Fingerprints of brain activity promising approaches

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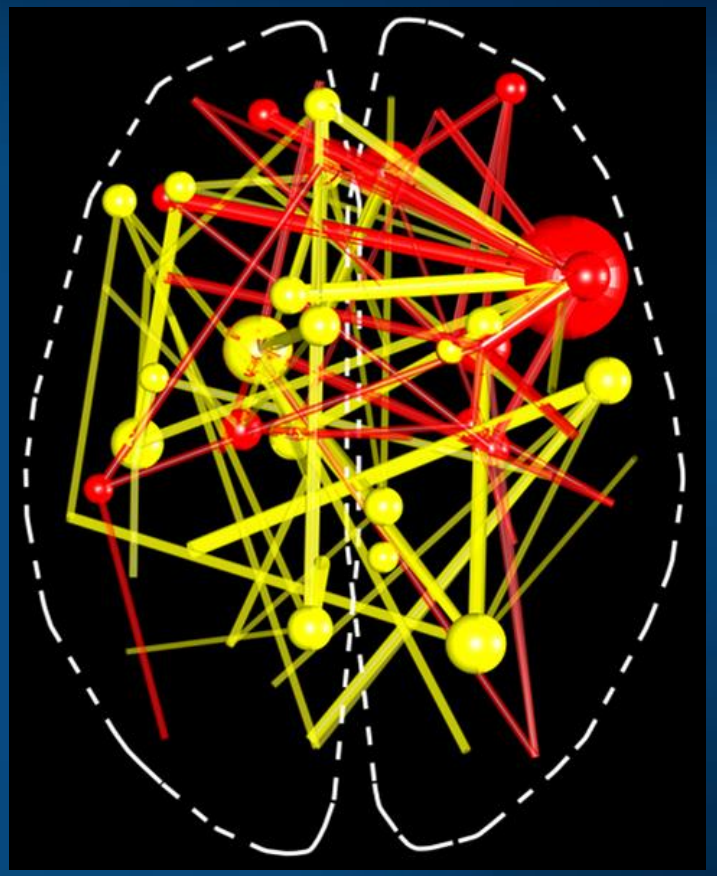
Questions

How can we interpret brain signals?

What can we use these signals for?

- Brain ⇔ Mind relations.
- BCI, BCNI, BCBI …
- Neurocognitive technologies.
- Neurocognitive Lab, UMK
- Understanding mental states.
- Mind control over brain.



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

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

Brain-Computer 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.

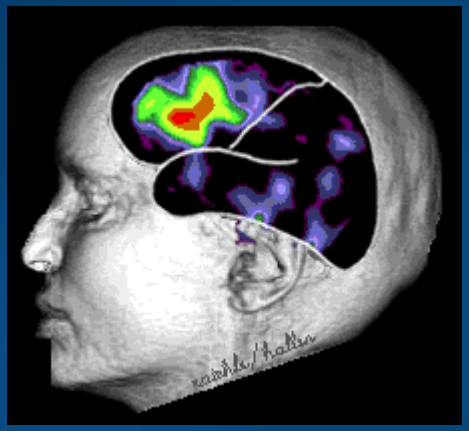
Emerging: **Mobile Brain/Body Imaging** (MoBI), recording movement, eye, various biosignals in natural situations.

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, BTBI.

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:

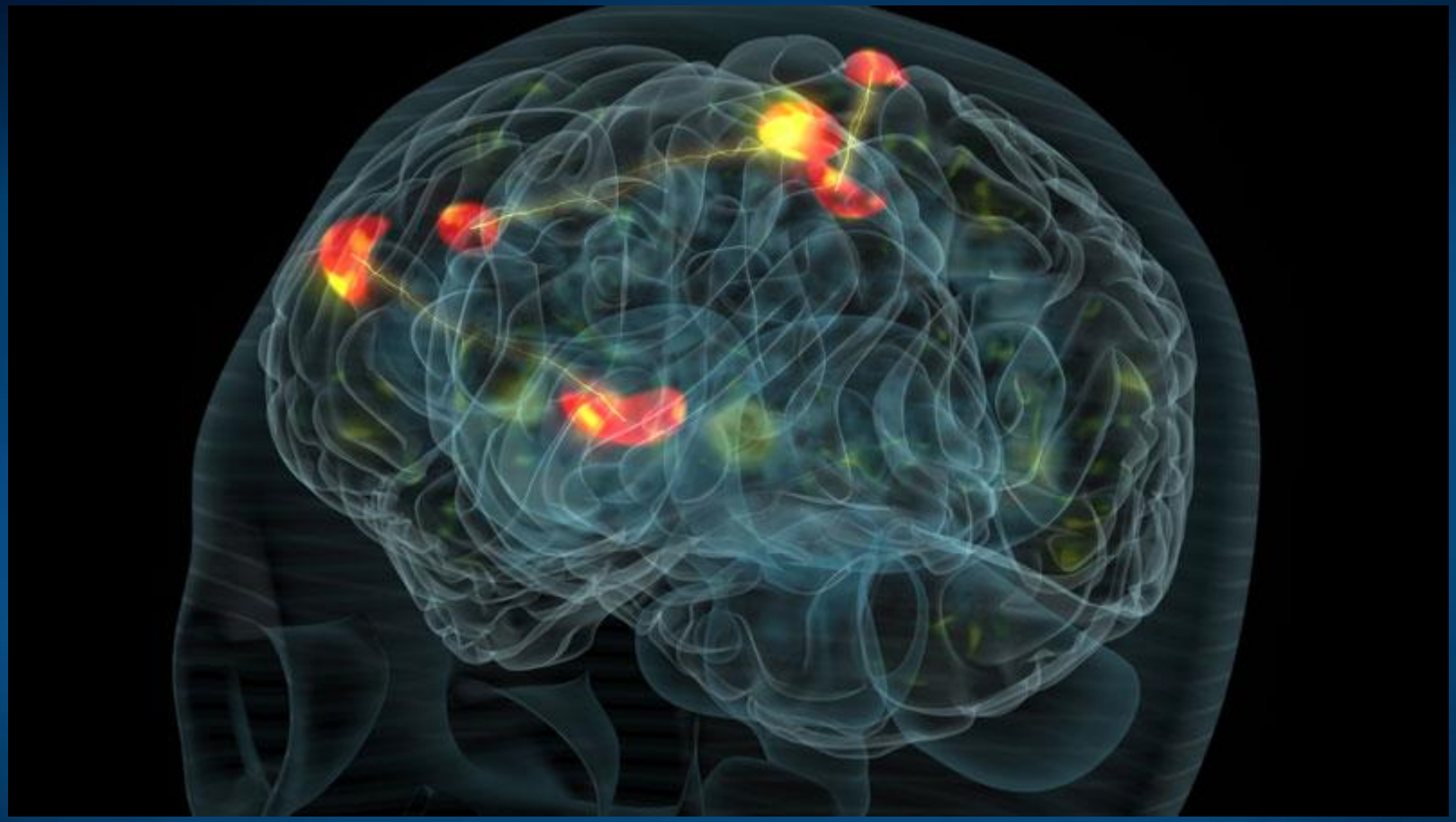
State(Brain)⇔State(Mind)

via intermediate BCI 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



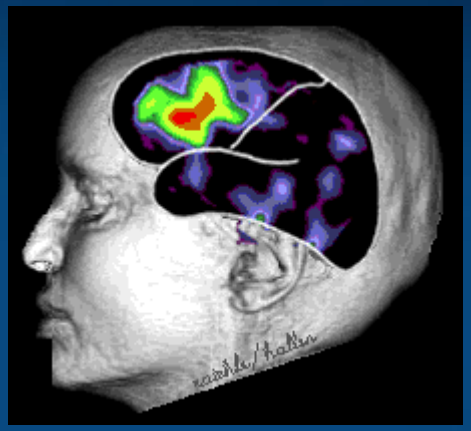
Many processes go on in parallel, controlling homeostasis and behavior.
Most are automatic, hidden from our Self. What goes on in my head?
Various subnetworks compete for access to consciousness, the highest level of control, using the winner-takes-most mechanism.
How to extract stable intentions in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

Geometric model of mind

Brain ⇔ Psyche

Objective ⇔ Subjective

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

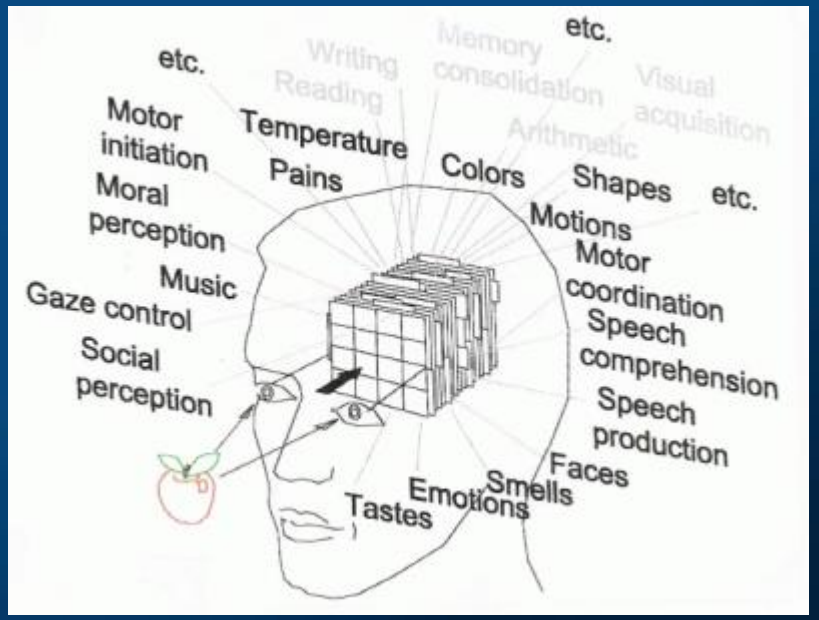


Mapping S(M)⇔S(B) but how do we describe the state of mind?

Verbal description is not sufficient. A space with dimensions that measure different aspects of experience is needed.

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

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



Hurlburt & Schwitzgabel, Describing Inner Experience? MIT Press 2007

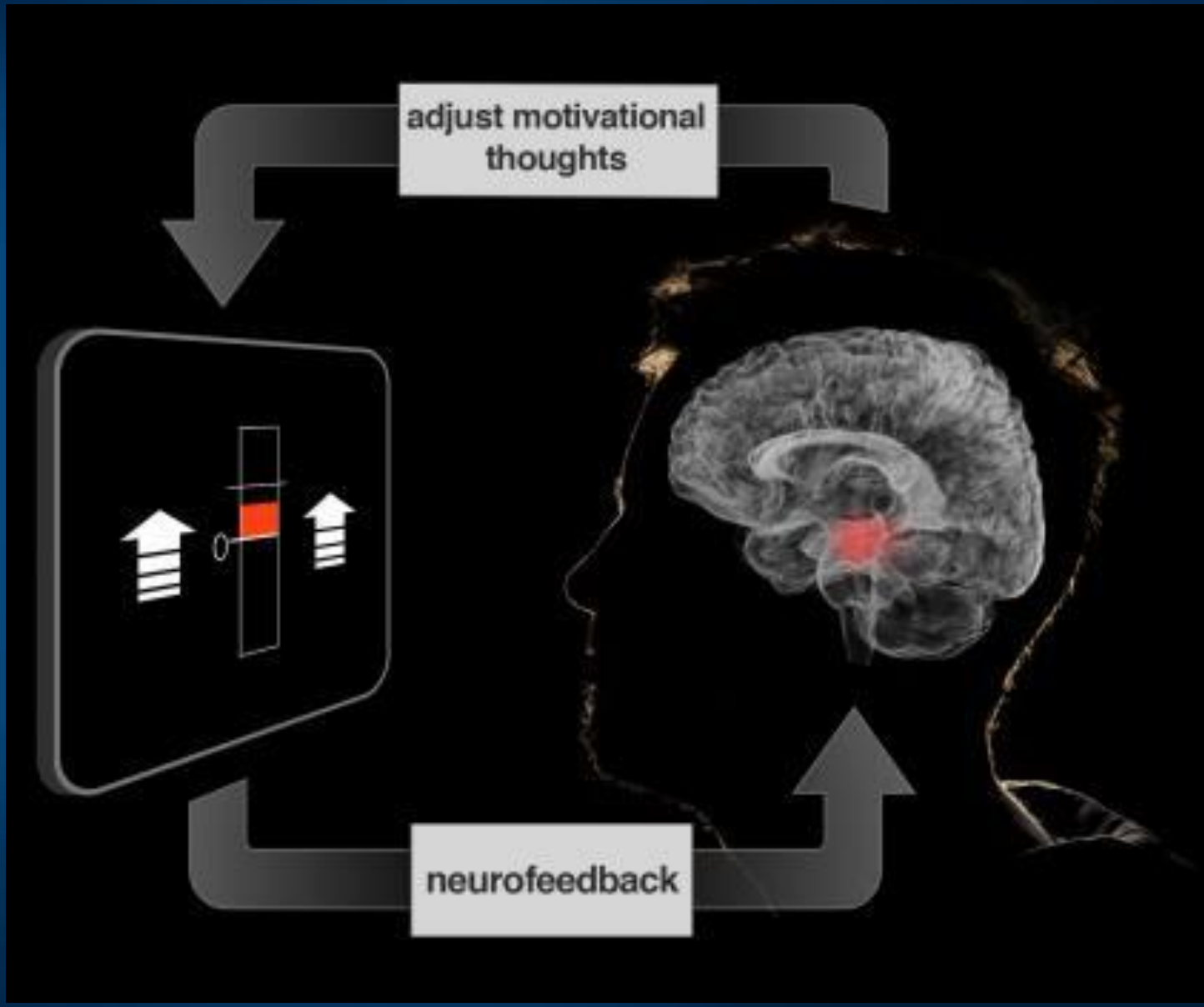
Neurofeedback: first BCI

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

Duch, Elektronika i stresy, 1978!

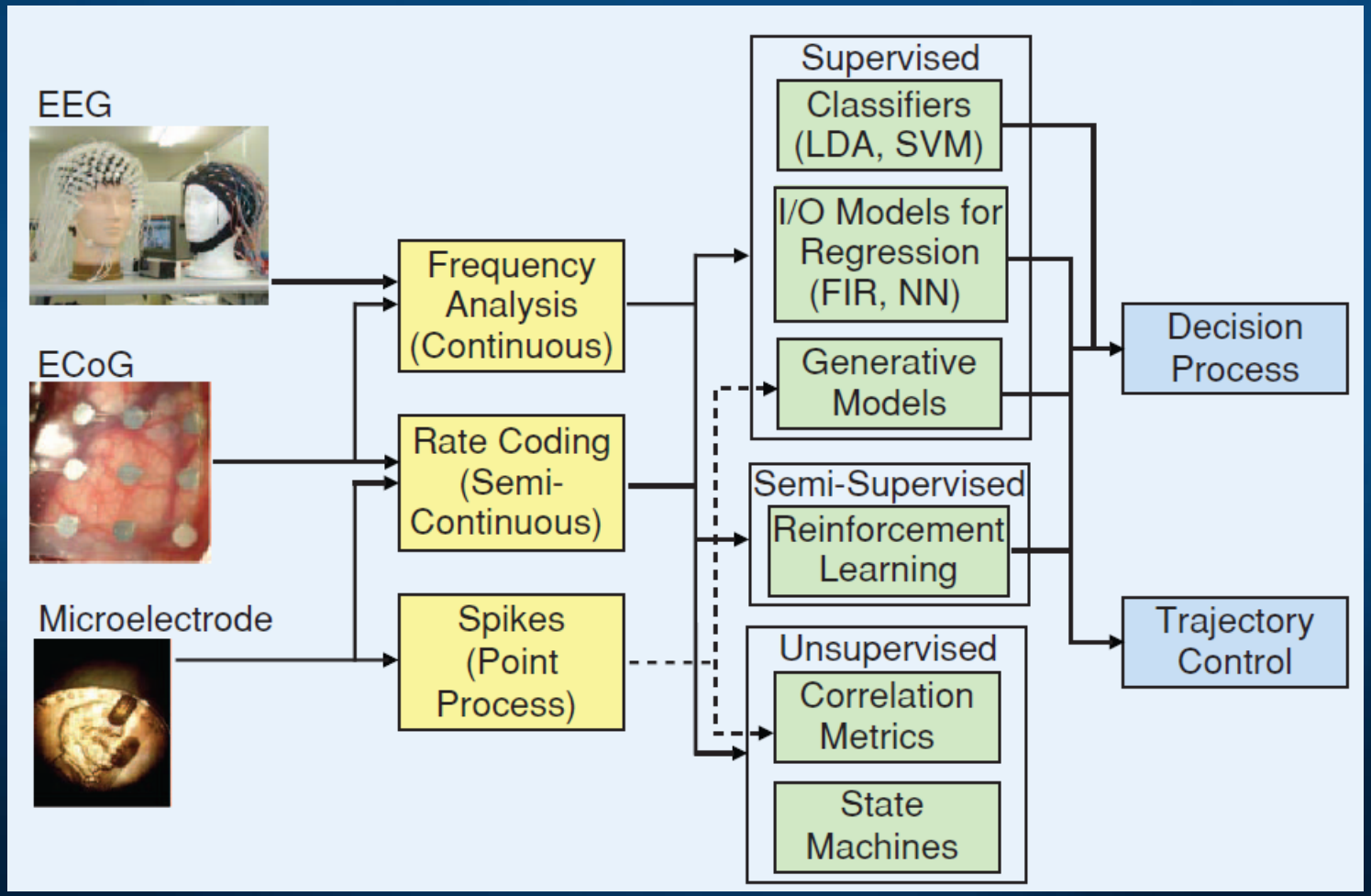
Critical review of existing literature shows that this is not effective.

New forms based on brain fingerprinting needed.

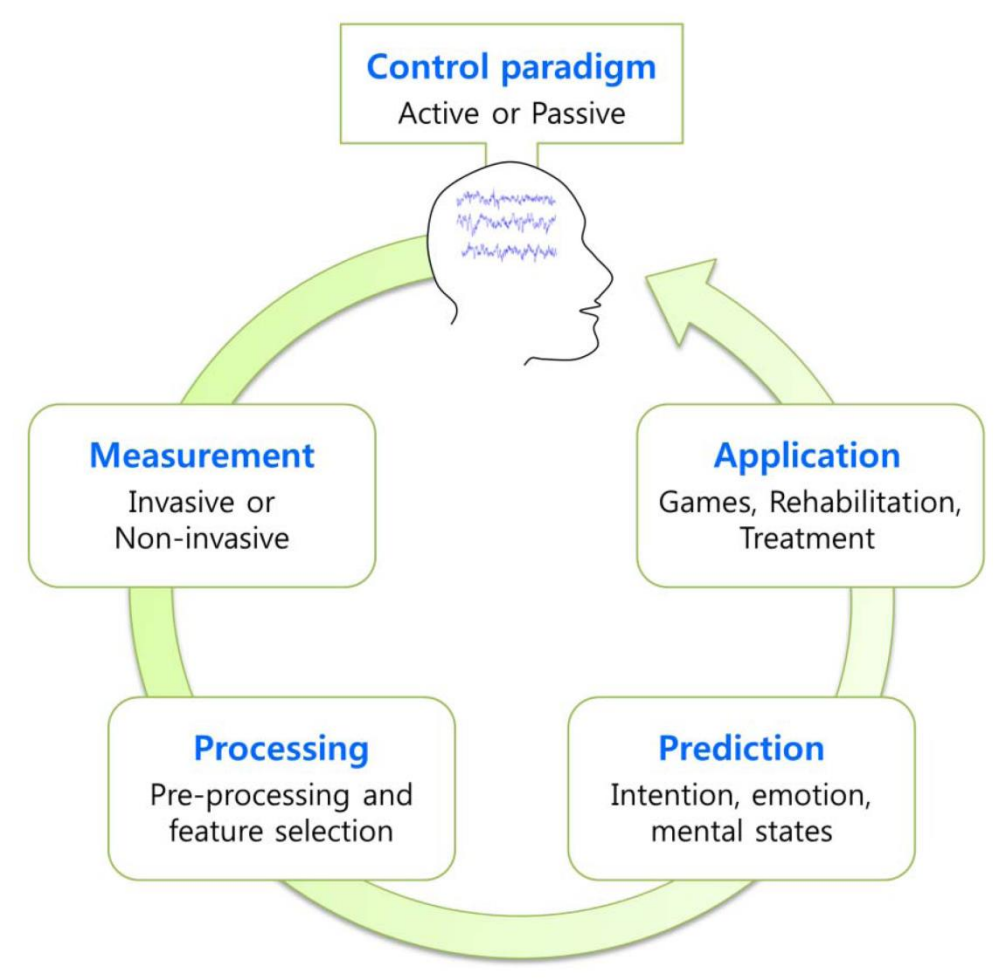


BCI: wire your brain …

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



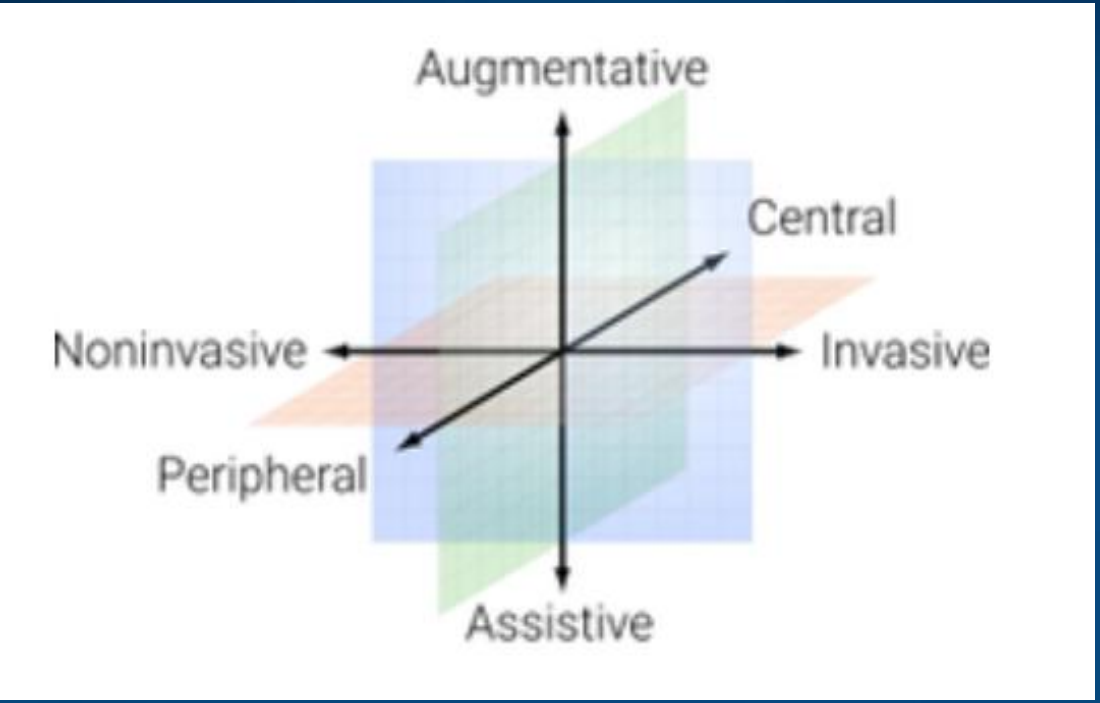
Features of BCI



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

BCI Infographics from Futurism.com shows a good summary.

