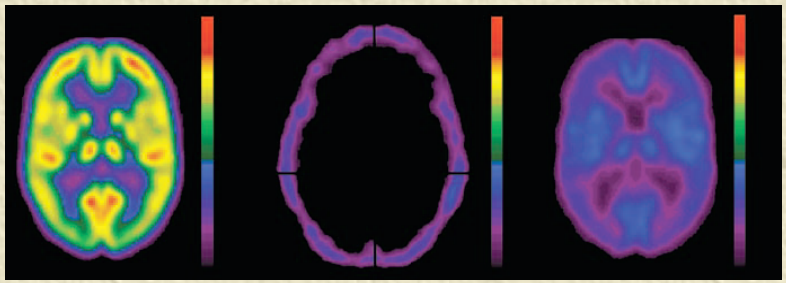

Neural Synchronization and Consciousness

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University of British Columbia

Professeur Etranger Invité, College de France

Funded by NSERC CRSNG

Main points

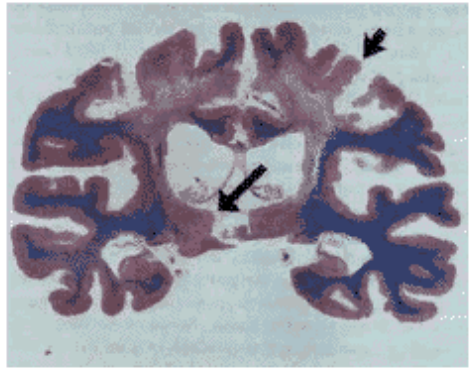
- Synchronized neural network associated with perceptual consciousness
- Network augmented when consciousness changes
- Brain-wide rhythm of neural activity associated with consciousness arises from interaction of theta and gamma frequency brain oscillations.
- Evidence:
  - Previous studies
  - Current analyses of synchronization between oscillations of activity, within and across frequency bands, in various brain loci, inferred from EEG data collected during an experiment in binocular rivalry.

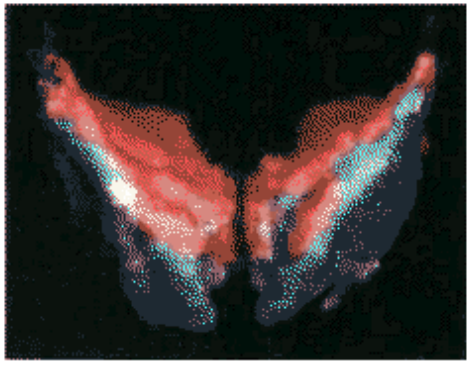
Why study the neuroscience of consciousness?

- Consciousness is a fundamental aspect of human life.
- Understanding its neural correlates (NCC) is important for our knowledge of what it is to be human.
- Vital to understanding and dealing with syndromes like vegetative state, brain death, autism, and so forth.
- Will demystifying consciousness "ruin" it?

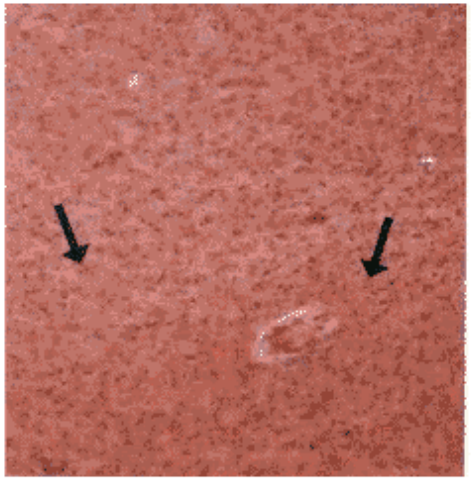
Karen Ann Quinlan – one face of vegetative state

Karen Ann Quinlan's Brain at Autopsy (see Kinney et al 1994)





