Information in Phase of Low Frequency Motor Cortex Generated Actions

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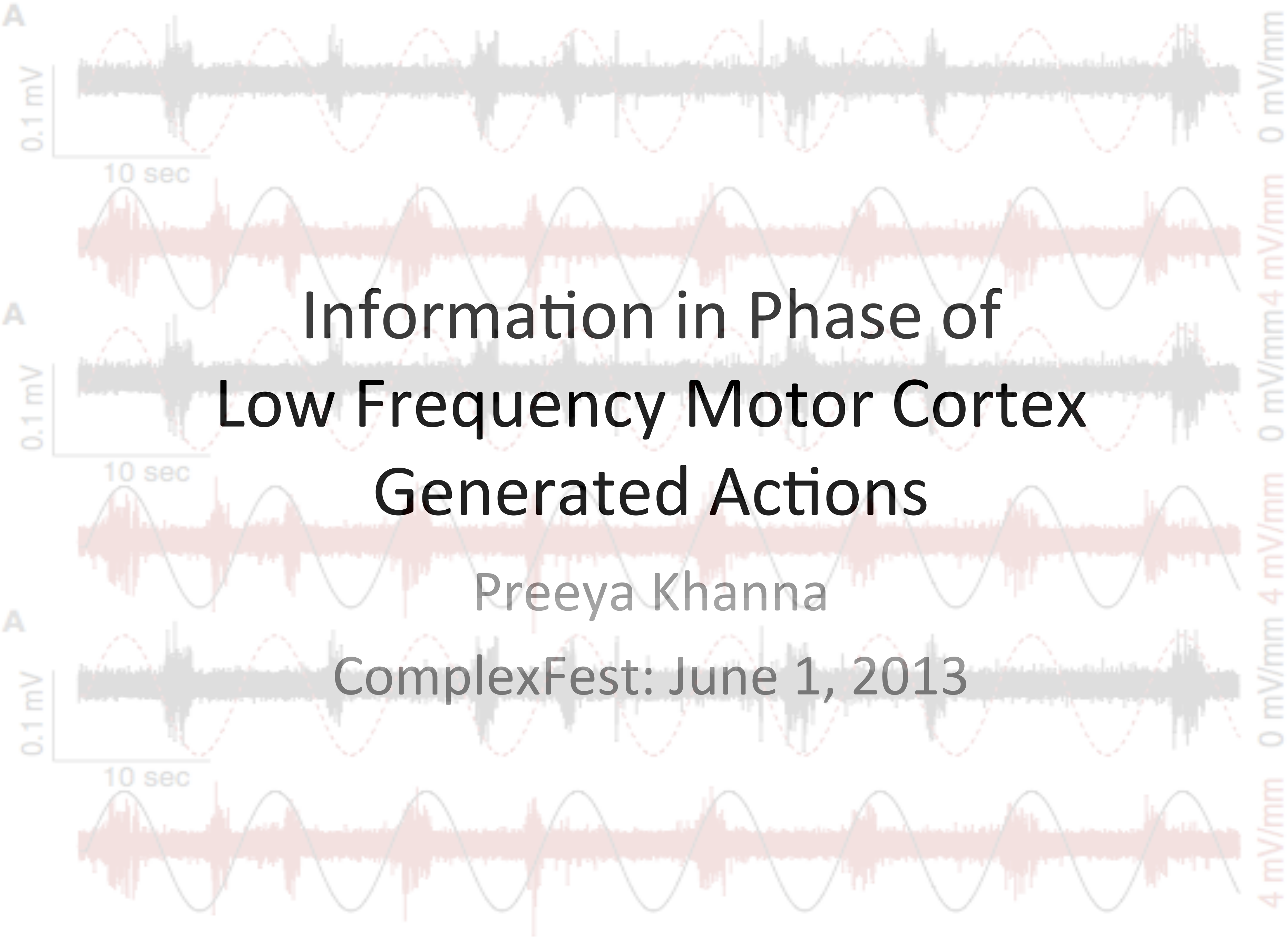
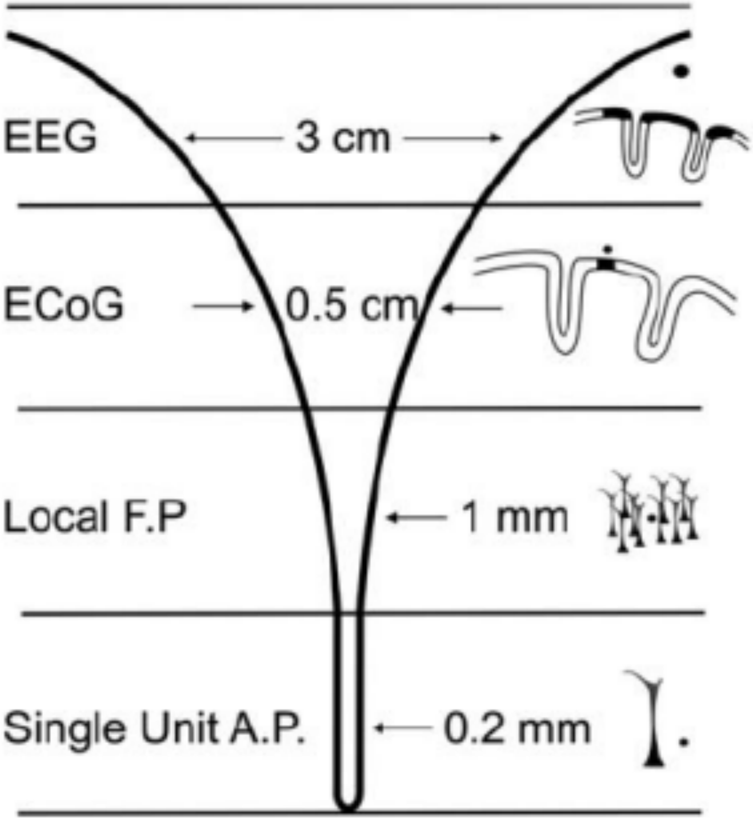
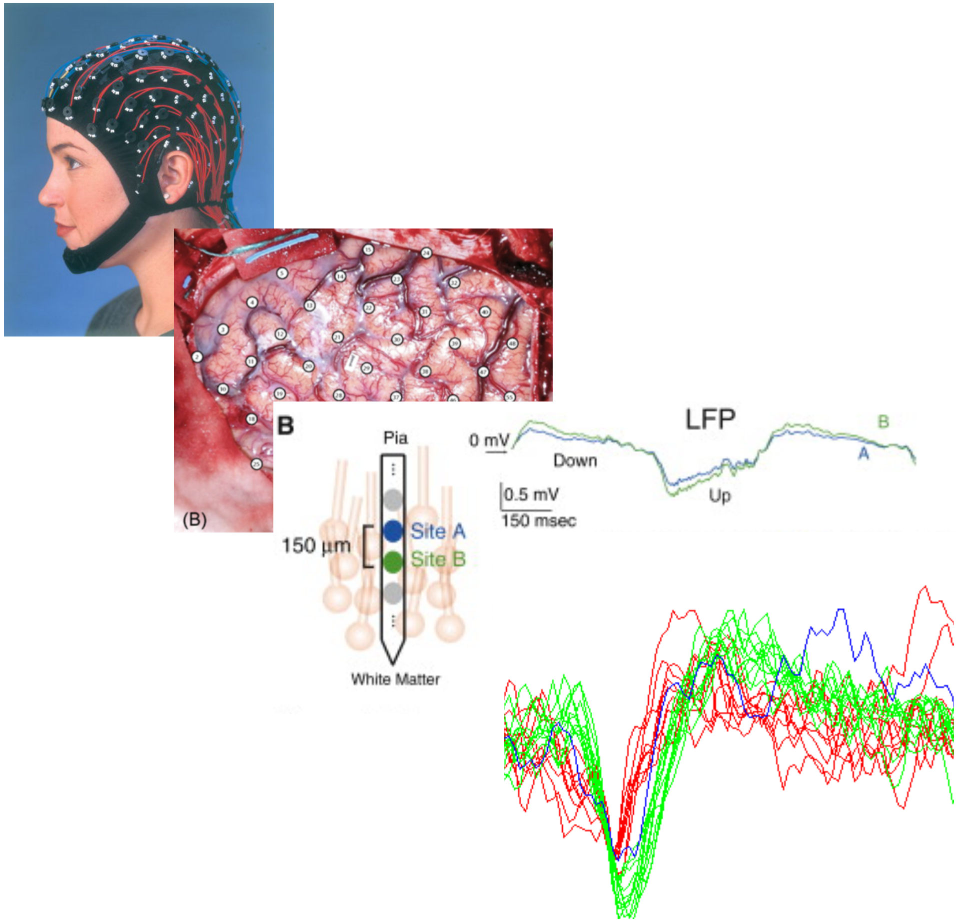
ComplexFest: June 1, 2013



