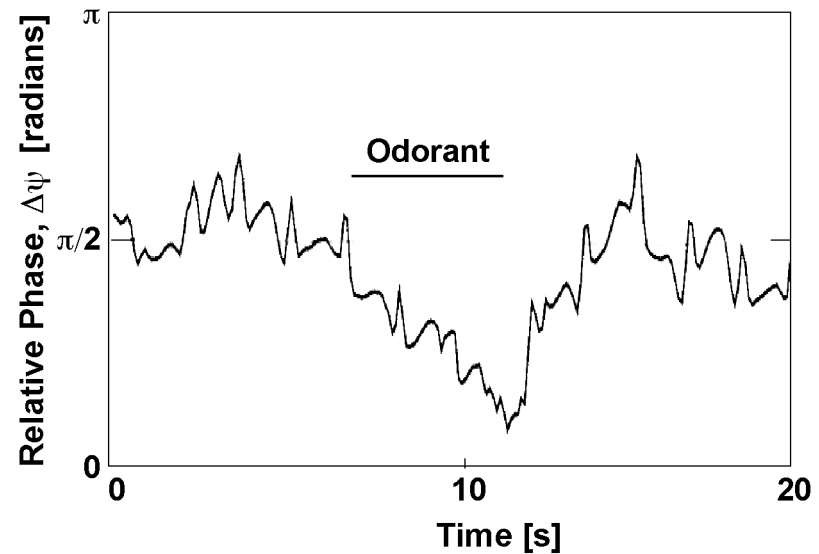
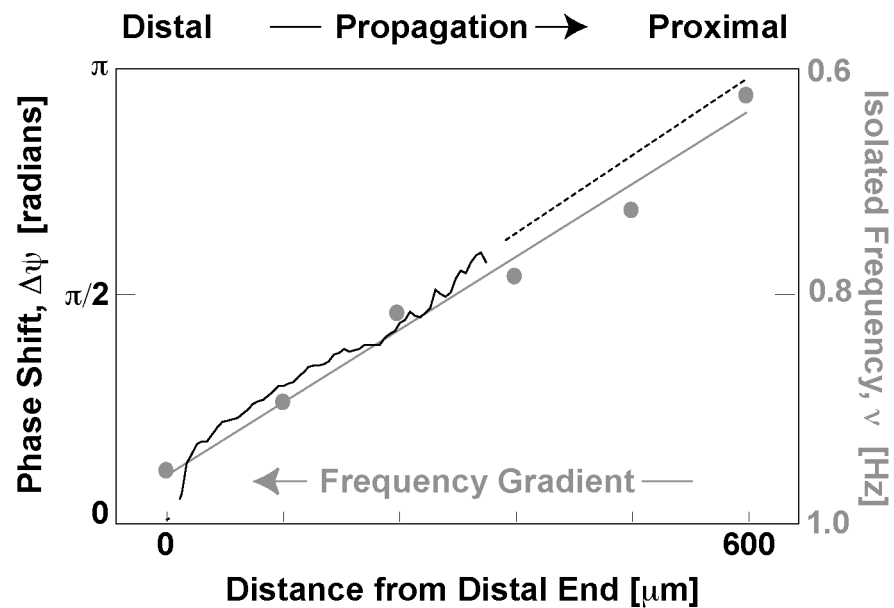
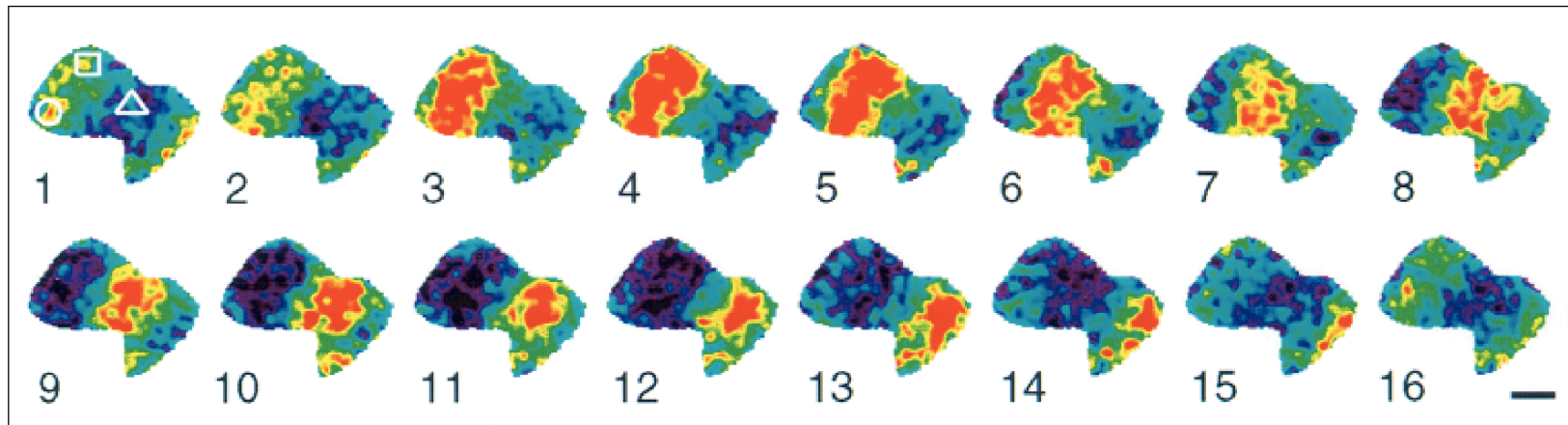