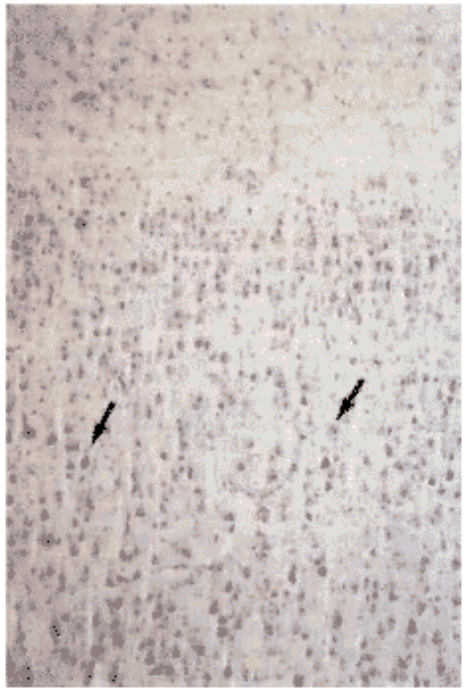
A



B

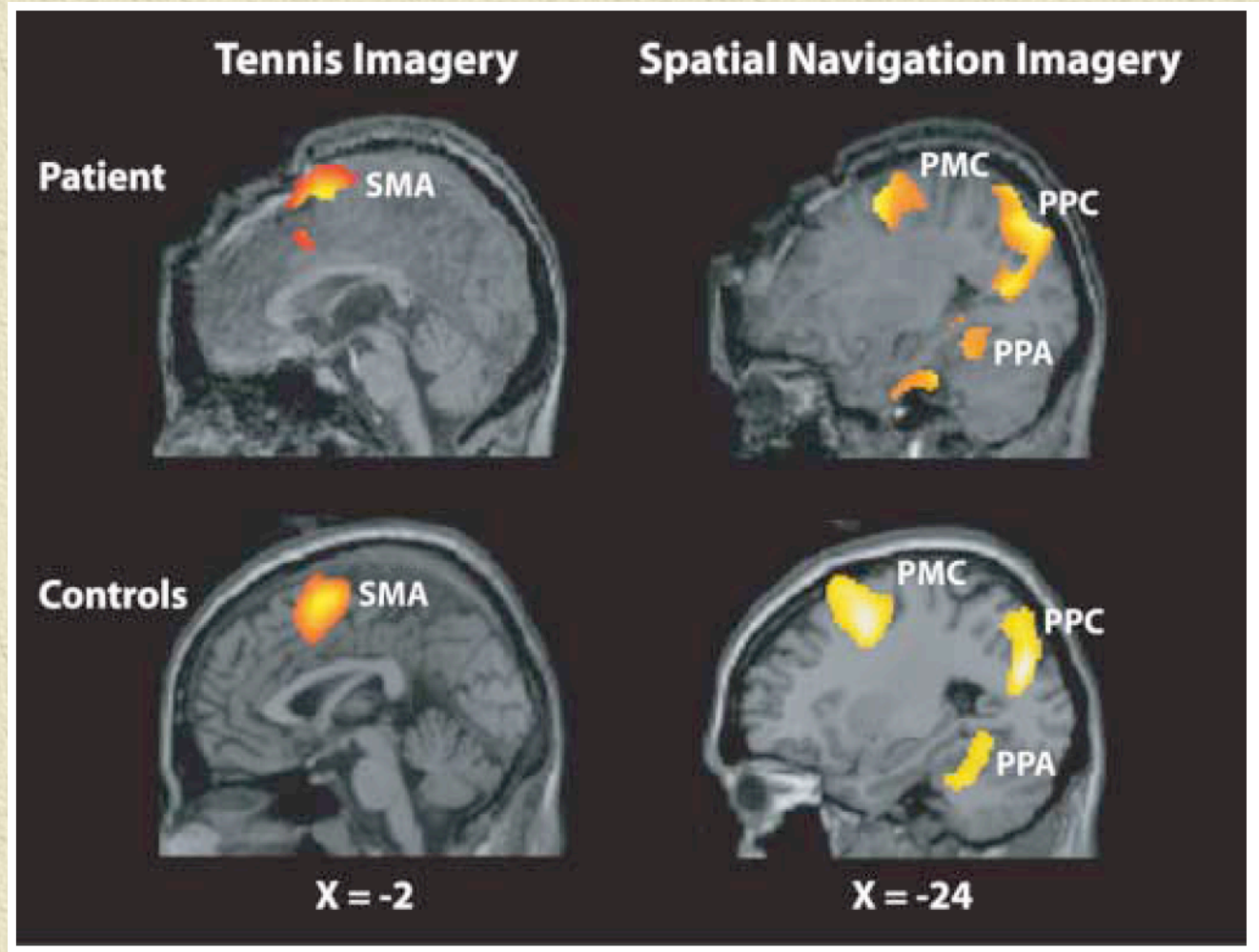
Thalamus-massive loss

Drug/alcohol reaction; permanent vegetative state for 14 years



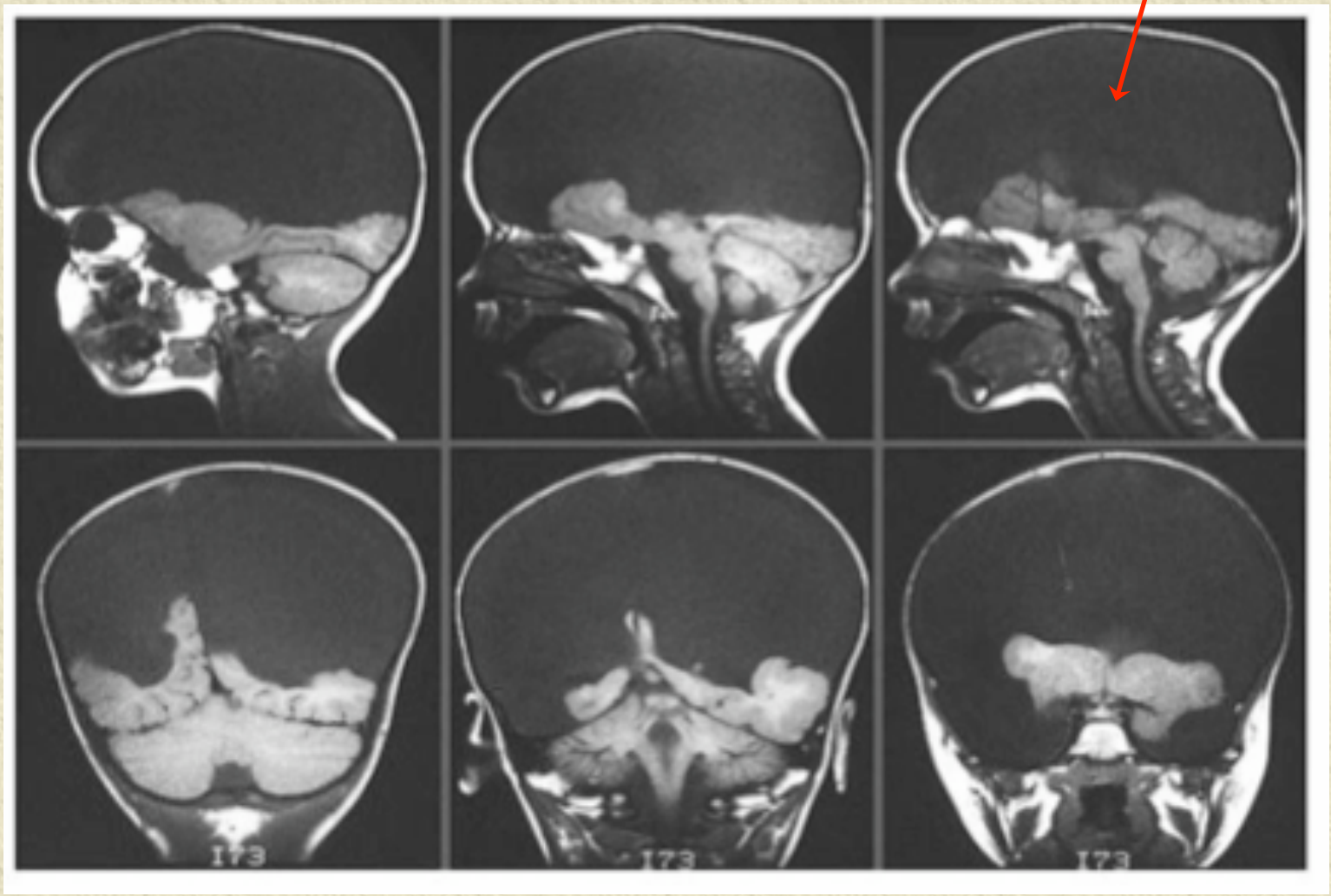
Cortex-little loss

She is vegetative. Is she conscious? fMRI reveals "normal" activity – she could be locked in



Owen et al, 8 Sept 2006, *Science*

Massive cortical deficiency (hydranencephaly)



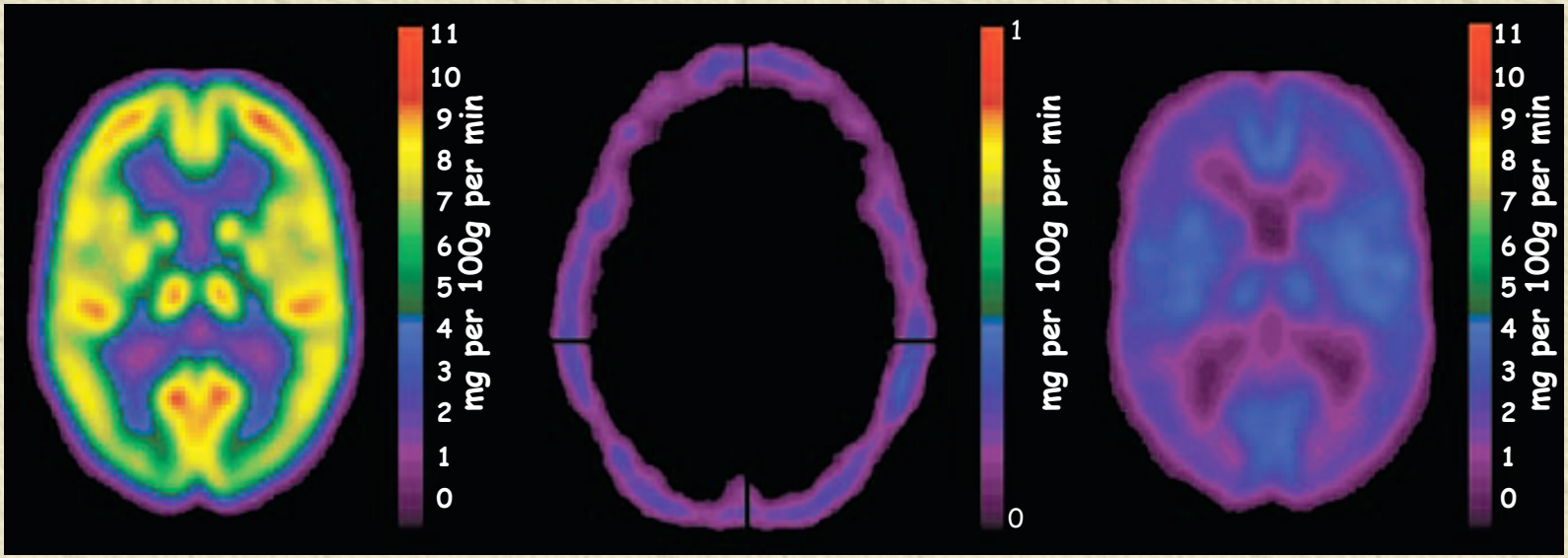
Conscious? (one study says yes)

Merker, BBS, 2006

Conscious?

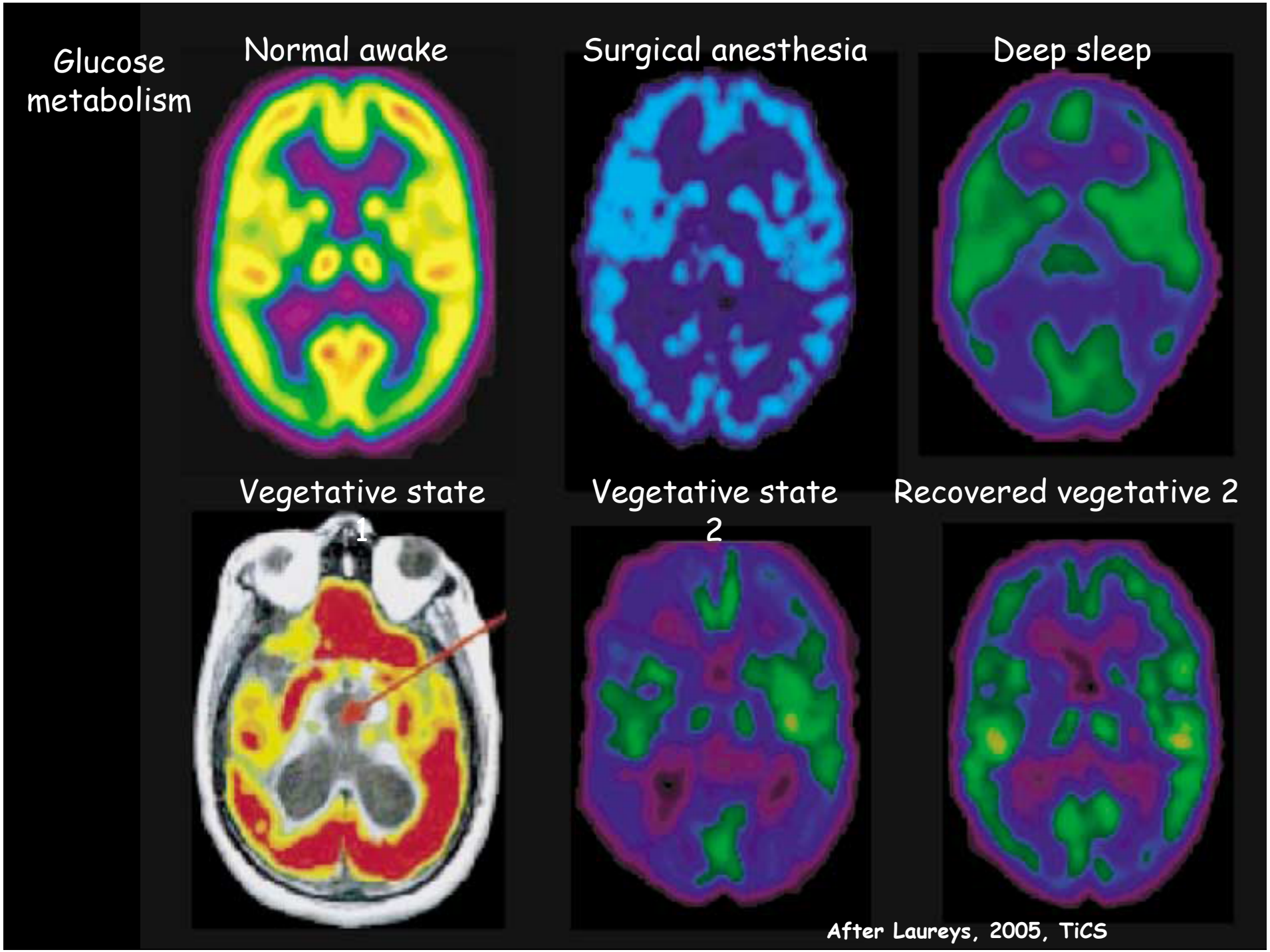
Brain death is "easy," vegetative state is difficult

