Rhythms in the Nervous System :

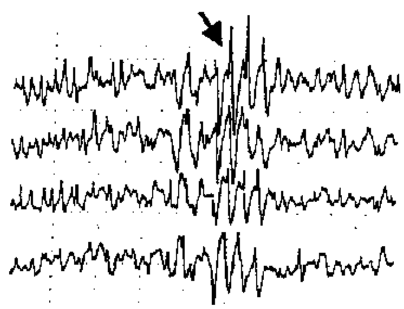
Synchronization and Beyond

Rhythms in the nervous system are classified by frequency.

Alpha	**8-12**	**Hz**
Beta	**12-30**	
Gamma	**30-80**	
Theta	**6-8**	

These rhythms are associated with

- **Sensory processing**
- **Cognitive States**



Theme: Use dynamical systems to understand

- **Origin of rhythms**
- **Potential functional uses**
- **New way to think about classifying rhythms**

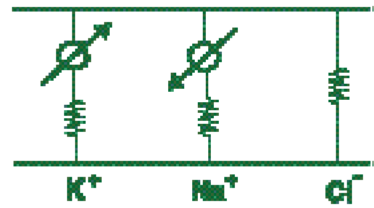
My problem has always been an overabundance of alpha waves

S. Harris

The Mathware

General Framework:

Hodgkin-Huxley Equations

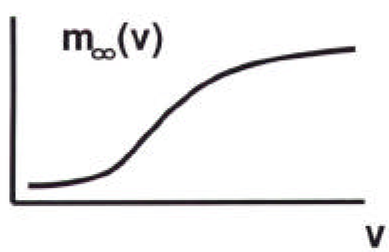


$$c\frac{dv}{dt} = -\sum I_{ion} + D\nabla^2 v - \sum I_{synapse}$$

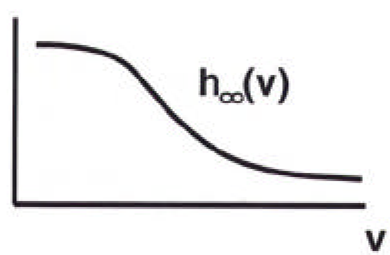
$$I_{ion} = g\, m^j h\, (v - V_R)$$

Conductance x Electromotive force

m **and** ***h*** **satisfy**



$$\frac{dx}{dt} = (x_\infty(v) - x)/\tau_x$$



Equations have
many time scales

Different Context,

Different Frequency

Different Properties

- Moving bars of light evoke gamma in primary visual cortex
- Sensory-motor tasks lead to beta
- Cortical rhythms in reward period : alpha

Synchronization properties :

- gamma/ beta display very precise synchronization across long distances
- alpha synchronization : sloppy/ nonexistent

Singer, Konig, Gray, Nature 1989;
Roelfsema et al Nature 1997

Why is Math Relevant?

- **What determines frequencies ?**
- **What causes activity to be coherent ?**
- **Are there different "dynamical structures" associated with different frequencies?**

- **What determines inclusion in a cell assembly?**
- **How is long distance synchronization possible?**

Objective of math: Understand how biophysical properties of cells and synapses help create and regulate assemblies of synchronous cells.

A Biological Model of Gamma/Beta

Gamma and beta are implicated in

- **Attention, perception, memory**
- **Thought disorders (schizophrenia)**

Coaxing rhythms from a slice

Whittington, Traub, Jefferys; Nature 1995

Gamma and transition to beta

- **Stimulation of slice evokes gamma**
- **More stimulation evokes gamma, then transition to beta**

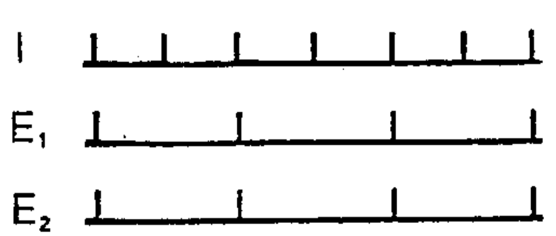
- **Later weak stimulation produces beta**

