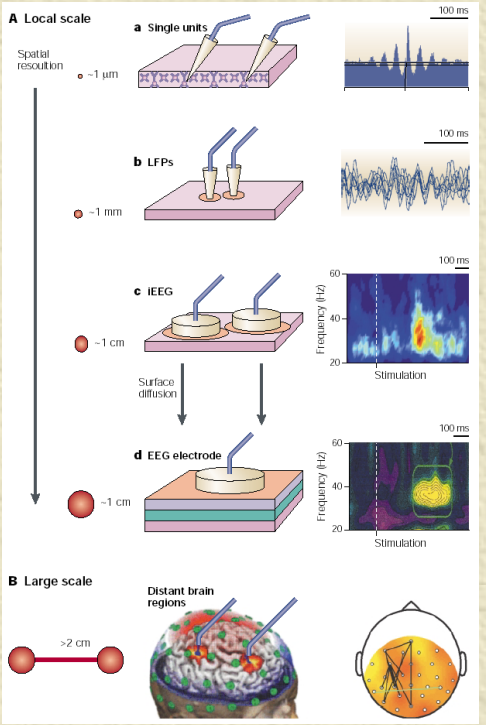
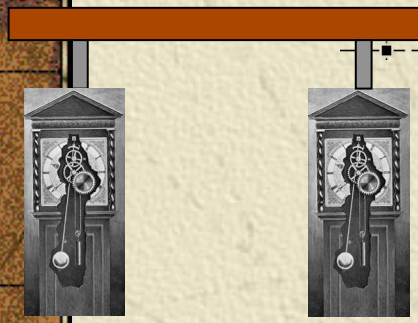
Neural Synchronization and Cognition





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Funded by NSERC

To come 11, 18, 25 May

2. le mardi 11 mai 2010 à 17 heures:
Neural synchronization and attention

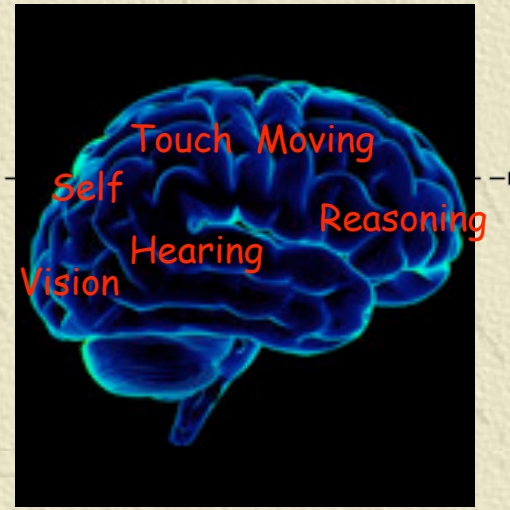
3. le mardi 18 mai 2010 à 17 heures:
Neural synchronization and consciousness

4. le mardi 25 mai 2010 à 17 heures:
The role of the thalamus in human consciousness

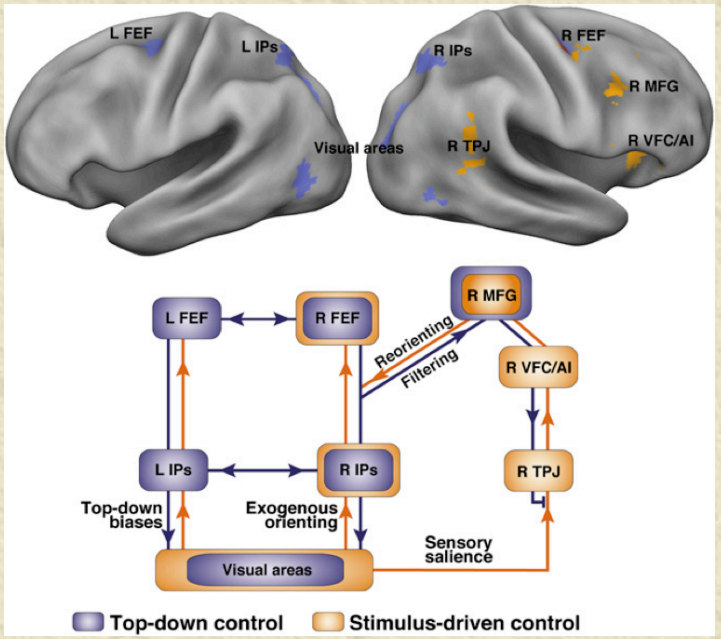
Overview

- How is cognition implemented in the brain?
- Synchronization
- Neural synchronization at many scales
- Possible functions of neural synchronization
  - MAE computation - Hopfield
- Synchronization in the cortex
- Synchronization related to perception and cognition
- Extended example from my lab: MMN

How is cognition implemented in the brain?



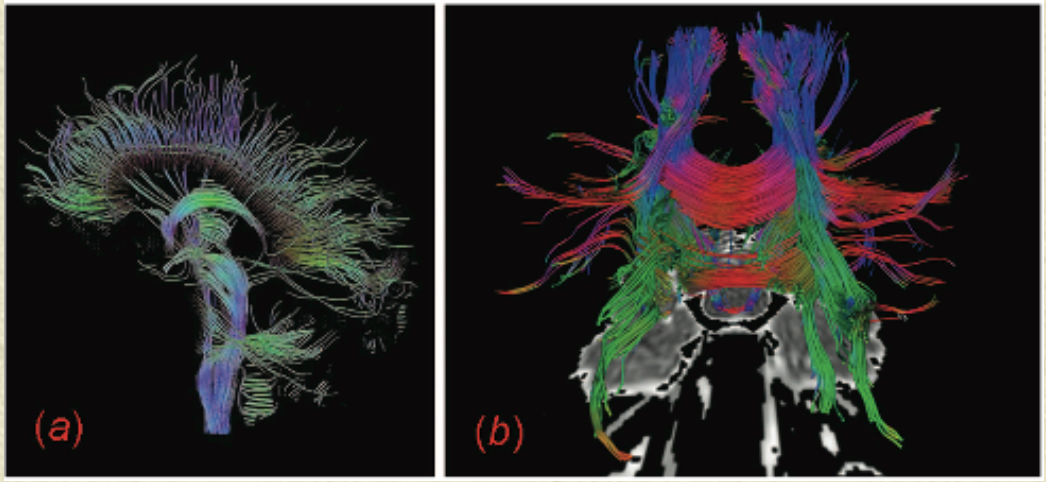
- Functionally specialized brain regions (grey matter)
  - E.g. visual cortex, auditory cortex, dorso-lateral prefrontal cortex
- Regions arranged in networks via neural pathways (white matter)
  - E.g., dorsal and ventral attention networks
- Each region participates in many different networks
- Regional function depends on active network: e.g. R MFG
- Functional networks are transient: e.g., attention shifts every 0.5 to 2 sec.

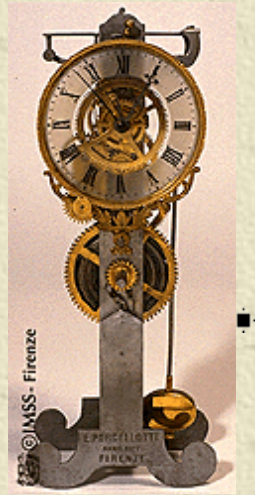


Corbetta, Patel, Shulman, 2008, *Neuron*

How are functional brain networks implemented?

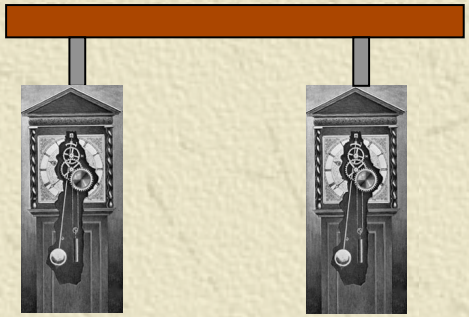
- Structural connections change on slow time scales – minutes-hours-days-years
- Functional networks form and dissolve on faster time scale – milliseconds – seconds
- Structural changes too slow - what mechanism could accomplish fast changes?
- Neural synchronization has been proposed to be this mechanism – operates on top of structural networks



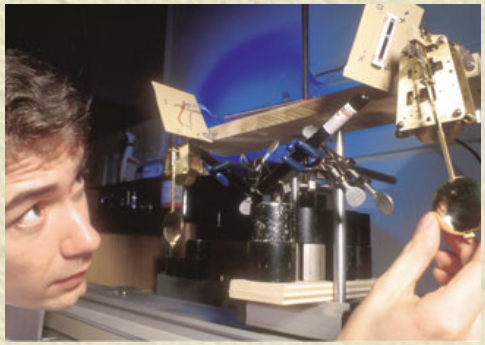


Synchronization

- Synchronization is a physical concept: Christiaan Huygens's synchronous pendulum clocks
- *Synchronization: A Universal Concept in Nonlinear Sciences* by Pikovsky, Rosenblum & Kurths
- Kuramoto, Winfree: phase oscillators, general theory of synchrony (See Strogatz: *Synch*)



Modern replication 2002



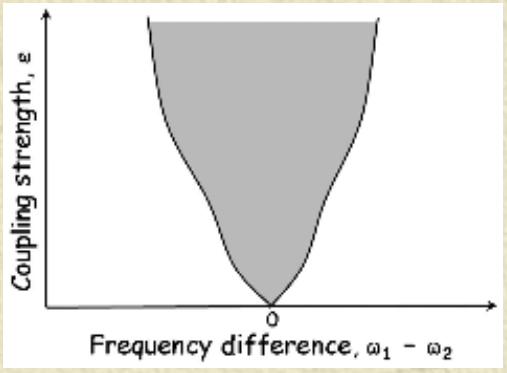
http://www.youtube.com/user/abahraminasab#p/u
http://www.scholarpedia.org/article/Synchronization

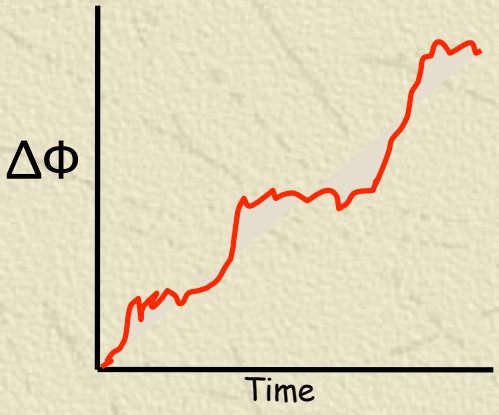
Synchronization

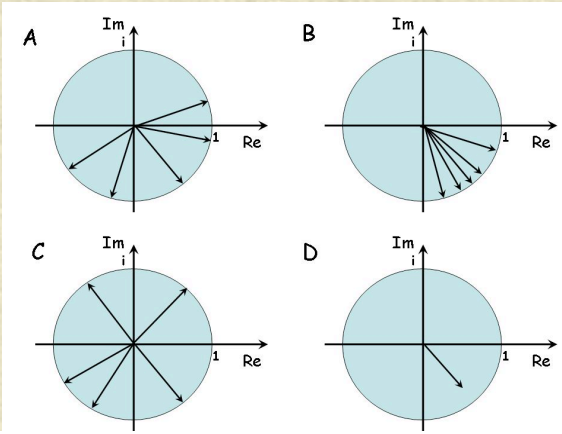
- Synchronization of weakly coupled autonomous oscillators:
- Frequencies must be close relative to coupling strength
- Natural oscillators are noisy so phase locking is stochastic
- Can observe continuously or across comparable time epochs

$$\varphi = \phi_2 - \phi_1$$

$$\dot{\varphi} = 0 \quad \begin{cases} \varphi = 0 & in\ phase \\ \varphi = \pi & out\ of\ phase \end{cases}$$







