BMIs for human enhancement: what has been done, and what is coming?

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Google: Wlodzislaw Duch

BMI Workshop, IEEE SMC, Prague 10/2022

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LATVIA
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North Sea
Baltic Sea
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Toulouse
MONACO
Sarajevo
BULGARIA
Andorra la Vella
Marseille
Ligurian Sea
Florence
Sofia
Porto
PYRENEES
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Toruń

Nicolaus Copernicus, born in 1473 in Toruń.
Studied in Krakow, Bologna, Padova and Ferrara

The rise of Braintech

Development of civilization

We are in extraordinary moment in the history of the world!

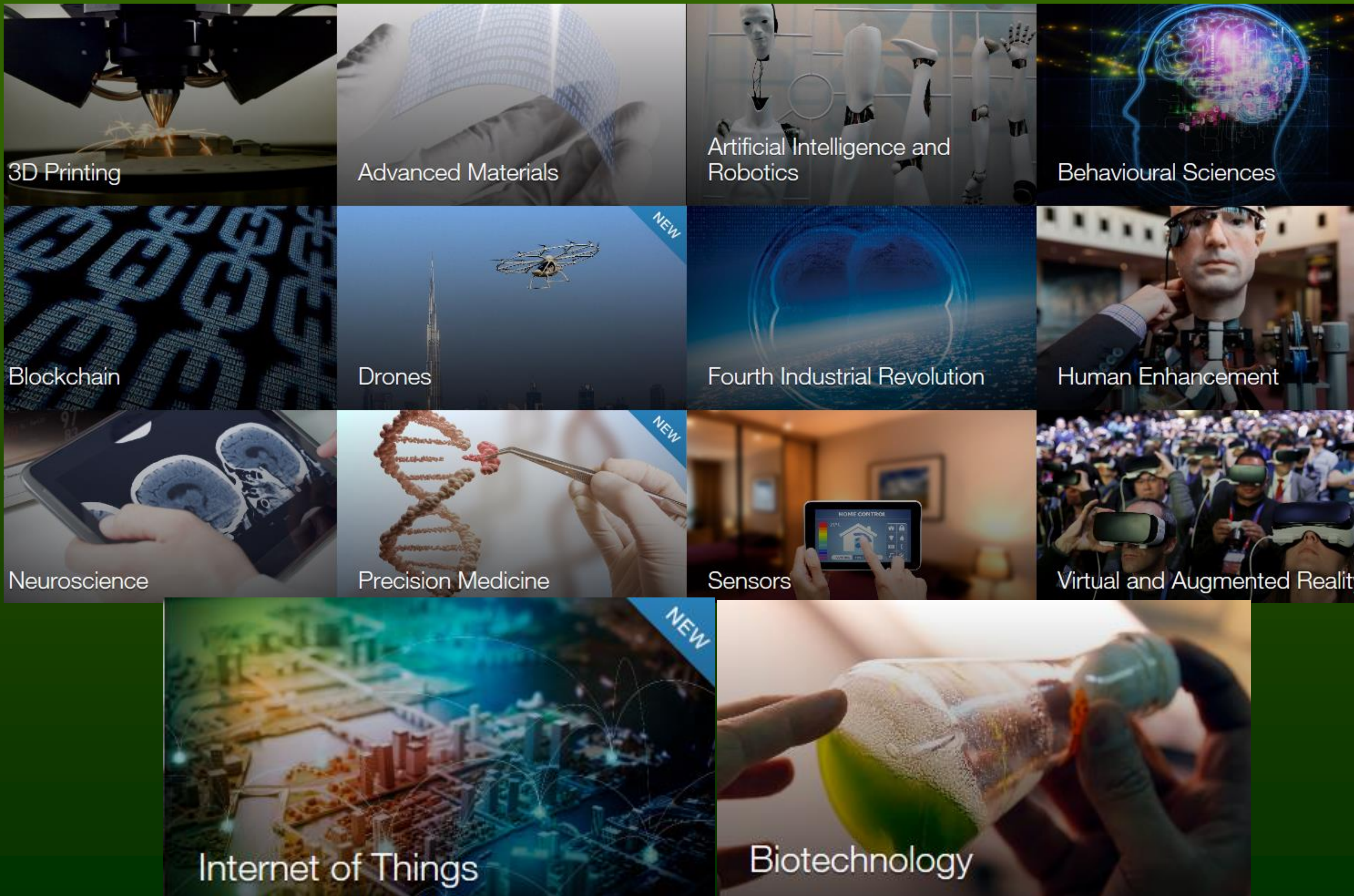
Growing understanding of the world, since antiquity:

1. Magical thinking, the whims of the gods, fatalism.
2. Causality, empirical observations, descriptive knowledge - protoscience.
3. Theories, empirical verification, math and statistics – classical science.
4. Computer simulations, complex systems, “new kind of science” (Wolfram).
5. Knowledge from data (KDD), collection and access to all information.
6. Artificial intelligence support for thinking, superhuman augmentation.
7. Autonomous AI + human augmentation, around the corner?

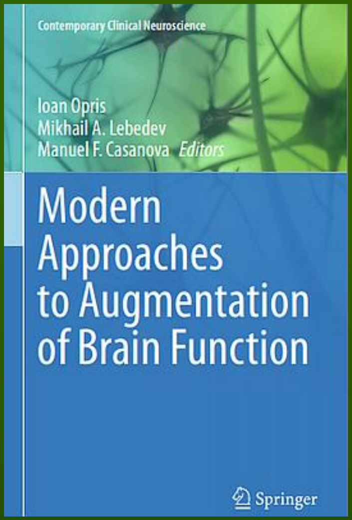
AI is based on increasingly complex data models: IBM Watson, CyC, GPT-3, Google Mixture of Experts (MoE), models with more than trillion parameters.

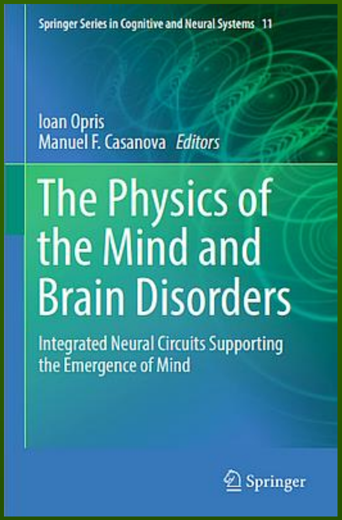
Can these models interact directly with our brains?

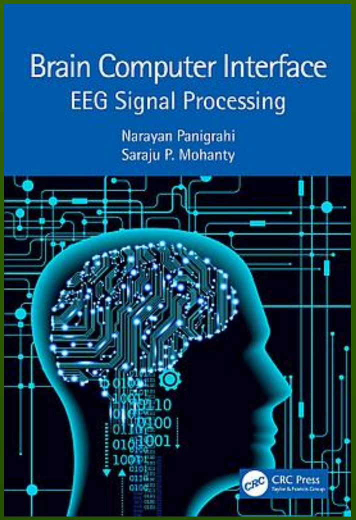
WEF: 4th Industrial Revolution driven by AI/neuro



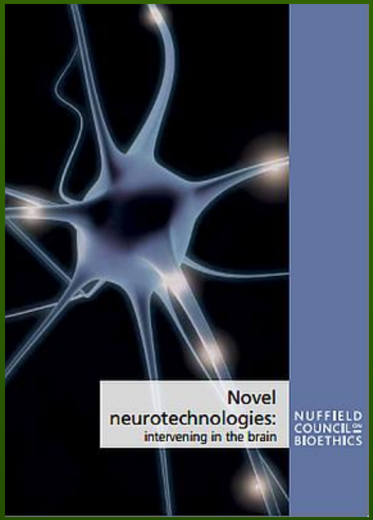
Books

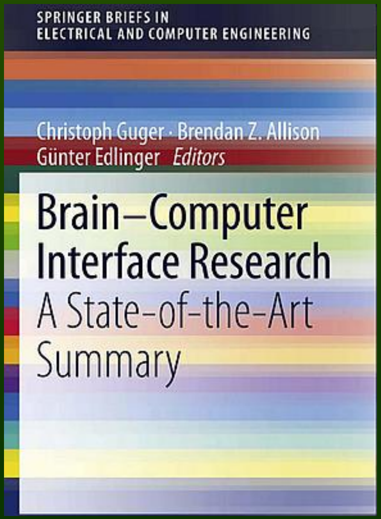

Contemporary Clinical Neuroscience
Ioan Opris
Mikhail A. Lebedev
Manuel F. Casanova Editors
Modern Approaches to Augmentation of Brain Function
Springer

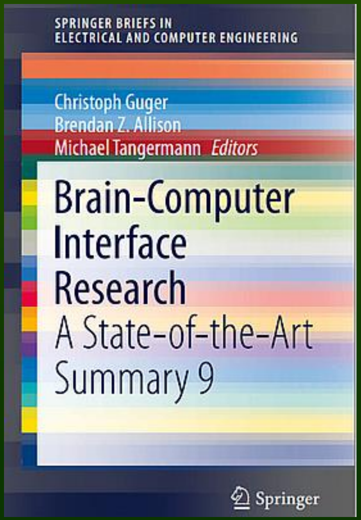

Springer Series in Cognitive and Neural Systems 11
Ioan Opris
Manuel F. Casanova Editors
The Physics of the Mind and Brain Disorders
Integrated Neural Circuits Supporting the Emergence of Mind
Springer


Brain Computer Interface
EEG Signal Processing
Narayan Panigrahi
Saraju P. Mohanty
CRC Press


