Brain-Computer-Brain Interfaces

Włodzisław Duch

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

Google: Wlodzislaw Duch

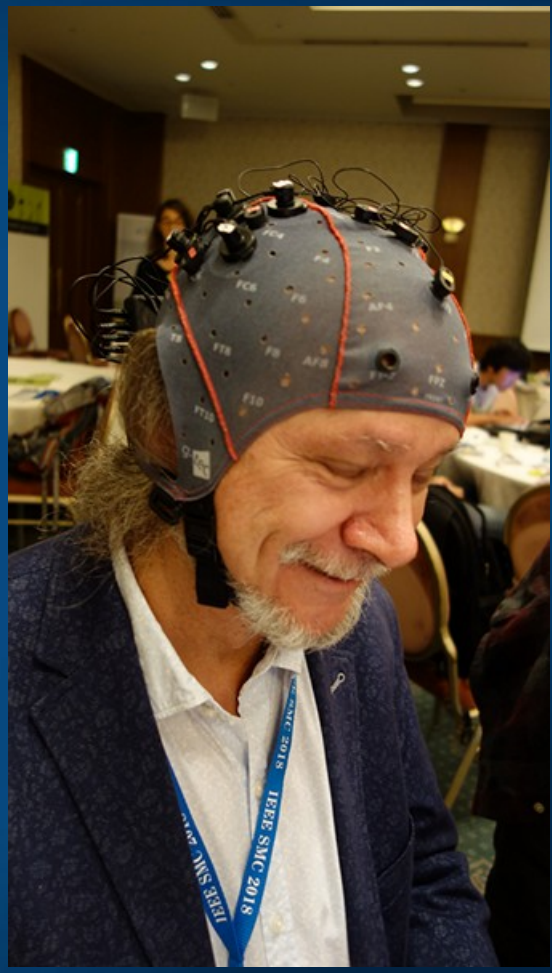
2021.05.21: Neurohackator

On the threshold of a dream …

Final goal: optimize brain processes!

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.

Brain-Computer Neural Interfaces

BCI is a XXI century science, only a few papers were written in XX century.

In the last decade EU contributed over 50M Euro for BCI research.

BCI Society: **brain/neuronal computer interaction (BNCI)**,
using any kinds of brain and body signals.
BNCI Horizon 2020, lists >100 companies involved in BCI.

Many EU projects:

BackHome – rehabilitation, assisting people with severe disabilities.

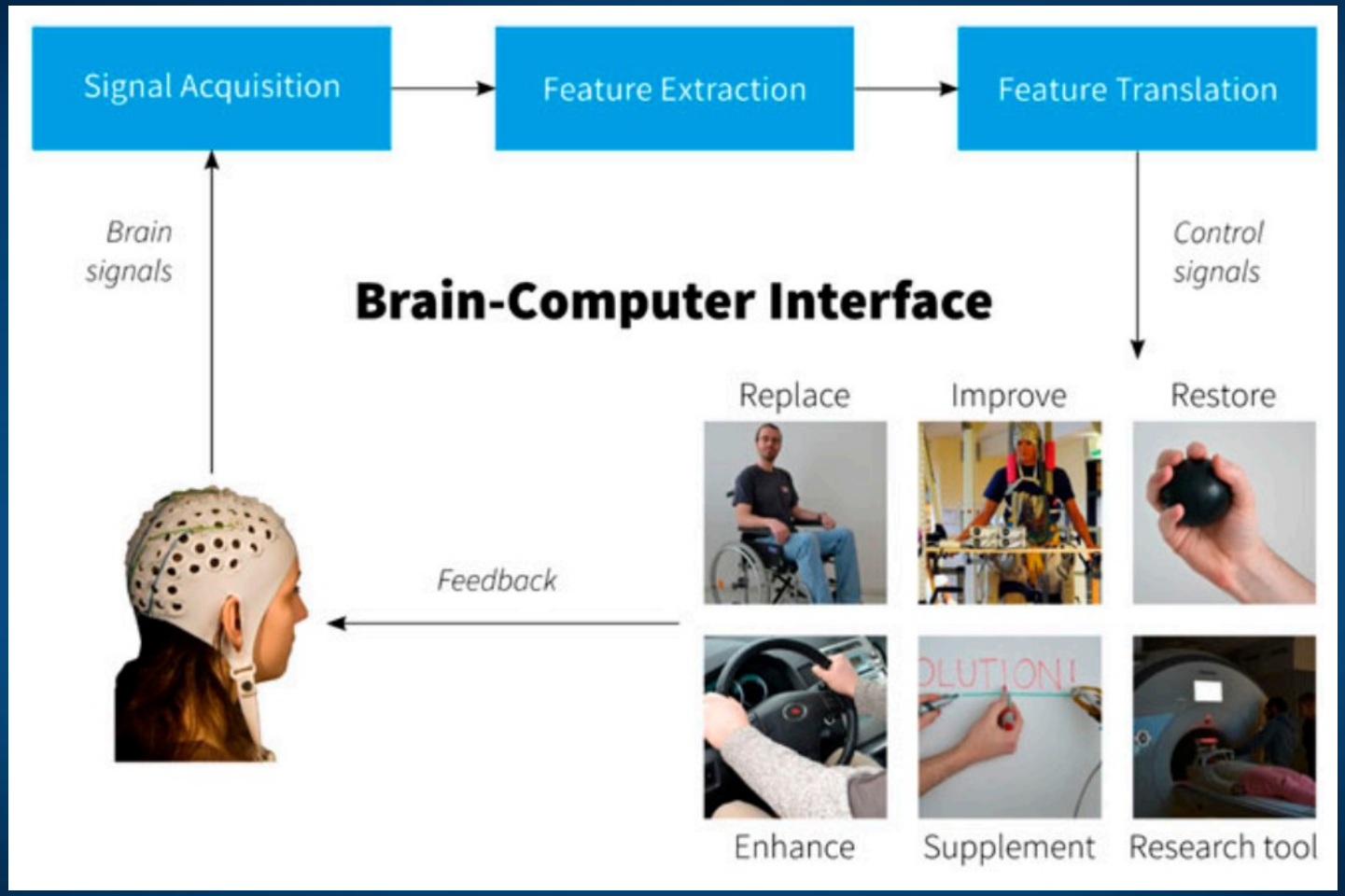
MindSee – EEG + physiological sensors (EDR, fEMG, eye gaze and pupillometry) measures of perception, cognition and emotion; scientific literature research.

MoreGrasp – multi-adaptive, multimodal neuroprothesis.

NEBIAS – neurocontrolled bidirectional artificial upper limb and hand prosthesis

SI-CODE – the state dependency of neuronal responses to external stimuli.

BCI Applications



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

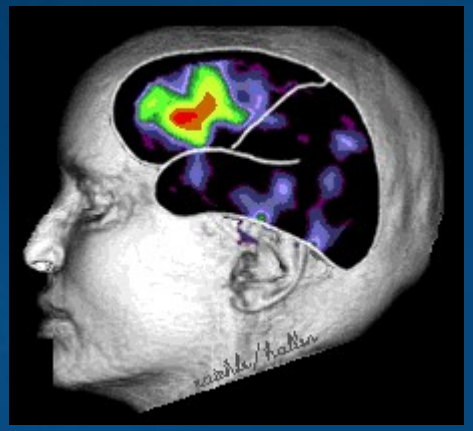
BNCI Grand Vision

BNCI-Horizon-2020 roadmap and vision for 2025.

- Routine applications in personal health monitoring and medical treatment.
- Humans and ITC are seamlessly connected by integrating various biosignals.
- People working in safety-relevant fields will anticipate fatigue.
- Game, health, education, lifestyle companies will link biosignals with apps.
- Monitoring brain states will provide reliable estimates of mental capacity.
- Rehabilitation after stroke will benefit from BCI-based treatments.
- New treatments of brain disorders will use corrective neurostimulation for epilepsy, depression, Parkinson's disease, and schizophrenia.
- Restoration of motor functions will use implants for recording and stimulation
- BCI-based locomotion systems will decoded brain signals to control an exoskeleton, activate limb muscle stimulation programs for walking, or control wheelchairs and mechanical arms.

Mapping brain states to mental images

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



Mapping:

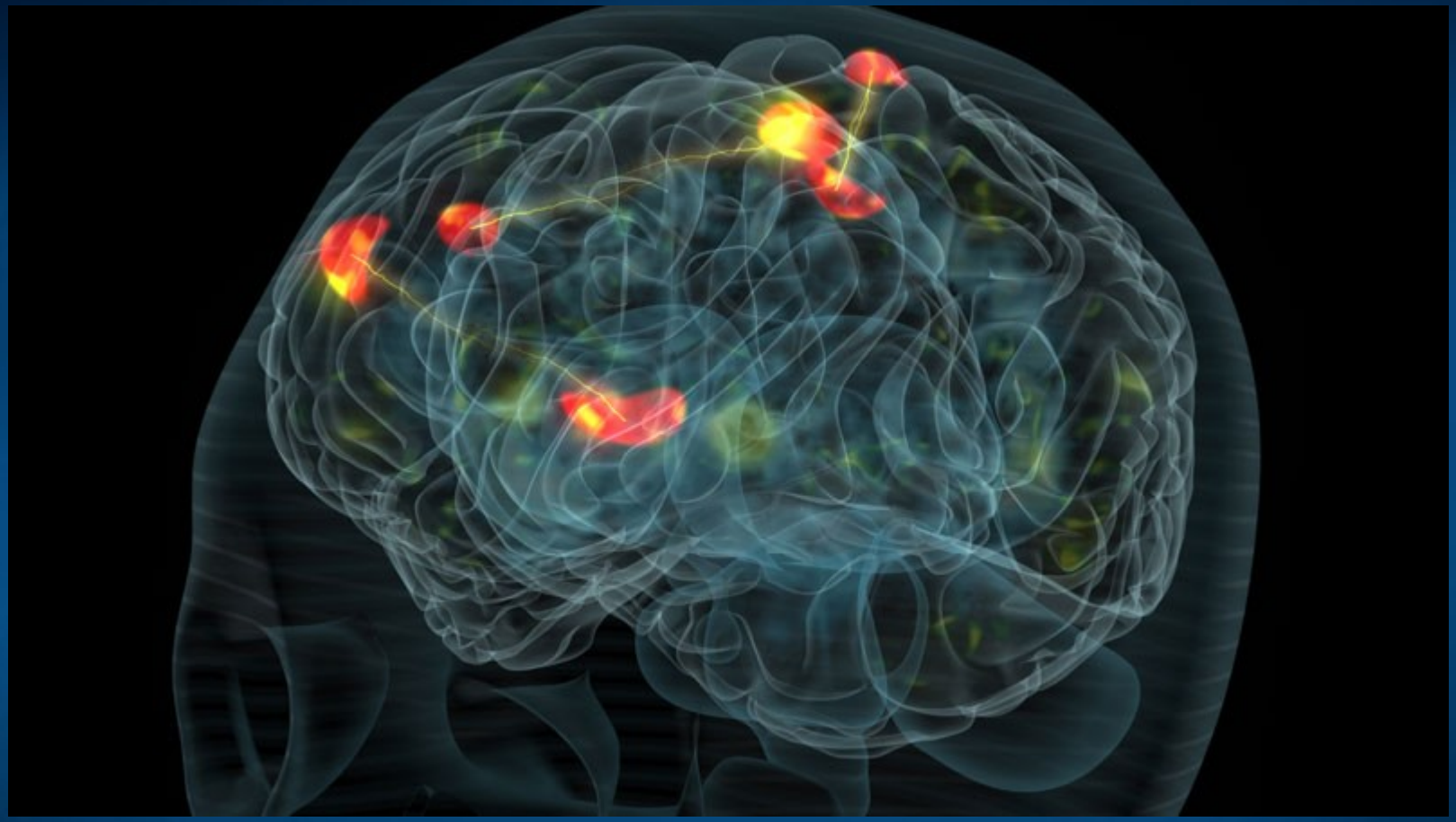
State(Brain)⇔State(Mind)

via intermediate BNCI models.

Mental states, movement of thoughts ⇔ trajectories in psychological spaces.