Neural synchronization

- Individual neurons are relaxation oscillators and coupled groups of neurons can act as phase oscillators
- Neural synchronization occurs when neural activity, spiking or dendritic or other currents, in disparate locations, rises and falls in a fixed relationship because of weak coupling of neurons or neural groups

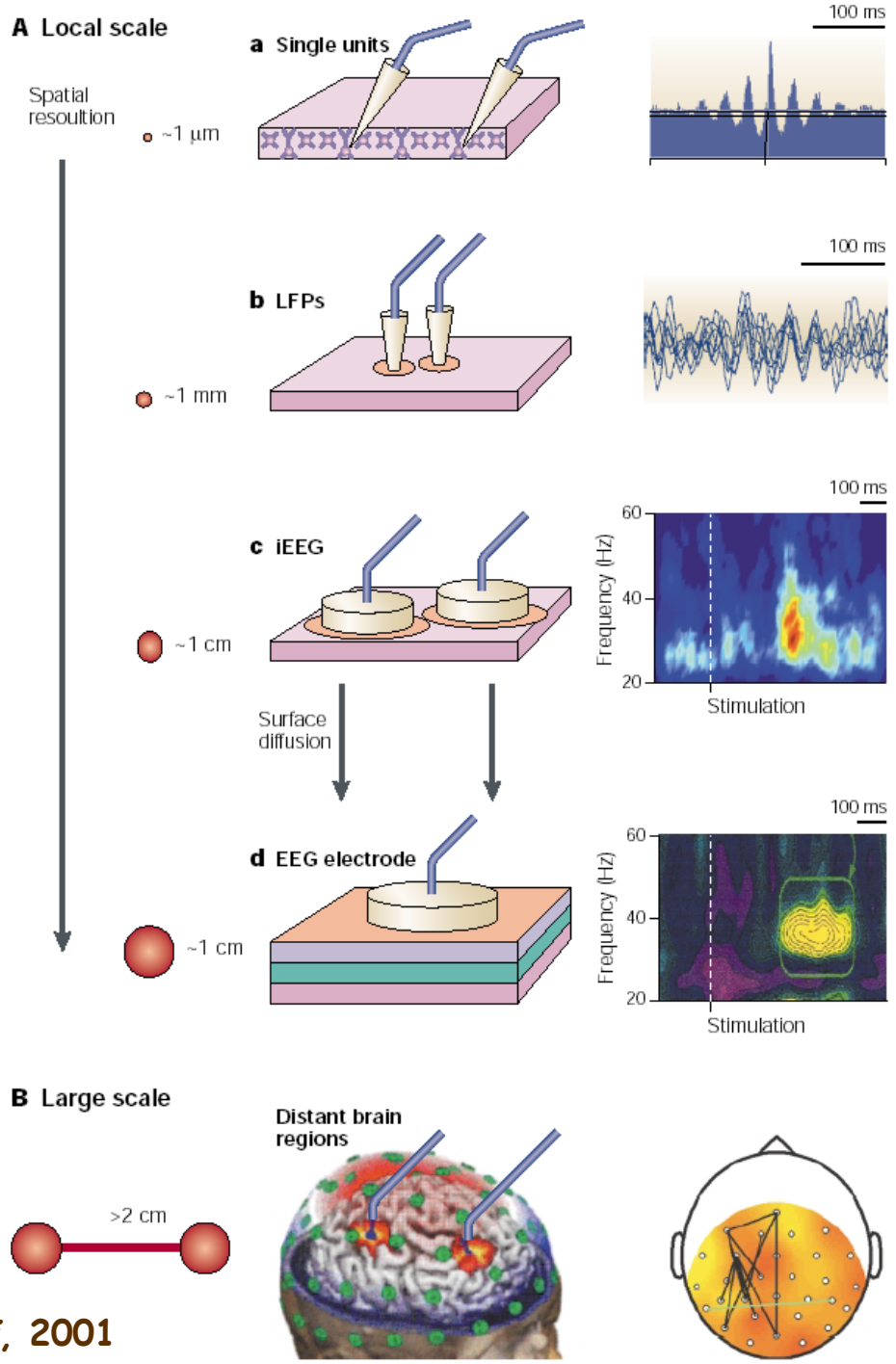
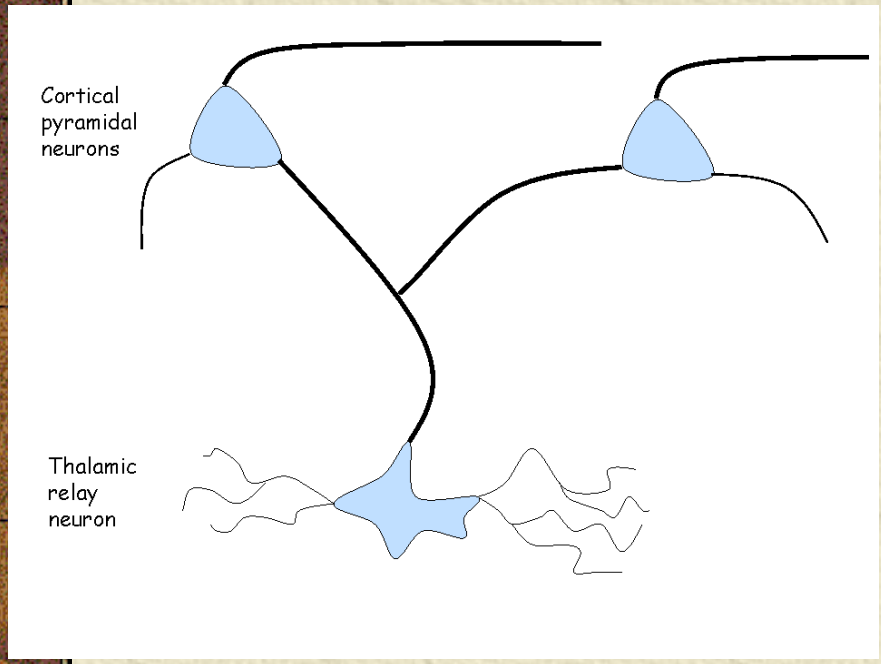


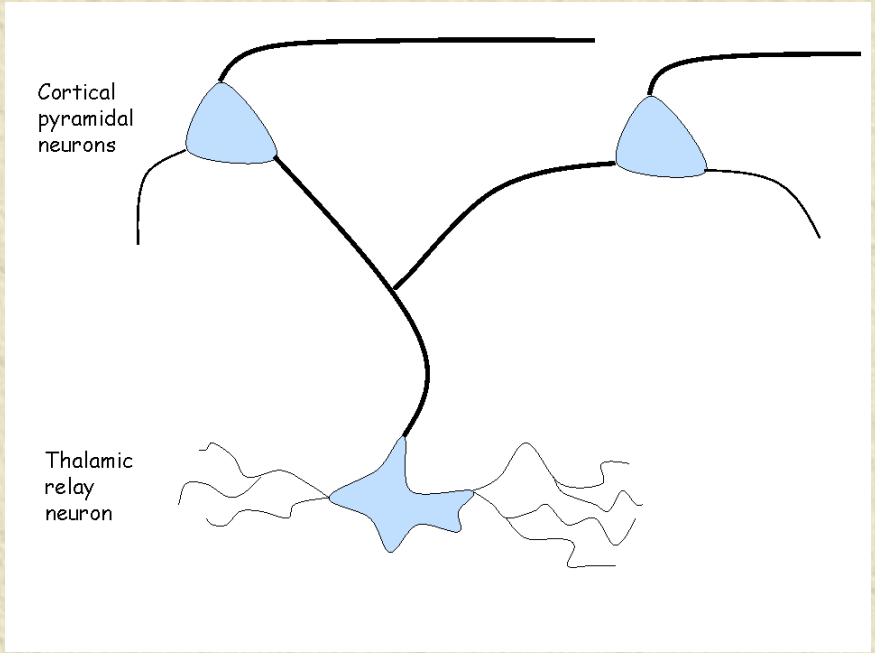
Fig. from Varela et al, *Nat. Rev. Neurosci*, 2001