Healthy control **Brain death** **Vegetative state**



Glucose metabolism

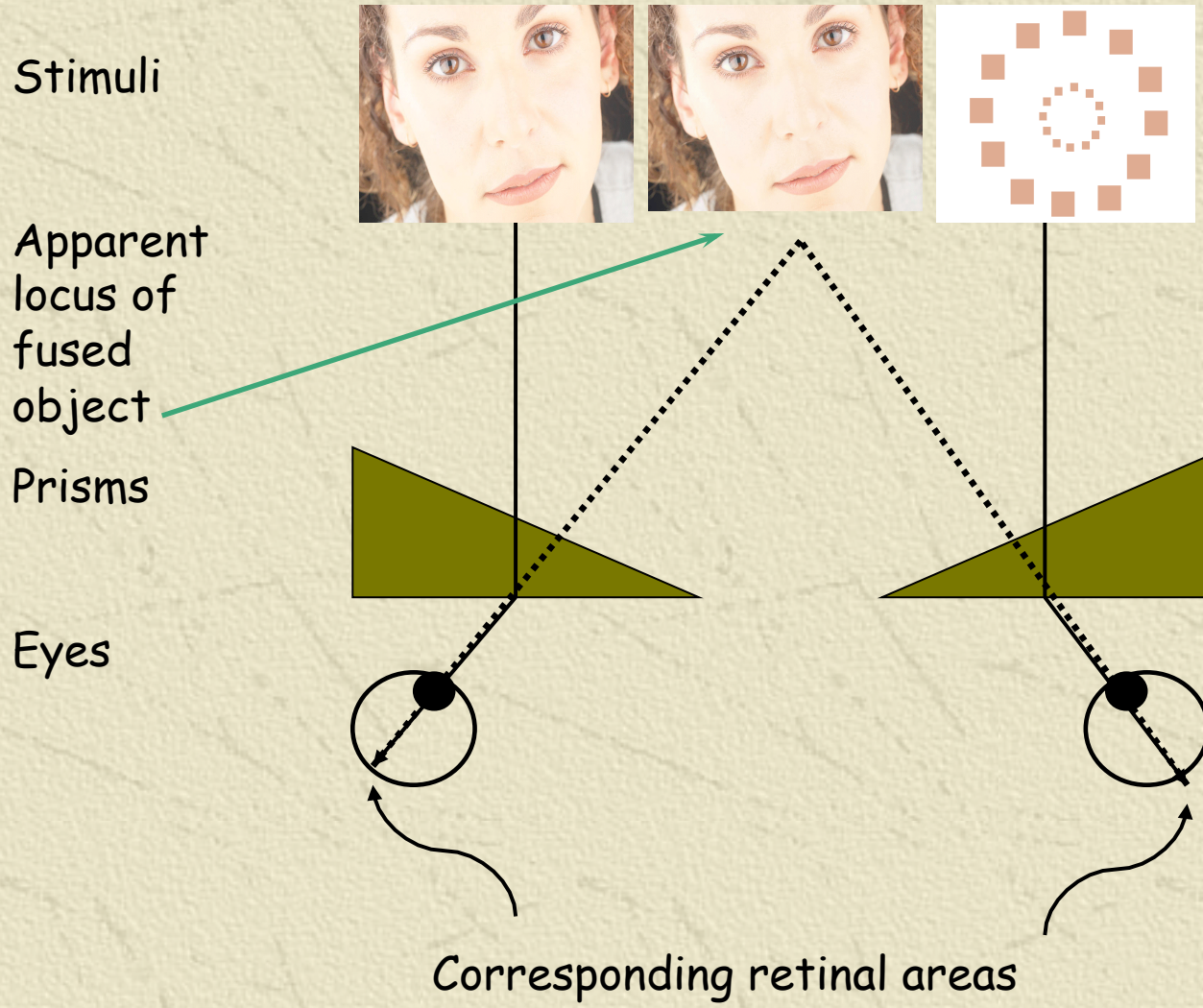
From Laureys, 2005, Nat Rev: Neuroscience


Glucose metabolism
Normal awake
Surgical anesthesia
Deep sleep
Vegetative state 1
Vegetative state 2
Recovered vegetative 2
After Laureys, 2005, TiCS

But, we need to know more……

- PET/metabolism useful in confirming brain death (need other tests too)
- fMRI is helping (recent news stories) but activation not sufficient – consciousness likely depends on networks of active areas communicating (Changeux/Deheane?)
- So….

Binocular rivalry: a window to the neural correlates of consciousness



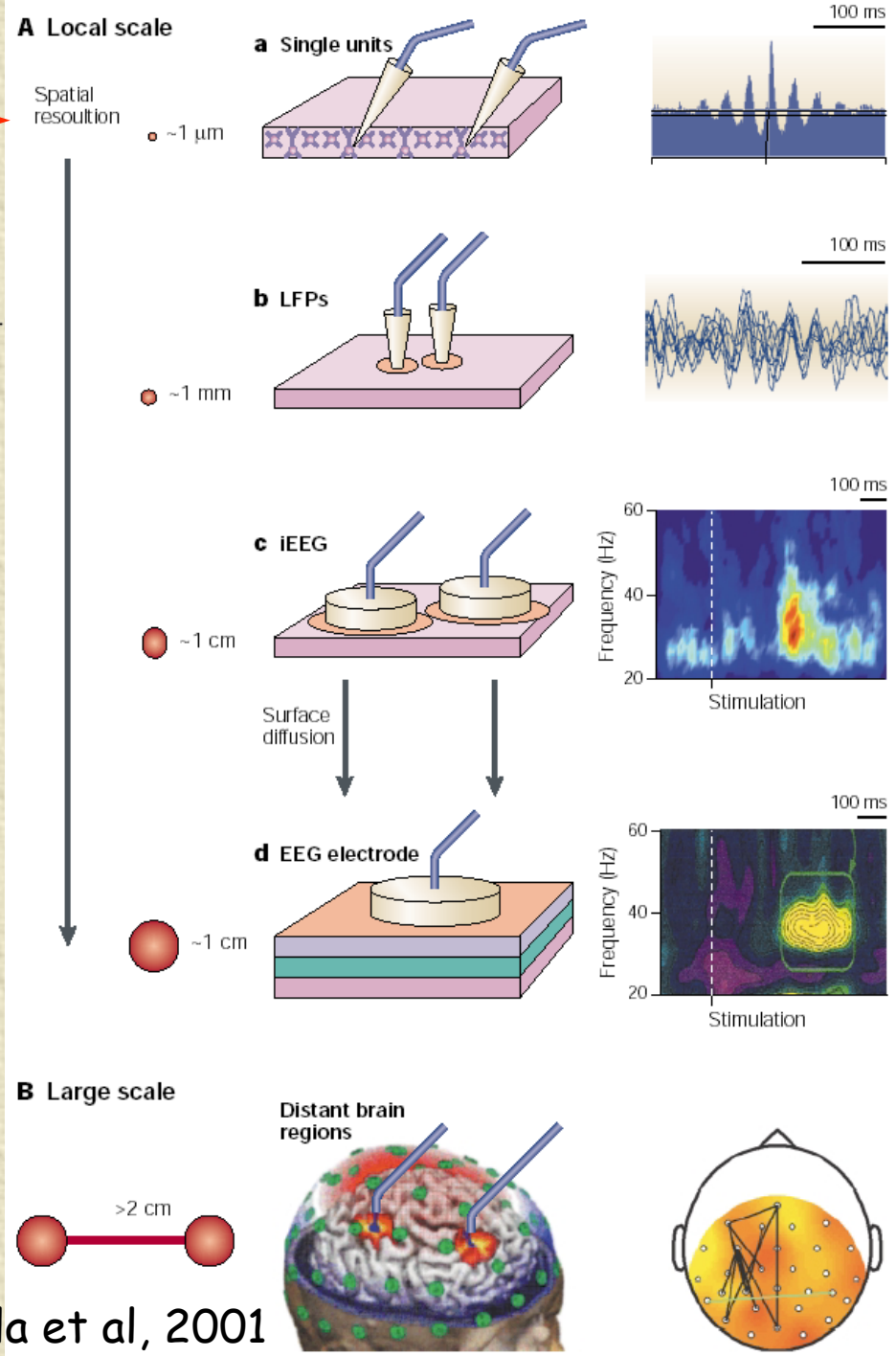
Constant stimulation, *involuntarily* alternating experience

Rivaling images from Cosmelli et al, (2004) NeuroImage

Gray & Singer's cats

Neural synchrony occurs when neural activity, spiking or dendritic currents, in disparate locations, rise(s) and fall(s) in a fixed relationship

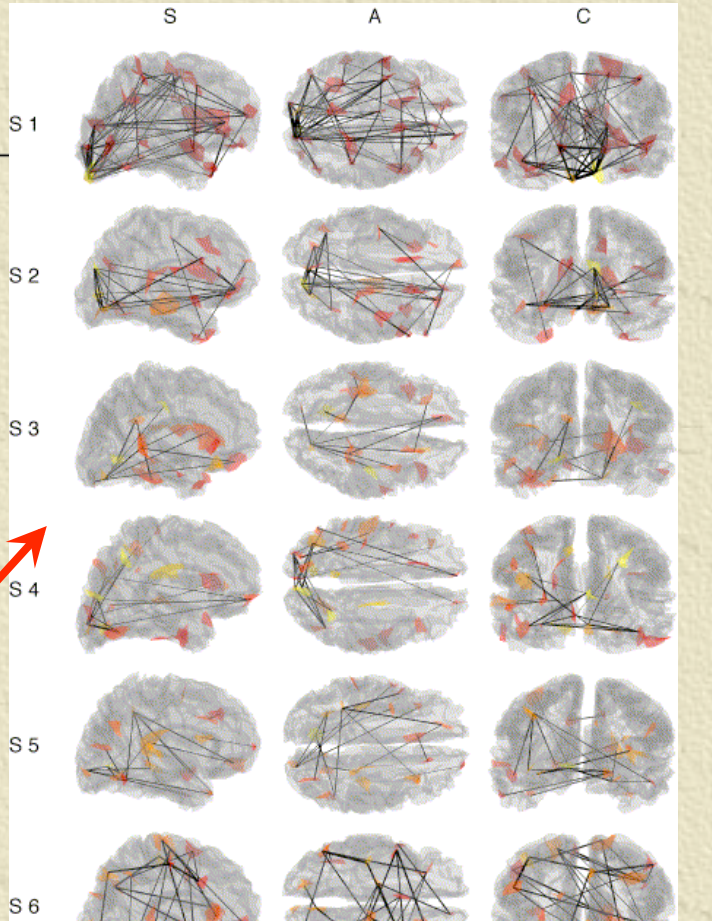
Ward etal's humans

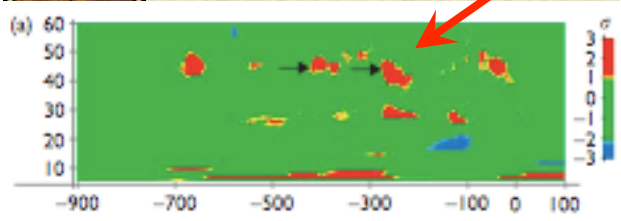


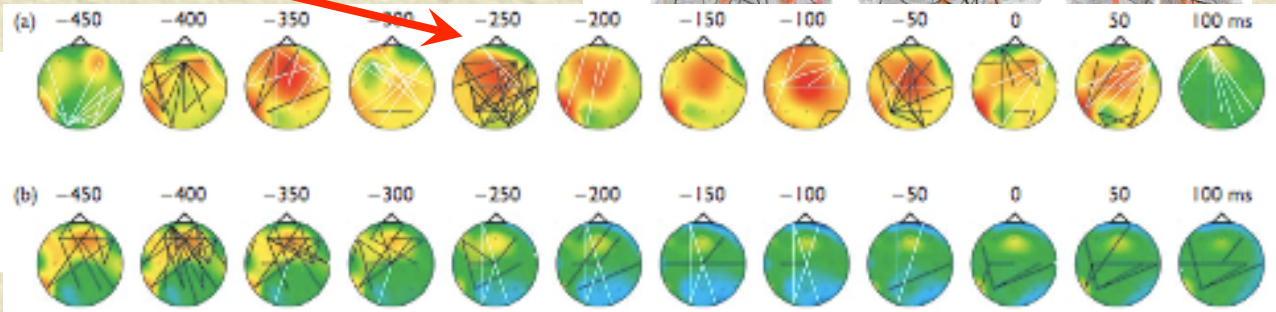
Varela et al, 2001

Neural synchrony and binocular rivalry (BR)

