INC talk

COGNITIVE INFORMATION DYNAMICS:

INFORMATION FLOWS INSTABILITIES AND COORDINATION

"Life is like giving a concert on the violin while learning to play the instrument. That, friends, is real wisdom."

Saul Bellow, "My Paris," 1983.

Mikhail Rabinovich December 8 2011

Real wisdom & Information Processing

When we think about information processing in the brain it is useful to paraphrase Bellow as follows: brain activity is like playing a violin in a concert while learning to play and creating the score as you are playing. To do this the brain has to sequentially use cognitive functions such as

* perception of auditory information produced by the violin,
* unsupervised learning of playing,
* working memory to remember the part of the concert already performed,
* decision making to choose the strategy for the next move,
* attention to keep the line of strategy,
* score creation for the following step, and
* generation of a motor program for the action.

In other words, brain information processing includes:

information perception,
transduction,
coordination,
storage, and
information creation.

COGNITION

Cognition - *control of environment and behavior by top-down attention feedback and functional connections*

Consciousness – *cognition + control of self*

Attention – *neuromodulators and brain rhythms (synchronization)*

Memory – *working memory capacity and interval timing*

Control of cognitive control: *Who's in charge ?*

Resting state & Dreams - *learning*

INFORMATION

Quantity – *Shannon entropy, mutual information, etc.*

Quality – *Semantic, functionality, sequential order, …*

Flows – *Transitivity, Capacity & Timing*

Creation *of the information and dynamical chaos*

DYNAMICS

Stability – *robust information flows*

Competition *for recourses (energy, attention, memory)*

Coordination – *Synchronization*

Binding- *stable bunch of information flows*

Bifurcations – *transitions through boundaries between regions with qualitatively different dynamics in the control parameters space*

Mental disorders – *different disorders -> different kind of information flows instabilities*

MAIN POINTS:

- Brain is a generator. It is able to create a new information. The environment just modulate brain activity.

- Brain is intrinsically organized into interactive functional distributed networks and their spatiotemporal activity can be described by dynamical models.

- Brain is characterized by a huge amount of informational feedbacks between it's elements.

We all stand on the shoulders of giants: Brain task-evoked responses & operations are mainly intrinsic dynamics

William James
(1842-1910)

Whilst part of what we perceive comes through our senses from the object before us, another part (and it may be the larger part) always comes out of our own head (1890)

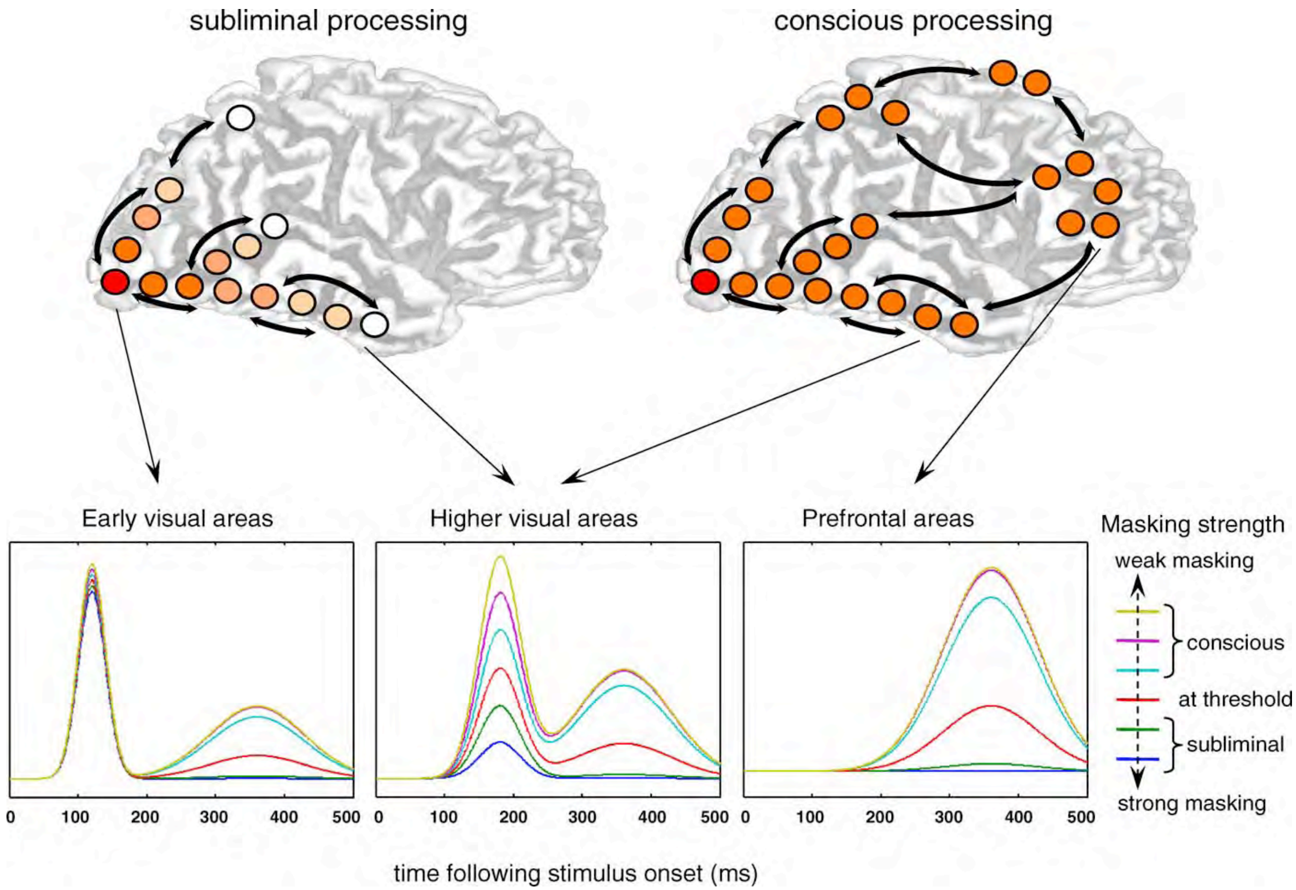
Henri Poincaré
(1854 –1912)

Science and Hypothesis (1905): Intuition & Creativity

Thomas Graham Brown
(1882-1965)

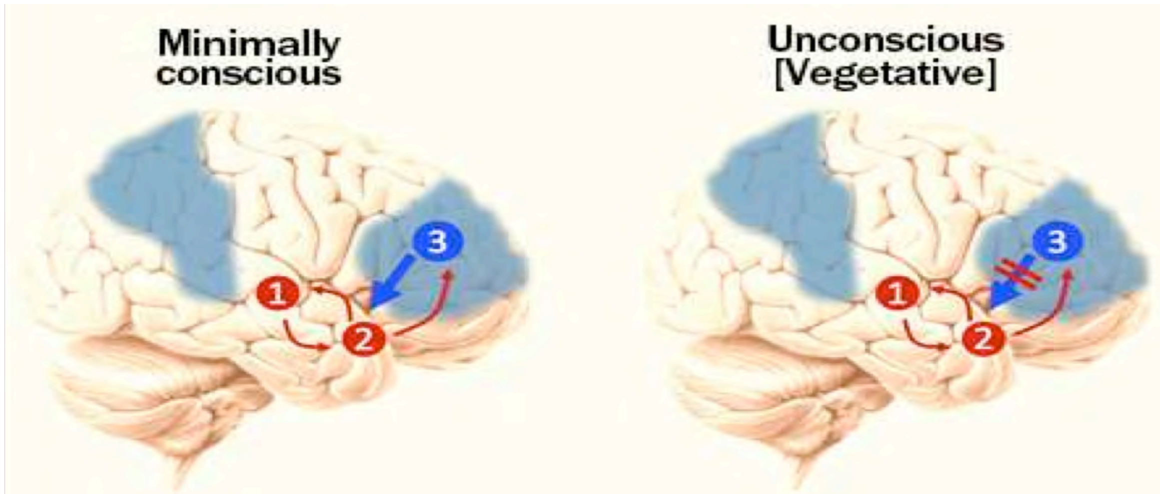
Brain's operations are mainly intrinsic maintenance of information for interpreting, responding and predicting…(1914)

