Artificial Intelligence and Neurocognitive Technologies for Human Augmentation.

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Google: Wlodzislaw Duch

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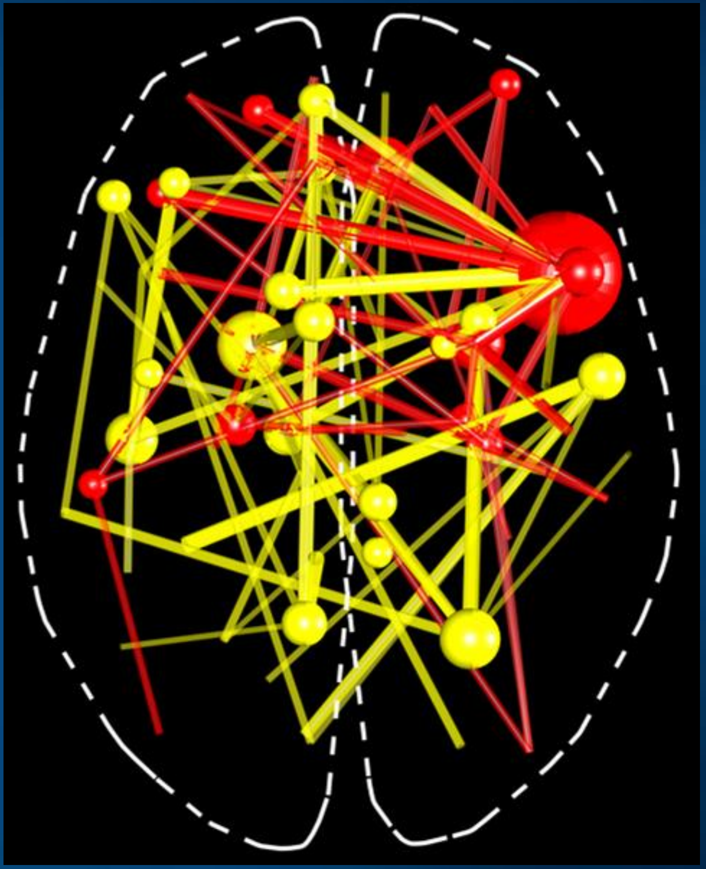
On the threshold of a dream …

How mental states arise from specific activity of the brain networks?

- Global brain neurotech initiatives.
- Brain networks – space for neurodynamics.
- Neurotech for human enhancements.
- Fingerprints of Mental Activity.
- Dynamic functional brain networks.
- Simulation of brain networks.



Final goal: Use your brain to the max!
Optimization/enhancement of brain processes?

Duch W (1996) *Computational physics of the mind*. Computer Physics Communication **97**: 136-153

Duch. W. (2019) Mind as a shadow of neurodynamics. Physics of Life Reviews 31

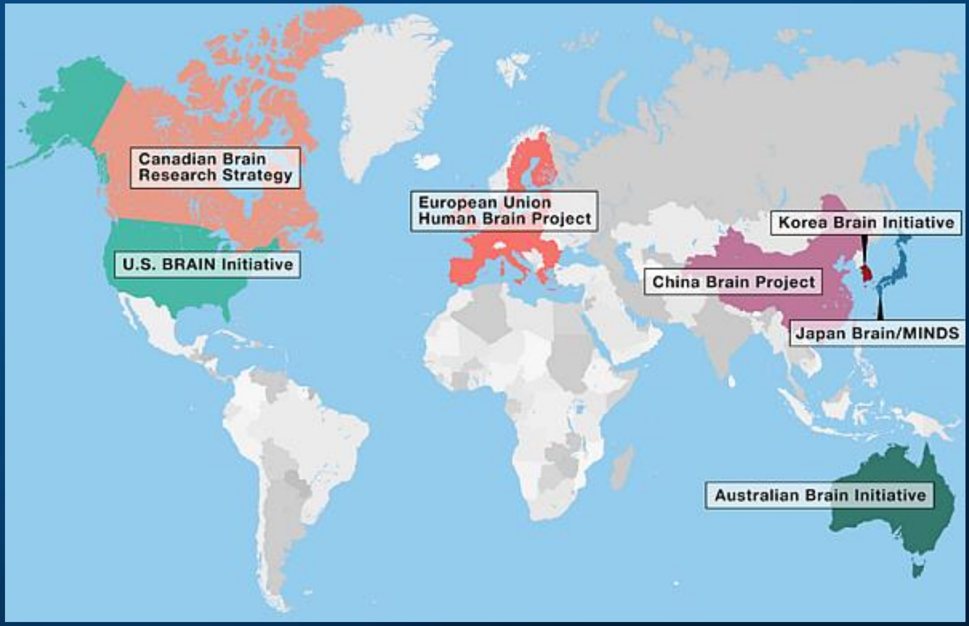
Costs of brain diseases

Total cost of brain disorders in EU in 2010: ~ 800 billion €/year,
45% of the total annual health budget of Europe!

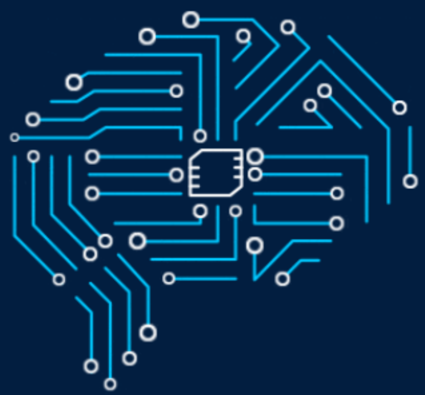
~ 180 millions, or 1/3 of all European citizens with at least one brain disorder during their lifetimes.

Gustavsson et al. (2011). Cost of disorders of the brain in Europe 2010. *European Neuropsychopharmacology*, *21*(10), 718–779.
China: > 20% of population (~250 mln) suffering from brain disorders.

Global Brain large initiatives in North America, Europe, China, Korea, Japan and Australia/NZ + a few other countries.



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 (2013), and Obama BRAIN Initiative (2013):
BRAIN=**B**rain **R**esearch through **A**dvancing **I**nnovative **N**eurotechnologies.

“Develop new technologies to explore how the brain’s cells and circuits interact … 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.

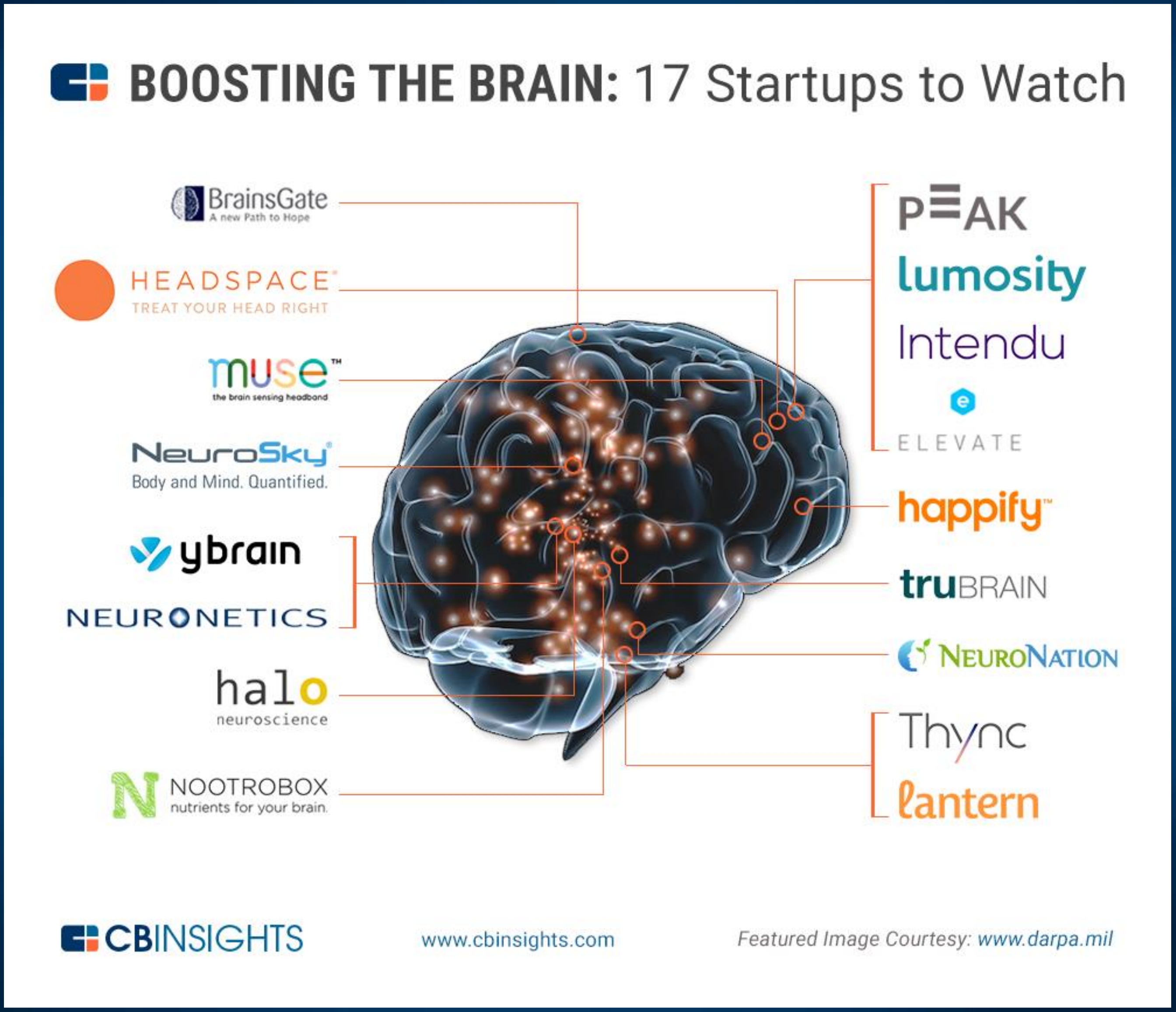
The mission of IEEE Brain is to facilitate cross-disciplinary collaboration and coordination to advance research, standardization and development of technologies in neuroscience to help improve the human condition.

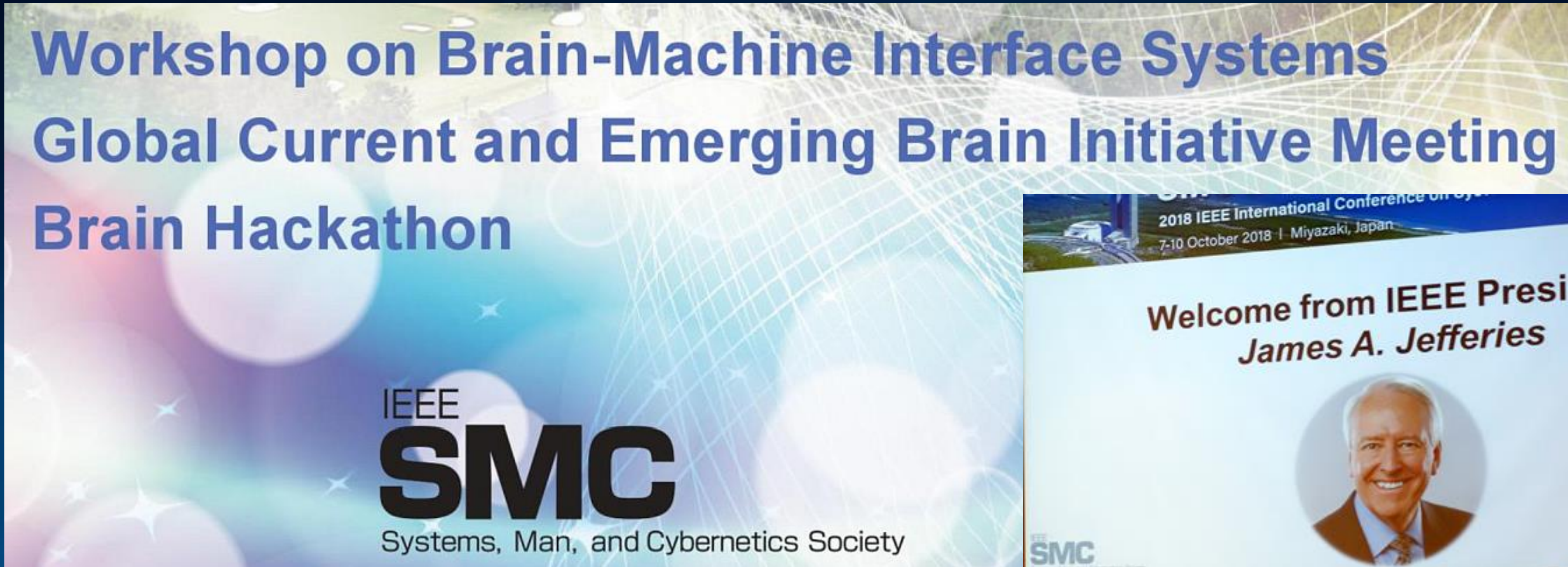
20 IEEE Societies are involved, including: **IEEE Computational Intelligence Society**; Computer Society; Consumer Electronics Society; Digital Senses Initiative; Robotics and Automation Society; Sensors Council; Signal Processing Society; Society on Social Implications of Technology; **Systems, Man, and Cybernetics Society**, Int. 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.

Startups around the world





Part of the Brain-Machines Interface Workshop and SMC2018.

The IEEE SMC Society and the IEEE President, James Jefferies, invited us 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.

incf | 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.

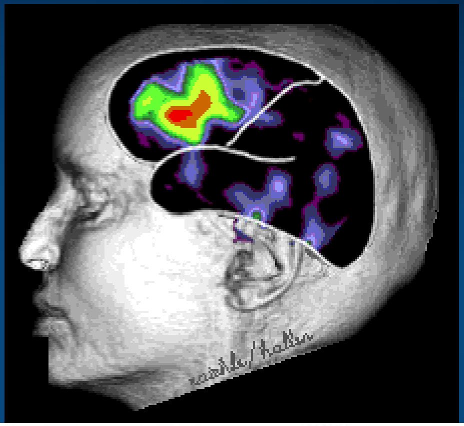
12th INCF Congress on Neuroinformatics and INCF Assembly, Warsaw 9/2019.
Neuroimaging, computational neuroscience, artificial intelligence.

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

Not only ANN models, but EEG/MEG/fMRI and other data from experiments with animal and human brains.

Neuroscience ⇔ BICA AI

Brains ⇔ Minds

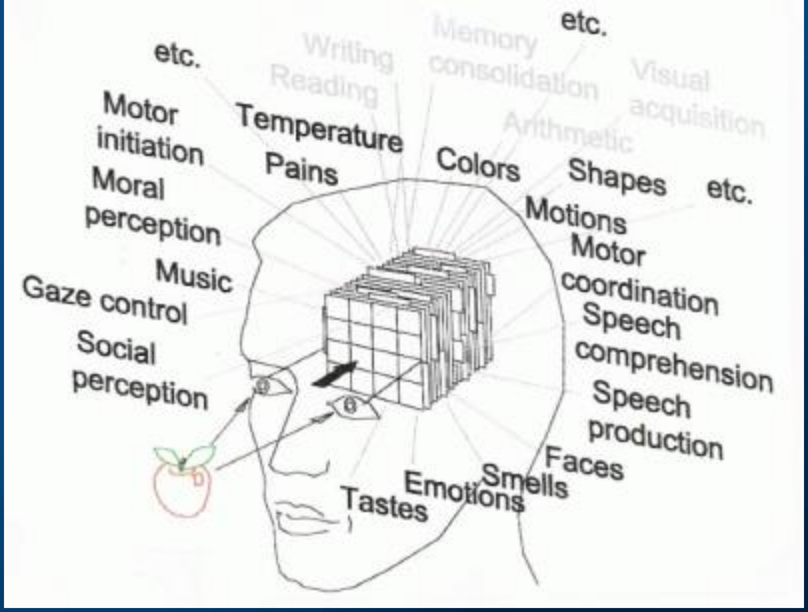


Define mapping S(M)⇔S(B), as in BCI.
How mental states arise/influence brain states?

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

Mental states should be represented in a space with dimensions that measure different aspects of inner experience.

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

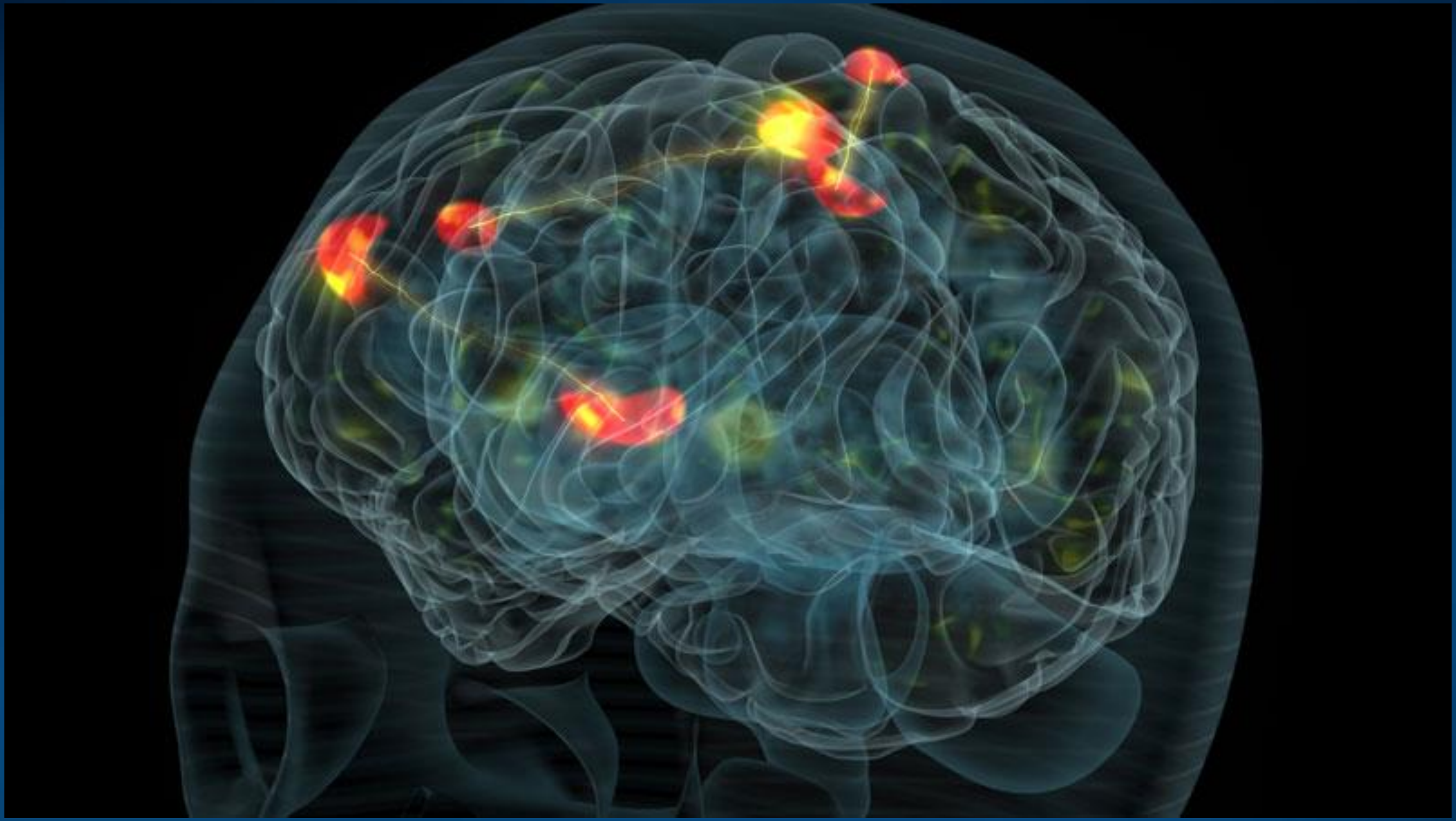


Two problems: discretization of continuous processes for symbolic models,
and lack of good phenomenology – we are not able to describe our mental states.