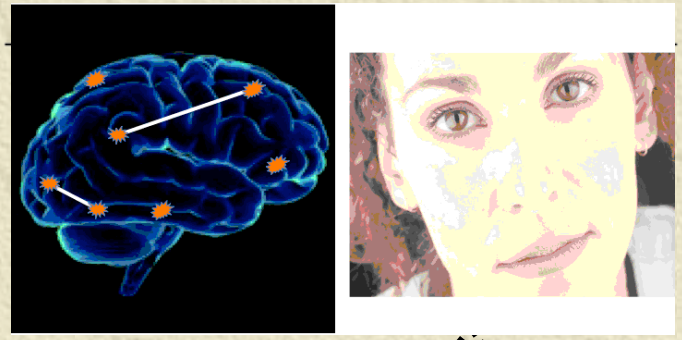
- Logothetis & Schall, 1989: single neuron activity in monkey STS specific to seen image during BR
- Fries et al 1997: demonstrated increased gamma-band (30-50 Hz) neural synchrony for seen vs suppressed drifting grating in cat early visual cortex
- Tononi, Edelman et al 1997-1998: more scalp-wide MEG-sensor coherence at driven frequency of seen grating in humans
- Cosmelli et al 2004: 5 Hz synchrony between diverse areas when 5 Hz driving stimulus seen by humans
- Doesburg Kitajo & Ward 2005: endogenous gamma-band synchrony between diverse electrodes at change in awareness in humans

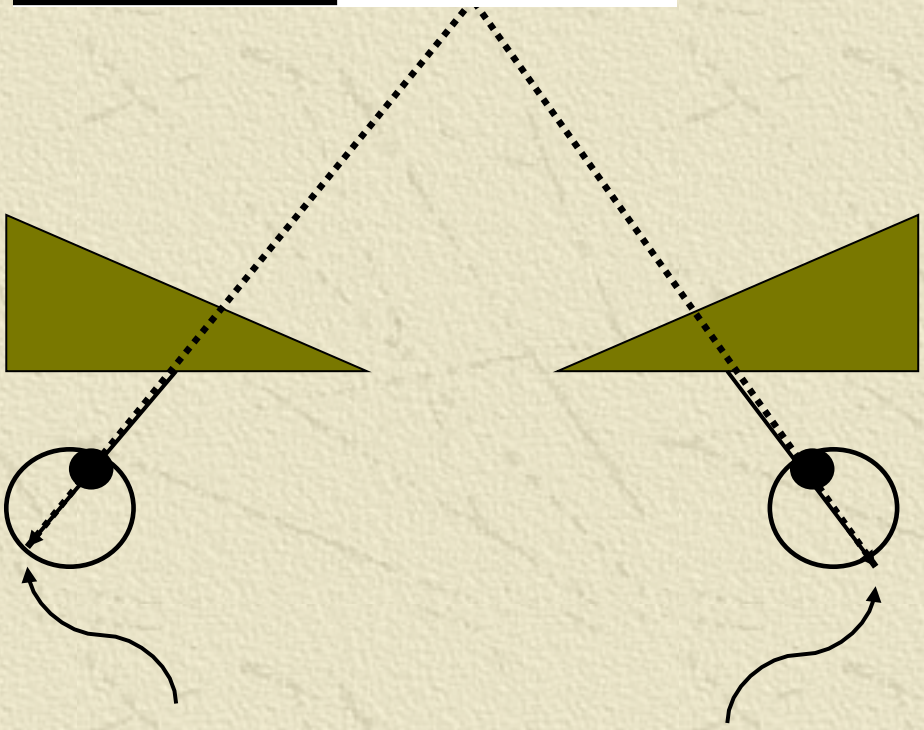






Binocular rivalry: a window to the neural correlates of consciousness





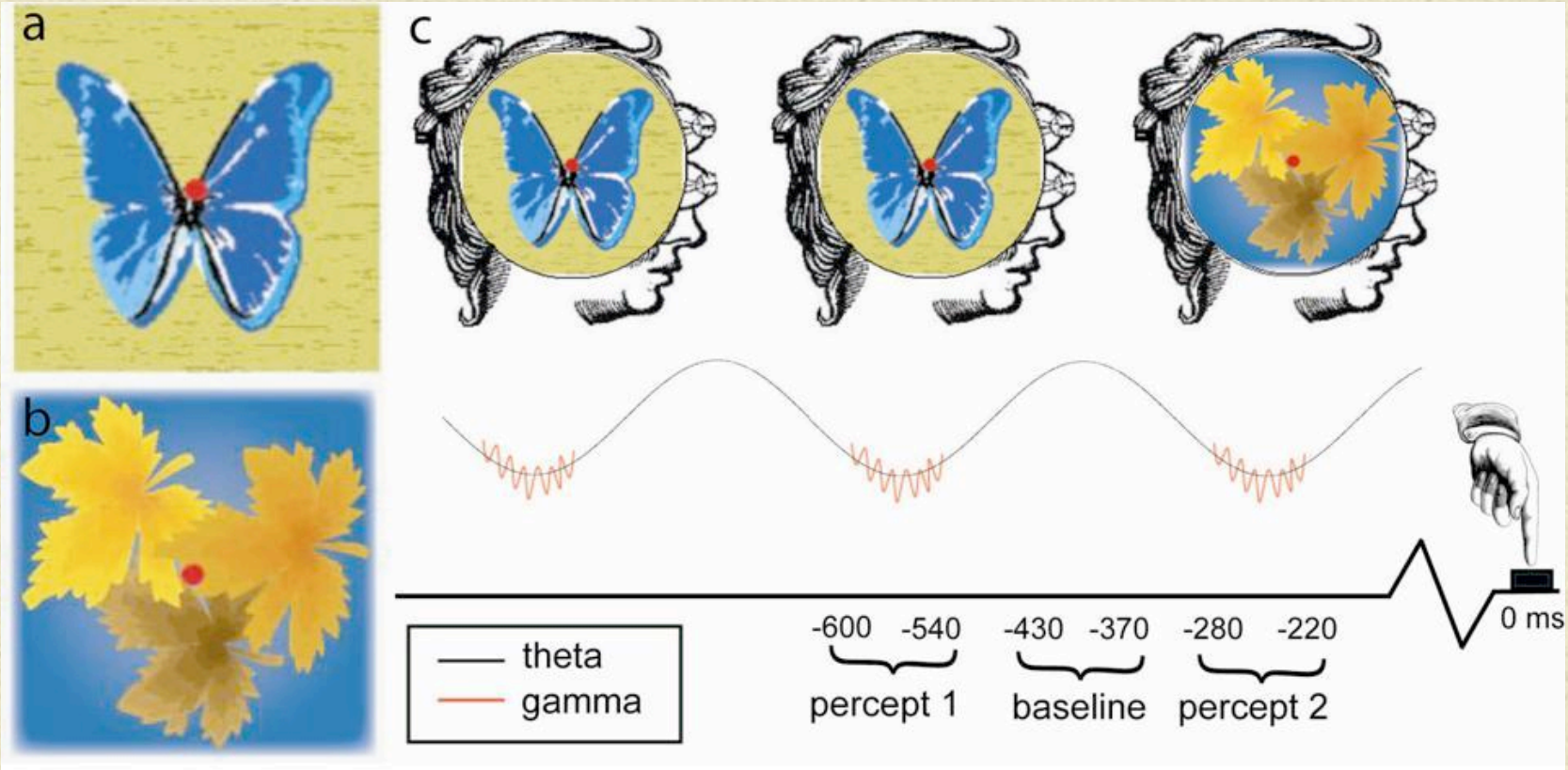
Constant stimulation, *involuntarily* alternating experience

Rivaling images from Cosmelli et al, (2004) NeuroImage

BR experiment: Rhythms of consciousness

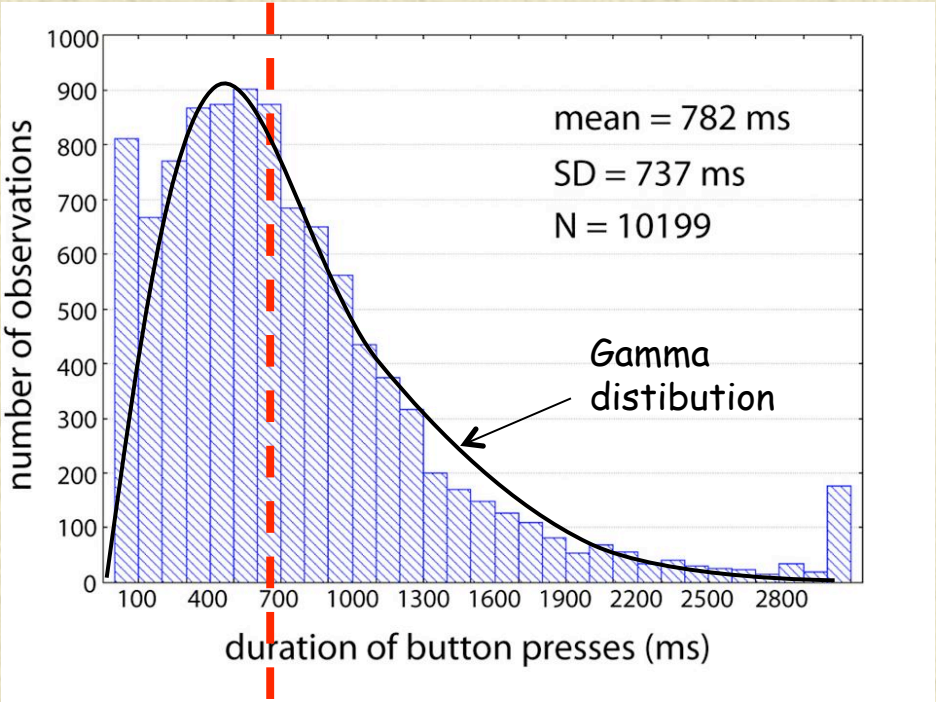
(Doesburg, Green, McDonald & Ward, *PLoS One*, 2009)