Brain information flows in physical space



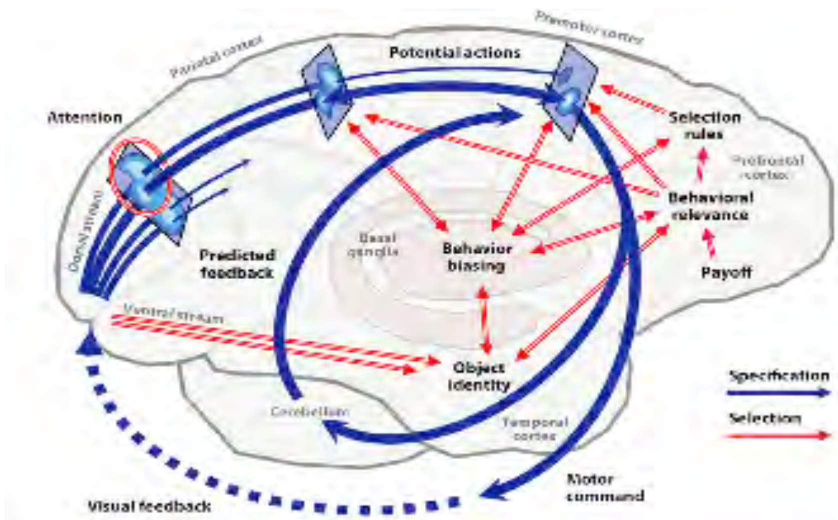
(PLoS Biology, 2007, Brain Dynamics Underlying the Nonlinear Threshold for Access to Consciousness, Del Cul, Baillet, Dehaene).

The role of information feedback



The flow of information in the brain might be a crucial element of why patients in vegetative states cant move or speak on their own accord. Signals can pass into the frontal cortex (area 3) considered the brains decision-making center but neurons there cant send messages back out (adapted from Gosseries et al. 2011).

Competition of the information flows in the brain



The primate brain is shown, emphasizing the cerebral cortex, cerebellum, and basal ganglia. Dark blue arrows represent processes of action specification, which begin in the visual cortex and proceed rightward across the parietal lobe, and which transform visual information into representations of potential actions. Polygons represent three neural populations along this route. Each population is depicted as a map where the lightest regions correspond to peaks of tuned activity, which compete for further processing. This competition is biased by input from the basal ganglia and prefrontal cortical regions that collect information for action selection (red double-line arrows). Modified from Cisek P, Kalaska JF. Neural mechanisms for interacting with a world full of action choices. Annu Rev Neurosci 2010;33:269–98.

No evolution - No cognitive function execution

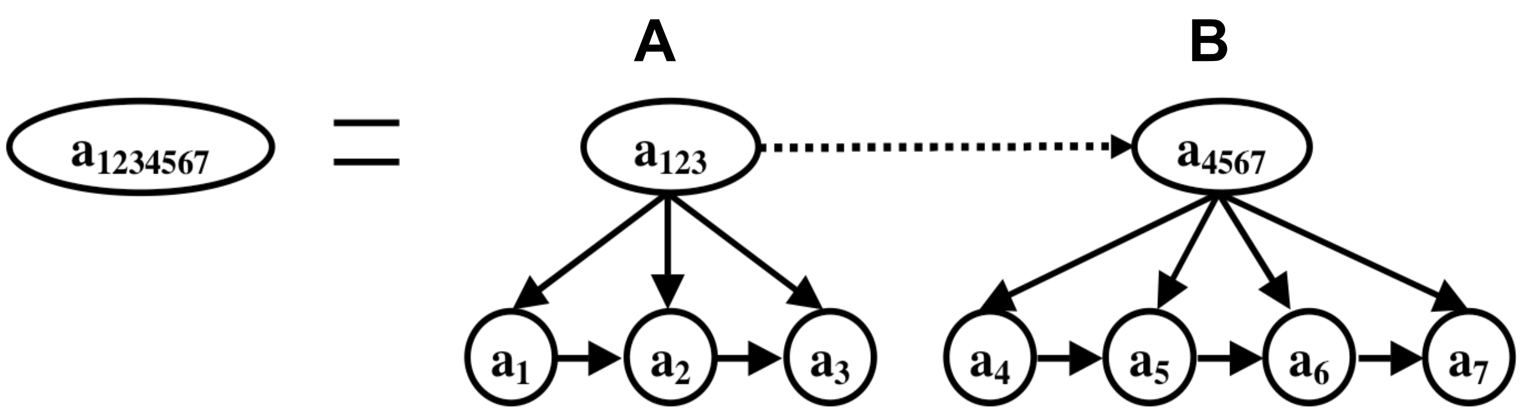
Time is a fundamental dimension of Brain functions. It is expressed in the sequential ordering of steps or intermittent states in a wide variety of activities such as language, motor control or in the broader domain of long range goal-directed actions. It is a lot of evidence that transient internal brain dynamics are a key feature governing mental function.

Karl Lashley (1890-1958)

In the paper "The Problem of Serial Order in Behavior" (1951) he pointed out that complex sequential behavior (such as playing a piece on the piano or speech) could not be executed by one response sending a proprioceptive signal back to the brain, which would then trigger the next response in the sequence. Behavior had to be controlled by a central, hierarchically organized program.

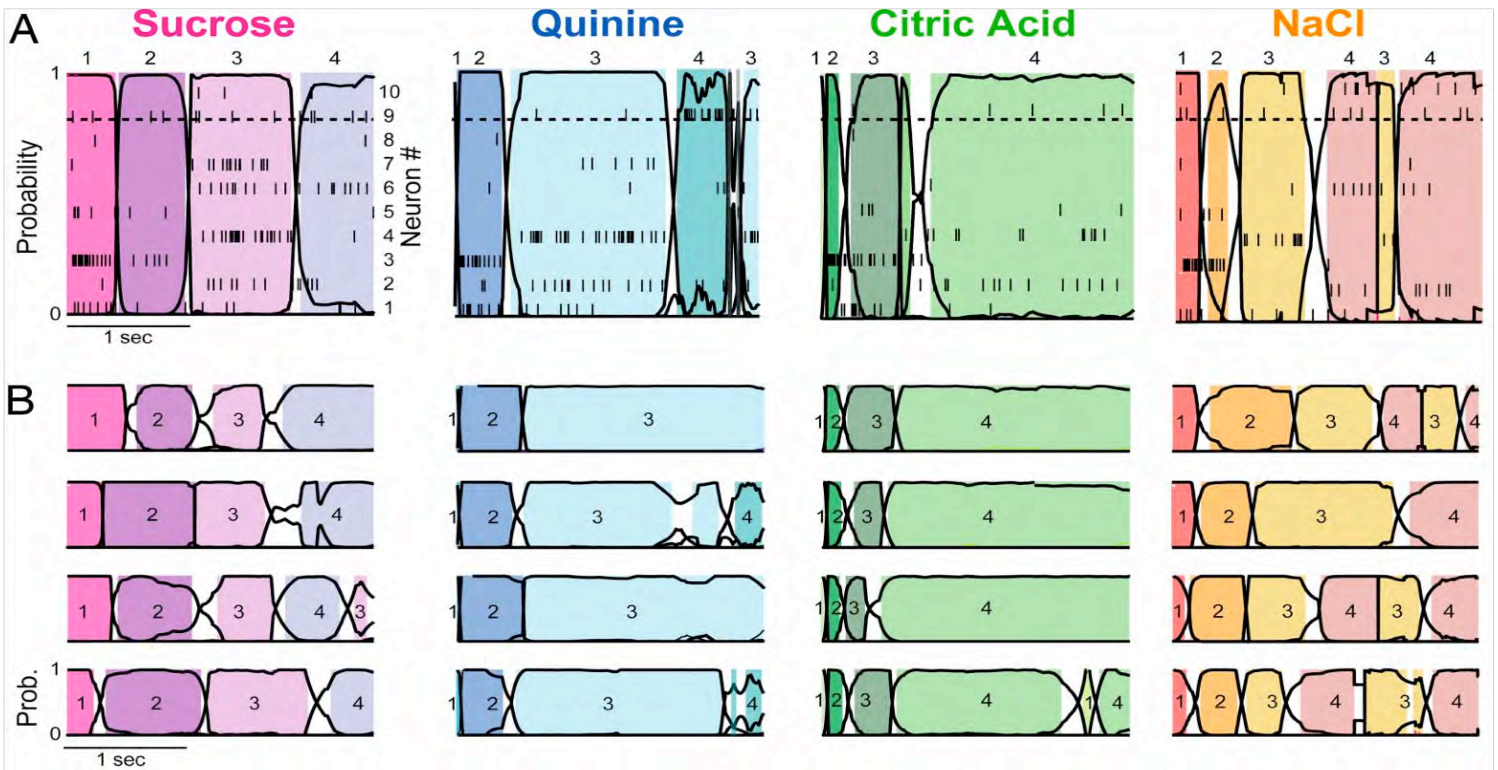
Robert Port & Timothy van Gelder
"Mind as Motion" 1995

