



# From understanding the brain to neurocognitive technologies

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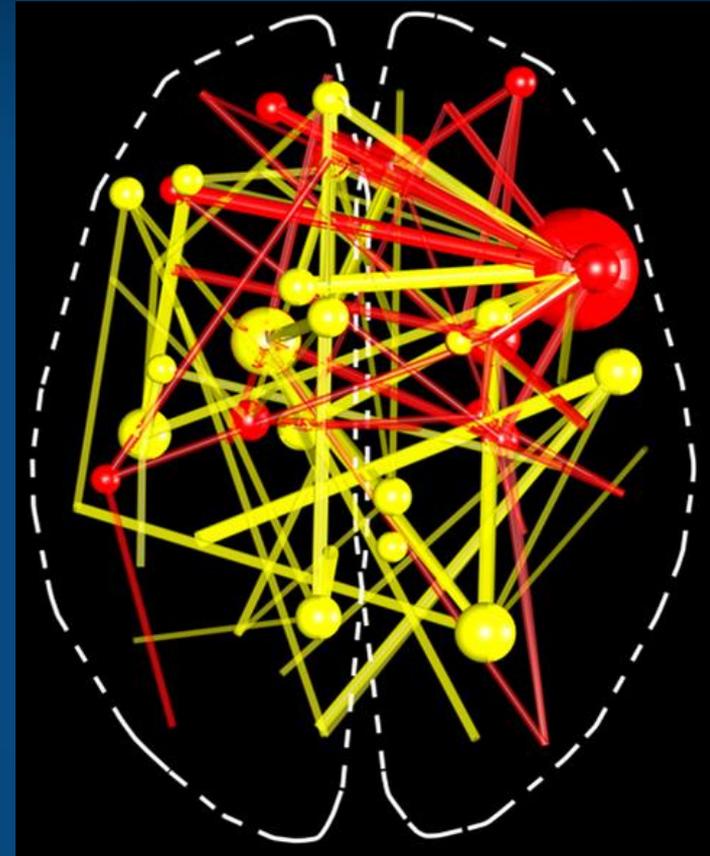
# My favorite organ! Who controls it?



# Questions

**What is the best way to understand and improve the efficiency of human brains?**

- Neurocognitive technologies now.
- Understanding brain-behavior relations.
- Decomposing brain dynamics.
- Reading mental states.
- From understanding to taking control over our brains.
- Brain-inspired cognitive architectures?

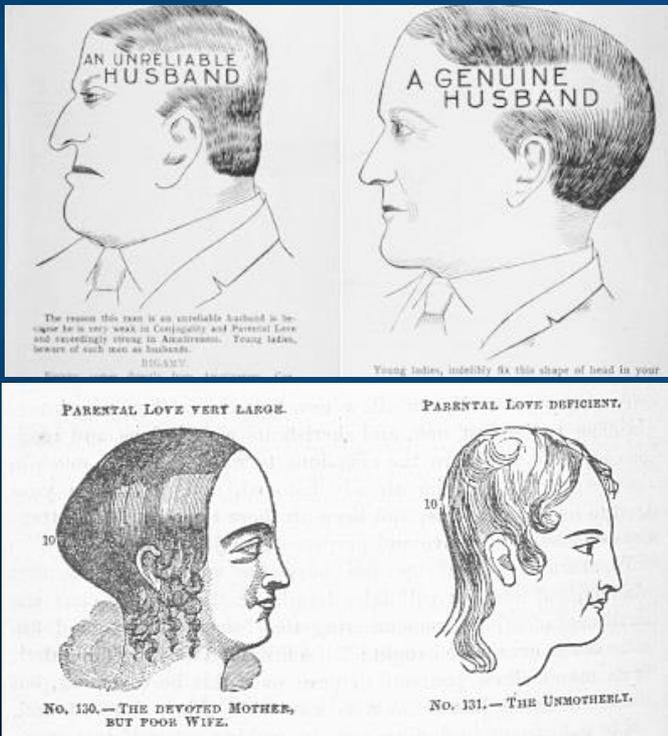


Duch W (1994) Towards Artificial Minds. First PNNS Conference, Kule 1994

Duch W (2009), Neurocognitive Informatics Manifesto. California Polytechnic State University, pp. 264-282.

# Phrenology

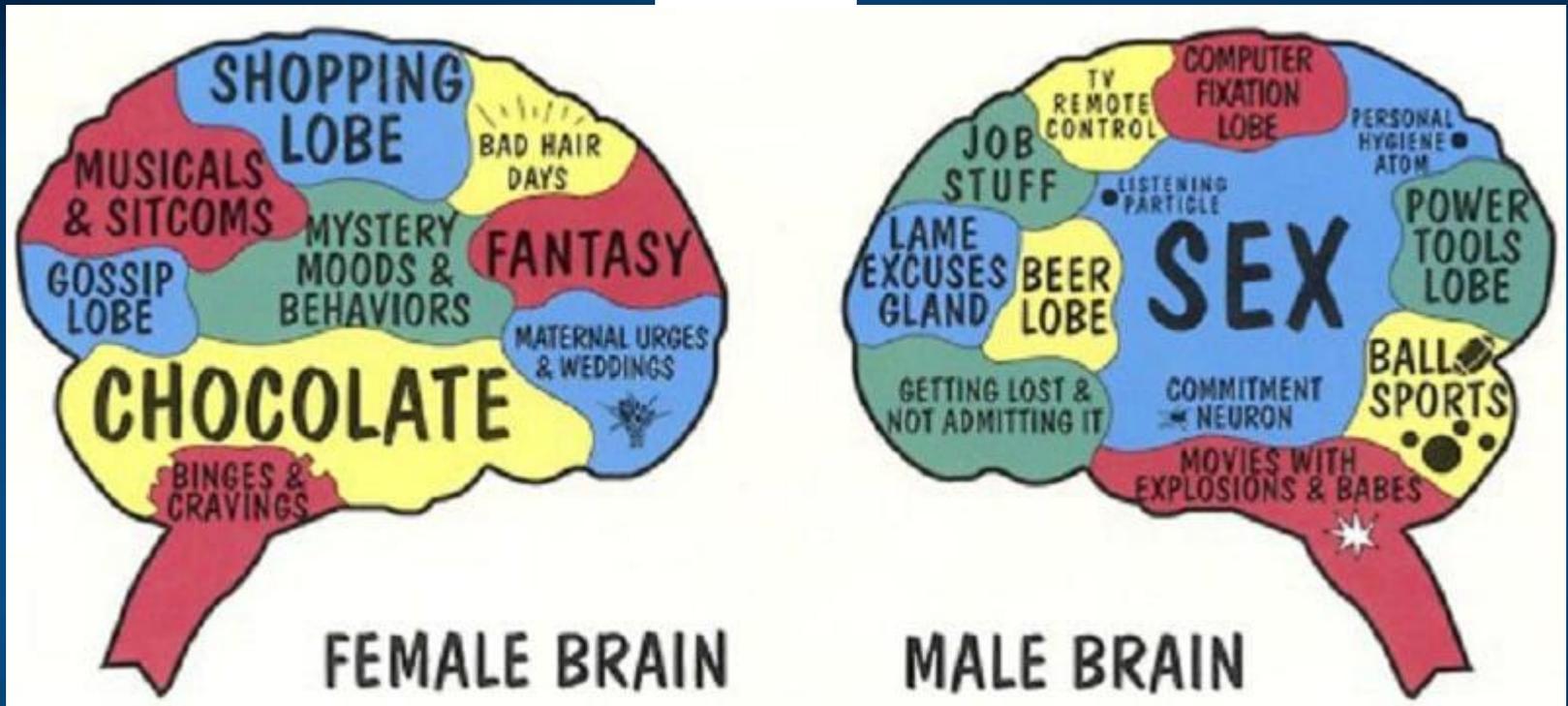
Phrenology was popular in 19 century, distinguishing 35 skull areas with specific functions. Amativeness, friendship, self esteem, hope, wit, veneration ...



"Know Thyself."

THE  
PHRENOLOGICAL JOURNAL  
AND  
SCIENCE OF HEALTH,  
A FIRST CLASS MONTHLY.

Specially Devoted to the "SCIENCE OF MAN." Contains PHRENOLOGY and PHYSIOGNOMY, with all the SIGNS of CHARACTER, and how to read them;" ETHNOLOGY, or the Natural History of Man in all his relations



This is also not what we have in the brain ...

But there are many neuromyth and pseudo-scientific organizations that promote ideas at this level.

Ex: Structogram Training System, Genetic Code for Personality.



# Human Potential



MISSION:  
IMPOSSIBLE

Mission impossible: develop full human potential.

Neurocognitive approach:

1. understand the brain (diagnostic part),
2. control its development (infant research),
3. increase its efficiency (therapeutic, well being, neurocognitive technologies),
4. consciously control your brain states (self-control),
5. create artificial brains (AI).

Great opportunities, but also great dangers.

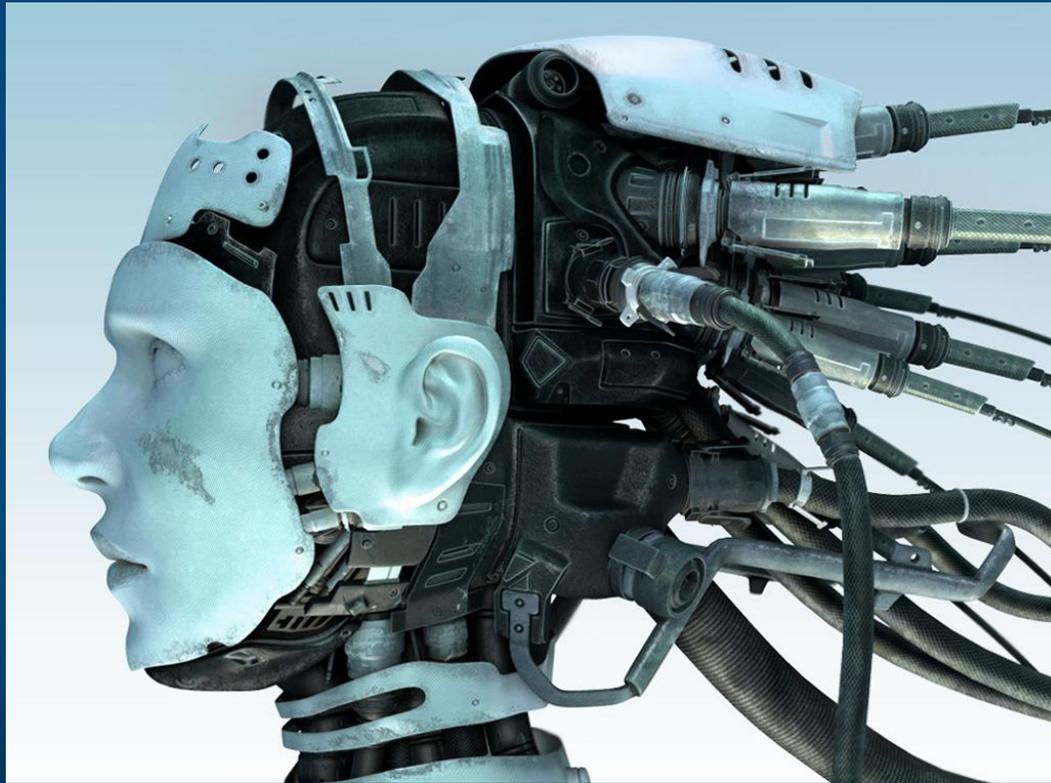


Brain processes (D. Kahneman, *Thinking, Fast and Slow* 2011):

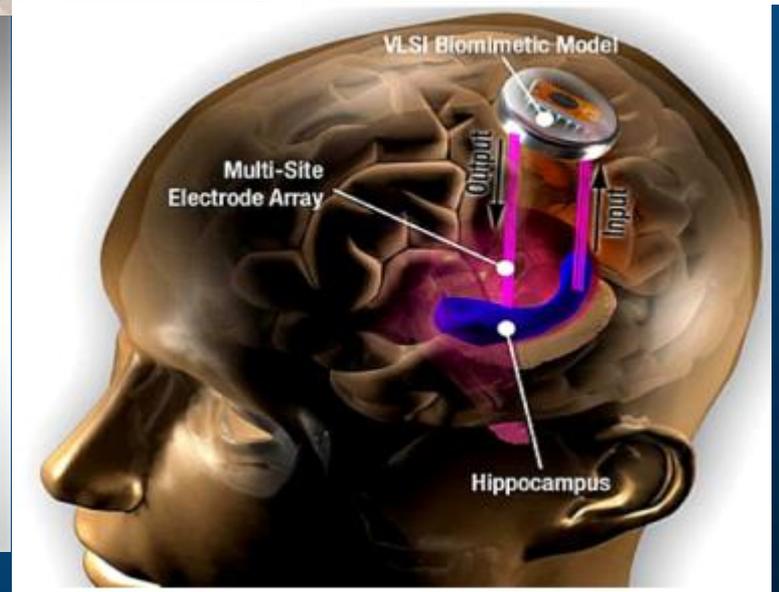
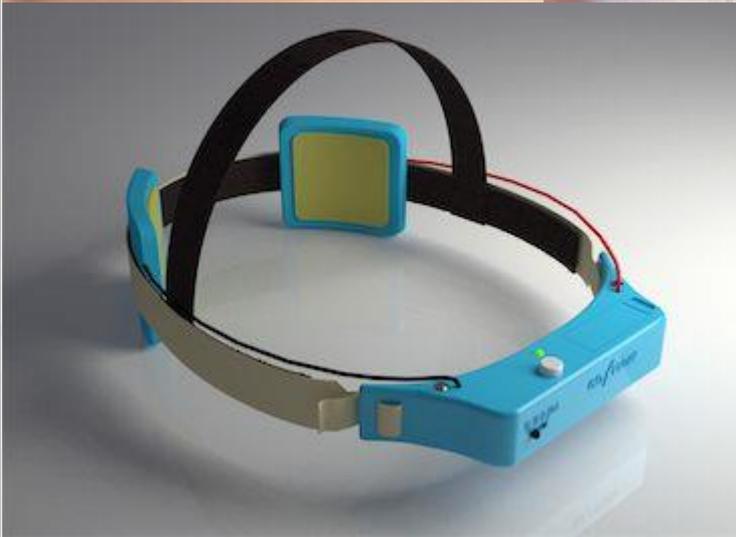
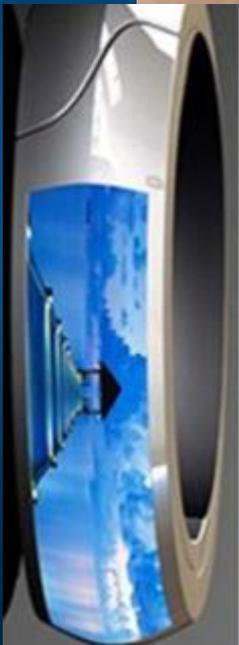
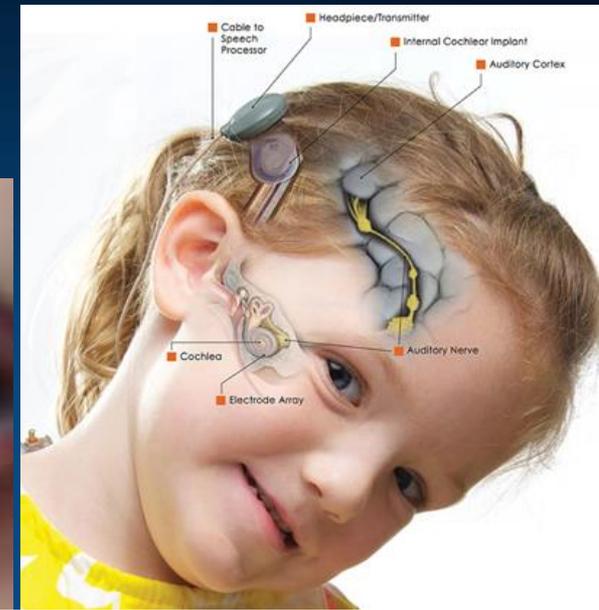
**System 1:** Fast, automatic, frequent, emotional, stereotypic, rigid, associative, responsible for perception, subconscious.

**System 2:** Slow, effortful, infrequent, logical, calculating, reasoning, conscious.

# Neurocognitive technologies



# Enhancing Perception



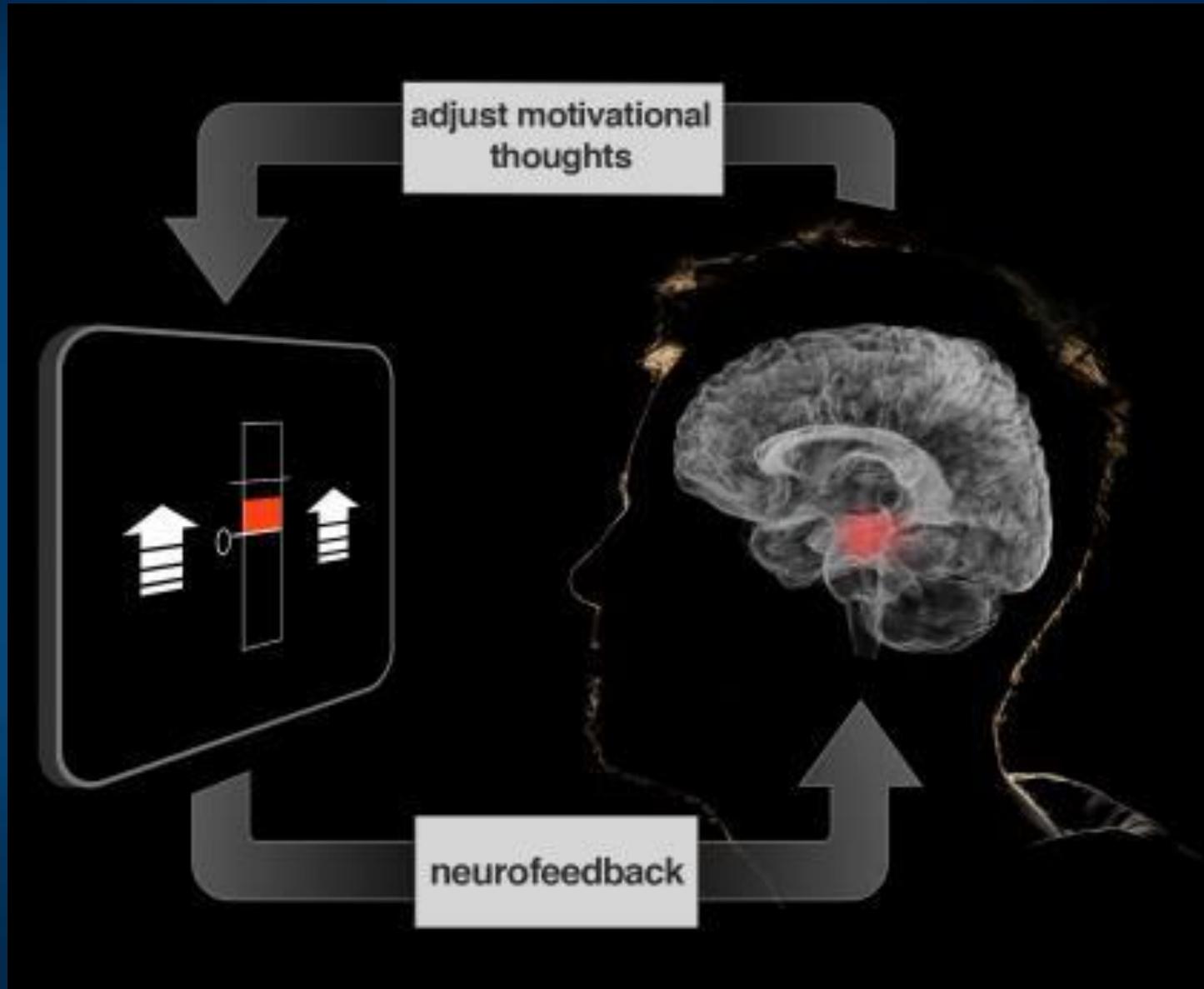
Improving eyes, ears, touch, but also memory and attention skills...  
Implantation of new neurons in the brain?

# Neurofeedback

Used in clinical practice, aimed mostly at the increase of alpha rhythms for relaxation, sometimes combined with theta rhythms.

Critical review of existing literature shows that this is not effective.

New forms based on brain fingerprinting needed.



# Neuro-relax

Sounds and music may have arousing or relaxing effects.

Melomind:

Simple EEG determines the relaxation level and adaptively creates sounds to increase it.

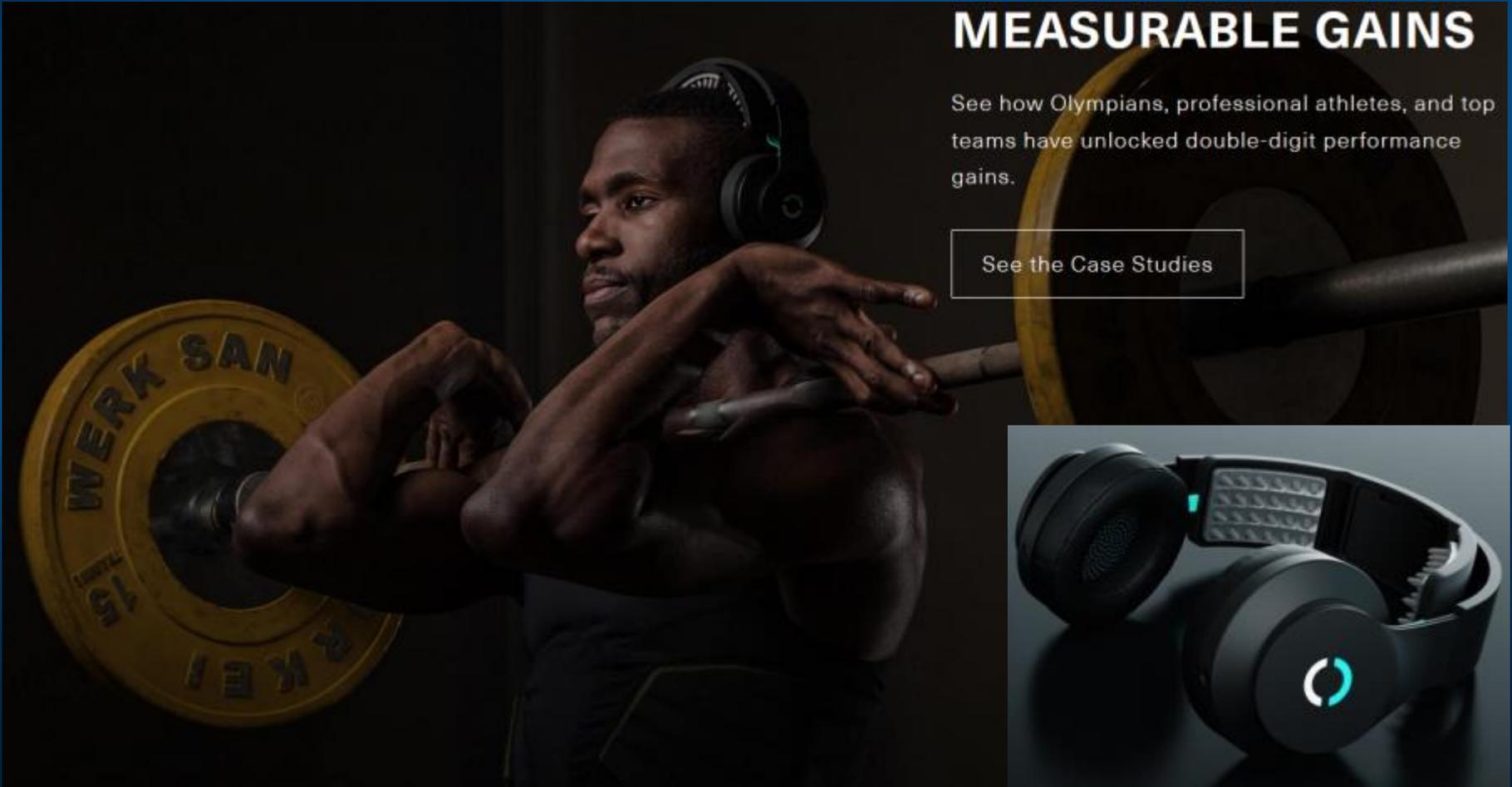
# Neuropriming

Effort, stamina, force in sports requires strong activation of muscles by motor cortex. Synchronize your effort with direct current cortex stimulation.

## MEASURABLE GAINS

See how Olympians, professional athletes, and top teams have unlocked double-digit performance gains.

[See the Case Studies](#)

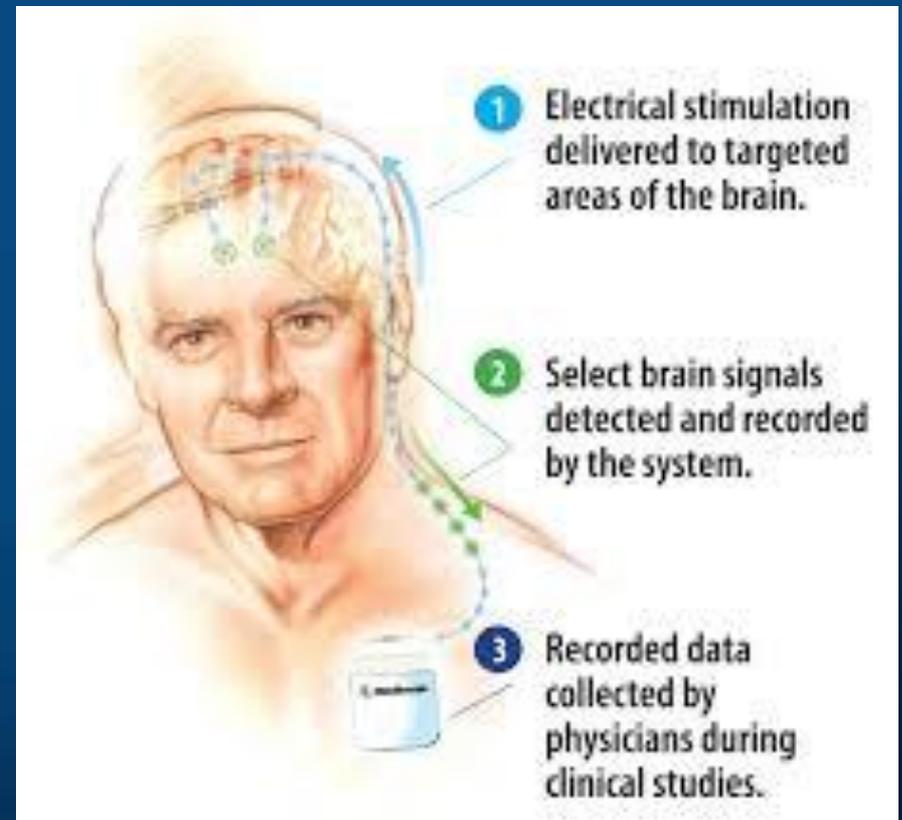


# Deep brain stimulation

In case of Parkinson's disease, OCD, coma, persistent pain and many other conditions stimulation of peripheral nerves (in particular vagus nerve) and certain parts of the brain using external controller can help.

Non-invasive approach using ultrasound interference is possible.

What brain functions can be consciously controlled?



# DCS, Direct Current Stimulation



# DCS for attention/relaxation

Focusing attention for a long time requires effort: PFC activates brain regions processing signals from various modalities. External stimulation using alternating currents (tDCS) or magnetic pulses (rTMS) gives good results in case of games, pilots, combat soldiers. Control yourself with a smartphone! **Thync** arouses the brain before action and relaxes after.



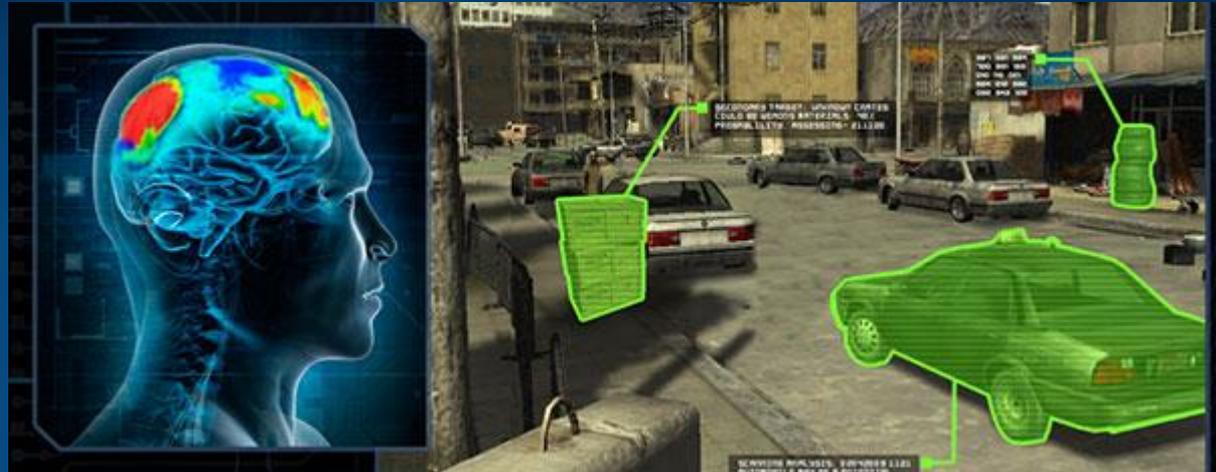
# Military applications

Engagement Skills Trainer (EST) procedures are used by USA army.

Intific Neuro-EST uses EEG analysis and multi-channel transcranial simulation (HD-DCS) to pre-activate the brain of the novice in areas where the expert brain is active.

