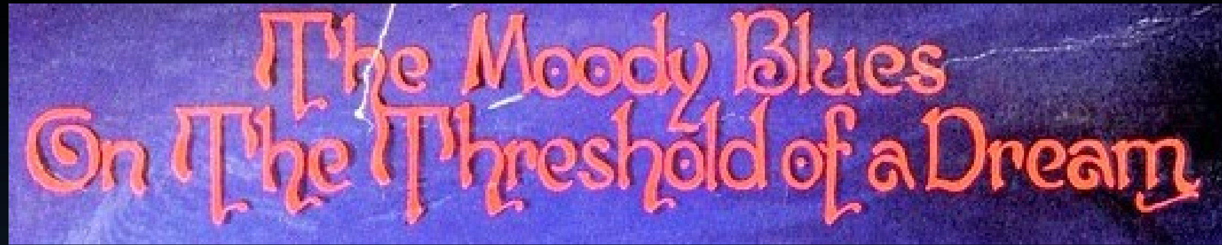
Artificial Intelligence & Neurocognitive Technologies for Human Augmentation

Włodzisław Duch

Neurocognitive Laboratory, Center for Modern Interdisciplinary Technologies, & Dept. of Informatics, Faculty of Physics, Astronomy & Informatics, Nicolaus Copernicus University

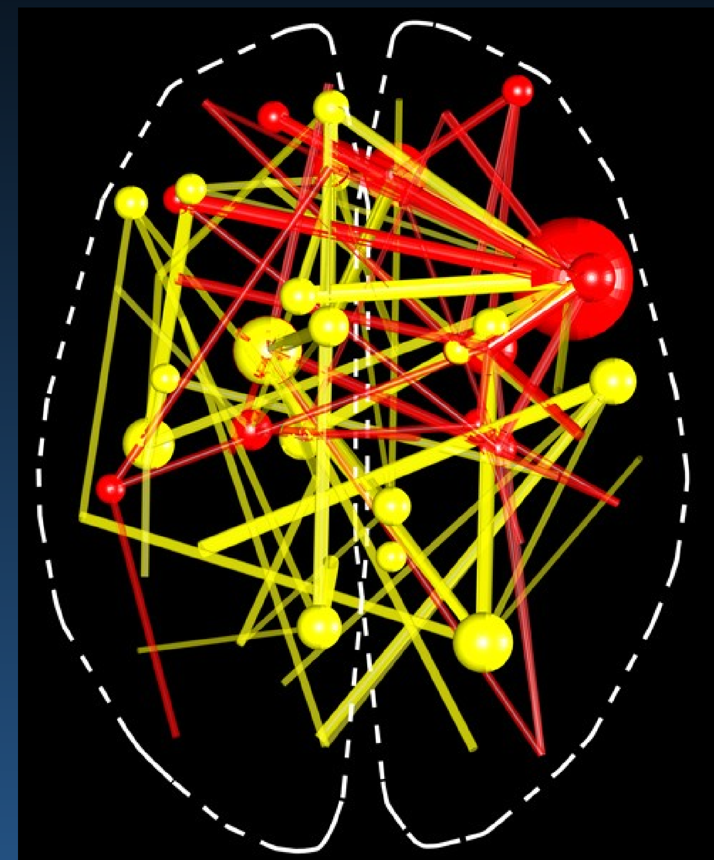
Google: Wlodzislaw Duch

ICAISC 2020, 12-15.09, Zakopane, Poland



How to use technology for enhancement of human cognitive capabilities?

- Global brain neurotech initiatives.
- Human Enhancement and Optimization of Brain Processes.
- Brain-computer-brain interfaces (BCBI)
- Understanding brain networks. Space for mental states.
- Fingerprints of Mental Activity.
- AI <=> Neuroscience.



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

Human Potential

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).

lifeboat foundation
SAFEGUARDING HUMANITY

Great opportunities, but also great dangers.

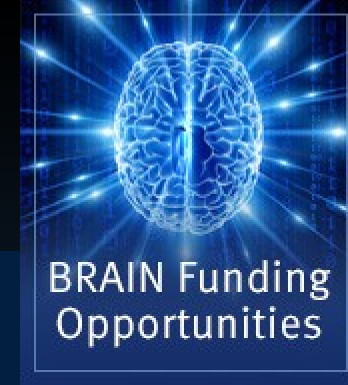
Brain processes (D. Khaneman, ***Thinking, Fast and Slow*** **2011**):

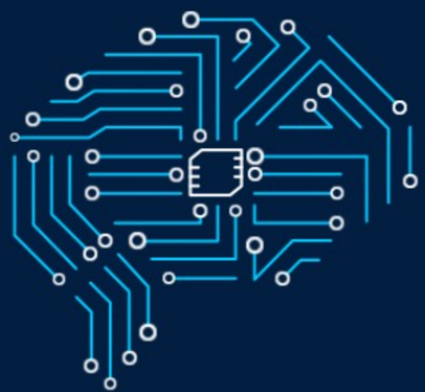
System 1: Fast, automatic, frequent, emotional, stereotypic, rigid, associative, responsible for perception, subconscious.

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

Move what you can to System 1.

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.

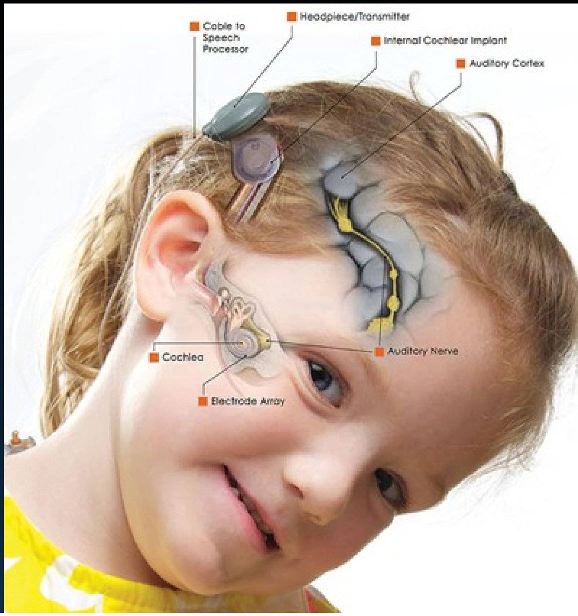
20 IEEE Societies are involved, including: **IEEE Computational Intelligence Society**; Computer Society; Consumer Electronics Society; Digital Senses Initiative; Robotics and Automation Society; Sensors Council; Signal Processing Society; Society on Social Implications of Technology; **Systems, Man,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

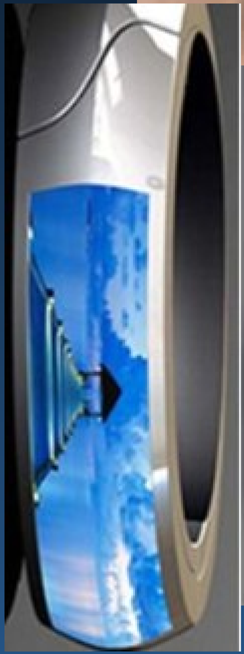
Most these societies are also involved in artificial intelligence.

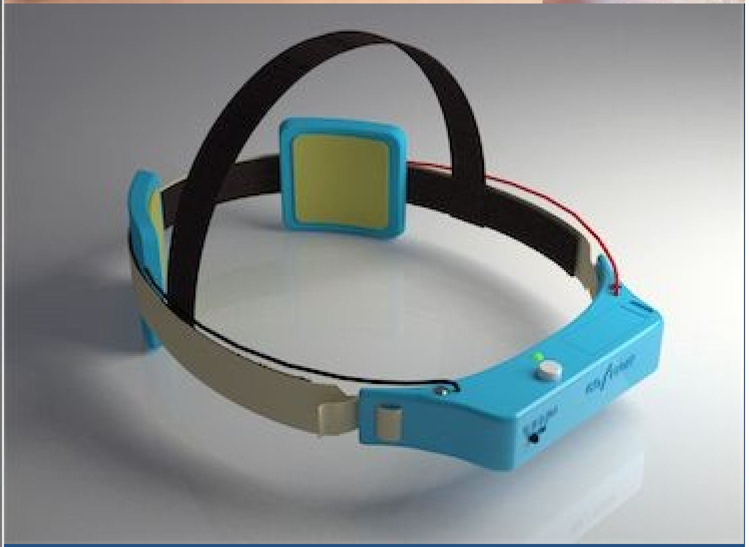
Satya Nadella (CEO, Microsoft): to celebrate National Disability Employment Awareness Month, I'm sharing examples of how technology can be applied to empower the more than one billion people with disabilities around the world.

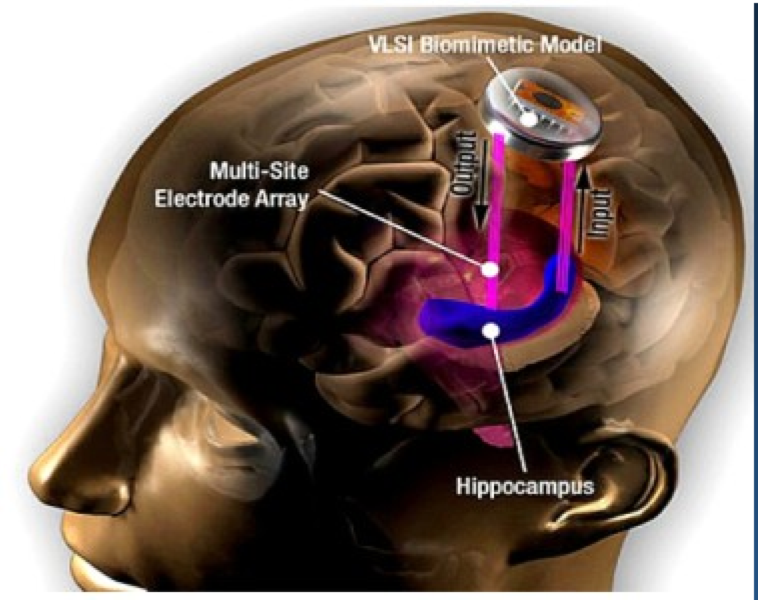
Human Enhancement
and
Optimization of Brain Processes

Enhancing Perception









Improving eyes, ears (cochlear implants), touch, balance, but also memory and attention skills… Implantation of new neurons in the brain?

Walking problems

Neuro-relax

Sounds and music may have arousing or relaxing effects.

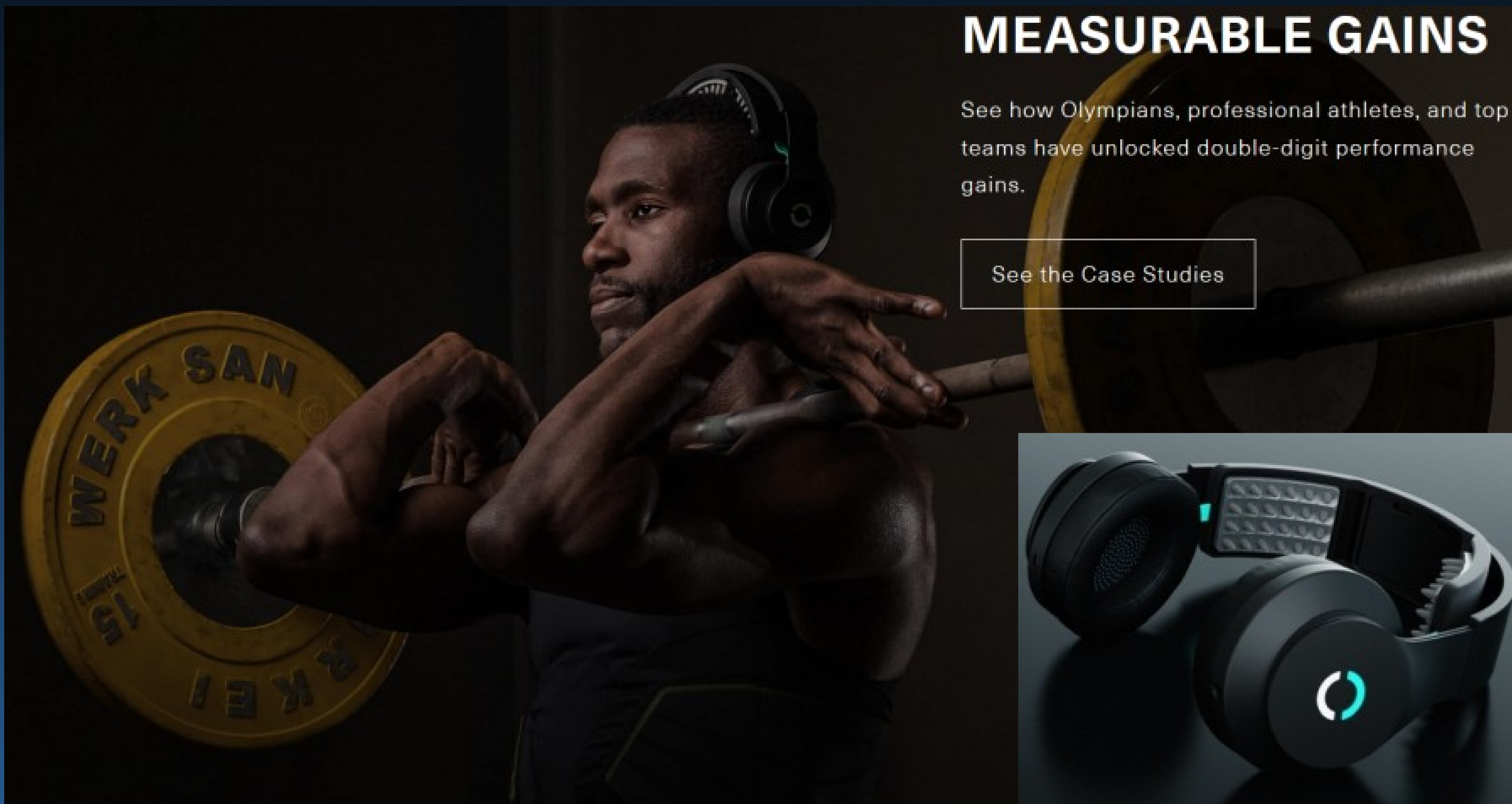
Melomind:

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

melomind

Neuropriming

Effort, stamina, force in sports requires strong activation of muscles by motor cortex. Synchronize your effort with direct current cortex stimulation-add 15%



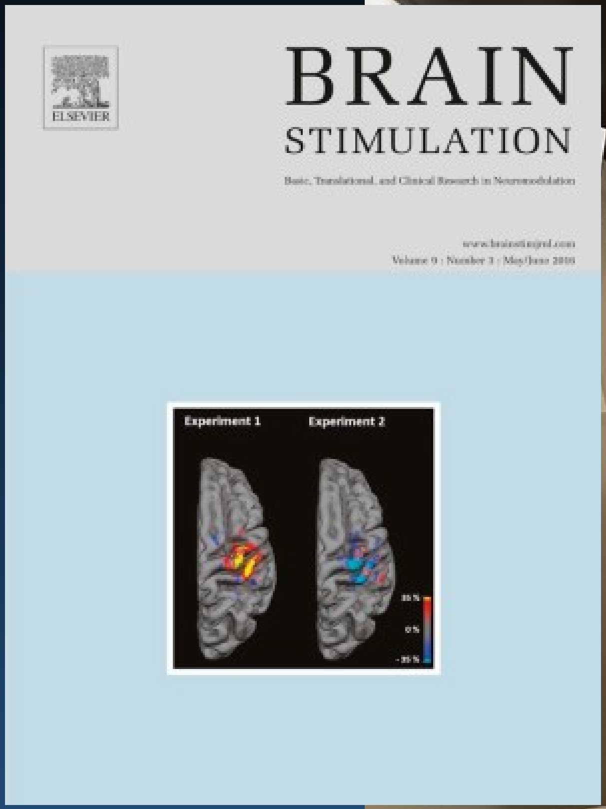
Prime for 20 min, benefit for 60 min.

Haloneuro.com

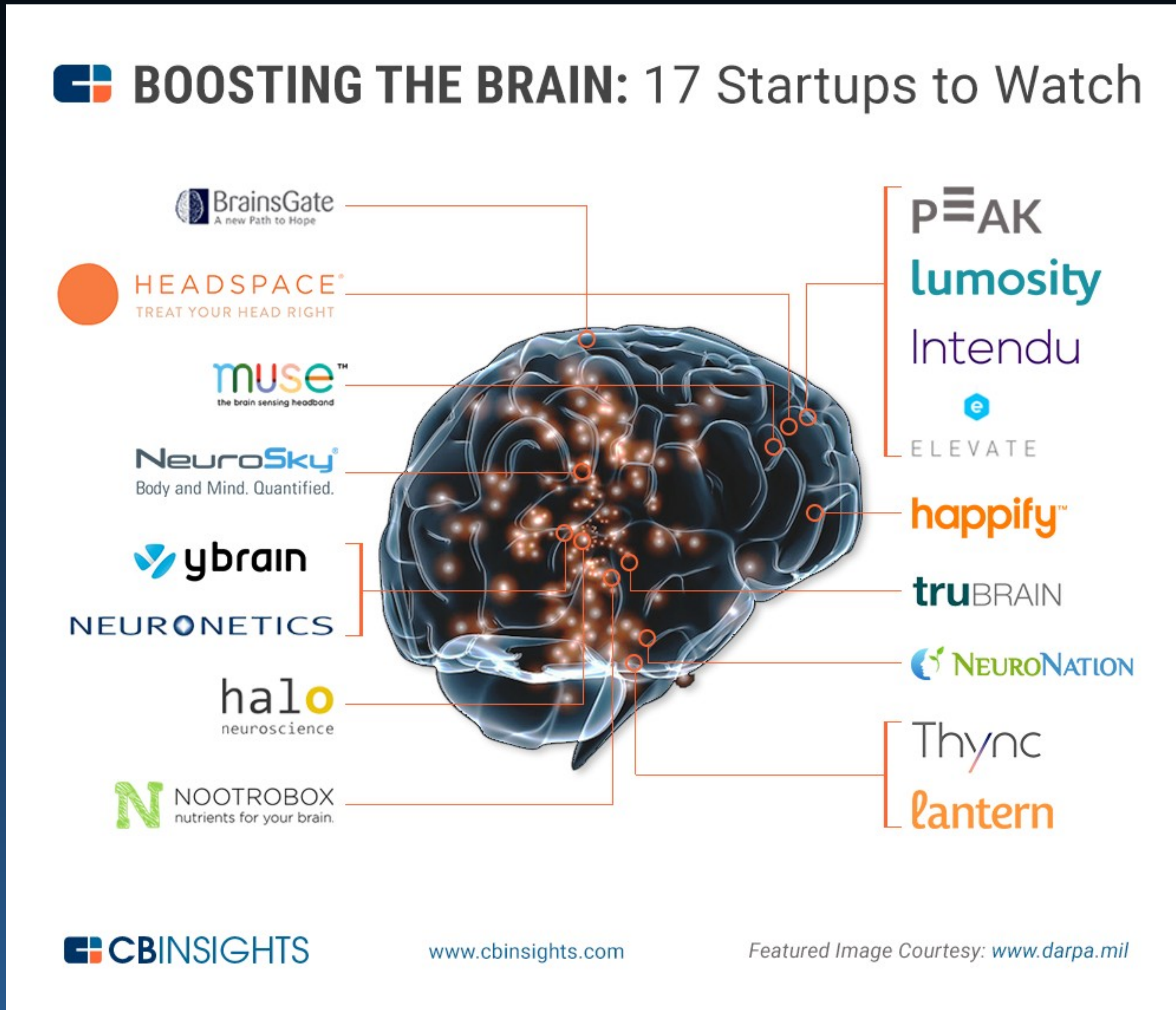
DCS for attention/relaxation

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.

DCS, Direct Current Stimulation



Startups around the world



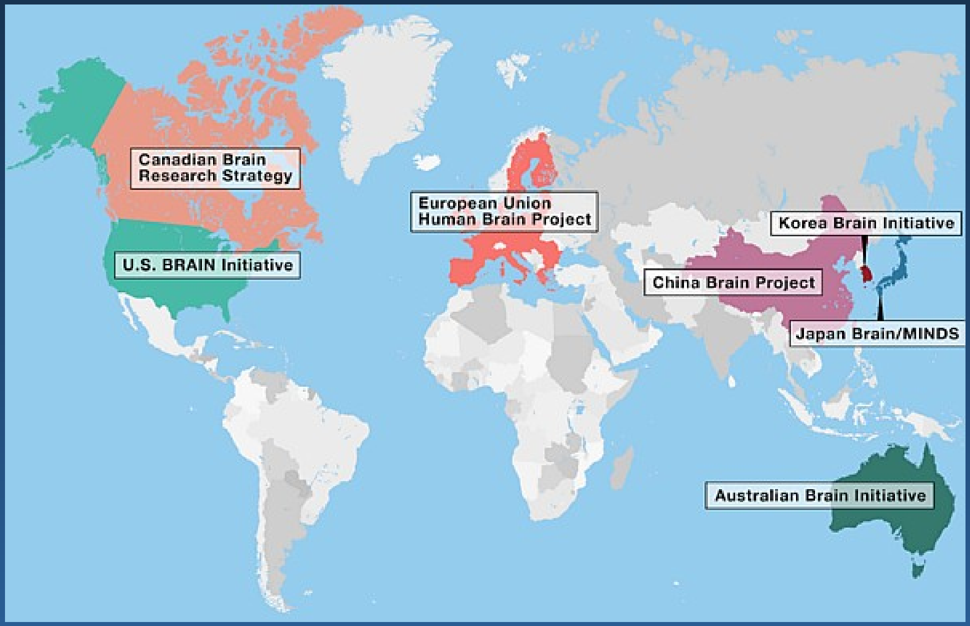
Costs of brain diseases

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.