Gamma, Beta and Dynamics

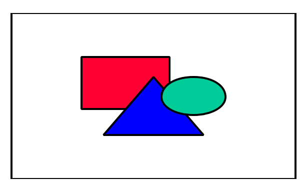
Whittington, Traub, Jefferys;
White, Chow, Ritt, Ermentrout, NK

Dynamical structure of beta in slice: network has underlying I-cell gamma

(Consistent with EEG data)



Gamma is inhibition-based rhythm: frequency and coherence is related to decay time of inhibition



Beta uses different intrinsic and synaptic currents

- Has extra slowly decaying outward current
- Has new E-E connections

(“Cells that fire together wire together”)

Analyzing Networks of Spiking Cells:

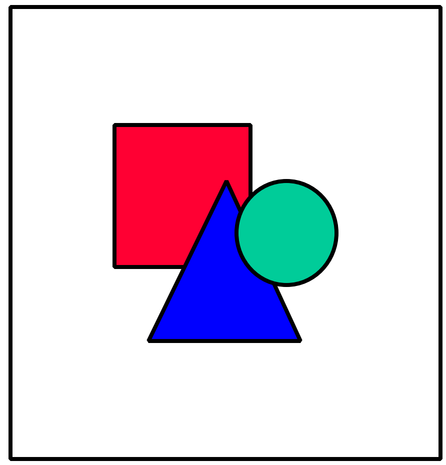
Treating high dimensional (Hodgkin-Huxley) systems as a collection of maps

- Networks are high-dimensional systems
- But: near some "dynamic configurations", they are low dimensional.
- For given connections/time scales, identify consistent configurations (depends on parameters)
- Use time scales to identify important degrees of freedom, construct/analyze map
- Reduction procedure allows answers to questions about physiology

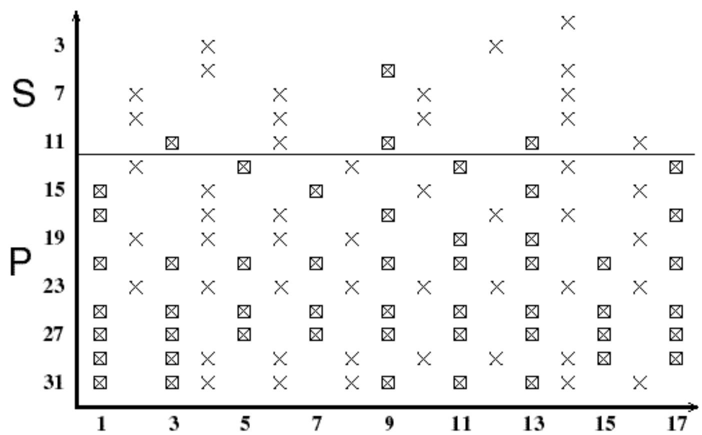
Population Tuning: Gamma as a Preprocessor for Beta.

Aim: create a well-defined cell assembly

Olufsen, Camperi, Whittington, NK



- With range of drives to E-cells, gamma rhythm creates threshold for cell assembly (P and S cells)

