Artificial Intelligence and Neurocognitive Technologies

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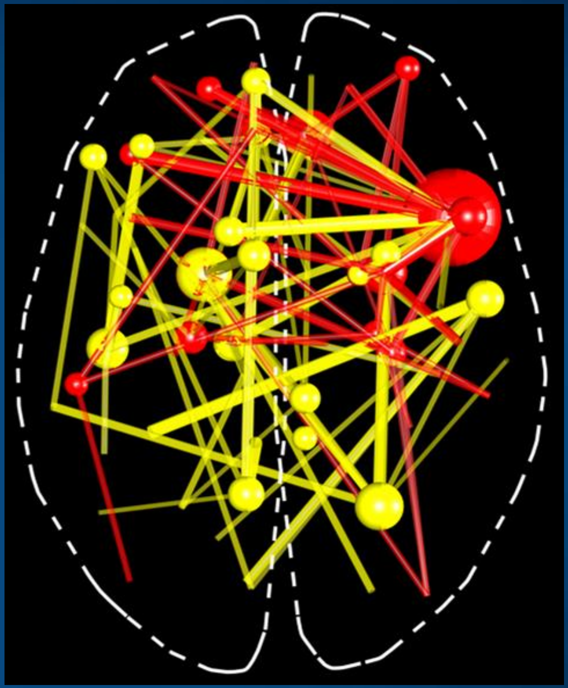
Google: W. Duch

PP-RAI 2018, 18-19.10, Poznań

Plan



- **Global and Emerging Brain Initiatives, or what is happening in large scale brain research collaborations.**
- **Why AI needs neurocognitive technologies?**
- **Why neurocognitive technologies need AI?**
- **Which neurocognitive technologies are already on the market?**
- **Perspectives and benefits.**
- **What are our chances for success?**

Duch W, *Neurocognitive Informatics Manifesto*. In: Series of Information and Management Sciences, California Polytechnic State Univ. 2009.

Global Brain Initiatives

Costs of brain diseases

European Brain Council (EBC) reports (2010; 2014).
Consensus Statement on European Brain Research (2015) includes a chapter on Computational Neuroscience, data repositories and analytics.

179 million, or 1/3 of all European citizens, had at least one brain disorder.
45% of the total annual health budget of Europe!

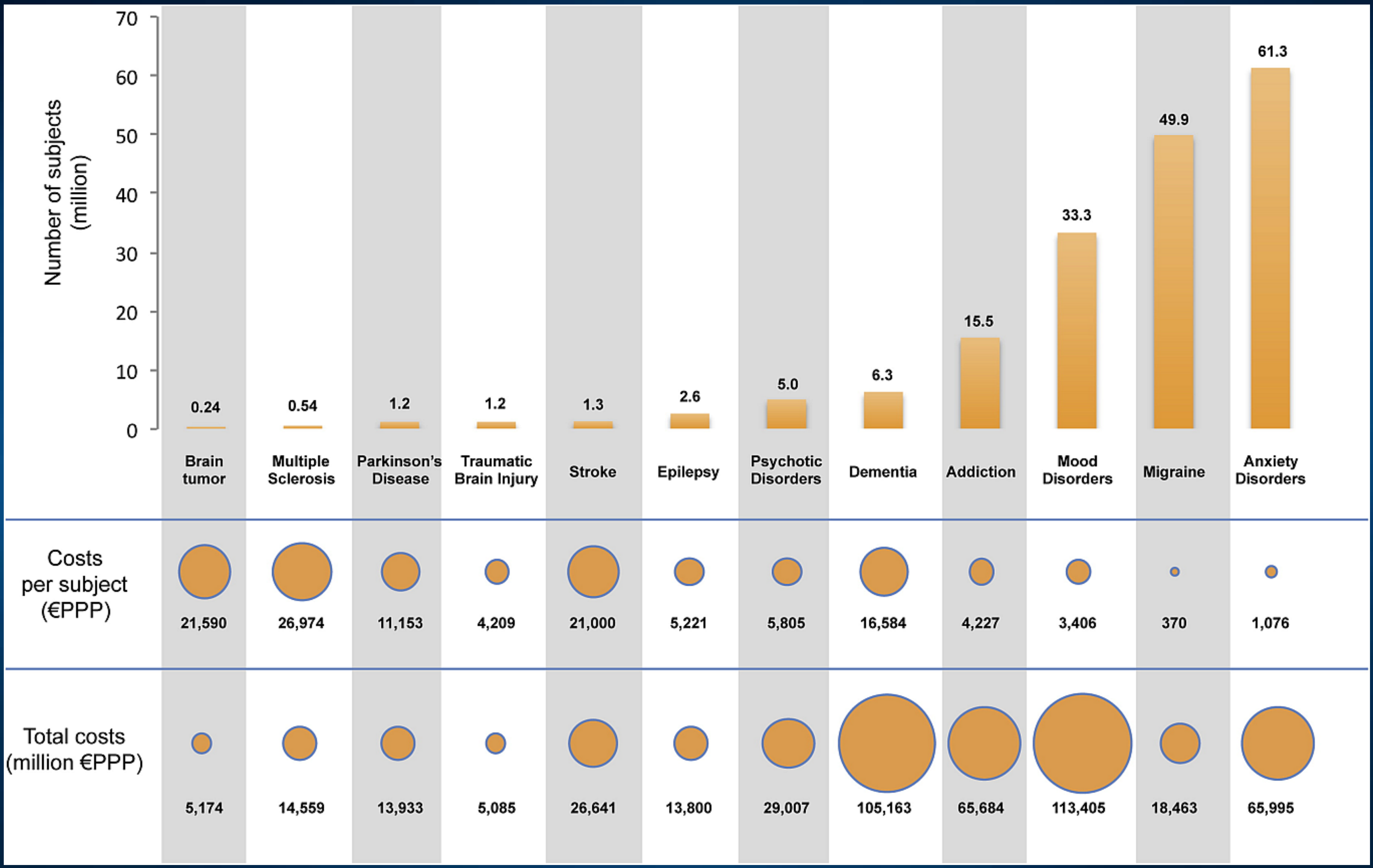
Total cost of brain disorders in EU estimated in 2010: 798 billion €/year,
average direct health care costs represent 37%,
direct nonmedical costs 23%, and indirect costs 40%.

China: >20% of population (~250 mln) suffering from some mental disorder.

Total costs of disorders of the brain in Poland, 2010 estimates.

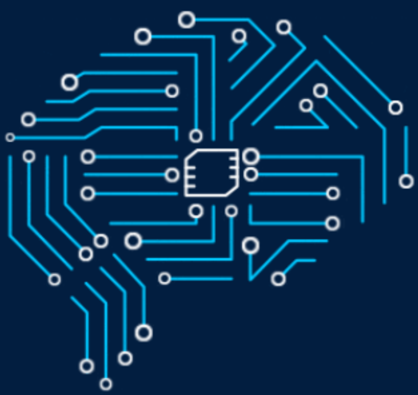
Addiction	Anxiety	Dementia	Epilepsy	Headache	Mood	Psychotic	Stroke	x1000
1 201	5 261	358	298	12 025	2 499	371	503	# people
2 501	2 882	2 480	745	1 559	4 489	3 723	2 187	mln €

Gustavsson et al. (2011). Cost of disorders of the brain in Europe 2010. *European Neuropsychopharmacology*, *21*(10), 718–779.



Number of subjects (million)
70
60
50
40
30
20
10
0
0.24
0.54
1.2
1.2
1.3
2.6
5.0
6.3
15.5
33.3
49.9
61.3
Brain tumor
Multiple Sclerosis
Parkinson's Disease
Traumatic Brain Injury
Stroke
Epilepsy
Psychotic Disorders
Dementia
Addiction
Mood Disorders
Migraine
Anxiety Disorders
Costs per subject (€PPP)
21,590
26,974
11,153
4,209
21,000
5,221
5,805
16,584
4,227
3,406
370
1,076
Total costs (million €PPP)
5,174
14,559
13,933
5,085
26,641
13,800
29,007
105,163
65,684
113,405
18,463
65,995

BRAIN INITIATIVE



Advance Neurotechnologies

Accelerate the development and application of new neurotechnologies.

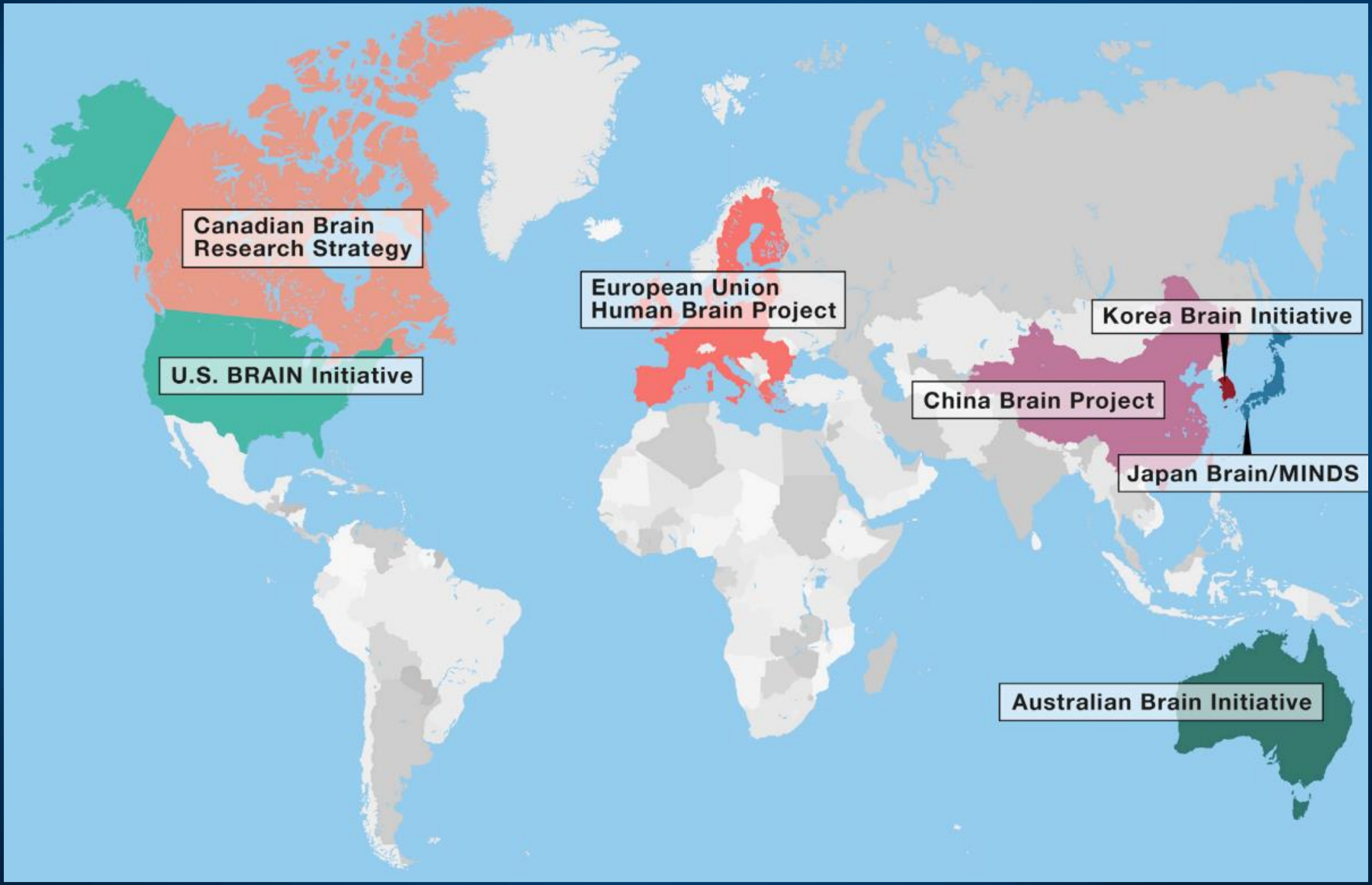
Support multi-disciplinary teams and stimulate research to rapidly enhance current neuroscience technologies and catalyze innovative scientific breakthroughs.

Human Brain Project, EU Flagship, and Obama BRAIN Initiative (2013): **B**rain **R**esearch through **A**dvancing **I**nnovative **N**eurotechnologies.

"Develop new technologies to explore how the brain's cells and circuits interact at the speed of thought, ultimately uncovering the complex links between brain function and behavior. Explore how the brain records, processes, uses, stores, and retrieves vast quantities of information. Help bring safe and effective products to patients and consumers."

Since 2013 numerous exciting developments in neurotechnology and our understanding of the brain have been made by scientists across the globe.

International Brain Initiatives



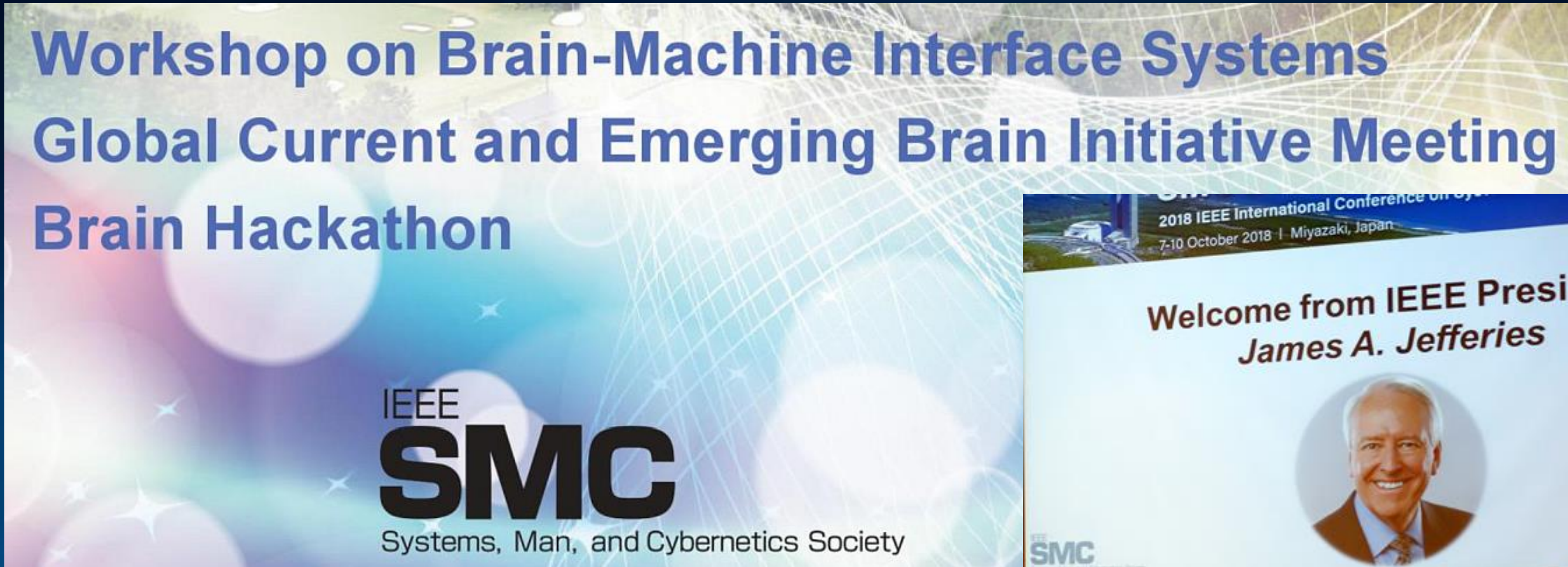
The mission of IEEE Brain is to facilitate cross-disciplinary collaboration and coordination to advance research, standardization and development of technologies in neuroscience to help improve the human condition.

20 IEEE Societies are involved, including:

IEEE Computational Intelligence Society; Computer Society; Consumer Electronics Society; Digital Senses Initiative; Robotics and Automation Society; Sensors Council; Signal Processing Society; Society on Social Implications of Technology; **Systems, Man, and Cybernetics Society**, International Neuroethics Society, and a few other societies.

Most these societies are also involved in artificial intelligence.

Satya Nadella (CEO, Microsoft): to celebrate National Disability Employment Awareness Month, I'm sharing examples of how technology can be applied to empower the more than one billion people with disabilities around the world.



Part of the Brain-Machines Interface Workshop and SMC2018.

The IEEE SMC Society and the IEEE President, James Jefferies, are proud to invite you on to a special meeting of **Global Current and Emerging Brain Initiative leaders** and representatives from other groups working on large-scale multi-year brain projects from Australia, Canada, China, Europe (HBP), Japan, Korea, New Zealand, **Poland**, Russia, and US (NSF and NIH), with representatives from the **IEEE Brain Initiative**, International Neuroethics Society, industry, and other stakeholders.

IEEE welcomes collaborative discussions with all stakeholders to better align and integrate IEEE with other existing brain efforts.

Neuro Informatics 2019

International Neuroinformatics Coordination Facility (INCF) goal: integrate and analyze diverse data across scales, techniques, and species to understand the brain and positively impact the health and well being of society.

Polish INCF Node, established in Warsaw at Nencki Institute, since 2017 at the Nicolaus Copernicus University in Toruń.

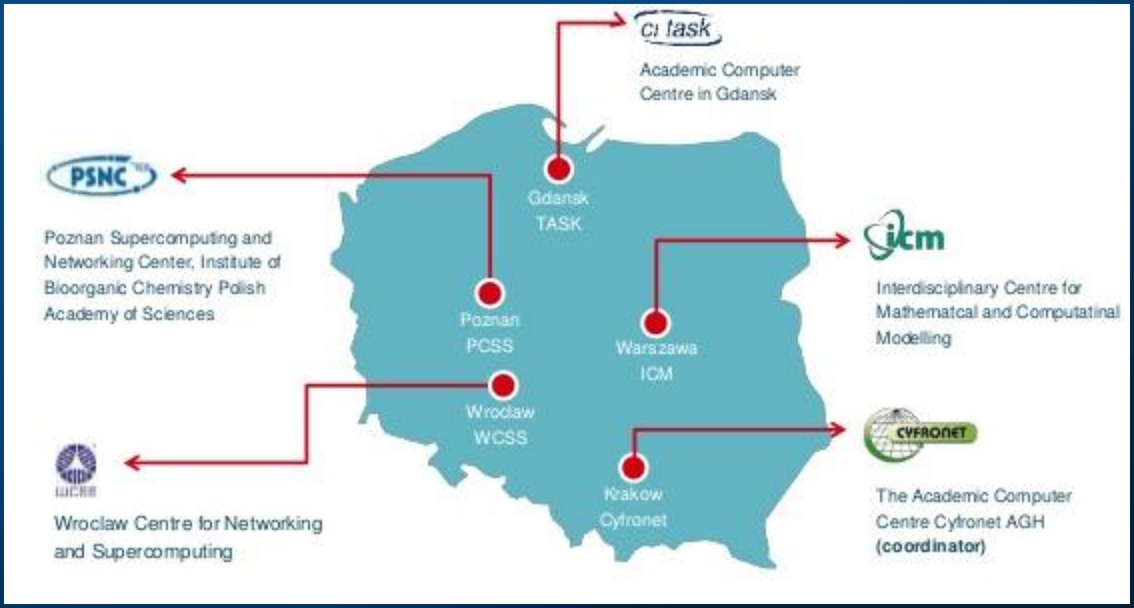
12th INCF Congress on Neuroinformatics and INCF Assembly, Warsaw 9/2019. Neuroimaging, computational neuroscience, artificial intelligence.

We hope to become a full member of INCF by that time.

Polish Brain Council (Polska Rada Mózgu) started in 2013, working on “Brain Plan for Poland – Strategy for People with Brain Diseases”.

PL-Grid HPC Infrastructure

- AI and neuroinformatics needs big data and computing power for analytics.
- The Polish Grid Infrastructure (NGI) connects 5 supercomputing centers, enabling research in various domains of e-Science.
- Supports research, integrating experimental data and results of advanced computer simulations in over 24 domains.
- A part of a pan-European infrastructure built in the framework of the EGI (European Grid Initiative). In future access to exaflop power.
- INCF-PL is working on creation of national neuroscience gateway.
- Collaboration with HBP medical platform: prof. R. Frackowiak, prof. P. Bogorodzki.



AI and abstract models of mind/brain

A Standard Model of the Mind

Laird JE, Lebiere C, & Rosenbloom, PS (2017). A Standard Model of the Mind: Toward a Common Computational Framework across Artificial Intelligence, Cognitive Science, Neuroscience, and Robotics. *AI Magazine*, *38*, 13–26.

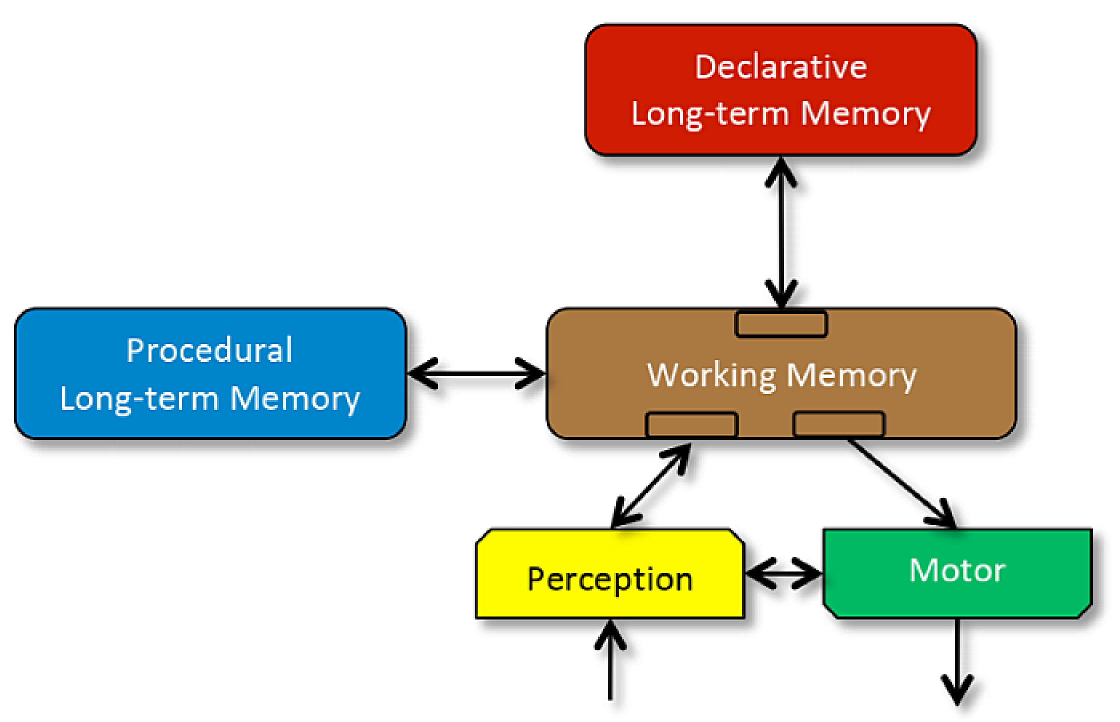
Laird: A mind is a functional entity that can think.

Newell: Mind is a control system that determines behavior of organism interacting with complex environment.

Cognitive informatics, Neurocognitive Informatics

BICA = Brain Inspired Cognitive Architecture.

Review: Duch, Oentaryo, Pasquier, Cognitive architectures: where do we go from here? 2008



Neuroscience => AI

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

Affiliations: DeepMind, Gatsby Computational Neuroscience, Institute of Cognitive Neuroscience, University College London, University of Oxford.

Artificial neural networks – simple inspirations, but led to many applications.

AI Systems inspired by Neural Models of Behavior:
(A) **Visual attention**, foveal locations for multiresolution ‘‘retinal’’ representation, prediction of next location to attend to.
(B) **Complementary learning systems** and episodic control: fast learning hippocampal system and parametric slow-learning neocortical system.
(C) Models of **working memory** and the Neural Turing Machine.

(D) Neurobiological models of **synaptic consolidation** and the elastic weight consolidation (EWC) algorithm.

(E) Bengio, Y. (2017). The **Consciousness Prior**. *ArXiv:1709.08568.*

(F) Amoset al. (2018). **Learning Awareness Models**. *ArXiv:1804.06318 [Cs]*.

Neuroscience => AI

Examples of recent AI systems inspired by neuroscience:

(A) **Intuitive physics knowledge**, reason and make predictions about the physical interaction between objects, predict trajectories, collisions, gravitational forces.

(B) **Scene understanding** through structured generative models. Recurrent network attends to one object at a time, infers its attributes, and performs the appropriate number of inference steps for each input image in realistic scene.

(C) **Unsupervised learning of core object properties** by deep generative model based on variational auto-encoder, that can learn intuitive concepts such as ''objectness,'' being able to support zero-shot transfer (i.e., reasoning about position or scale of an unseen object with a novel shape).

(D) **One-shot generalization** in deep sequential generative models that specify a causal process for generating the observed data using a hierarchy of latent variables, with attentional mechanisms supporting sequential inference, mirroring human abilities to generalize from a single concept.

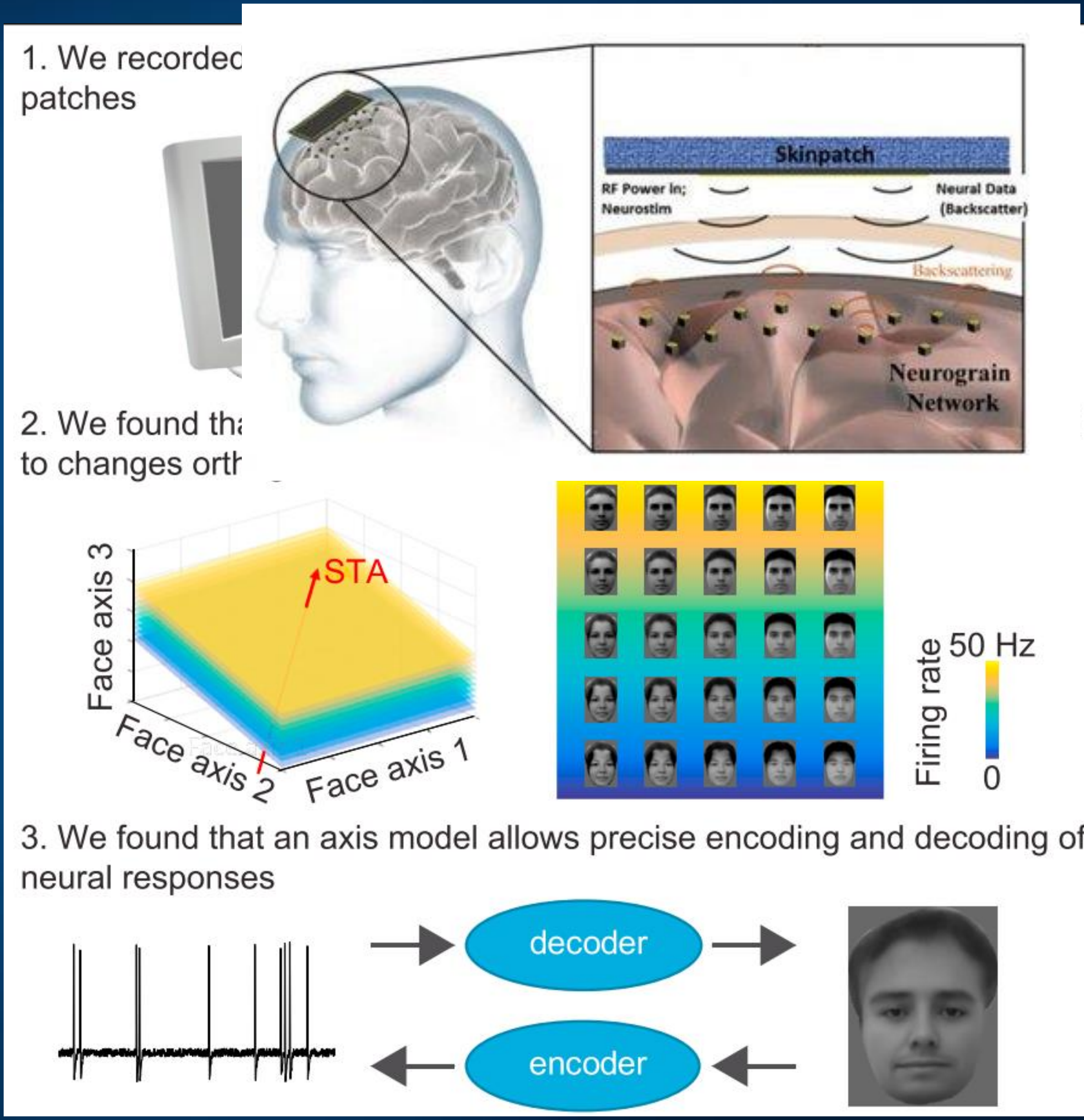
(E) **Imagination of realistic 3D environments** in deep neural networks by an action-conditional recurrent network model, reinforcement learning in simulation-based planning.

Neural screen

Features are discovered, and their combination remembered as face, but detailed recognition needs detailed recording from neurons – 205 neurons in various visual areas used.

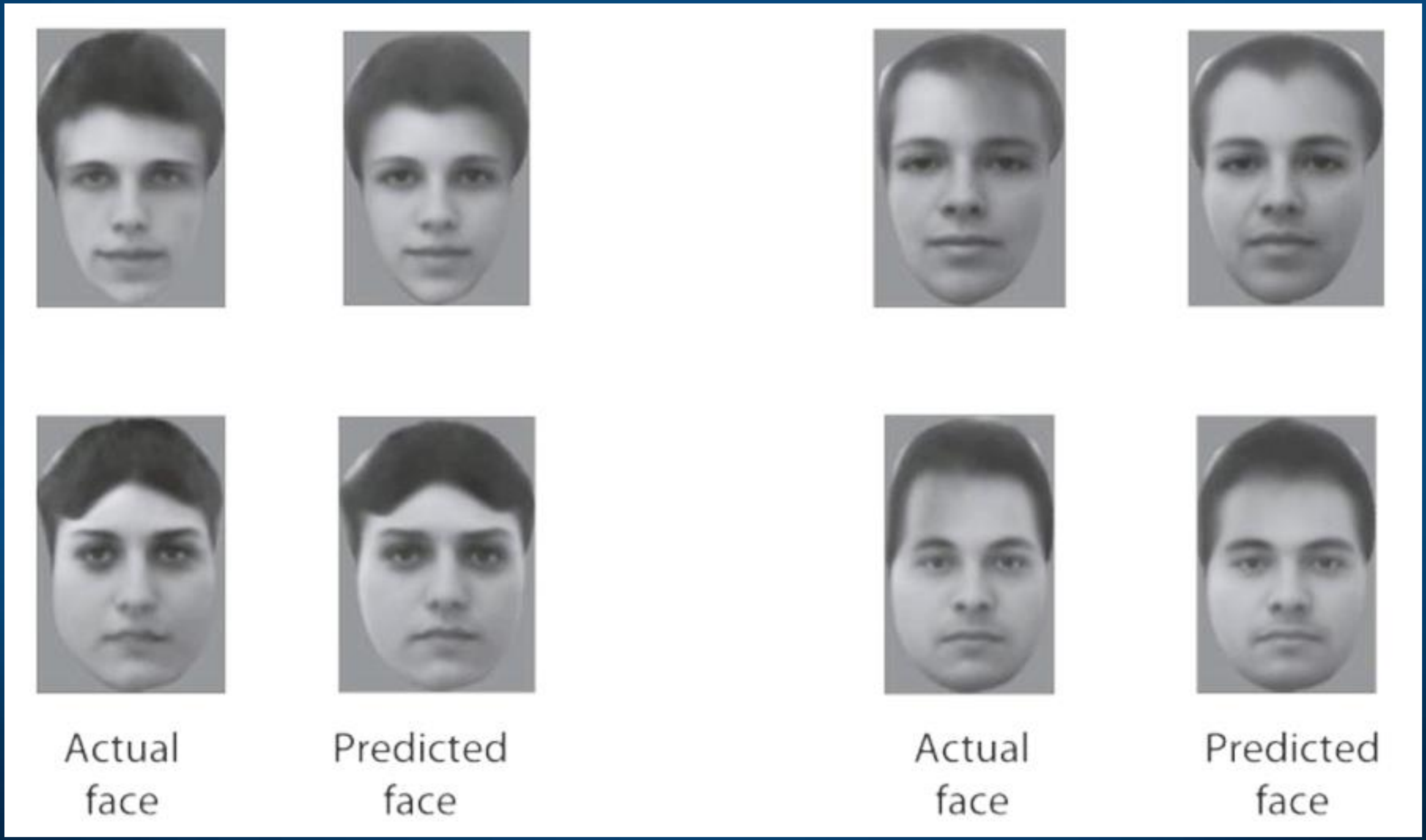
L. Chang and D.Y. Tsao, "**The code for facial identity in the primate brain**" *Cell* 2017

DARPA (2016): put million nanowires in the brain! Use them to read neural responses and 10% of them to activate neurons.



Mental images

Facial identity is encoded via a **simple neural code** that relies on the ability of neurons to distinguish facial features along **specific axes in the face space**.



L. Chang and D.Y. Tsao, *Cell* 2017

AI=>Neuroscience

Machine learning techniques are basic tools for analysis of neuroimaging data.

Ideas from animal psychology helped to give birth to reinforcement learning (RL) research. Now **key concepts from RL inform neuroscience**.

Activity of midbrain dopaminergic neurons in conditioning paradigms has a striking resemblance to temporal difference (TD) generated prediction errors - **brain implements a form of TD learning!**

CNN ⇔ interpret neural representations in high-level ventral visual stream of humans and monkeys, finding evidence for deep supervised networks.

LSTM architecture provides key insights for development of working memory, gating-based maintenance of task-relevant information in the prefrontal cortex.

Backpropagation with symmetric feedback and feedforward connectivity is not realistic, but random backward connections allow the backpropagation algorithm to function effectively through a process whereby adjustment of the forward weights allows backward projections to transmit useful teaching signals.