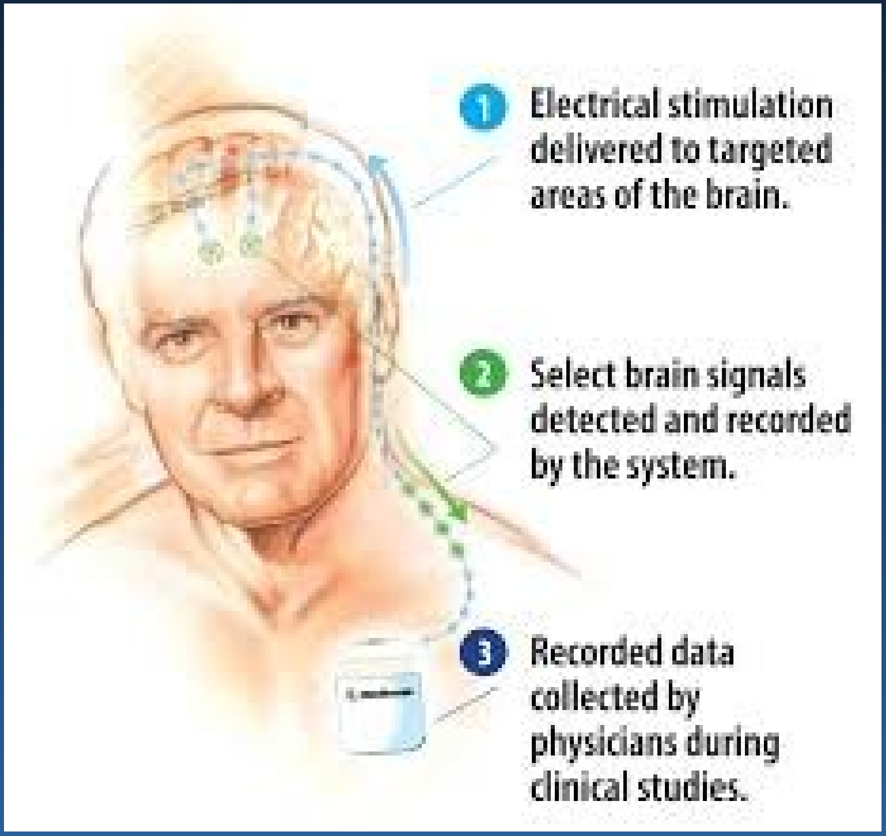
Global Brain large initiatives in North America, Europe, China, Korea, Japan and Australia/NZ + a few other countries.



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.

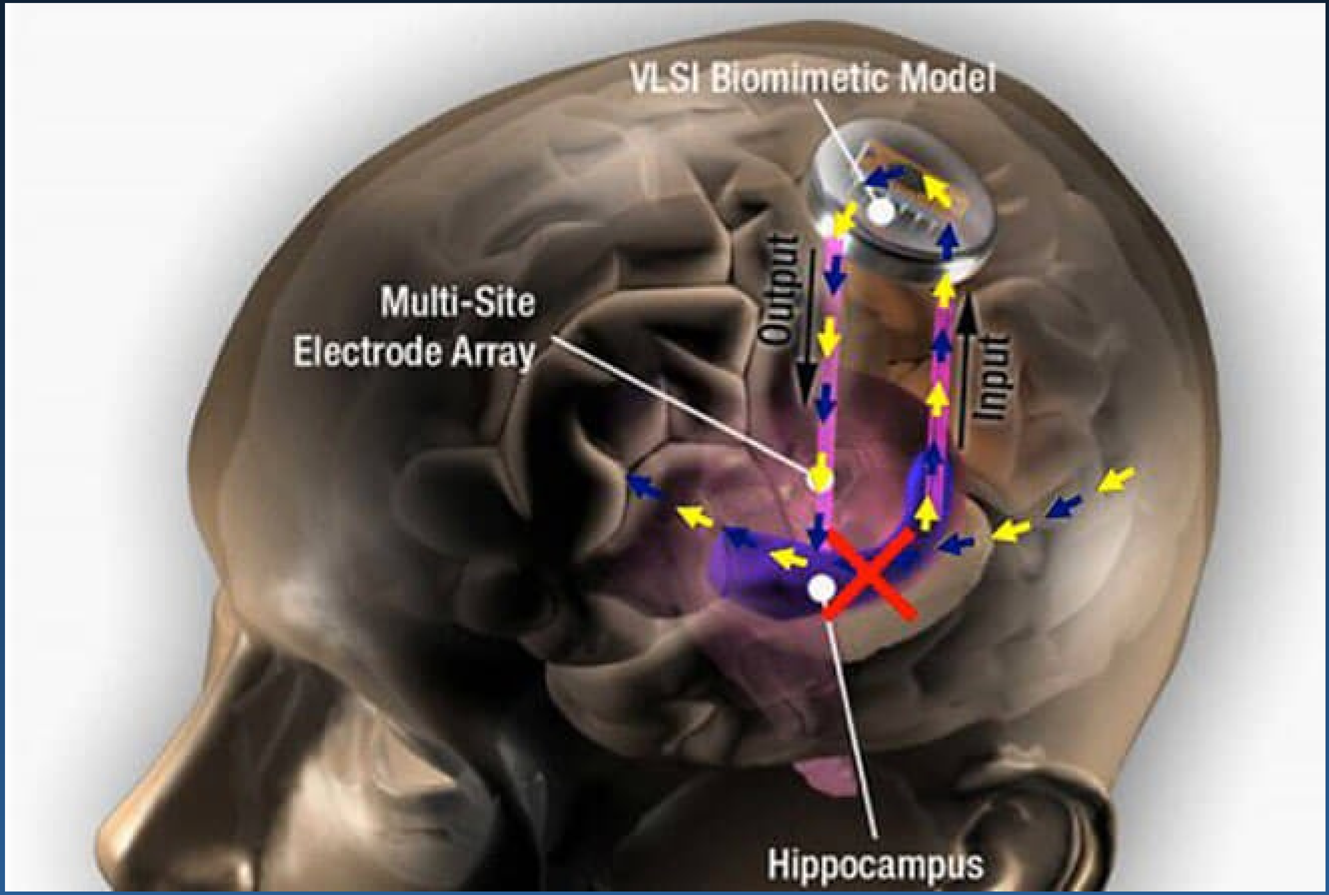
What brain functions can be consciously controlled?



Memory implants

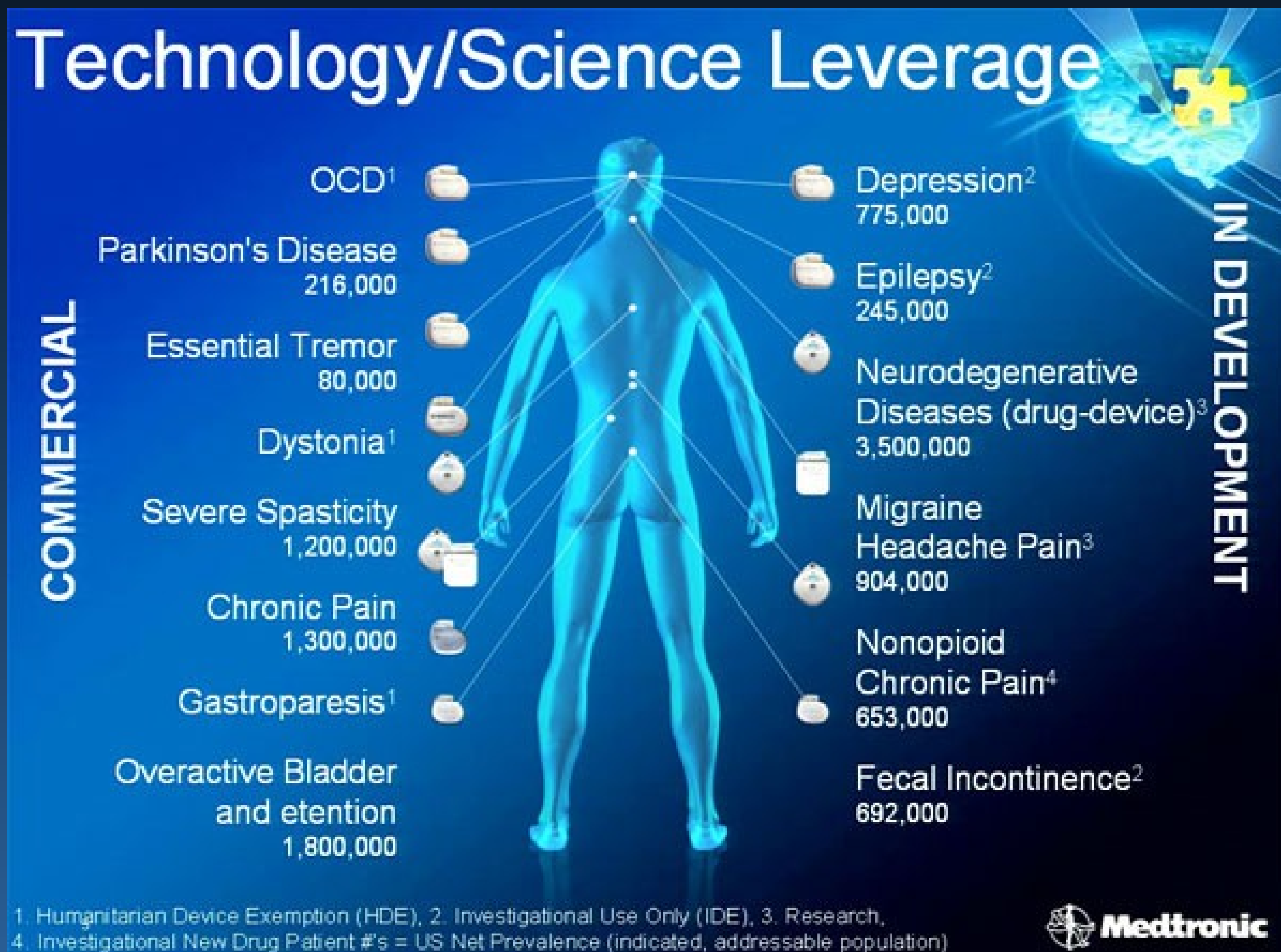
Ted Berger (USC, Kernel): hippocampal neural prosthetics facilitate human memory encoding and recall using the patient's own hippocampal spatiotemporal neural codes. Tests on rats, monkeys and on people gave memory improvements on about 35% (J. Neural Engineering 15, 2018).

DARPA: Restoring Active Memory (RAM), new closed-loop, non-invasive systems that leverage the role of neural “replay” in the formation and recall of memory to help individuals better remember specific episodic events and learned skills.



Neuromodulation

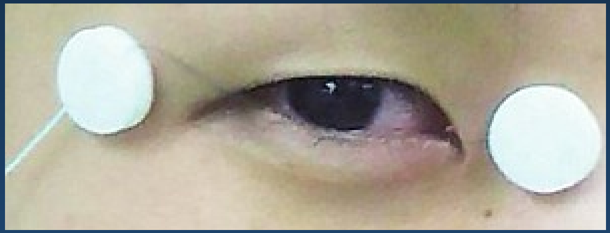
Cochlear implants are common, but deeper implants that stimulate or even replace some brain structures start to appear, not only for deficits at the level of perception, but to regulate neural processes.



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.

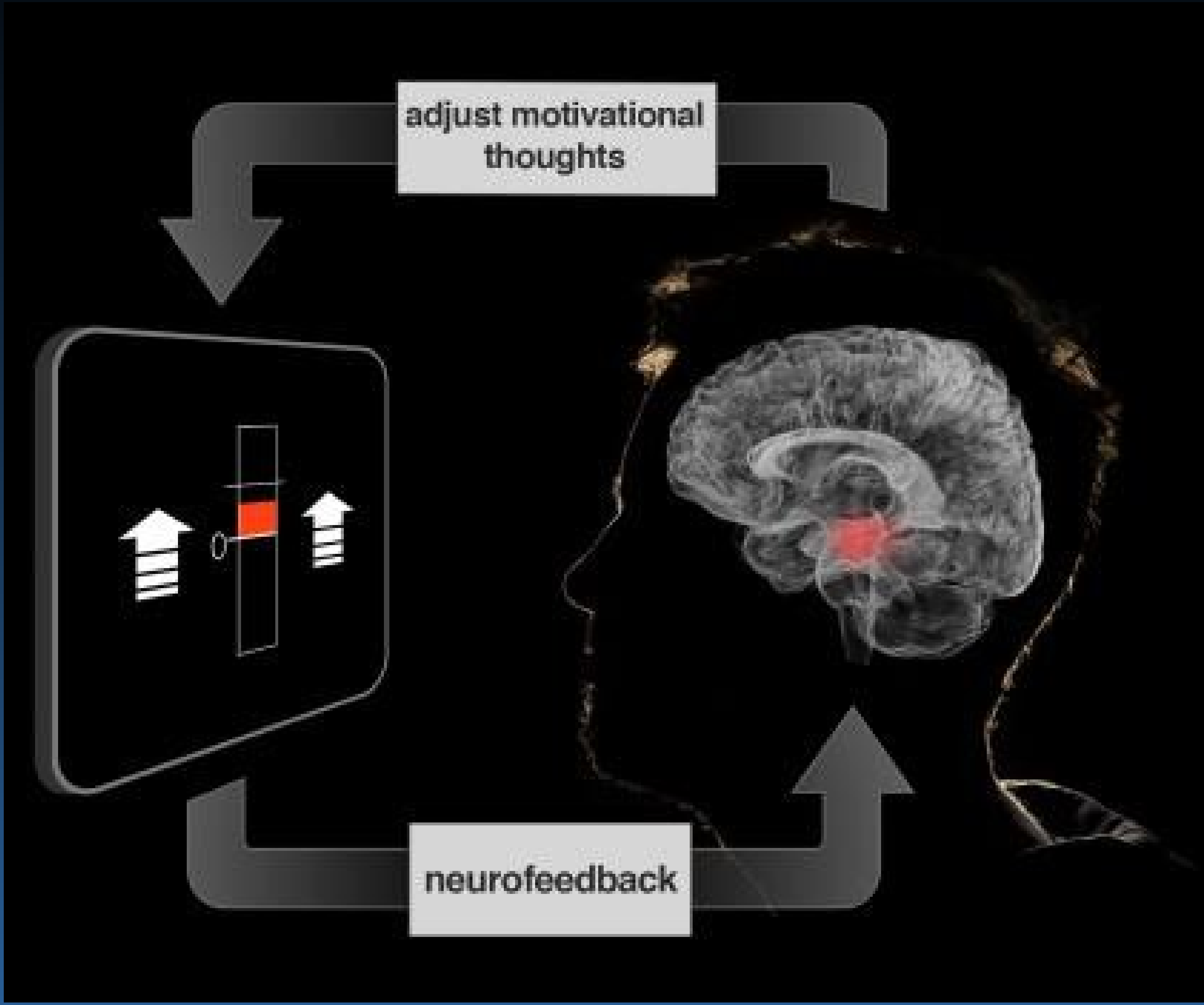
Brain-computer-brain interfaces

Neurofeedback: hearing the brain

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

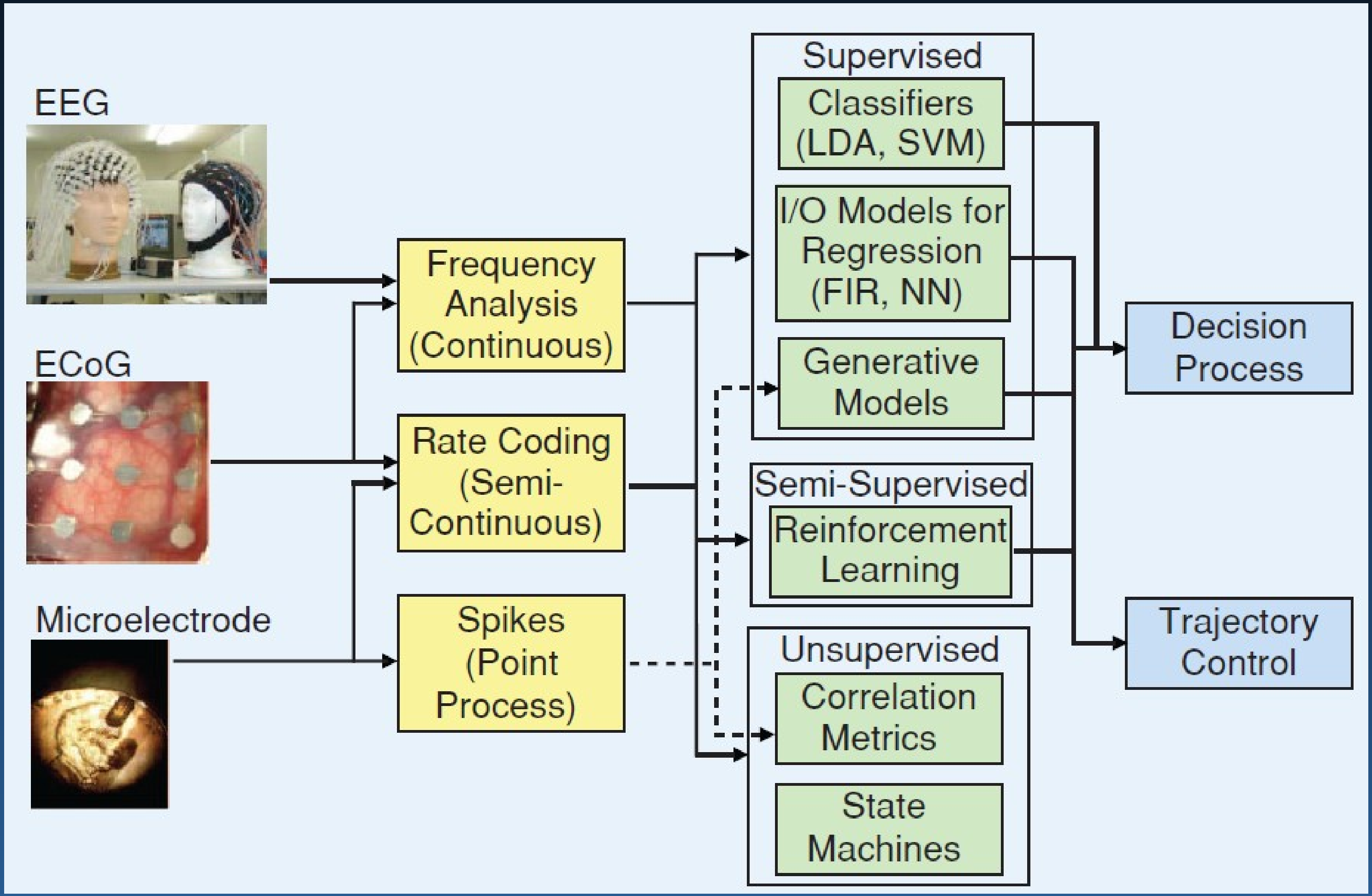
Critical review of existing literature shows that this is not effective.

New forms based on brain fingerprinting needed.

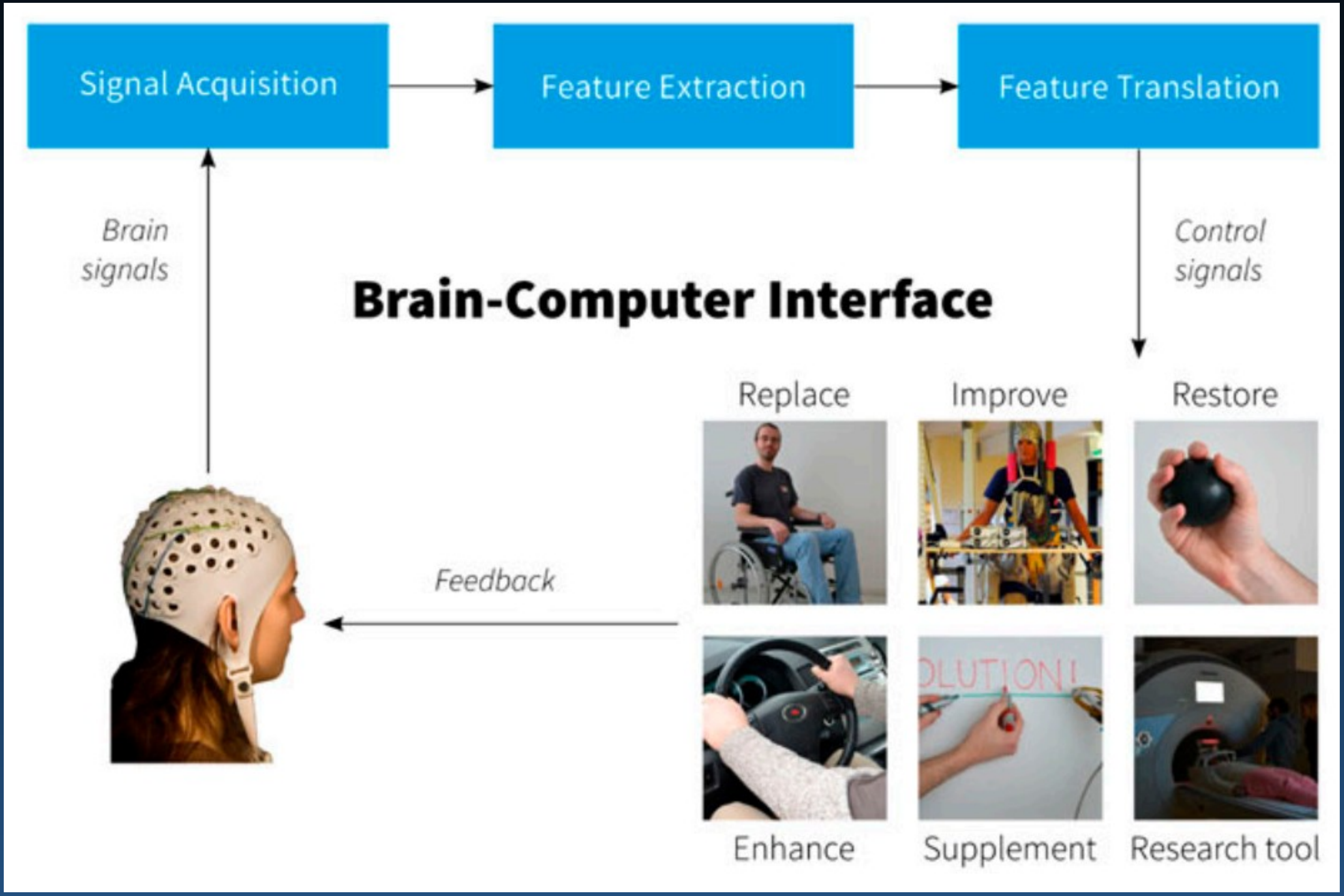


BCI: wire your brain ...

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

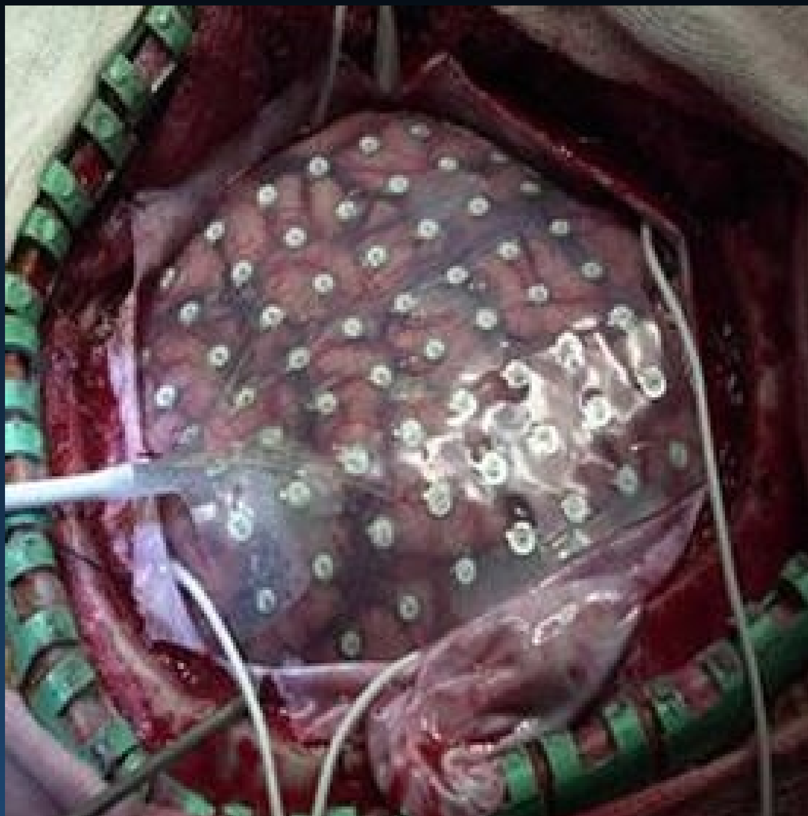


BCI Applications



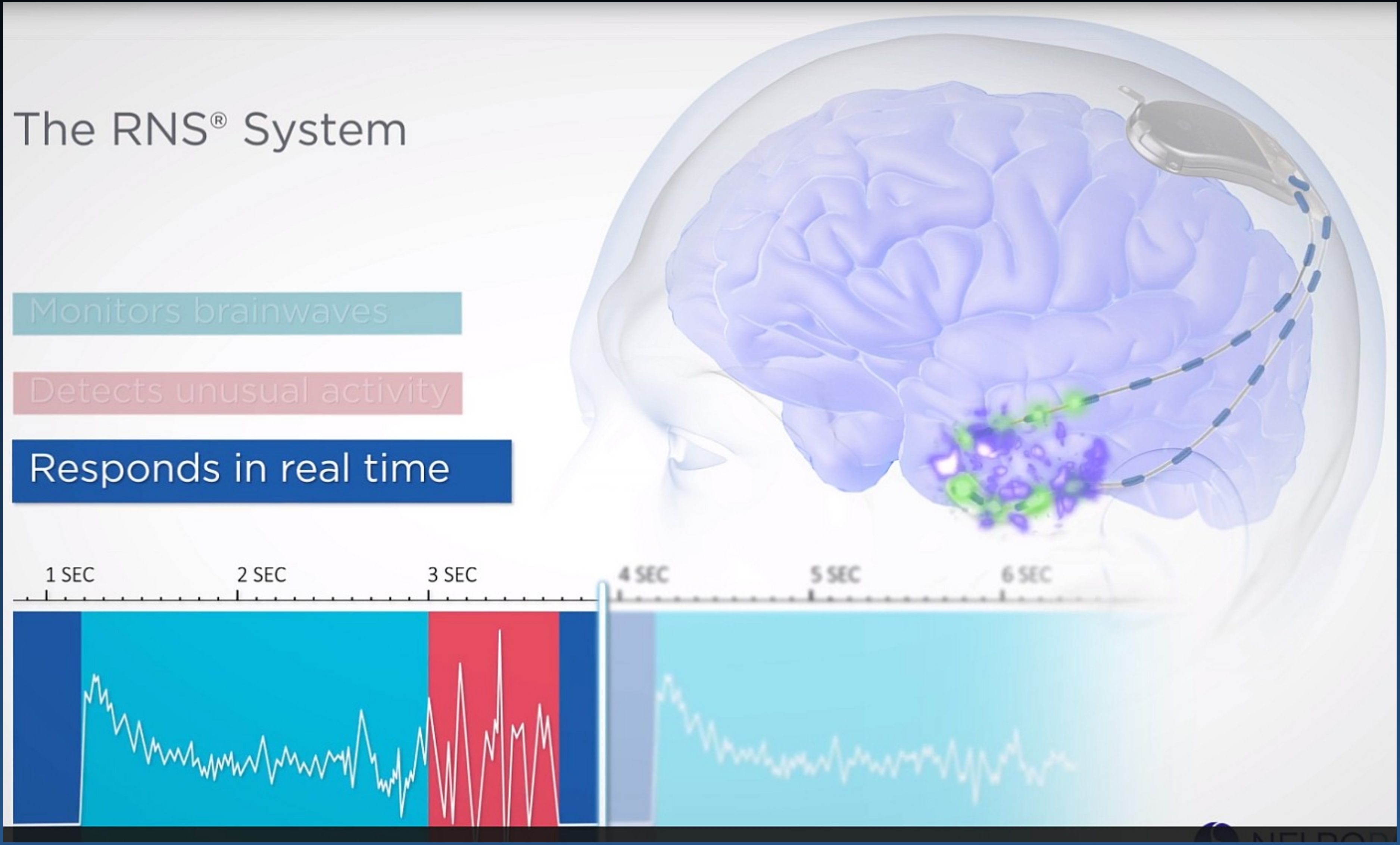
Signals: invasive (brain implants), partially invasive (ECoG), and non-invasive.

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!

Epilepsy



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

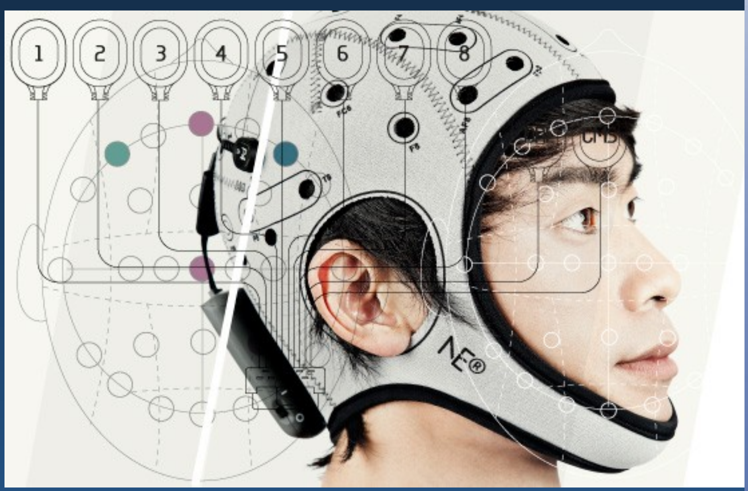
Learning skills

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 …

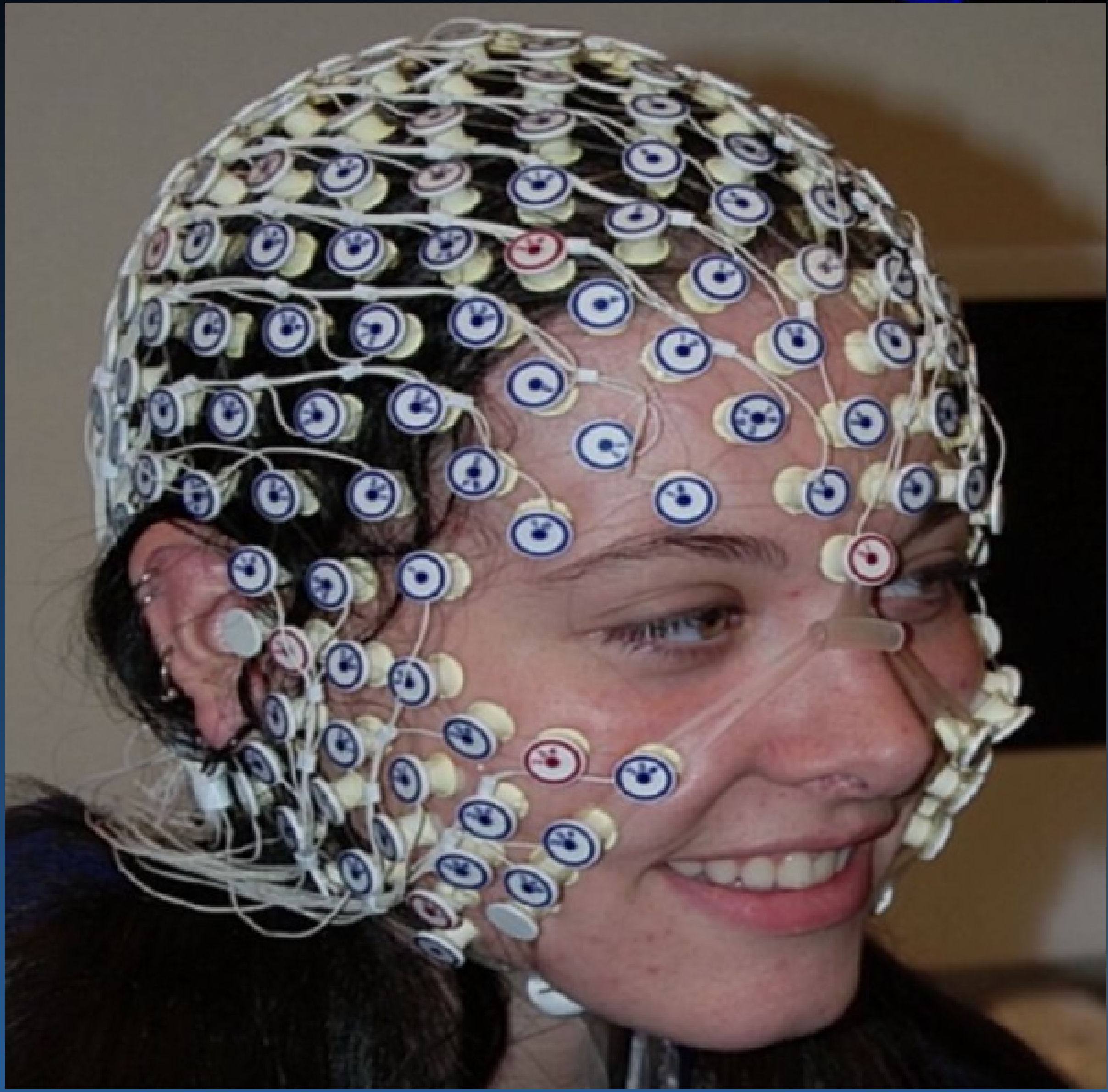
Resonance through HD DCS?

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 really knows** why it works …

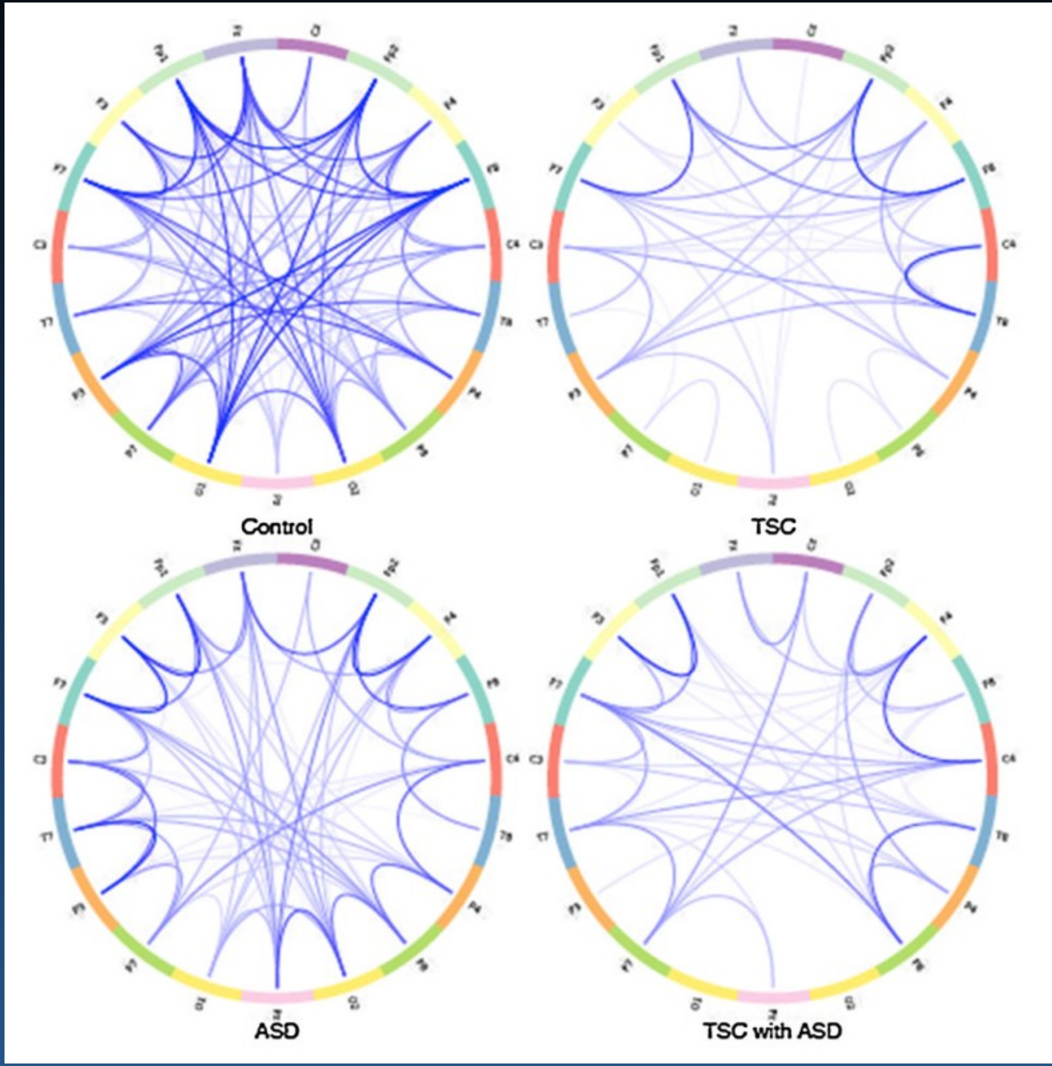


ASD: pathological connections

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

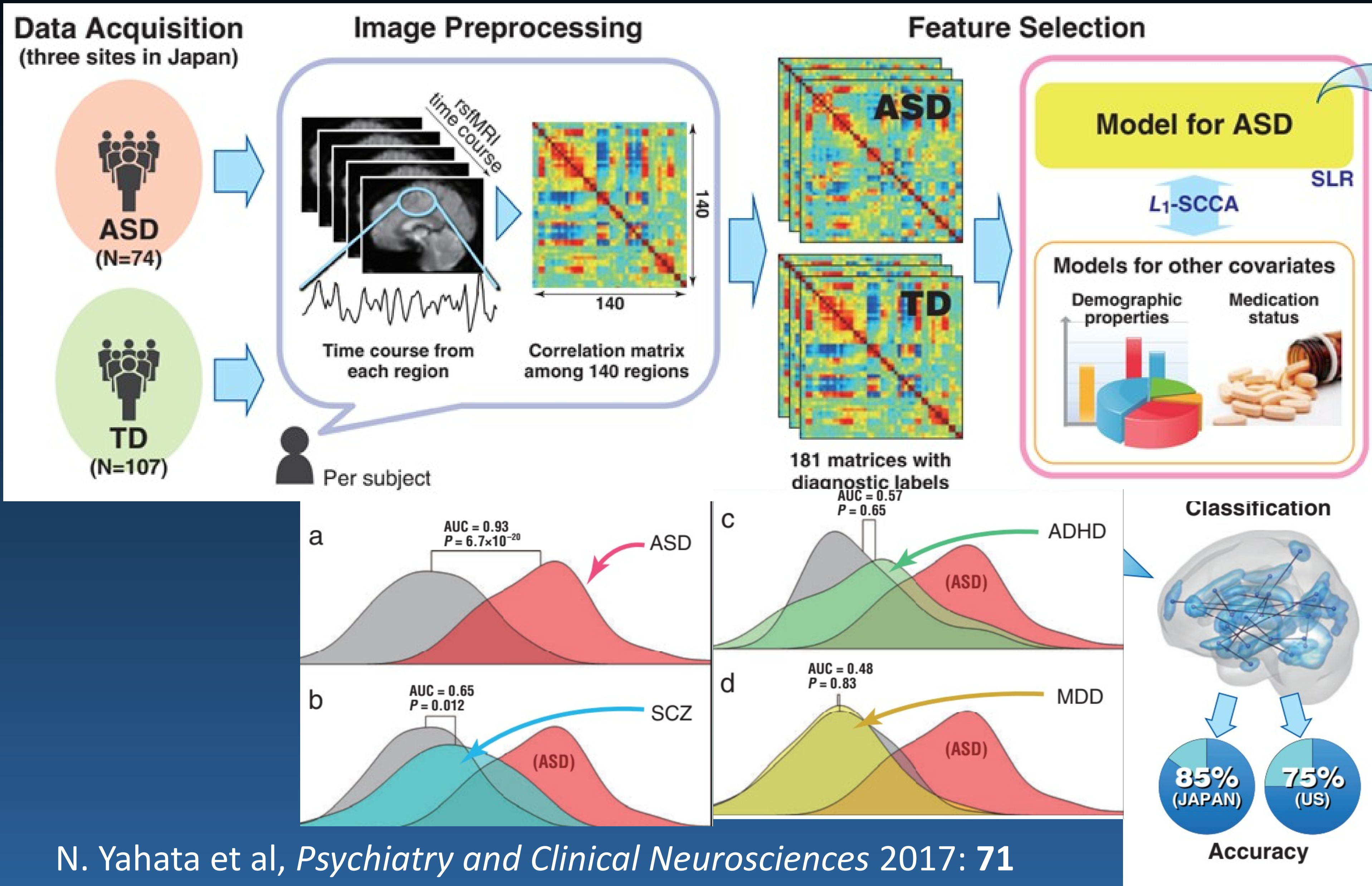
Coherence between electrodes. Weak or missing connections between distant regions prevent ASD/TSC patients from solving more demanding cognitive tasks.

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



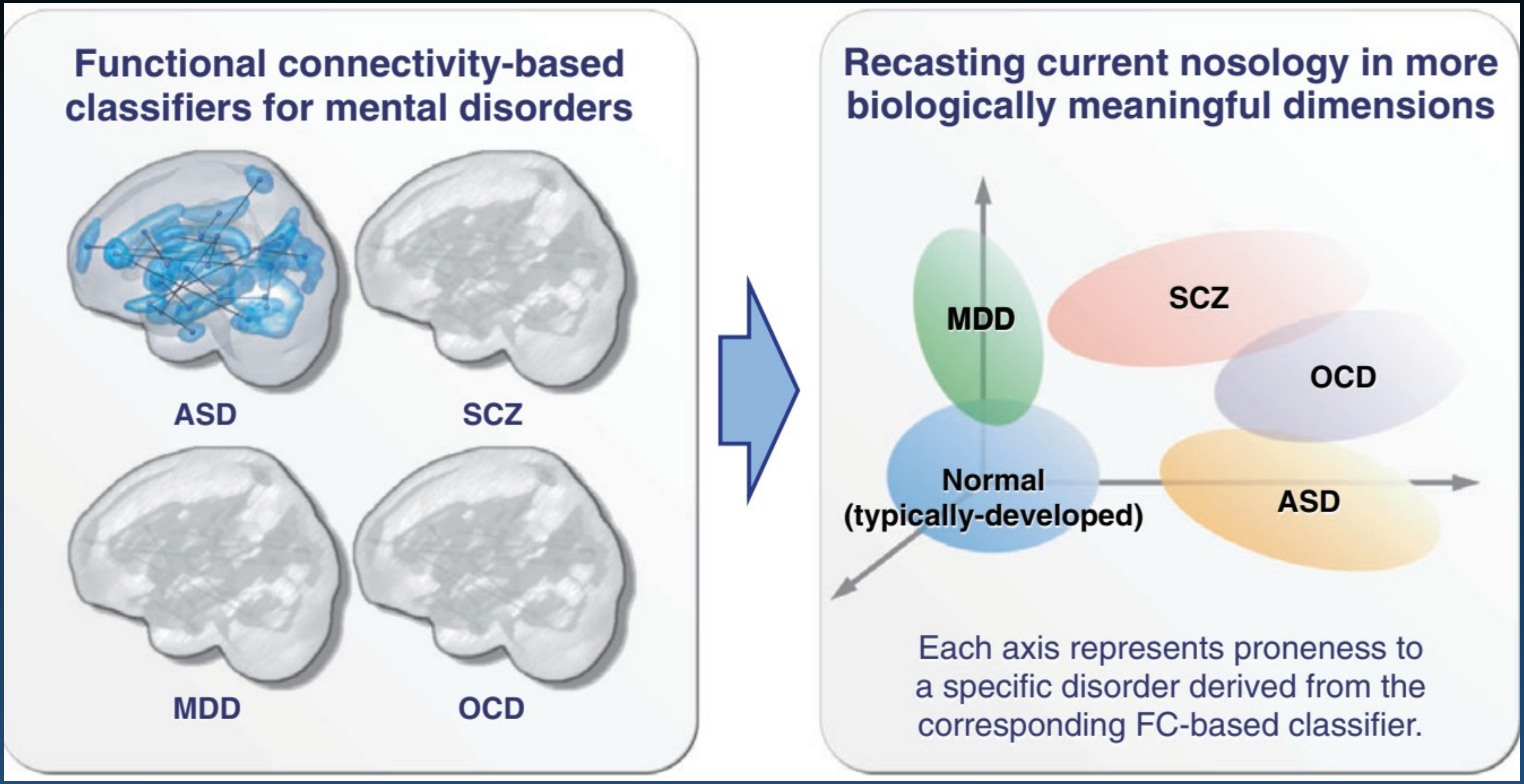
J.F. Glazebrook, R. Wallace, Pathologies in functional connectivity, feedback control and robustness. Cogn Process (2015) 16:1–16

Biomarkers from neuroimaging



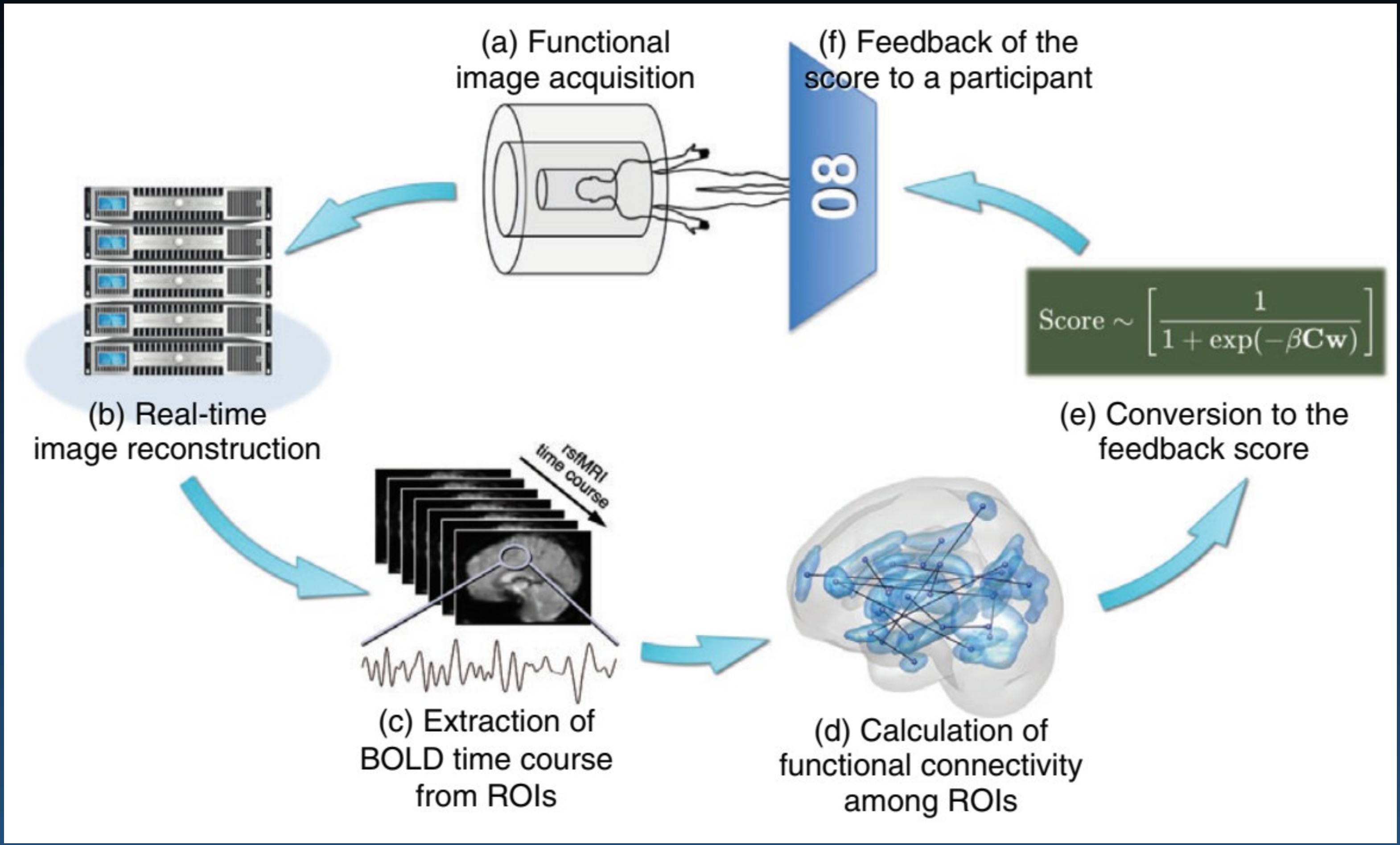
N. Yahata et al, *Psychiatry and Clinical Neurosciences* 2017: **71**

Biomarkers of mental disorders



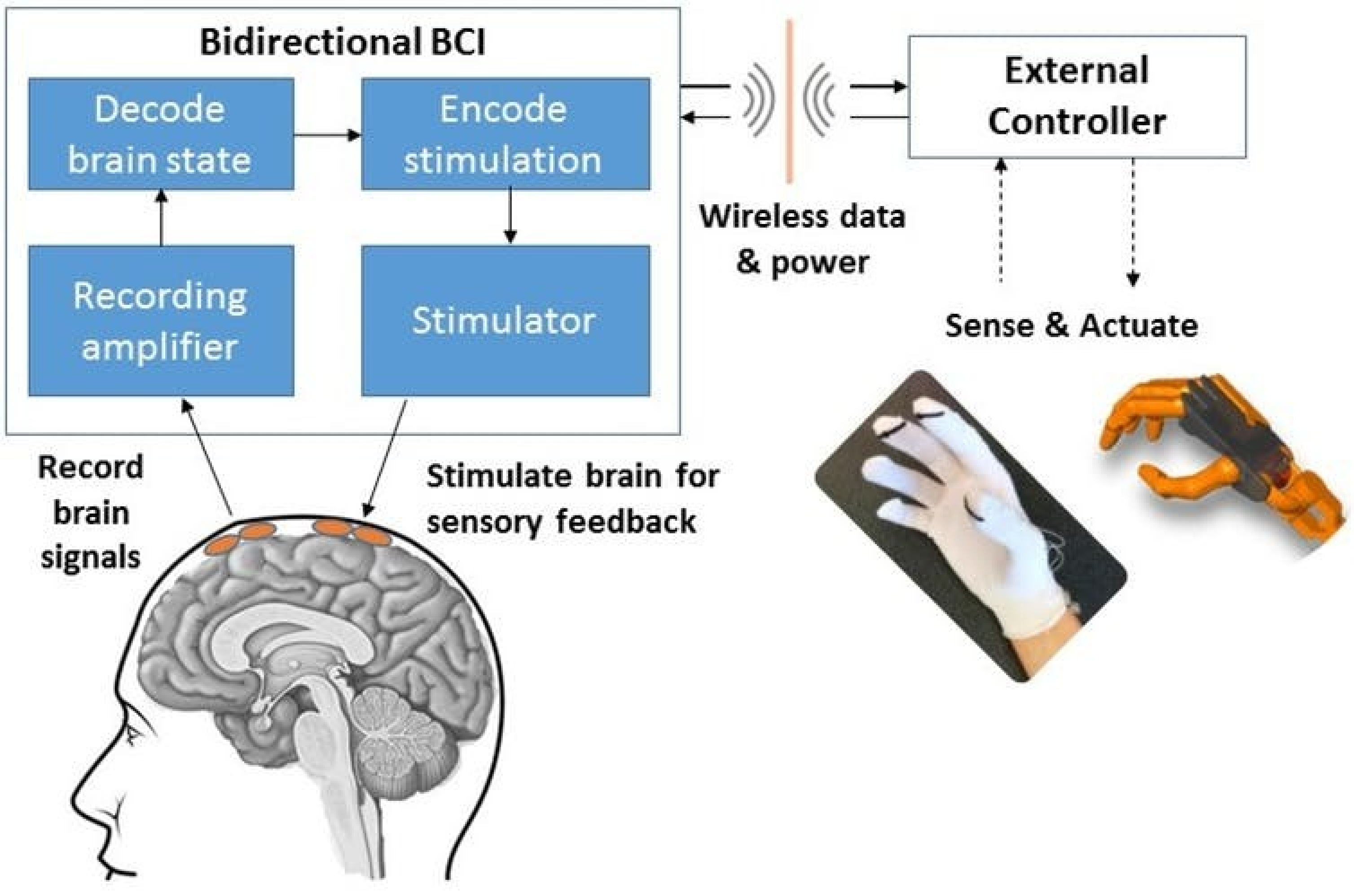
MDD, deep depression, SCZ, schizophrenia, OCD, obsessive-compulsive disorder, ASD autism spectrum disorder. fMRI biomarkers allow for objective diagnosis.
N. Yahata et al, *Psychiatry & Clinical Neurosciences* 2017; **71**: 215–237

Neurofeedback may repair network?



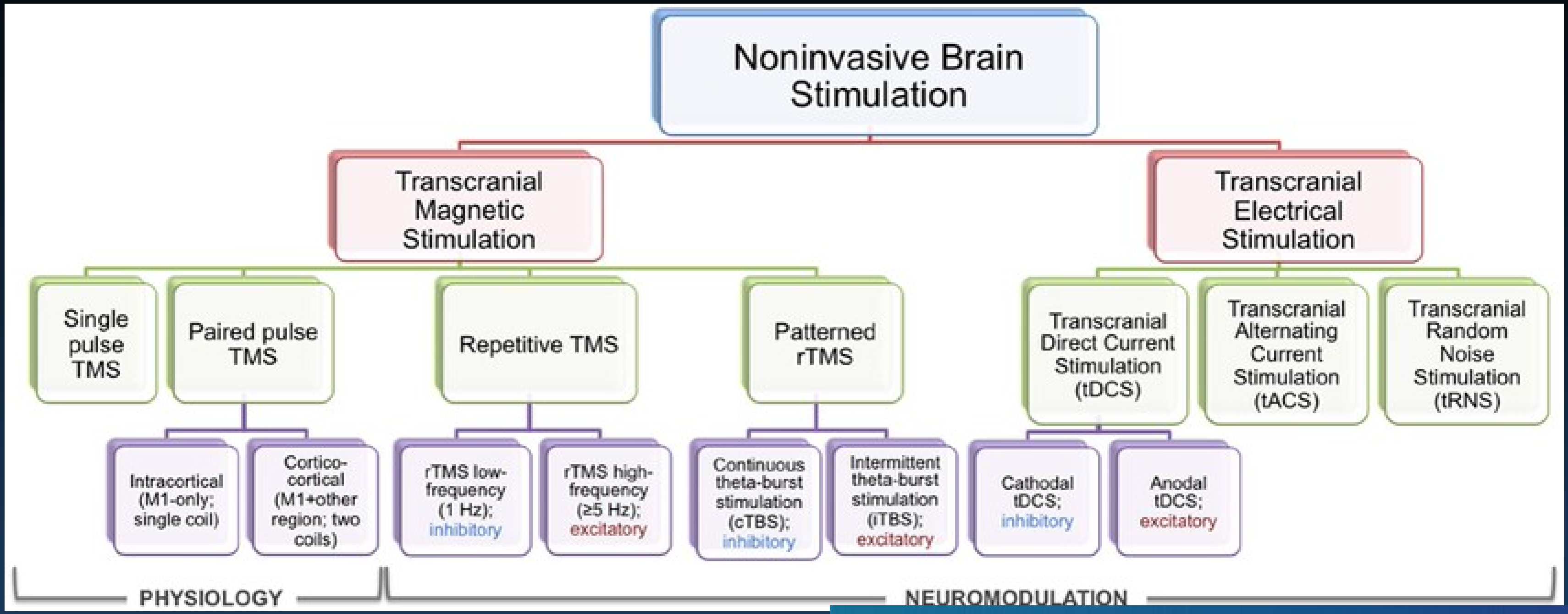
Megumi F, Yamashita A, Kawato M, Imamizu H. Functional MRI neurofeedback training on connectivity between two regions induces long-lasting changes in intrinsic functional network. *Front. Hum. Neurosci.* 2015; **9**: 160.

Brain-Computer-Brain Interfaces (BCBI)



Closed loop system with brain stimulation for self-regulation.
Body reactions may be evaluated using sensory signals Virtual Reality.

Brain stimulation



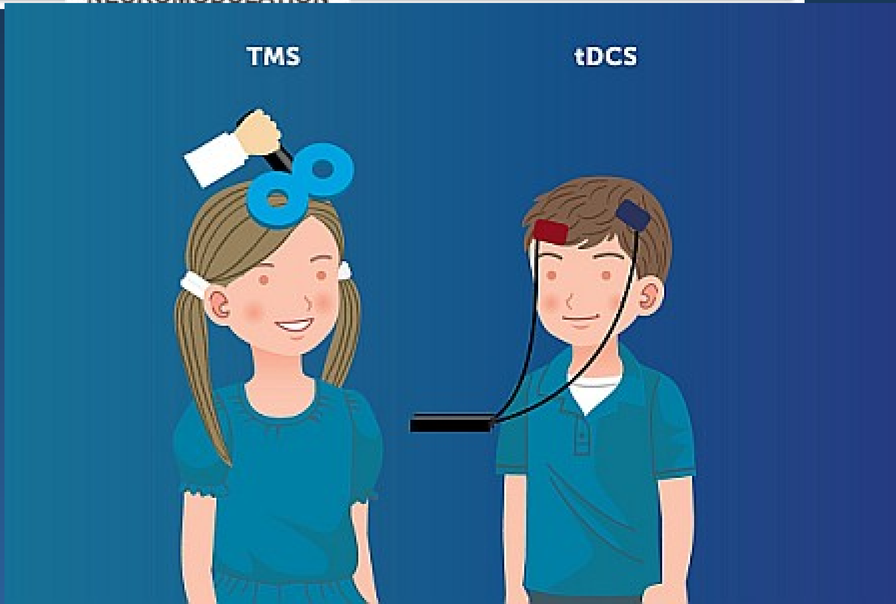
ECT – Electroconvulsive Therapy

VNS – Vagus Nerve Stimulation

Ultrasound, laser … stimulation.

Complex techniques?
Smartphones are also complex.

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

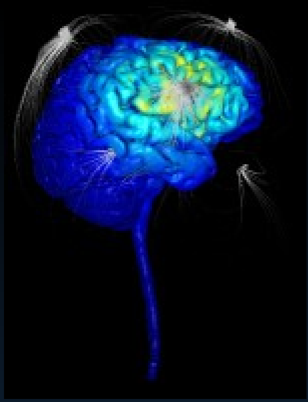


Mobile deep brain recording and stimulation platform in 4-kg backpack.

Real-time data collection from deep brain implant, using EEG cap and various heart and breathing sensors plus intracranial EEG and stimulation.

U. Topalovic, et al. 2020. Wireless Programmable Recording and Stimulation of Deep Brain Activity in Freely Moving Humans. Neuron 17/09/2020.

BCBI for learning

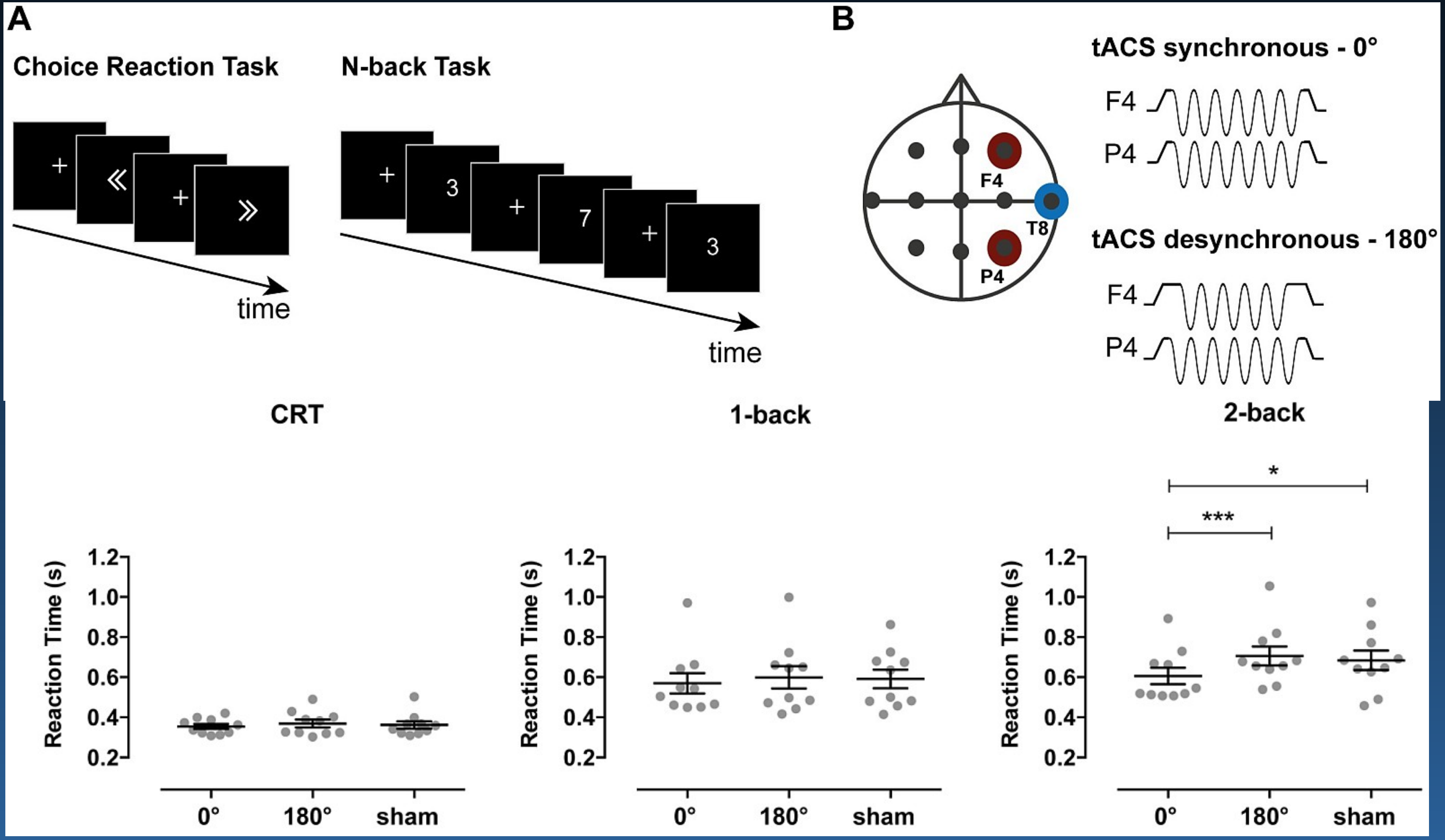


Your brain knows better what is interesting than you do!
How to make this information consciously available?

