Active Sensory Dynamics

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OUTLINE

- Definition of Field
- What I do: Dynamics of Sensory Coding

(saccades, stimulus-driven network oscillations, noise, multi-scale signal separation)

- Research Highlights in the field
- Critical Considerations for those entering
- Ideal type of Training
- Suggested Changes

But tomorrow at CNS…

Computational and Mathematical Neuroscience

Obvious Definition of the Field:

intersection of computational sciences and mathematics with neuroscience.

But the key word "intersection" implies any percentage of overlap and relevance.

Open mind: from one extreme (99% math) to the other (99% neuro)

Varying degree of experiment-theory interaction

I call my own field: "Neurophysics and Nonlinear Dynamics"

Cellular biophysics

electric field modeling

nonlinear dynamics

Langevin and Fokker-Planck equations

Nonequilibrium statistical mechanics

information theory

computational physics, …

Neuroscience Fields of Interest (to me)

- Sensory acquisition and processing
- Role of feedback, delays, noise
- Sensory-motor integration (posture, timing)
- Interesting problems in bifurcation theory/nonequilibrium statistical mechanics that arise from those neuroscience interests

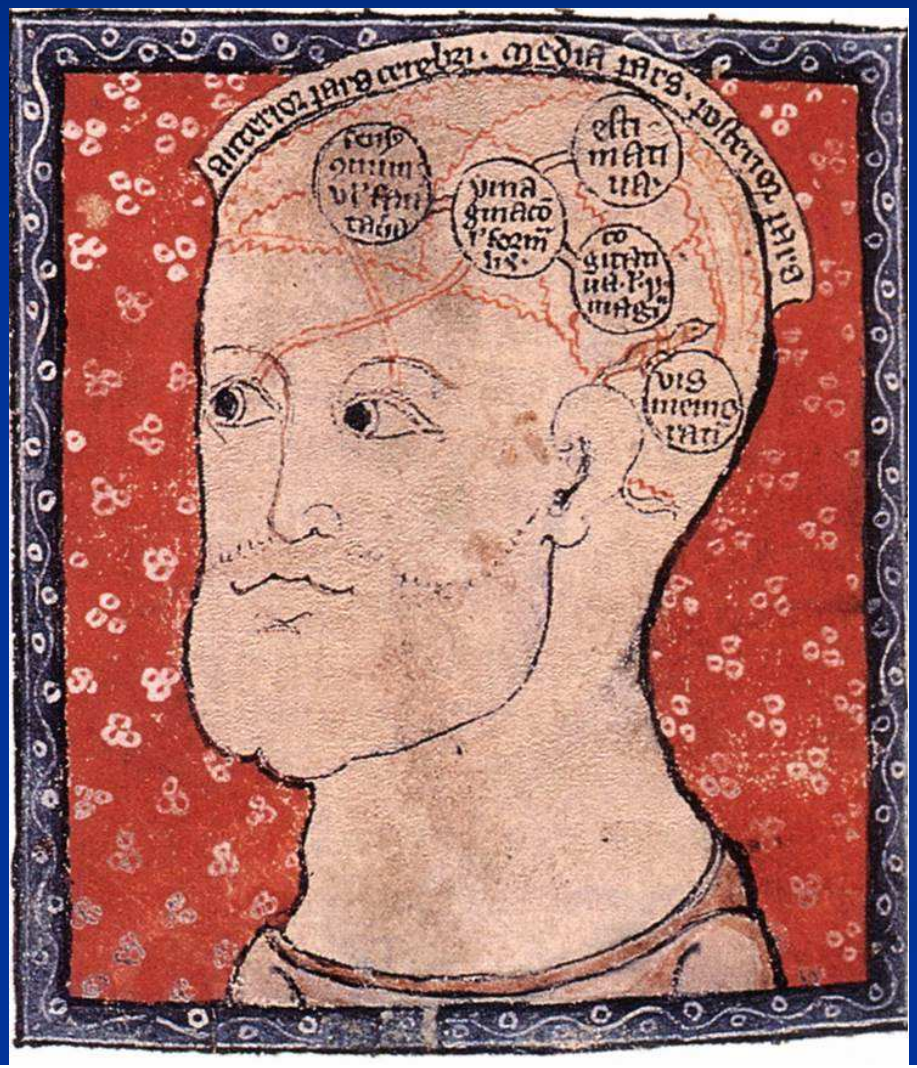
Many Approaches out there

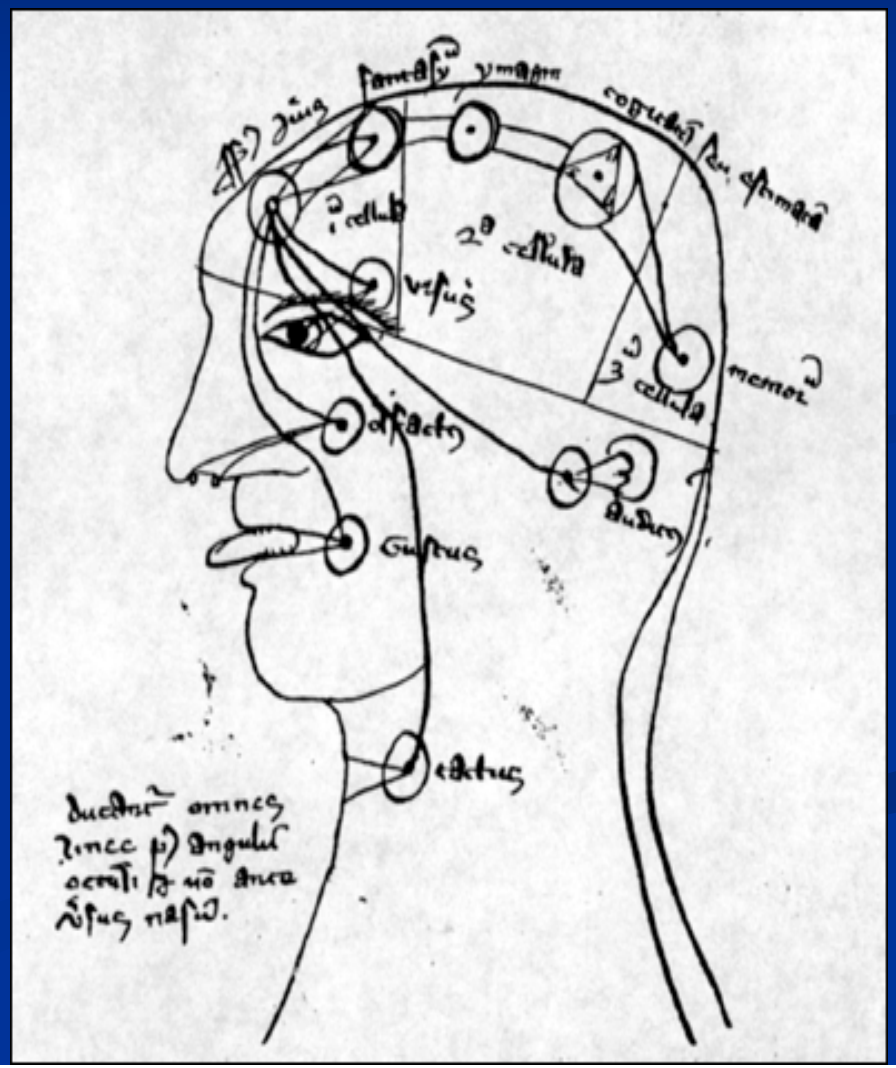
- Specialize in a few analytical tools, and look for the right nuts to put into your "nutcracker".
- Specialize on one neurobiological system, study it well enough using a variety of tools to get at fundamental principles of neural design.