Neural Recordings

Recorded neural activity
spatial domains

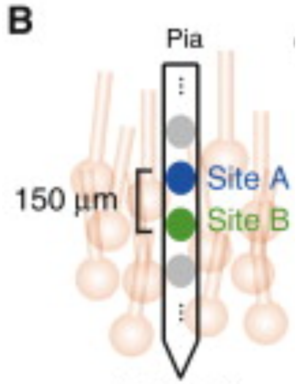




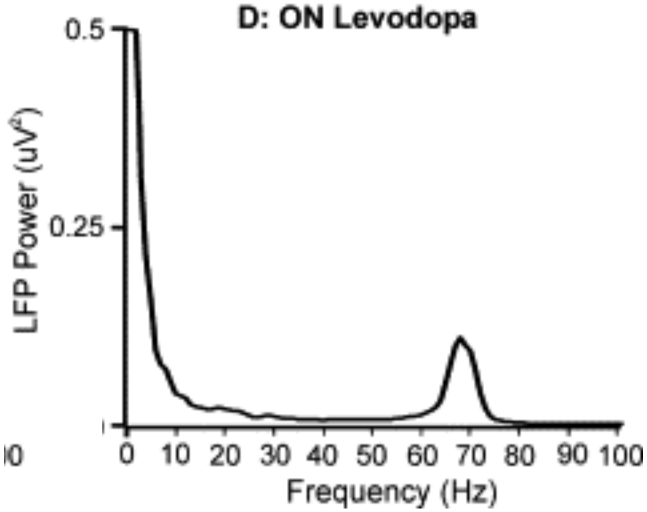
Schwartz et. al, *Neuron* 2006
Frolich & McCormick, *Neuron* 2010

Local Field Potentials

- Extracellular Potentials
  - Synaptic Input to cells



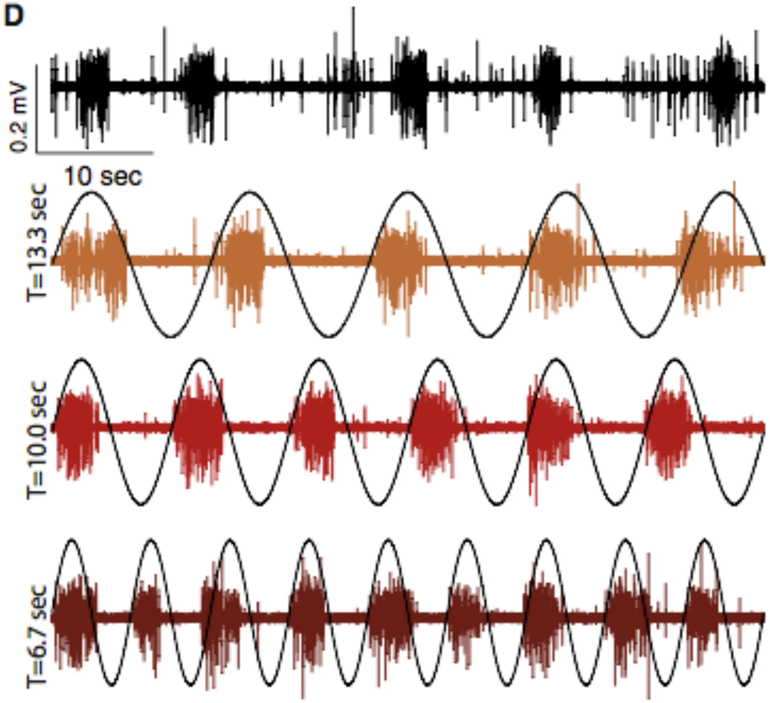
- Slow Oscillatory Components of LFP
  - 1/*f* pattern
  - Low Frequency Bands
    - Delta (0.5 – 4 Hz)
    - Alpha (4 – 8 Hz)
    - Theta (8 -12 Hz)
    - Beta (15-40 Hz)
    - Gamma (40 – 60 Hz)
    - High Gamma (60 – 300 Hz)



Brown and Williams, *Clinical Neurophysiology* 2005

LFP / Spike Interactions

- In slice spikes lock to a preferred phase of oscillation from applied electric field

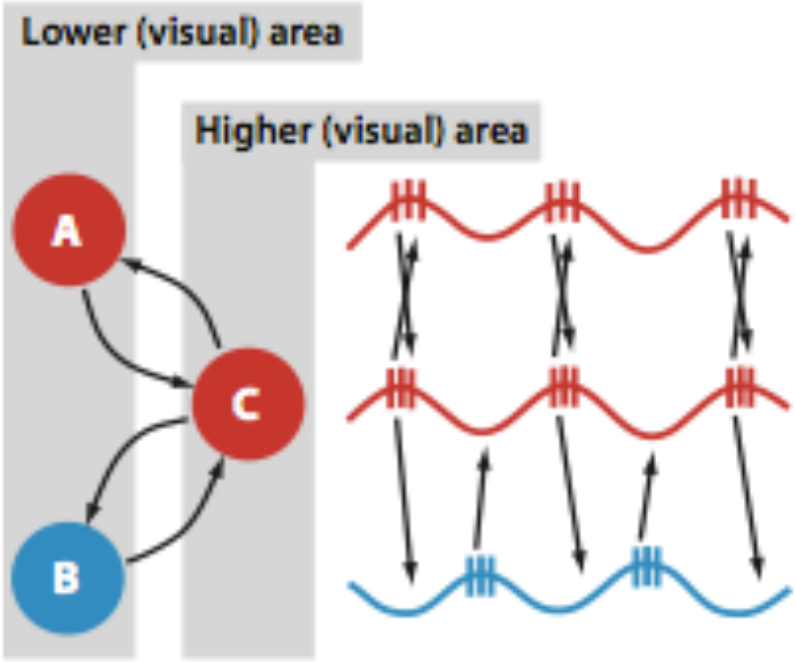


- Questions: Is there information is in the LFP? Does it represent summed ensemble activity? Does it play a role in information processing in the brain?

Frolich & McCormick, *Neuron* 2010

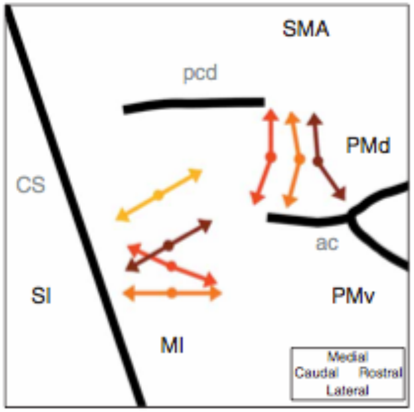
Role of Phase-Locking

- Enables communication through modulation of coherence
- Modulation of coherence ‘opens the window’ for processing spikes from lower areas

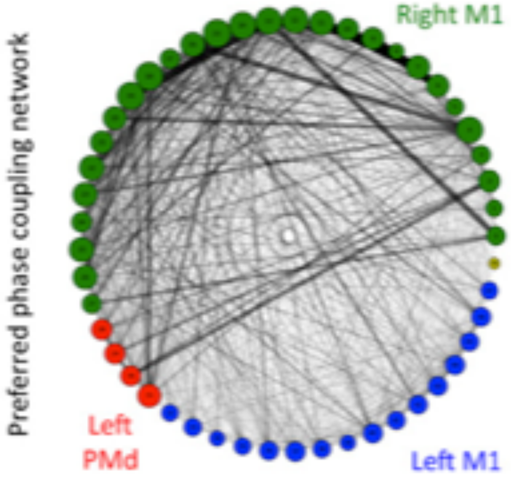


Fries, 2009

Phase in Motor Cortex



- Rubino & Hatsopolous (2006)
  - Calculated Beta Phase gradient before ‘Go’ cue
  - Rippling beta waves through PMd, M1



- Canolty et. al (2010)
  - Phase-coupling networks to predict spiking
  - Distal LFPs and LFP-LFP coupling
- Fetz (2013)
  - Oscillations are result of attention