Example of neural spike synchronization

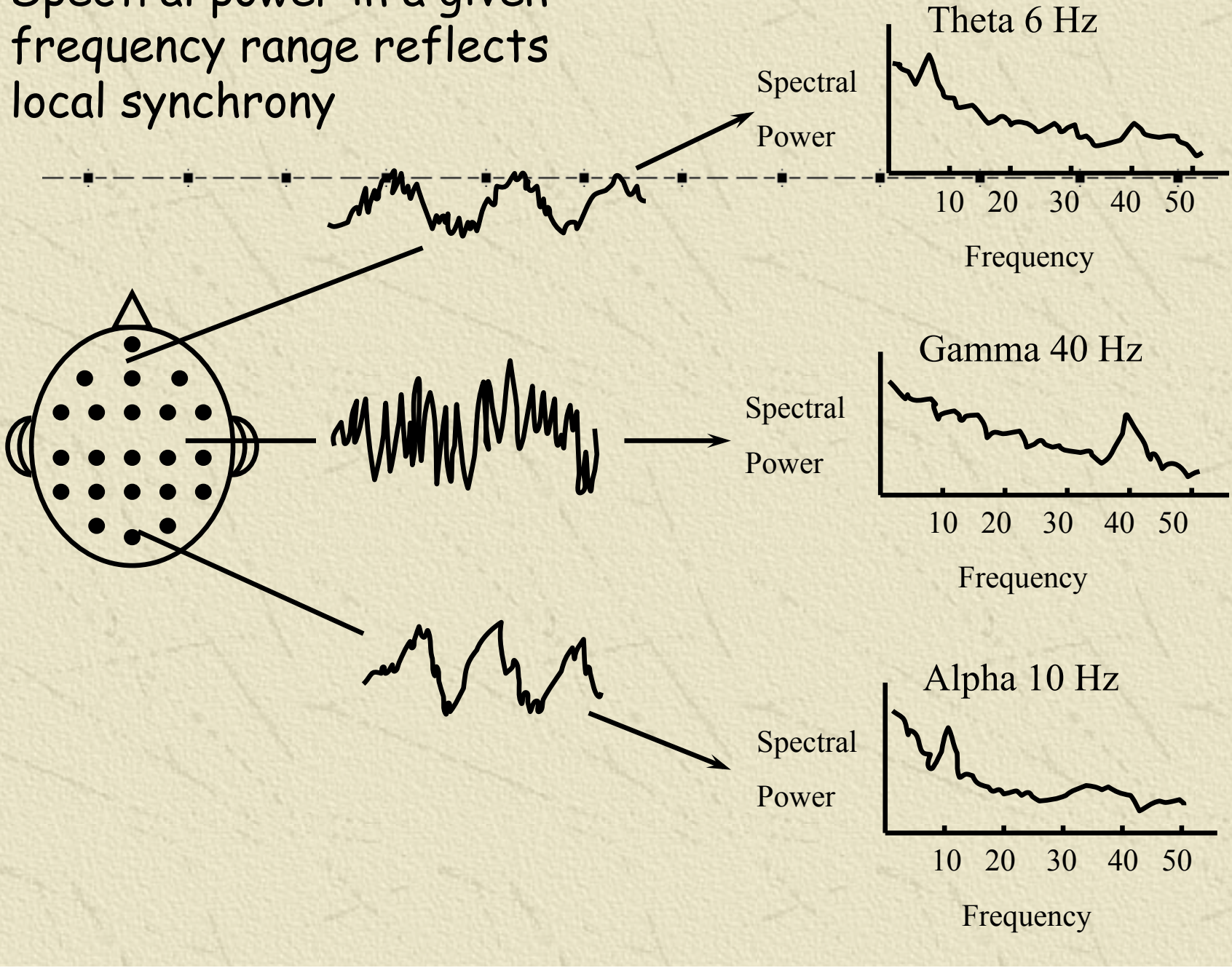
Asynchronous neural firing



Synchronous neural firing

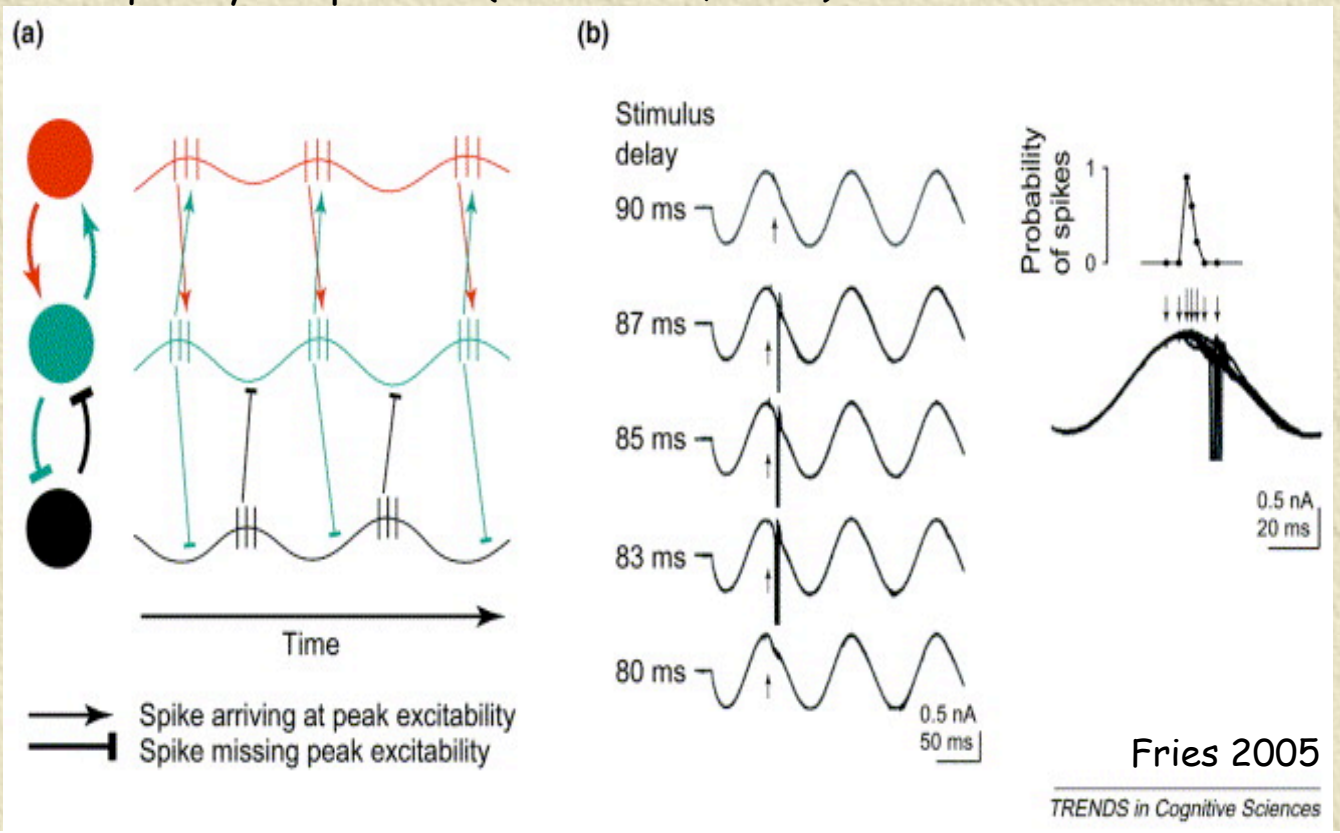


Spectral power in a given frequency range reflects local synchrony



Possible roles of intra-regional (local) neural synchrony

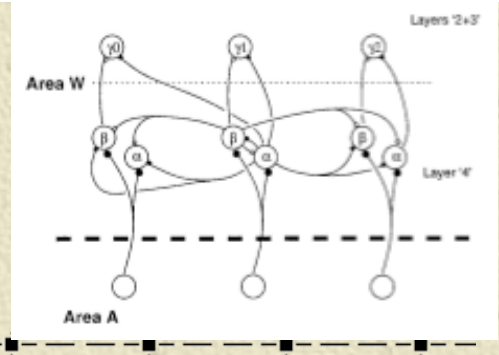
- High fidelity neural communication
- Perceptual/memorial/motor…. Binding (Singer et al):
  - *Increase 30-70 Hz:* amplify post-synaptic effect by increasing spike co-occurrence (Fries et al, 2001)
  - *Decrease 6-15 Hz:* increase post-synaptic impact by avoiding spike-frequency adaptation (Fries et al, 2001)



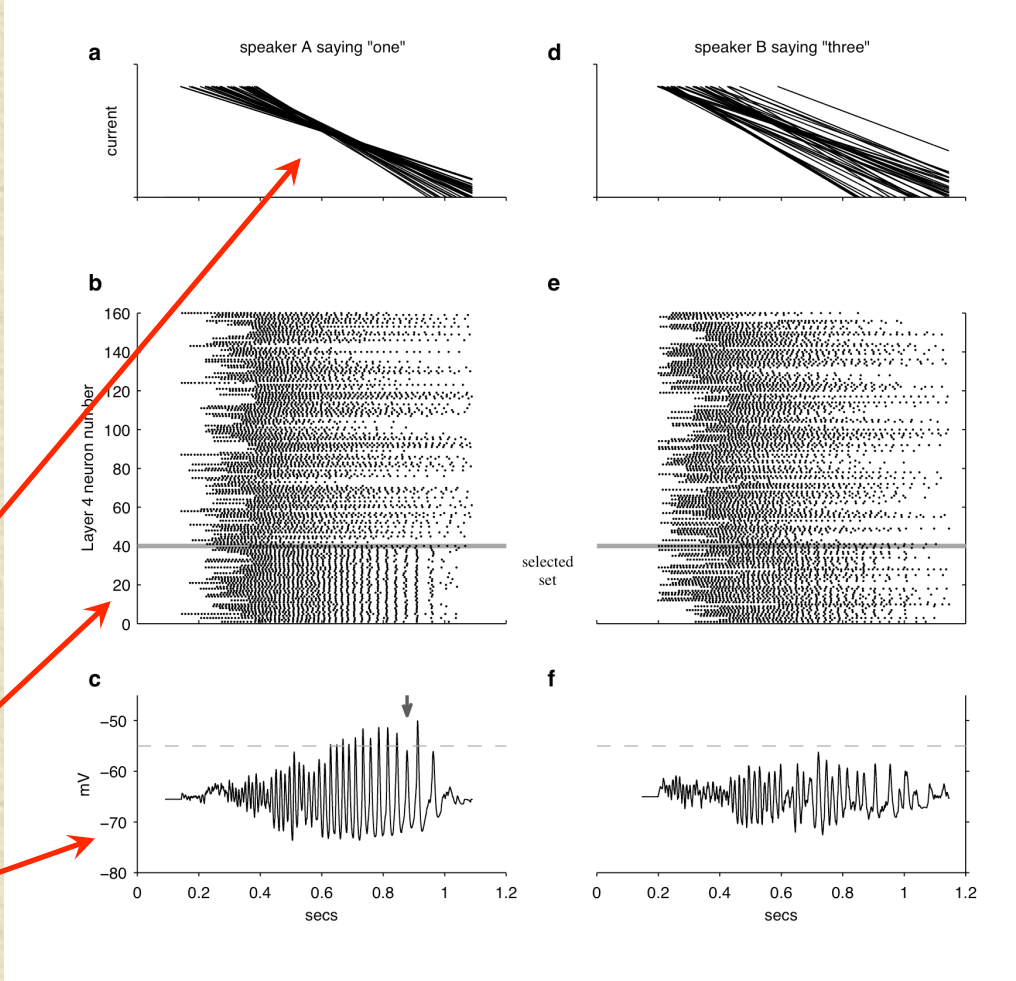
Possible roles of inter-regional (global) neural synchronization

- High fidelity neural communication
- Integration of neural activity through reciprocal (re-entrant) interactions between diverse brain regions (e.g., Varela et al, 2001)
  - Exchange of data (upward) and hypotheses/templates (downward); sensory/perceptual processing
  - Modulation of one region (e.g., hippocampus) by another (e.g., visual cortex) to store a memory (e.g., of a visual scene)
  - Modulation of one region (e.g., visual cortex) by another (e.g., prefrontal cortex) to enhance processing of attended information (e.g., a sign for a sushi bar)
  - Initiating an action in motor regions by computations from cognitive regions
  - Consciousness (?)