- **Like studying the evolution of one class of stars, and end up being able to estimate the age of the universe.**

Brain Diagram by Arab philosopher Avicenna (circa 1300)
Five ventricles: common sense, imagination, judging, second imagination (composing/combining images), memory.
(University Library, Cambridge)

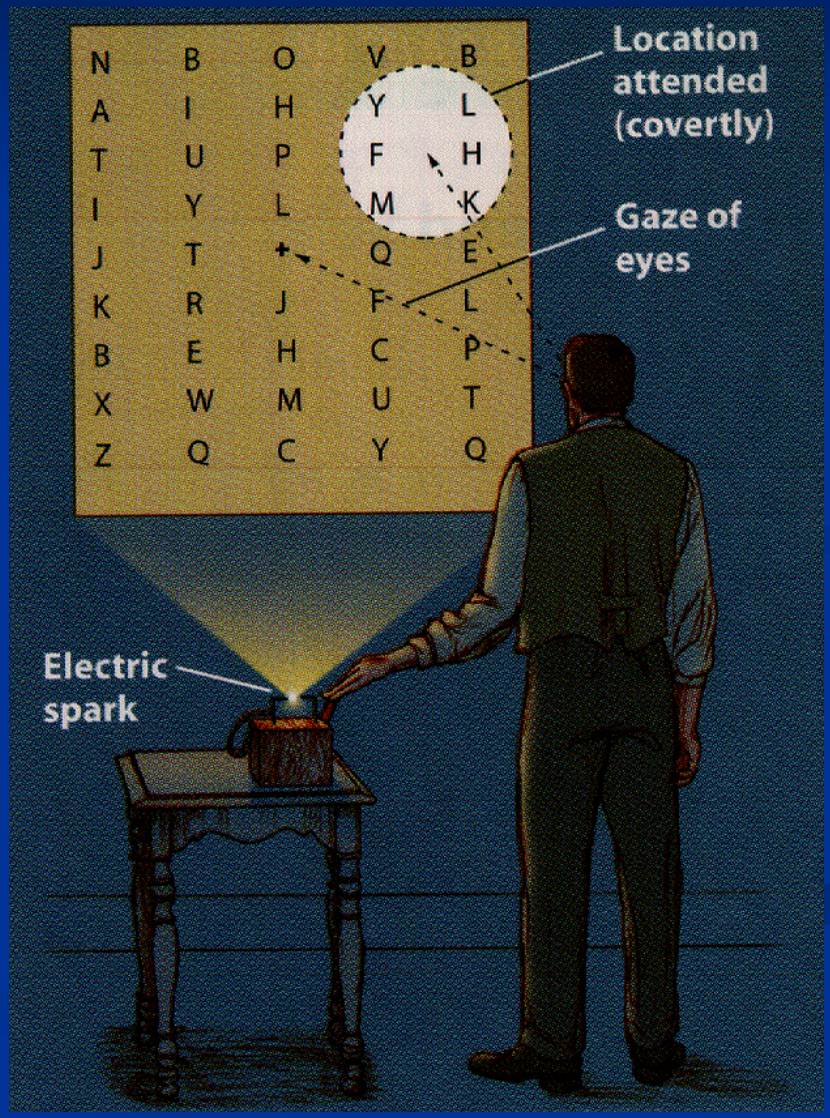
From Da Vinci's notes





Shifts of (covert) attention

Hermann von Helmholtz
(1821-1894)



Hermann von Helmholtz (1821-1894) "neurophysics pioneer"

- Law of conservation of energy (etc…)
- Auditory perception (scales, consonance)
- Visual perception (covert attention)
- Propagation speed of nerve pulse: **27m/s** !

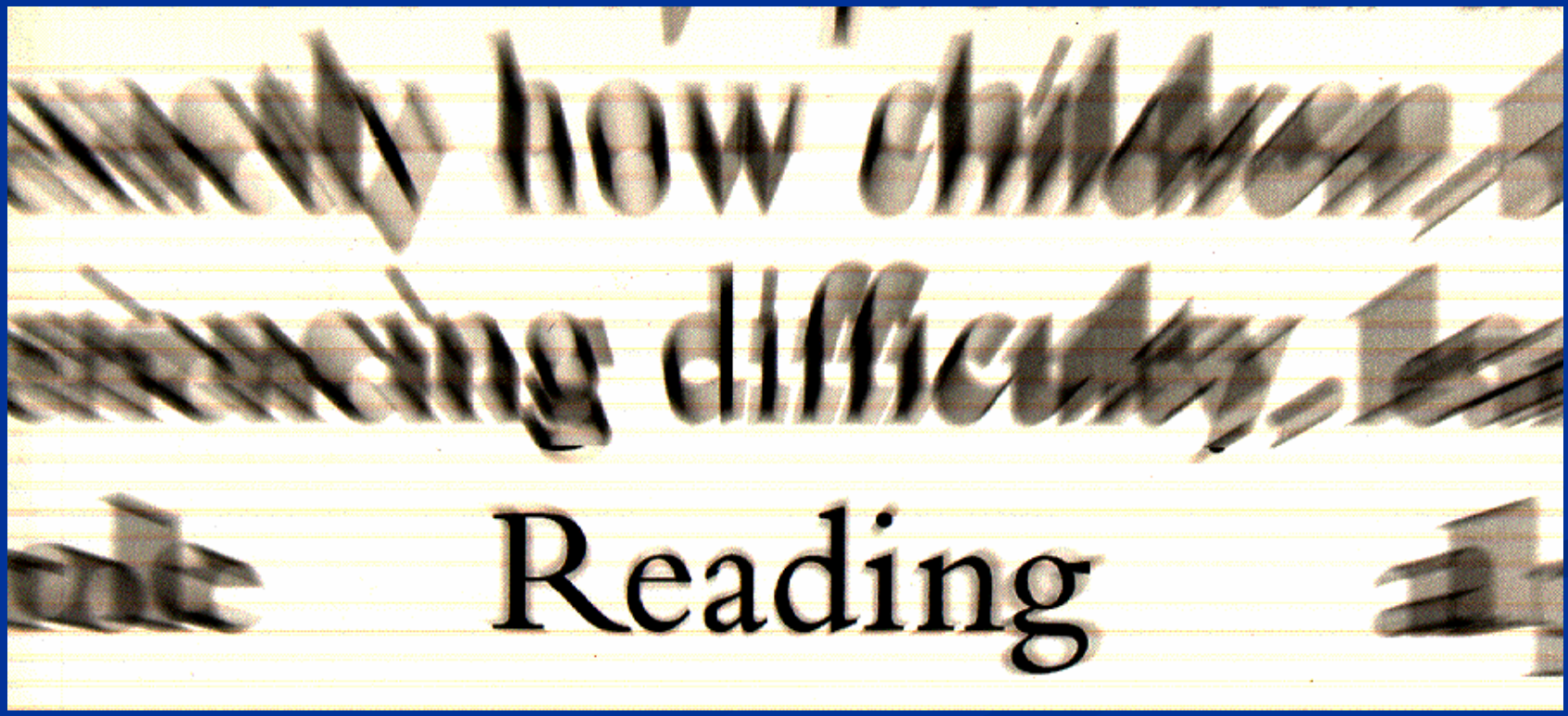
Big Debate: Delay between volition and action !

His hypothesis: "cytoplasmic flow"

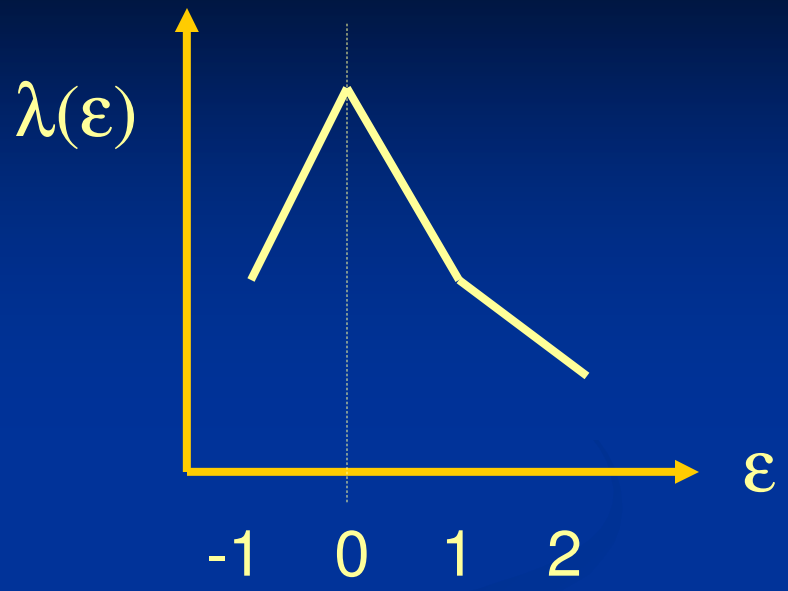
(wait for Hodgkin-Huxley (1952): nonlinear diffusion).