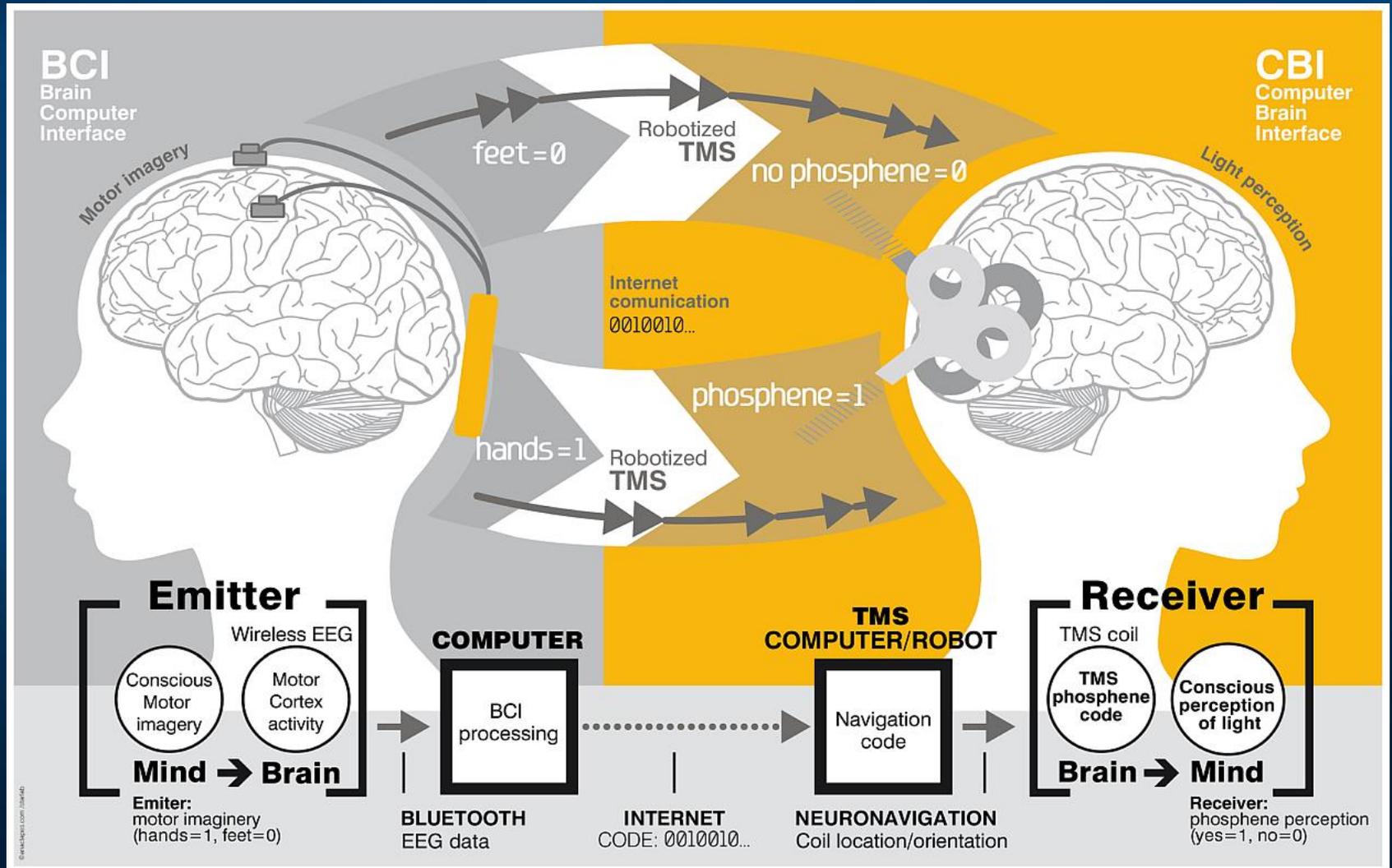
Real-life transfer learning ...

HD-tDCS may have 100 channels, but how to control it?



# Brain-brain communication

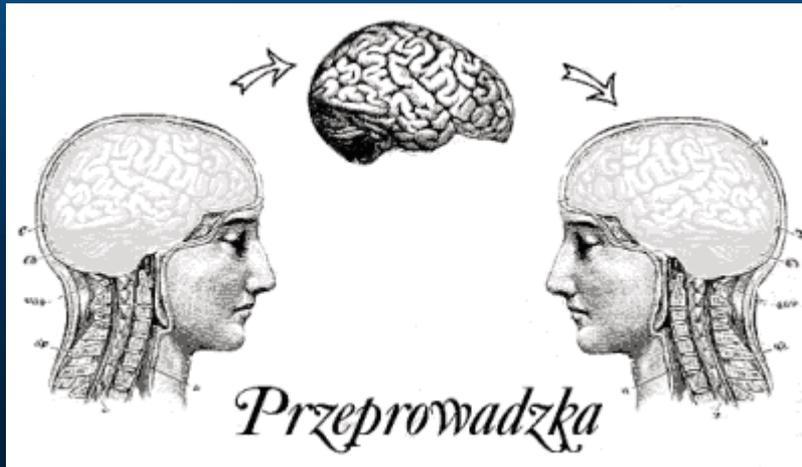
Read the brain states and transmit them to another person?



# Thought transfer?



EEG + TMS/DCS has been used to transfer simple motor commands using Morse alphabet. Can this technique be more subtle?



# Resonance through HD DCS?

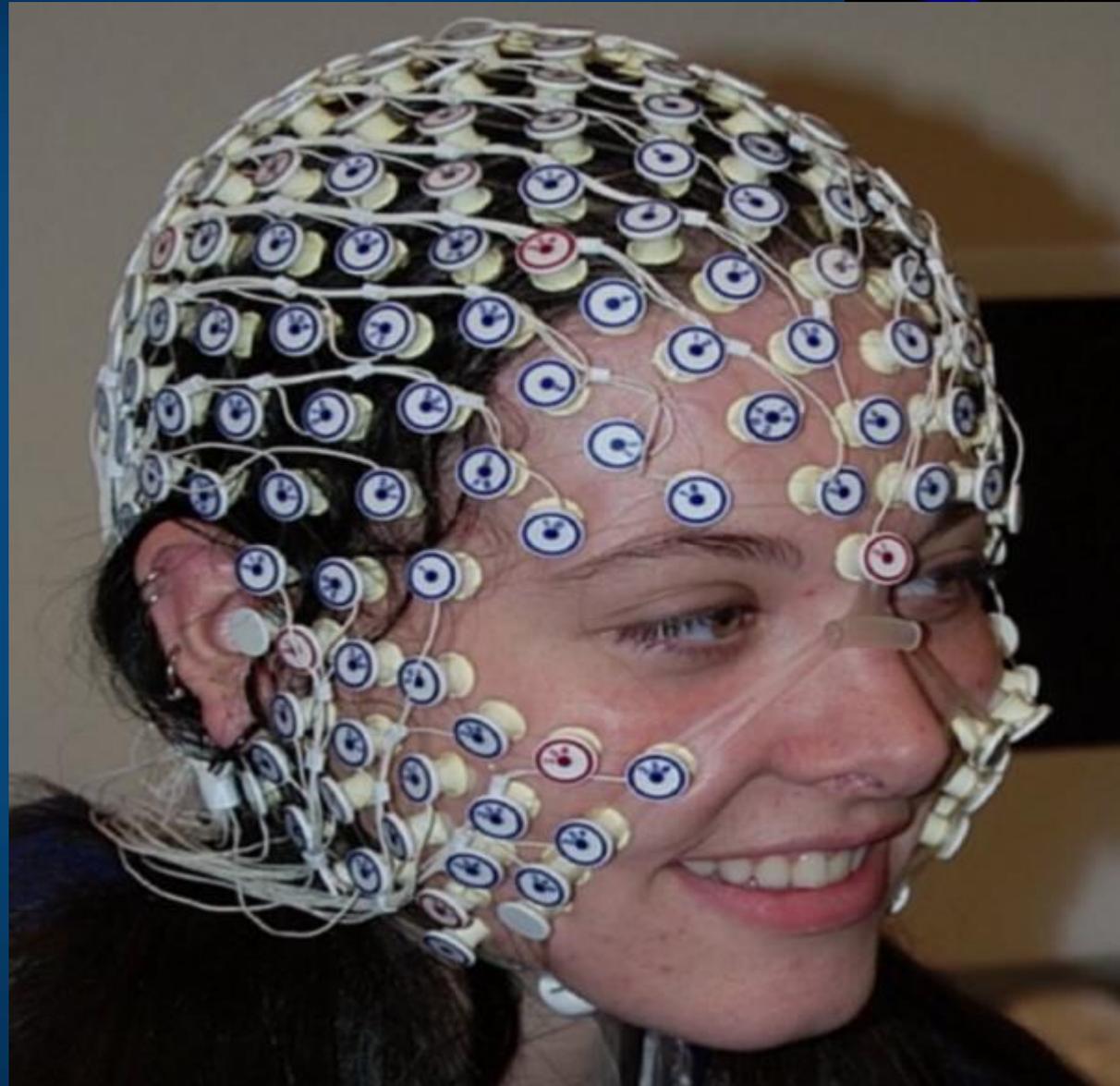


Reading brain states  
=> transforming to  
common space  
=> duplicating in other  
brains ...

Depression, neuro-  
plasticity, pain,  
psychosomatic  
disorders, teaching!

Multielectrode DCS  
stimulation with 256  
electrodes induces  
changes in the brain  
increasing neuroplasticity.

But no-one knows how  
does it work ...



# Understanding=Phenomics

*Phenomics* is the branch of science concerned with identification and description of measurable physical, biochemical and psychological traits of organisms. *Genom, proteom, interactom, exposome, virusom, connectom ... omics.org* has a list of over 400 various ...omics !

*Human Genome Project*, since 1990.

*Human Epigenome Project*, since 2003.

*Human Connectome Project*, since 2009.

*Developing Human Connectome Project*, UK 2013 + many others.

Behavior, personality, cognitive abilities  $\leq$  phenotypes at all levels.  
Still many white spots on maps of various phenomes.

Can neurocognitive phenomics be developed to understand general behavior of people and find better ways for flexible artificial intelligence?



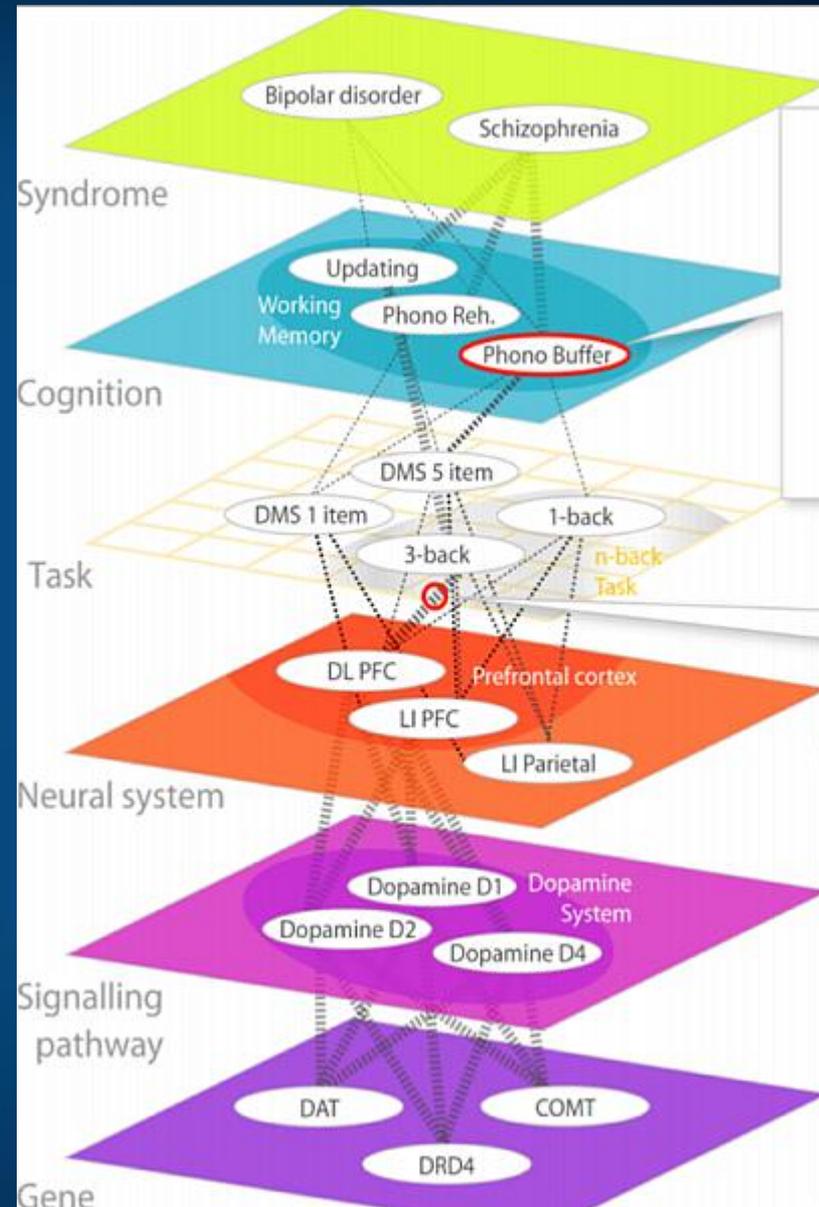
# Neuropsychiatric Phenomics in 6 Levels

Consortium for Neuropsychiatric Phenomics (CNP)/NIMH RoDC approach:

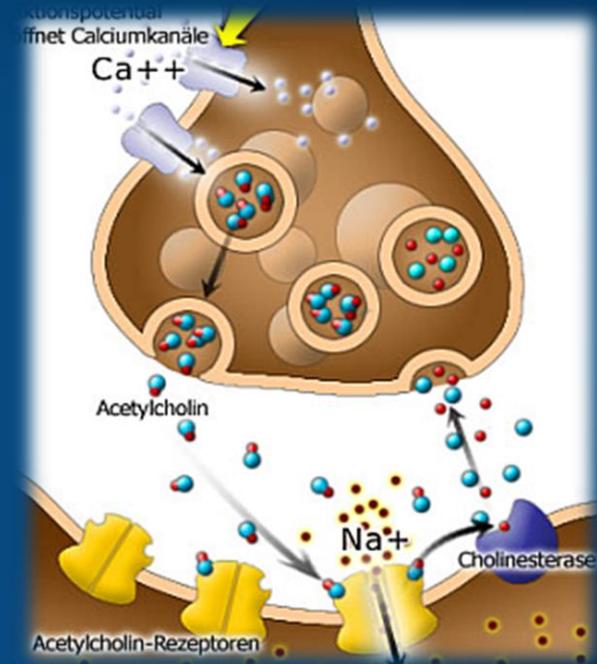
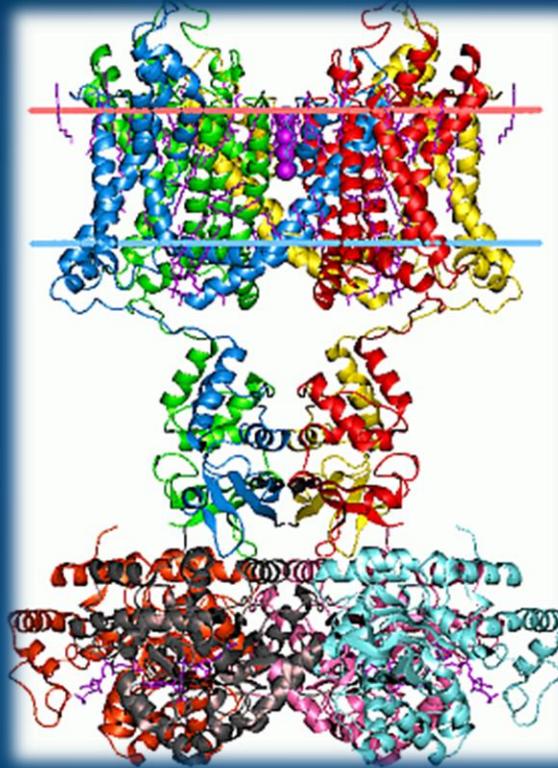
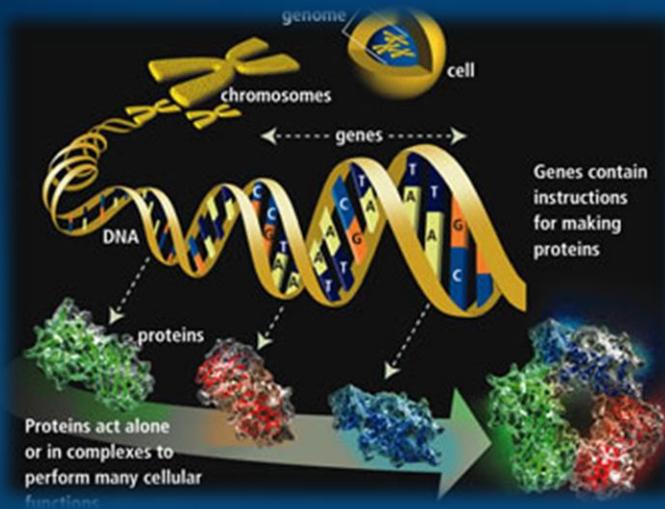
**Research Domain Criteria (RoDC)** analyzes 5 large brain systems – negative/positive valence systems, arousal, cognitive, affective systems – through interaction of Genes, Molecules, Cells, Circuits, Physiology, Behavior, Self-Report, and Research Paradigms.

From genes to cognitive subsystems and behavior, neurons and networks are **right in the middle** of this hierarchy.

=> **Neurodynamics is the key!**

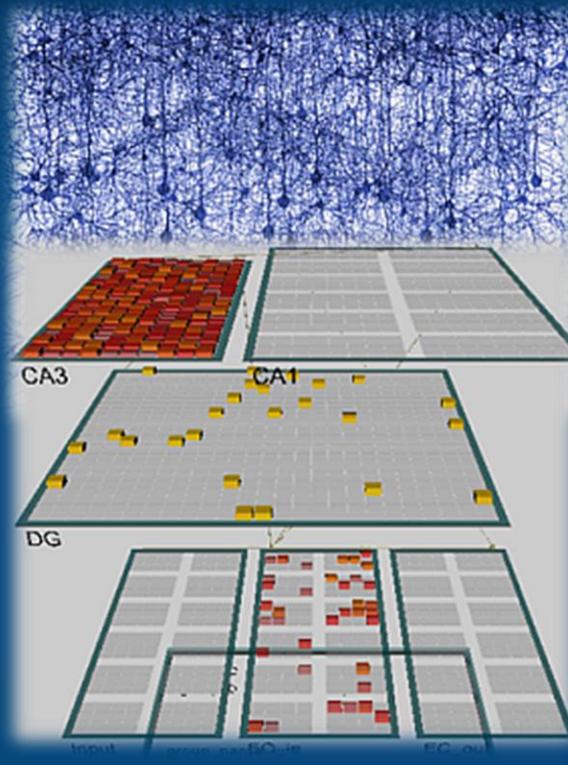
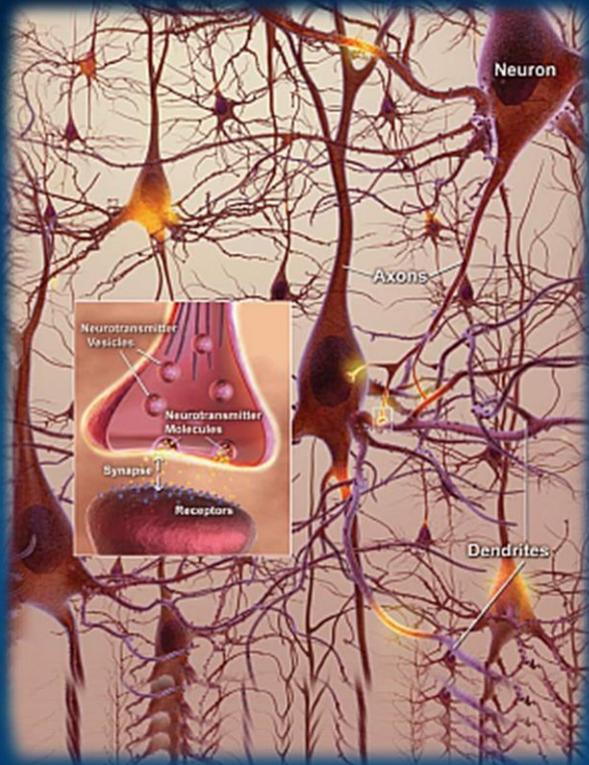


# From Genes to Neurons



Genes => Proteins => receptors, ion channels, synapses  
=> neuron properties, networks, neurodynamics  
=> cognitive phenotypes, abnormal behavior, syndromes.

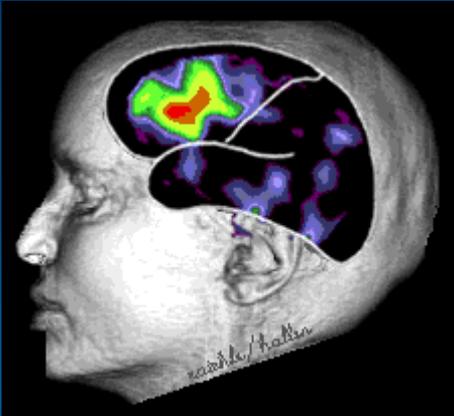
# From Neurons to Behavior



Genes => Proteins => receptors, ion channels, synapses  
=> neuron properties, networks  
=> **neurodynamics** => cognitive phenotypes, abnormal behavior!

# Mapping brain states to mental images

Neurodynamics: bioelectrical activity of the brain, neural activity measured using EEG, MEG, NIRS-OT, PET, fMRI, other techniques.



Mapping State(Brian)  $\leftrightarrow$  State(Mind)  
Via intermediate models.



Mental states, movement of thoughts  $\leftrightarrow$  trajectories in psychological spaces.

1. From simulations and neuroimaging to mental trajectories.
2. From neuroimaging to mental images.

# Geometric model of mind

Brain  $\leftrightarrow$  Psyche

Objective  $\leftrightarrow$  Subjective

Neurodynamics: bioelectrical activity of the brain, neural activity measured using EEG, MEG, NIRS-OT, PET, fMRI, other techniques.

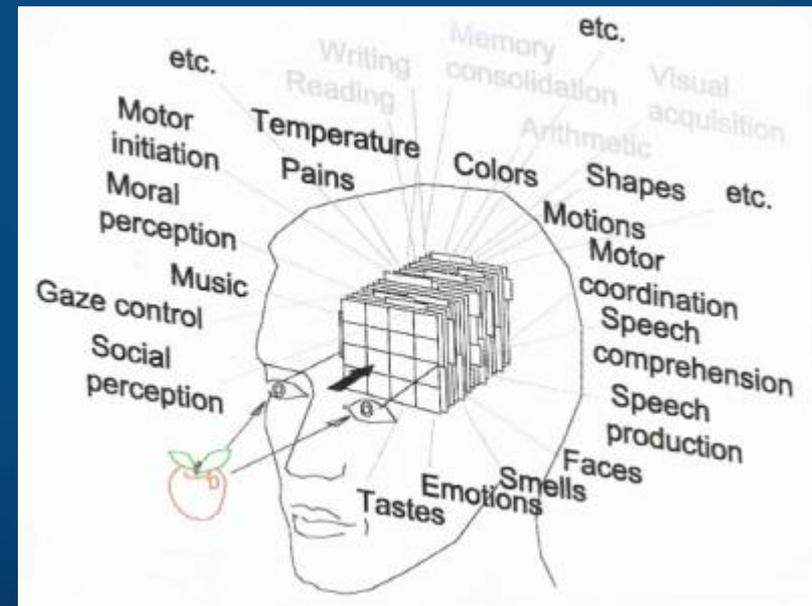
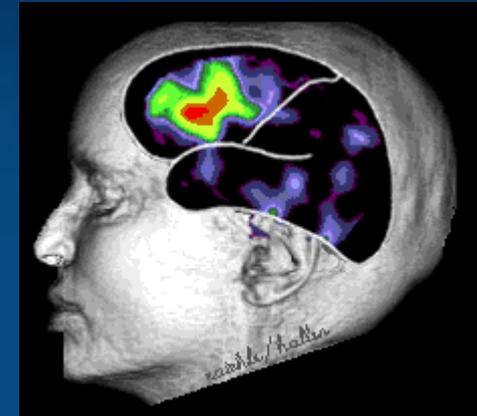
Mapping  $S(M) \leftrightarrow S(B)$  but how do we describe the state of mind?

Verbal description is not sufficient.

A space with dimensions that measure different aspects of experience is needed.

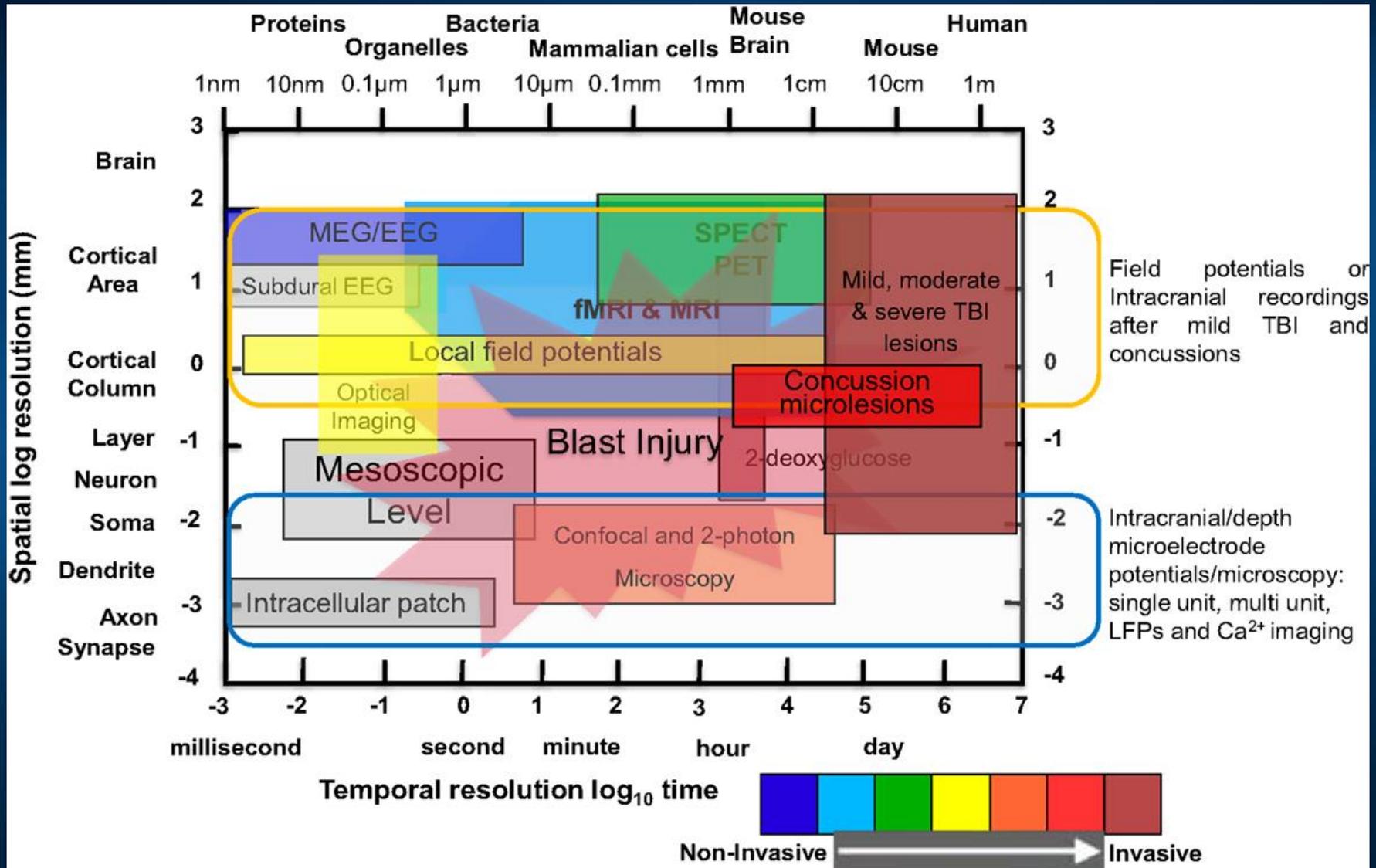
Mental states, movement of thoughts  $\leftrightarrow$  trajectories in psychological spaces.

Problem: good phenomenology. We are not able to describe our mental states.