Internal representations of words are not symbols but location in State Space, the lexicon or dictionary is the structure in this space, and processing rules are not symbolic specifications but the dynamics of the system which push the system state in certain direction rather than others. (Ch.8 Language as Dynamical System)

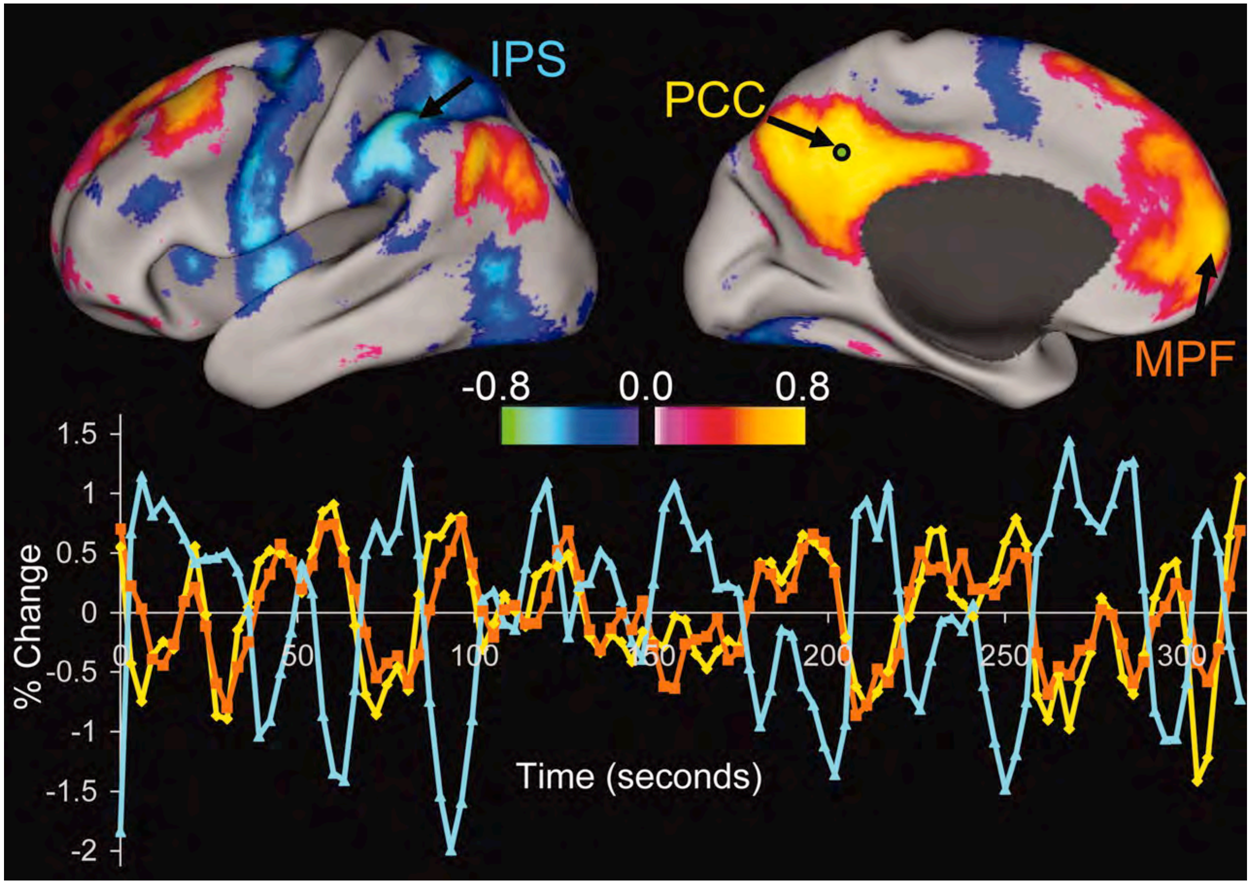


Representation of the Tastes by Transients

A. Taste-specific sequences in rat's GC for 4 different tastes (among 10 GC neurons). B. The sequences of metastable states are reproducible in spite of the irregularity in their switching times (Jones et al PNAS 2007).

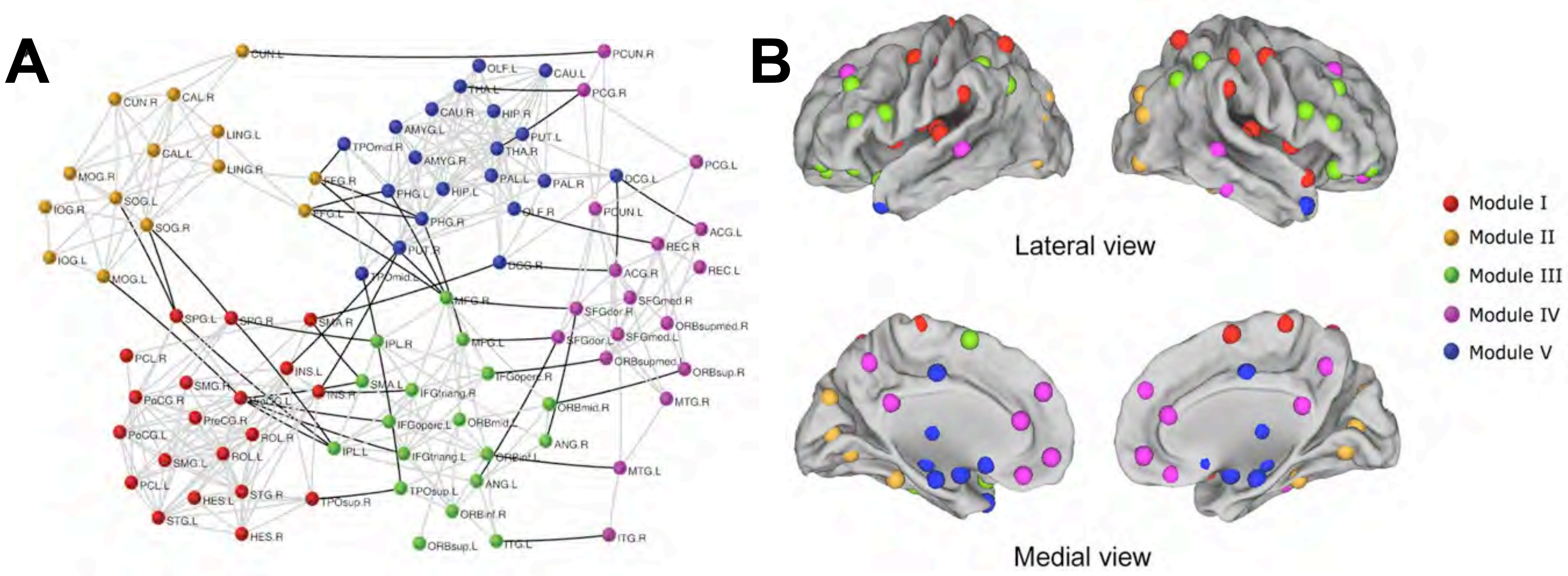


Default Modes Flip-Flop Competition



Fox et al, PNAS, 2005

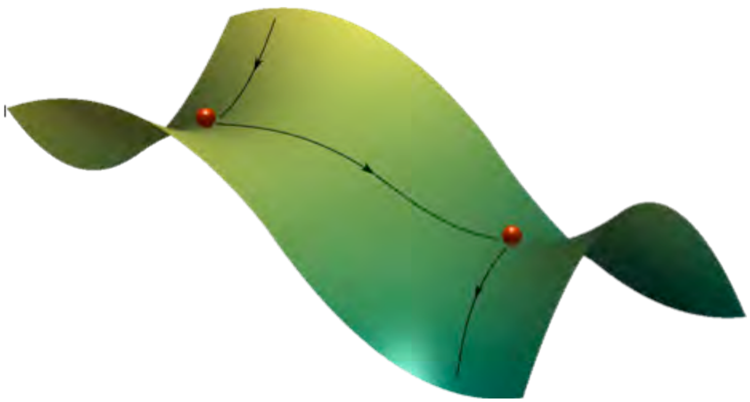
The structure of resting-state brain modes (He et al., 2009)