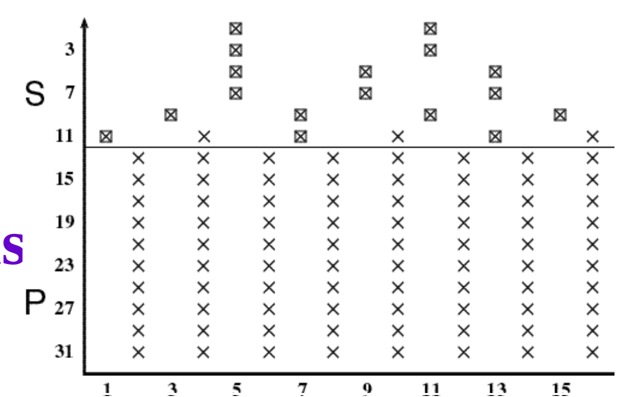


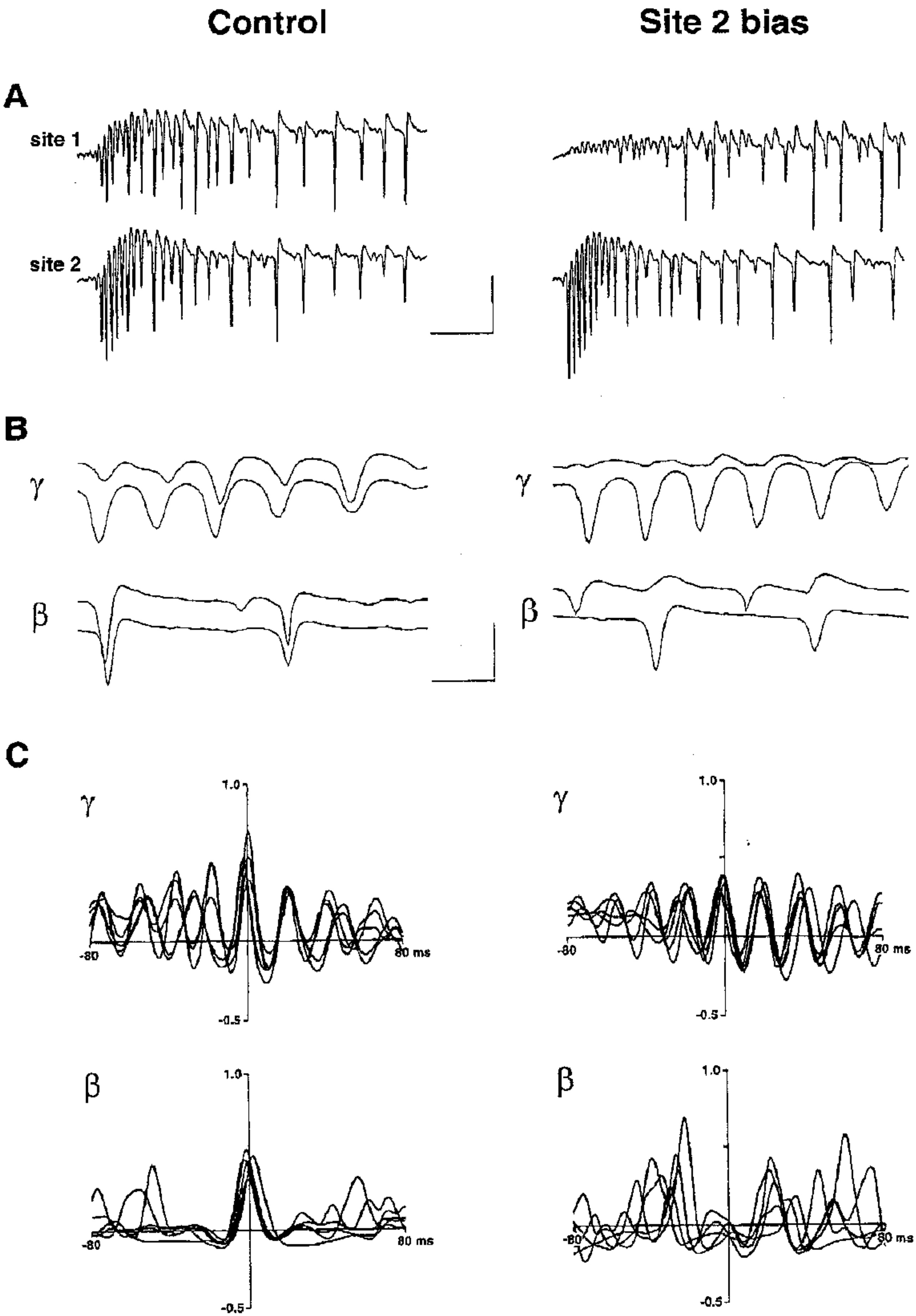
- Slow outward current ruins threshold

- To create assembly of cells that fire together at beta frequency and exclude other cells