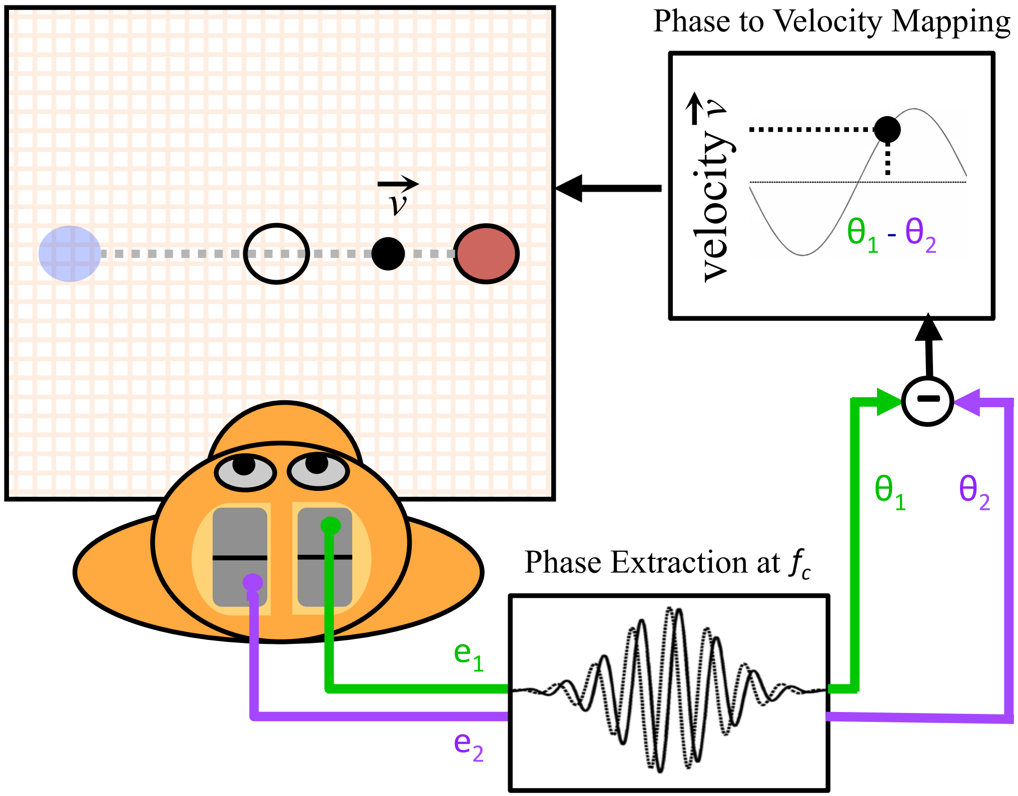
One Approach: Phase-BMI

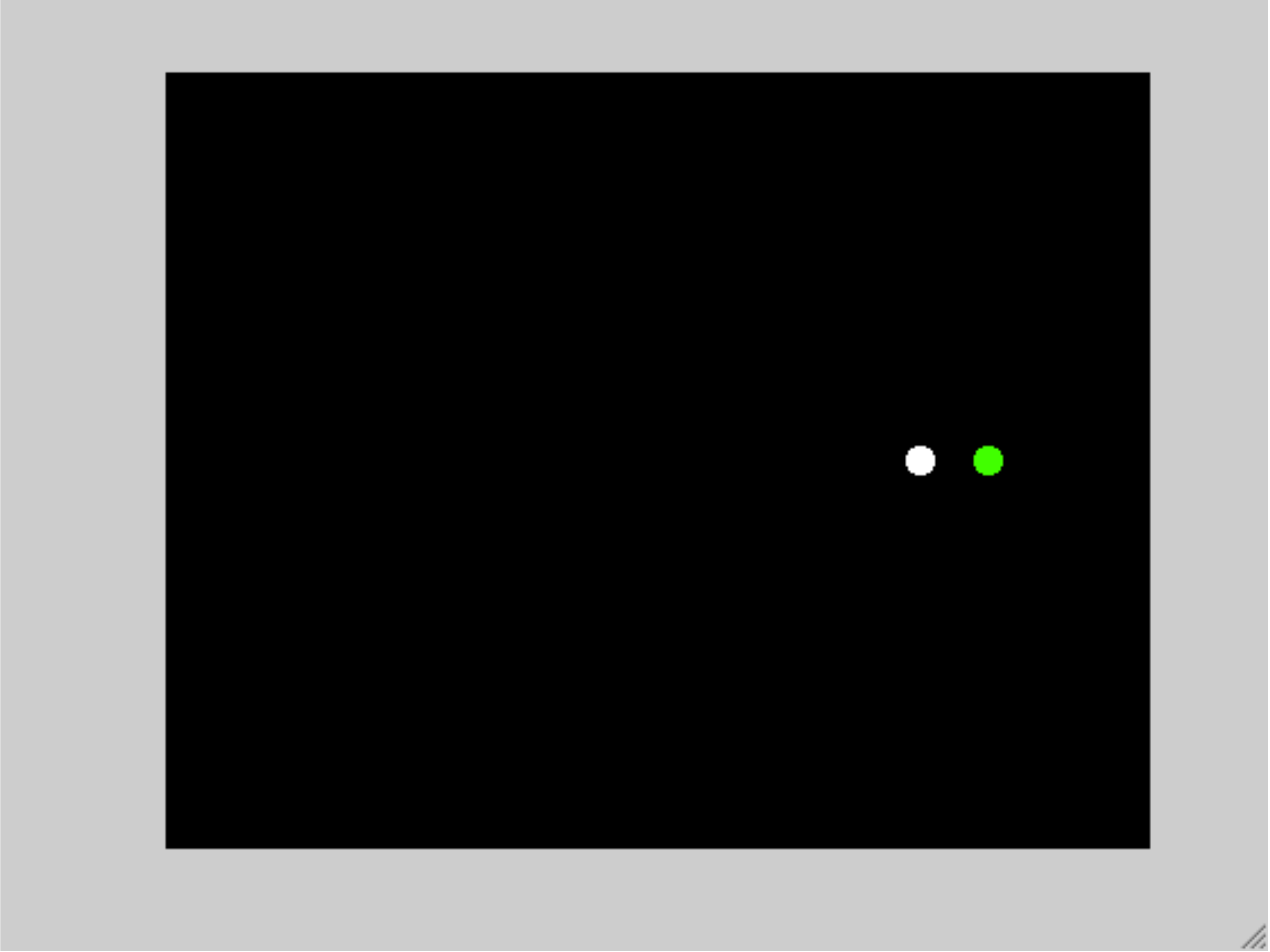
- Brain – Machine Interface task controlled by phase differences

- Question: Can subjects volitionally modulate phase differences?

- If so, can be used as a useful paradigm to study oscillations?

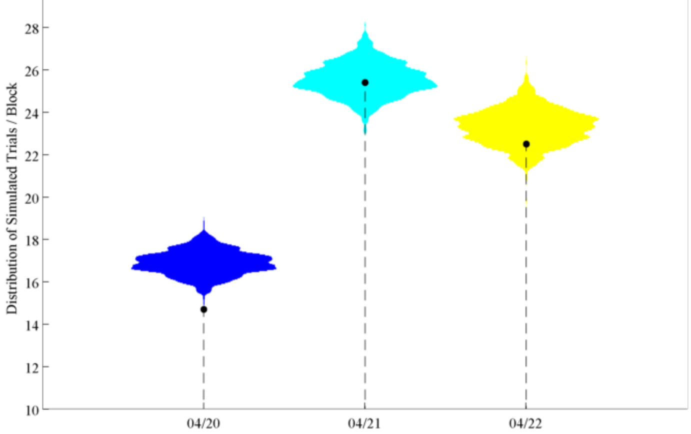
BMI Task


Phase to Velocity Mapping
velocity $\vec{v}$
$\theta_1 - \theta_2$
$\vec{v}$
θ_1
θ_2
Phase Extraction at f_c
e_1
e_2