# Central Olfactory Organ in the Terrestrial Mollusk *Limax*



# Electrical Wave Propagation in the Central Olfactory Organ of Limax

(Delaney et al 1994; Kleinfeld et al 1994; Ermentrout et al 1996)



# Coupling of Two Oscillators with Different Intrinsic Frequencies

We take  $\Gamma(\psi - \psi') \equiv -\Gamma_0 \sin(\psi - \psi')$

Then

$$\frac{d\psi}{dt} = \Gamma_0 \sin(\psi' - \psi) + \omega$$
$$\frac{d\psi'}{dt} = \Gamma_0 \sin(\psi - \psi') + \omega'$$

Lock, i.e.,  $\frac{d\psi}{dt} = \frac{d\psi'}{dt}$  so long as  $\Gamma_0 \sin(\psi' - \psi) - \Gamma_0 \sin(\psi - \psi') = \omega - \omega'$

or

$$\frac{2\Gamma_0}{|\omega' - \omega|} > 1$$

The phase shift is  $\Delta\psi \equiv \psi - \psi' = \sin^{-1} \left( \frac{\omega' - \omega}{2\Gamma_0} \right)$

# Wave Model for Limax

(Ermentrout, Flores & Gelperin 1998; Ermentrout, Wang, Flores & Gelperin 2001)

Chain of Oscillators with  $\delta\omega \propto x$

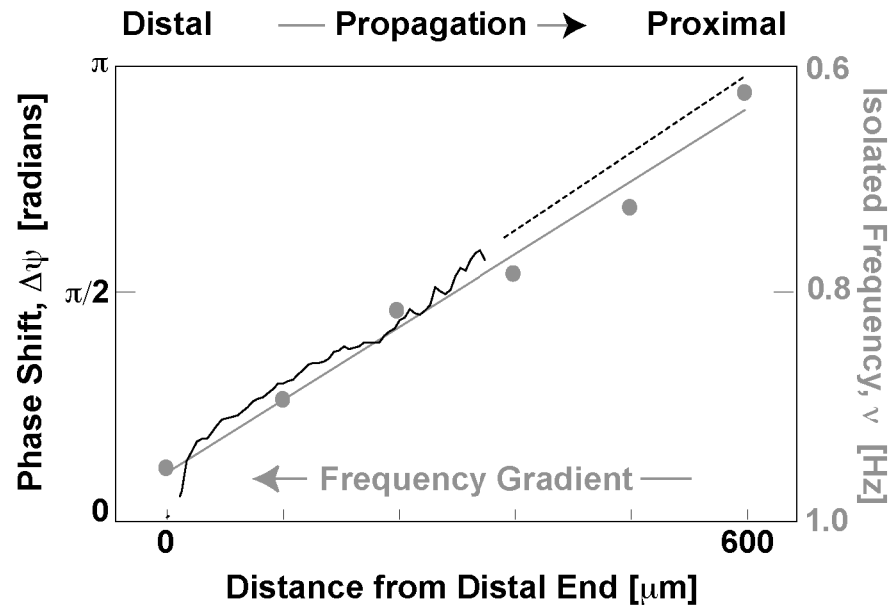
$$\frac{d\psi_x}{dt} = (\omega + \delta\omega_x) + \sum_{x \neq x'} \Gamma(\psi_x - \psi_{x'})$$

$\delta\omega_x \propto x$

Single frequency

When the network locks:

Gradient of phase shifts with  $\frac{\psi_x}{dx} \propto \text{constant}$ .