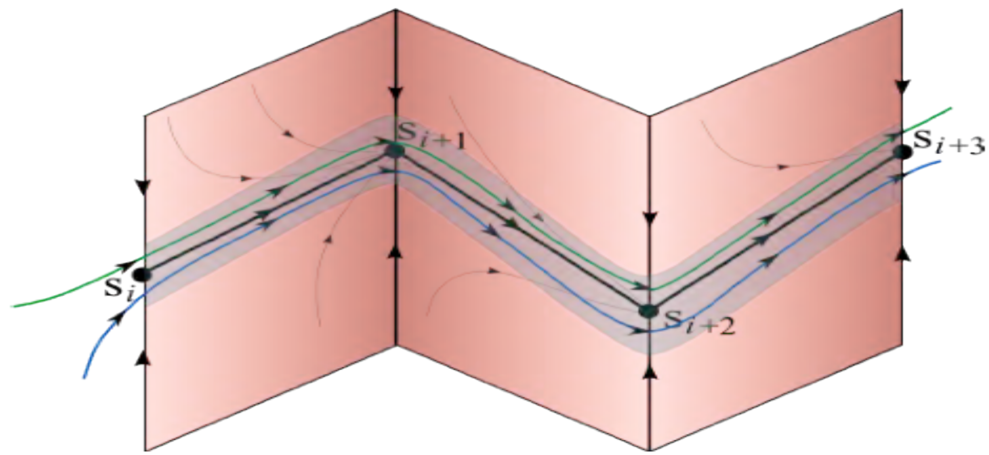
A) The intra-mode and inter-mode connections are shown in gray and dark lines, respectively.

B) Surface representation of modes architecture of resting brain. All 90 brain clusters are marked by using different colored spheres (different colors represent distinct modes).

Image of Stable Information Flow in State Space



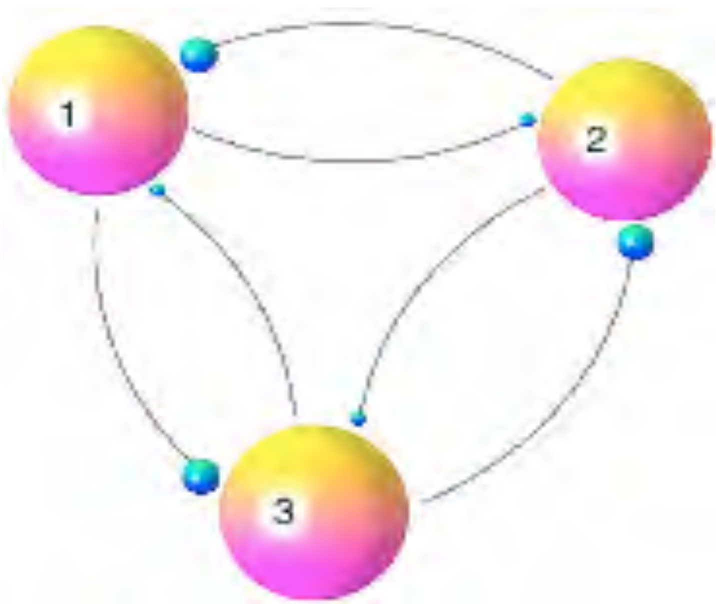
Simple Heteroclinic Chain

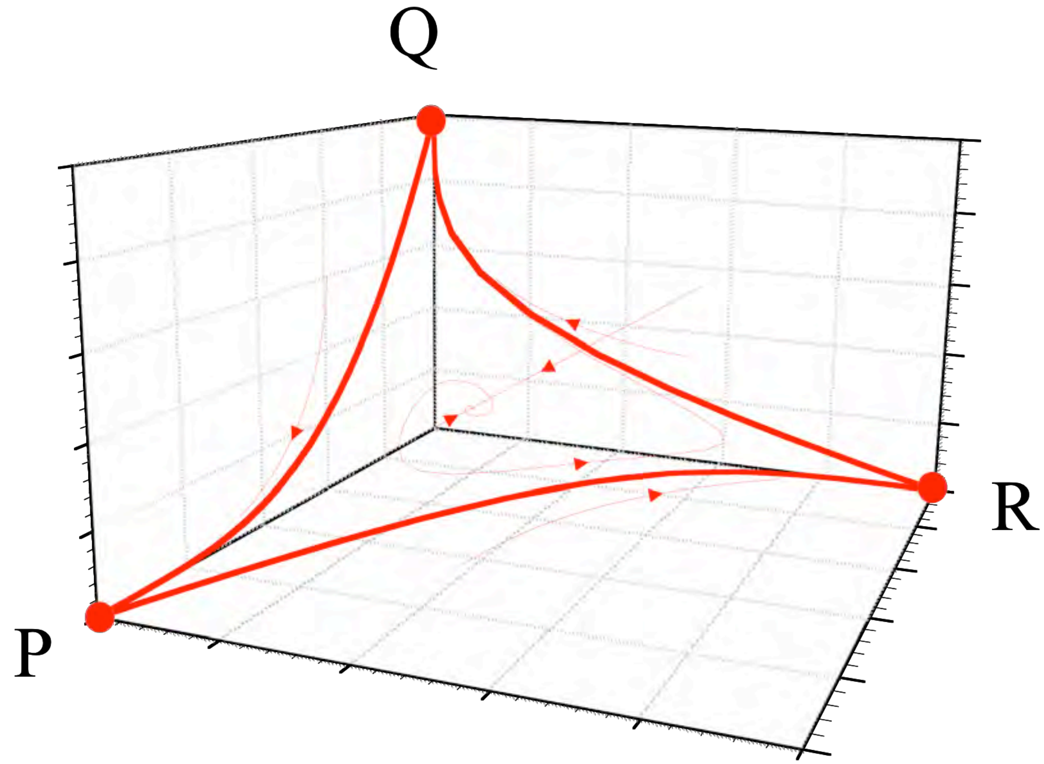


Robust Sequence of Brain Metastable States

Afraimovich et al., Chaos, 2004; Rabinovich et al., PLoS Comp. Biol. 2008; Rabinovich et al., SCIENCE 2008.