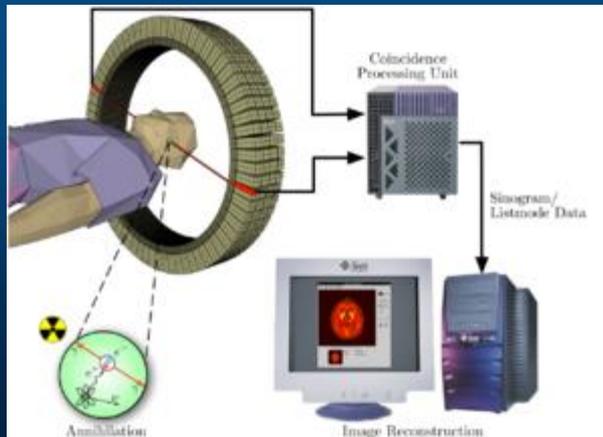


Hurlburt & Schwitzgabel, Describing Inner Experience? MIT Press 2007

# Experimental techniques



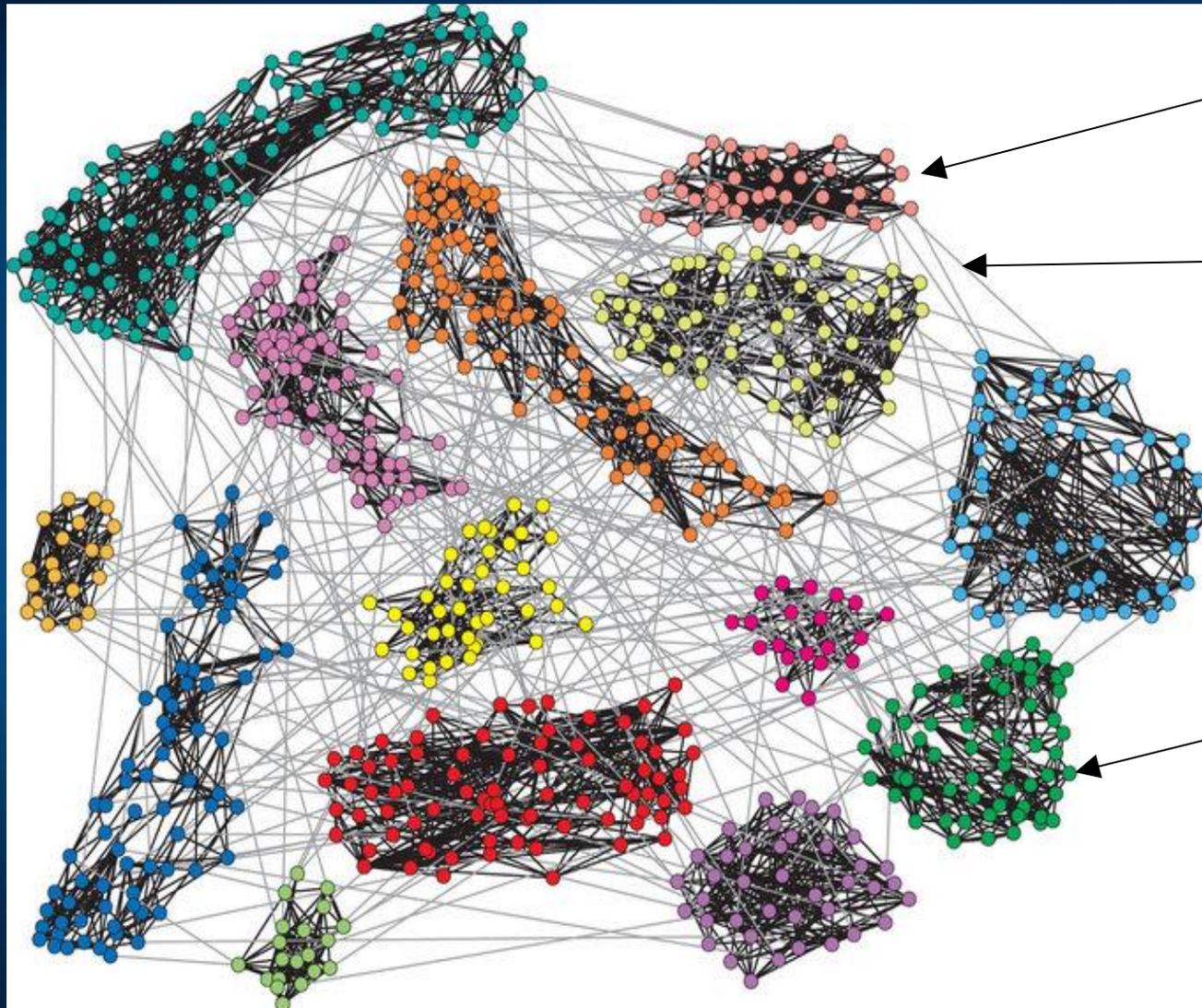
# Neuroimaging



# ICNT: scanner GE Discovery MR750 3T



# Brain networks



Brain regions

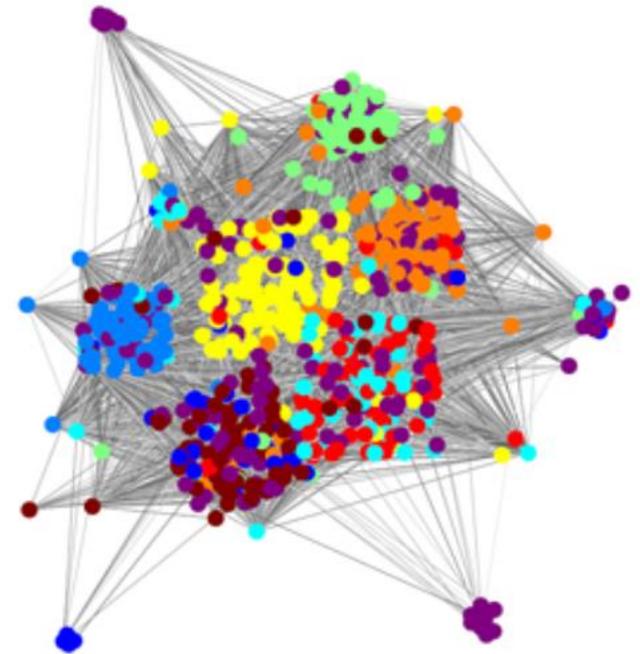
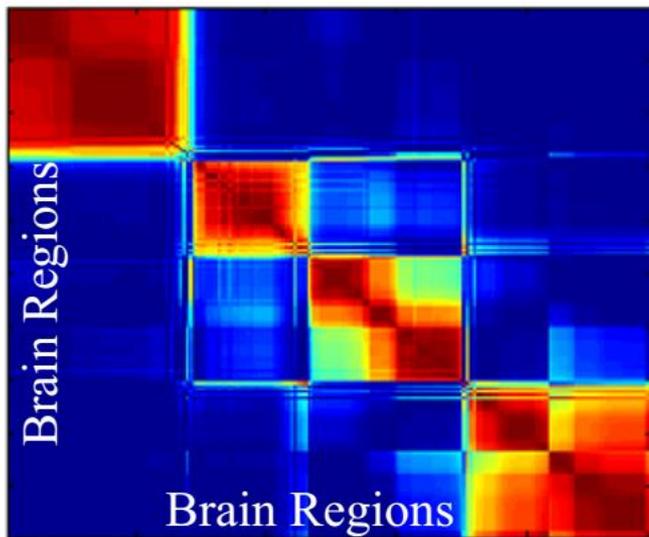
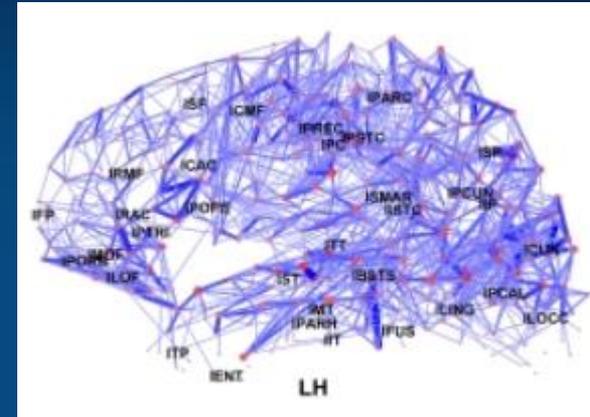
Connections

Nodes

# Neuronal subnetworks

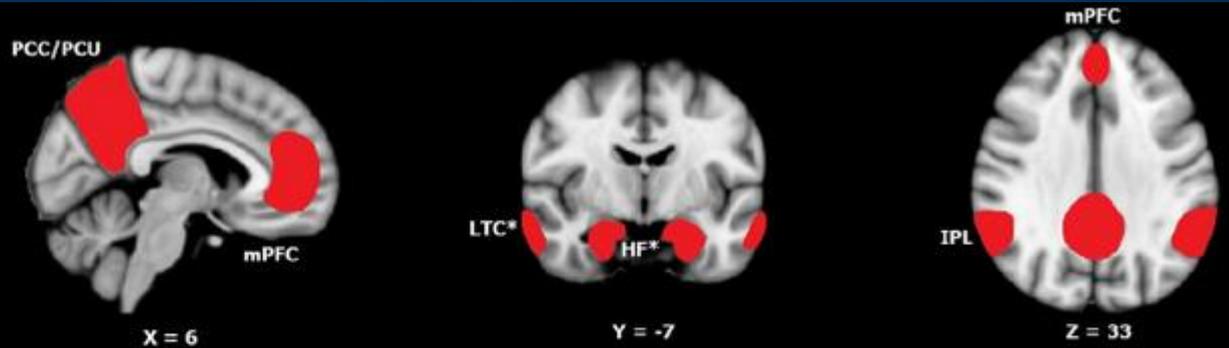
Hierarchy and modularity is observed at large scale: several subnetworks responsible for arousal, attention, positive/negative valence, perception.

At the microcircuit level similar hierarchy/modularity is seen.

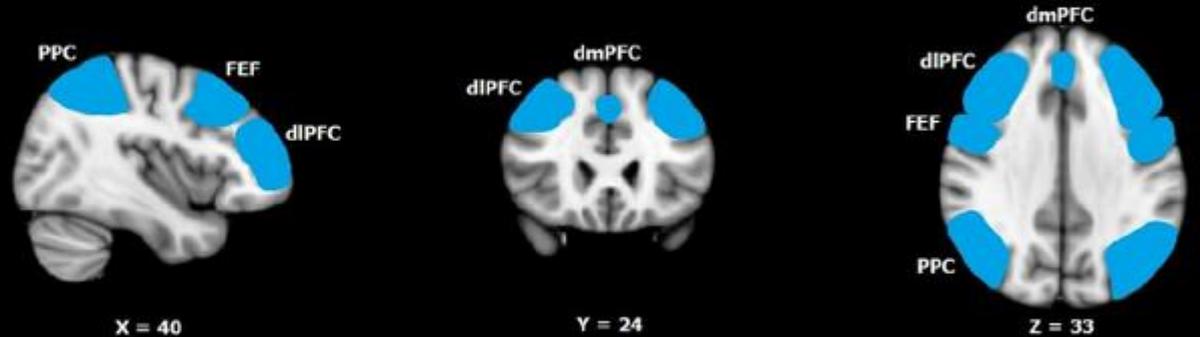


# DMN, CEN and SN networks

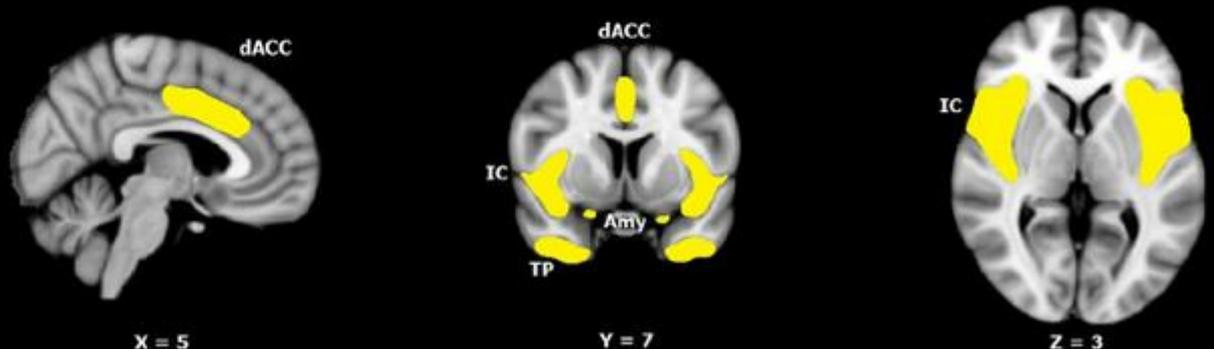
default mode network



central executive network



salience network





## NIMH RD0C Matrix for deregulation of large brain systems.

Instead of classification of mental disease by symptoms use **Research Domain Criteria** (RD0C) based on multi-level neuropsychiatric phenomics.

1. **Negative Valence Systems**, primarily responsible for responses to aversive situations or context, such as fear, anxiety, and loss.
2. **Positive Valence Systems** are primarily responsible for responses to positive motivational situations or contexts, such as reward seeking, consummatory behavior, and reward/habit learning.
3. **Cognitive Systems** are responsible for various cognitive processes.
4. **Social Processes Systems** mediate responses in interpersonal settings of various types, including perception and interpretation of others' actions.
5. **Arousal/Regulatory Systems** are responsible for generating activation of neural systems as appropriate for various contexts, providing appropriate homeostatic regulation of such systems as energy balance and sleep.

# RDoC Matrix for „cognitive domain”

Construct/Subconstruct		Genes	Molecules	Cells	Circuits	Physiology	Behavior	Self-Report	Paradigms
Attention		Elements	Elements	Elements	Elements	Elements	Elements		Elements
Perception	Visual Perception	Elements	Elements	Elements	Elements	Elements	Elements	Elements	Elements
	Auditory Perception	Elements	Elements	Elements	Elements	Elements	Elements	Elements	Elements
	Olfactory/Somatosensory/Multimodal/Perception								Elements
Declarative Memory		Elements	Elements	Elements	Elements	Elements	Elements	Elements	Elements
Language		Elements			Elements	Elements	Elements	Elements	Elements
Cognitive Control	Goal Selection; Updating, Representation, and Maintenance ⇒ Focus 1 of 2 ⇒ Goal Selection				Elements			Elements	Elements
	Goal Selection; Updating, Representation, and Maintenance ⇒ Focus 2 of 2 ⇒ Updating, Representation, and Maintenance	Elements	Elements	Elements	Elements	Elements	Elements	Elements	Elements
	Response Selection; Inhibition/Suppression ⇒ Focus 1 of 2 ⇒ Response Selection	Elements	Elements	Elements	Elements	Elements	Elements	Elements	Elements
	Response Selection; Inhibition/Suppression ⇒ Focus 2 of 2 ⇒ Inhibition/Suppression	Elements	Elements	Elements	Elements	Elements	Elements	Elements	Elements
	Performance Monitoring	Elements	Elements		Elements	Elements	Elements	Elements	Elements
Working Memory	Active Maintenance	Elements	Elements	Elements	Elements	Elements			Elements
	Flexible Updating	Elements	Elements	Elements	Elements	Elements			Elements
	Limited Capacity	Elements	Elements		Elements	Elements			Elements
	Interference Control	Elements	Elements	Elements	Elements	Elements			Elements

# Psychological spaces

Psychological spaces:

Kurt Lewin, The conceptual representation and the measurement of psychological forces (1938), cognitive dynamic movement in **phenomenological space**.

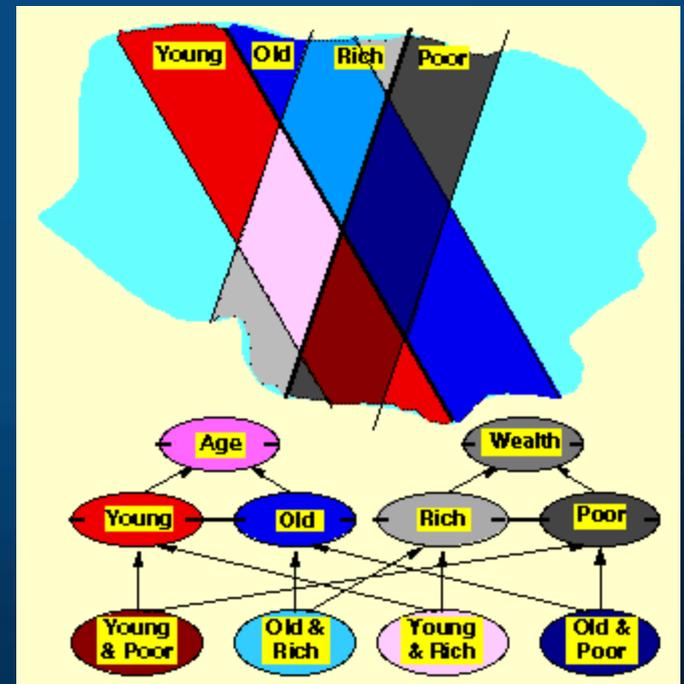
George Kelly (1955), personal construct psychology, geometry of psychological spaces as alternative to logic.

A complete theory of cognition, action, learning and intention.

P-space: region in which we may place and classify elements of our experience, constructed and evolving, „a space without distance”, divided by dichotomies.

P-spaces (Roger Shepard 1957-2001):

- minimal dimensionality
- distances that monotonically decrease with increasing similarity (multi-dimensional non-metric scaling).



# Some connections

Geometric/dynamical ideas related to mind may be found in many fields:

**Philosophy:** Mind as motion, ed. R.F. Port, T. van Gelder (MIT Press 1995)

**Linguistics:** G. Fauconnier, Mental Spaces (Cambridge U.P. 1994).  
Mental spaces and non-classical feature spaces.

J. Elman, Language as a dynamical system (San Diego, 1997).  
Stream of thoughts, sentence as a trajectory in P-space.

**Psycholinguistics:** T. Landauer, S. Dumais, Latent Semantic Analysis Theory,  
Psych. Rev. (1997) Semantics requires about 300 dim. to capture associations.

M.J. Spivey, The Continuity of Mind (OUP 2007)

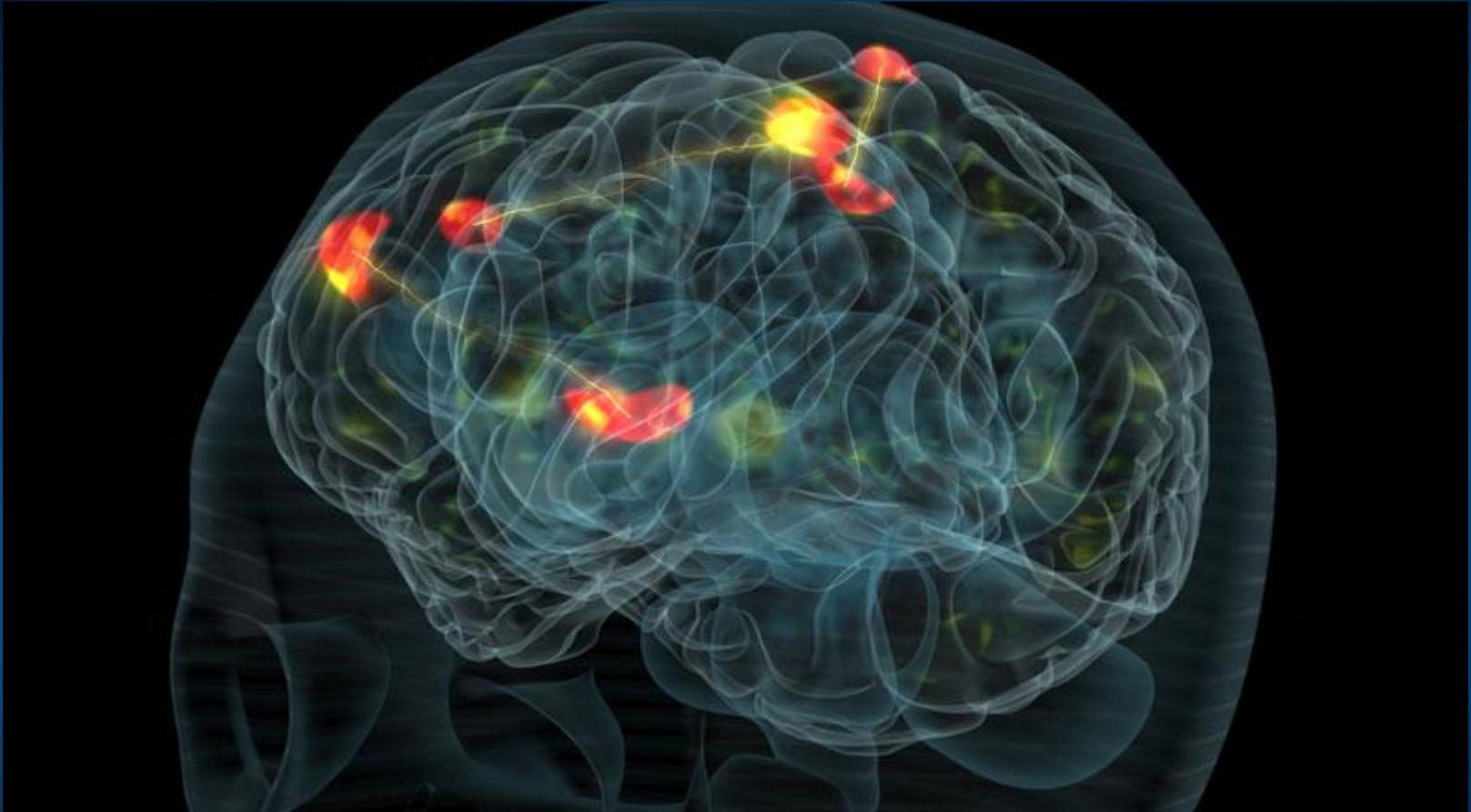
**Neuroscience:** Anderson, van Essen (1994): Superior Colliculus maps as PDFs

**AI:** problem spaces - reasoning, problem solving, SOAR, ACT-R

**Folk psychology:** to put in mind, to have in mind, to keep in mind, to make up one's mind, be of one mind ... (space).



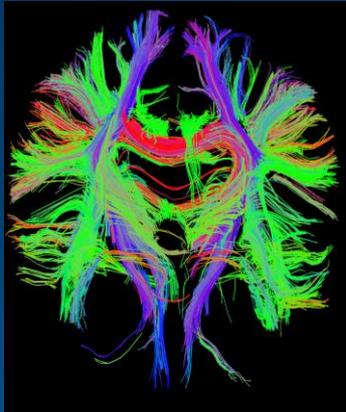
# Thought: strong, coherent activation



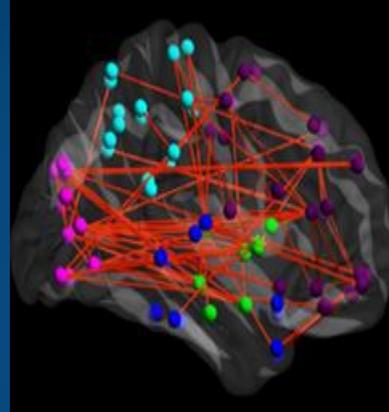
Many processes go on in parallel, controlling the state of our bodies. Most are automatic, hidden from our Self. Processes implemented by subnetworks compete for access to the highest level of control, consciousness, using the winner-takes-most mechanism. Such processes may activate representation of Self in the brain.

# Human connectome and MRI/fMRI

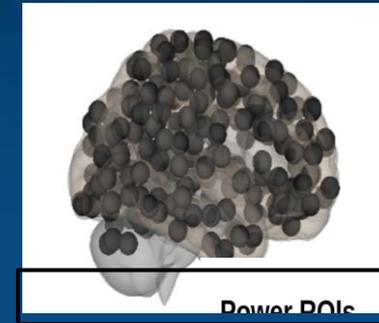
Structural connectivity



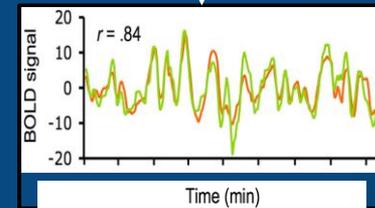
Functional connectivity



Node definition (parcelation)



Signal extraction

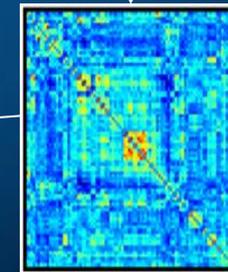


Correlation calculation

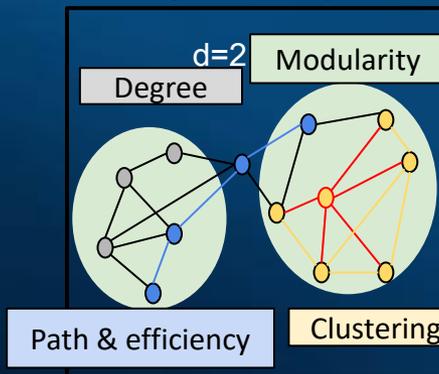
Binary matrix



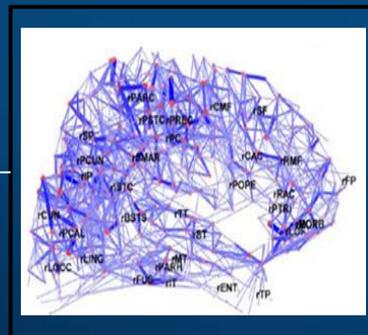
Correlation matrix



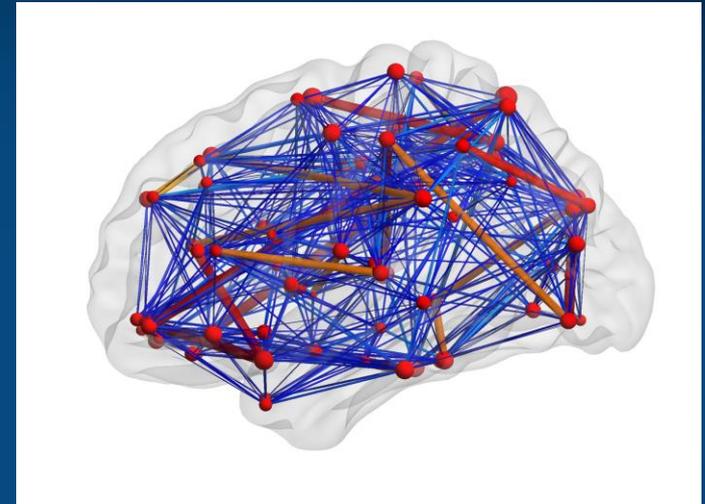
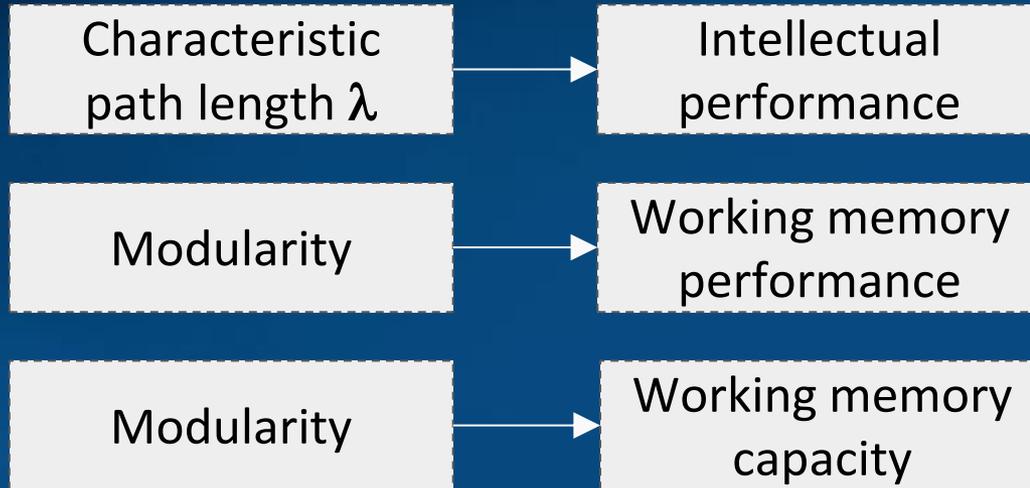
Graph theory



Whole-brain graph

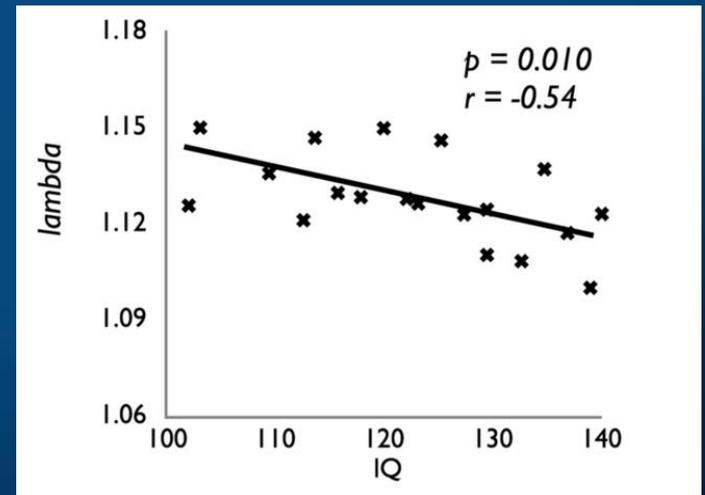


# Resting state/cognitive performance



Network modularity  $\Leftrightarrow$  higher working memory capacity and performance.

High connectivity within modules and sparse connections between modules increases effective cooperation of brain regions, is associated with higher IQ.



# Questions

1. Can the whole-brain network properties change during active task performance?
2. Is modularity, path length, global and local efficiency dependent on the cognitive load?

**Global Neuronal Workspace Theory (Dehaene et al. 1998):** brain processes underlying effortful tasks require two main computational spaces:

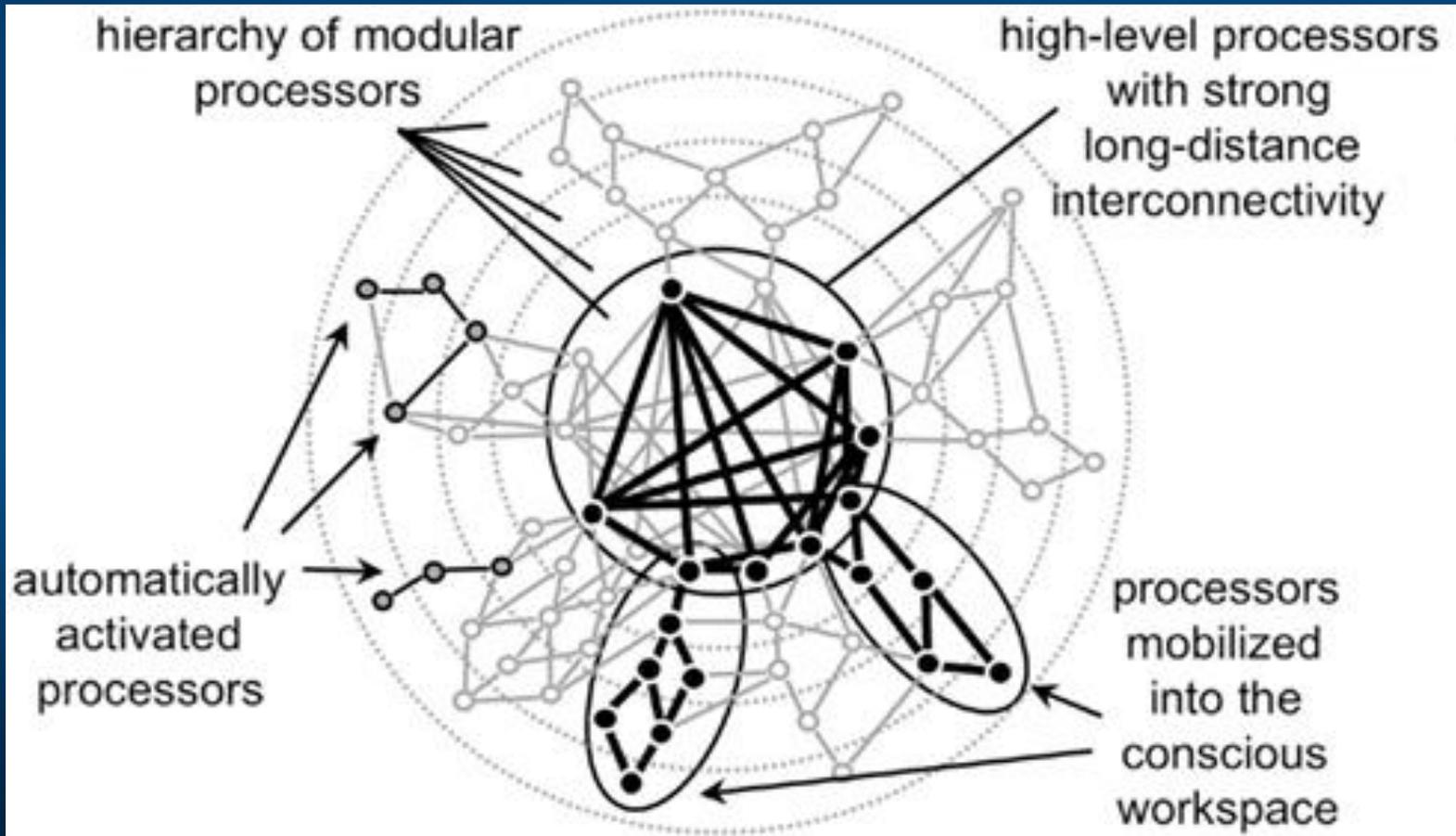
- a set of specialized and modular perceptual, motor, memory, evaluative, and attentional processors;
- a unique global workspace composed of distributed and heavily interconnected neurons with long-range axons.