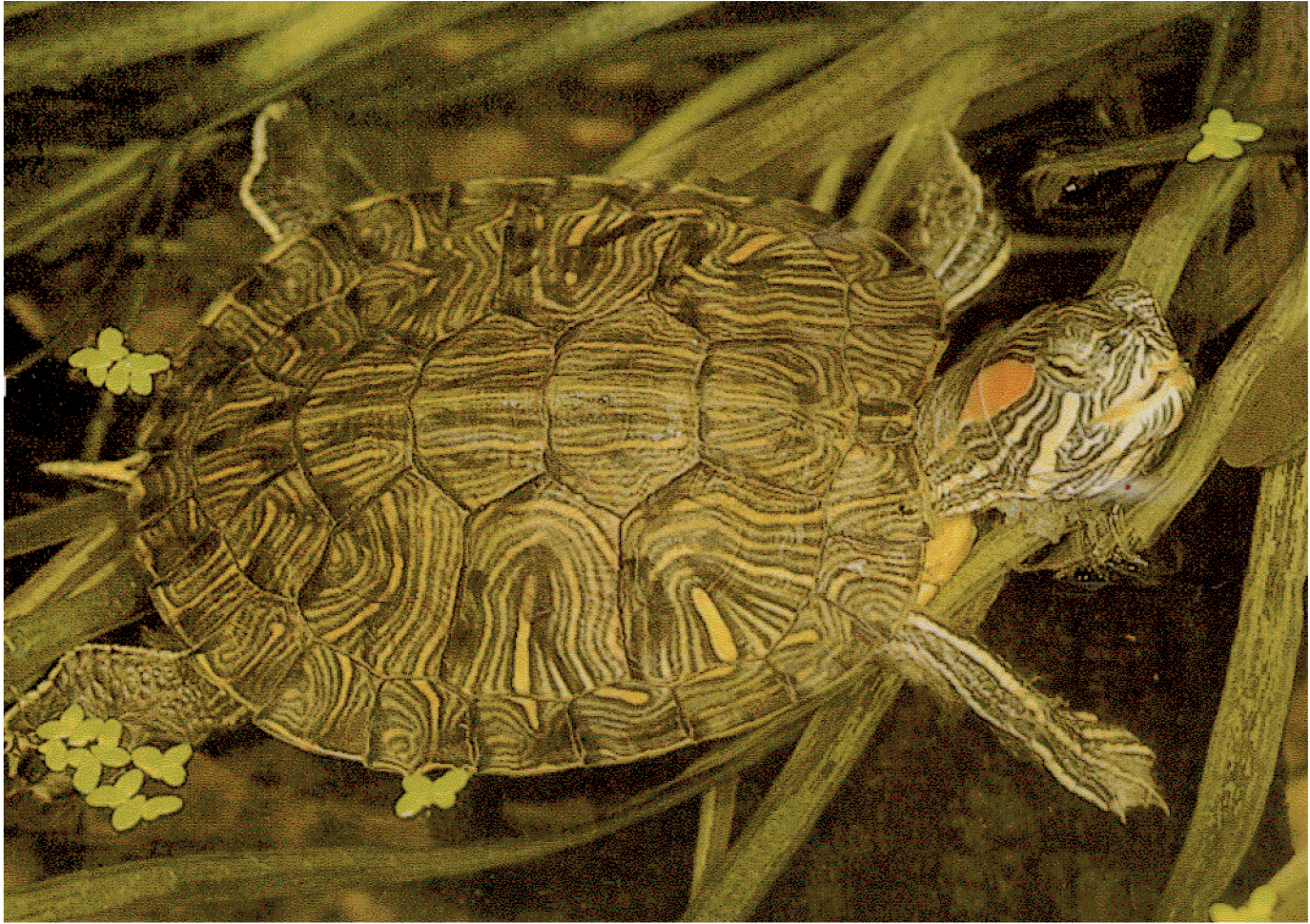
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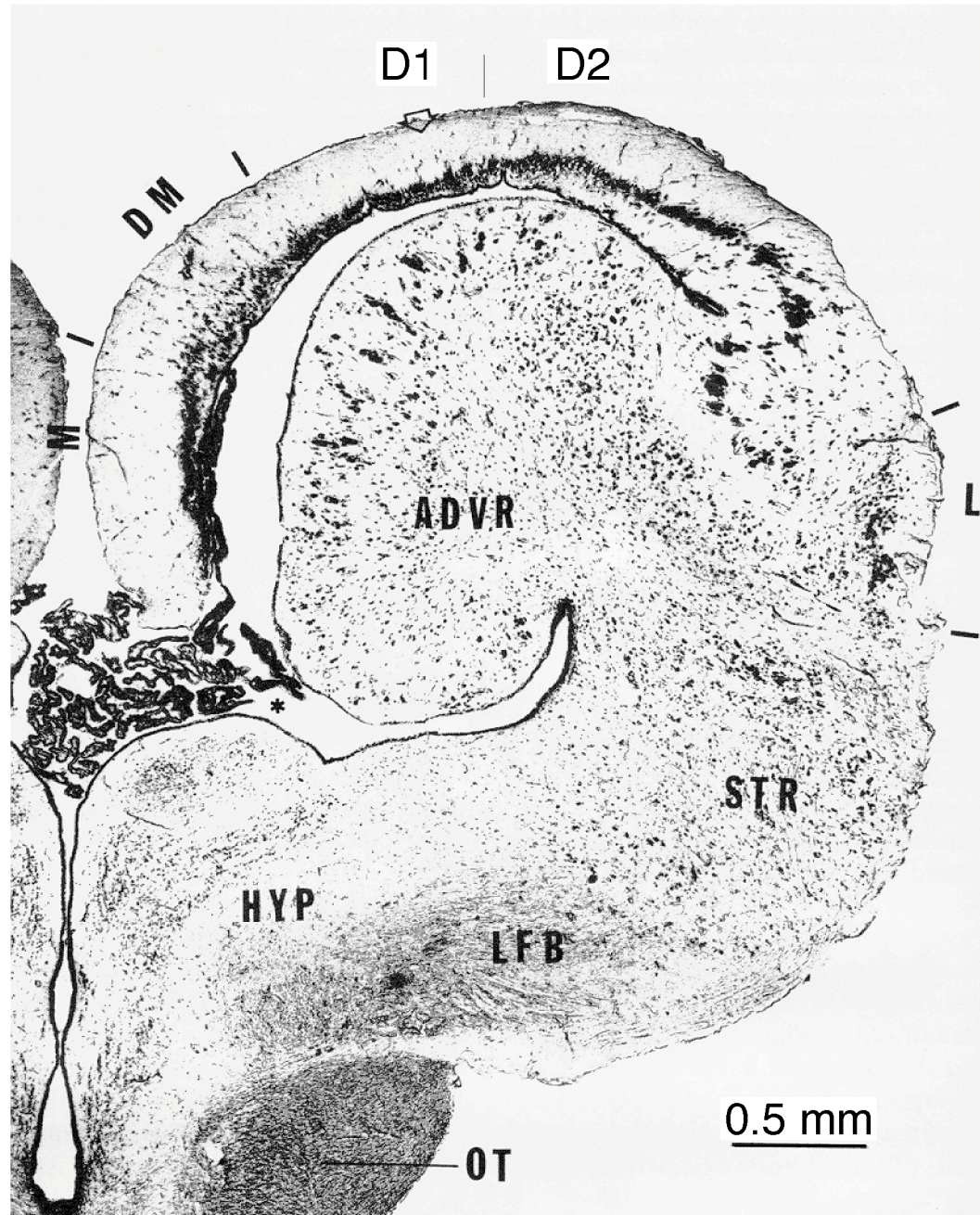