Winnerless Competition - closed heteroclinic chain





Conditions of the Information Flow Stability

Different information inputs (external or internal stimuli) are represented in the phase space by different sequences of global modes activity – different chains of metastable states. The specific topology of the signal-dependent information flow is a key feature that helps to solve a problem of information flow stability against stationary noise.

$$\lambda_1^{(i)} > 0 > \mathrm{Re}\,\lambda_2^{(i)} \geq \mathrm{Re}\,\lambda_3^{(i)} \geq \ldots \geq \mathrm{Re}\,\lambda_d^{(i)}$$

The number $\nu_i = -\mathrm{Re}\,\lambda_2^{(i)} / \lambda_1^{(i)}$ is called the saddle value. If $\nu_i > 1$ (the compressing is larger than the stretching), the saddle is named as a dissipative saddle. Intuitively it is clear that the trajectories do not leave the heteroclinic channel if all saddles in the heteroclinic chain are dissipative

Information flow Capacity

$$\Delta C_{IF}(l) = J_l + \sum_{j=1}^{J_l} \frac{\operatorname{Re}\lambda_j^l}{|\lambda_{J_{l+1}}^l|} \qquad (5)$$

$$\operatorname{Re}\lambda_1^{(i)} > 0 > \operatorname{Re}\lambda_2^{(i)} \geq \operatorname{Re}\lambda_3^{(i)} \geq \ldots \geq \operatorname{Re}\lambda_d^{(i)}$$

$$\sum_{j=1}^{J} \operatorname{Re}\lambda_j > 0, \sum_{j=1}^{J+1} \operatorname{Re}\lambda_j < 0$$

If the unstable separatricies of all saddles along the flow are one dimensional, such that $J_l = 1$ we have:

Lessons from the experiments. How to build a model:

A *FUNCTIONAL COMPETITION: ecological principle – mental resources are limited (Kahneman D. 1973)*

B *METASTABILITY and STABLE TRANSIENTS – In complex nonequilibrium systems, like Brain, they are generic phenomena.*

Ideas for dynamical modeling:

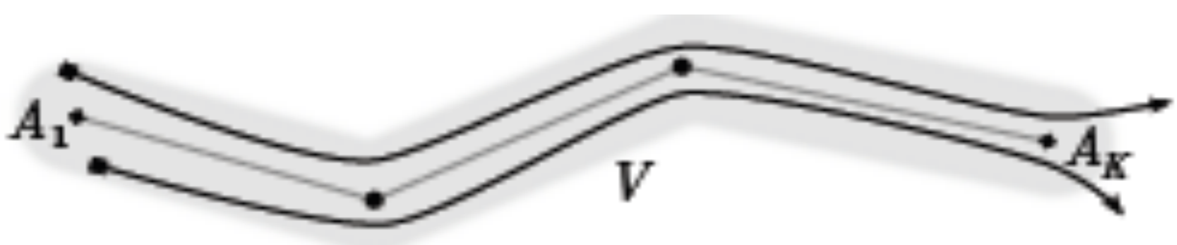
1) Linear increments must be stabilized by self- and mutual-inhibition (modes competition);
2) The existence in a phase space of metastable states that represent the activity of individual modes;
3) Metastable states must be connected by separatrices to build the sequence.

Rabinovich et al., PRL, 2001, Afraimovich et al., Chaos, 2004;

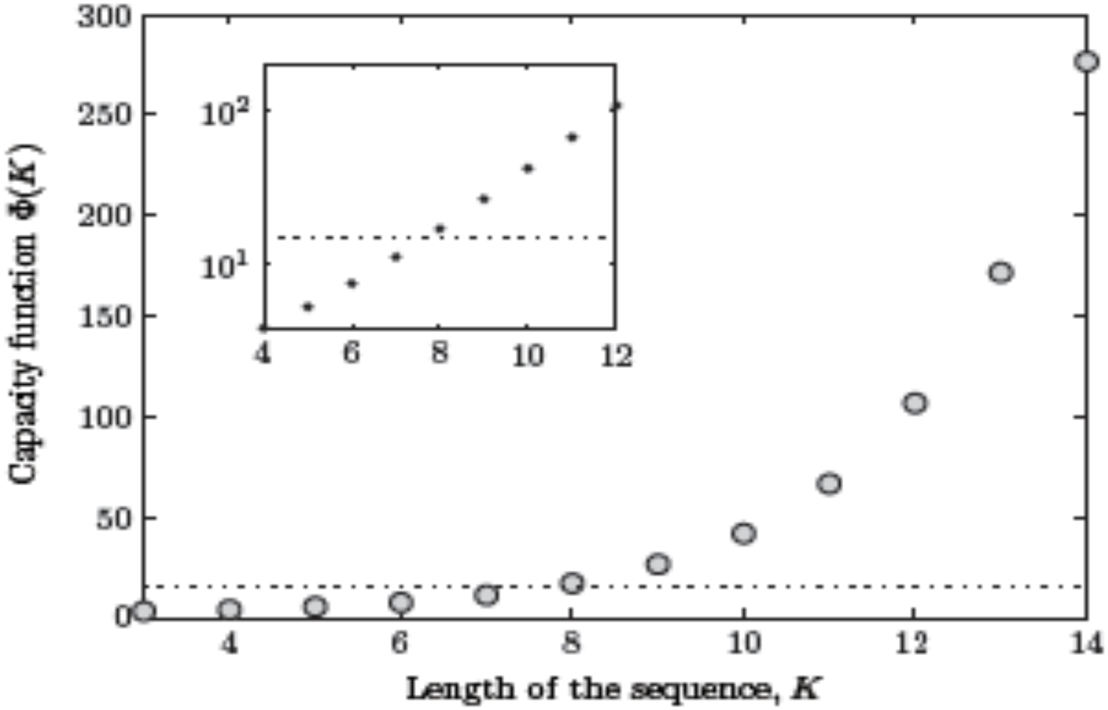
Sequential working memory capacity:

it is the number of items in the chain that can be recalled without error - length of the information flow before it loose its stability

$$\dot{a}_i = a_i \left(\sigma_i(M,S) - \left(a_i + \sum_{j \neq i} \varrho_{ij}(M,S) a_j \right) \right)$$



SWM - Dynamical origin of the "magic number" seven

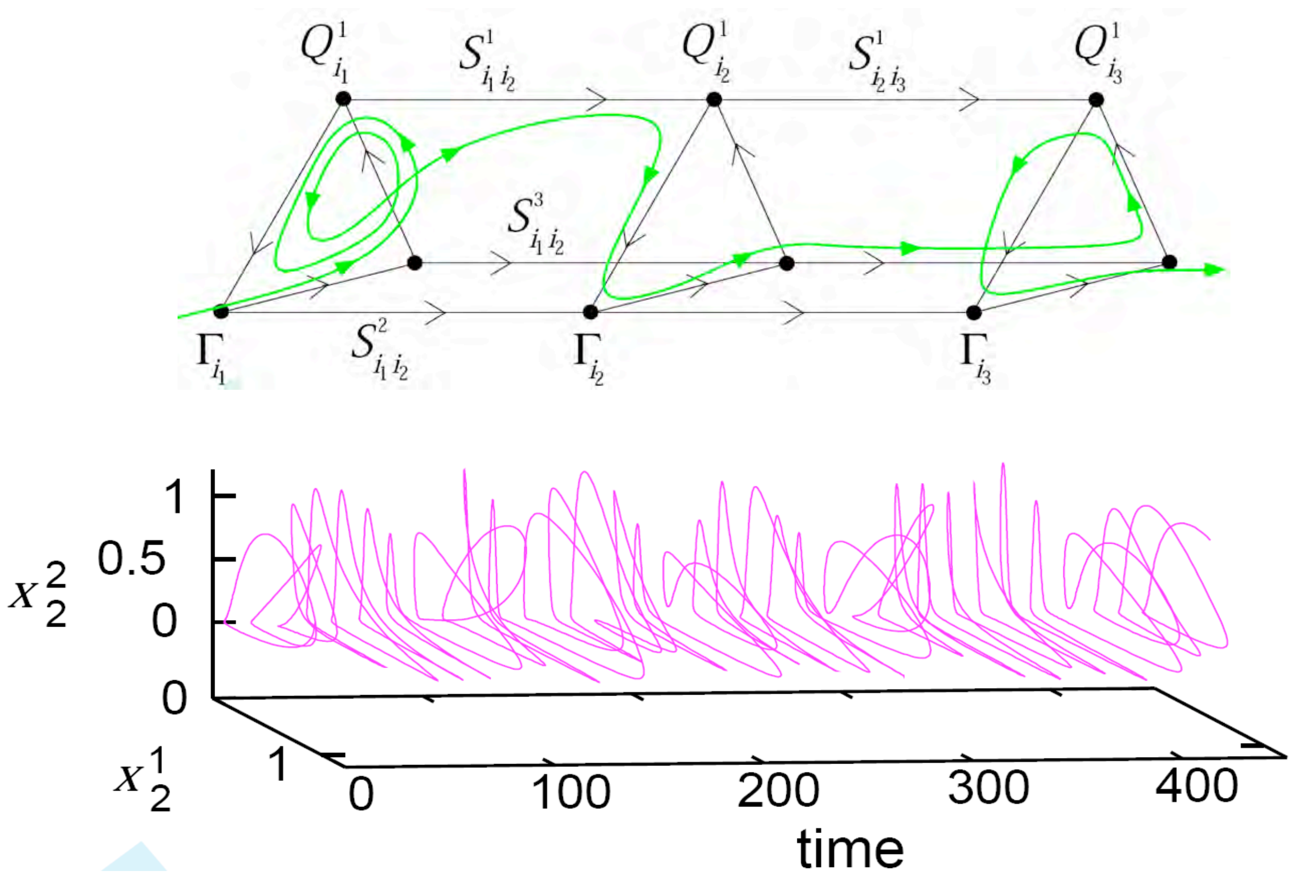


Bick & Rabinovich PRL (2009), Dynamical Syst. (2009)

Integrating information across the senses can enhance our ability to detect and classify objects in the environment.