1. Violante I.R. … Sharp D.J. 2017. "Externally Induced Frontoparietal Synchronization Modulates Network Dynamics and Enhances Working Memory Performance." ELife 6:e22001.
2. Eugster, M.J.A. … Kaski S. 2016. "Natural Brain-Information Interfaces: Recommending Information by Relevance Inferred from Human Brain Signals." Scientific Reports 6:38580.
3. Mazurek K.A & Schieber M.H, 2017. "Injecting Instructions into Premotor Cortex". Neuron, 96(6), 1282–1289.e4. Teaching skills by microstimulation of premotor cortex, too low to evoke muscle activation, facilitates specific actions.
4. Yuan Han … West S.G. 2017. "Universal Design for Learning in the Framework of Neuroscience-Based Education and Neuroimaging-Based Assessment." In 2017 2nd Int. Conf. on Bio-engineering for Smart Technologies (BioSMART) 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).

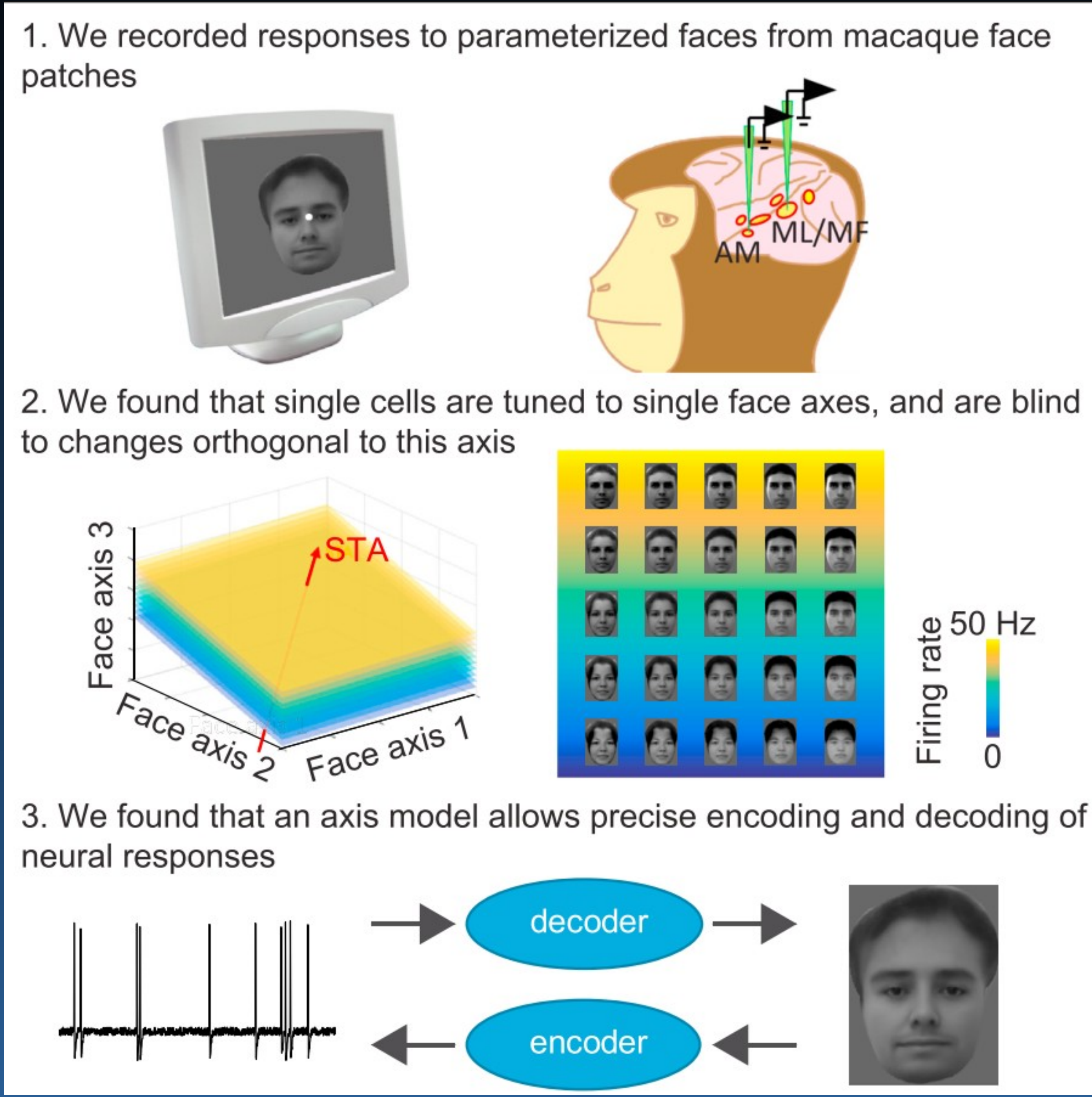


Neural screen

How are images coded in brains and recreated in conscious experiences?

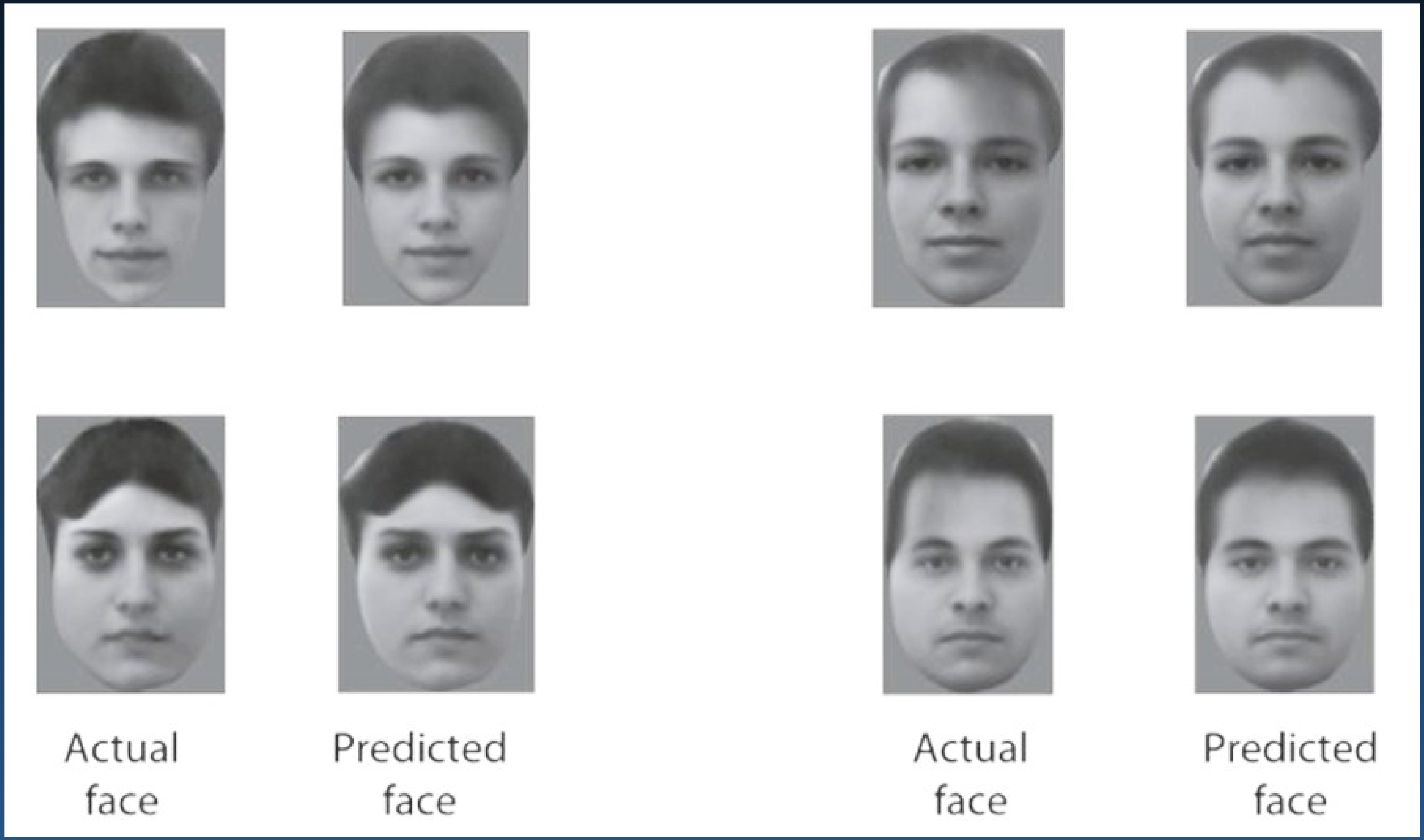
Visual cortex extracts specific features and their combinations are remembered as face. Detailed recognition is possible recording from a small number of neurons.

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



Conscious Perception

Spikes recorded from 205 neurons were sufficient to recreate almost perfectly images of faces that monkeys have seen.

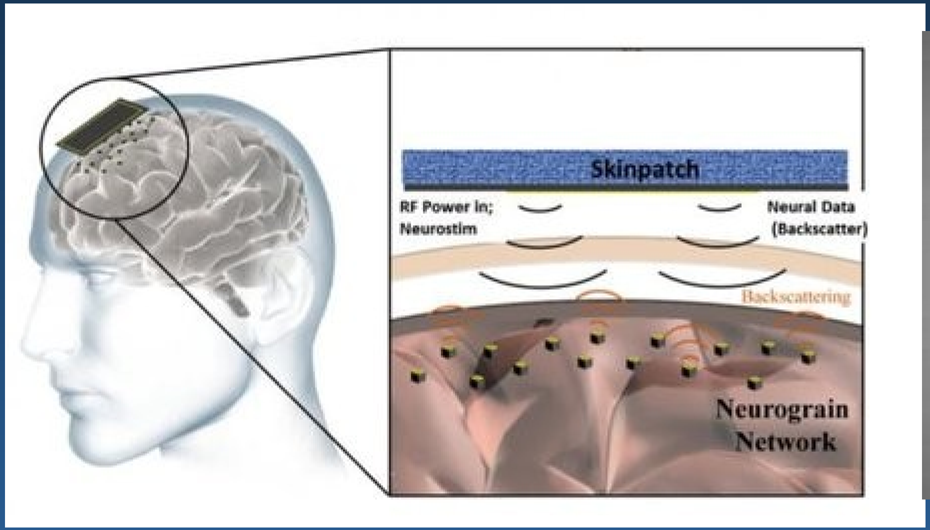


Million nanowires in your brain?

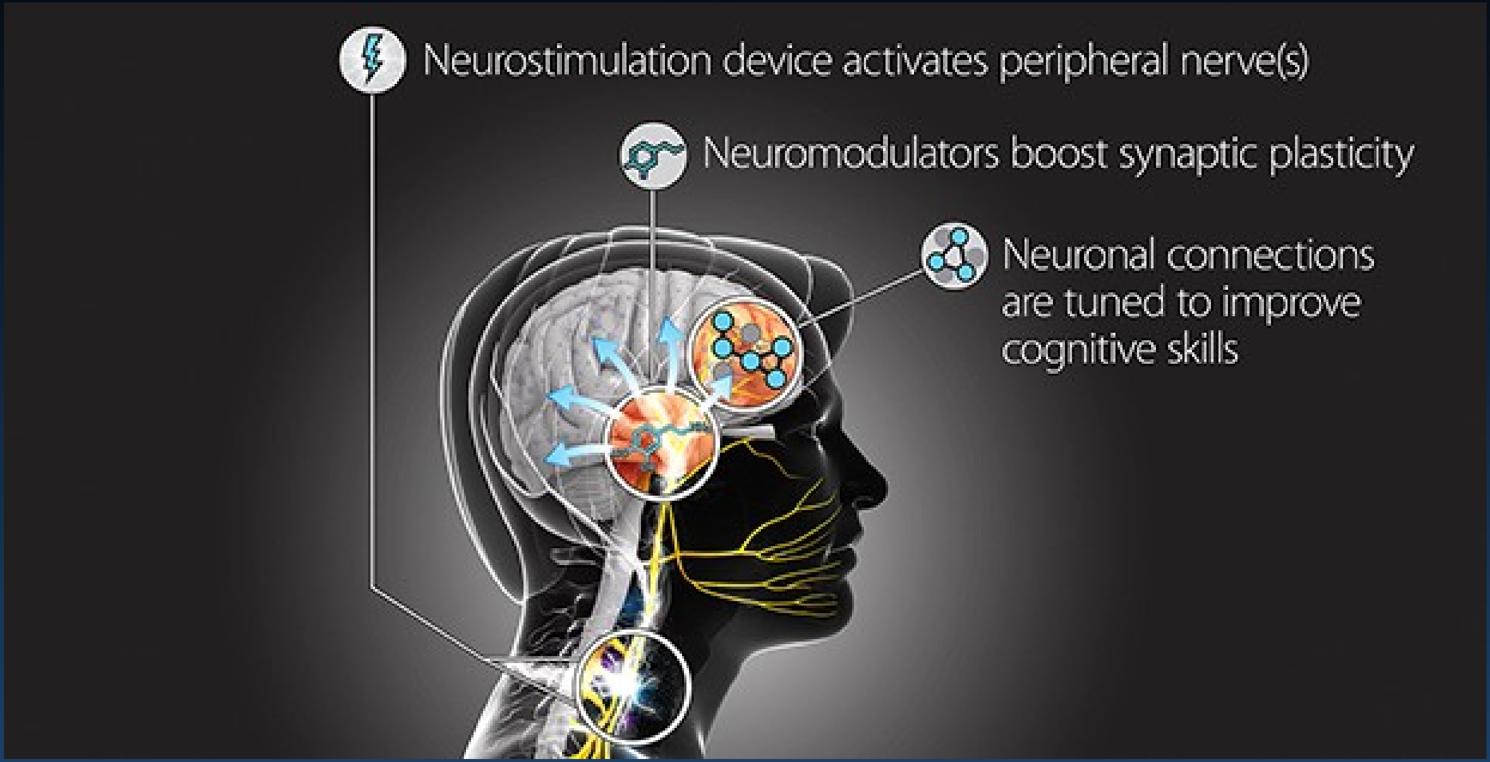
DARPA (2016): **Neural Engineering System Design (NESD)**
Interface that reads impulses of 10^6 neurons, injecting currents to 10^5 neurons, and reading/activating 10^3 neurons.

DARPA Electrical Prescriptions (ElectRx) project enables “artificial modulation of peripheral nerves to restore healthy patterns of signaling in these neural circuits. ElectRx devices and therapeutic systems under development are entering into clinical studies.”

Elon Musk **Neuralink** project for cortex stimulation – control your brain!



Targeted Neuroplasticity Training



DARPA (2017) Programs: **TNT to** enhance learning of cognitive skills, tuning neurons reduce cost and duration of the Defense Department's extensive training regimen, while improving outcomes, accelerate learning time needed to train foreign language specialists, intelligence analysts, cryptographers etc. **Restoring Active Memory** (RAM) program is aimed at neurotechnologies to facilitate memory formation/recall in the injured brain.

Understanding brain networks. Space for mental states

Brains ⇔ Minds

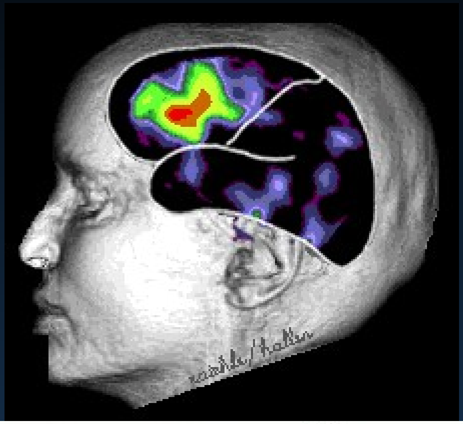
Define mapping S(M)⇔S(B), as in BCI.
How mental states arise/influence brain states?

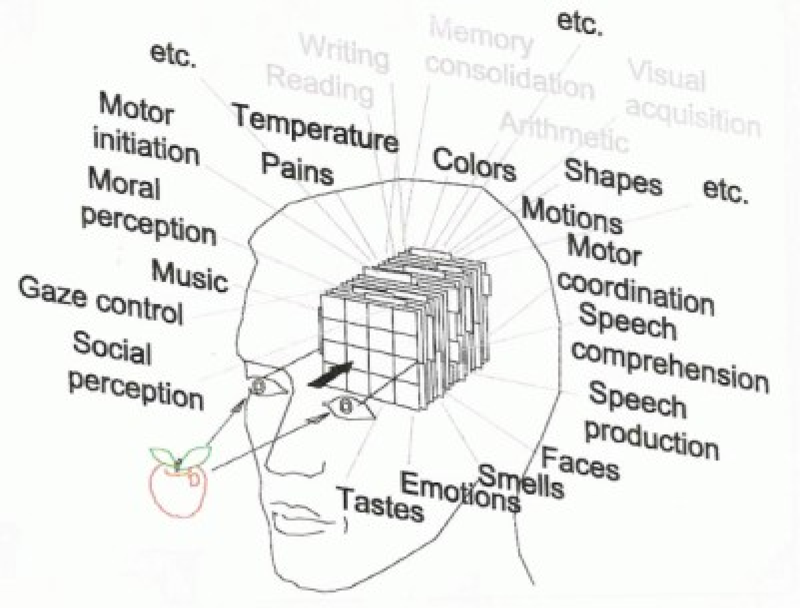
Neurodynamics: bioelectrical activity of the brain, neural activity measured using
EEG, MEG, NIRS-OT, PET, fMRI ...

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.

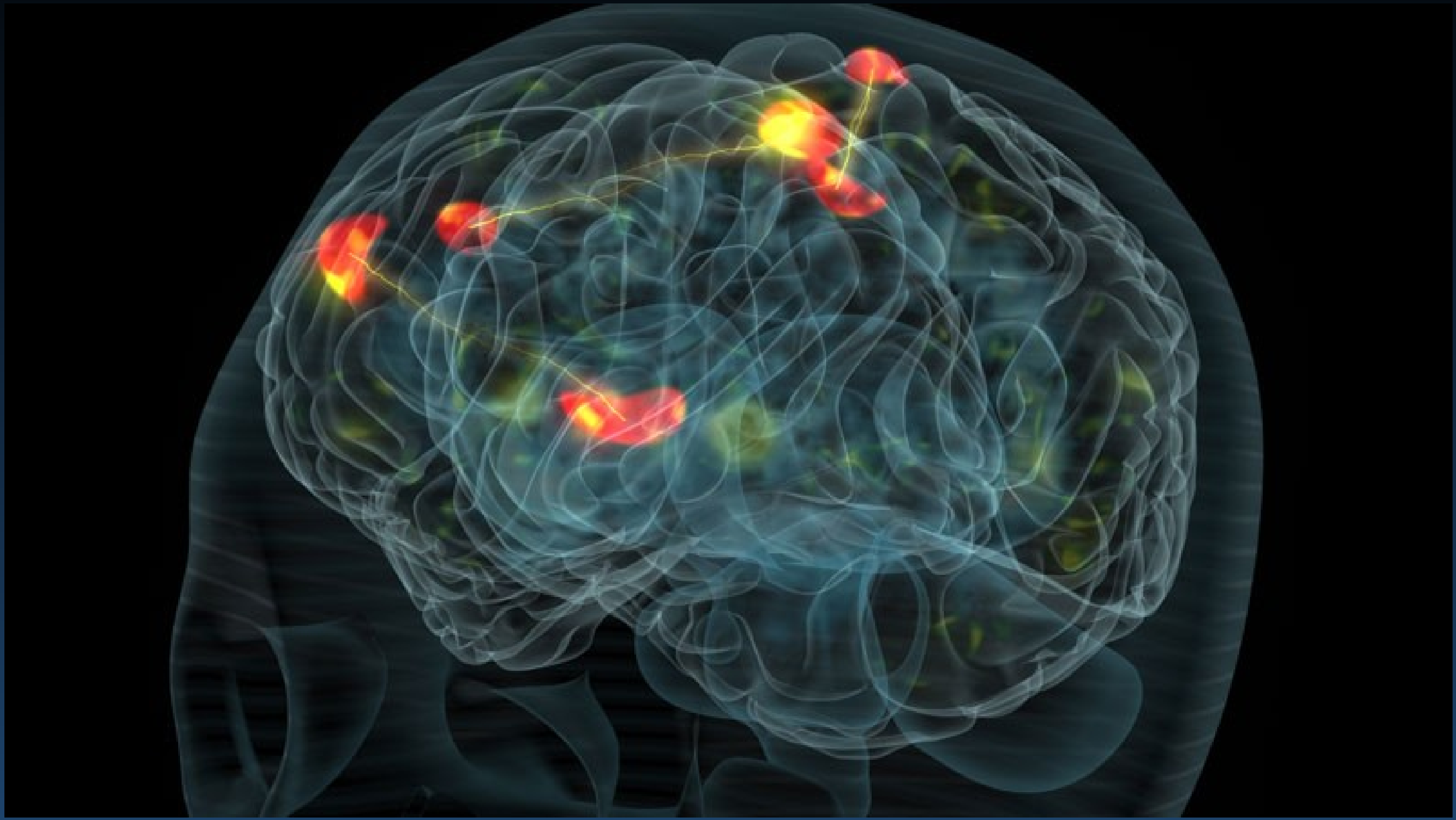
Two problems: discretization of continuous processes for symbolic models,
and lack of good phenomenology – we are not able to describe our mental states.