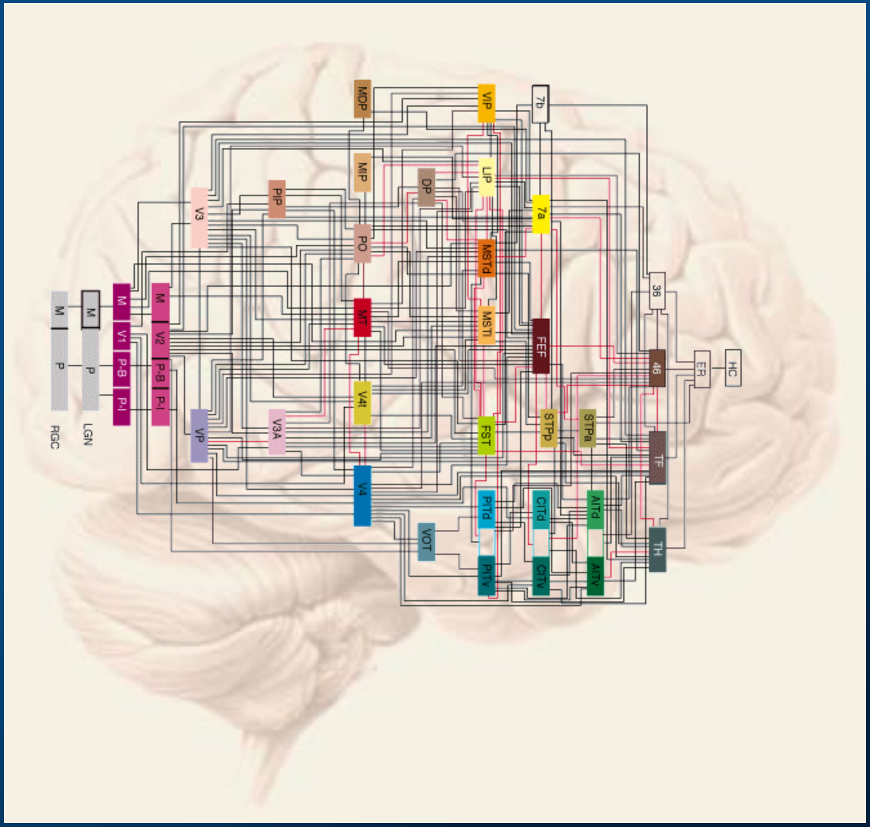
Free energy

The free-energy principle (FEP): any self-organizing system that is at equilibrium with its environment must minimize its free energy = predict by active inference limiting number and dimensionality of internal states (K. Friston, 2006).

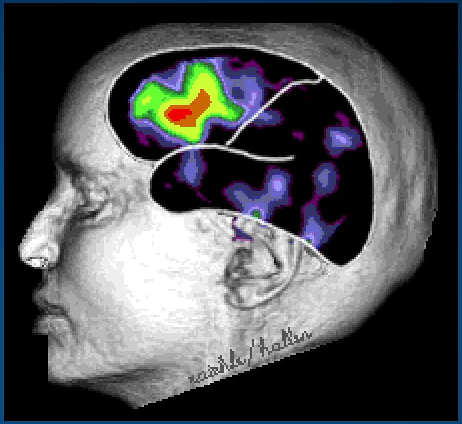
Constraints for brain architecture: EST, Evolutionary Systems Theory (Badcock, 2012).

Combination of FEP with EST
is a candidate for standard theory of cognitive systems.

Still only a sketch of a theory.
Can FEP be derived from computational neuroscience?



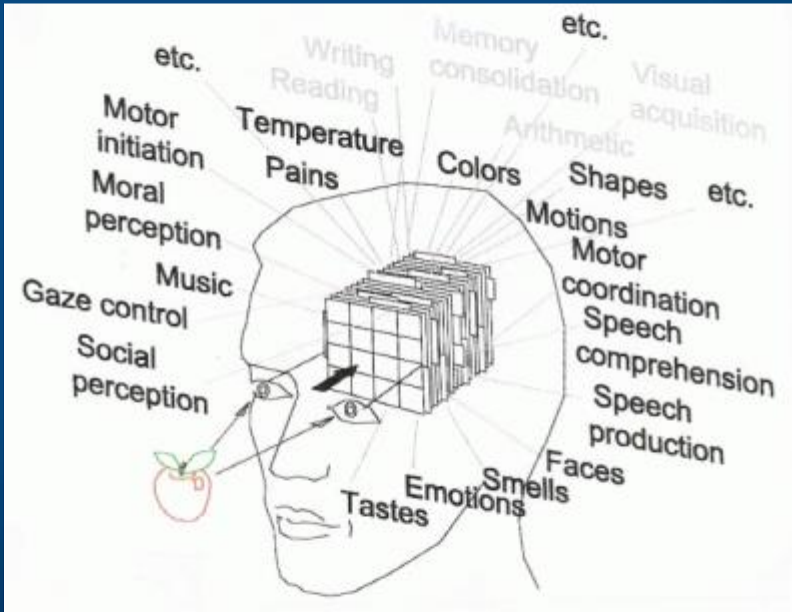
Brains ⇔ Minds



Define mapping S(M)⇔S(B), as in BCI.
How do we describe the state of mind?

Verbal description is not sufficient unless words are represented in a space with dimensions that measure different aspects of experience.

Stream of mental states, movement of thoughts ⇔ trajectories in psychological spaces.

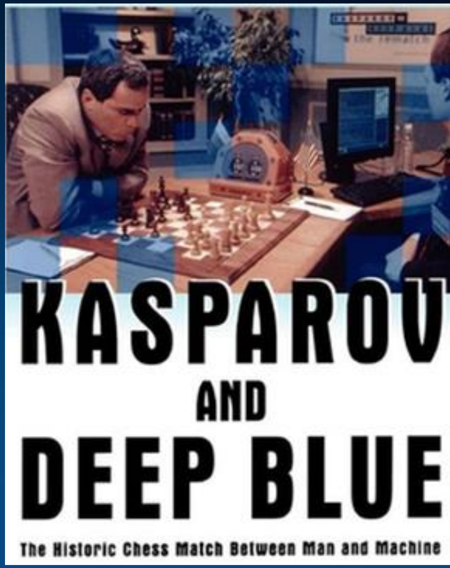


Two problems: discretization of continuous processes for symbolic models,
and lack of good phenomenology – we are not able to describe our mental states.

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

W. Duch, Mind space (1994);
E. Schwitzgabel, Perplexities of Consciousness. MIT Press 2011.

Cognitive computing



IBM avoids the name “Artificial Intelligence”, prefers “cognitive computing” or predictive analytics”.

1997 –Deep Blue wins with Gary Kasparow.

2011 – IBM Watson wins in Jeopardy (Va Banque), game requiring general world knowledge, with two best players. This was a turning point for IBM.

IBM Cognos Analytics, driven by AI.
Goes beyond data visualizations by enhancing IBM platform with new capabilities:
an AI conversational assistant, advanced analytics,
AI-recommended visualizations and insights,
and user-centric data prep and modeling.

Future of AI: knowledge based, natural language, user-centric data modeling and understanding, combining AI reasoning techniques with deep learning for pattern recognition.

Brain networks:
space for neurodynamics

On the threshold of a dream …

Final goal: optimization of brain processes!

Although whole brain is always active we are far from achieving full human potential.
To repair damaged brains and increase efficiency of healthy brains we need to understand brain processes:

1. Find fingerprints of specific activity of brain structures (regions, networks) using neuroimaging technology (and new neurotechnologies).
2. Create models of cognitive architectures that help to understand information processing in the brain.
3. Create new diagnostic and therapeutic procedures.
4. Use neurofeedback based on decoding and changes in connectivity and close-loop system that directly stimulate the brain.

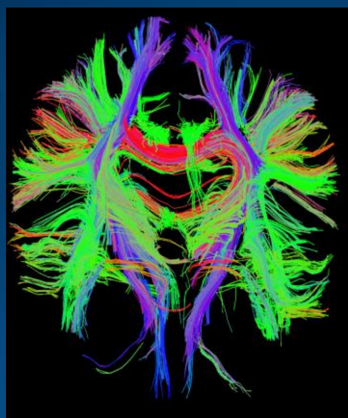
G-tec wireless NIRS/EEG on my head.

Duch W, *Neurocognitive Informatics Manifesto*. 2009.

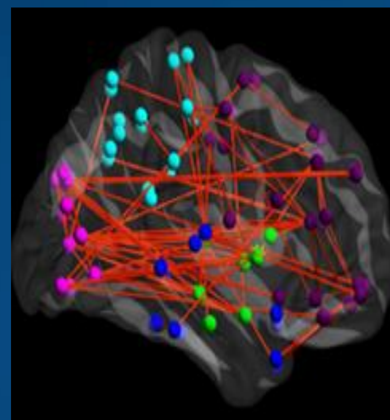
CMIT: scanner GE Discovery MR750 3T

Human connectome and MRI/fMRI

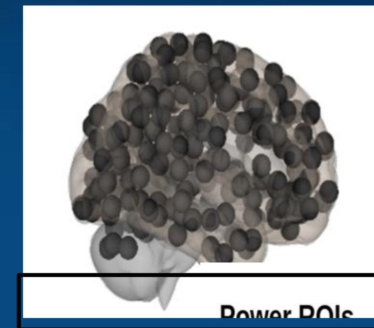
Structural connectivity



Functional connectivity

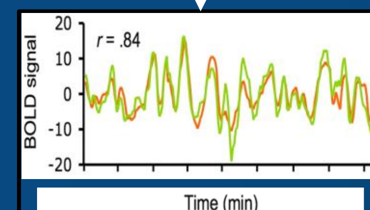


Node definition (parcelation)

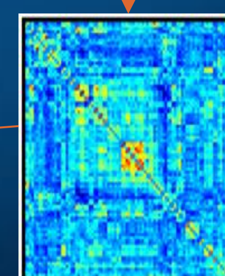


Signal extraction

Correlation calculation

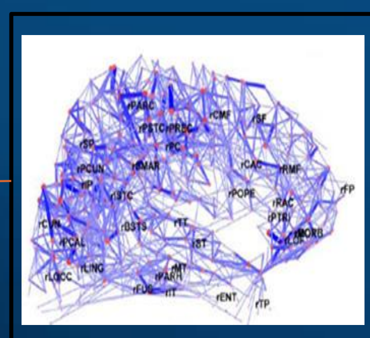


Correlation matrix

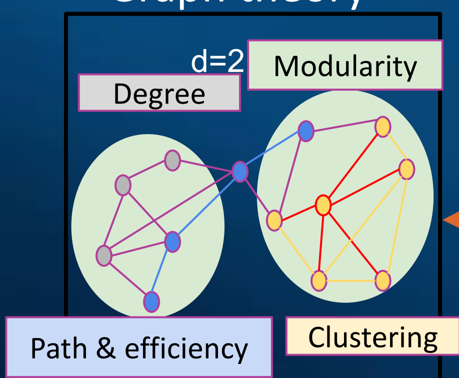


Binary matrix

Whole-brain graph



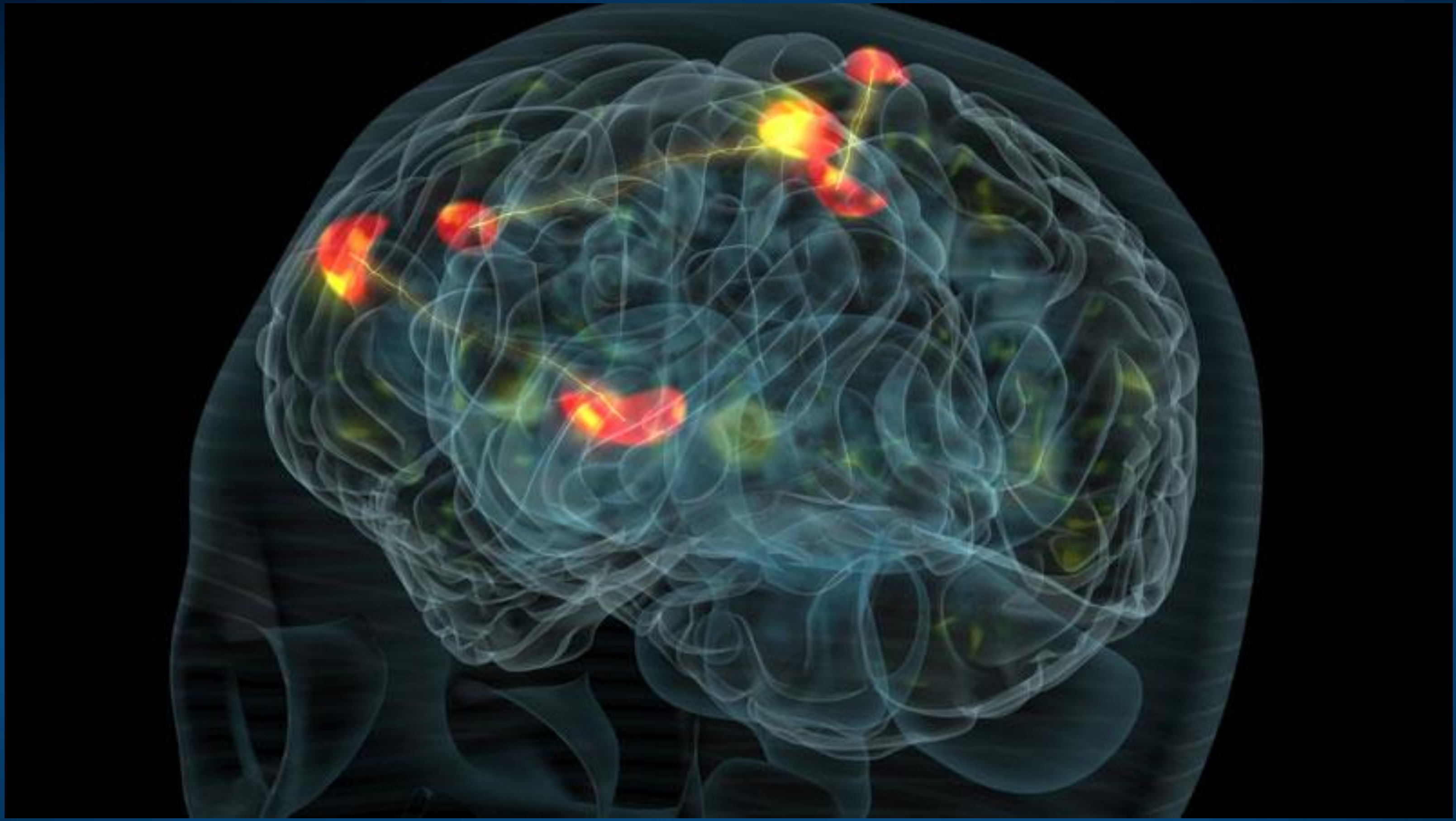
Graph theory



Many toolboxes available for such analysis.

Bullmore & Sporns (2009)

Mental state: strong coherent activation



Many processes go on in parallel, controlling homeostasis and behavior. Most are automatic, hidden from our Self. What goes on in my head?

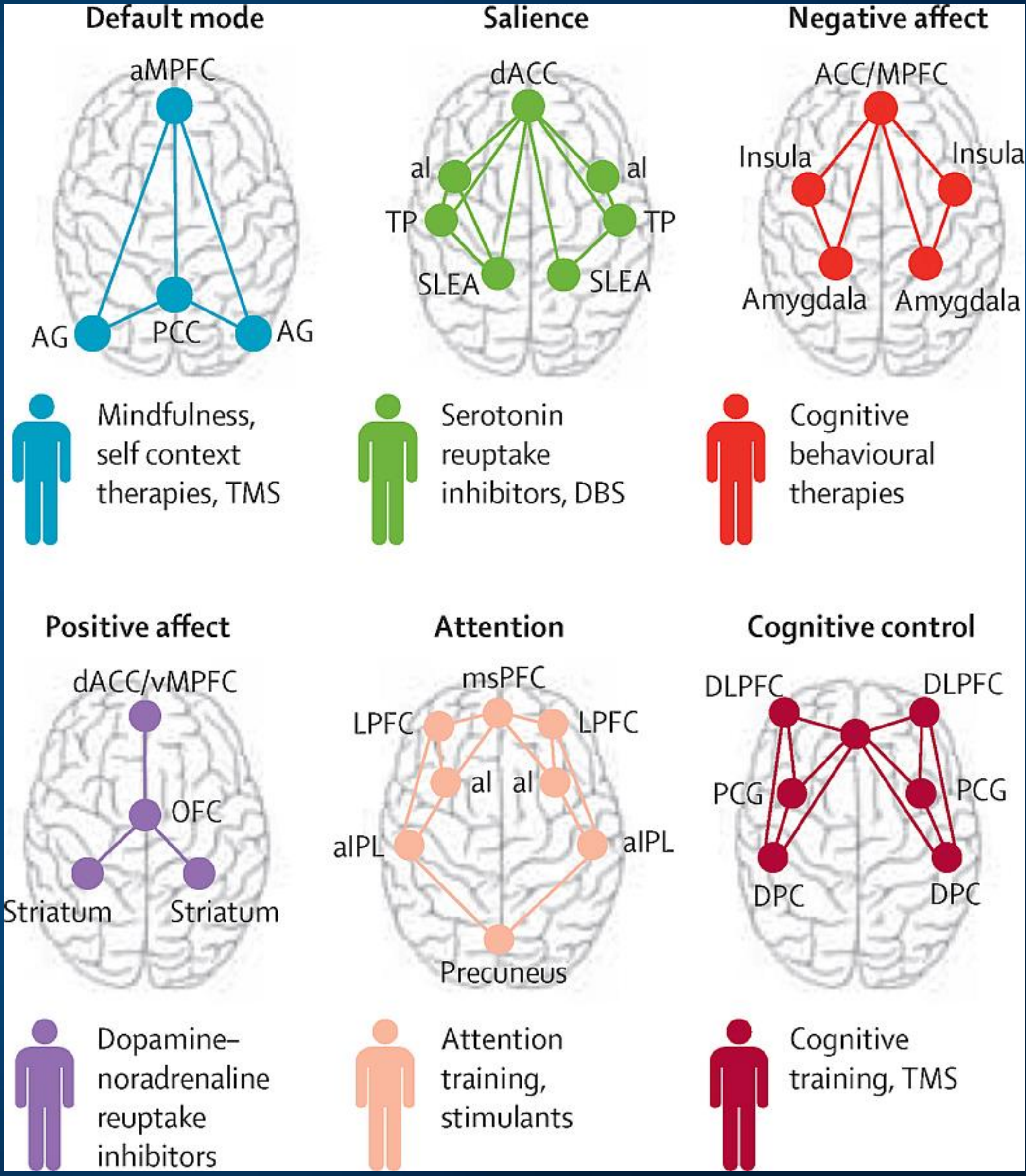
Various subnetworks compete for access to the highest level of control - consciousness, the winner-takes-most mechanism leaves only the strongest. How to extract stable intentions from such chaos? BCI is never easy.

Multi-level phenomics

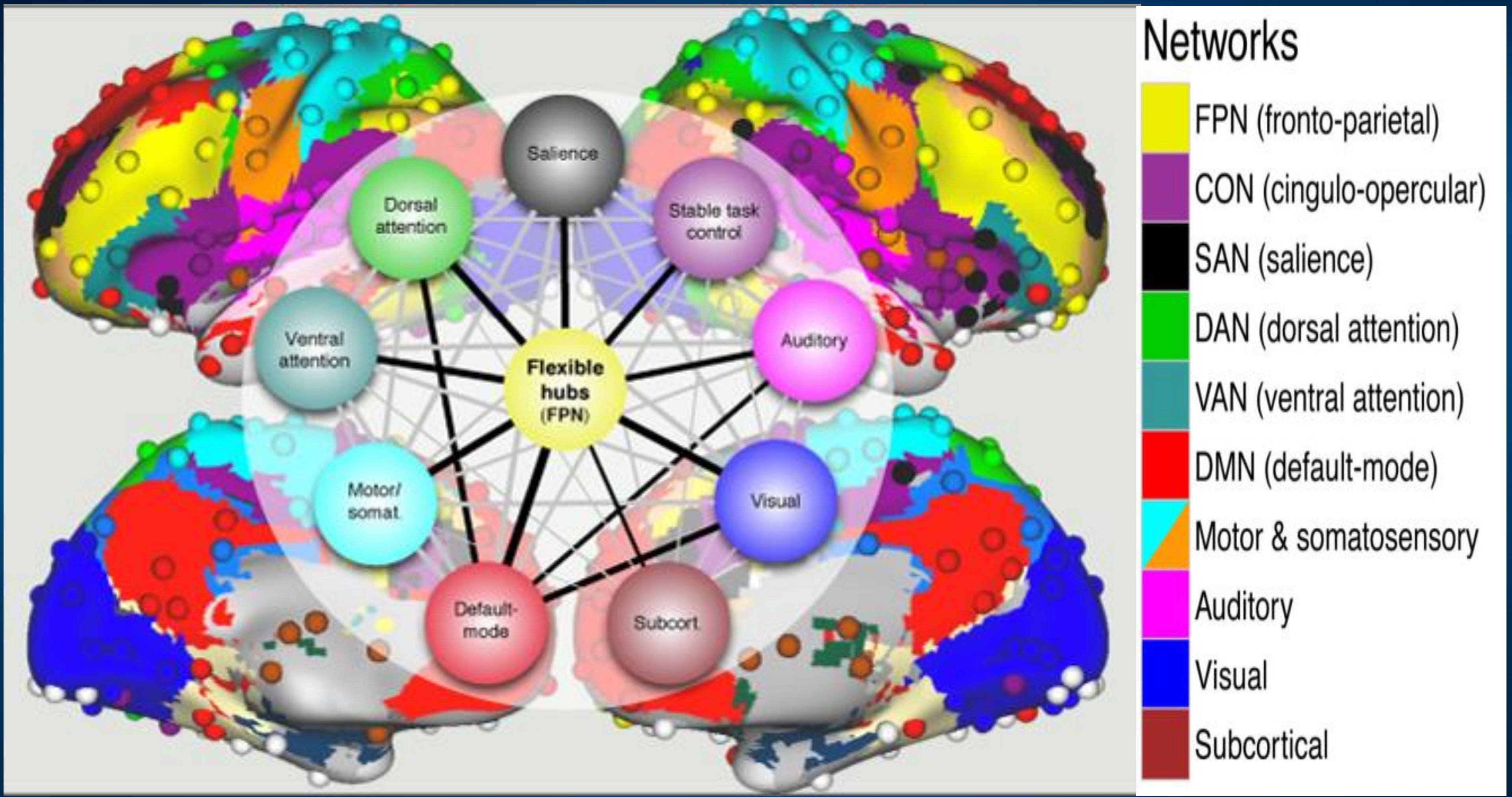
Instead of classification of mental disease by symptoms use **Research Domain Criteria** (RDoC) matrix based on **multi-level neuropsychiatric phenomics** describing large brain systems deregulation.

1. **Negative Valence Systems**,
2. **Positive Valence Systems**
3. **Cognitive Systems**
4. **Social Processes Systems**
5. **Arousal/Regulatory Systems**

Include genes, molecules, cells, **circuits**, physiology, behavior, self-reports and paradigms.



Neurocognitive Basis of Cognitive Control



Central role of fronto-parietal (FPN) flexible hubs in cognitive control and adaptive implementation of task demands (black lines=correlations significantly above network average). Cole et al. (2013).

Possible form of Brain Fingerprints

fMRI: BFP is based on **V(X,t)** voxel intensity of fMRI BOLD signal changes, contrasted between task and reference activity or resting state.
EEG: spatial, spatio-temporal, ERP maps/shapes, coherence, various phase synchronization indices.

1. **Spatial/Power**: direct localization/reconstruction of sources.
2. **Spatial/Synch**: changes in functional graph network structure.
3. **Frequency/Power**: ERS/ERD smoothed patterns E(X,t,f).
4. **ERP power maps**: spatio-temporal averaged energy distributions.
5. **EEG decomposition into components:** ICA, CCA, tensor, RP ...
6. **EEG** microstates, sequences & transitions, dynamics in ROI space.
7. Model-based: **The Virtual Brain**, integrating EEG/neuroimaging data.
8. Spectral fingerprinting (MEG, EEG), power distributions.

Neuroplastic changes of connectomes and functional connections as results of training for optimization of brain processes.

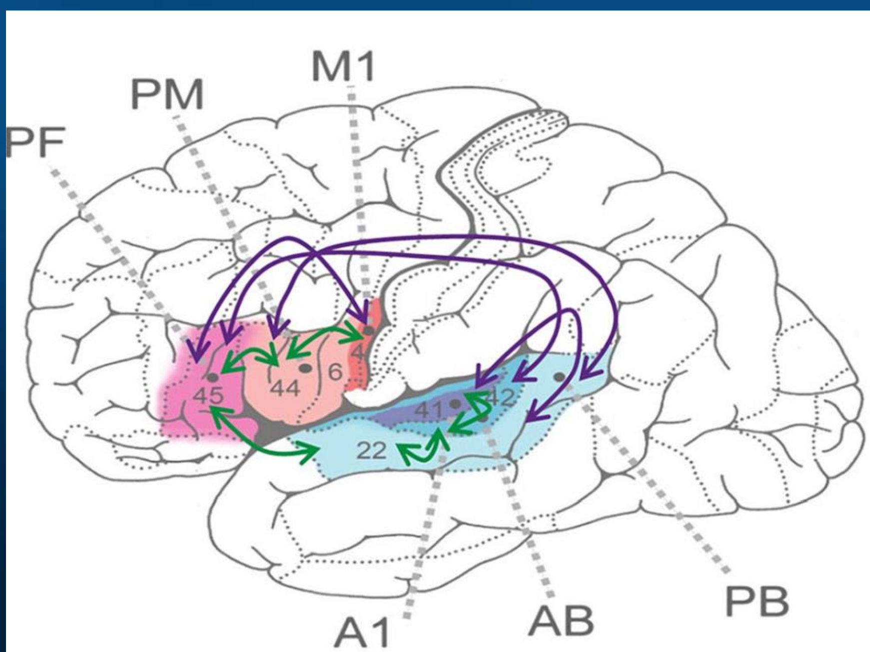
Fluid nature

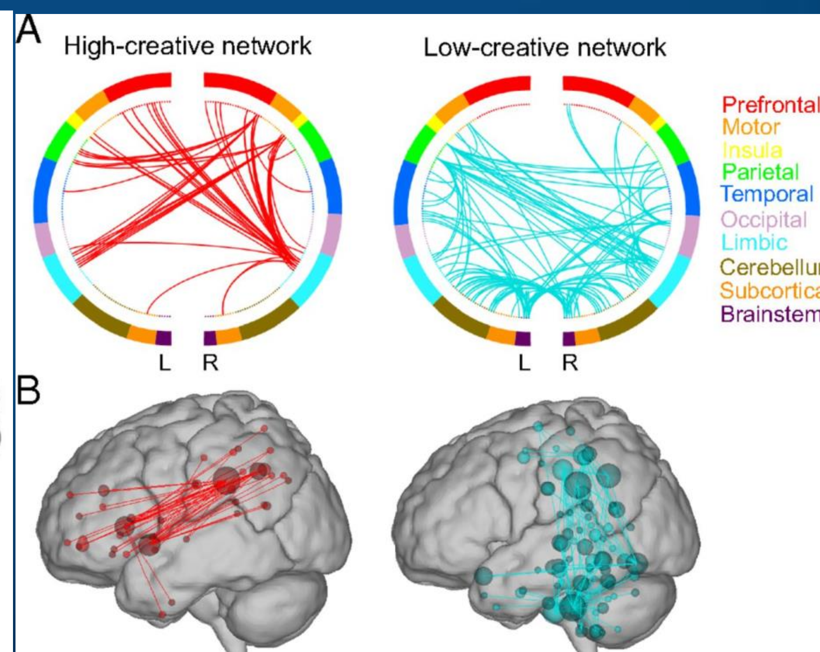
BABY Connectome Project — a UNC / UMN collaboration

Development of brain in infancy: first learning how to move, sensorimotor activity organizes brain network processes.

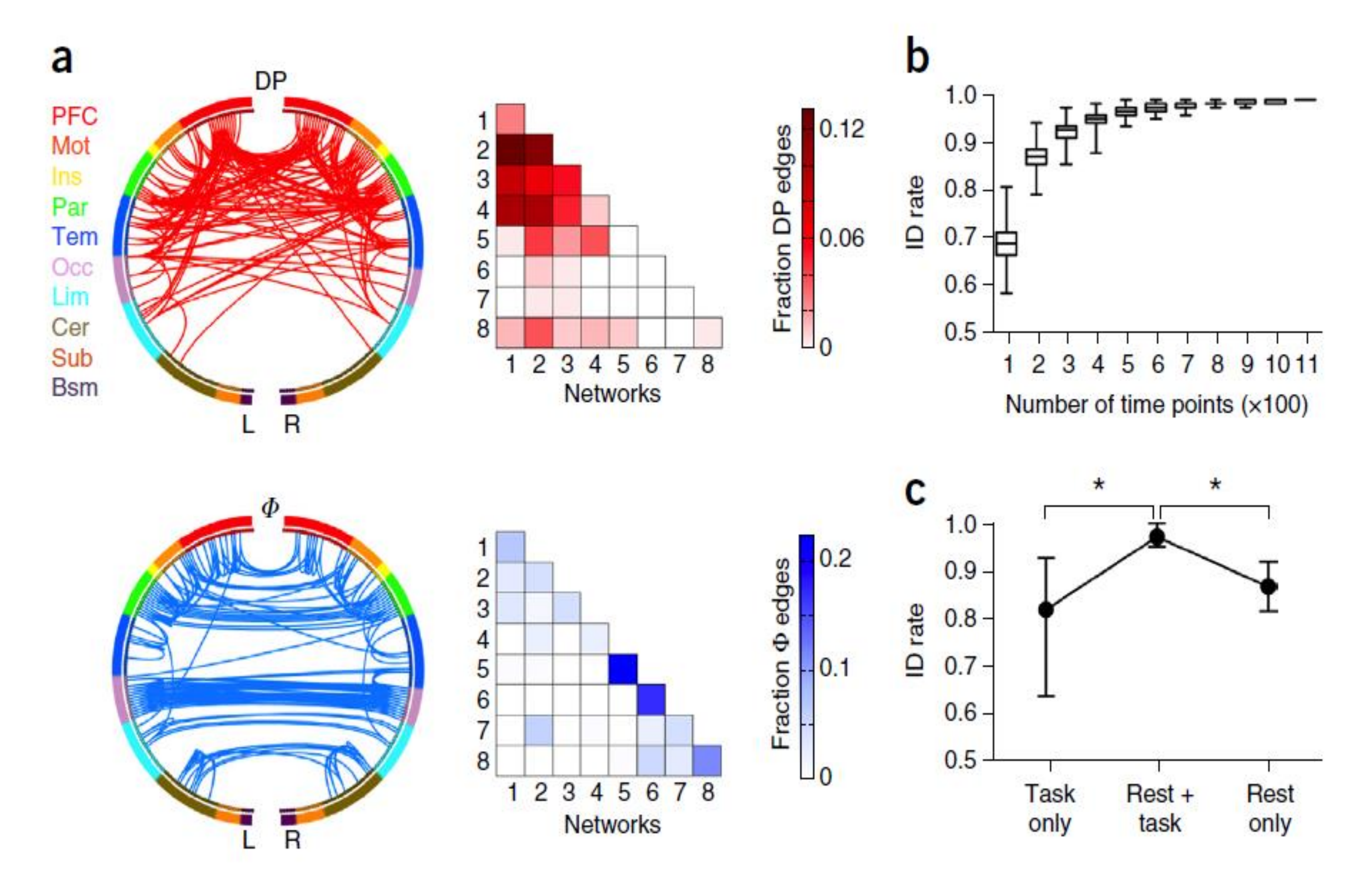
The Developing Human Connectome Project: create a dynamic map of human brain connectivity from 20 to 44 weeks post-conceptional age, linking together imaging, clinical, behavioral, and genetic information.

Pointing, gestures, pre-linguistic (our BabyLab), environments for infants.