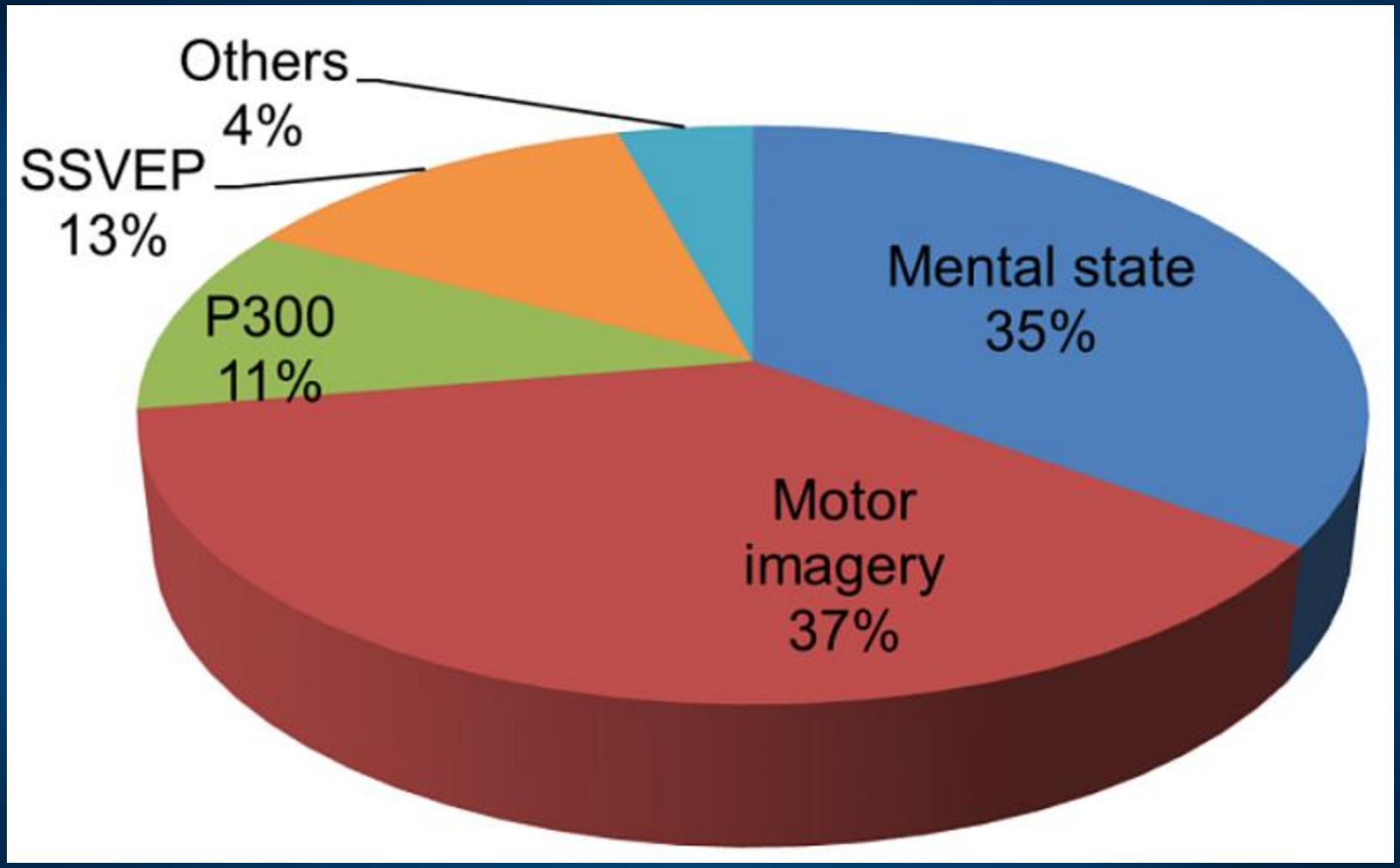
5 dimensions of BCI



4th dimension: passive – reactive – active systems.

5th dimension: open-closed loop.

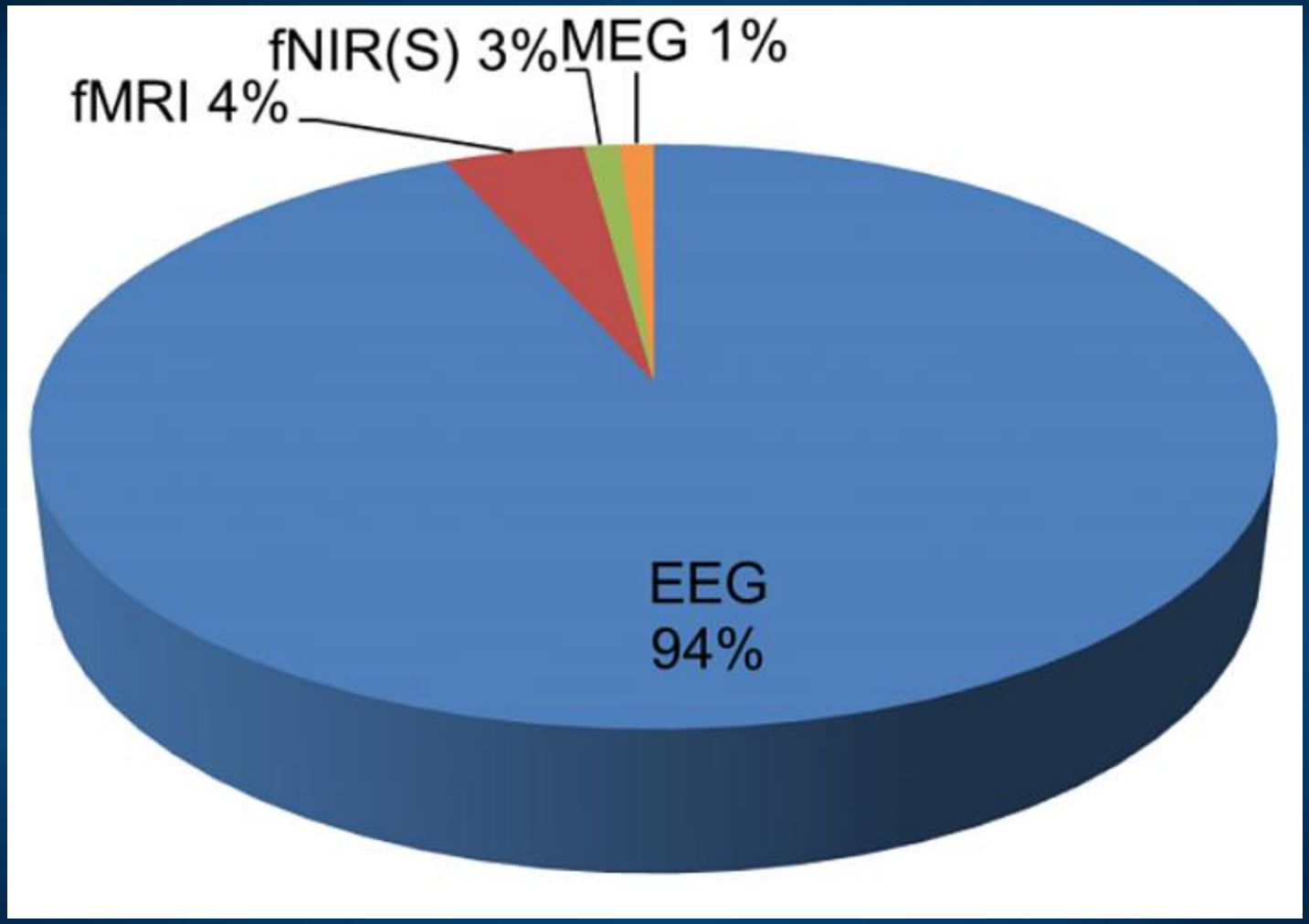
Control paradigm



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

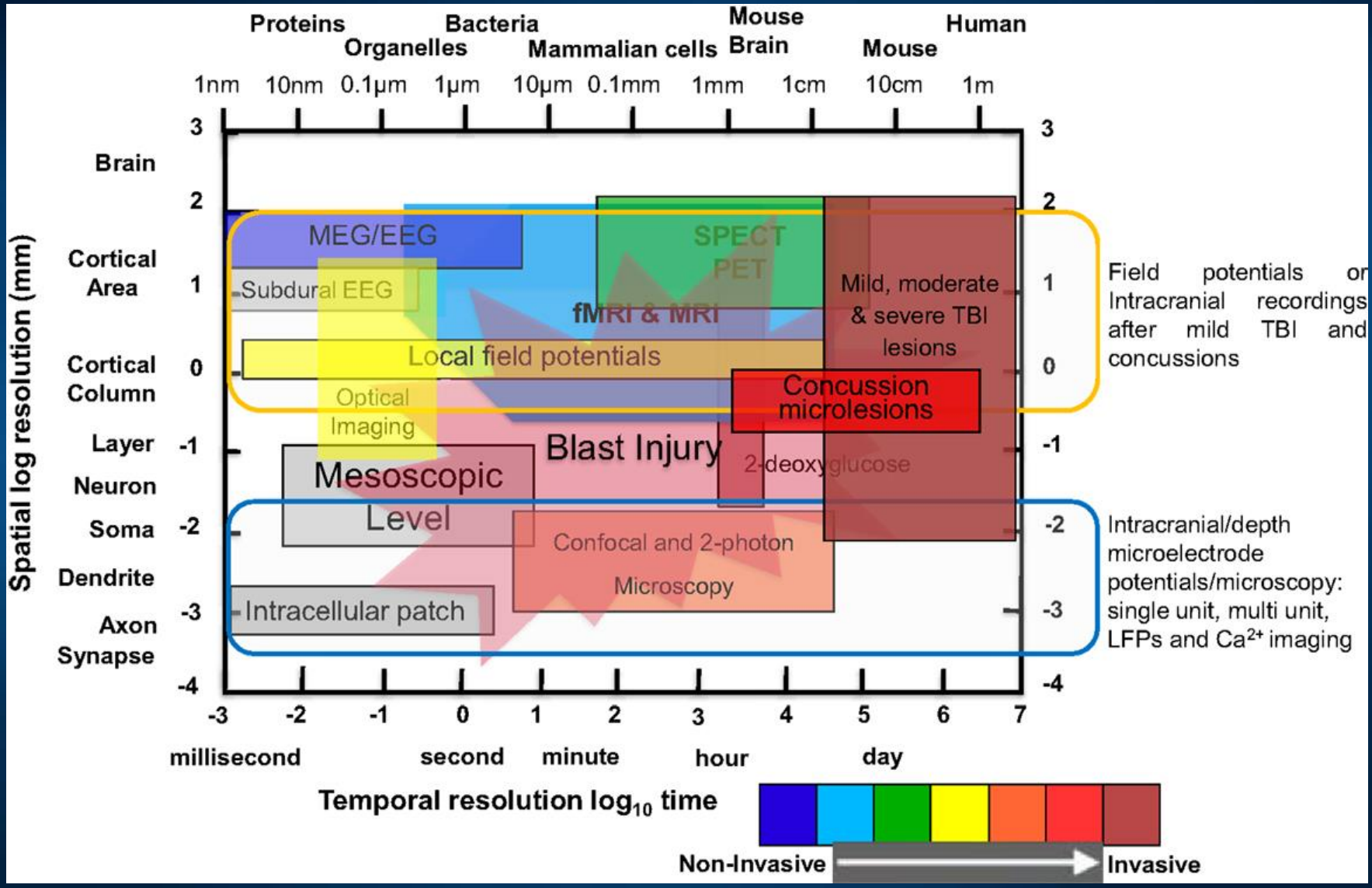
Mental state is frequently based on emotions or attention.

Signal source



In BCI research EEG is used most frequently, it may also be used wirelessly.

Neuroimaging techniques



ICNT: scanner GE Discovery MR750 3T

Active, Reactive and Passive BCI

- Active BCI systems: brain activity is consciously, intentionally modulated in order to control some application (e.g. motor imagery, relaxation).
- Reactive BCI: using brain activity evoked by external stimulation, modulated indirectly through voluntary attention (e.g. P300 amplitudes modulated by attention shifts).
- Passive BCI system: 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.

Distinction between active-reactive-passive is sometimes blurred, depends on the user's behavior.

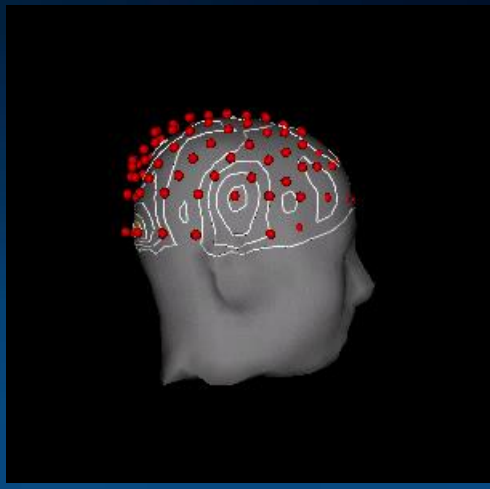
Passive BCI types

pBCI types:

- **mental state assessment**, eg. cognitive workload, neuroergonomics, lie detectors, neuromarketing;
- **open-loop adaptation**, specific brain state => specific action, providing feedback based on mental state assessment, eg. error corrections based on error-related negativity (ERN) overriding 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.

Passive BCI



Passive BCI uses EEG signal arising in automatic, non-intentional way, in combination with other signals.

Tracking eye movements to control technical systems is used in many applications. Directing a cursor in HCI is gaining popularity for both healthy and disabled users alike.

We use it for infant research, and for computer control by DOC patients.

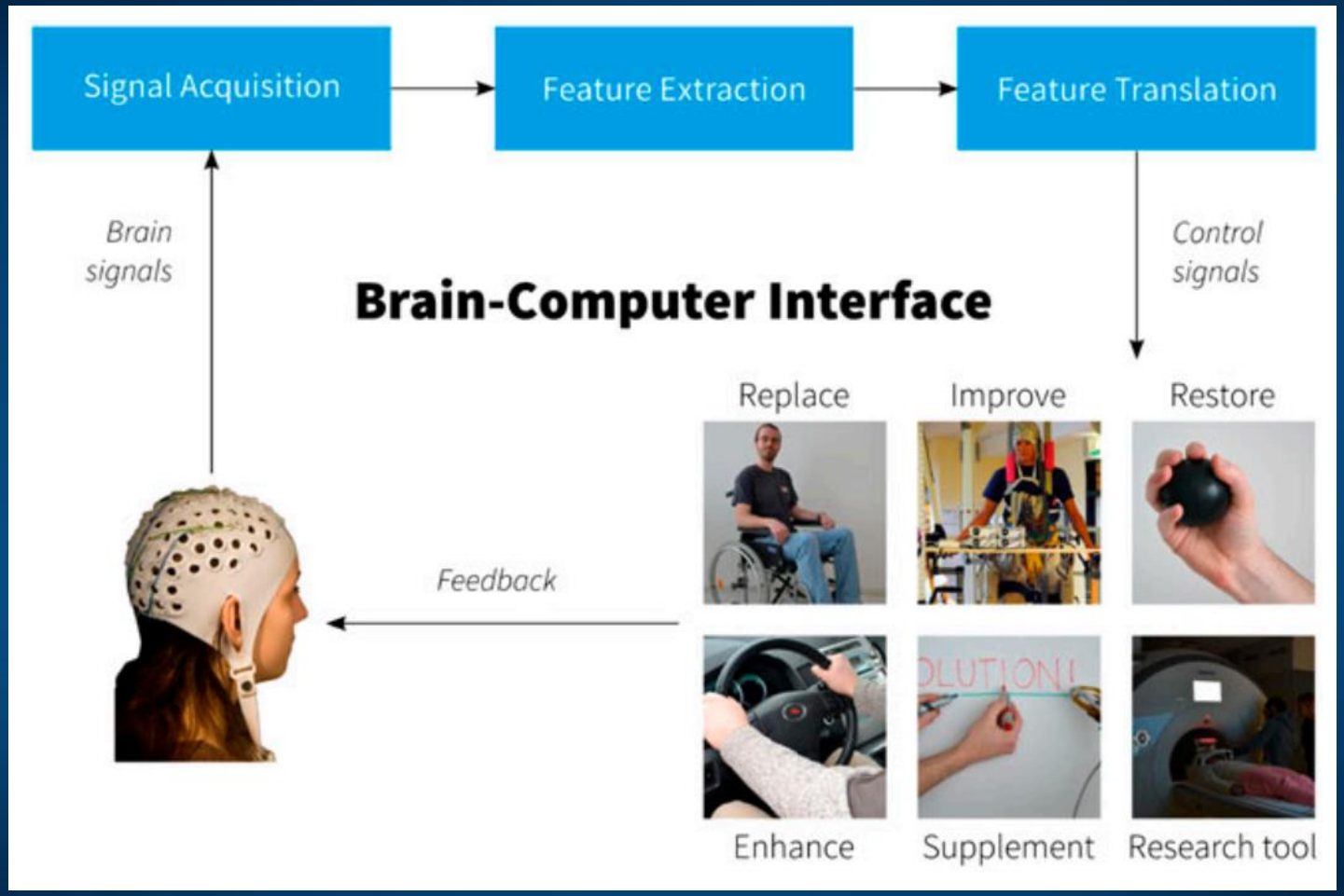
Dwell-times may incorrectly interpret accidental fixations, or spontaneous dwellings as a user command – this is called “Midas touch” effect.

Event-related potentials (ERPs) might indicate a user’s intention to select. Negativity over parietal electrodes for the intention of item selection gave an average accuracy of 81%.

The intention to interact evokes specific brain activity that can be detected by passive EEG-based BCI technology.