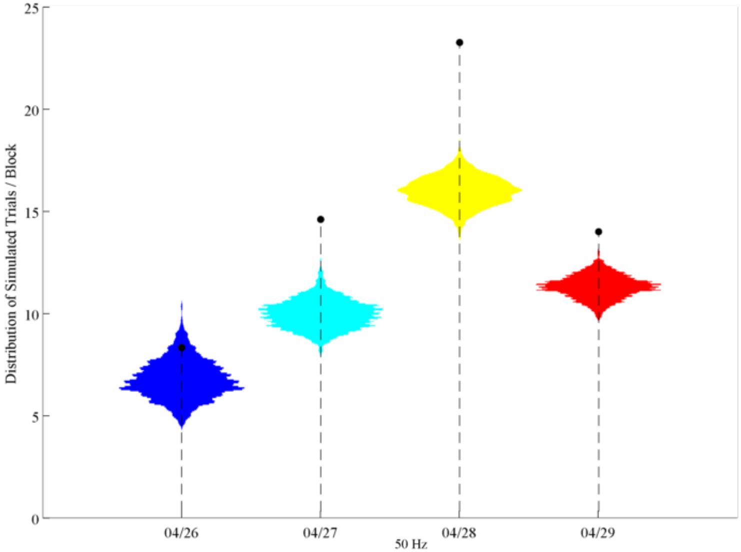

Hz31
Distribution of Simulated Trials / Block
35
30
25
20
15
10
04/10

- 10 Hz



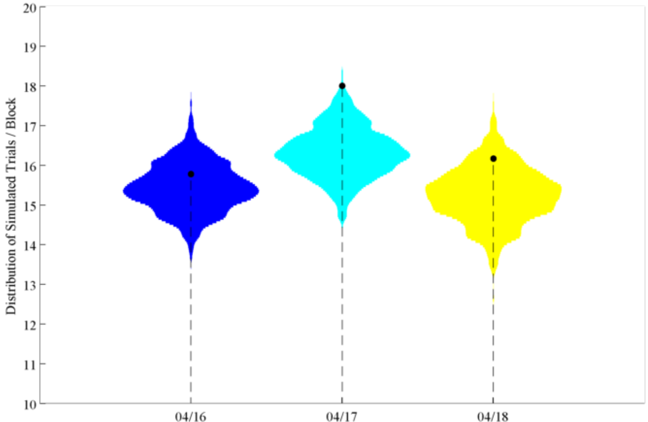
- 20 Hz

Hz20, Speed=0.5



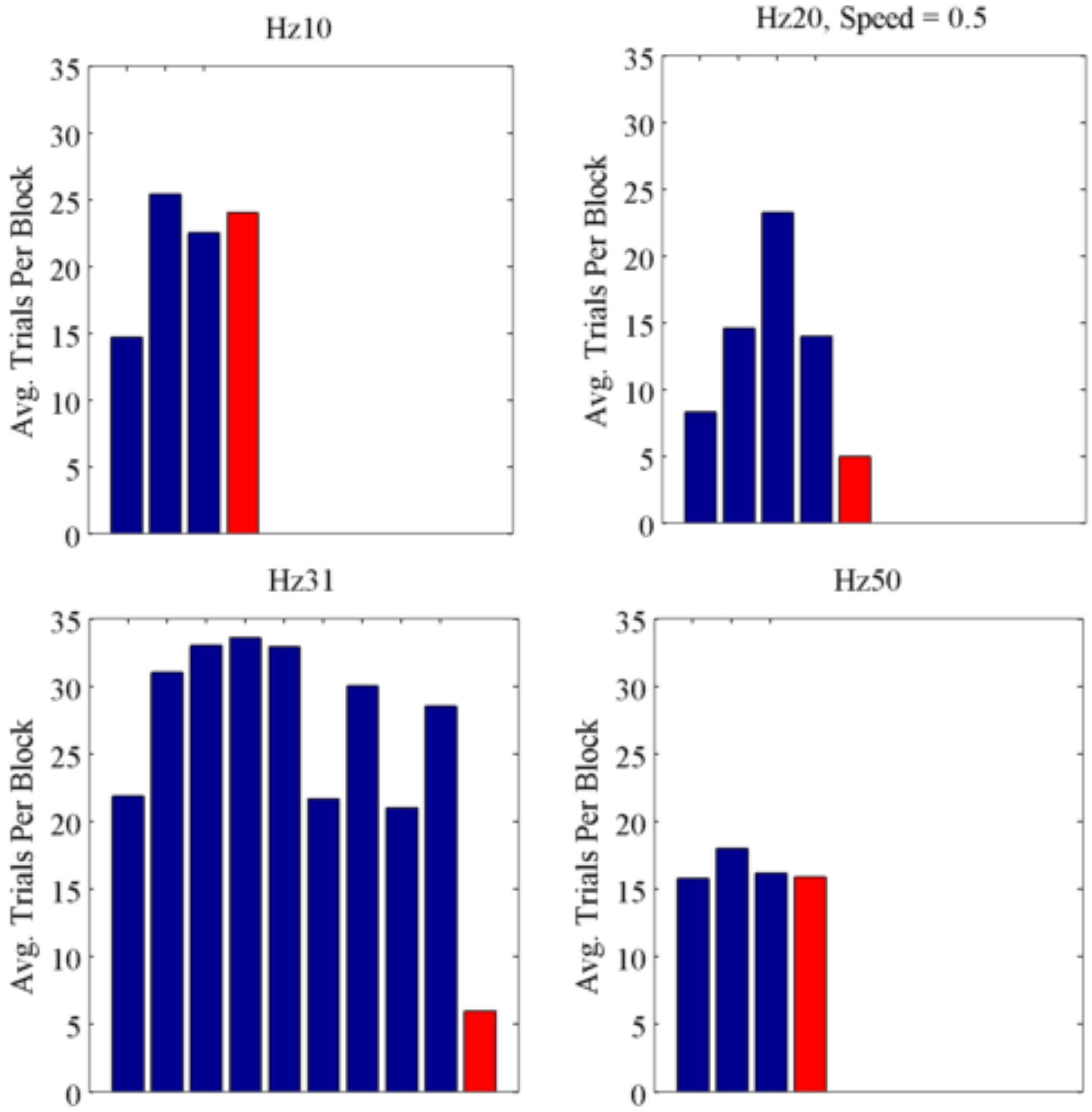
- 50 Hz

50 Hz



Other Chance Calculations

- Avg. Trials Per Block vs. Screen Off



Transition to Modeling

- Questions:
  - How is he doing this?
  - What are the differences between moving left, right, and baseline when he excels at the task?

- Approaches
  - Coupled Oscillator Model
    - With Phase Resetting Curve
  - Comparison of Epsilon Machines for Left/Right Conditions

Coupled Oscillator Model

$$\frac{\partial}{\partial t}\theta_1(t) = \omega - \kappa_{12}\sin(\theta_1 - \theta_2 - \mu_{12}) + \nu_1(t)$$

$$\frac{\partial}{\partial t}\theta_2(t) = \omega - \kappa_{12}\sin(\theta_2 - \theta_1 - \mu_{12}) + \nu_2(t)$$

ω = center frequency

κ_{12}=coupling strength between two oscillators

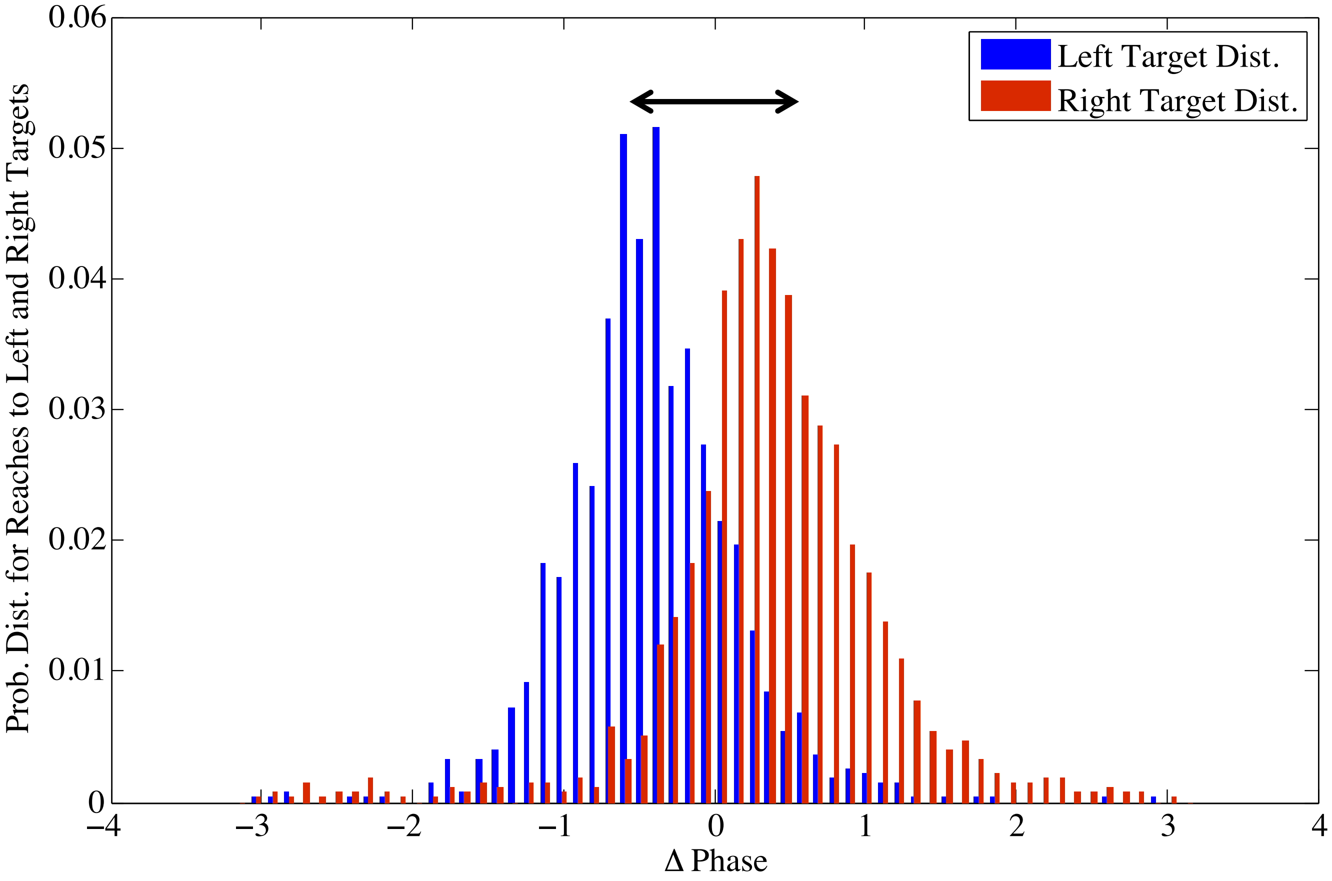
μ_{12}= intrinsic preferred phase between two oscillators

$\nu_i(t)$ = zero-mean Gaussian noise term

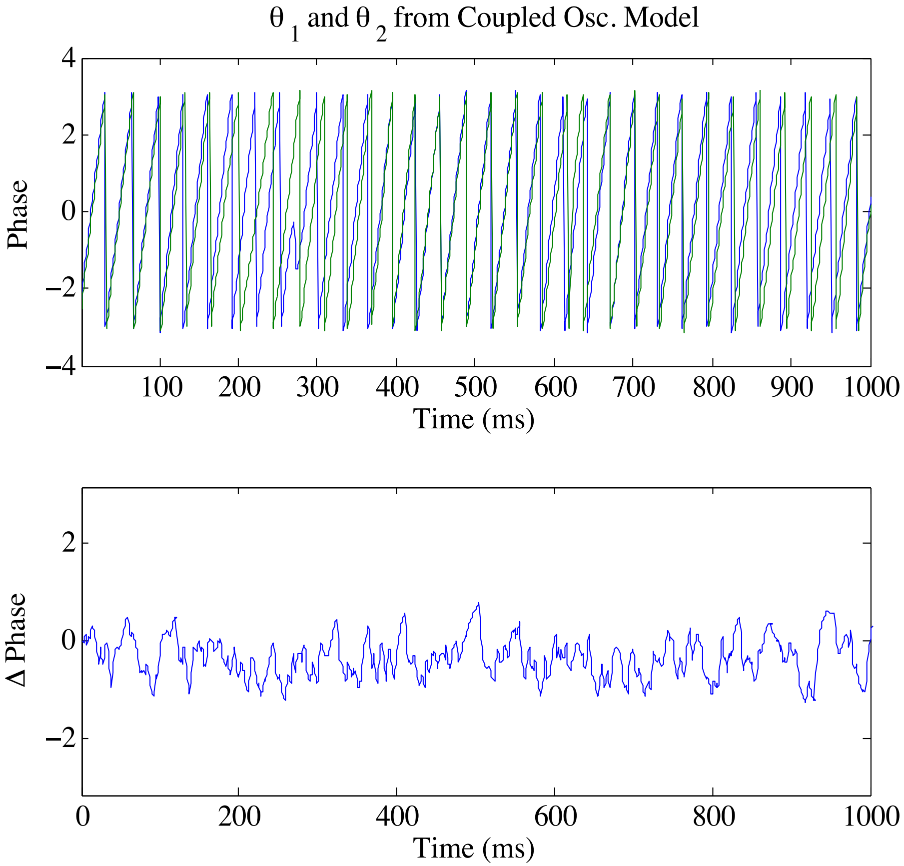
Canolty et. al, 2010
Cadieu & Koepsell, 2010