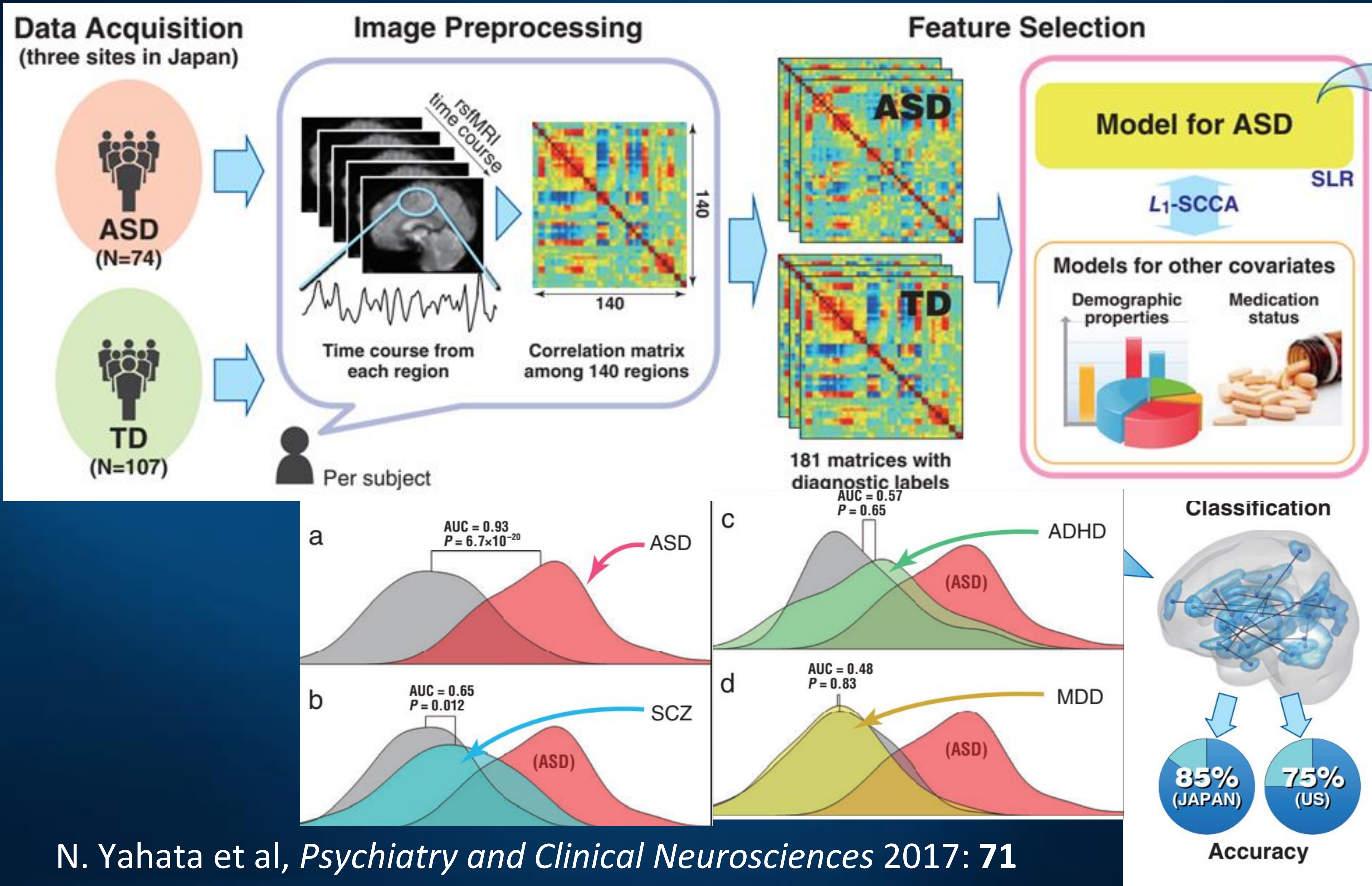




Finn et al. (2015), **Functional connectome fingerprinting**: identifying individuals using patterns of brain connectivity. Nature Neuroscience. Top: highly unique; Bottom: highly consistent connections.

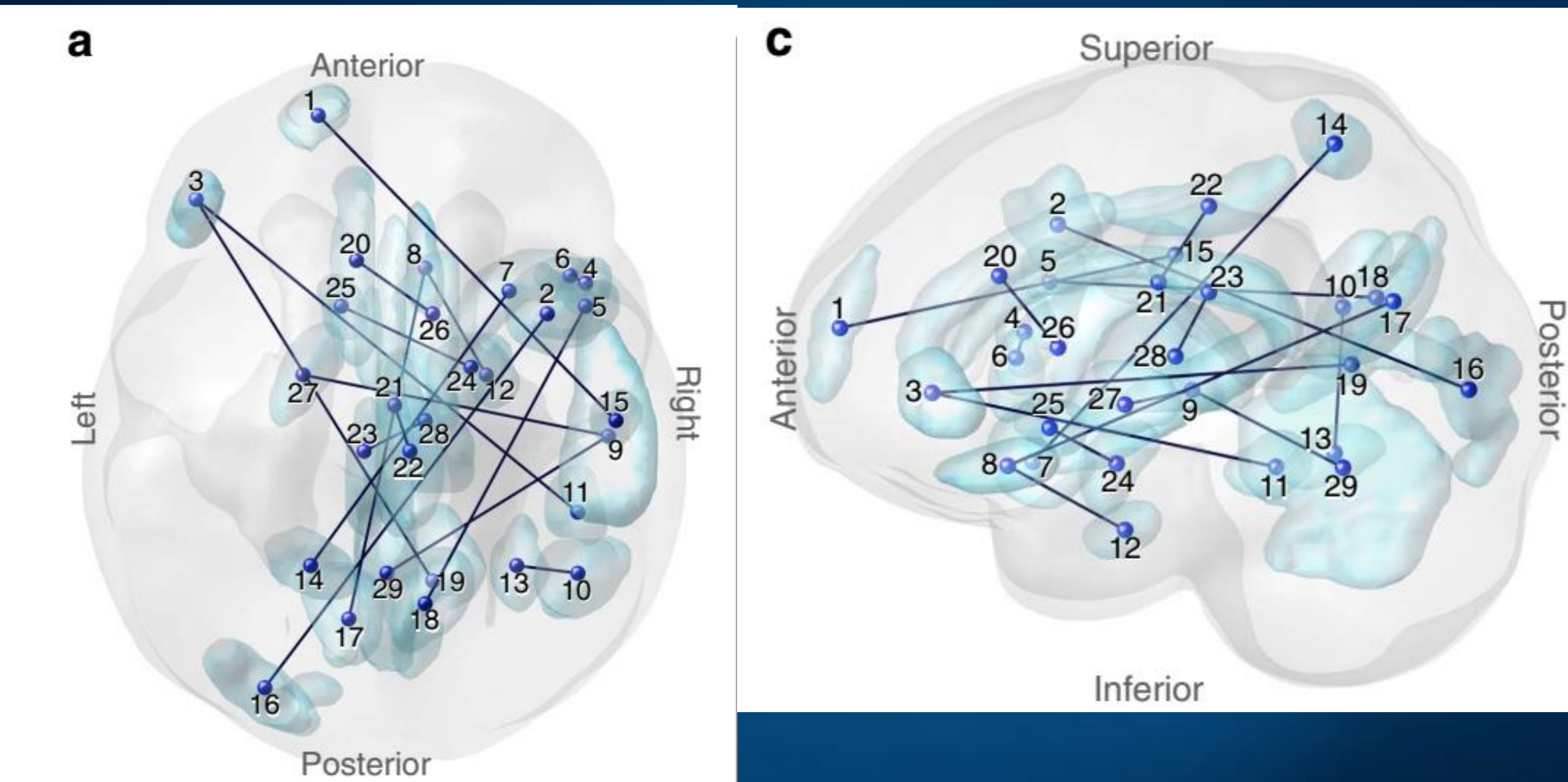


Diagnosis based on fMRI



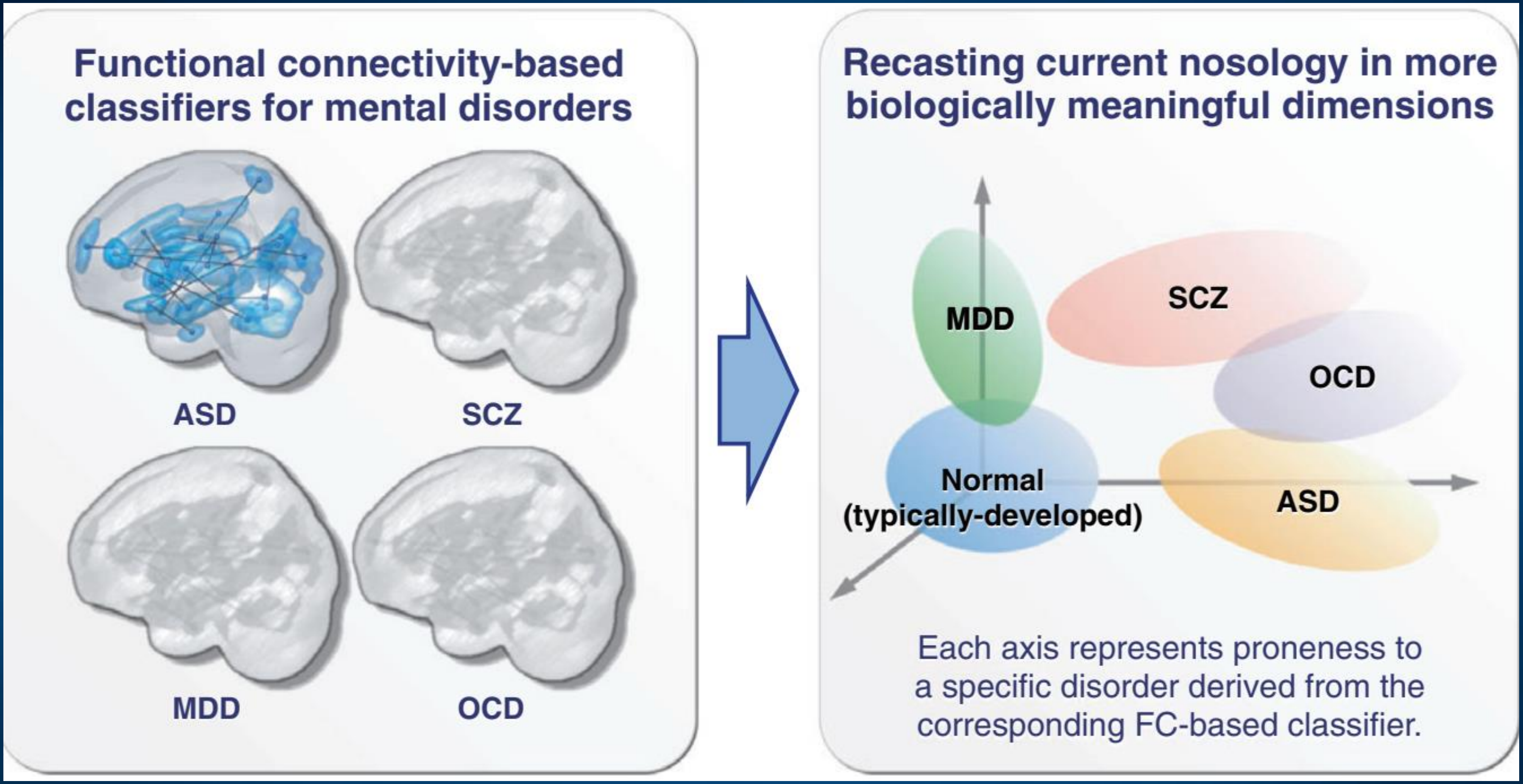
N. Yahata et al, *Psychiatry and Clinical Neurosciences* 2017: **71**

Selected connections



N. Yahata et al (2016): 29 selected regions (ROI) and 16 connections are sufficient to recognize ASD with 85% accuracy in 74 Japanese adult patients vs. 107 people in control group; without re-training accuracy was 75% on US patients.

Propensity to 4 disorders



MDD, major depressive disorder, SCZ, schizophrenia, OCD, obsessive compulsive disorder, in ASD and SCZ axis.

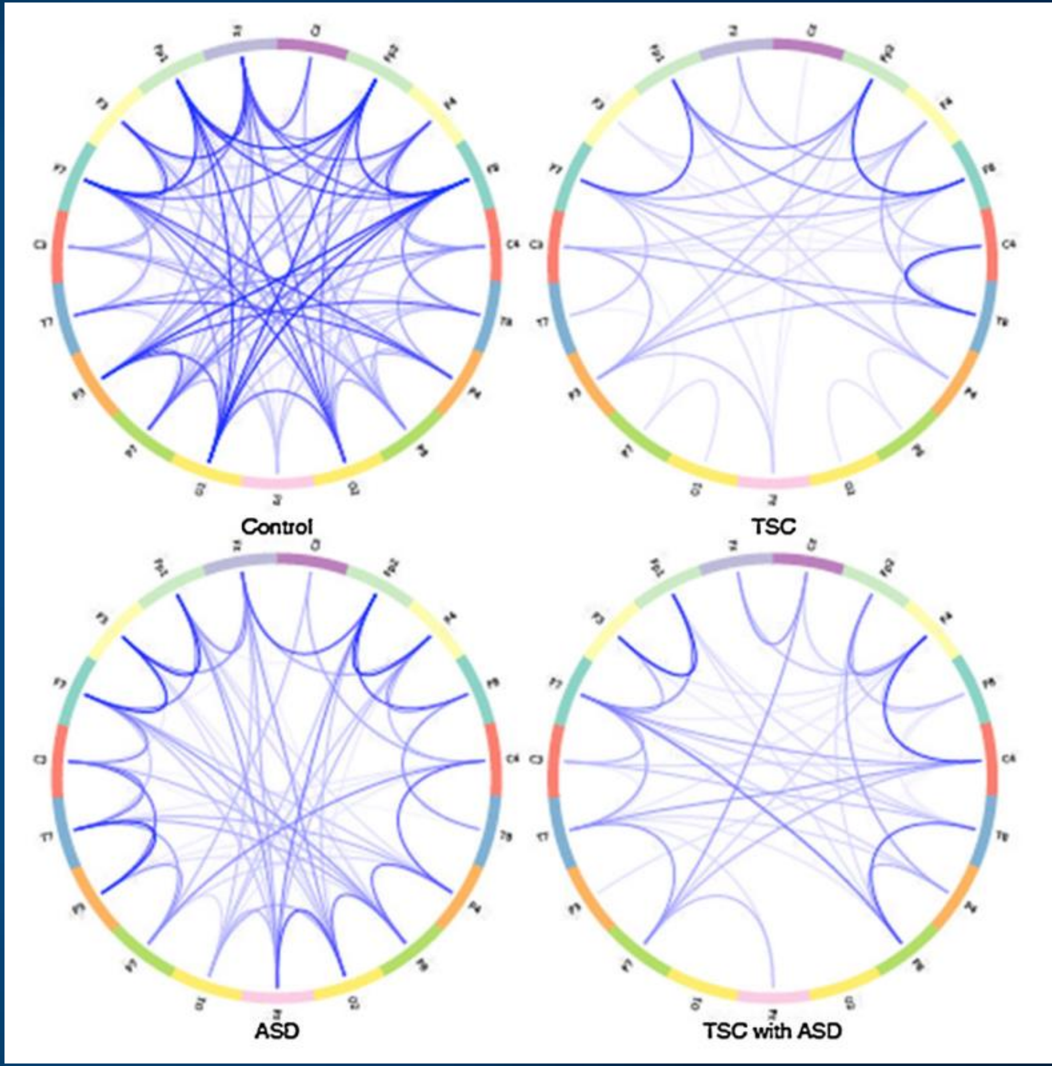
N. Yahata et al, *Psychiatry and Clinical Neurosciences* 2017; **71**: 215–237

ASD: pathological connections

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

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

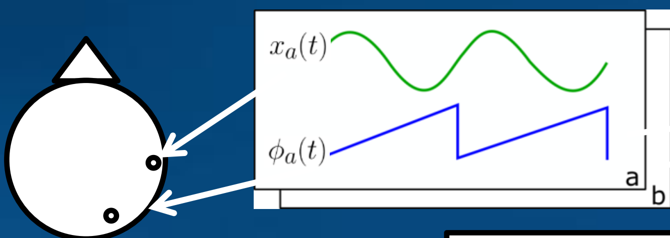
Network analysis becomes very useful for diagnosis of changes due to the disease and learning; **correct your networks**!



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

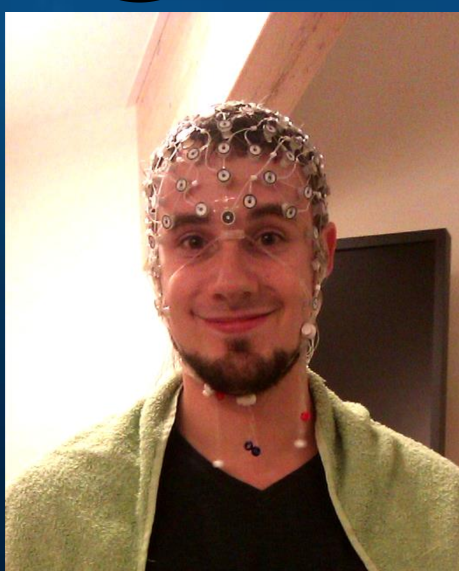
Functional connectivity changes

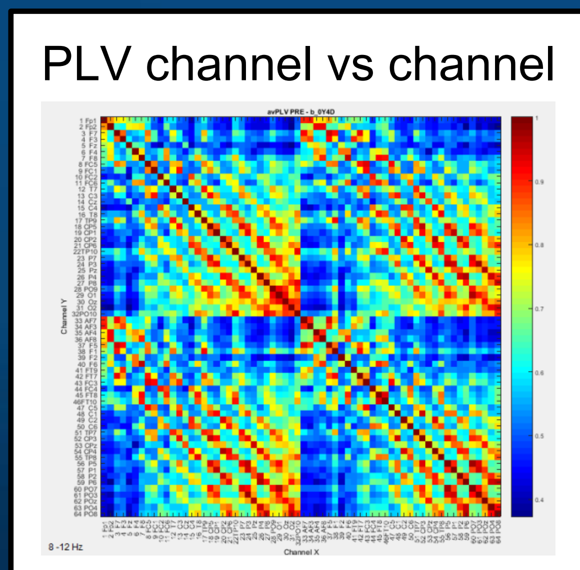
Influence of brain games on functional connectivity: **Phase Locking Value** (Burgess, 2013; Lachaux 1999), phase differences between signals measured at each electrode. PLV => synchronization maps, info flow.

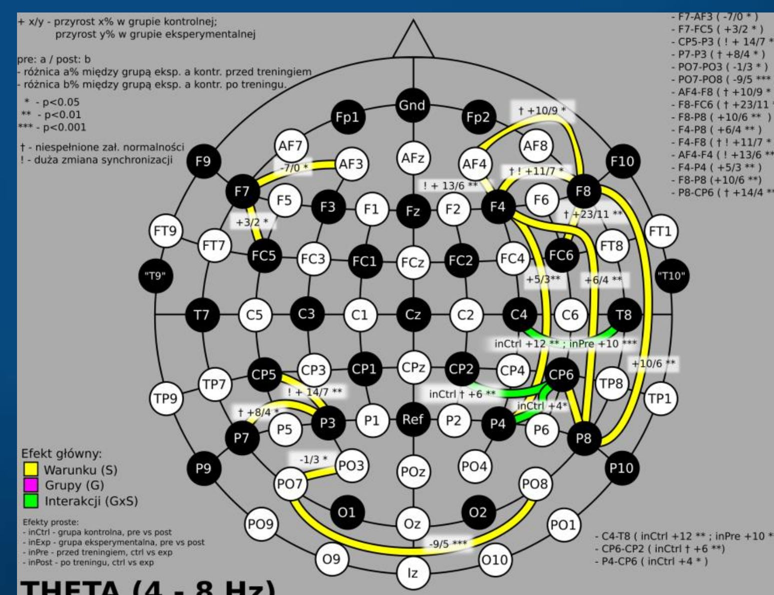


$$\Phi(t) = \phi_a(t) - \phi_b(t)$$

$$PLV(a,b) = \frac{1}{T}\left|\sum_{t}^{T} e^{i\Phi(t)}\right|$$





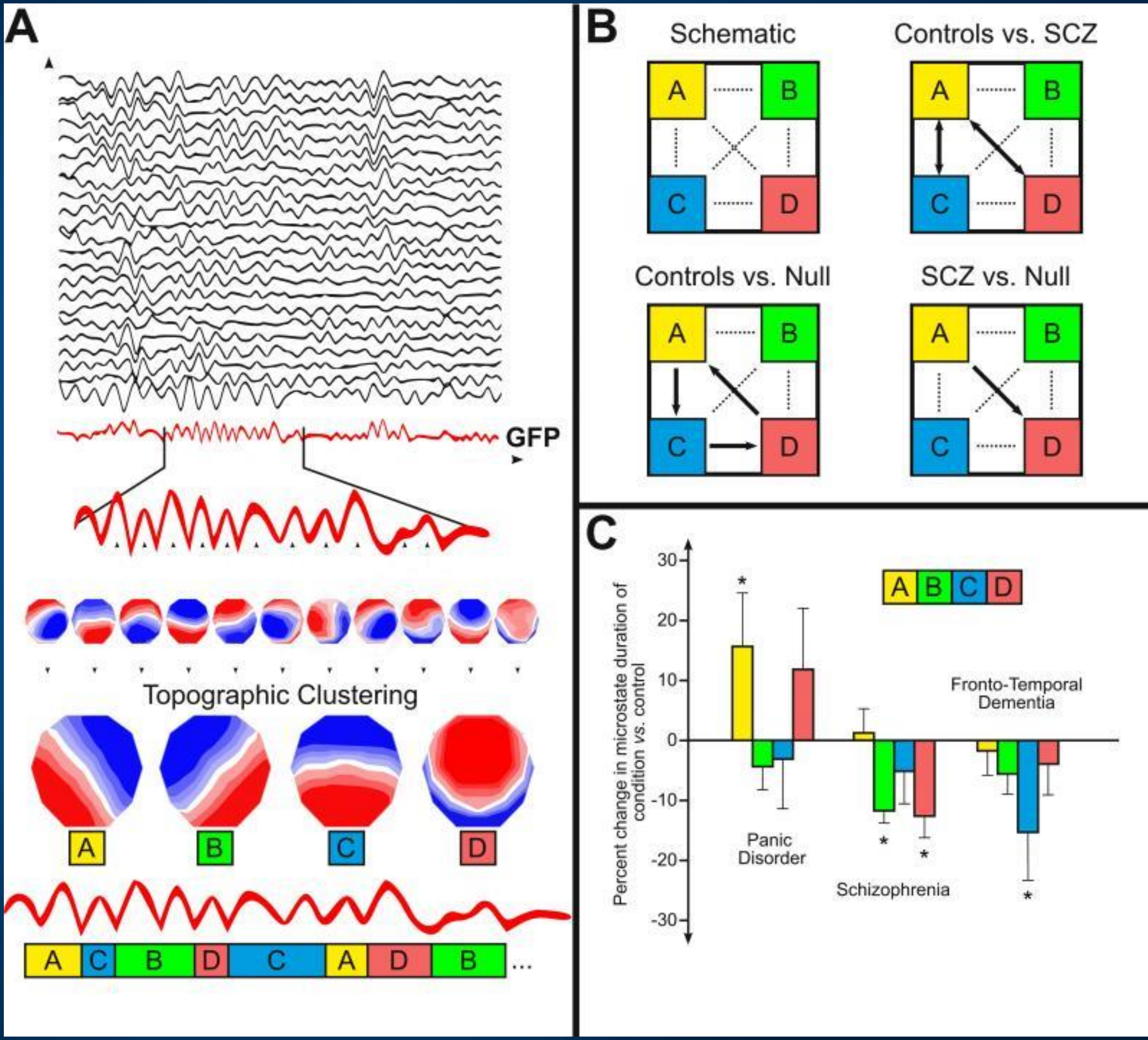


Microstates

Lehmann et al.
EEG microstate duration and syntax in acute, medication-naïve, first-episode schizophrenia: a multi-center study. Psychiatry Research Neuroimaging, 2005

Khanna et al.
Microstates in Resting-State EEG: Current Status and Future Directions. *Neuroscience and Biobehavioral Reviews*, 2015

Symbolic dynamics.

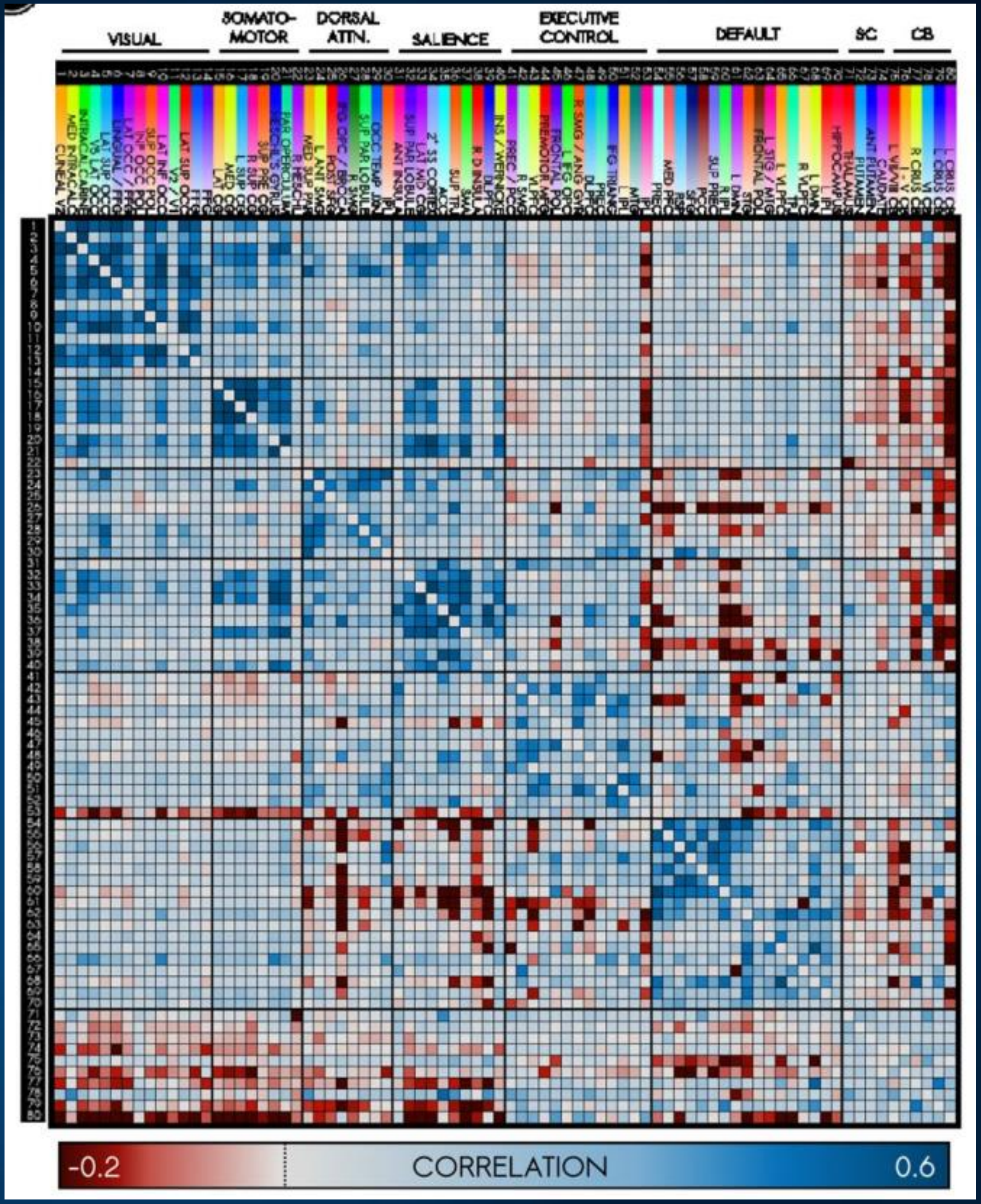


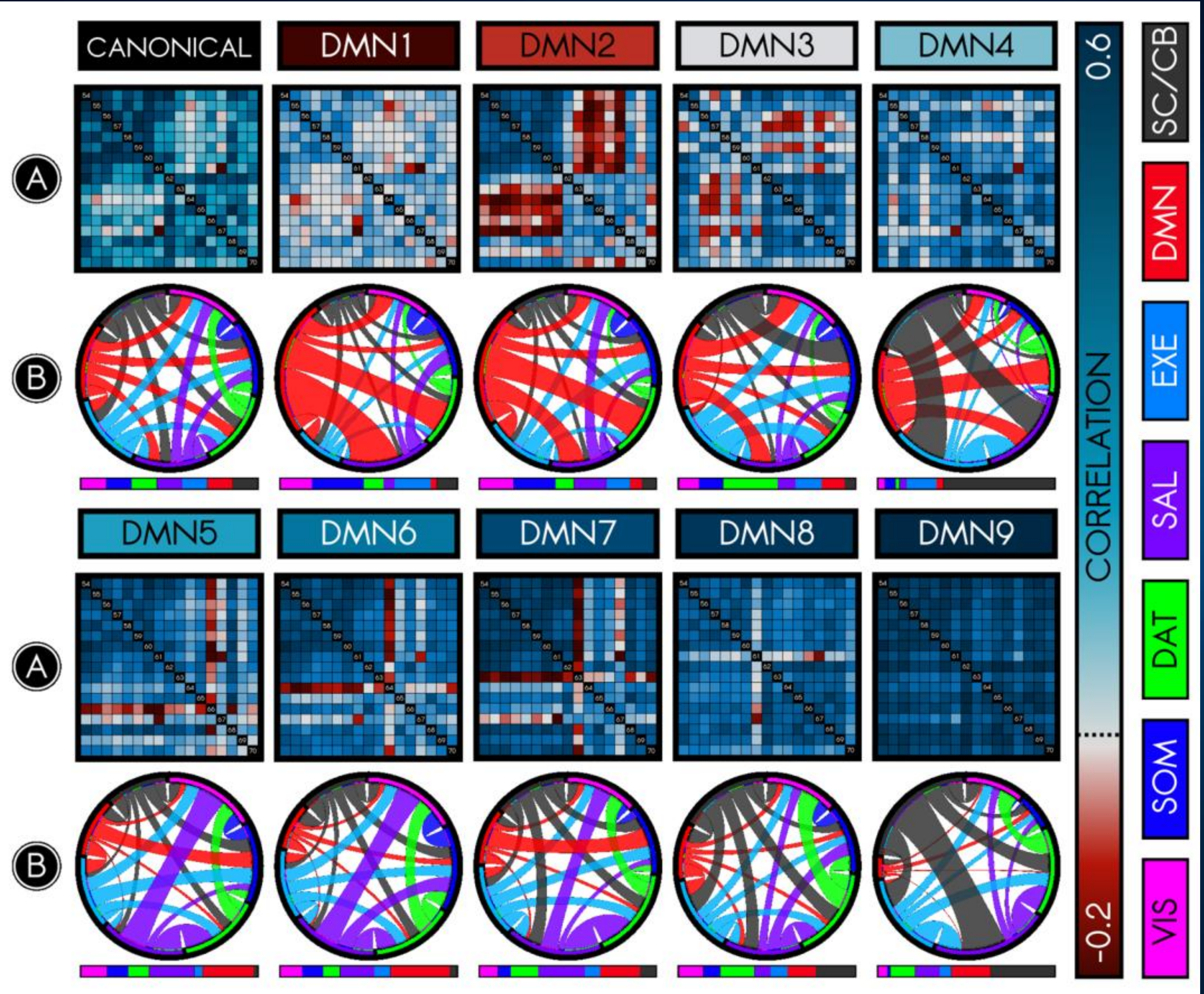
Ciric et.al. (2017). Contextual connectivity: A framework for understanding the intrinsic dynamic architecture of large-scale functional brain networks. *Scientific Reports*.

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.




CANONICAL
DMN1
DMN2
DMN3
DMN4
DMN5
DMN6
DMN7
DMN8
DMN9
A
B
A
B
CORRELATION
0.6
-0.2
SC/CB
DMN
EXE
SAL
DAT
SOM
VIS

Model of reading & dyslexia

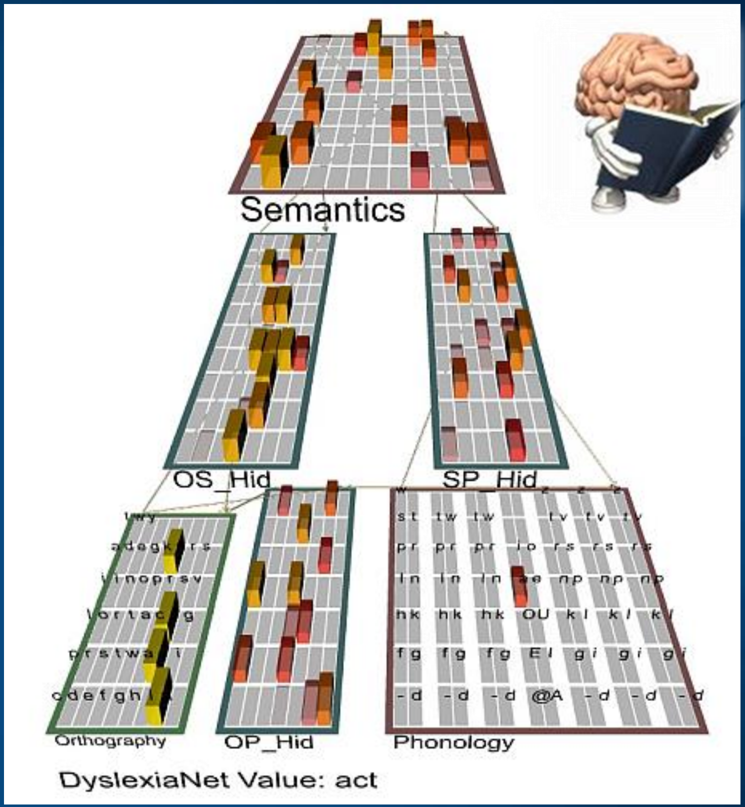
Emergent neural simulator:

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

3-layer model of reading:

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

In the brain: microfeature=subnetwork.
Hidden layers OS/OP/SP_Hid in between.