Workspace neurons are mobilized in effortful tasks for which the specialized processors (System 1) do not suffice (Kahneman's System 2).

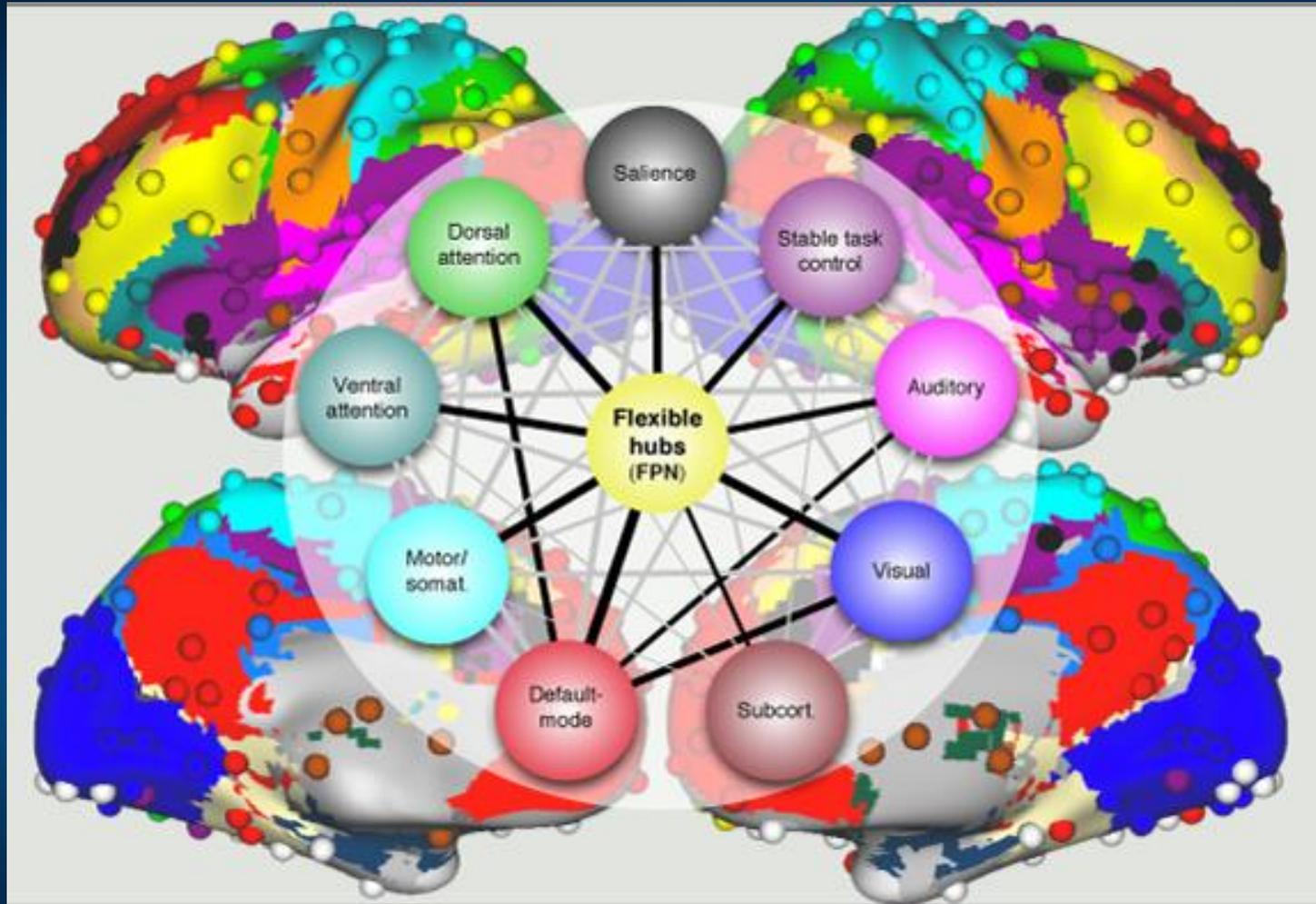
They selectively mobilize or suppress, through descending connections, the contribution of specific processor neurons.

# GNWT

Global Neuronal Workspace Theory (Dehaene et al. 1998)



# Neurocognitive Basis of Cognitive Control



Cole M.W. et al. (2013). Multi-task connectivity reveals flexible hubs for adaptive task control. *Nature Neuroscience*; 2013

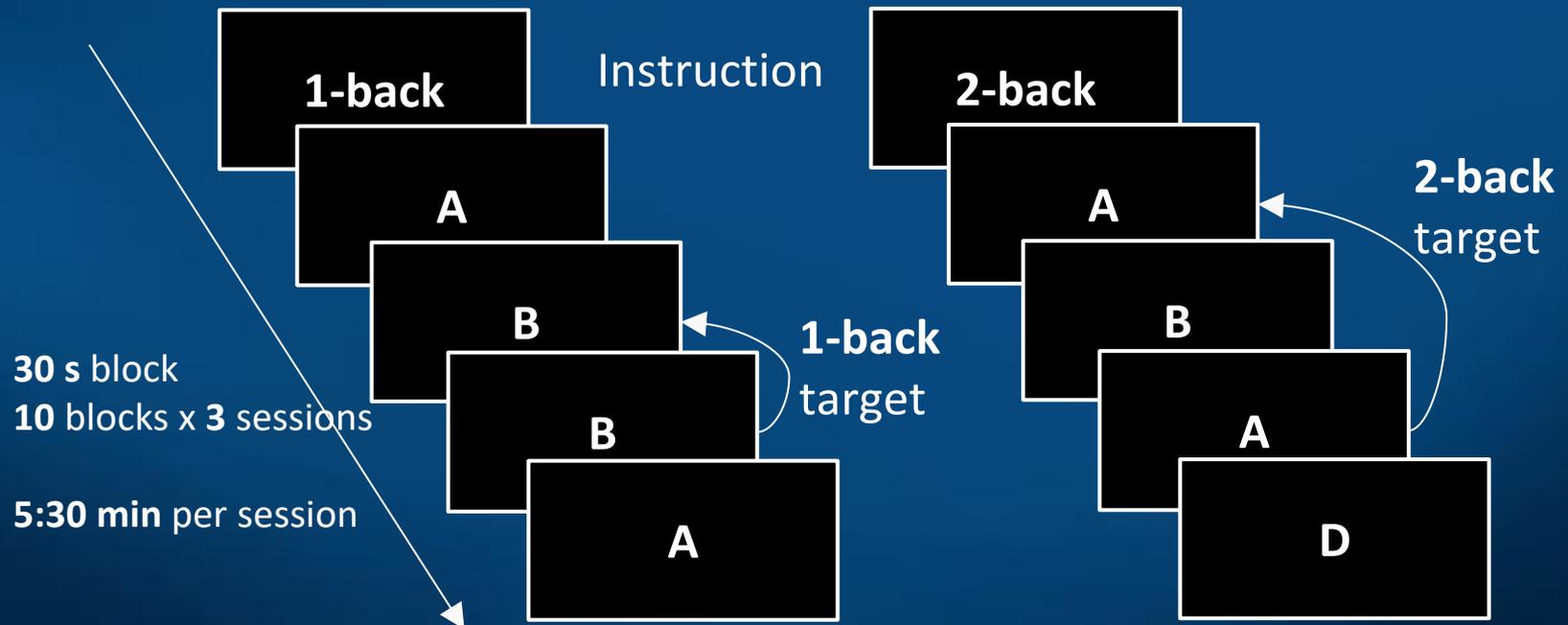
# Cognitive load on whole-brain network

35 participants (17 females; Mean age =  $22.6 \pm 3.1$ ; 19-31).

## Letter *n*-back task

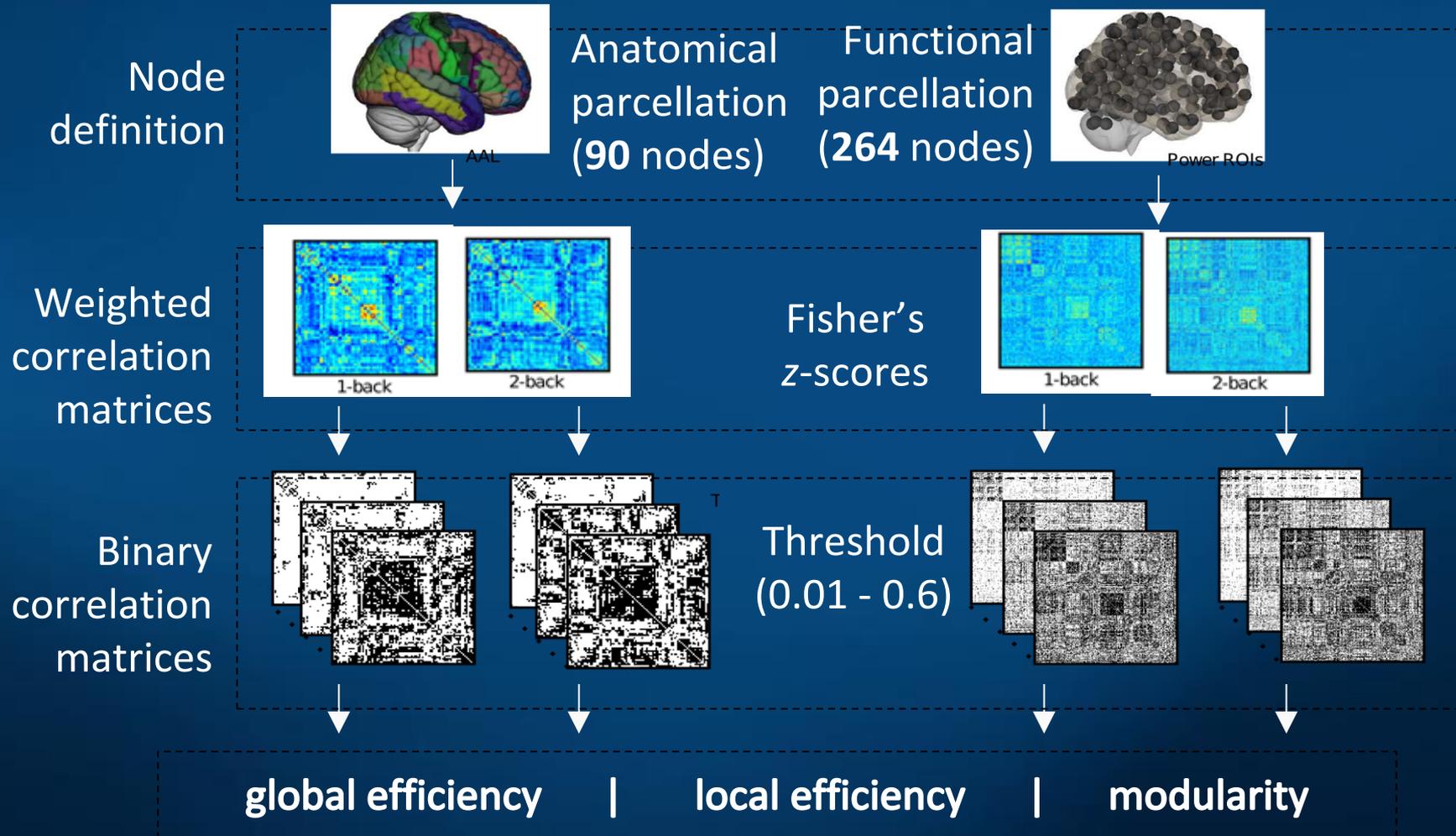
Low cognitive effort

High cognitive effort



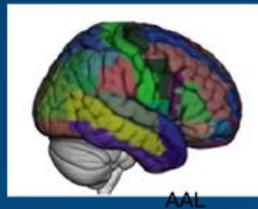
# Data workflow

Two experimental conditions: 1-back, 2-back



# Changes in modularity

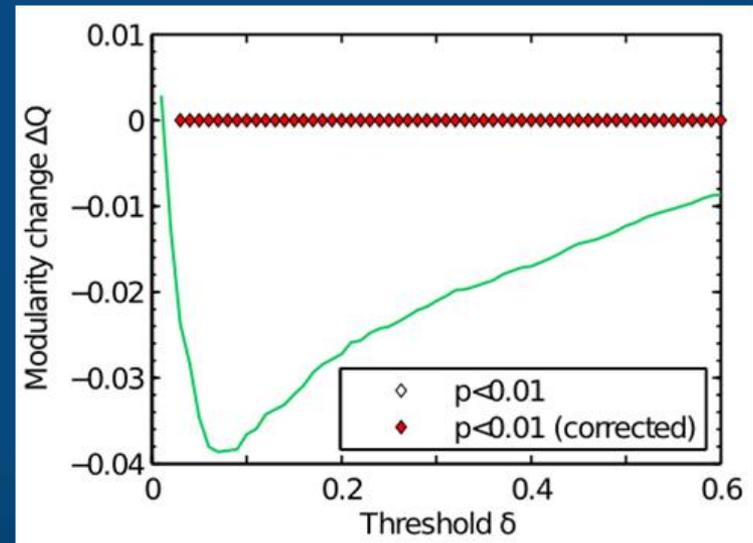
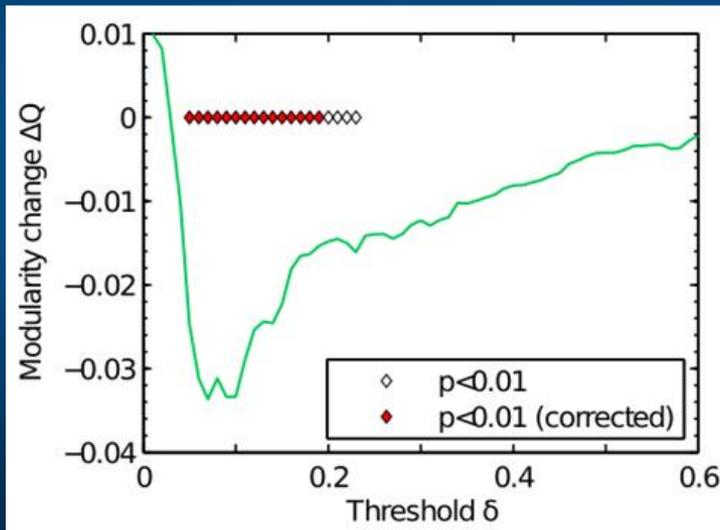
Modularity metric: fraction of within-community edges in the network minus such fraction for randomly connected network with unchanged community structure.



Parcellation  
AAL, 90 ROI



Parcellation  
264 ROI  
functional

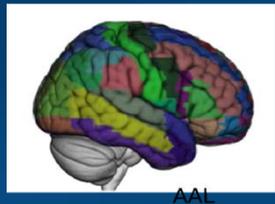


Modularity for both parcellations significantly decreases for thresholds  $\sim 0.1$ .  
Coarse parcellation washes out many effects, especially strong correlations.

# Changes in efficiency

Global efficiency  $\sim$  inverse characteristic path length

Local efficiency  $\sim$  clustering coefficient (Latora & Marchiori, 2001).



AAL

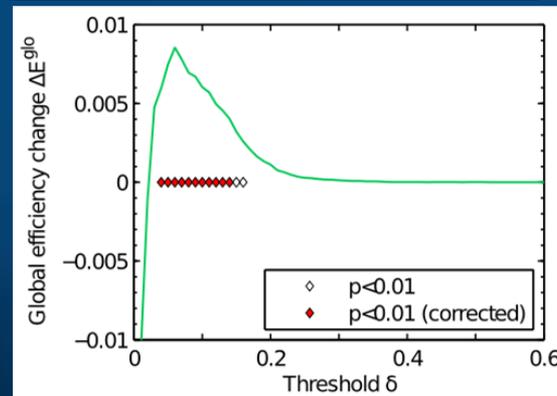
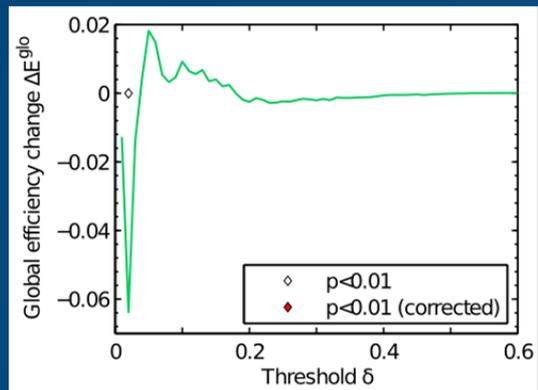
Parcelation  
AAL, 90 ROI



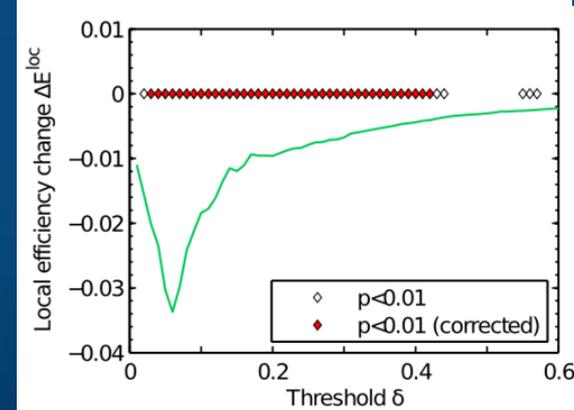
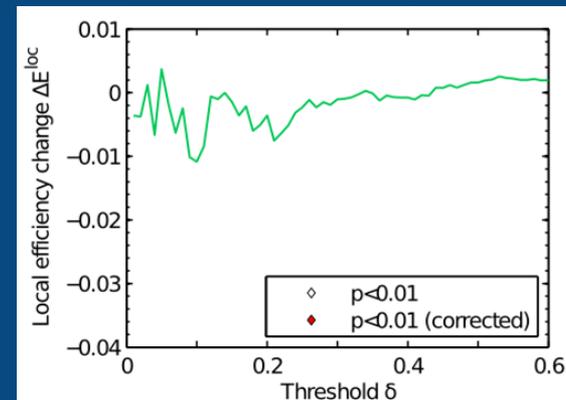
Power ROIs

Parcelation  
264 ROI  
functional

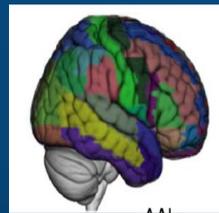
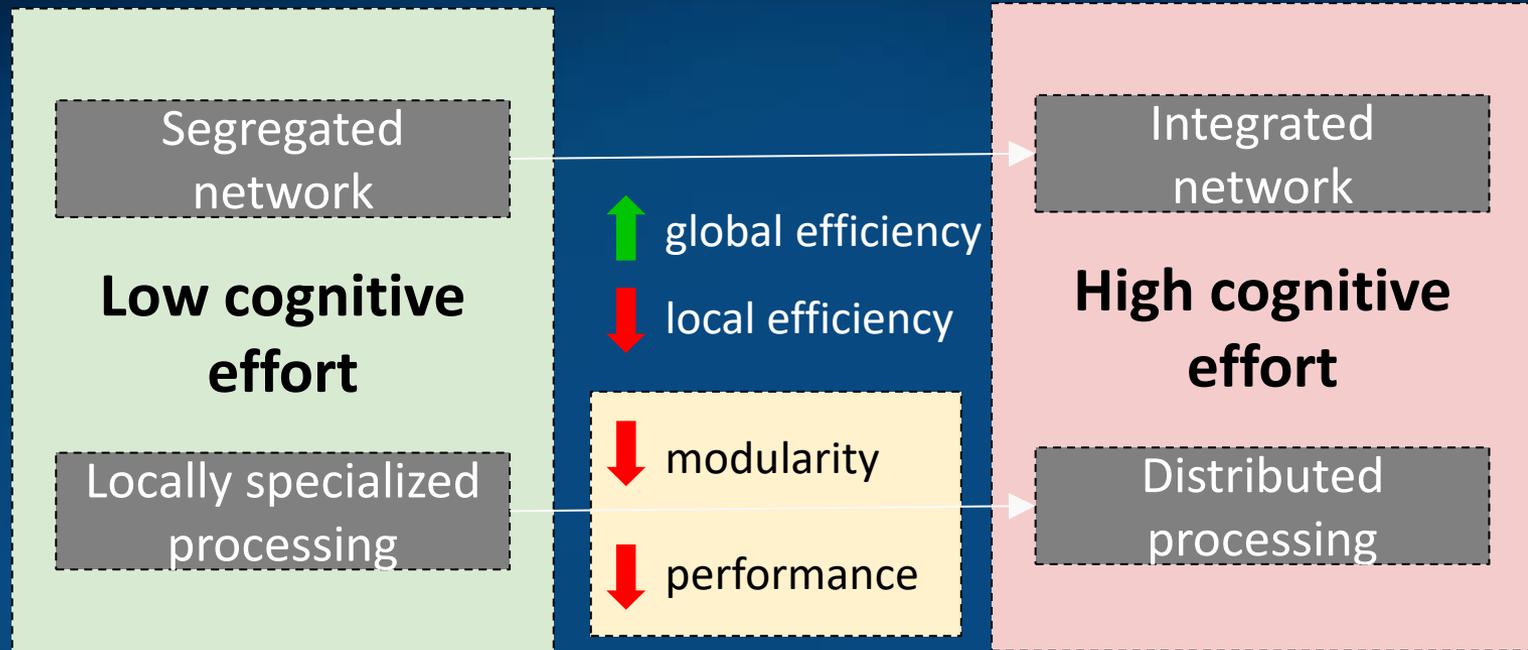
## Global efficiency



## Local efficiency



# Conclusions



≠



Parcellation into 264 regions (10 mm spheres) shows subnetworks more precisely than for 90 regions; only a small subgroup of neurons in each ROI is strongly correlated.

# Brain modules and cognitive processes

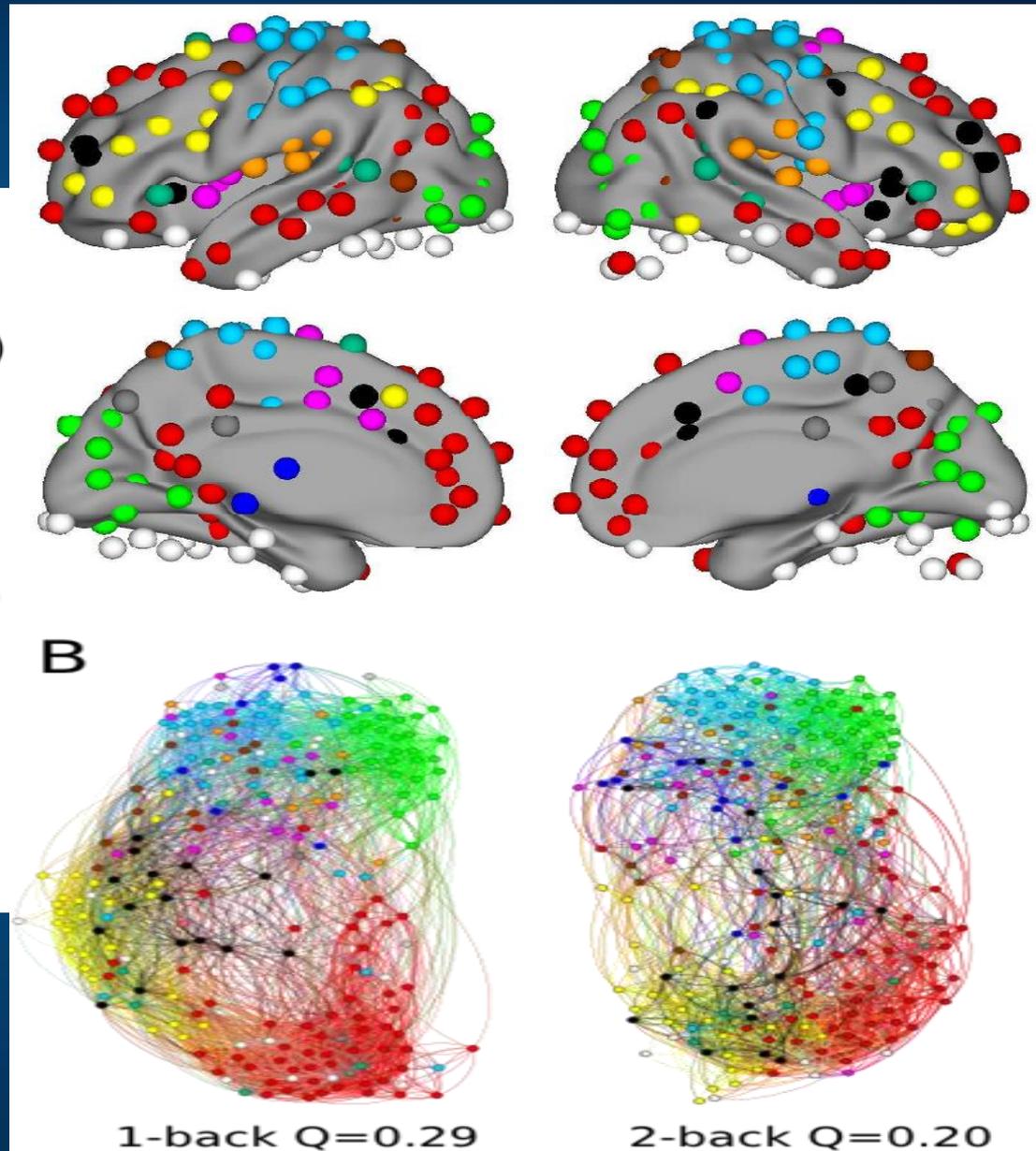
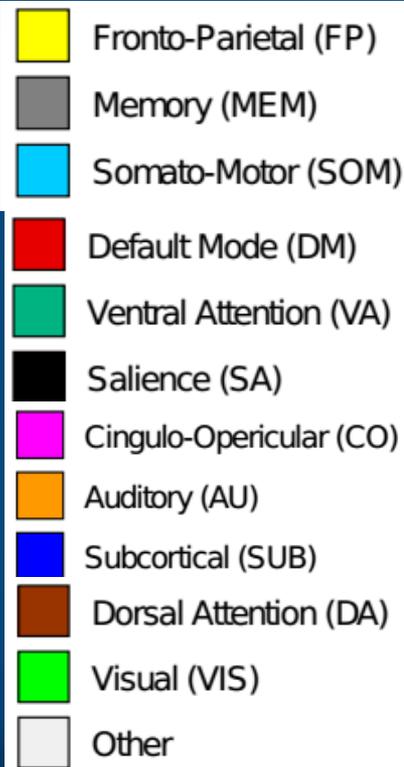
Simple and more difficult tasks, requiring the whole-brain network reorganization.

Left: 1-back

Right: 2-back

Average over 35 participants.

Left and midline sections.



K. Finc et al, HBM (2017).

# Brain modules and cognitive processes

Simple and more difficult tasks, requiring the whole-brain network reorganization.

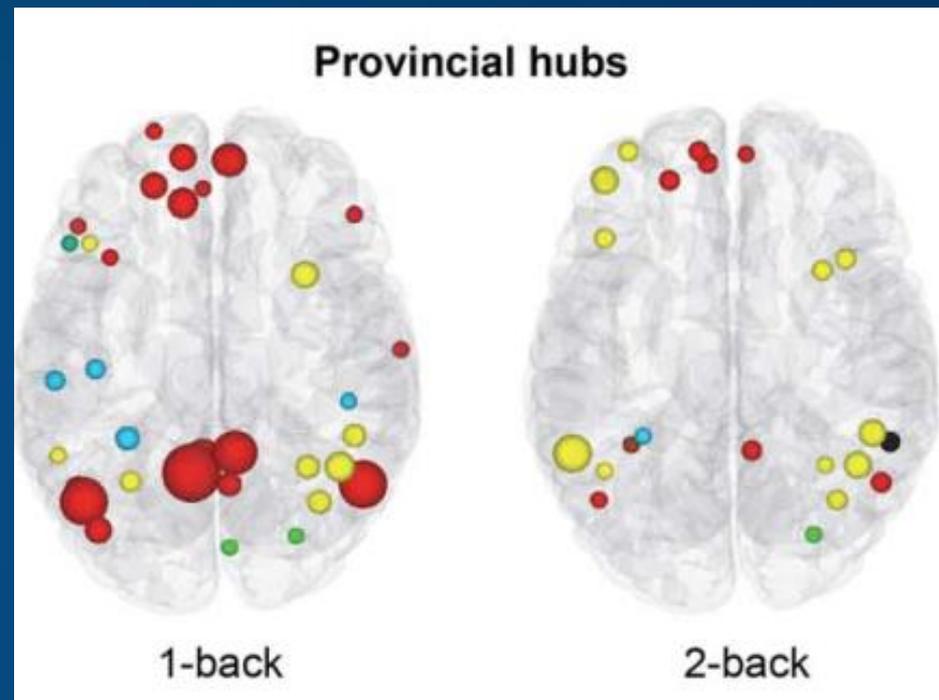
Left: 1-back local hubs

Right: 2-back local hubs

Average over 35 *participants*.

Dynamical change of the landscape of attractors, depending on the cognitive load.

Less local (especially in DMN), more global binding (especially in PFC).



K. Finc et al, HBM (2017).

# Brain modules and cognitive processes

Simple and more difficult tasks, requiring the whole-brain network reorganization.

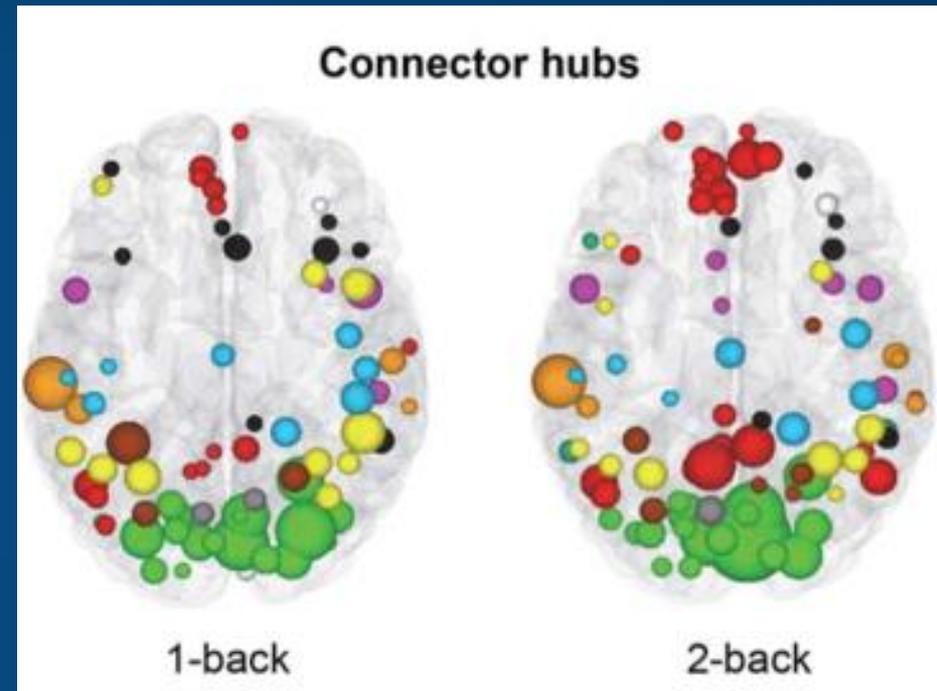
Left: 1-back connector hubs

Right: 2-back connector hubs

Average over 35 *participants*.