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

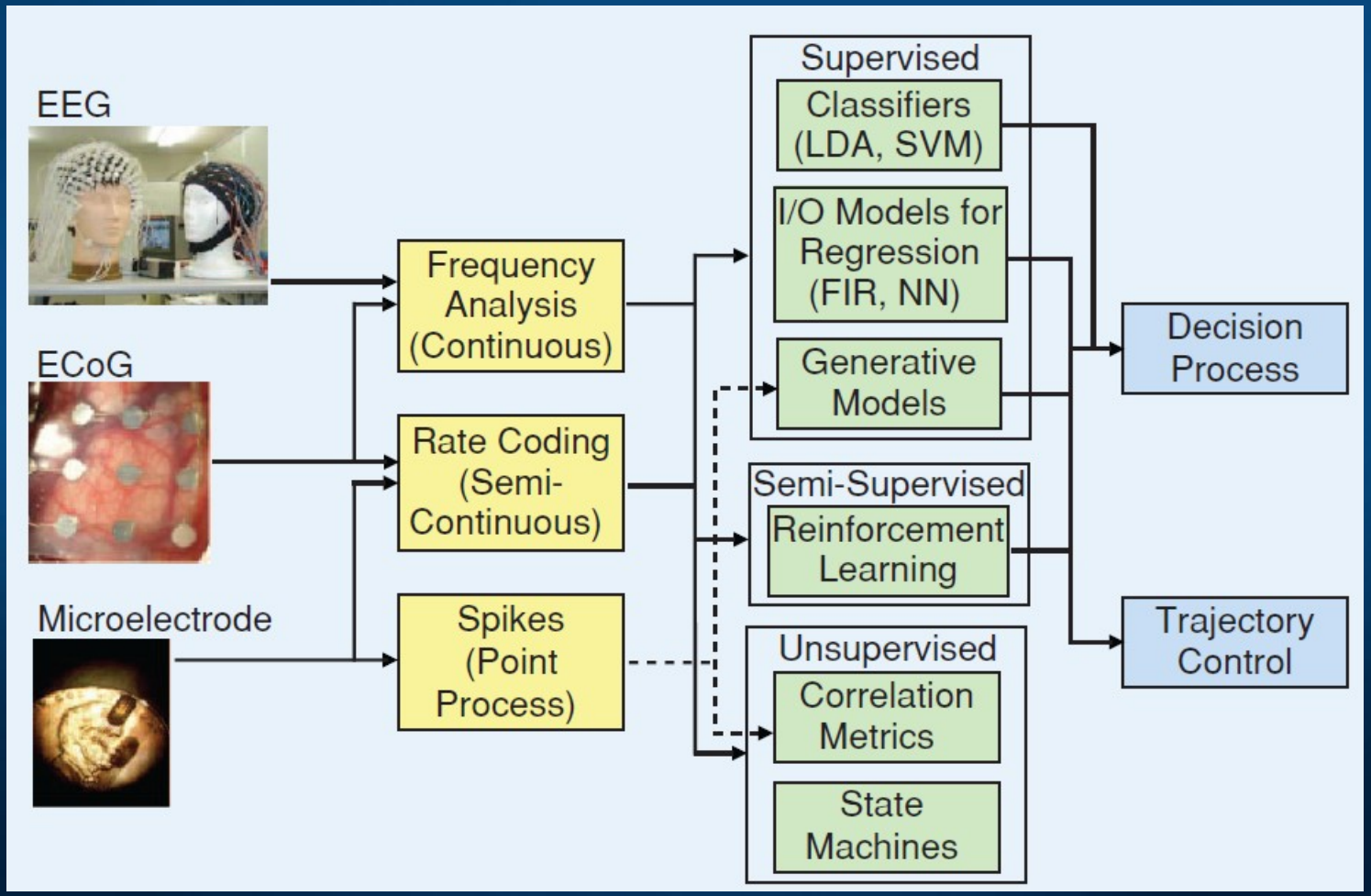
Mental state: strong coherent activation



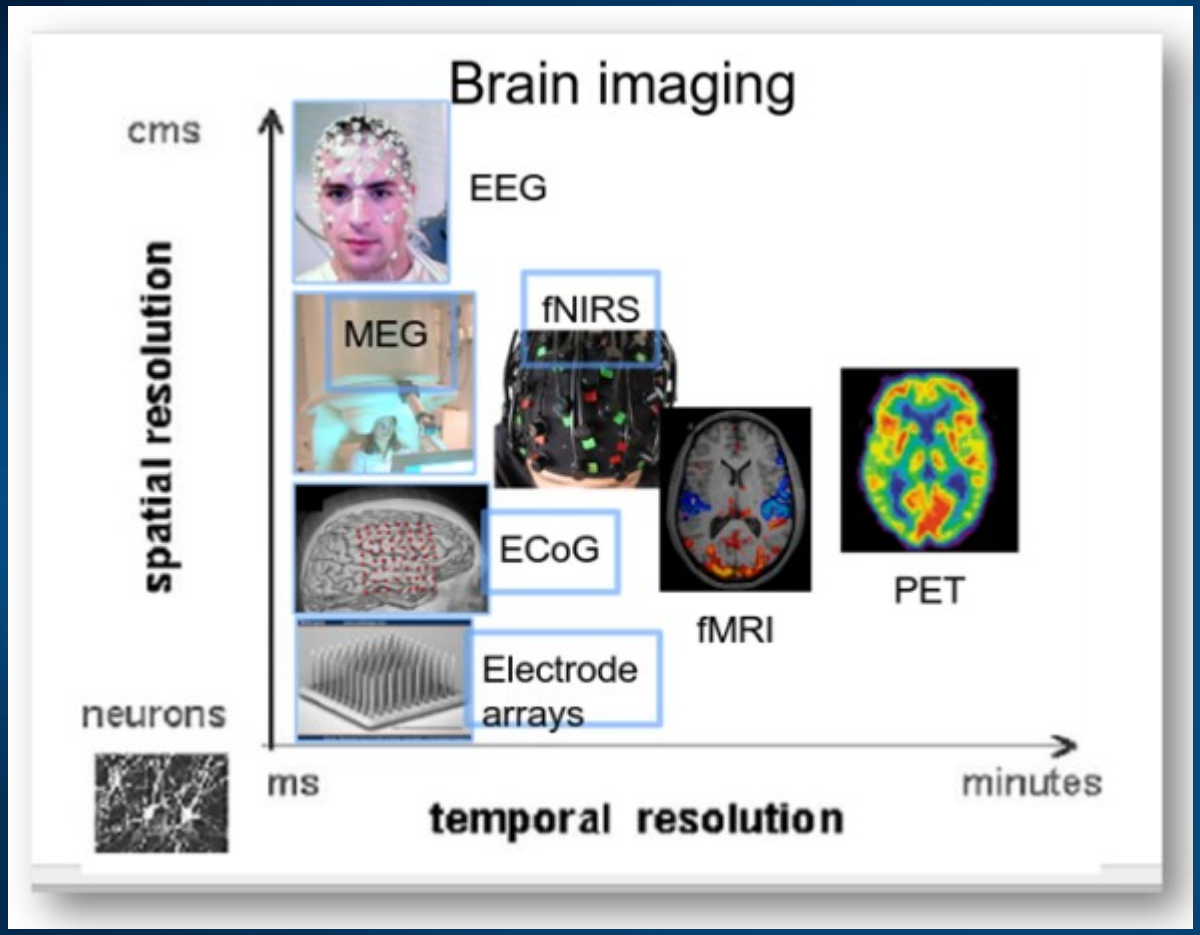
Many processes go on in parallel.
Most are automatic, hidden from our Self. What goes on in my head?
Various subnetworks compete for access to consciousness, the highest level of control, using the WTA/WTM mechanism.
How to extract stable intentions in such chaos? BCI is never easy.

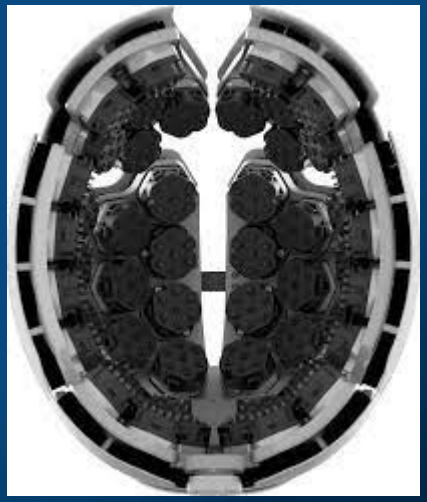
BCI: wire your brain …

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

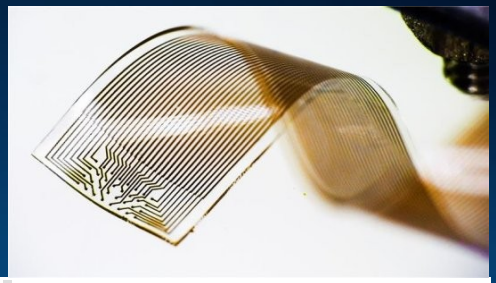


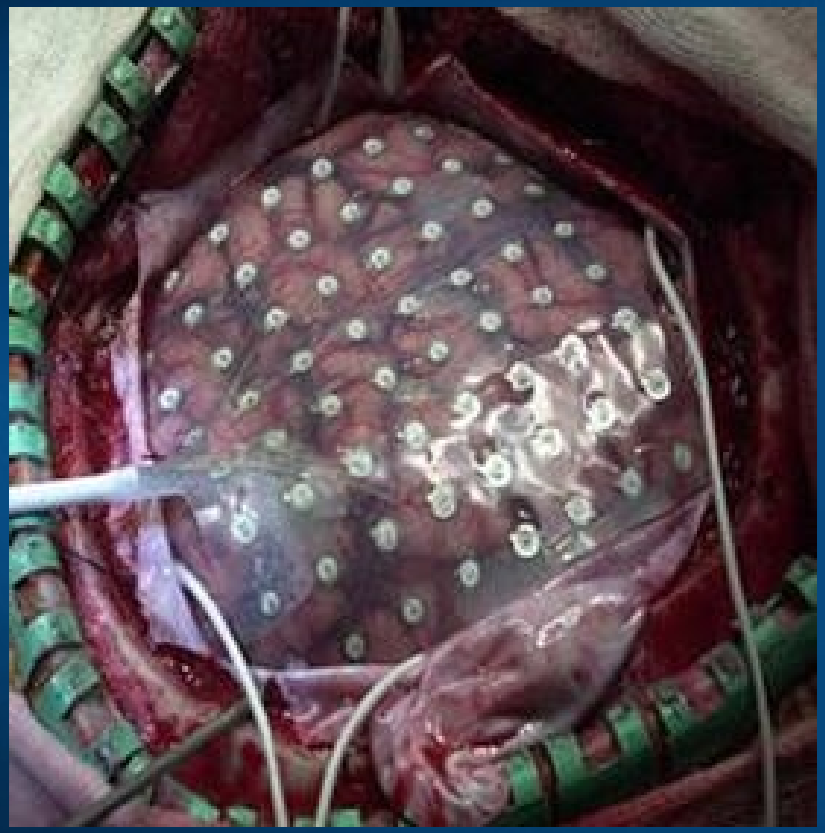
Signal acquisition





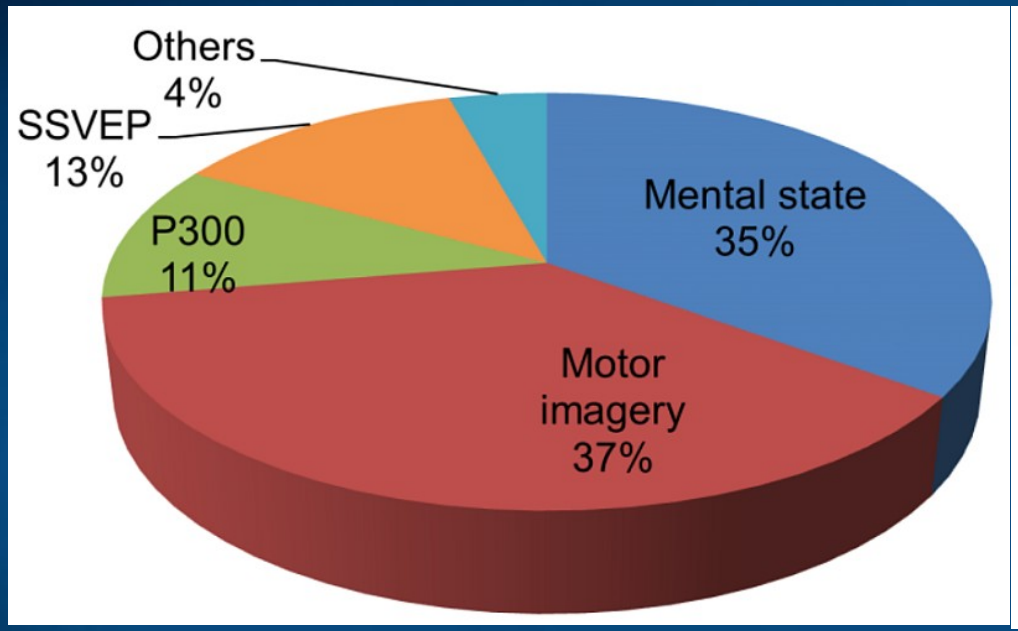
Partially invasive interfaces

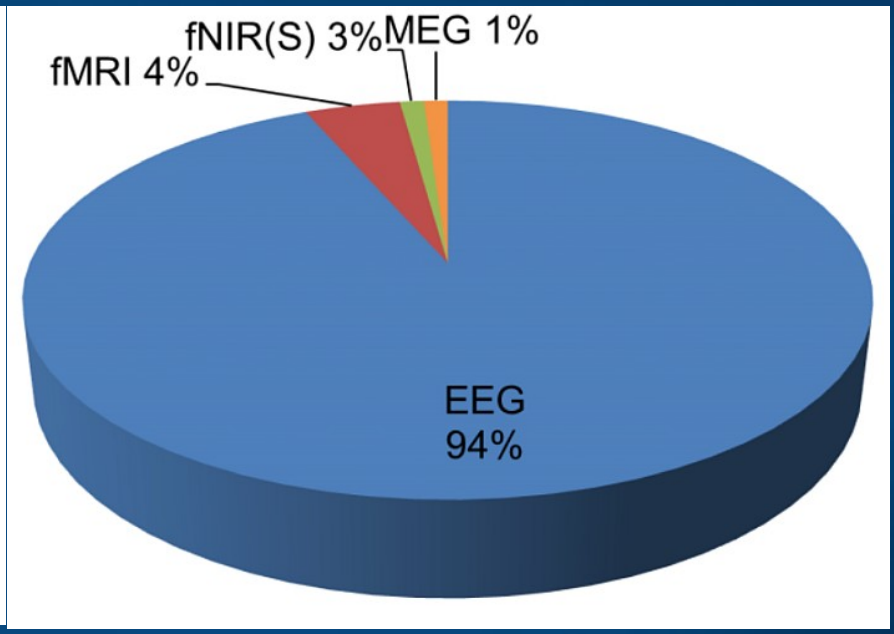




Epilepsy, Obsessive-Compulsive Disorder, Phobias … if you know how to run electric currents through your brain you can control your mental states in a conscious way. Commercial RSN system for epilepsy.