Coupled Oscillator Model

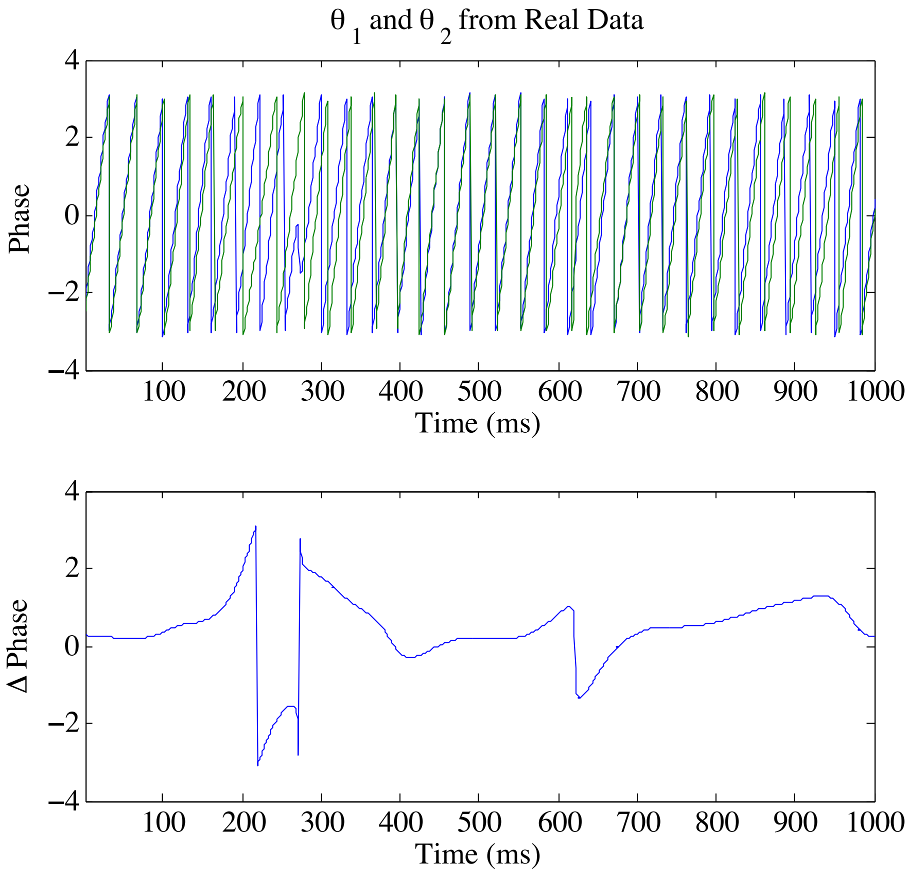
$$\frac{\partial}{\partial t}\theta_1(t) = \omega - \kappa_{12}\sin(\theta_1 - \theta_2 - \boxed{\mu_{12}}) + \nu_1(t)$$