Duch W. (2019) Mind as a shadow of neurodynamics.
Physics of Life Reviews 31: 28

Brain networks: space for mental states

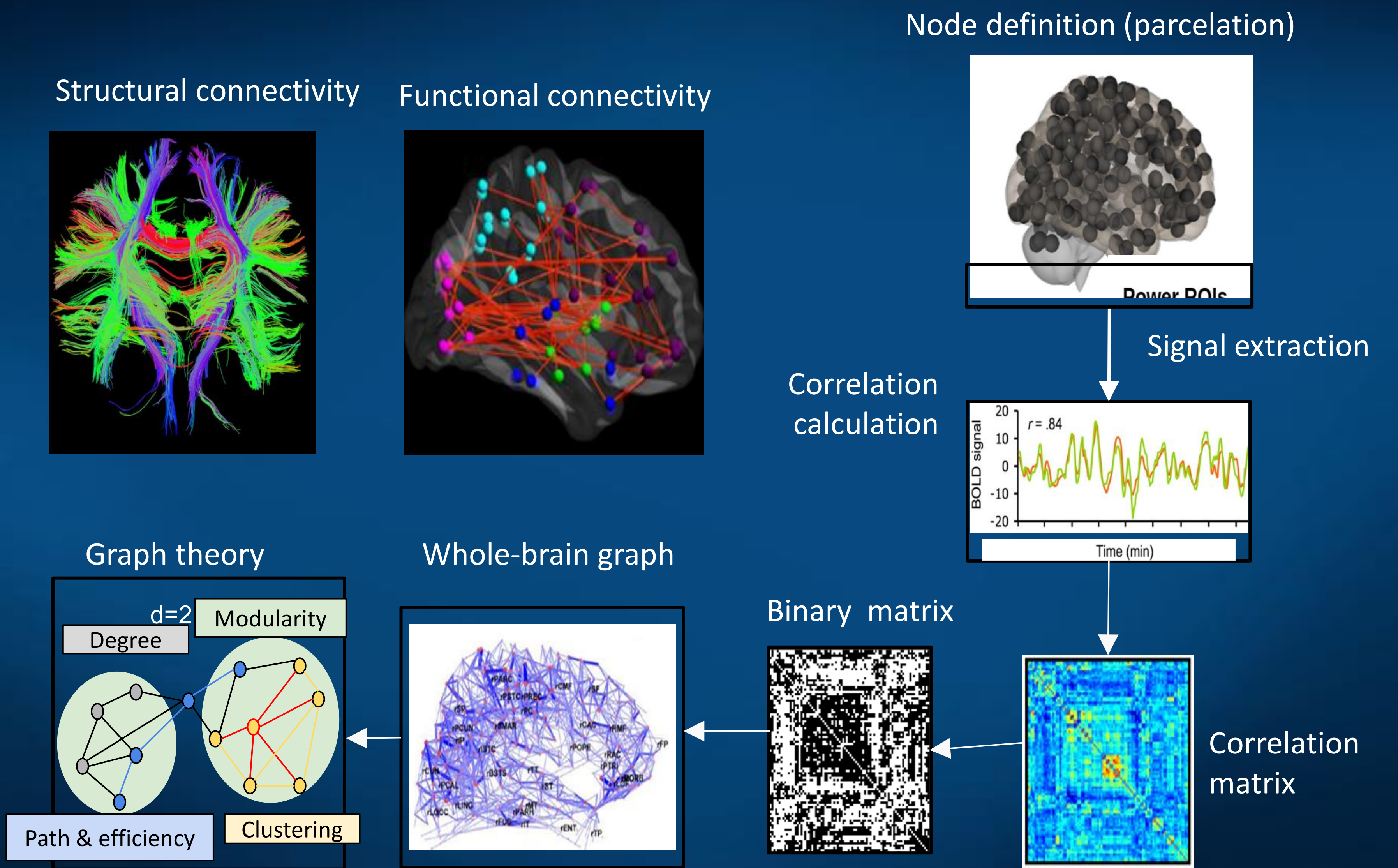
Mental state: strong coherent activation



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.

Human connectome and MRI/fMRI



Many toolboxes available for such analysis.

Bullmore & Sporns (2009)

Multi-level phenomics

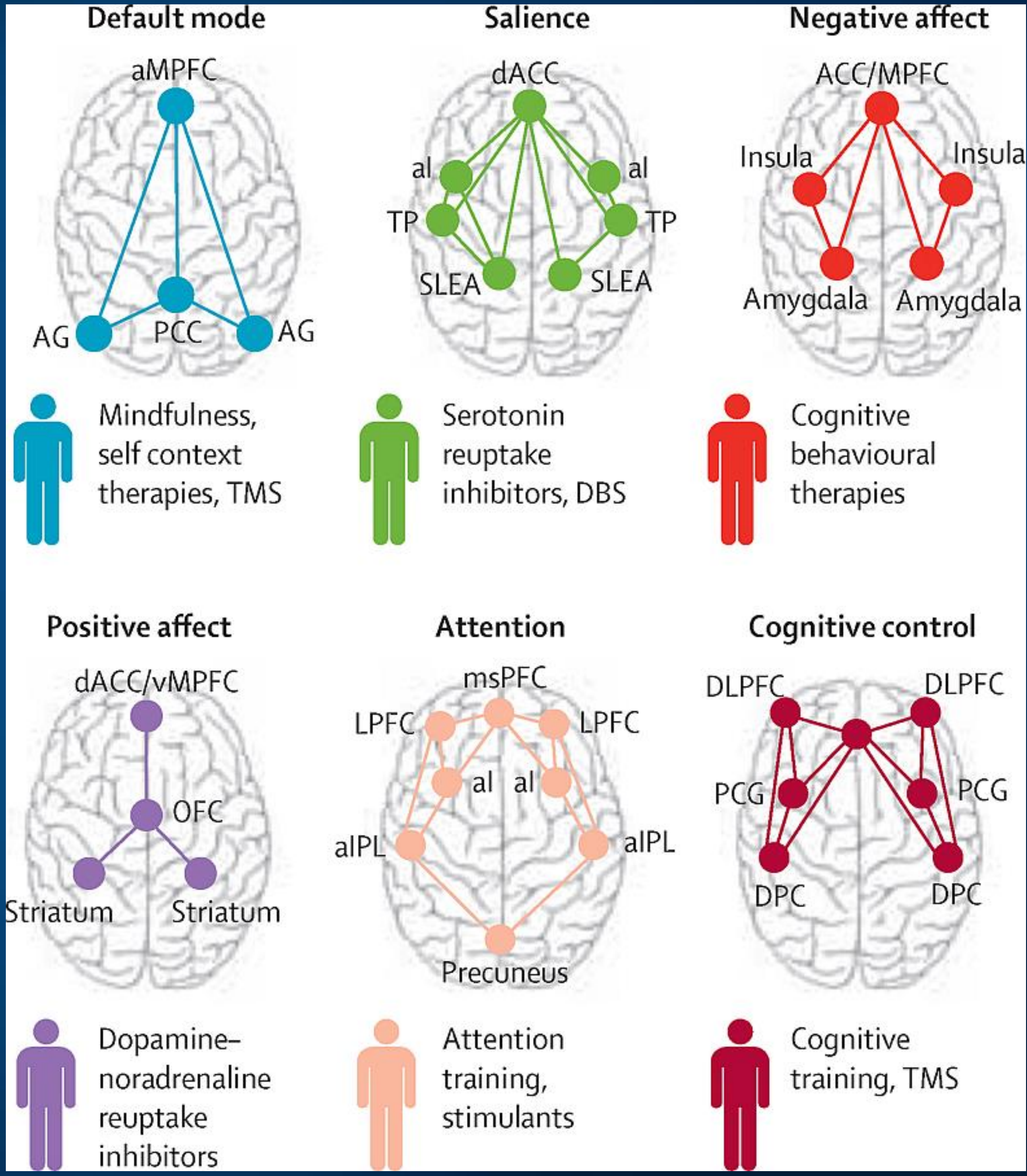
M. Minsky, Society of mind (1986)

Decompose brain network dynamics into meaningful components of activity related to complex brain functions.

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.

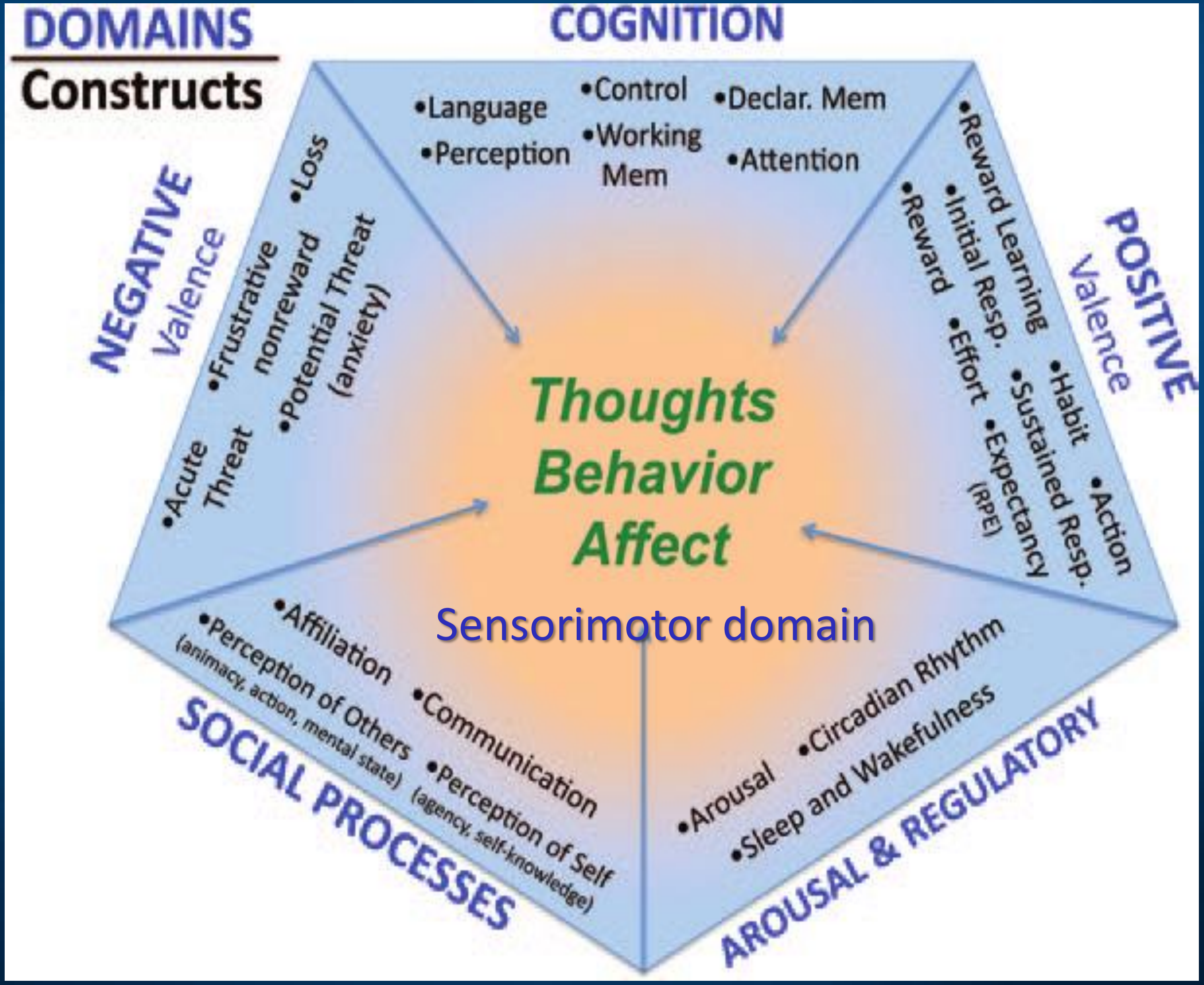
Include influence of genes, molecules, cells, **neural networks**, physiology, behavior, self-reports on network functions.

Neurodynamics is the key.



RDoC
Research Domain Criteria Initiative

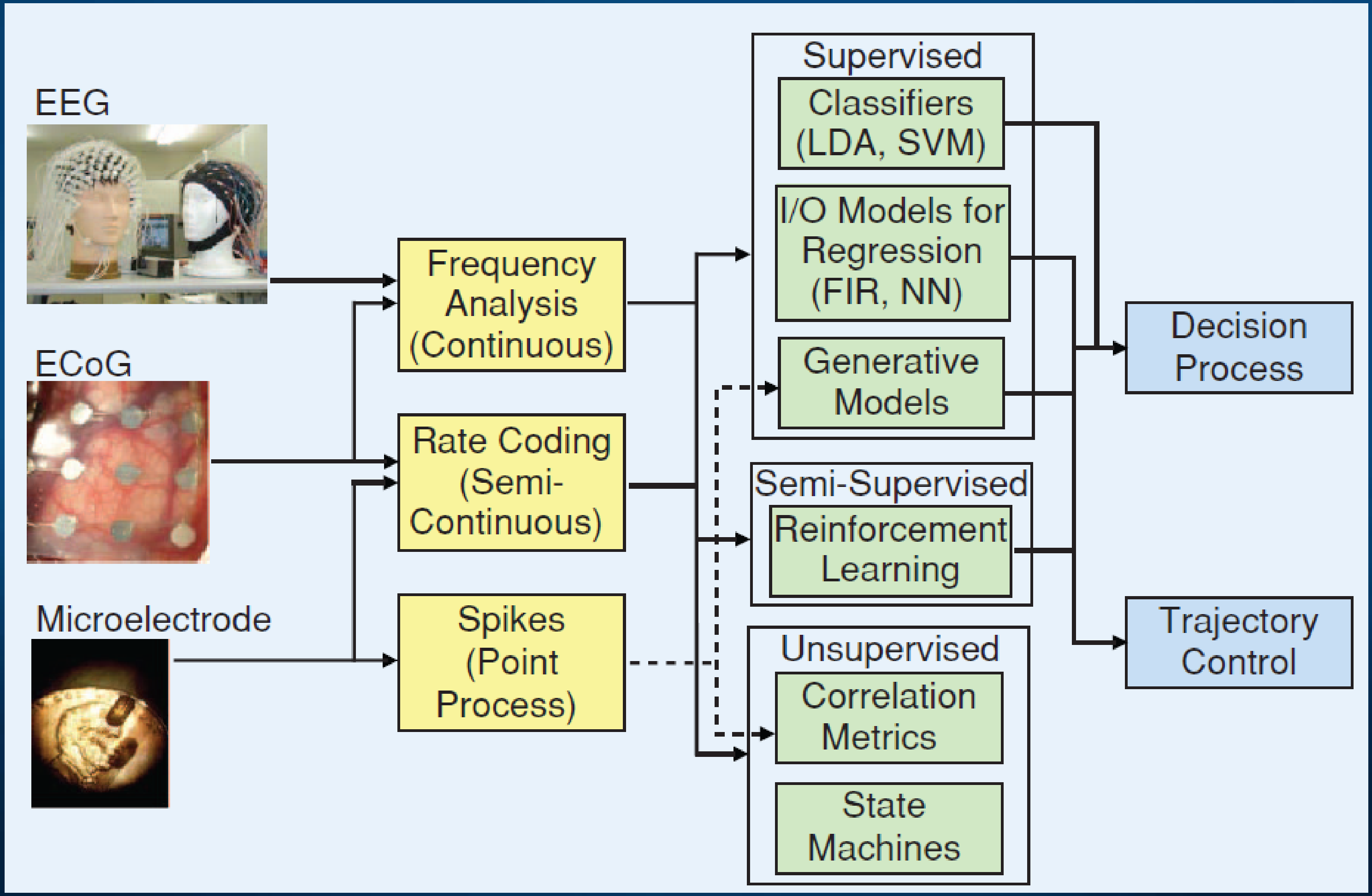
NIMH RDoC Matrix for deregulation of 6 large brain systems.



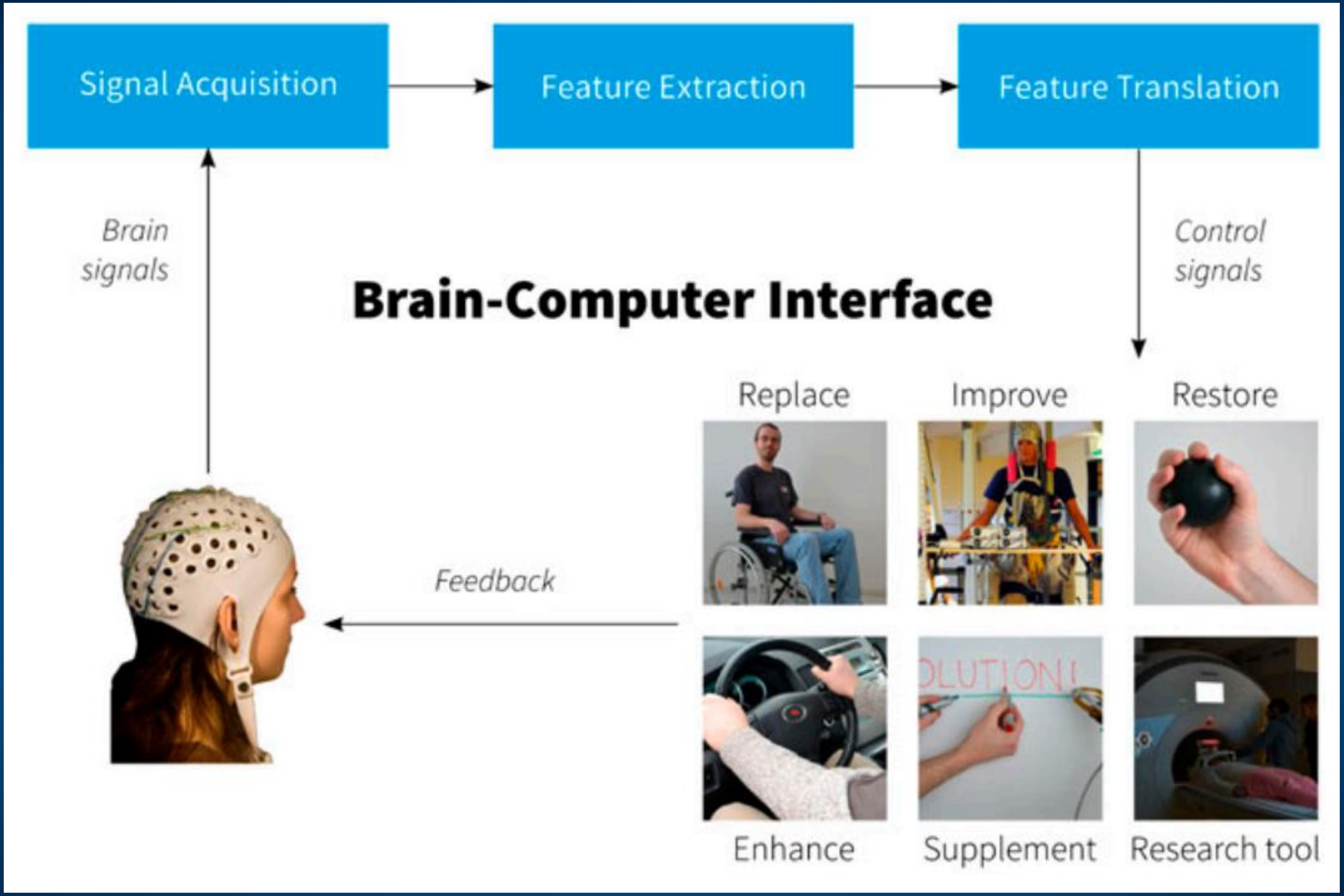
Human Enhancement
and
Optimization of Brain Processes

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!

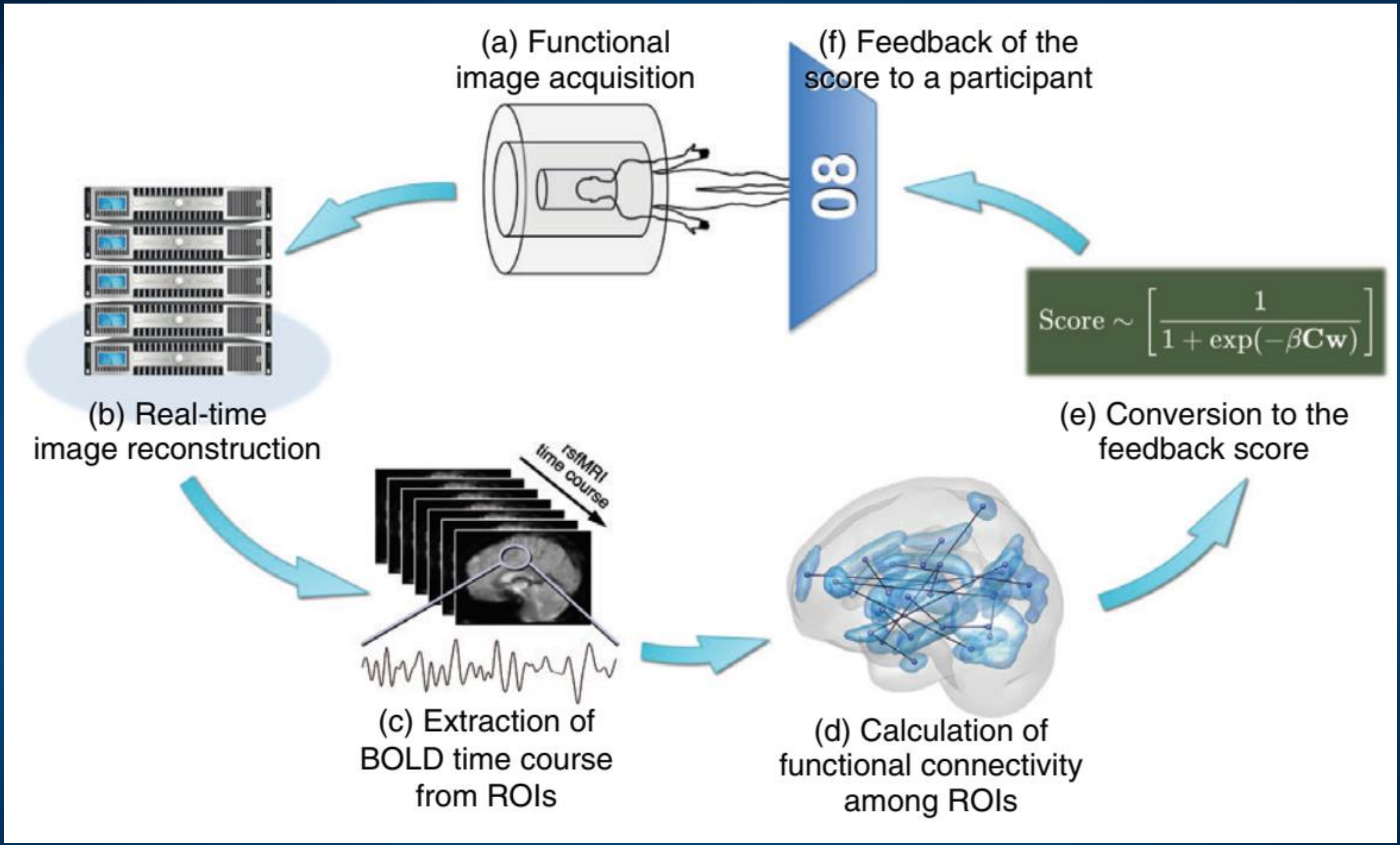


BCI Applications



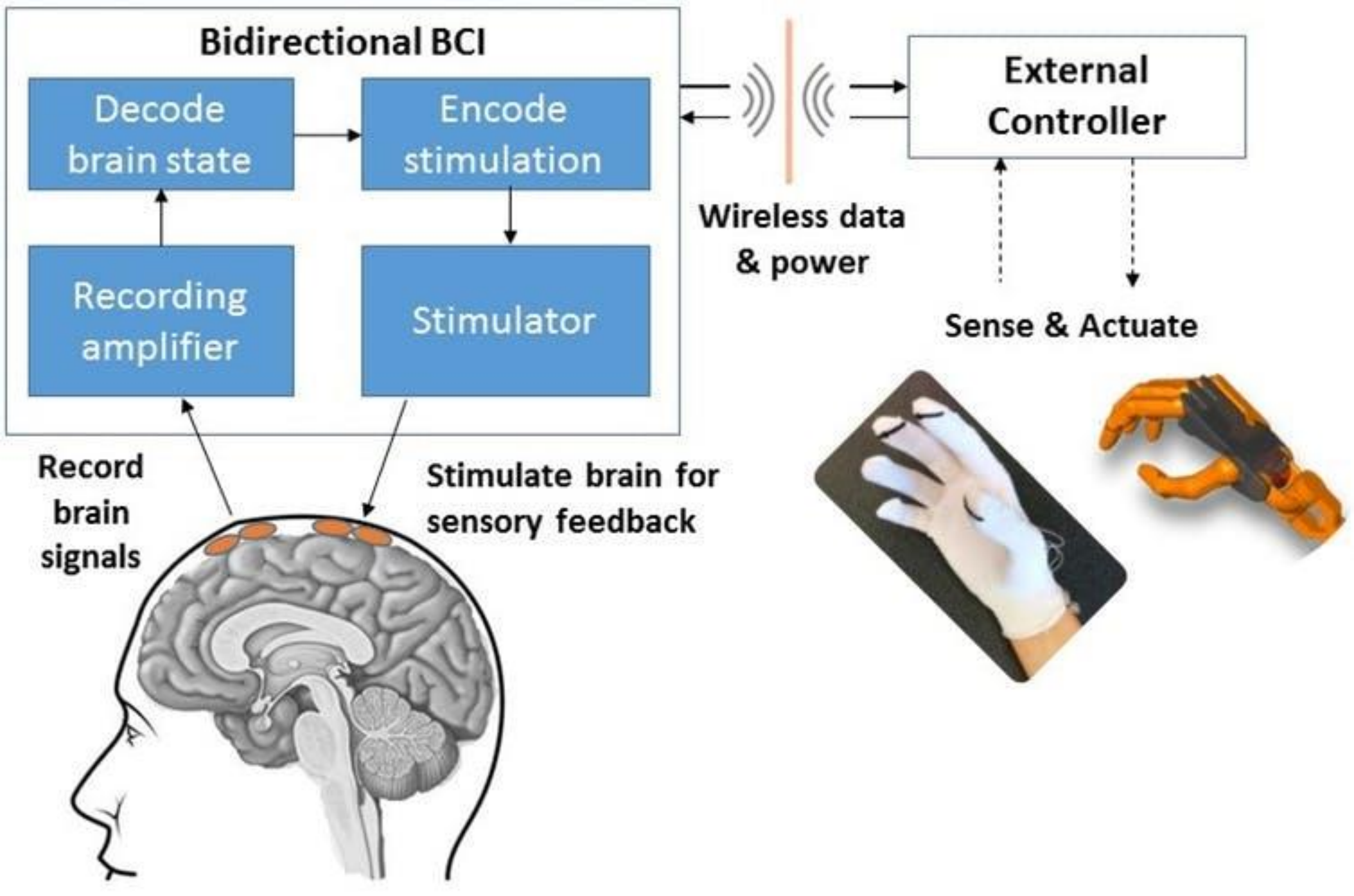
Signals: invasive (brain implants), partially invasive (ECoG), and non-invasive.

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.

Brain-Computer-Brain Interfaces (BCBI)



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

Learning skills

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

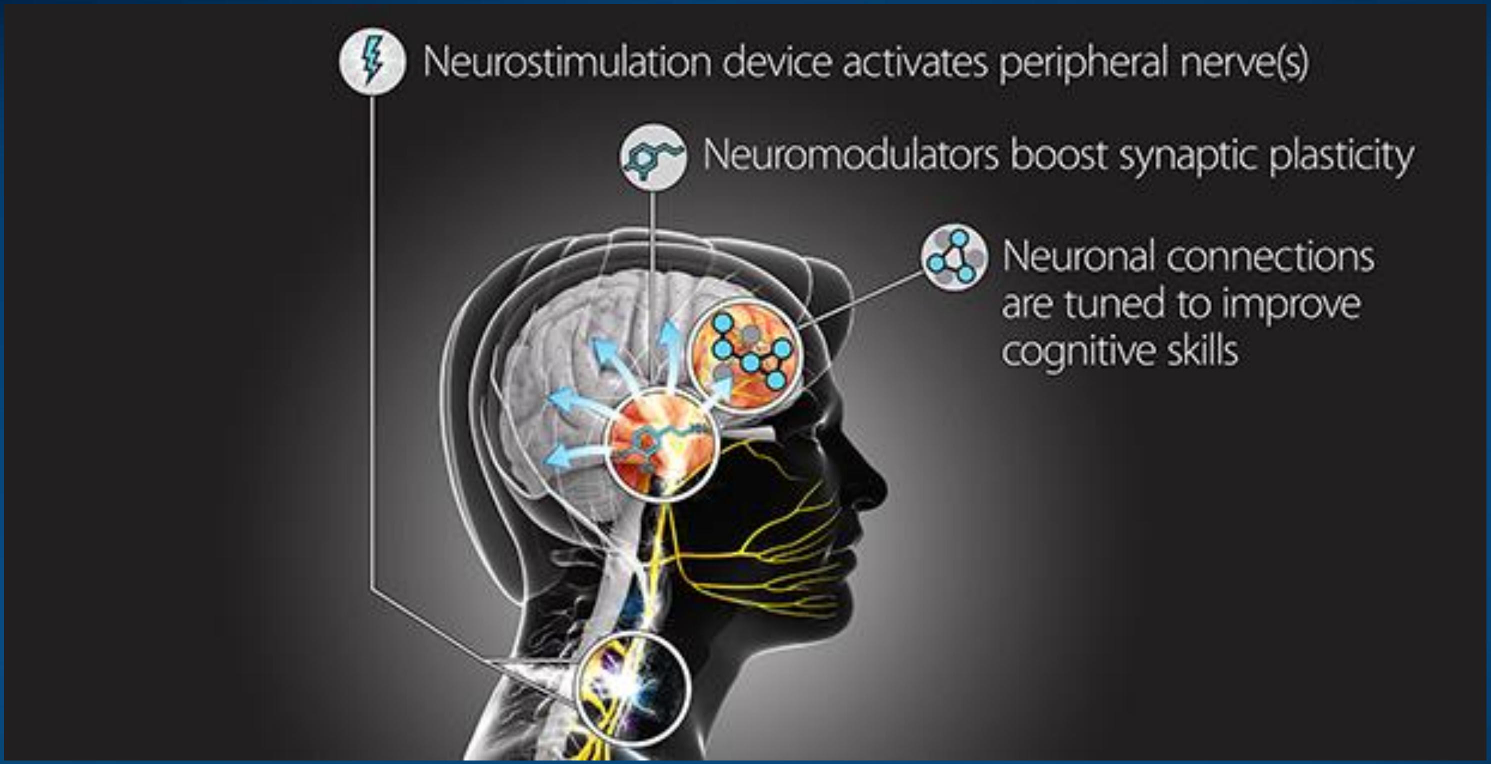
Intific Neuro-EST uses EEG analysis and mulit-channel transcranial simulation (HD-DCS) to pre-activate the brain of the novice in areas where the expert brain is active.

Real-life transfer learning …

HD-tDCS may have 100 channels, neurolace and nanowires much more.

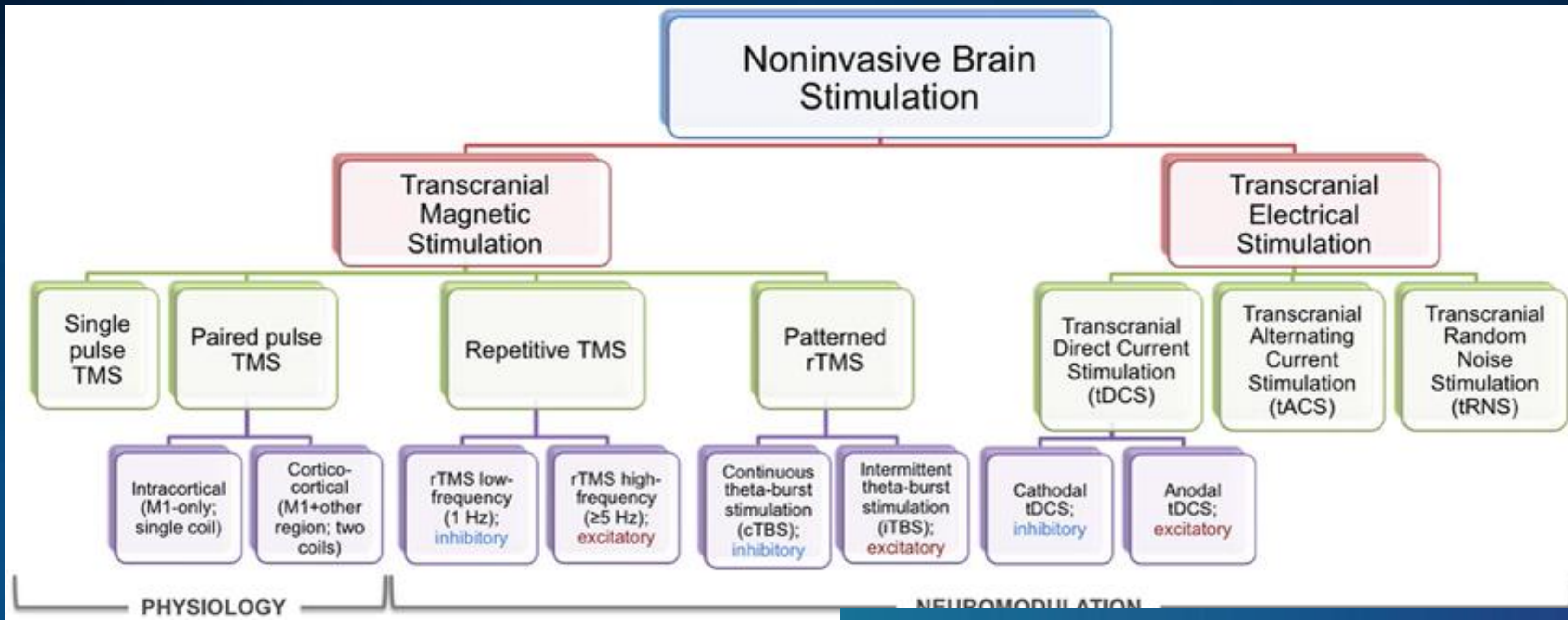
Inject microcurrents into the motor cortex …

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.

Brain stimulation



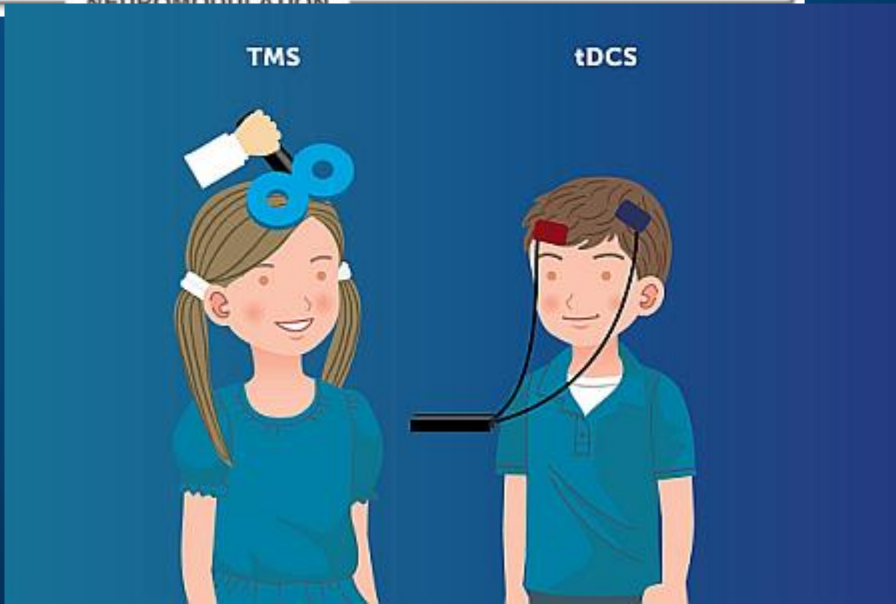
ECT – Electroconvulsive Therapy

VNS – Vagus Nerve Stimulation

Ultrasound, laser … stimulation.

Complex techniques?
Smartphones are also complex.

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



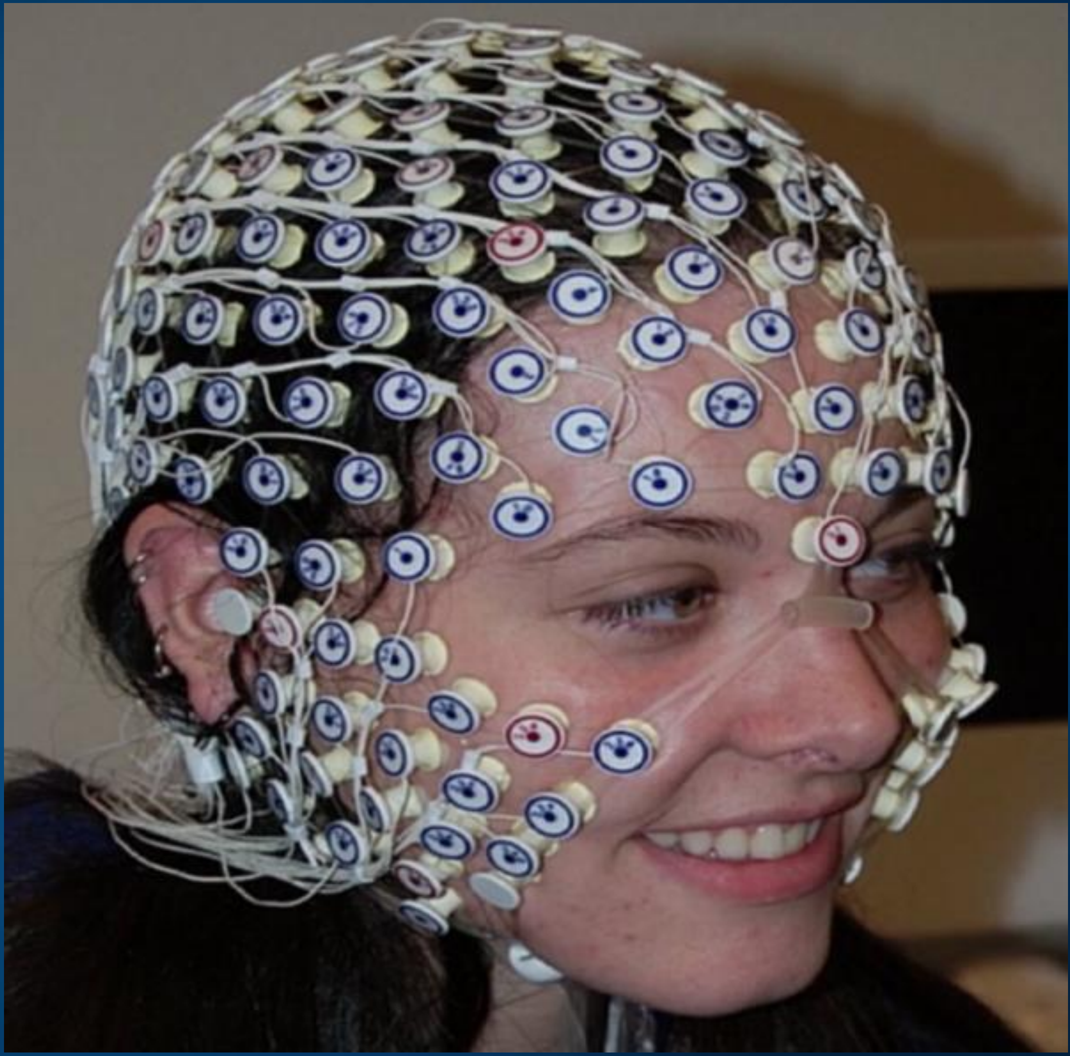
HD EEG/DCS?

EEG electrodes + DCS.

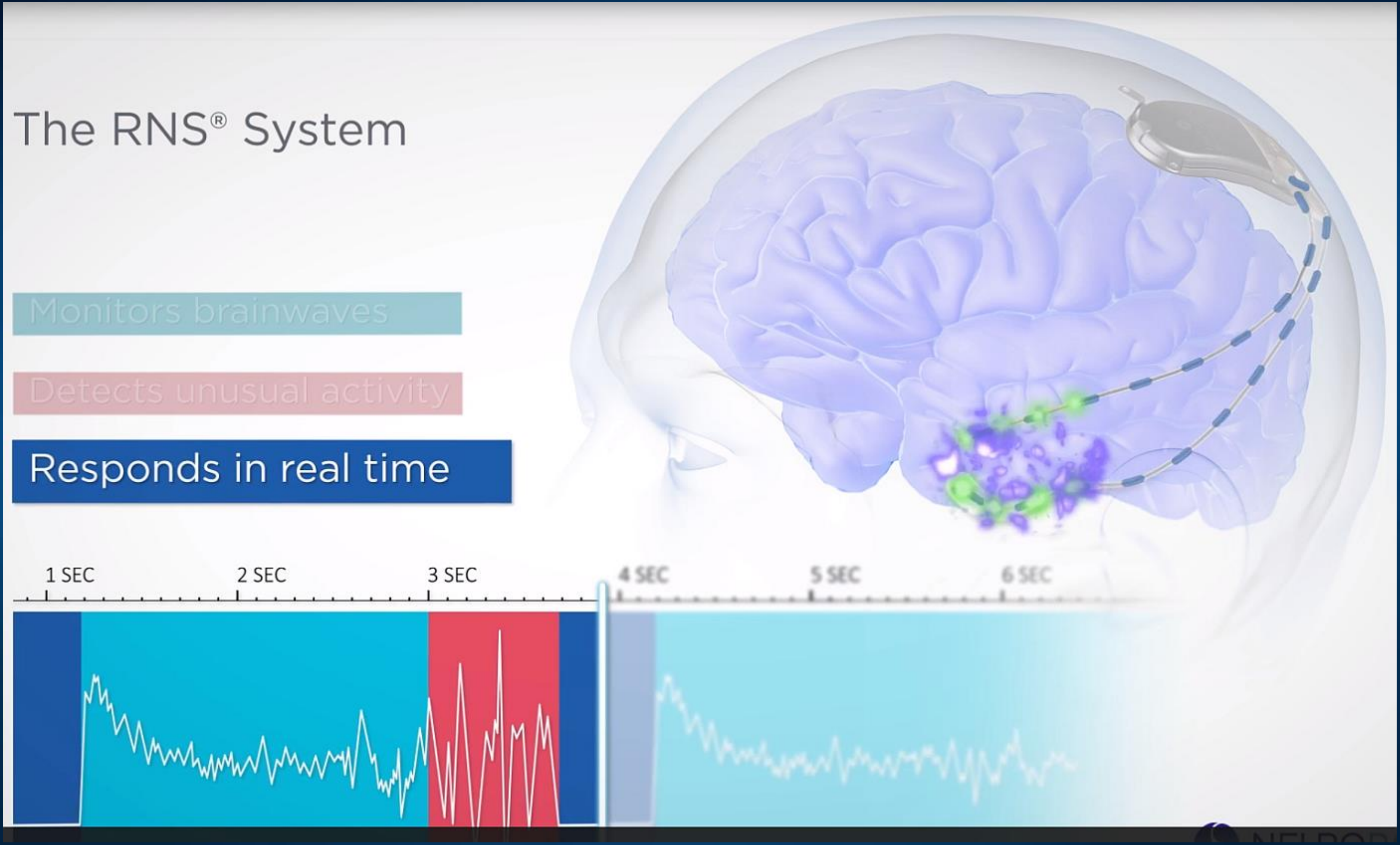
Reading brain states
=> transforming to common space
=> duplicating in other brains
Applications:

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

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

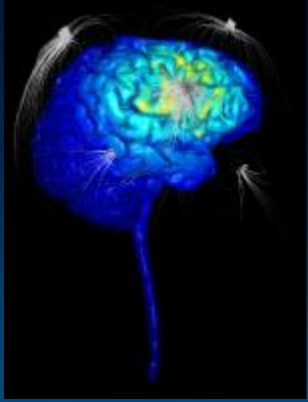


Epilepsy



1% of population suffers from epilepsy, if pharmacology does not help neurostimulation based on close loop may help – RNS system is now commercial.

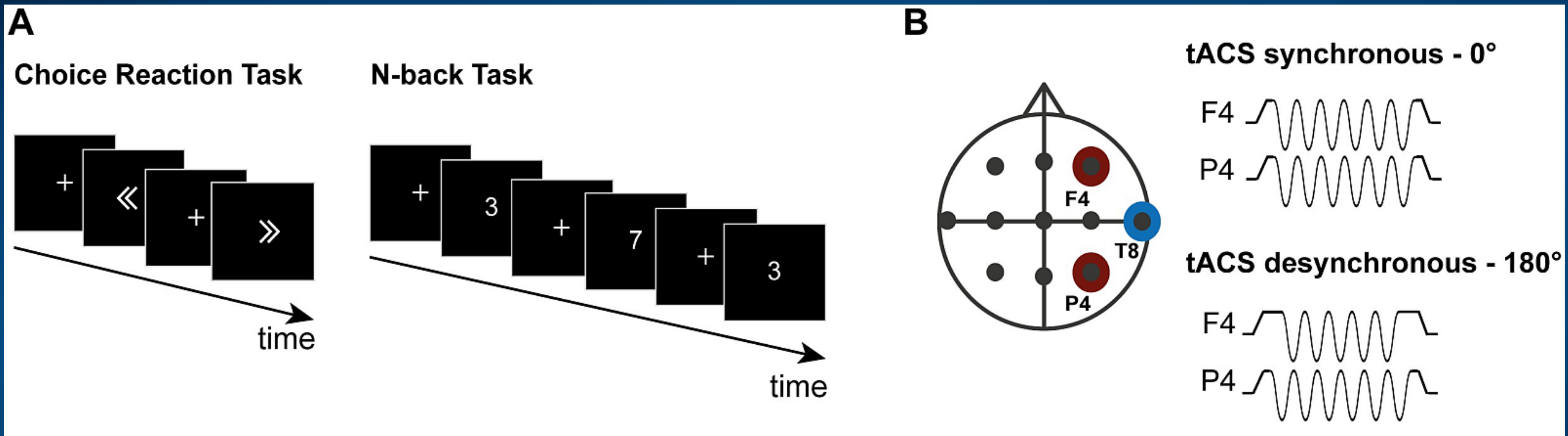
BCBI for learning

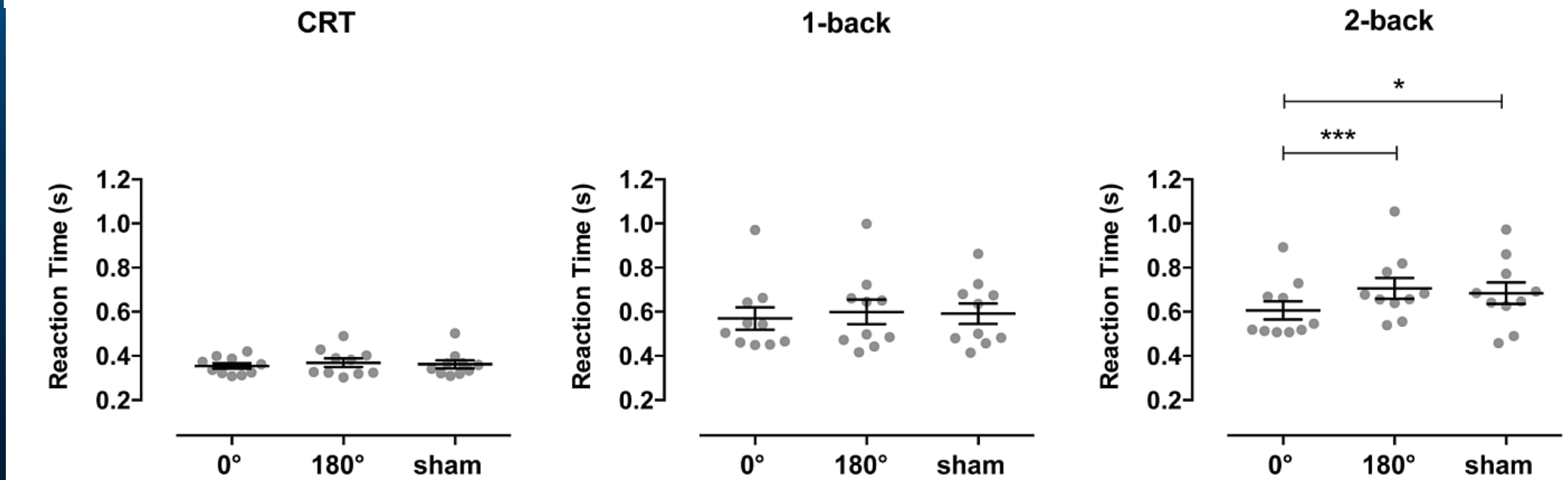


1. **Teaching skills by stimulating cortex:** microstimulation too low to evoke muscle activation, applied in premotor cortex, instructed specific actions.
   Mazurek & Schieber (2017). Injecting Instructions into Premotor Cortex.
2. Eugster et al. (2016). Natural brain-information interfaces: Recommending information by relevance inferred from brain signals. Your brain knows better what is interesting than you do, so use EEG to model search intent while searching, watching or analyzing data.
3. Externally induced frontoparietal synchronization modulates network dynamics & enhances working memory performance (Violante et al 2017).
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.

Synchronize PFC/PC

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





Fingerprints of mental activity

Possible form of Brain Fingerprints

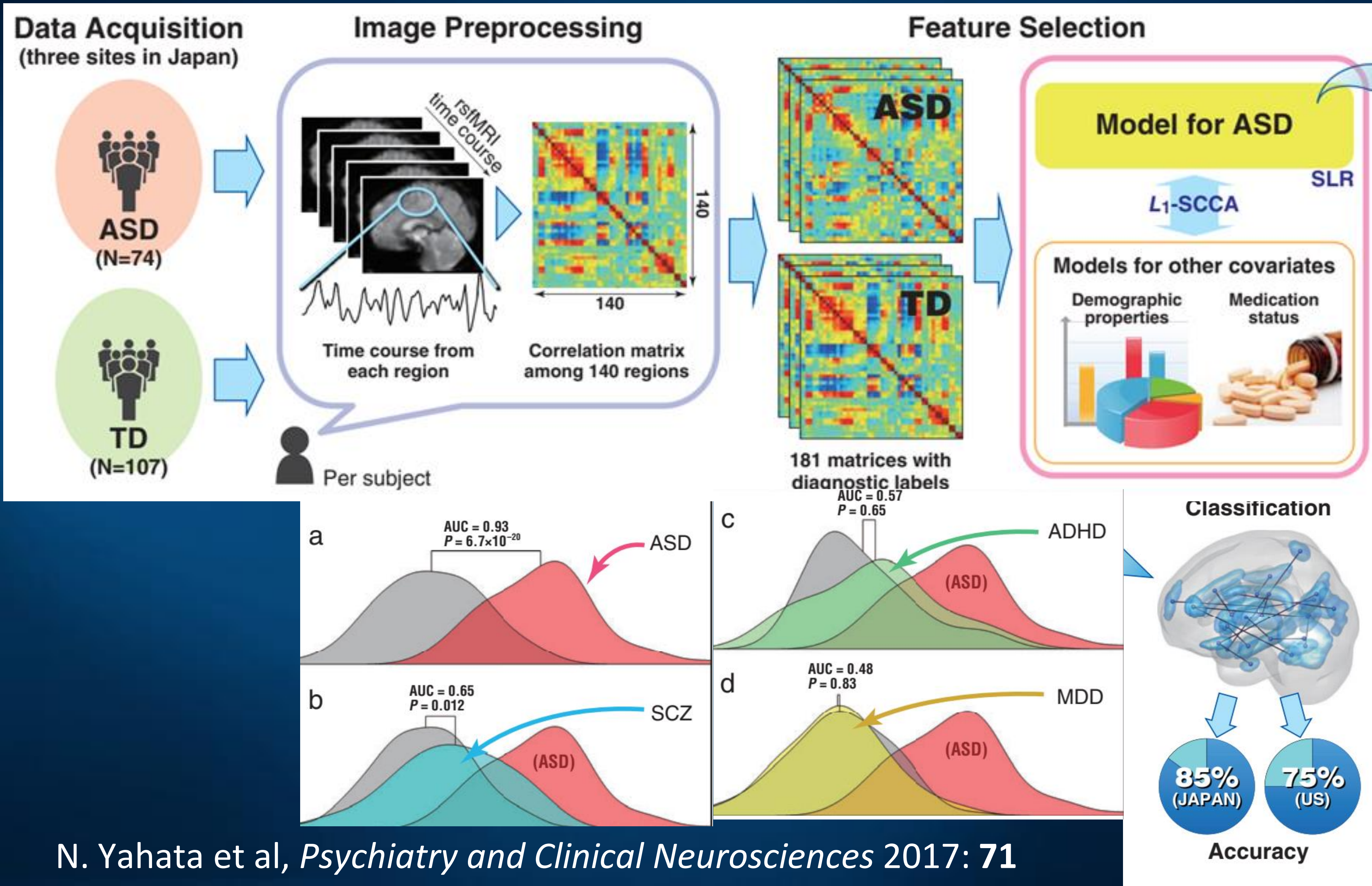
How to link patterns of brain activity to active regions/networks, S(M)⇔S(B)

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. Spectral fingerprinting (MEG, EEG), power distributions.
8. Model-based: **The Virtual Brain**, integrating EEG/neuroimaging data.

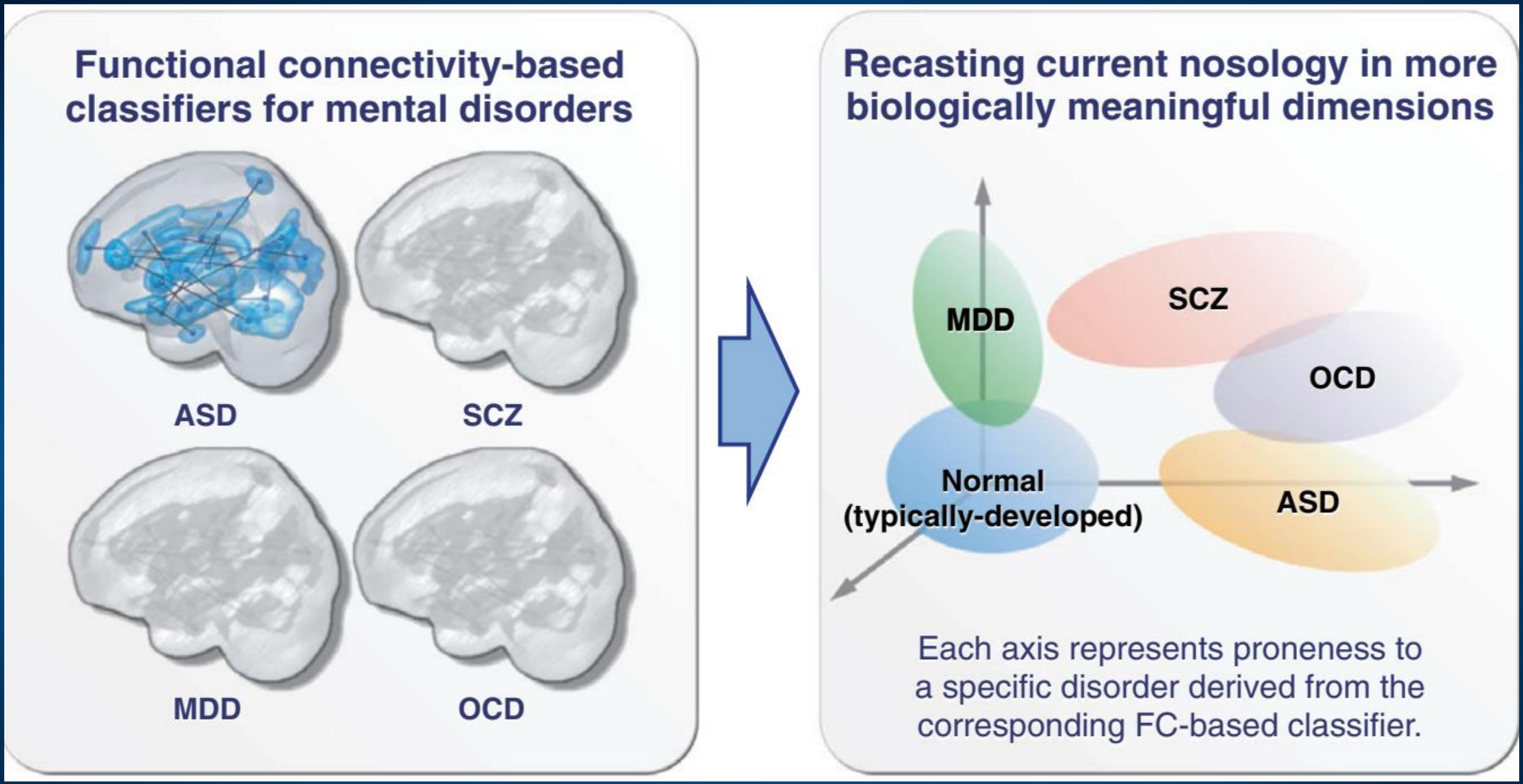
Neuroplastic changes of connectomes and functional connections as results of training for optimization of brain processes.

Biomarkers from neuroimaging



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

Biomarkers of mental disorders



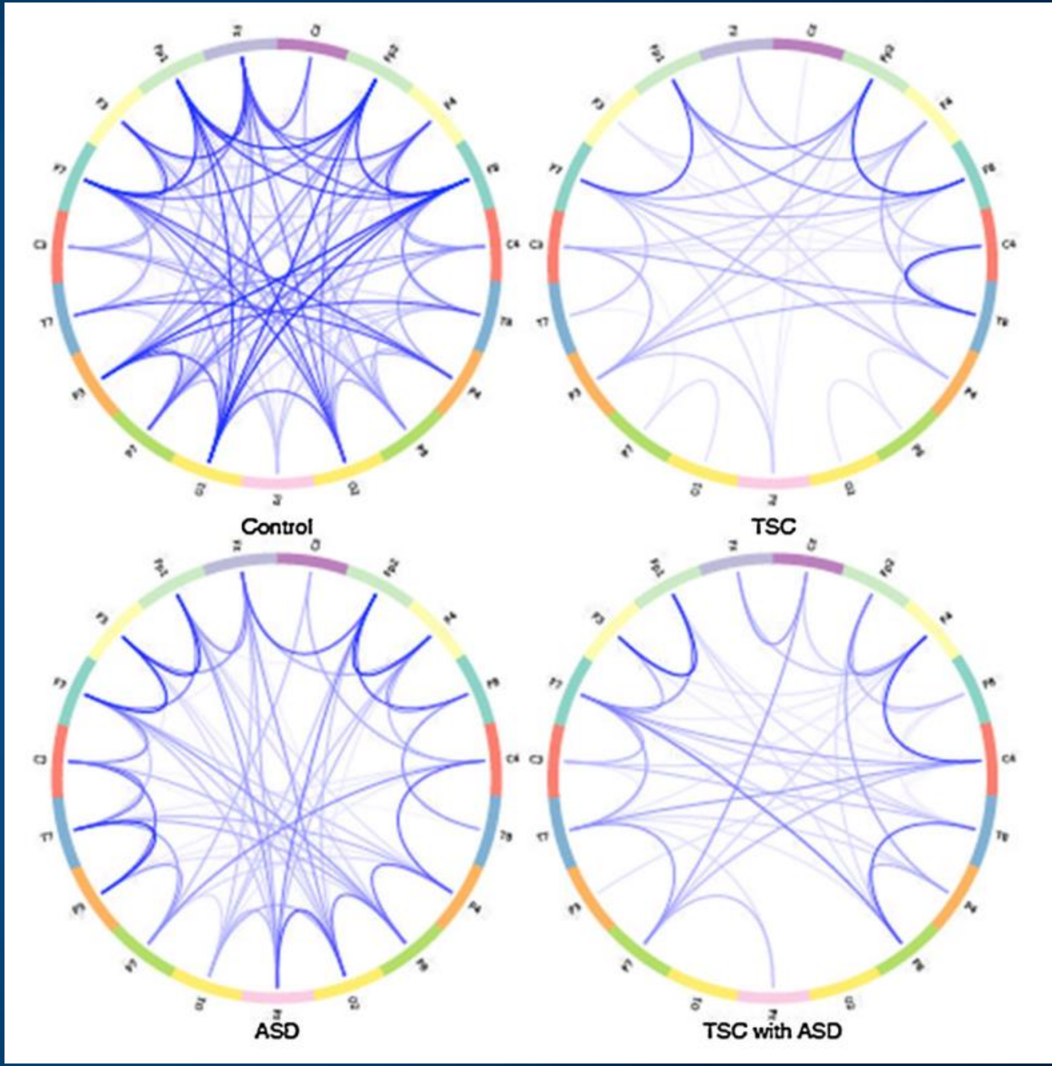
MDD, deep depression, SCZ, schizophrenia, OCD, obsessive-compulsive disorder, ASD autism spectrum disorder. fMRI biomarkers allow for objective diagnosis.
N. Yahata et al, *Psychiatry & Clinical Neurosciences* 2017; **71**: 215–237

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**!



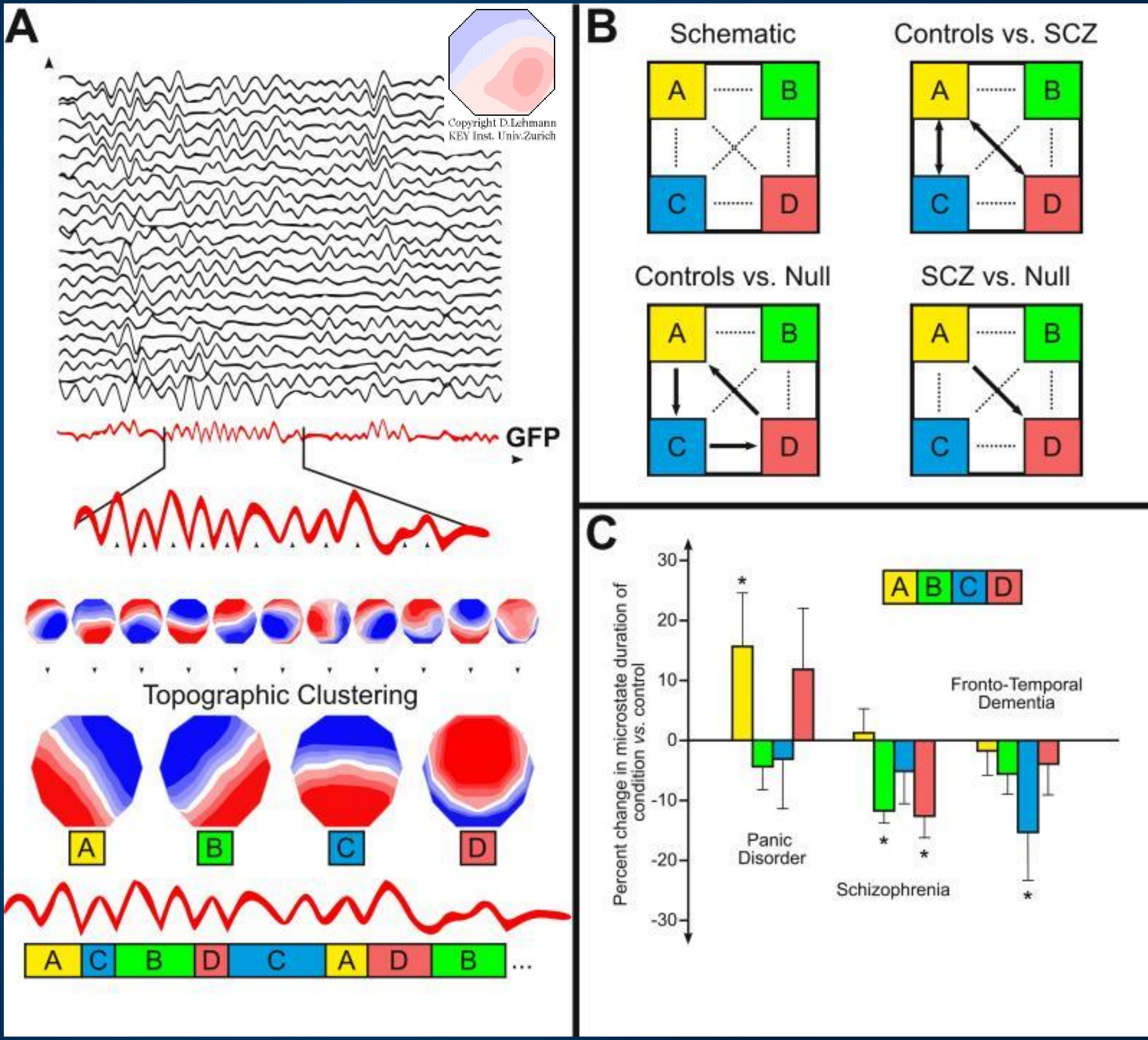
J.F. Glazebrook, R. Wallace, Pathologies in functional connectivity, feedback control and robustness. Cogn Process (2015) 16:1–16

Microstates

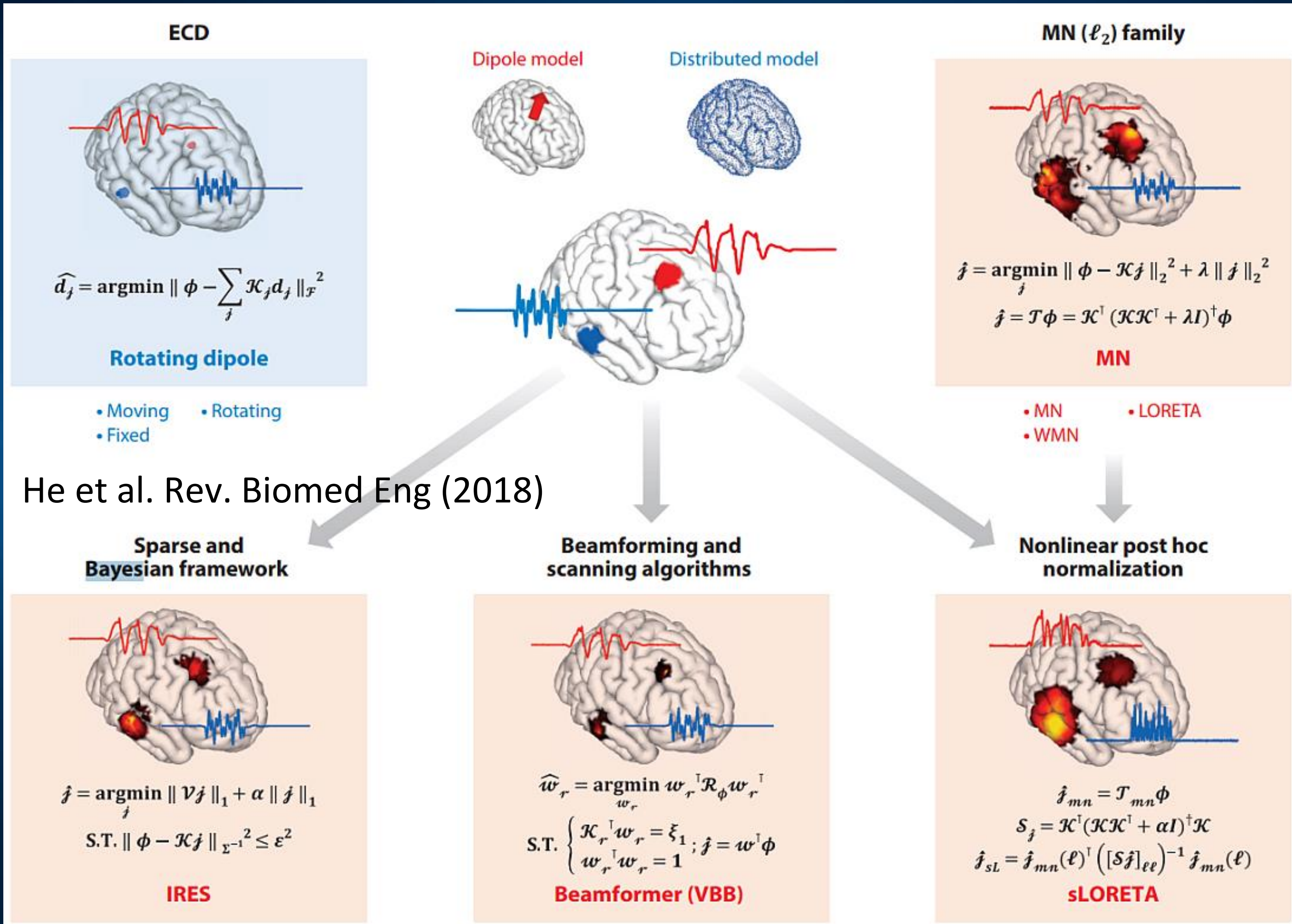
Lehmann et al.
EEG microstate duration and syntax in acute, medication-naïve, first-episode schizophrenia.
Psychiatry Research Neuroimaging, 2005

Khanna et al.
Microstates in Resting-State EEG.
Neuroscience and Biobehavioral Reviews, 2015

4-7 states 60-150 ms
Symbolic dynamics.



EEG localization and reconstruction



He et al. Rev. Biomed Eng (2018)

SupFunSim

SupFunSim: our library/Matlab /tollbox, direct models for EEG/MEG, on GitHub.

Provides many spatial filters for reconstruction of EEG sources: linearly constrained minimum-variance (LCMV), eigenspace LCMV, nulling (NL), minimum-variance pseudo-unbiased reduced-rank (MV-PURE) …

Source-level directed connectivity analysis: partial directed coherence (PDC), directed transfer function (DTF) measures.

Works with FieldTrip EEG/ MEG software. Modular, object-oriented, using Jupyter notes, allowing for comments and equations in LaTex.

$$A := H_{Src,R} := R^{-1/2} H \quad (34)$$

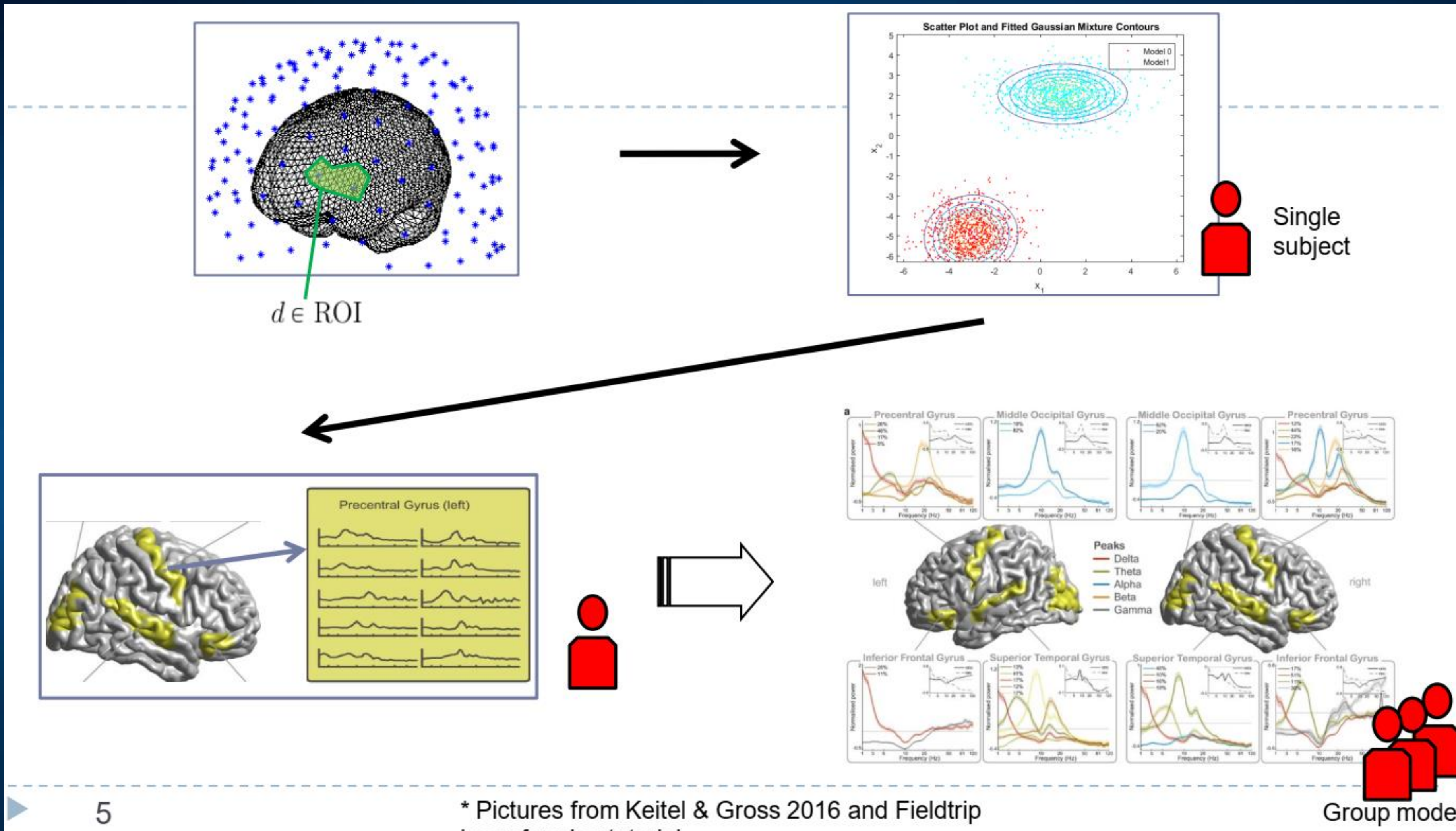
$$B := H_{Src,N} := N^{-1/2} H \quad (35)$$

```
%%file calculate_H_Src.m
function model = calculate_H_Src(MODEL)
    model = MODEL;

    model.H_Src_R = pinv(sqrtm(model.R)) * model.H_Src;
    model.H_Src_N = pinv(sqrtm(model.N)) * model.H_Src;
end
```

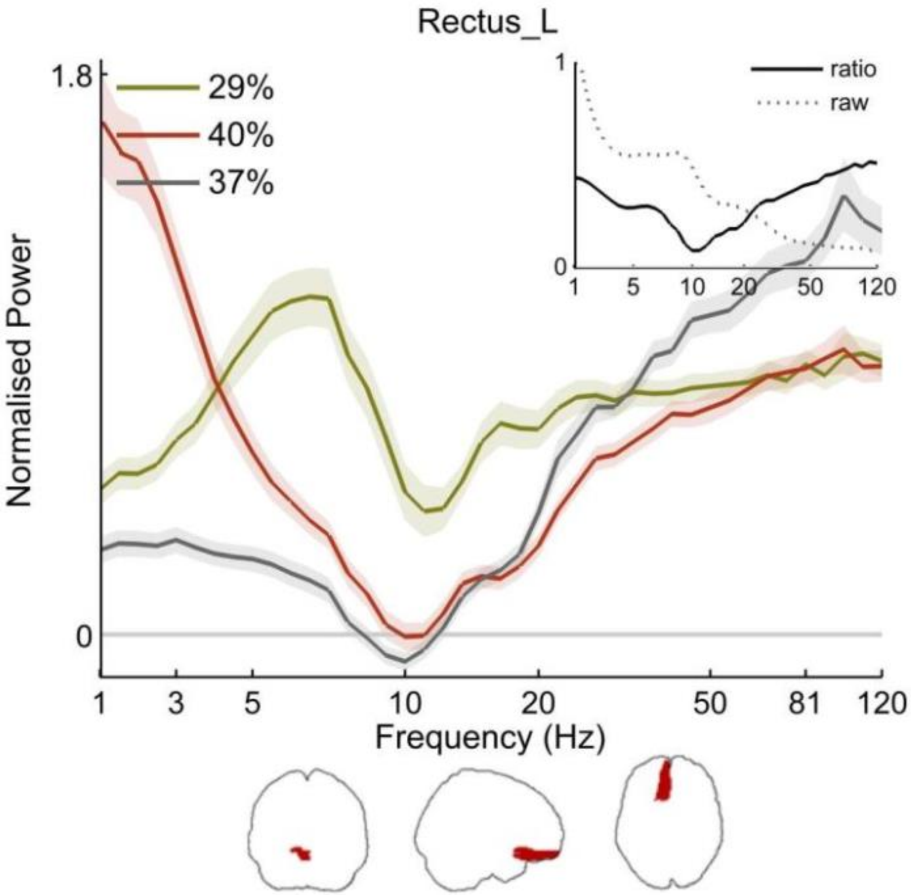
Rykaczewski, K., Nikadon, J., Duch, W., & Piotrowski, T. (2020). *Neuroinformatics.*

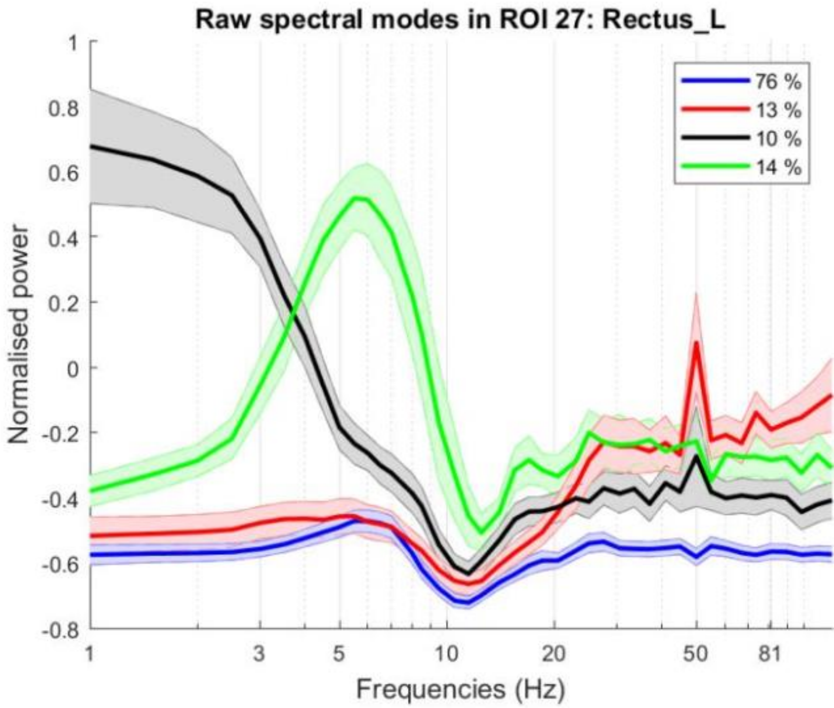
Spectral fingerprints



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

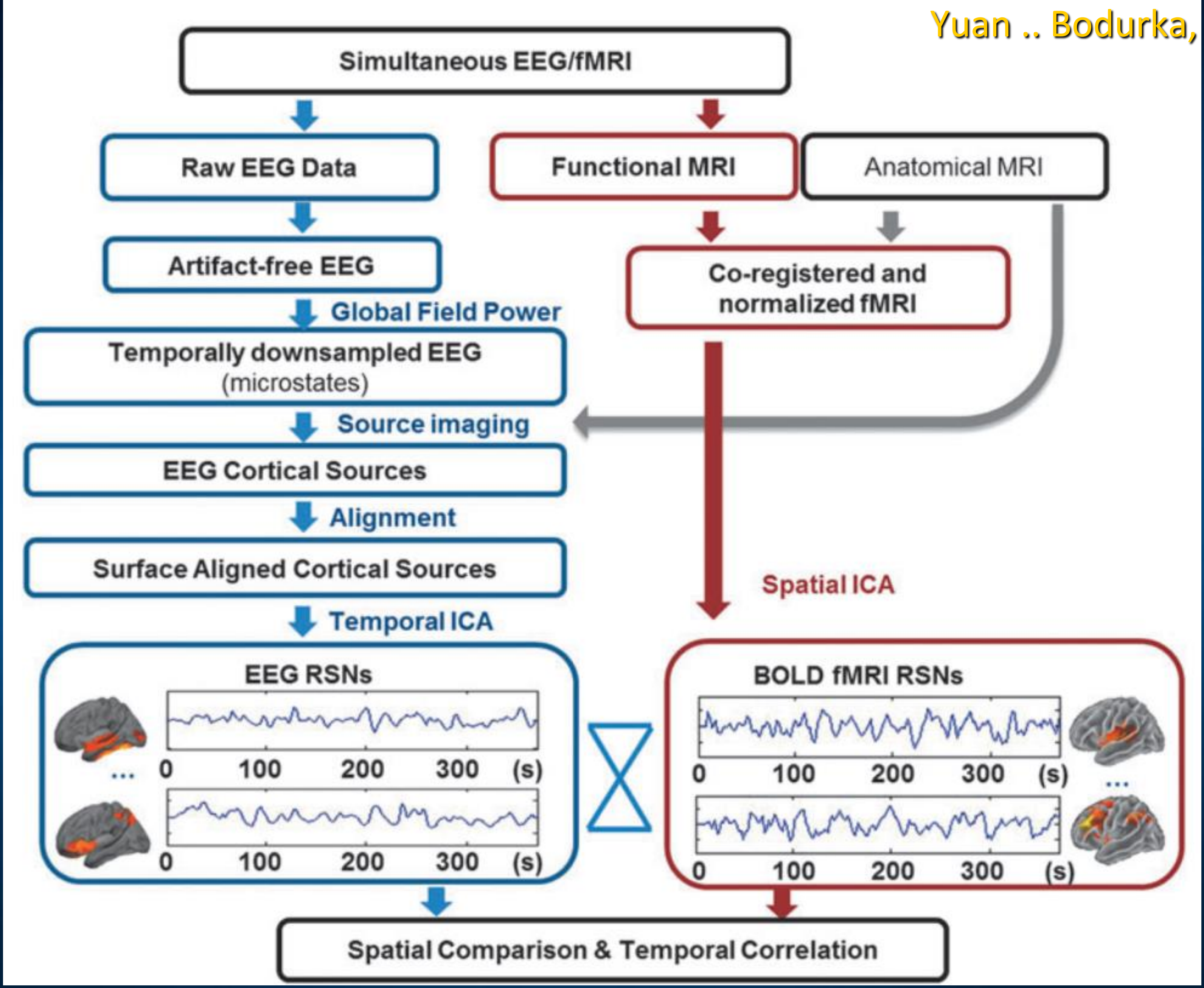
Spectral fingerprints



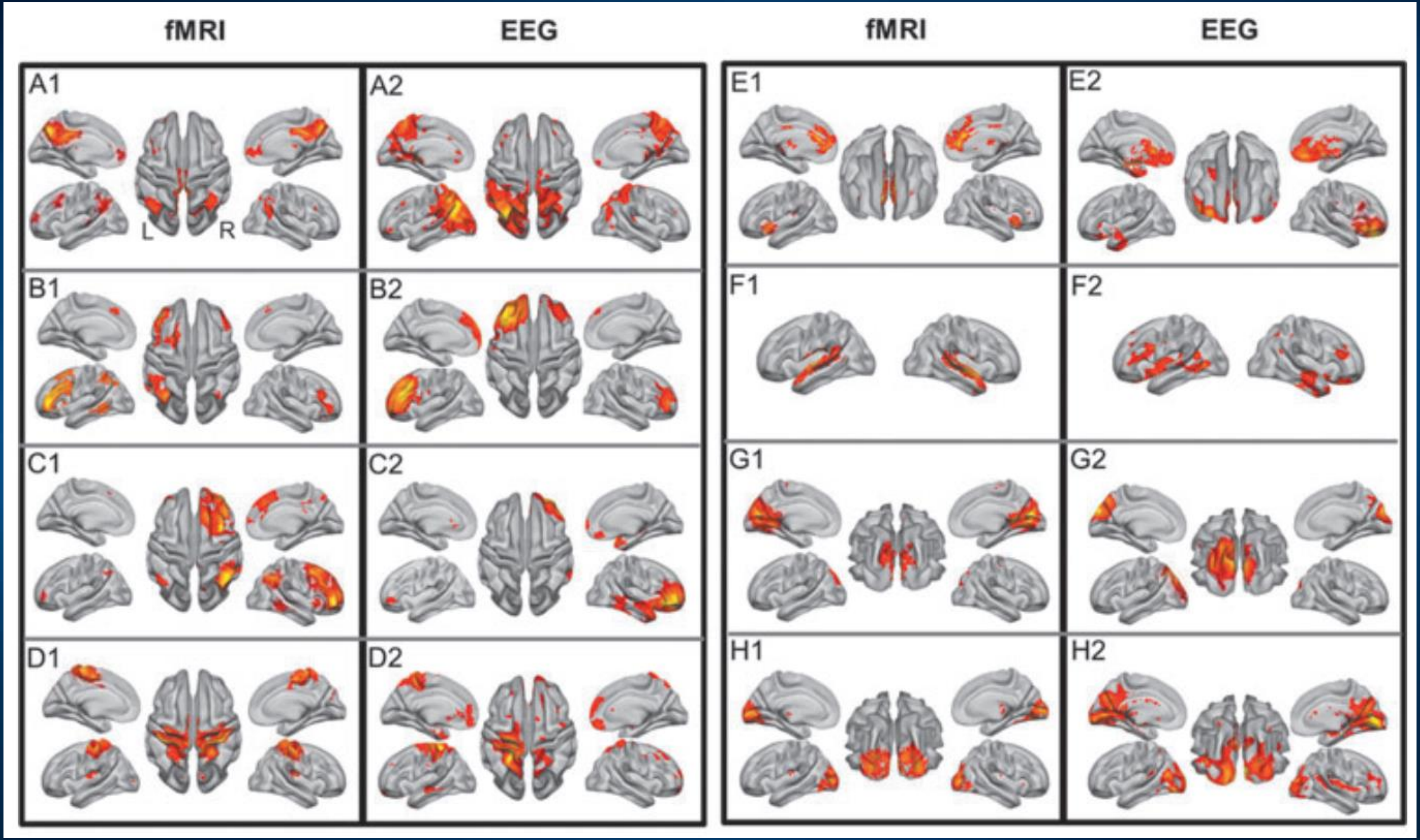


A. Keitel i J. Gross, „Individual human brain areas can be identified from their characteristic spectral activation fingerprints”, *PLoS Biol* 14, e1002498, 2016

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)

Dynamic functional brain networks

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.

EEG non-linear features

Features: not only structure, but also dynamics.

Nonlinear invariant measures of a time series and their physical interpretation, recurrence quantification analysis (RQA).

For example:

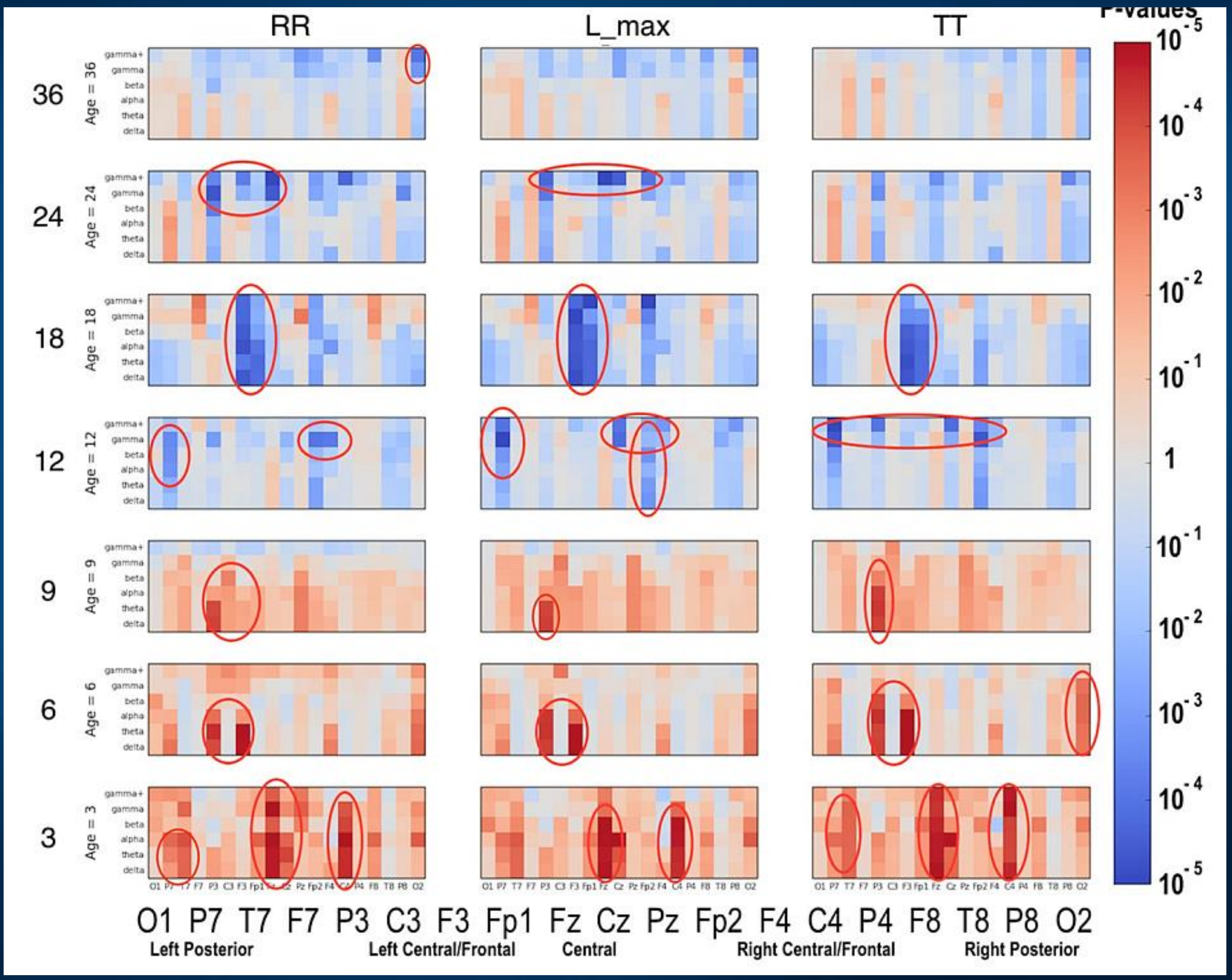
1. Sample Entropy (SampE)
2. Entropy derived from recurrence plot (L_entr).
3. Recurrence rate (RR), probability of recurrence.
4. Determinism (DET), repeating patterns in the system.
5. Laminarity (LAM), frequency of transitions between states.
6. Trapping time (TT), time in a given state.

ASD vs Low Risk Healthy

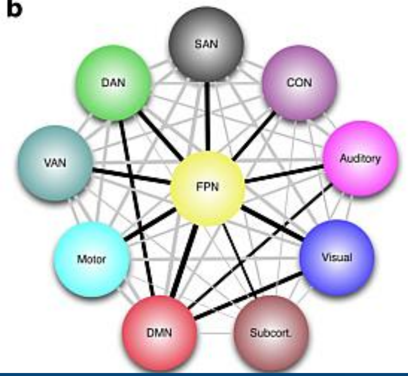
RR = recurrence rate

L_max = max line length, related to Lyapunov exponent

TT = trapping time



Reorganization of brain nets



Global Neuronal Workspace Theory (Deahene et al. 1998): brain processes underlying effortful tasks require:

- Specialized modular processors: perceptual, motor, memory, attentional;
- global workspace for activation patterns 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).

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.

Finc K, Bonna K, He X, Lydon-Staley D, Kühn S, Duch W, Bassett D.S. (2020) Dynamic reconfiguration of functional brain network during working memory training. Nature Communications 11, 2435, 2020

Brain modules and cognitive processes

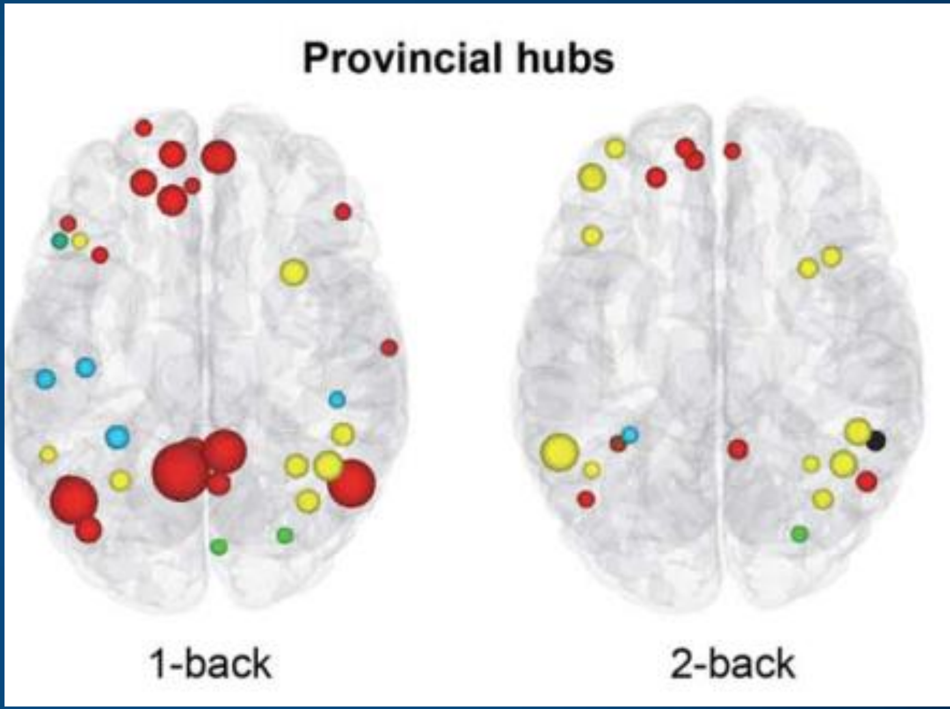
Simple and more difficult tasks, requiring the whole-brain network reorganization.

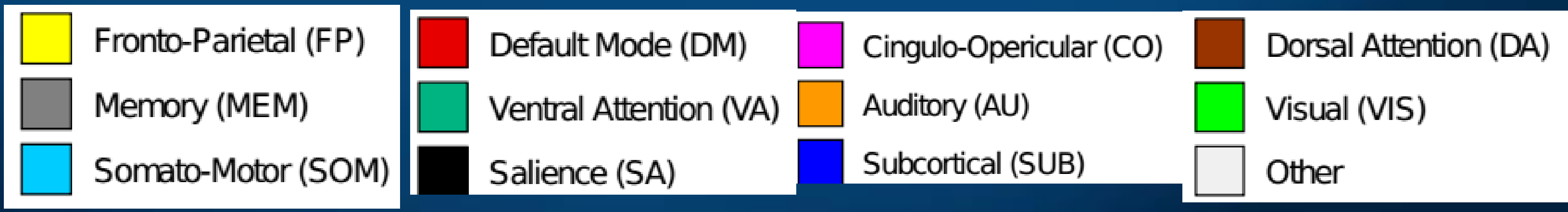
Left: 1-back local hubs

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

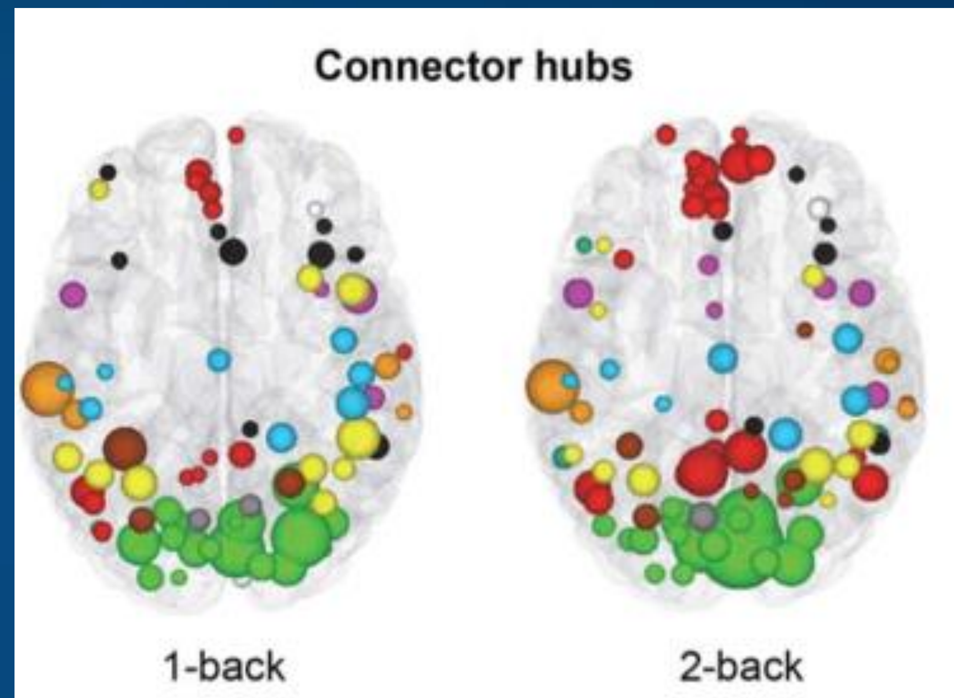
Simple and more difficult tasks, requiring the whole-brain network reorganization.

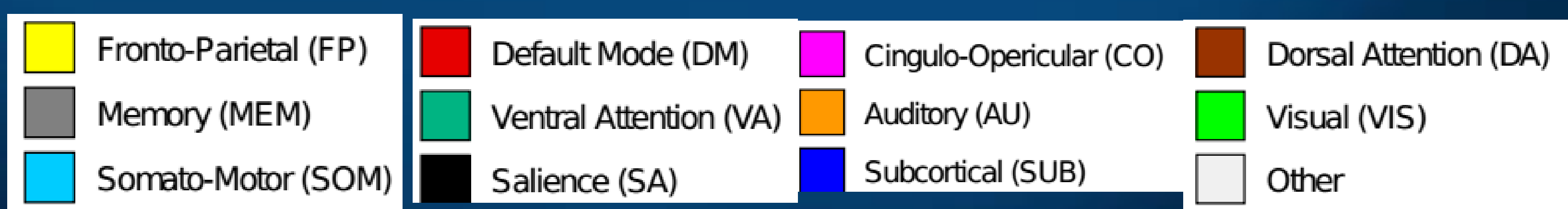
Left: 1-back connector hubs

Right: 2-back connector hubs

Average over 35 *participants.*

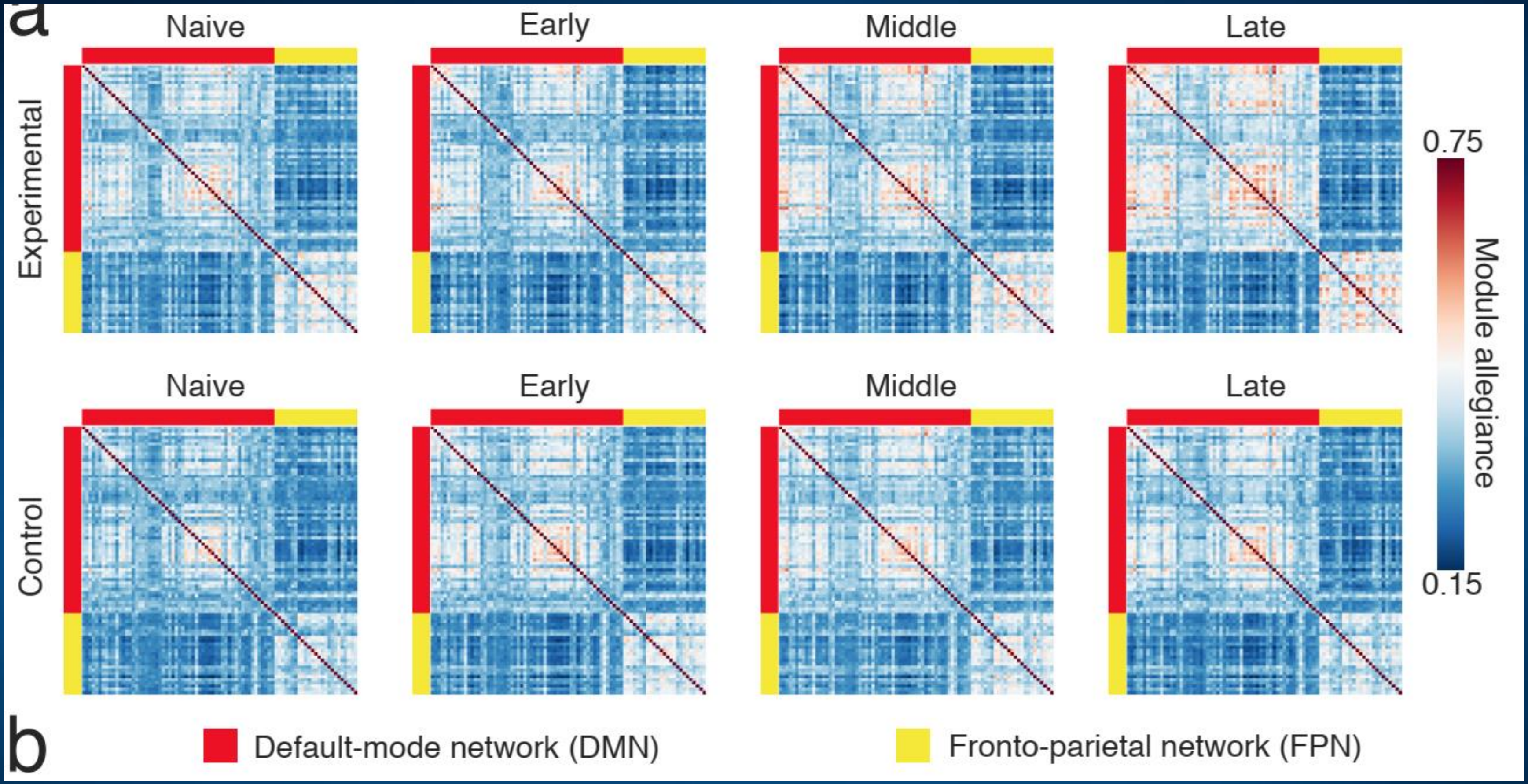
Dynamical change of the landscape of attractors, depending on the cognitive load – System 2 (Khaneman).
DMN areas engaged in global binding!





K. Finc et al, HBM (2017).

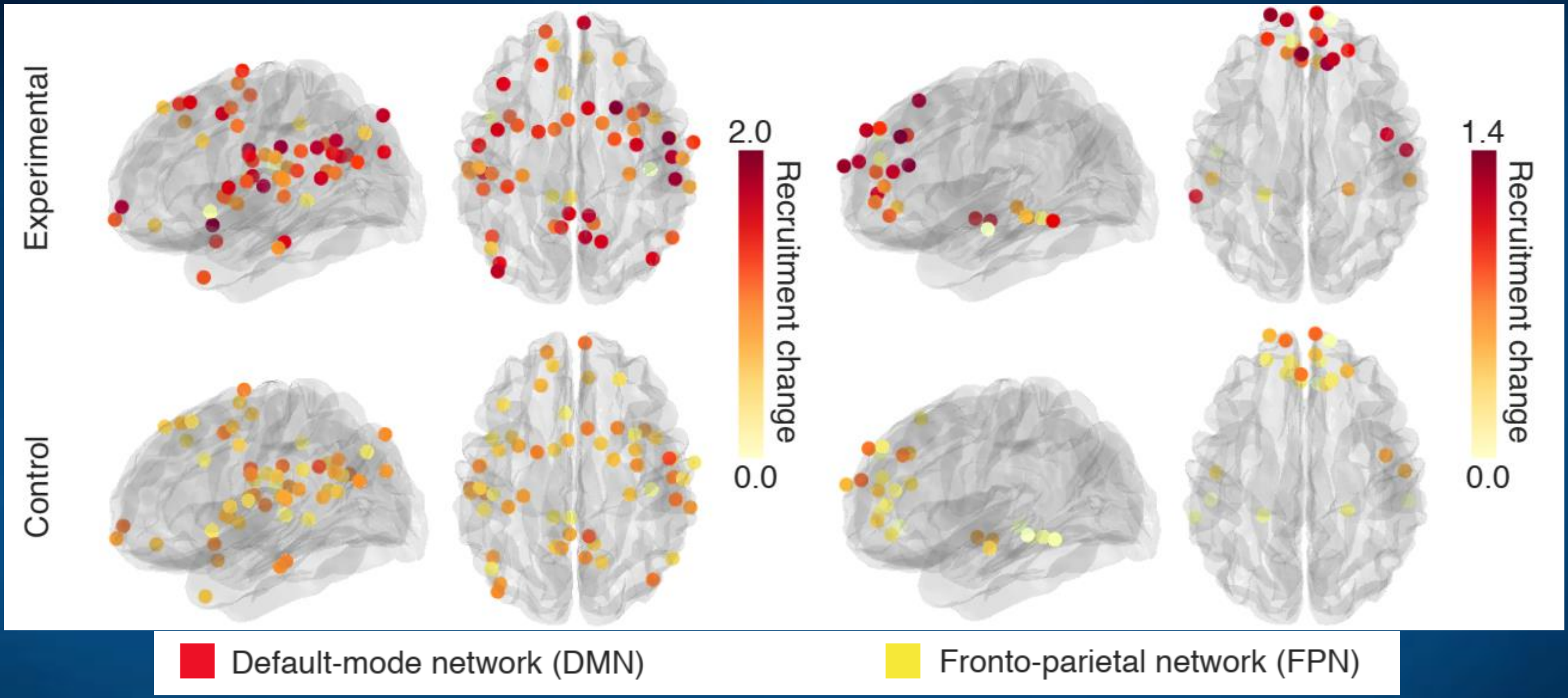
Working memory training



6-week training, dual n-back task, **changes in module allegiance of fronto-parietal and default-mode networks.** Each matrix element represents the probability that the pair of nodes is assigned to the same community.

Segregation of task-relevant DMN and FPN regions is a result of training and complex task automation.

Working memory training



Recruitment changes from the ‘Naive’ to the ‘Late’ stage of training.

Both control and experimental groups exhibited increase of the DMN recruitment but FPN recruitment only increased in experimental group.

No consistent changes in FPN-DMN networks integration was noticed.

Finc et al. Nature Neuroscience 2020

Simulations of brain networks

Model of reading & dyslexia

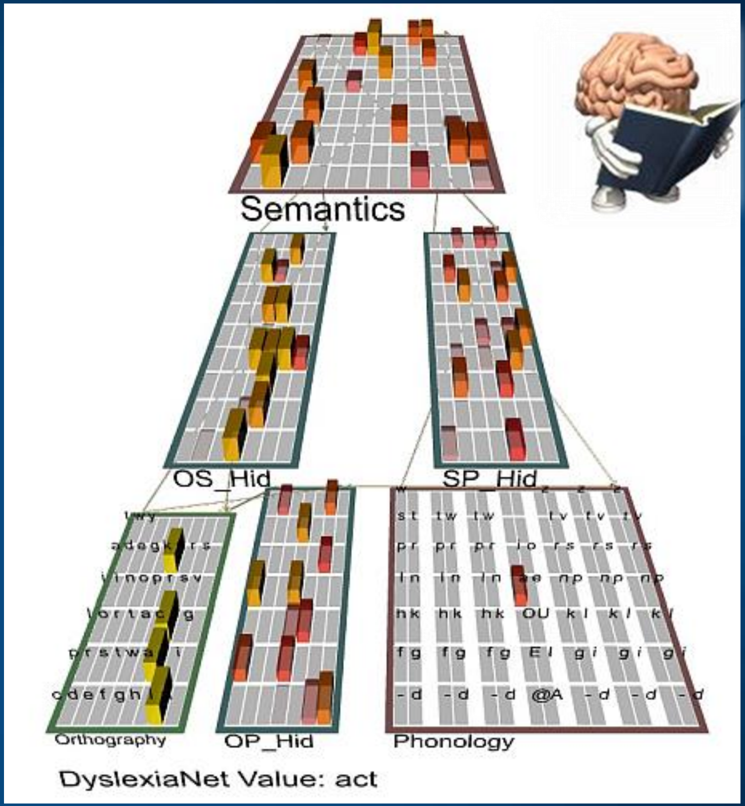
Emergent neural simulator:

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.

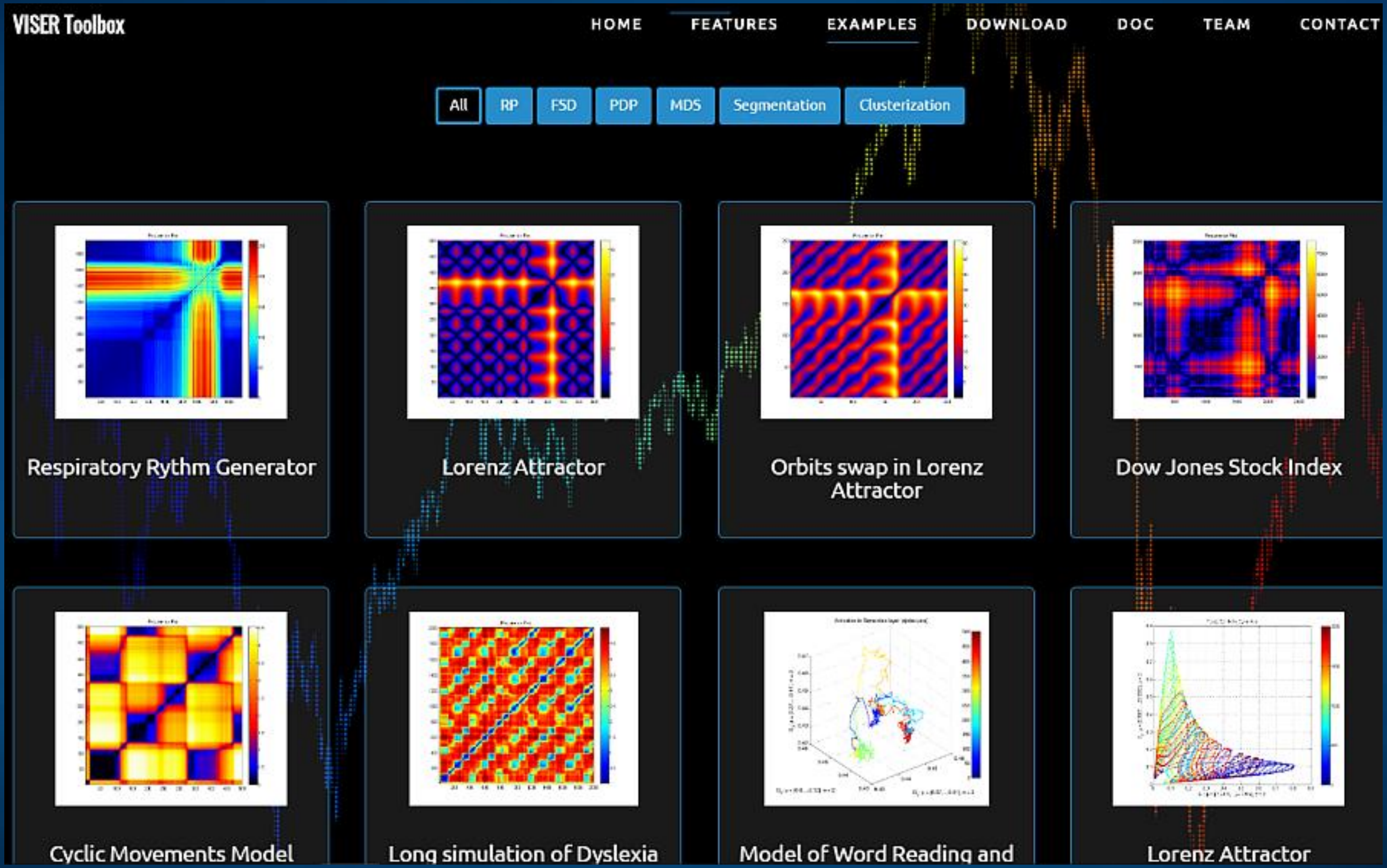


Learning: mapping one of the 3 layers to the other two.

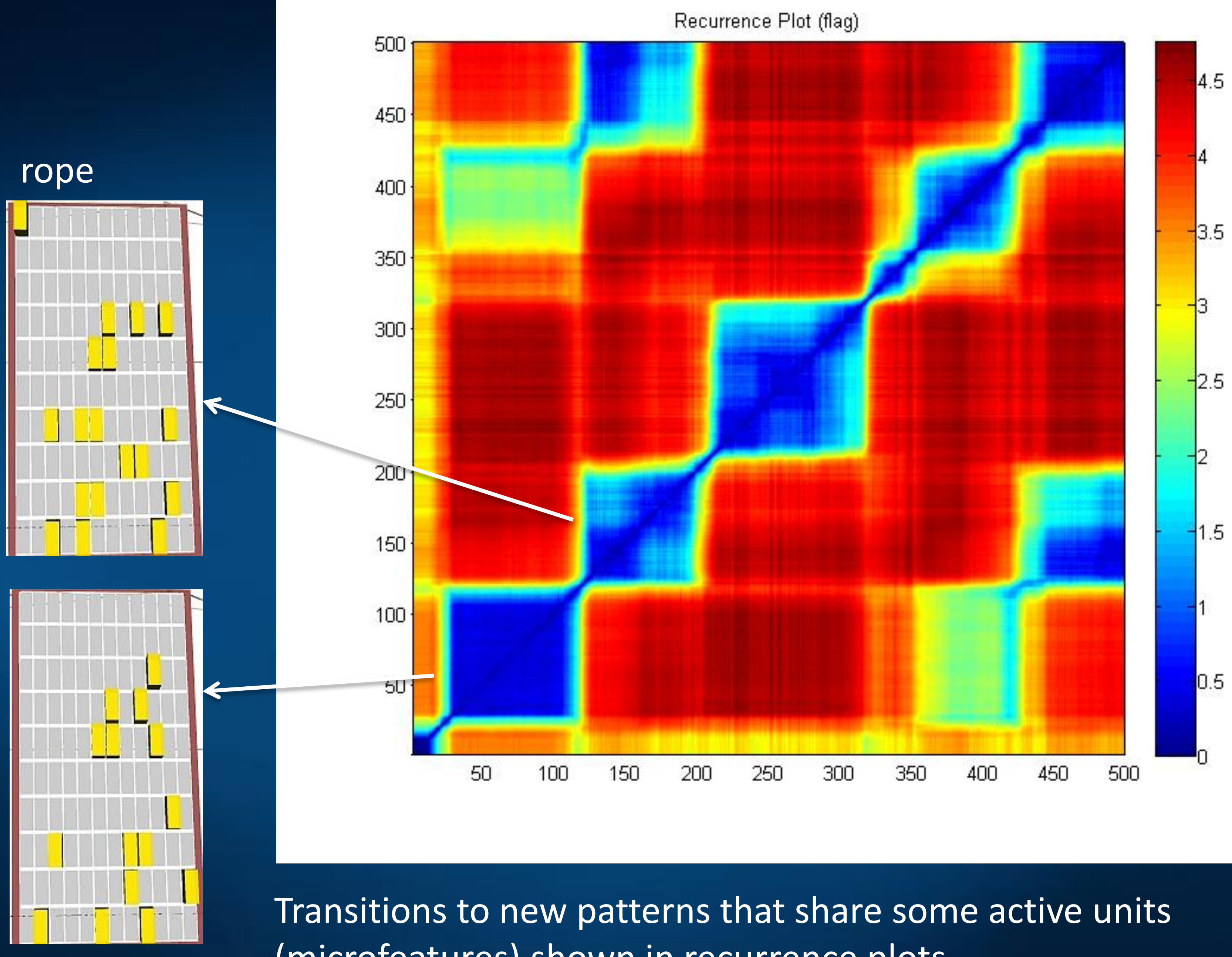
Fluctuations around final configuration = attractors representing concepts.

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

Viser toolbox

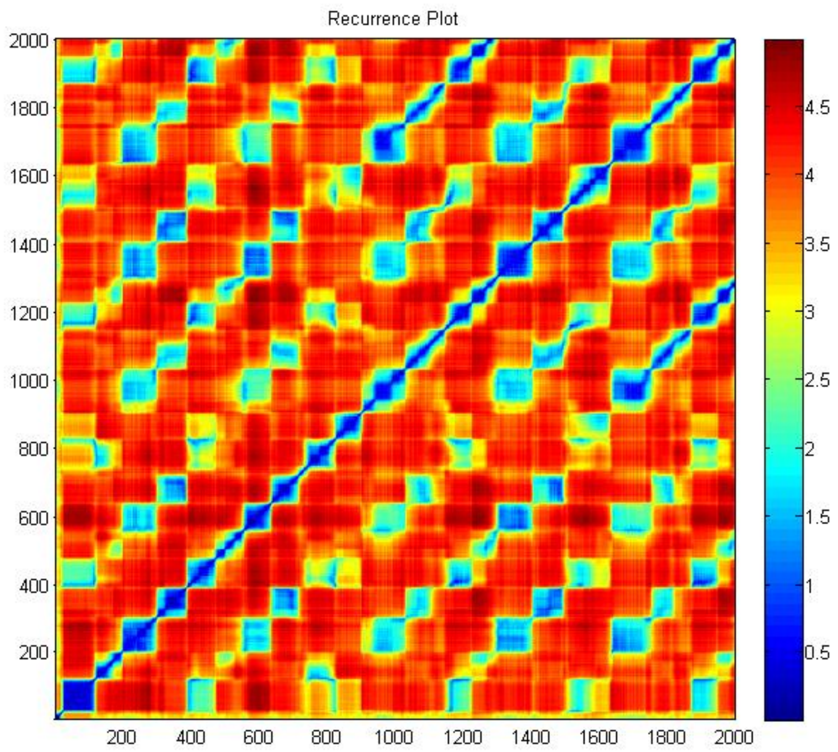


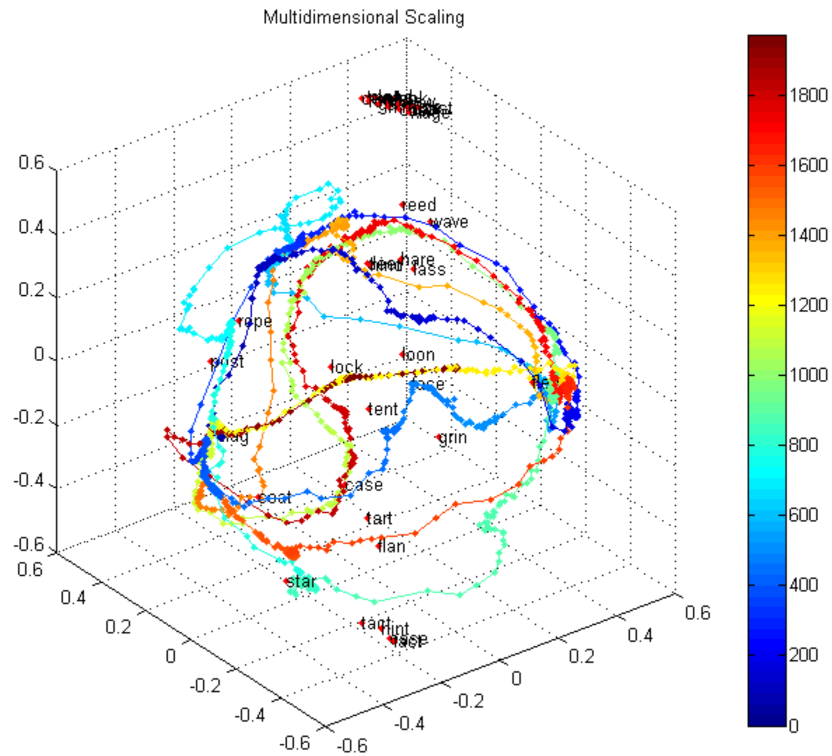
Nasz Viser toolbox (Dobosz, Duch) do wizualizacji szeregów czasowych w wielu wymiarach różnymi technikami.



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

Trajectory visualization

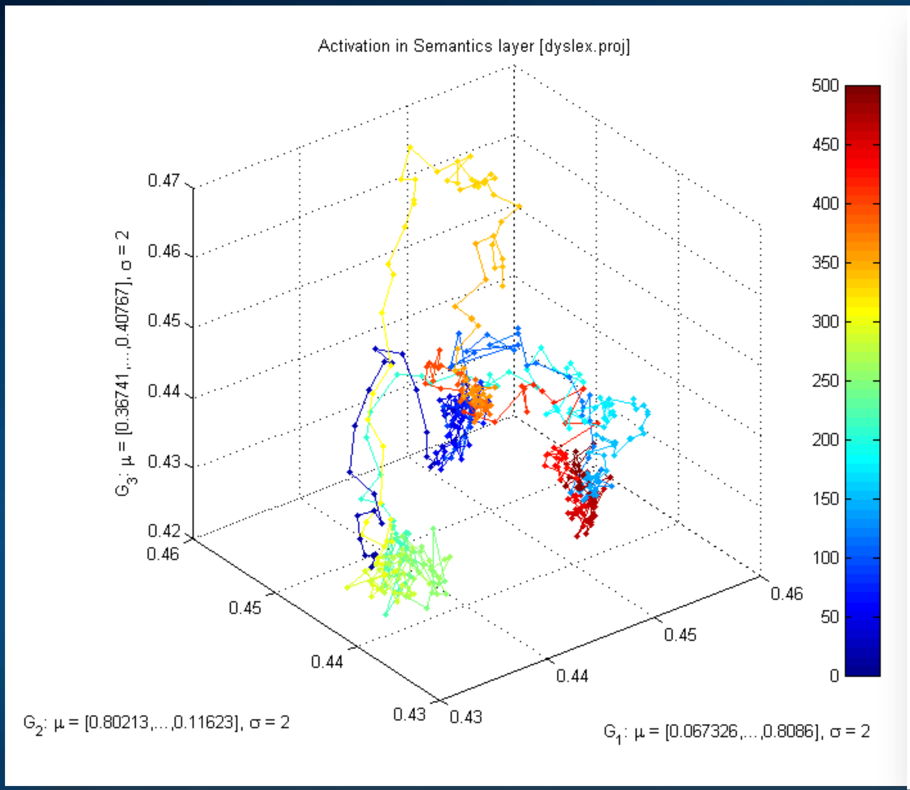


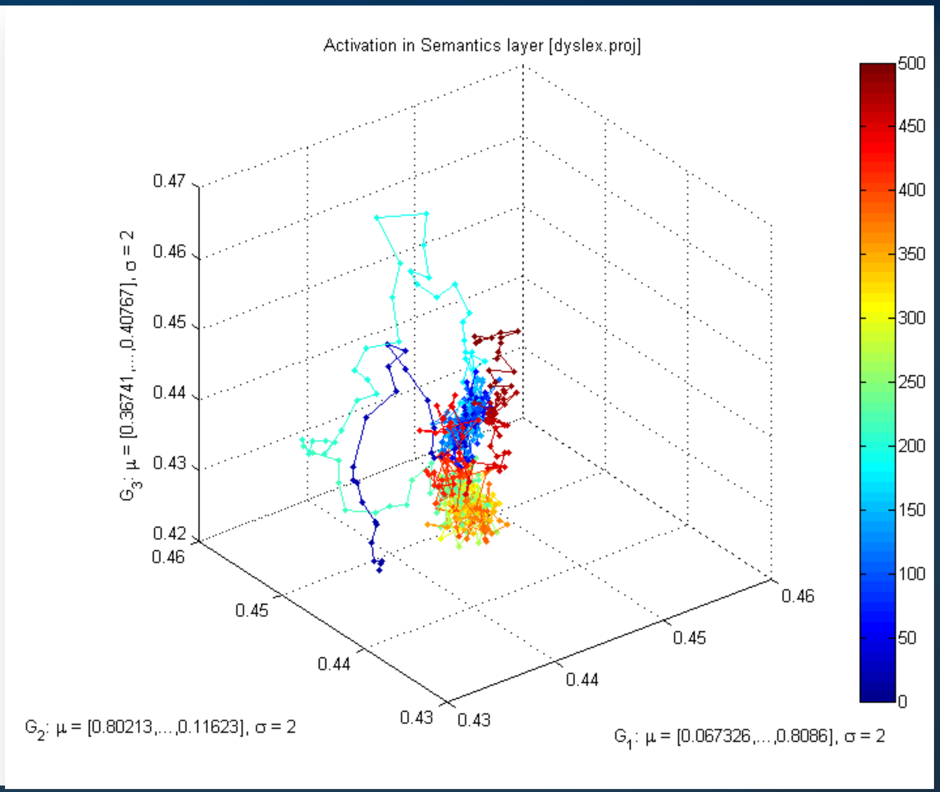


Recurrence plots and MDS/FSD/SNE visualization of trajectories of the brain activity. Here data from 140-dim semantic layer activity during spontaneous associations in the 40-words microdomain, starting with the word “flag”.