Control paradigm/signal source

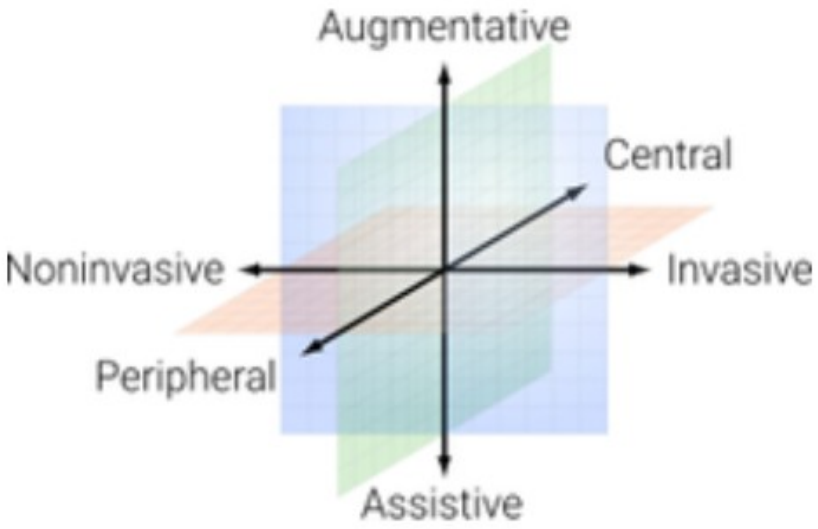


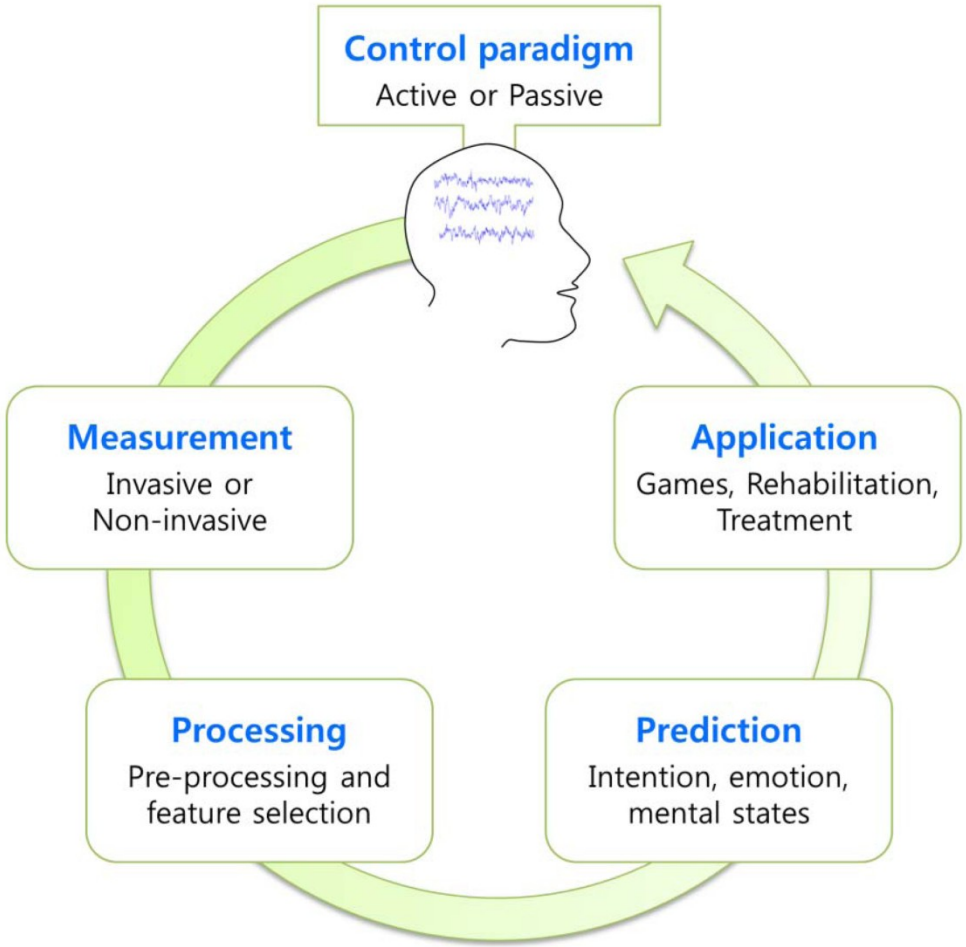


SSVEP, Steady State Visual Evoked Potentials, is perhaps the simplest.

Mental state is frequently based on emotions or attention.

5 dimensions of BCI





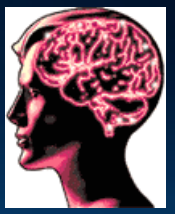
4th D: passive – reactive – active

5th D: open – closed loop.

Source: Ahn et al. (2014) *Sensors*, *14*(8), 14601–14633.

BCI Infographics from Futurism.com shows a good summary.

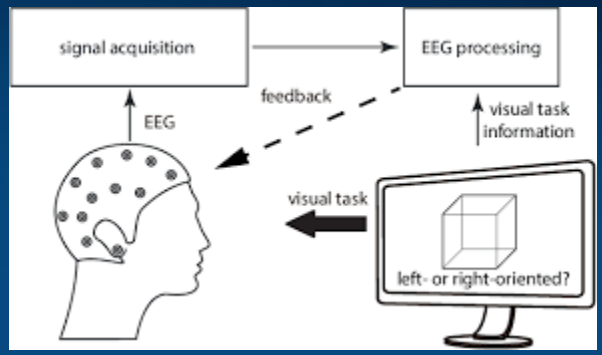
Active, Reactive and Passive BCI



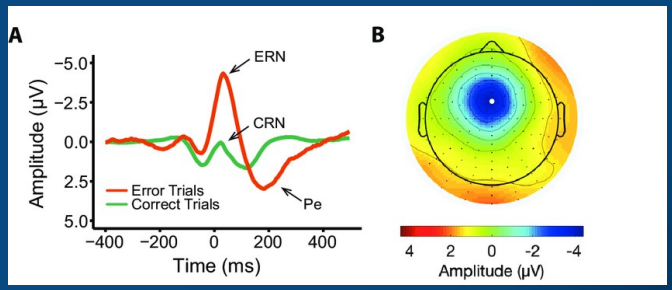
- **Active BCI systems**: brain activity is intentionally modulated in order to control some application (motor imagery, relaxation).
- **Reactive BCI**: brain activity evoked by external stimulation is modulated indirectly through voluntary attention (SSVEP, P300 vs. attention shifts).
- **Passive BCI**: automatic, involuntary brain activity (arousal, stress, workload, vigilance, emotions, surprise) is measured and interpreted in a given context, used as input to support an ongoing task.

Passive BCI types

pBCI types:



- **mental state assessment:**
  eg. cognitive workload, neuroergonomics, lie detectors, neuromarketing;
- **open-loop adaptation:**
  specific brain state => specific action, feedback based on mental state assessment, ex. error-related negativity (ERN) may override human errors;



- **closed-loop adaptation:**
  specific brain state => mental state assessment
  => response to state/changes of states => actions that influence mental state.

Closed-loop adaptation is especially effective combining BCI with direct brain stimulation (TMS, DCS) enhancing activation of specific brain structures.

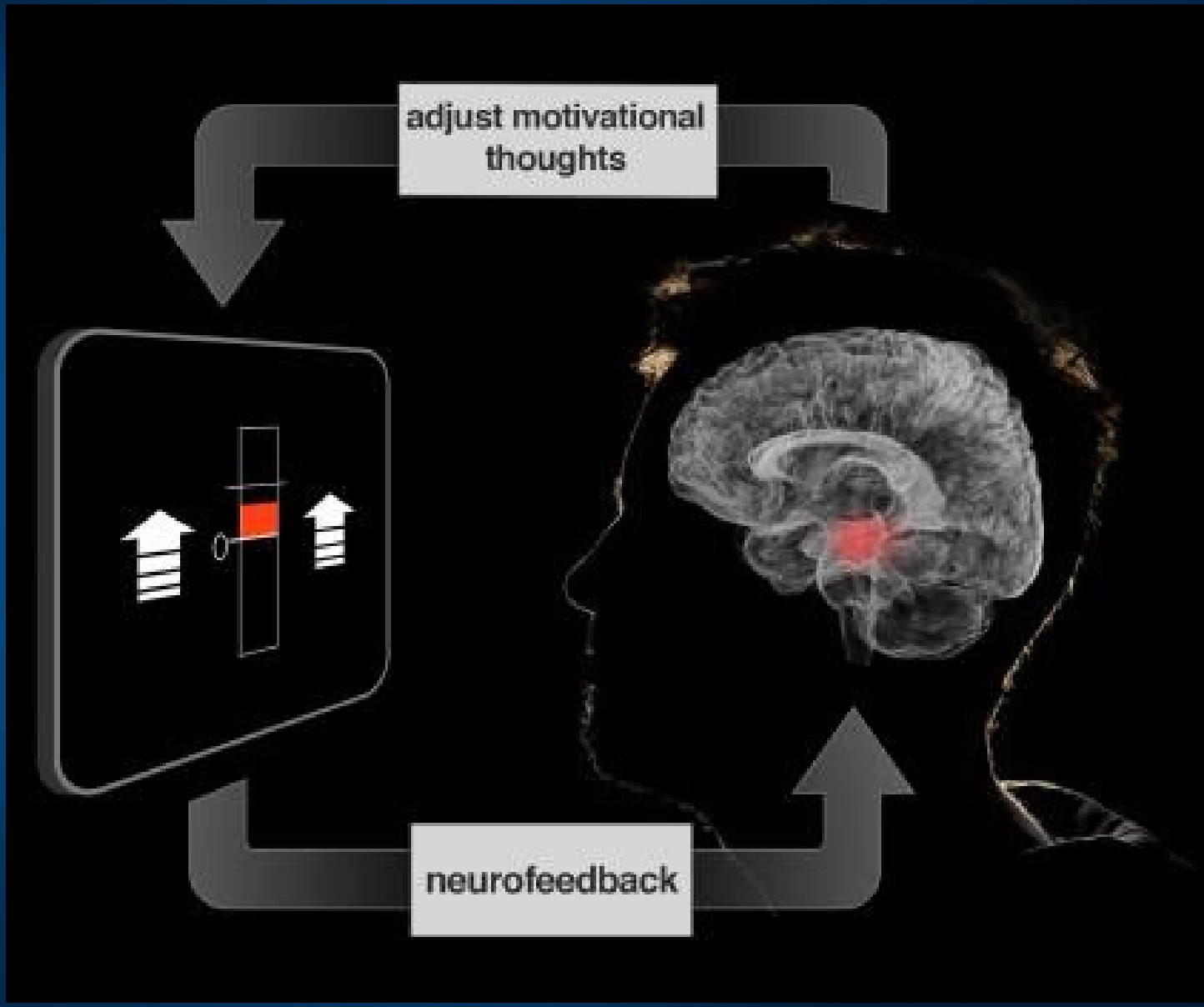
Neurofeedback: first BCI

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

W. Duch, Elektronika i stresy, Przekrój 1978!

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

New forms based on brain fingerprinting needed.



BCNI Future

BCI Society wants “to foster research leading to technologies that enable people to interact with the world through brain signals.”

Emerging: **Mobile Brain/Body Imaging** (MoBI), recording movement, eye tracking, various sensors for reading biosignals in natural situations.

MoBI: Modeling of human cognitive event-related brain dynamics as captured by high-dimensional EEG, MEG and other imaging modalities including simultaneous eye tracking and body motion capture (Scott Makeig, UCSD).

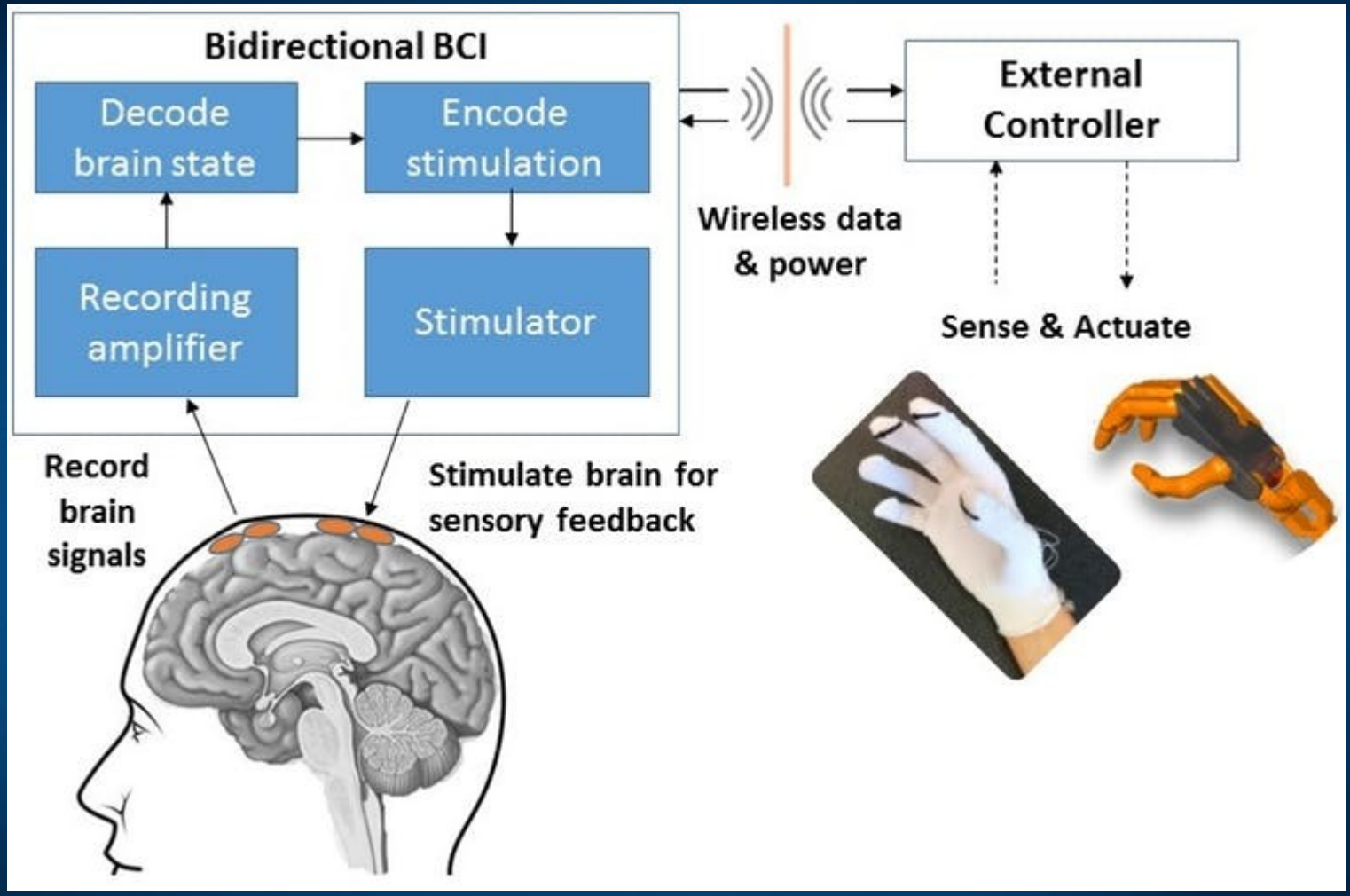
Brain-Computer-Brain interfaces – BCBI, closed-loop neurofeedback.