Coupled Oscillatory Model – Fit to Baseline

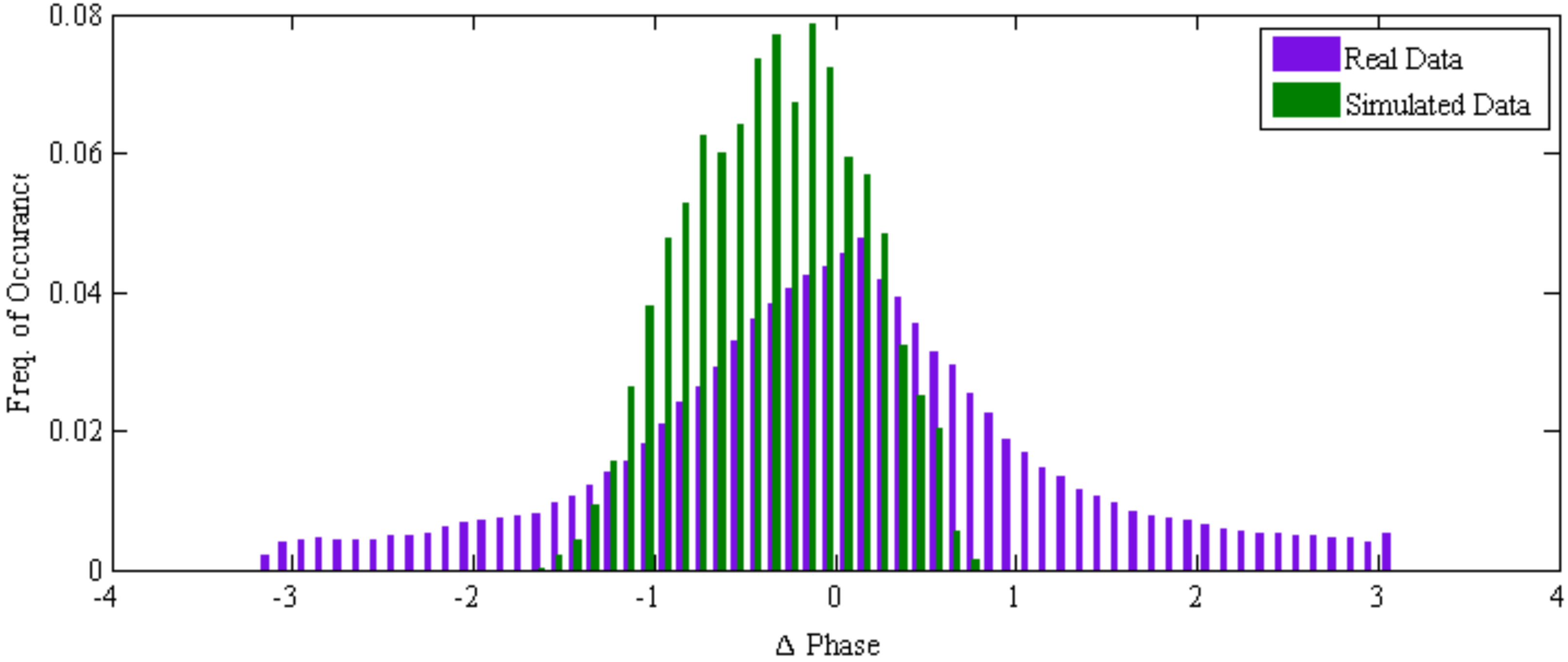


θ_1 and θ_2 from Coupled Osc. Model

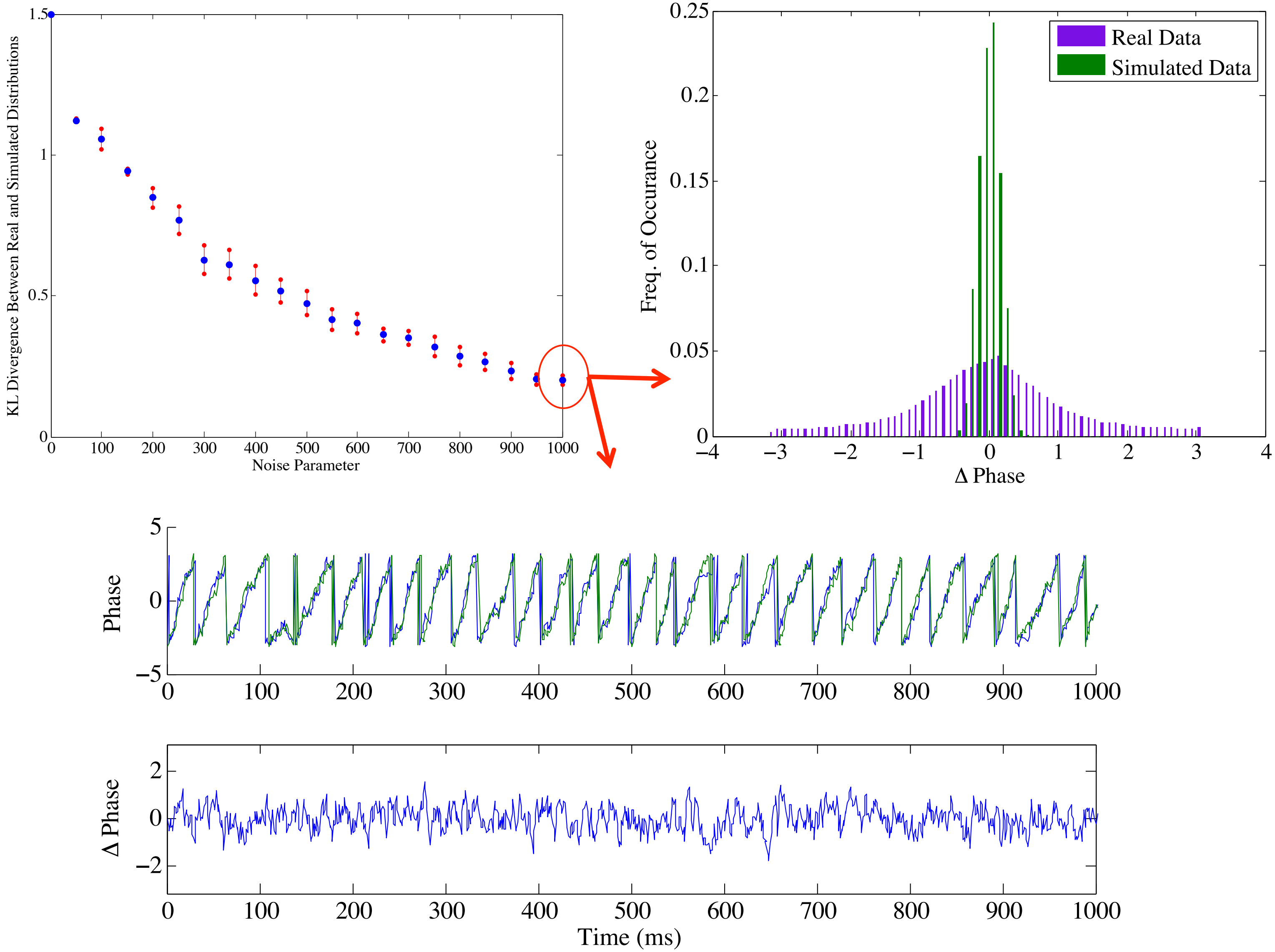


θ_1 and θ_2 from Real Data

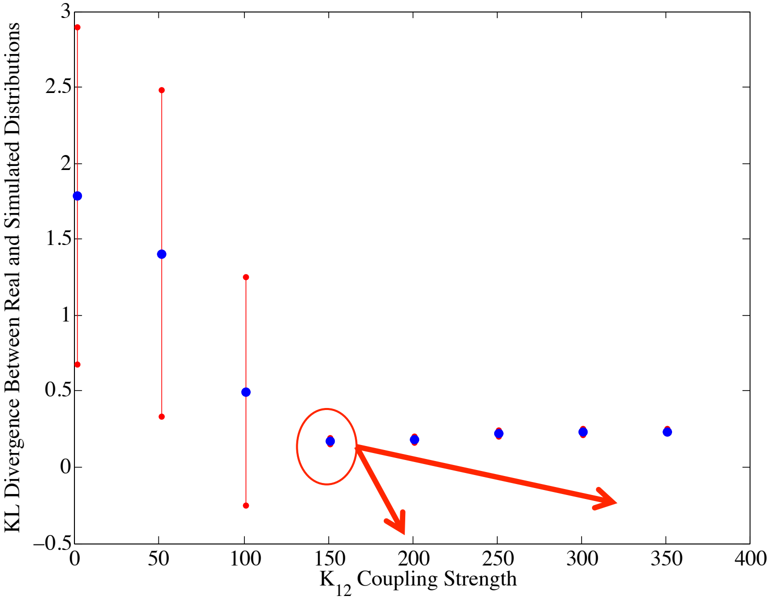
Coupled Oscillatory Model ctd.

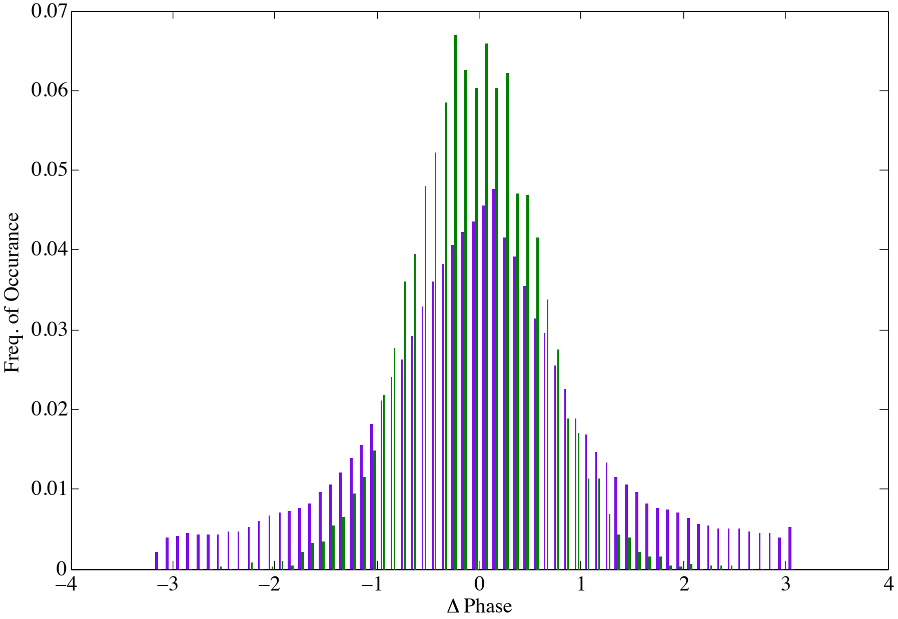


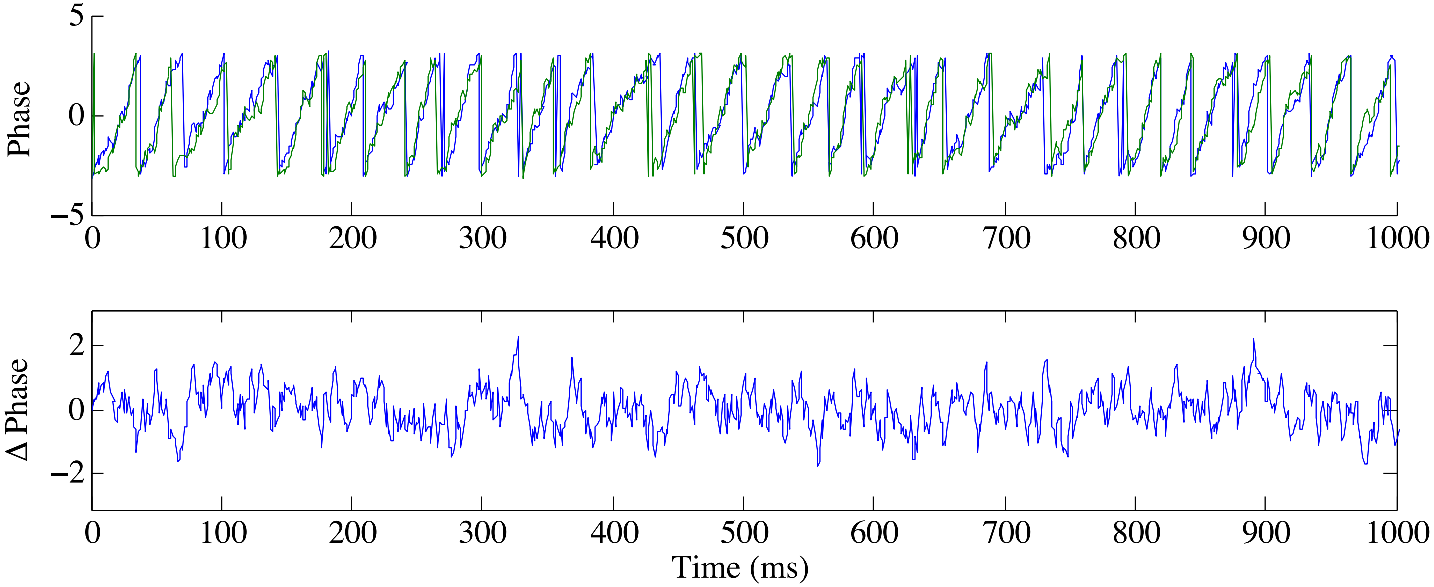
$$\frac{\partial}{\partial t}\theta_1(t) = \omega - \kappa_{12}\sin(\theta_1 - \theta_2 - \mu_{12}) + \boxed{\nu_1(t)}$$



Coupled Oscillatory Model ctd.