Visual attention during reading

- Fovea: central ~ 2° degrees of the visual field
- Parafovea: up to ~ 5°, decreased acuity



(i) Lexical processing



- attentional window:
  lexical processing rate
  $\lambda(\varepsilon)$
  depends on eccentricity
  ε
- two levels: preprocessing & lexical access

(ii) Timing of saccades

lexical processing

saccade execution

target selection

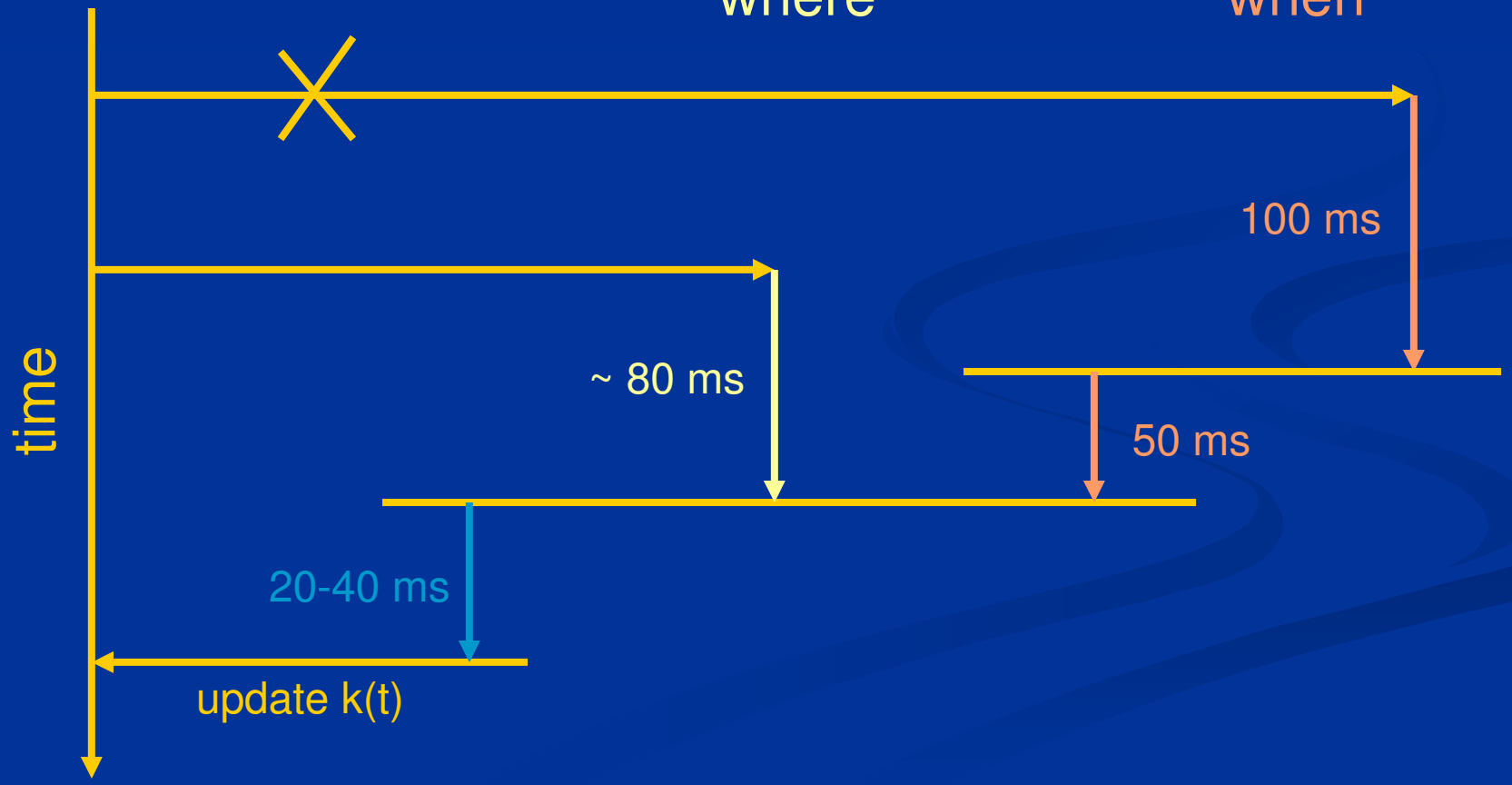
non-labile program

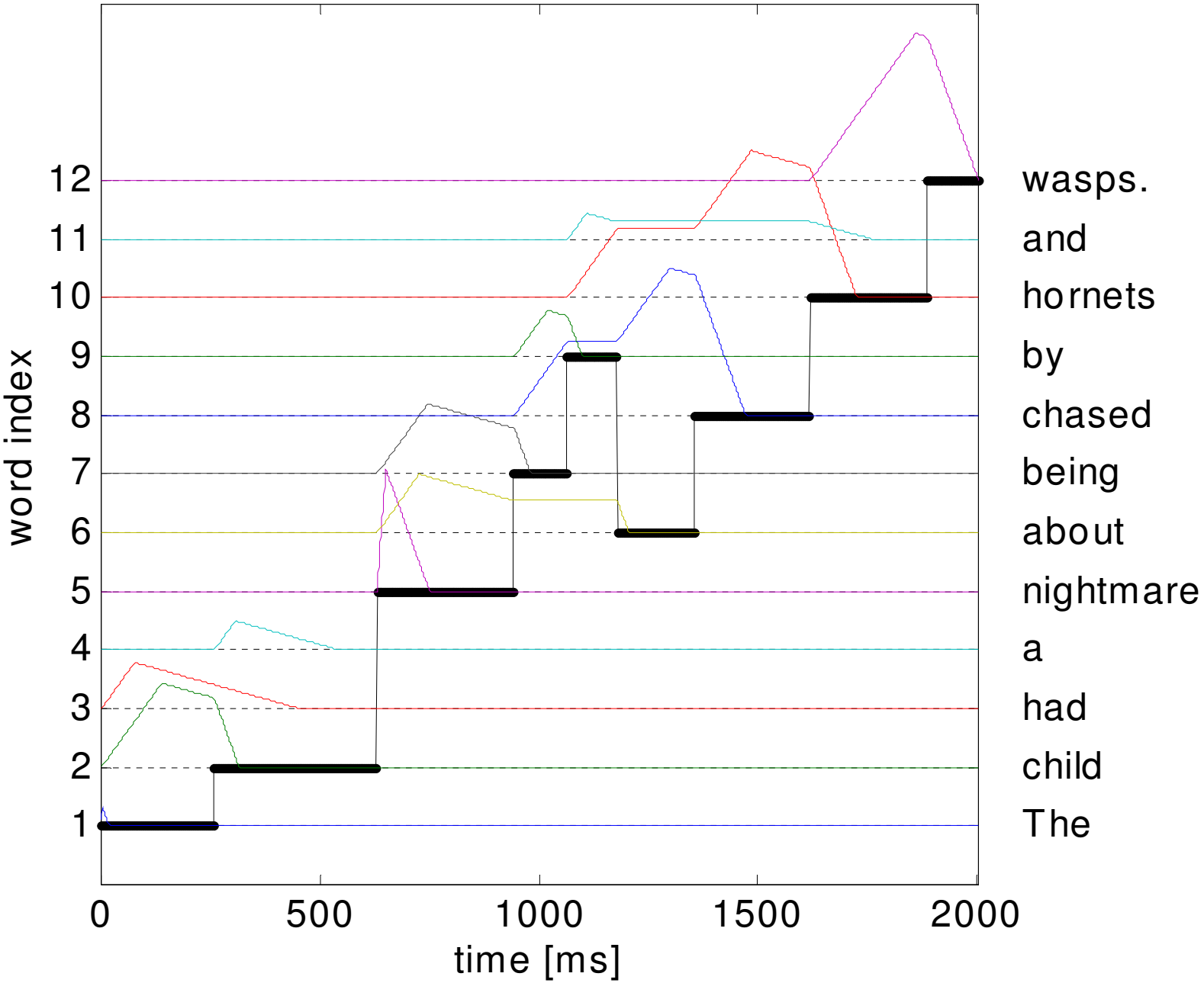
labile program

$\{a_n(t), k(t)\}$

'where'

'when'