  - Strengthen E-E only between P-cells

  - Weaken E-I connections from S-cells

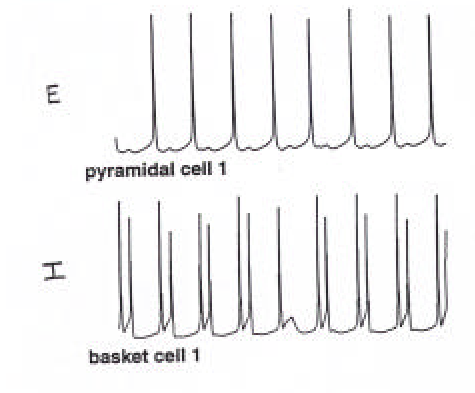



Control
Site 2 bias
A
site 1
site 2
B
γ
β
C
γ
β
1.0
-0.5
-80
80 ms

"Doublets" and Long-Distance Synchronization

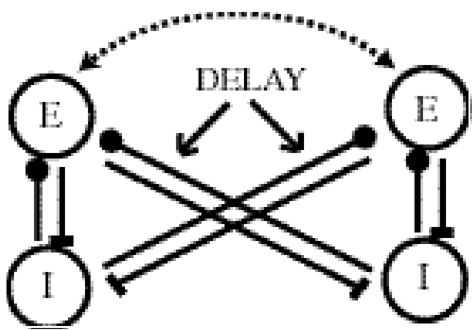
Observation from data and large-scale numerics:
Whittington, Traub, Jefferys

Synchrony iff doublets in I-cells



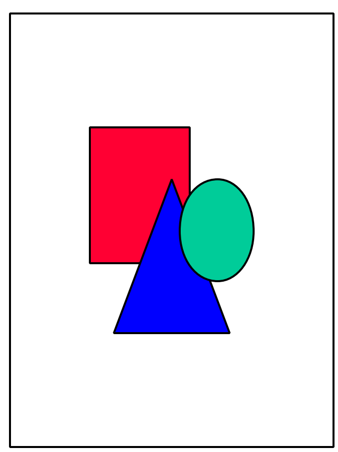
Map analysis of gamma in a minimal network

Ermentrout , NK



Second spike encodes timing from distant circuit

- **E cells fire when inhibition wears off**
- **Key property of I-cells: Wait between excitation and firing (**history dependent)



Alpha, Beta, Gamma and Long-Distance Synchronization

Alpha 8-12 Hz ; Beta 12-30; Gamma 30-80

Different rhythms are associated with different biophysics

Math reveals different synchronization properties

- **Beta can synchronize over a much larger range of conduction delays than gamma** (NK, Ermentrout, Whittington, Traub)
- **Alpha actively desynchronizes over distances** (S.R. Jones, Pinto, Kaper, NK)
  - **Can synchronize locally – or not**
- **Results match data, confirmed by simulations**

Frequency Differences Have (?) Functional Implications

Bio Background

- **Figure/ground <u>segregation is done early</u> in visual processing**
- **<u>Higher-order</u> processing requires coordination across <u>distances</u>**
- **Gamma and beta are used in different ways:**
  - **Local vs. distant coordination, (von Stein et al.)**
  - **Beta is associated with <u>novelty</u> in auditory paradigms. (Whittington, Gruzelier)**

Insights from Math (gamma/beta)

- **Gamma is excellent for figure/ground separation**
- **Beta is needed for higher-order coordination**
- **Gamma is needed as a preprocessor for beta**

More Rhythms, More Math …

Suggestion (von Stein):

Gamma, beta are used for feedforward processing, alpha for feedback.

Suggestion (Hasselmo, Lisman, Recce …):

Theta is important for learning/recalling sequences.

Mathematical tasks: understand more deeply

- **Spatio-temporal properties of rhythms with different biophysical bases**
- **How networks with different rhythms process structured input**
- **Transformations among rhythms/ simultaneous rhythms (gamma/theta)**
- **How different rhythms work together in information processing**