Many Are Equal - Hopfield



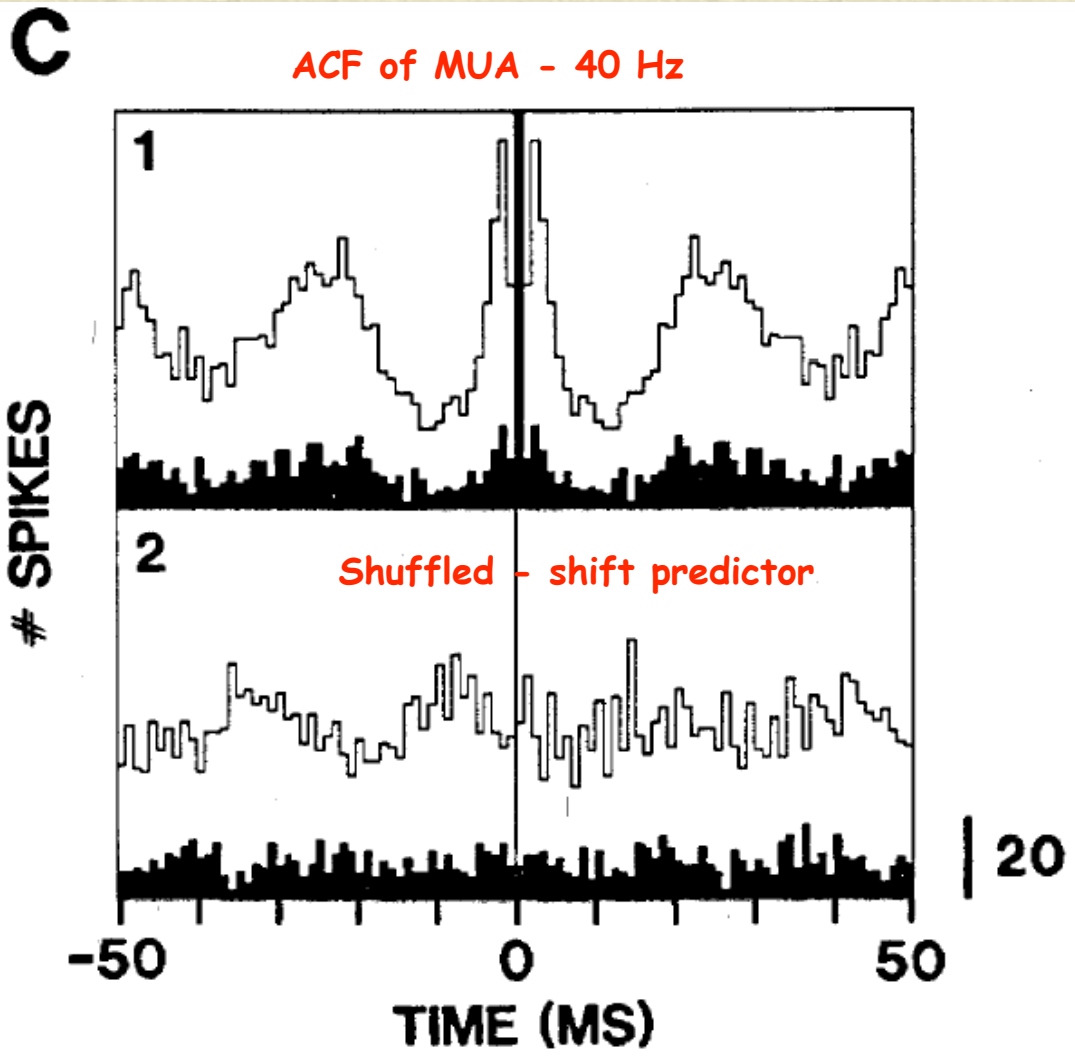
- How transient synchronization in a neural network accomplishes temporal integration
- Spike rate decay (adaptation) at many decay rates accomplishes implicit temporal coding
- When decaying spike rates are roughly equal, synchronization (recognition event in neural network) occurs
- Results in burst of roughly 40 Hz activity



Hopfield & Brody *PNAS* 2000, et seq.

40 Hz oscillation in cat visual cortex

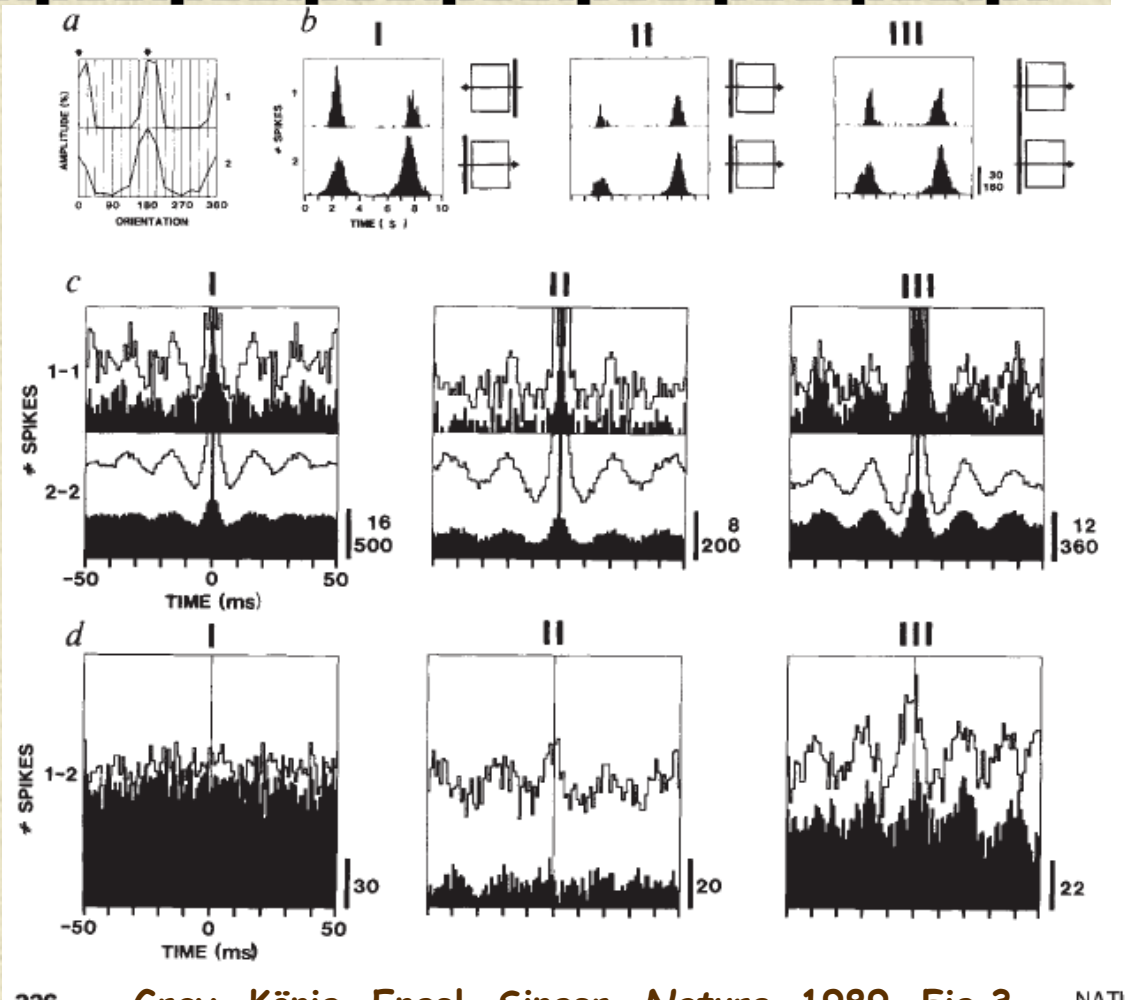
- Anticipated by, among others, Adrian (1950), Edelman (1978), Freeman (1975)
- LFP closely related to MUA



Gray & Singer, *PNAS*, 1989, Fig 1

Intercolumnar synchronization reflects stimulus properties

- 7 mm separation
- Zero phase lag synchrony
- Reflects similarity of orientation pref
- Reflects global stimulus properties
- Mechanism: local excitatory collaterals, inhibitory interneurons



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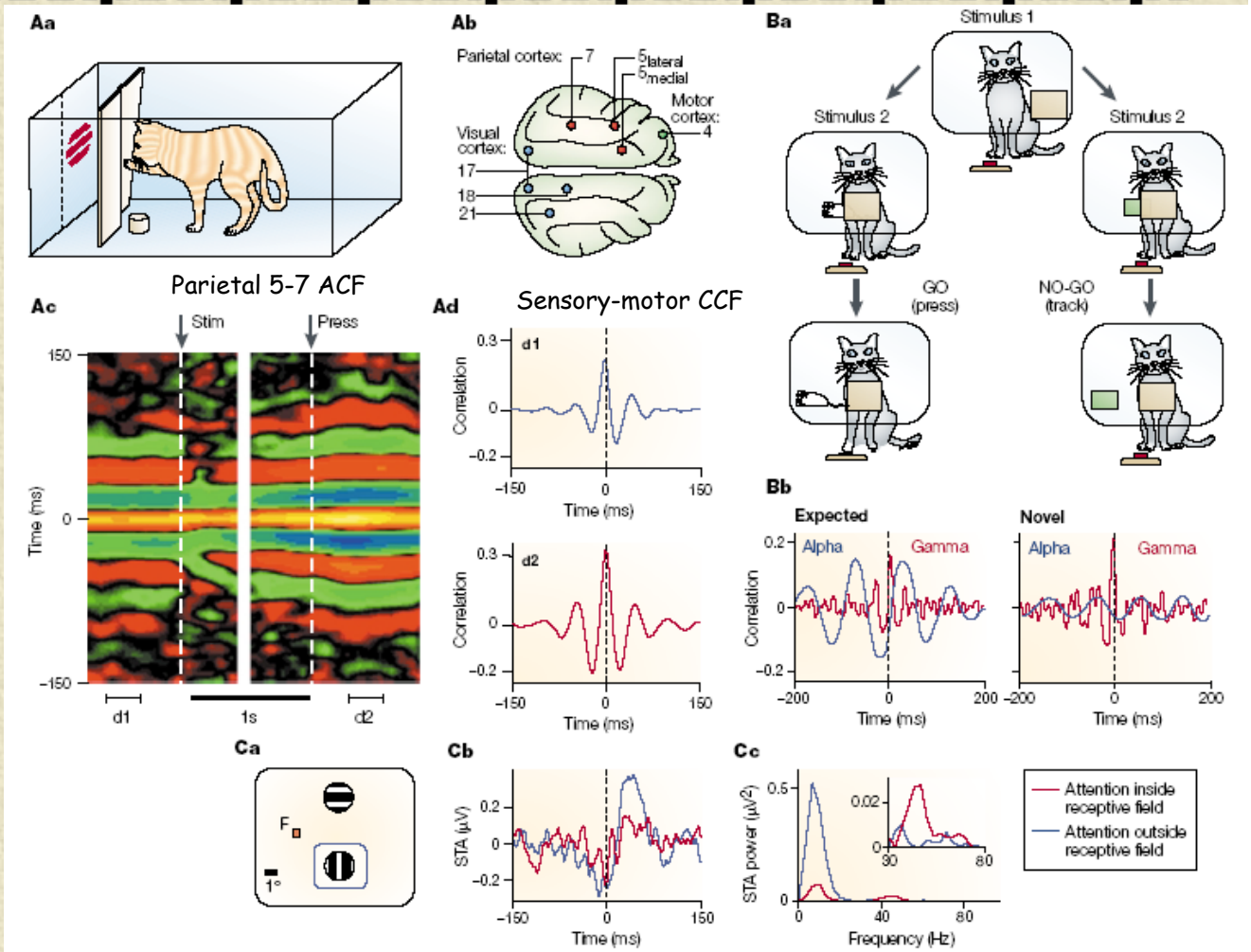
336 **Gray, König, Engel, Singer, *Nature*, 1989, Fig 3** NATURE · V