Dynamical change of the landscape of attractors, depending on the cognitive load – System 2 (Khaneman).

DMN areas engaged in global binding!



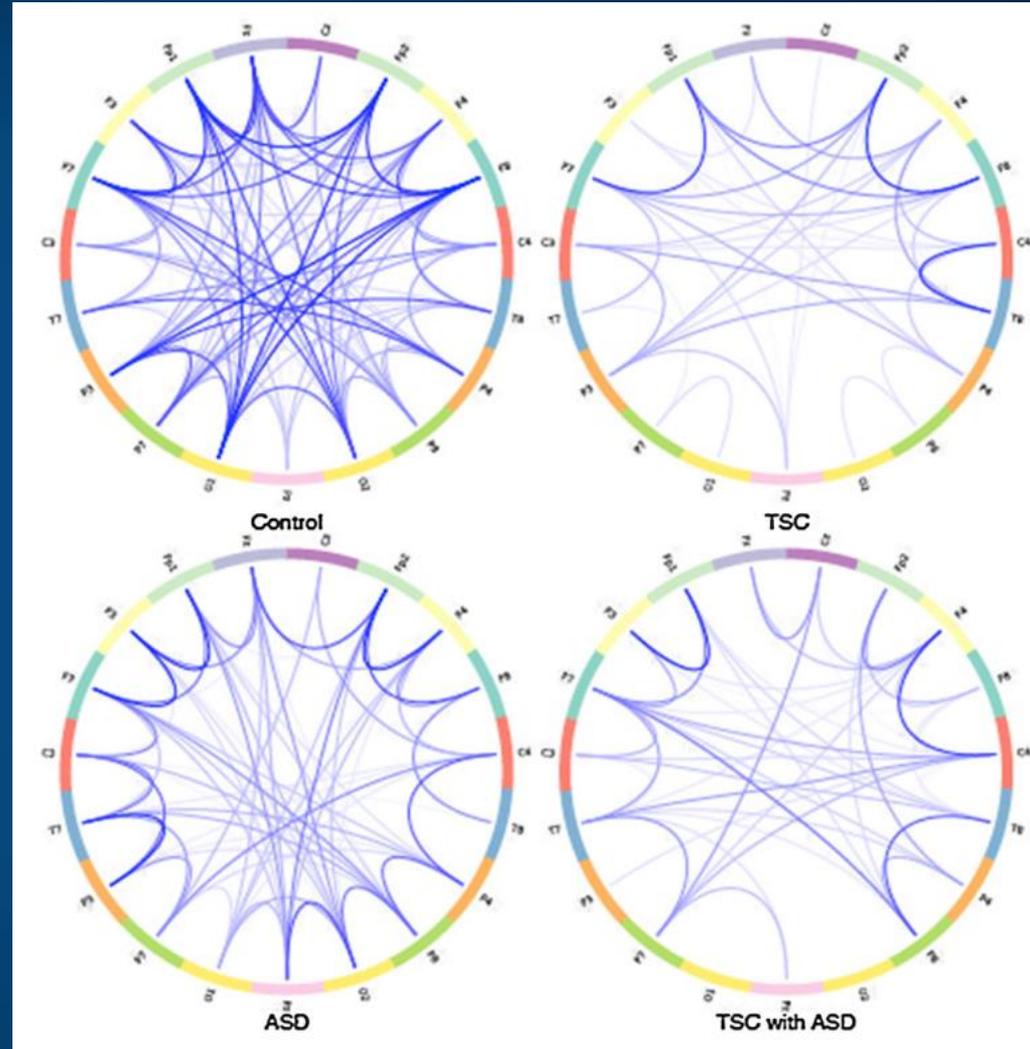
K. Finc et al, HBM (2017).

# ASD: pathological connections

Comparison of connections for patients with ASD (autism spectrum), TSC (Tuberous Sclerosis), and ASD+TSC.

Weak or missing connections between distant regions prevent ASD/TSC patients from solving more demanding cognitive tasks.

Network analysis becomes very useful for diagnosis of changes due to the disease and learning.

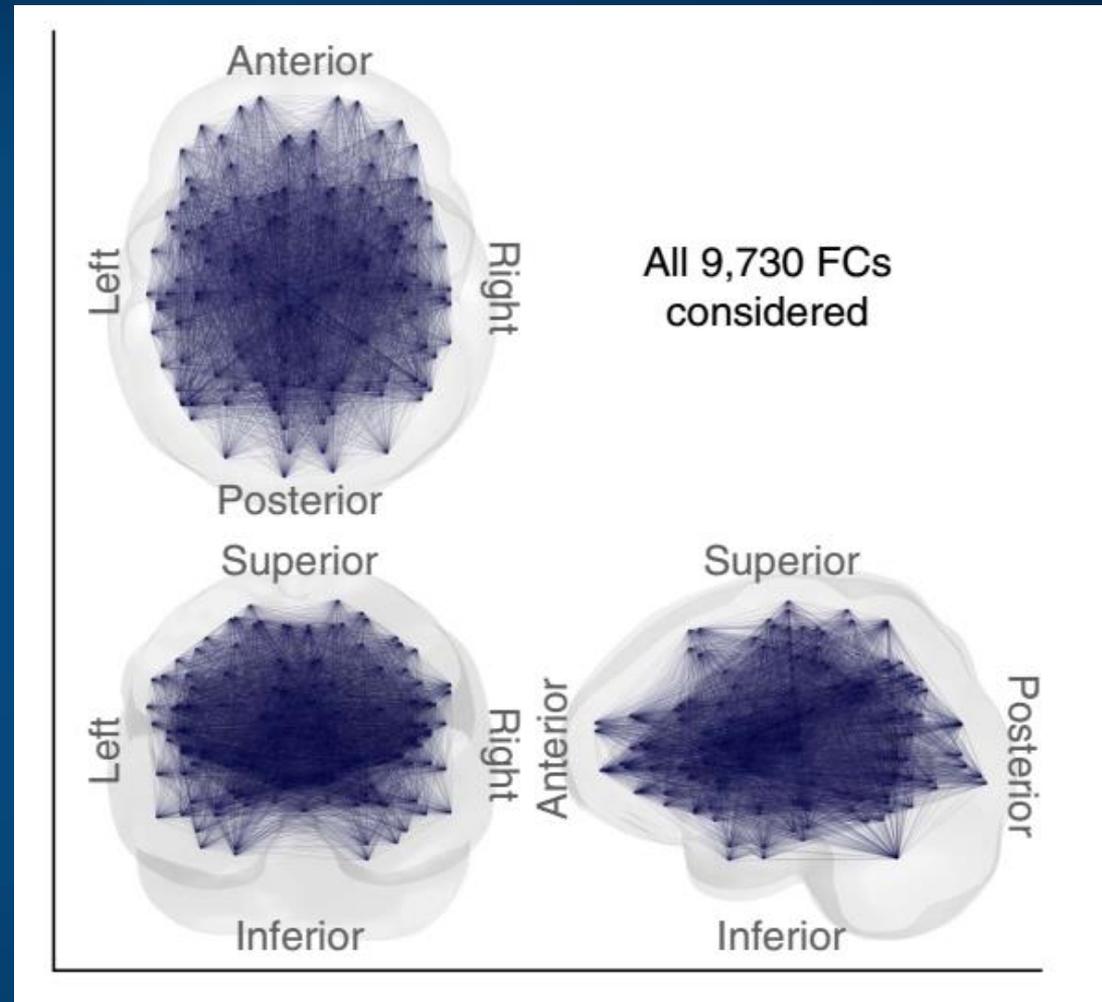


J.F. Glazebrook, R. Wallace, Pathologies in functional connectivity, feedback control and robustness. *Cogn Process* (2015) 16:1–16

# ASD connectome

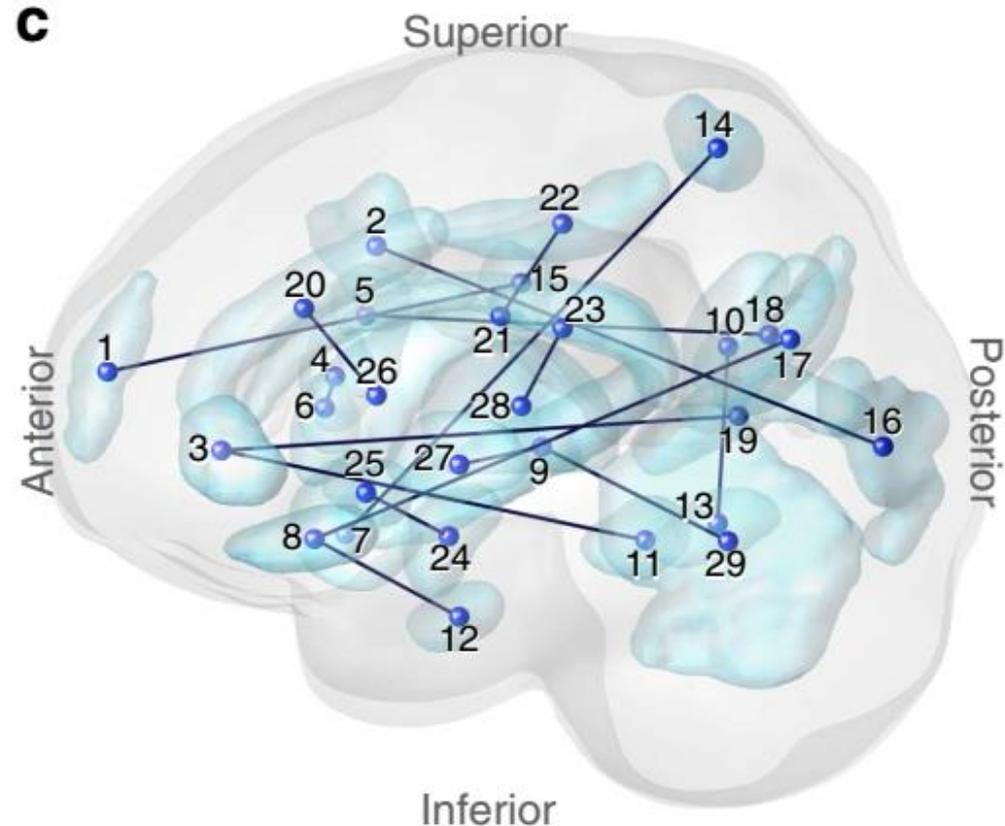
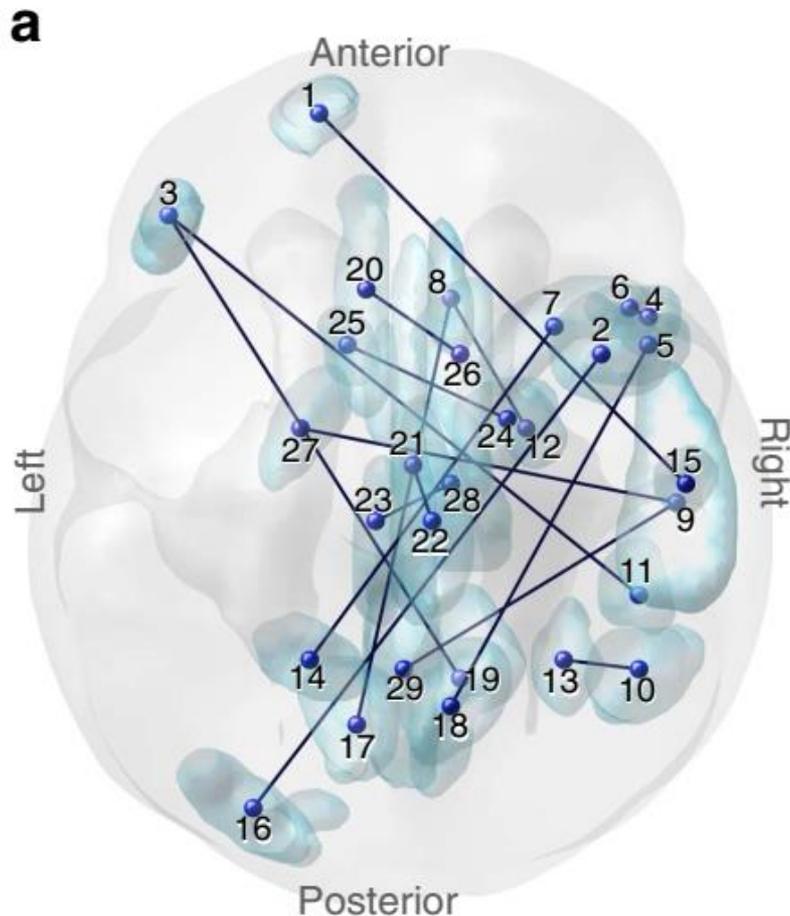
Analysis of functional connections (correlated activity) between brain regions measured using fMRI in the resting state between 140 ROIs has 9730 possible interactions.

Selecting the most important and using L1-SCCA classifier 16 connections were left, sufficient to reach 85% of accuracy distinguishing ASD people from the healthy ones.



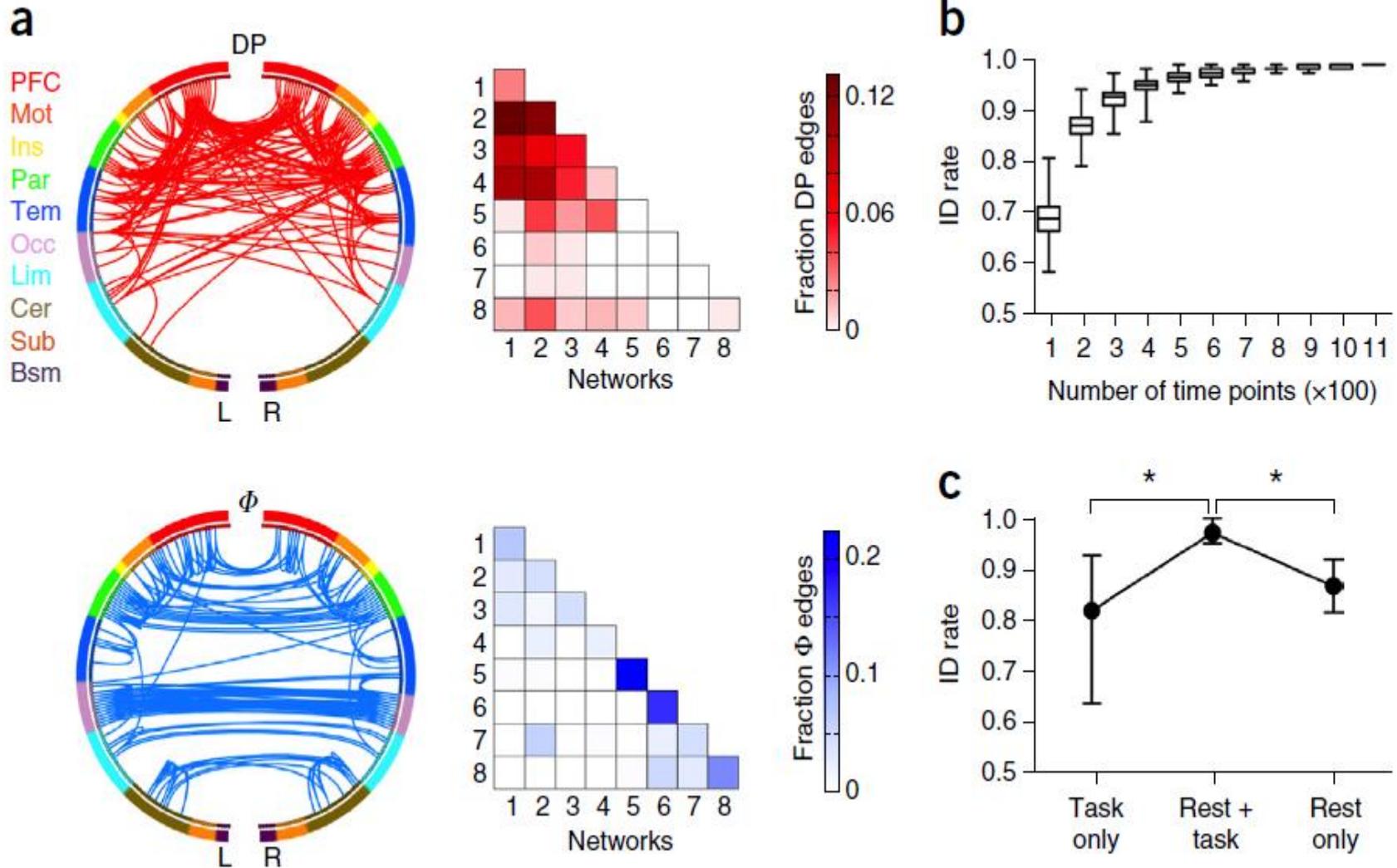
N. Yahata *et al.*, A small number of abnormal brain connections predicts adult autism spectrum disorder. *Nature Communications* (2016)

# Selected connections

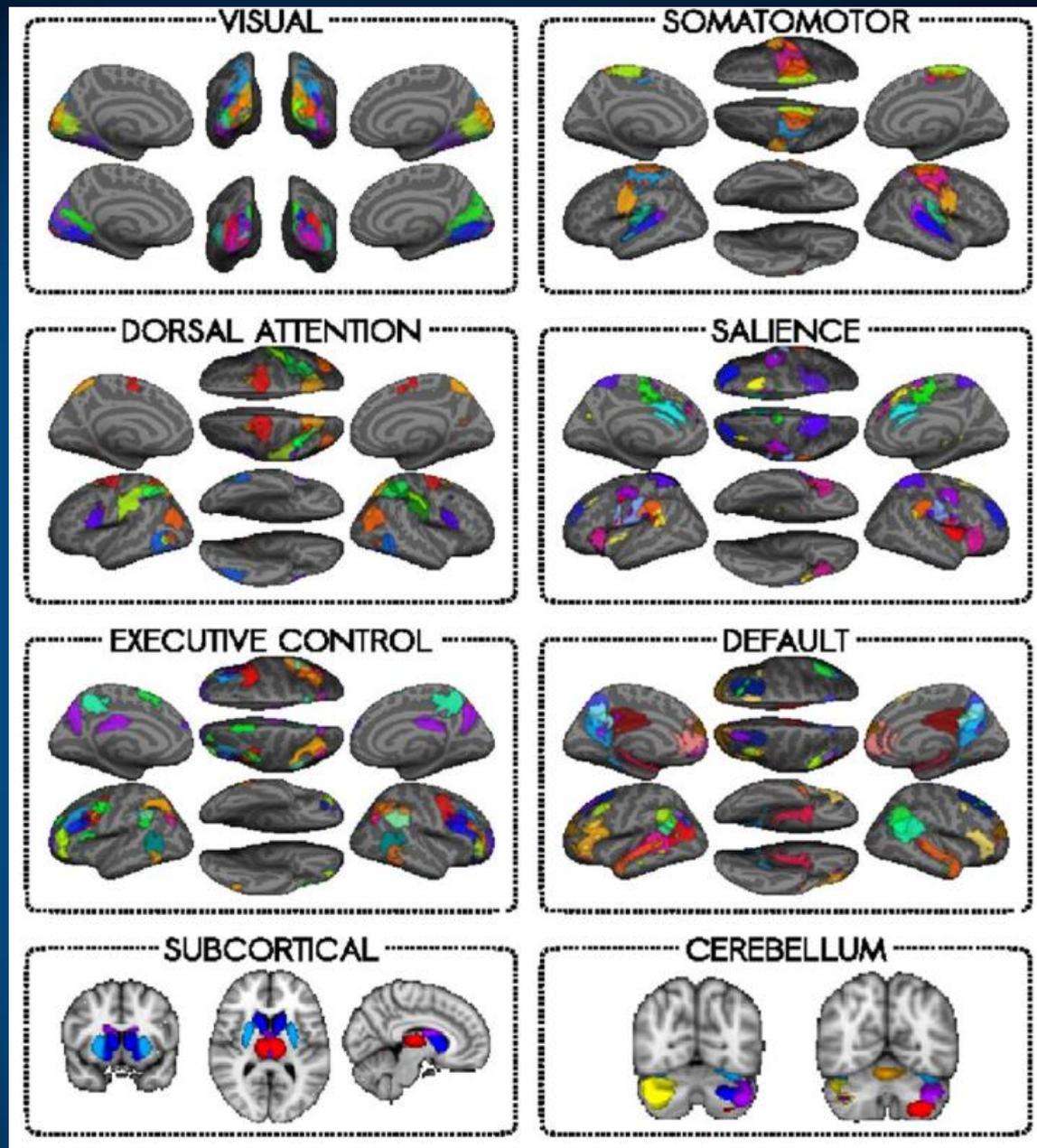
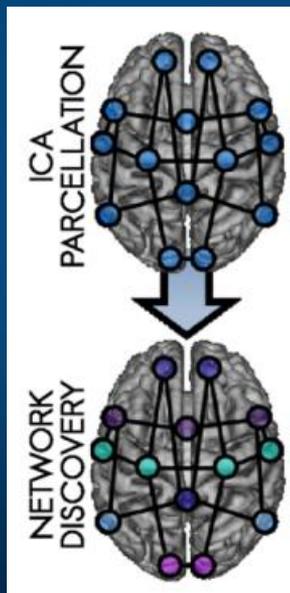


N. Yahata et al, 29 selected regions (ROI) and 16 connections were sufficient to recognize ASD with 85% accuracy in 74 Japanese adult patients, and 107 control group, and without re-training on 75% on US patients.

Finn et al. (2015), Functional connectome fingerprinting: identifying individuals using patterns of brain connectivity. Nature Neuroscience  
 Top: highly unique; Bottom: highly consistent connections.



# 6 canonical networks + subcortical + cerebellum

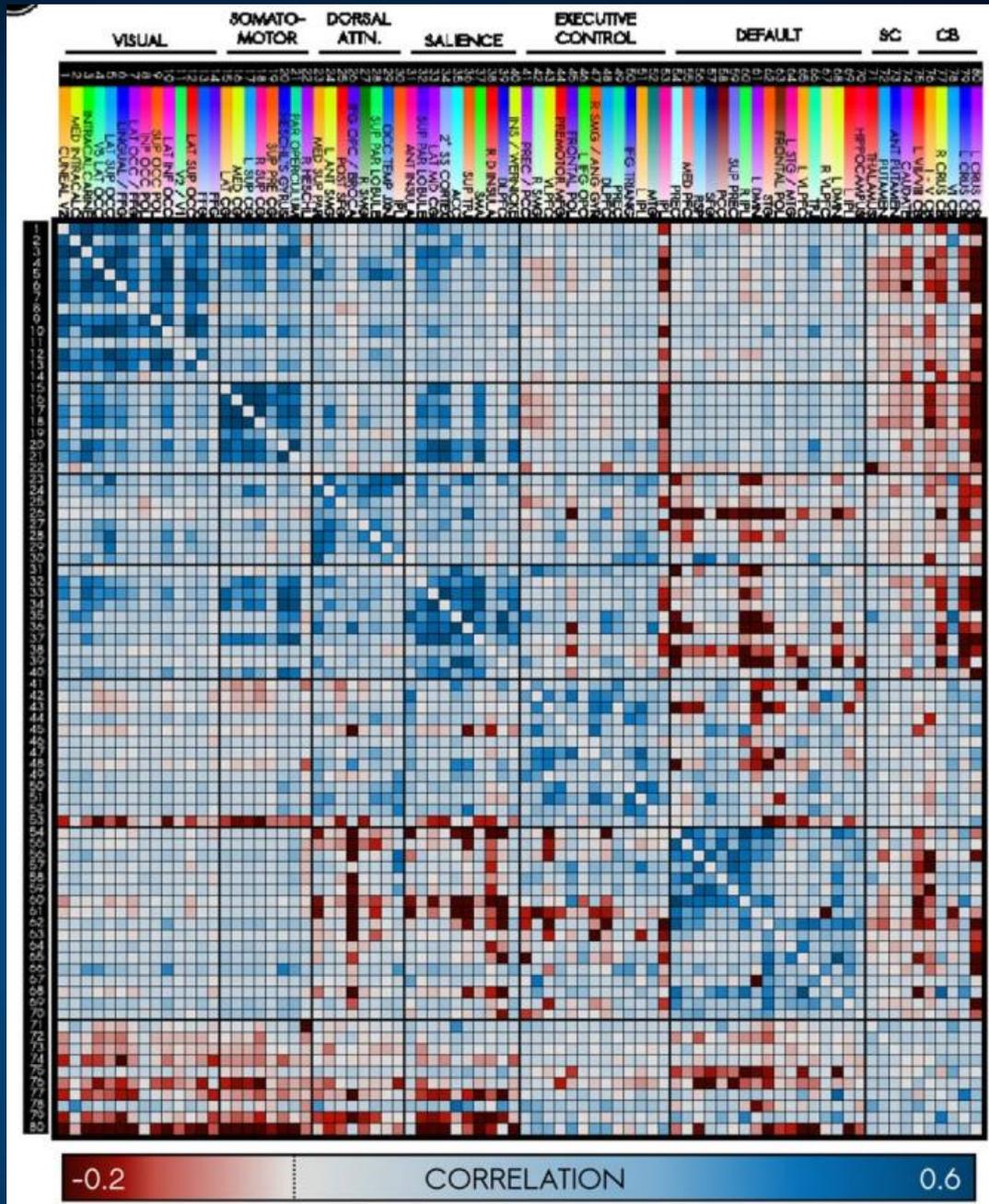


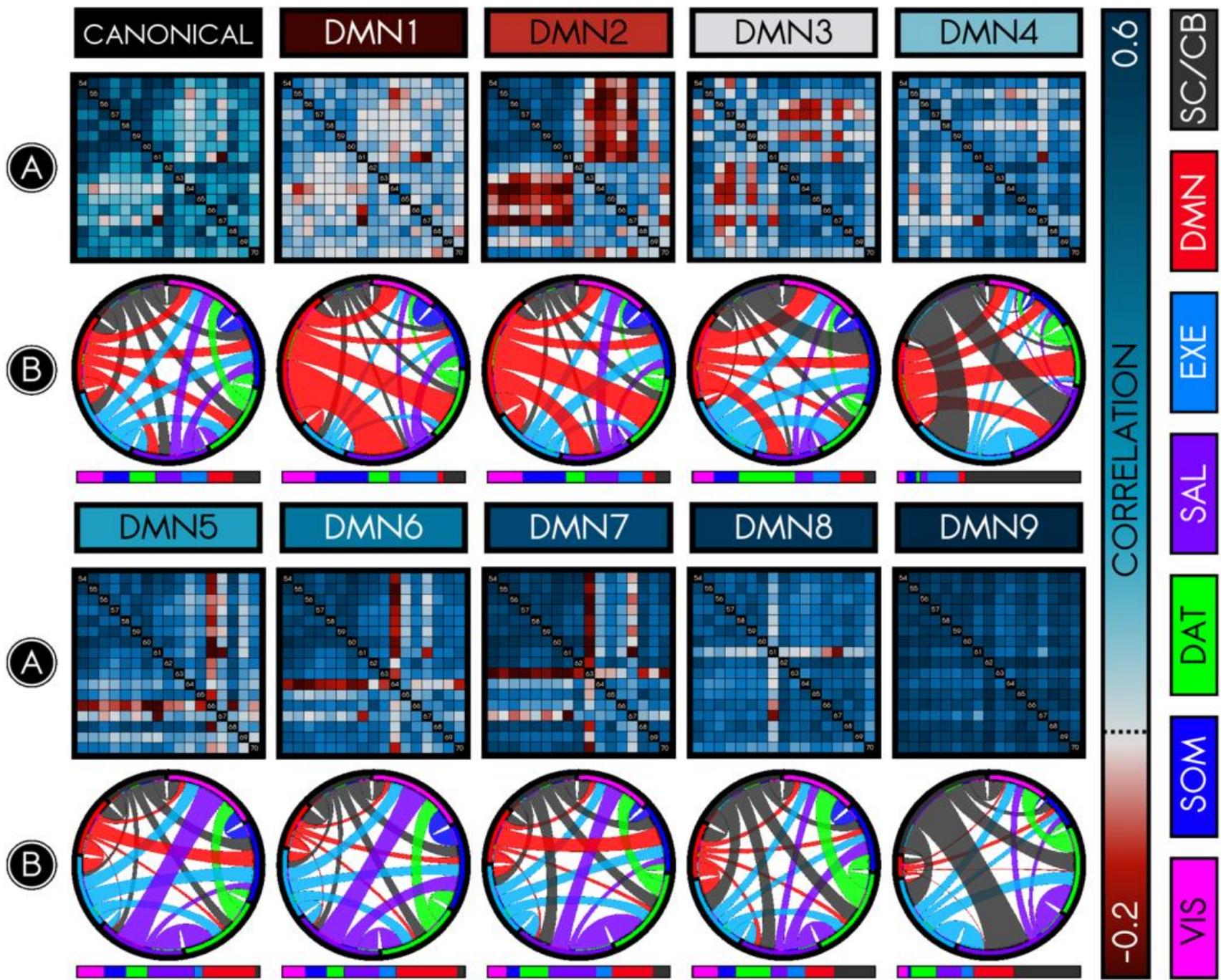
Correlations of 6 canonical networks.

Perception,  
Action-attention  
DMN (Default Mode Network)

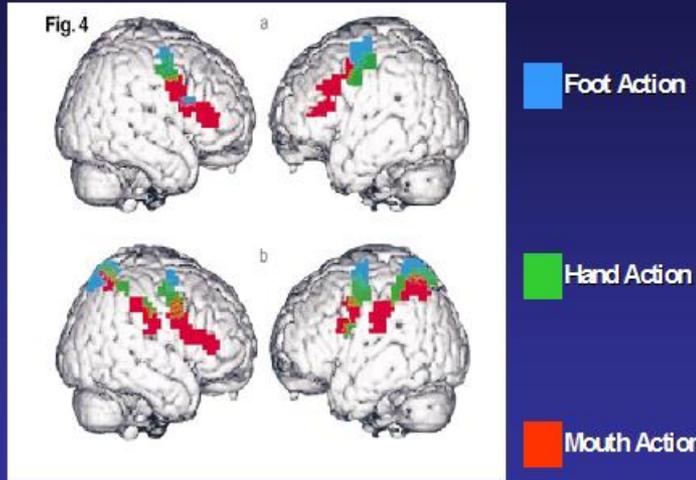
Each has up to 10 different network connectivity states (NC-states), rather stable for single subjects, ex. DMN has usually 7-9.