Suppose that we are testing a sample of wine. Flavour perception reflects processing of inputs from multiple sensory systems: from gustation (through the stimulation of receptors on the tongue and in the mouth), smell (through the stimulation of receptors in the olfactory mucosa) and oral somato-sensation (through the stimulation of diverse receptors in the oral cavity, providing information about viscosity, temperature, pungency). Even though they derive from signals transmitted over several nerves, flavours often appear remarkably coherent in phenomenal perception.

Heteroclinic Binding – Bunching of flows corresponding to different modalities



Rabinovich MI, Afraimovich VS, Varona P. Heteroclinic binding. Dyn Syst Internat J 2010;25(3):433–42

Information flow Capacity

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$$\operatorname{Re}\lambda_1^{(i)} > 0 > \operatorname{Re}\lambda_2^{(i)} \geq \operatorname{Re}\lambda_3^{(i)} \geq \ldots \geq \operatorname{Re}\lambda_d^{(i)}$$

$$\sum_{j=1}^{J} \operatorname{Re}\lambda_j > 0, \sum_{j=1}^{J+1} \operatorname{Re}\lambda_j < 0$$

If the unstable separatricies of all saddles along the flow are one dimensional, such that $J_l = 1$ we have:

Mental Modes & Mental Variables

Cognitive field	$K_f = \sum_i A_i(t) U_i(n_f),$
Emotional field	$E = \sum_i B_i(t) W_i(m),$
Resources	$P = \sum_i R_i(t) Y_i(l),$
Variables	$A_i, B_i, R_i \geq 0$

Recent functional brain imaging on human subjects has begun to reveal neural substrates that are the elements of the modes U, W and Y

Ecological Model of Mental Dynamics

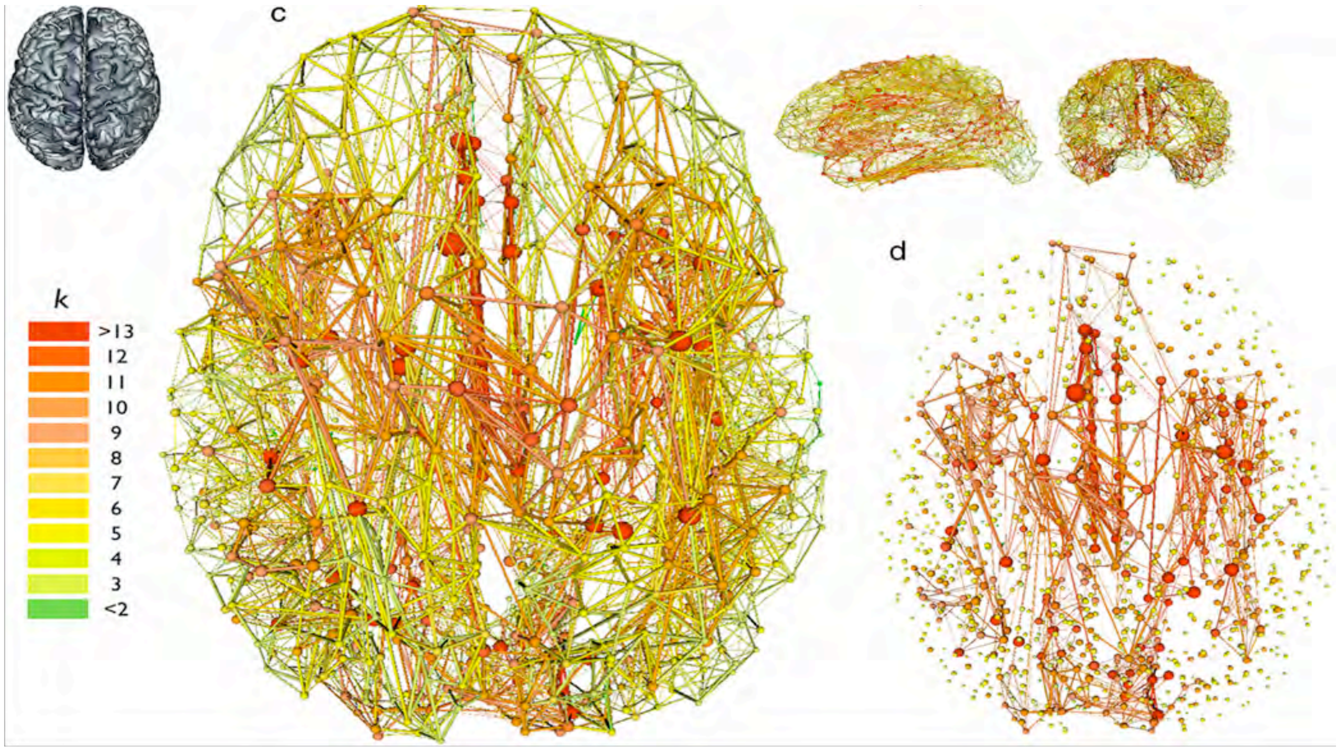
$$\tau_{A_i} \frac{d}{dt} A_i(t) = A_i(t) \cdot F(\mathbf{A}, \mathbf{B}, \mathbf{R}, \mathbf{S})$$

$$\tau_{B_i} \frac{d}{dt} B_i(t) = B_i(t) \cdot \Phi(\mathbf{A}, \mathbf{B}, \mathbf{R}, \mathbf{S})$$

$$\theta_i \frac{d}{dt} R_i(t) = R_i(t) \cdot Q(\mathbf{A}, \mathbf{B}, \mathbf{R}, \mathbf{S})$$

F(…), Φ(…),Q(…) describe an interaction of mental modes & can be identified, in principle, by brain imaging (fMRI)

“Rich Club” connections



This image shows the group connectome, with the nodes and connections colored according to their rich-club participation. Green represents few connections. Red represents the most: **c** shows the all, **d** shows just rich club – k>9 *(Van den Heuvel & Sporns, J. Neuroscience 2011).*

Emotion-Cognition Interaction

Set of Cognitive Modes:

$$\tau_{A_i}\frac{d}{dt}A_i(t)=A_i(t)\cdot\left[\sigma_i(\mathbf{S},\mathbf{B},\mathbf{R}_A)-\sum_{j=1}^{N}\rho_{ij}A_i(t)\right]+A_i(t)\eta_A(t),$$

Set of Emotional Modes:

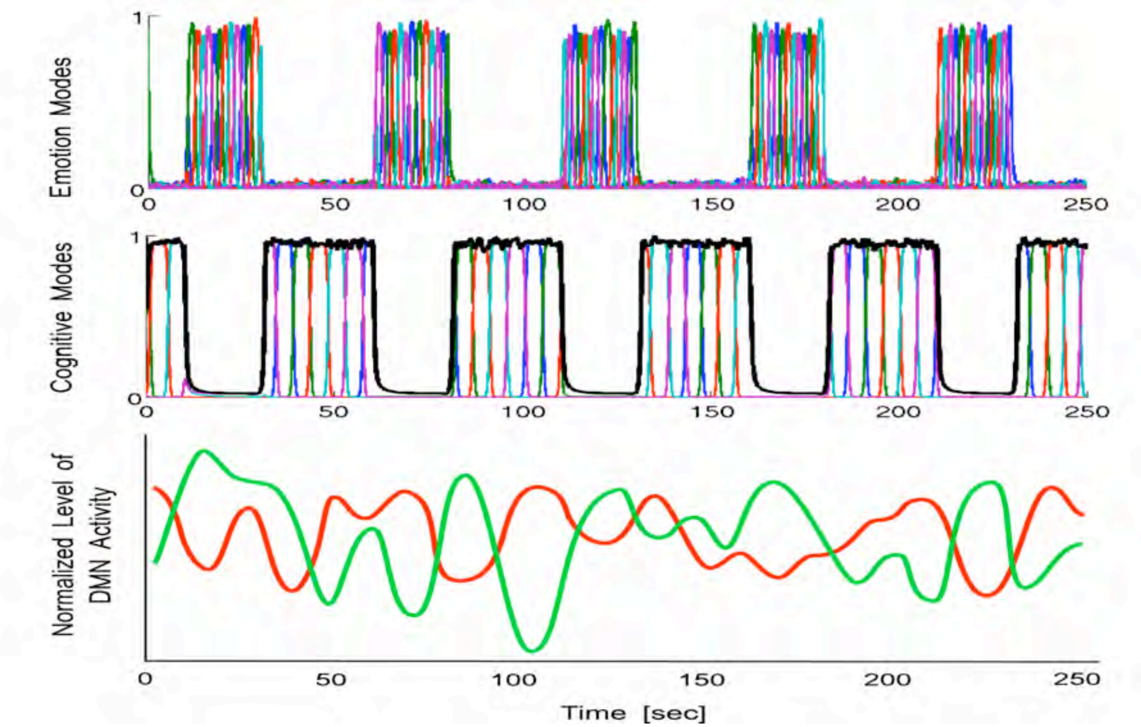
$$\tau_{B_i}\frac{d}{dt}B_i(t)=B_i(t)\cdot\left[\zeta_i(\mathbf{S},\mathbf{A},\mathbf{R}_B)-\sum_{j=1}^{M}\xi_{ij}B_i(t)\right]+B_i(t)\eta_B(t),$$

Mental Resources Modes:

$$\theta_A^i\frac{d}{dt}R_A^i(t)=R_A^i(t)\cdot\left[\sum_{j=1}^{M}A_j(t)-\Gamma_A-\phi_A\Gamma_B+d_A(t)\right],$$

$$\theta_B^i\frac{d}{dt}R_B^i(t)=R_B^i(t)\cdot\left[\sum_{j=1}^{M}B_j(t)-\Gamma_B-\phi_B\Gamma_A+d_B(t)\right]$$

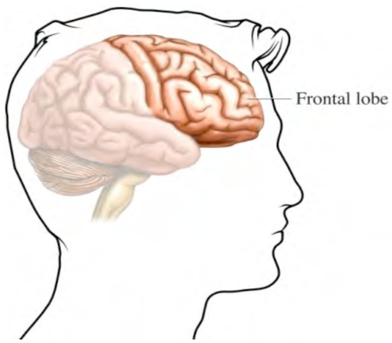
Low Frequency Activity in Resting State: Modulation Instability

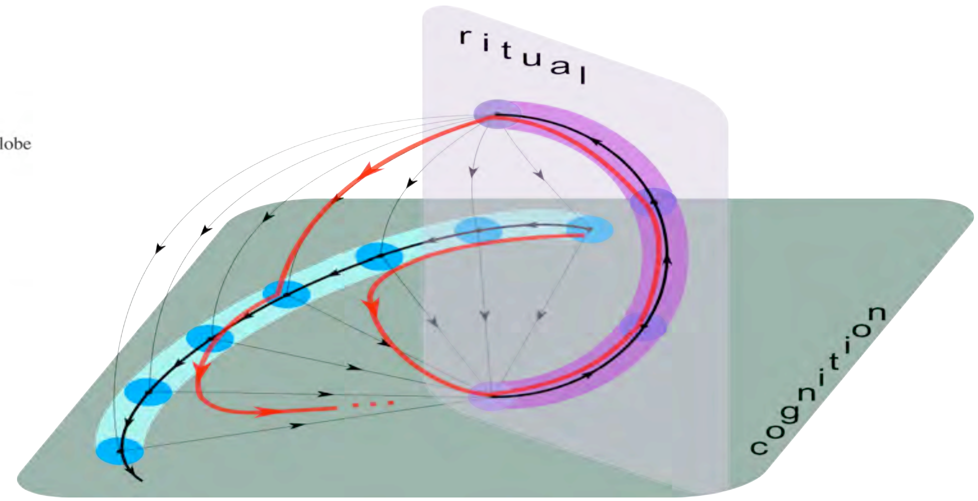


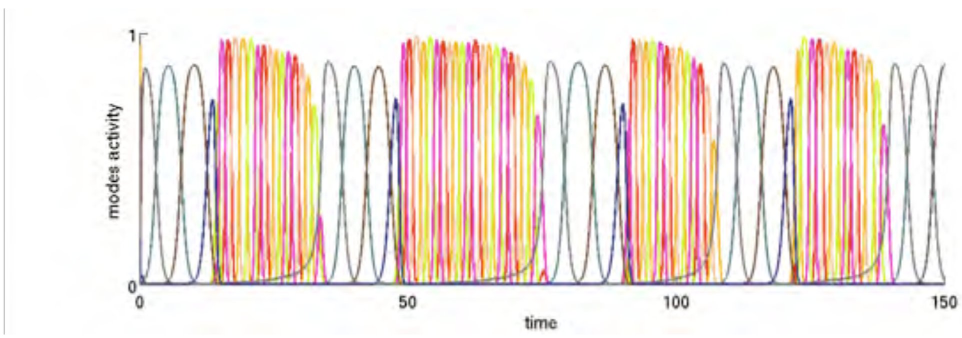
Rabinovich, Muezzinoglu, Strigo, Bystritsky: PLoS Comp. Biology. September 2010, Volume 5, Issue 9

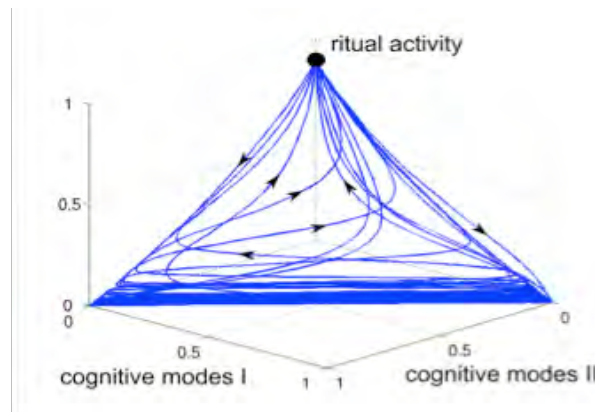
Obsessive Compulsive Disorder (OCD):