Top-down effects on neural synchrony: Expectations, attention, movement prep,…

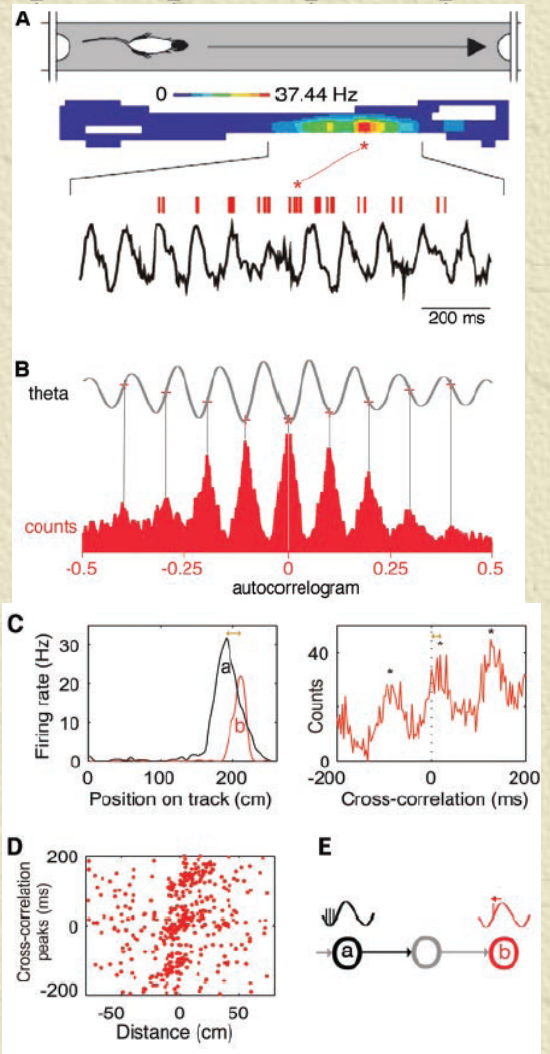
- A. Withhold response (d1 before stim, d2 after press)
- B. GO-NOGO (visual cortex-parietal)
- C. Attention enhances 40 Hz synchrony and depresses 10 Hz synchrony



Engel, Fries, Singer, *Nat. Rev. Neurosci.*, 2001, Fig 1

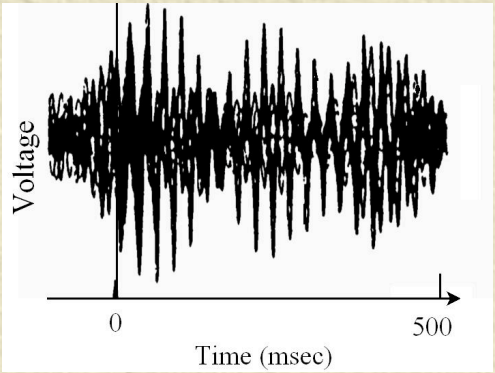
Gyorgy Buzsáki: Memory and hippocampal oscillations

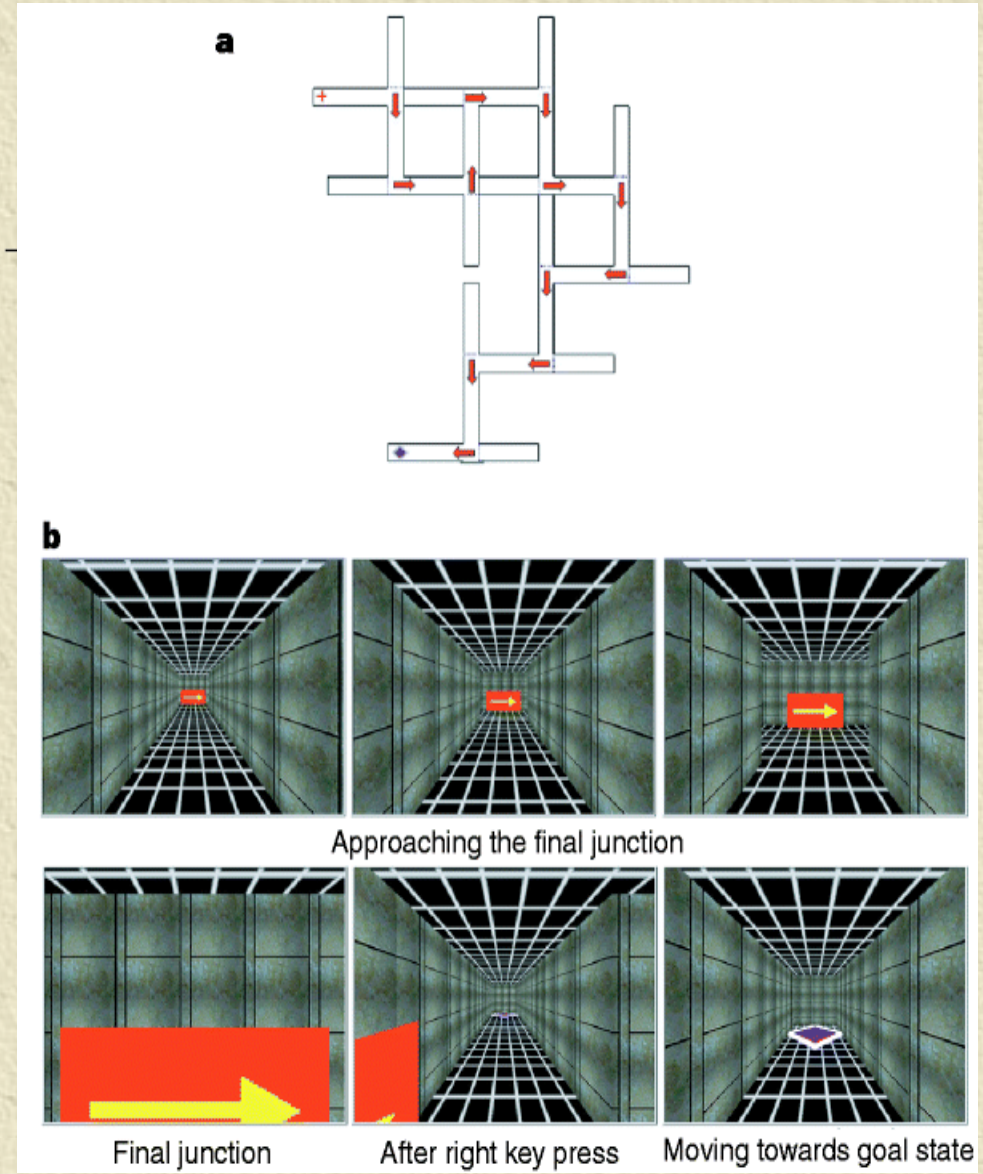
- Hippocampus responsible for first person experience; gives access to conscious experiential record
- Episodic memory: spatial-temporal reference for an event
- H is largest continuous neural space; 10^{10} synapses; 65 km of axons; $GABA_A$ cells direct traffic
- Trough of theta (5 Hz) rhythm is an attractor of place cell firing because of low inhibition there
- Whole H space searched every theta cycle (100-200 ms)
- Spatial position encoded by temporal relationships between place cell peak activity; distance encoded by theta assemblies
- Spontaneous phase precession of CA3 neurons is place cells "telling story to cortex" => episodic memory in rats



Theta, Gamma and Memory

- Theta increased in encoding, retrieval (iEEG; Kahana et al)
- Gamma-coupling during memory formation and recollection (iEEG)
- Theta-modulated gamma observed





Kahana et al (1999) *Nature* **399**, 781 - 784

Even simple perceptual processing involves brain networks

- An example: auditory change detection using MMN task
- New from my lab (Shannon McLean PhD dissertation)
- Features analyses of intra- and inter-regional synchronization of neural sources inferred from EEG recordings

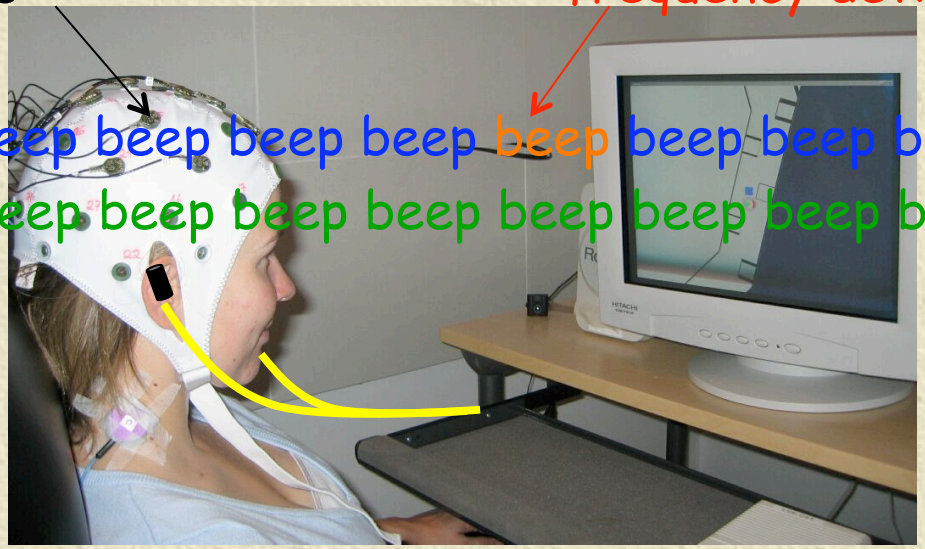
MMN task: watch (subtitled) movie and ignore sounds (Expt 1)

standards

frequency deviants

LE….beep beep beep beep beep beep beep beep beep beep beep beep beep….

RE….beep beep beep beep beep beep beep beep beep beep beep beep beep….