- 64-channel EEG recorded at 500 Hz while 9 subjects viewed rivaling stimuli in 4-min blocks
- Subjects ran for 2-6 hours depending on rivalry patterns
- Subjects pressed indicated button for butterfly or for maple leaves with fingers of right hand when *only* that image seen; neither button for fragmented or blended image



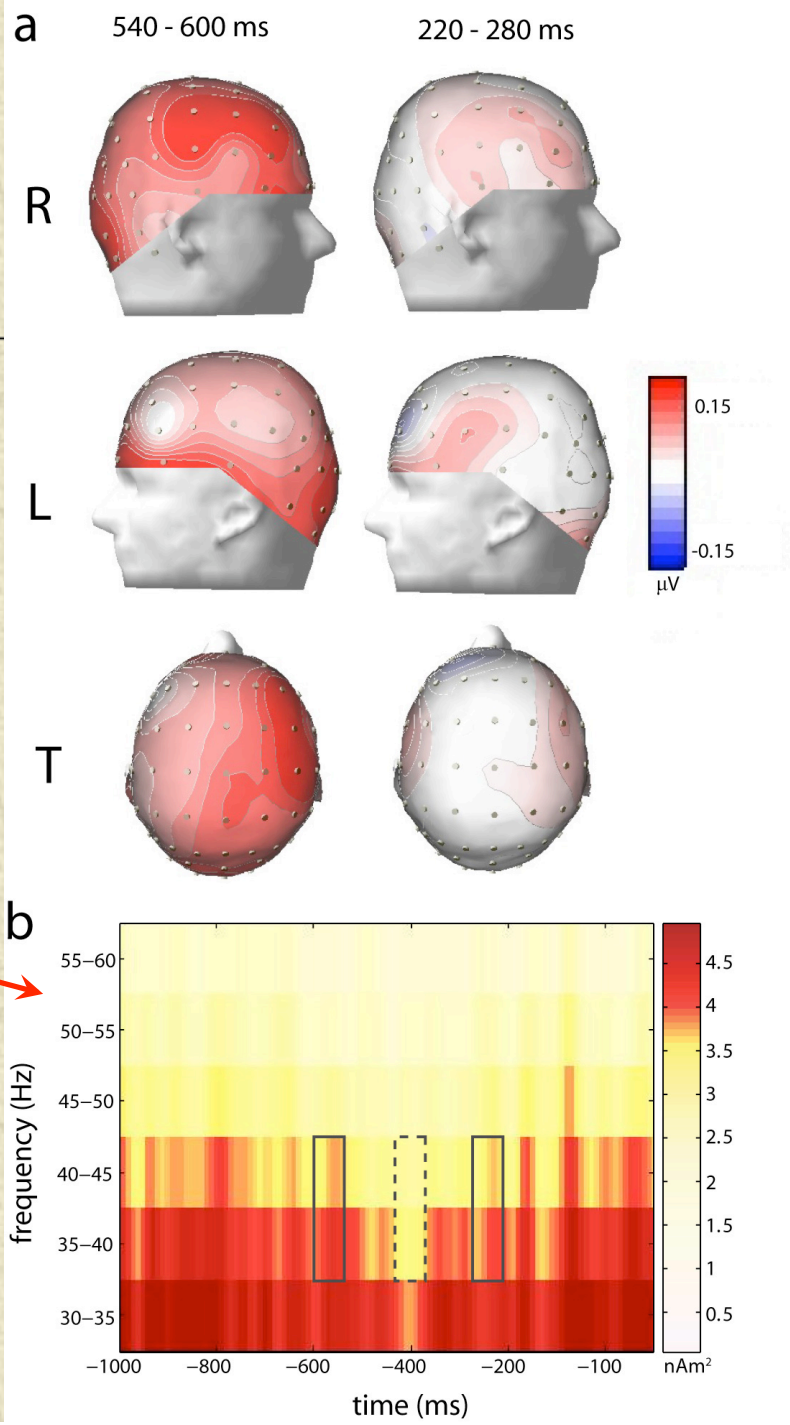
Behavioral rivalry data

- Analyzed only artifact-free epochs where stable percept followed button press for 700 ms or more
- 3281 such epochs (1805 left eye; 1476 right eye)



Gamma band activity (35-45 Hz)

- Gamma-band activity at scalp fronto-central; more prominent on right side
- Analyzed time windows indicated by solid rectangles relative to that indicated by dashed line (baseline)
- Windows chosen based on previous work, esp. -220-280 ms re Doesburg et al, 2005, and gamma-power relationships.

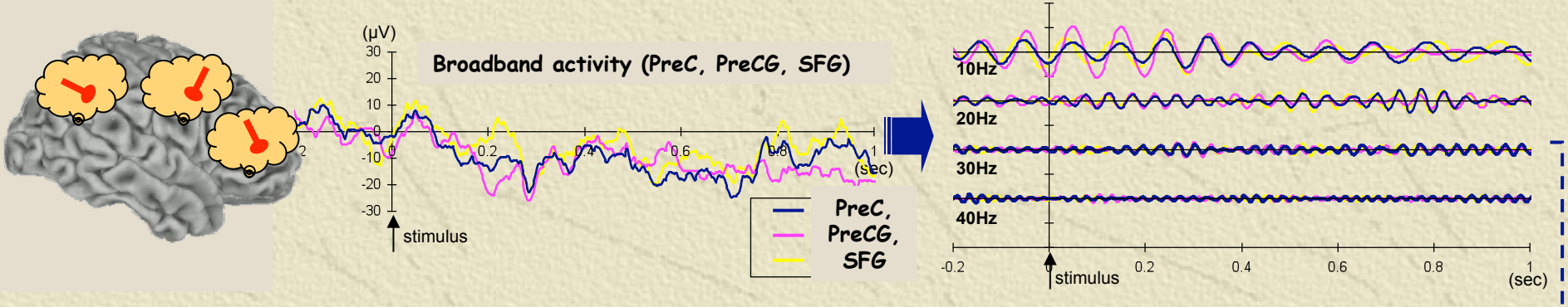


BESA Beamformer-> dipole source montage->analytic signal for instantaneous phase and amplitude

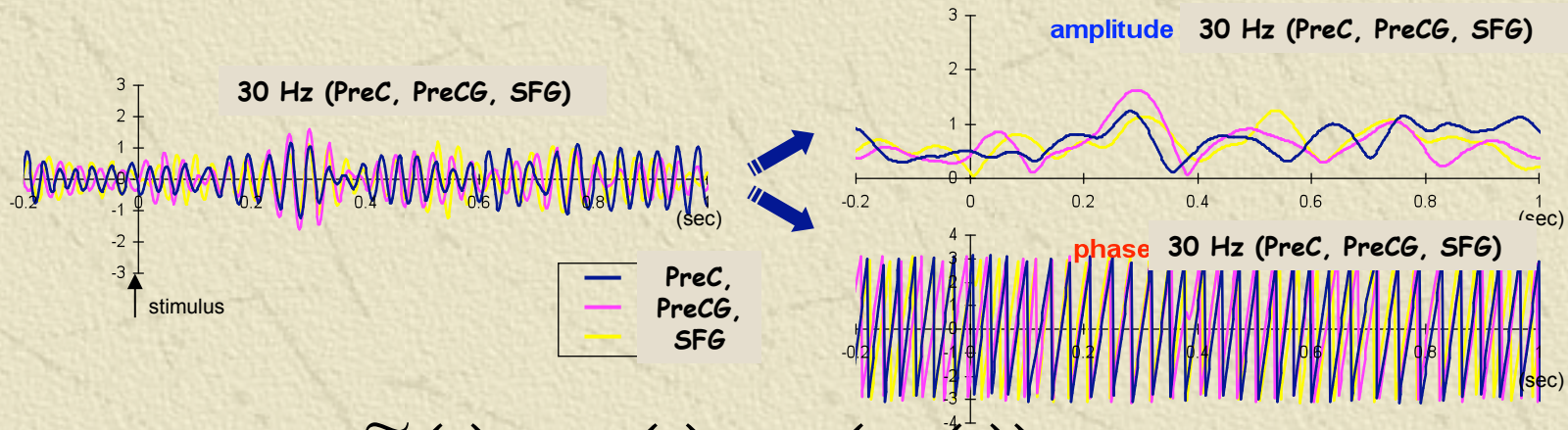
- BESA beamformer: spatial filter voxel-wise using BESA MRI average brain
- Seeded dipoles at peak voxel of each significant region and computed broadband signals for this source montage (BESA)
- Filtered dipole activations into into narrow bands at 1 Hz intervals 1-60 Hz; bandwidth = $f \pm 0.05f$
- Computed analytic signal via Hilbert transform epoch-wise (1600 ms epochs; discarded 300 ms at each end) at each center frequency
- Computed normalized phase locking value (re baseline) from instantaneous phase
- Used normalized amplitude and un-normalized phase for other analyses

EEG synchronization analysis: calculation of phase locking value (PLV)

Step.1 Obtain filtered signals *f(t)* via bandpass filtering at chosen frequencies