word index
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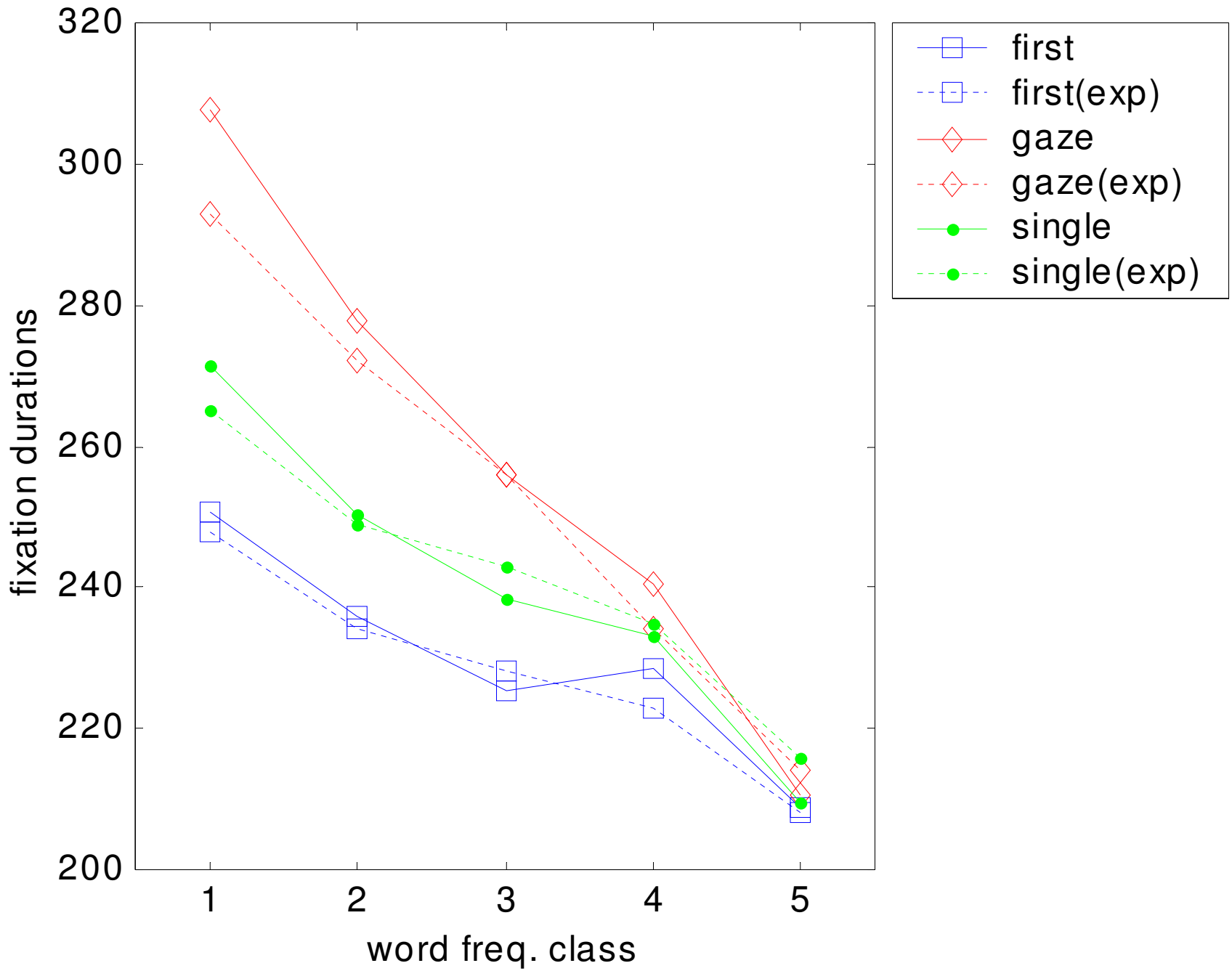
320
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240
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2
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5
word freq. class
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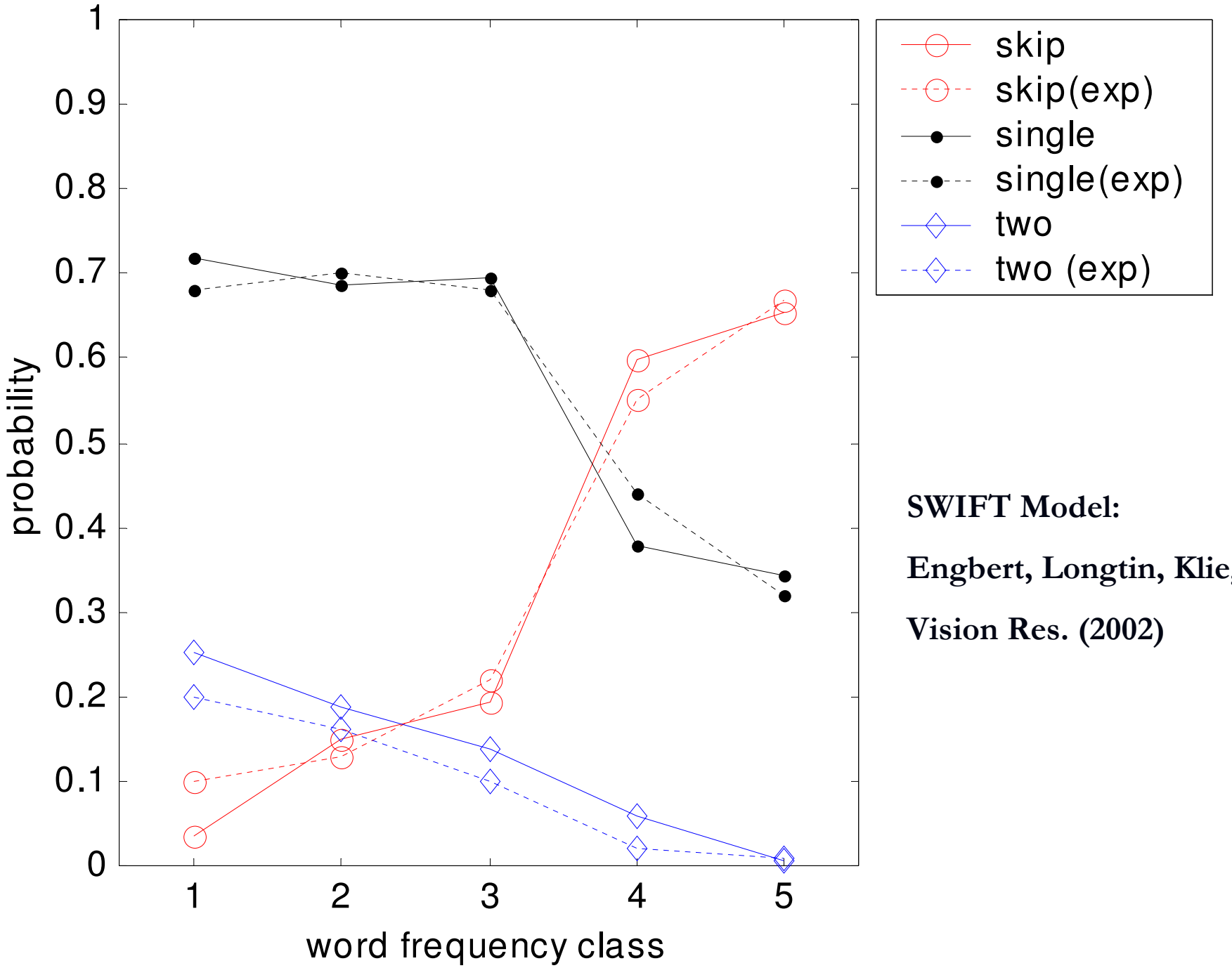
gaze
gaze(exp)
single
single(exp)



SWIFT Model:

Engbert, Longtin, Kliegl,

Vision Res. (2002)

Linking High Level and Low Level

- Without noise, just a few model trajectories occur
- Optimal noise tuning to properly sample input space of "sentences" while reading at decent speed ?
- How does saccade target selection really work ?

→ Noise is important determinant of target selection in biophysical neural net models (X.J. Wang at Yale)

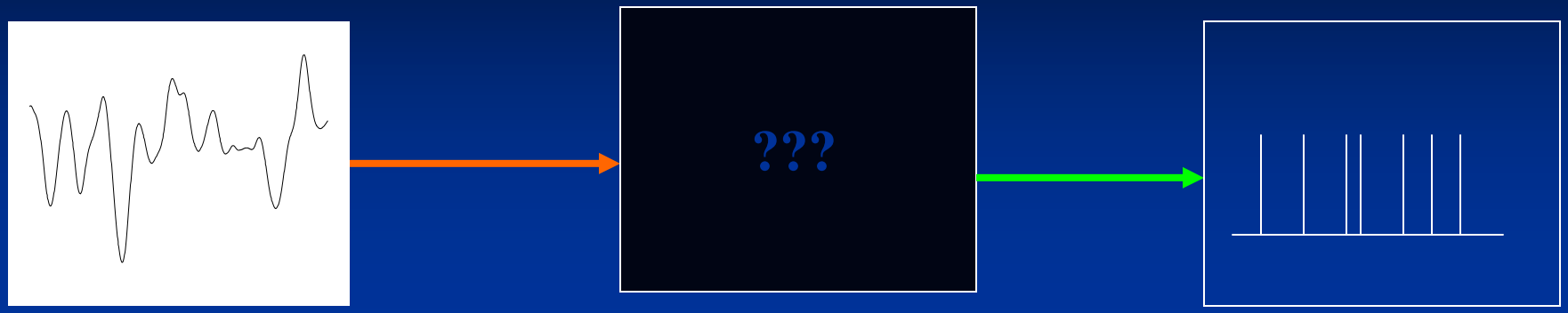
→ Need to team up with those doing measurements in superior colliculus and LIP areas (M. Pare at Queens)

→ Can we predict neural correlates of e.g. dyslexia?