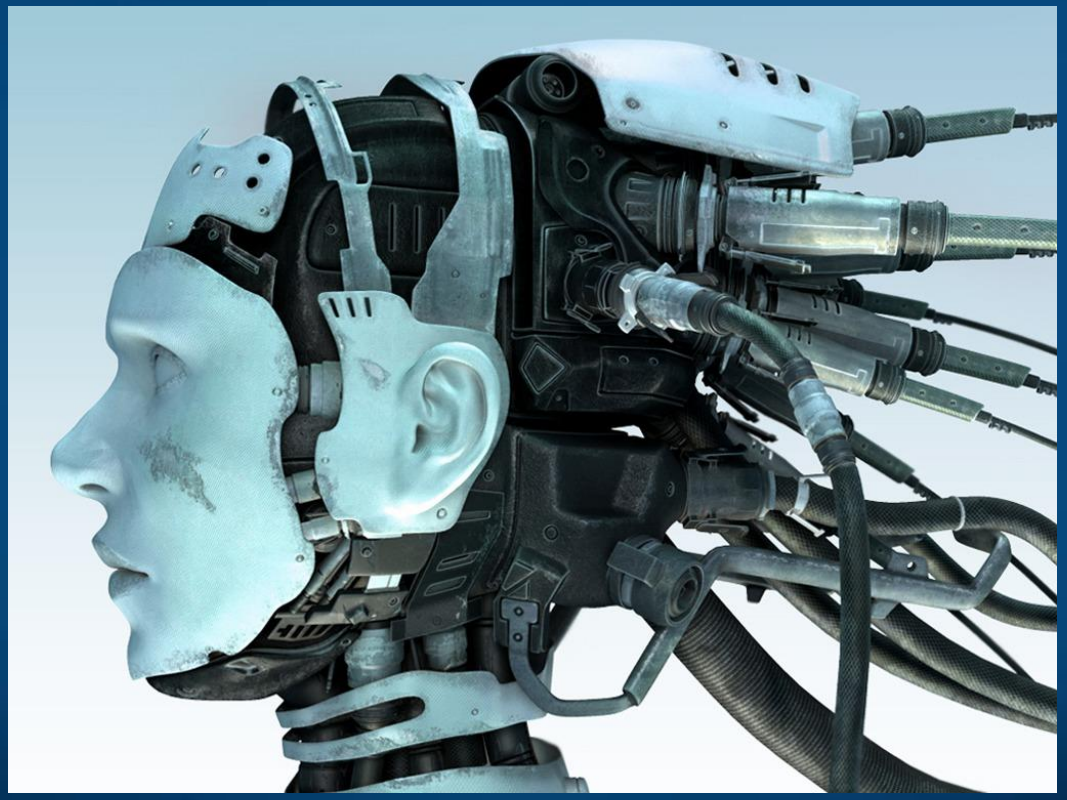
- Protzak J, Ihme K, & Zander T.O. (2013). A Passive Brain-Computer Interface for Supporting Gaze-Based Human-Machine Interaction.

BCI Applications

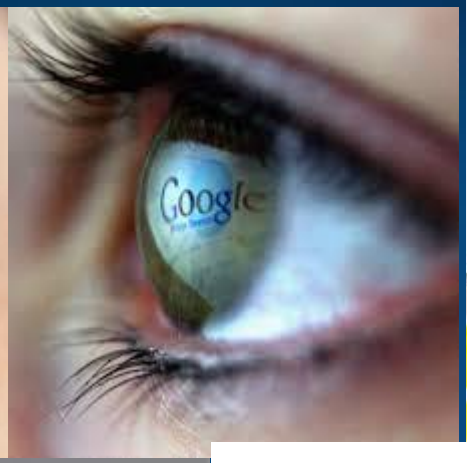


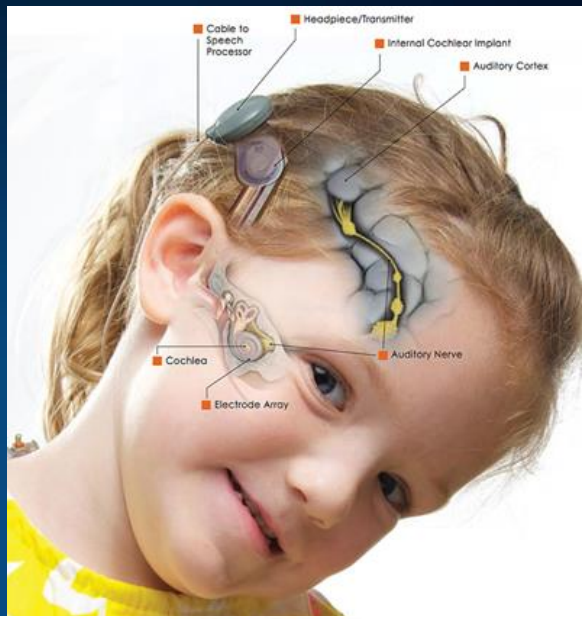
Signals: invasive (brain implants), partially invasive (ECoG), and non-invasive.

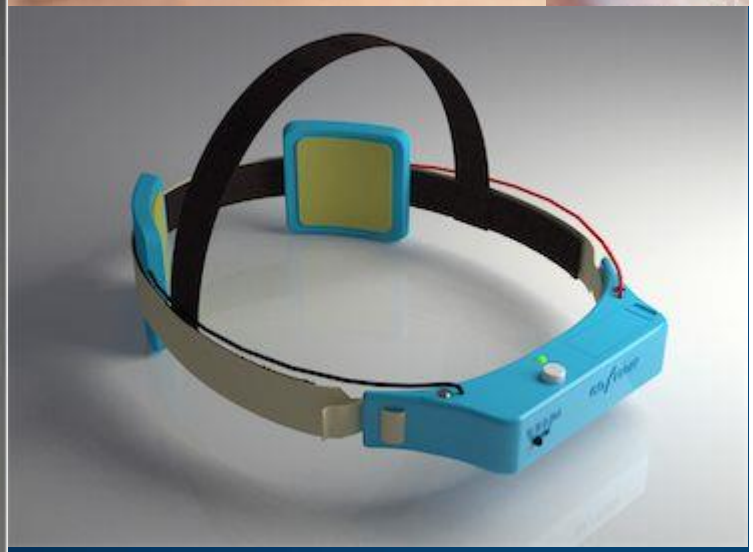
Neurocognitive technologies

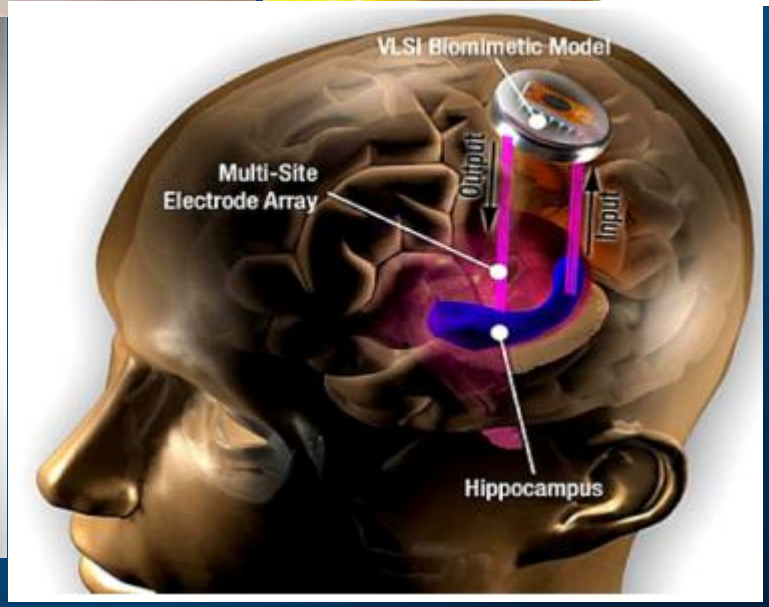


Enhancing Perception



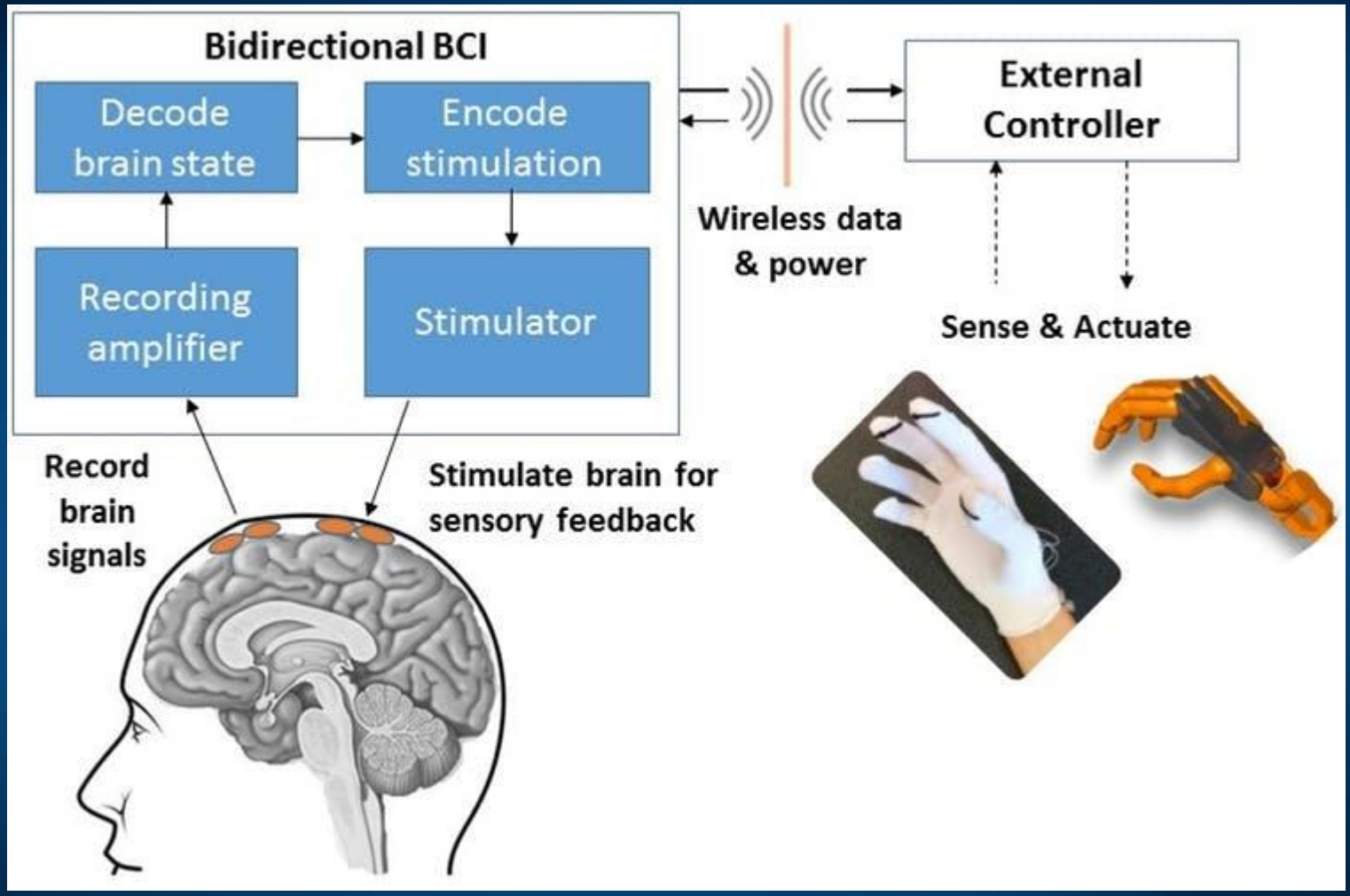






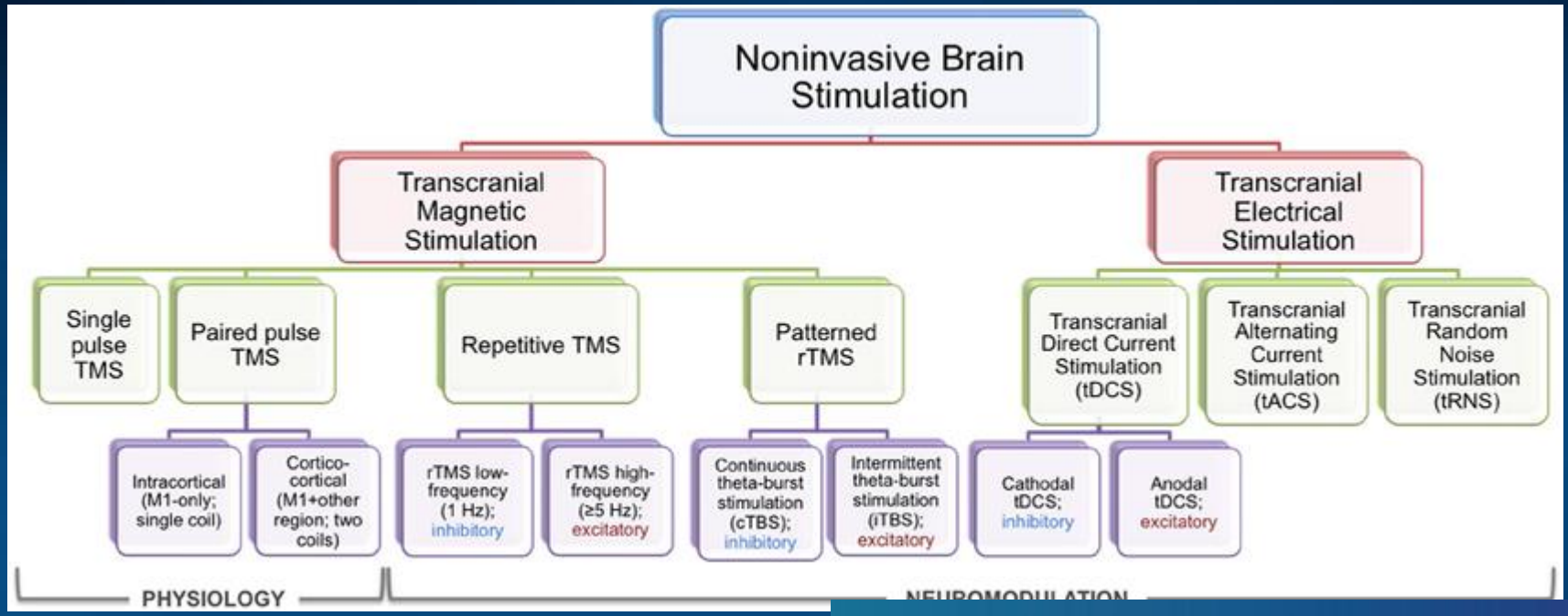
Improving eyes, ears, touch, but also memory and attention skills…
Implantation of new neurons in the brain?

Brain-Computer-Brain interfaces



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

Brain stimulation



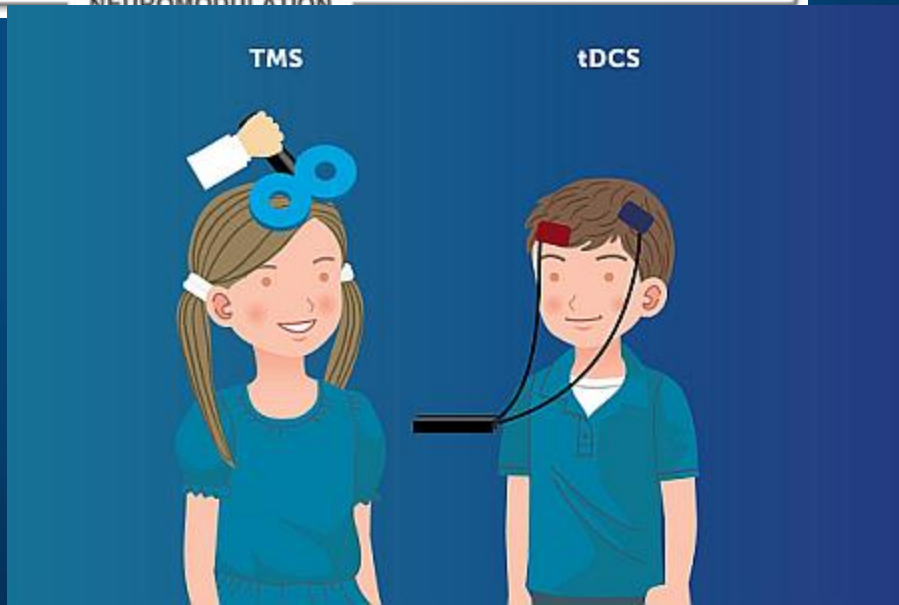
ECT – Electroconvulsive Therapy

VNS – Vagus Nerve Stimulation

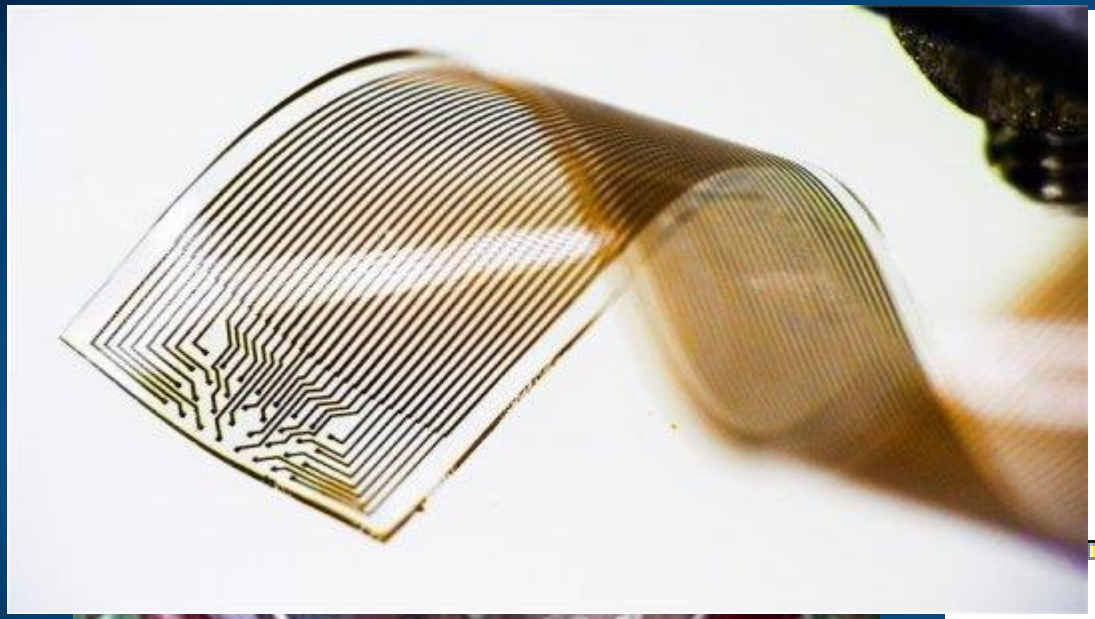
Ultrasound, laser … stimulation.

Complex techniques, but portable phones are also complex.

Attention? Just activate your cortex!



Partially invasive interfaces

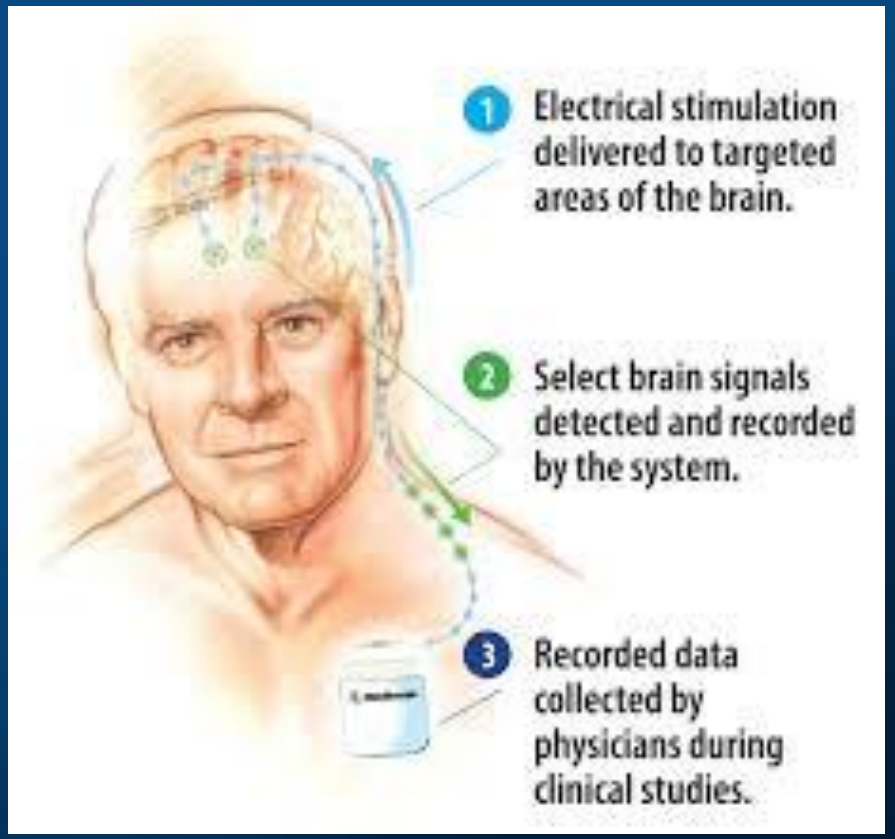


Epilepsy, Obsessive-Compulsive Disorder, Phobias … if you know how to run electric currents through your brain you can control your mental states in a conscious way. New stable electrodes are coming!

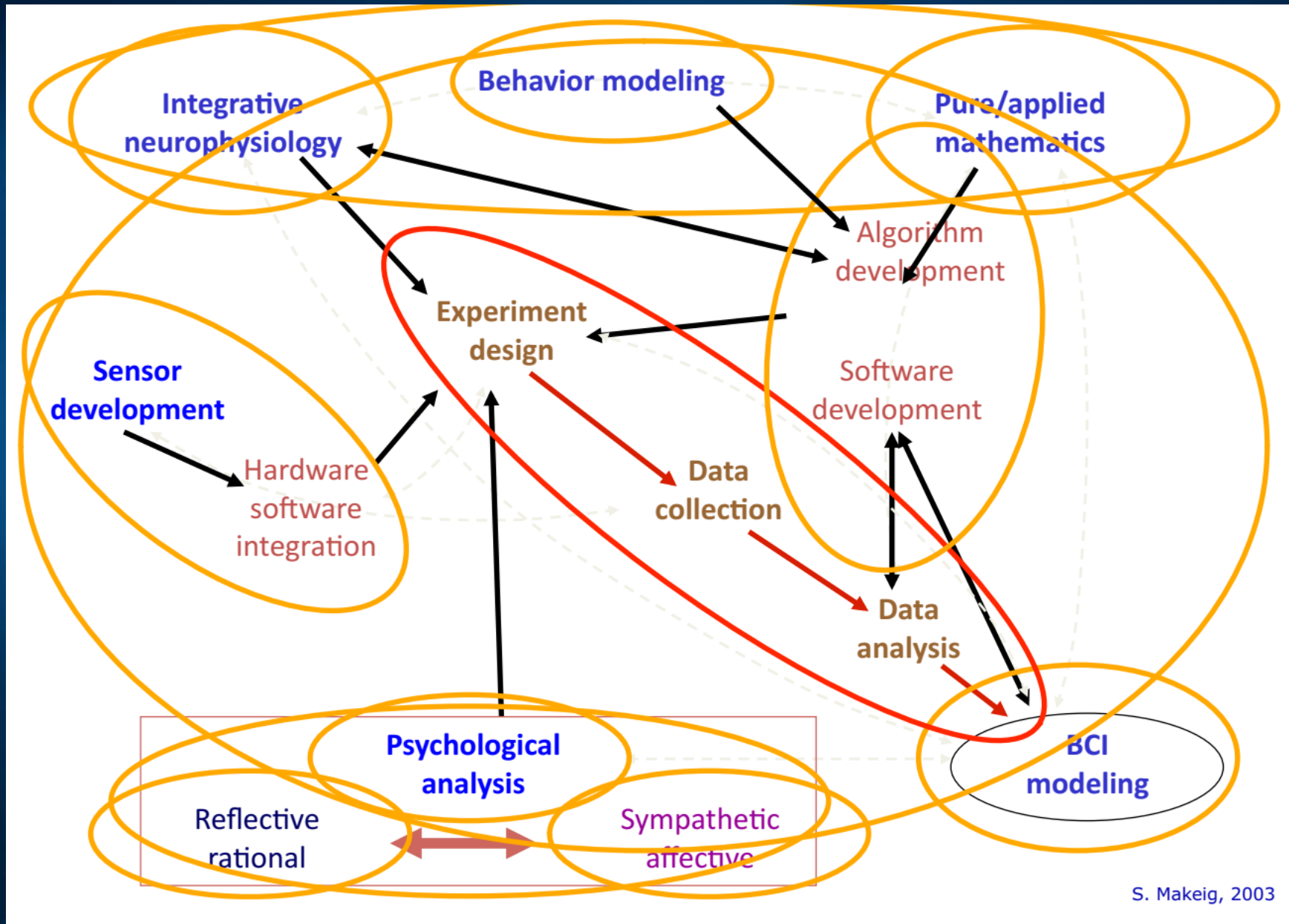
Deep brain stimulation

In case of Parkinson's disease, OCD, coma, persistent pain and many other conditions stimulation of peripheral nerves (in particular the vagus nerve), thalamus or certain other parts of the brain using external controller can help. Non-invasive approach using ultrasound interference is possible.

What brain functions can be consciously controlled?



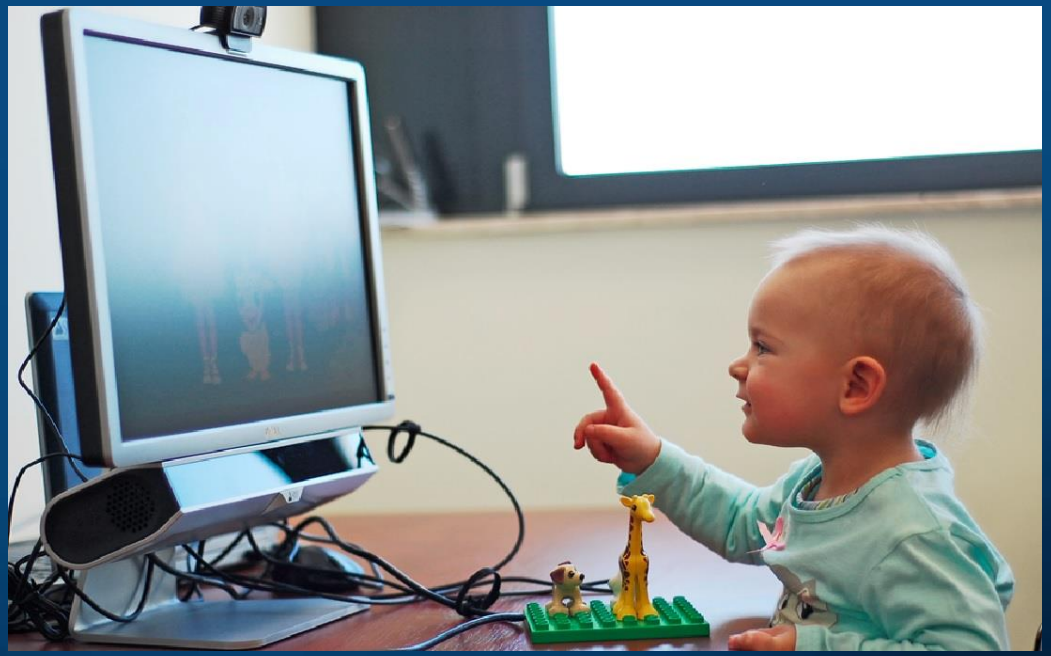
Interdisciplinary nature



My group of neuro-cog-fanatics

GCAF

Gaze Controlled Application Framework (**GCAF**)
A platform for easy programming of applications controlled by gaze direction with various eyetrackers (J. Matulewski et al).
Does not require programming skills.
Used for infants and disabled people.



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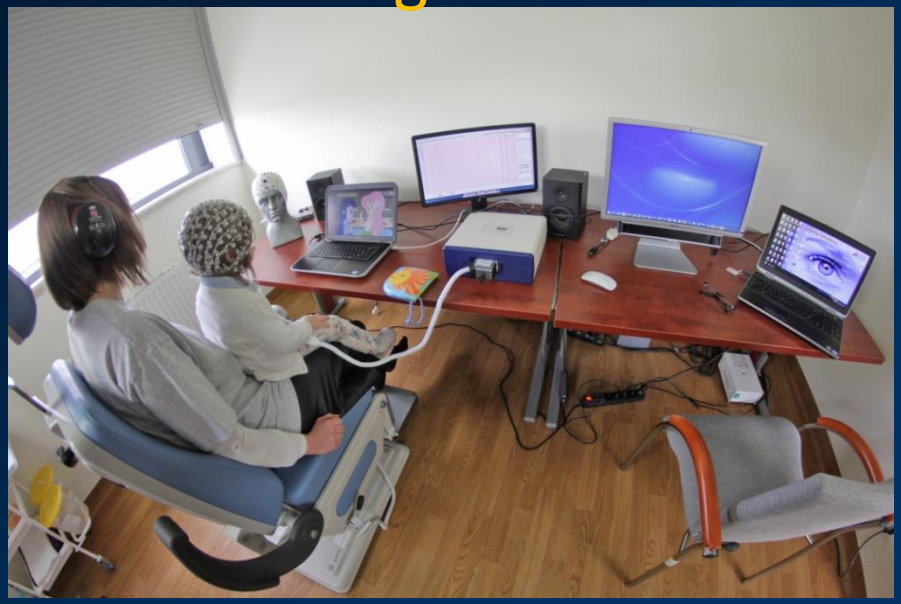
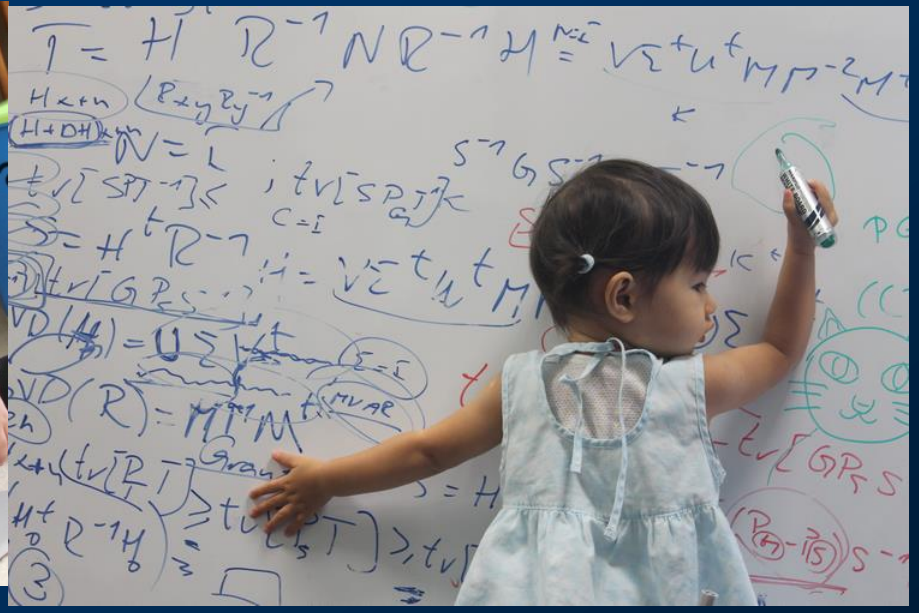
Neurocognitive Lab - BabyLab EEG and Eye Tracking



Training room

Preparation room



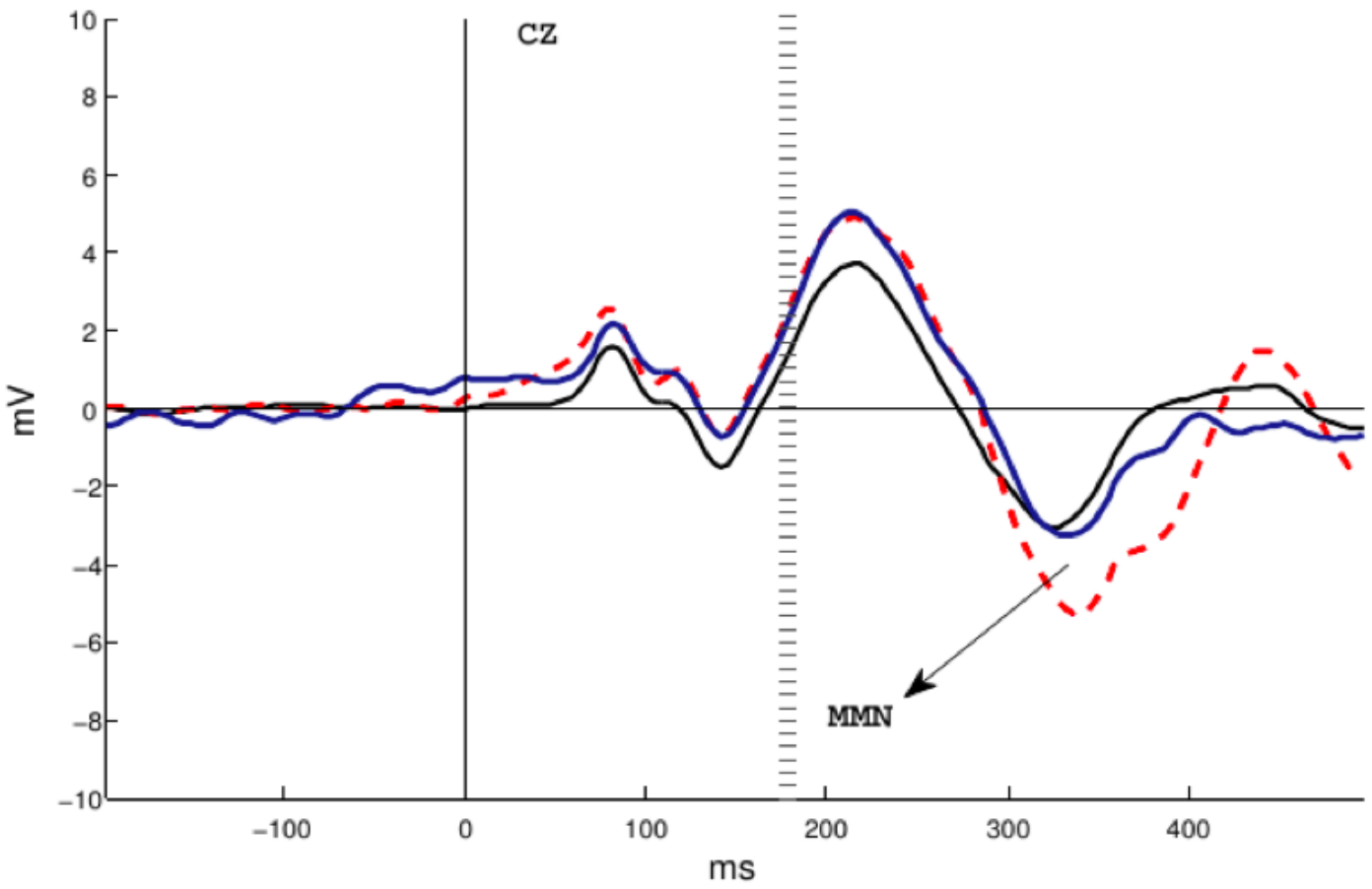
NARODOWE CENTRUM NAUKI

EEG/ET with infants

- EEG

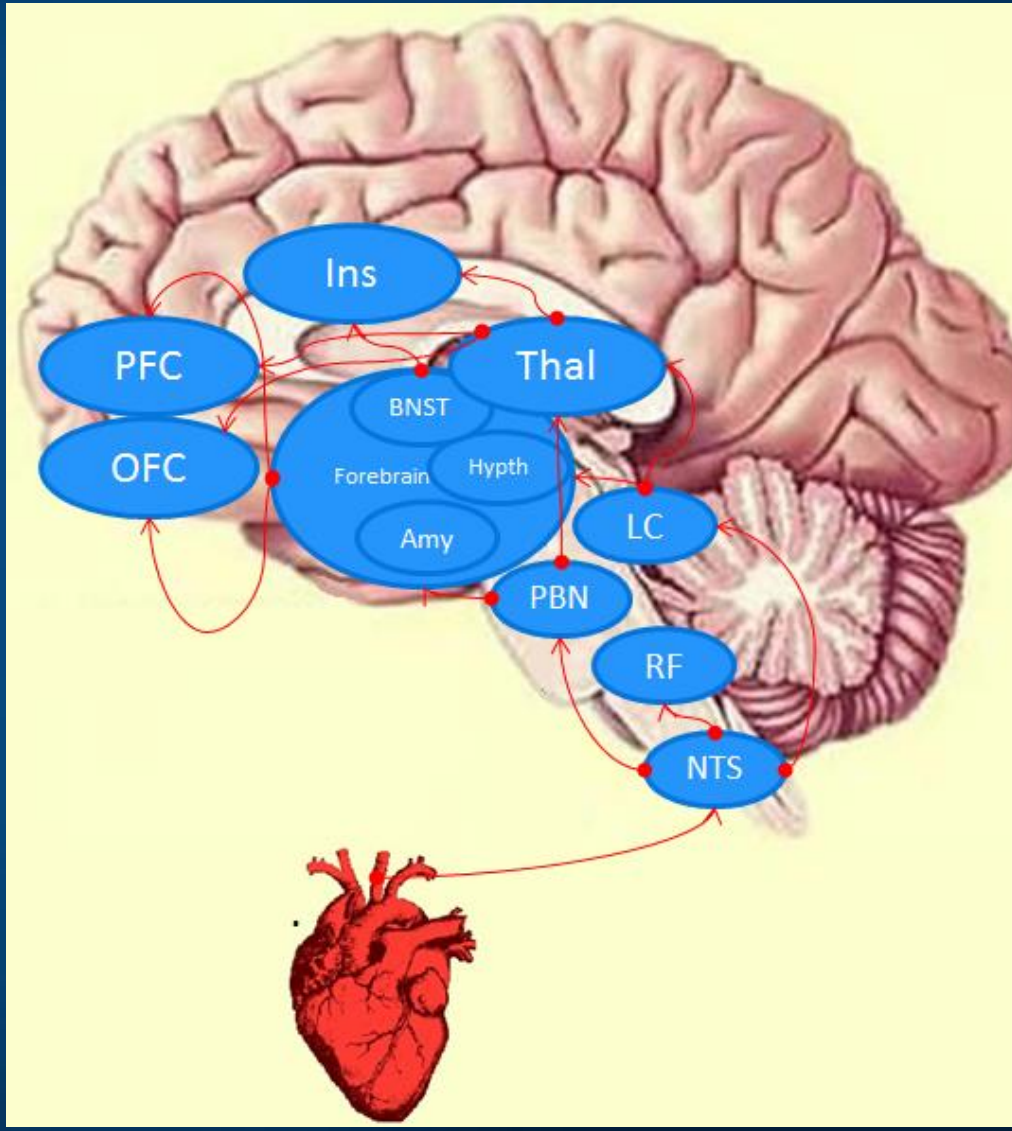
- Eyetracking

Our ERP study with adults: Mismatch Negativity and language

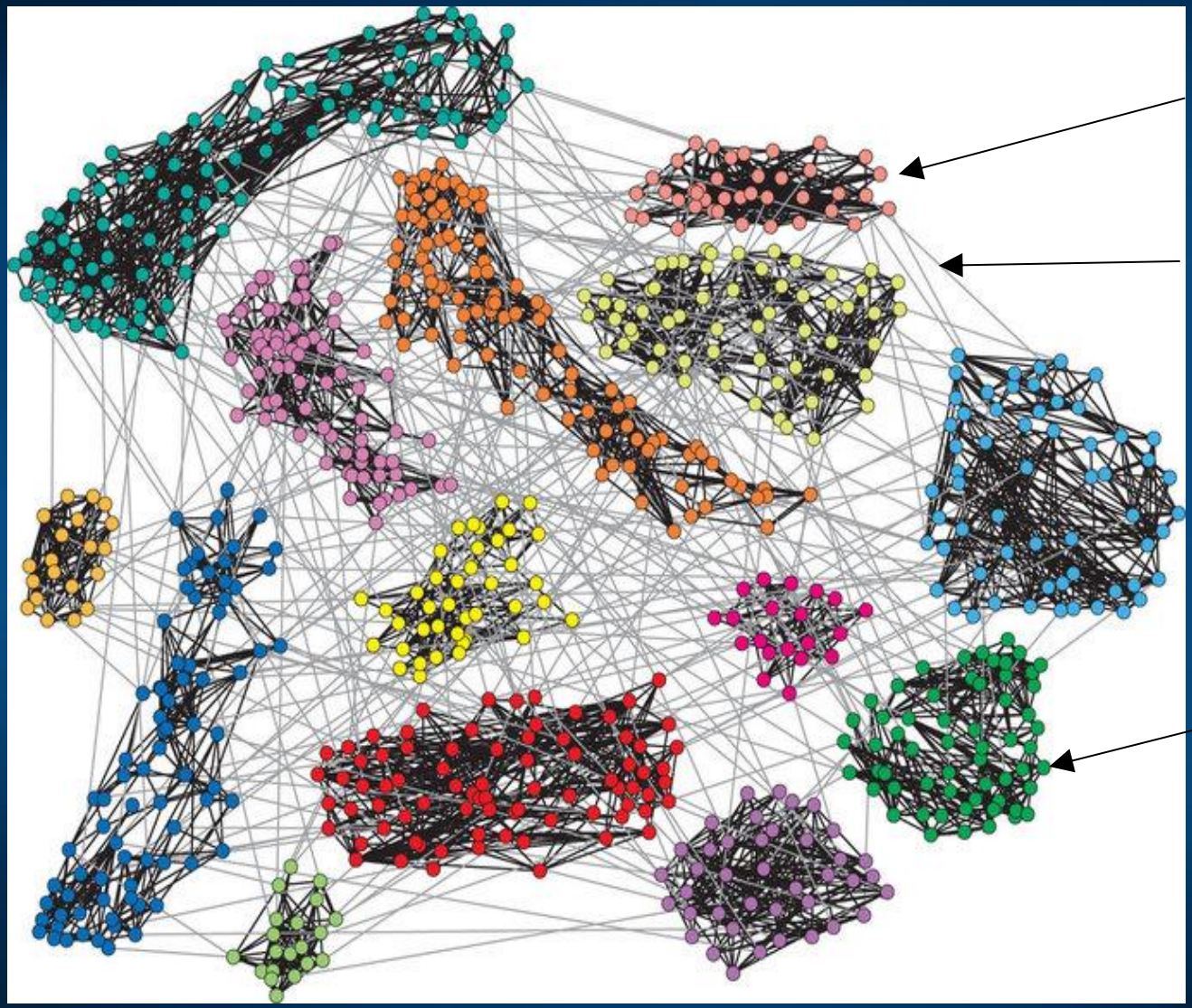


Brain-heart interactions (HRV biofeedback)

- **Bidirectional** (efferent/afferent)
- Action on consecutive CNS levels
- Increased neurocardiac afferent input to the **forebrain** and **PFC:**
- **Generalized inhibitory effect** on the brain [Vaschillo 2011]
- **Synchronization** of cortical activity [McCraty 2009]:
  - alpha band: long-distance communication
  - gamma band: local information transfer; top-down and bottom-up interactions
- **Reduced „neuronal noise"** (unsynchronized background gamma activity) [Gruzelier 2009].



Brain networks



NIMH RDoC Matrix for deregulation of large brain systems.

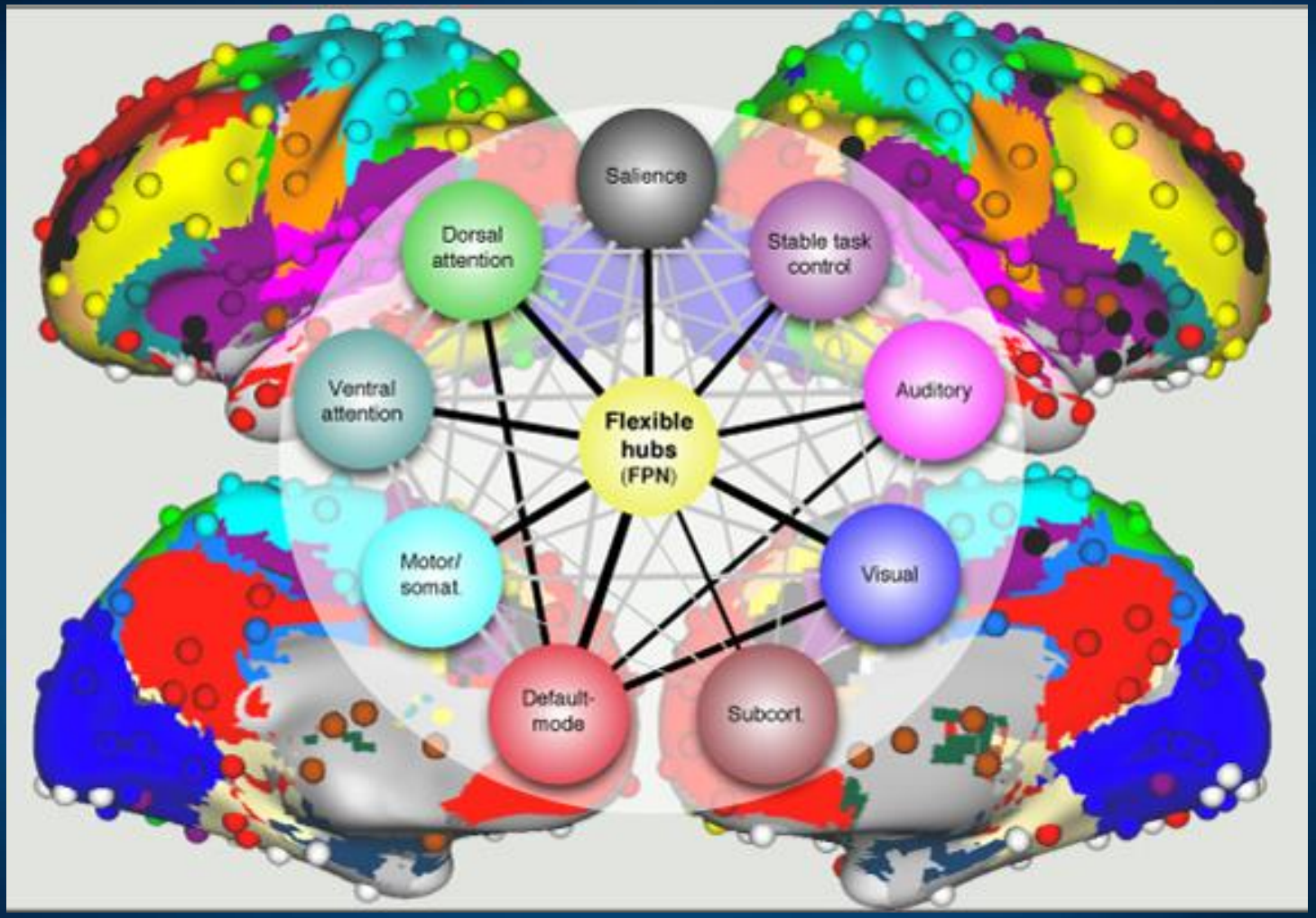
Instead of classification of mental disease by symptoms use **Research Domain Criteria** (RDoC) based on multi-level neuropsychiatric phenomics.

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.

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

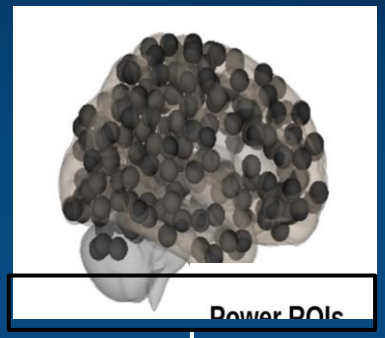
Neurocognitive Basis of Cognitive Control



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

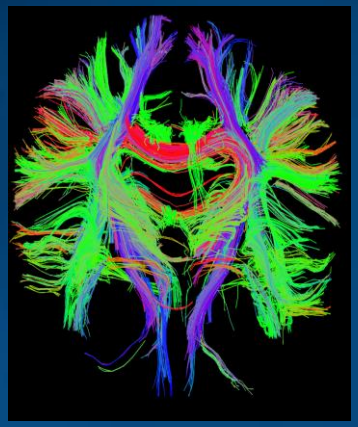
Human connectome and MRI/fMRI

Node definition (parcelation)

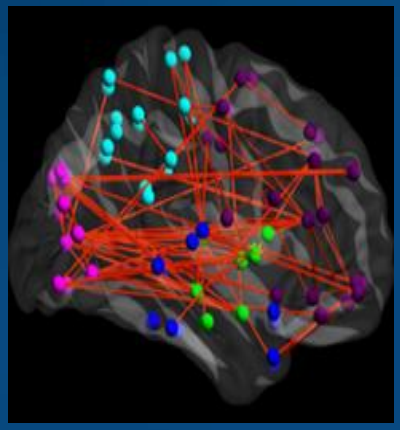


Signal extraction

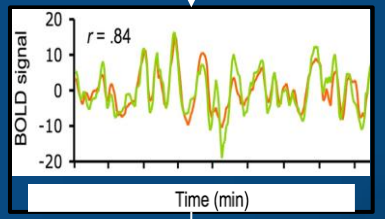
Structural connectivity



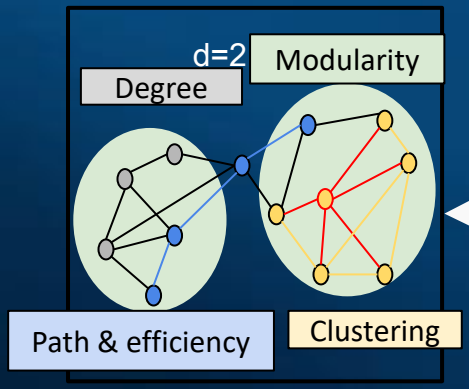
Functional connectivity



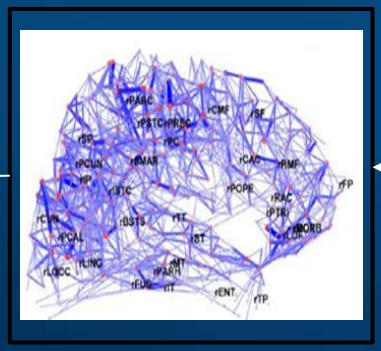
Correlation calculation



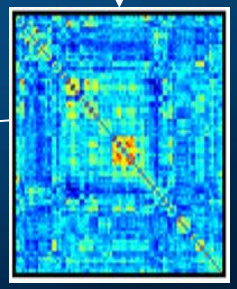
Graph theory



Whole-brain graph



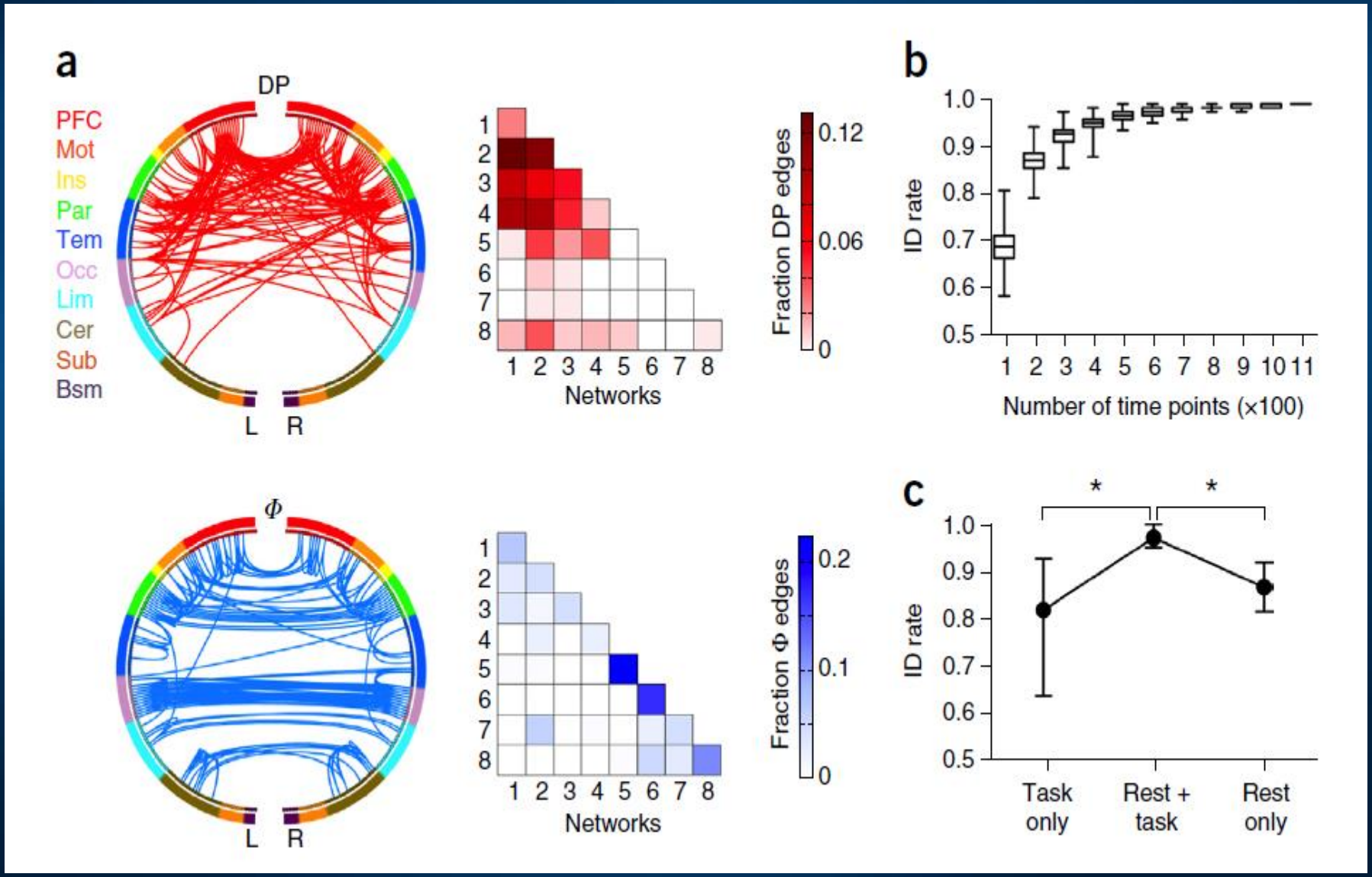
Binary matrix



Correlation matrix

Bullmore & Sporns (2009)

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



In search of the sources of brain's cognitive activity

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

FACULTY OF PHYSICS, ASTRONOMY AND INFORMATICS

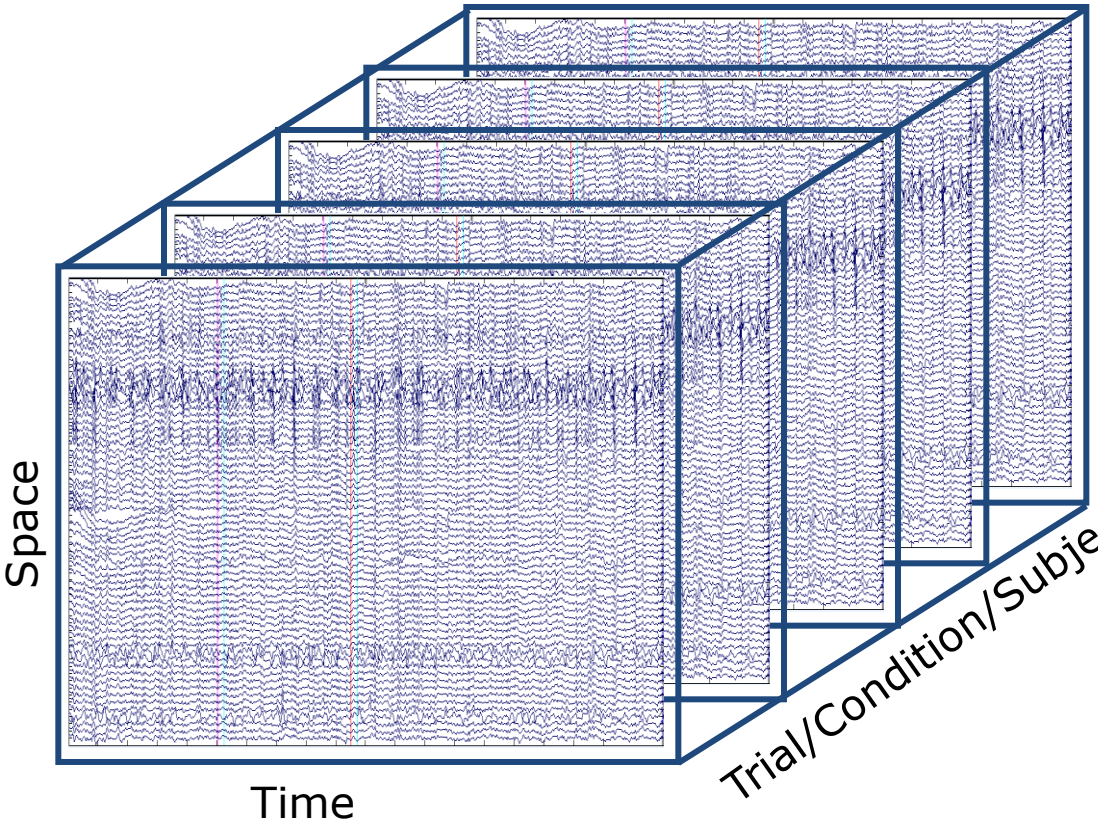
CENTRE FOR MODERN INTERDISCIPLINARY TECHNOLOGIES

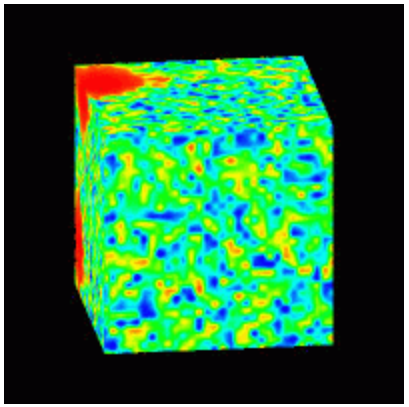
INSTITUTE OF PHYSIOLOGY AND PATHOLOGY OF HEARING

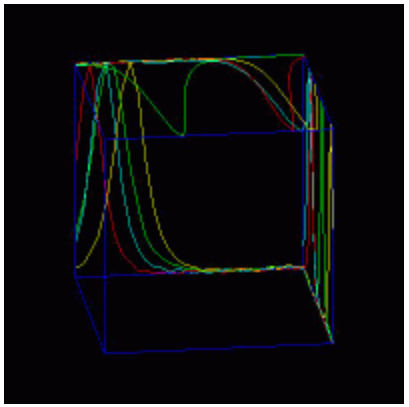
nencki institute of experimental biology

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

Prof. Cichocki Lab
RIKEN BSI



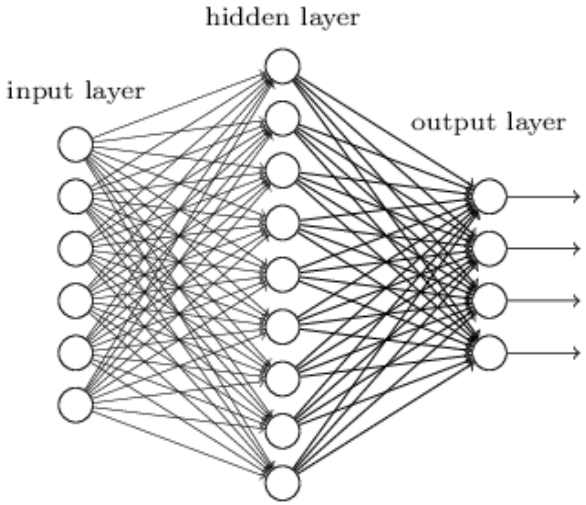




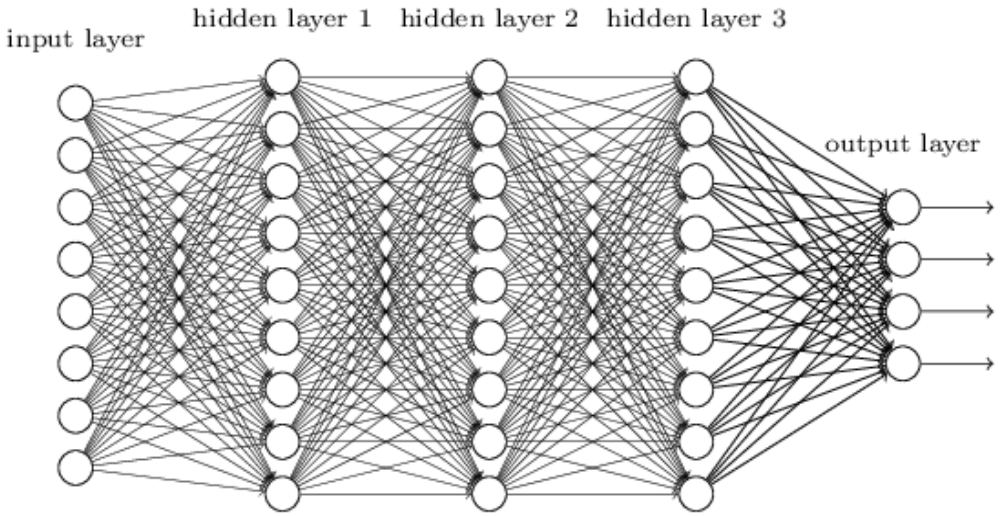
Exploratory and multi-way blind source separation and tensor factorizations: unsupervised learning methods and software to find the hidden causes & underlying hidden structure in the data.

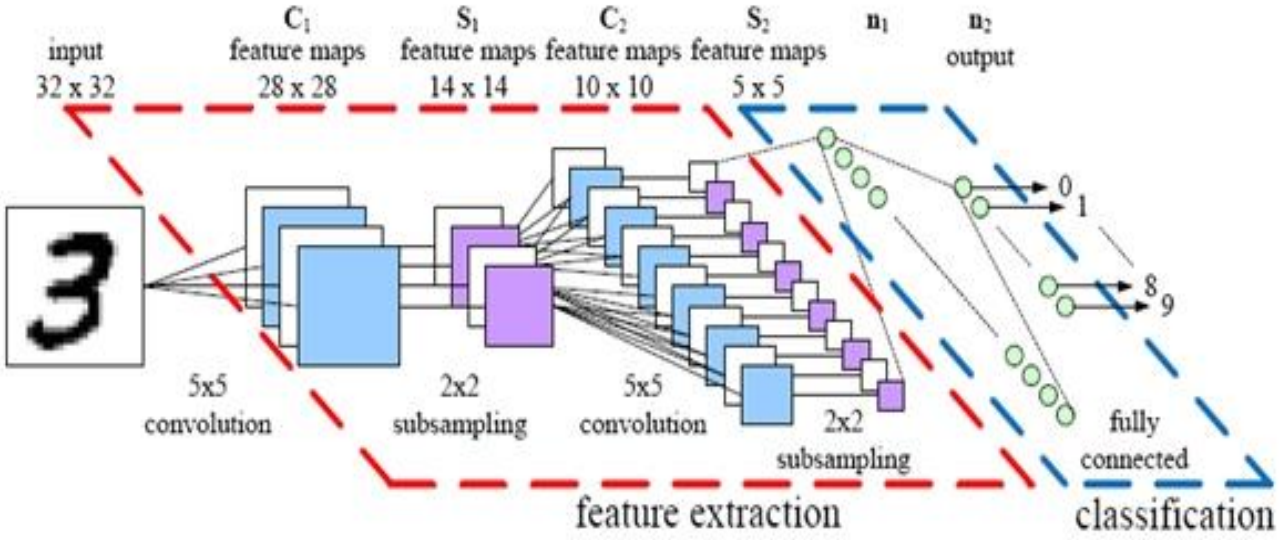
Tensorization of Convolutive Deep Learning NN

"Non-deep" feedforward neural network



Deep neural network





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Brain modules and cognitive processes

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

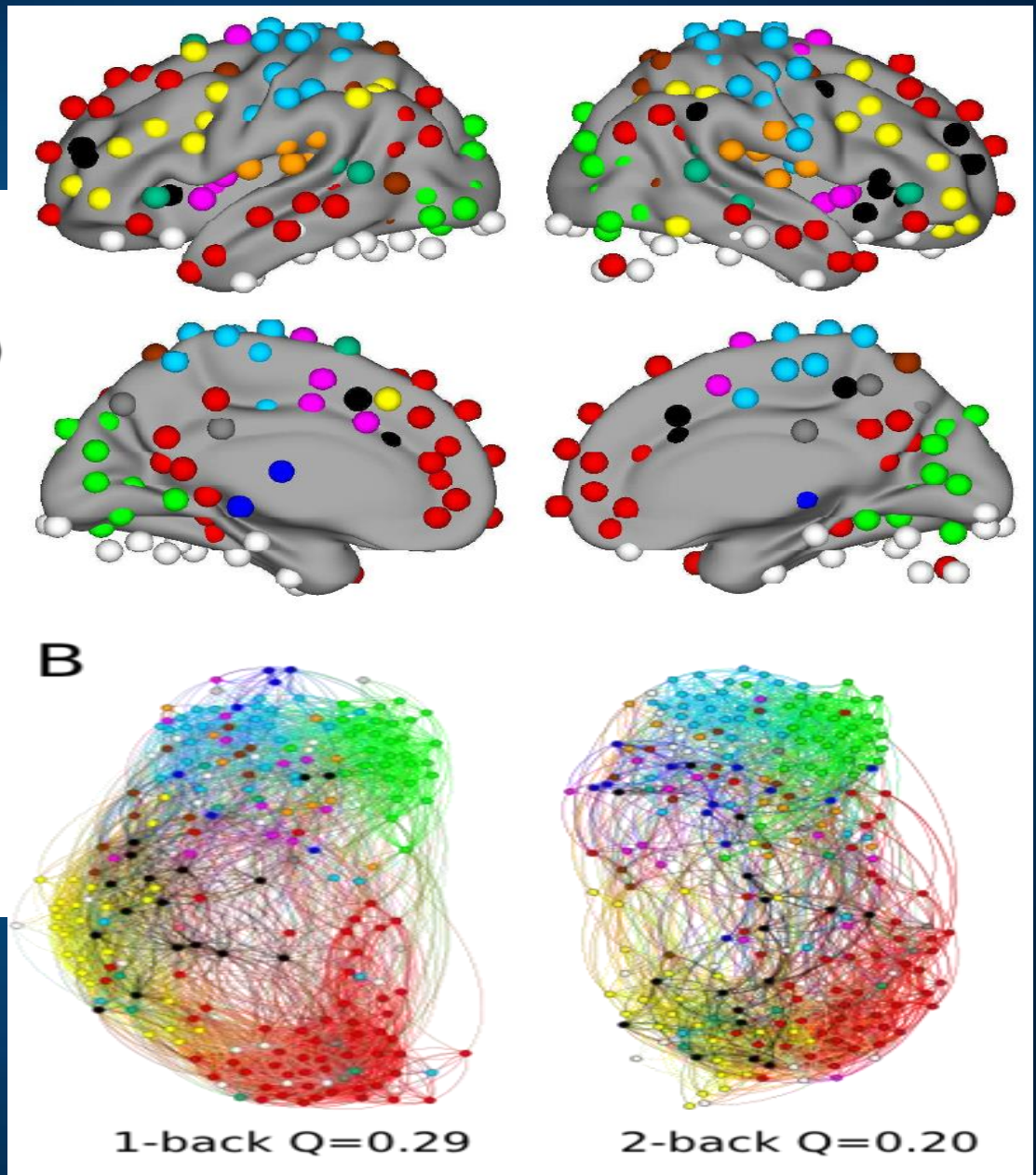
Left: 1-back

Right: 2-back

Average over 35 participants.

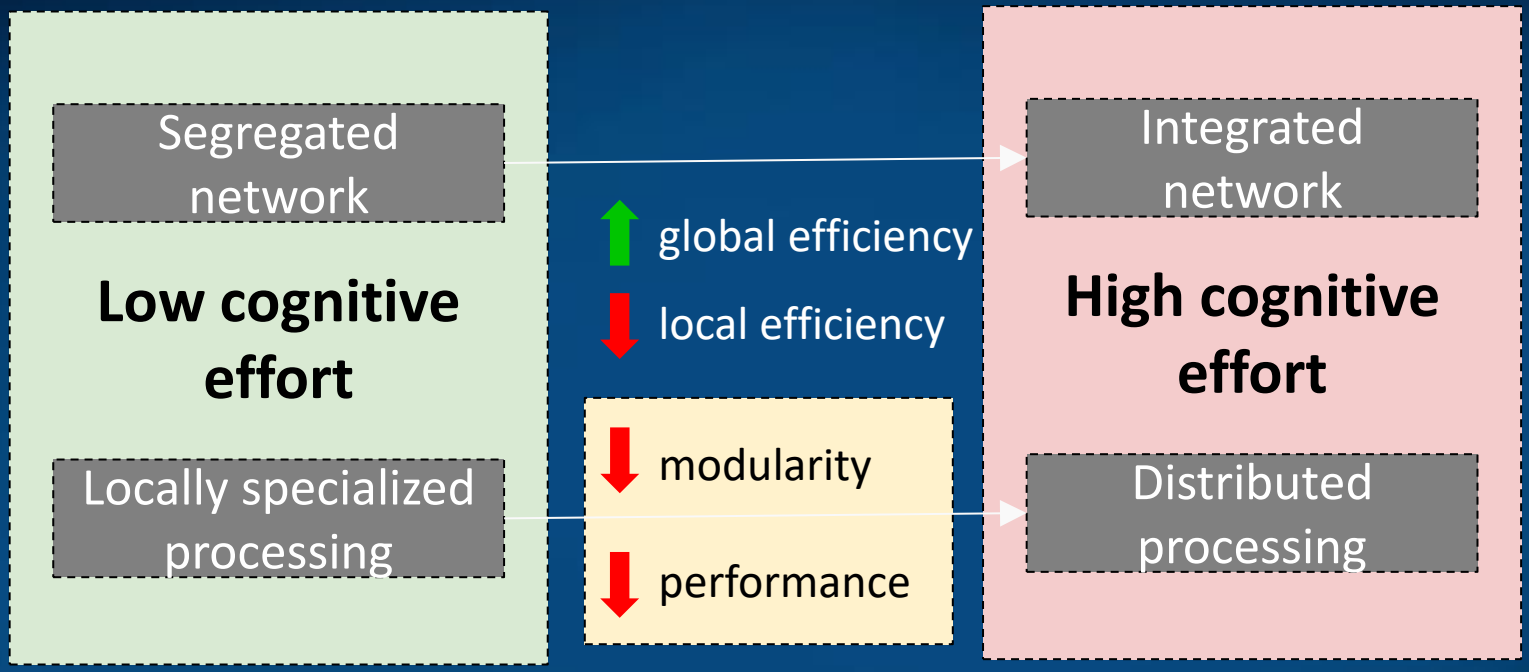
Left and midline sections.

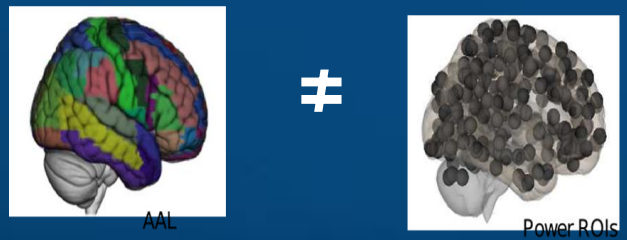
- Fronto-Parietal (FP)
- Memory (MEM)
- Somato-Motor (SOM)
- Default Mode (DM)
- Ventral Attention (VA)
- Salience (SA)
- Cingulo-Opericular (CO)
- Auditory (AU)
- Subcortical (SUB)
- Dorsal Attention (DA)
- Visual (VIS)
- Other



K. Finc et al, HBM (2017).

Cognitive load

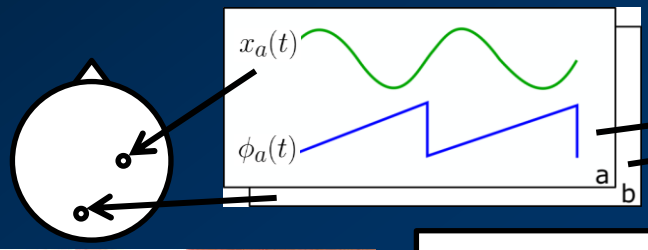




Parcellation into 264 regions (10 mm spheres) shows subnetworks more precisely than for 90 regions; only a small subgroup of neurons in each ROI is strongly correlated.

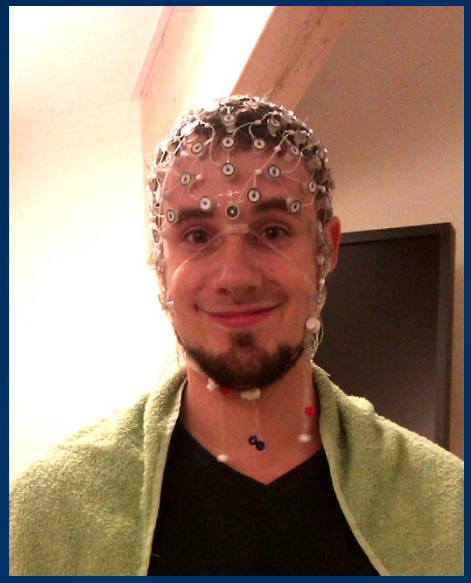
Functional connectivity changes

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

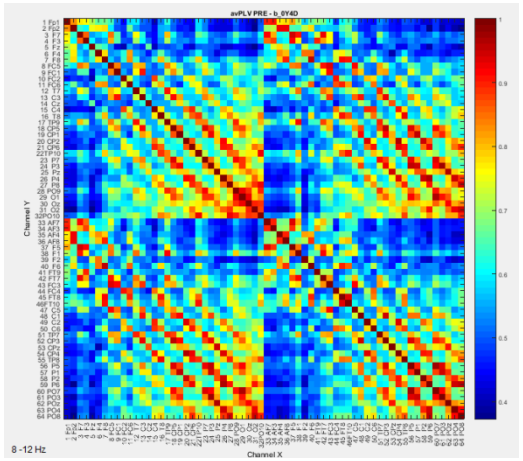


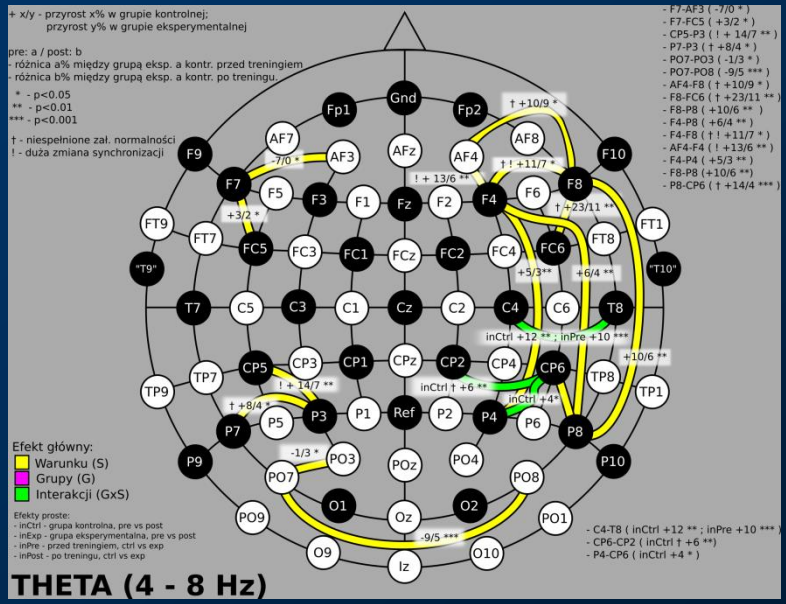
$$\Phi(t) = \phi_a(t) - \phi_b(t)$$

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



PLV channel vs channel





Possible form of BFP

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

1. **Spatial/Power**: direct localization of sources in selected ROIs.
2. **Spatial/Synch**: changes in functional 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, many other methods.
6. **EEG** microstates, their sequences and transitions.

How? 8 selected approaches

1. **Source Reconstruction/Localization**, from fMRI to EEG.
2. **Graph-based approaches:** functional network activity.
3. **Connectome-based**: signal propagation on connectome networks.
4. **Spatio-temporal EEG maps** using ERD/ERS.
5. **EEG component analysis:** ICA, EMD, ERM, tensor decomposition …
6. **ERP shape analysis** in component space.
7. **Model-based approaches, ex.** The Virtual Brain.
8. **Feature-based approaches –** microstates, trajectories.

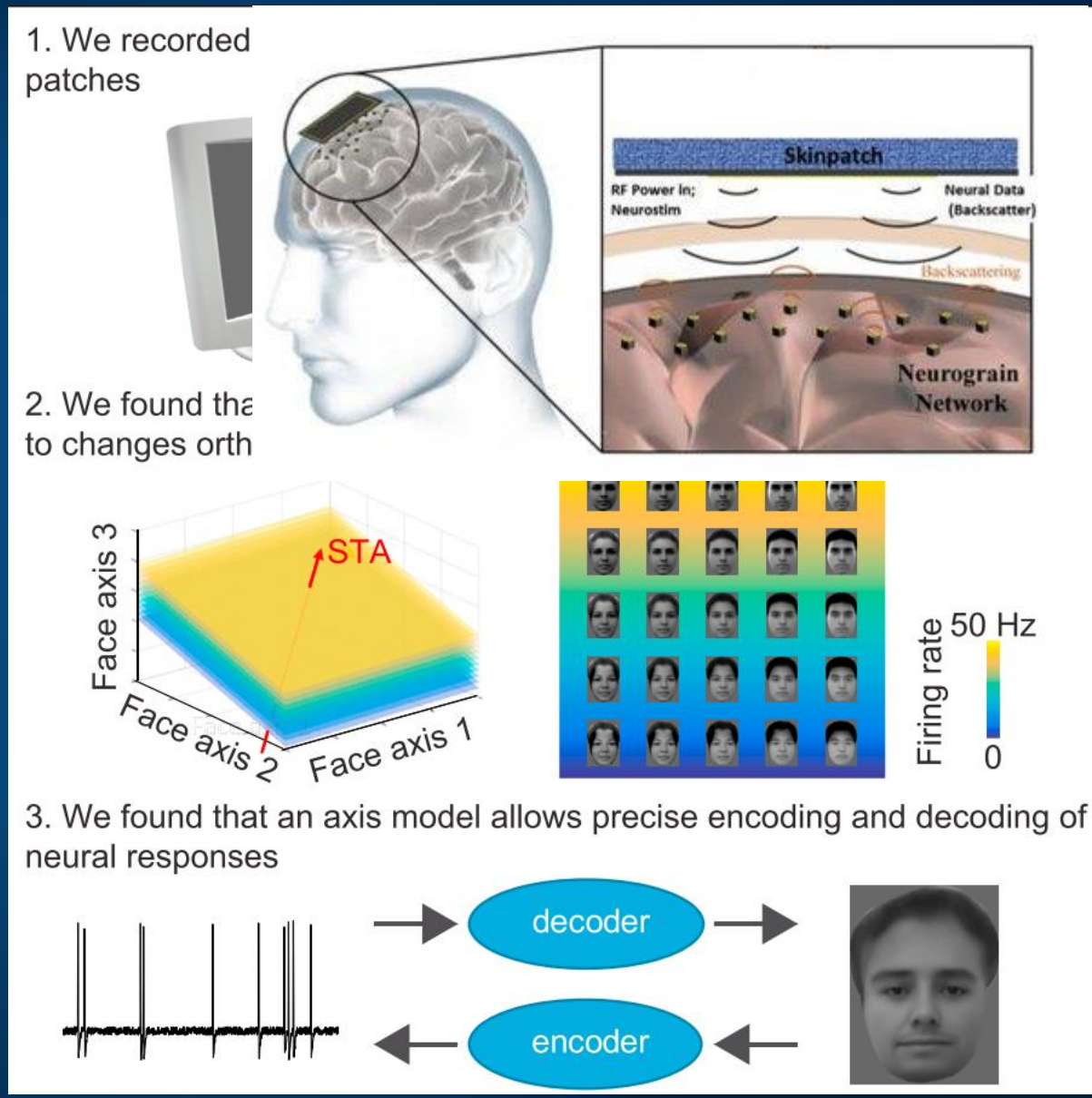
Transformation of average spiking rates measured directly in selected brain regions may be more accurate than source localization.

Neural screen

Features are discovered, and their combination remembered as face, but detailed recognition needs detailed recording from neurons – 200 neurons in various visual areas used.