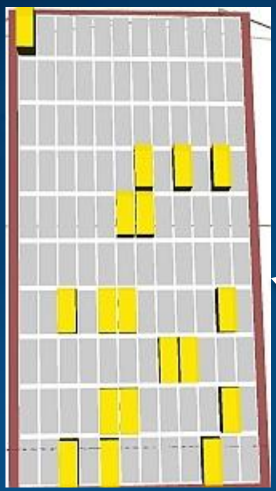


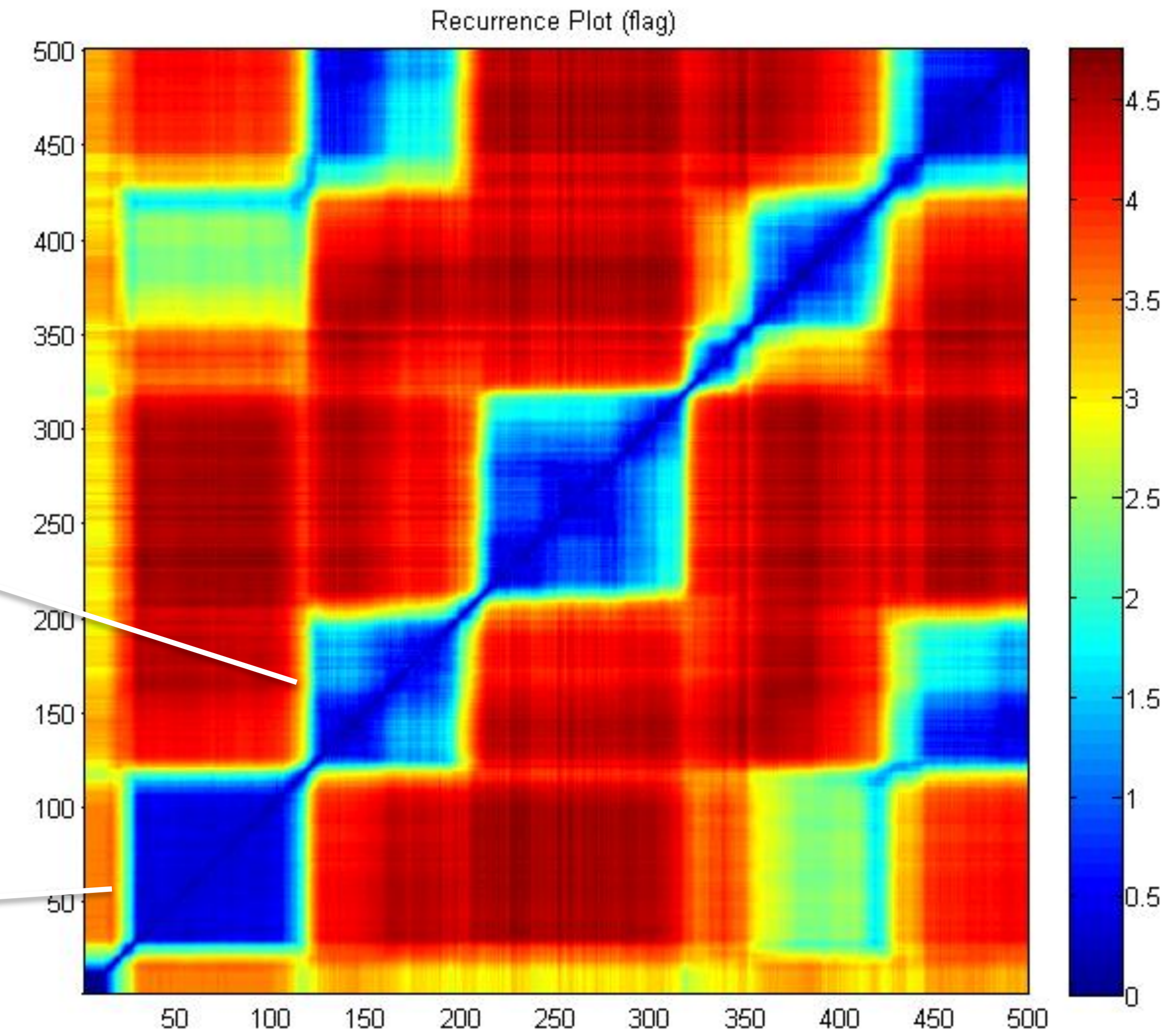
Learning: mapping one of the 3 layers to the other two.

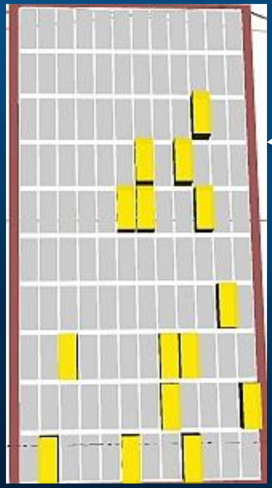
Fluctuations around final configuration = attractors representing concepts.

How to see properties of their basins, their relations?
Model in **Genesis**: more detailed neuron description.

rope



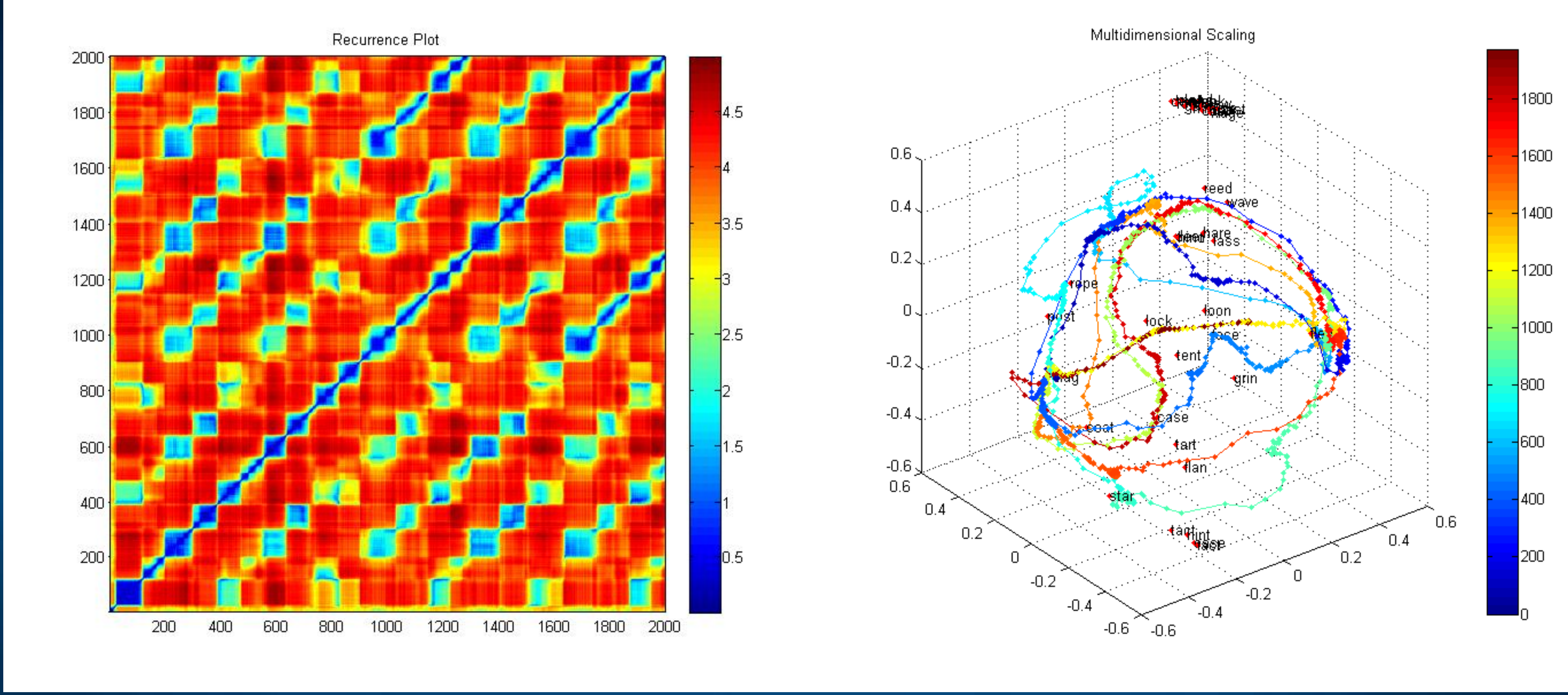




flag

Transitions to new patterns that share some active units (microfeatures) shown in recurrence plots.

Trajectory visualization



Recurrence plots and MDS/FSD/SNE visualization of trajectories of the brain activity. Here data from 140-dim semantic layer activity during spontaneous associations in the 40-words microdomain, starting with the word “flag”.

Our toolbox: http://fizyka.umk.pl/~kdobosz/visertoolbox/

EEG early ASD detection

Bosl, W. J., Tager-Flusberg, H., & Nelson, C. A. (2018). EEG Analytics for Early Detection of Autism Spectrum Disorder: A data-driven approach. Scientific Reports, 8(1), 6828.

EEG of 3 to 36-month old babies, 19 electrodes selected from 64 or 128.

Daubechies (DB4) wavelets transform EEG signal into 6 bands.

7 features from Recurrence Quantitative Analysis (RQA): RP entropy, recurrence rate, laminarity, repetition, max/mean line length, trapping time.

In addition sample entropy and Detrended Fluctuation Analysis was used.

Nonlinear features were computed from EEG signals and used as input to statistical learning methods. Prediction of the clinical diagnostic outcome of ASD or not ASD was highly accurate.

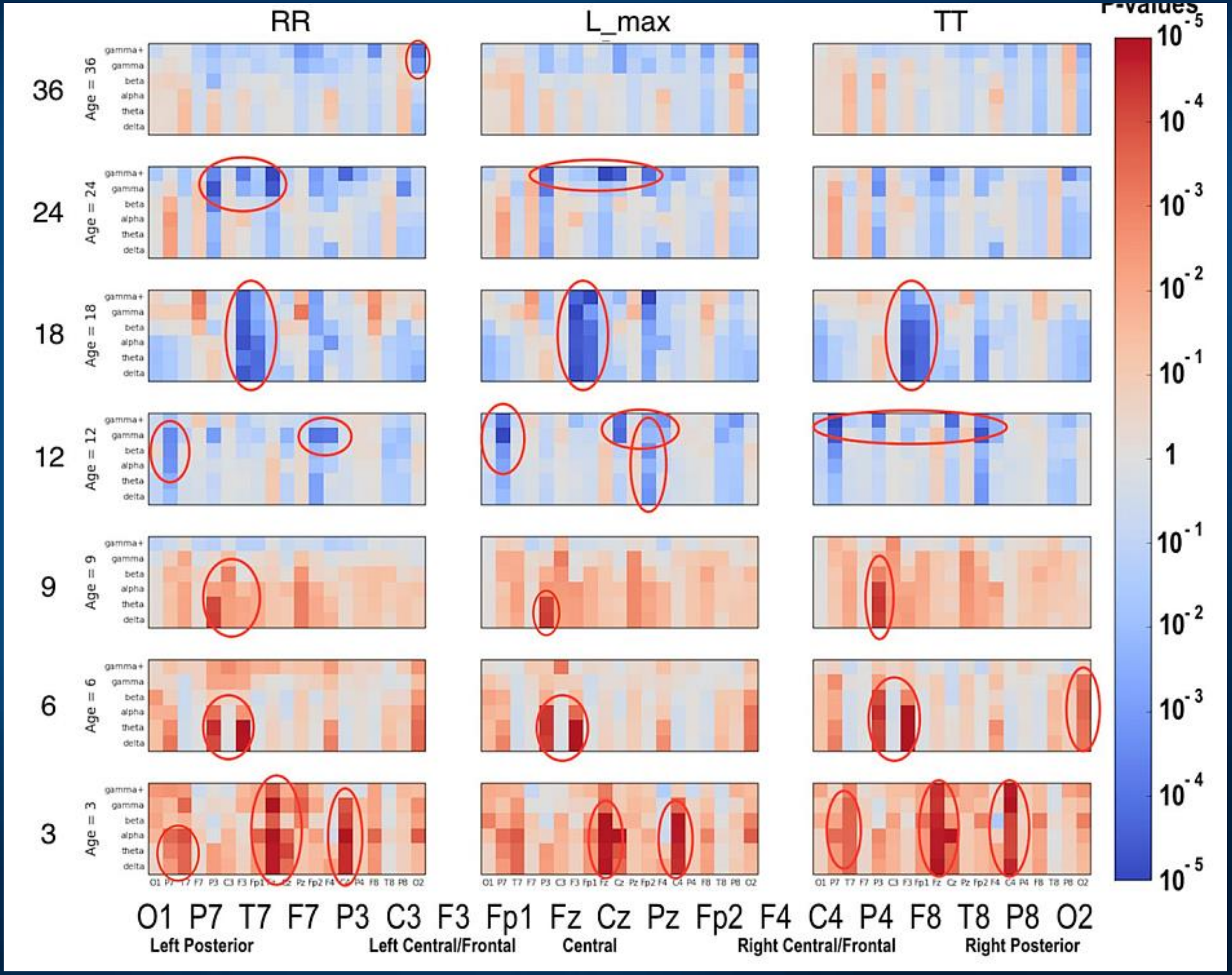
SVM classification with 9 features gave high specificity and sensitivity, exceeding 95% at some ages. Prediction using only EEG data taken as early as 3 months of age was strongly correlated with the actual measured scores.

ASD vs Low Risk Healthy

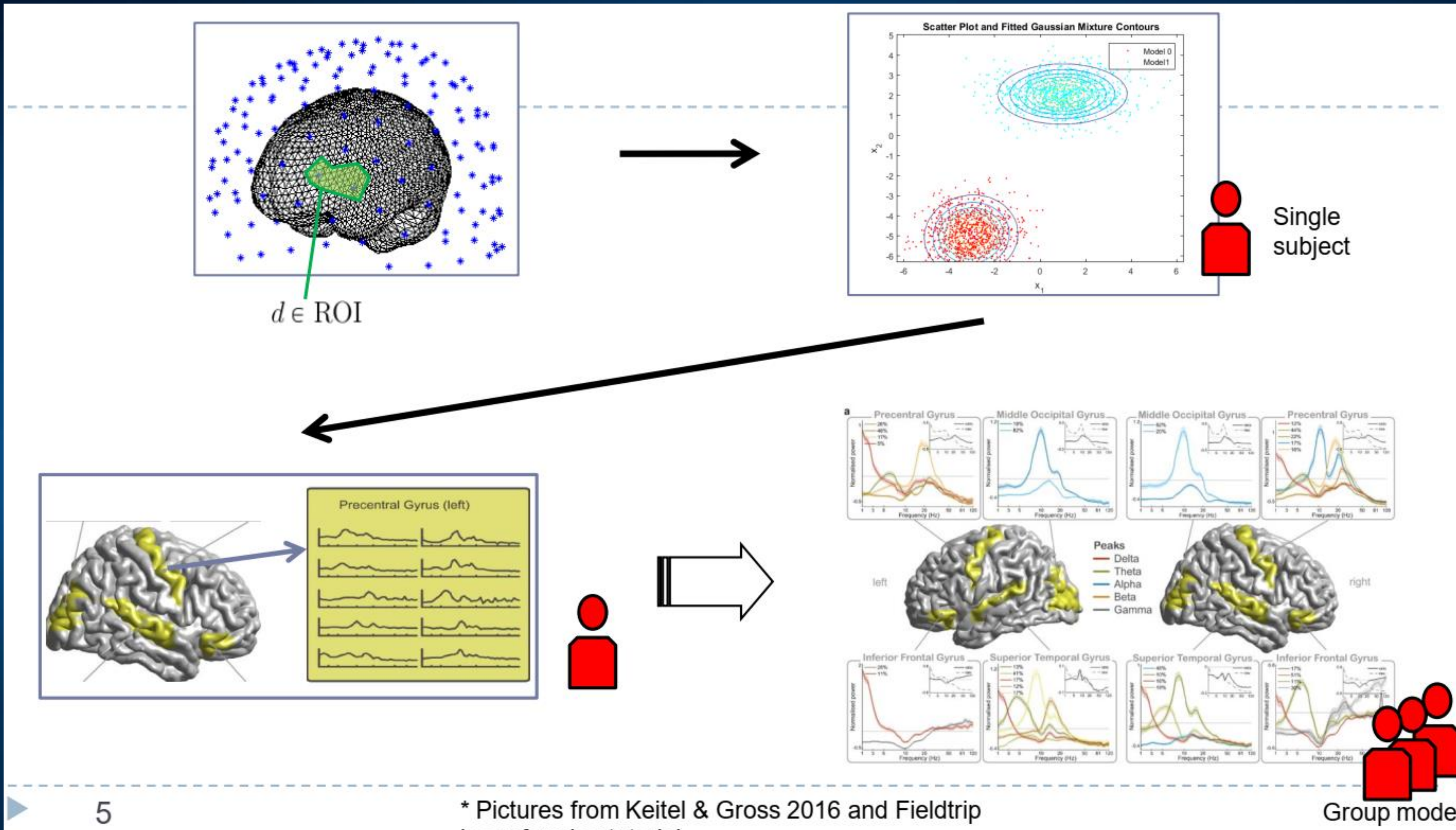
RR = recurrence rate

L_max = max line length, related to Lyapunov exponent

TT = trapping time

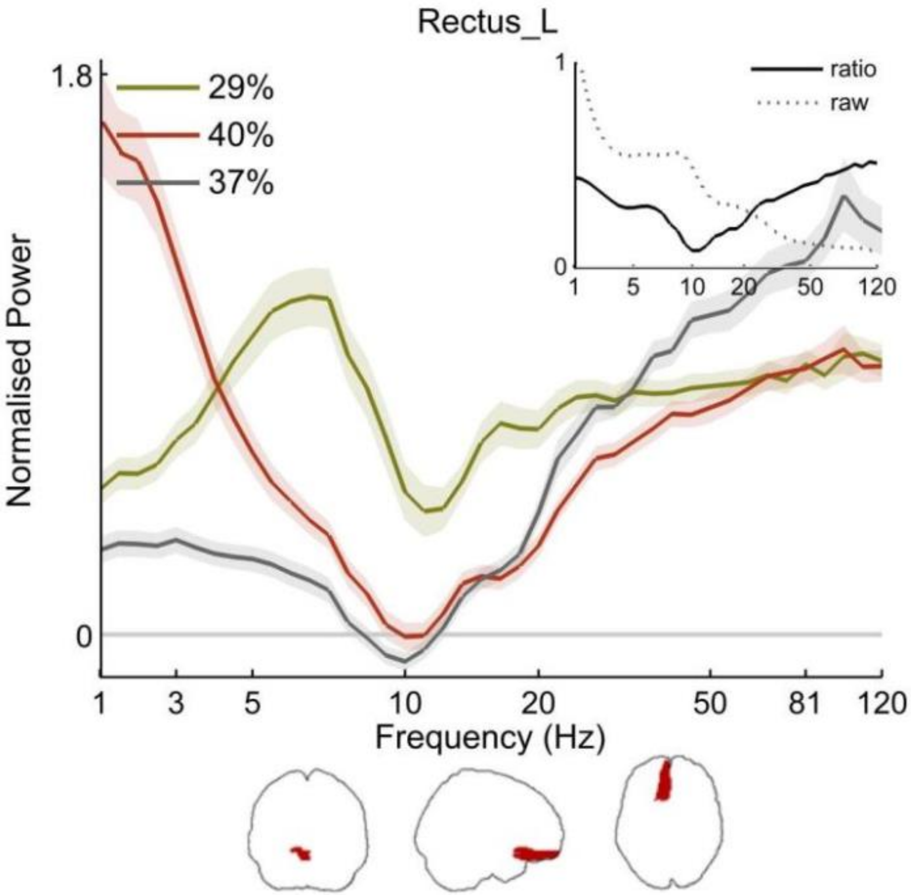


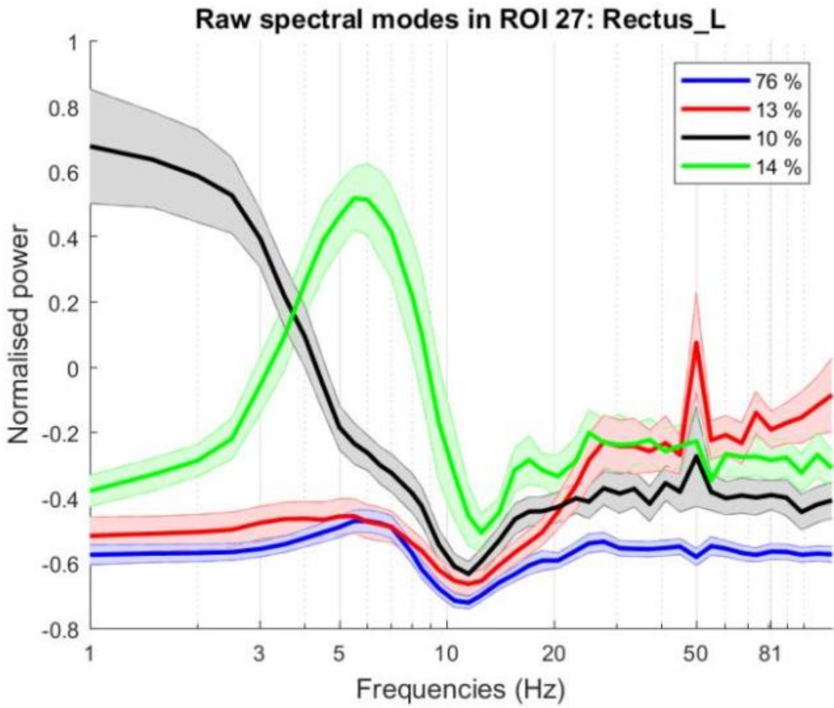
Spectral fingerprints



A. Keitel i J. Gross, „Individual human brain areas can be identified from their characteristic spectral activation fingerprints”, *PLoS Biol* 14(6), e1002498, 2016

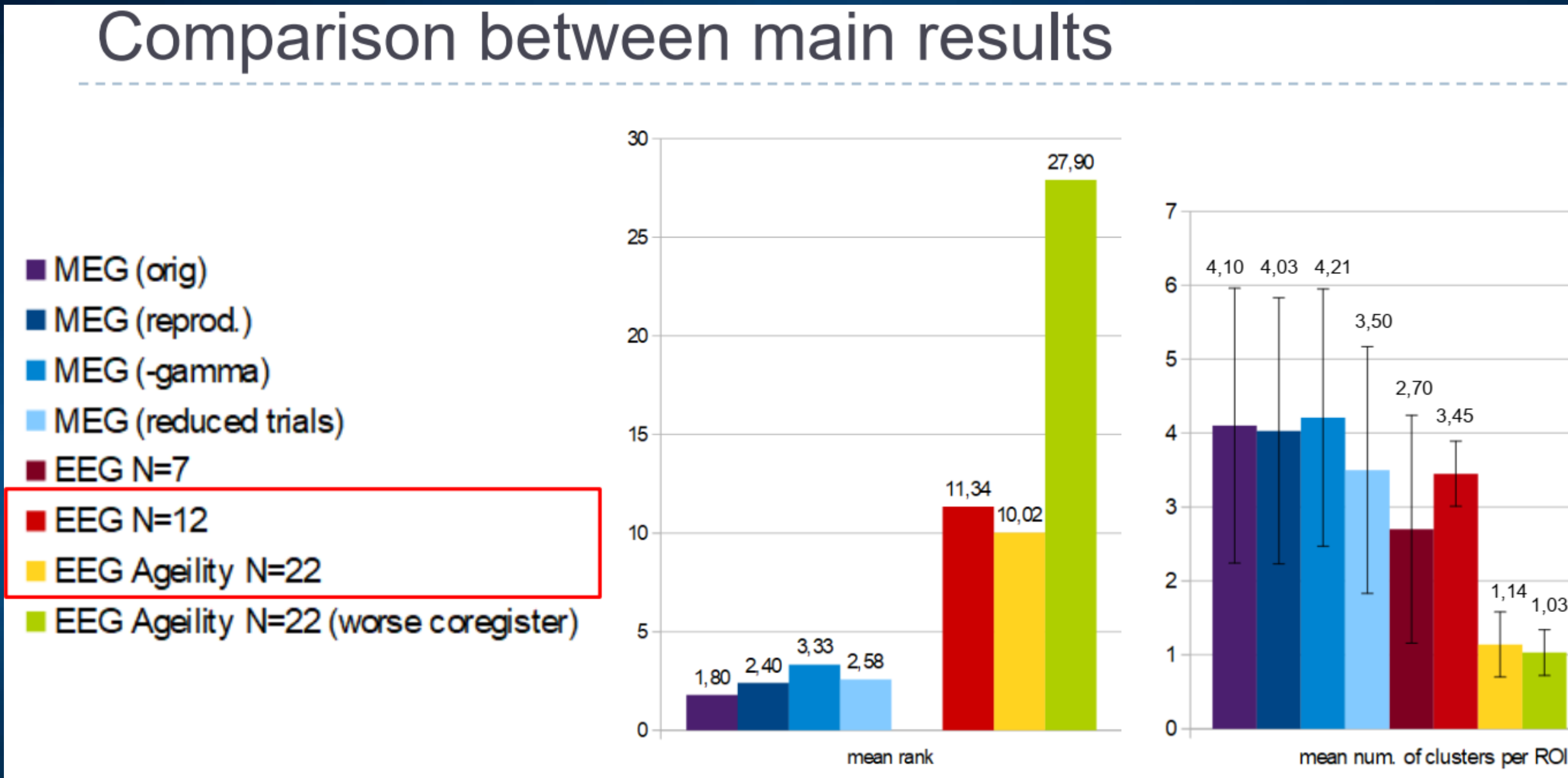
Spectral fingerprints





A. Keitel i J. Gross, „Individual human brain areas can be identified from their characteristic spectral activation fingerprints”, *PLoS Biol* 14, e1002498, 2016

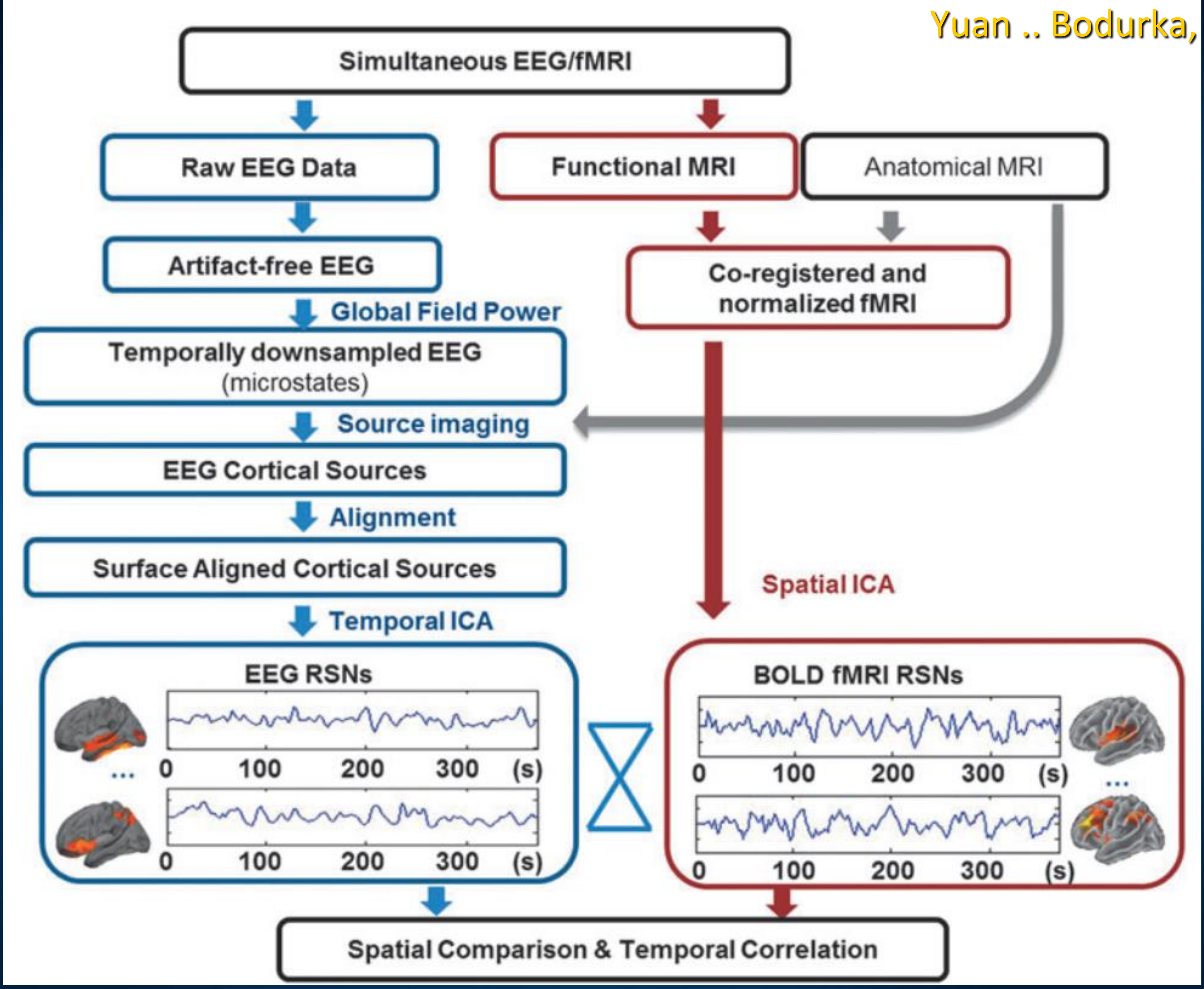
MEG-EEG preliminary comparison



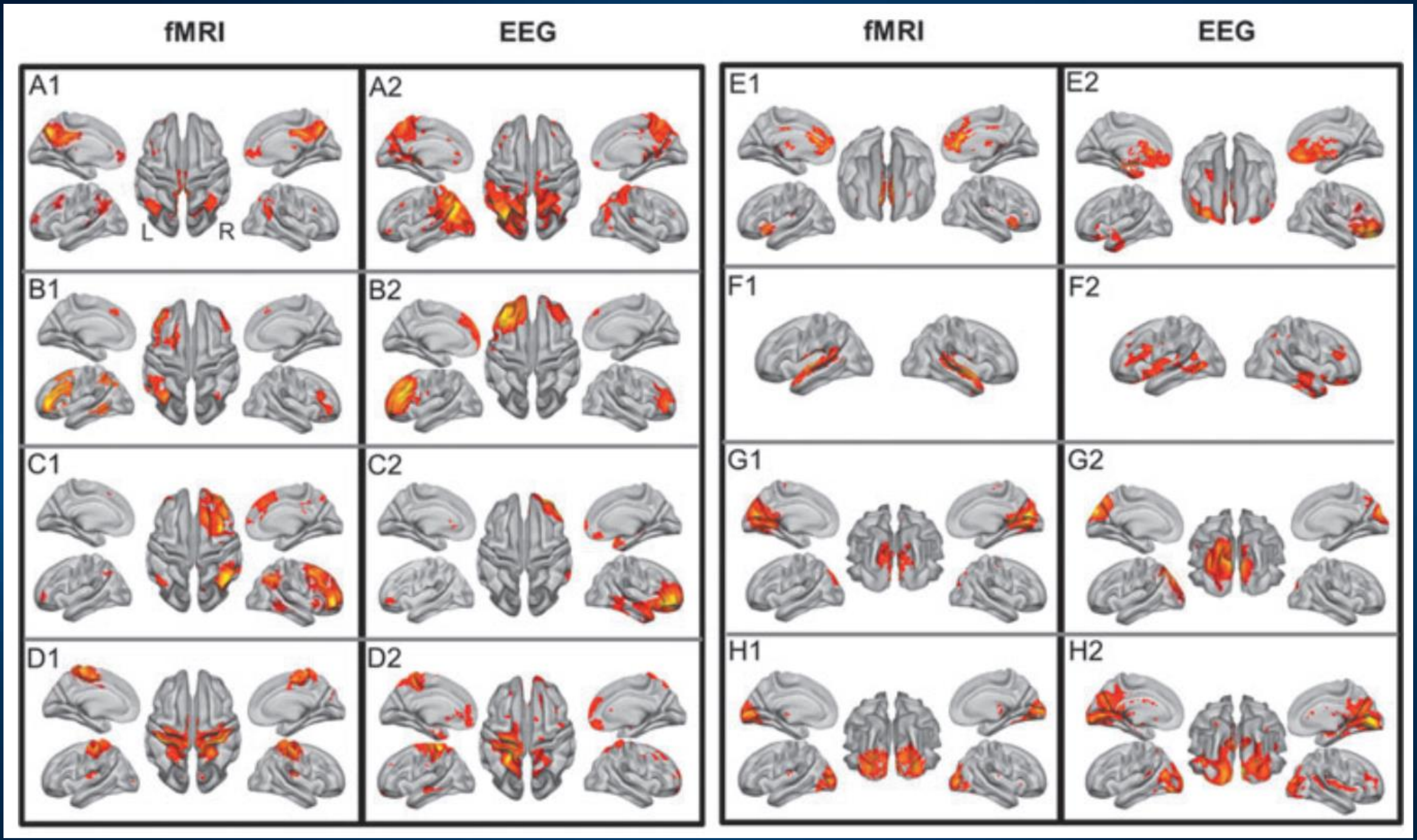
Ageility data have no information on sensor positions and results (in green) are quite poor; yellow – a bit of guessing where to place sensors on the head.

Our own experiment to collect EEG data with precise position of electrodes to enable good source reconstruction for 7 and 12 cases.