Experimental-Theoretical Collaborations (if that is of interest to you)

- They take a while to develop
- You have to learn each other's language
- You have to learn the folklore in a given subfield
- Personalities have to "click"
- After a number of years you start thinking alike…for good or for worse…

Information Theoretic Calculations:



Stimulus S

Neuron

Spike Train X

Coherence Function:

$$C(f) = \frac{\left|\left\langle \tilde{X}^{*}\tilde{S}\right\rangle\right|^{2}}{\left\langle \tilde{X}^{*}\tilde{X}\right\rangle\left\langle \tilde{S}^{*}\tilde{S}\right\rangle}$$

Mutual Information Rate:

$$MI = -\frac{1}{2}\int_{-f_c}^{f_c} df\, \log_2[1 - C(f)]$$

Information Theoretic Calculations:

Stimulus S

Neuron

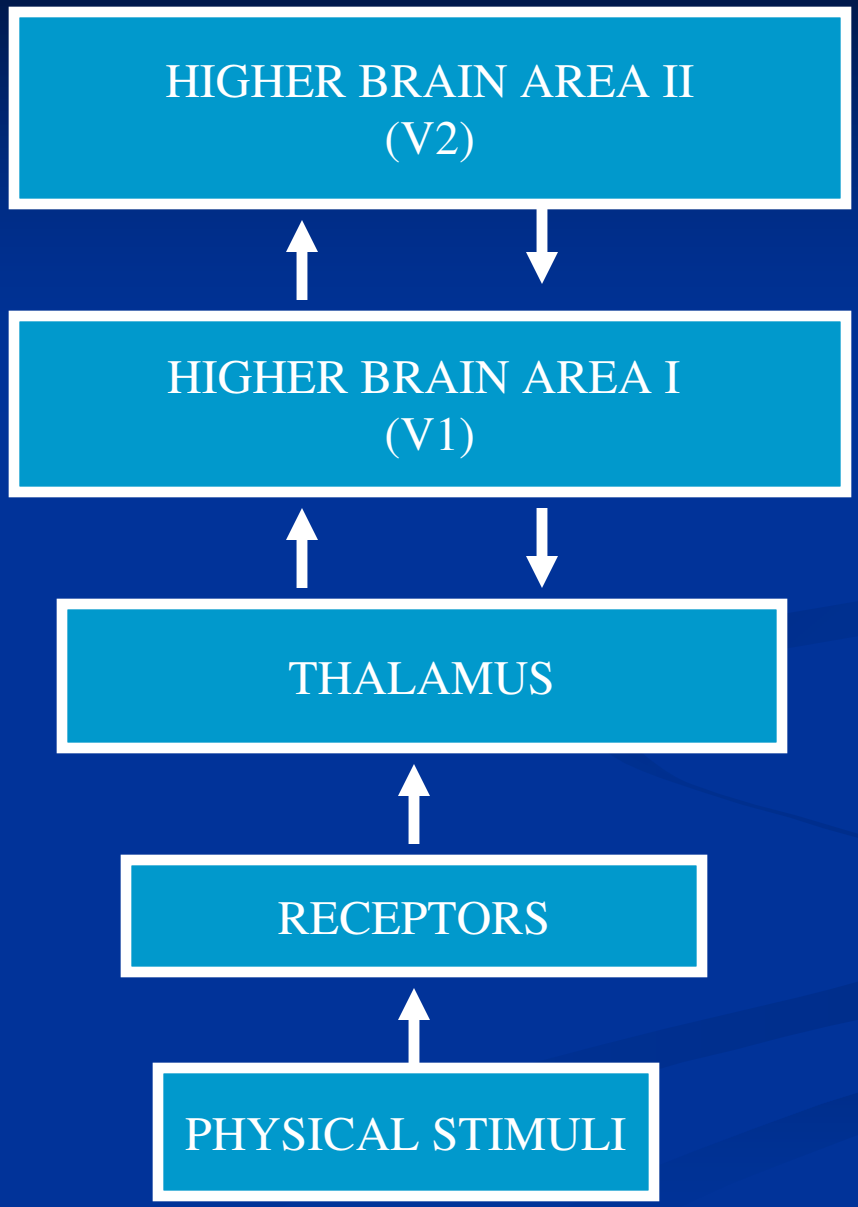
Spike Train X

"First Principles" :

$$\frac{d}{dt}V_i(t) = \mu - V_i(t) + \sqrt{2D_i}\xi_{i,bg}(t)$$
$$+\beta I_i(t) + \frac{g}{N}\sum_j K_{\tau_d} * \sigma_j(t)$$

Interesting theory along the way

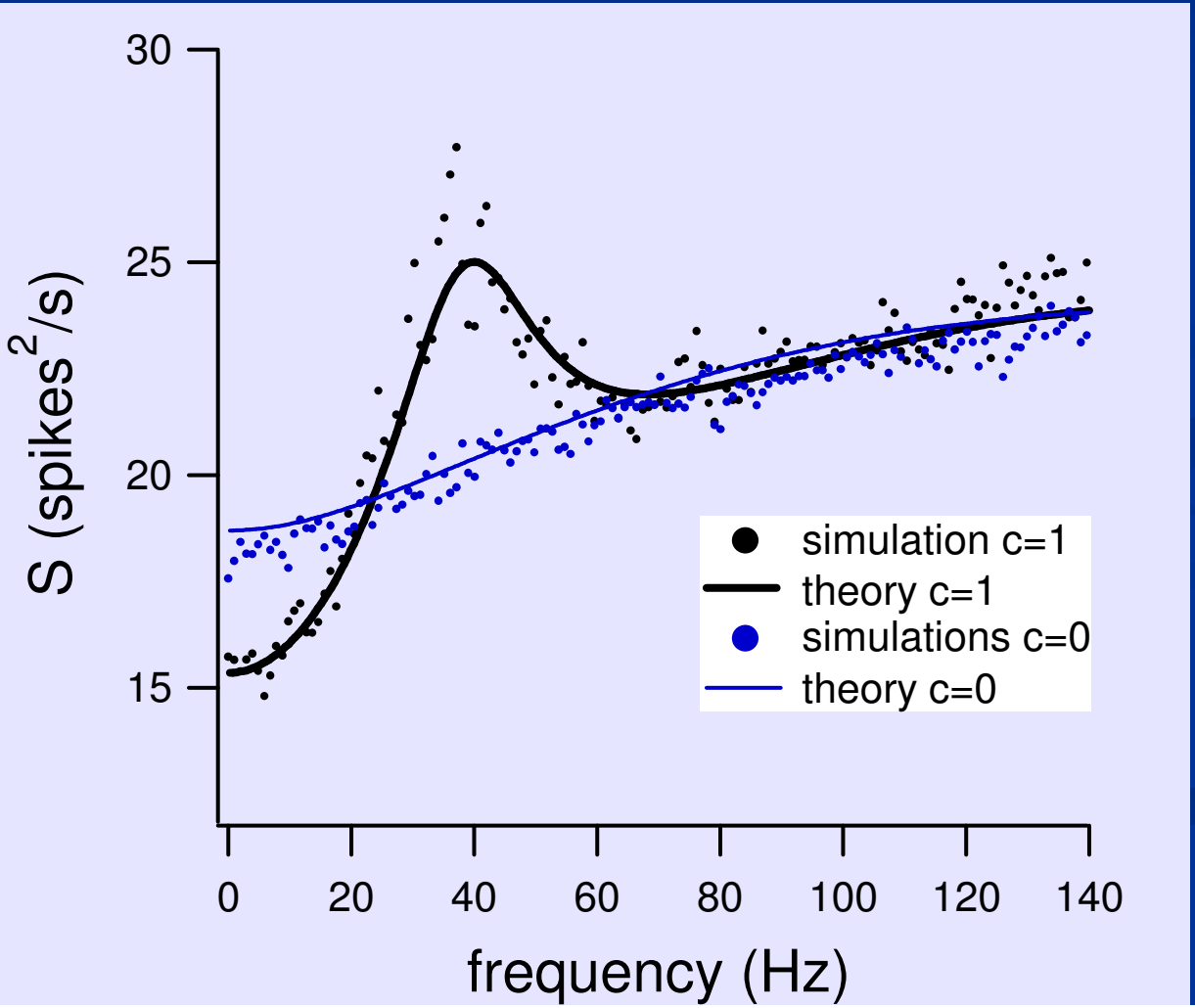
DESIGN: FEEDFORWARD + FEEDBACK



Fokker-Planck analysis on noisy Leaky Integrate-and-fire neurons

Doiron, Lindner, Longtin, Bastian and Maler, *Phys. Rev. Lett.* 93, 048101 (2004)