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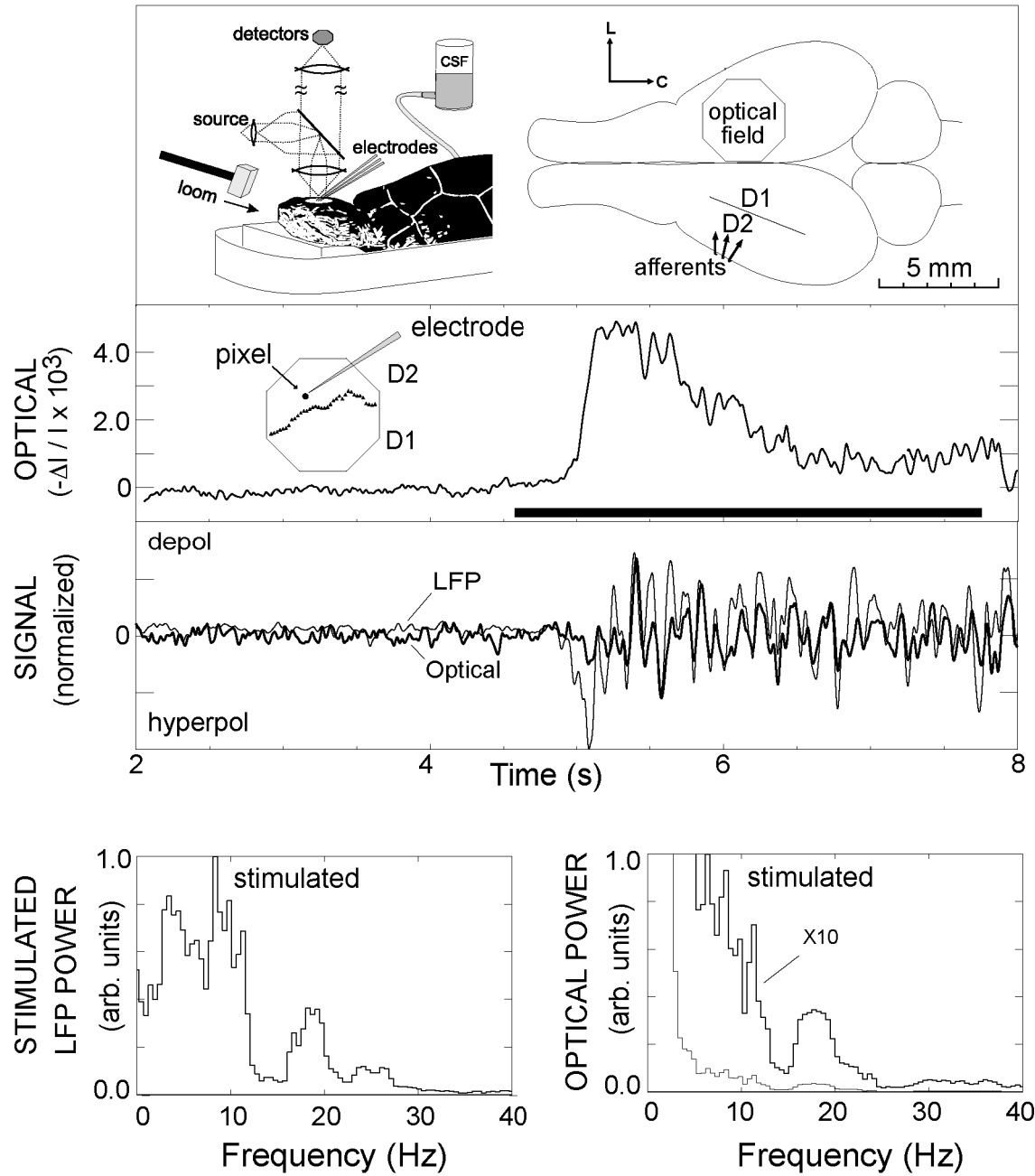