Step.2 instantaneous phase and amplitude

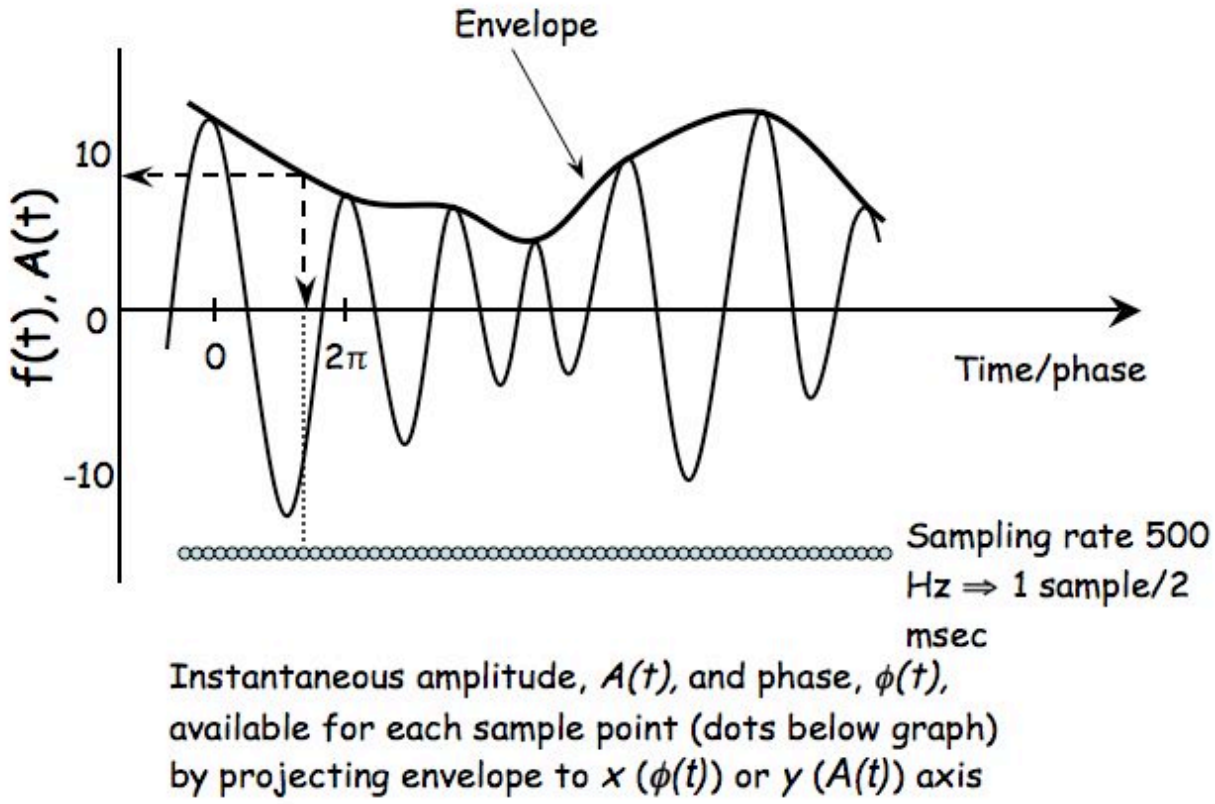


$$\zeta(t) = f(t) + i\tilde{f}(t) = \underline{A(t)}\exp(i\underline{\phi(t)})$$

amplitude phase

where $\tilde{f}(t)$ *is Hilbert transform of* $f(t)$, $\tilde{f}(t) = \pi^{-1} P.V. \int_{-\infty}^{\infty} \frac{f(\tau)}{t-\tau} d\tau$

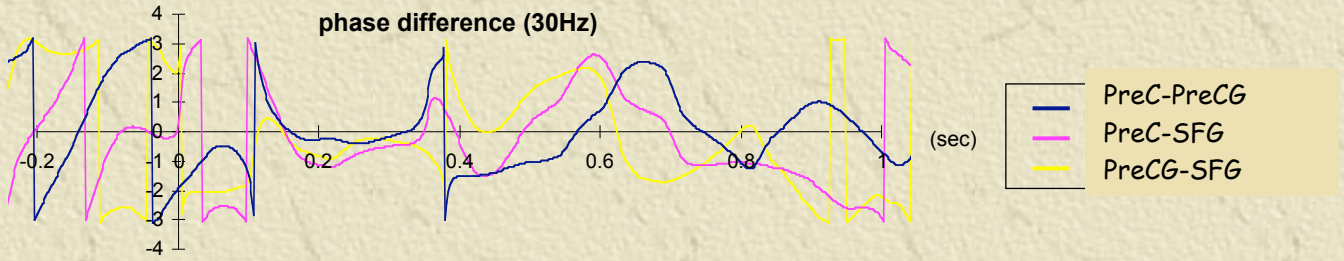
Analytic signal via Hilbert transform



Instantaneous amplitude, *A(t)*, and phase, $\phi(t)$, available for each sample point (dots below graph) by projecting envelope to *x* ($\phi(t)$) or *y* (*A(t)*) axis

Ward & Doesburg, 2009, in Handy (Ed) *Brain Signal Analysis*

Step.3 Calculation of phase locking value (PLV) for each time point



$$PLV(t)_{1,2} = \frac{1}{N}\left|\sum_{n=1}^{N} e^{i\theta(t,n)}\right| \quad \Rightarrow \begin{cases} \text{complete synchronization:1} \\ \text{random phase difference:0} \end{cases}$$

where

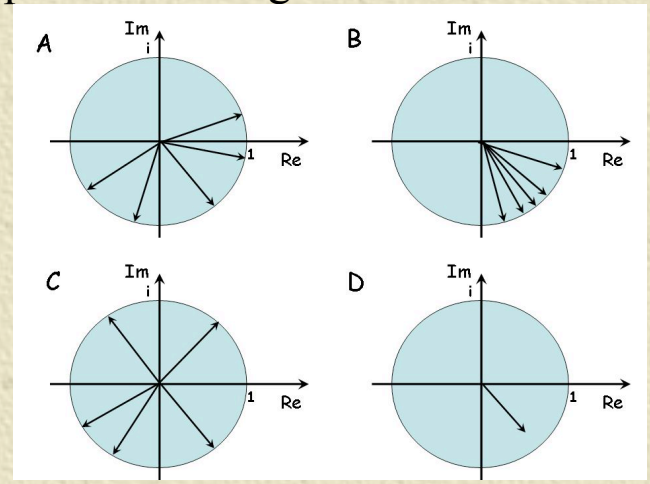
$\theta(t,n) = \phi_1(t,n) - \phi_2(t,n)$ (phase difference)

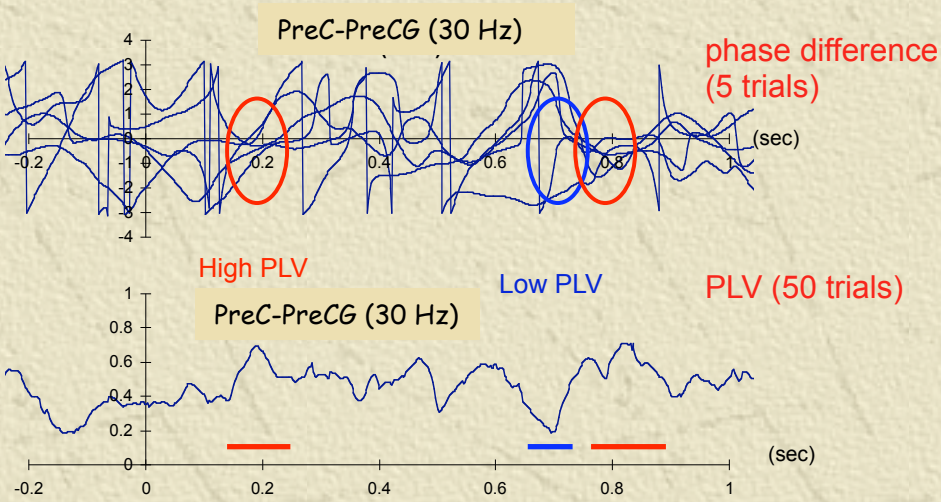
N : the number of trials

t : time points

ϕ_1 : the phase of the signal from electrode 1

ϕ_2 : the phase of the signal from electrode 2





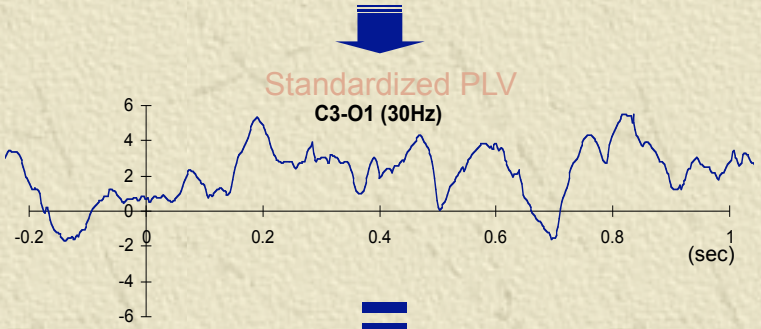
Step.4 standardization of PLV

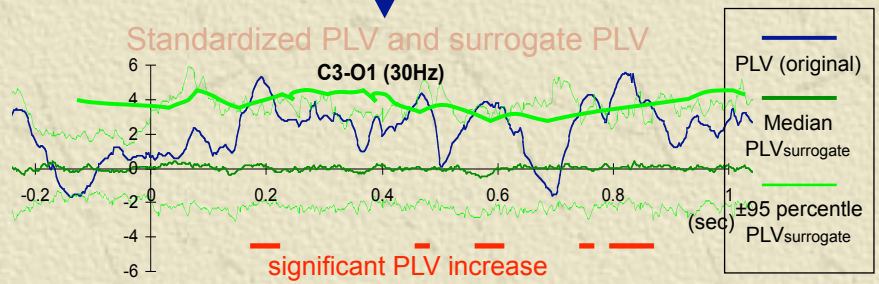
To reduce the effect of volume conduction of stable sources and compare between electrode pairs at different distances

$$PLVz(t) = \frac{\left(PLV - PLV_{Bmean}\right)}{PLV_{Bsd}}$$

PLV_{Bmean} : the mean of PLV in the baseline period (400ms)