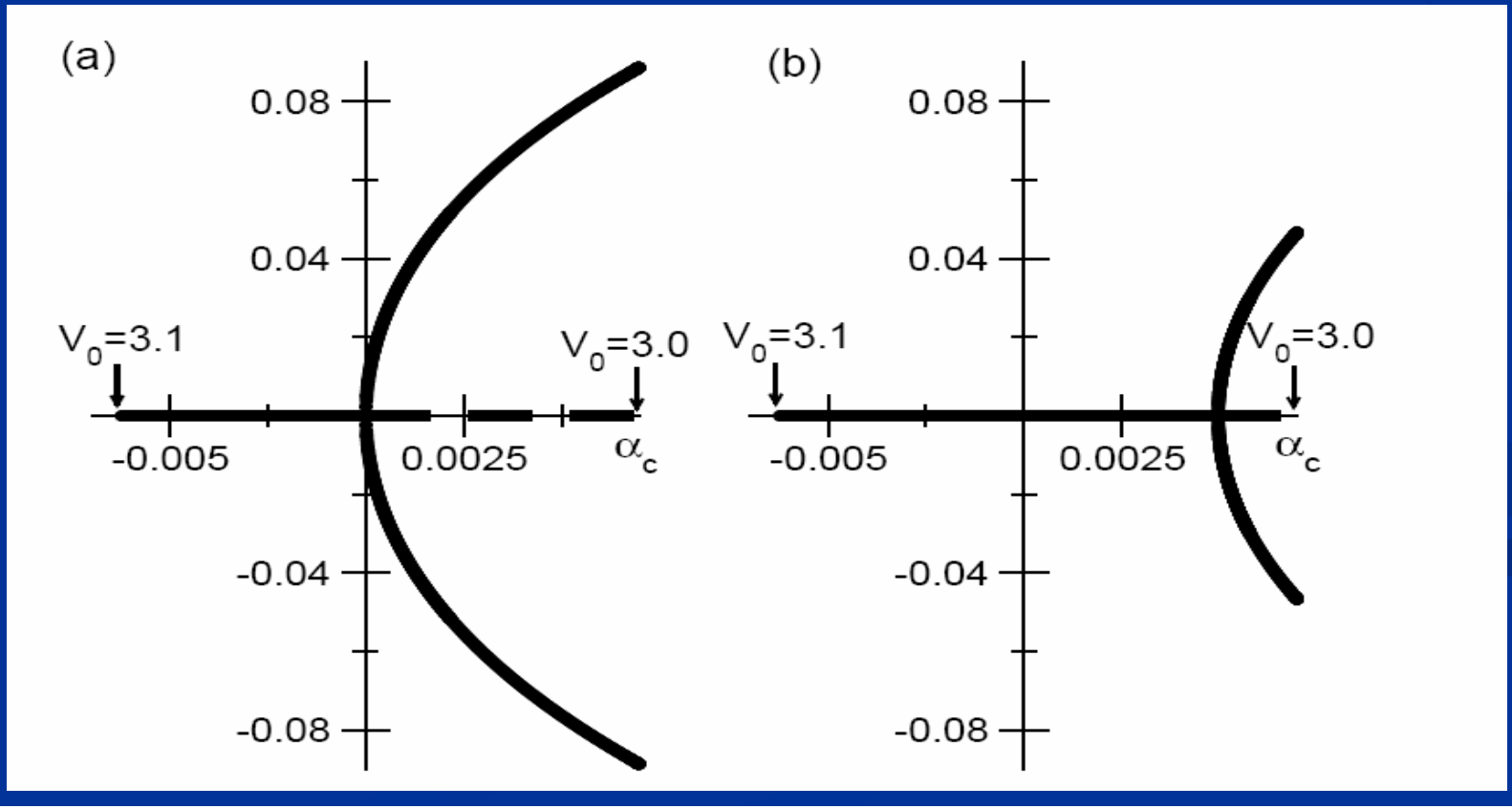
Explains how Gamma rhythm arises from delayed neural nets with spatiotemporal input

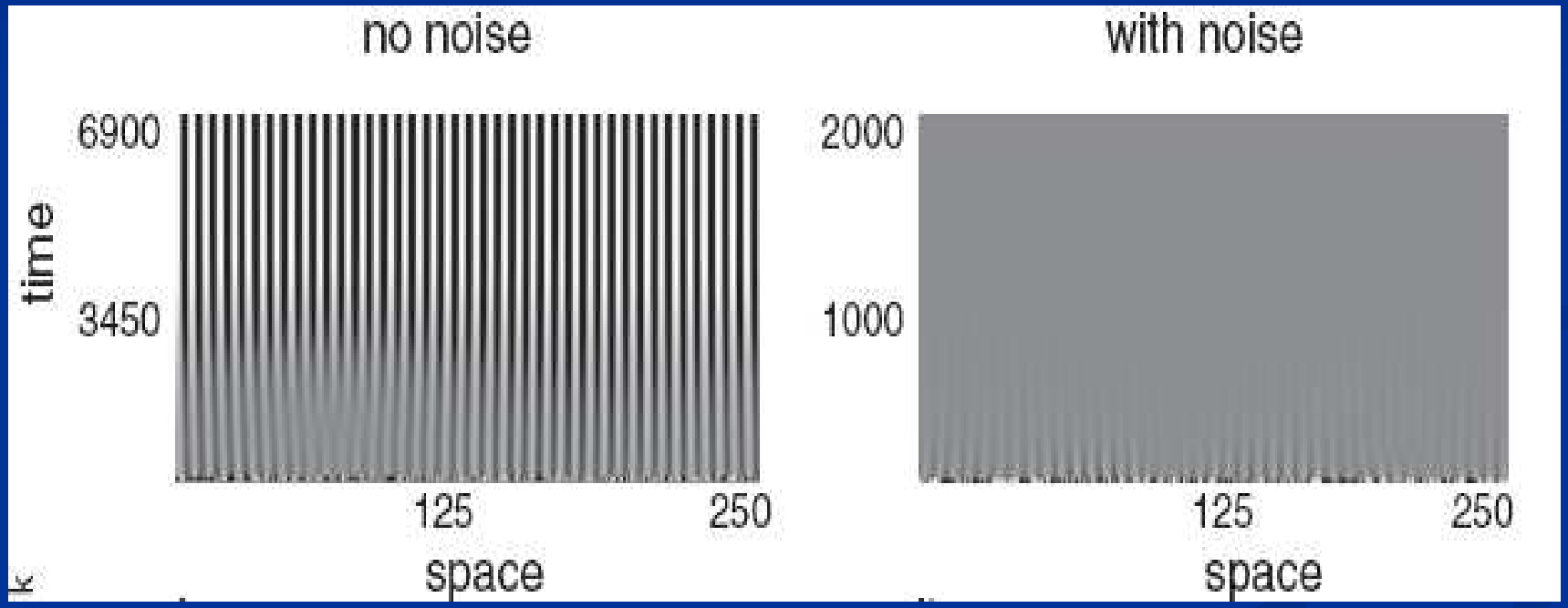


Additive global noise delays Turing bifurcations

(Axel Hutt, Andre Longtin, Lutz Schimansky-Geier, Phys. Rev. Lett. 2007)

$$\frac{\partial V(x,t)}{\partial t} + V(x,t) = \int_\Omega K(x-y) S_e(V(y, t - \frac{|x-y|}{v_K})) + L(x-y) S_i(V(y, t - \frac{|x-y|}{v_L}))\, dy + I(x,t)$$