Transverse Nissl section through cerebral hemisphere of *Pseudemys scripta elegans*

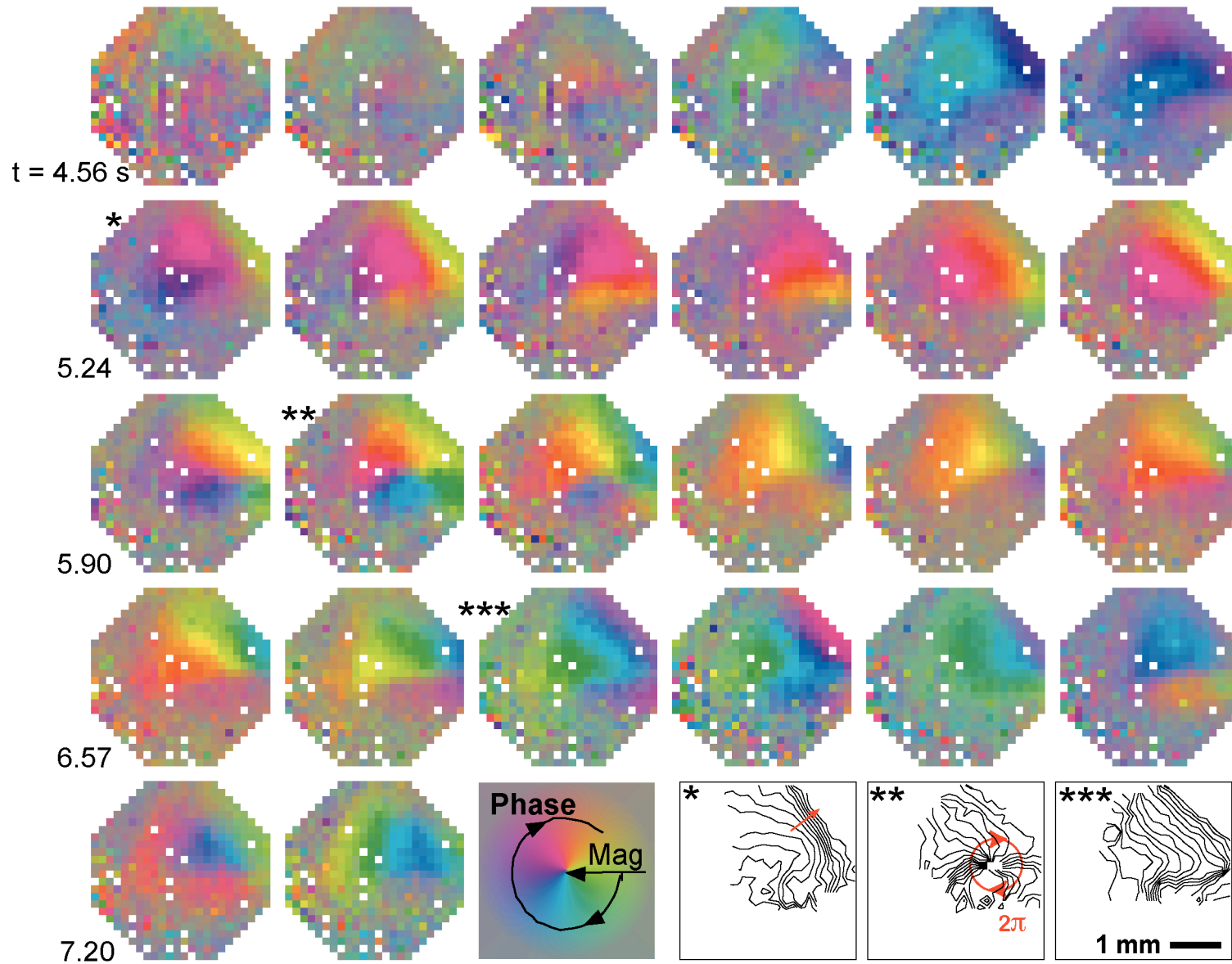
- from P. S. Ulinski