Intermittent Chaos



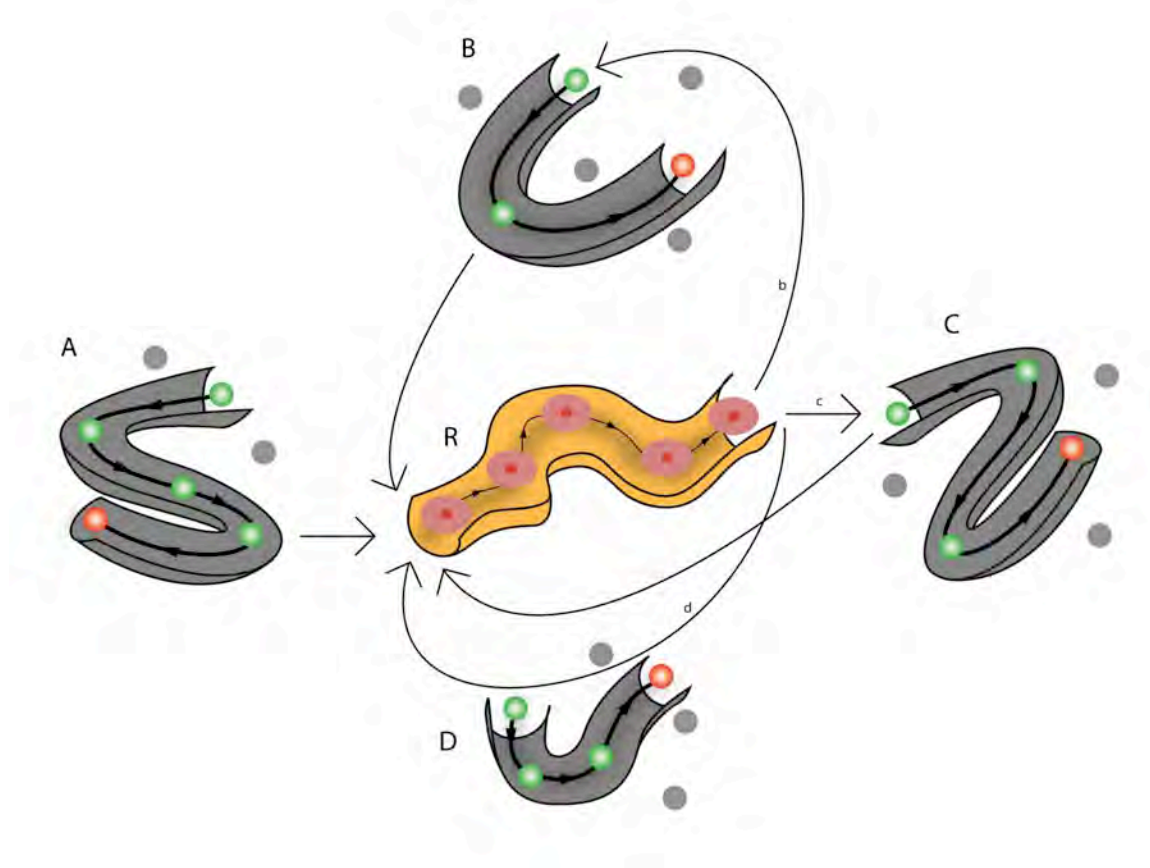






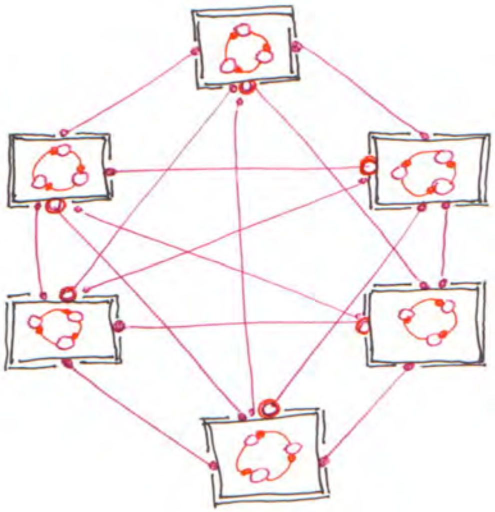
Rabinovich, Muezzinoglu, Strigo, Bystritsky, PLoS Comp.Biol. 2010, v.5 (9)

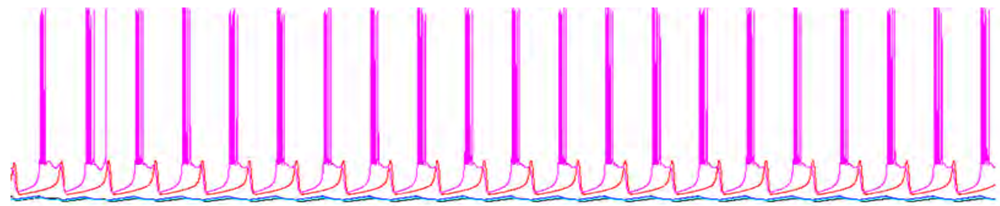
Dynamical image of obsessive compulsive behavior



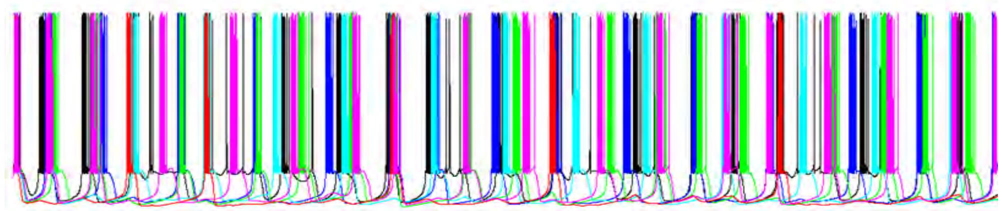
Bystritsky et al. Computational non-linear dynamical psychiatry: A new methodological paradigm for diagnosis and course of illness. *J. Psychiatric Research. 2011 (December)*.

Functionally dependent network dynamics





A



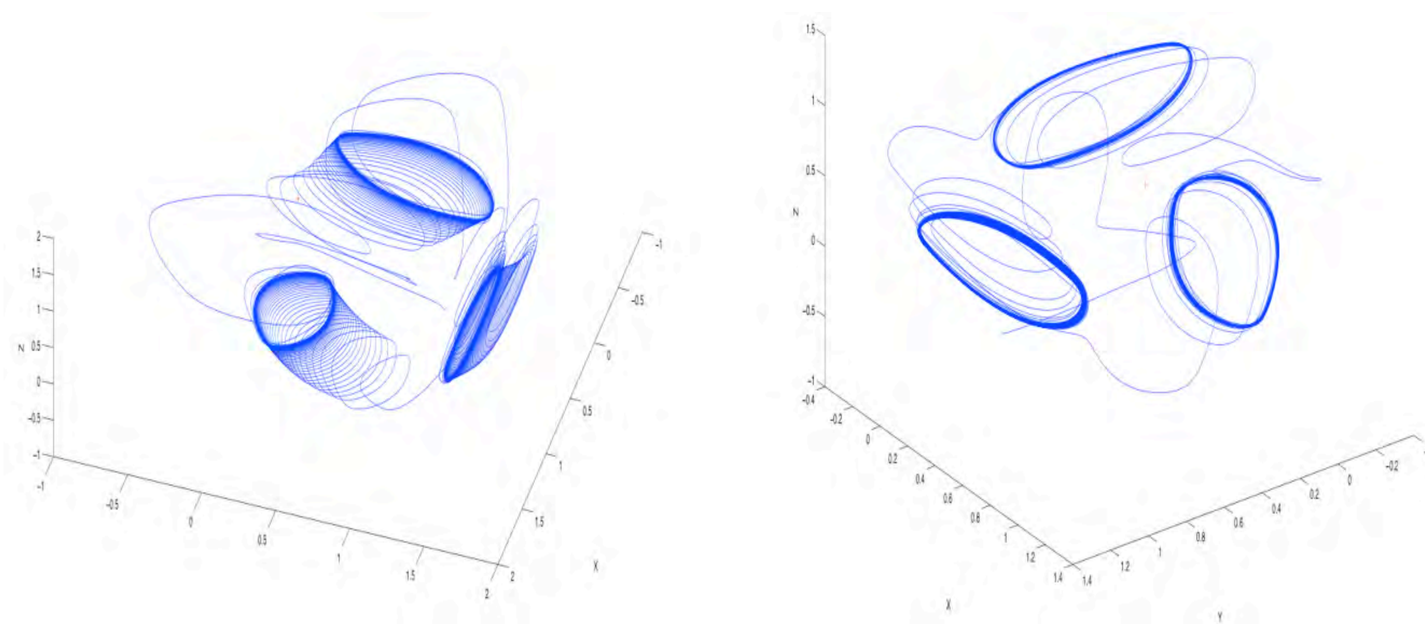
B

$$\dot{A}_j = A_j[\varsigma_j - \sum_{l=1}^{N}(\rho^0_{jl} + \rho^f_{jl}(\frac{1}{\tau}\int_{t-\tau}^{t} F(\psi_j - \psi_l)dt))A_l]$$

$$\dot{\psi}_j = \omega_j + Qsin(\psi_j - \Omega t)$$

P. Varona et all. Basic model of functional brain networks – Chaotic synchronization. 2011 (in prep.)

Closed stable heteroclinic flow: triangle network of inhibitory coupled spiking neurons



Guilhem Sommeria-Klein et al., 2011 (in prep.)

Future Directions

- Role of the synchronization in information flow stability
- Stability of sequential order and information quality
- Feedback Control of flow instability – A possible mechanism for dynamical control of mental disorders

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Allan Simmons,
Irina Strigo
& Pablo Varona

Thank you