Yuan .. Bodurka, 2015

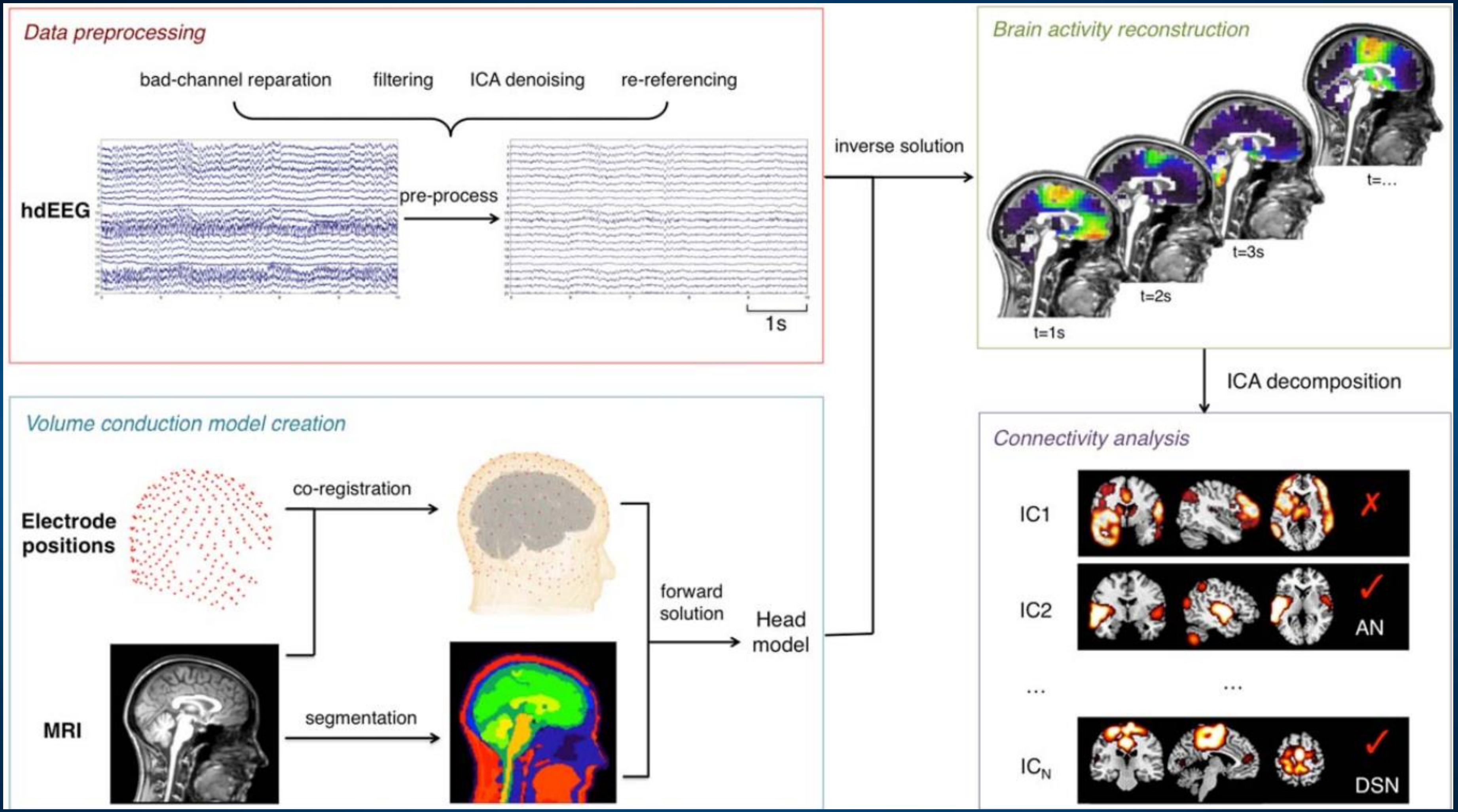


8 large networks from BOLD-EEG



DMN, FP (frontoparietal)-left, right, sensorimotor, ex, control, auditory, visual (medial), (H) visual (lateral). Yuan … Bodurka (2015)

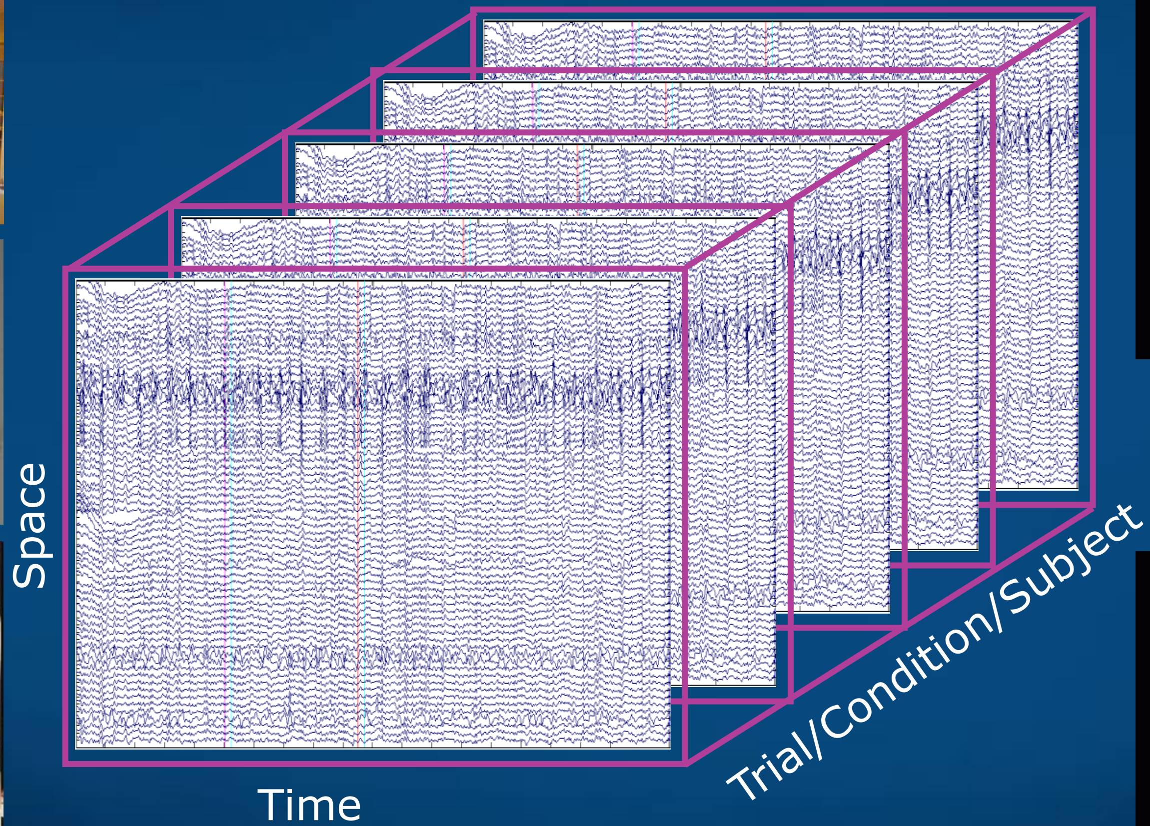
14 networks from BOLD-EEG

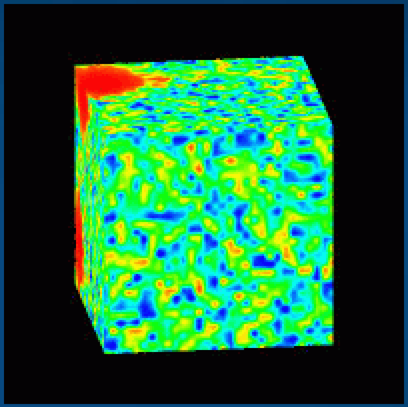


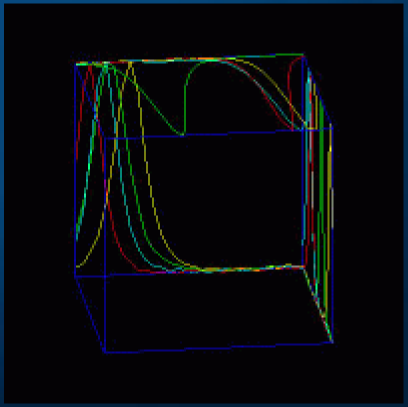
Liu et al. Detecting large-scale networks in the human brain. HBM (2017; 2018).

From Two-way to Multi-way Analysis
Integration and Fusion of Various Modalites
EEG+fNIRS +fMRI

A. Cichocki Lab
RIKEN Brain Science Inst.

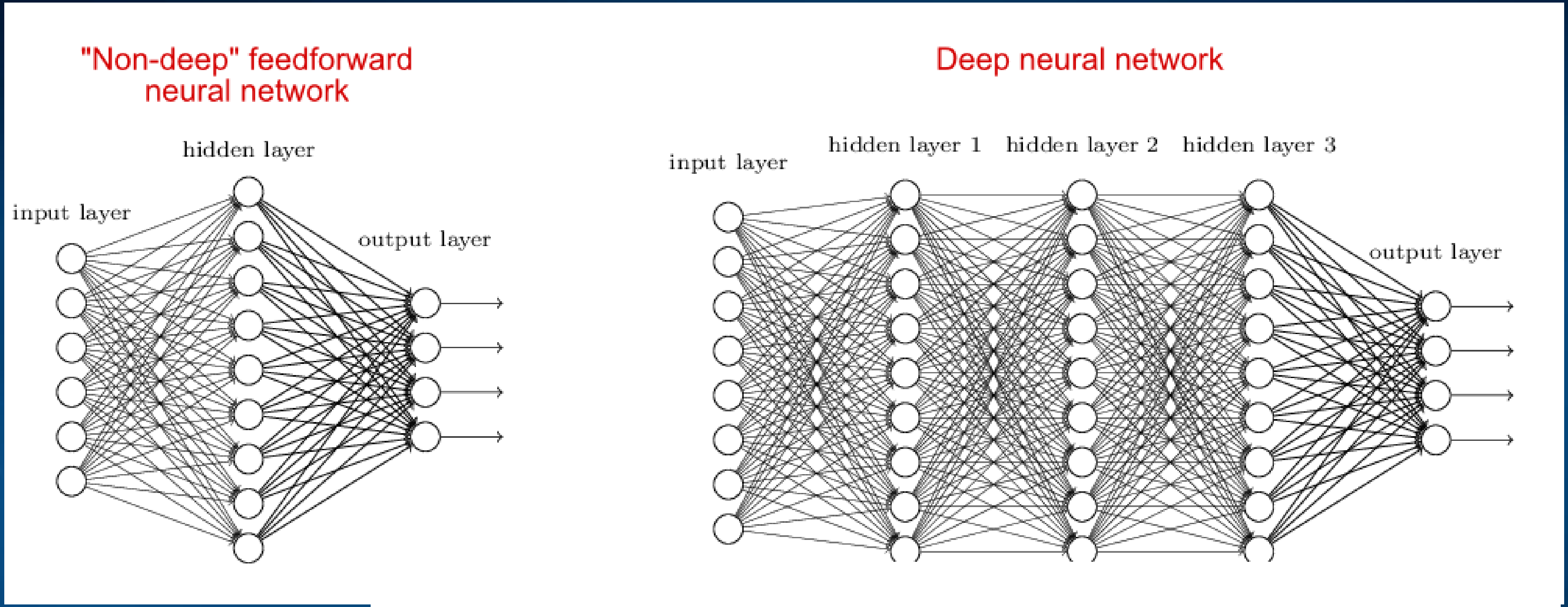




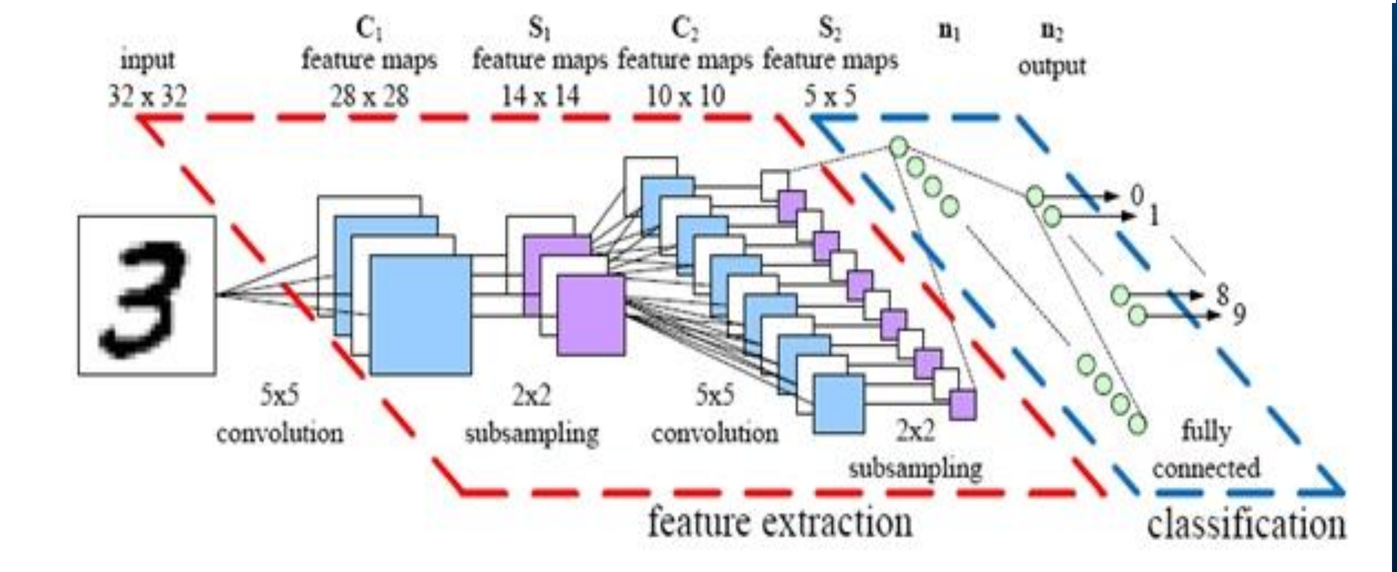


Exploratory and multi-way blind source separation and tensor factorizations: unsupervised learning methods and software to find the hidden causes & underlying hidden structure in the data.

Tensorization of Convolutive Deep Learning NN



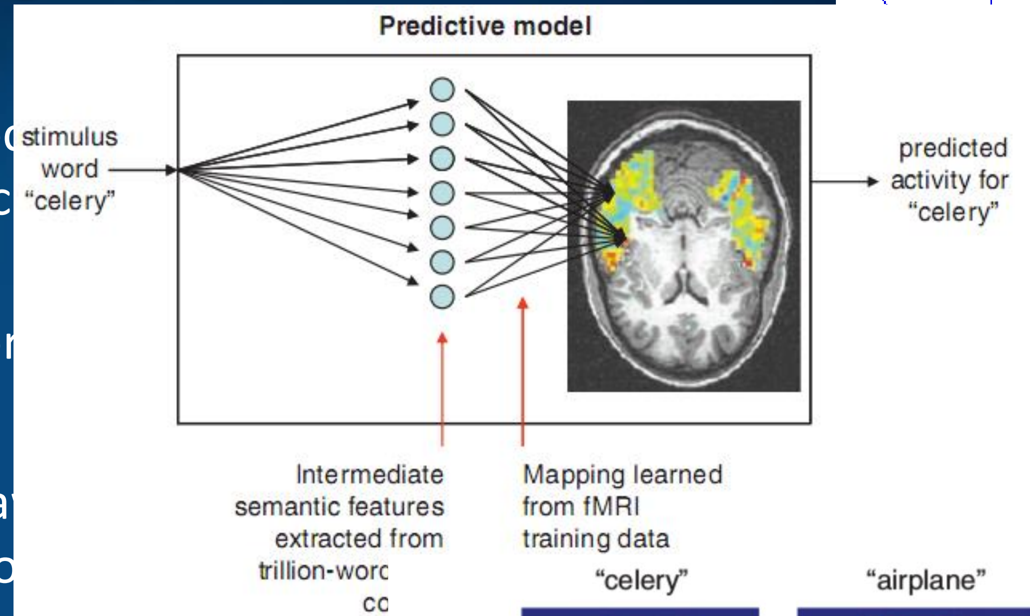
A. Cichocki Lab
RIKEN BSI



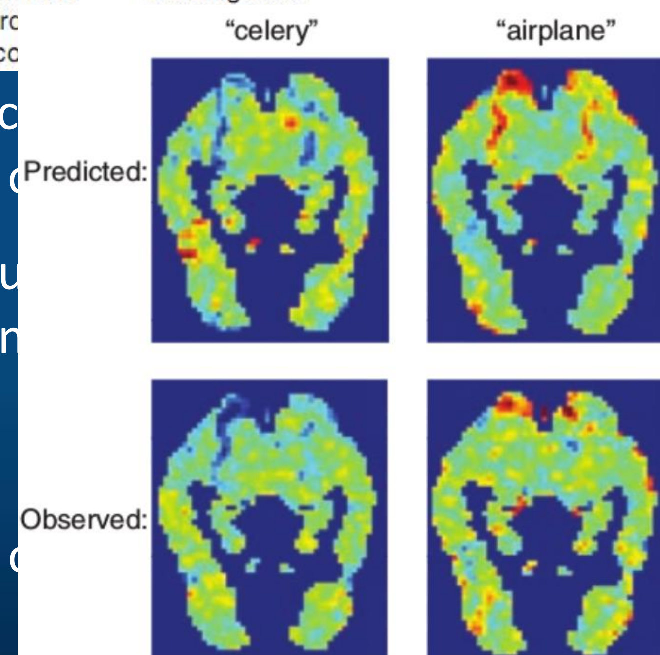
Fingerprints of Mental Activity

Neuroimaging words

Predicting Human Brain Activity Assoc
of Nouns," T. M. Mitchell et al, Scienc

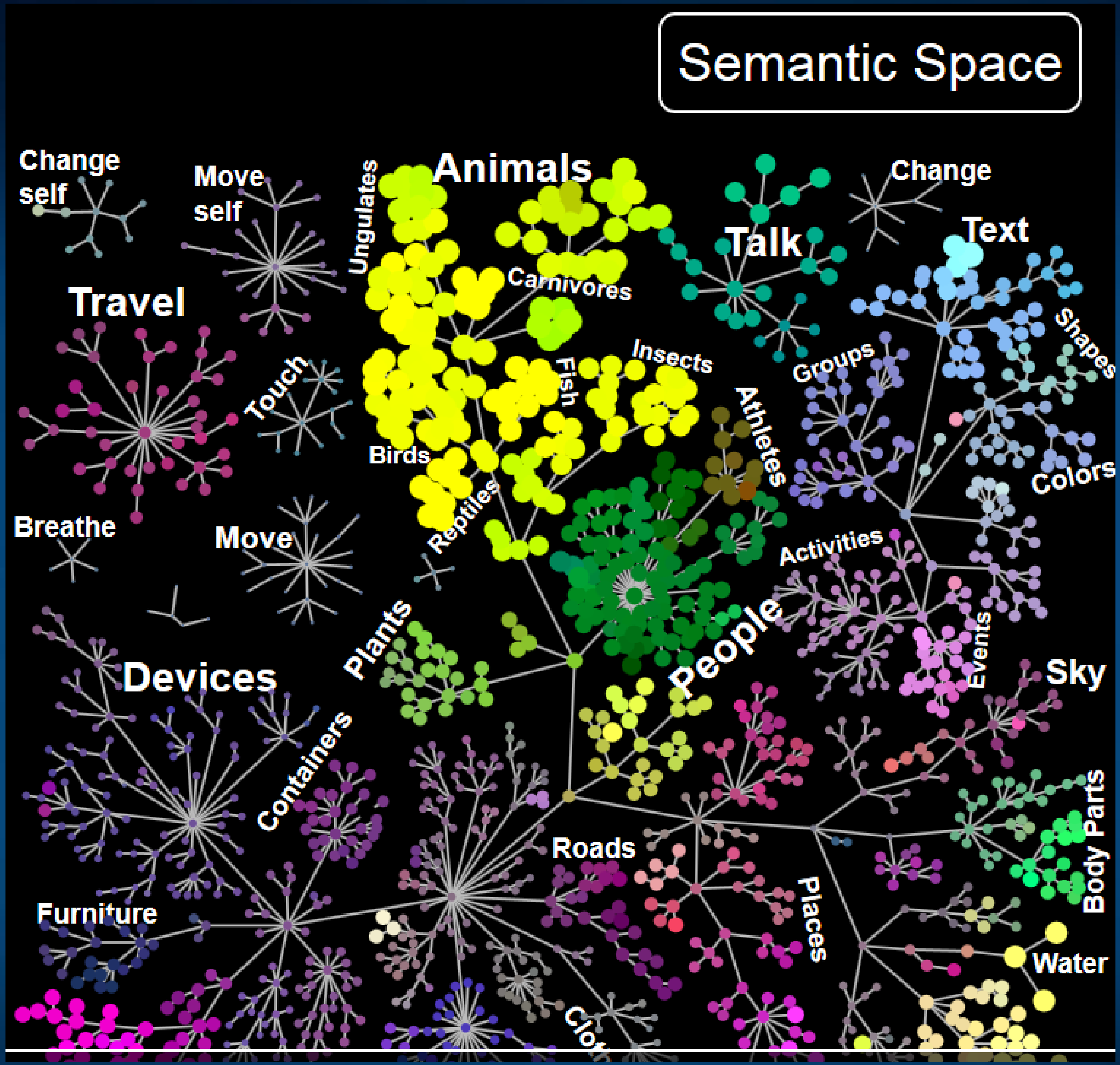


- Clear differences between fMRI br
about different nouns.
- Reading words and seeing the dra
presumably reflecting semantics o
- Although individual variance is significant similar ac
of different people, a classifier may still be trained o
- Model trained on ~10 fMRI scans + very large corpu
activity for over 100 nouns for which fMRI has been



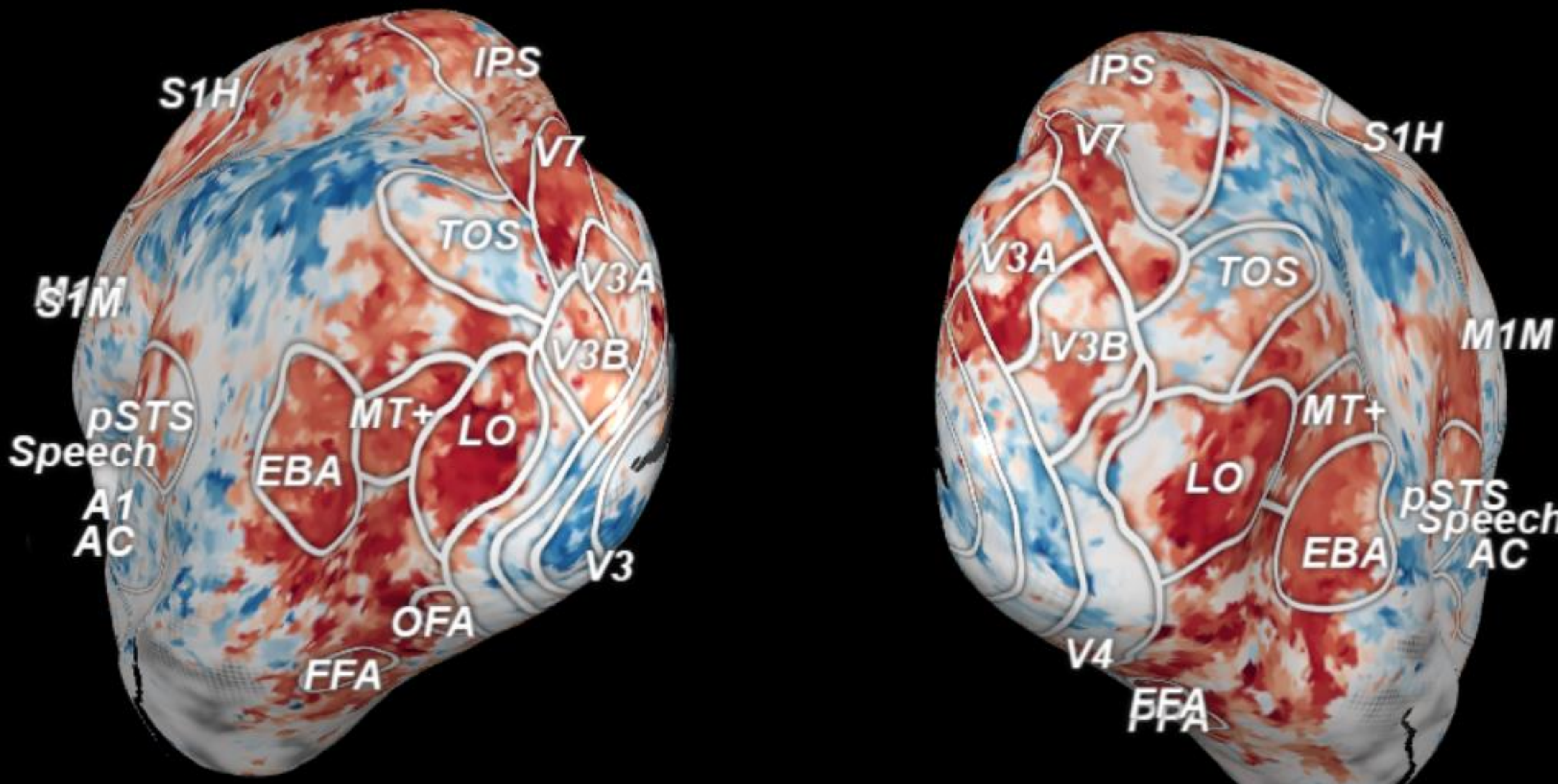
Sensory: fear, hear, listen, see, smell, taste, touch
Motor: eat, lift, manipulate, move, push, rub, run, say
Abstract: approach, break, clean, drive, enter, fill, near, o

Are these 25 features defining brain-based semantics?

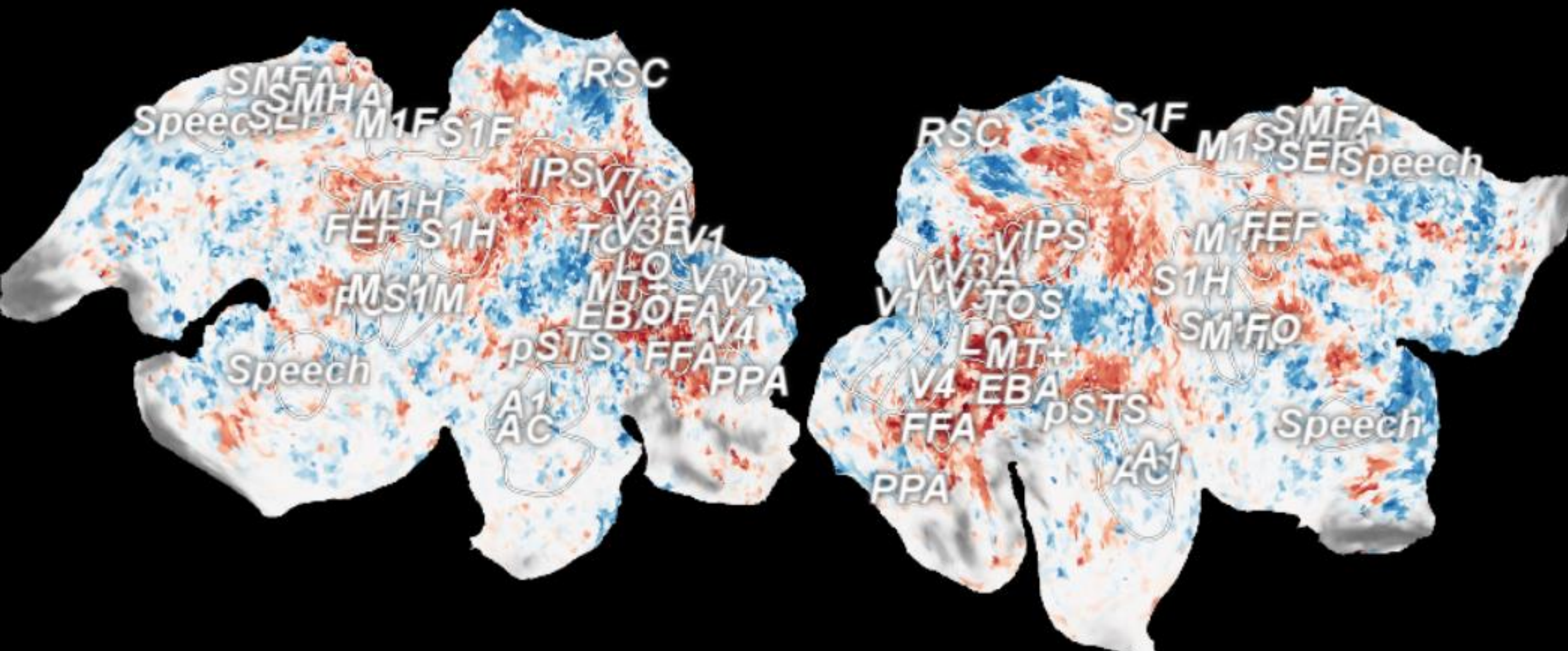


Words in the semantic space are grouped by their similarity (Gallant Lab, 2016).
Words activate specific ROIs, similar words create similar maps of brain activity.
Each voxel may be activated by many words. Video or audio stimuli, fMRI scans.

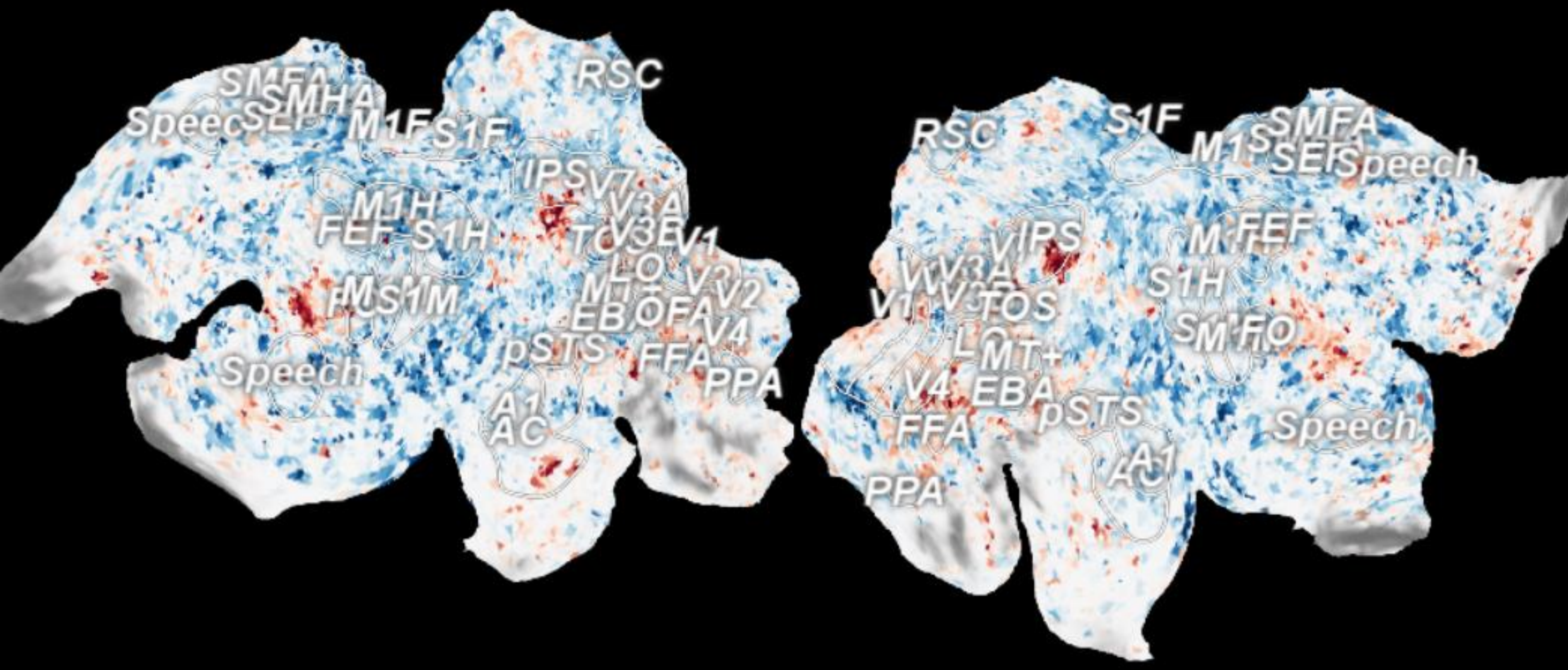
Category zebra: Passive Viewing

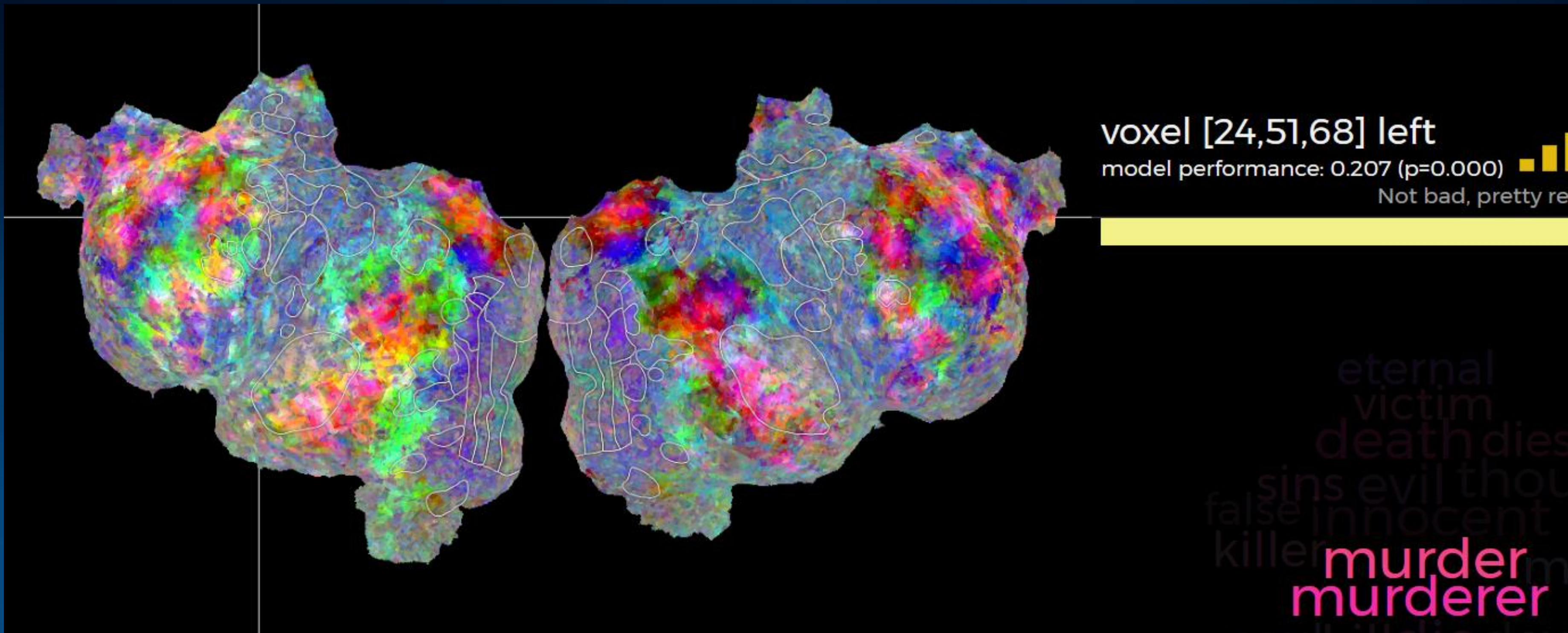


Category zebra: Passive Viewing



Category traffic light: Passive Viewing



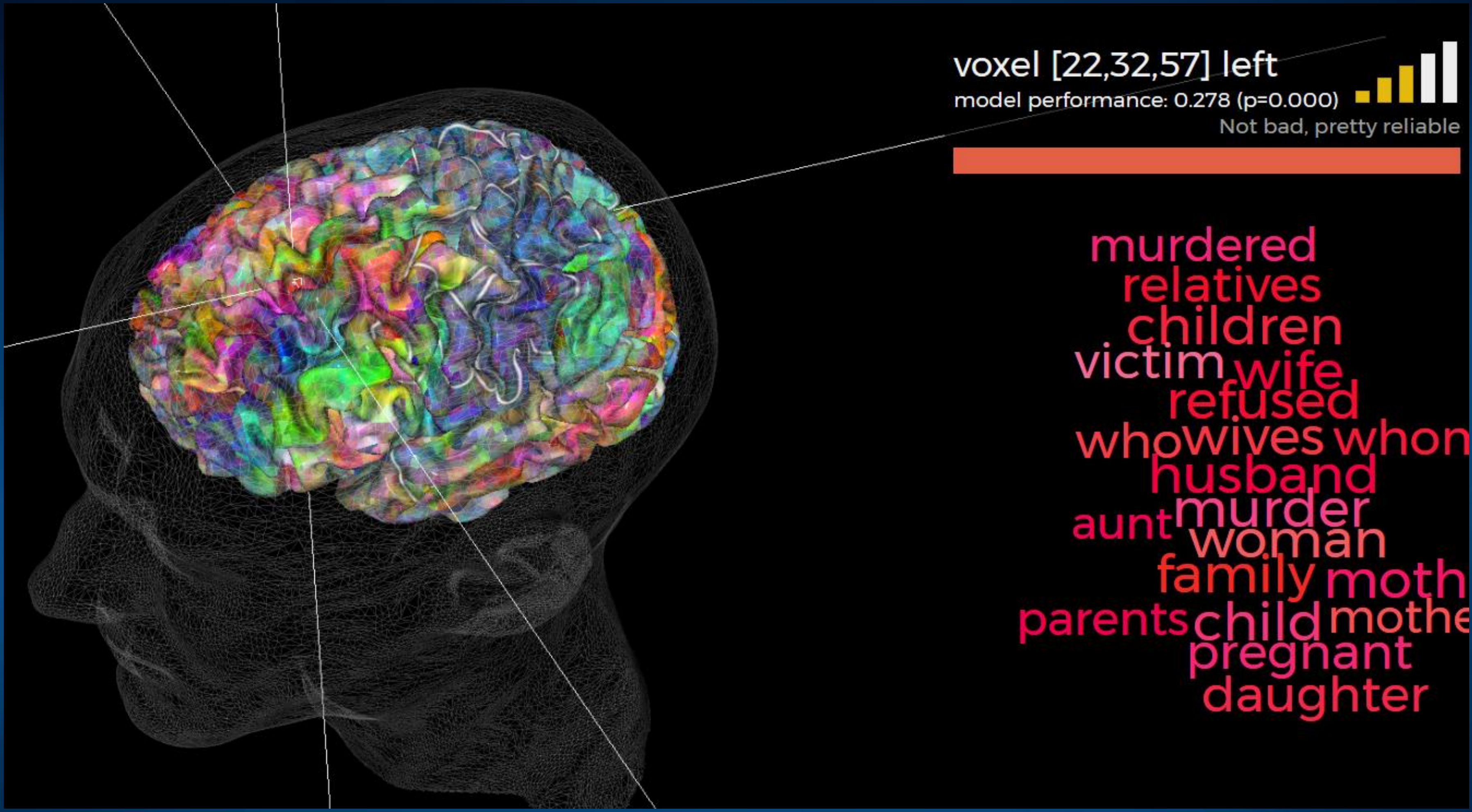


Whole fMRI activity map for the word "murder" shown on the flattened cortex.