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

Typical Development vs. Autism



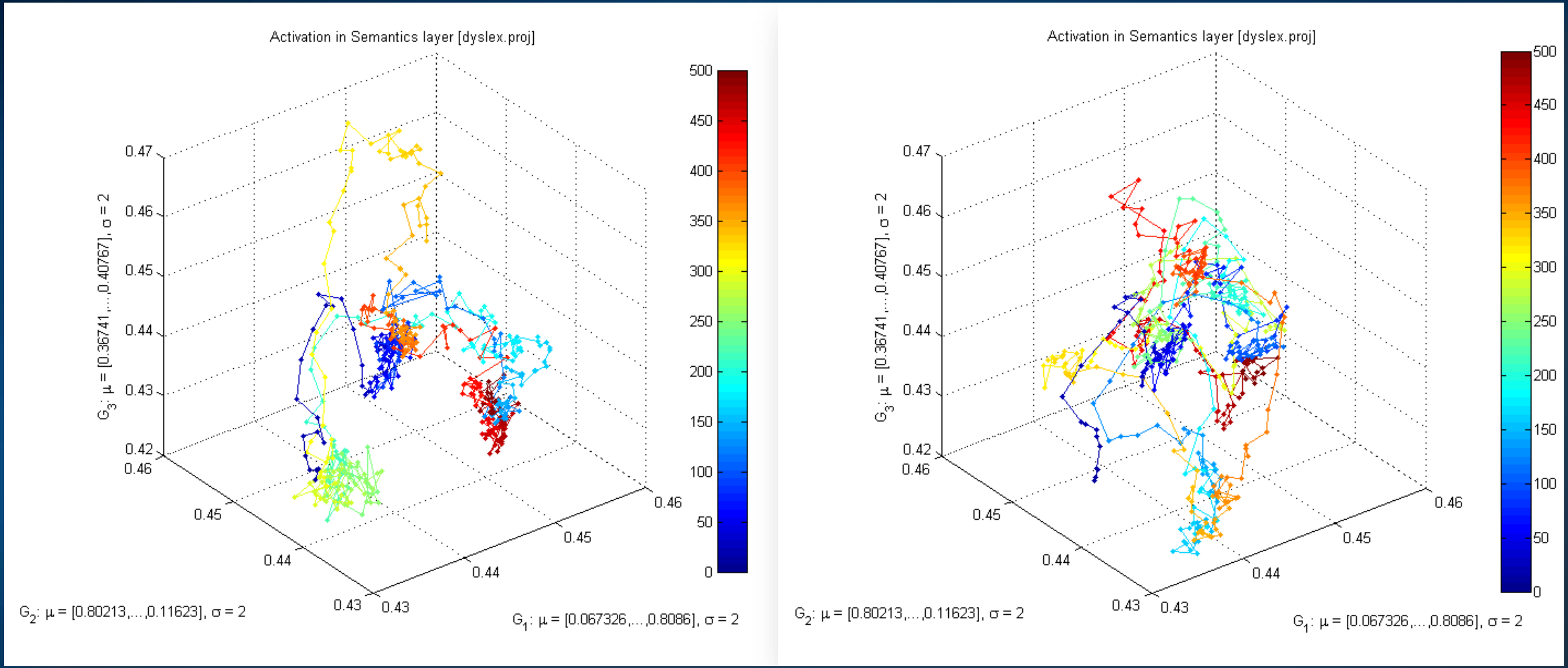


All plots for the flag word, different values of b_inc_dt parameter in the accommodation mechanism. b_inc_dt = 0.01 & b_inc_dt = 0.005

b_inc_dt = time constant for increases in intracellular calcium building up slowly as a function of activation, controls voltage-dependent leak channels.

http://kdobosz.wikidot.com/dyslexia-accommodation-parameters

Typical Development vs ADHD

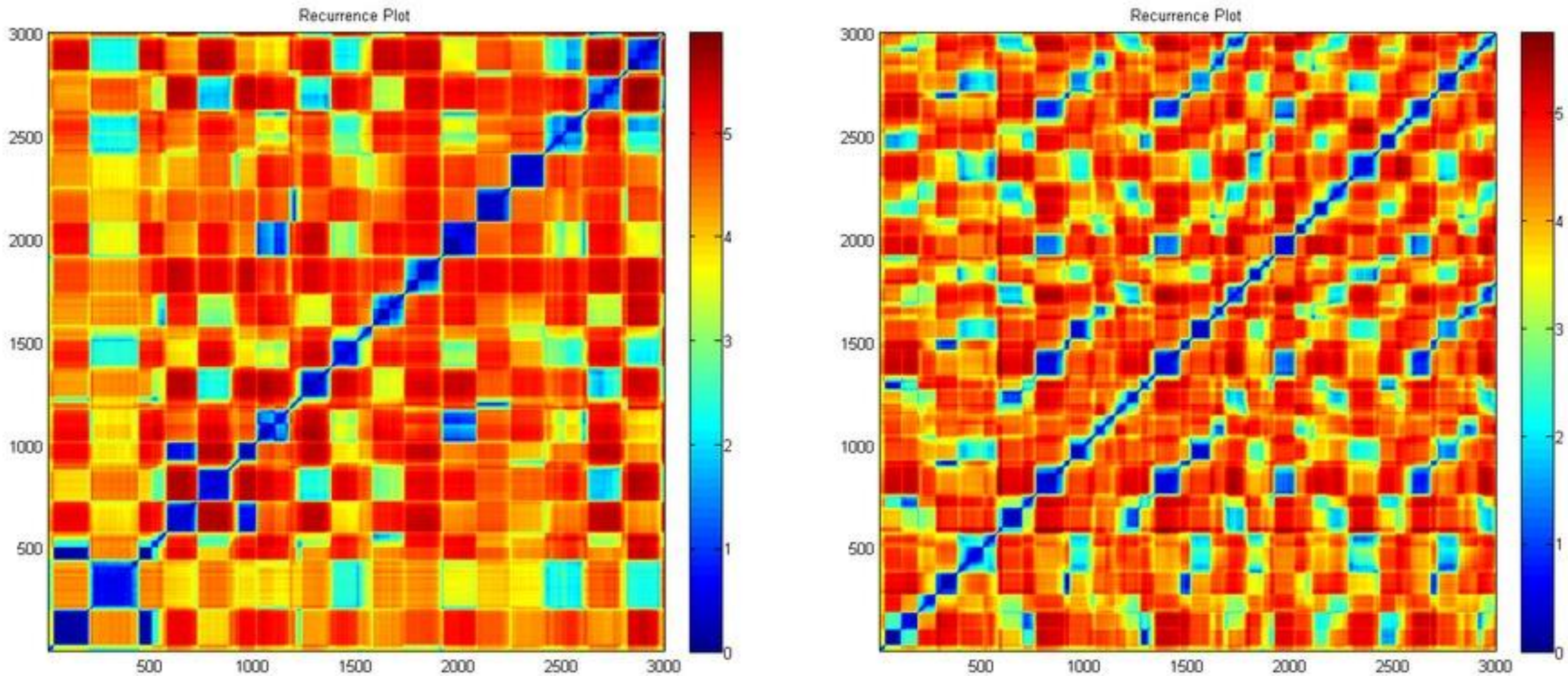


All plots for the flag word, different values of b_inc_dt parameter in the accommodation mechanism. b_inc_dt = 0.01 & b_inc_dt = 0.02.

b_inc_dt = time constant for increases in intracellular calcium which builds up slowly as a function of activation.

http://kdobosz.wikidot.com/dyslexia-accommodation-parameters

Rapid stimulation in HF ASD

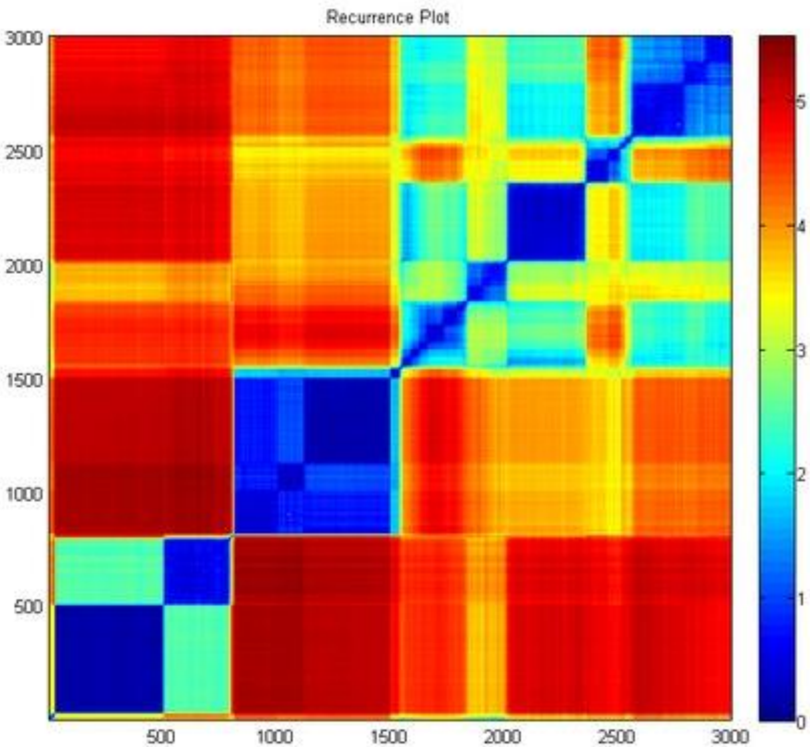


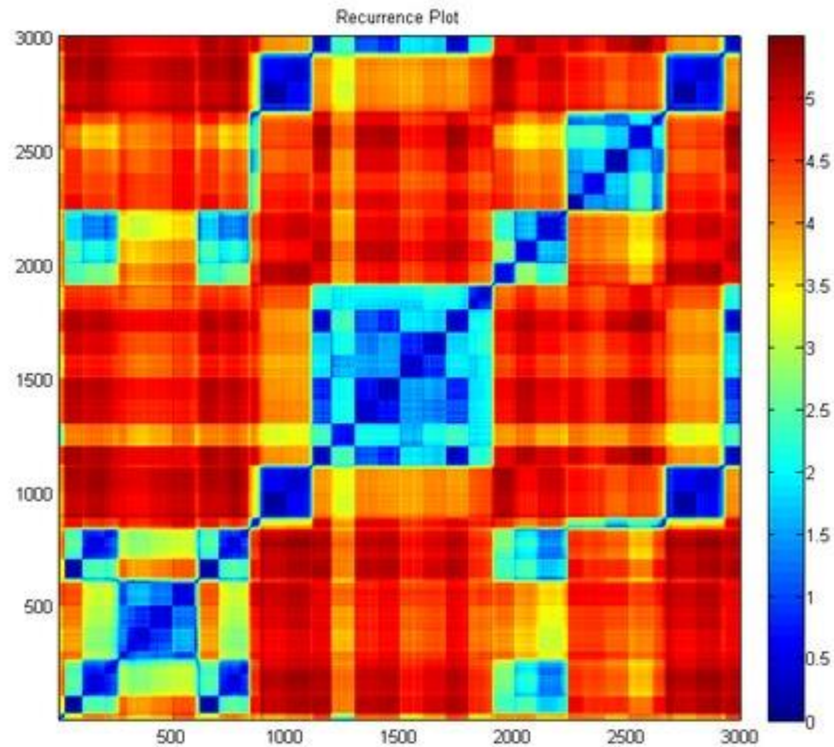
High functioning ASD case (HFA):

normal speed of presentation
long dwelling times

fast presentation
enforced quick resynchronization
more internal stimuli.

Rapid stimulation in deep autism



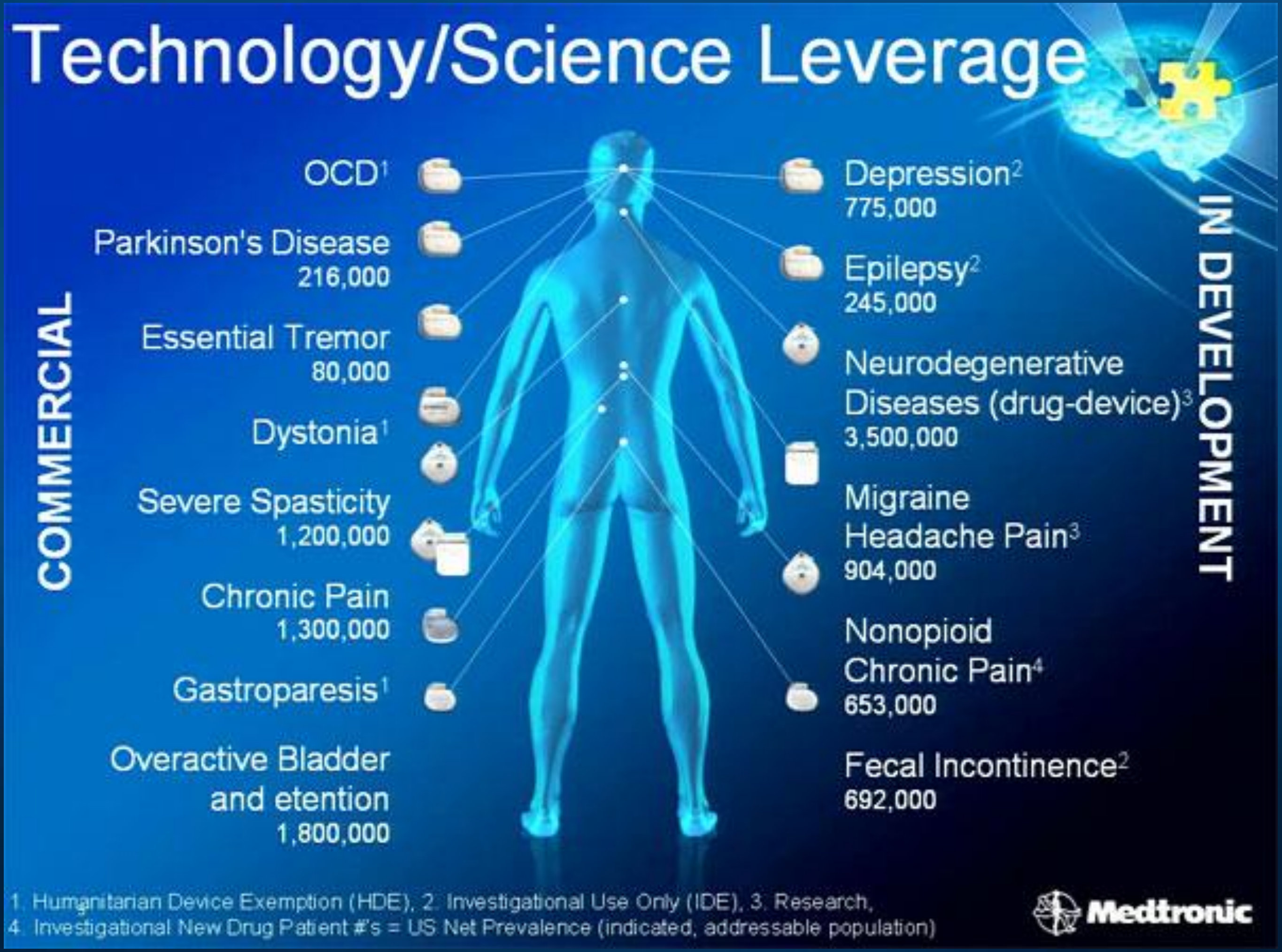


Normal speed
skipping some words,
no associations

fast presentation
more internal states
some associations arise

Neuromodulation

Cochlear implants are common, but deeper implants that stimulate or even replace some brain structures start to appear, not only for deficits at the level of perception, but to regulate neural processes.



Why neuromodulation works?

- Neurorehabilitation: many successes but mechanism is unknown.
- Hypothesis 1: changing the activation thresholds of neurons (sensitization and inhibition) changes the way brain networks work.
- Hypothesis 2: neuromodulation leads to changes in cardiovascular coupling to neurons, improving blood flow in microvessels.

This can be tested with non-invasive transorbital Alternating Current micro-stimulation device (hACS), used in Magdeburg and Berlin clinics.

Sabel (2018) **Restoring Low Vision.** Amazon, 251 pp.

We need to show how to optimize parameters of neuromodulation to increase flow of visual information in the brain.

Conclusions

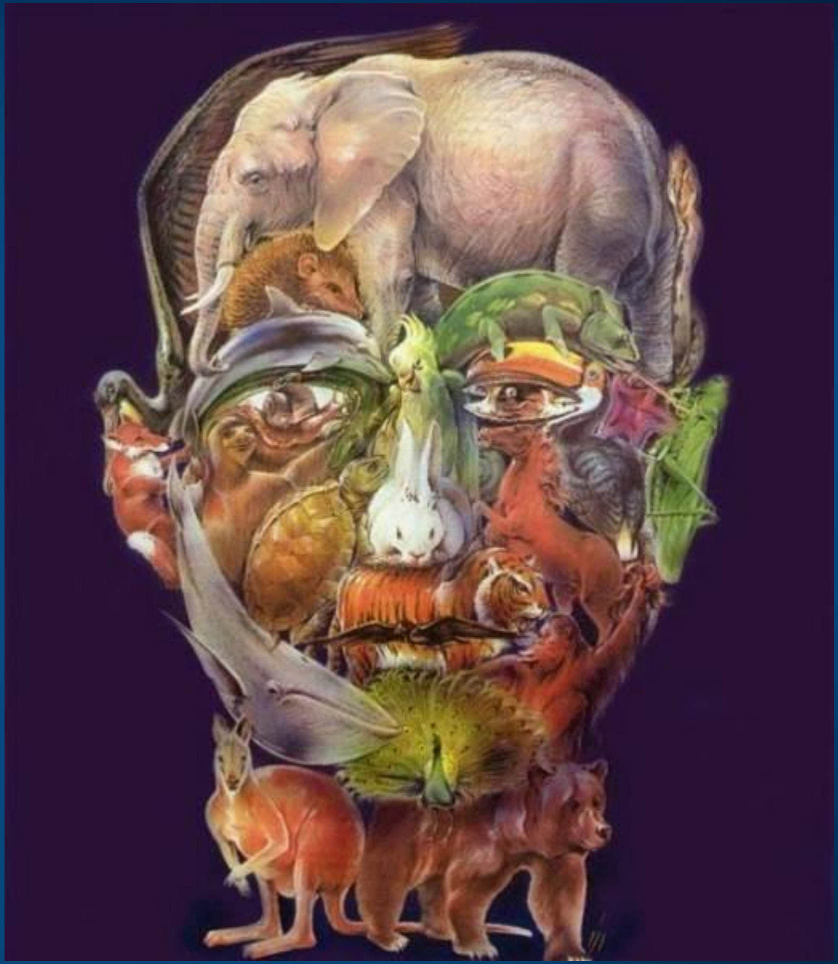
- **Neurocognitive technologies** are used to diagnose, repair and optimize brain processes, helping in neurorehabilitation, pain management, conscious control of brain states. Neuroprostheses for sensory systems and limb control facilitate **enhancement of human cognition** and activity. This is much safer approach than genetic manipulation.
- Mental states – such as motor intentions, plans, images, inner voices – result from brain states that can be measured and interpreted.
- Influence of molecular/genetic levels on the brain may be understood indirectly, via changes in neurodynamics, using analysis of brain signals and computer simulations. This is the key to understanding mental states.
- The future belongs to cyborgs!

My group of neuro-cog-fanatics

Thank you for synchronizing your neurons!

Our Center of Excellence in Neuroinformatics has open positions for PhD students, postdocs and visiting profs!

Info is on my webpage.



Google: Wlodek Duch

=> talks, papers, lectures, Flipboard …