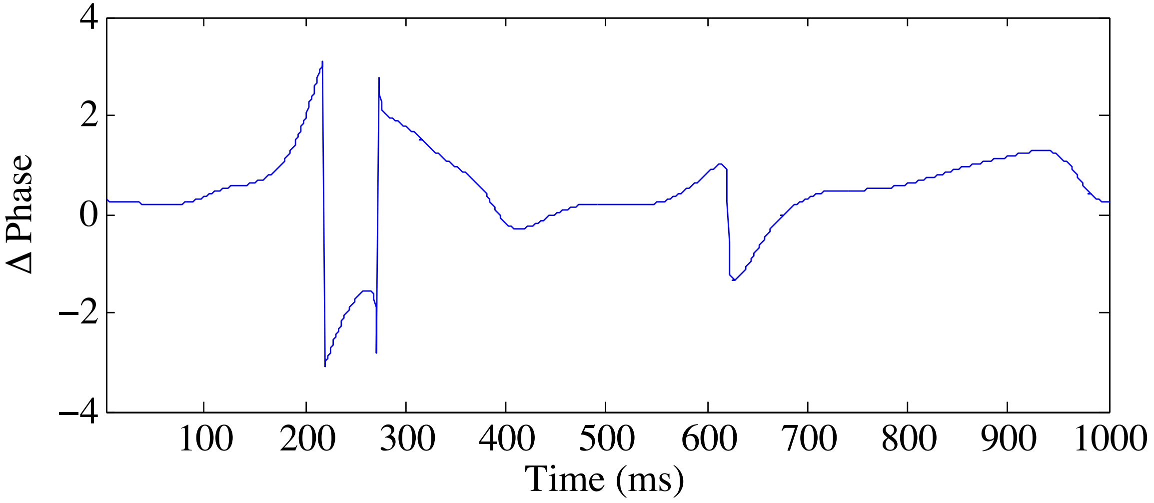




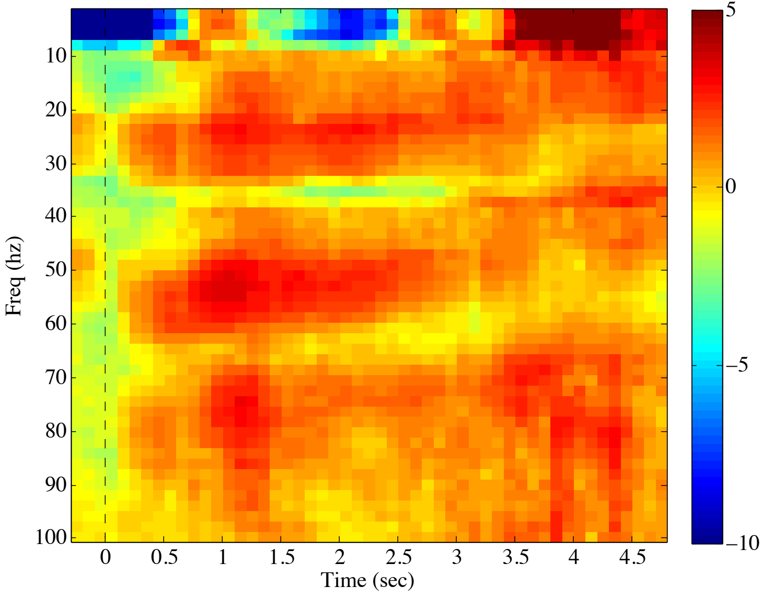


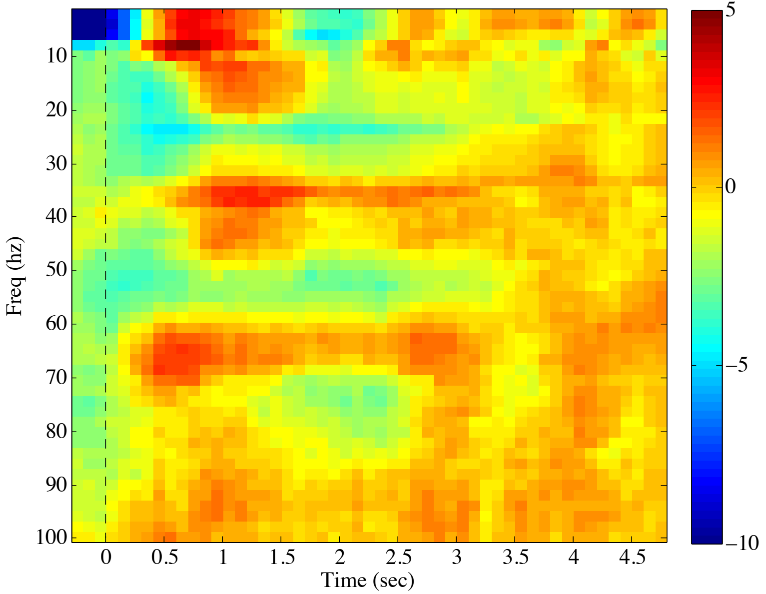
Coupled Oscillatory Model ctd.

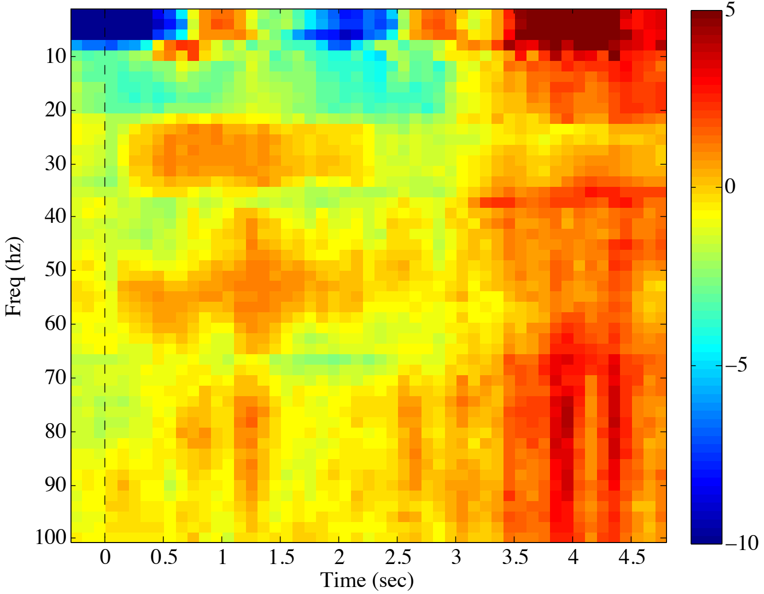
- Observations:
  - Phase must be smoother, must vary more
  - “Impulses”
    - Spectrogram

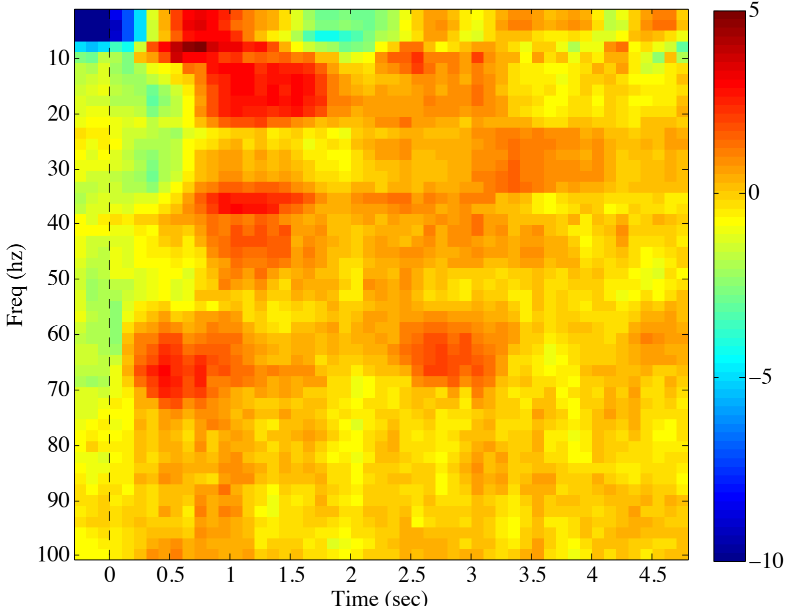


What about during L/R movements?


Left Target, Channel 1


Right Target, Channel 1


Left Target, Channel 2


Right Target, Channel 2

Phase Resetting Curve

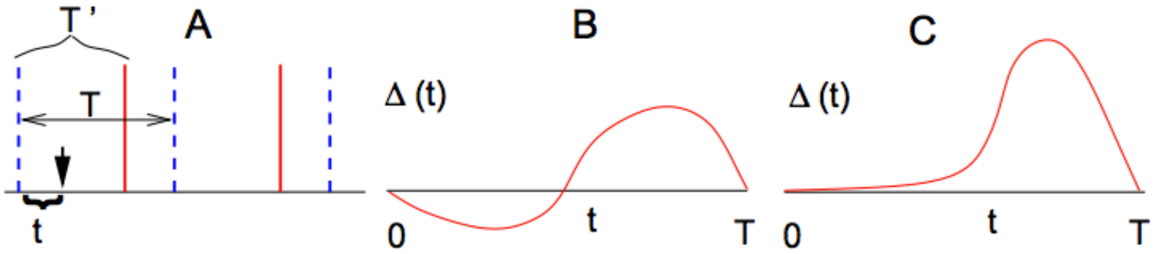


Figure 2: Phase response curves (PRC). (A) Construction of the PRC. Natural period is T. A perturbation arrives at t after the last spike causing the spike to change its time to T'. The PRC, $\Delta(t) = 1 - T'/T$. Dashed pulses show the times at which the oscillator fires without the perturbatioin and the solid curves show the perturbed firing times. Note that a key assumption is that effect of the perturbation occurs only during the cycle it was given. (B) PRC for the firefly *P. Malaccae*. (C) PRC for a cortical neuron.