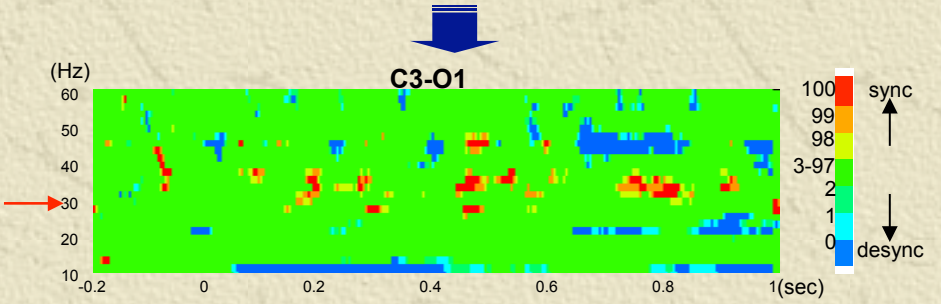
PLV_{Bsd} : the standard deviation of PLV in the baseline period (400ms)





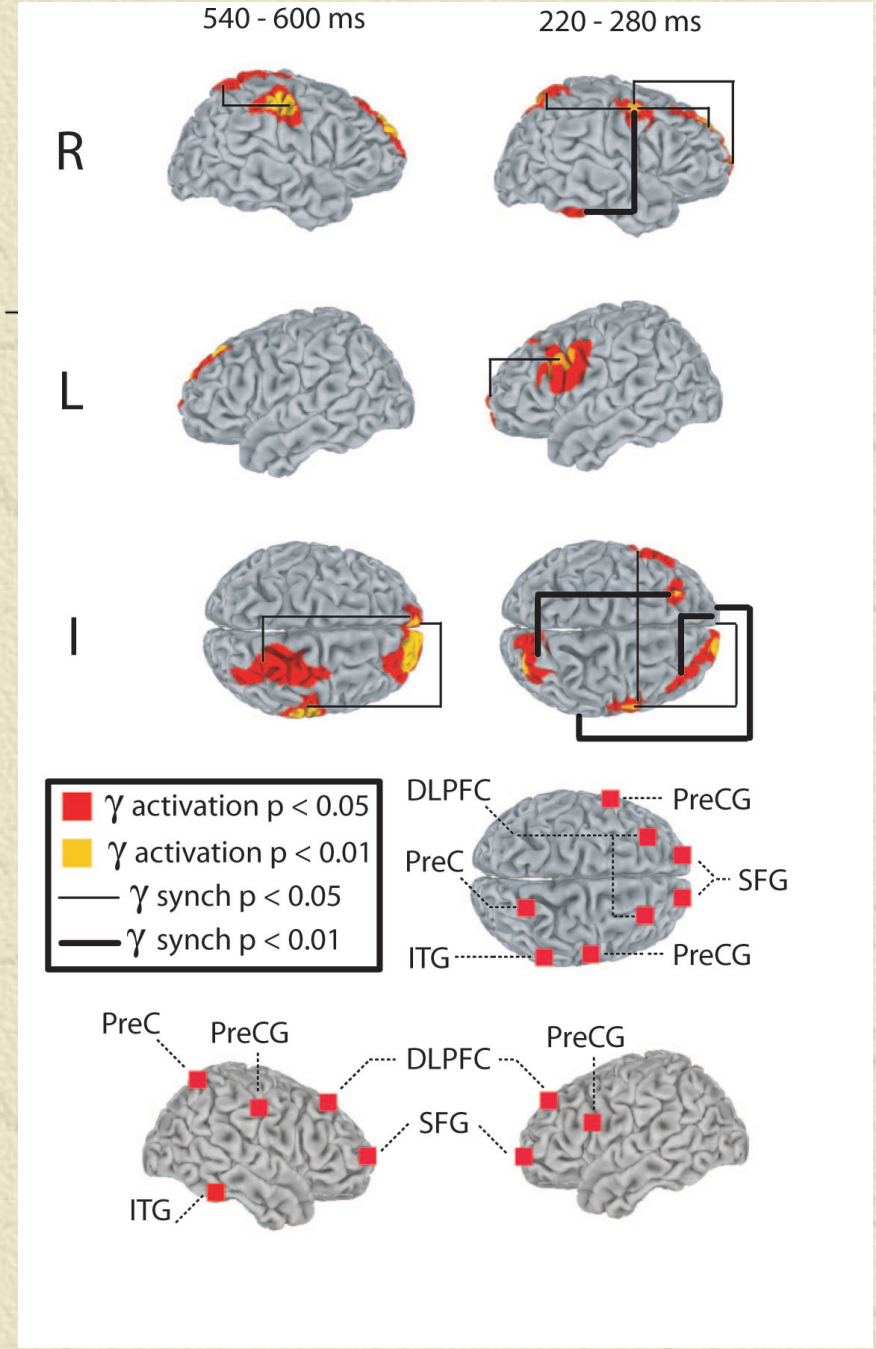
Step.5 statistical test using surrogate data

Note: Amplitude and long-range PLV_z must change together for spurious synchronization to be indicated (Doesburg, Roggeveen, Kitajo, Ward, *Cerebral Cortex*, 2007)



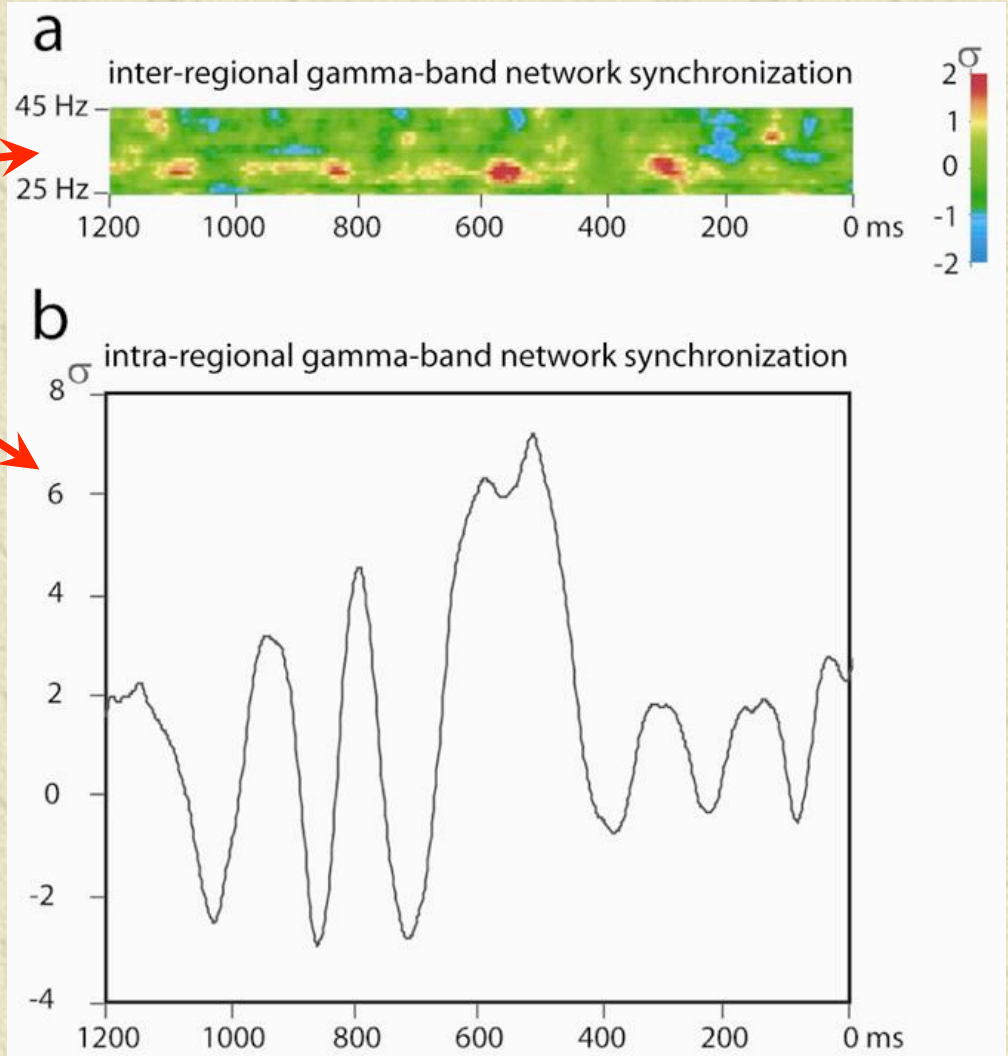
Gamma-band consciousness network

- biSFG, biDLPFC, RPreC and RPreCG active with some inter-regional synchrony at 540-600 ms constitute a consciousness maintenance network
- RITG (visual pattern) and LPreCG (RH response) also active at 220-280 ms ⇒ switch of percept
- Widespread synchrony in this network during perceptual switch