Localized BCBI, Decoded neurofeedback - DecNef.

Synchronized BCBI, Functional connectivity neurofeedback - FCNef.

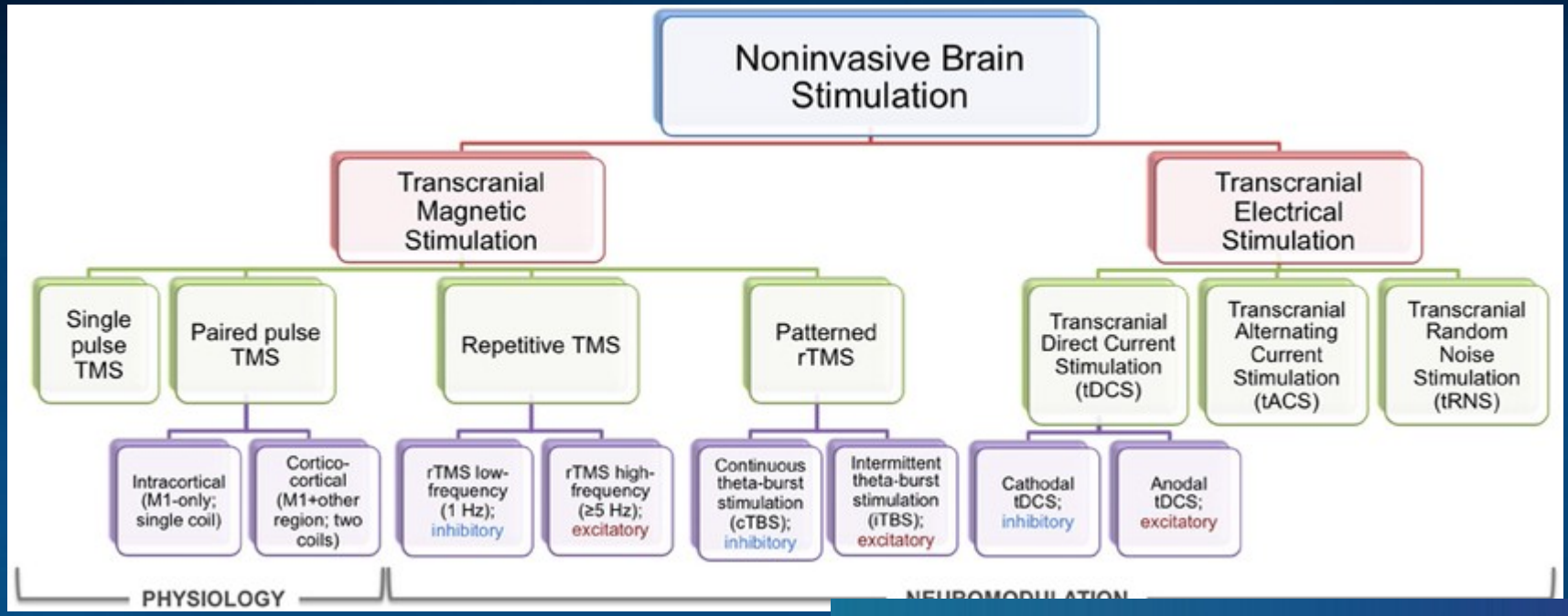
We need brain fingerprinting!

Brain-Computer-Brain interfaces



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

Brain stimulation



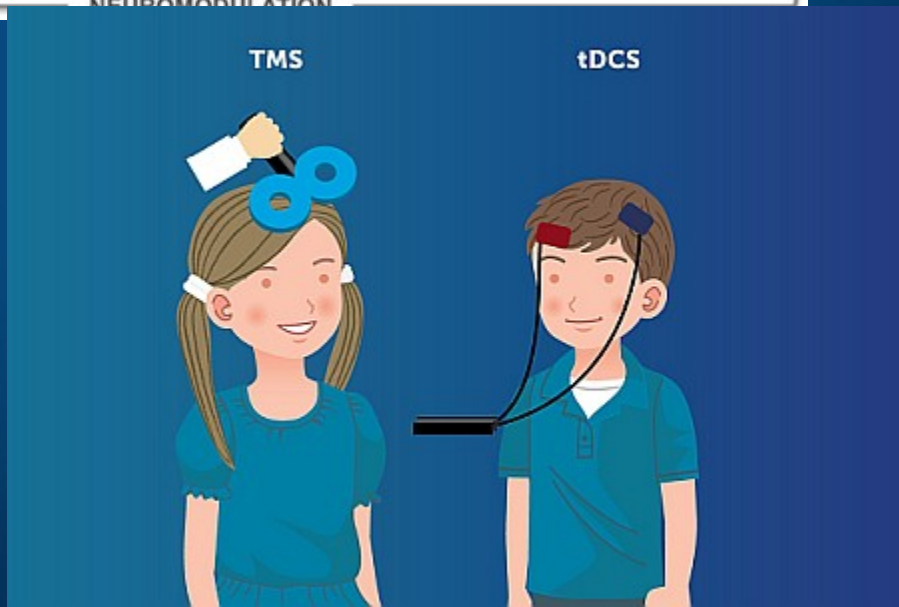
ECT – Electroconvulsive Therapy

VNS – Vagus Nerve Stimulation

Ultrasound, laser … stimulation.

Complex techniques, but portable phones are also complex.

Attention? Just activate your cortex!

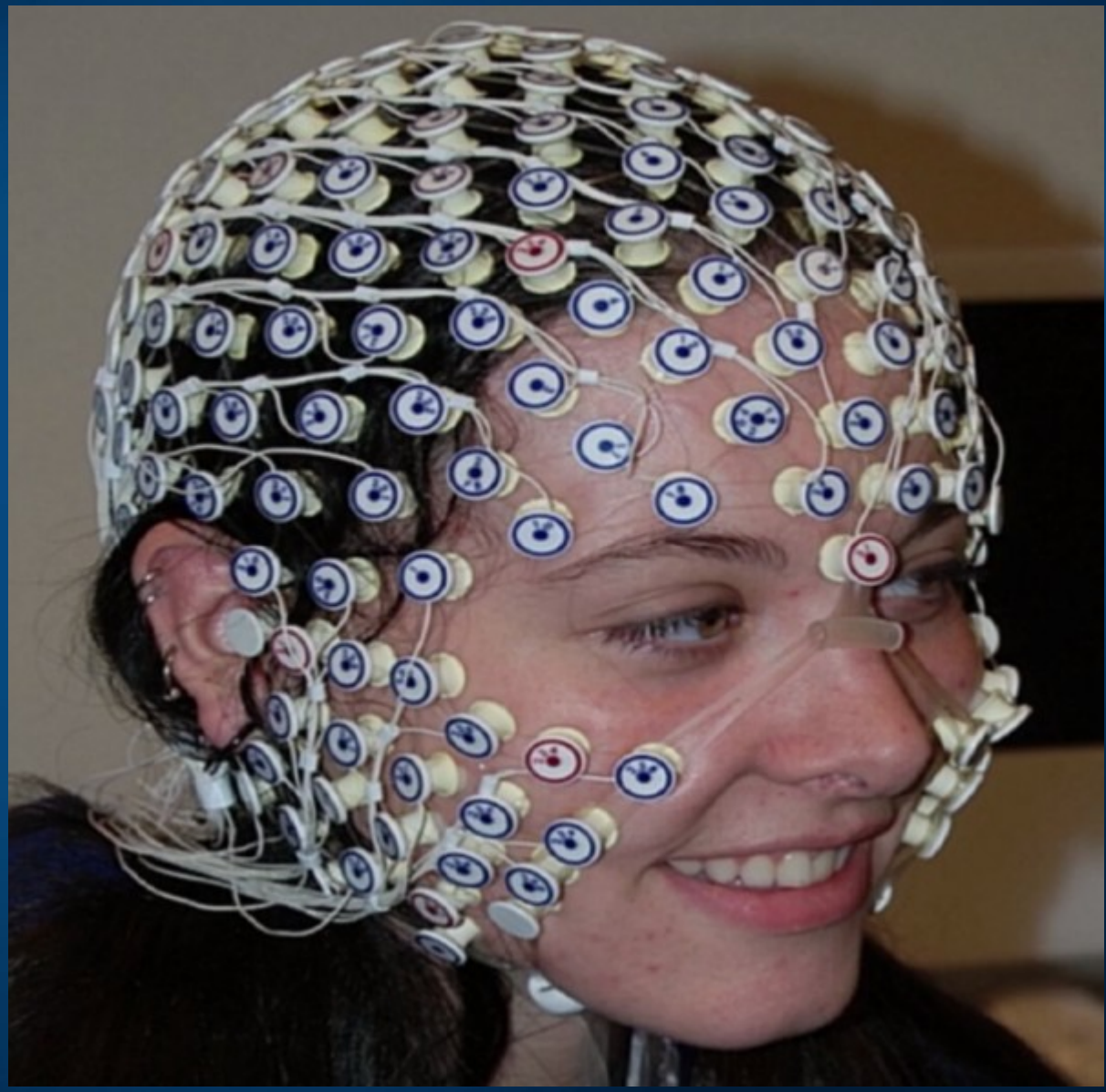


HD EEG/DCS

EEG electrodes + DCS.

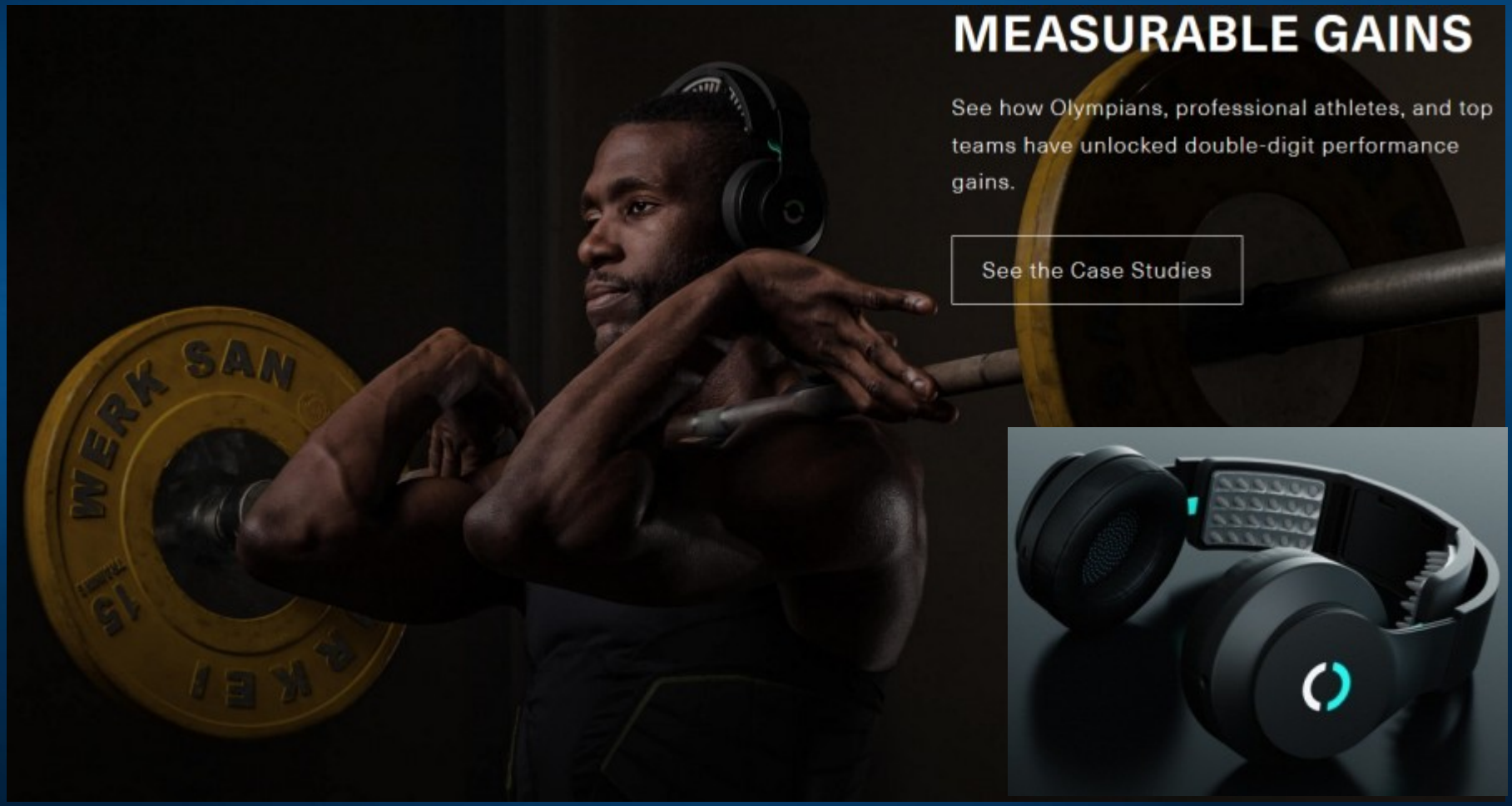
Reading brain states
=> transforming to
common space
=> duplicate in other brain …

Treatment of depression, pain, psychosomatic disorders, regulation of neuro-plasticity for rapid learning.