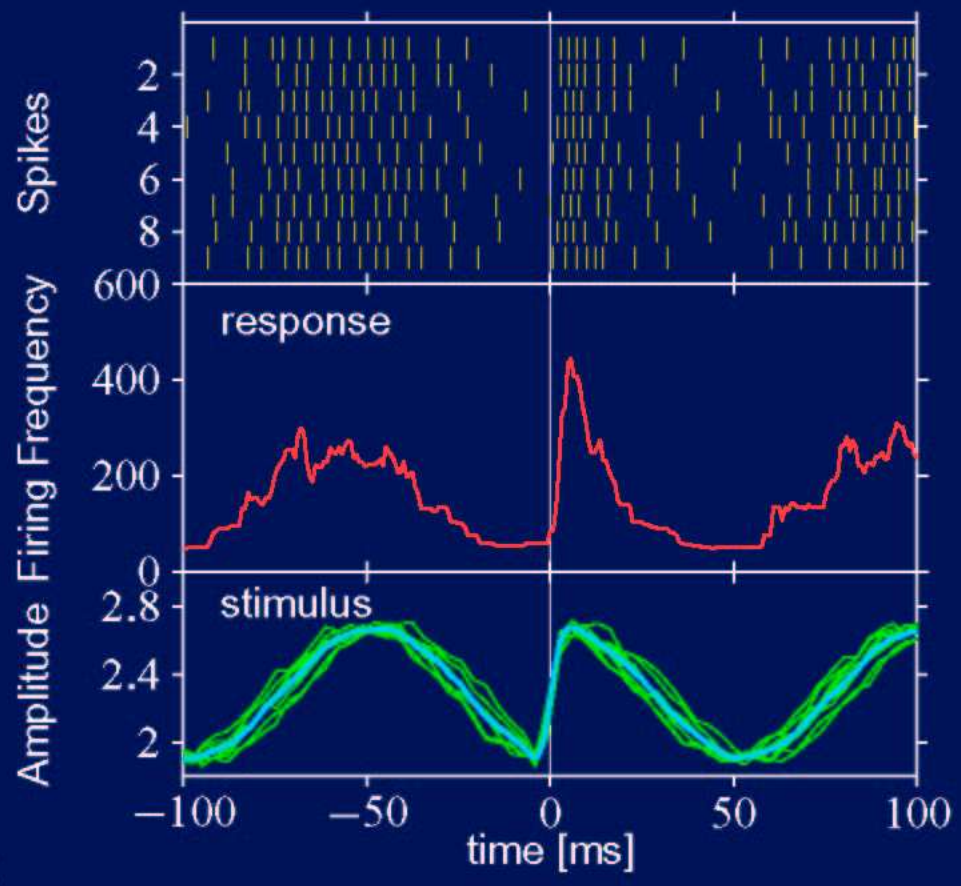



no noise
with noise
6900
3450
time
125
250
space
2000
1000
125
250
space

WHY STUDY **NOISE** ?

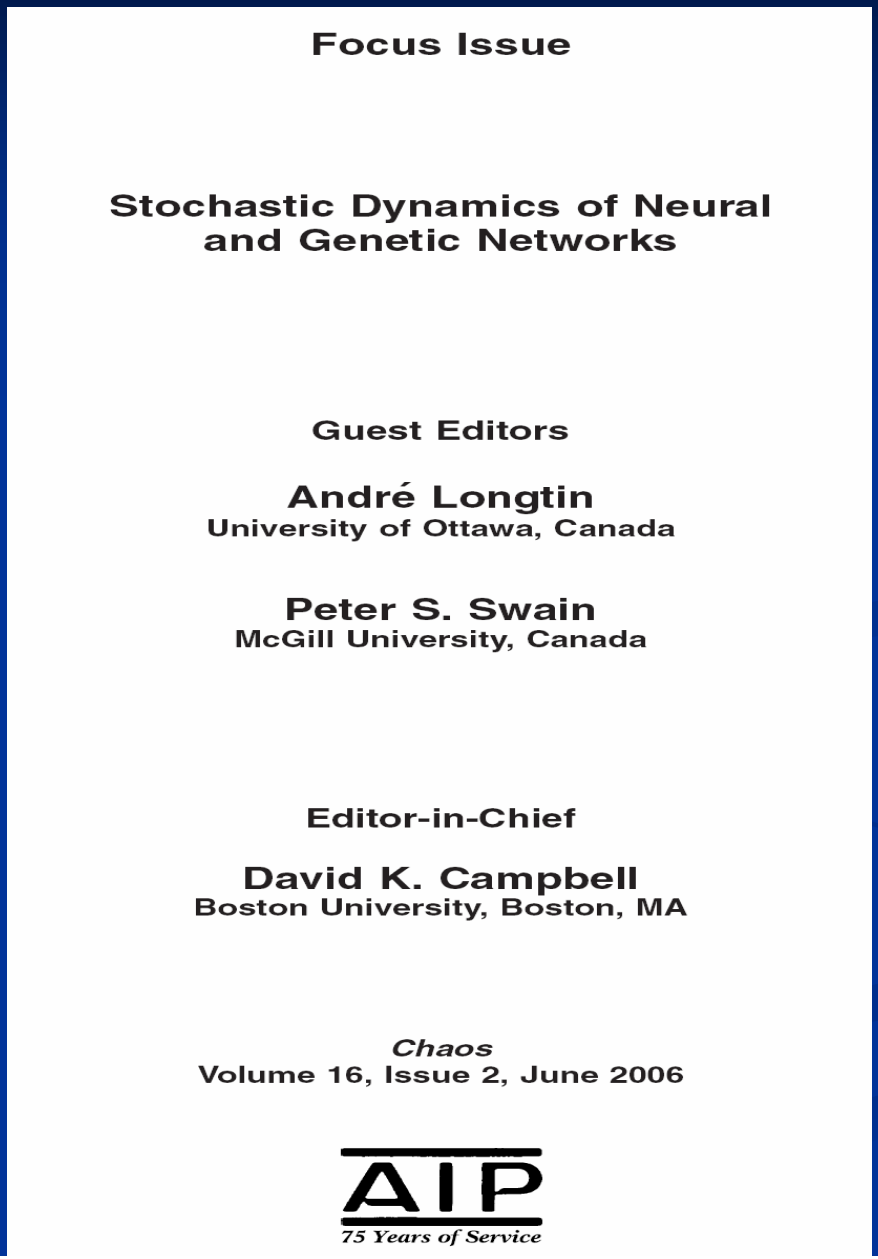
Response

In vivo recording of electroreceptor afferents (P-units)



$\Delta f = 10\,\text{Hz}$

WARNING: WE ARE NOT ALONE



Ex: HEARING IMPLANTS

- **DAMAGED COCHLEA**
  - à **Bypass it by stimulating acoustic nerve: Feedforward**
    problem: poor at noisy cocktail parties

- **DAMAGED COCHLEAR NUCLEUS (next station)**
  - à **feedforward input from acoustic space**
  - à **MOSTLY feedback input from higher brain**

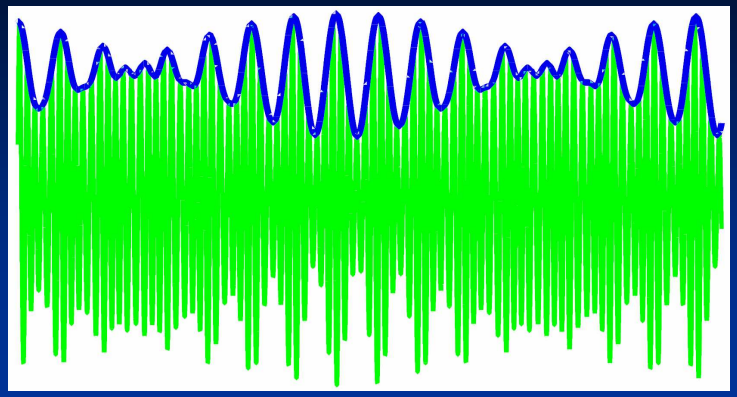
Need to figure out: feedforward AND feedback

And we need to figure out how the brain does…

- Blind source separation on-line

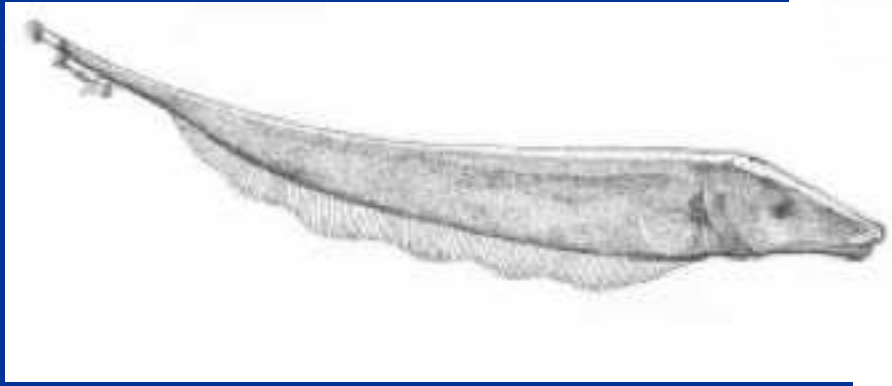
→ Look at how e-fish do it: electrocommunication