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

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

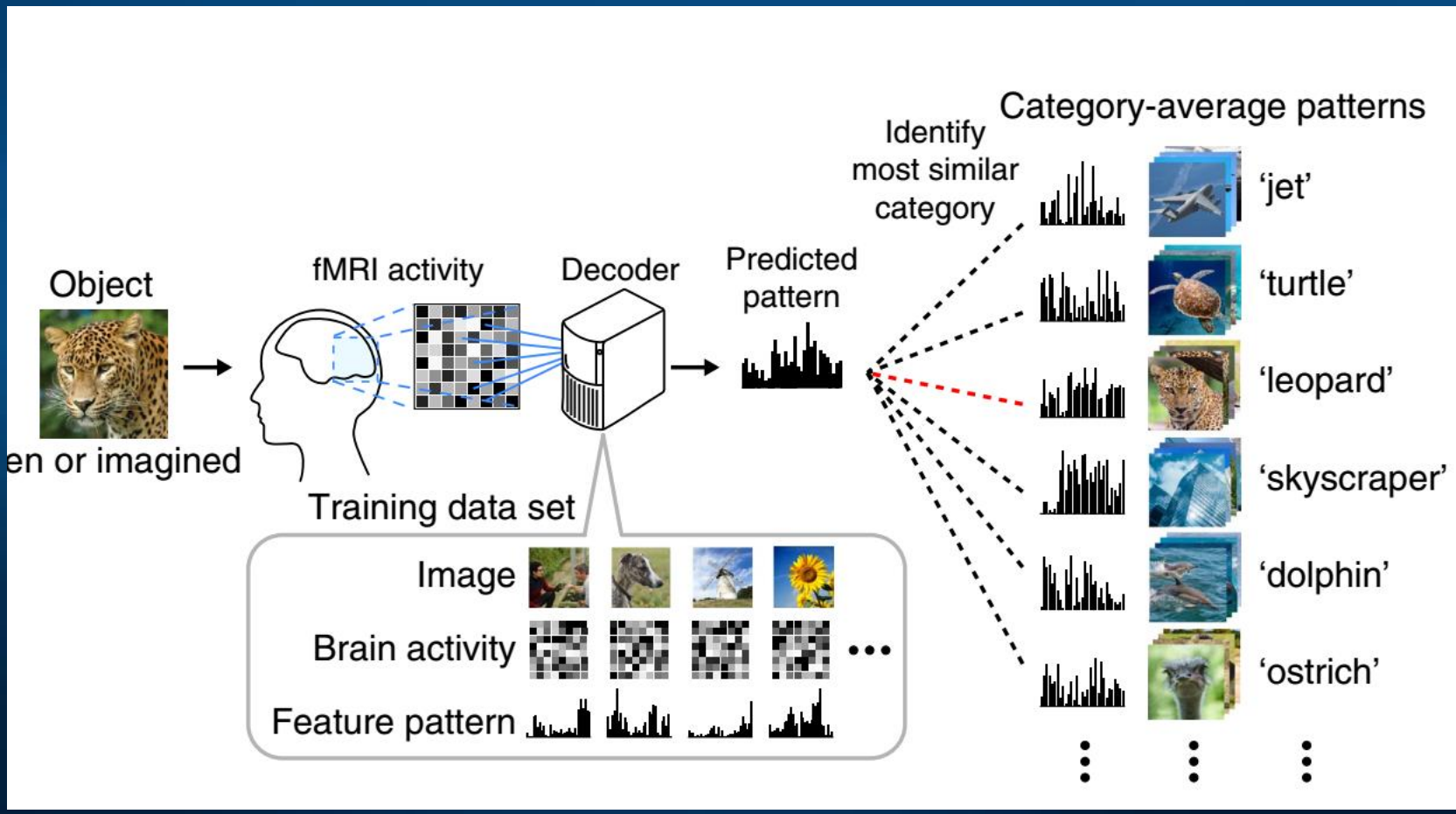


Mental images

Measurement of spiking rates of 205 neurons in visual regions are sufficient to recreate in details faces that monkeys have seen.

Brain activity ⇔ Mental image

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

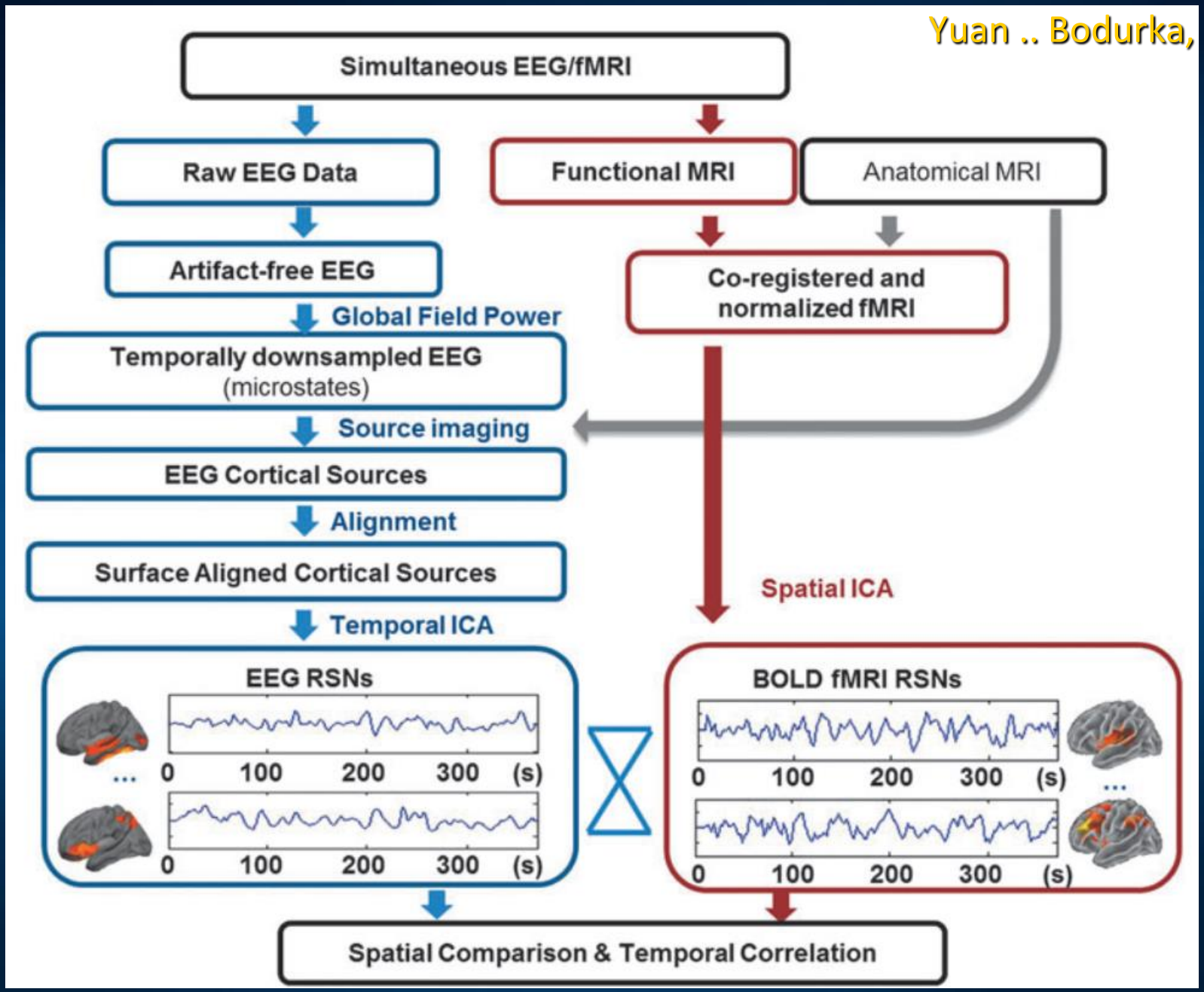


Decoding Dreams

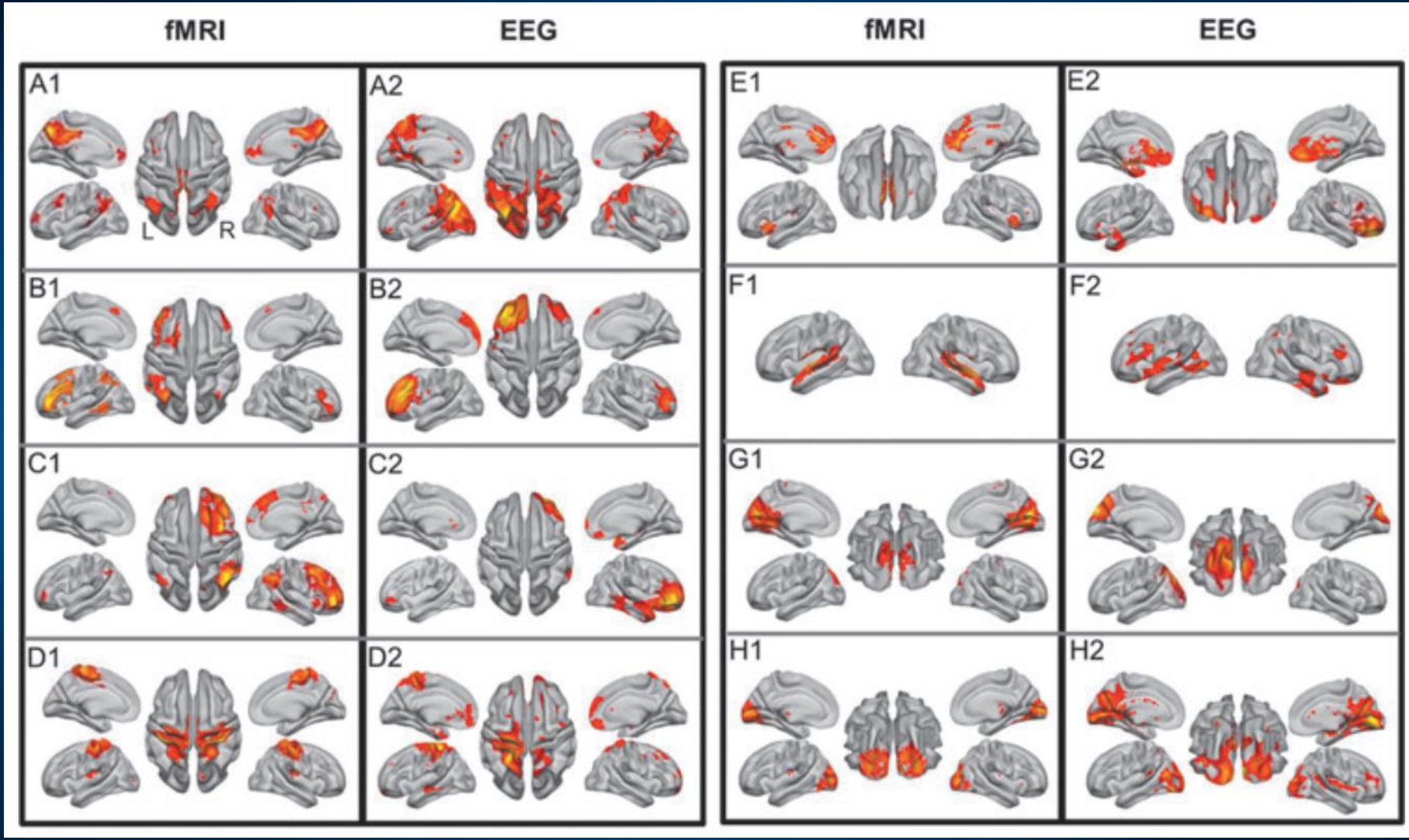
Decoding Dreams, ATR Kyoto, Kamitani Lab. fMRI images analysed during REM phase or while falling asleep allows for dream categorisation.

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

Yuan .. Bodurka, 2015



8 areas from BOLD-EEG



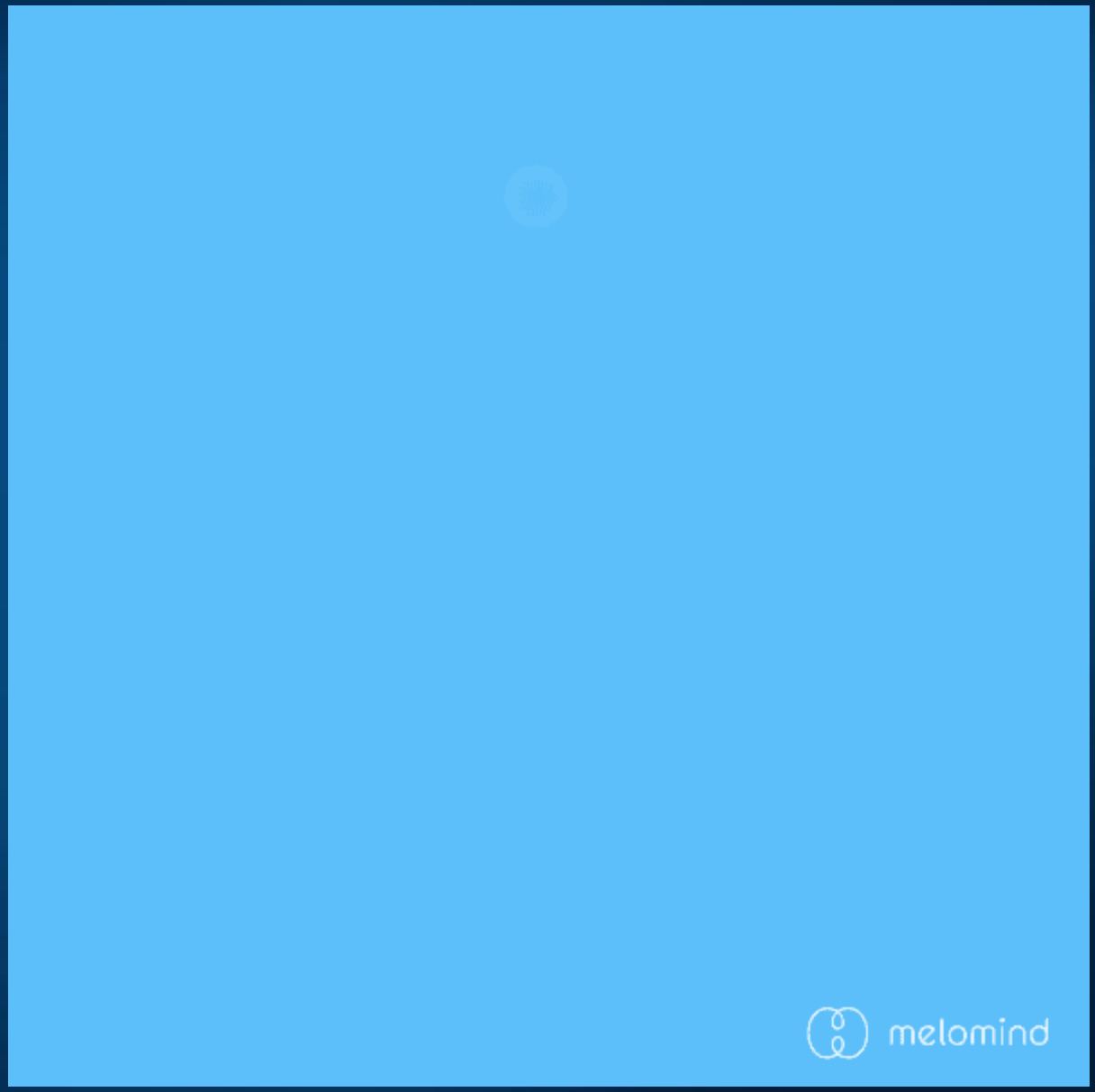
DMN, FP (frontoparietal)-left, right, sensorimotor, ex, control, auditory, visual (medial), (H) visual (lateral).

Neuro-relax

Sounds and music may have arousing or relaxing effects.

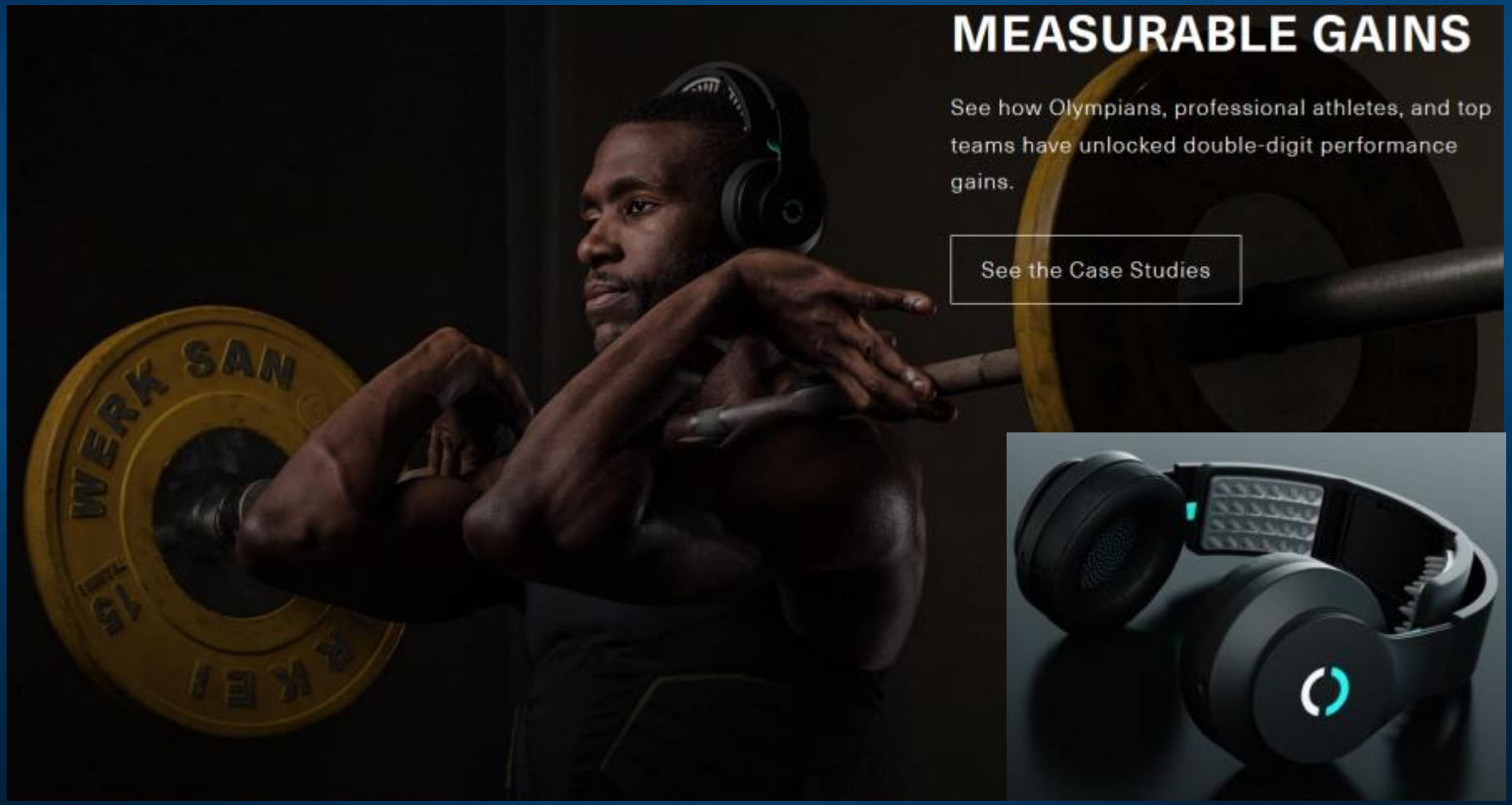
Melomind:

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



Neuropriming

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



Haloneuro.com

DCS for attention/relaxation

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

BCI and learning

Your brain knows better what is interesting than you do! Information relevance inferred directly from brain signals to model search intent.

- Eugster et al. (2016). Natural brain-information interfaces: Recommending information by relevance inferred from human brain signals.

Externally induced frontoparietal synchronization modulates network dynamics and enhances working memory performance (Violante et al. 2017).

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.

Microstimulation too low to evoke muscle activation, applied in premotor cortex, instructed specific actions.

- Mazurek & Schieber (2017). Injecting Instructions into Premotor Cortex. *Neuron*, *96*(6), 1282–1289.e4.