Each word activates a whole map of activity in the brain, depending on sensory features, motor actions and affective components associated with this word. 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?



Each voxel responds usually to many related words, whole categories.
http://gallantlab.org/huth2016/
Huth et al. (2016). Decoding the Semantic Content of Natural Movies from Human Brain Activity. Frontiers in Systems Neuroscience 10, pp. 81

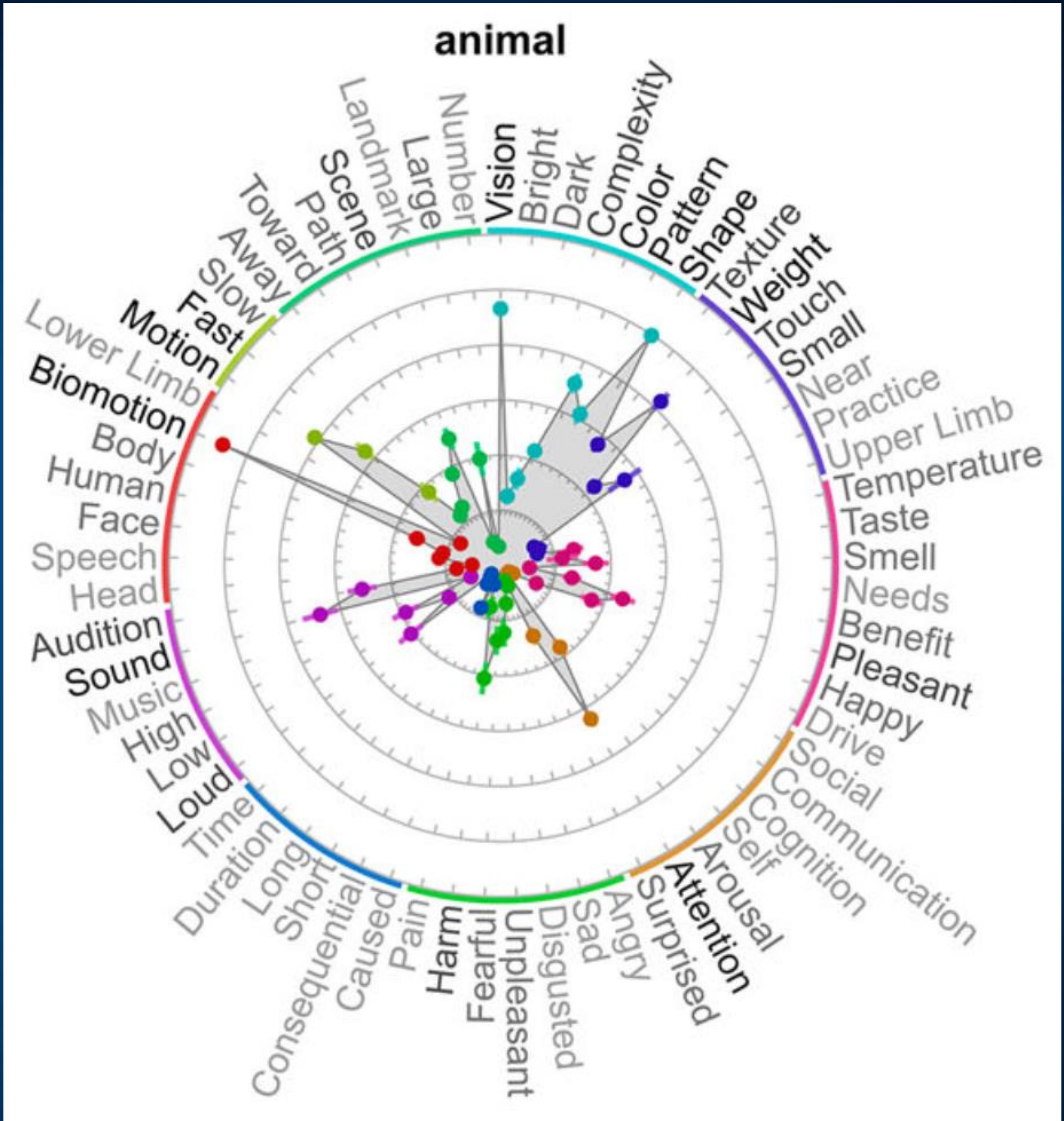
65 attributes related to neural processes;

Colors on circle: general domains.

J.R. Binder et al

Toward a Brain-Based Componential Semantic Representation, 2016

More than just visual objects!



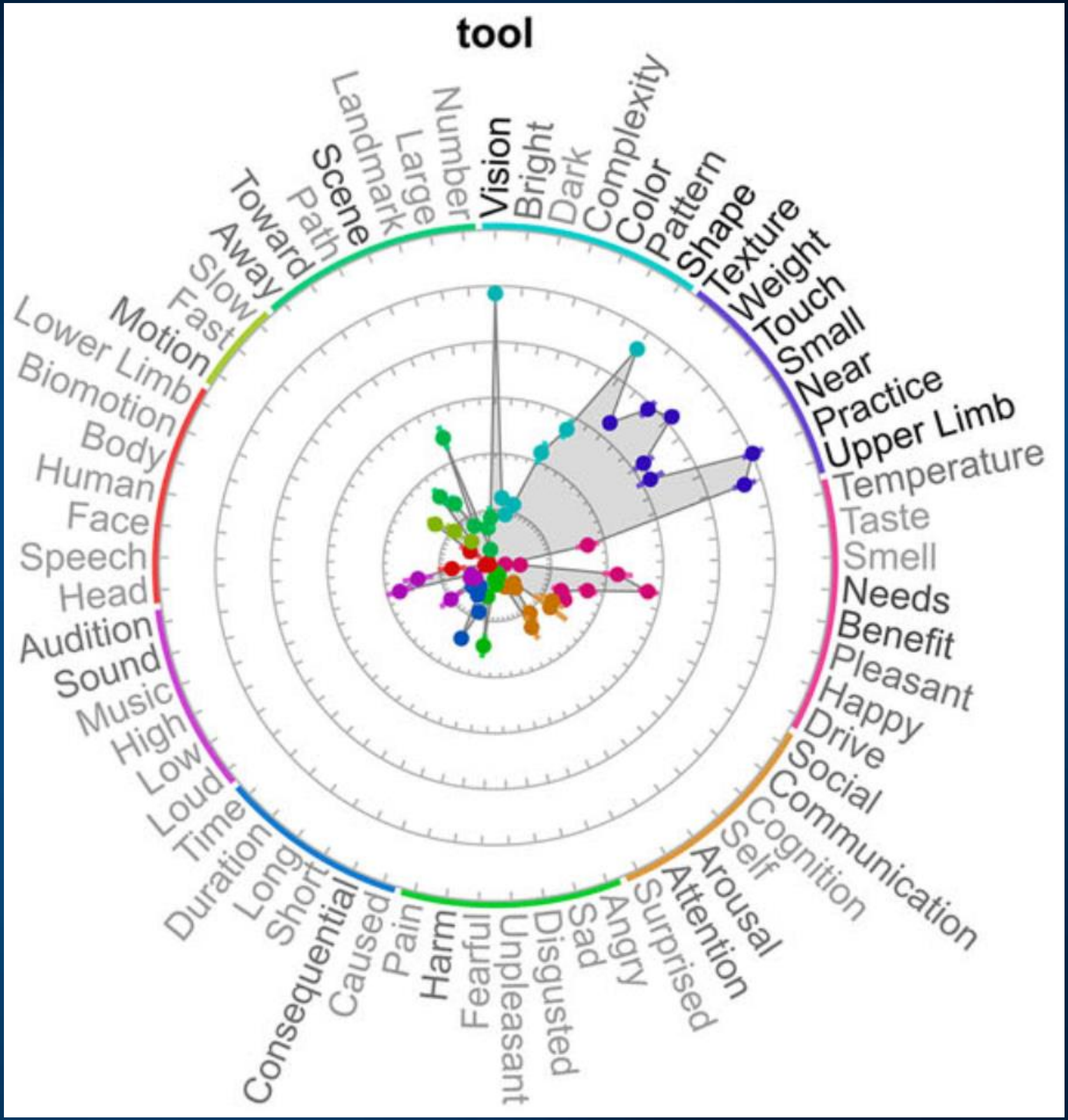
65 attributes related to neural processes.

Brain-Based Representation of tools.

J.R. Binder et al

Toward a Brain-Based Componential Semantic Representation

Cognitive Neuropsychology 2016



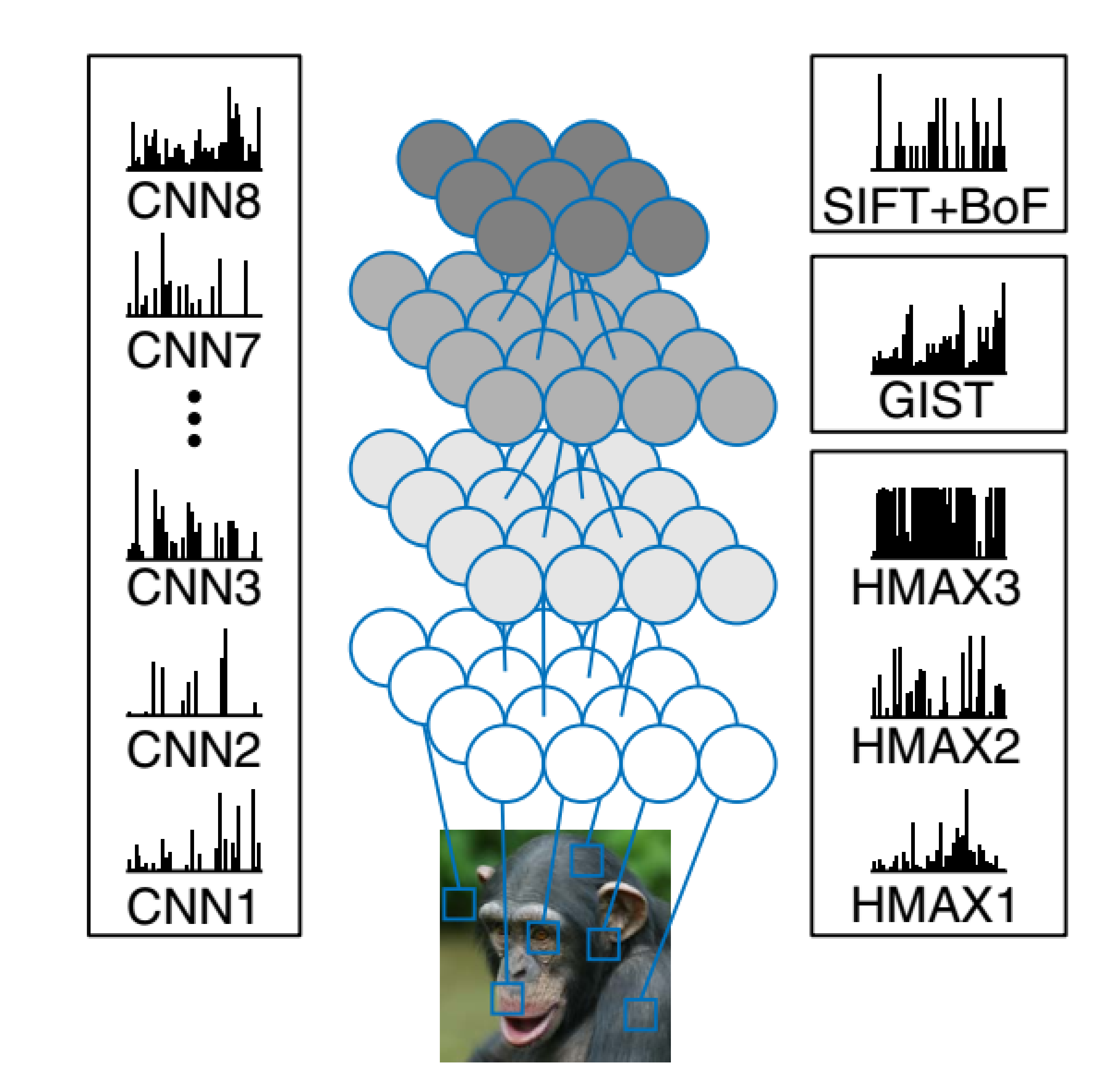
Mental images from brain activity

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

Try to estimate features at different layers.

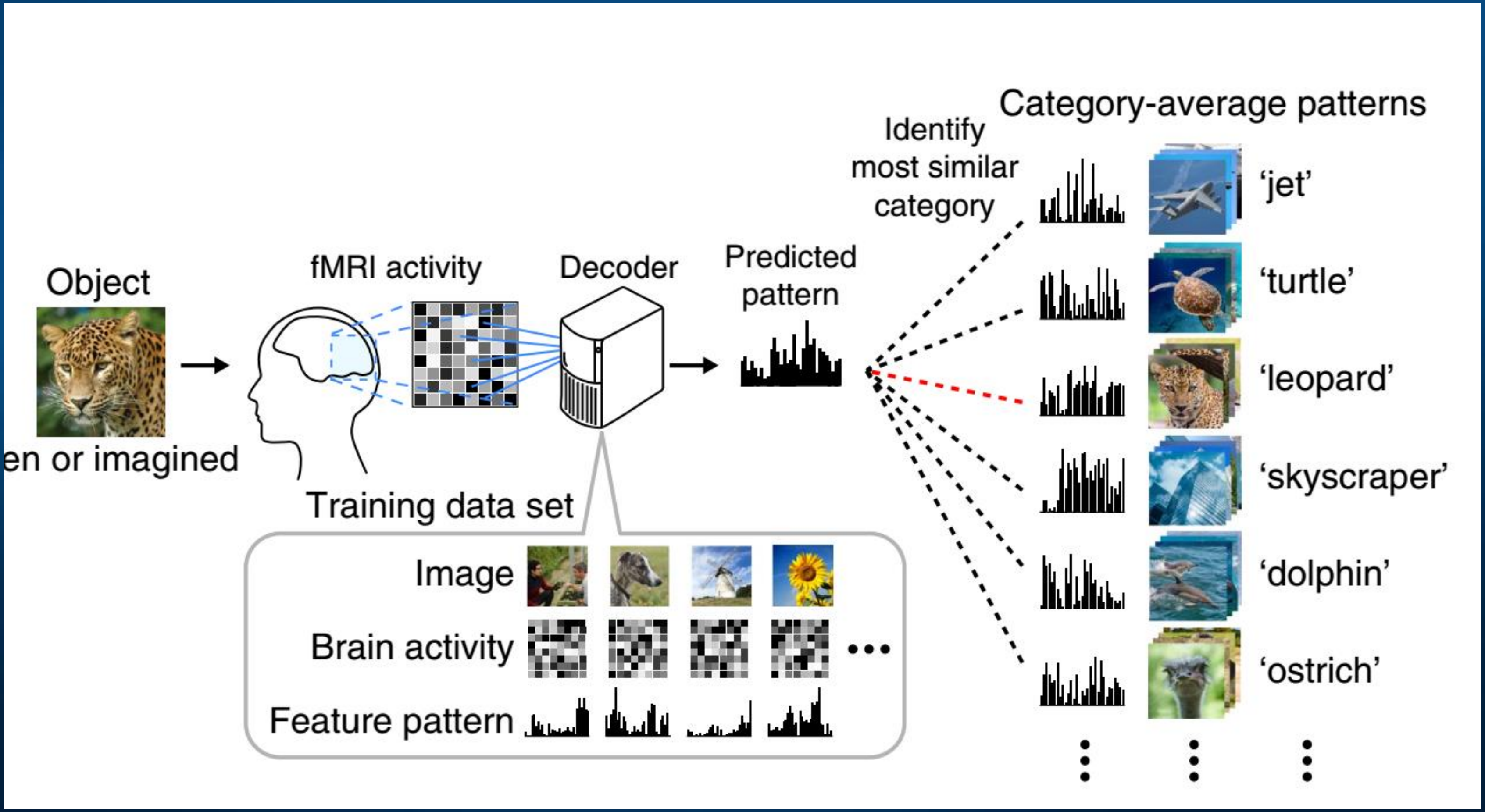
8-layer convolution network, ~60 mln parameters, feature vectors from randomly selected 1000 units in each layer to simplify calculations.

Output: 1000 images.



Brain activity ⇔ 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.



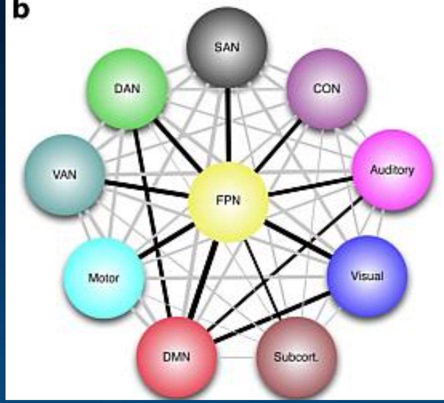
Decoding Dreams

Decoding Dreams, ATR Kyoto, Kamitani Lab. fMRI images analysed during REM phase or while falling asleep allows for dream categorization (~20 categories).

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

Dynamic functional brain networks

Questions



Global Neuronal Workspace Theory (Deahene 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.

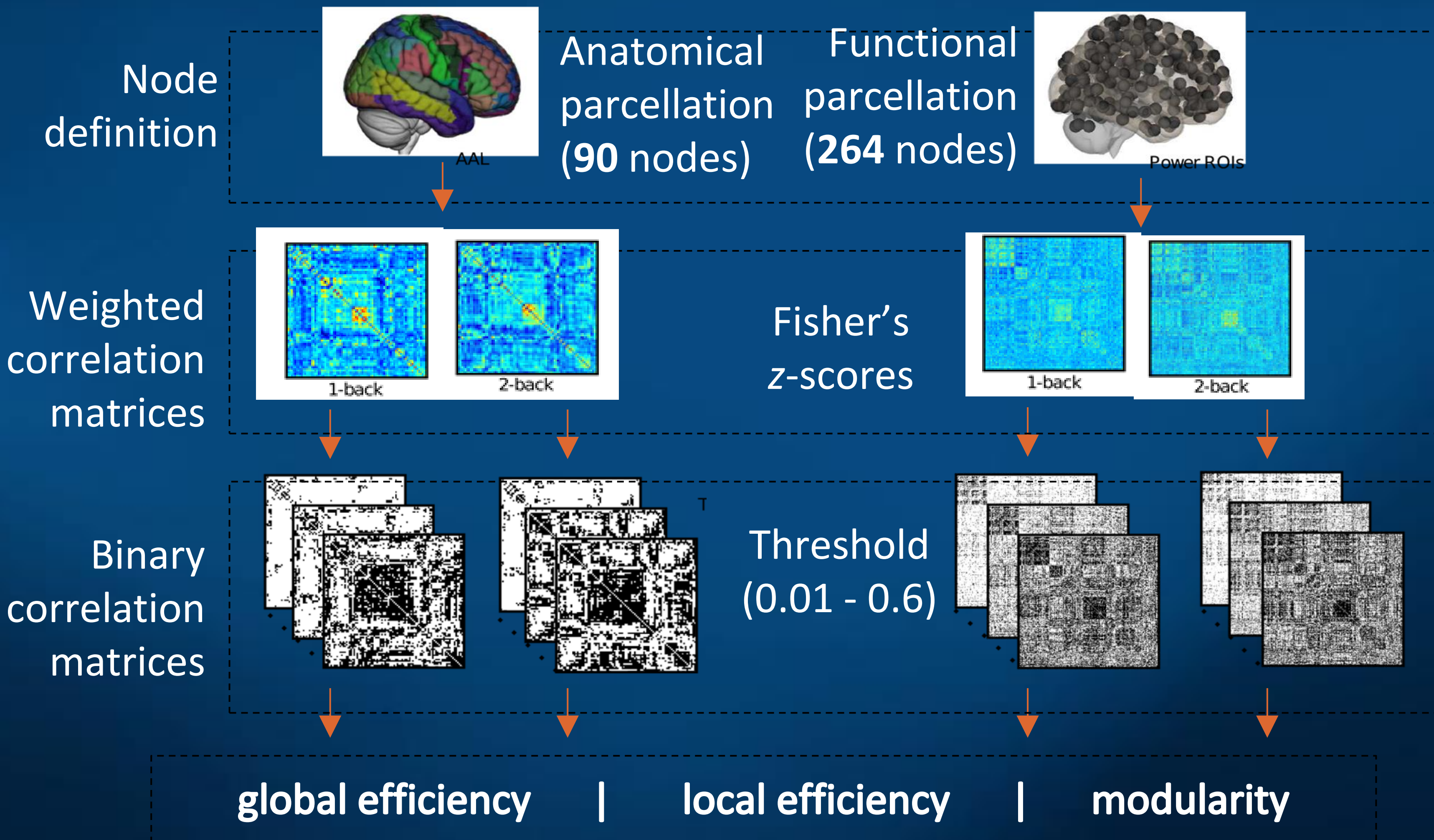
Workspace neurons are mobilized in effortful tasks for which the specialized processors (Kahneman's System 1) do not suffice (System 2), mobilize or suppress contribution of specific processor neurons.

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

Finc, K., Bonna, K., Lewandowska, M., Wolak, T., Nikadon, J., Dreszer, J., Duch W, Kühn, S. (2017). Transition of the functional brain network related to increasing cognitive demands. Human Brain Mapping, 38(7), 3659–3674.

Data workflow

Two experimental conditions: 1-back, 2-back



Brain modules and cognitive processes

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

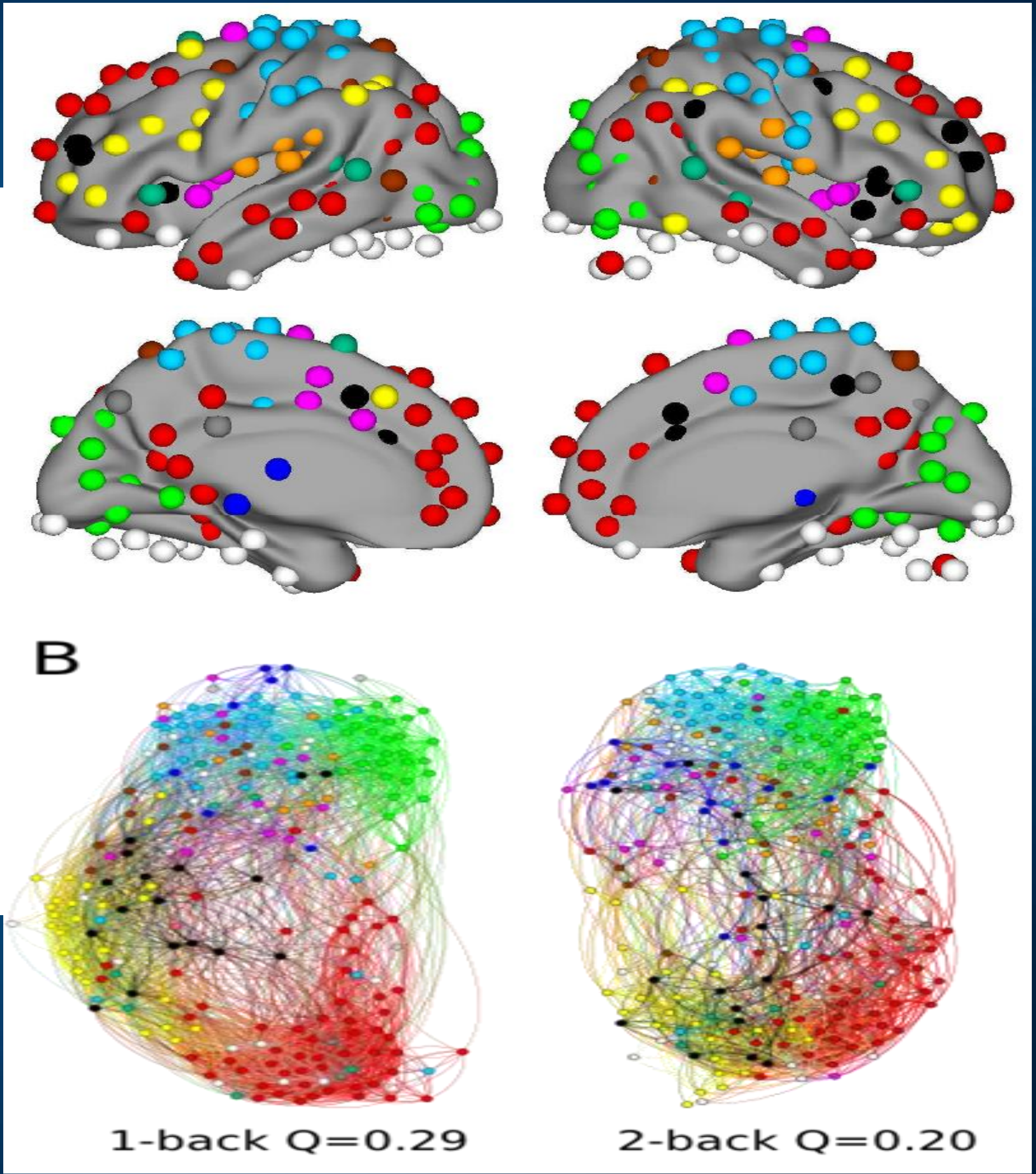
Left: 1-back

Right: 2-back

Average over 35 participants.

Left and midline sections.

- Fronto-Parietal (FP)
- Memory (MEM)
- Somato-Motor (SOM)
- Default Mode (DM)
- Ventral Attention (VA)
- Salience (SA)
- Cingulo-Opercular (CO)
- Auditory (AU)
- Subcortical (SUB)
- Dorsal Attention (DA)
- Visual (VIS)
- Other



K. Finc et al, HBM (2017).

Brain modules and cognitive processes

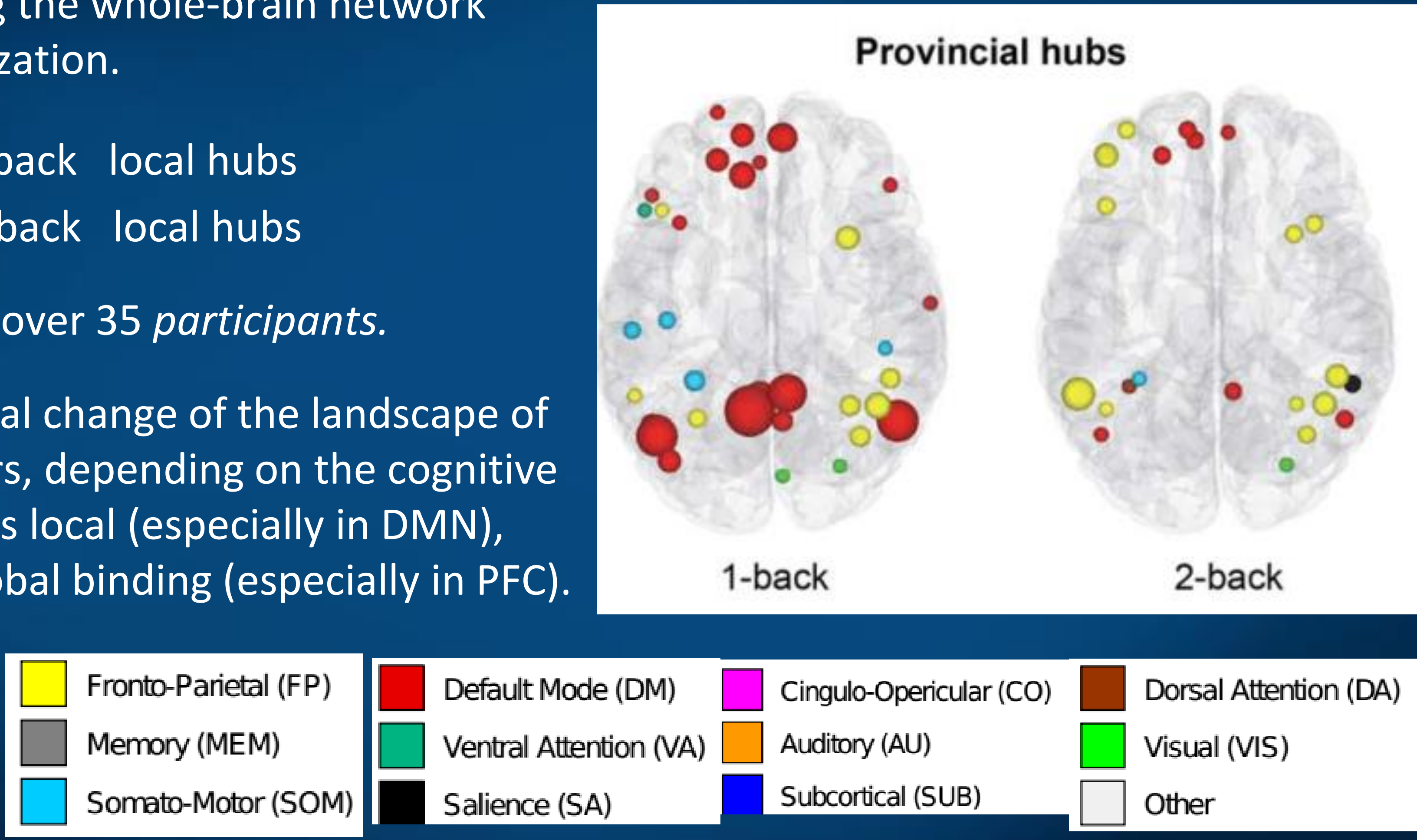
Simple and more difficult tasks, requiring the whole-brain network reorganization.