Vahid Asadpour
Andries Engelbrecht
Brain-Computer Interface


Novel neurotechnologies: intervening in the brain
NUFFIELD
COUNCIL
BIOETHICS


SPRINGER BRIEFS IN ELECTRICAL AND COMPUTER ENGINEERING
Christoph Guger · Brendan Z. Allison
Günter Edlinger Editors
Brain–Computer Interface Research
A State-of-the-Art Summary


SPRINGER BRIEFS IN ELECTRICAL AND COMPUTER ENGINEERING
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Brain-Computer Interface Research
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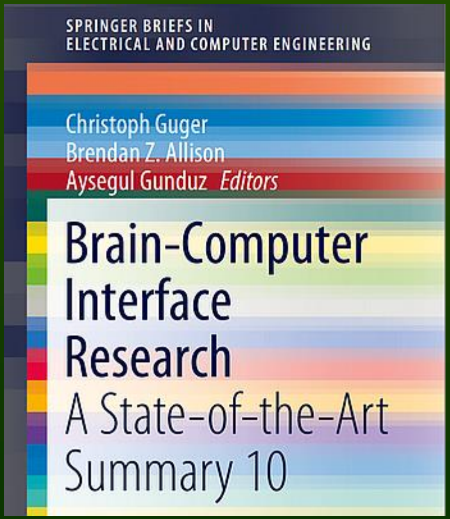
Springer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Christoph Guger
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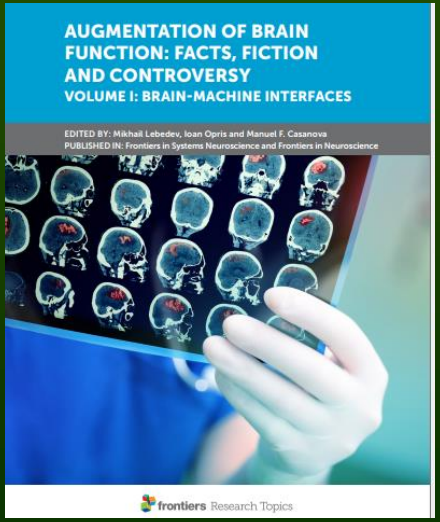
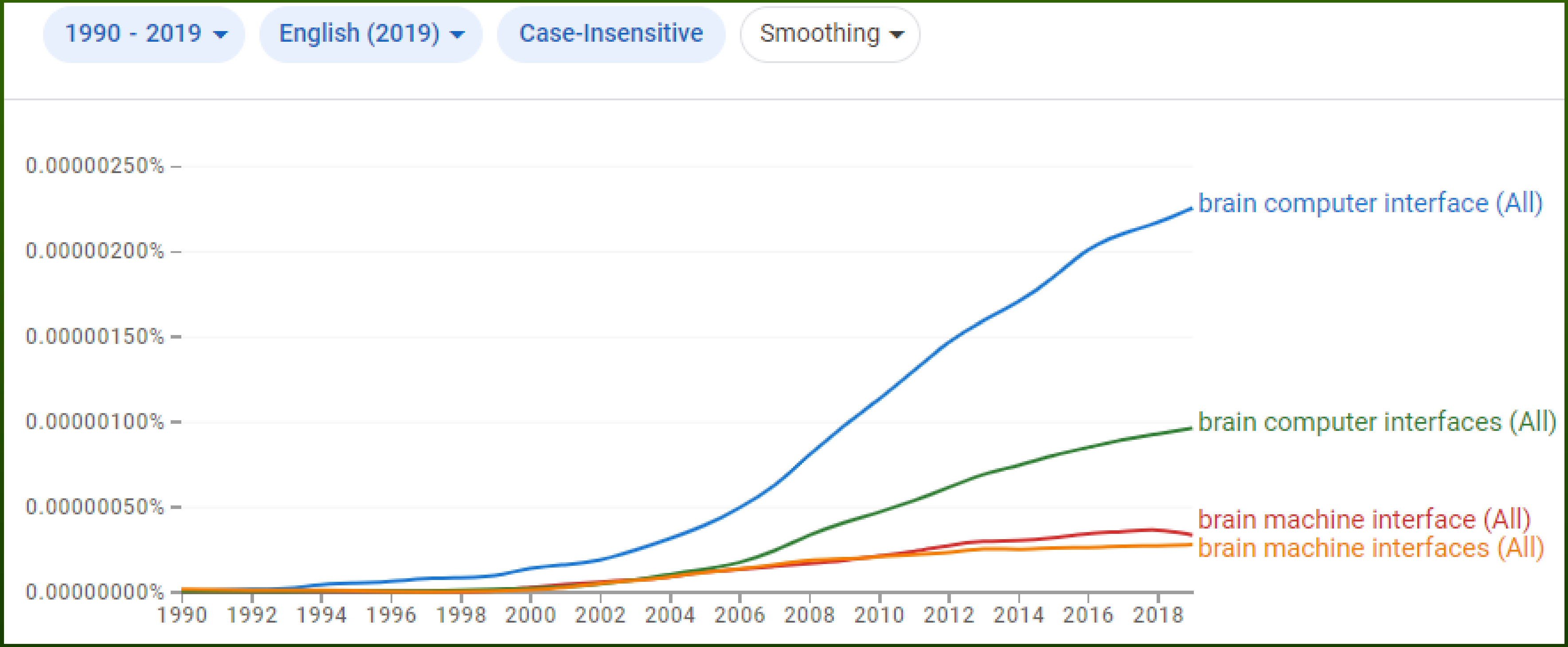

AUGMENTATION OF BRAIN FUNCTION: FACTS, FICTION AND CONTROVERSY
VOLUME I: BRAIN-MACHINE INTERFACES
EDITED BY: Mikhail Lebedev, Ioan Opris and Manuel F. Casanova
PUBLISHED IN: Frontiers in Systems Neuroscience and Frontiers in Neuroscience
frontiers Research Topics

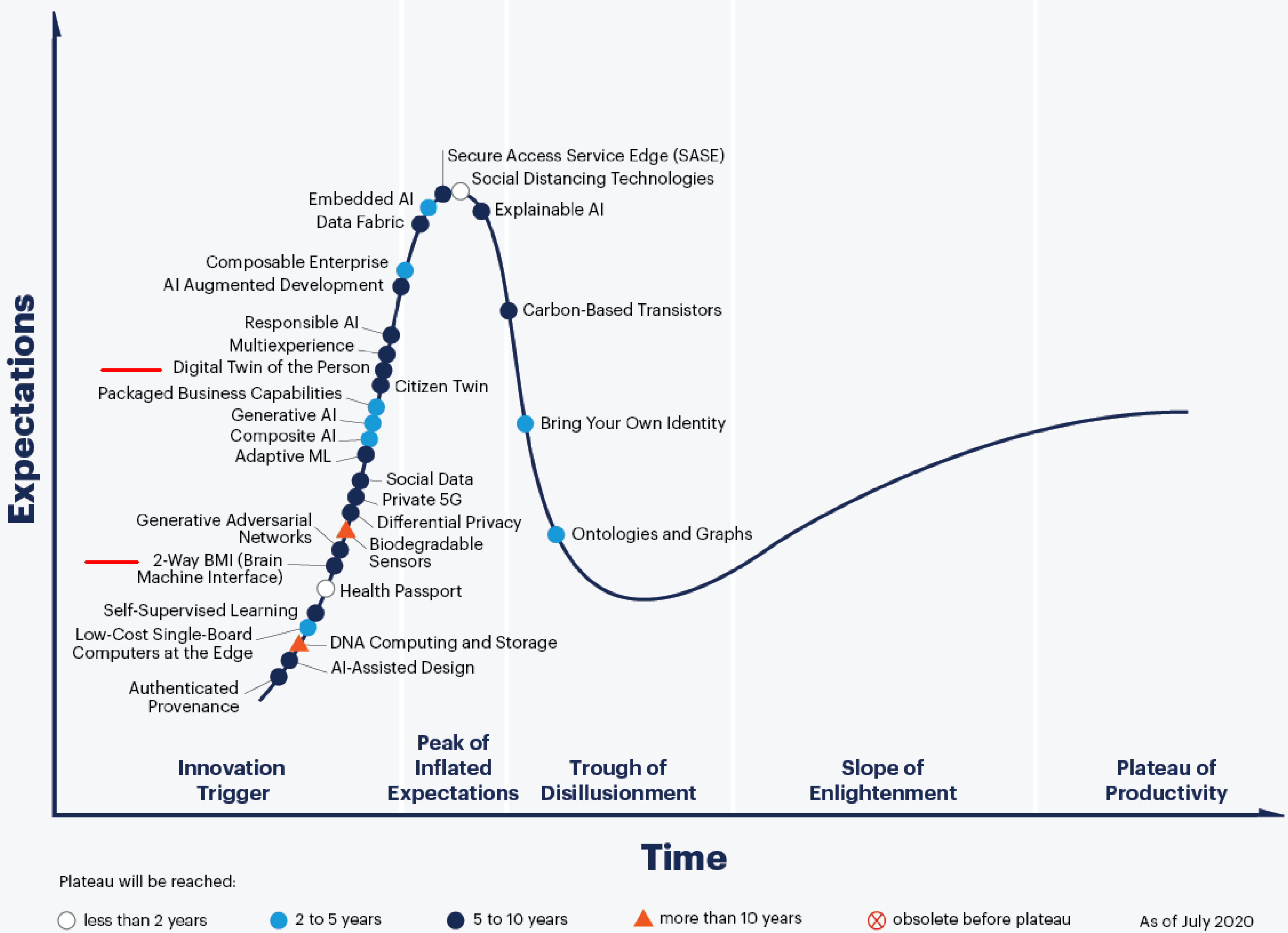
BMI and BCI

XXI century science! But still exotic, in 2019 it was mentioned only 2.5 times in 100 M books. “Brain” was mentioned almost 90 000 times per 100 M books.

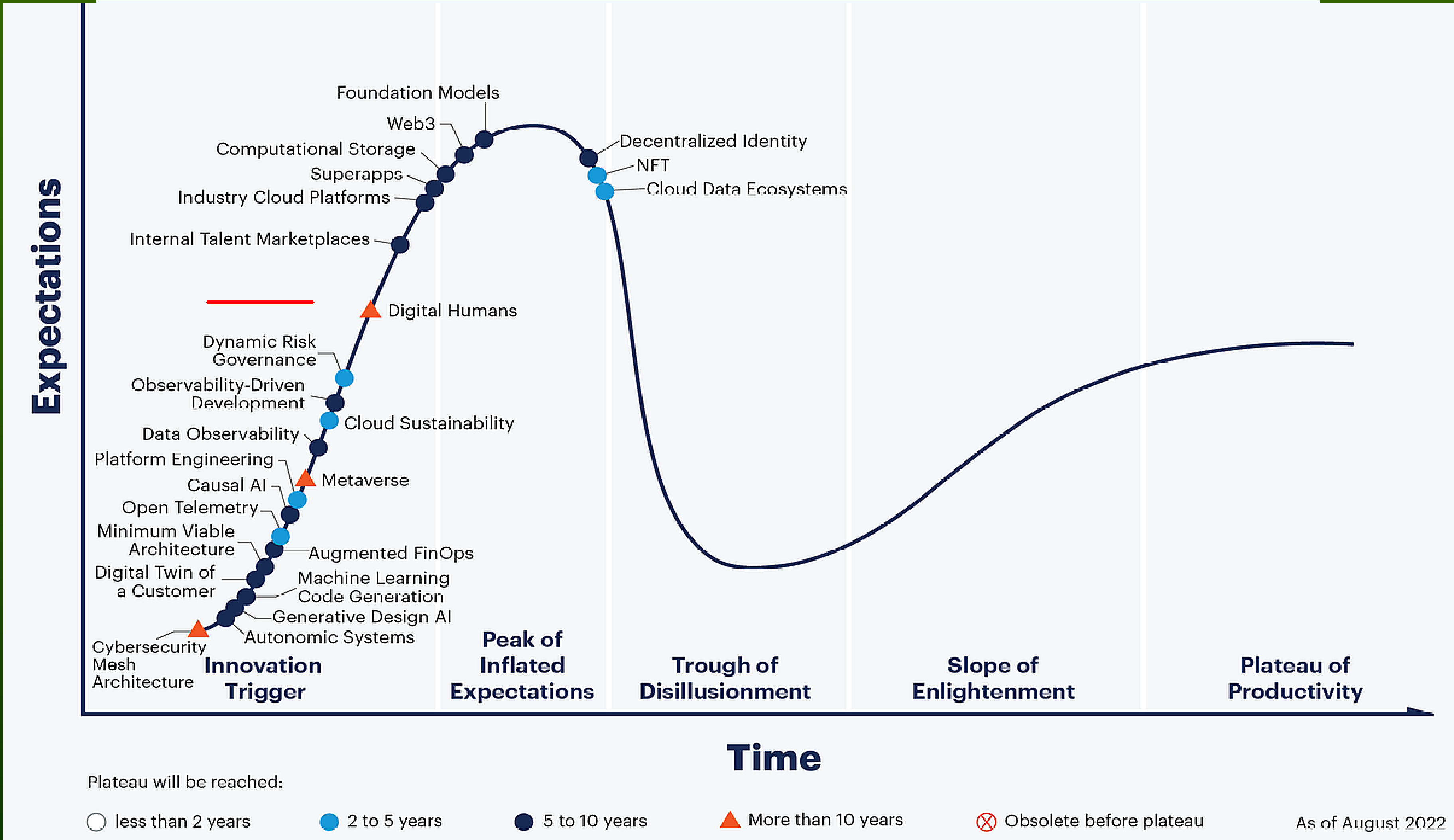


IEEE SMCS Human-Machine Systems covers integrated human/machine systems: human/machine interaction; cognitive ergonomics/ engineering; assistive / companion technologies; human/machine system modeling, testing and evaluation; and human-centered phenomena in engineered systems.

Technologies, 2020 Gartner Hype Cycle

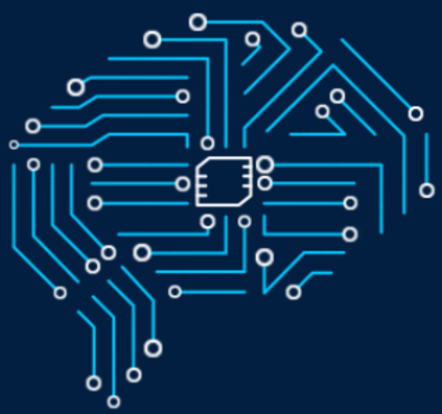


Hype Cycle for Emerging Tech, 2022



Sylvain Fabre, Gartner senior director: digital me, digital humans: bidirectional brain machine interface. Important, but > 10 years to plateau.

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.

G20+/N20+ WORLD BRAIN MAPPING & THERAPEUTICS INITIATIVE

IEEE brain

IEEE brain

Join the IEEE Brain Community

JOIN FREE

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

Cogni
Cognitive sciences

Biohybrids

Bio
Neuroscience

Nano
Quantum Technologies

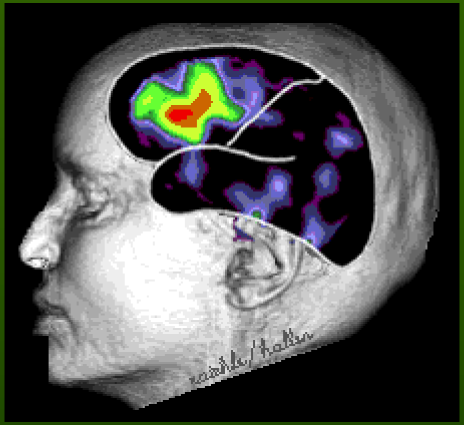
Neurocognitive Informatics

Info
Artificial/Computational Intelligence, Machine Learning, Neural Networks

AI, brains and mind

Mapping brain states to mental images

Neurodynamics: bioelectrical activity of the brain.
Mental states: shadows of neurodynamics that can be subjectively interpreted.



Mapping:
State(Brain) ⬄ State(Mind)
via intermediate BCI models.

Brain states, activation patterns ⬄ trajectories in psychological spaces, movement of thoughts.

- From neuroimaging to mental images.
- From computer simulations and brain signals to mental trajectories.

On the threshold of a dream …

Final goal: optimize brain processes!

To repair damaged brains and increase efficiency of healthy brains we need to understand brain processes:

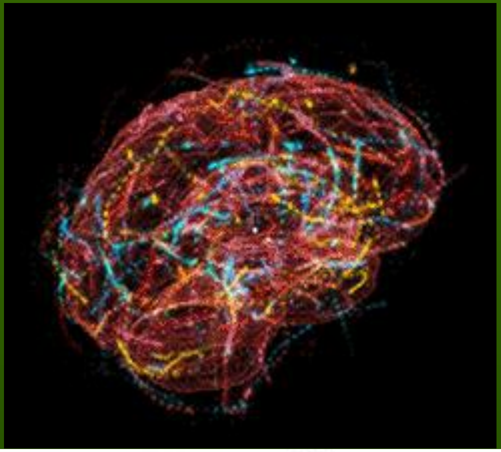
1. Create models of cognitive architectures that help to understand information processing in the brain.
2. Find fingerprints of specific brain activity (regions, subnetworks) using neurotechnologies.
3. Create diagnostic and therapeutic procedures.
4. Use neurofeedback decoding local activity and functional connectivity to stimulate the brain.
5. Stimulate neuroplasticity in a closed loop, monitoring brain activity and applying TMS, DCS, EM and other forms of neuromodulation.

G-tec wireless NIRS/EEG on my head.

Brain-mind relations

Brain, physical space S(B) ⇔ S(M) Mind, mental space

S(B)=neurodynamics, estimated by EEG, MEG, NIRS-OT, fMRI, PET, or other techniques.



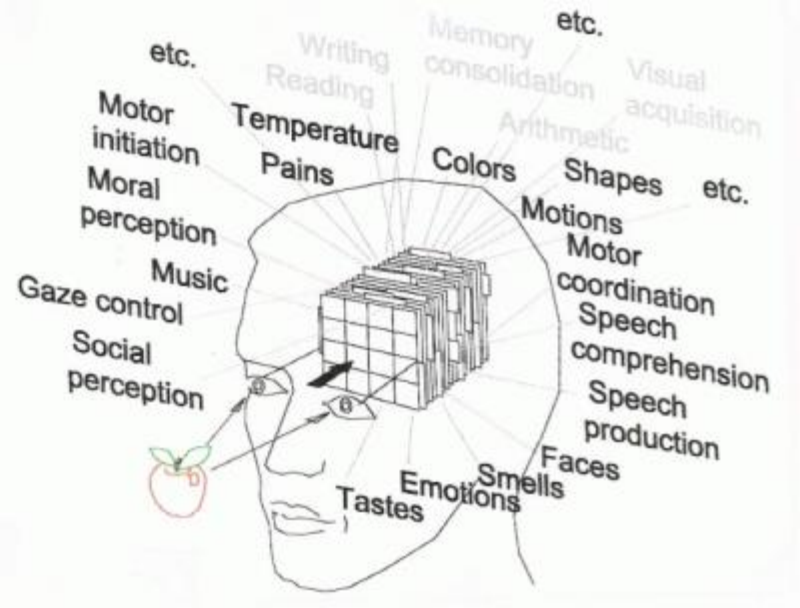
Map = interpret brain activations in terms of subjective mental states: attention, saliency, intentions, percepts, emotions …

S(M) = space based on such dimensions.

Neurodynamics => dynamics of mental states, movement of thoughts in S(M).

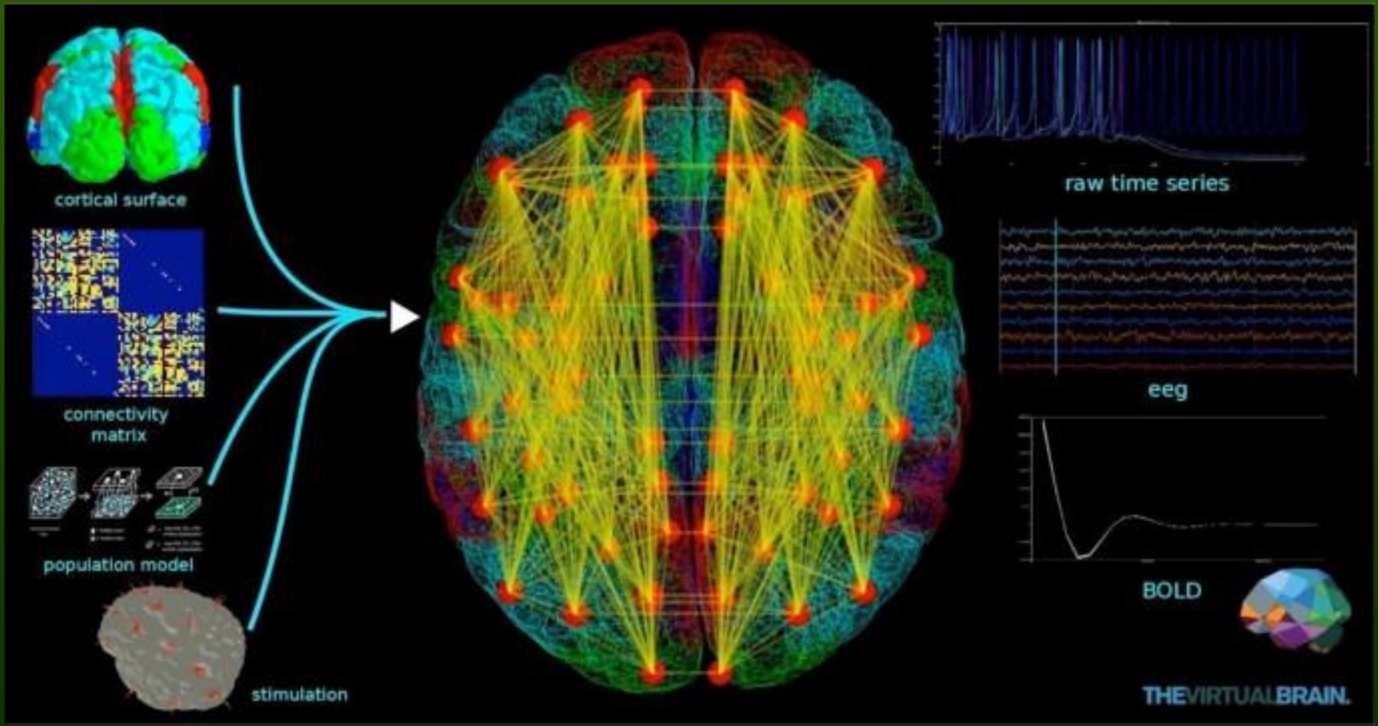
Motor intentions – relatively easy.

Emotions, feelings, pains, thoughts … hard, fluid nature of mental states.



Hurlburt & Schwitzgabel,
Describing Inner Experience? MIT Press 2007

Cognitive architectures



AGI & BICA

From an engineer's perspective: understand the brain = build a working model that exhibits the same functions.

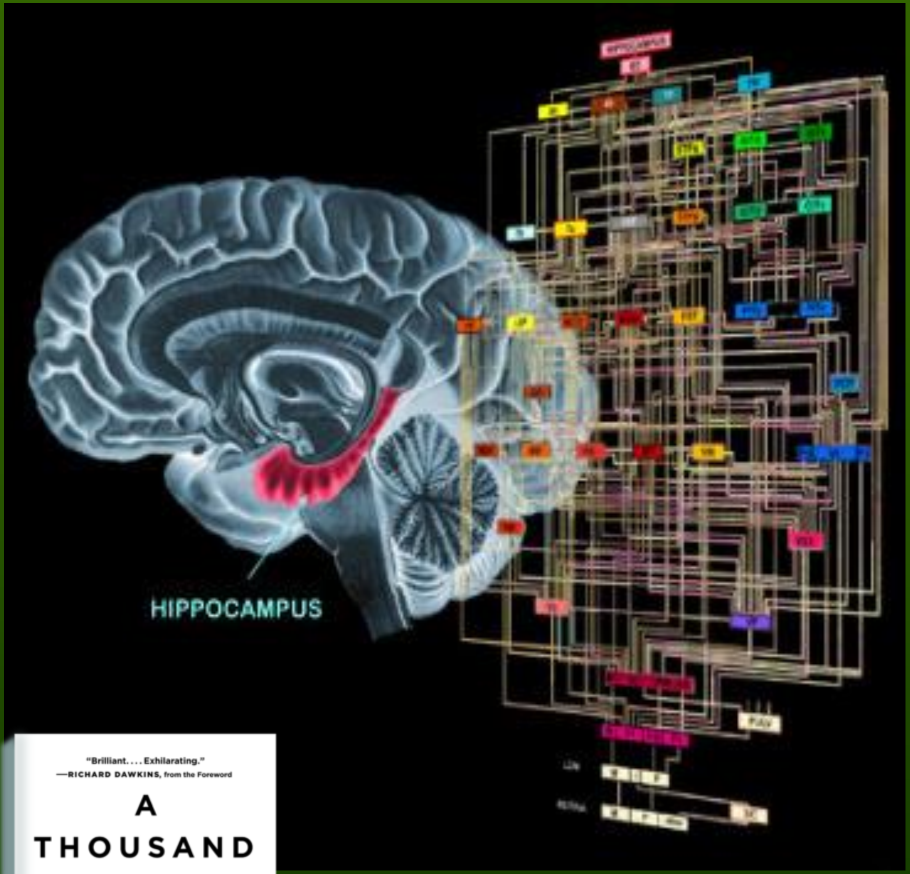
AGI = Artificial General Intelligence, Deep Mind Gato learned 600 tasks.

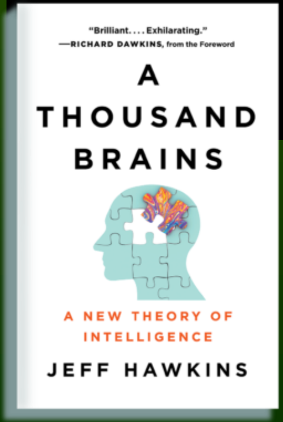
BICA (Brain-Inspired Cognitive Architecture) brain-like intelligence.

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

"We'll never have true AI without first understanding the brain"
Jeff Hawkins (2020).

The Virtual Brain – population model, enables model-based inference of macroscopic brain processes.

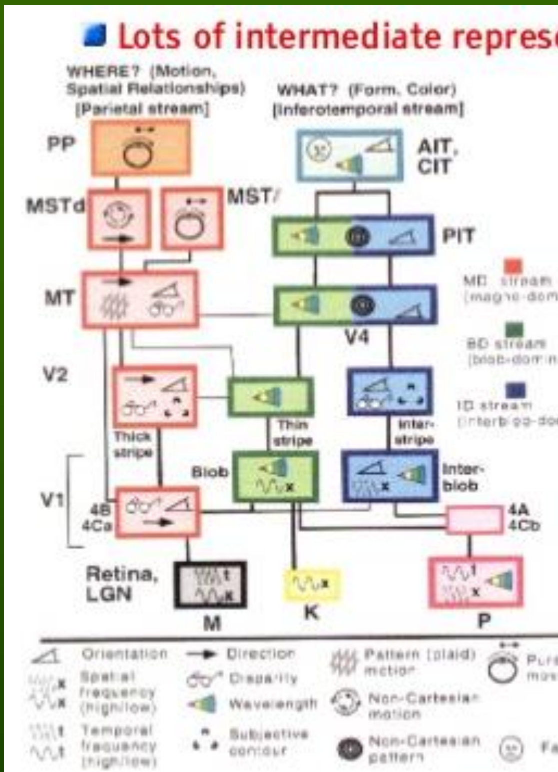




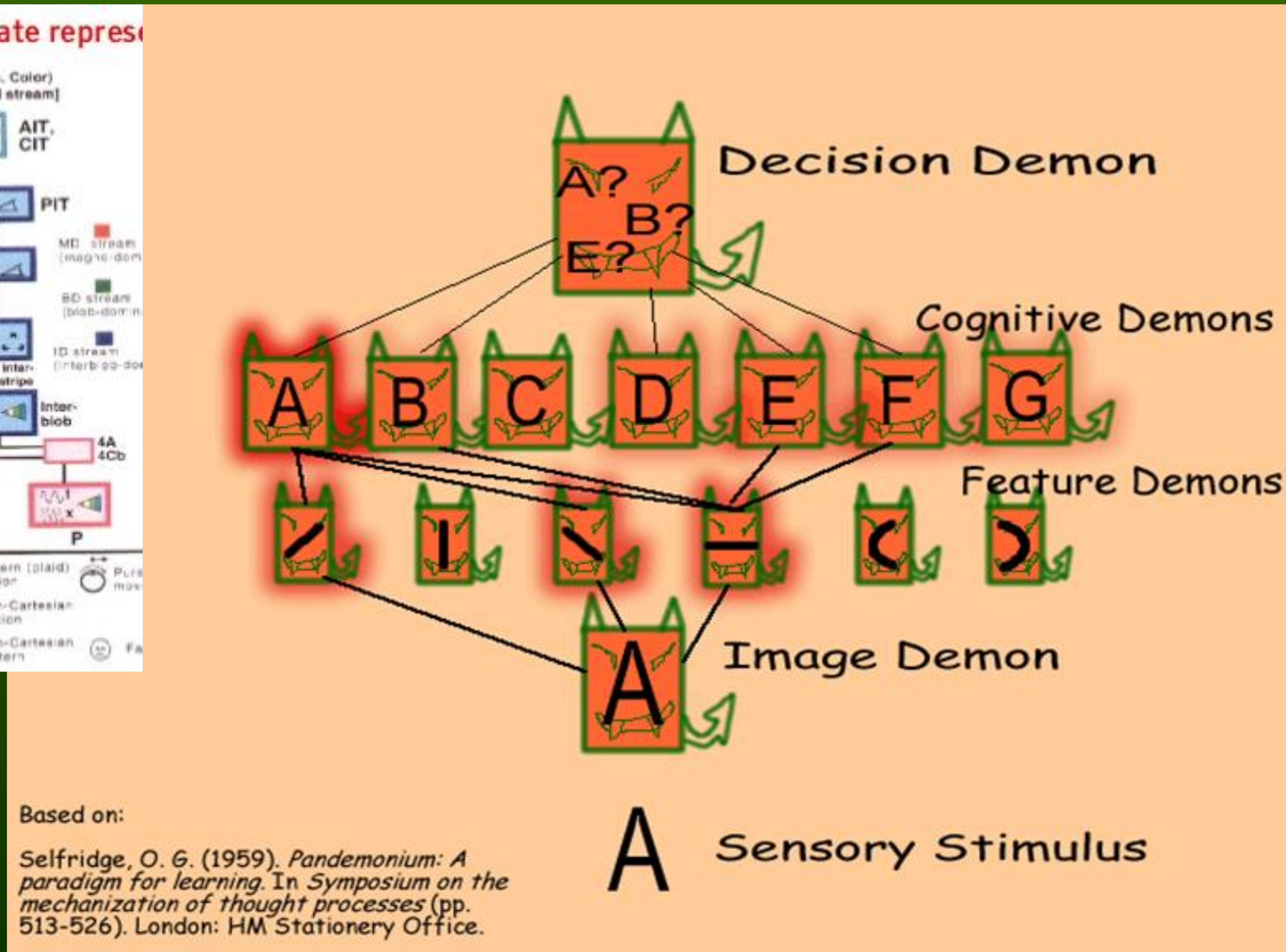
Marr/Poggio (1976)

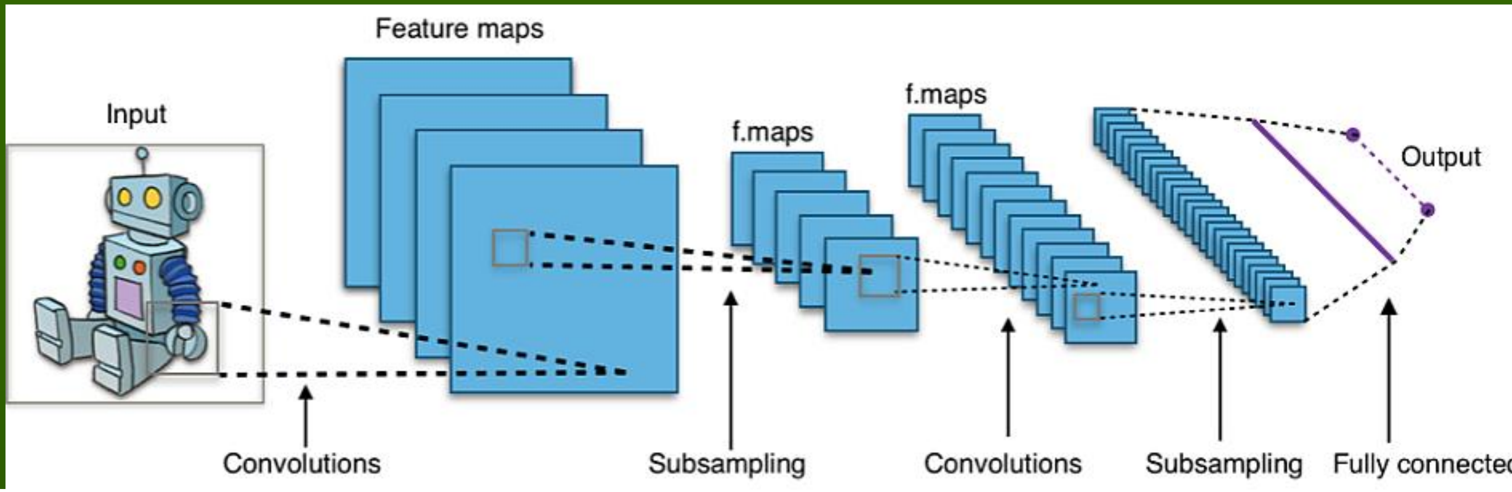
- Purpose - why, goals
- Algorithm - how
- Implementation

Selfridge NN Model (1959)

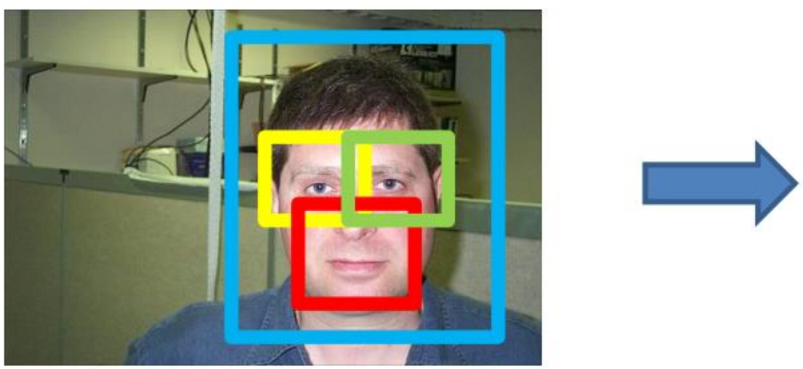


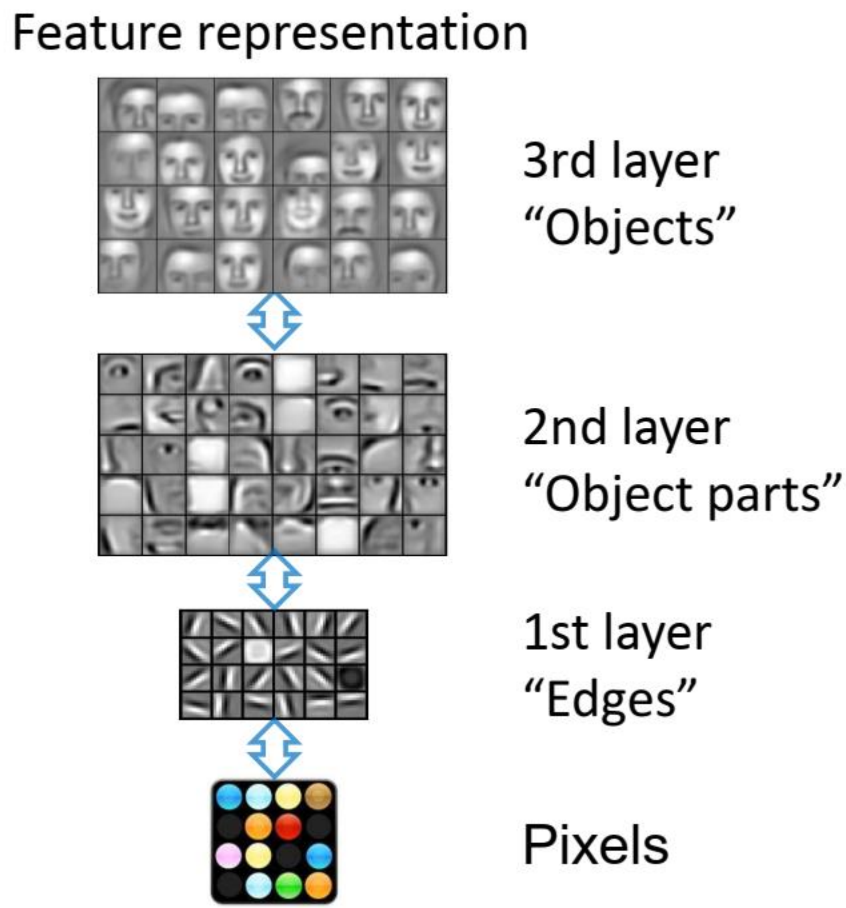
32 visual cortical areas were known already in 1991!





Input data





Lee et al., ICML 2009;
CACM 2011

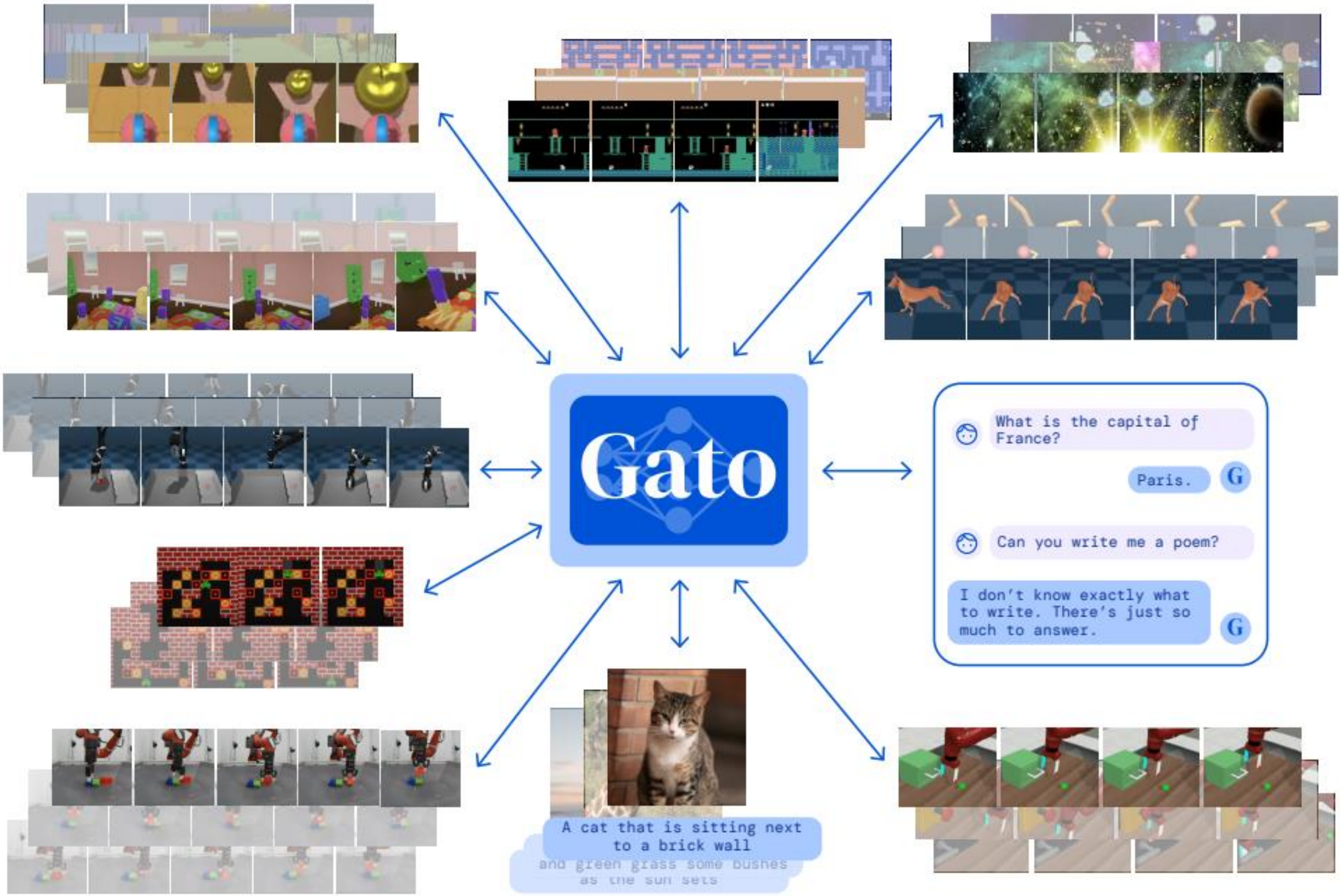
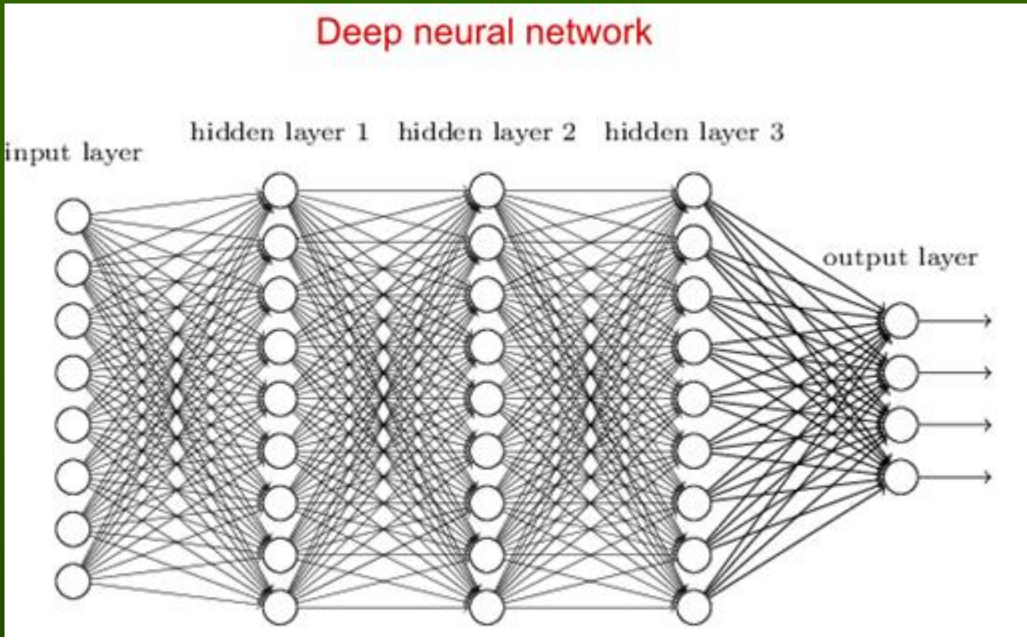


Figure 1 | **A generalist agent.** Gato can sense and act with different embodiments across a wide range of environments using a single neural network with the same set of weights. Gato was trained on 604 distinct tasks with varying modalities, observations and action specifications.

Tensorization of Convolutive Deep Learning NN

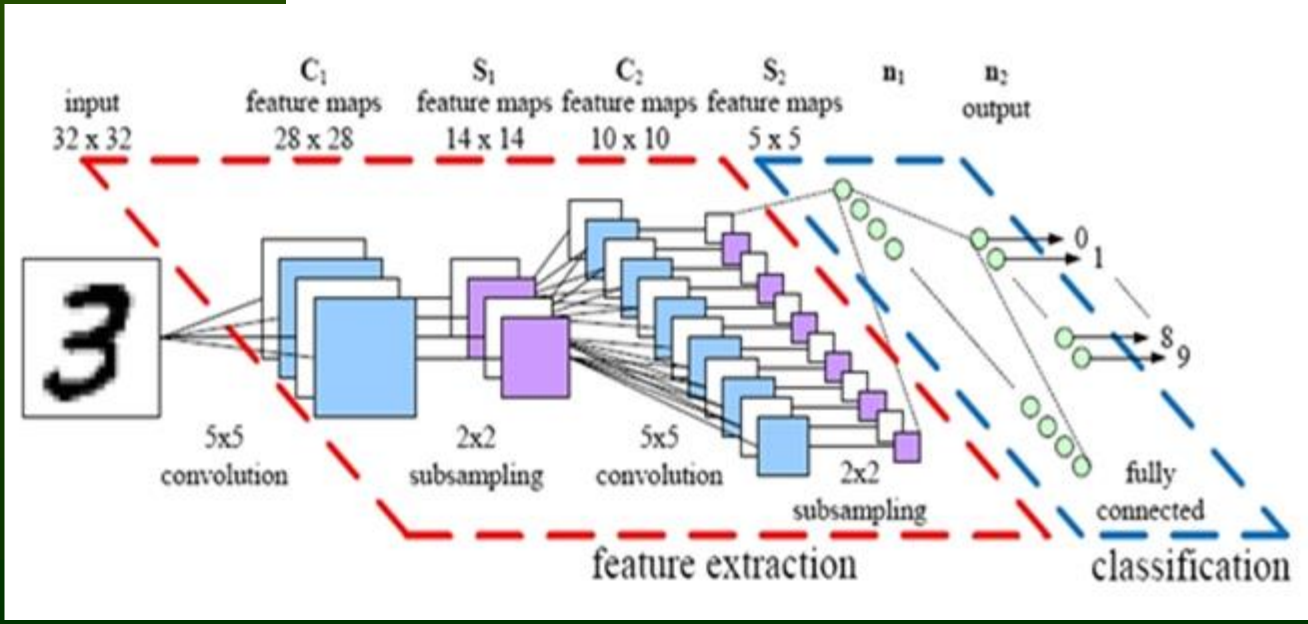
NN "neurons" perform elementary nonlinear functions, semi-linear ReLu, exchanging information through fixed connections, correcting adaptive coefficients to learn transformations.
All this is far from biology.

Tensor networks discover latent features (Cichocki Lab, RIKEN BSI).



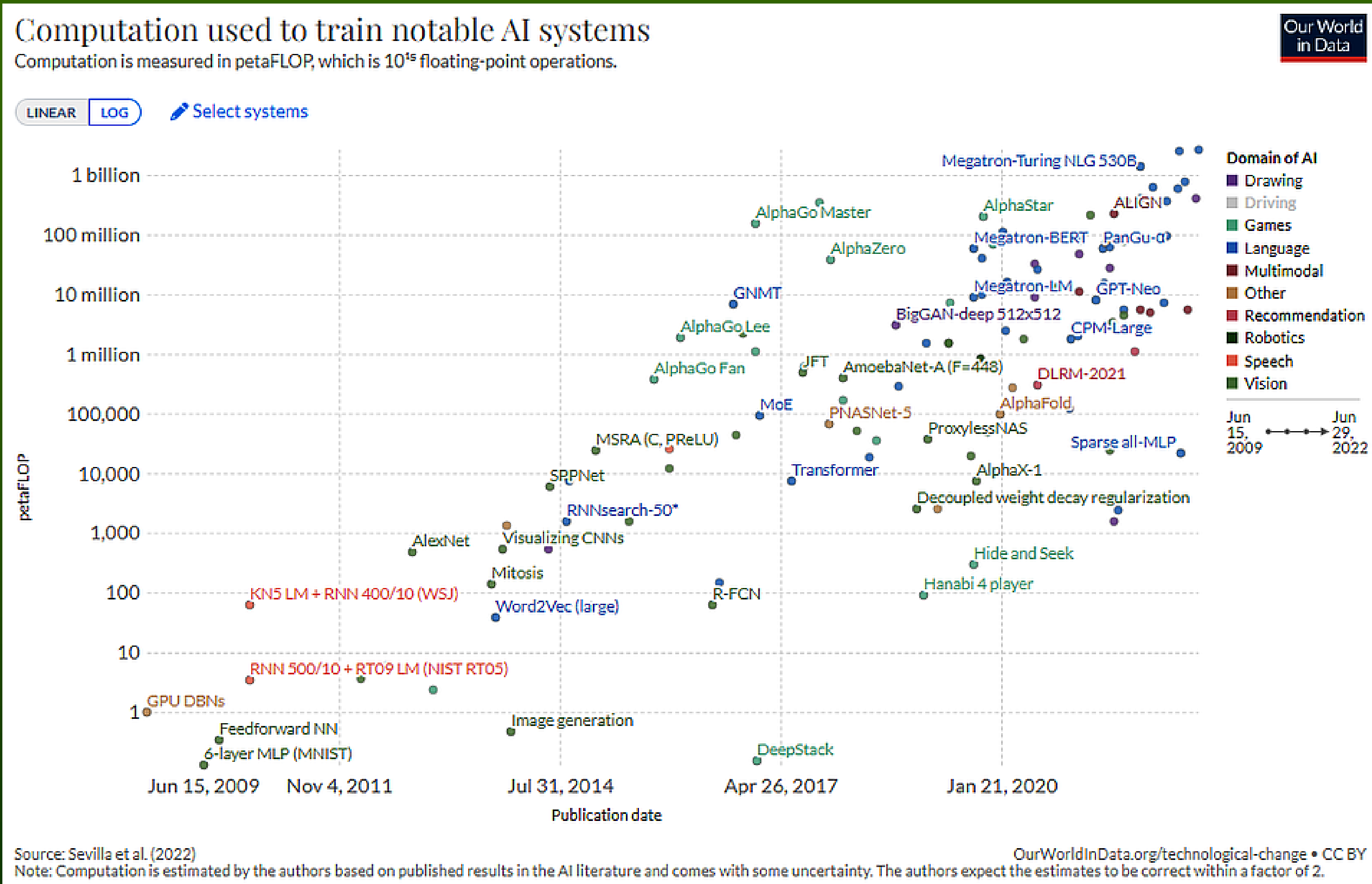
Neocognitron is using complex neurons.

We don't know how to use oscillators for calculations.



WD: Support Feature Machines (2011).

AI Training



ML training training: in 10 years from 1 Pflop to 10^9 Petaflops! Brain ≈10 years?

Neuromorphic future

Wall with 1024 TrueNorth chips, equivalent of 1 Billion neurons, 256 B synapses. 1/6 of chimp brain. Cerebras CS-2 chip has 2600 B transistors, almost 1M cores!

Integration:

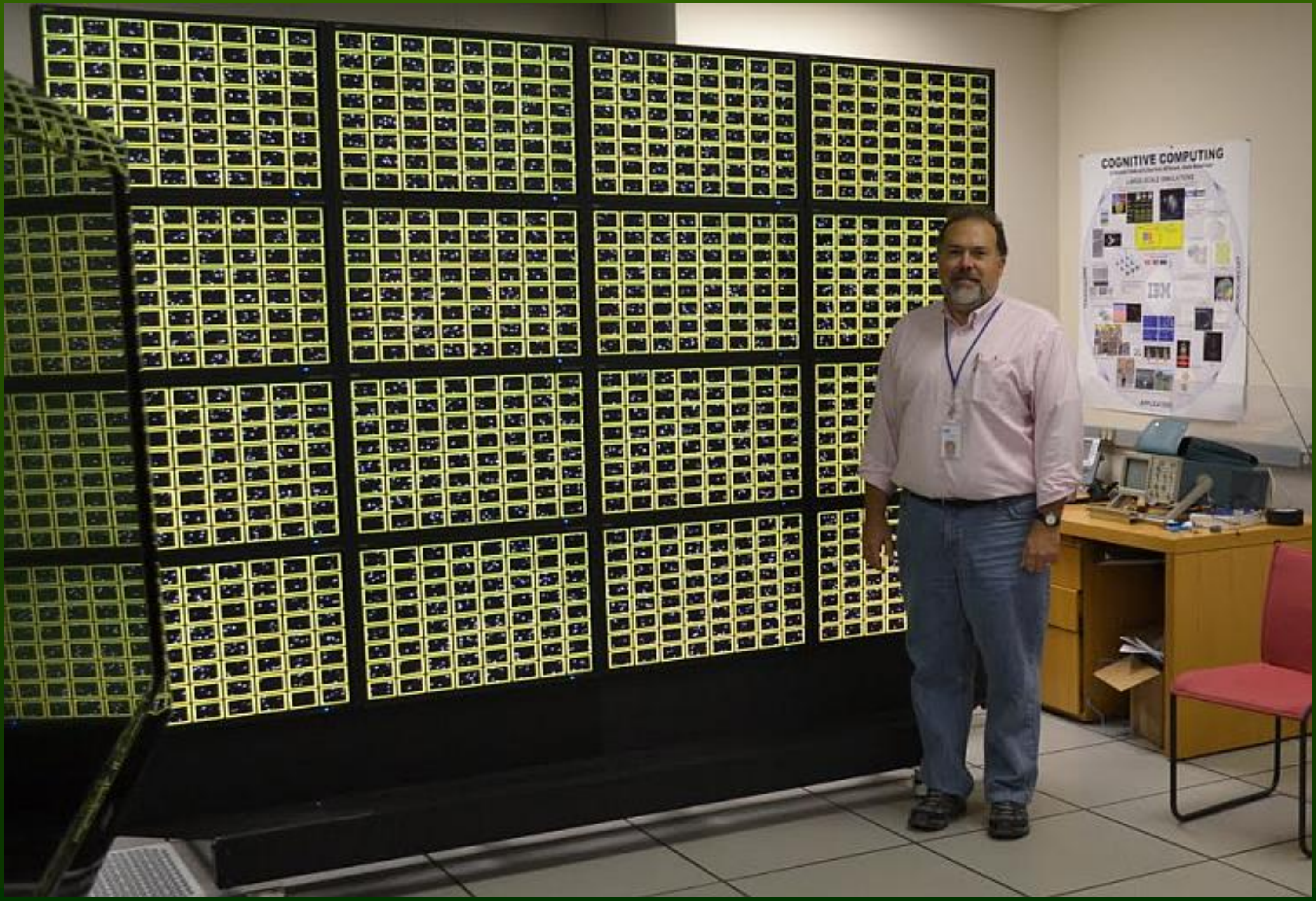
Nano +

Neuro +

Info +

Kogni

Neural AI accelerators AD 2021 200 x CS-2, models > 10^{14} parameters.



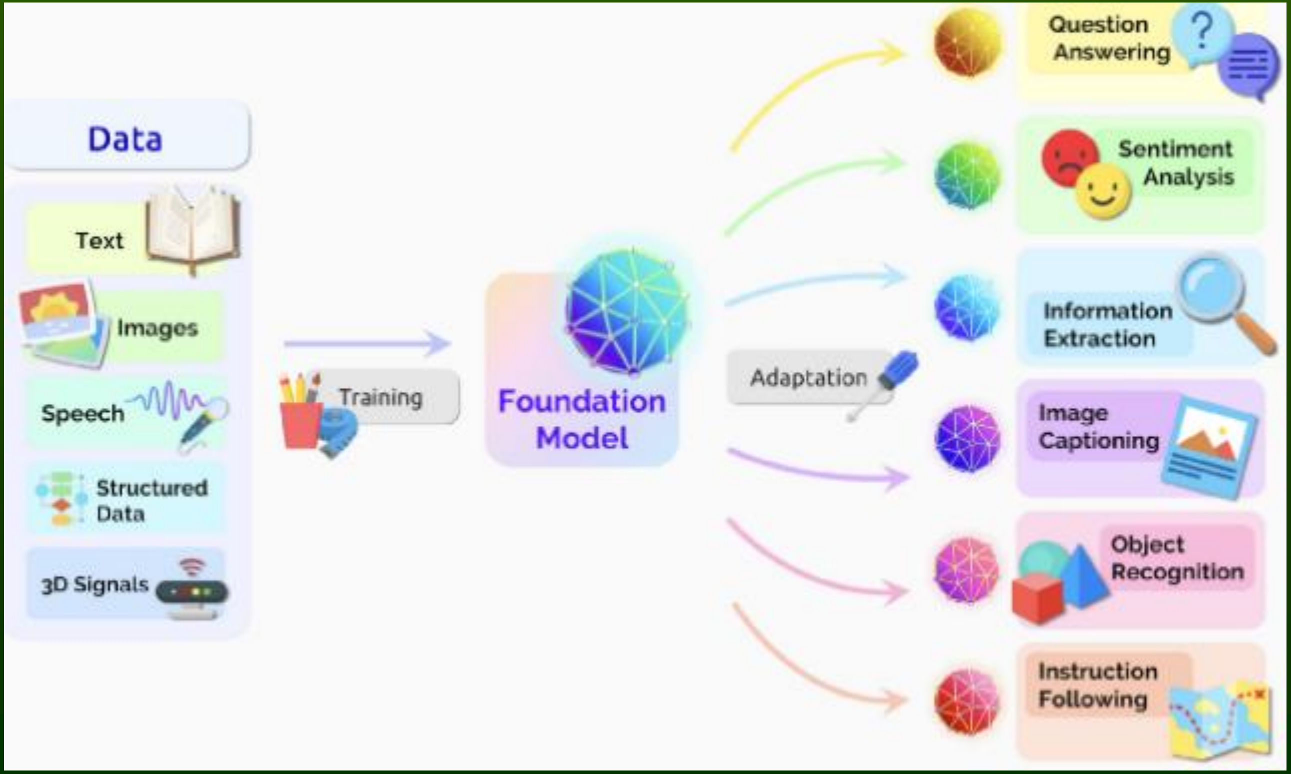
Mulitimodal foundational models

Multimodal transfer learning - different types of modalities with different statistical properties, embedded in the same model.