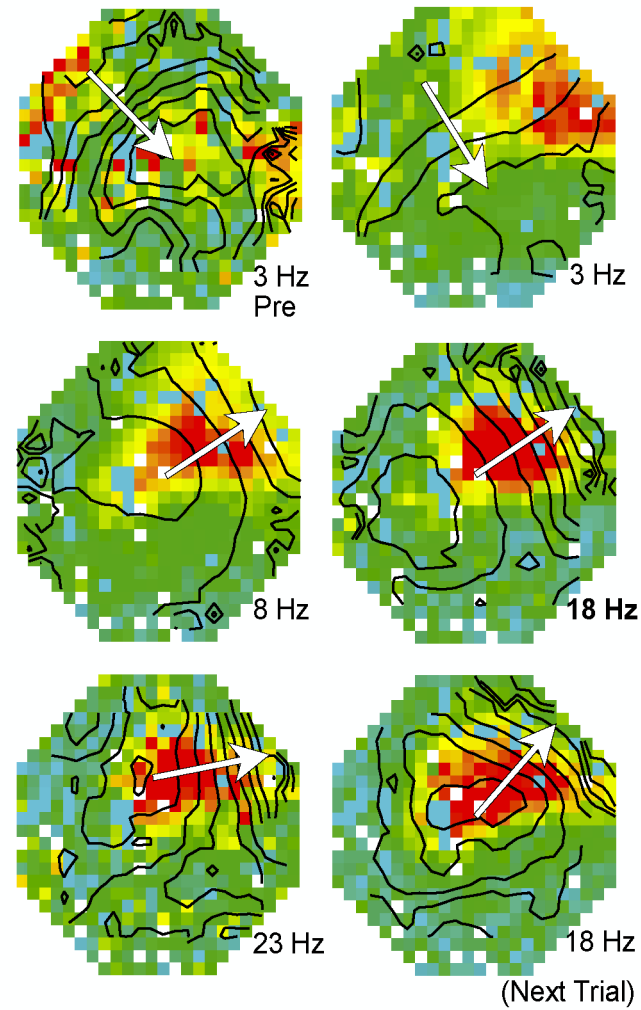
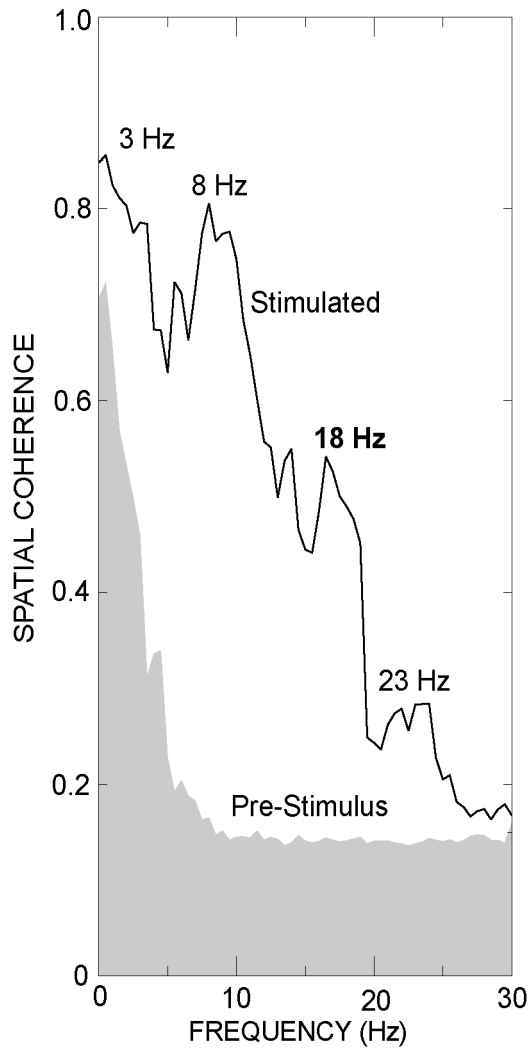
# Voltage Sensitive Dye Imaging of Turtle Visual Cortex