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

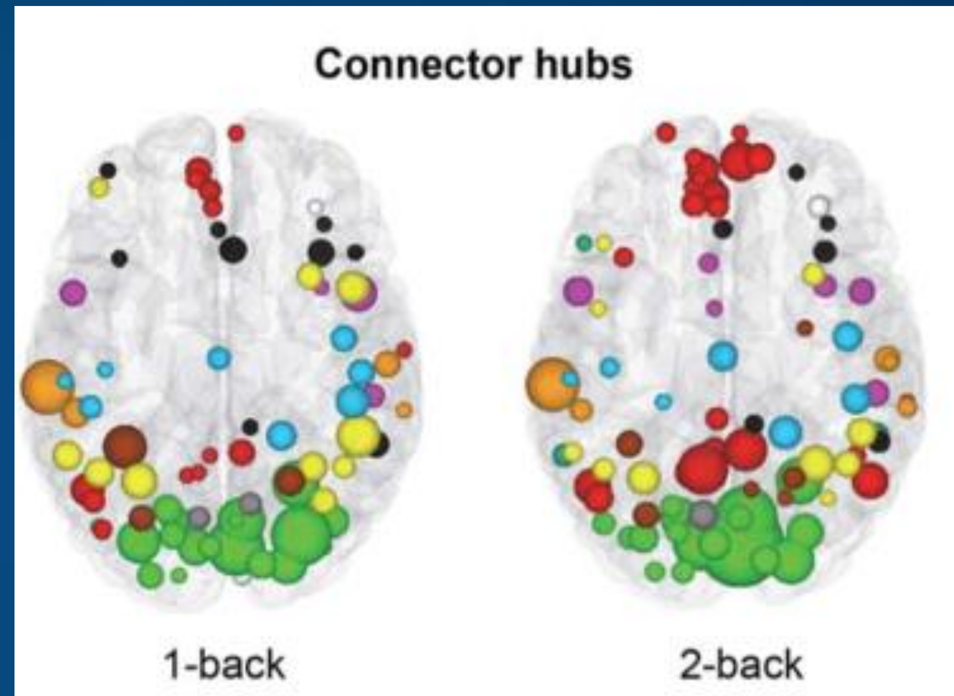
Simple and more difficult tasks, requiring the whole-brain network reorganization.

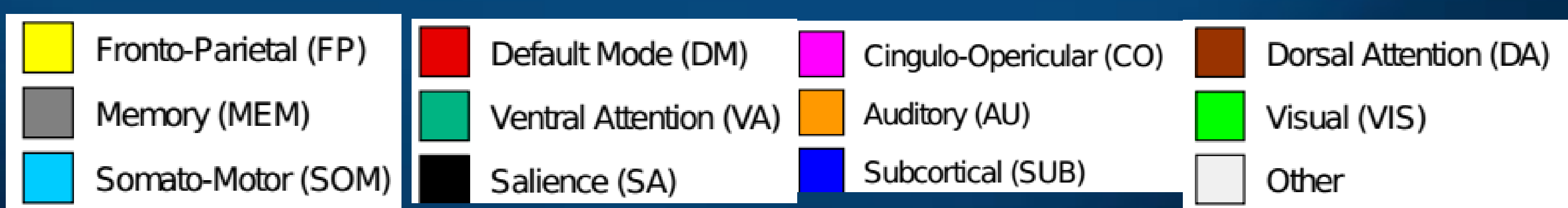
Left: 1-back connector hubs

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!





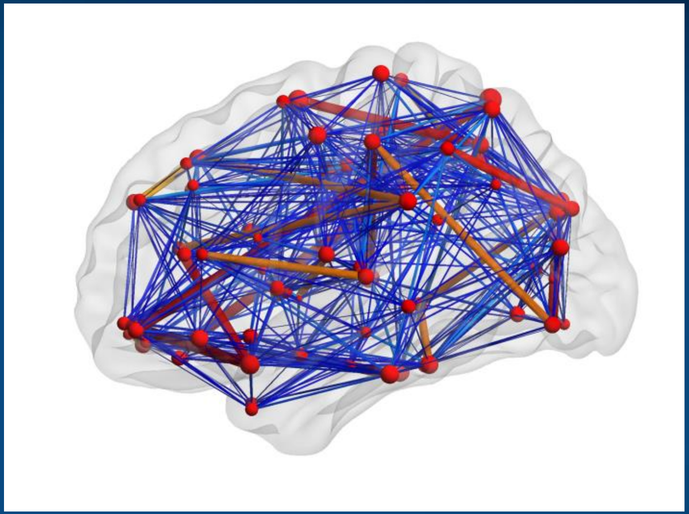
K. Finc et al, HBM (2017).

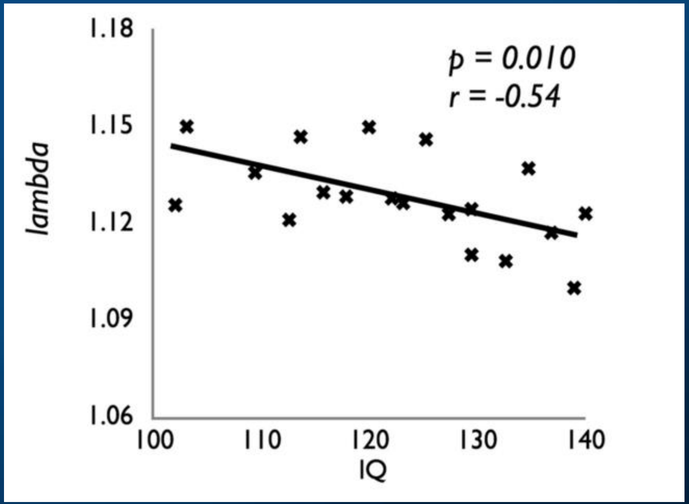
Resting state/cognitive performance

Characteristic path length λ → Intellectual performance

Modularity → Working memory performance

Modularity → Working memory capacity





Network modularity ⇔ 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.

van den Heuvel *et al.* (2009) | Stevens *et al*. (2012)

Human Enhancement
and
Optimization of Brain Processes

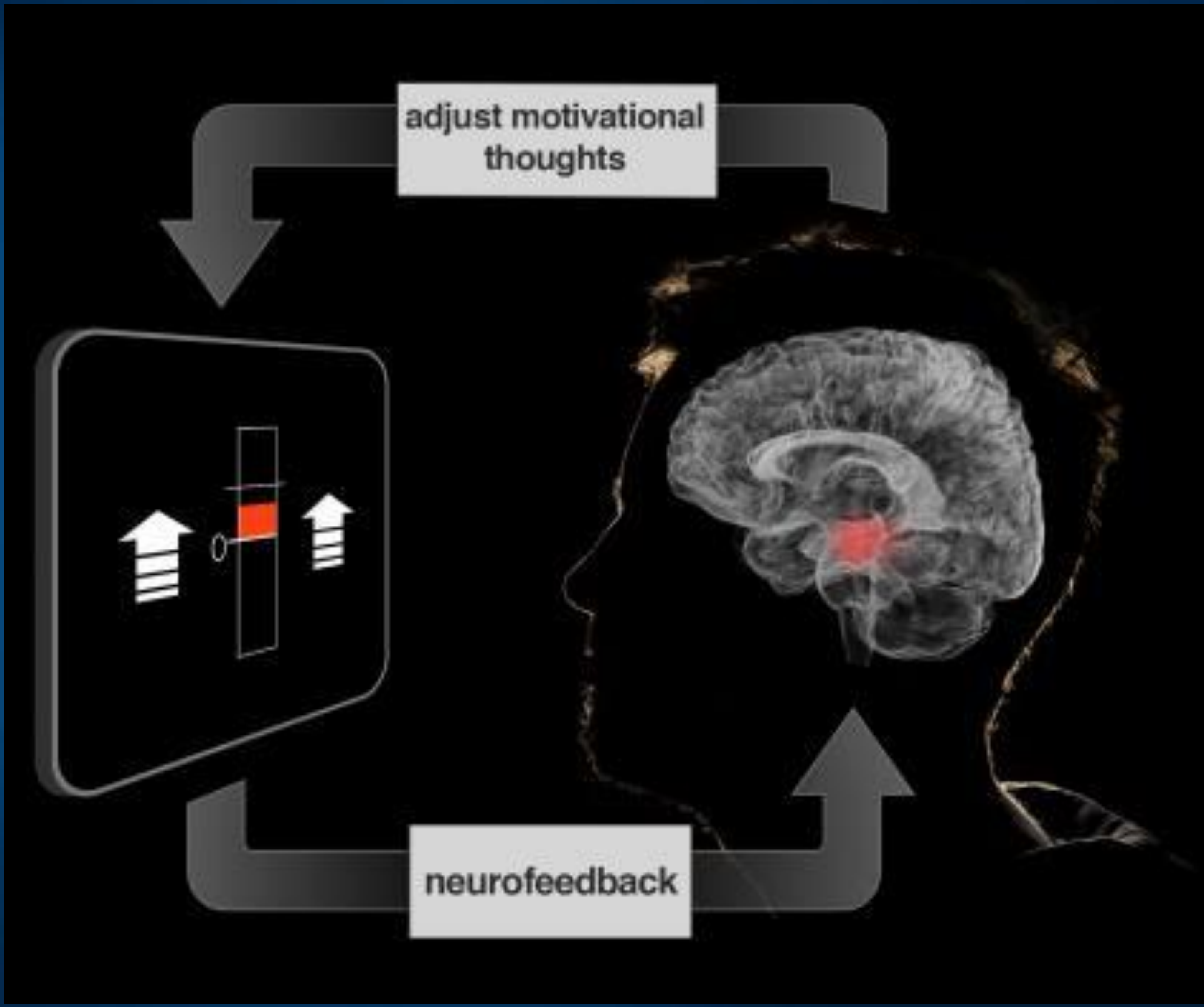
Neurofeedback: first BCI

Used in clinical practice, α/θ rhythms for relaxation.

Duch, Elektronika i stresy, 1978!

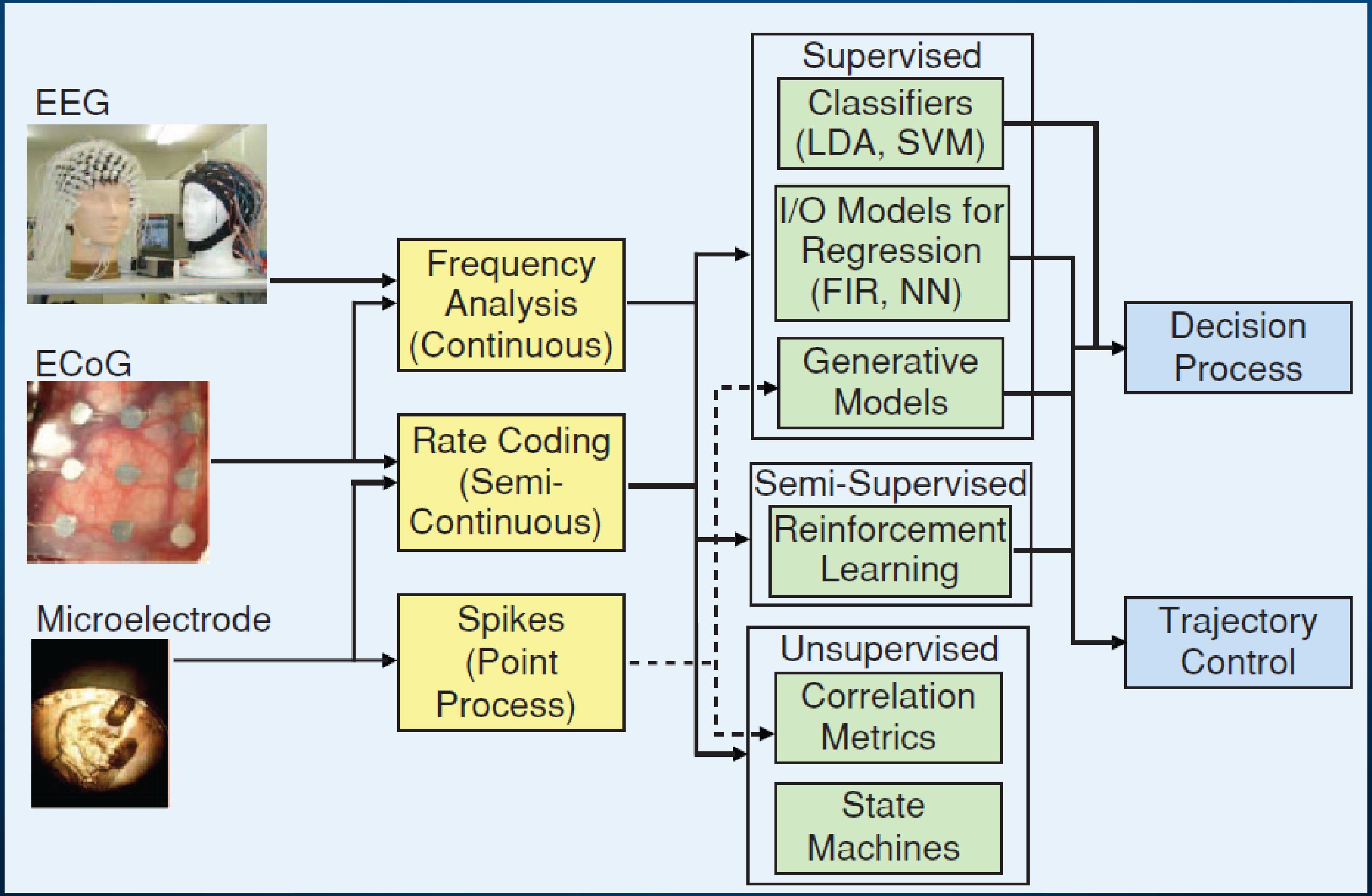
Critical review of existing literature shows that this is not effective.

New forms based on brain fingerprinting needed.

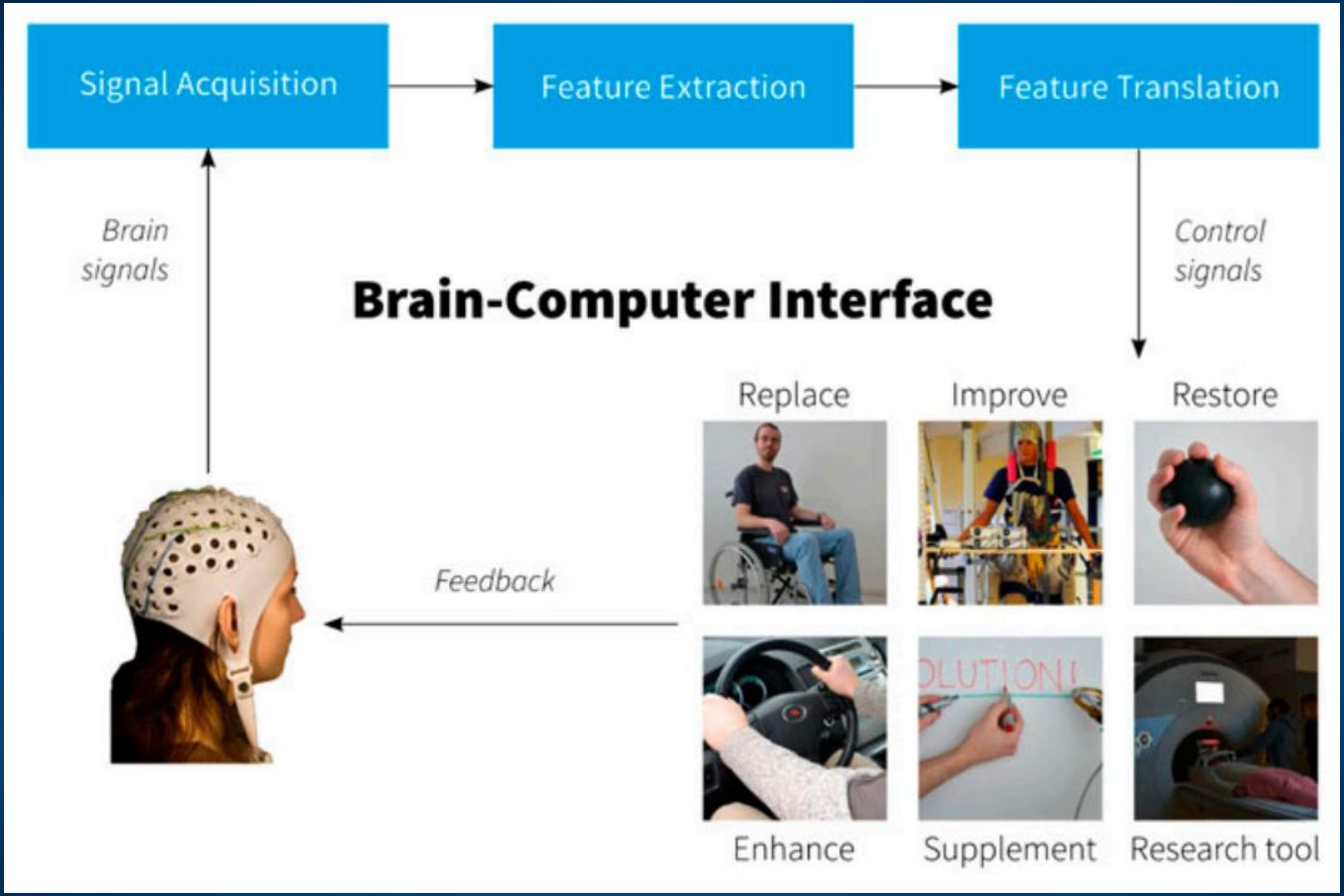


BCI: wire your brain …

Non-invasive, partially invasive and invasive signals carry progressively more information, but are also harder to implement. EEG is still the king!

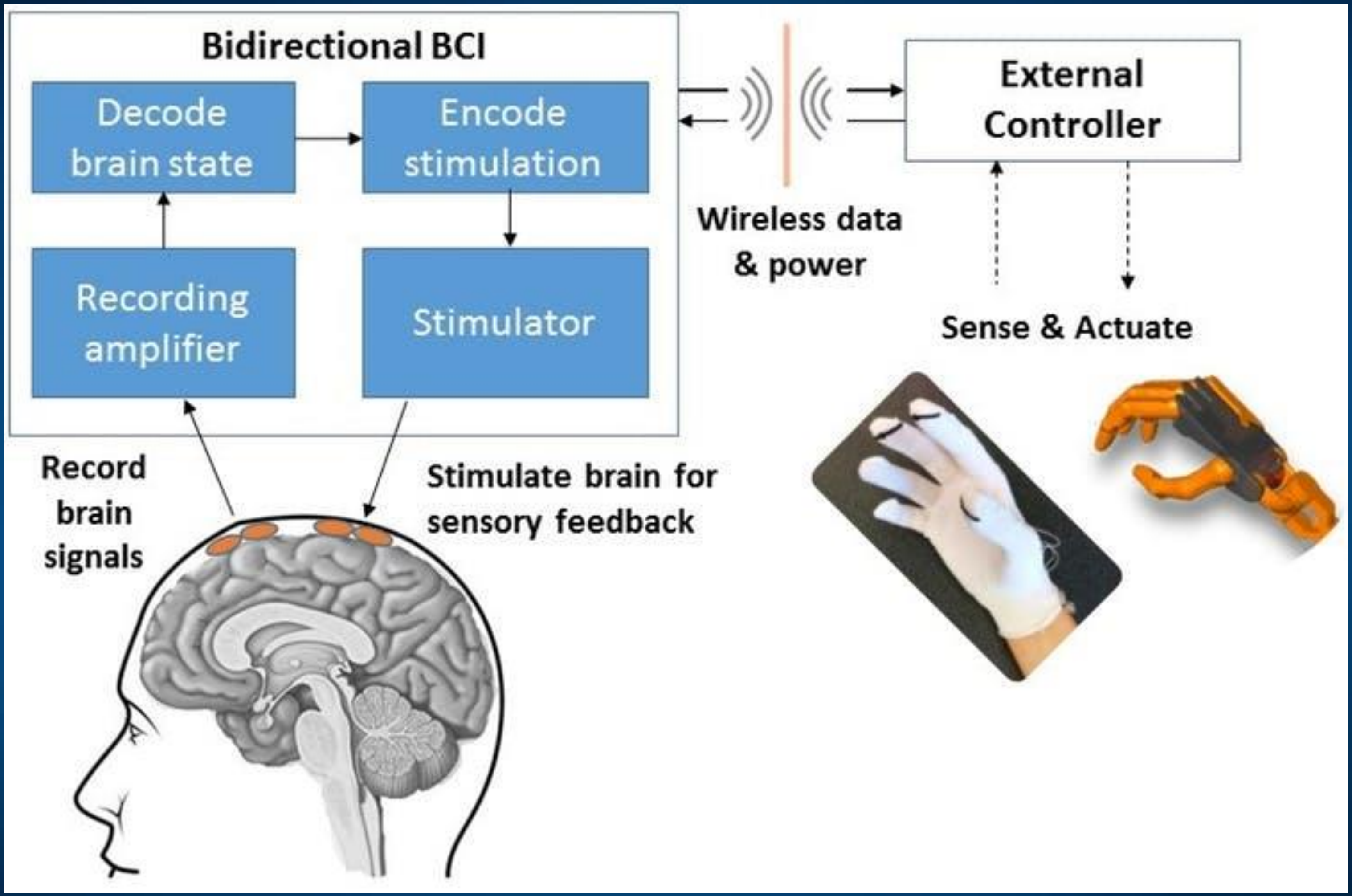


BCI Applications



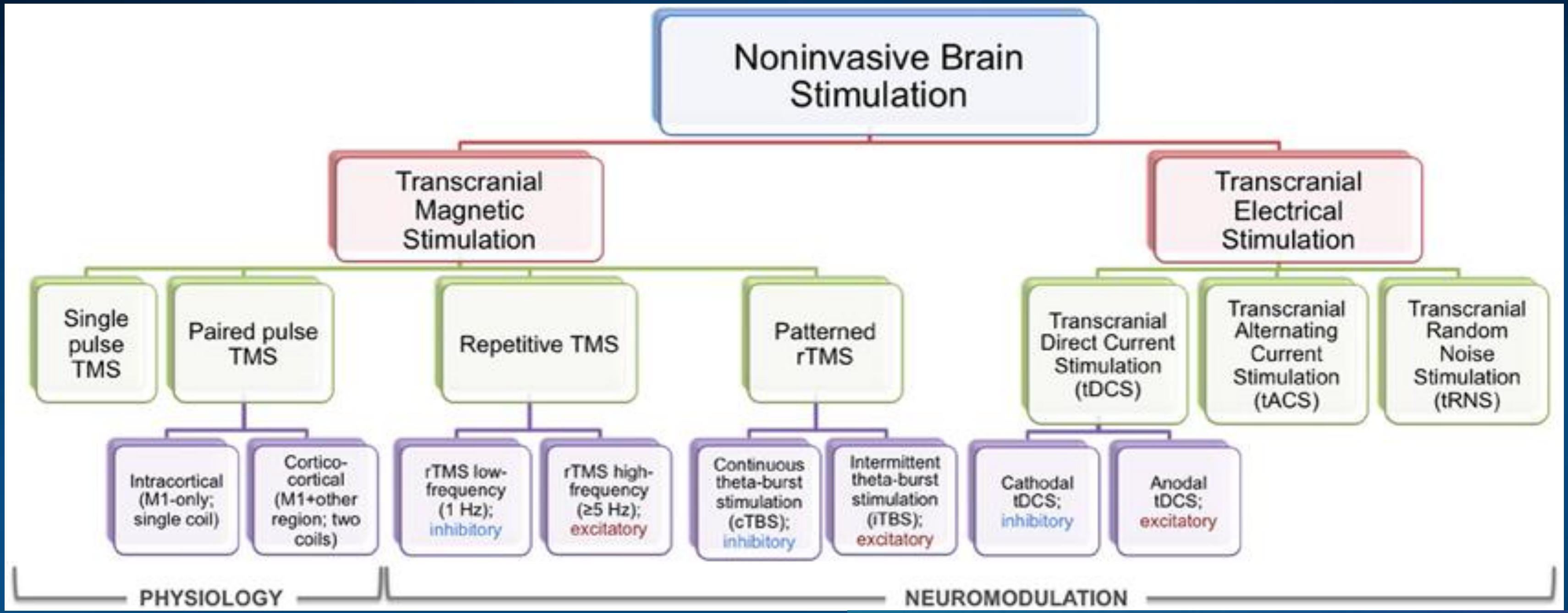
Signals: invasive (brain implants), partially invasive (ECoG), and non-invasive.

Brain-Computer-Brain Interfaces



Closed loop system with brain stimulation for self-regulation.
Body may be replaced by sensory signals in Virtual Reality.

Brain stimulation



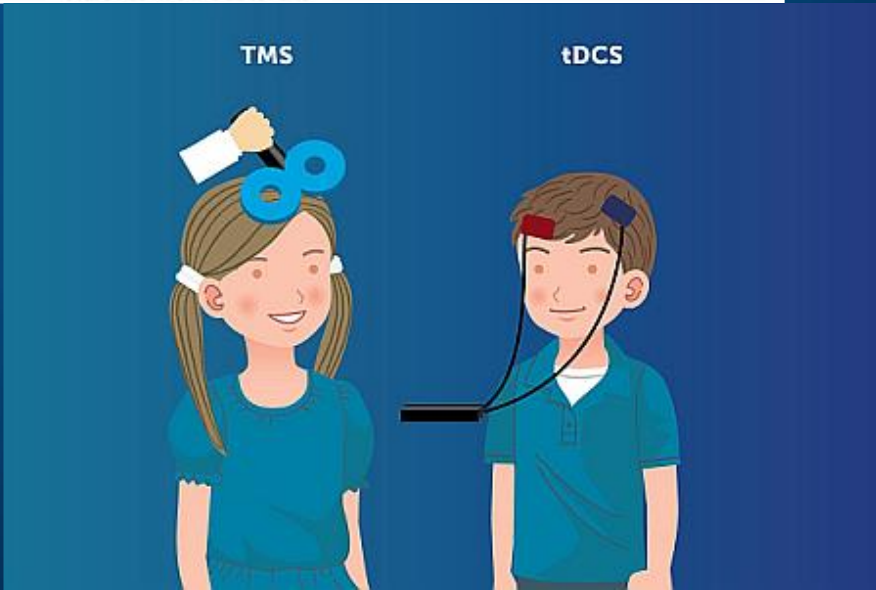
ECT – Electroconvulsive Therapy

VNS – Vagus Nerve Stimulation

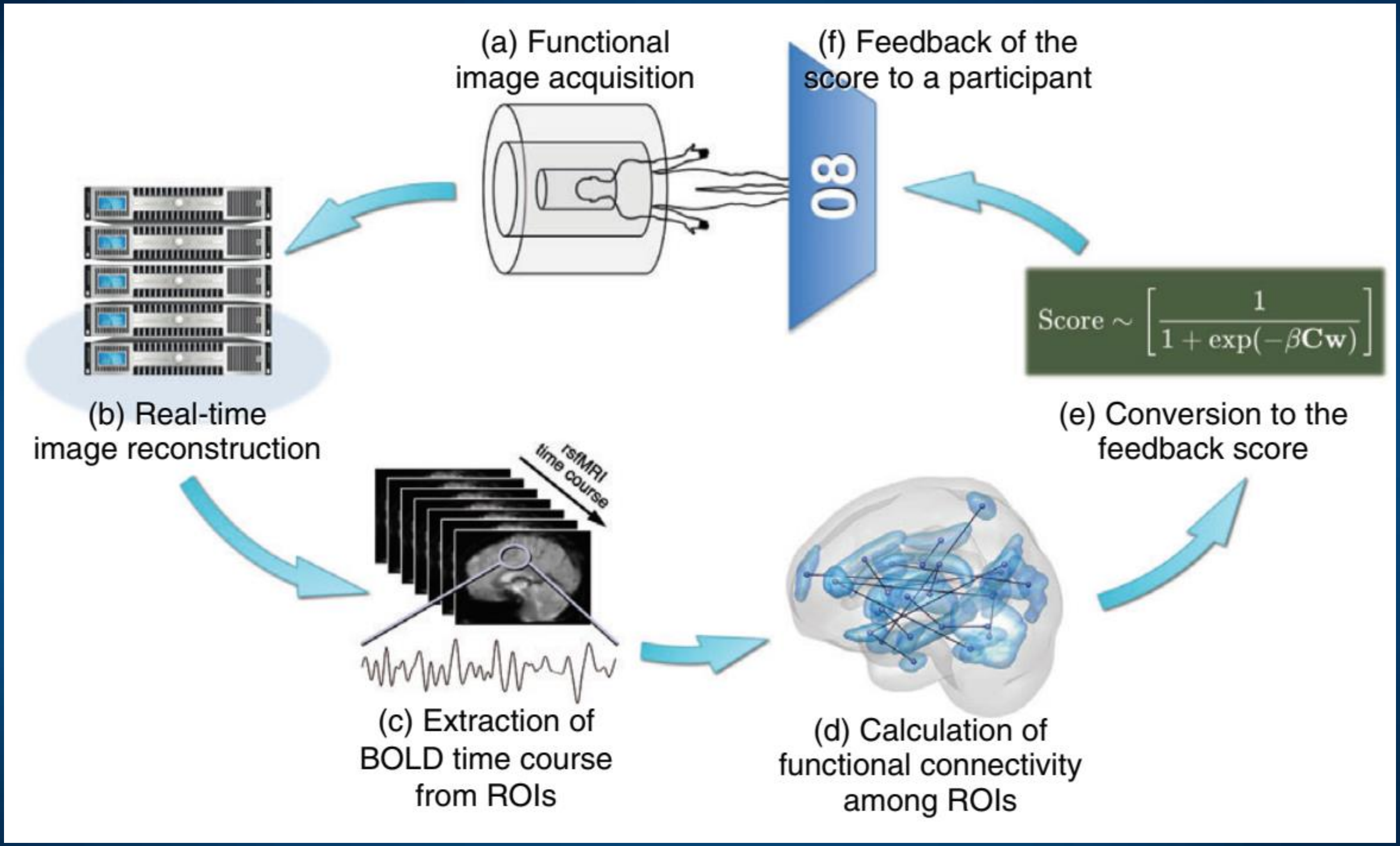
Ultrasound, laser … stimulation.

Complex techniques, but portable phones are also complex.

Attention? Just activate your cortex, no effort is needed!

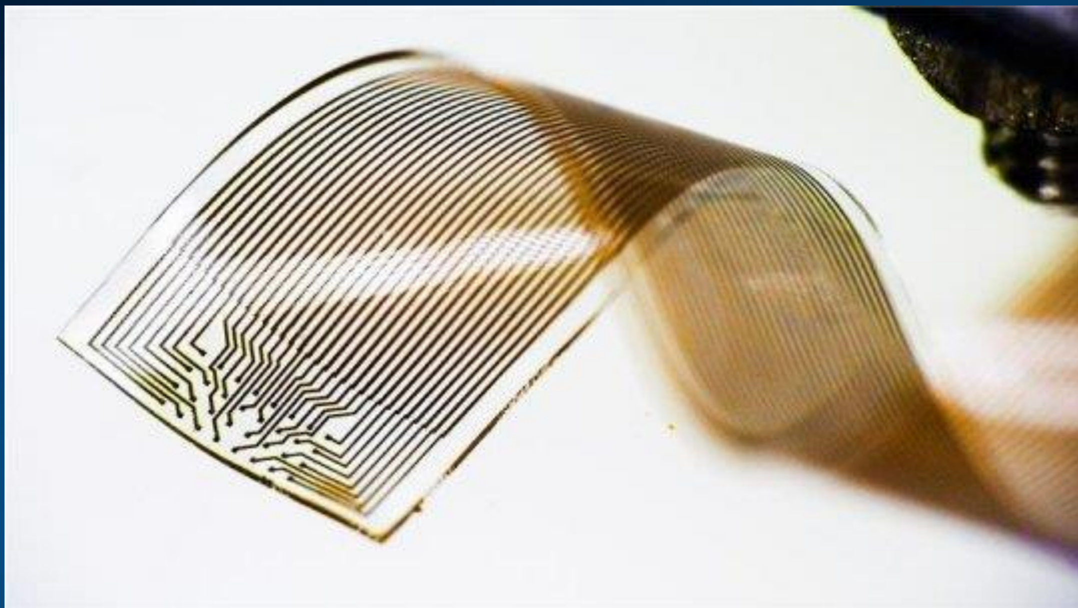


Neurofeedback may repair network?



Megumi F, Yamashita A, Kawato M, Imamizu H. Functional MRI neurofeedback training on connectivity between two regions induces long-lasting changes in intrinsic functional network. *Front. Hum. Neurosci.* 2015; **9**: 160.