Neuropriming

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

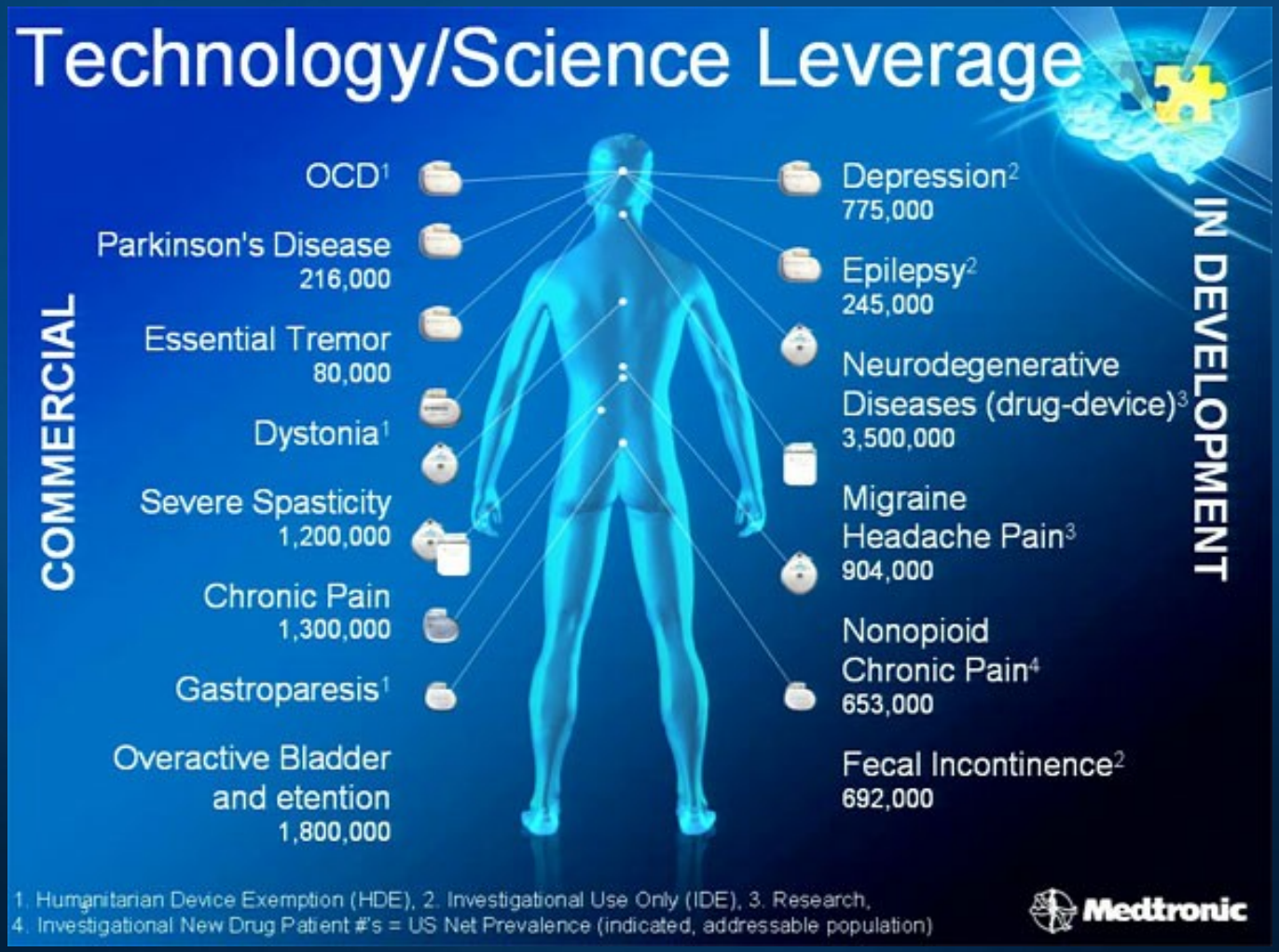


Prime for 20 min, benefit for 60 min.

Haloneuro.com

Neuromodulation

Cochlear implants are common, but deeper implants that stimulate or even replace some brain structures start to appear to regulate neural processes, ex. memory implants in hipocampus.



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.

In search of the sources of brain's cognitive activity

Project „Symfonia”, 2016-22

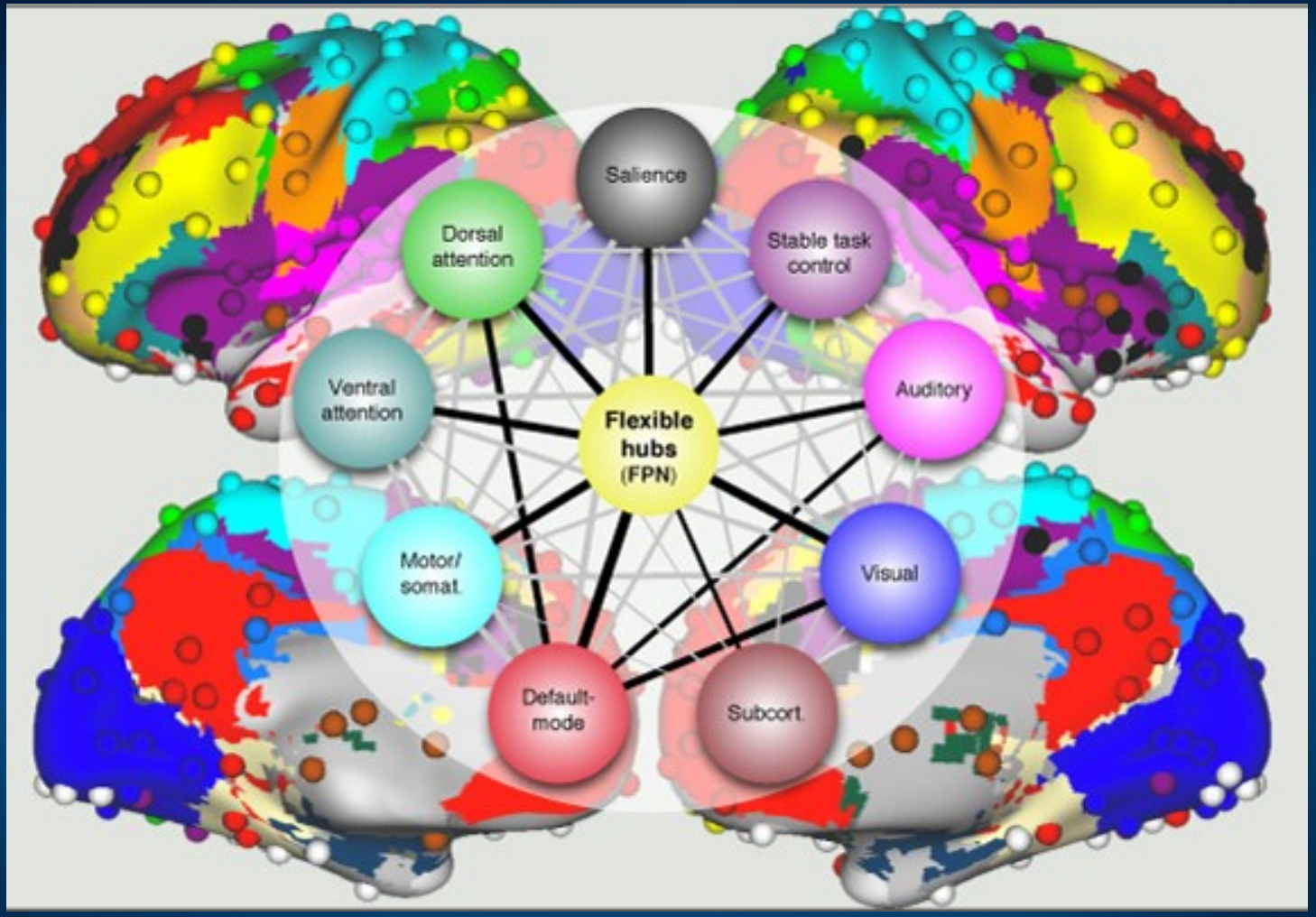
FACULTY OF PHYSICS, ASTRONOMY AND INFORMATICS

CENTRE FOR MODERN INTERDISCIPLINARY TECHNOLOGIES

INSTITUTE OF PHYSIOLOGY AND PATHOLOGY OF HEARING

nencki institute of experimental biology

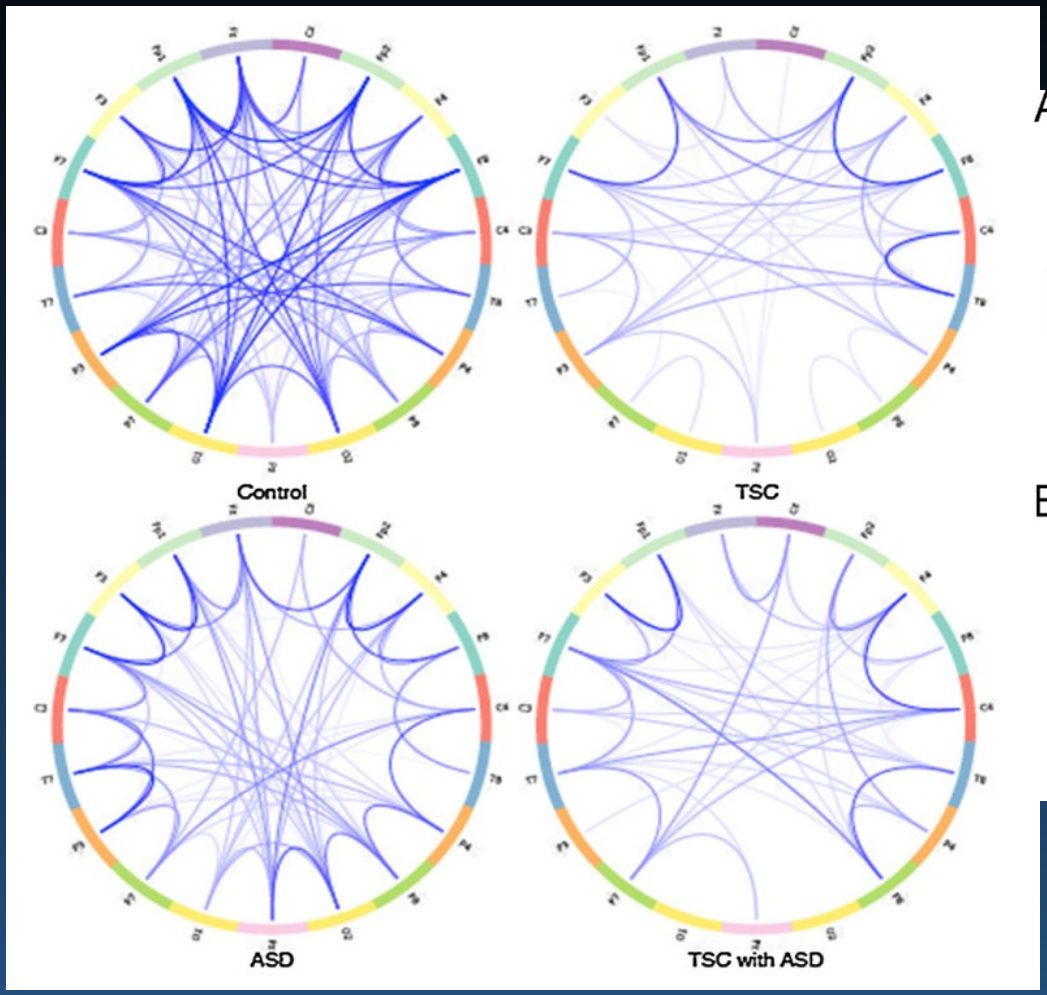
Large-Scale Networks

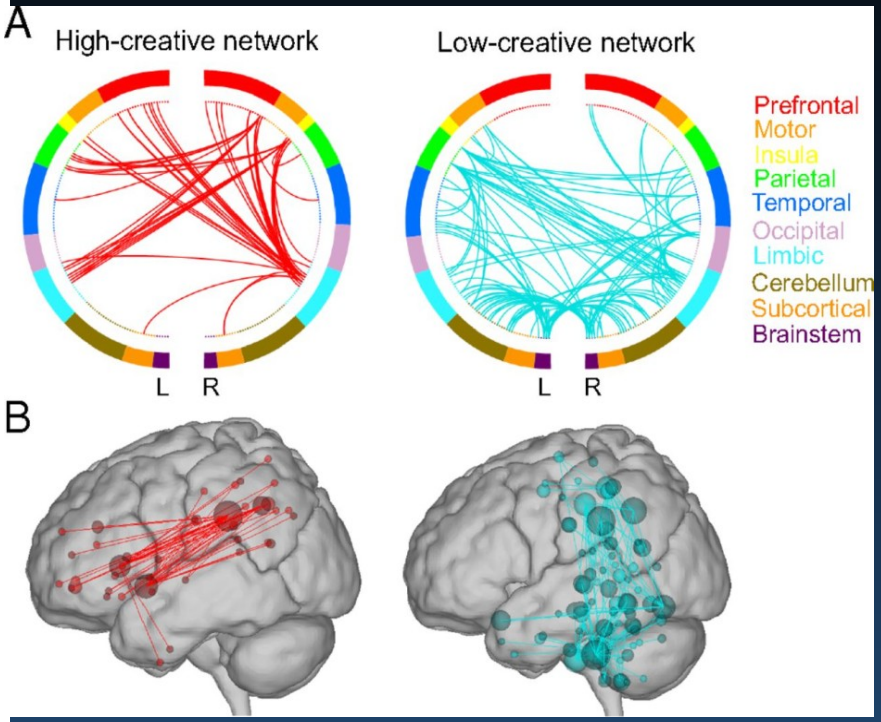


Cole M.W. et al. (2013). Multi-task connectivity reveals flexible hubs for adaptive task control. *Nature Neuroscience*.

rs-fMRI => 128 functional networks of cognition/behavior (Sung … 2018)!