→ Look at how frogs do it: calls in swamp

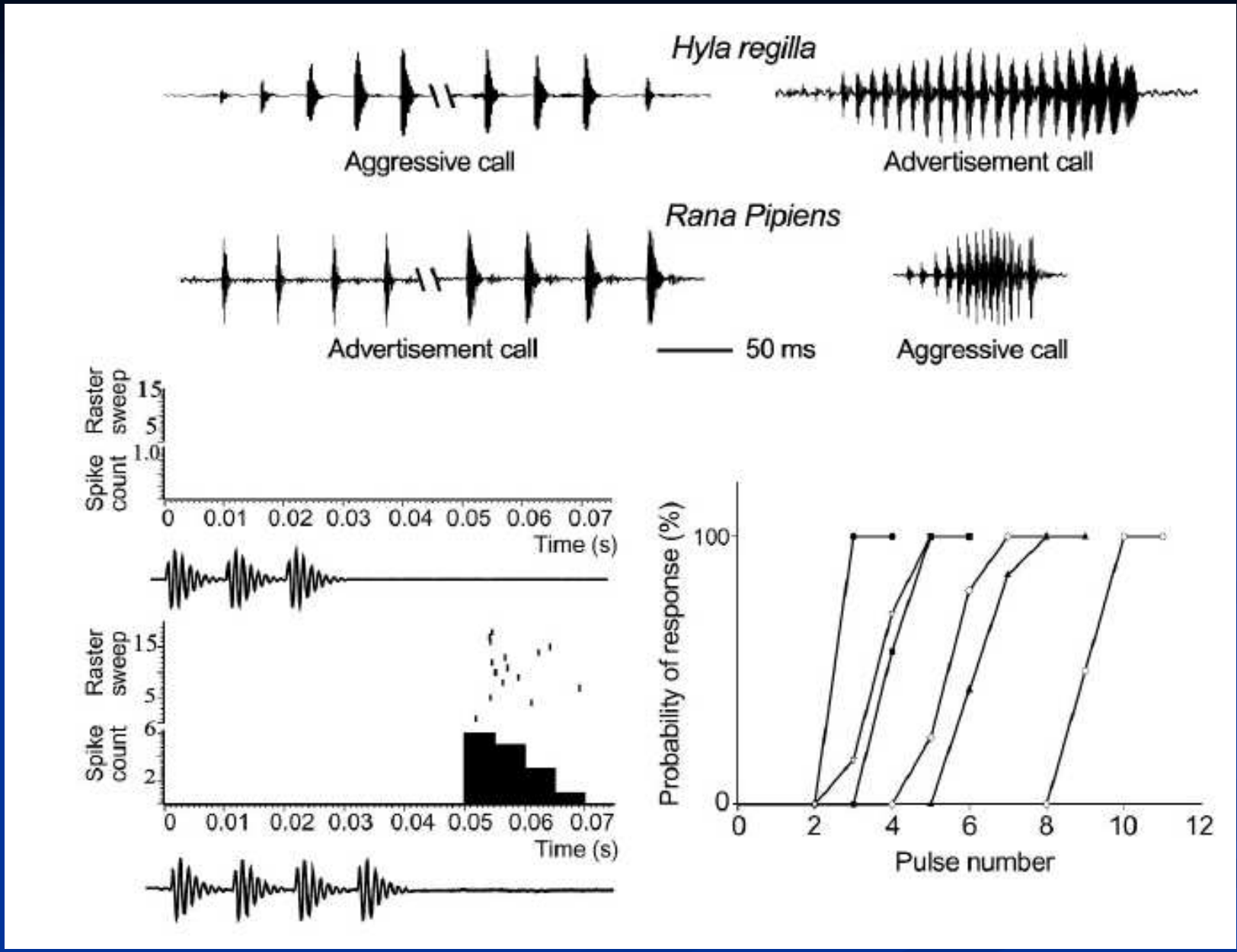


EOD amplitude

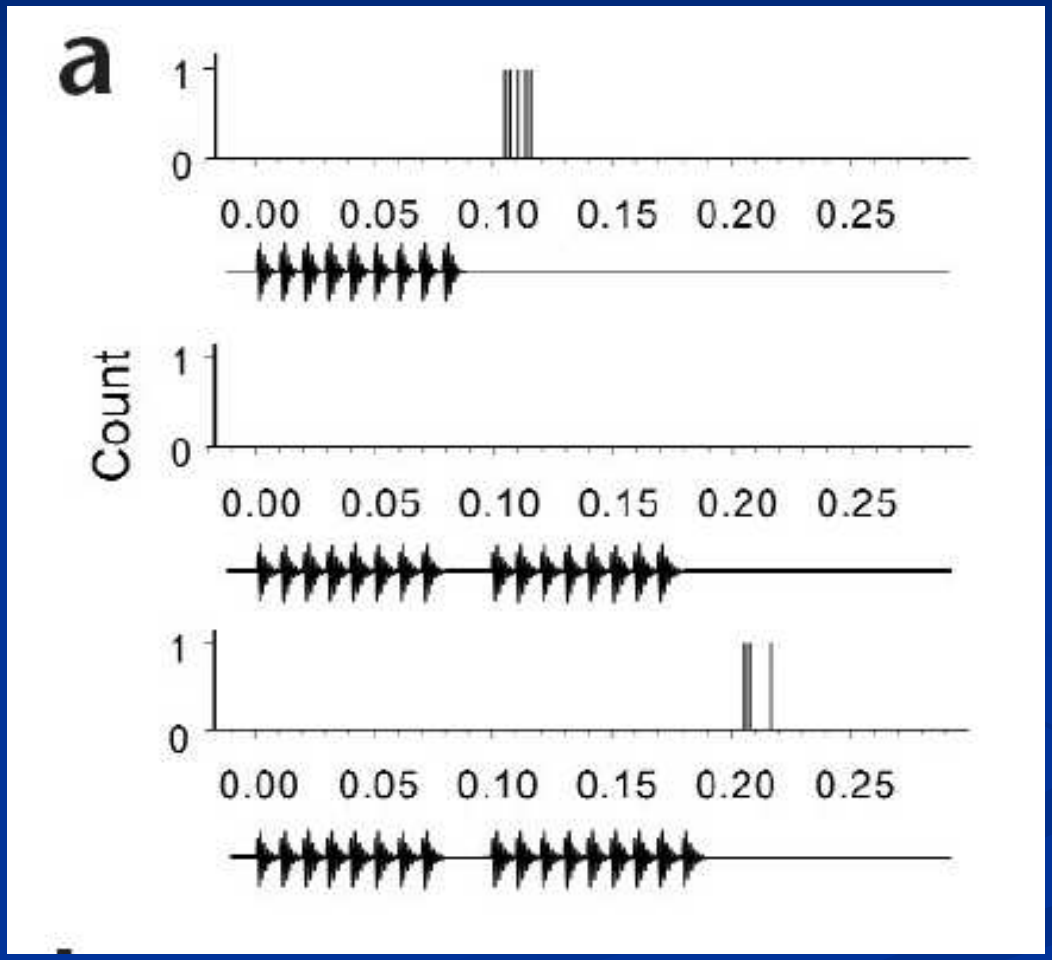
EOD



Hey guys



Edwards, Alder and Rose, Nature Neurosci. 5, 2002.


a
Count
1
0
0.00
0.05
0.10
0.15
0.20
0.25

Of interest to mathematicians: Numerical Cognition

Nieder, A. & E. K. Miller (2003), "Coding of cognitive magnitude: Compressed scaling of numerical information in the primate prefrontal cortex", *Neuron* 37, 149.

Nieder, A. & E. K. Miller (2004), "A parieto-frontal network for visual numerical information in the monkey", *PNAS* 101, 7457.

Piazza M, Pinel P, Le Bihan D, Dehaene S. (2007) A magnitude code common to numerosities and number symbols in human intraparietal cortex. *Neuron* 53, 293.

Research Highlights

- Too many at too many levels
- One thing is for sure: models have made their mark, from the early days of Kybernetik to Neuron, Nature Neuroscience etc…
- Real test maybe still to come (but it is coming): strong predictions with medical impact will get attention

Critical Consideration for those entering the field

- What do you like? Do you want to:

- à become a hybrid (do experiment and theory)?
- à talk actively with neuroscientists?
- à do theory/computation, with some relevance to neuroscience?
- à just devise interesting theory?

- à All of it is needed !

Ideal Training

- See preceding slide: what do you like?
- Do training accordingly

Ex: **Maurice Chacron**: Ph.D. theoretical neurophysics, wanted to do experiment as well: went to Woods Hole Neural Systems and Behavior course, then did an experimental postdoc;

now Prof. of Physiology at McGill

Ex: **Brent Doiron**: Ph.D. theoretical neurophysics, wanted to continue in that field: did theoretical postdoc with both a theoretical and an experimental advisor;

now Prof. of Mathematics, U. Pittsburgh

Training

- Summer schools (University of Ottawa-MITACS)
- Workshops
- Work placements in another group in Canada and abroad
- Multidisciplinary graduate programs

(or programs that allow you flexibility in course selection)

Suggested Changes

- Canadian Funding Structure still somewhat archaic for this new field
- Close to nothing from CIHR (unless you collaborate with experimentalist)
- NSERC: Interdisciplinary, Animal Biology, Applied Math, Psychology
- More exposure for our undergrads in math, physics and engineering à modeling courses
  à summer schools

National Linking: it has begun.

Mathematical Neuroscience Meeting
September 16-19, 2007

Centre de Recherches Mathématiques

Université de Montréal

Organized by:

Steve Coombes (Nottingham)

André Longtin (Ottawa)

Jon Rubin (Pittsburgh)

Sponsored by CRM (NSERC), MITACS, U. OTTAWA, MATHEON