Model:

$$\frac{\partial}{\partial t}\theta_1(t) = \omega - \delta(\theta_2)\Delta\theta_1$$

$$\frac{\partial}{\partial t}\theta_2(t) = \omega - \delta(\theta_1)\Delta\theta_2$$

Ermentrout, 2004

Modeling

- Dynamical System Model
  - Coupled Oscillator
  - …with Phase Resetting

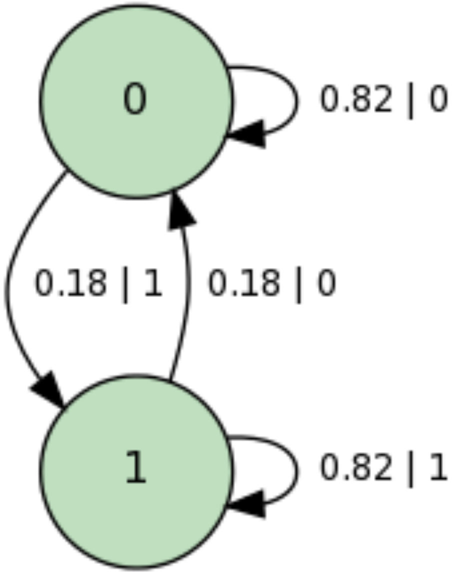
- Epsilon Machine comparisons:
  - To Left and Right targets
  - Partitioned as:
    - **θ** > 0, **θ** ≤ 0
    - **dθ** > 0, **dθ** ≤ 0

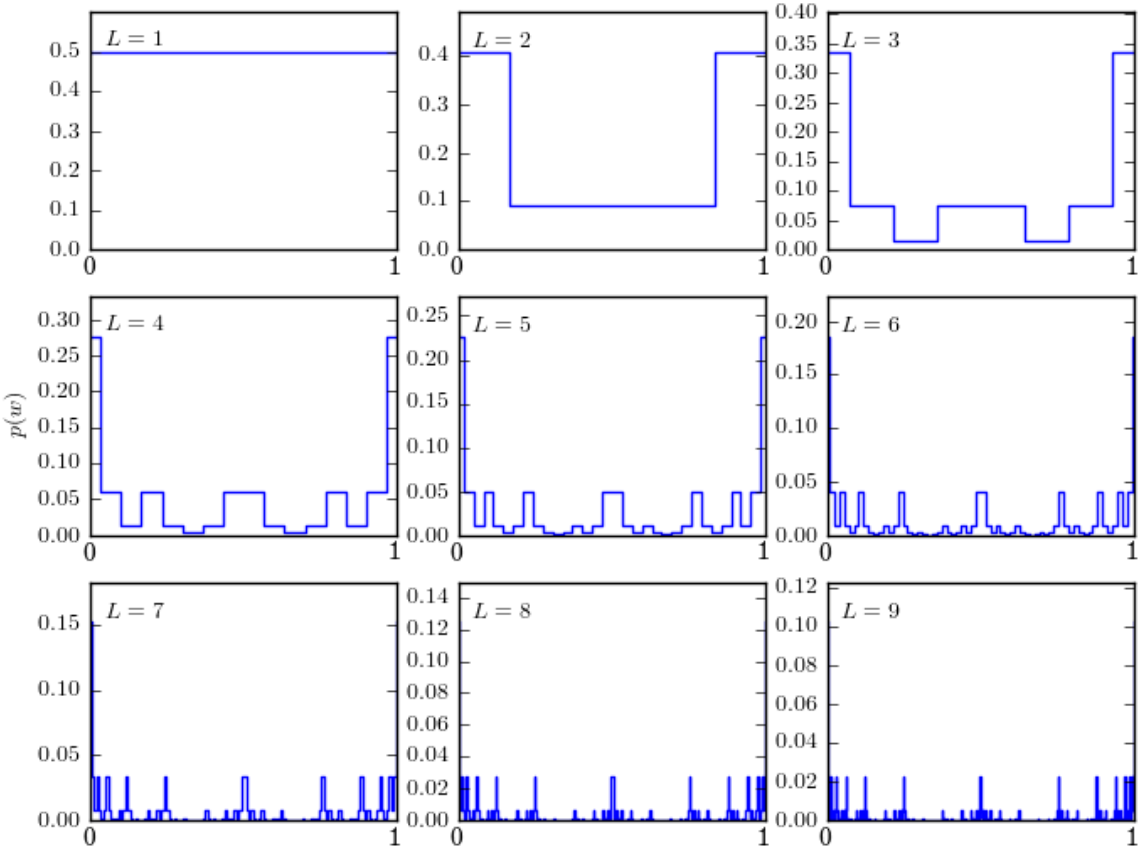
Partition Data

- Epsilon Machine comparisons:
  - Baseline, Left, and Right targets
  - Partitioned as:
    - $\boldsymbol{\theta} > 0$, $\boldsymbol{\theta} \leq 0$
    - $\mathbf{d}\boldsymbol{\theta} > 0$, $\mathbf{d}\boldsymbol{\theta} \leq 0$

Baseline

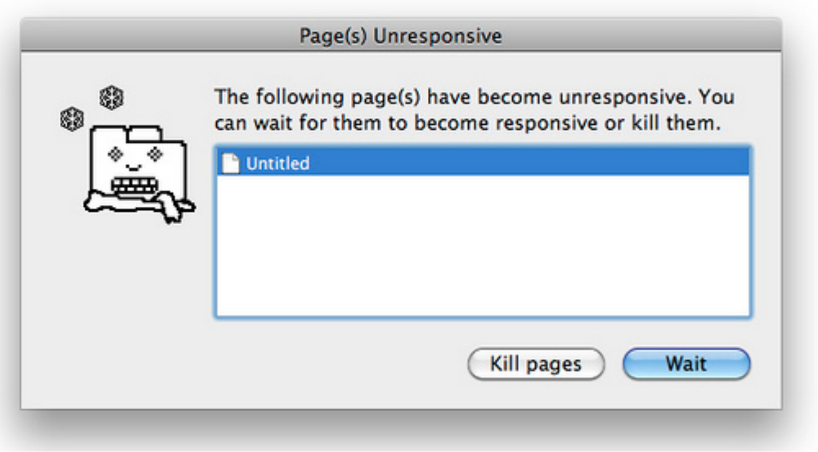
- Baseline phase during Screen Off





Baseline

Inferred Machine	hμ	Cμ	E
Baseline	0.67647	0.99996	0.32348
Right			
Left			



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…but then I kept crashing my browser

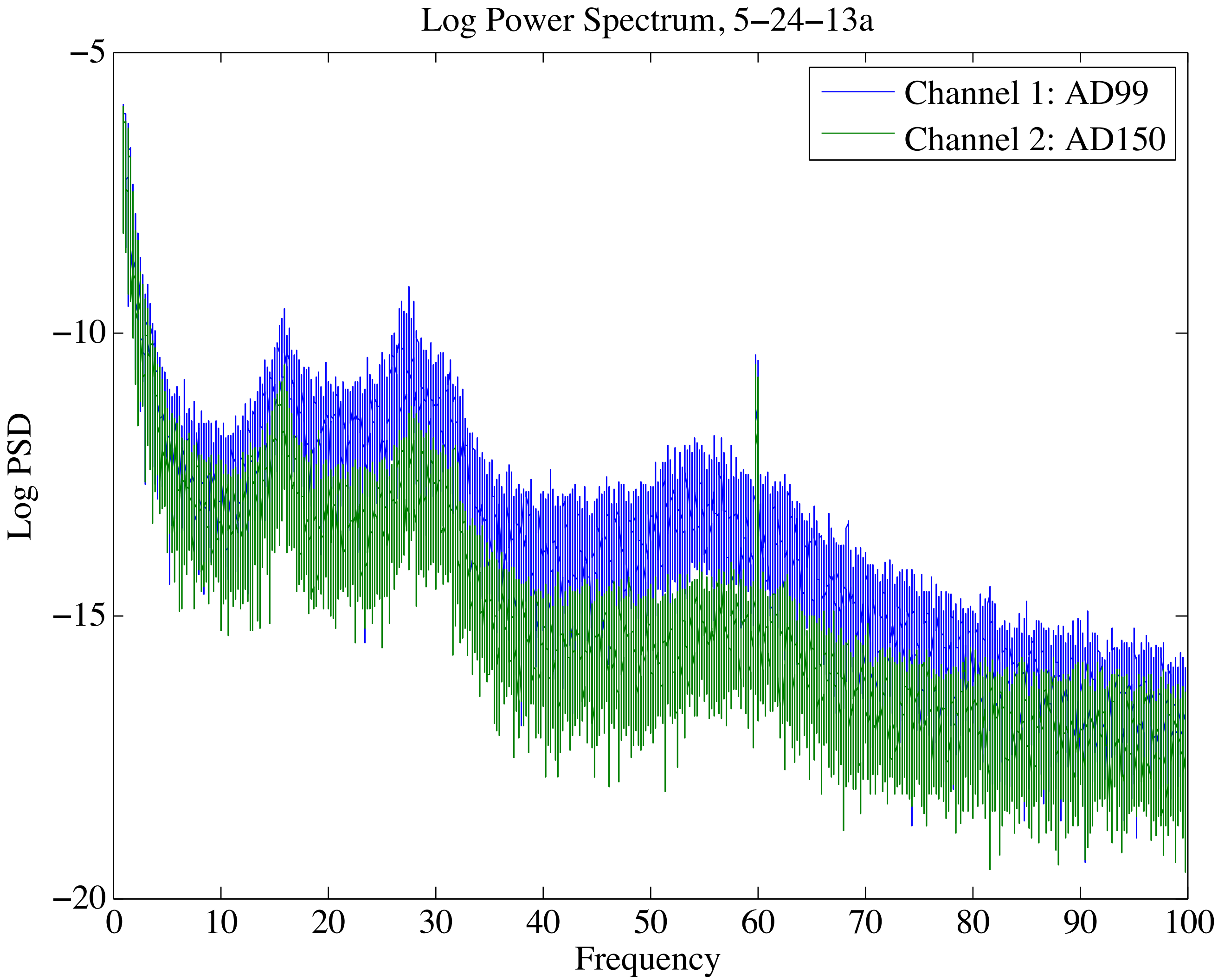
Conclusions / Future Directions

- Conclusions
  - Dynamic Coupled Oscillating Model may not be sufficient to describe Phase-BMI
  - Adding Phase Resetting Curve may capture impulses
- Future Directions
  - Comparison of Epsilon Machine for moving left vs. moving right

Thanks!

- Dr. Crutchfield
- The Carmena Lab
- Sebastian

Why 20, 30, 40 Hz?
Why not 10, 50 Hz?



Why 20, 30, 40 Hz?
Why not 10, 50 Hz?

- Correlation Coefficients of frequency decomposition: