Neurobiology of multisensory perception: A complex system perspetive

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Overview

I. Multisensory perception

II. Dynamic framework of multisensory perception

III. Neurocognitive networks (NCN) underlying multisensory perception

IV. Computational models of NCN dynamics

I. Multisensory perception

Synaesthesia (Milieu of senses, multisensory)

“With blue, uncertain, stumbling buzz,
Between the light and me;
And then the windows failed, and then
could not see to see”

---- Emily Dickinson in *Dying*

Jimi Hendrix called the chord E7#9—often referred to by guitarists as the Hendrix chord—as "the purple chord," and used it to help form the verse of his song, Purple Haze.

Multisensory perception in speech

People in conversation

Why speech is important

- Most fundamental mode of human communication (before Facebook!) which is affected in brain injuries (stroke), spectrum disorders

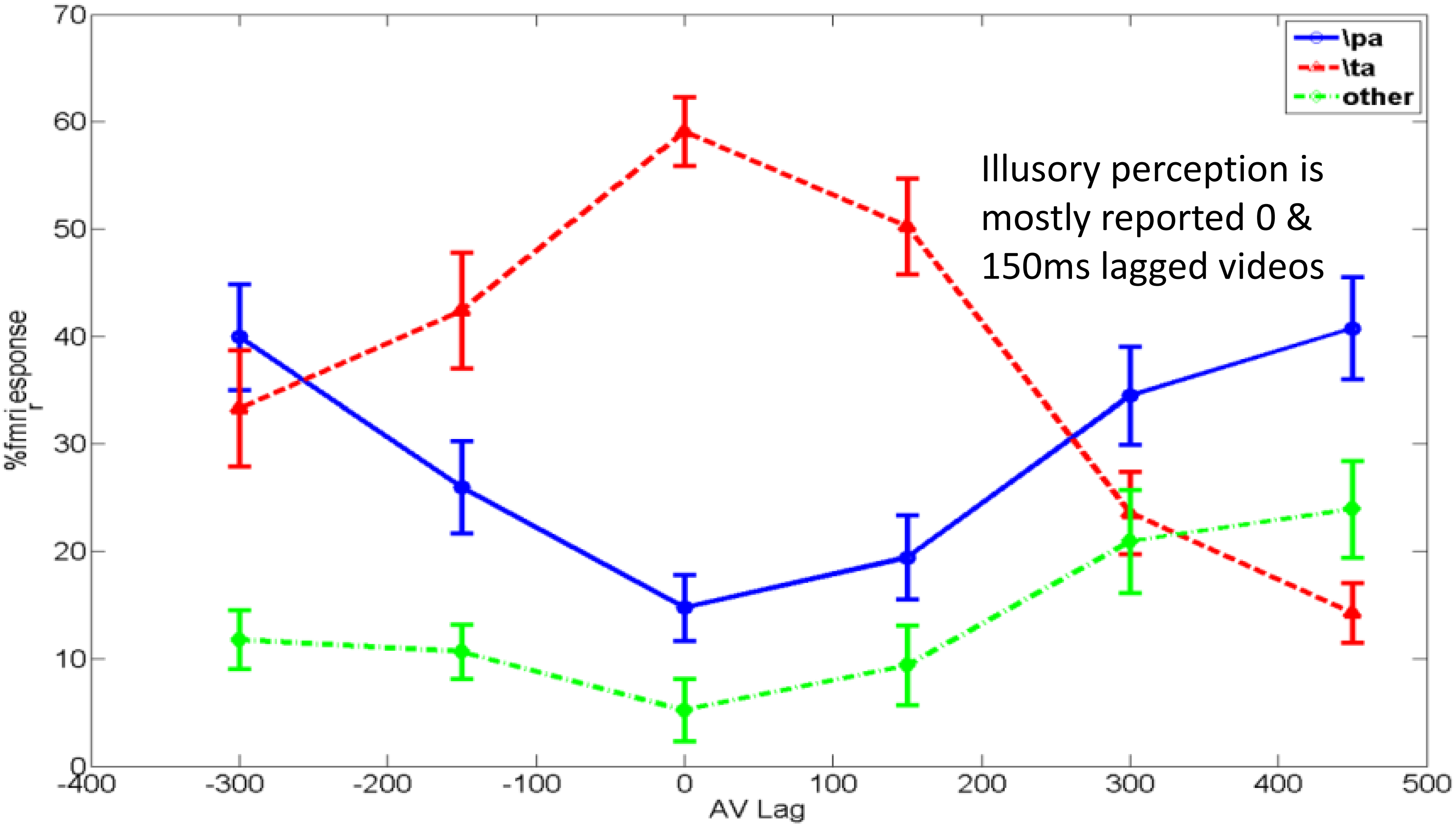
- Animal models are hard to construct

- **Key question: What is the representational space that processes the acts of listening and speaking?**

Multisensory perception in speech

McGurk and McDonald, 1976

Behavior as a function of time lags



Illusory perception is mostly reported 0 & 150ms lagged videos

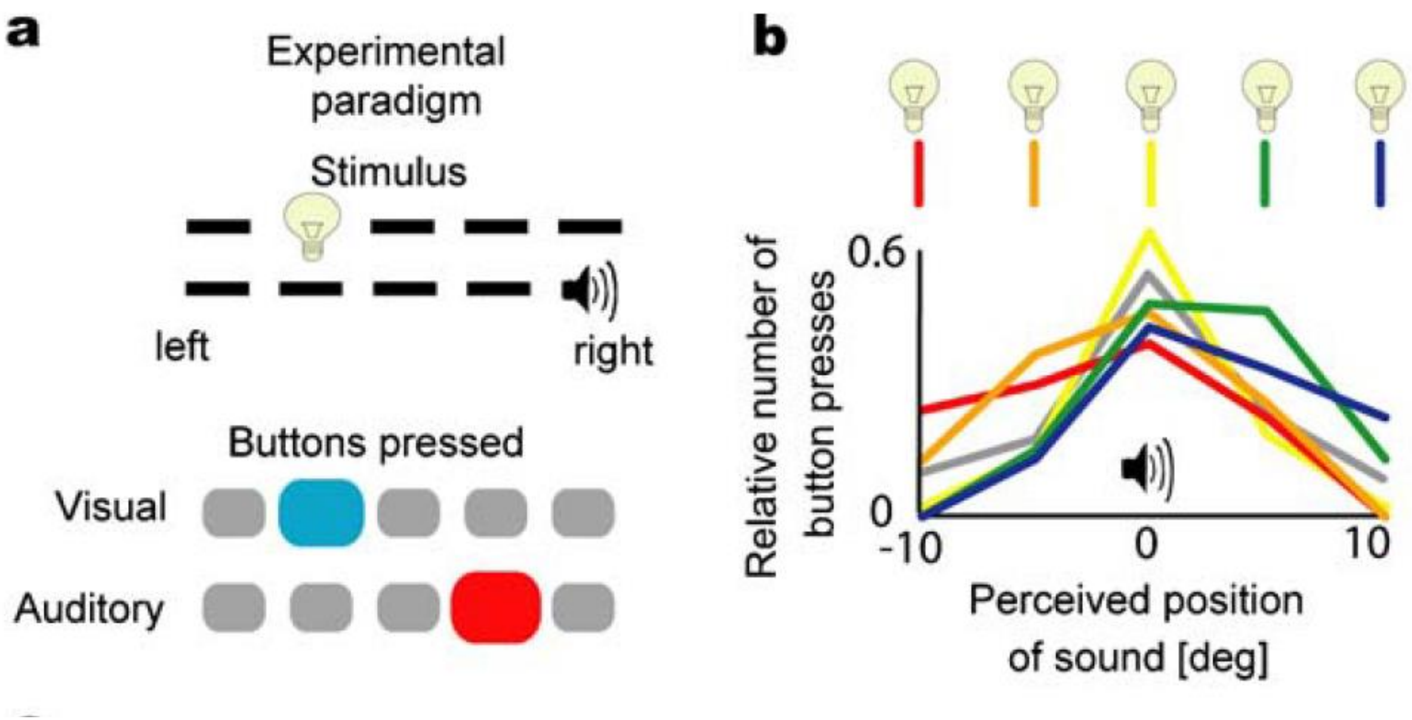
Munhall, 1996

Mukherjee et al (in prep)

Points to conceptualize

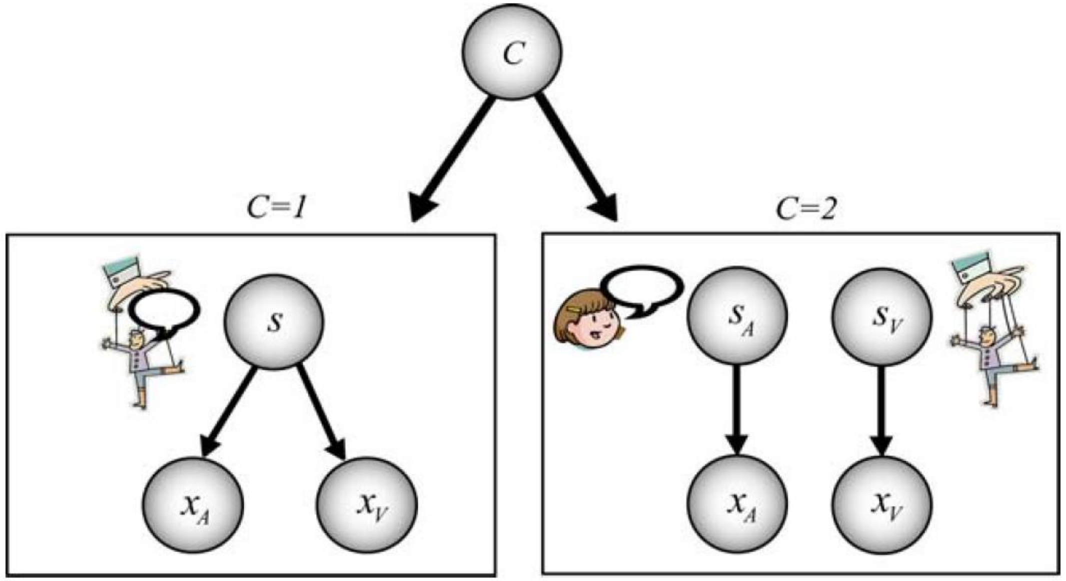
- Multiple senses interact to give rise to perception, sometimes illusory.
- Ecological (environmental) contexts give rise to stability and instability of perception, e.g. variation with AV lags
- What are the minimum requirements of a multisensory experience

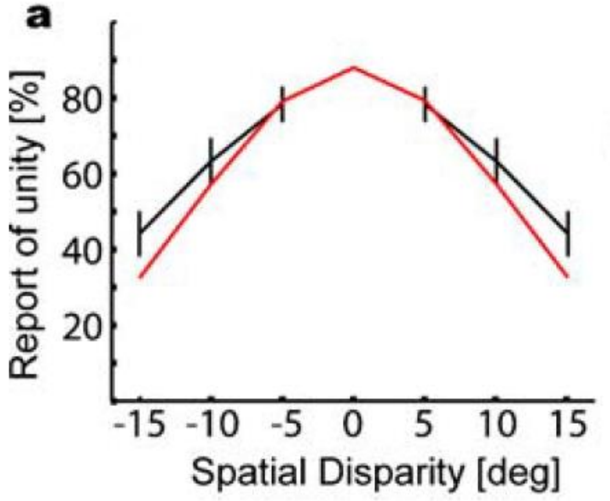
II. Models of multisensory perception



Kording et al *PLOS One* (2007)

Bayesian model of multisensory perception

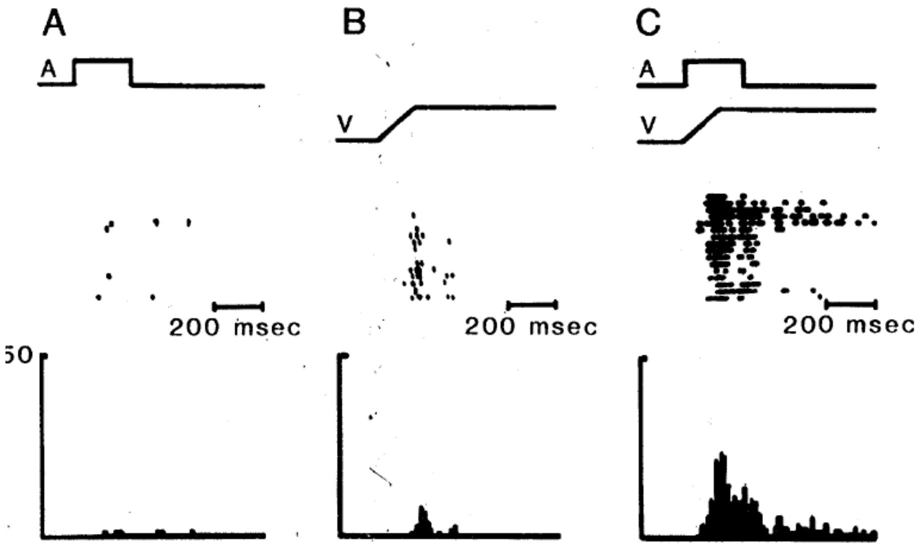




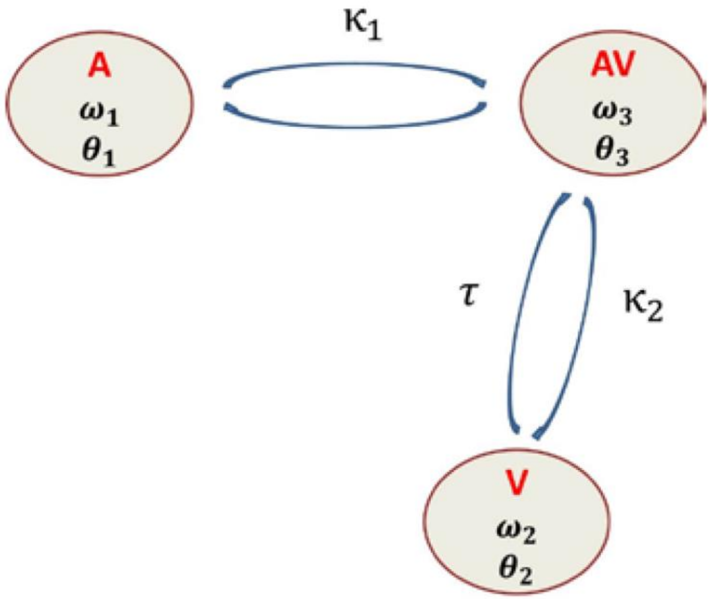
Spatial integration happens a superposition of variabilities embedded in two processes

Kording et al Plos One (2007)

Dynamic framework: *Of fireflies and men*



Meredith & Stein 1983

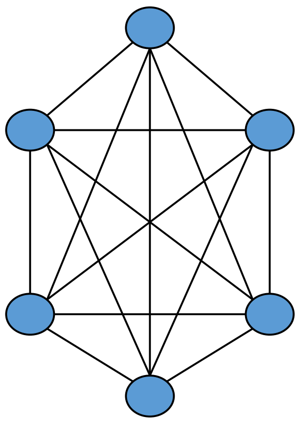


Network models

- Cellular clocks in the brain
- Pacemaker cells in the heart
- Pedestrians on a bridge
- Electric circuits
- Laser arrays
- Oscillating chemical reactions
- Bubbly fluids
- Neutrino oscillations
- Synchronous firings of male fireflies

http://heimhenge.com/skylights/2014/06/02/qa-why-fireflies-synchronize/

Kuramoto Model: All-to-All Coupling



$$\frac{d\theta_n}{dt} = \omega_n + k\sum_{m=1}^{N}\sin(\theta_m - \theta_n)$$

$n = 1, 2, \ldots, N$ k = (coupling constant)

- Assumes sinusoidal *all-to-all* coupling.
- Macroscopic coherence of the system is characterized by

$$r = \left|\frac{1}{N}\sum_{m=1}^{N}\exp(i\theta_m)\right|$$ = "order parameter"

Dynamic model of multisensory perception

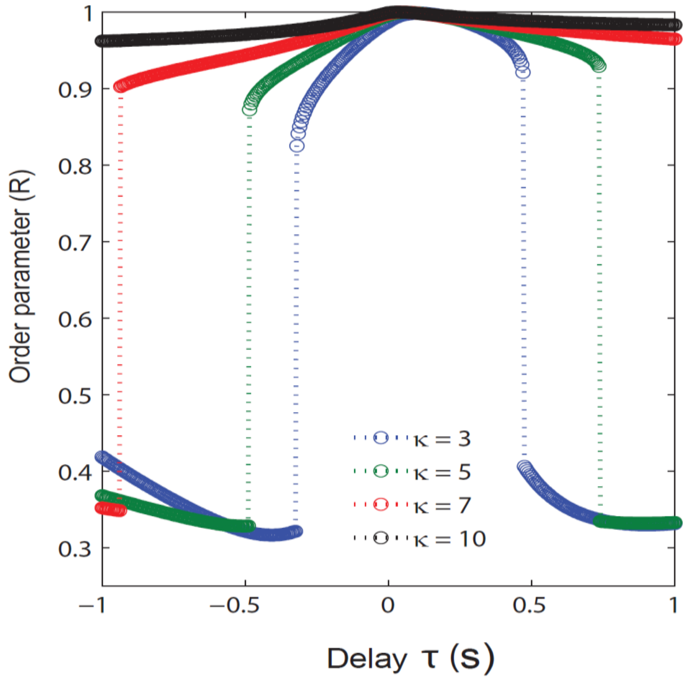
$$\dot{\theta}_1(t) = \omega_1 + \kappa_1 \sin\left(\theta_3(t) - \theta_1(t)\right),$$

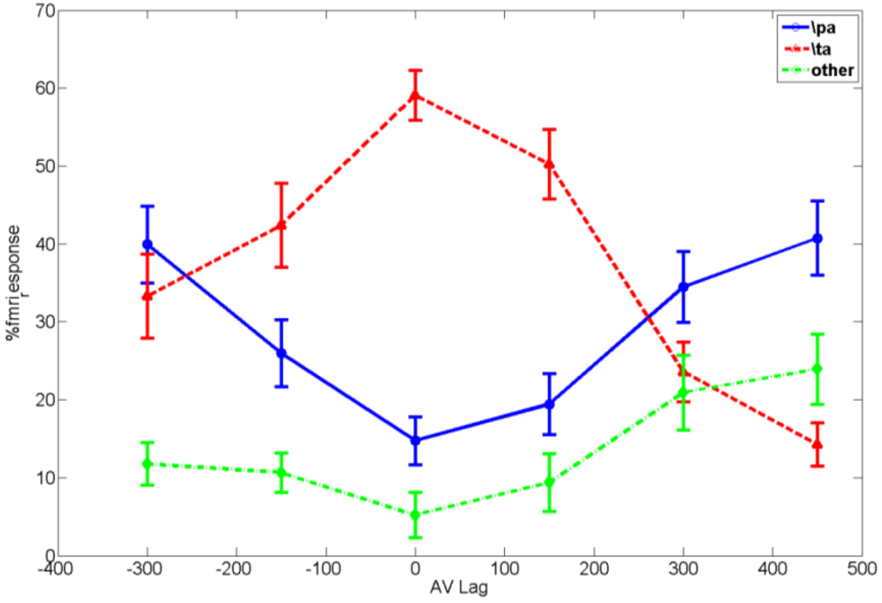
$$\dot{\theta}_2(t) = \omega_2 + \kappa_2 \sin\left(\theta_3(t-\tau) - \theta_2(t)\right),$$

$$\dot{\theta}_3(t) = \omega_3 + \kappa_1 \sin\left(\theta_1(t) - \theta_3(t)\right) + \kappa_2 \sin\left(\theta_2(t-\tau) - \theta_3(t)\right)$$

Order parameter

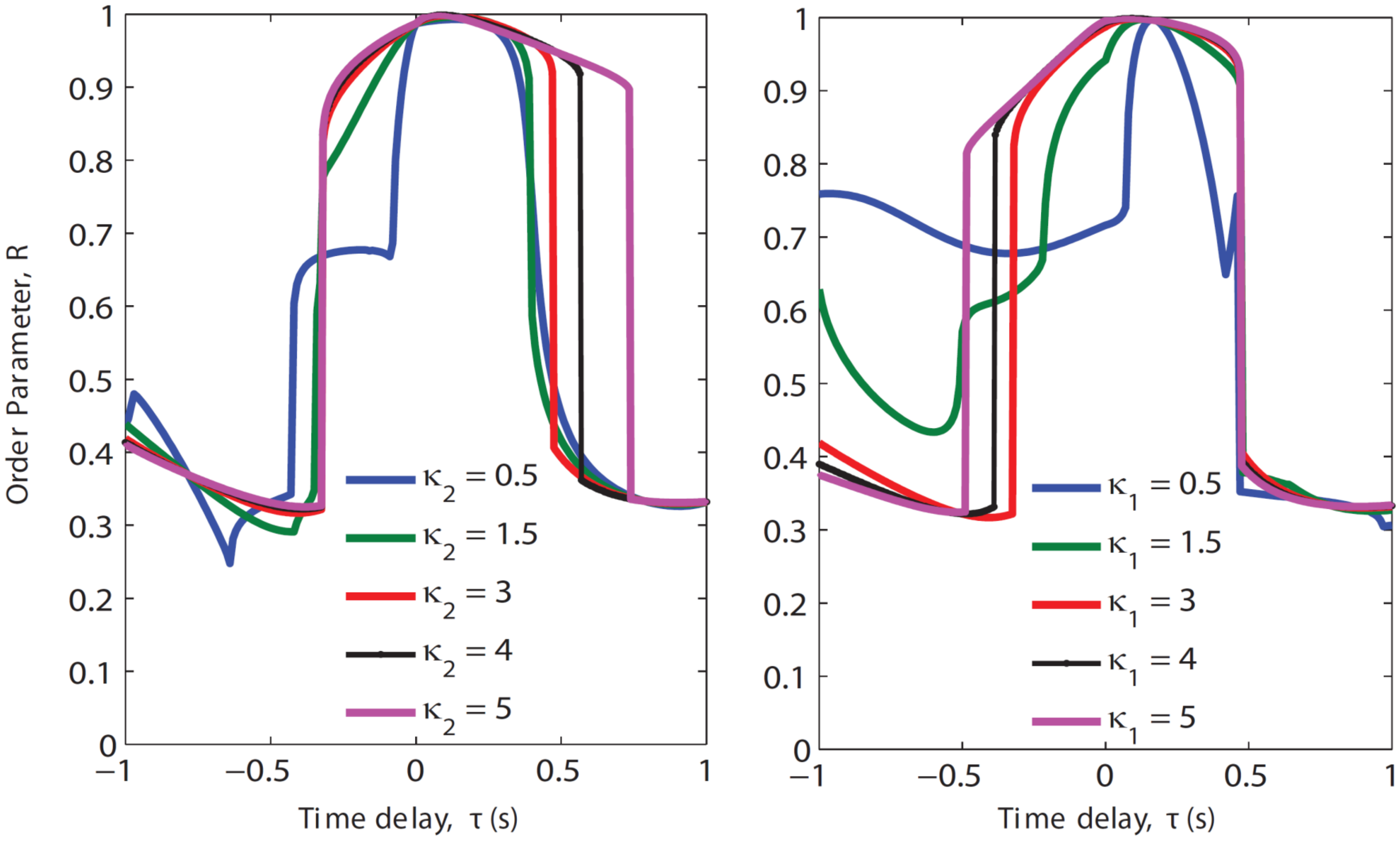
$$Re^{i\Phi} = \frac{1}{3}\sum_{j=1}^{3} e^{i\theta_j}.$$





Thakur et al. *Scientific Reports* (2016)

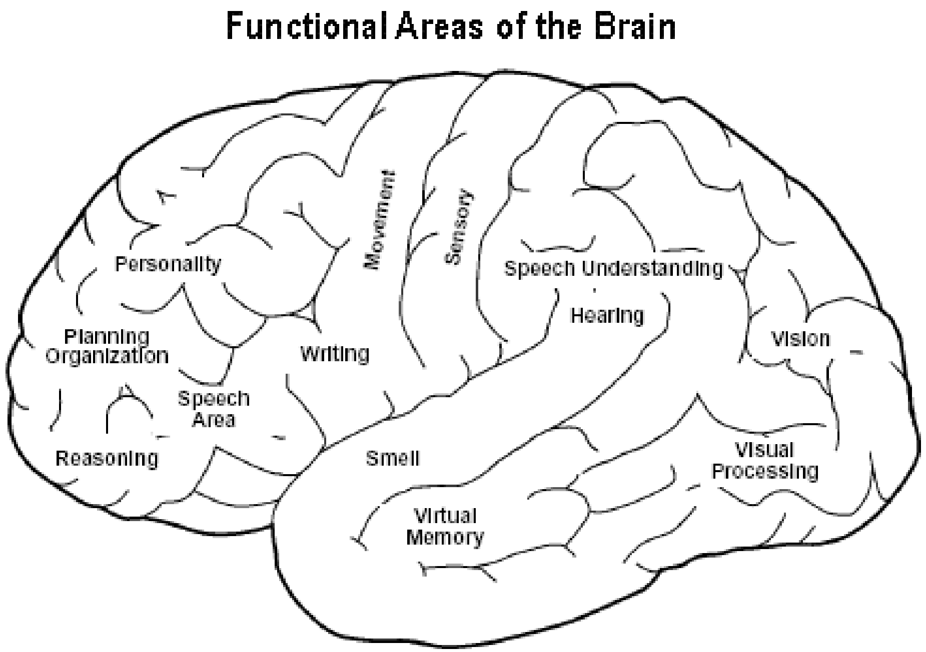
Unbalanced coupling



Interim summary

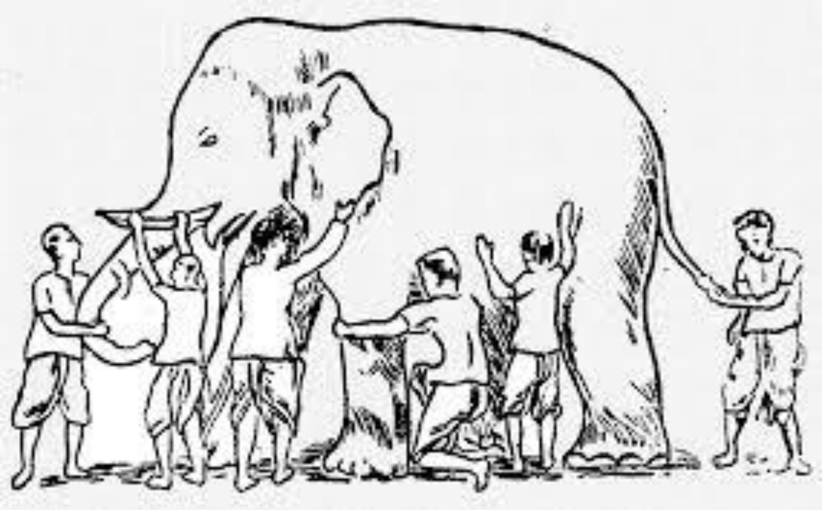
- Dynamic framework capture the behavioural experience as a function of AV lags
- Time delay and coupling are the key parameters in the dynamical model
- We can study the role of underlying symmetries imposed by neuronal connectivity and as well as environmental context and their interaction in one single model

III. Neurocognitive networks …



Functional segregation in the brain

Functional integration ??



Blind men describing an elephant

Neuro-cognitive networks

Def: Large-scale systems of distributed, interconnected and degenerate neuronal populations organized to perform cognitive functions.

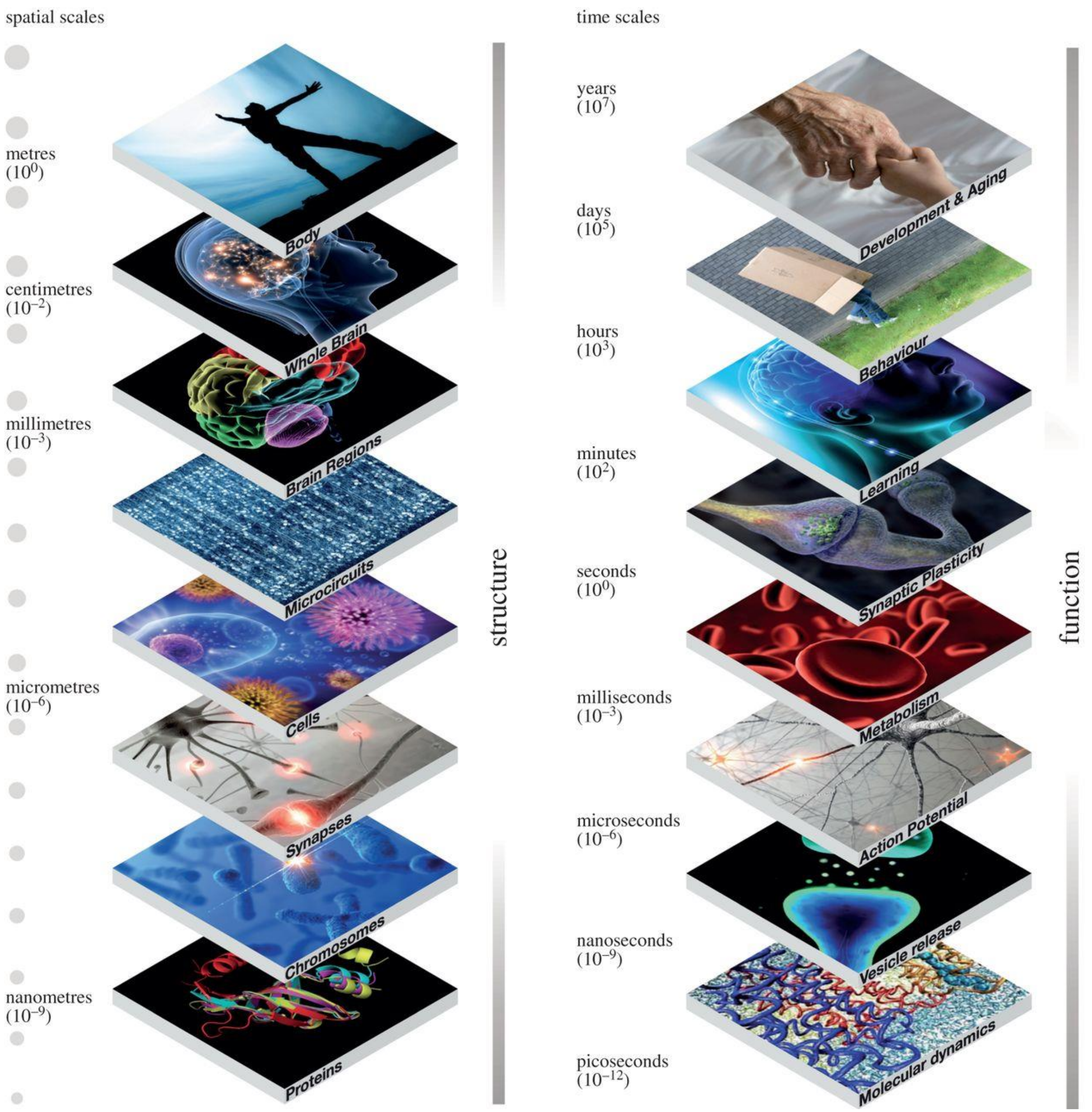
Bressler et al 1993, Tononi et al 1999, McIntosh 2000, Bressler & Menon 2010

Hypothesis: Neuro-cognitive networks can be characterized from the spatiotemporal patterns of brain electromagnetic and metabolic activity at **multiple scales**

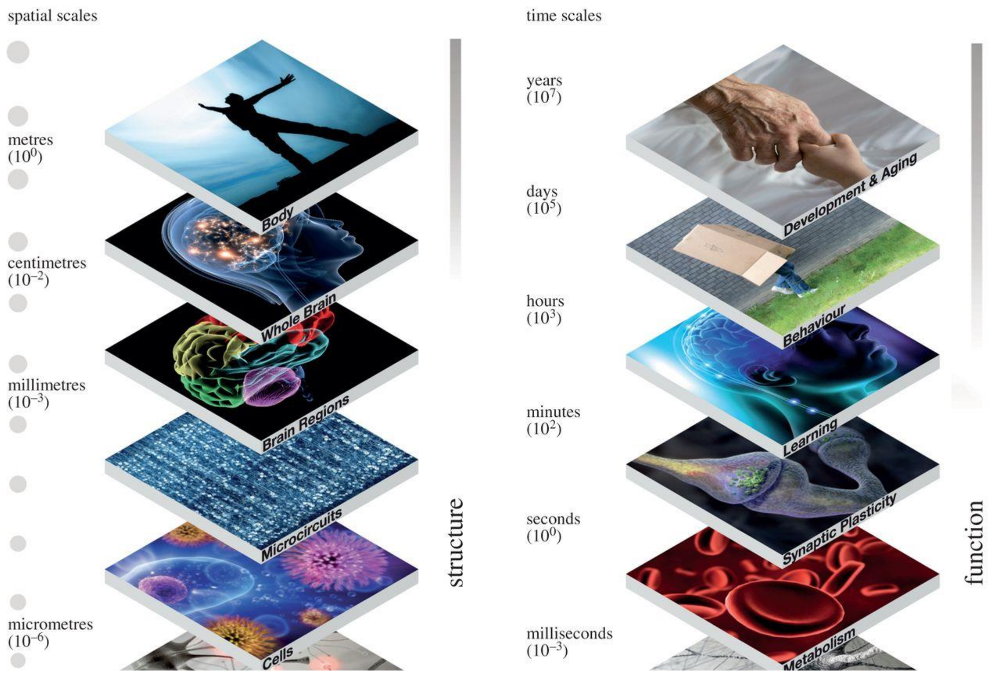
Bressler and Menon 2010, Banerjee et. al, 2011, 2012a &b

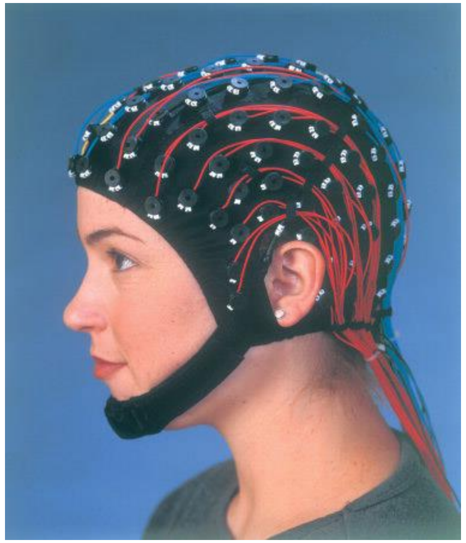
The multiscale brain

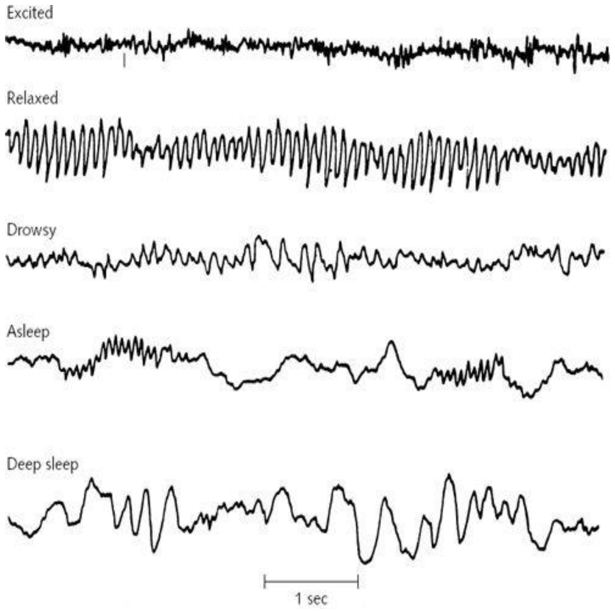
Frackowiak & Markram 2015

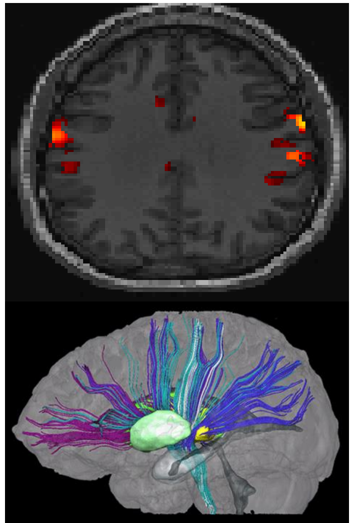


Measuring NCN: EEG, MEG, MRI



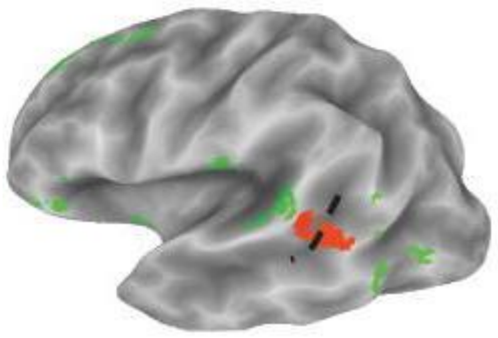






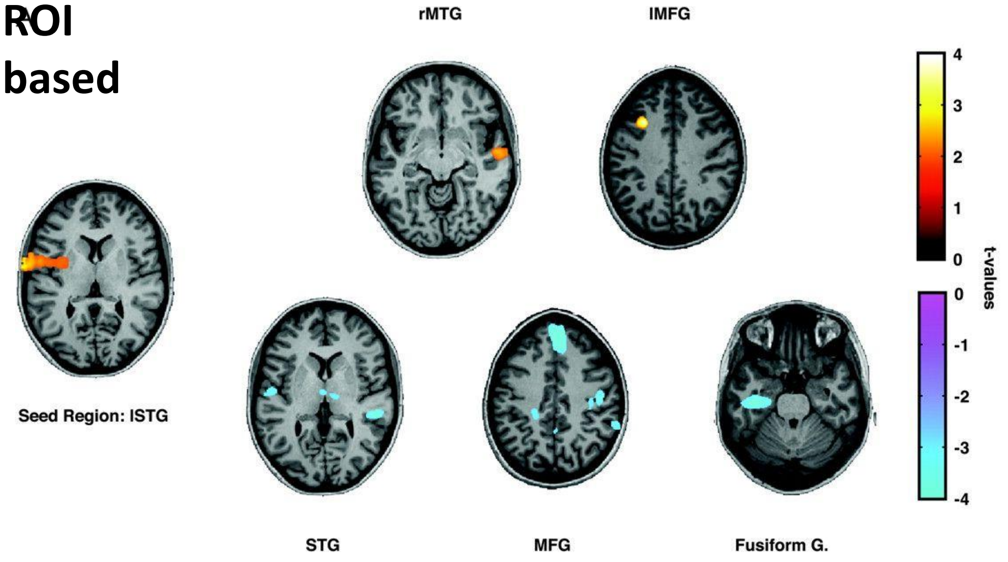
Neural basis of multisensory perception

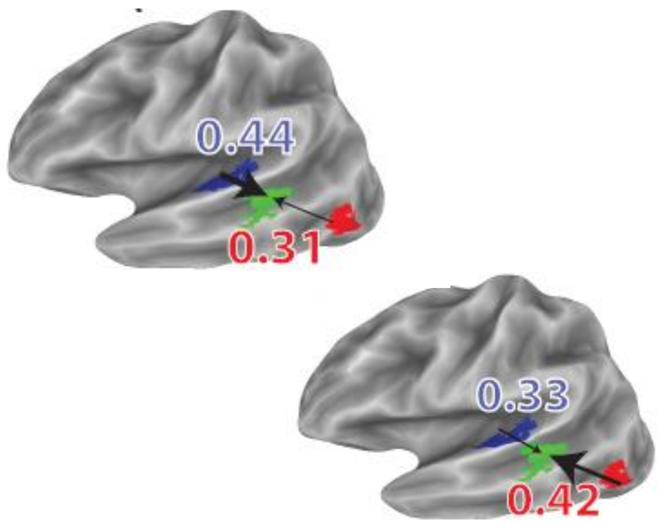
Cortical loci based



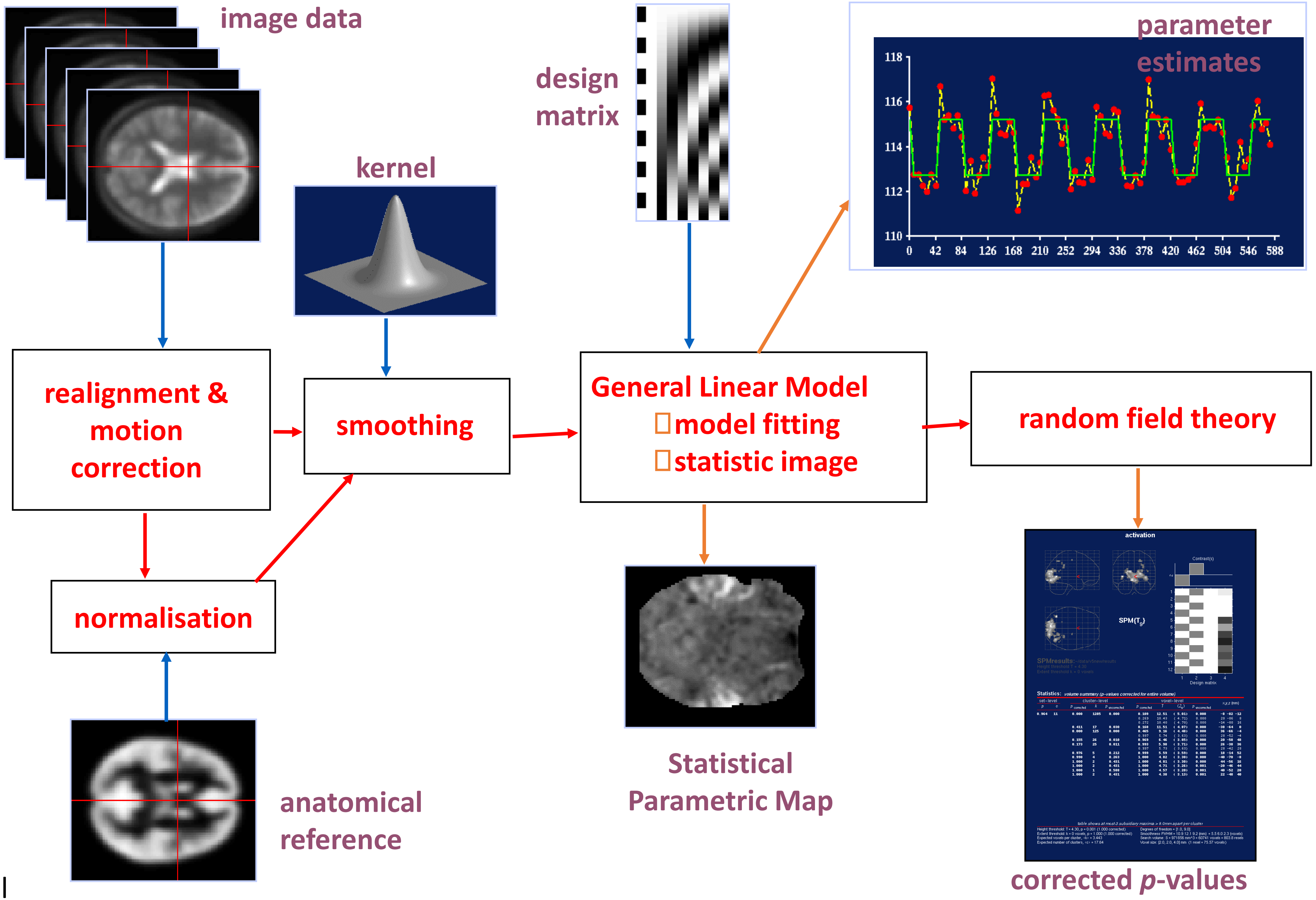
Beauchamp et. al, 2011

ROI based





Keil et. al, 2011, Nath and Beauchamp 2011



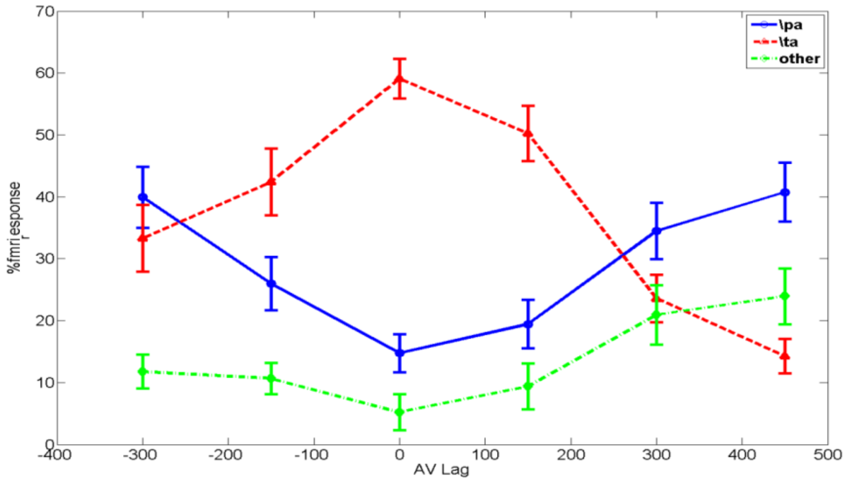
Courtesy
Kiebel et al

Spatial boundaries of perceptual networks

- fMRI of 55 human subjects
- 3T scanner at NBRC, Manesar
- Right handed healthy normals, bilingual population

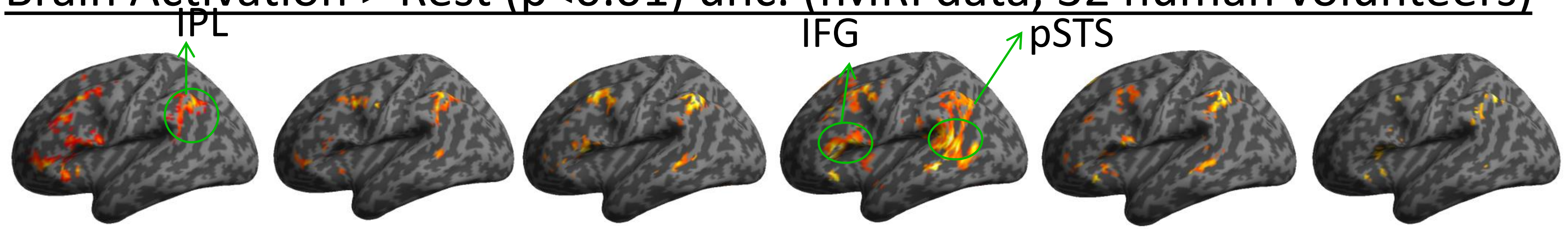
Functional segregation during multisensory perception

Behavior



Illusory perception is mostly reported 0 & 150ms lagged videos

<u>Brain Activation > Rest (p<0.01) unc. (fMRI data, 32 human volunteers)</u>

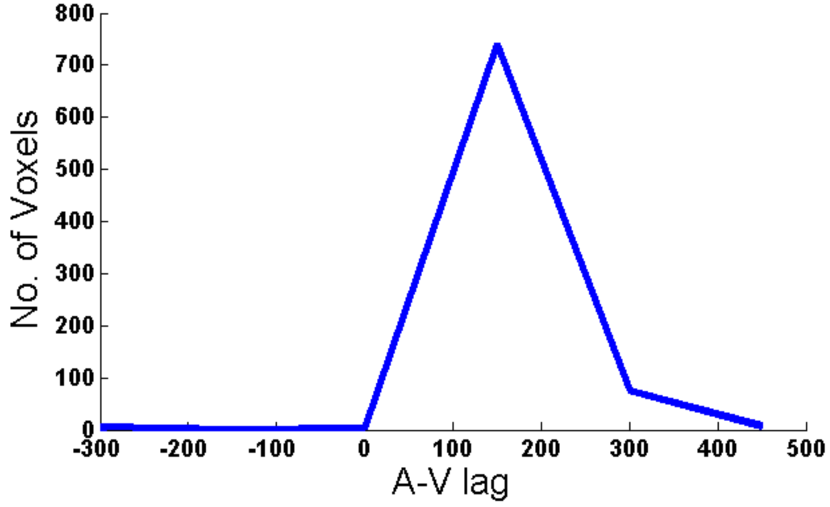


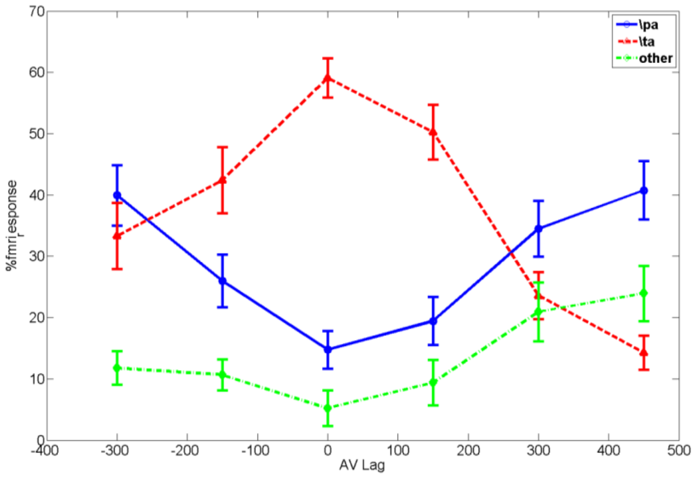
Lag(-300) Lag(-150) Lag(0) Lag(150) Lag(300) Lag(450)

Result: More activity in pSTS only when lags are 0 and 150ms, along with increase in connectivity between IPL, pSTS and IFG

Mukherjee, Raghunathan & Banerjee (in prep)

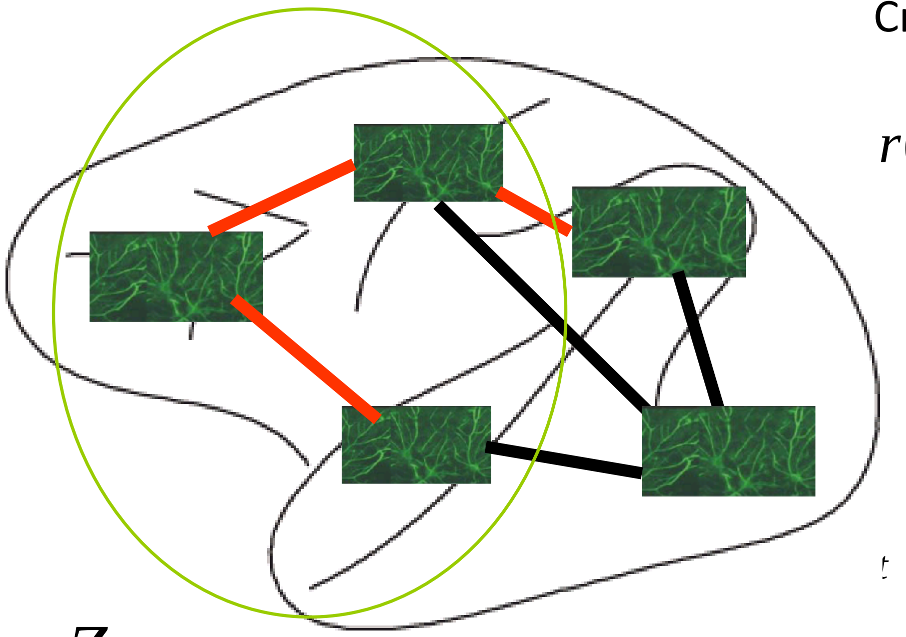
Activity of pSTS voxels





Functional connectivity

Measuring linear relationships (time domain)



Z_t

Cross correlation (Bivariate)

$$r(x,y)=\frac{\langle x_t y_t\rangle-\langle x_t\rangle\langle y_t\rangle}{\sqrt{(\langle x_t^{\,2}\rangle-\langle x_t\rangle^2)}\sqrt{(\langle y_t^{\,2}\rangle-\langle y_t\rangle^2)}}$$

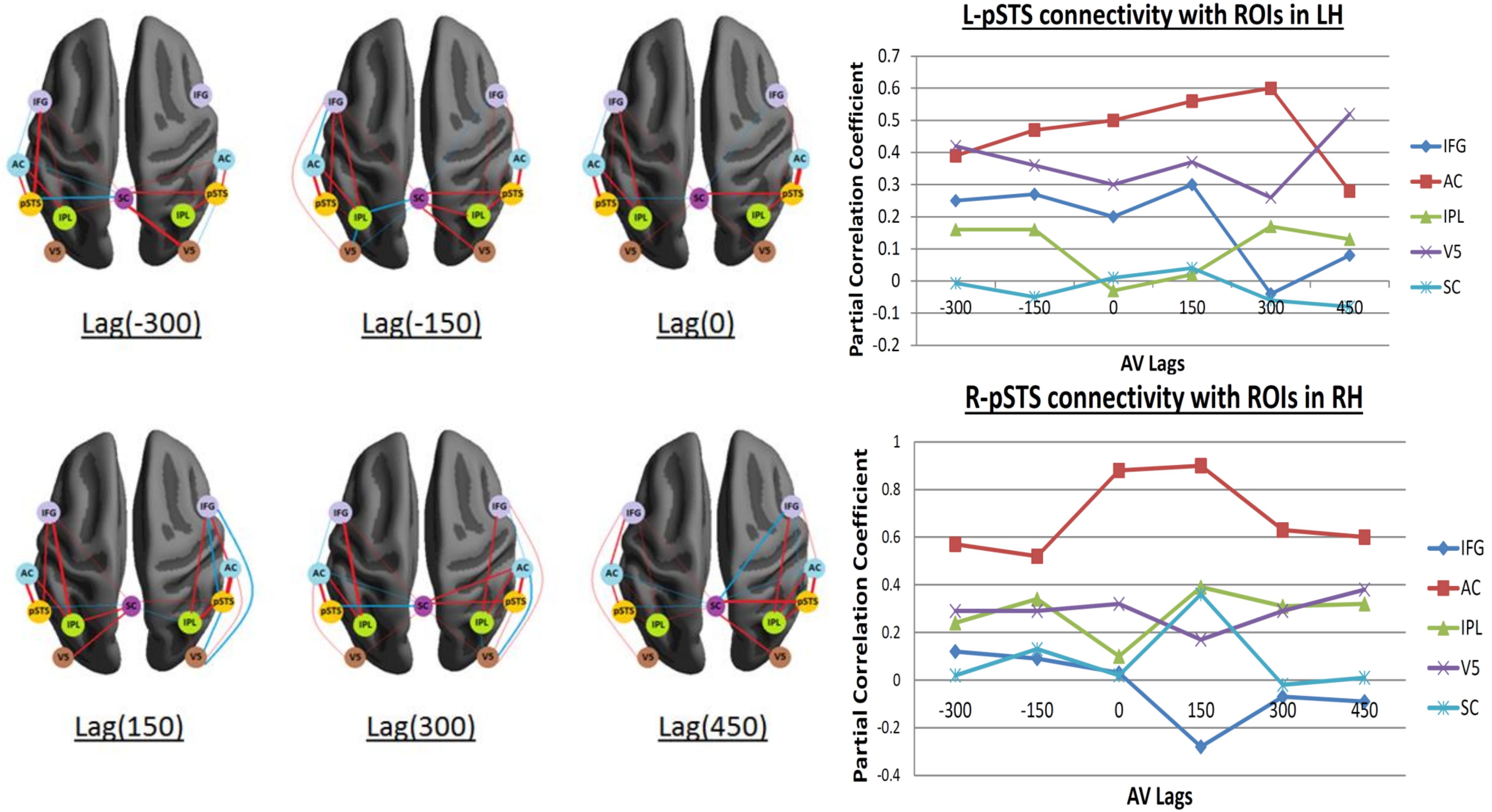
Assuming stationarity

Partial correlation (Multivariate)

$$r(x,y\,|\,Z)=\frac{r(x,y)-r(x,Z)r(y,Z)}{\sqrt{1-r^2(x,Z)}\sqrt{1-r^2(y,Z)}}$$

Andersen, T. W: An Introduction to Multivariate Statistics

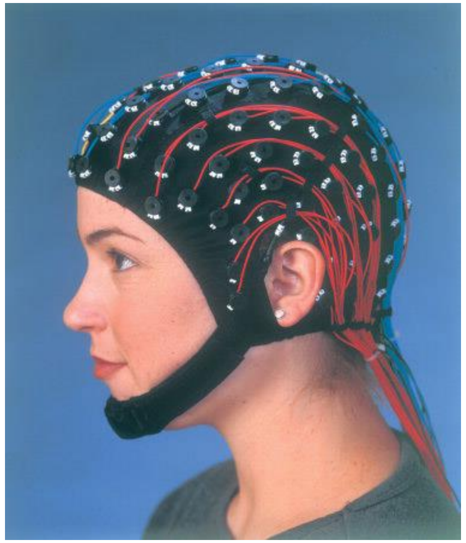
Functional integration- Connectivity analysis

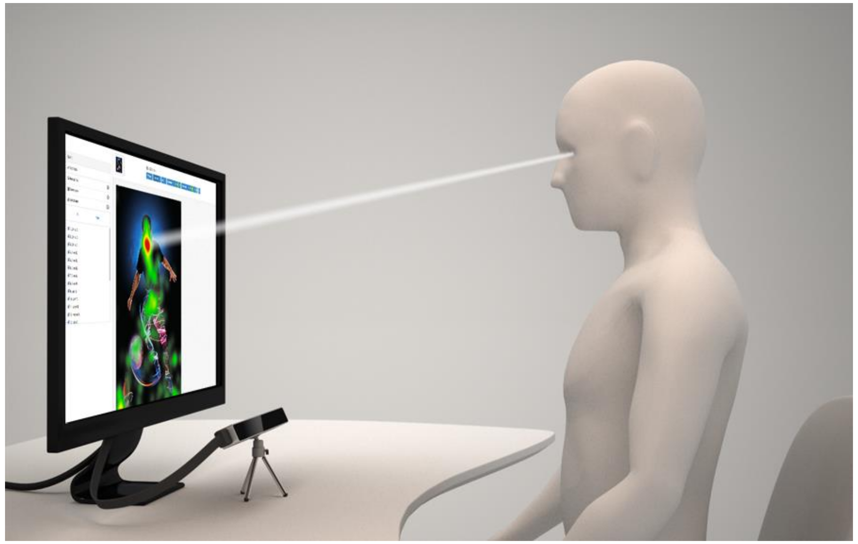


Summary from fMRI investigation

- Identification of spatially distinct areas involved in multisensory perception
- Inter-areal connectivity is a a key variable in mediating perception
- We are currently investigating the causality among the network nodes

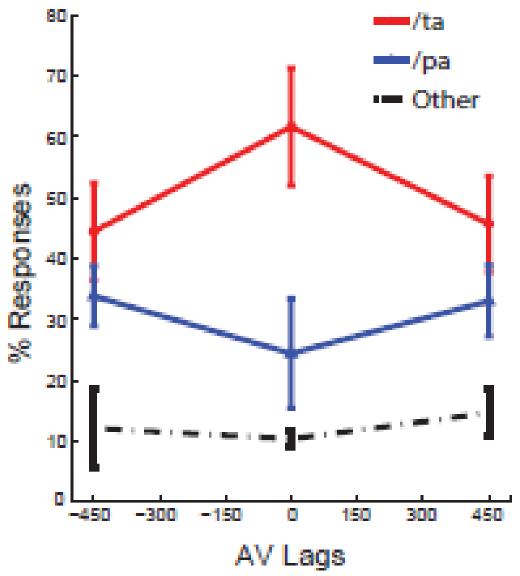
Temporal organization: EEG

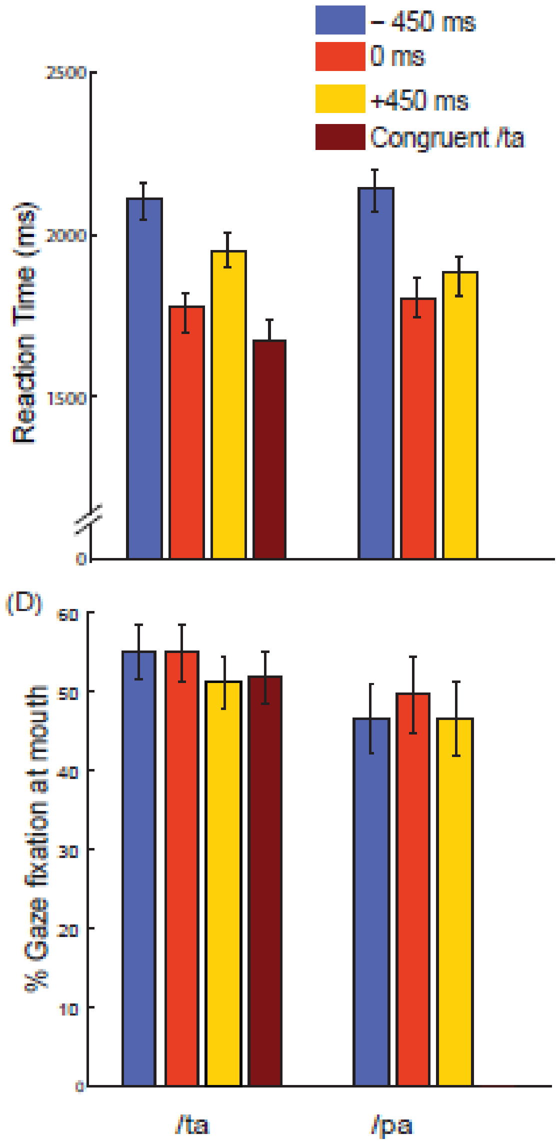




- 25 healthy normal humans , right handed and bilingual
- No history of imapaired auditory processing/ neurological disorders

Temporal signatures of multisensory perception (EEG, 15 subjects)

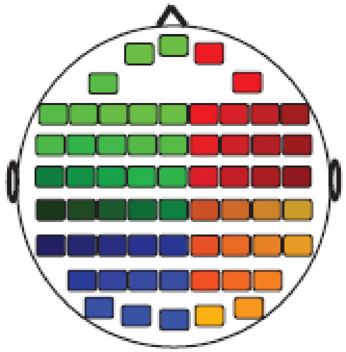




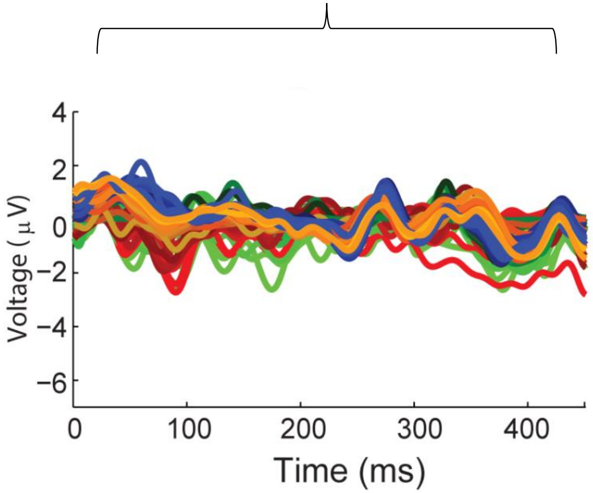
Kumar et. al (2016)

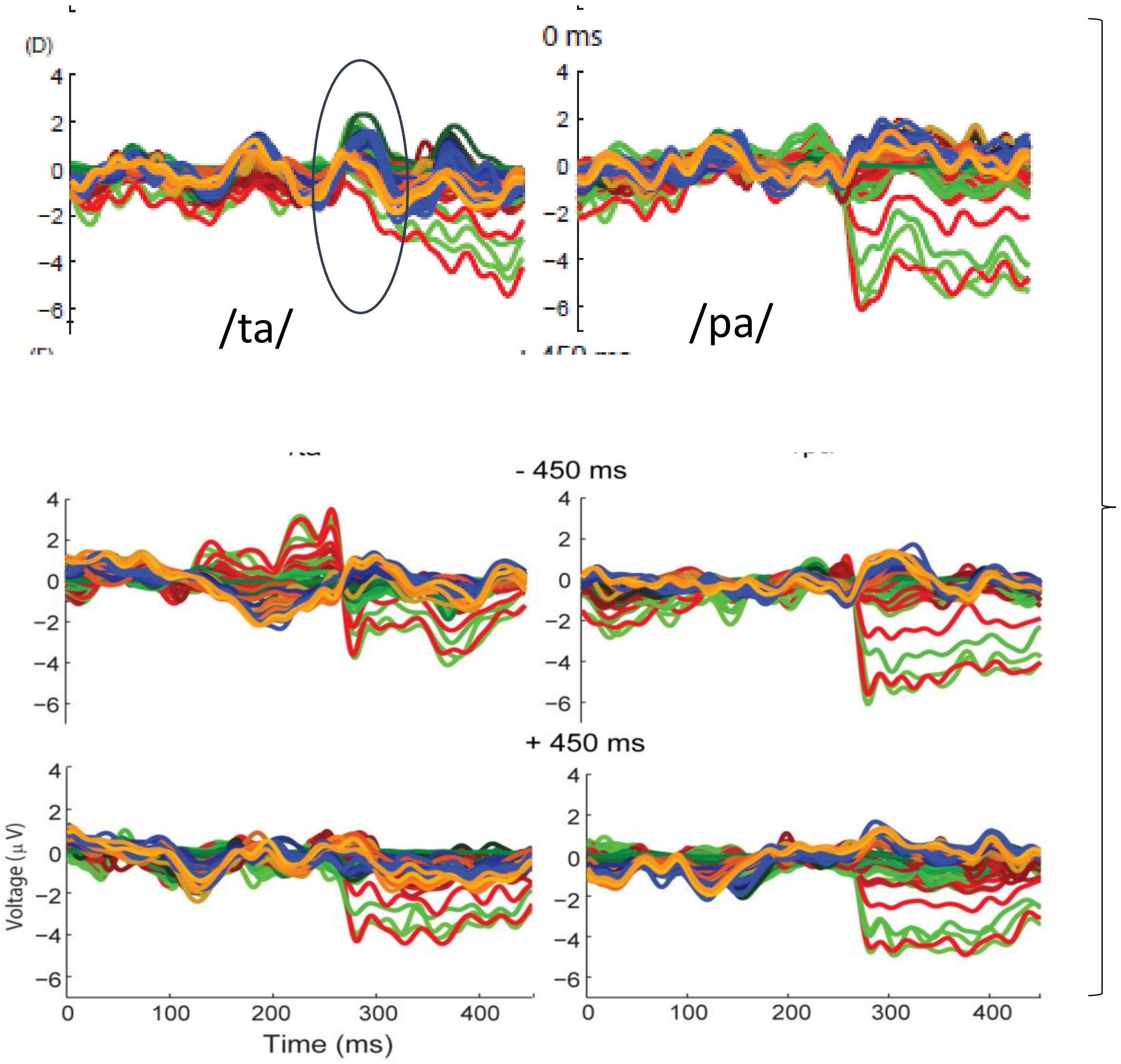
Results: ERP level (whole-brain patterns)

Functional segregation



Congruent AV stimuli



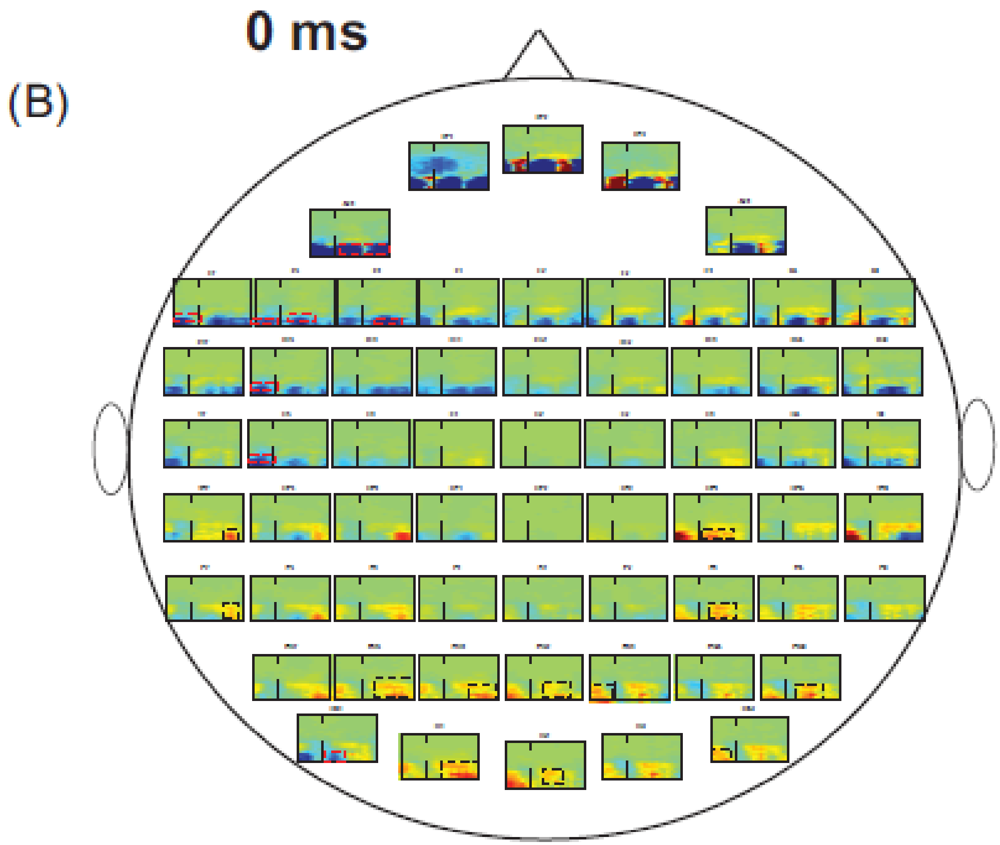


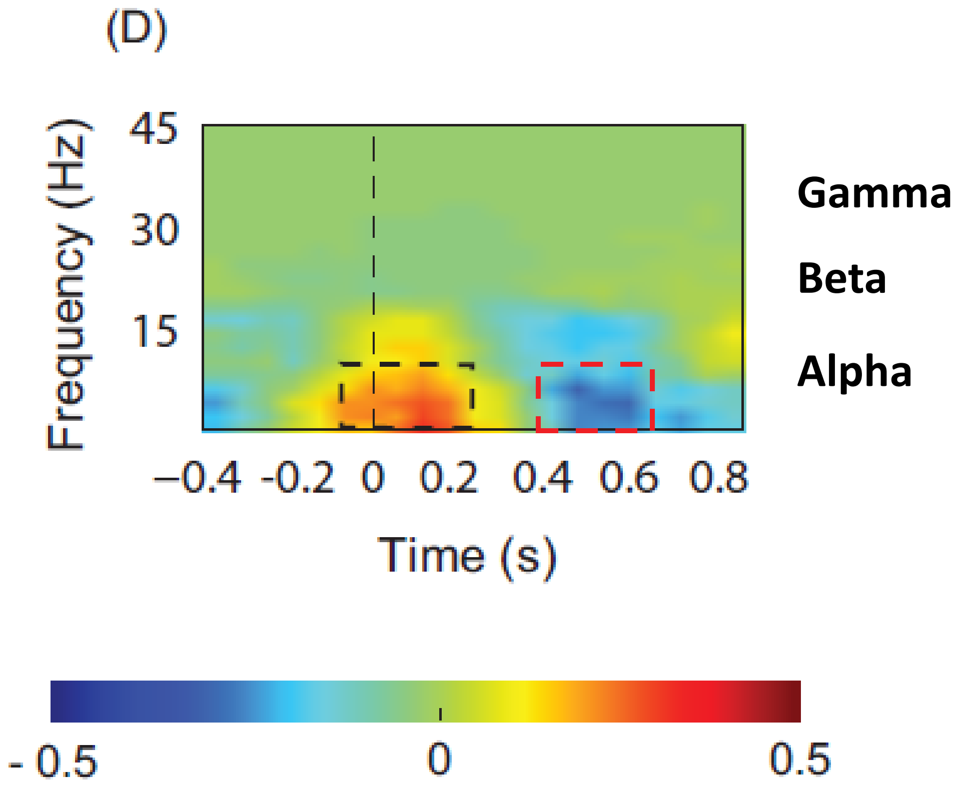
Incongruent AV stimuli

Kumar et. al *Frontiers in Psychology* (2016)

EEG Spectral signatures

/ta/ - /pa/



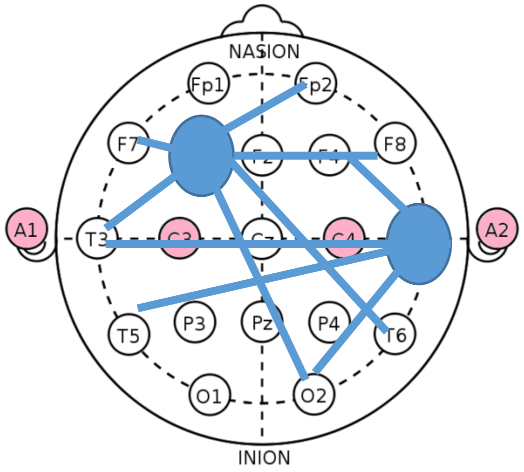


Kumar et al *Multisensory Res* (2017)

Coherence: Spectral representation of neuronal coordination

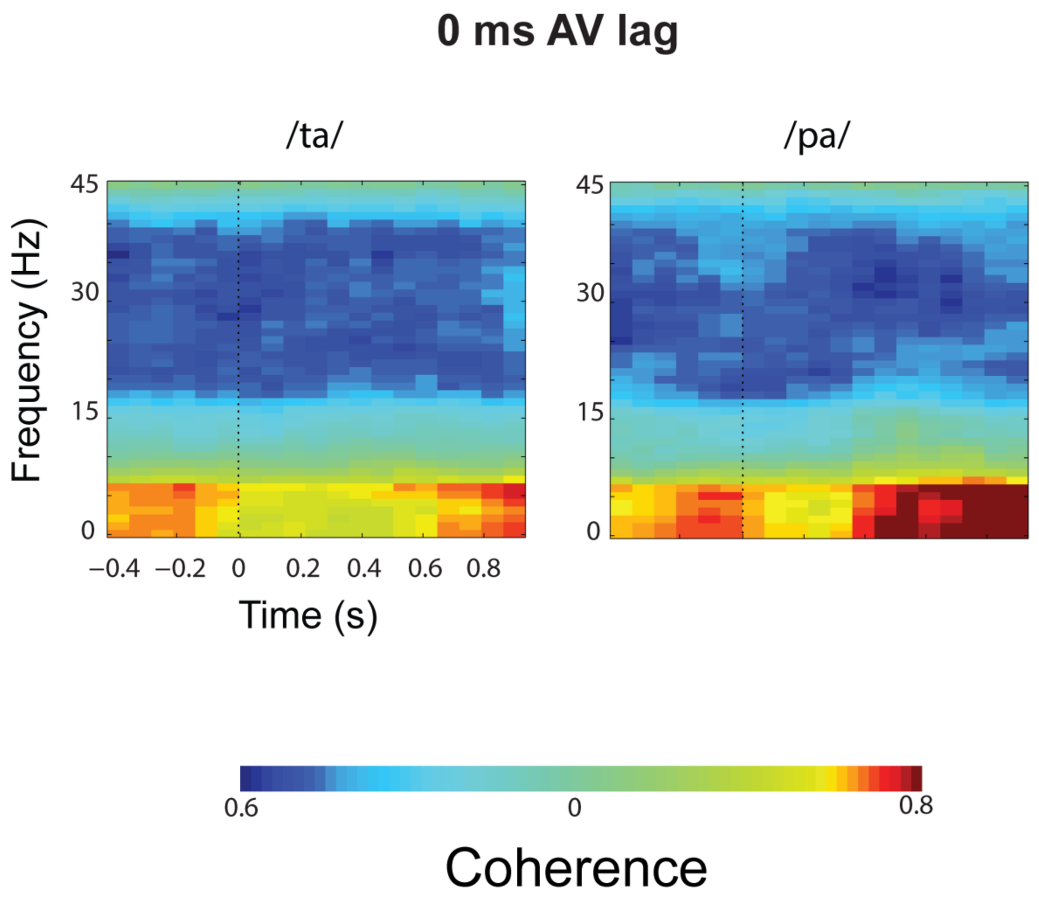
- Coherence is an estimator of the brain network

$$C(f) = \frac{S^{XY}(f)}{\sqrt{S^{XX}(f) S^{YY}(f)}}$$



- Global coherence could provide a label that binds those neuronal assemblies that represent same perceptual object

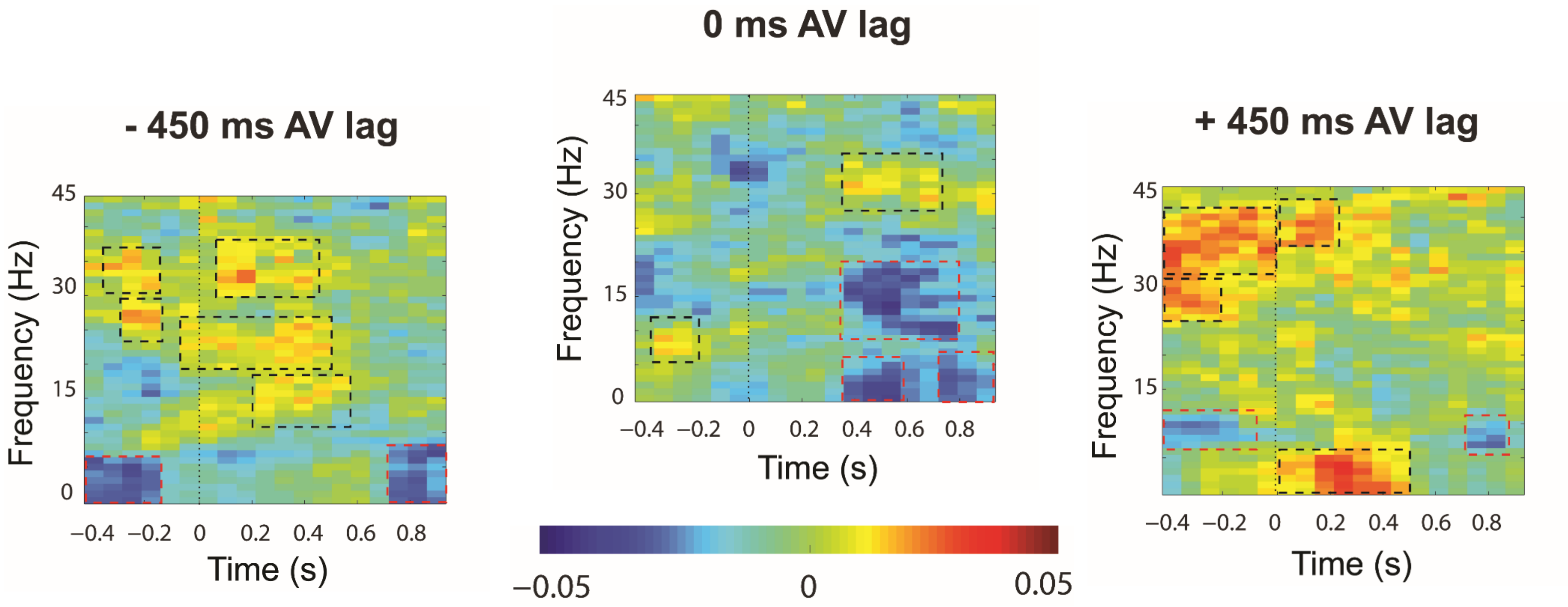
Large-scale connectivity dynamics: Time-Frequency global coherogram



Global coherogram differences (percievers)

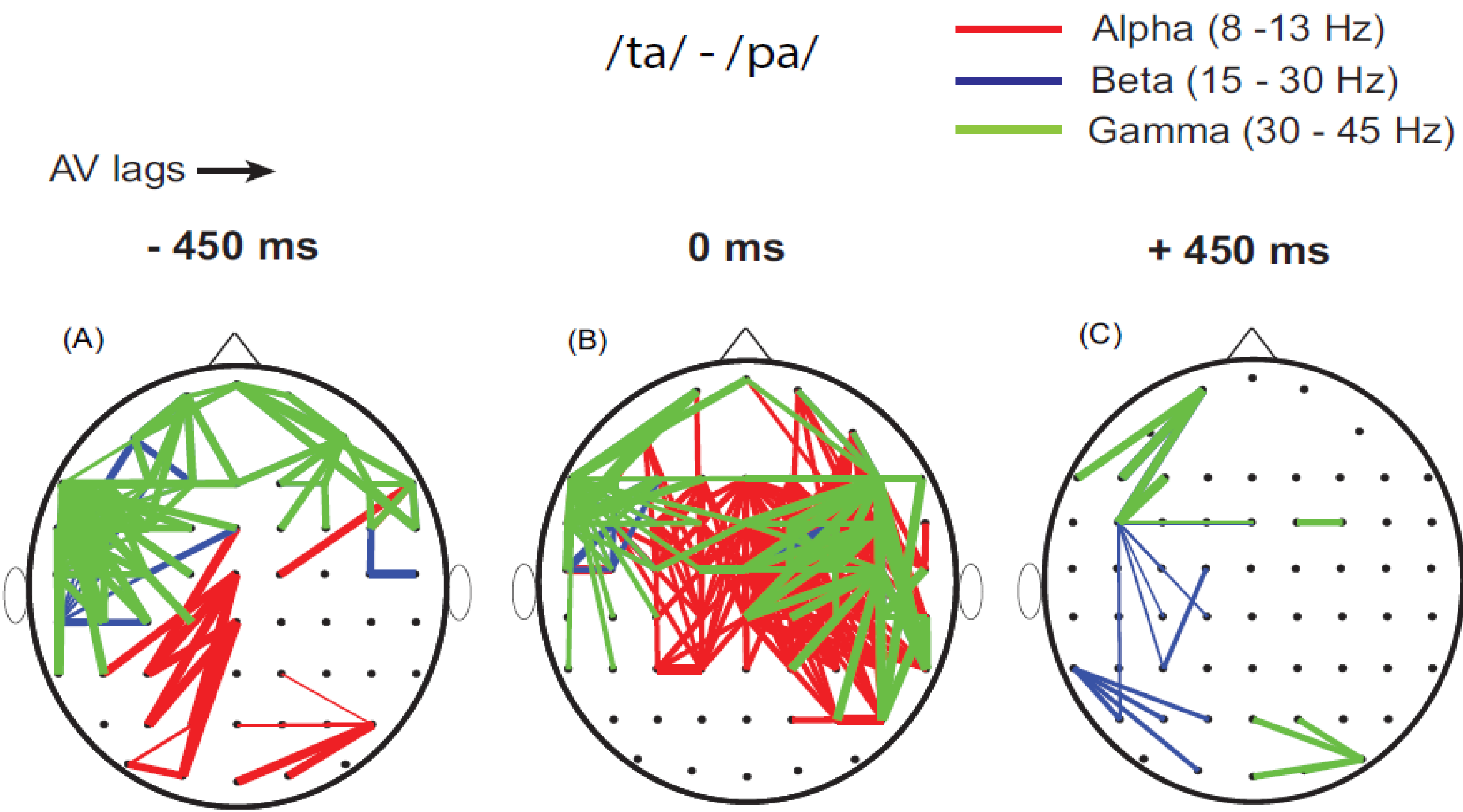
/ta/ < /pa/, synchrony DECREASED

/ta/ > /pa/, synchrony INCREASED



Kumar et. al *Frontiers in Psychology* (2016)

Subnetworks underlying multisensory perception



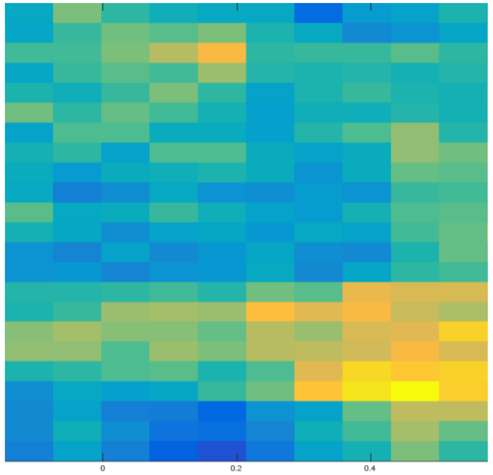
Kumar et. al *Multisensory Research* (2017, in press)

Global coherogram differences (rare- percievers)

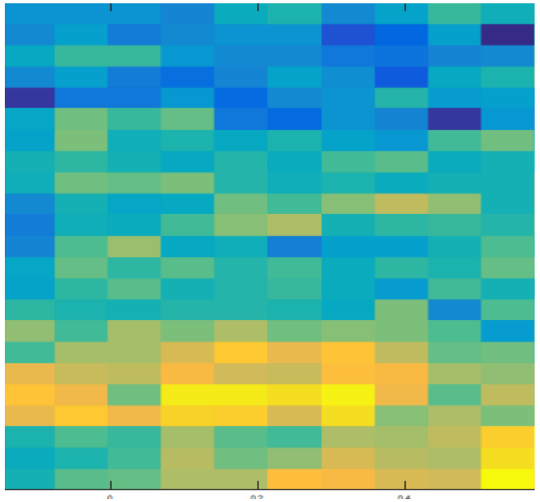
/ta/ < /pa/, synchrony DECREASED

/ta/ > /pa/, synchrony INCREASED

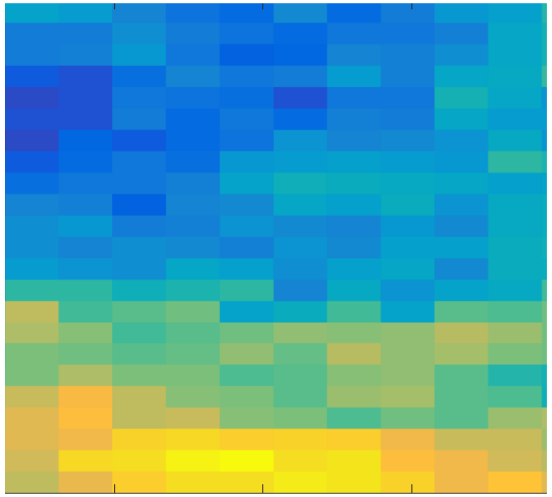
- 450 ms



0 ms

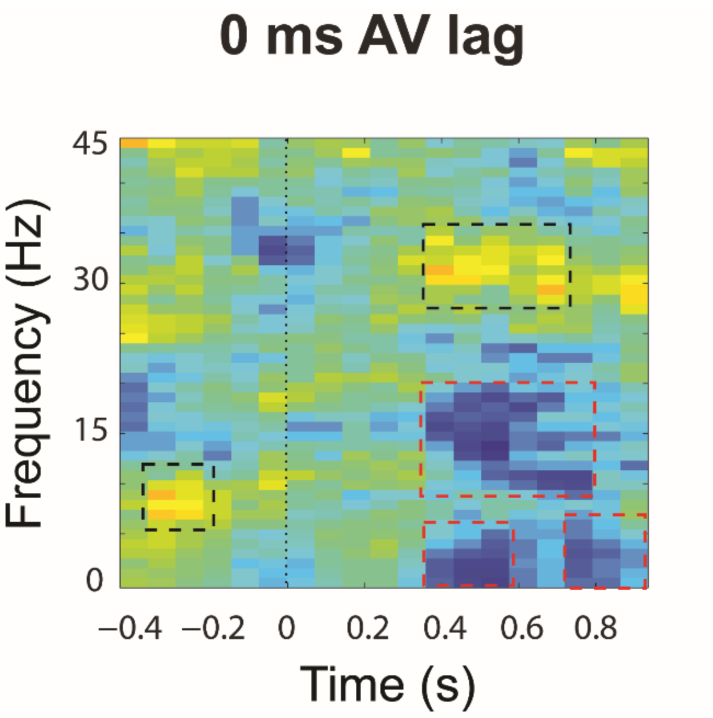


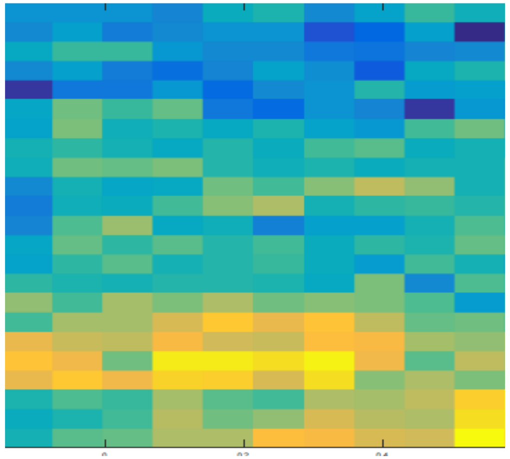
+ 450 ms



Take home message

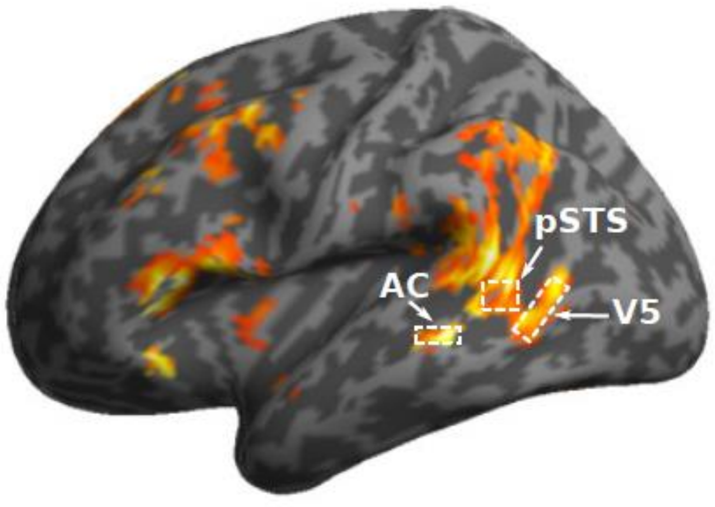
Frequent-percievers rare- percievers

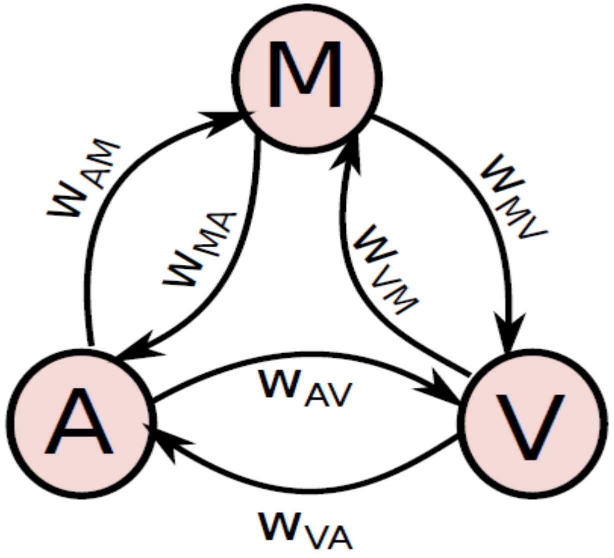




Communication at high frequency, gamma (30-45 Hz) is required for illusory perception