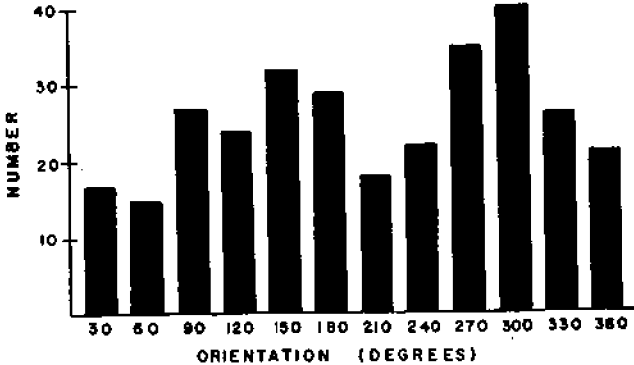
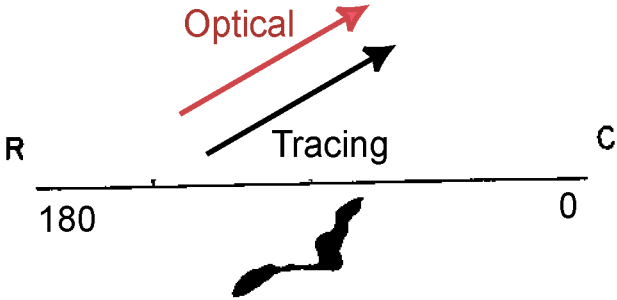
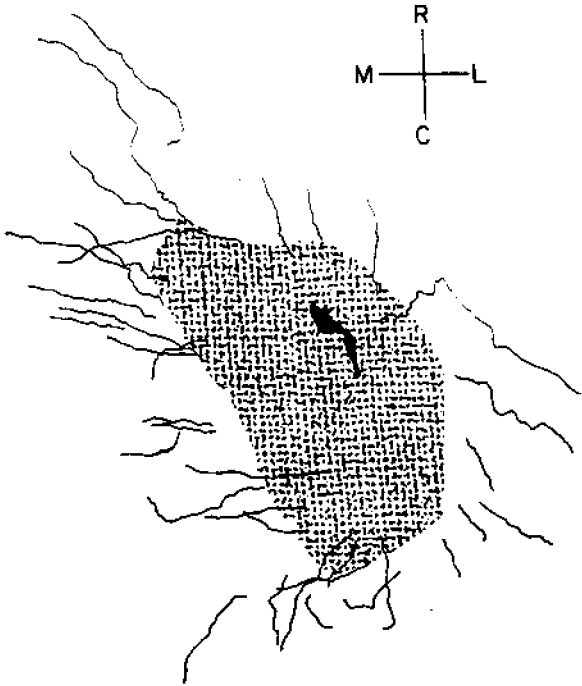
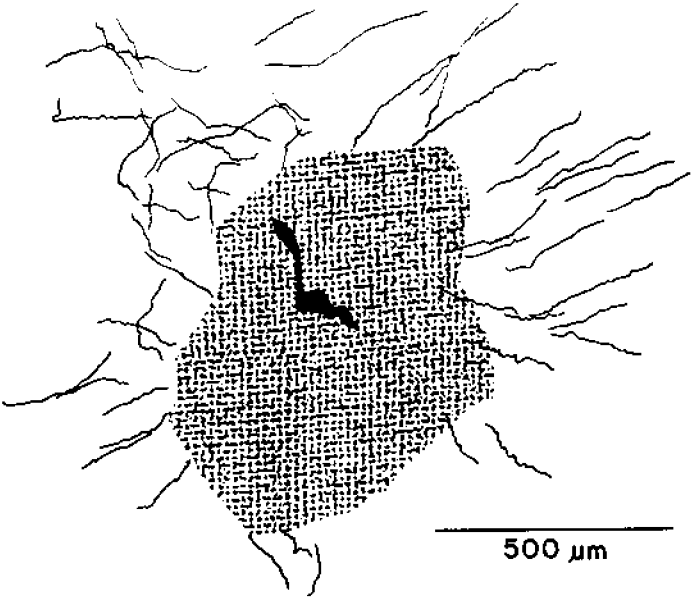