Ciric et.al. (2017). Contextual connectivity: A framework for understanding the intrinsic dynamic architecture of large-scale functional brain networks. *Scientific Reports*.





## Somatotopy of Action Observation



Buccino et al. Eur J Neurosci 2001

## Words in the brain



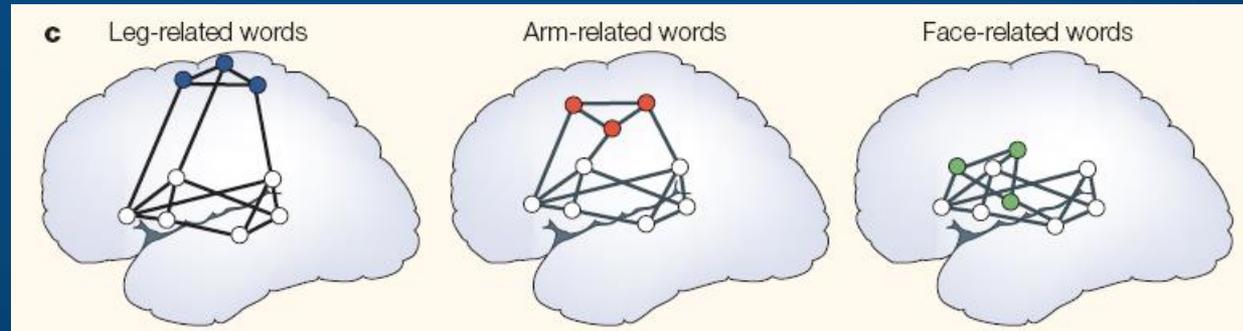
show that phonological and semantic representations.

=> words => semantic concepts.

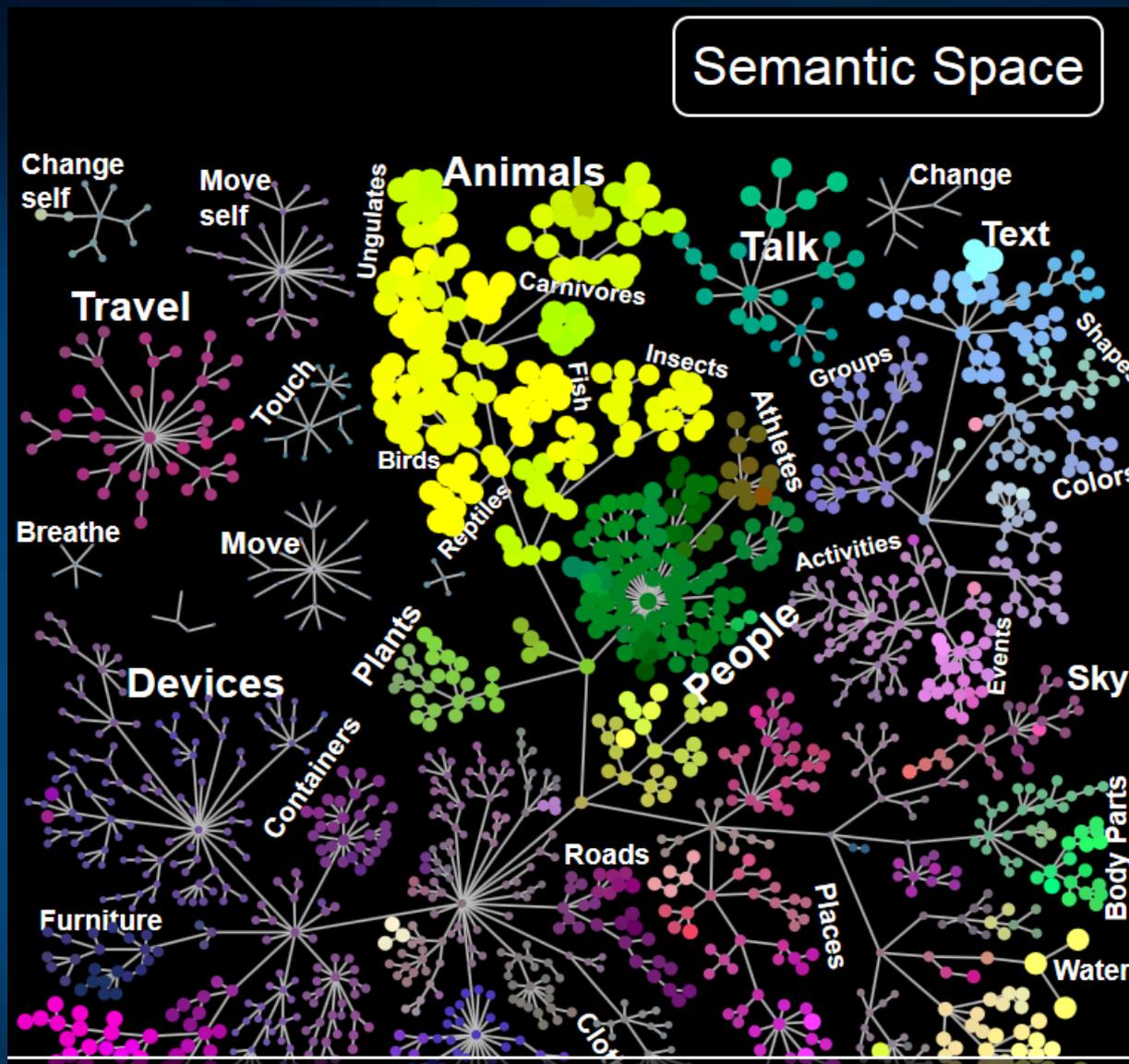
precedes semantic by 90 ms (from N200 ERPs).

Neuroscience of Language. On Brain Circuits of Language. Cambridge University Press.

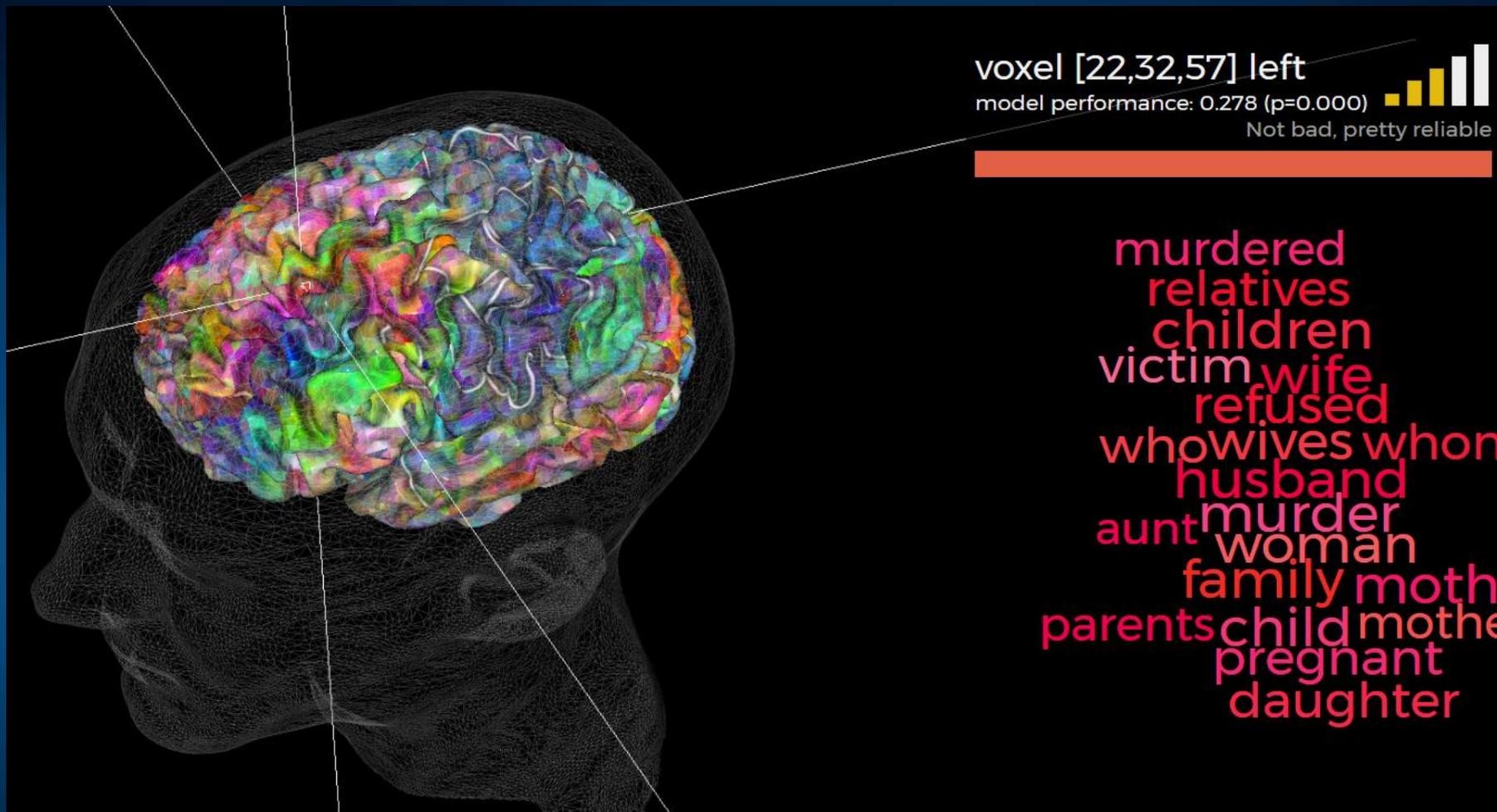
Action-perception networks inferred from ERP and fMRI



Left hemisphere: precise representations of symbols, including phonological components. Right hemisphere sees clusters of concepts, the gist.

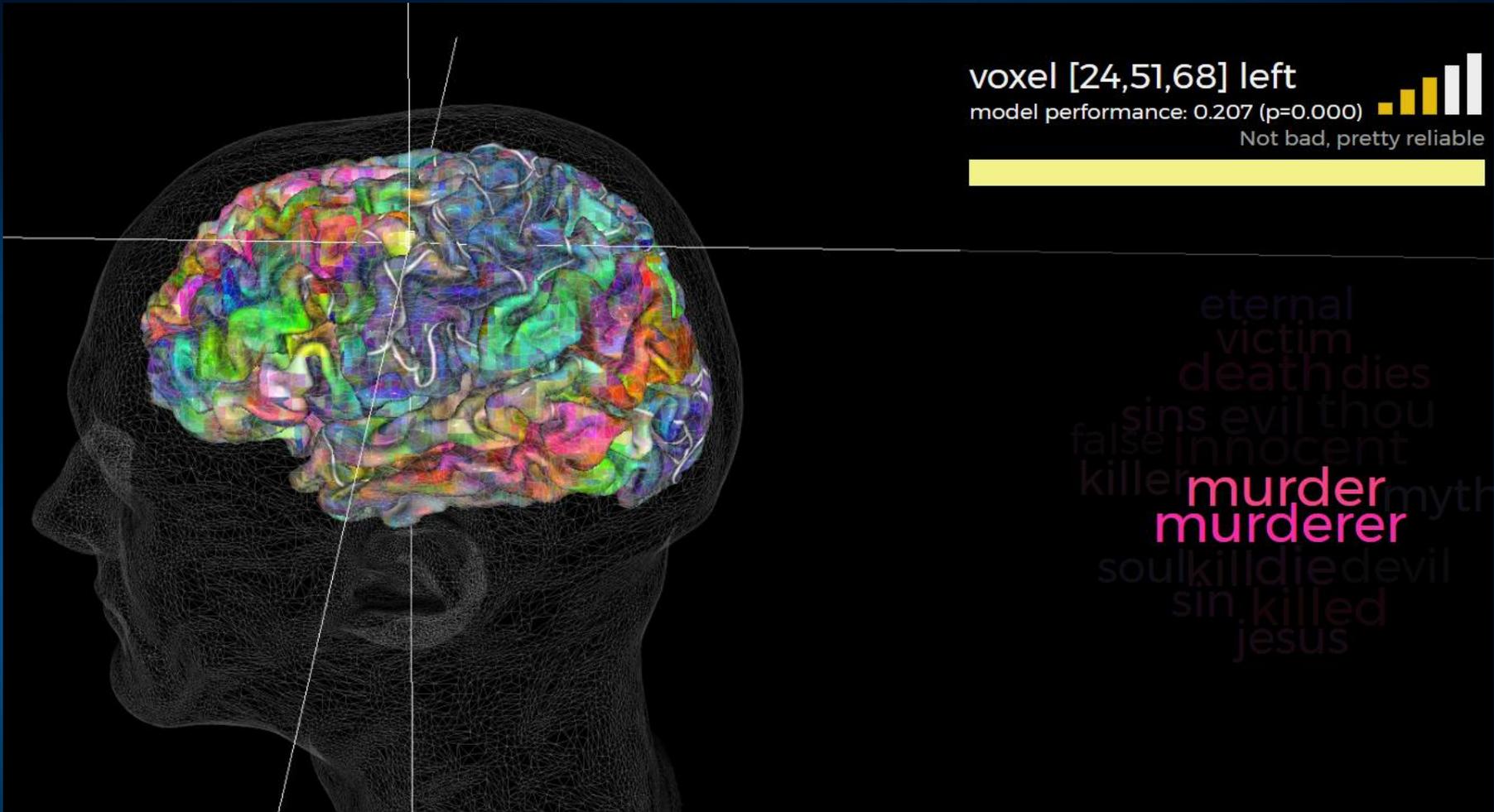


Words in the semantic space are grouped by their similarity.  
Words activate specific brain maps, similar words create similar maps.  
Each pixel may be activated by many words.



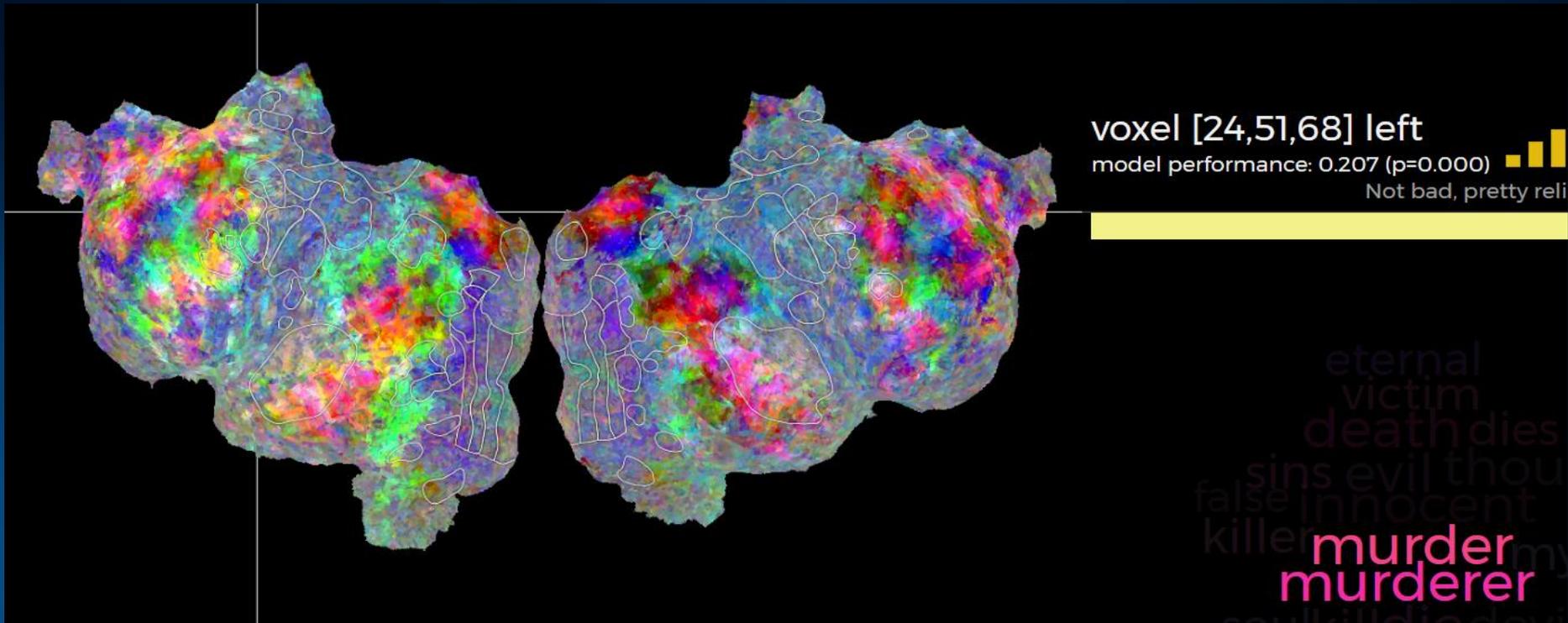
Each voxel responds usually to many related words, whole categories.

<http://gallantlab.org/huth2016/>



Voxel may also responds in quite specific way.

<http://gallantlab.org/huth2016/>



Each word activates a whole map of activity in the brain.

Whole map for the word “murder” shown on the flattened cortex.

Why such activity patterns arise? Brain subnetworks connect active areas.

<http://gallantlab.org/huth2016/> and [short movie intro](#).

Can one do something like that with EEG or MEG?

If it can, there will be great application opportunities.

# Narration

Nicole Speer et al.  
 Reading Stories Activates Neural  
 Repre-sentations of Visual and  
 Motor Experiences. Psychological  
 Science 2009; 20(8): 989–999.

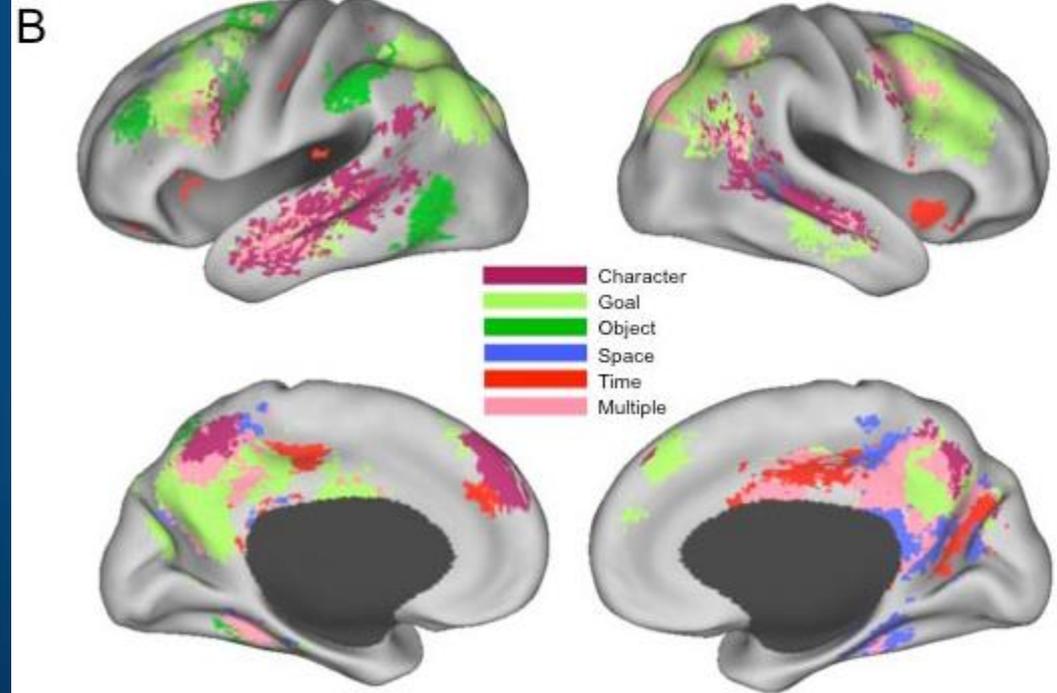
**Thought:** spatiotemporal pattern

**Meaning:** always slightly  
 different, depending on the  
 context, but still may be  
 clusterized into relatively small  
 number of distinct meanings.

Sentences: trajectories in  
 semantic space, building scenes,  
 mind models with characters,  
 objects, spatio-temporal  
 relations.

A

Clause	Cause	Character	Goal	Object	Space	Time
...[Mrs. Birch] went through the front door into the kitchen.	●				●	
Mr. Birch came in	●	●			●	
and, after a friendly greeting,	●					●
chatted with her for a minute or so.	●					●
Mrs. Birch needed to awaken Raymond.		●				
Mrs. Birch stepped into Raymond's bedroom, pulled a light cord hanging from the center of the room,			●		●	
and turned to the bed.						
Mrs. Birch said with pleasant casualness, "Raymond, wake up."						
With a little more urgency in her voice she spoke again:						
Son, are you going to school today?						
Raymond didn't respond immediately.		●				●
He screwed up his face			●			
And whimpered a little.						

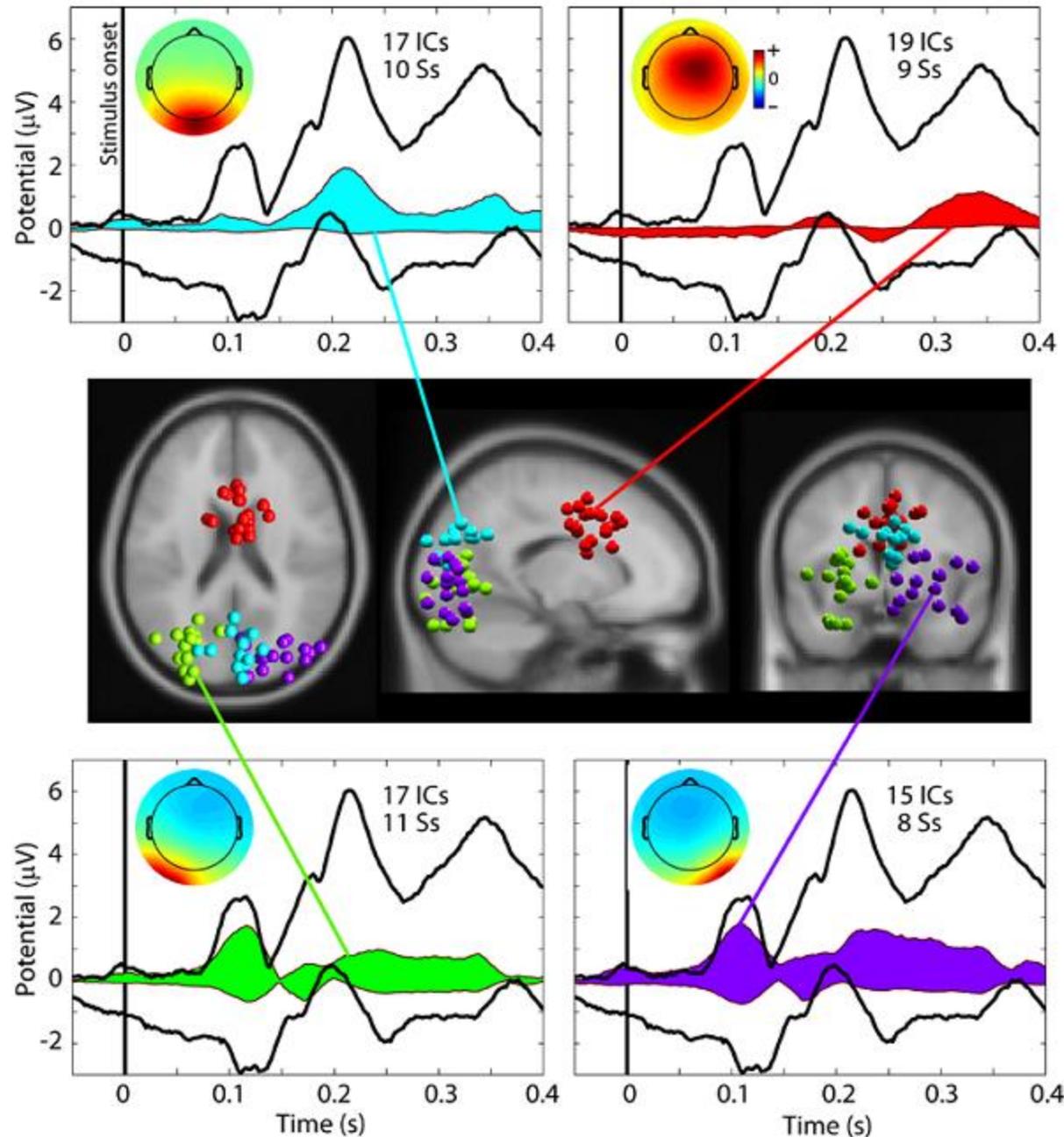


Source localization maps brain activity to attractor dynamics.

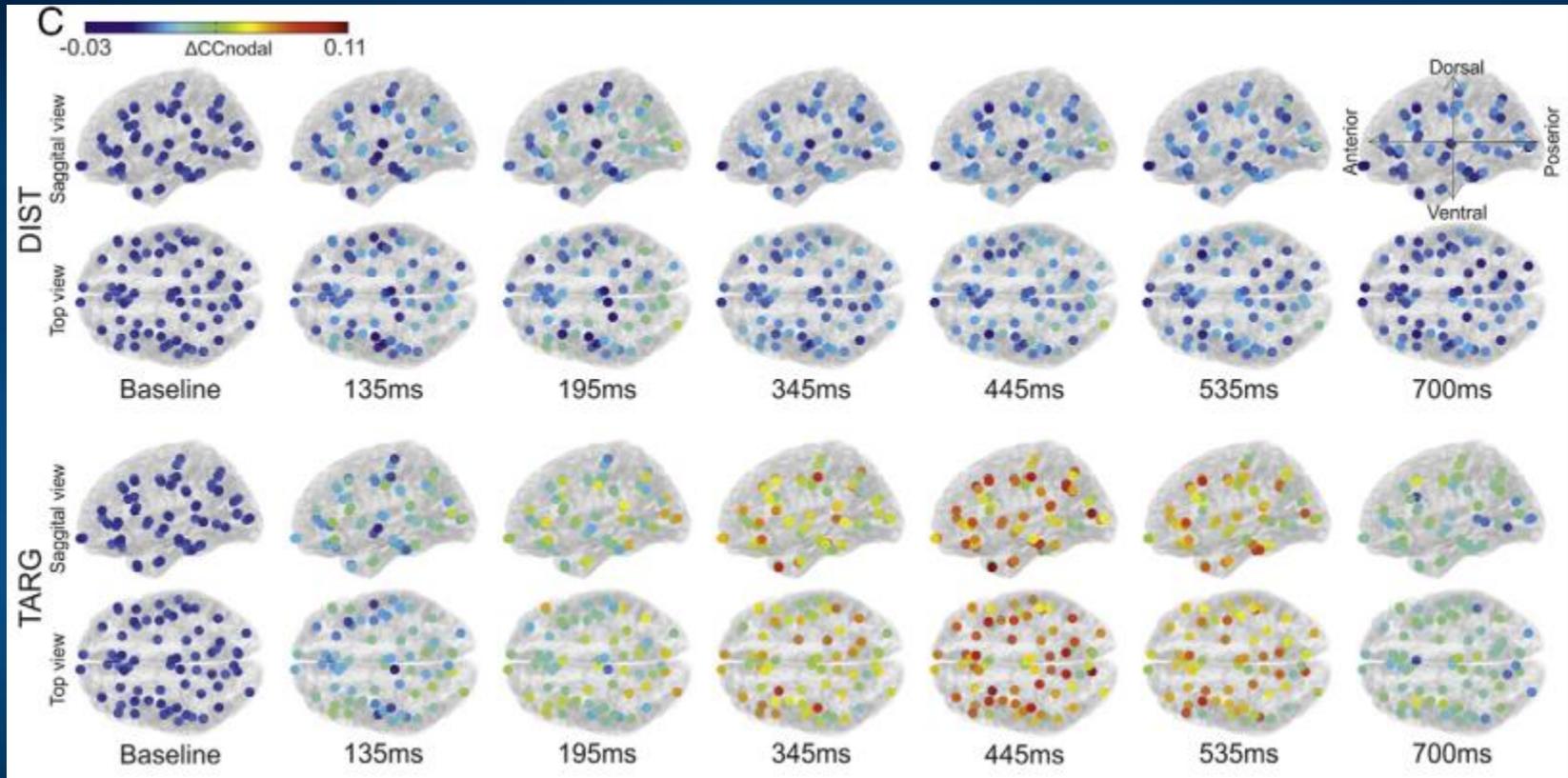
Problem: these sources pop up and vanish in different places.

Fig. from:  
Makeig, Onton, 2009  
ERP Features and  
EEG Dynamics:  
An ICA Perspective.

**Brain fingerprinting:**  
discover in EEG specific  
patterns for attractor  
dynamics = subnetwork  
activation.



# Phase Locking Value analysis



Changes in theta EEG band in the space of cluster coefficients. Anticipation of stimuli creates weak priming activation that is inhibited if this is not the target stimuli (Bola, Sabel, 2015). Pre-activation solves the frame problem?

# Model of reading & dyslexia



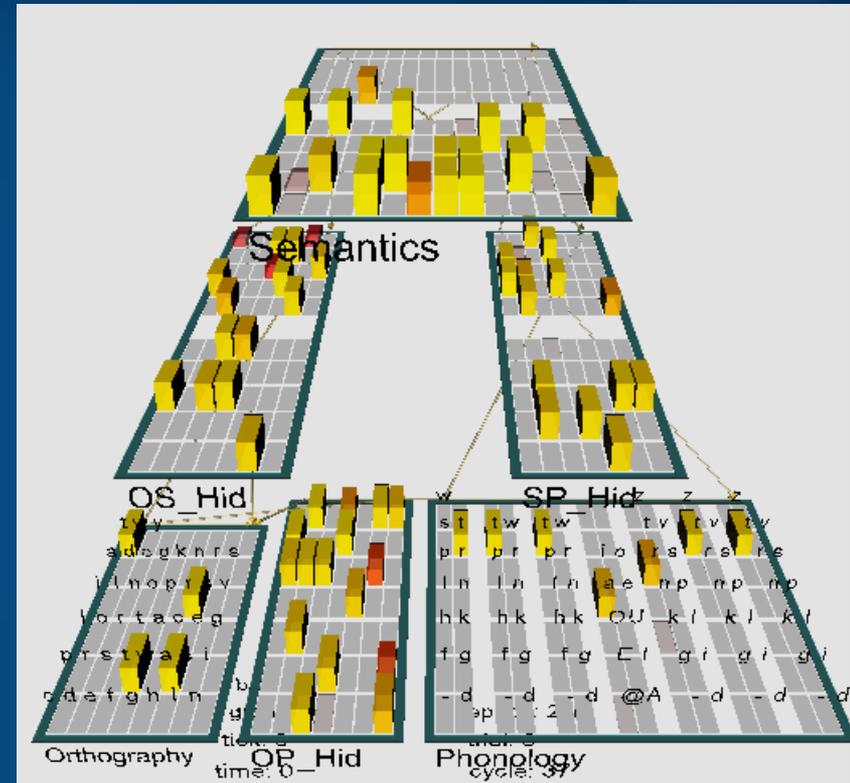
Emergent neural simulator:

Aisa, B., Mingus, B., and O'Reilly, R.  
The emergent neural modeling system.  
Neural Networks,  
21, 1045-1212, 2008.