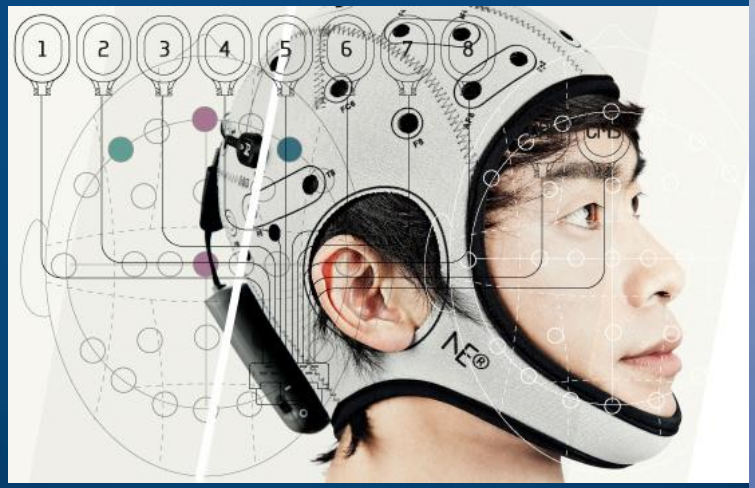
Military applications

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

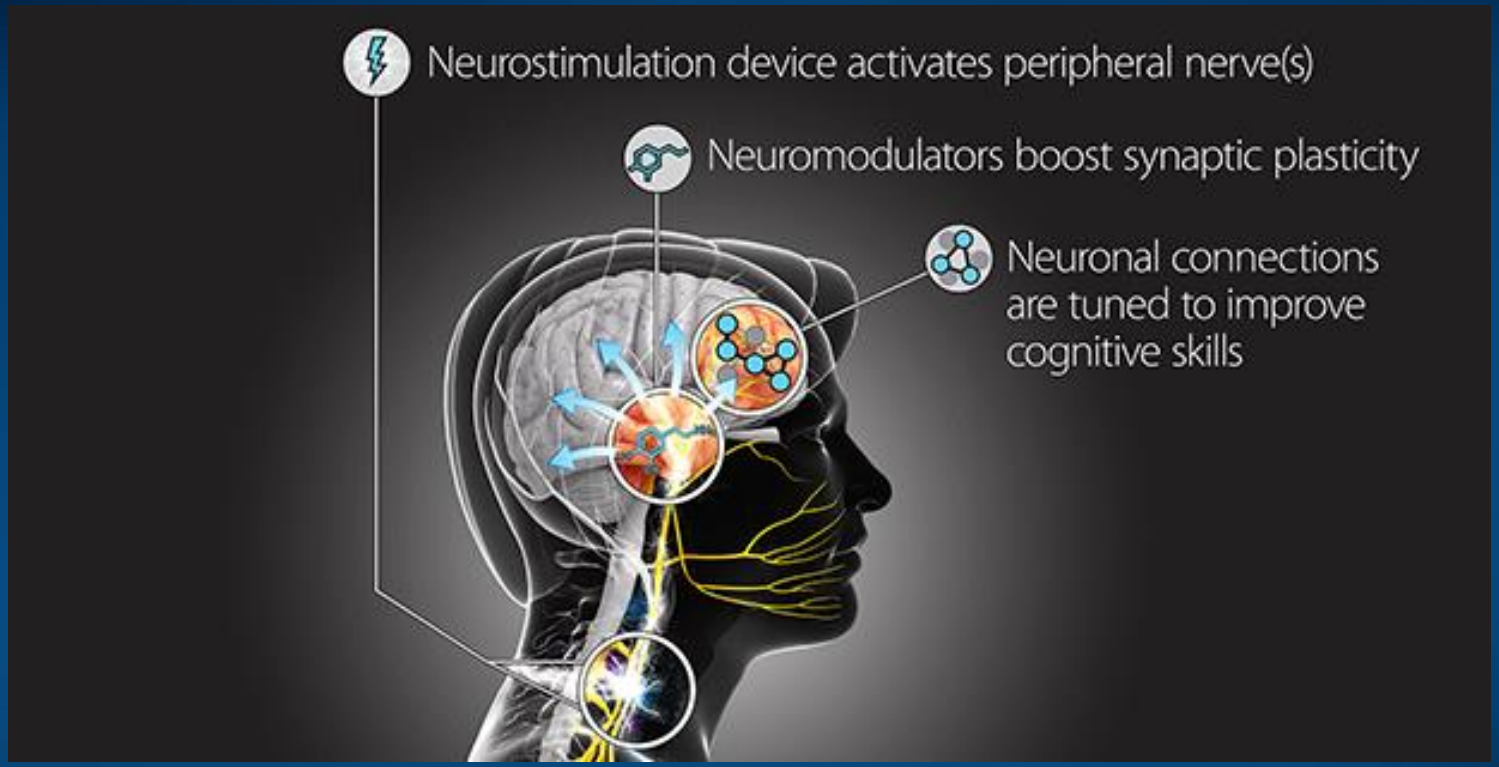
Intific Neuro-EST uses EEG analysis and mulit-channel transcranial simulation (HD-DCS) to pre-activate the brain of the novice in areas where the expert brain is active.

Real-life transfer learning …

HD-tDCS may have 100 channels.

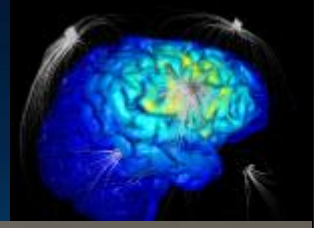


Targeted Neuroplasticity Training



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.

HD EEG/DCS?

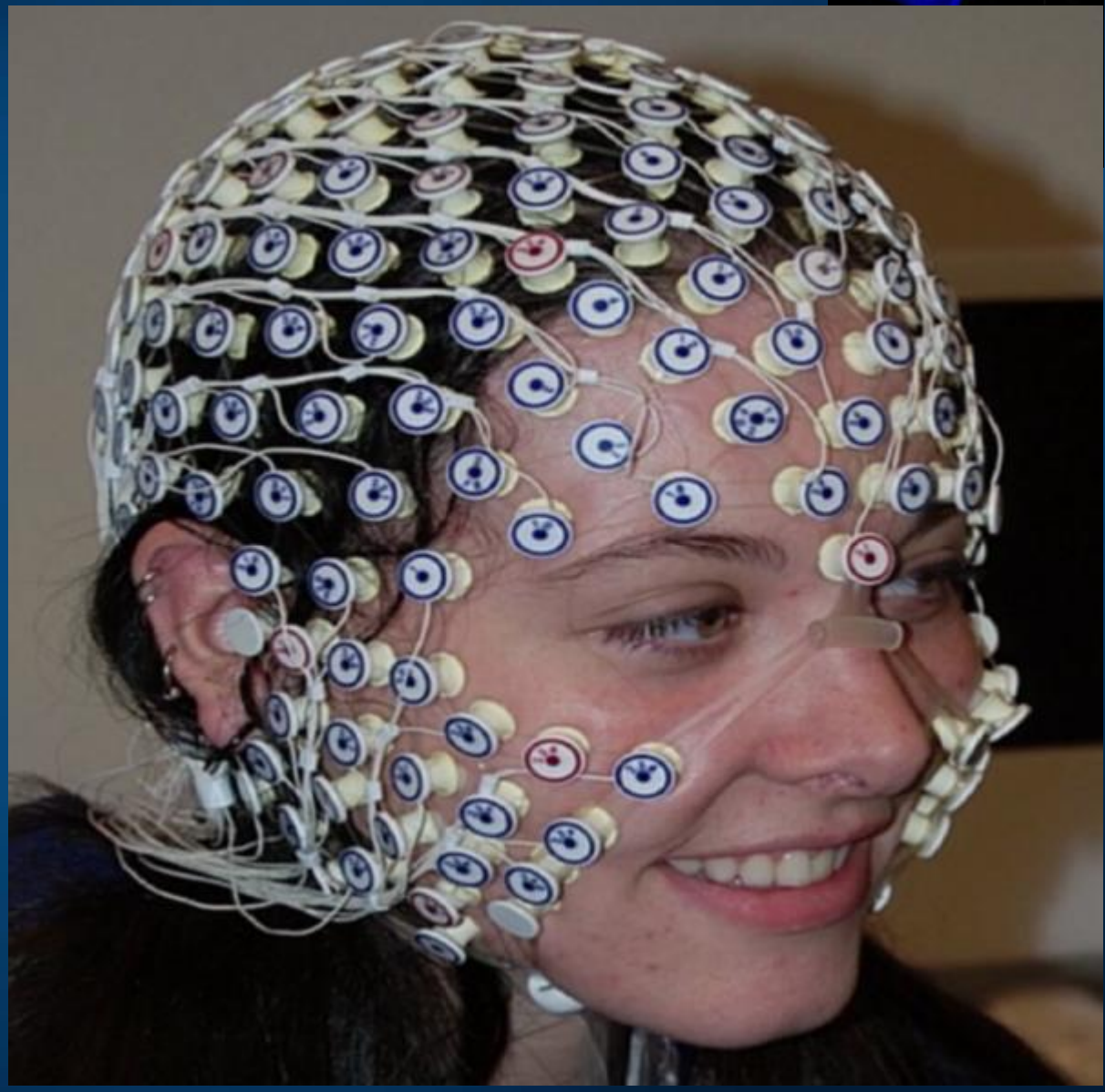


EEG electrodes + DCS.

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

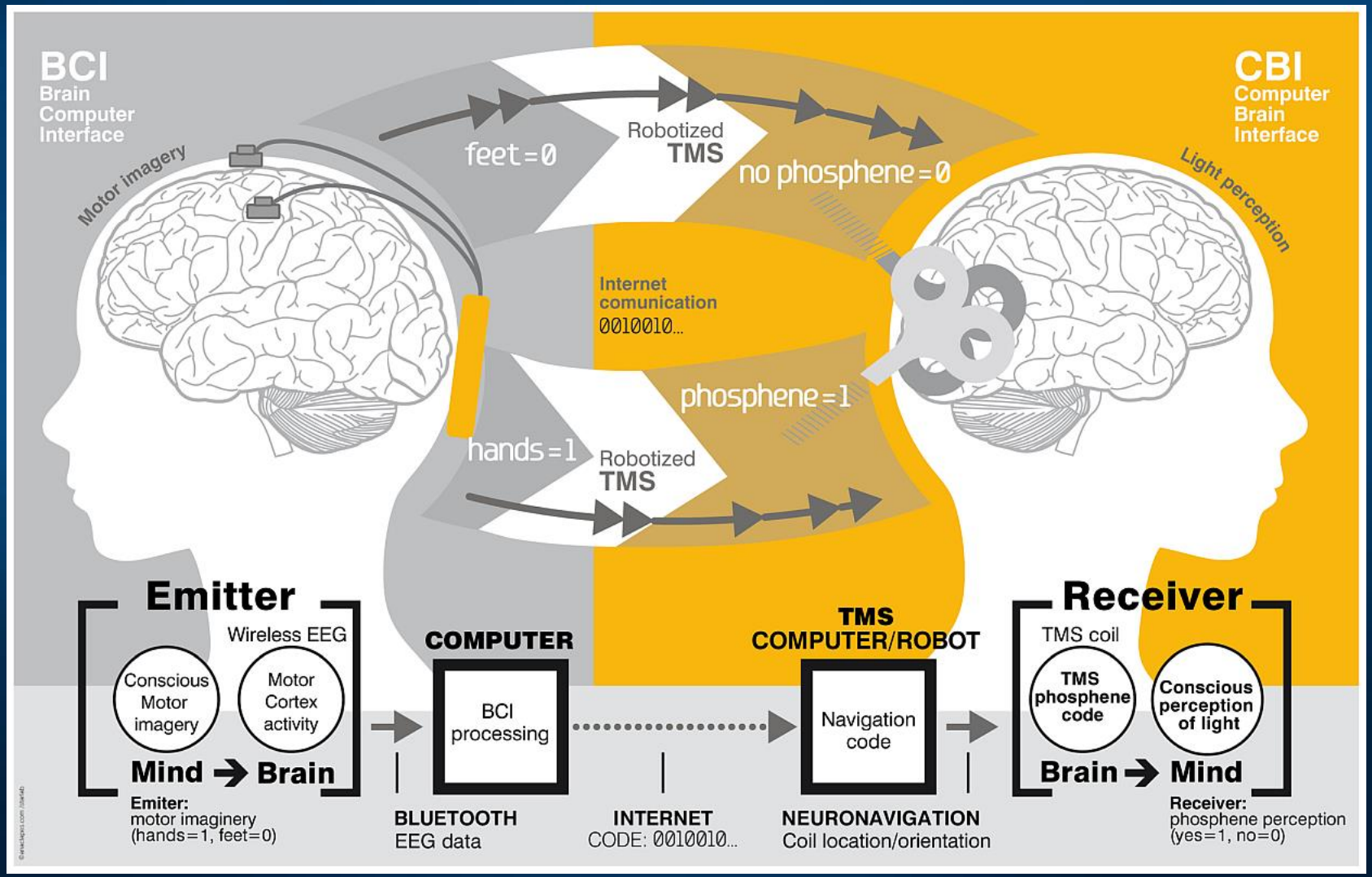
Depression, neuro-plasticity, pain, psychosomatic disorders, teaching!

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

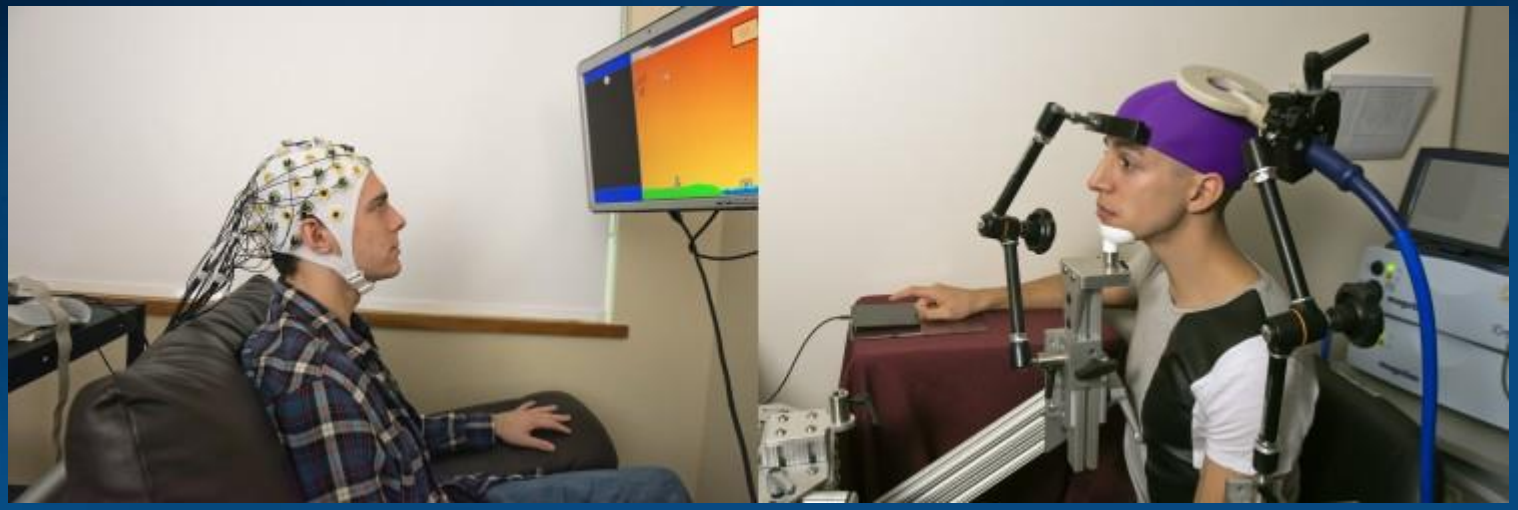


Synthetic telepathy, B-B communication

Read the brain states and transmit them to another person?



Thought transfer?

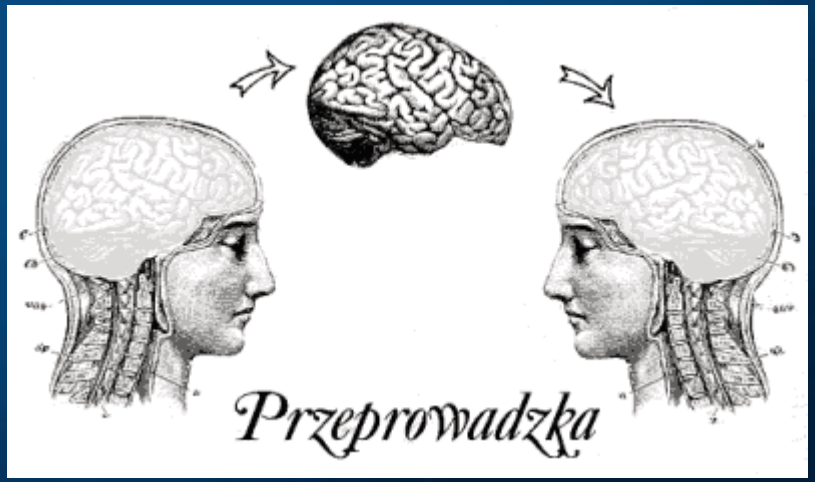


EEG + TMS/DCS has been used to transfer simple motor commands using Morse alphabet. Can this technique be more subtle?

Can this technique be more subtle?

Will mind transfer be possible in future?
Long way but remember:

Telegraph => Radio => TV => VR …



Conclusions

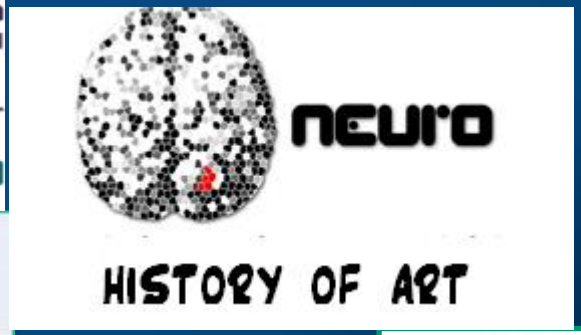
- Contrary to what people say, we know a lot about the brain and consciousness, begin to understand the mappings between brain states and mental states – but its still a tip of iceberg.
- Brain reading and stimulation, understanding neurodynamics and neurocognitive phenomics, are the key to BCI for voluntary self-regulation of brain functions, and numerous therapeutic applications.
- Roadmap: Brain neuroimaging ⇔ The Virtual Brain, graphical models ⇔ mental models ⇔ closed loop BCI for conscious control of our brains.
- Neuromorphic hardware with complexity beyond the human brain is coming (ex. IBM Synapse project) and will enable construction of new brain models, deeper understanding of brain functions, and practical applications.
- Neurolace from Neuralink, DARPA project to put million electrodes in human brain and many other developments will integrate brains with artificial systems and change the BCI game.

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

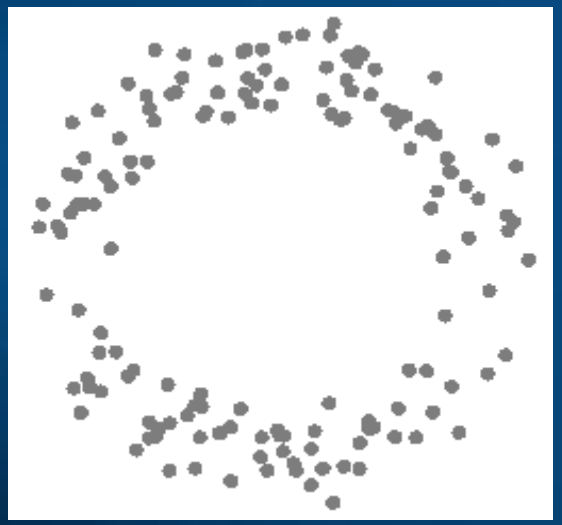
Monthly international developmental seminars (2017): Infants, learning, and cognitive development

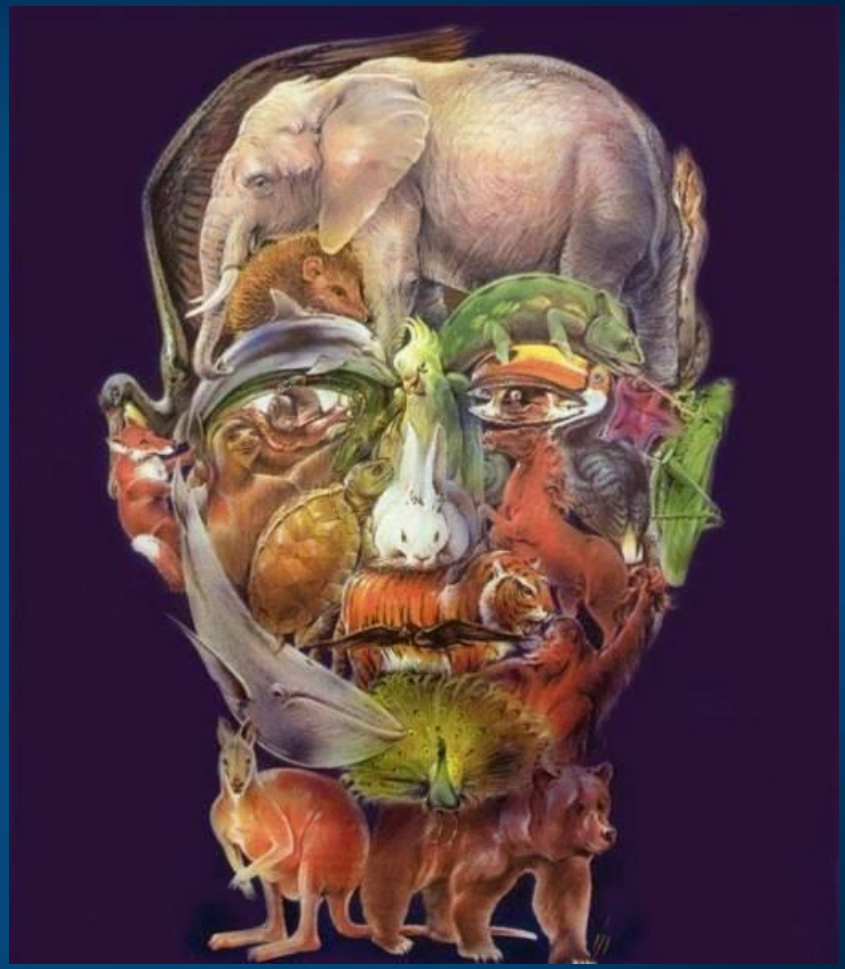
Disorders of consciousness 17-21.09.2017

Autism: science, therapies 23.05.2017



Thank you for synchronization of your neurons





Google: W. Duch

=> talks, papers, lectures, Flipboard …