Duch W. (2019) Mind as a shadow of neurodynamics. Physics of Life Rev 31: 28
Duch W. (1996) Computational physics of the mind. Comp. Phys. Comm. 97: 136

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? Signal detection theory

Multi-level phenomics

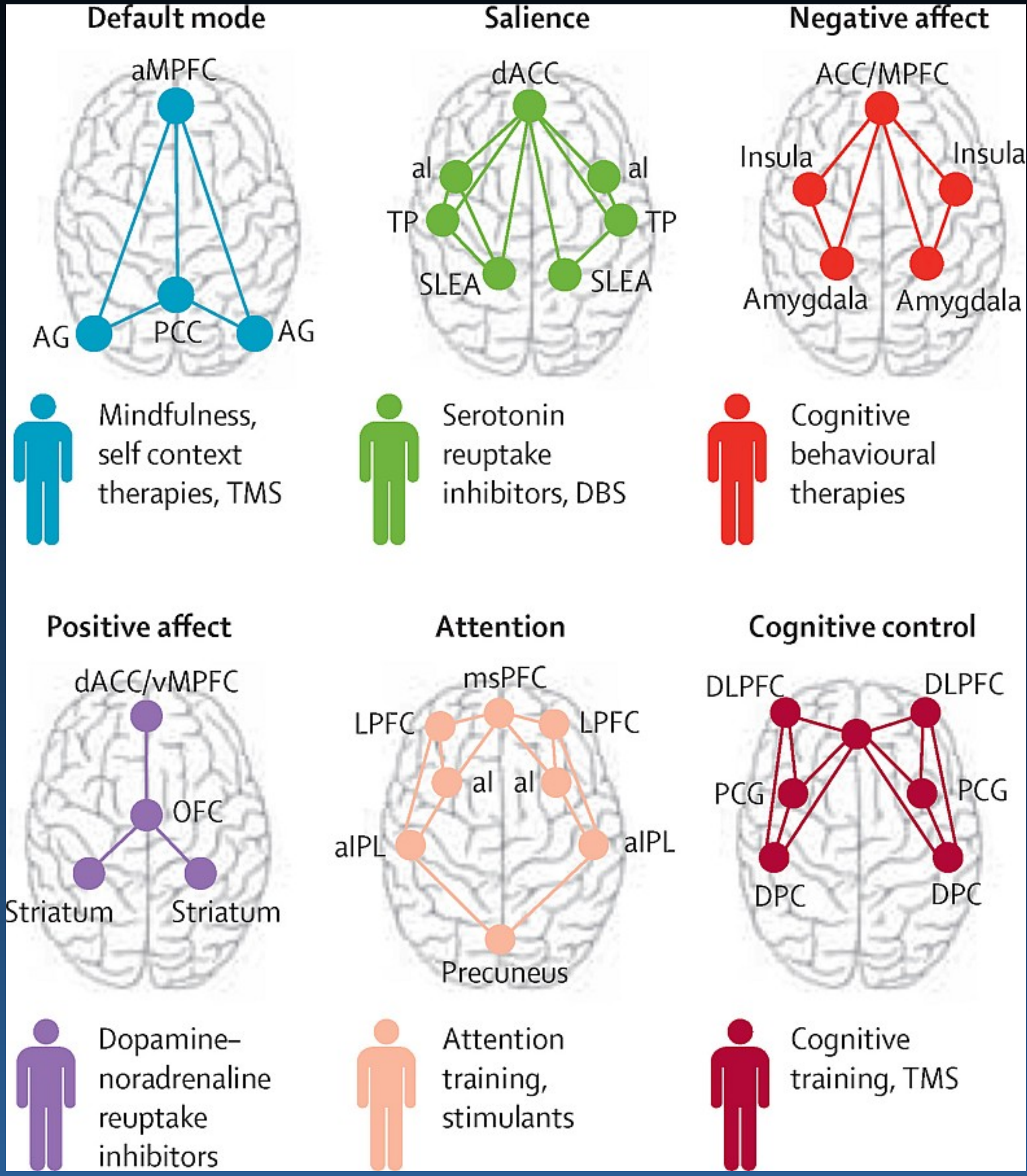
M. Minsky, Society of mind (1986)

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

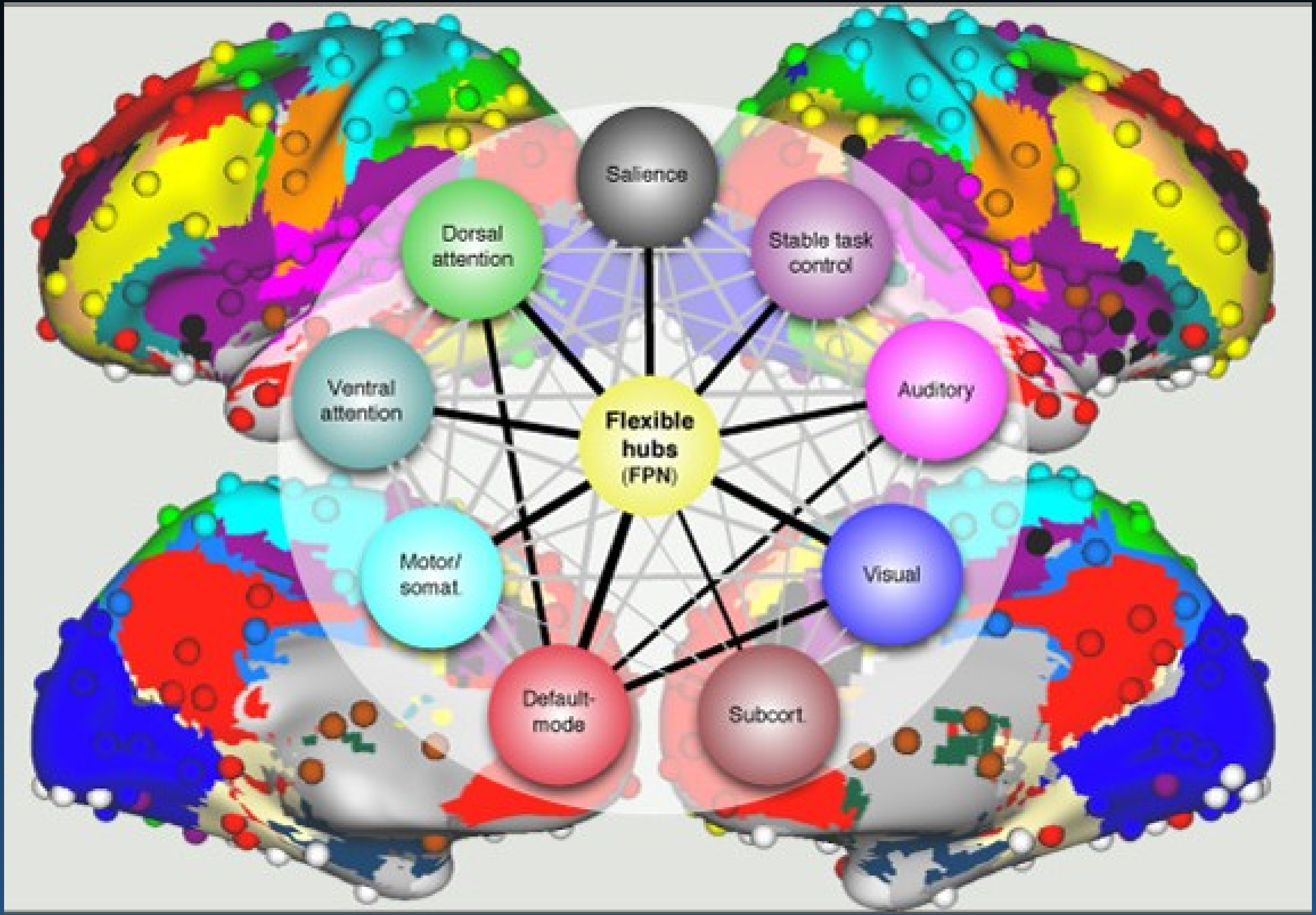
Instead of classification of mental disease by symptoms use **Research Domain Criteria** (RDoC) matrix based on **multi-level neuropsychiatric phenomics** describing large brain systems deregulation.

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

Neurodynamics is the key.

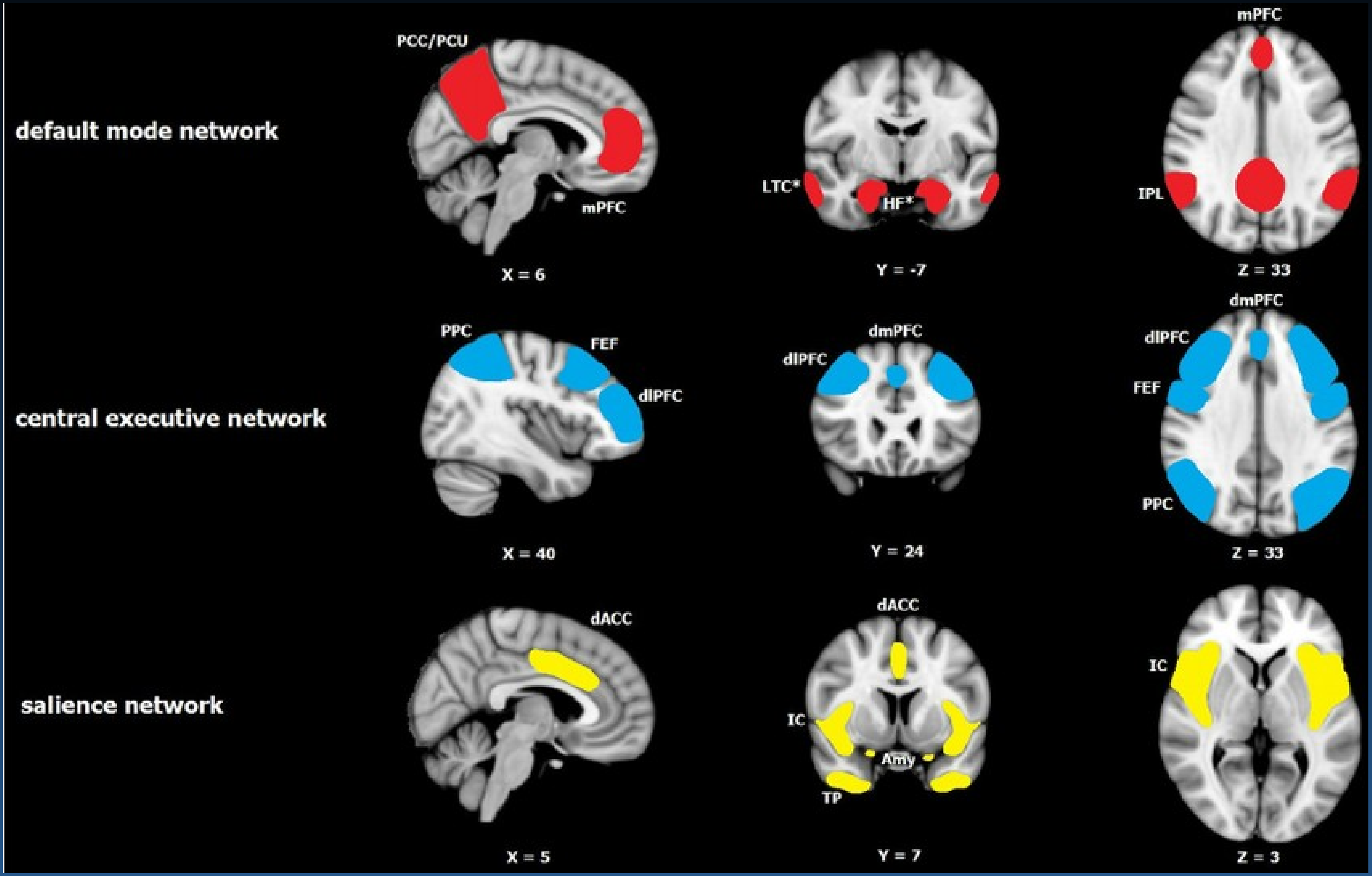


Neurocognitive Basis of Cognitive Control



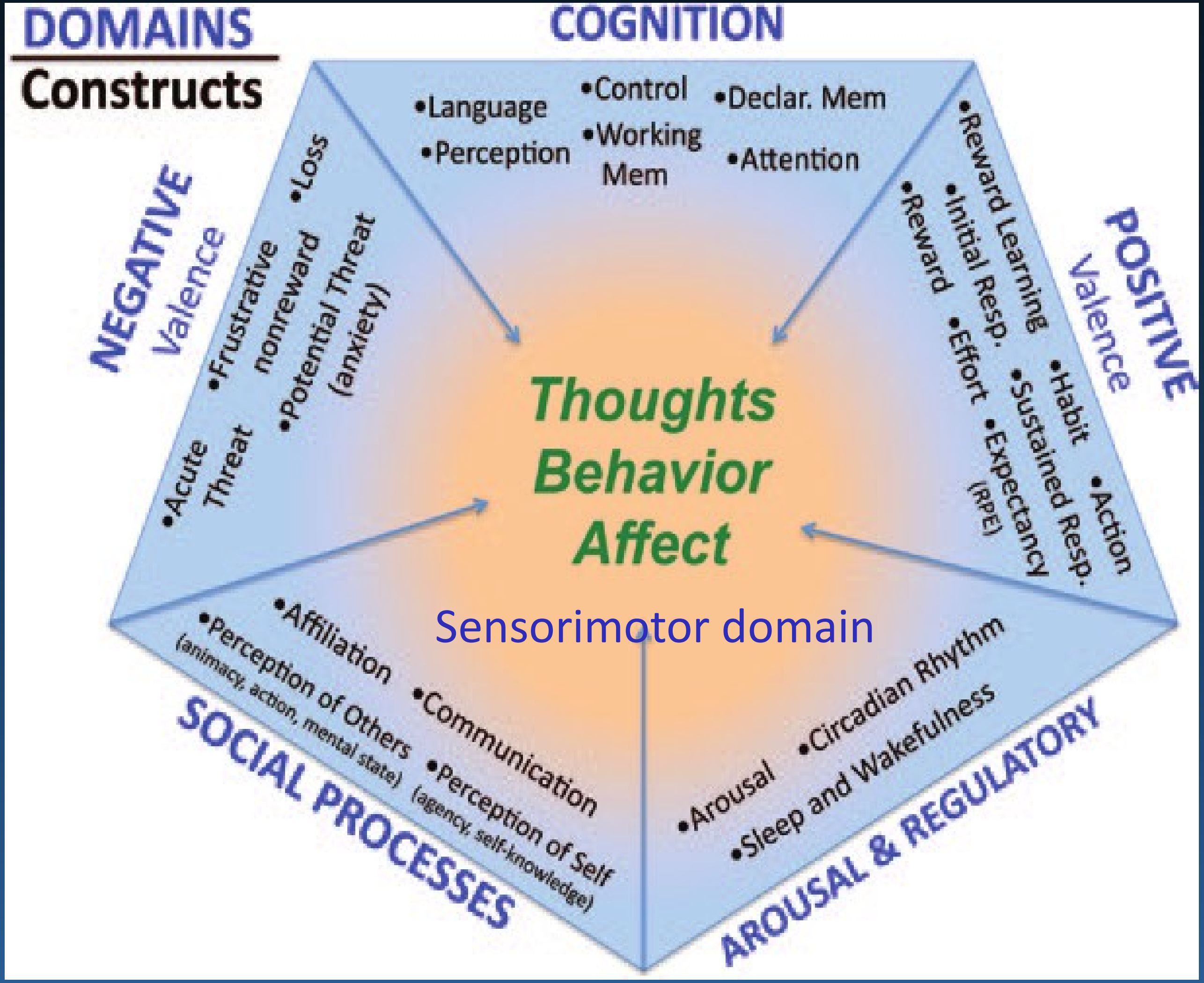
Fronto-Parietal theory of intelligence, control information flow of specialized subnetworks. Ex. Cole M.W. et al. Nature Neuroscience (2013). Multi-task connectivity reveals flexible hubs for adaptive task control.

DMN, CEN and SN networks



Mulders et al. (2015)

NIMH RDoC Matrix for deregulation of 6 large brain systems.



NIMH RDoC Matrix for deregulation of large brain systems.

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

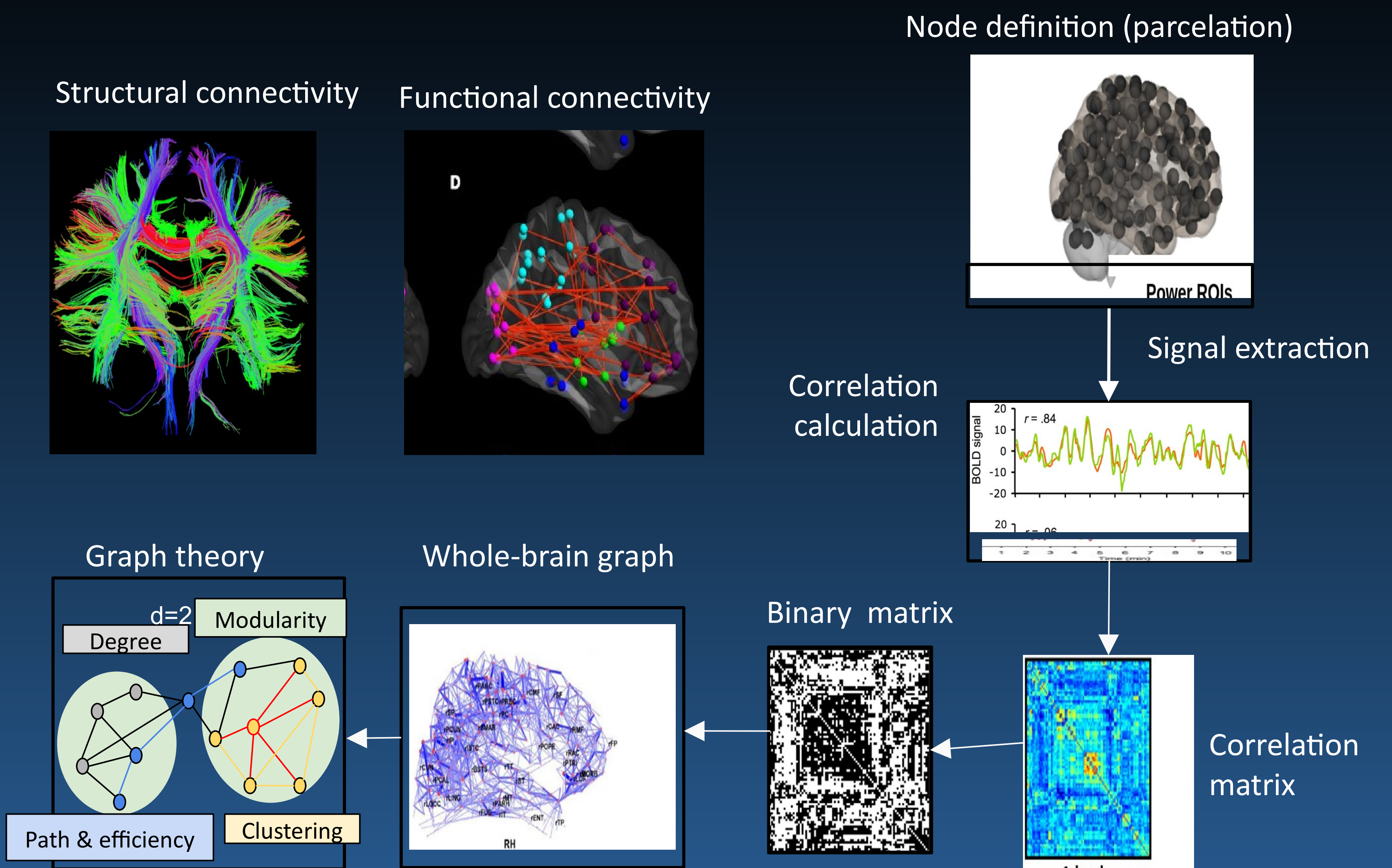
1. **Negative Valence Systems**, primarily responsible for responses to aversive situations or context, such as fear, anxiety, and loss.
2. **Positive Valence Systems** are primarily responsible for responses to positive motivational situations or contexts, such as reward seeking, consummatory behavior, 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.
6. **Sensorimotor systems**, regulate perception-action.

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

Fingerprints of mental activity

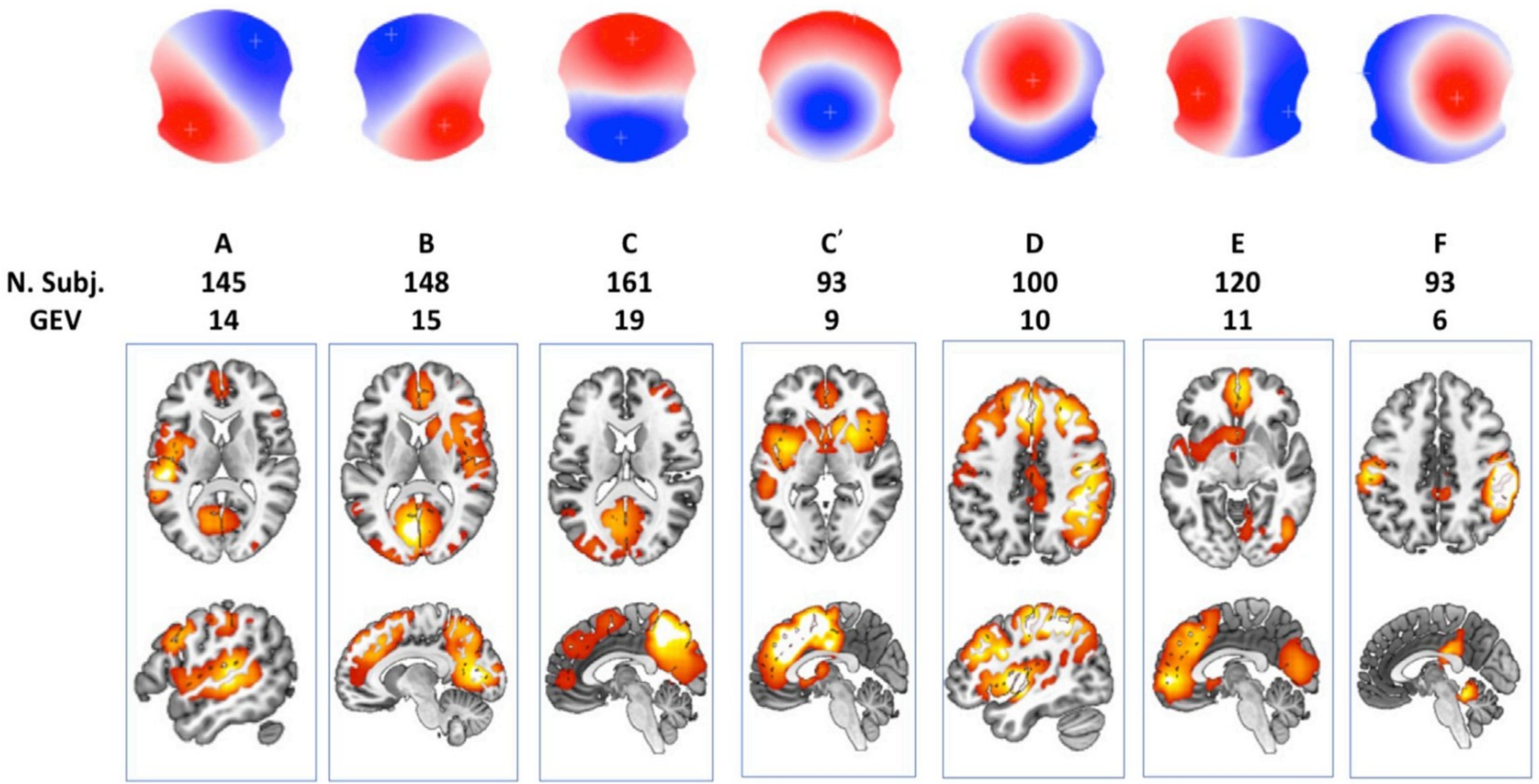
Human connectome and MRI/fMRI



Many toolboxes are available for such analysis.

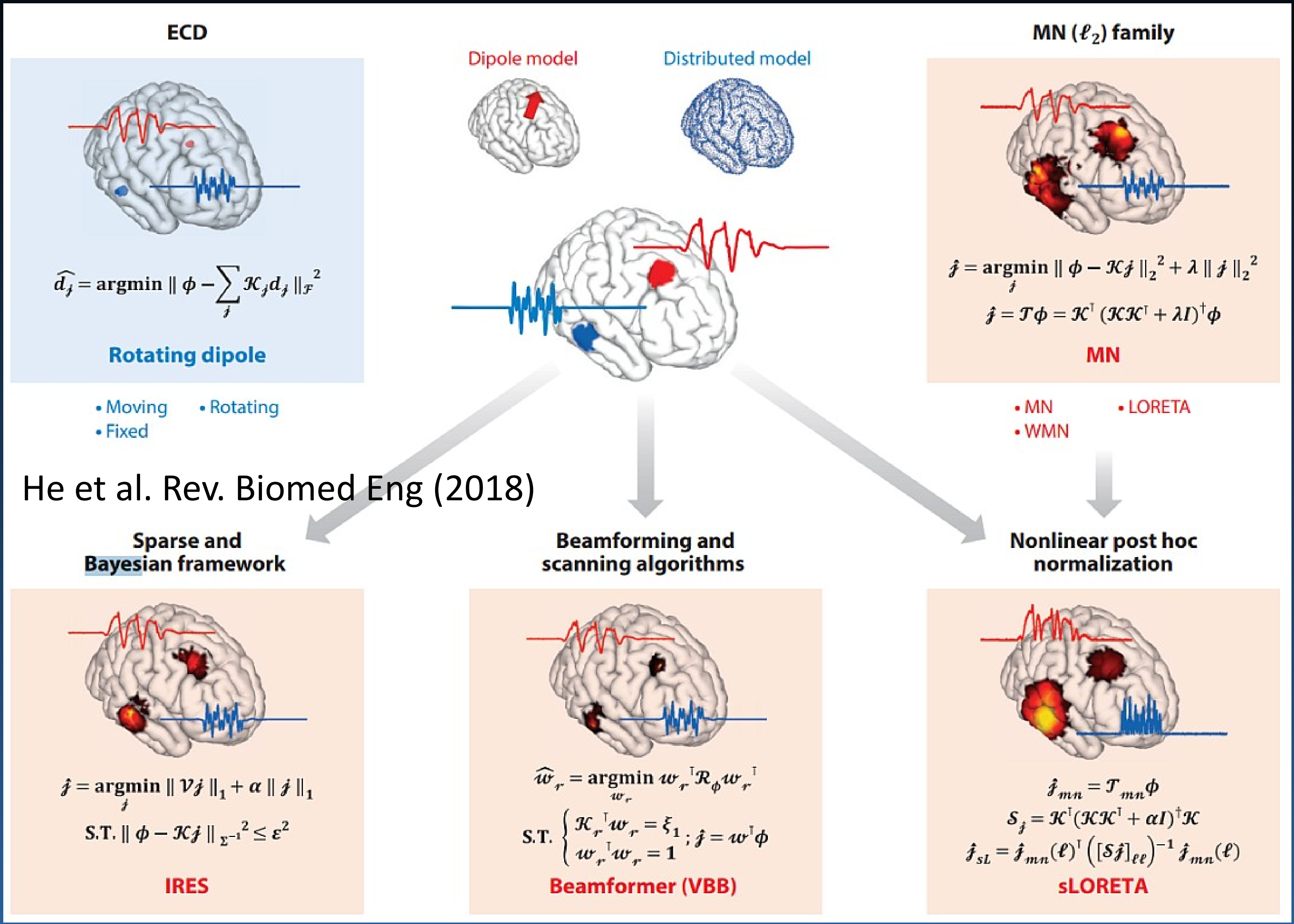
Bullmore & Sporns (2009)

Microstates sources



Michel, C. M., & Koenig, T. (2018). EEG microstates as a tool for studying the temporal dynamics of whole-brain neuronal networks: A review. *NeuroImage*, *180*, 577–593. https://doi.org/10.1016/j.neuroimage.2017.11.062

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.

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

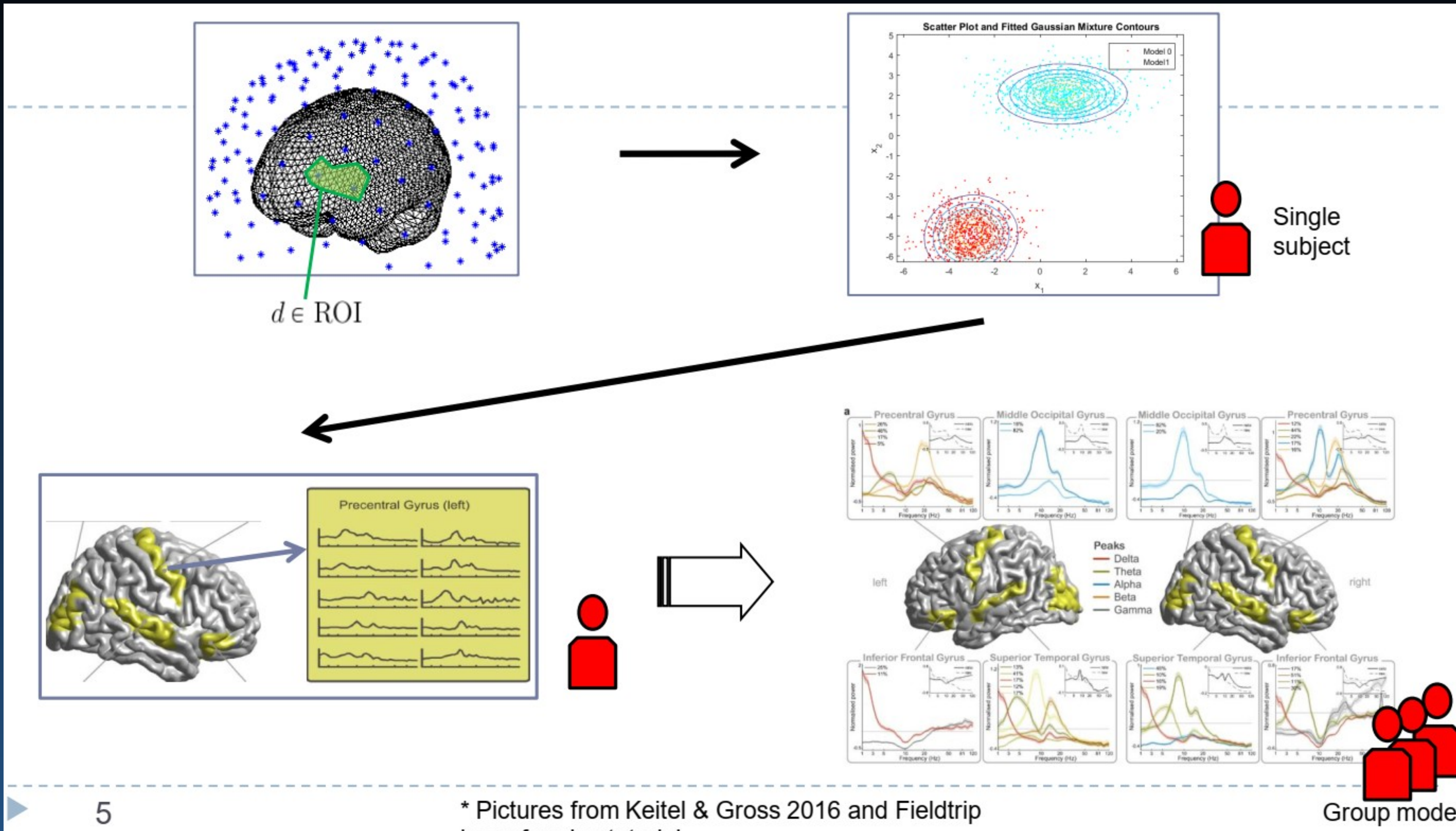
$$B := H_{Src,N} := N^{-1/2} H \tag{35}$$

```
%%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
```

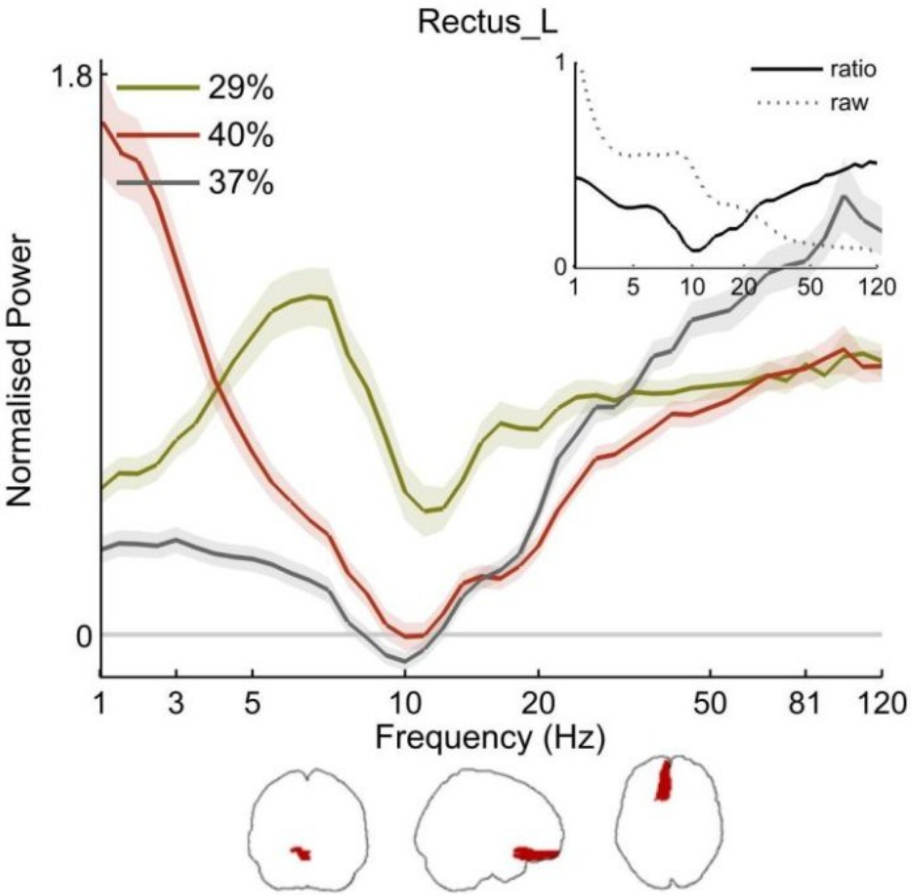
Rykaczewski, K., Nikadon, J., Duch, W., & Piotrowski, T. (2020). *Neuroinformatics.*

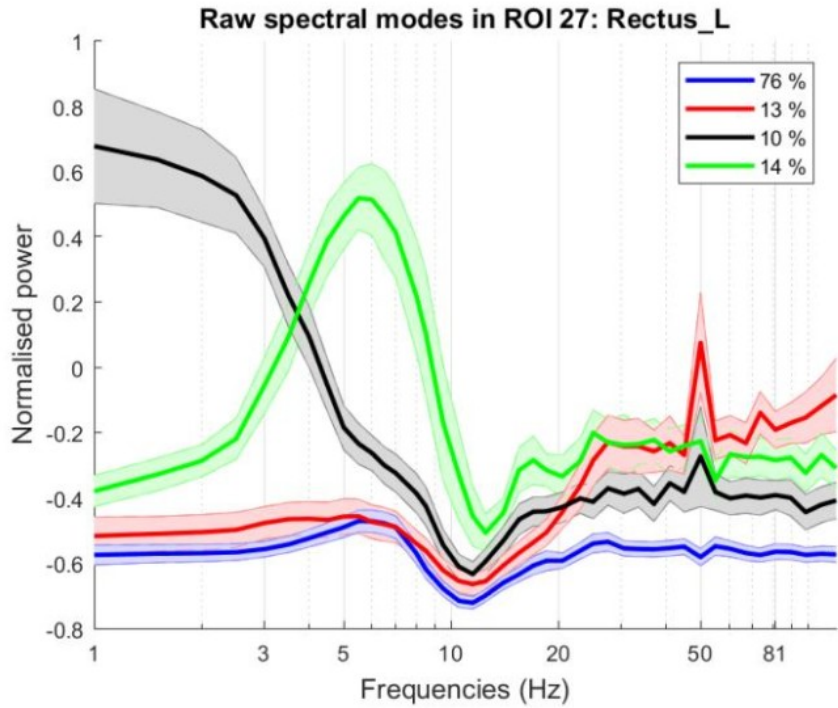
Spectral fingerprints



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

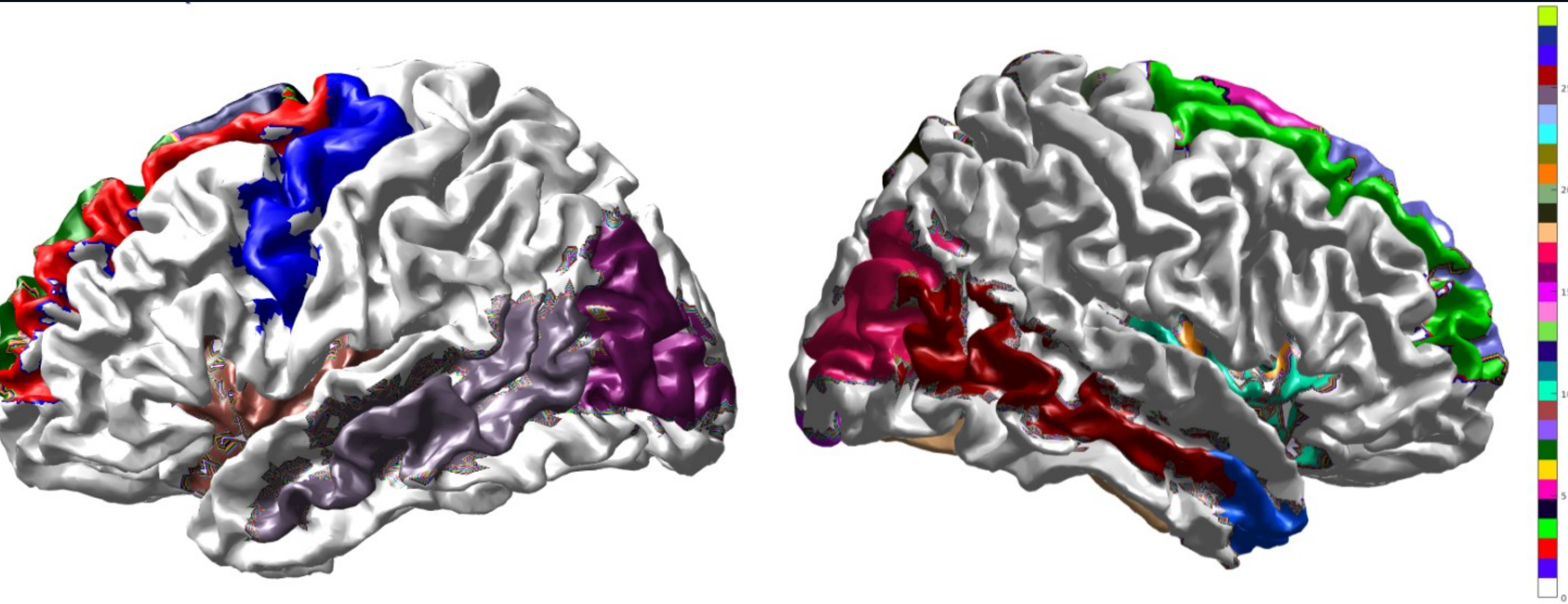
Spectral fingerprints





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

Most reliable ROI, homologous ≤ 1.5

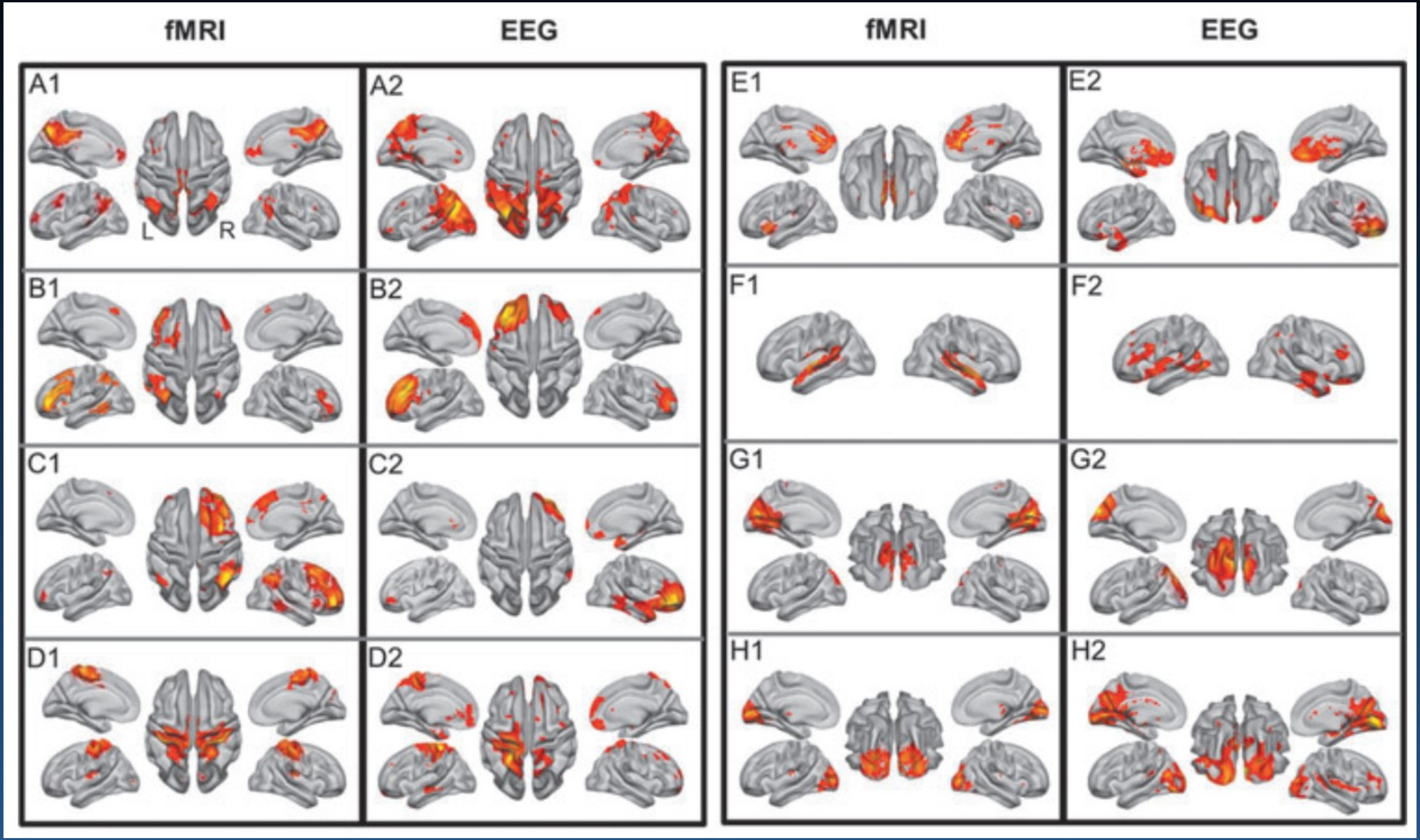


MEG data from the Human Connectome Project (HCP) for 1200 subjects.