3-layer model of reading:

orthography, phonology, semantics, or  
distribution of activity over  
**140 microfeatures** defining concepts.

Hidden layers in between.



Learning: mapping one of the 3 layers to the other two.

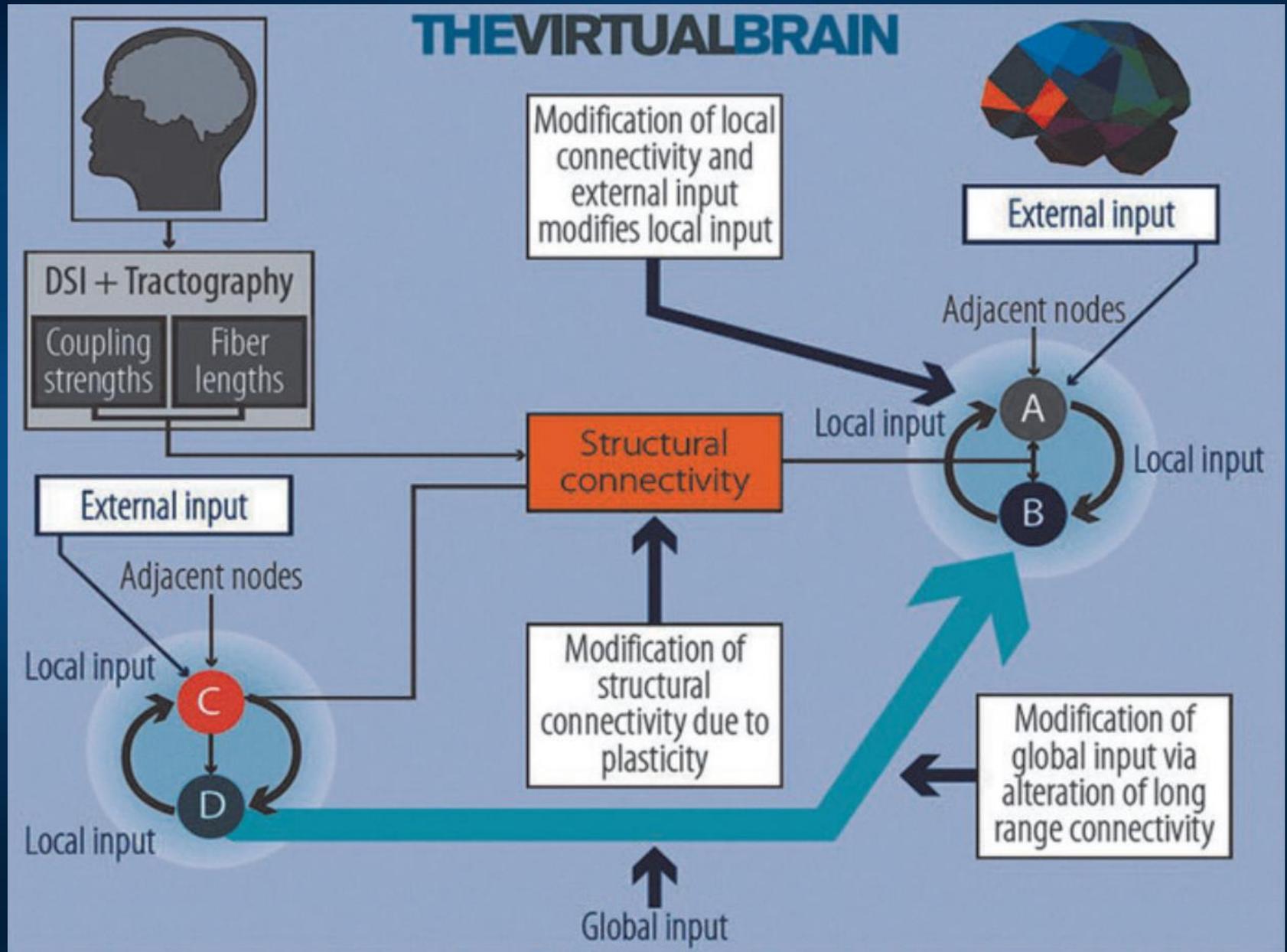
Fluctuations around final configuration = attractors representing concepts.

How to see properties of their basins, their relations?

Model in **Genesis**: more detailed neuron description.

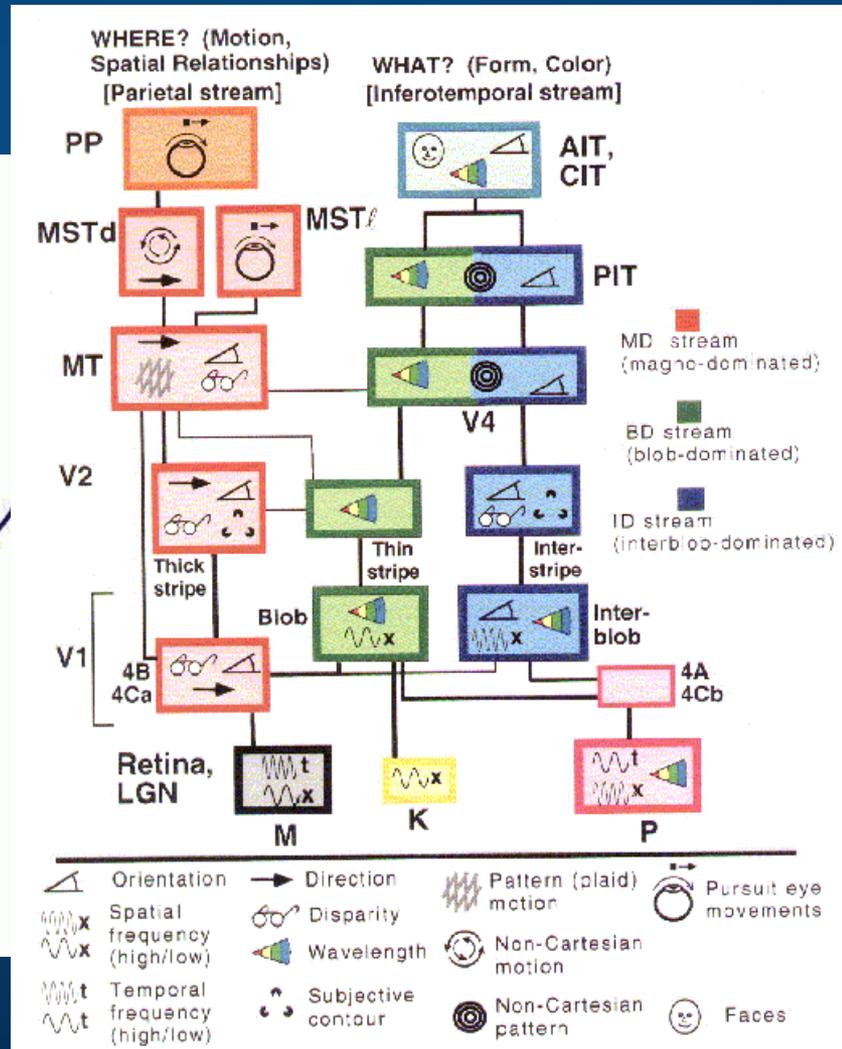
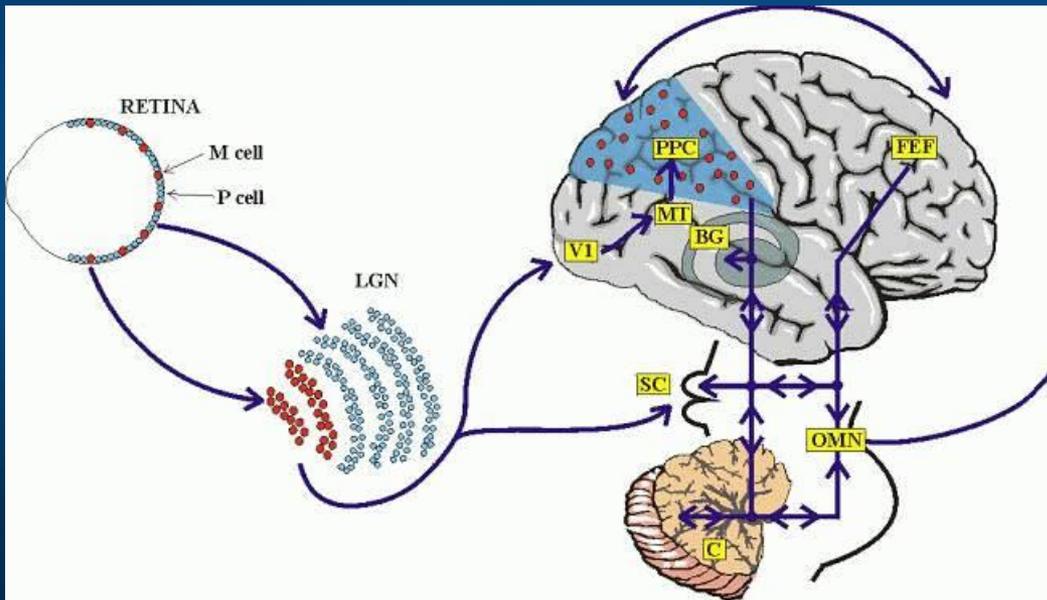


# Population dynamics TVB model



# Mental images - Vision

From retina through LGN (thalamus, lateral geniculate body) to the primary visual cortex V1, through dorsal and ventral pathways, information flows through many layers, receptive fields react to the complex stimuli in an invariant way.



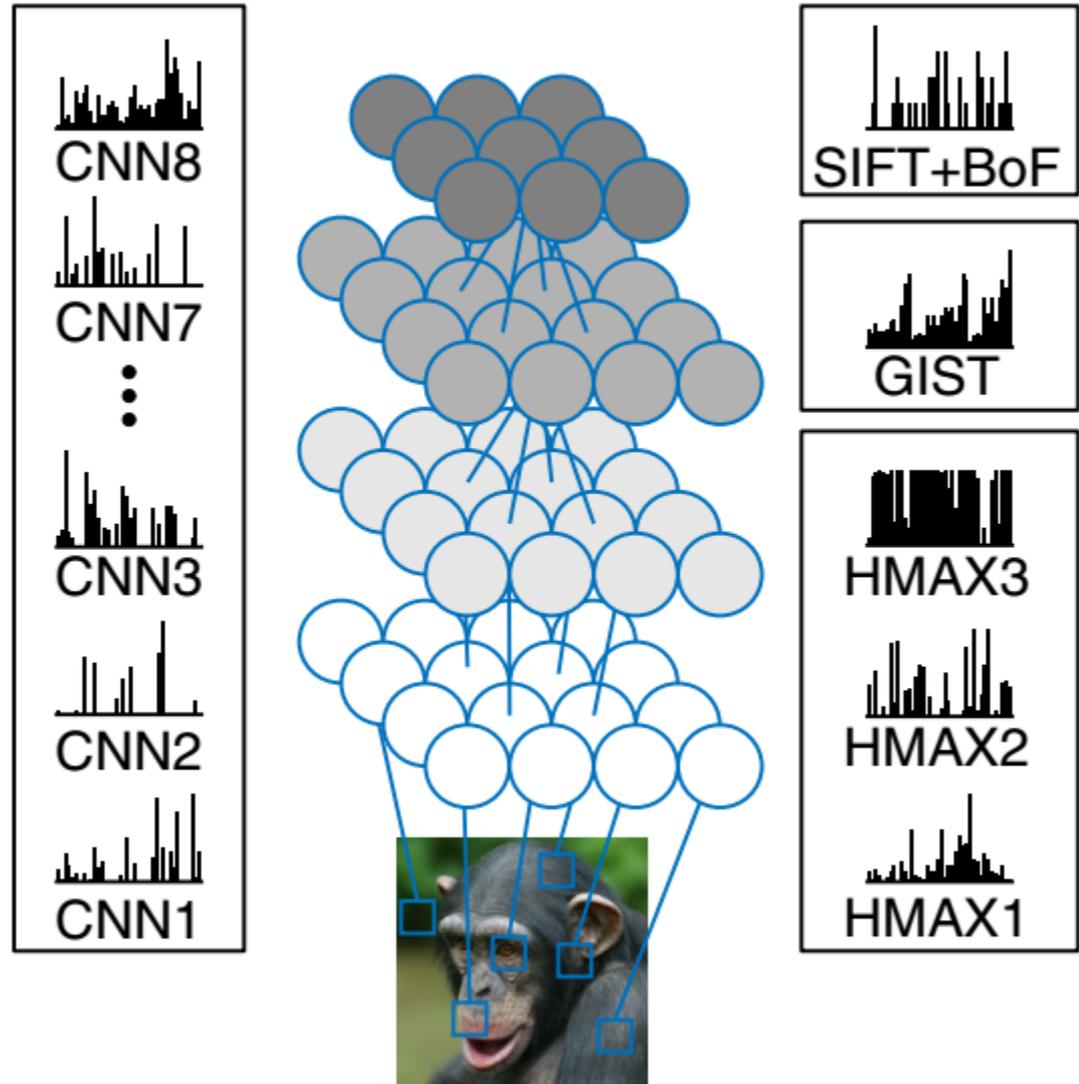
# Mental images from brain activity

Can we convert activity of the brain into the mental images that we are conscious of?

Try to estimate features at different layers.

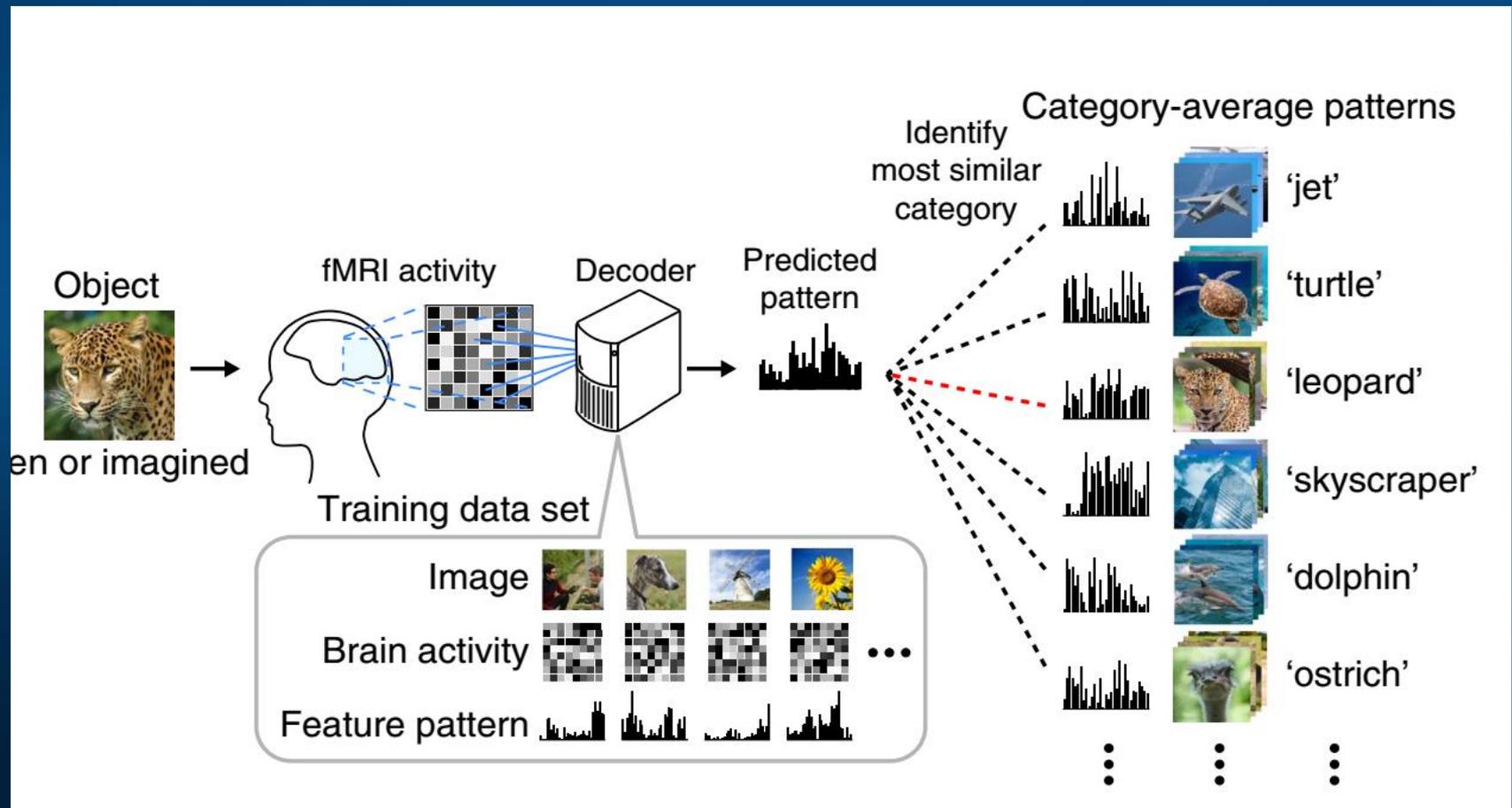
8-layer convolution network, ~60 mln parameters, feature vectors from randomly selected 1000 units in each layer to simplify calculations.

Output: 1000 images.



# Brain activity $\leftrightarrow$ Mental image

fMRI activity can be correlated with deep CNN network features; using these features closest image from large database is selected. Horikawa, Kamitani, Generic decoding of seen and imagined objects using hierarchical visual features. Nature Comm. 2017.



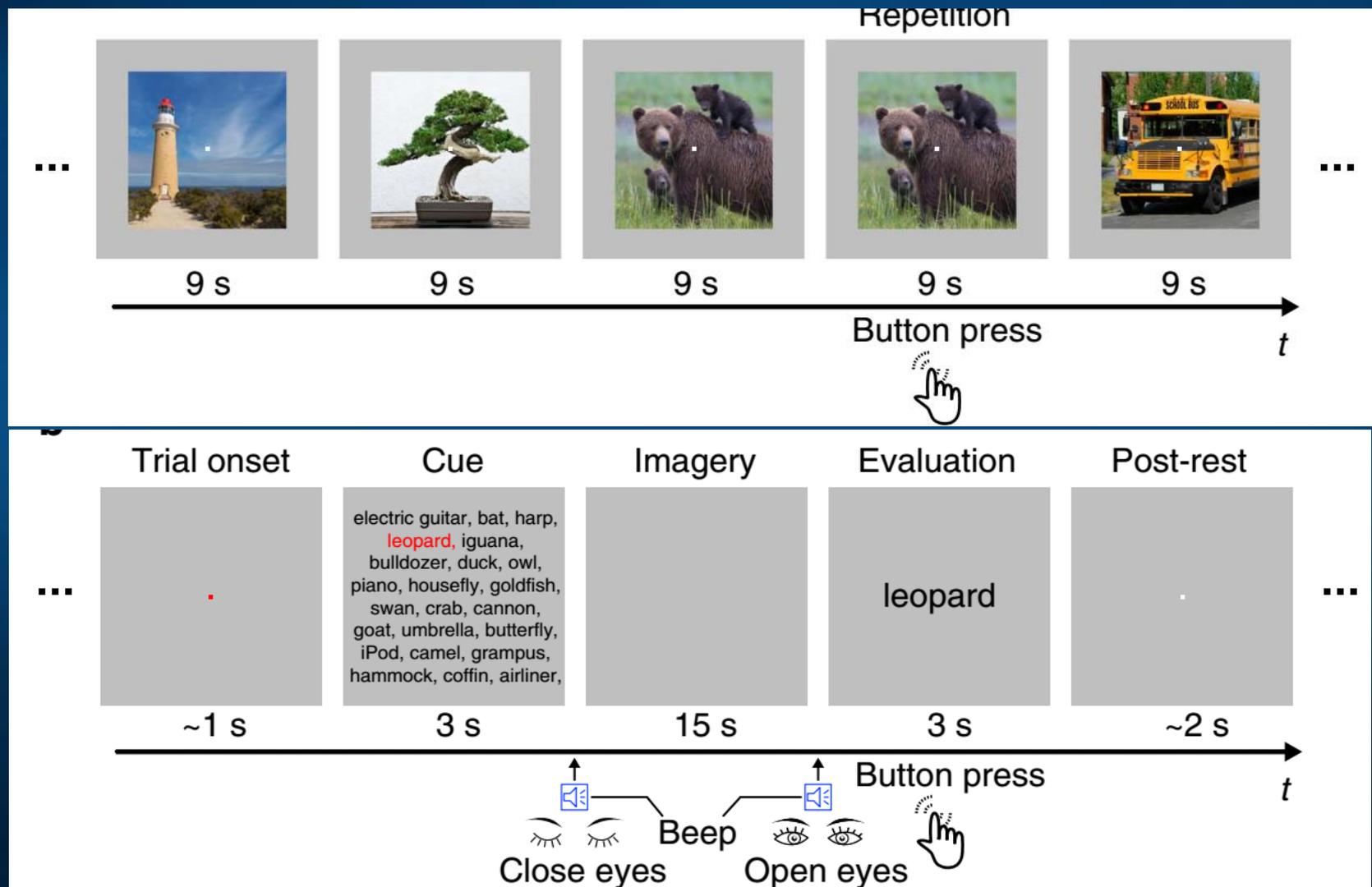
# fMRI $\Leftrightarrow$ CNN

Generic decoding: recognizing also images that did not appear in training.  
Data from dreams, imagery, visual activity.

1. Use CNN to analyze >15.000 images  $O_i$  from ImagNet database classifying them into 1000 categories; for each image generate 13 types of features (CNN1–8, HMAX1–3, GIST and SIFT + BoF) coded as template feature vectors  $V(O_i)$  for images.
2. Analyze fMRI data  $F(O_i)$  for 150 image categories (8 examples in each), select 500 voxels for V1–V4, LOC, FFA and PPA responding strongly to images vs scrambled images; decode feature values  $V(O_i)$  using regression analysis  $R[F(O_i)] = V(O_i)$ .
3. For a new image  $O_n$  (test, imagery, dream) use regression to calculate feature vector  $R[F(O_n)] = V(O_n)$ .
4. Find in the database vector  $V(O)$  for category of images most similar to the predicted  $V(O_n)$ , representing mental image, or recreate using activation maximization method an image from  $V(O_n)$  vector.

# Recognizing mental image

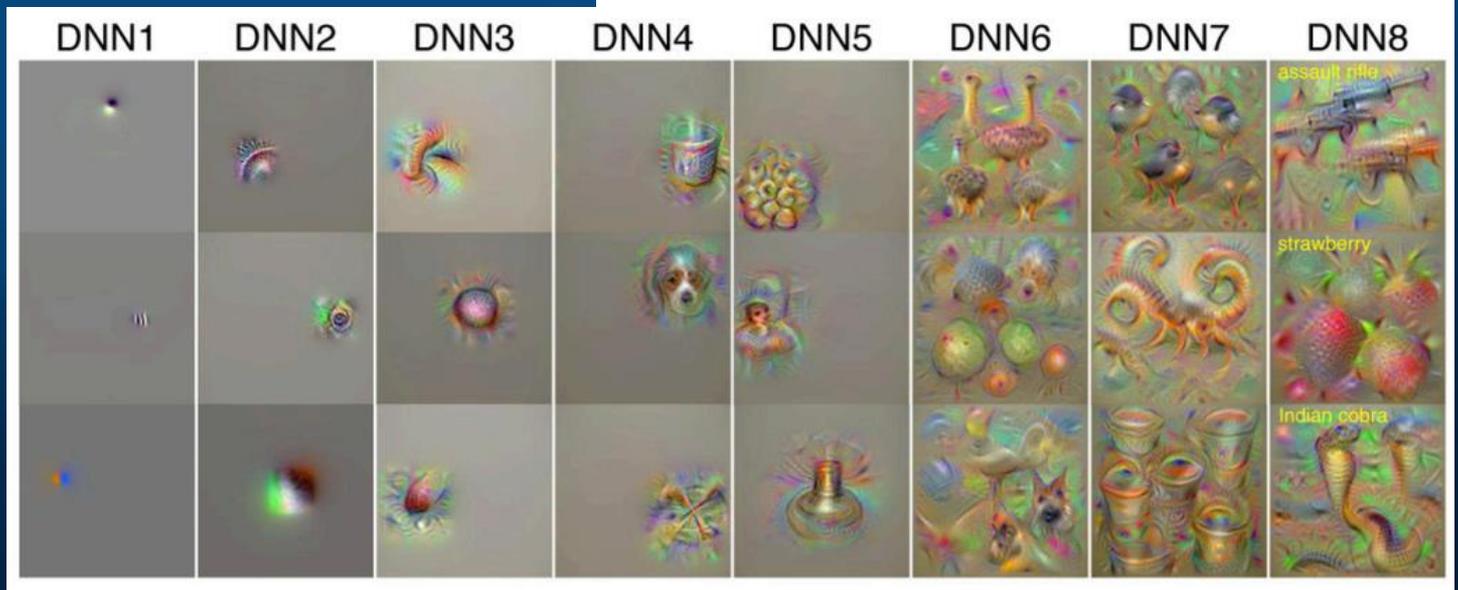
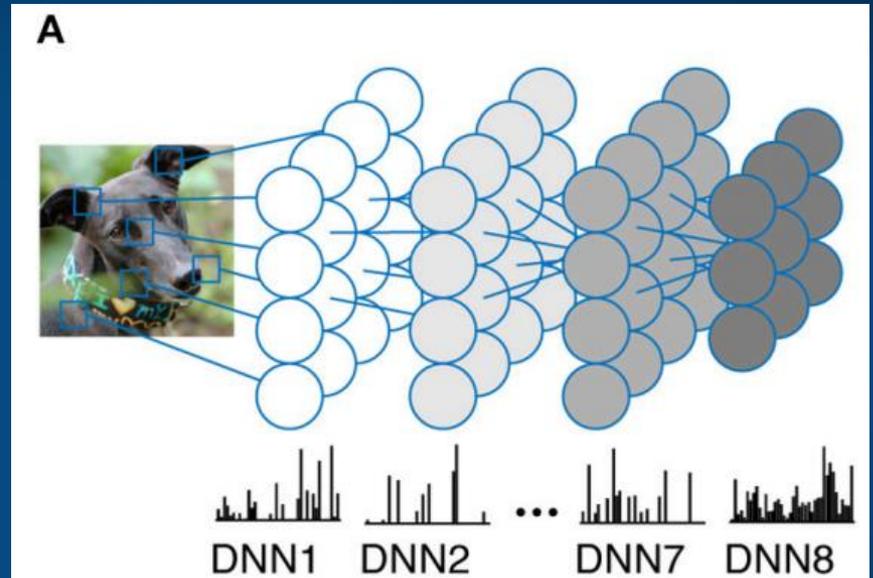
Horikawa, Kamitani, Nature Comm. 2017.



# fMRI $\leftrightarrow$ CNN

CNN with 8 layers,  
~1000 units selected/layer;  
layers 6, 7, 8 are fully connected,  
synthesis of preferred images by  
the output layer was done using  
activation maximization method.

Same approach was used to  
decode dreams (Horikawa,  
Kamitani, FCN 2017)



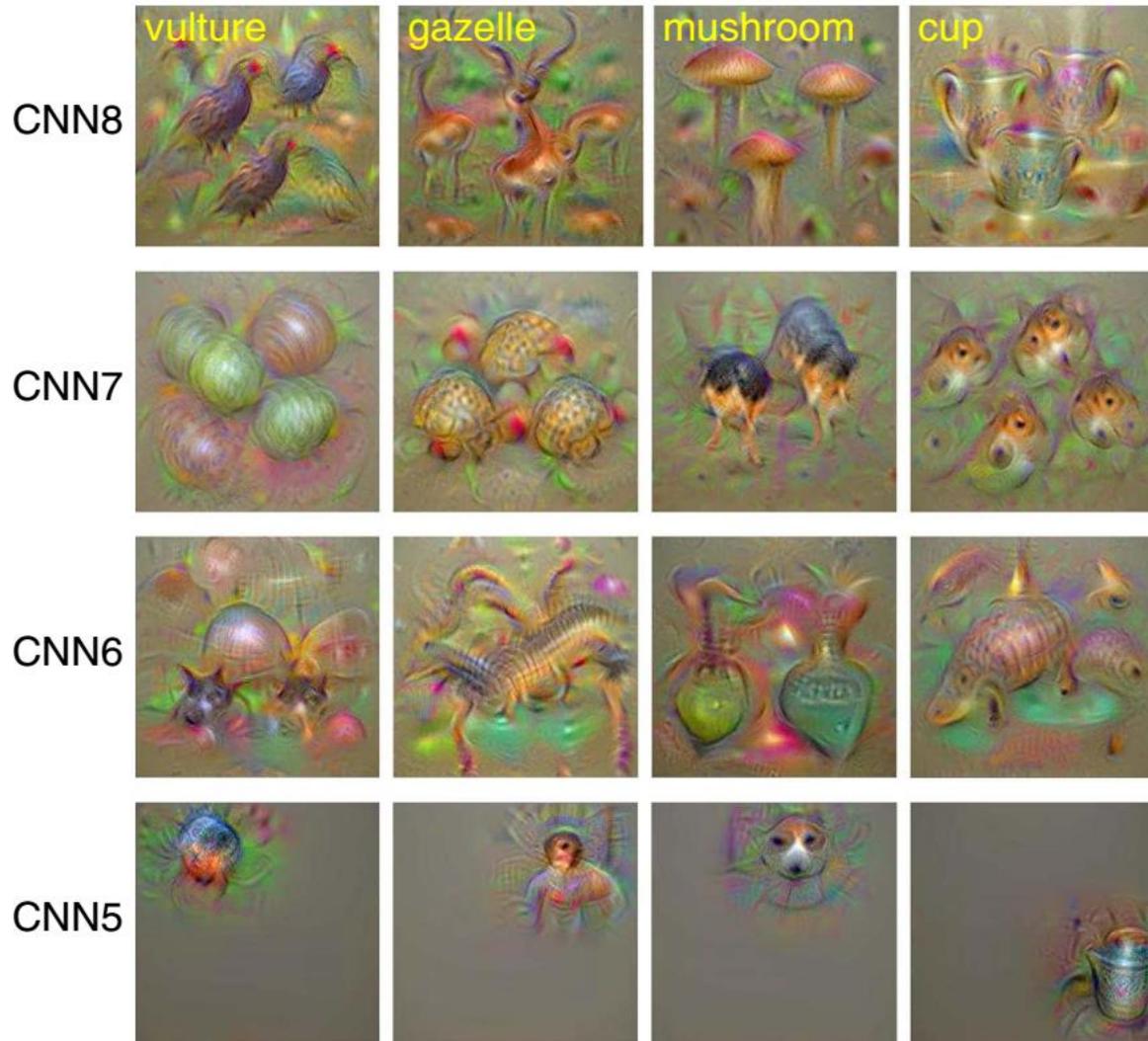
# fMRI $\leftrightarrow$ CNN

4 units randomly selected from 1000 in each layer.