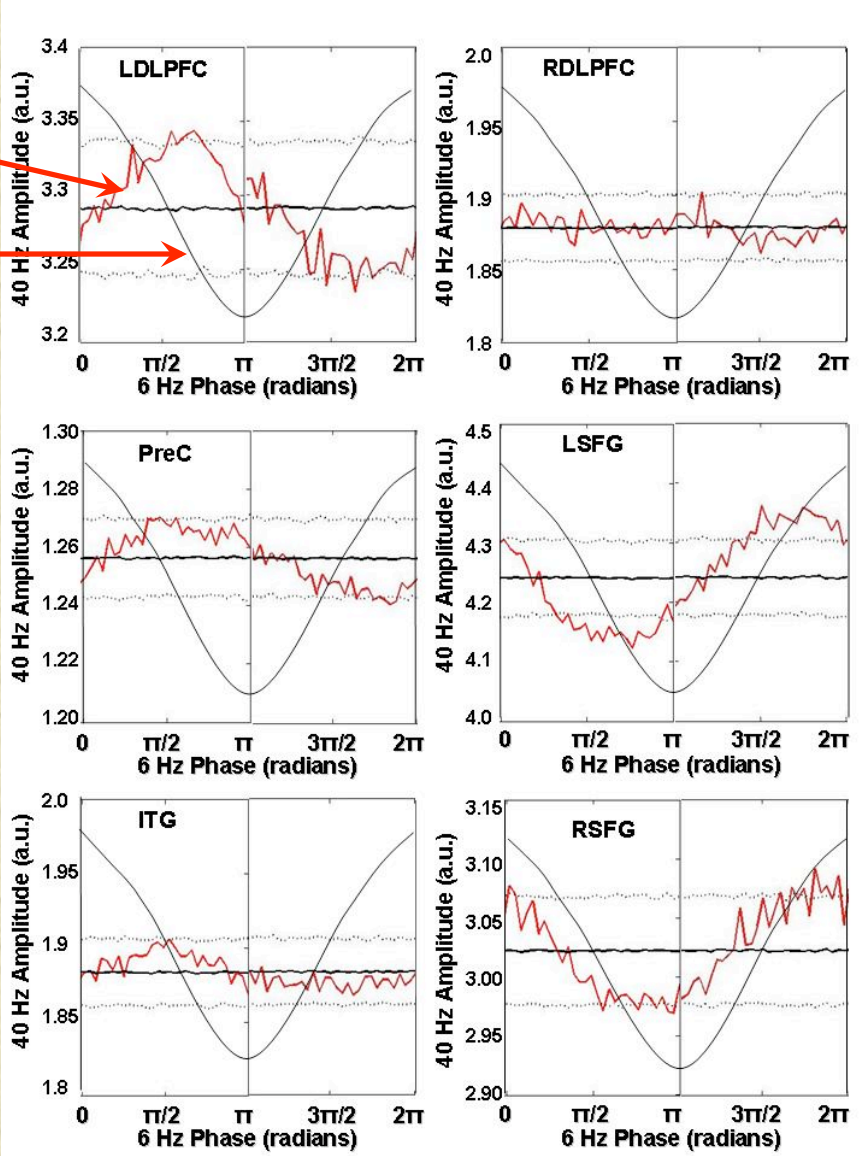
Rhythms of consciousness

- Bursts of inter-regional synchrony roughly every 167-250 ms ⇒ 4-6 Hz rhythm
- Bursts of intra-regional synchrony (local power) roughly every 167 ms ⇒ 6 Hz rhythm
- Consistent with other consciousness results, e.g. attention blink strongest at T1-T2 interval of 225 ms ⇒ 4.4 Hz
- Cross-frequency theta-gamma coupling?



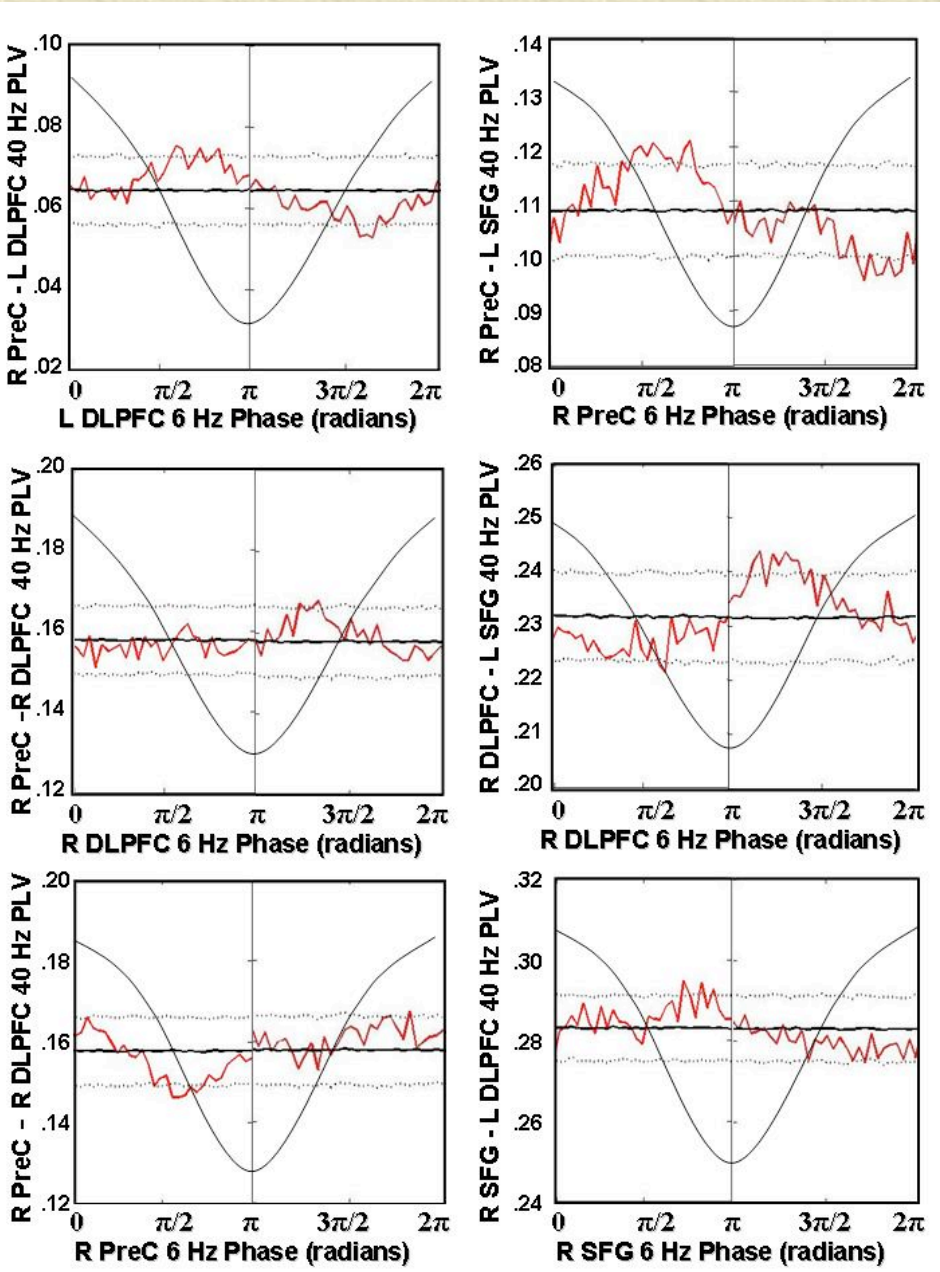
Theta phase-gamma amplitude coupling

- Jagged red lines are gamma amplitude
- Smooth black curves are one theta cycle (theta phase)
- Thick black line is mean of surrogates; thin lines are 2.5th and 97.5th percentiles of surrogates
- Clearly gamma amplitude waxes and wanes with theta phase in most areas shown (does ***not*** in RDLPFC, biPreCG)
- Gamma maximum ***not*** at theta trough as it is for 80-150 Hz gamma (Canolty et al, 2006)
- Theta-gamma relationship differs in biSFG from the others by Π radians



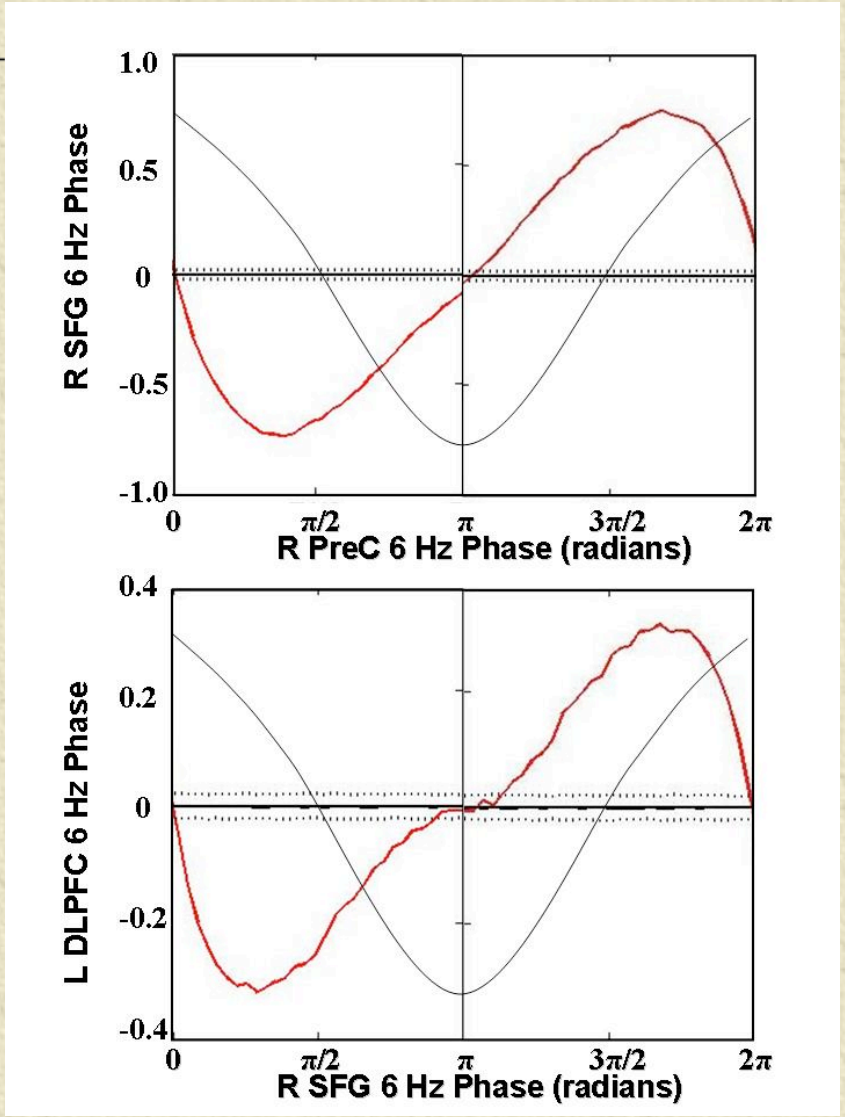
Theta phase – gamma PLV coupling

- Here jagged red lines are gamma PLV
- Again, significant modulation of gamma PLV by theta phase
- Again, different modulations in different pairs
- Ten of 15 pairs modulated by at least one area's theta phase, five by both (see Table 2 in paper)



Theta-theta phase coupling

- Here jagged red lines are theta phase in y-axis area
- Significant theta phase locking between all areas modeled
- Implies phase-locked theta rhythm everywhere but not all same phase
- Perceptual awareness, mediated by gamma synchrony, follows a theta rhythm



Take this home

- Synchronized frontal-parietal gamma-band network associated with ongoing perceptual awareness
- Change in perceptual awareness associated with augmented, more synchronized network
- Gamma-band synchronization linked to theta cycle, the rhythm of consciousness

To come 25 May

4. le mardi 25 mai 2010 à 17 heures:

The role of the thalamus in human consciousness