Left Ear

beep 660 Hz

beep 740 Hz

Right Ear

beep 932 Hz

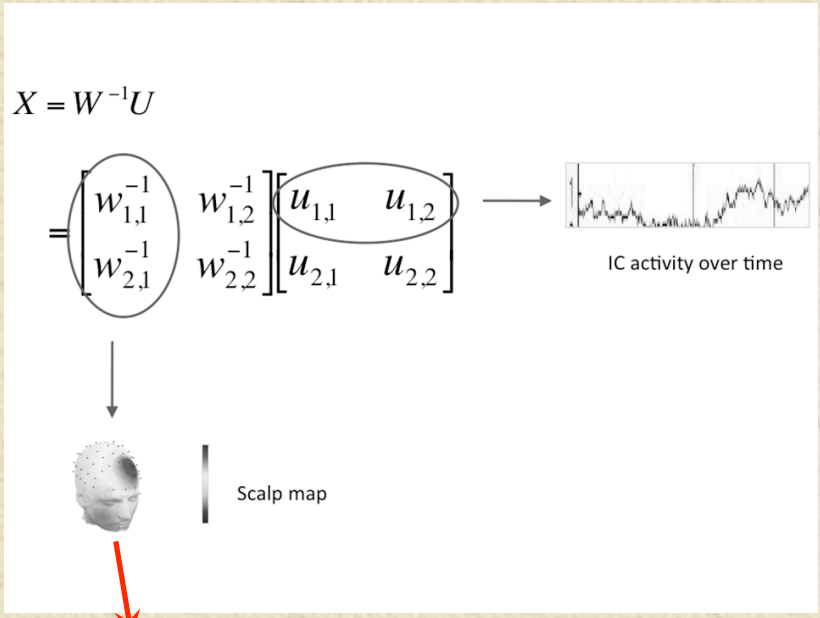
beep 830 Hz

Block 1 as shown; Block 2 ears switched; Block 3 freqs switched

Independent component analysis technique

- Find matrix W that unmixes linear combination of neural sources at scalp
- Project ICs to scalp
- Use scalp topographies to infer single dipole locations of sources represented by various ICs
- Use time series of IC activations to infer local (spectral power) and global synchronization in specific frequency bands via wavelet analysis

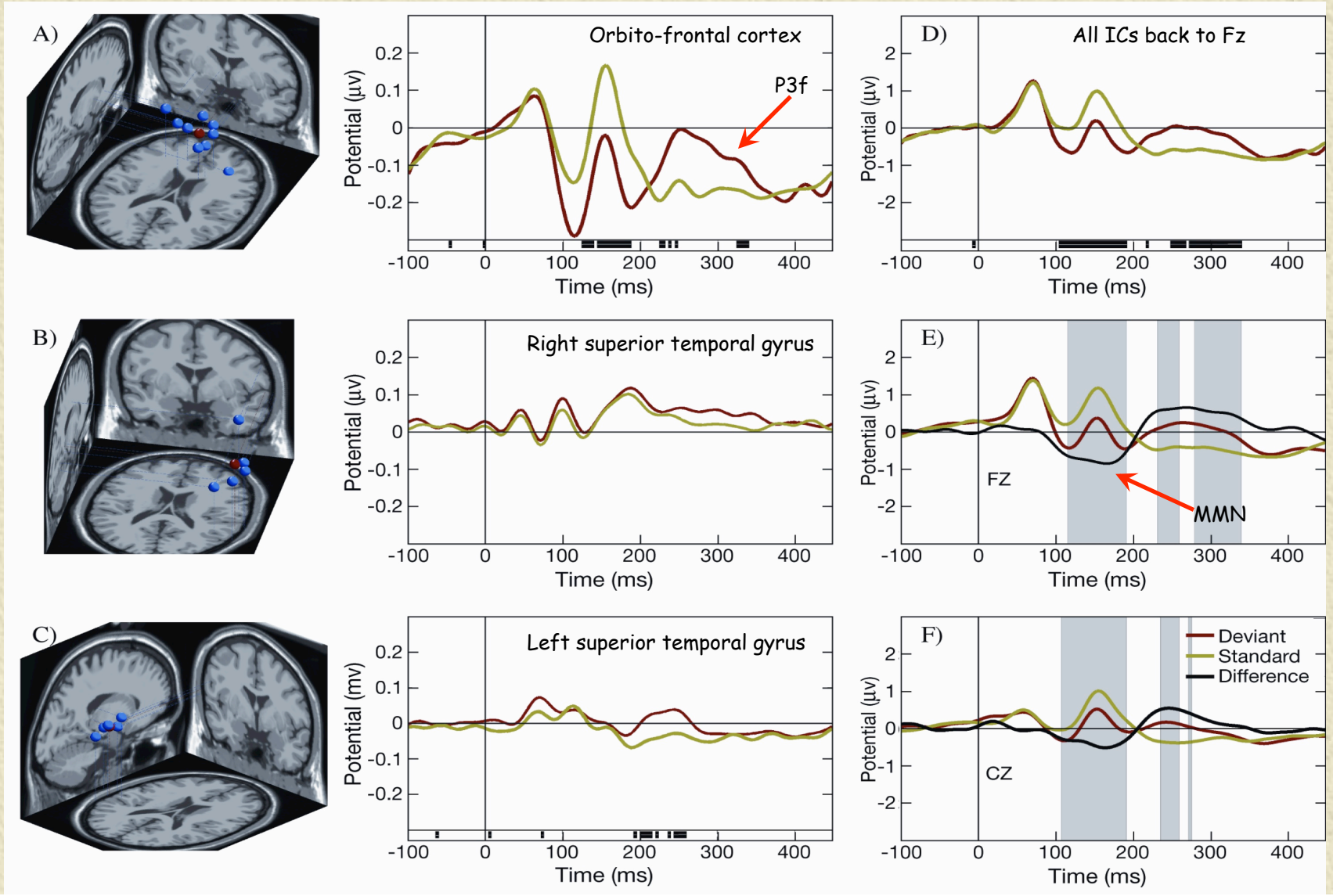
$$U = WX \Rightarrow$$



Dipole fitting using model brain

Basic results: sources and event-related potentials for three of 11 consistent sources involving most subjects

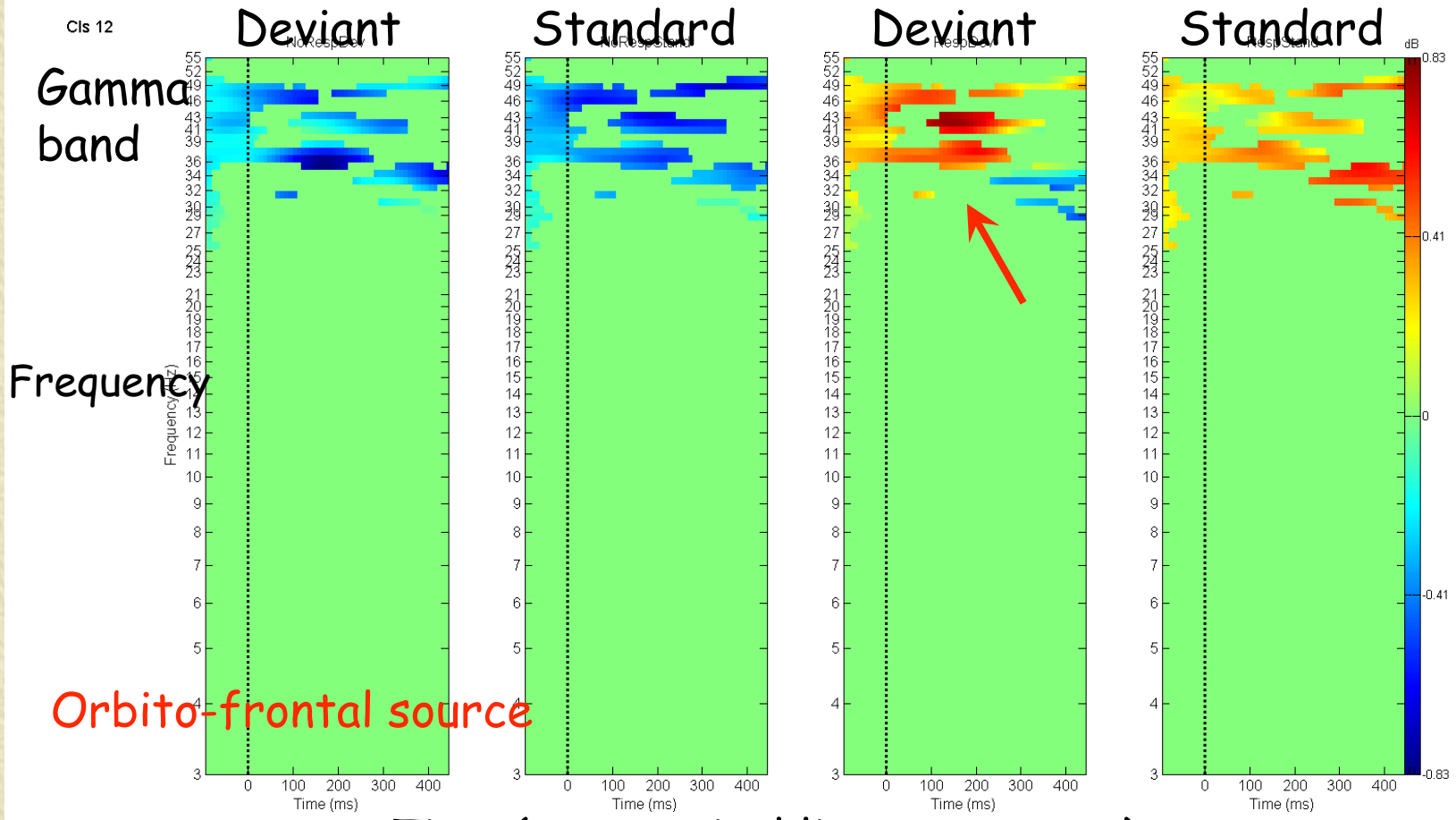
Note: analysis across all blocks so STG sources smeared



Event-related spectral perturbations: oscillation power analysis of Expt 2: ignore sounds or respond to deviant