Complexity and invariance (rotation, translation, scaling) grows in each layer.

CNN8 has labels for 1000 categories.

Accuracy of seen object can reach >92% and for imagined objects >72%.



# CNN preferred images

CNN8



CNN7



CNN6



# Decoding Dreams



Decoding Dreams, ATR Kyoto, Kamitani Lab. fMRI images analysed during REM phase or while falling asleep allows for dream categorisation.

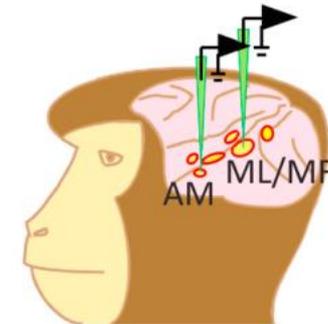
Dreams, thoughts ... can one hide what has been seen and experienced?

# Neural screen

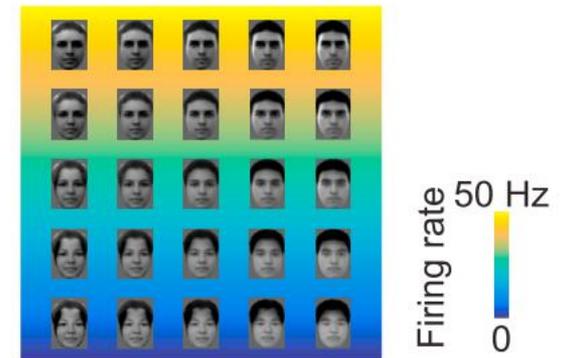
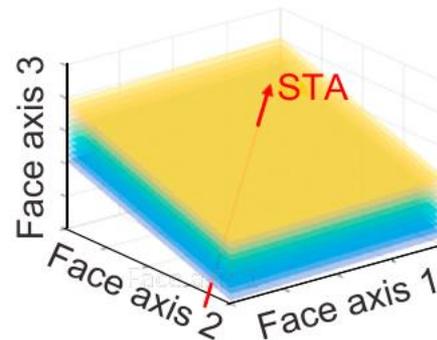
Consciousness of inner images. Features are discovered, and their combination remembered as face, but detailed recognition needs detailed recording from neurons.

L. Chang and D.Y. Tsao, "The code for facial identity in the primate brain," *Cell*, doi:10.1016/j.cell.2017.05.011, 2017

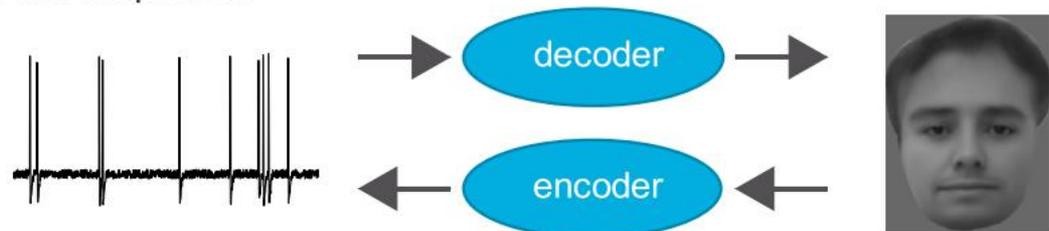
1. We recorded responses to parameterized faces from macaque face patches



2. We found that single cells are tuned to single face axes, and are blind to changes orthogonal to this axis

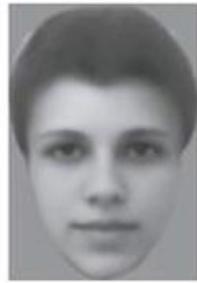


3. We found that an axis model allows precise encoding and decoding of neural responses



# Conscious Perception

205 neurons were sufficient to recreate faces monkey has seen.



Actual  
face

Predicted  
face

Actual  
face

Predicted  
face

# Understanding by creating brains

“Here, we aim to understand the brain to the extent that we can make humanoid robots solve tasks typically solved by the human brain by essentially the same principles.

I postulate that this ‘**Understanding the Brain by Creating the Brain**’ approach is the only way to fully understand neural mechanisms in a rigorous sense.”

Humanoid robot may be used for exploring and examining neuroscience theories about human brain.

- M. Kawato, From ‘Understanding the Brain by Creating the Brain’ towards manipulative neuroscience (*Phil. Trans. R. Soc. B* 27, 2008).

Engineering goal: build artificial devices at the brain level of competence.

- Hassabis, D., Kumaran, D., Summerfield, C., & Botvinick, M. (2017). Neuroscience-Inspired Artificial Intelligence. *Neuron*, 95(2), 245–258.



# Few Steps Towards HLI

**IEEE** Computational Intelligence Society Task Force (J. Mandziuk & W. Duch),  
**Towards Human-like Intelligence.**

**IEEE SSCI The 5th IEEE Symposium on Computational Intelligence for Human-like Intelligence**, Honolulu, HAWAII, USA, Nov. 27 – Dec. 1, 2017.

**World Congress of Computational Intelligence 2014**, Special Session:  
Towards Human-like Intelligence (A-H Tan, J. Mandziuk, W. Duch)

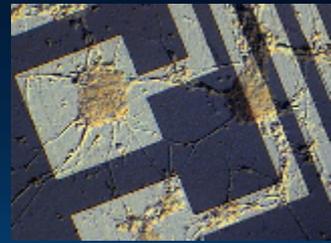


**AGI**: conference, Journal of Artificial General Intelligence comments on Cognitive Architectures and Autonomy: A Comparative Review (eds. Tan, Franklin, Duch).

**BICA**: Annual International Conf. on Biologically Inspired Cognitive Architectures, 8rd Annual Meeting of the BICA Society, Moscow, August 1-5, 2017

**Brain-Mind Institute Schools**, International Conference on Brain-Mind (ICBM) and Brain-Mind Magazine (Juyang Weng, Michigan SU).

# The Great Artificial Brain Race



**BLUE BRAIN, HBP**: École Polytechnique Fédérale de Lausanne, in Switzerland, use an IBM supercomputer to simulate minicolumn.

**C2**: 2009 IBM Almaden built a cortical simulator on Dawn, a Blue Gene/P supercomputer at Lawrence Livermore National Lab. C2 simulator re-creates  $10^9$  neurons connected by  $10^{13}$  synapses, small mammal brain.

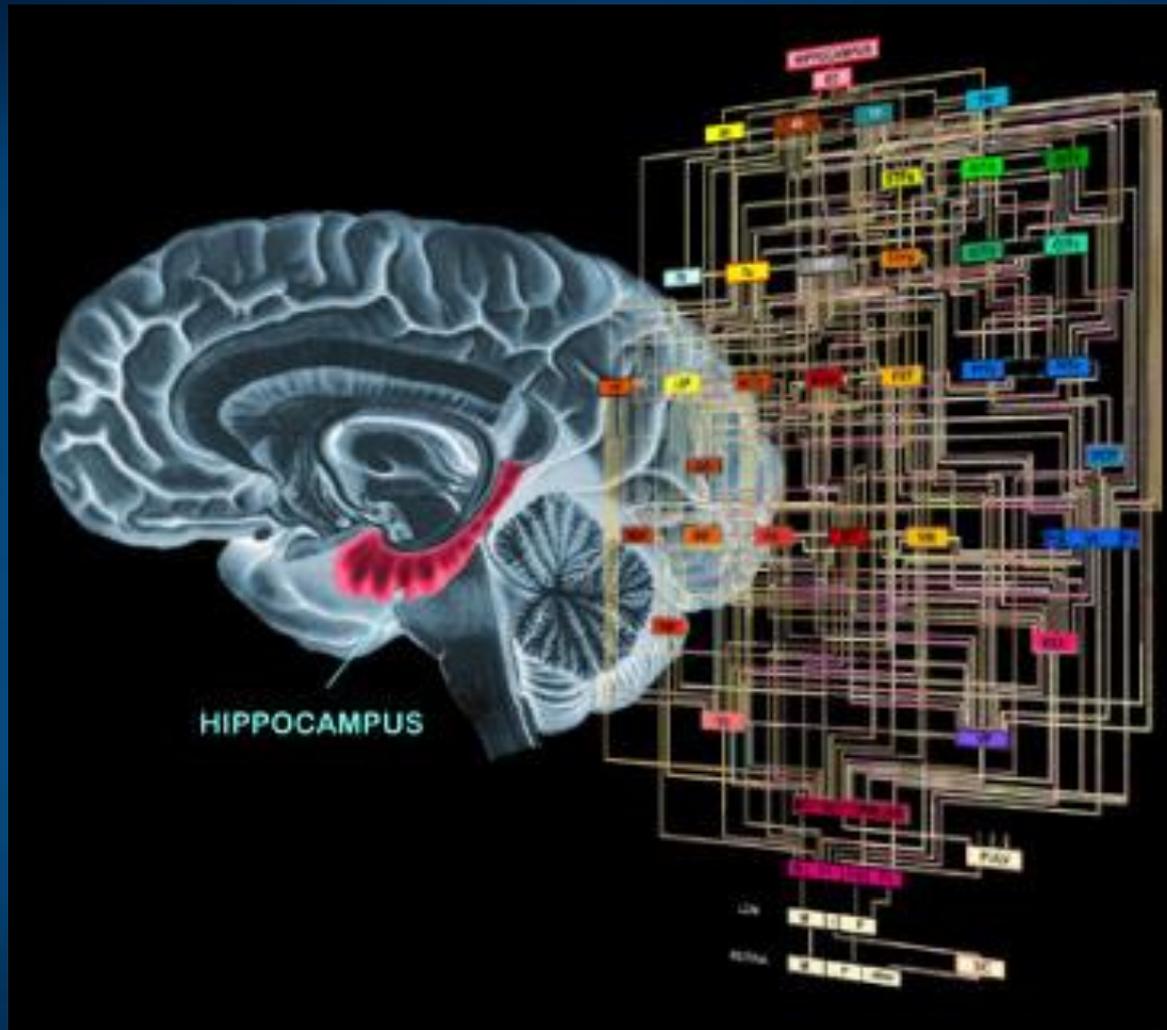
**NEUROGRID**: Stanford (K. Boahen), developing chip for  $\sim 10^6$  neurons and  $\sim 10^{10}$  synapses, aiming at artificial retinas for the blind.

**IFAT 4G**: Johns Hopkins Uni (R.Etienne-Cummings) Integrate and Fire Array Transceiver, over 60K neurons with 120M connections, visual cortex model.

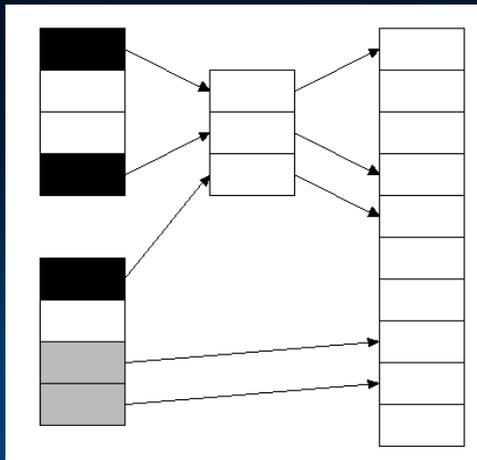
**Brain Corporation**: San Diego (E. Izhakievich), neuromorphic vision.

**BRAINSCALES**: EU neuromorphic chip project, FACETS, Fast Analog Computing with Emergent Transient States, now BrainScaleS, complex neuron model  $\sim 16K$  synaptic inputs/neuron, integrated closed loop network-of-networks mimicking a distributed hierarchy of sensory, decision and motor cortical areas, linking perception to action.

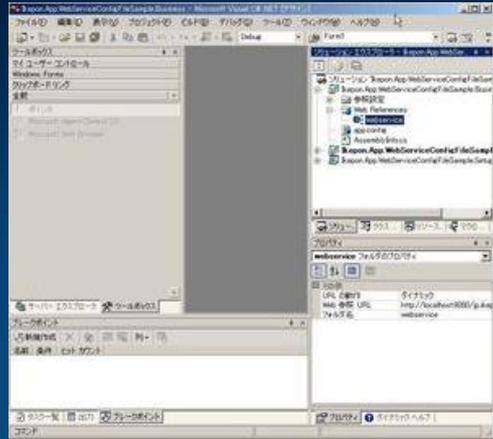
# BICA, Brain-Inspired Cognitive Architecture



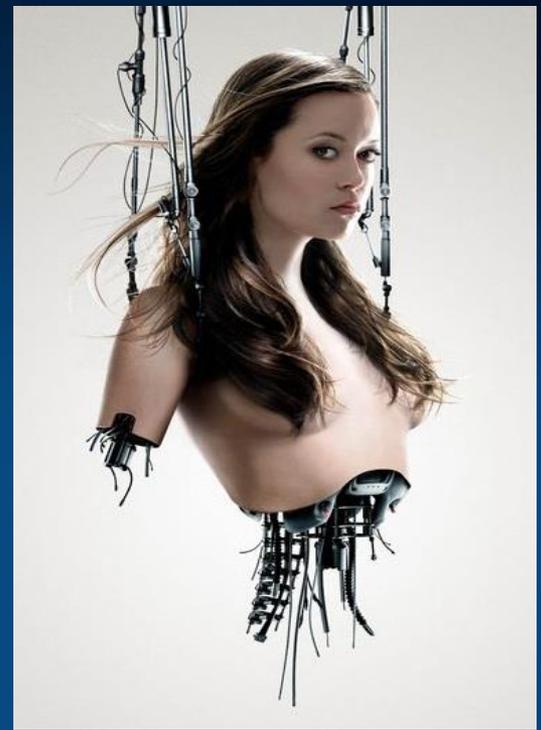
Understanding subtle mental processes requires a model that should show how internal states create narrative “stream of consciousness”.



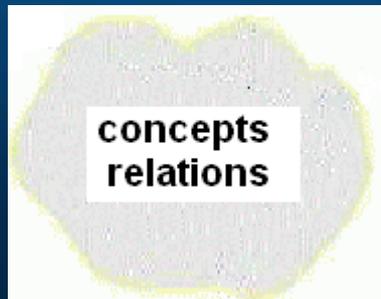
Semantic memory



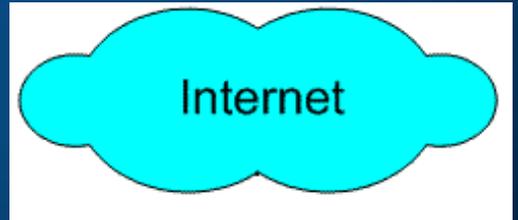
Applications, search,  
20 questions game.



Store



Part of speech tagger  
& phrase extractor



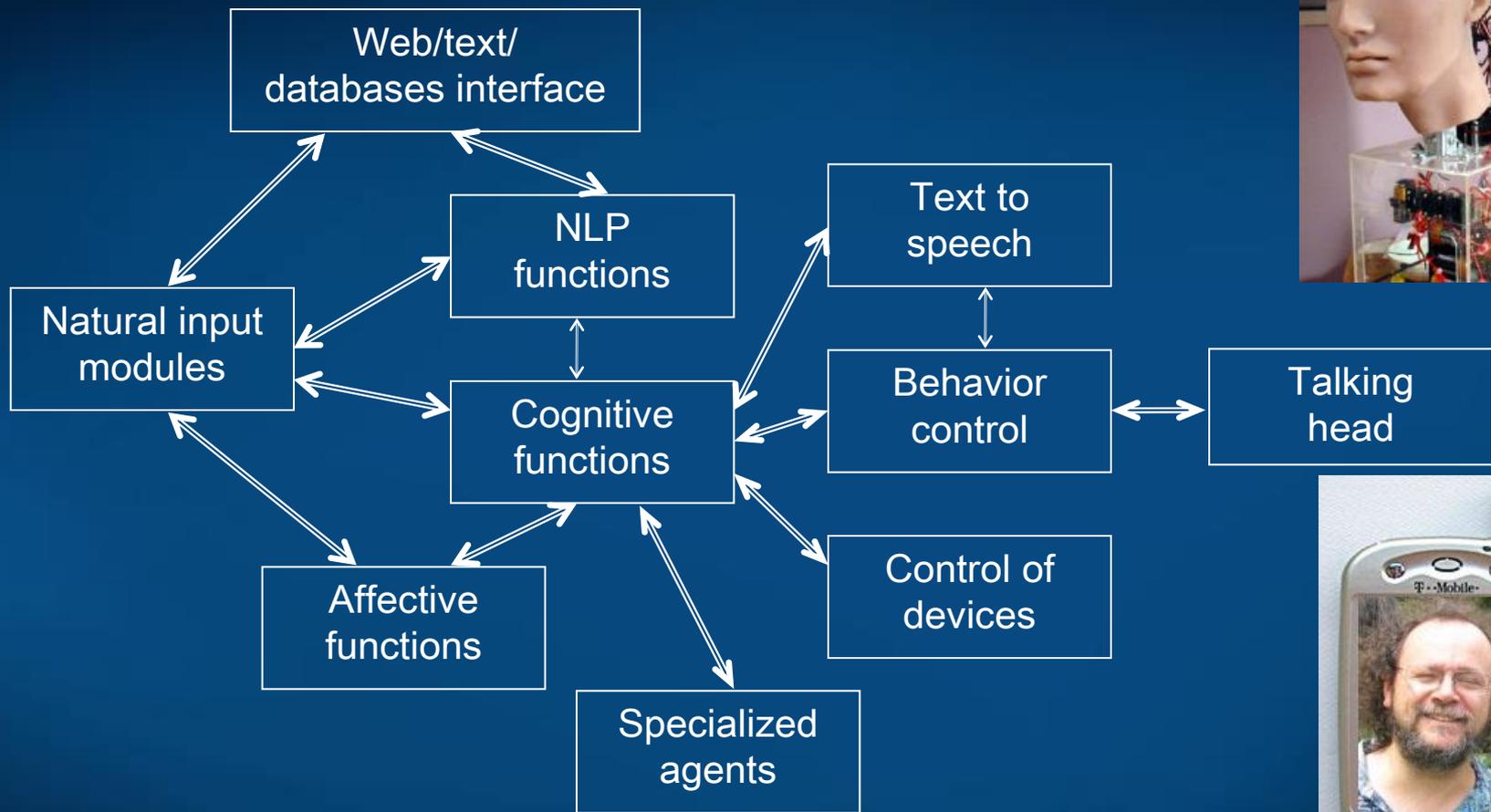
verification

Manual

Parser

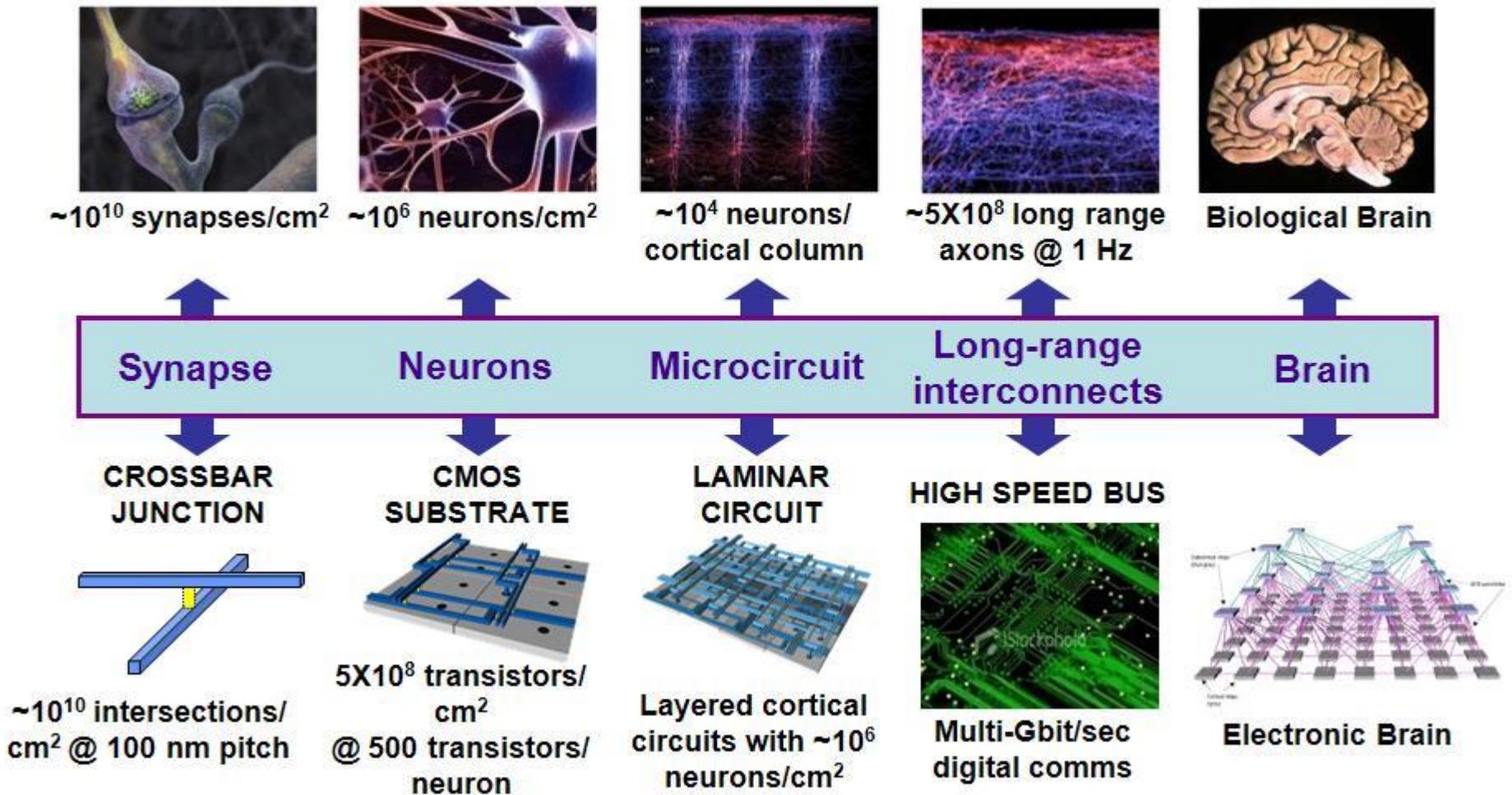
On line dictionaries  
Active search and  
dialogues with users

# DREAM top-level architecture



DREAM project (2003), focused on perception (visual, auditory, text inputs), cognitive functions (reasoning based on perceptions), natural language communication in well defined contexts, real time control of the simulated/physical head. Now Amazon, Google, Apple do it ...

# From brains to machines



Source: DARPA Synapse project

# Neuromorphic computers

Synapse 2015: IBM TrueNorth chip:

~**1M** neurons and  $\frac{1}{4}$ **G** synapses, **5.4G** transistors, 70 mW.

NS16e module=16 chips=16**M** neurons, >**4G** synapses, requires only 1.1 W!

Scaling: 256 modules, ~**4G** neurons, ~**1T** =  $10^{12}$  synapses < 300 W power!

IBM Neuromorphic System can reach **complexity of the human brain**.

Integrate & fire neurons,  
programming of such  
devices will not be easy.

IBM Research created  
[SyNAPSE University](#).

Samsung Dynamic Vision  
Sensor (DVS) based on TN  
will appear in phones, and  
will give people a [superman  
style vision](#).



# Conclusions



- We begin to understand the mappings between brain states and mental images – but its still a tip of iceberg.
- Understanding neurodynamics and neurocognitive phenomics are the key to brain's self-regulation.
- Brain neuroimaging ↔ The Virtual Brain, graphical models ↔ mental models ↔ Conscious control of our brains.
- Brains solve the AI frame problem by creating dynamical search spaces that restrict all plausible interpretations/solutions.
- Neuromorphic hardware is coming and will enable construction of new brain models and many applications.

# In search of the sources of brain's cognitive activity

Project „Symfonia”, NCN, Kraków, 18 July 2016

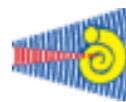
## Thank you



FACULTY OF PHYSICS,  
ASTRONOMY AND INFORMATICS



CENTRE FOR MODERN  
INTERDISCIPLINARY  
TECHNOLOGIES



INSTITUTE OF PHYSIOLOGY  
AND PATHOLOGY OF HEARING



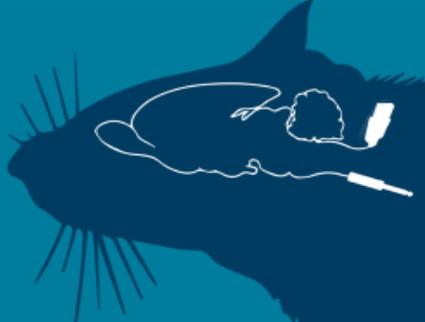
nencki institute  
of experimental biology

# My group of neuro-cog-fanatics



Soul or brain: what makes us human?  
Interdisciplinary Workshop with theologians,  
Toruń 19-21.10.2016

konferencja studencko-doktorancka  
**NeuroMania IV**  
28-29 maja 2016, Toruń



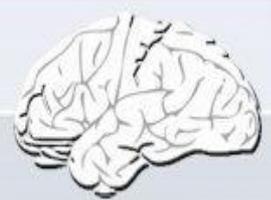
**HOMO COMMUNICATIVUS**  
WSPÓŁCZESNE OBlicZA KOMUNIKACJI I INFORMACJI

Toruń, 24-25 VI 2013 r.



Cognitivist Autumn in Toruń 2011  
**PHANTOMOLOGY:**  
the virtual reality of the body

2011 Torun, Poland



Cognitivist Autumn in Toruń 2010  
**MIRROR NEURONS:**  
from action to empathy

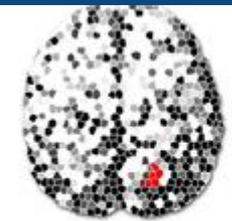
April, 14-16 2010 Torun, Poland



Monthly international  
developmental seminars  
(2017): Infants, learning,  
and cognitive development

Disorders of consciousness  
17-21.09.2017

Autism: science, therapies  
23.05.2017



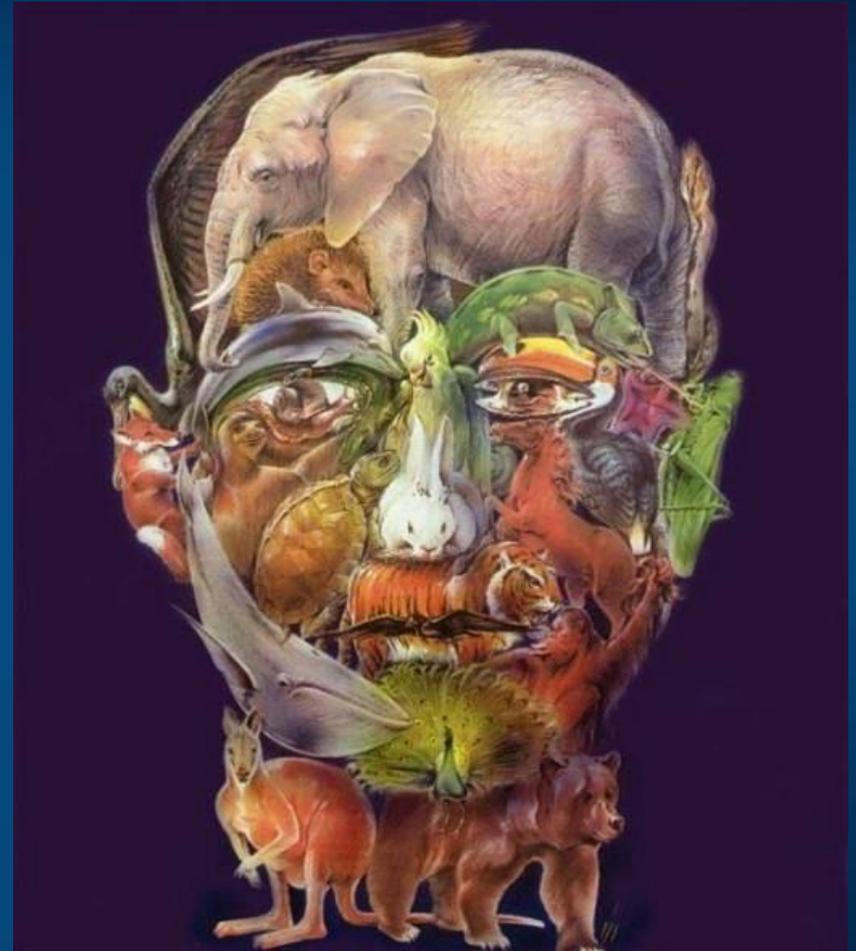
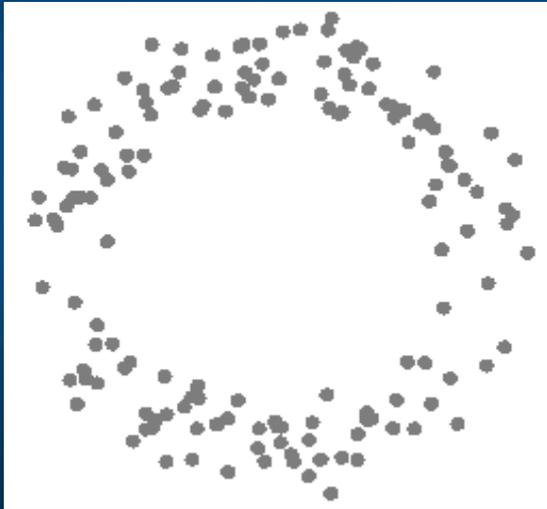
**NEURO**

**HISTORY OF ART**



**COGNITIVIST  
AUTUMN IN  
TORUŃ**

Thank for  
synchronization  
of your neurons



Google: W. Duch  
=> talks, papers, lectures ...

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