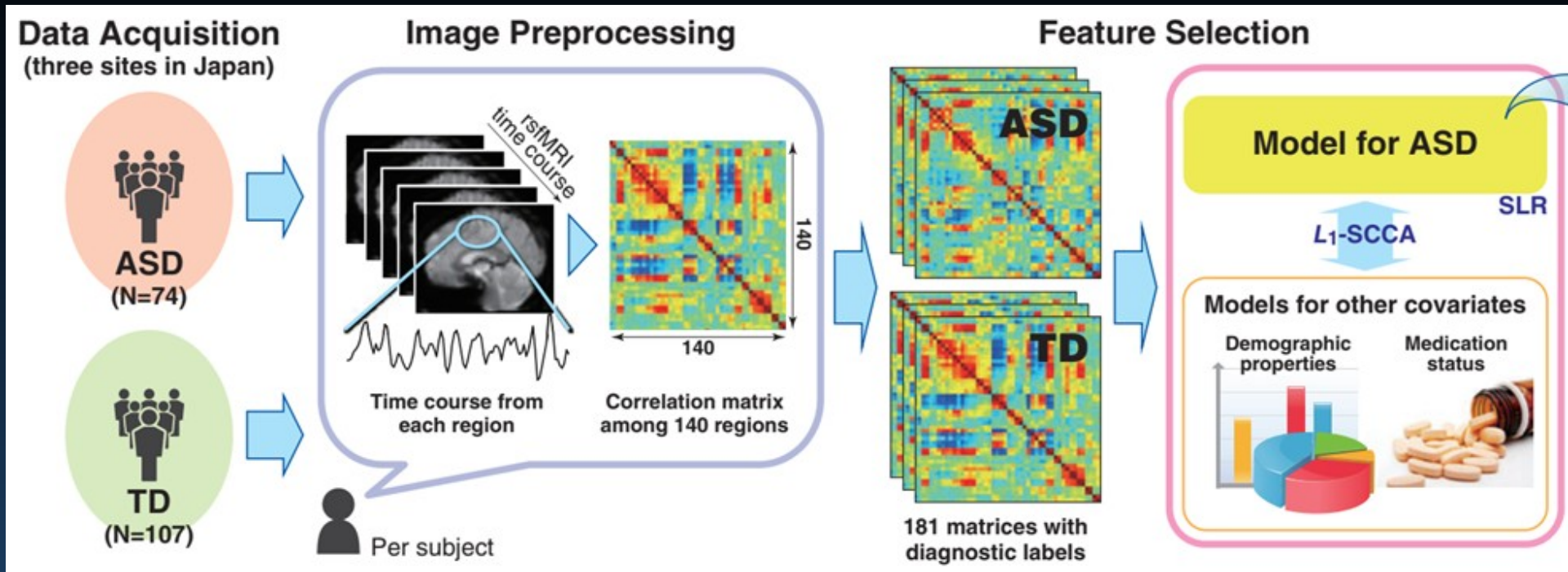
Pathological connections

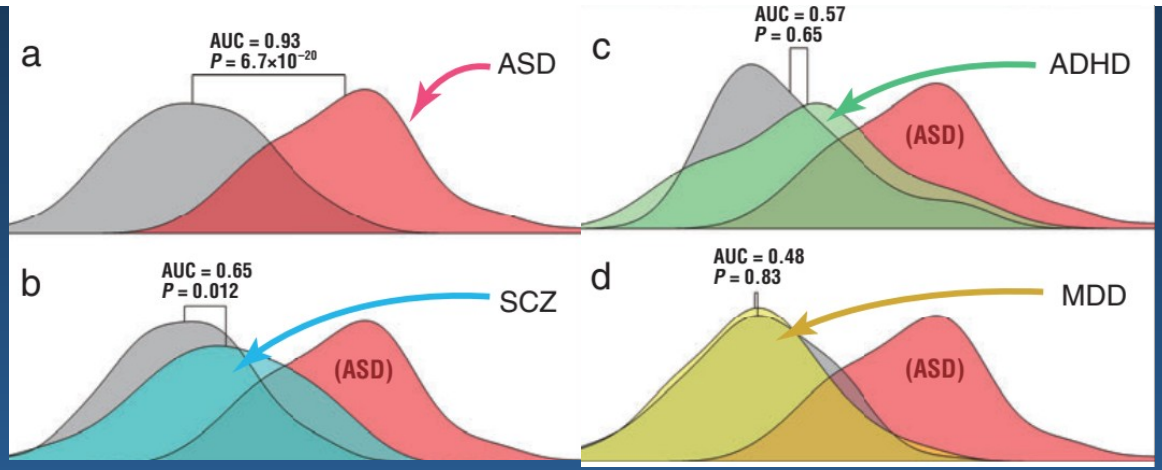


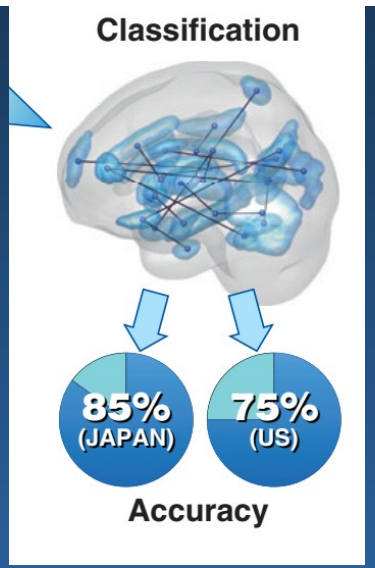


J.F. Glazebrook, R. Wallace, Pathologies in functional connectivity, feedback control and robustness. Cogn Process (2015) 16:1–16

Biomarkers from neuroimaging

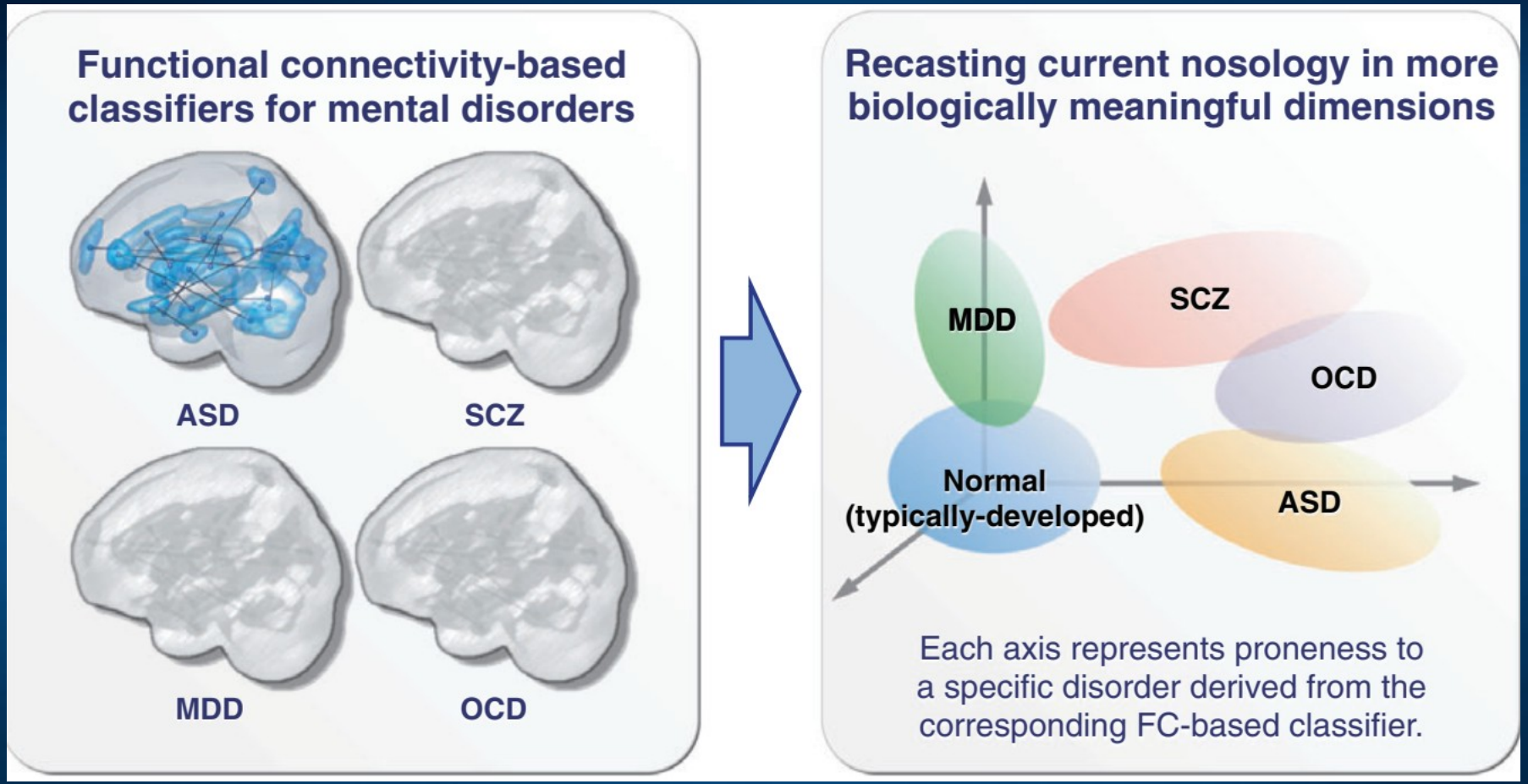






N. Yahata et al, *Psychiatry and Clinical Neurosciences* 2017: **71**

Biomarkers of mental disorders



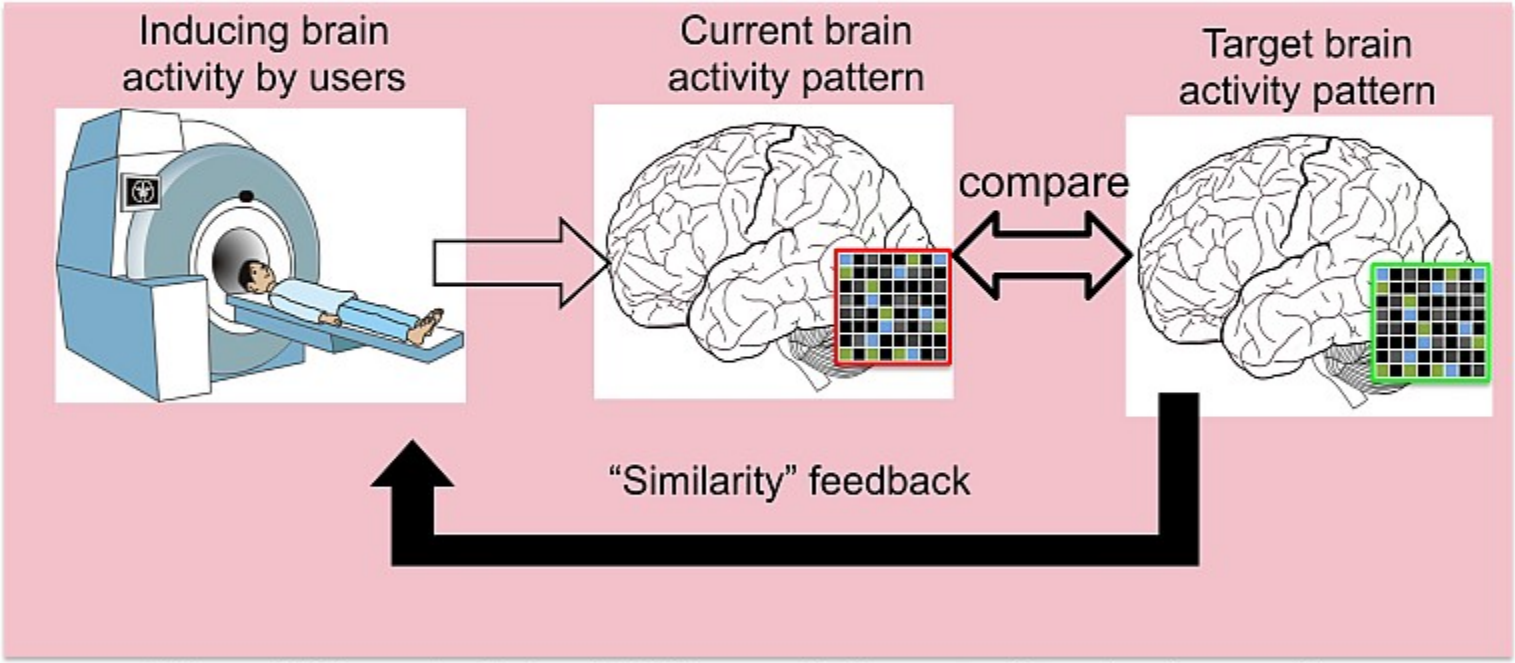
MDD, deep depression, SCZ, schizophrenia, OCD, obsessive-compulsive disorder, ASD autism spectrum disorder. fMRI biomarkers allow for objective diagnosis. N. Yahata et al, *Psychiatry & Clinical Neurosciences* 2017; **71**: 215–237

Realt-time fMRI neurofeedback – BRAINTRAIN.

Real-time fMRI neurofeedback

DecNef: OCD, Pain

; needs a decoder for each patient and its application is currently limited to OCD and pain. In cases of high decoding performance, the success rate is 10/10. The long-term effect depends on the situation; from three to five months in 2/3 studies.