Ignore sounds

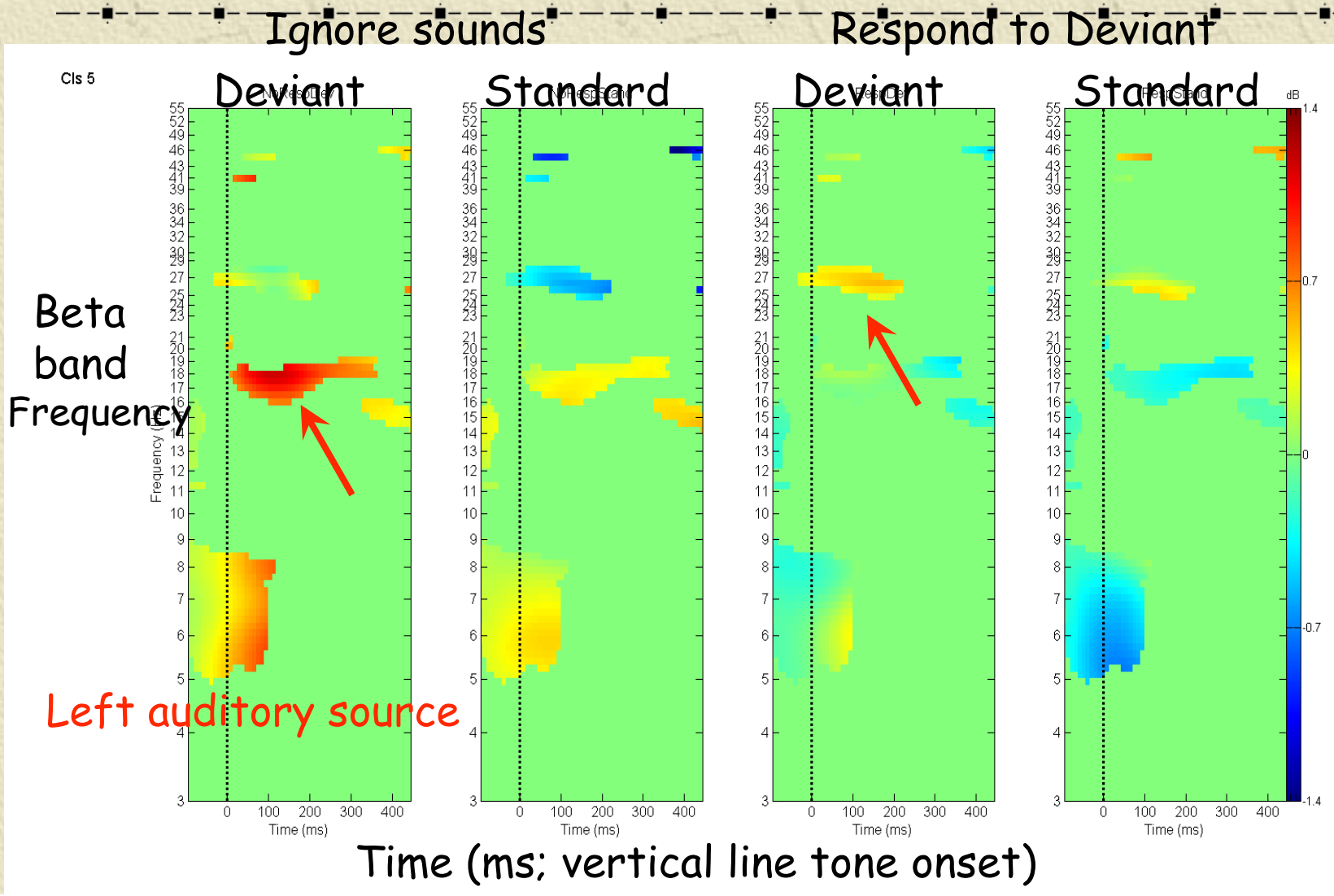
Respond to Deviant



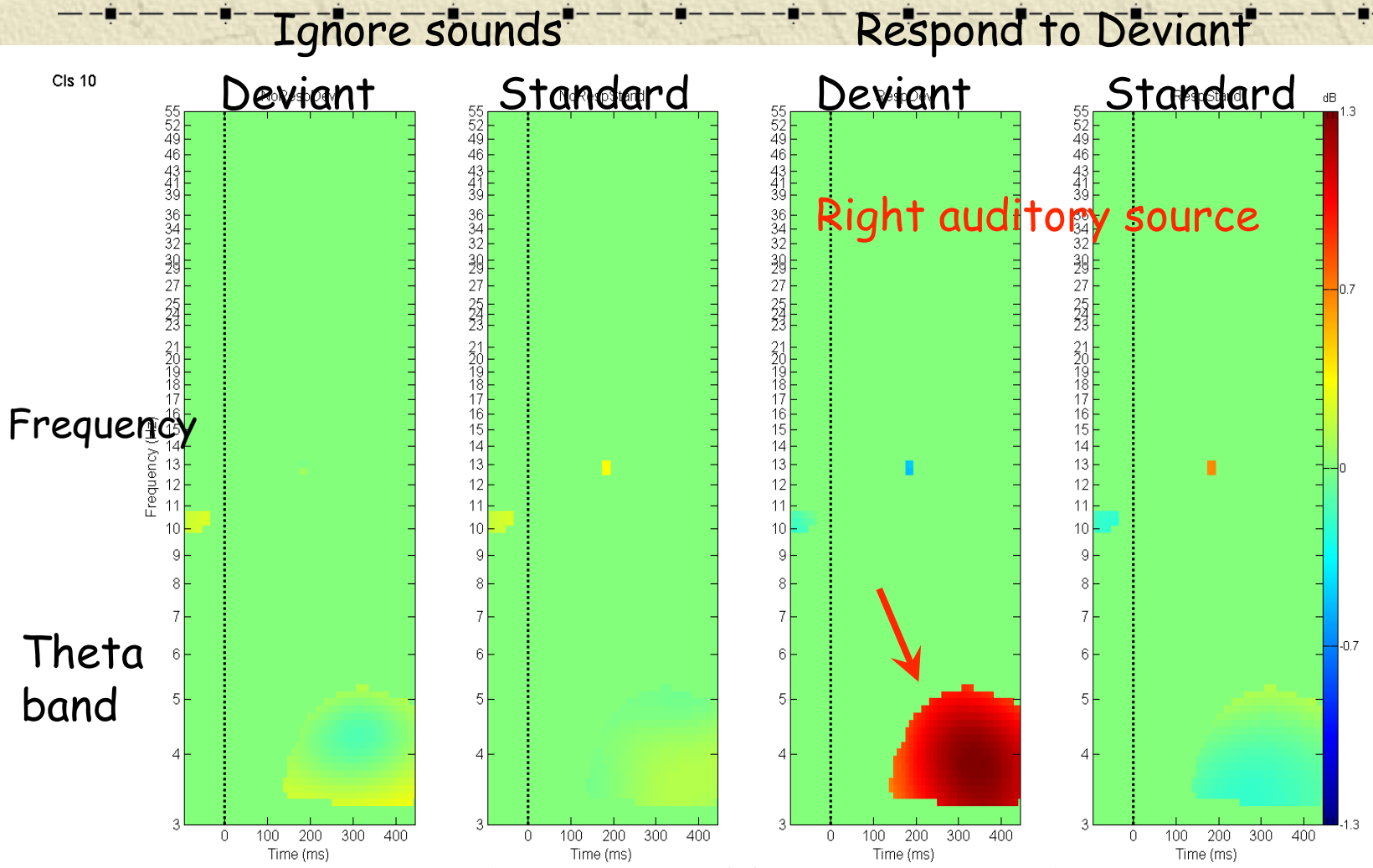
Orbito-frontal source

Time (ms; vertical line tone onset)

Event-related spectral perturbations: oscillation power analysis of Expt 2: ignore sounds or respond to deviant

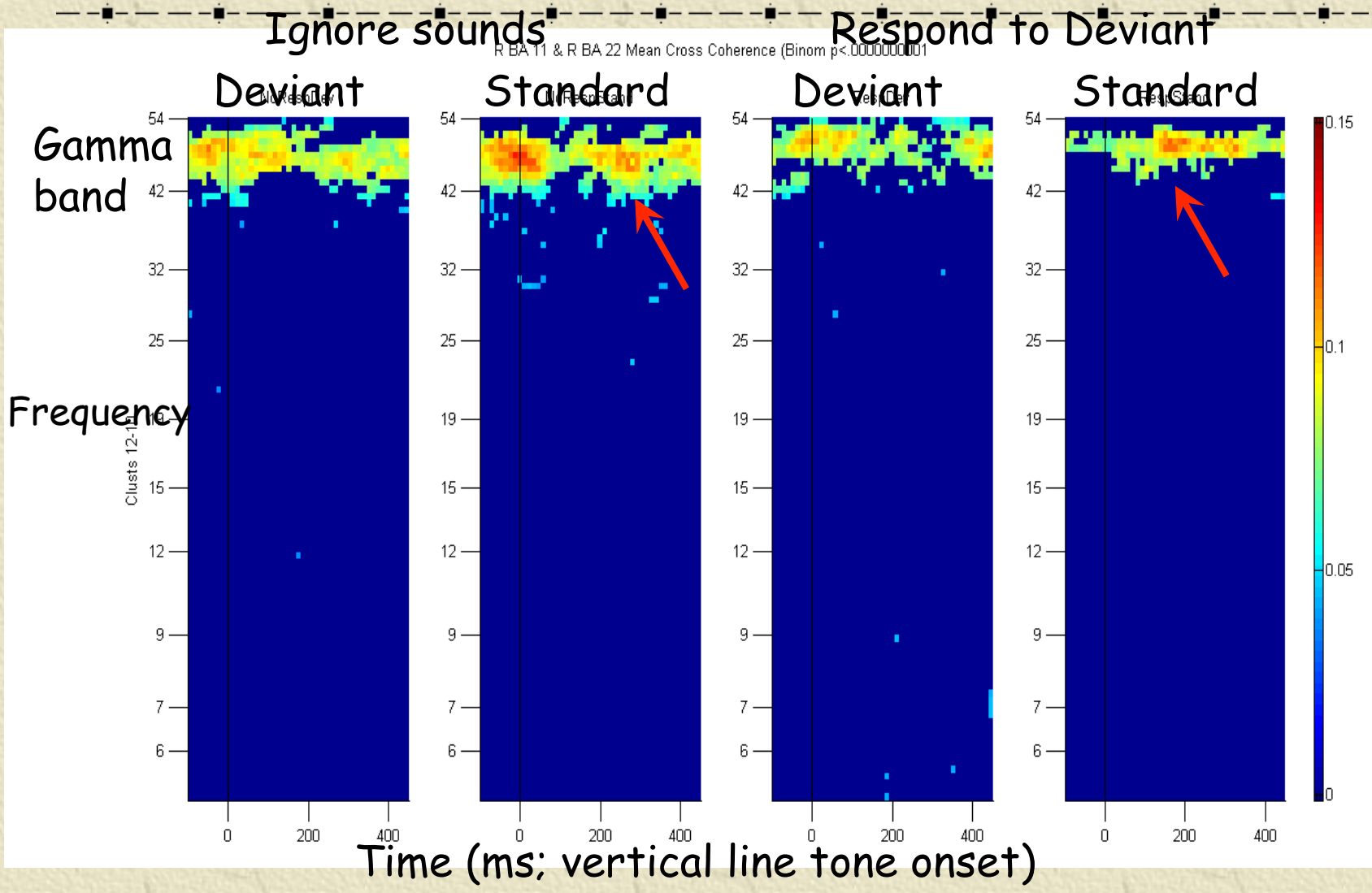


Event-related spectral perturbations: oscillation power analysis of Expt 2: ignore sounds or respond to deviant