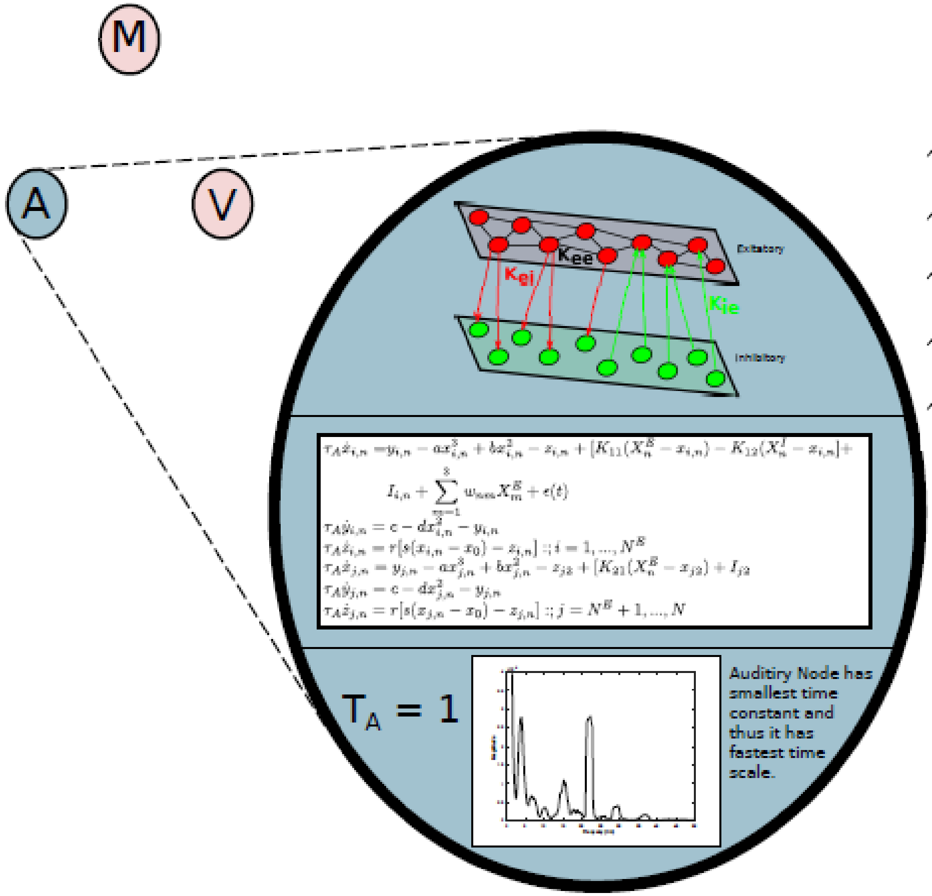
IV. “Somewhat” detailed model of NCN

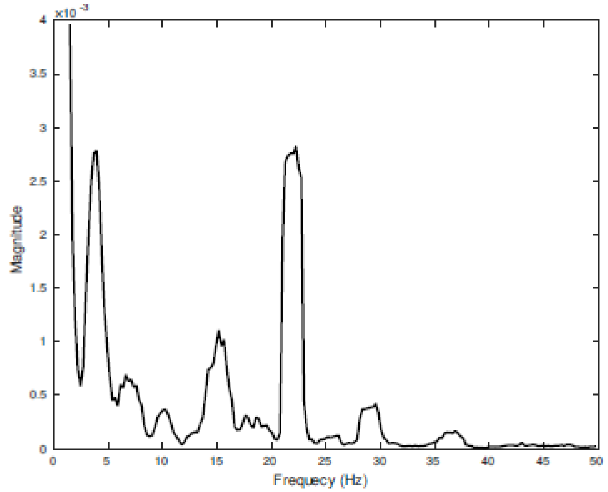




Large-scale model of multisensory of perception

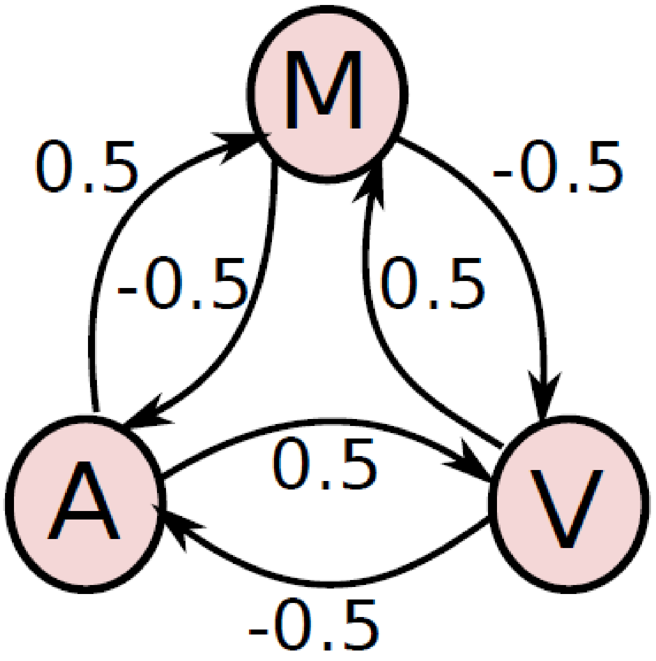
$$\tau_A \dot{x}_{i,n} = y_{i,n} - a x_{i,n}^3 + b x_{i,n}^2 - z_{i,n} + [K_{11}(X_n^E - x_{i,n}) - K_{12}(X_n^I - x_{i,n}] +$$
$$I_{i,n} + \sum_{m=1}^{3} w_{nm} X_m^E + \epsilon(t)$$
$$\tau_A \dot{y}_{i,n} = c - d x_{i,n}^2 - y_{i,n}$$
$$\tau_A \dot{z}_{i,n} = r[s(x_{i,n} - x_0) - z_{i,n}] \;;\; i = 1, ..., N^E$$
$$\tau_A \dot{x}_{j,n} = y_{j,n} - a x_{j,n}^3 + b x_{j,n}^2 - z_{j2} + [K_{21}(X_n^E - x_{j2}) + I_{j2}$$
$$\tau_A \dot{y}_{j,n} = c - d x_{j,n}^2 - y_{j,n}$$
$$\tau_A \dot{z}_{j,n} = r[s(x_{j,n} - x_0) - z_{j,n}] \;;\; j = N^E + 1, ..., N$$





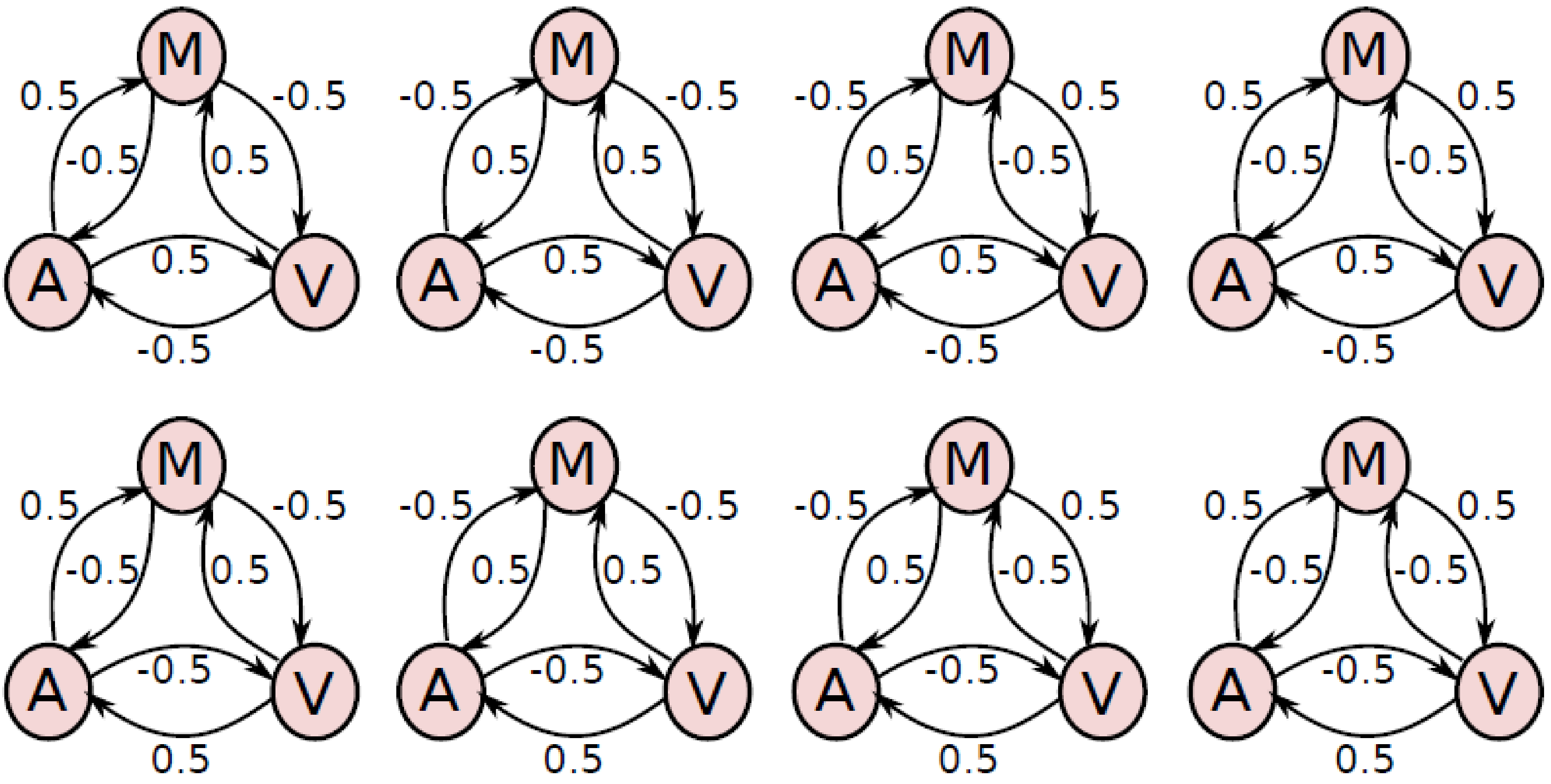
Dutta, Kumar et al (in progress)

Choosing parameters

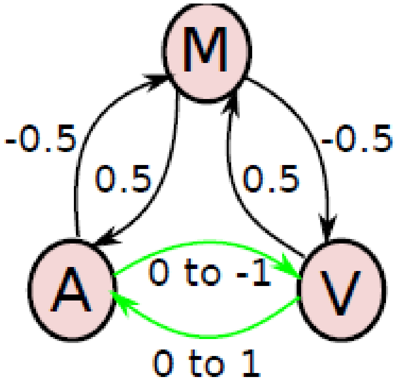


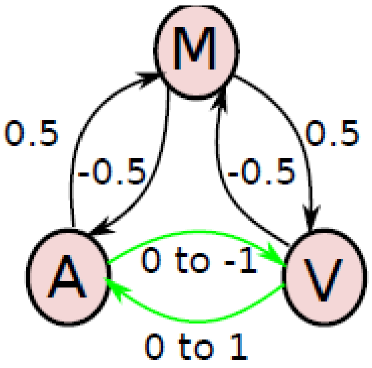
- Coupling of any two nodes is done in a balanced manner.
- Coupling strength of 0.5 is chosen arbitrarily.
- Different values of coupling strength would be experimented

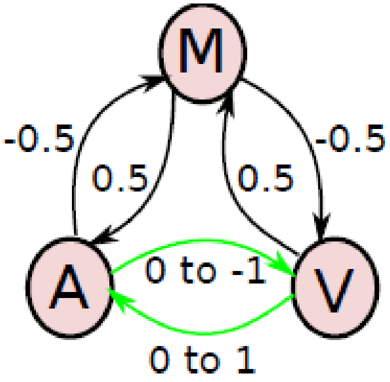
Possible model configurations

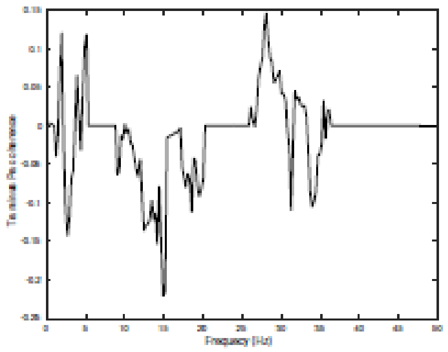


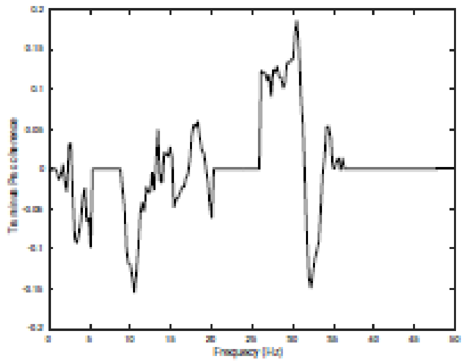
Template matching with empirical data

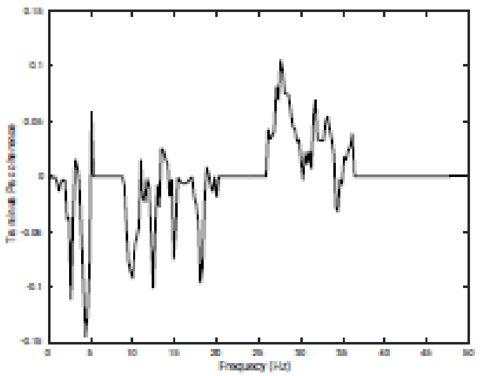












3.96

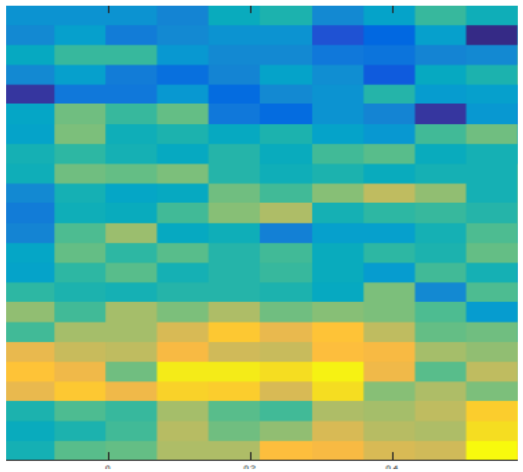
3.76

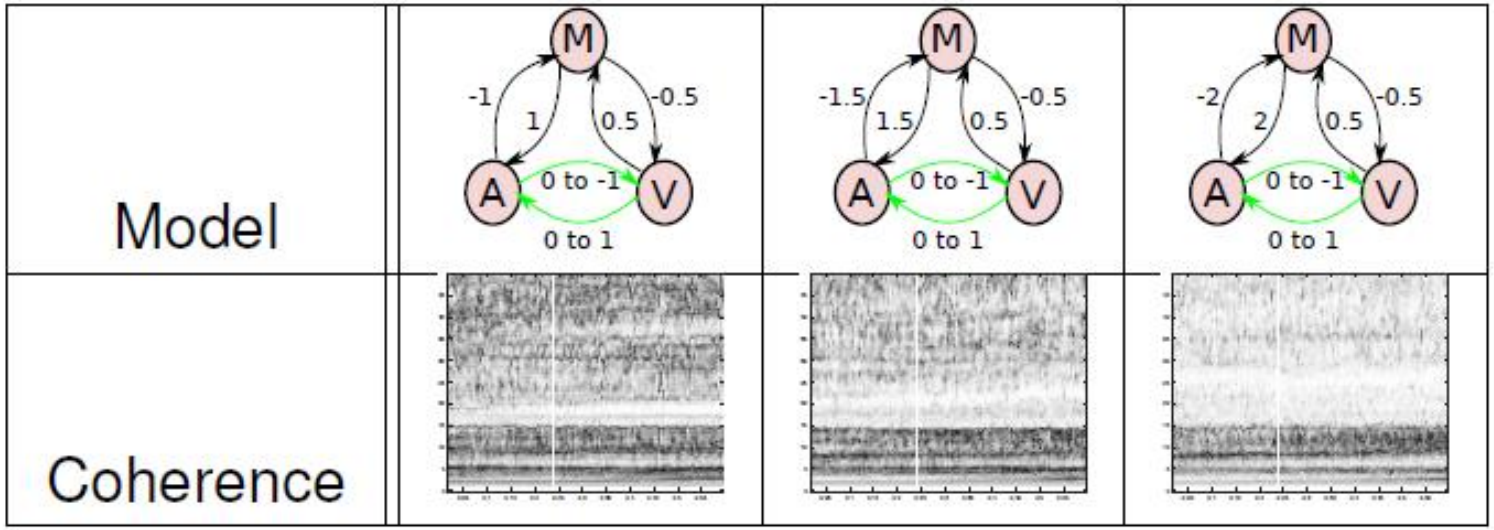
3.36

Interactions of the fast and slow time-scale systems is very crucial for modulating perception

Predicting the neural dynamics of rare perceivers

Empirical





- With increase in A-M coupling , we observe that the resulting coherence pattern shifts towards that of rare percievers.
- Decrease in 7 - 15 Hz coherence as the AV coupling increases. We obeserve no sigficant change in other frequency ranges.

Summary

Dynamic framework of multisensory experience that captures biophysically realistic functional connectivity and environmental constraints as key mediators of perceptual experience

Multimodal (EEG/MRI) and multi-level representation (segregation/ integration/ coherence of EEG signals) of perceptual experience in the brain

Whole-brain analysis techniques give insights to the representational space of multisensory perception

Interactions between fast and slow time-scale systems are crucial in multisensory integration

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THANK YOU