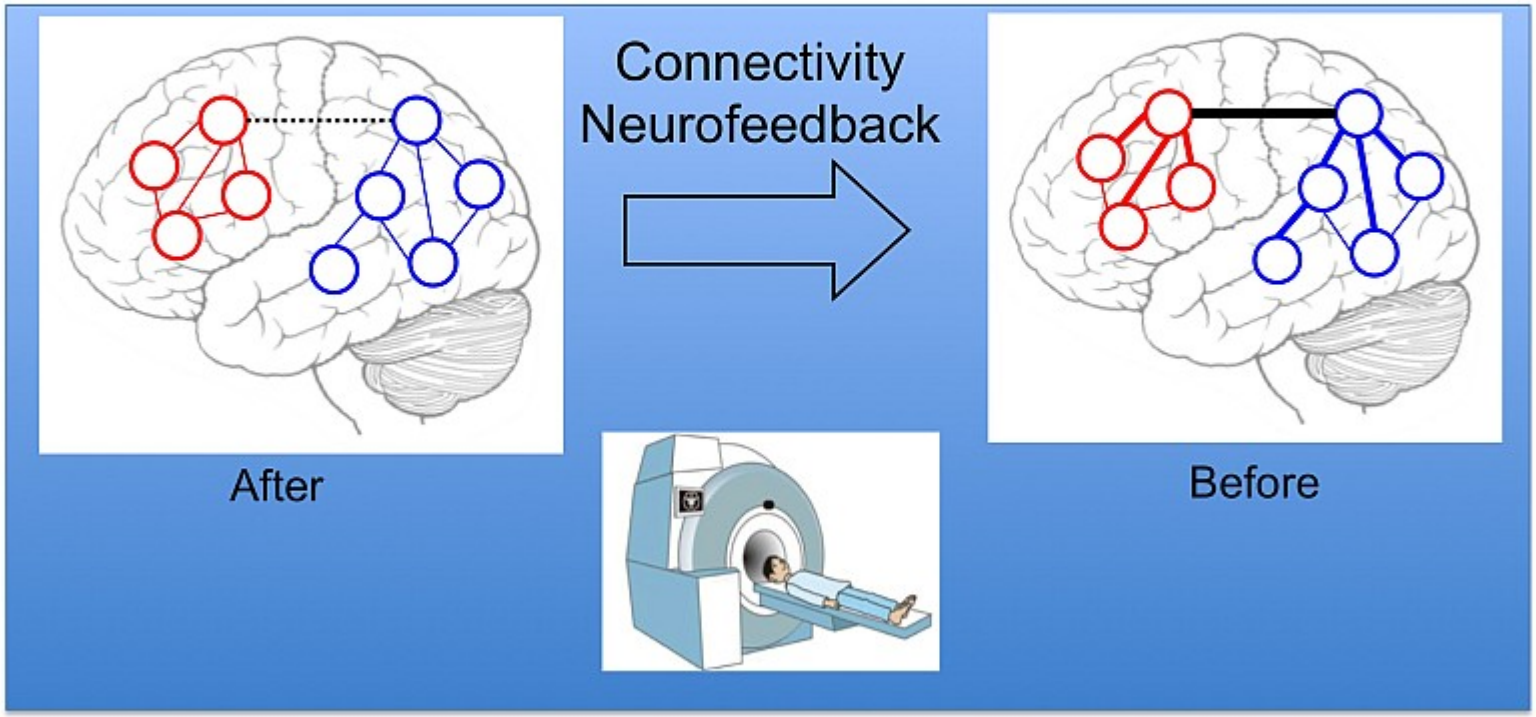
Shibata K, Watanabe T, Sasaki Y, Kawato M: Perceptual learning incepted by decoded fMRI neurofeedback without stimulus presentation. *Science*, **334(6061)**, 1413-1415 (2011)

Real-time fMRI neurofeedback

Connectivity Neurofeedback: FCNef

ASD, Depression, Schizophrenia

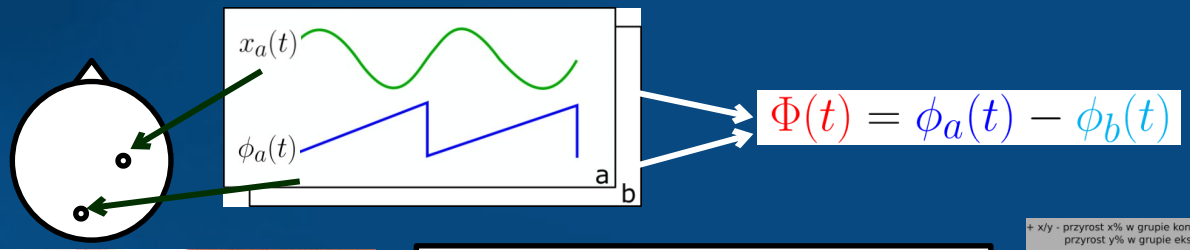
Ready-made treatment based on an across-patient functional-connectivity biomarker. NF training for four days has long-term effect at least two months.



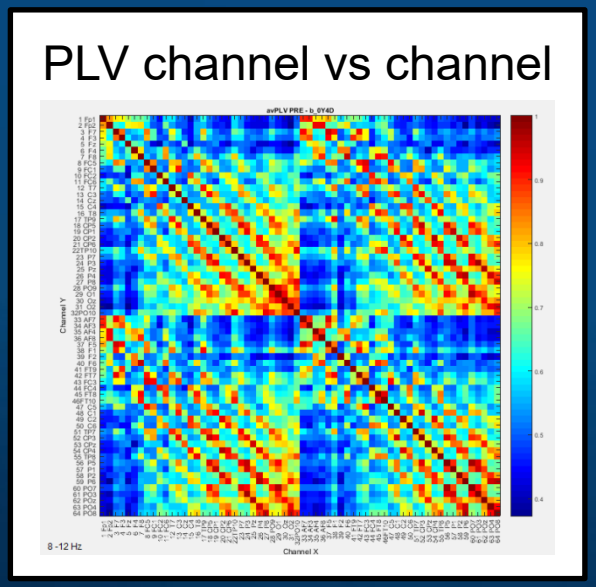
Megumi F, Yamashita A, Kawato M, Imamizu H: Functional MRI neurofeedback training on connectivity between two regions induces long-lasting changes in intrinsic functional network. *Frontiers in Human Neuroscience*, **9(160)**, doi: 10.3389/fnhum.2015.00160 (2015)

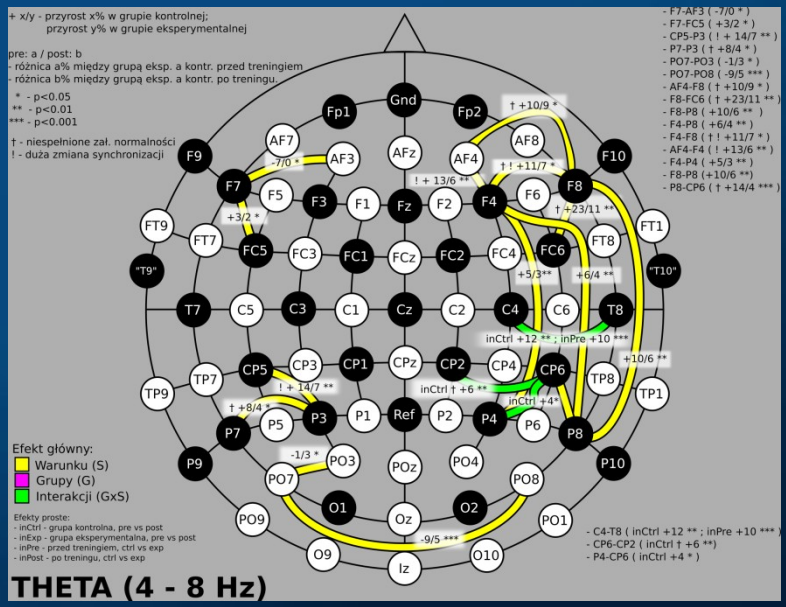
Functional connectivity changes

- **Phase Locking Value** (Burgess, 2013; Lachaux 1999), phase differences between signals measured at each electrode.
- PLV => synchronization maps, info flow.

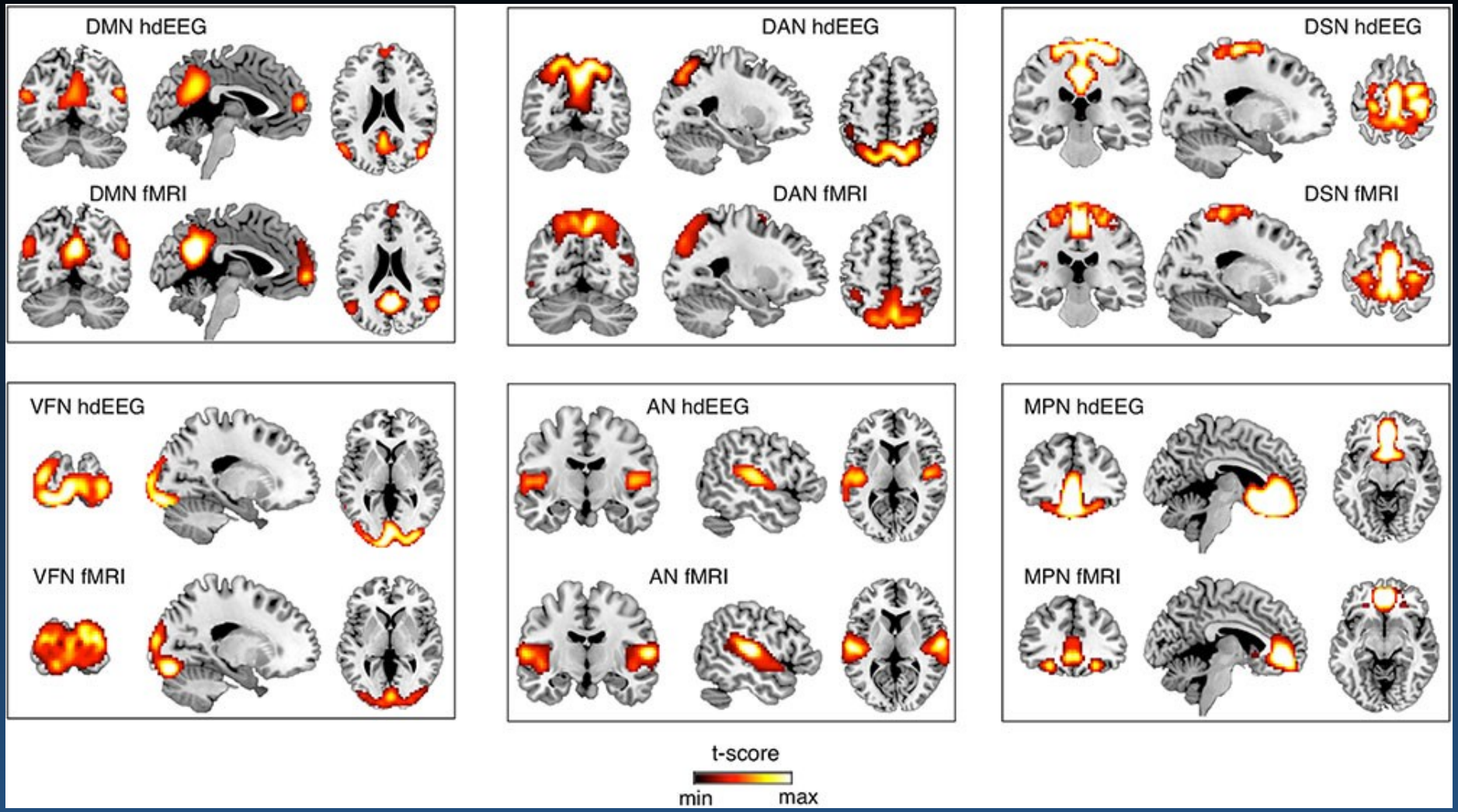


$$PLV(a,b) = \frac{1}{T}\left|\sum_{t}^{T} e^{i\Phi(t)}\right|$$





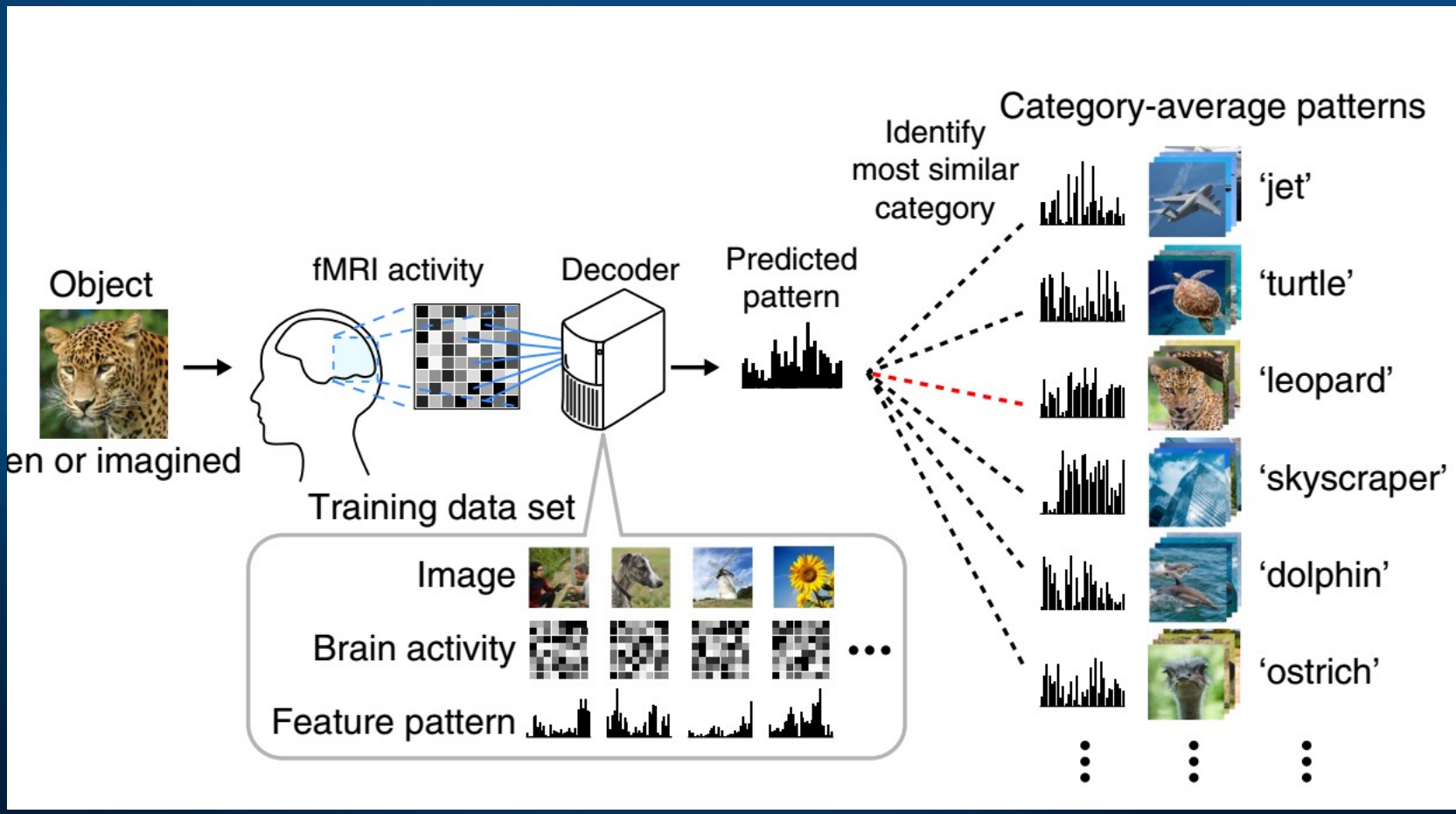
14 networks from BOLD-EEG



Spatial ICA, 10-min fMRI (*N* = 24). Networks: DMN, default mode; DAN, dorsal attention; DSN, dorsal somatomotor; VFN, visual foveal; AN, auditory; MPN, medial prefrontal. Liu et al. Detecting large-scale networks in the human brain. HBM (2018).