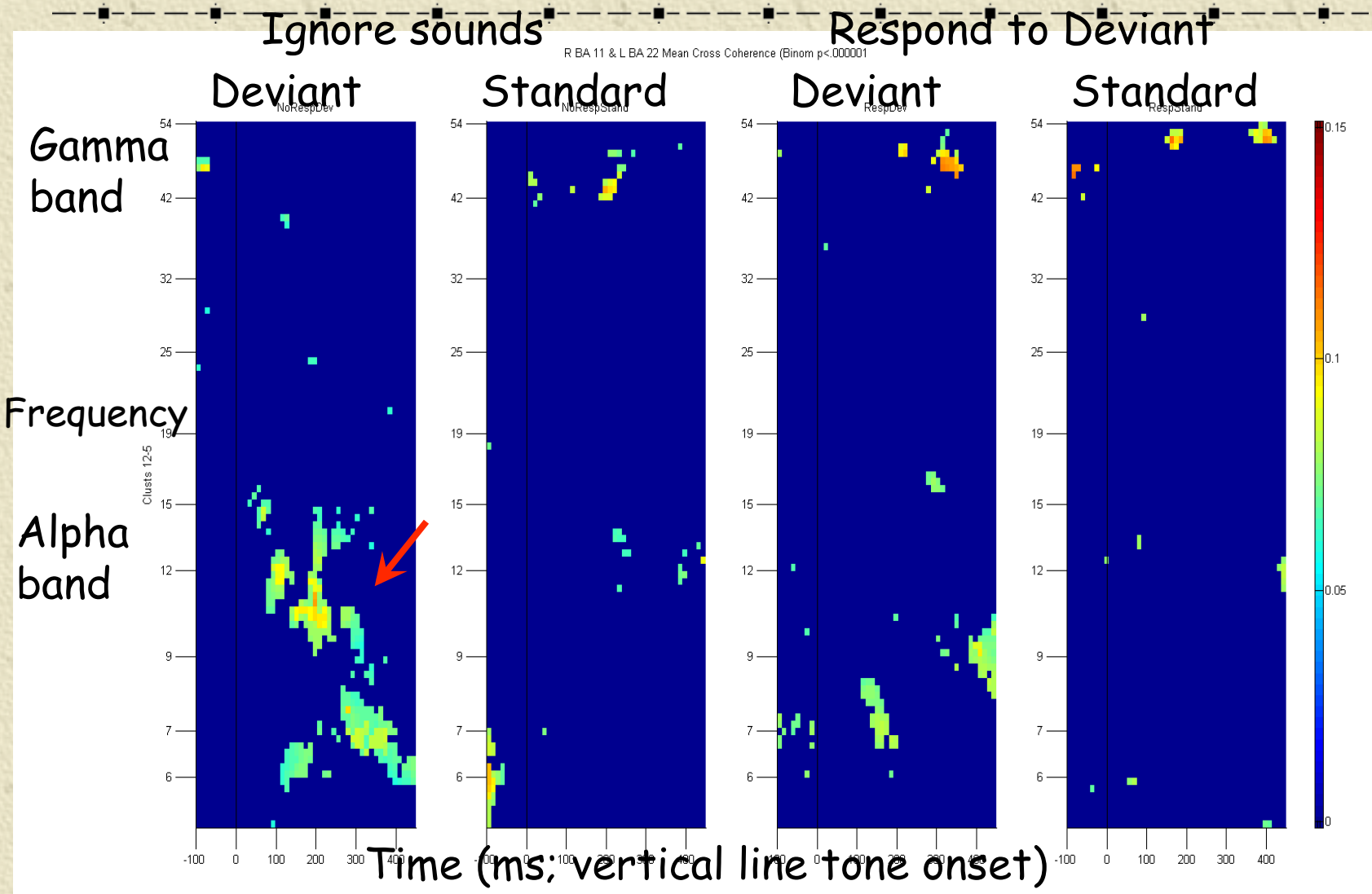
Oscillation phase synchrony analysis of Expt 2: ignore sounds or respond to deviant

Orbito-frontal with left auditory



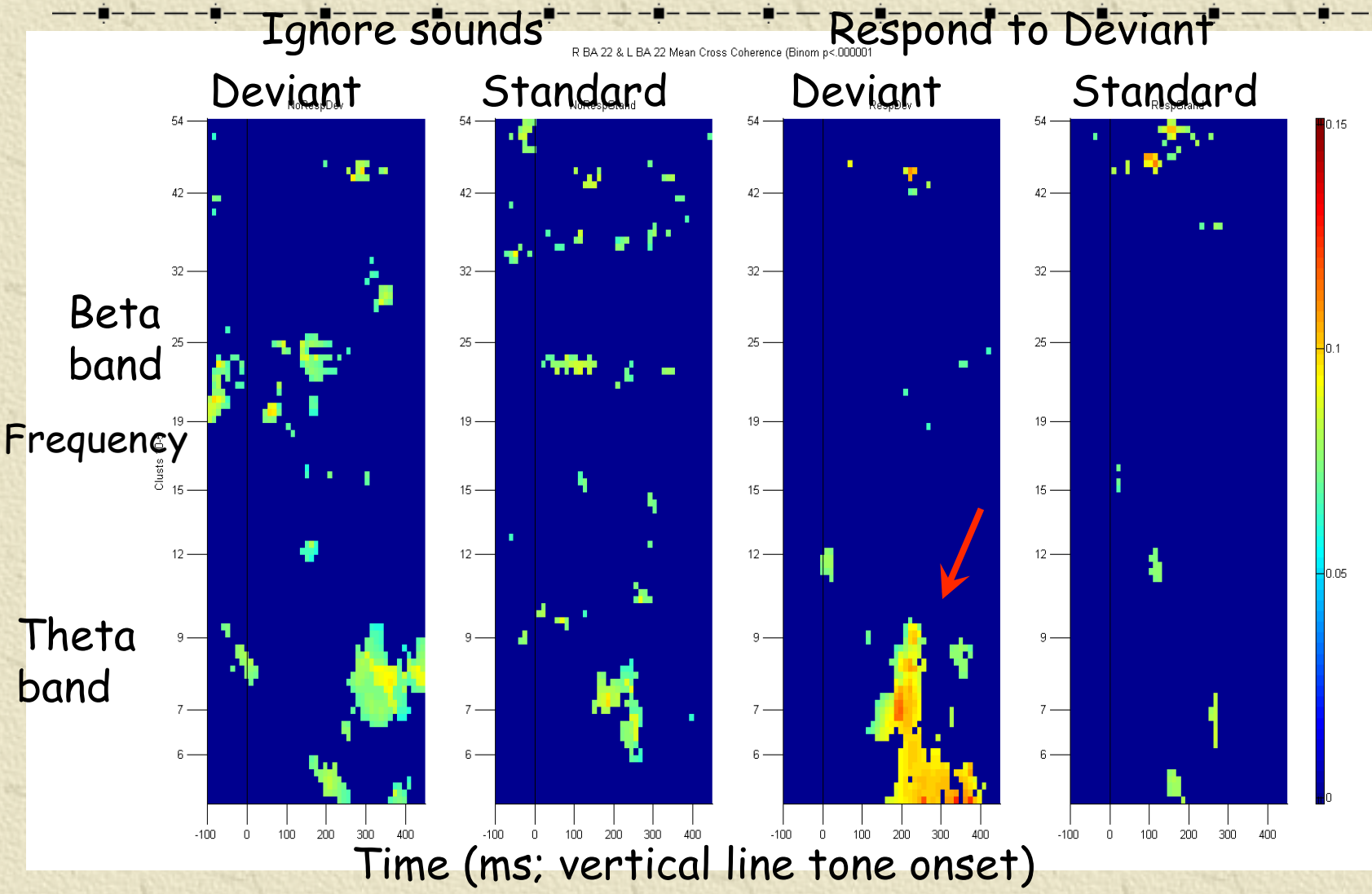
Oscillation phase synchrony analysis of Expt 2: ignore sounds or respond to deviant

Orbito-frontal with right auditory



Oscillation phase synchrony analysis of Expt 2: ignore sounds or respond to deviant

Right auditory with left auditory



Take This Home

- Cognition implemented in brain by transiently changing networks of functionally specialized brain regions
- Hypothesis: oscillatory synchronization serves to create these transient networks
- Can study synchronization within and between brain regions at large scale with EEG
- MMN: even simple unattended perceptual operations involve such synchronization

Phase Synchrony by Lawrence Ward

Phase synchrony they say to me
Is everything
Including even a symphony
and a poem.

Phase synchrony they say to me
Is how my brain
Talks to itself and running free
Makes me aware.

Phase synchrony they say to me
Is not at all
Like the dualist ghost story
Told by Descartes.

Phase synchrony they say to me
Will set us free
So will and won't and ecstacy
We all can see.

To come 11, 18, 25 May

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Neural synchronization and consciousness

4. le mardi 25 mai 2010 à 17 heures:
The role of the thalamus in human consciousness

Table 2. Cluster Properties

Cluster Brain Region	% of Subjects involved	Total ICs	BA	Centroid Talairach x, y, z	Mean RV % of dipole fit	SD	MMN p<.05
R STG	70	20	42	67,-25,7	10.33	3.35	-
L MFG	90	26	9	-50,14,26	11.07	3.07	205-240
L STG	90	15	42	-71,-24,5	10.35	2.80	190-230
L SPL	80	21	5	-16,-40,47	6.71	3.00	-
L MOG	100	20	19	-36,-72,8	9.15	3.25	-
OFG	100	23	11	0,33,-24	10.14	2.92	120-185
L CT	60	9	N/A	-20,-48,-41	11.35	3.47	-
R IFG	70	12	46	52,42,8	11.53	3.57	-
R TPJ	90	20	W/M	27,-59,23	7.96	3.23	120-150
R LG	70	18	18	9,-91,-14	6.92	4.00	-
R MFG	100	24	6	23,02,40	8.05	4.10	-

BA Brodmann Area; **CT** cerebellar tonsil, **IFG** inferior frontal gyrus; **IC** independent component; **L** left; **LG** lingual gyrus; **MFG** middle frontal gyrus; **MMN** mismatch negativity; **MOG** middle occipital gyrus, **N/A** not applicable, **OFG** orbital frontal gyrus; **R** right; **SD** standard deviation, **SPL** superior parietal lobule; **STG** superior temporal gyrus, **TPJ** temporo parietal junction, **W/M** white matter; **p<.05 by permutations.**

- **H1**: inter-regional and intra-regional synchronization play different roles. For example, local alpha power signifies suppression of processing whereas long-distance alpha synchronization might serve to maintain attention at a particular locus.
- **H2**: the role of synchronization depends on oscillation frequency. For example, synchronization of low-frequency (theta and alpha) oscillations might establish transient networks of brain areas that implement cognitive processes, whereas synchronization of high frequency oscillations might serve to communicate information about the results of those processes .
- **H3**: across-frequency modulation of either power or phase locking serves to coordinate information processing and communication of results as well as to facilitate communication. In binocular rivalry, for example, theta phase in each of the active regions modulates gamma amplitude and gamma synchronization between brain regions in a rhythmical way as the conscious percept alternates.

Some suggested functions of neural synchronization

- Greater downstream effect (40 Hz, Singer)
- Avoid spike adaptation (*A*synch at 10 Hz, Fries)
- Sensory binding, integration (40 Hz, Singer)
- Memory encoding, consolidation, retrieval (5 Hz)
- Temporal coordination (polychronization?)
- Temporal coding – MAE coding
- (?) AM coding
- (?) Computation in PDP neural networks; different fixed phases could select different computations – related to MAE coding
- (?) Strong, coherent E-M field

Cf. Buzsáki & Draguhn, *Science*, 2004