# Demodulated Response at 18 Hz Versus Time (Magnitude and Phase Plots)



# Dominant Spatial Modes are Revealed from a Spectral Decomposition (SVD) in Position ( $x$ ) and Frequency ( $f$ )





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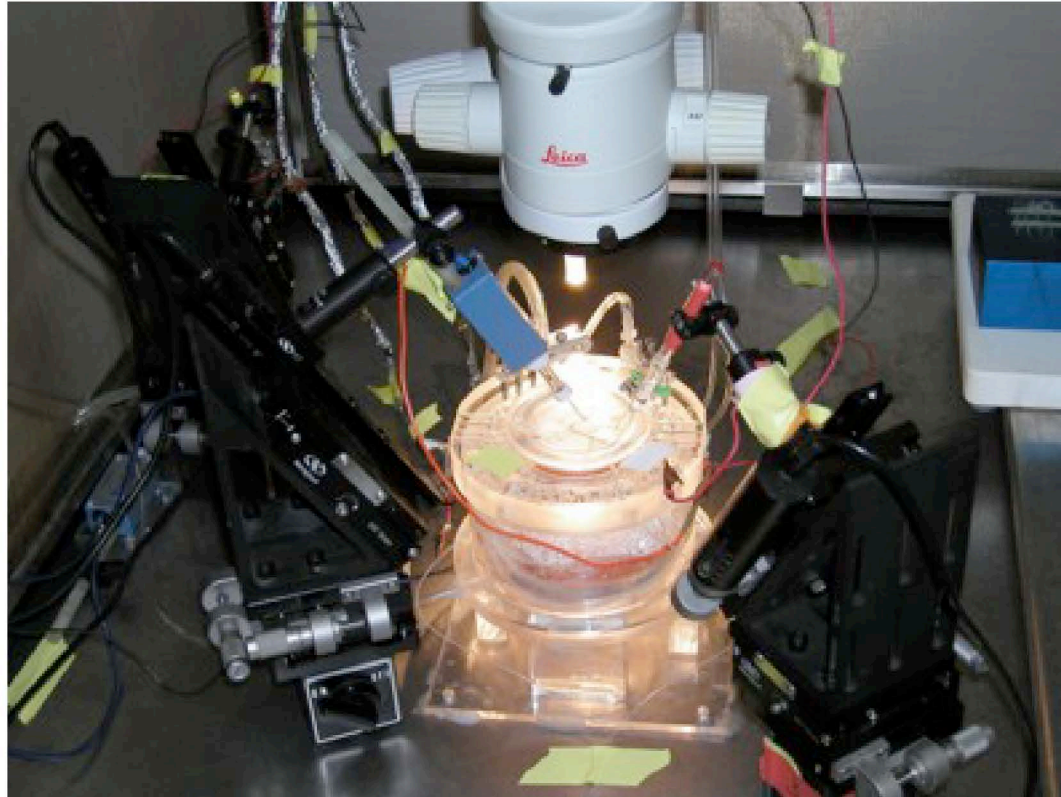
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# Upcoming Applications for Kuromoto-like Coupling

## Spiral Waves in Disinhibited Mammalian Neocortex (Huang, Troy, Yang, Ma, Laing, Schiff and Wu, 2004)



Electrical (local field potential) and optical (voltage sensitive dyes and brightfield illumination) recording of spatially averaged ( $\sim 100 \mu\text{m}$ ) activity across layer 2/3 tangential slice

# Spiral Waves in Disinhibited Mammalian Neocortex

(Huang, Troy, Yang, Ma, Laing, Schiff and Wu, 2004)