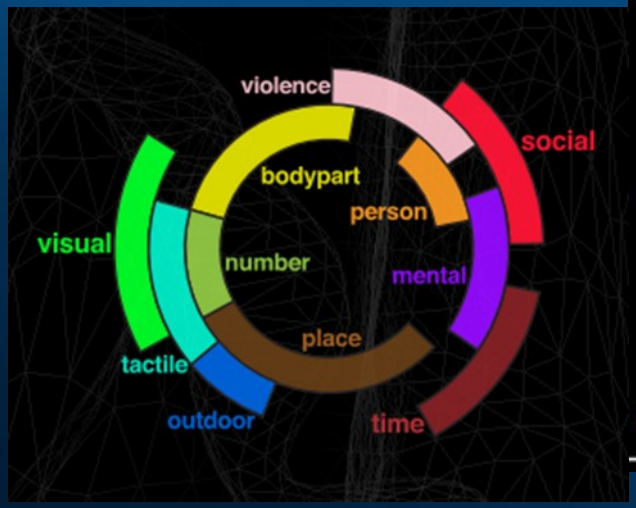
Brain activity ⇔ Mental image

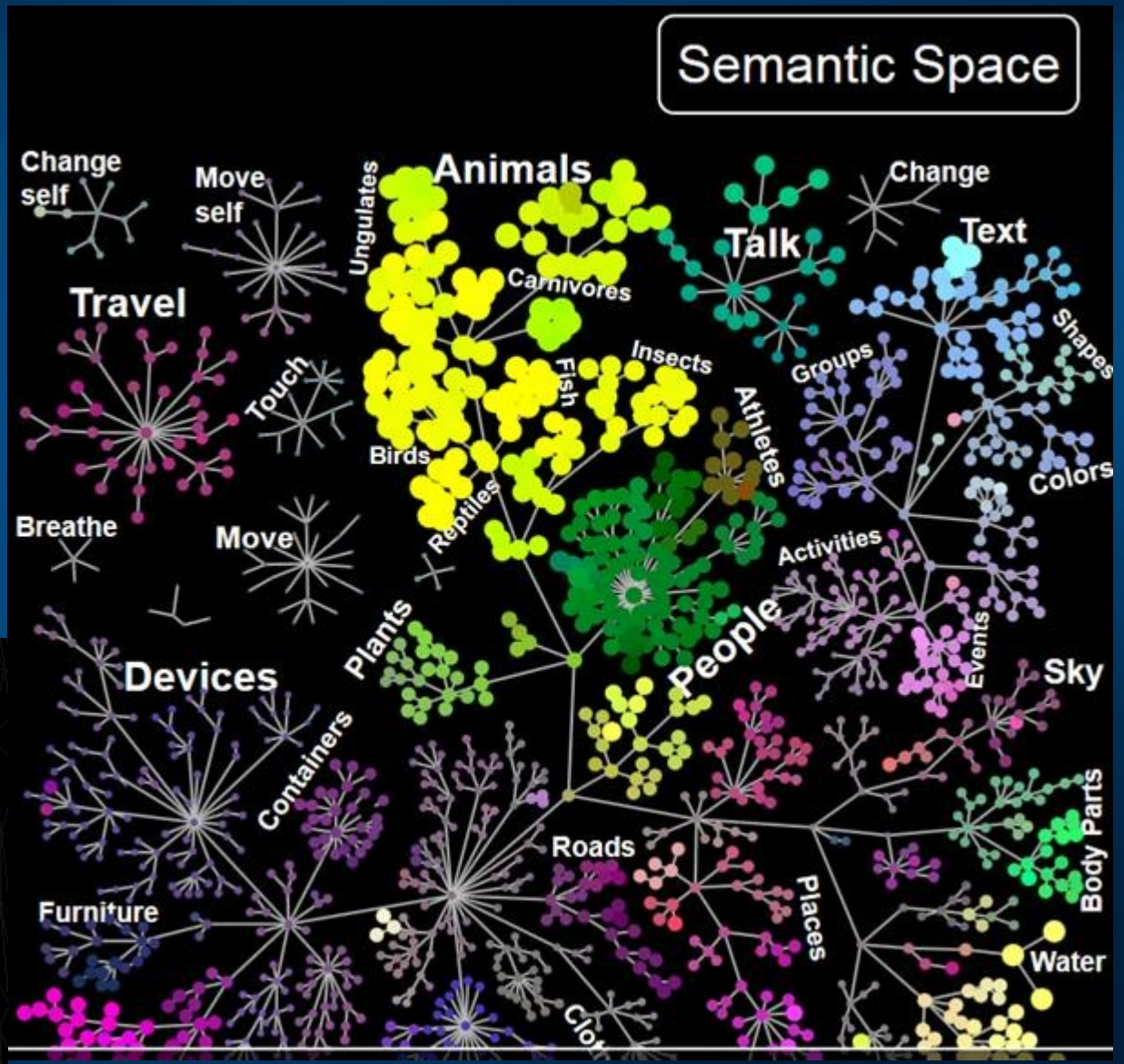
fMRI activity can be correlated with deep CNN network features;
using these features closest image from large database is selected.
Horikawa, Kamitani, Generic decoding of seen and imagined objects using hierarchical visual features. Nature Comm. 2017.

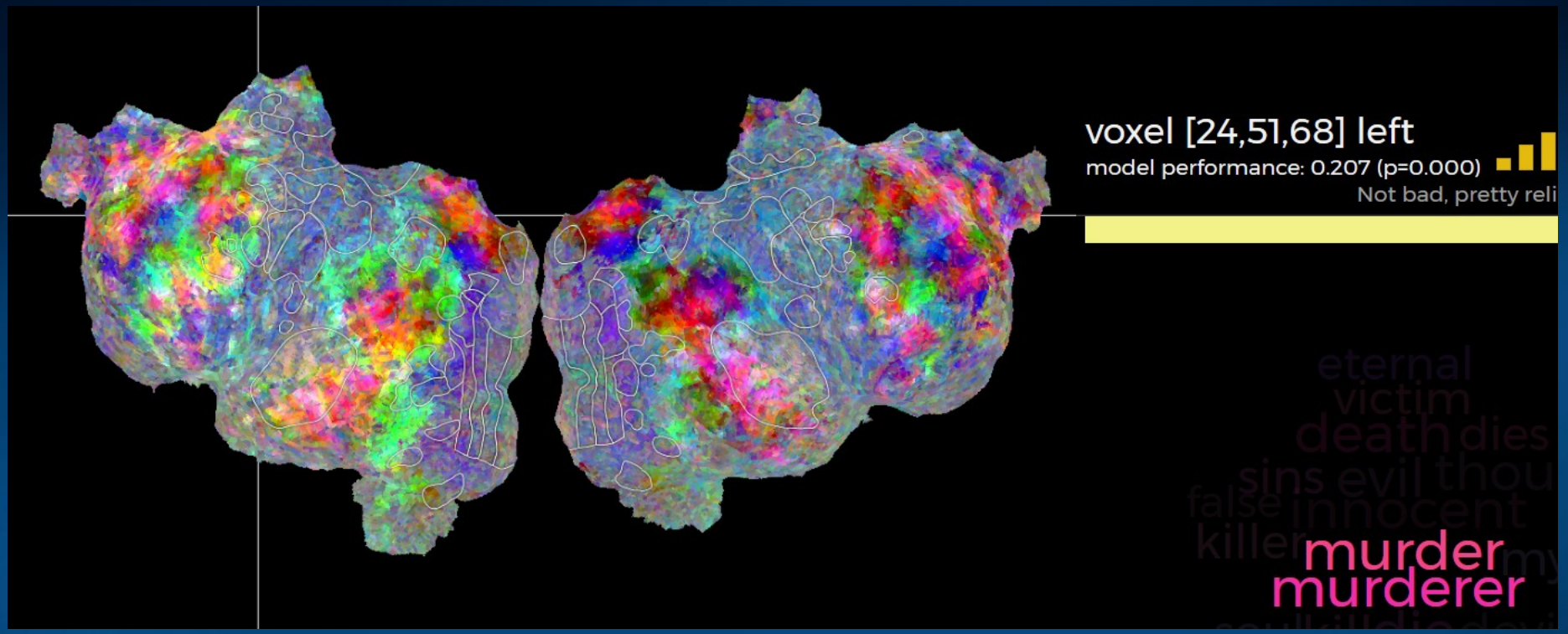


Semantic neuronal space

Words in the semantic space are grouped by their similarity.
Words activate specific ROIs, similar words create similar maps
of brain activity.
Video or audio stimuli, fMRI 60.000 voxel).
Gallant lab, Berkeley.







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?

Conclusions

- BNCI: many approaches but progres was rather slow.
- Closed loop approaches: DecNef, FCNef work with real-time fMRI for diagnosis and neurofeedback therapy, but not easy.
- Brain fingerprinting based on EEG or fNIRS may in principle achieve similar results, but it is a challenge.
- Brain reading and stimulation requires sophisticated data models and understanding of neurodynamics.
- Roadmap: brain fingerprinting based on EEG, sensory stimulation to activate subnetworks and selected regions $\Leftrightarrow$ closed loop BNCI for really effective neurofeedback.
- Neuromorphic hardware with complexity beyond the human brain is coming and will enable construction of new brain models, deeper understanding of brain functions, and practical applications.
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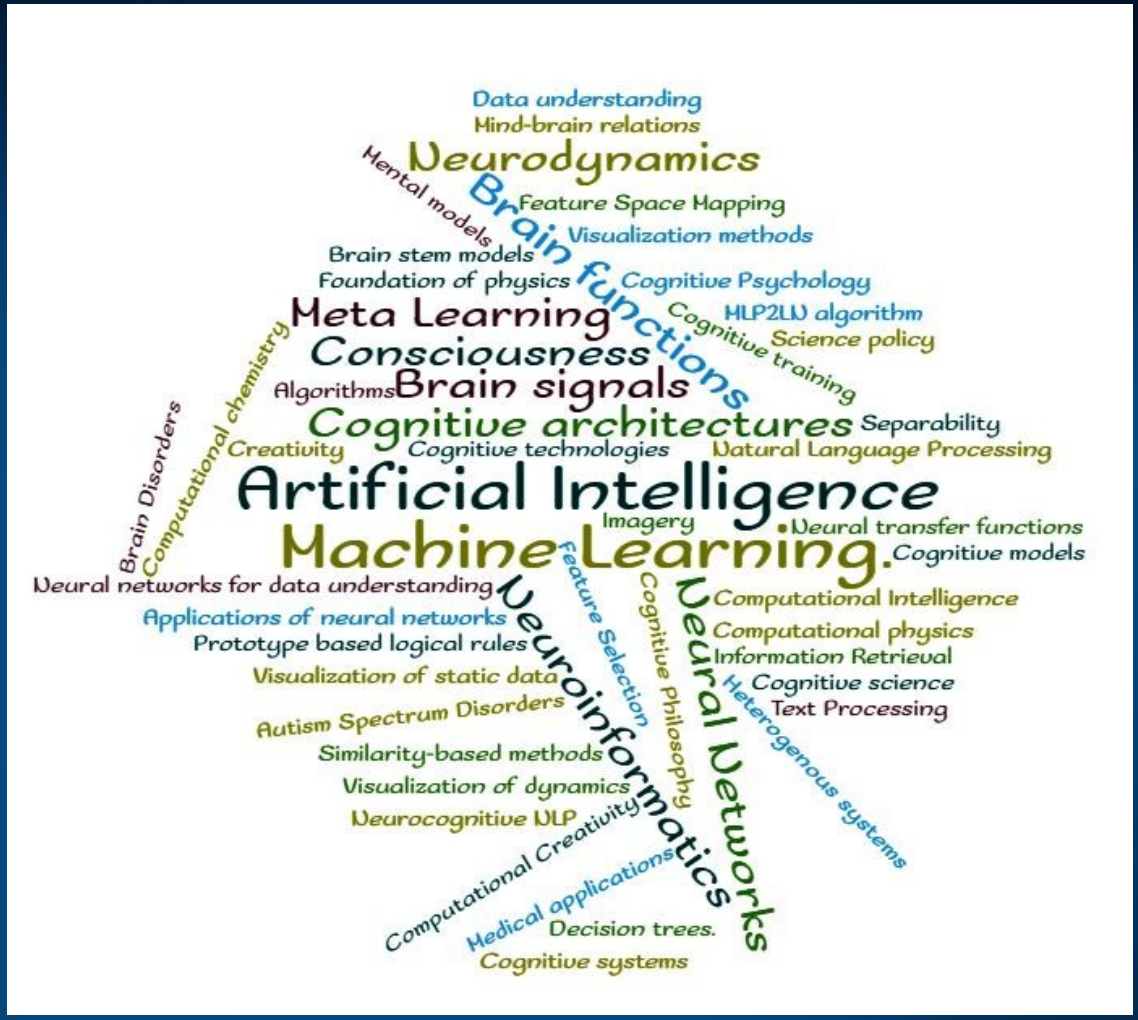
We have many interesting topics in ML/neuro research.

Our group "Neuroinformatics and Artificial Intelligence" in the University Centre of Excellence in Dynamics, Mathematical Analysis and Artificial Intelligence (DAMSI) is looking for students and visiting professors, please see:

Grants for experienced researchers from abroad.

Grants for young researchers from abroad.



Google: Wlodzislaw Duch

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