Some ROI can be recognized quite reliably.

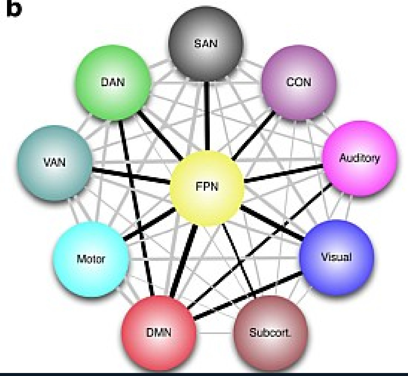
If homologues are not distinguished we have 29 ROIs, many sub-cortical, that can be reliably identified. Still working on EEG data …

8 large networks from BOLD-EEG



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

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

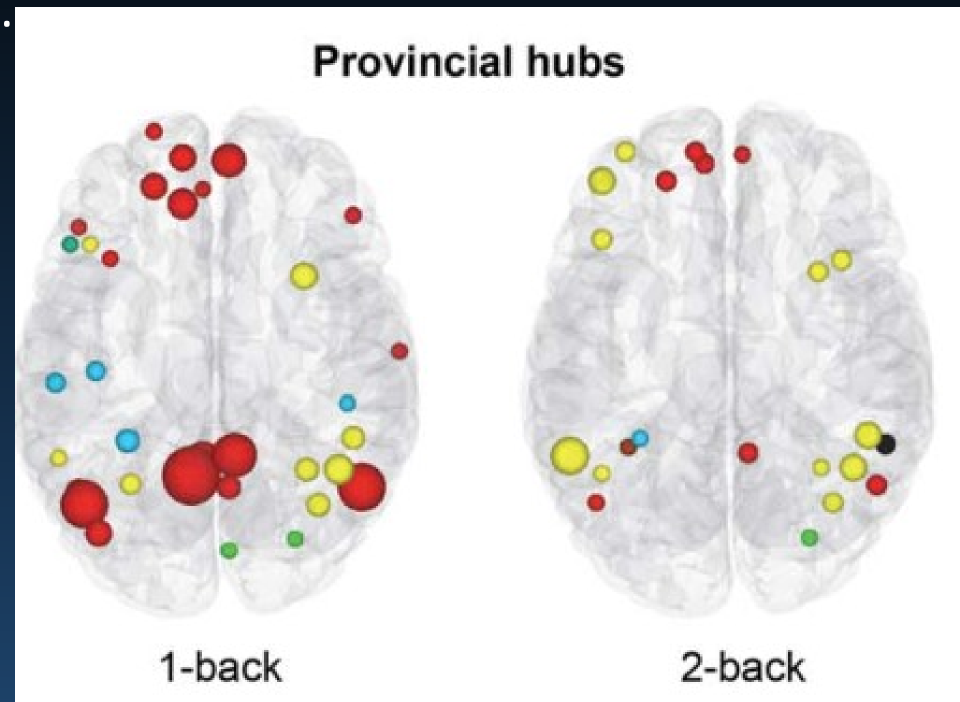
Simple and more difficult tasks, requiring the whole-brain network reorganization.

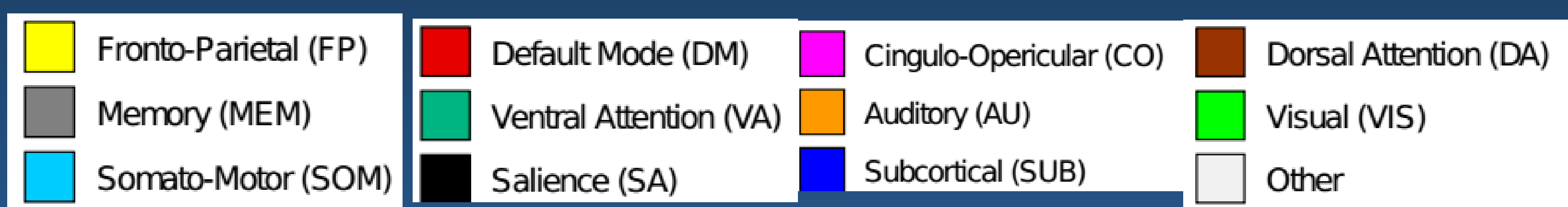
Left: 1-back local hubs

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

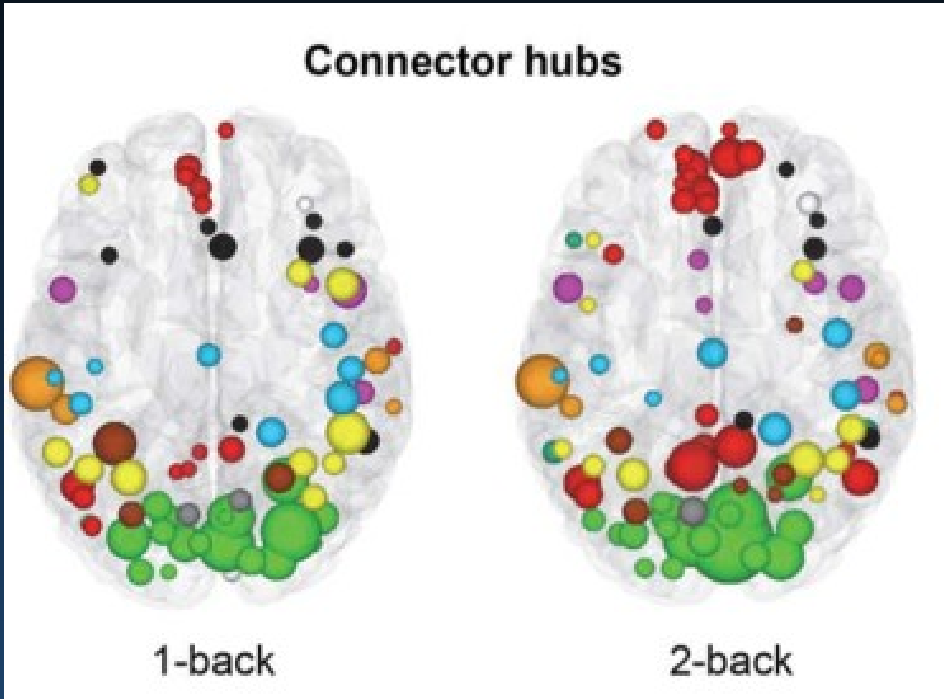
Simple and more difficult tasks, requiring the whole-brain network reorganization.

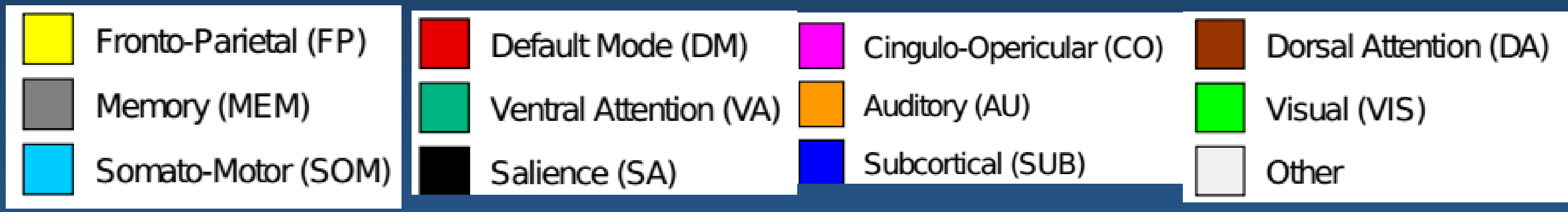
Left: 1-back   connector hubs

Right: 2-back   connector hubs

Average over 35 *participants.*

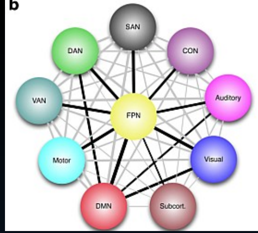
Dynamical change of the landscape of attractors, depending on the cognitive load – System 2 (Khaneman).
DMN areas engaged in global binding!





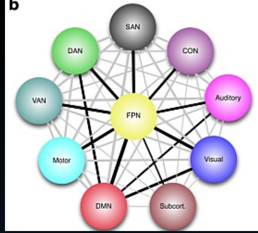
K. Finc et al, HBM (2017).

2020 in our lab



- Finc K, … Bassett, D.S. (2020). Dynamic reconfiguration of functional brain networks during working memory training. **Nature Communications** 11, 2435.
- Esteban, O. … Gorgolewski, K. J. (2020). Analysis of task-based functional MRI data preprocessed with fMRIPrep. **Nature Protocols** (in print)
- Thompson, W.H. … Poldrack, R. A. (2020). Time-varying nodal measures with temporal community structure: A cautionary note to avoid misinterpretation. **Human Brain Mapping**, 41(9), 2347-2356.
- Bonna, K … Szwed, M. (2019). Early deafness leads to re-shaping of global functional connectivity beyond the auditory cortex. Brain Imaging and Behaviour (in print).
- Asanowicz, D. … Binder, M. (2020). The response relevance of visual stimuli modulates the P3 component and the underlying sensorimotor network. Scientific Reports, 10(1), 1-20.
- Rykaczewski, K. … Piotrowski, T. (2020). SupFunSim: spatial filtering toolbox for EEG. **Neuroinformatics** (in print)

2020 in our lab



Dreszer J. ... Piotrowski T. (2020) . Spatiotemporal Complexity Patterns of Resting-state Bioelectrical Activity Explain Fluid Intelligence: Sex Matters. **Human Brain Mapping** (in print).

Piotrowski T., Nikadon J., Moiseev A. (2020). Localization of Brain Activity from EEG/MEG Using MV-PURE Framework.
Biomedical Signal Processing and Control (in print).

Meina, M. … Krasuski, A. (2020). Heart Rate Variability and accelerometry as classification tools for monitoring perceived stress levels: a pilot study on firefighters. **Sensors** (in print).

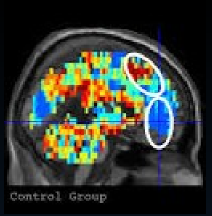
Duch. W. (2020) IDyOT architecture – is this how minds operate?
Physics of Life Reviews (in print).

Duch W, Mikołajewski D. (2020) Modelling effects of consciousness disorders in brainstem computational model – Preliminary findings.
Bio-Algorithms and Med-Systems 16(2), 1-10, 20190059, 2020.

Duch. W. (2020) Experiential Learning Styles and Neurocognitive Phenomics.
PsyArXiv. August 30.


AI for Neuroscience
&
Neuroscience for AI
Irina Rish
AI Foundations
IBM T.J. Watson Research Center

Searching for Brain Fingerprints



Challenge: Link patterns of brain activity to active regions/networks, and provide interpretation of mental events S(M)⇔S(B).

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

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

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.

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).

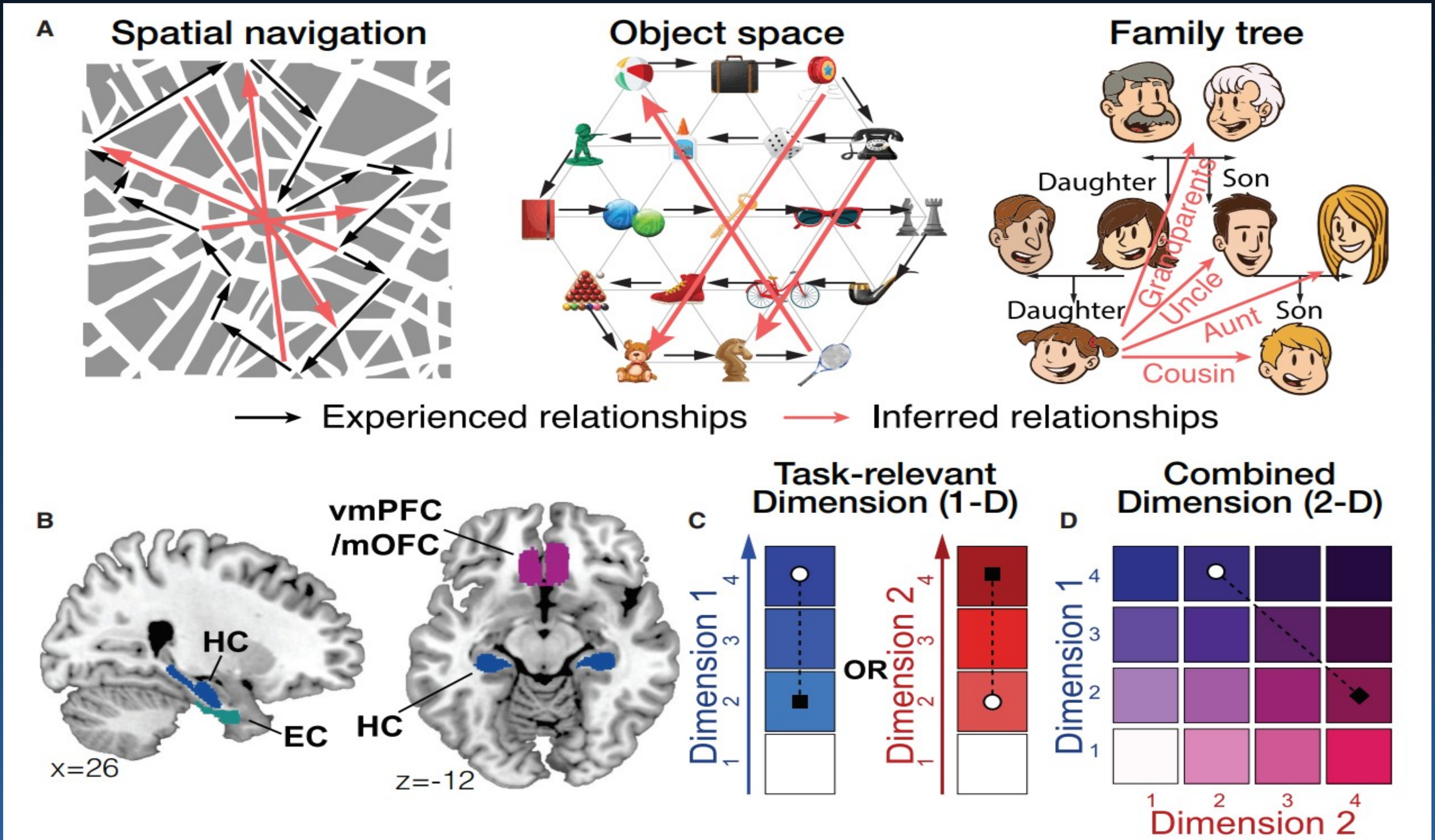
(D) **One-shot generalization** in deep sequential generative models that specify a causal process for generating the observed data using a hierarchy of latent variables, with attentional mechanisms supporting sequential inference, mirroring human abilities to generalize from a single concept.

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

Abstract Cognitive Maps

Nobel Prize for grid/place cells to Edvard & May-Britt Moser and J. O'Keefe.

S.A. Park et al, Map Making: Constructing, Combining, and Inferring on Abstract Cognitive Maps. Neuron 07, 1226-1238.E8, 2020.



Most interesting applications

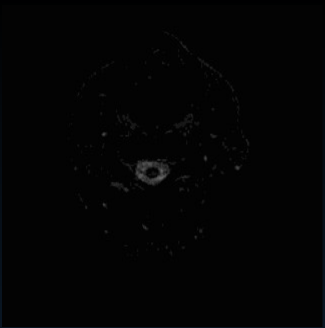
- **Monitoring development** of children and infants, perception, working memory, curiosity, unfolding full potential of children!
- Precise **diagnosis** of various subtypes of mental disorders: organic problems, schizophrenia, epilepsy, learning disabilities, depression, anhedonia, mild cognitive impairment, Alzheimer etc,
  based on brain connectivity and functional large scale networks.
- Enabling early ASD diagnosis and other **developmental problems**.
- 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 closed-loop neuromodulation**; distinguishing between organic, chronic, psychogenic and faking pain, and provide treatment based on neuromodulation.

Estimation: 27 B$ market for neural devices in 2025.

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 EEG-based **brain-computer interfaces**, new neurofedback/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.

Hard road



Neurocognitive technologies are hard, **complex & interdisciplinary**.

- **Roadmap**: Brain neuroimaging ⇔ models of brain processes ⇔ links with AI mental models ⇔ closed loop BCBI for conscious control/brain optimization.
- **Brain reading**, understanding neurodynamics and neurocognitive phenomics, are the key to self-regulation of brain functions, and therapeutic applications.
- 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.
- **Neuromorphic hardware** with complexity beyond the human brain is coming and we should learn how to use it in practical applications.
- **Basic research**: methods for discovering brain fingerprints of cognitive activity, mapping between brain and mental states, still need development.
- Should we improve over our weaknesses in strategic areas, or focus on a few already developed AI research areas? **Can we afford ignorance**?
- Global AI/Brain initiatives give us hope, but are they going in right direction?

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

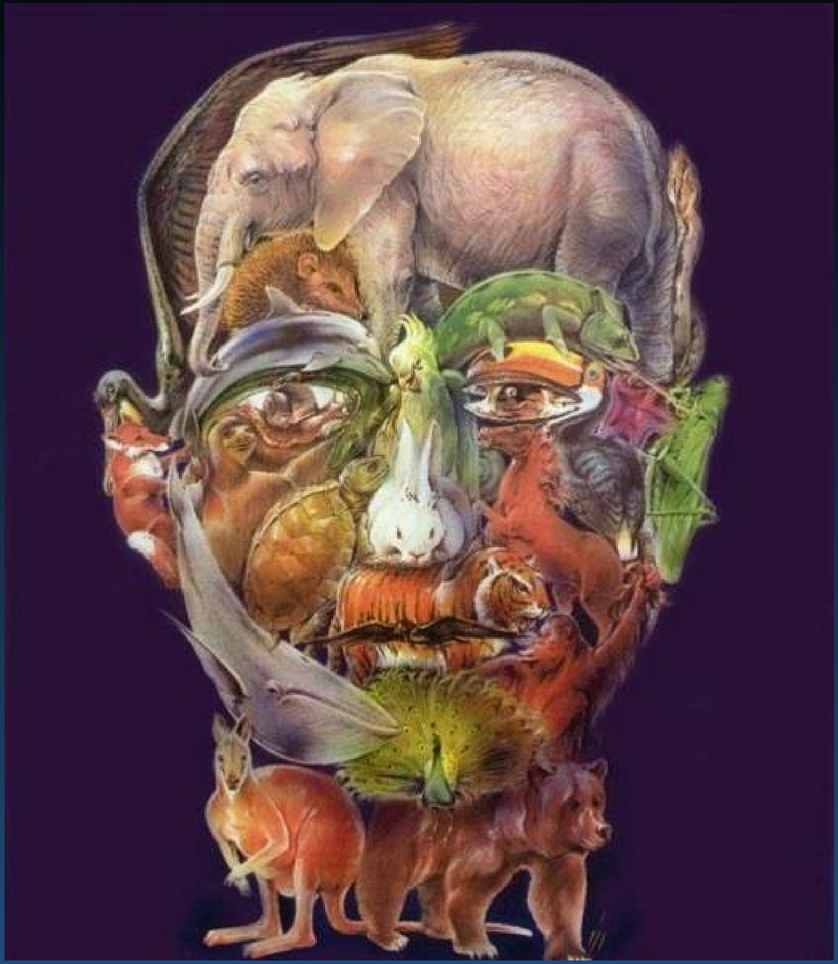
INSTITUTE OF PHYSIOLOGY AND PATHOLOGY OF HEARING

nencki institute of experimental biology

Thank you for synchronizing your neurons!

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

Info is on my webpage.



Google: Wlodek Duch
=> talks, papers, lectures, Flipboard …