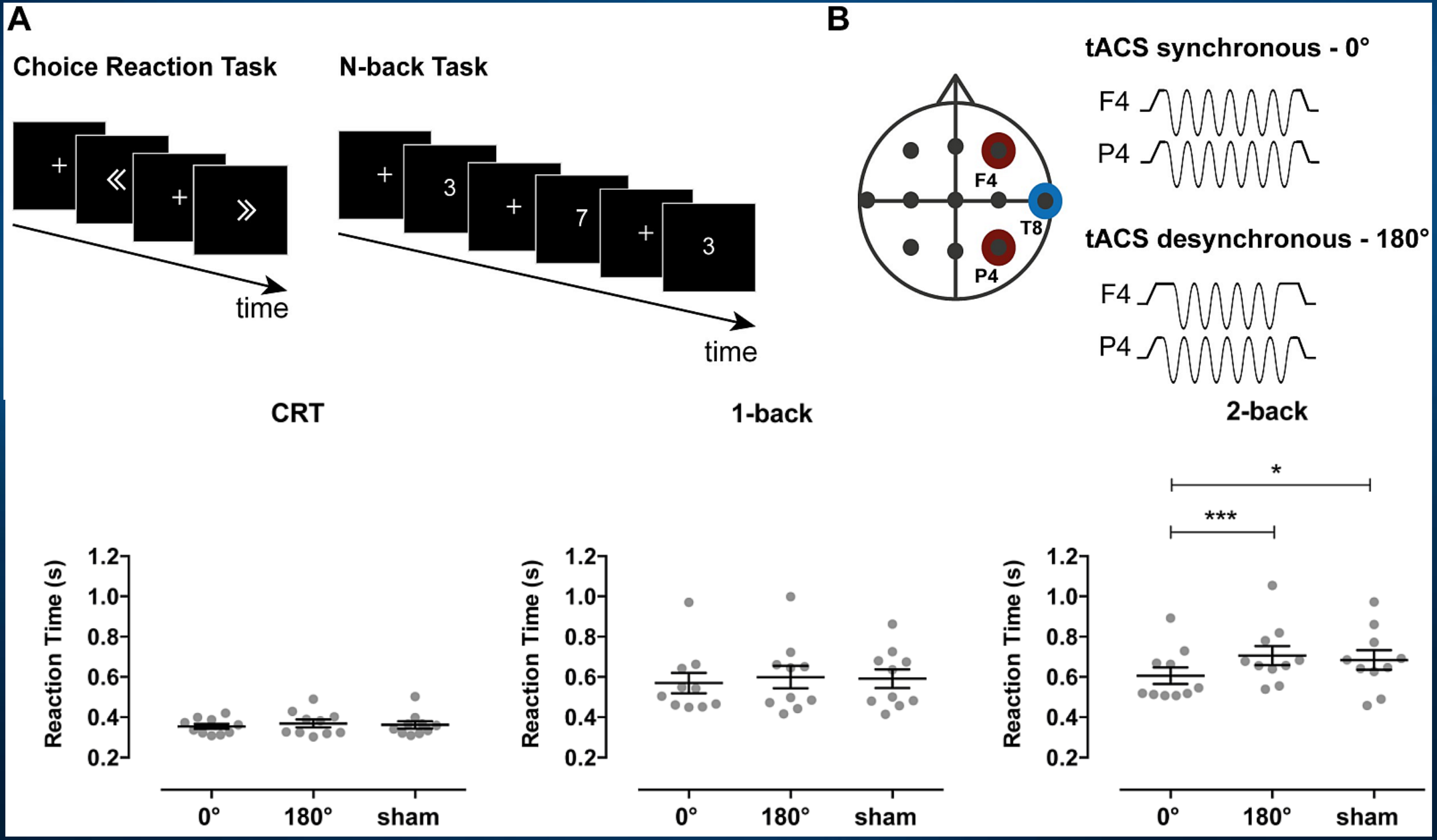
Partially invasive interfaces



Epilepsy, Obsessive-Compulsive Disorder, Phobias … if you know how to run electric currents through your brain you can control your mental states in a conscious way. New stable electrodes are coming!

Synchronize PFC/PC

Violante, I.R. et al. Externally induced frontoparietal synchronization modulates network dynamics and enhances working memory performance. ELife, 6 (2017).



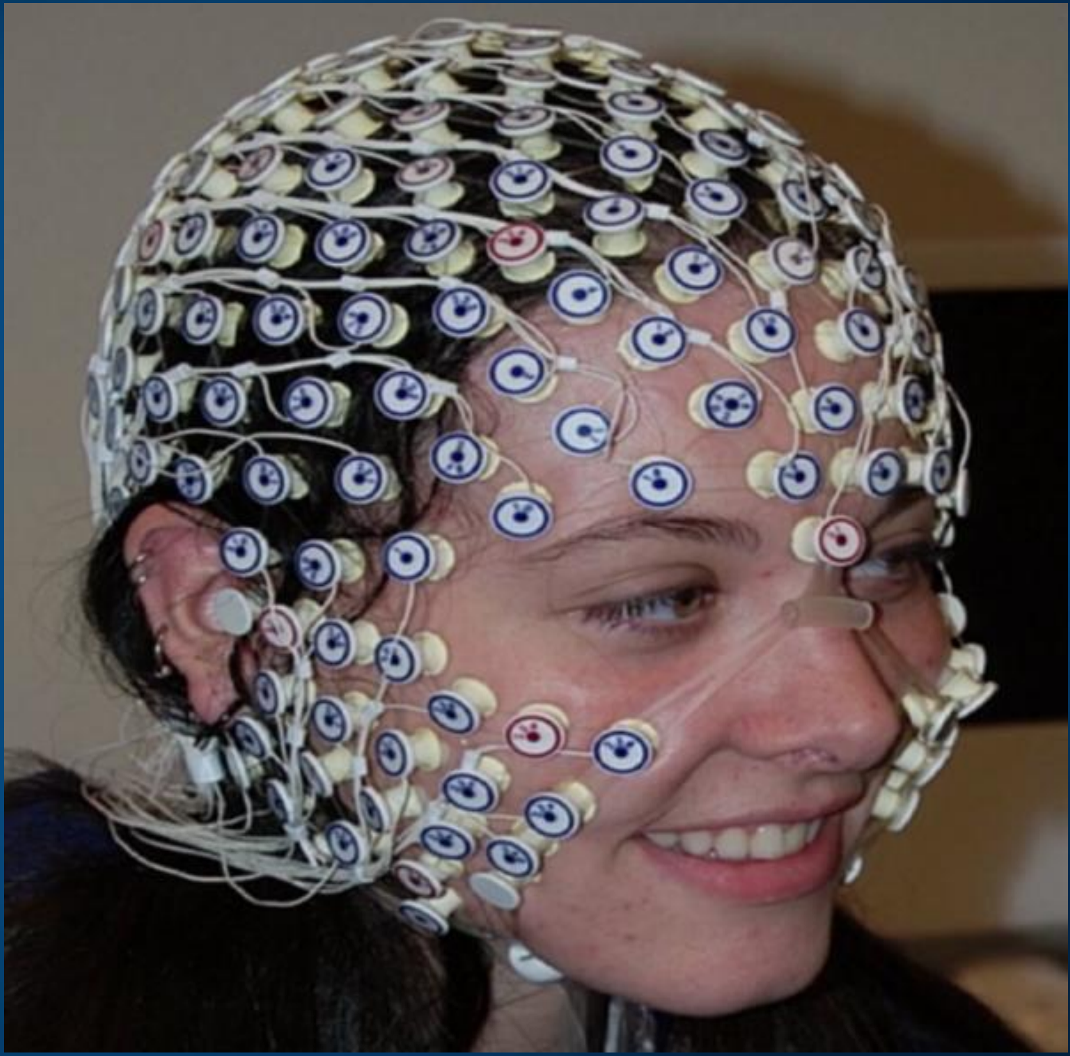
HD EEG/DCS?

EEG electrodes + DCS.

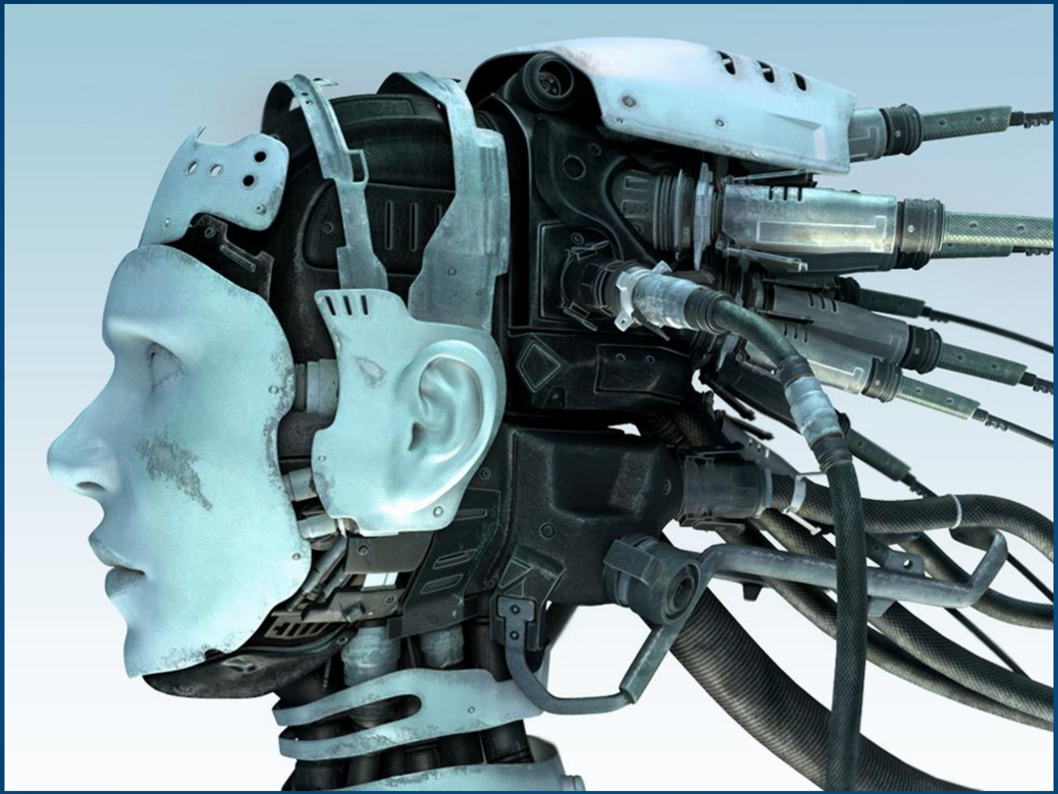
Reading brain states
=> transforming to common space
=> duplicating in other brains
Applications:

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

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

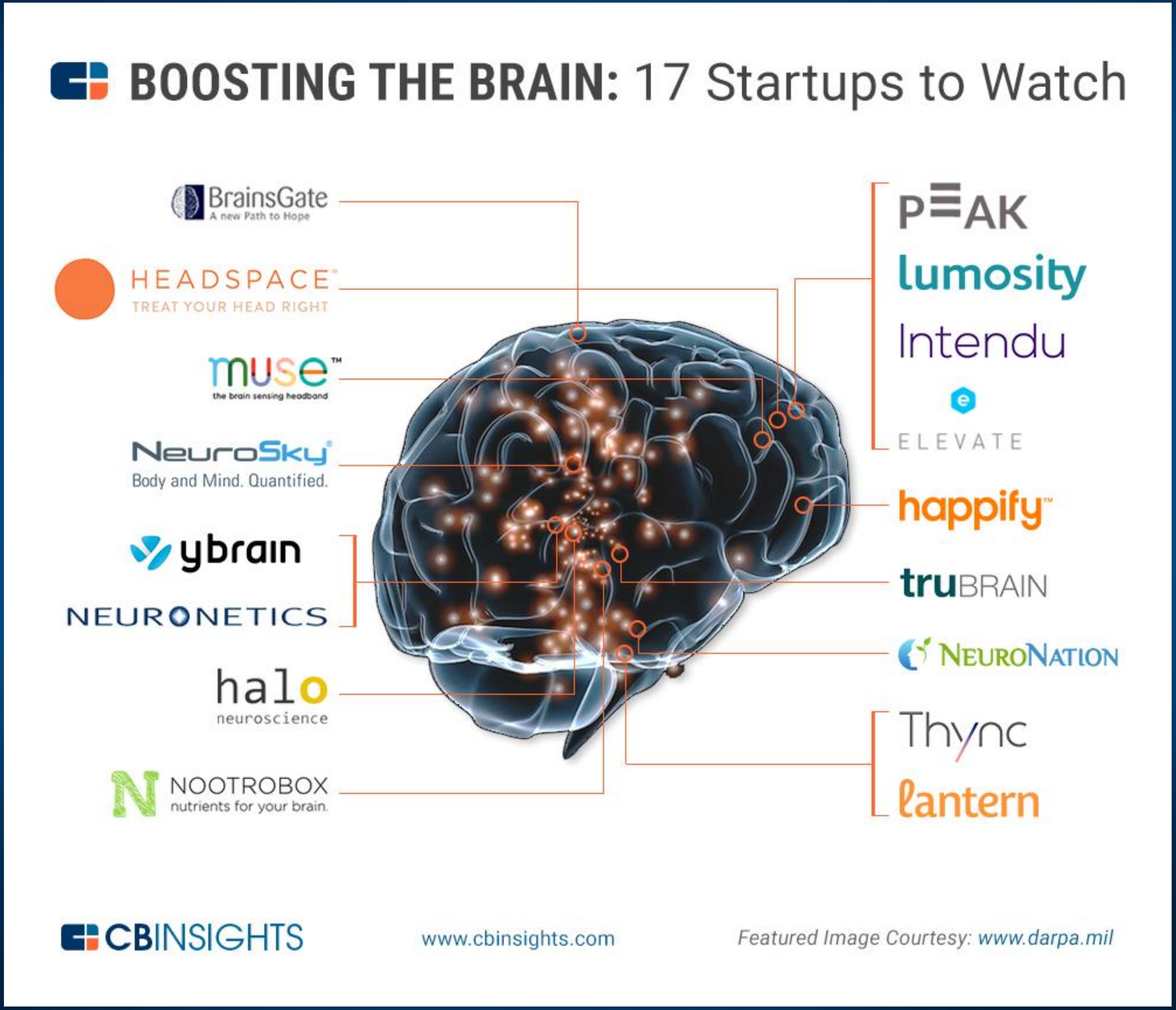


Neurocognitive technologies



There are about 100,000 cyborgs worldwide.
The human augmentation market may grow tenfold, to $2.3 billion, by 2025.
Bloomberg Businessweek 10/2018

Startups around the world

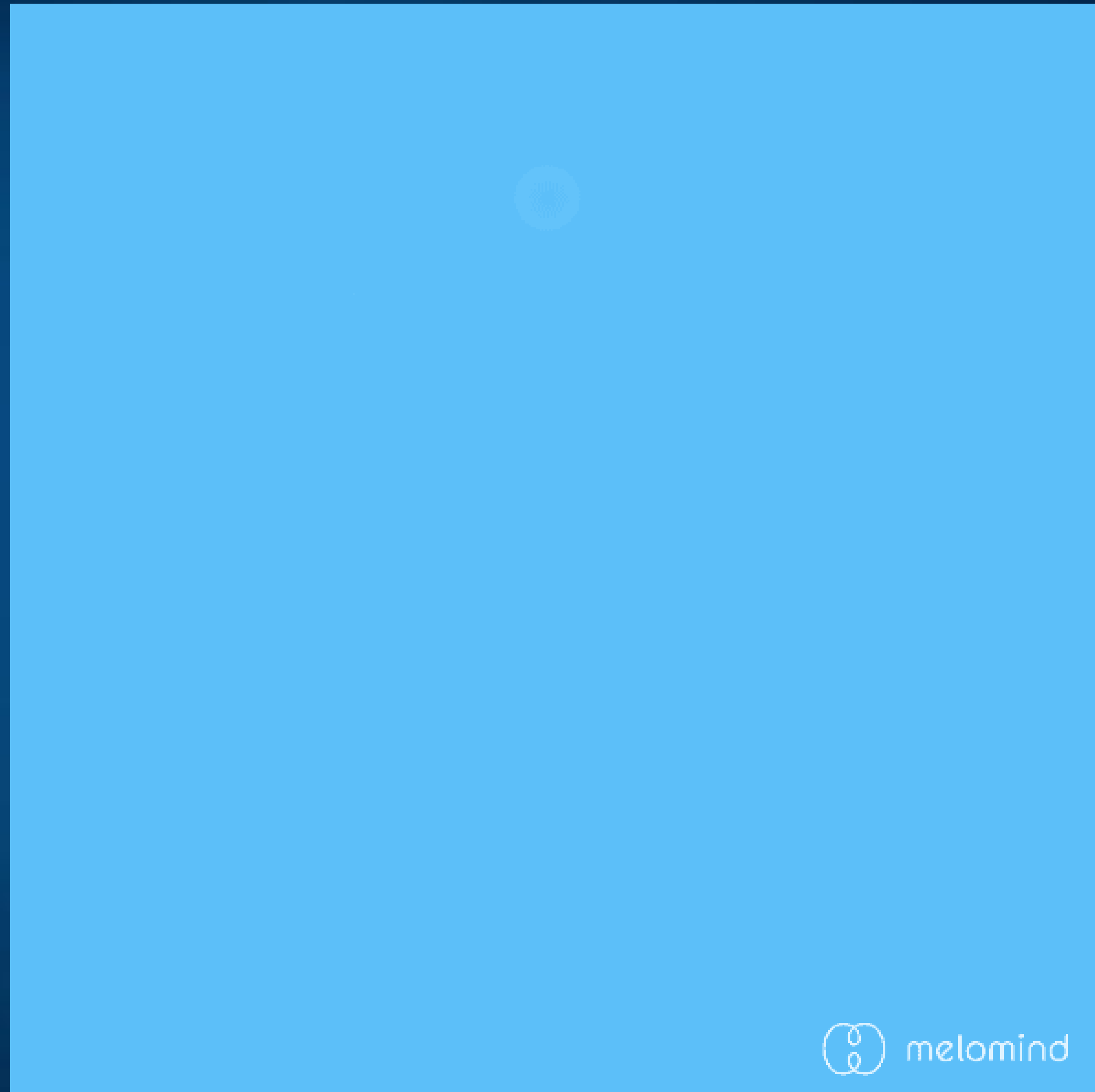


Neuro-relax

Sounds and music may have arousing or relaxing effects.

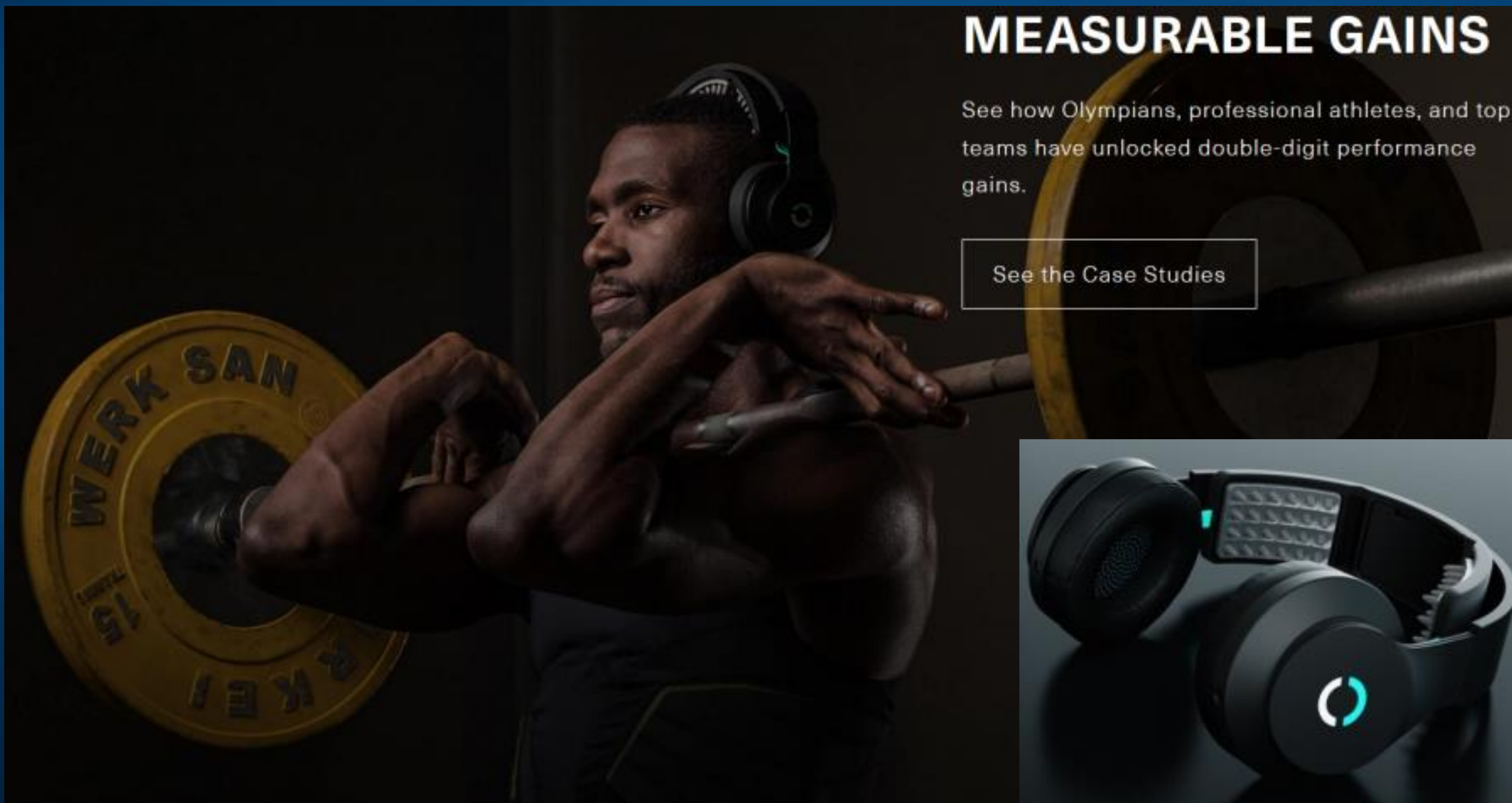
Melomind:

Simple EEG determins 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.

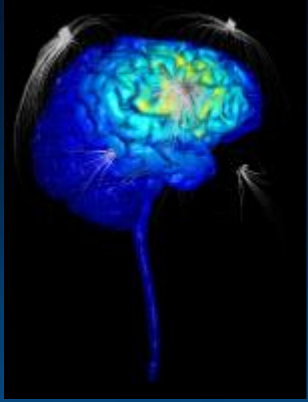


Haloneuro.com

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.

BCBI for learning



Your brain knows better what is interesting than you do!
How to make this information consciously available?

1. Externally induced frontoparietal synchronization modulates network dynamics and enhances working memory performance (Violante 2017).
2. Natural brain-information interfaces: recommending information by **relevance inferred from human brain signals** (Eugster et al. 2016).
3. **Teaching skills by stimulating cortex:** microstimulation too low to evoke muscle activation, applied in premotor cortex, instructed specific actions. Mazurek & Schieber (2017). **Injecting Instructions into Premotor Cortex**. *Neuron*, *96*(6), 1282–1289.e4.
4. Neuroimaging based assessment strategy may provide an **objective means of evaluating learning outcomes** in the application of **Universal Design for Learning** (UDL), an educational framework created to guide the development of flexible learning environments that adapt to individual learning differences.

Military applications

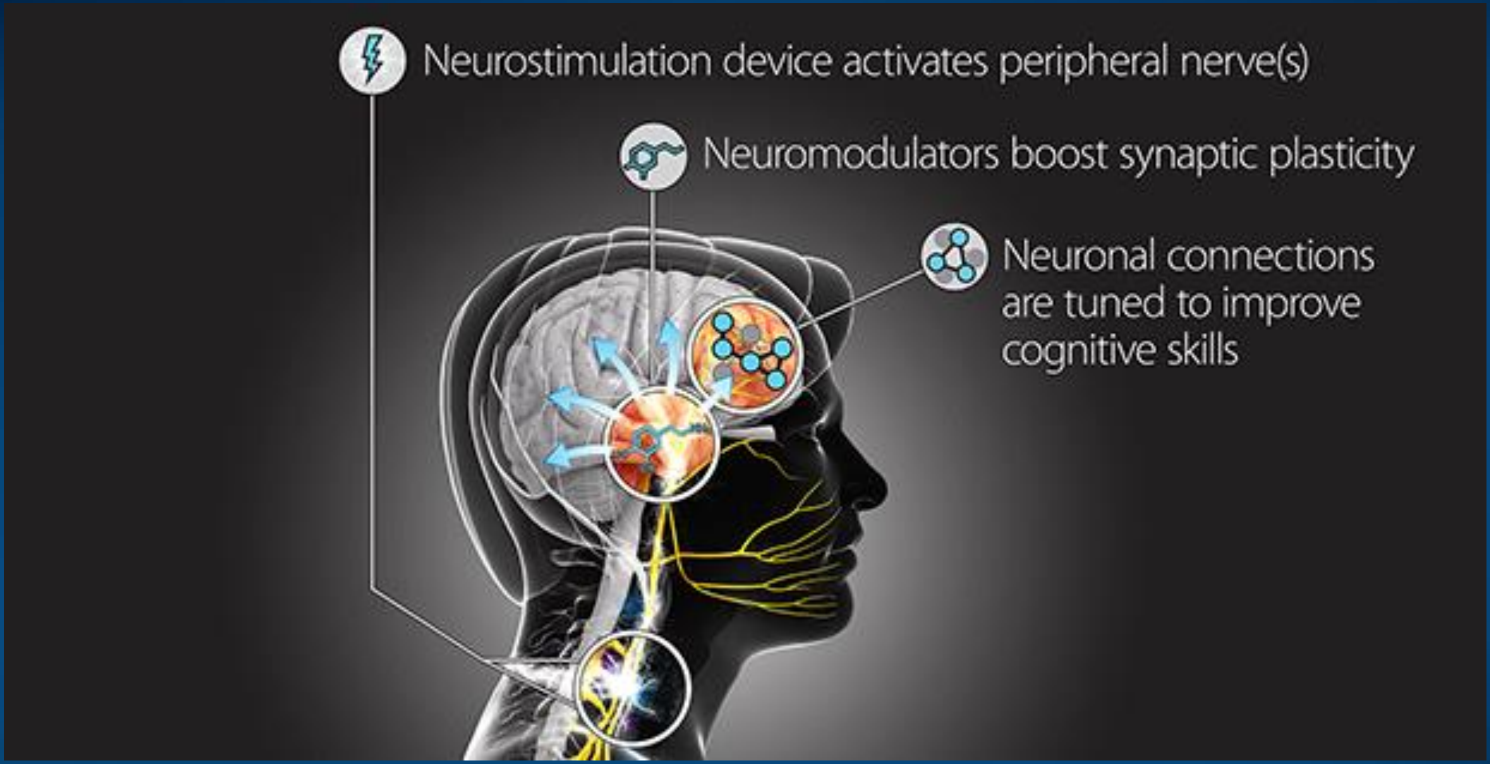
Engagement Skills Trainer (EST) procedures are used by USA army.

Intific Neuro-EST uses EEG analysis and mulit-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, neurolace and nanowires much more.

Targeted Neuroplasticity Training



DARPA (2017): Enhance learning of a wide range of cognitive skills, with a goal of reducing the cost and duration of the Defense Department's extensive training regimen, while improving outcomes. TNT could accelerate learning and reduce the time needed to train foreign language specialists, intelligence analysts, cryptographers, and others.

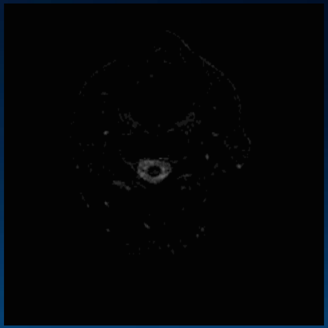
Expected benefits

- **Monitoring development** of children and infants, unfolding full developmental potential of children!
- Enabling early ASD diagnosis and other **developmental problems**.
- Precise **diagnosis** of various subtypes of mental disorders: organic problems, schizophrenia, epilepsy, learning disabilities, depression, anhedonia, mild cognitive impairment, Alzheimer etc,
  based on brain connectivity and functional large scale networks.
- Novel more effective forms of **neurofeedback**; for attention deficits, drug addiction, ASD, MCI and other problems.
- Nonpharmacological approaches to various forms of **pain management through neuromodulation**; distinguishing between organic, chronic, psychogenic and faking pain, and provide treatment based on neuromodulation.

More benefits

- **Closed loop neurofeedback for neurorehabilitation**: discovering deficits in information flow in the brain, targeting neuroplasticity in specific brain areas to form new functional connections.
- Improvement in **brain-computer interfaces**, new applications of BCI in information retrieval and situation awareness.
- **Disorders of consciousness** – better diagnosis and communication with patients in coma.
- **Applications in education**: testing for problems such as dyslexia or dyscalculia, lack of musical imagery, objective assessment of learning outcomes and individual learning differences.
- **Memory improvement** through neuromodulation and in future deep brain stimulation.
- Neurocognitive technologies for general optimization of brain processes, for entertainment, games.

Strategic Questions



- Neurocognitive technologies are complex. Any volunteers?
- AI and neurocognitive informatics are **mutually beneficial**, and give a chance to build **artificial general human-level intelligent systems**, but only the best AI groups understand it and use inspirations from neuroscience.
- **Roadmap**: Brain neuroimaging ⇔ models of brain processes ⇔ links with AI mental models ⇔ closed loop BCBI for conscious control/brain optimization.
- **Neuromorphic hardware** with complexity beyond the human brain is coming and we should learn how to use it in practical applications.
- **Still basic research**: methods for discovering brain fingerprints of cognitive activity, mapping between brain and mental states is our main goal.
- **Brain reading**, understanding neurodynamics and neurocognitive phenomics, are the key to self-regulation of brain functions, and therapeutic applications.
- Should we improve over our weaknesses in strategic areas, or focus on a few already developed AI research areas? **Can we afford ignorance**?
- With new global AI initiatives anything is possible!

Few Steps Towards Human-like Intelligence

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

IEEE SSCI 2018 Symposium on Computational Intelligence for Human-like Intelligence, Honolulu, HAWAII, USA, 27.11 –1.12.2017.
18-21.11.2018, Bengalur, India

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

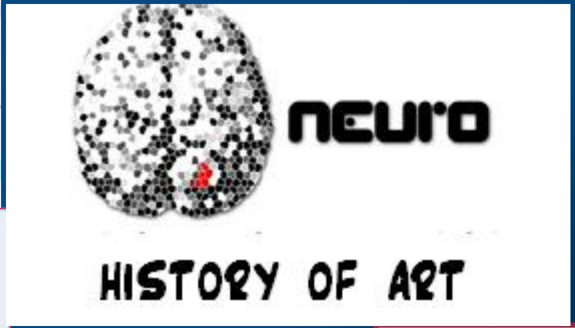
Brain-Mind Institute Schools, International Conference on Brain-Mind (ICBM) and Brain-Mind Magazine (Juyang Weng, Michigan SU).

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

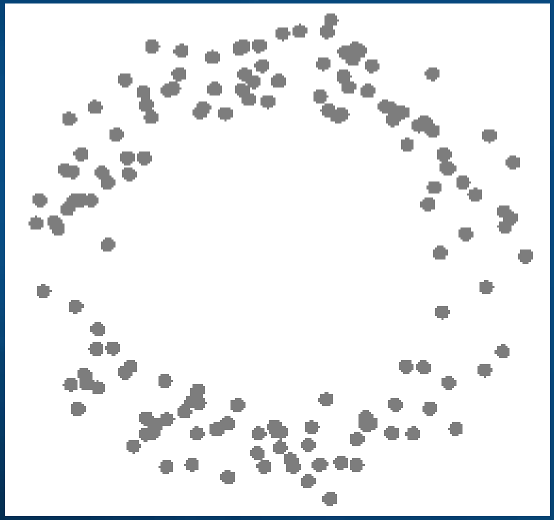
Monthly international developmental seminars (2017): Infants, learning, and cognitive development

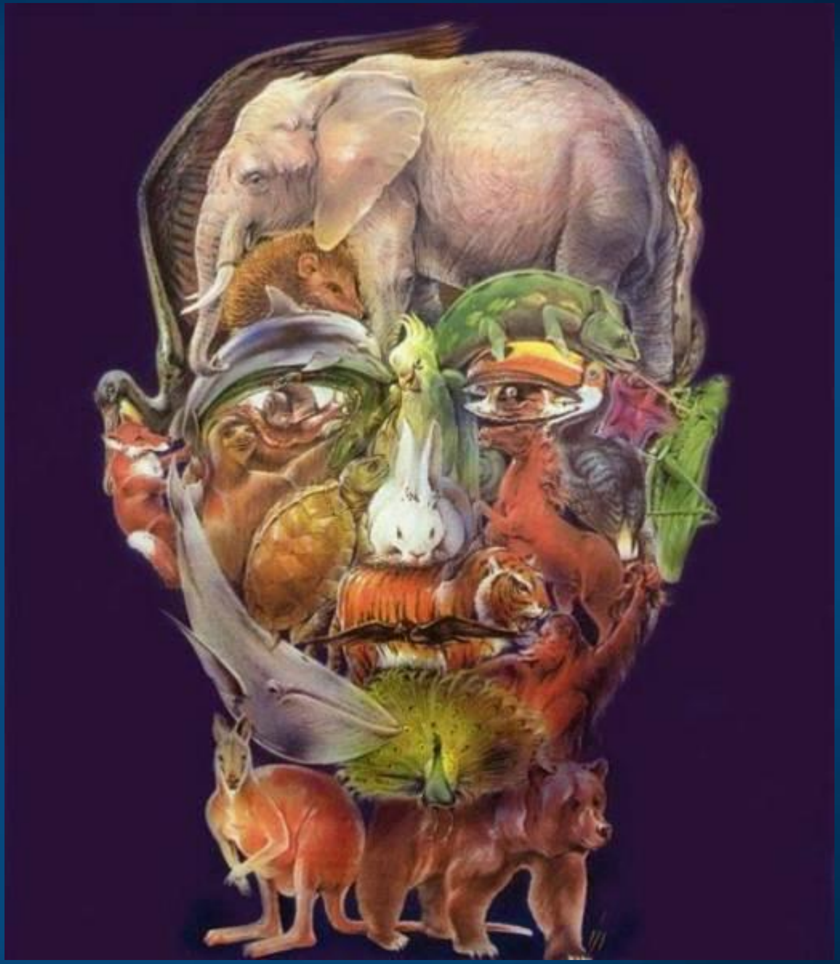
Disorders of consciousness 17-21.09.2017

Autism: science, therapies 23.05.2017



Thank you for synchronization of your neurons





Google: W. Duch

=> talks, papers, lectures, Flipboard …

In search of the sources of brain's cognitive activity

Project „Symfonia", 2016-21

FACULTY OF PHYSICS, ASTRONOMY AND INFORMATICS

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My group of neuro-cog-fanatics