- Multimodal Affective Computing (MAC), sentiment analysis.
- Natural Language for Visual Reasoning (NLVR).
- Multimodal Machine Translation (MMT).
- Visual Retrieval (VR) and Vision-Language Navigation (VLN).

Image: Center for Research on Foundation Models (CRFM), Stanford Institute for Human-Centered Artificial Intelligence (HAI)

Can this be used to analyze brain signal patterns?



Vision-language models

MS BEiT-3 (BERT Pretraining of Image Transformers), a general-purpose state-of-the-art multimodal foundation model for vision-language tasks.

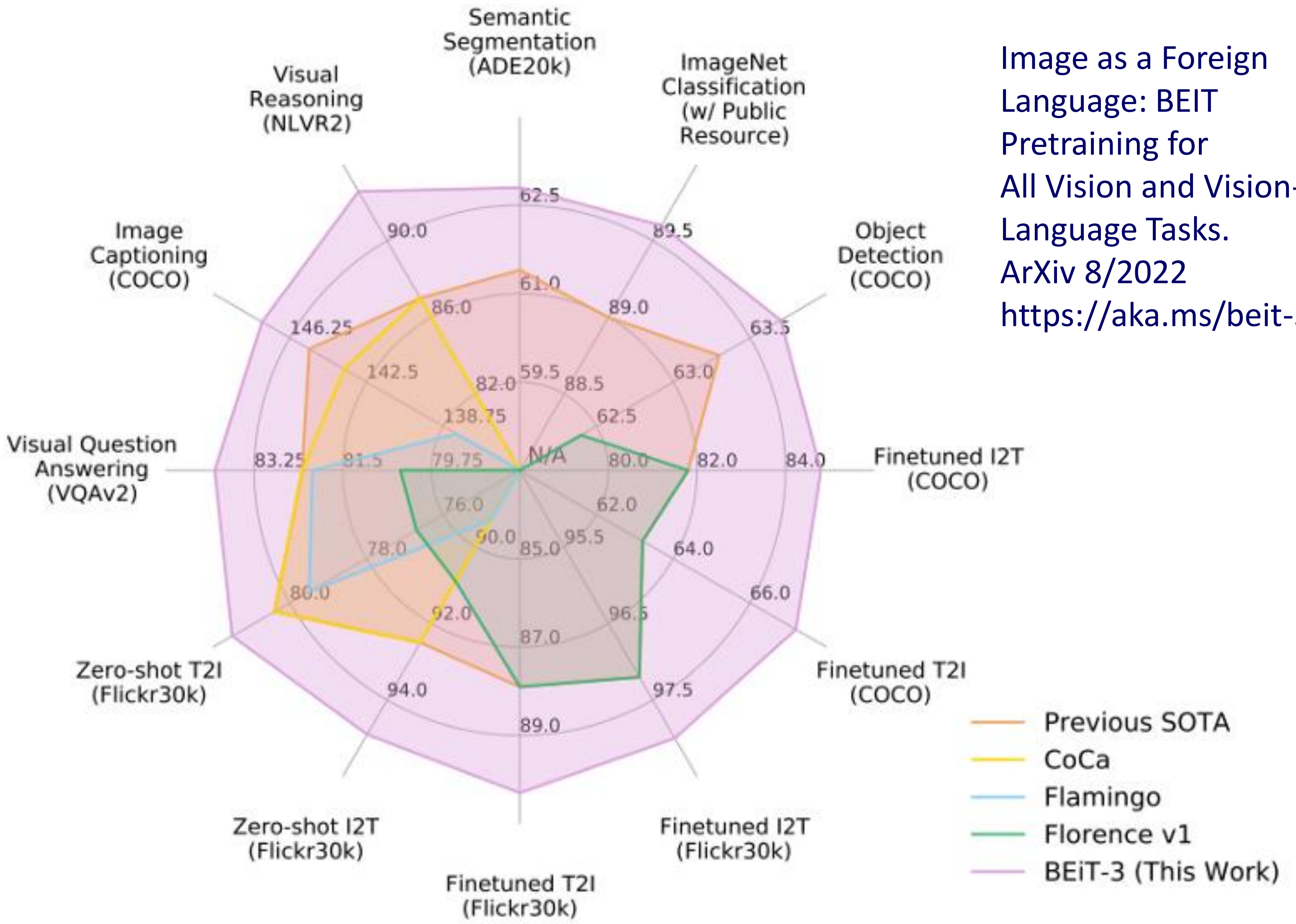
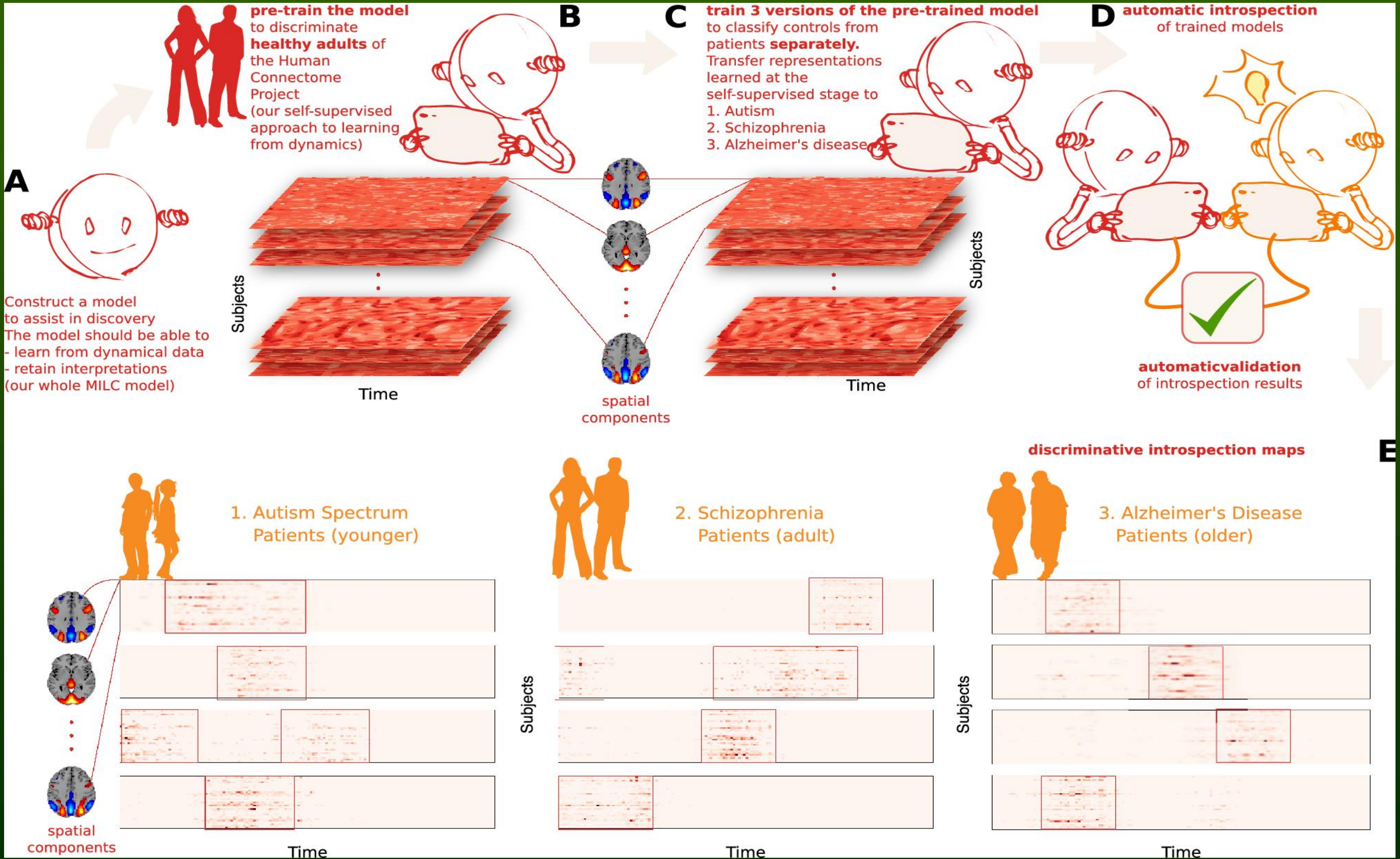


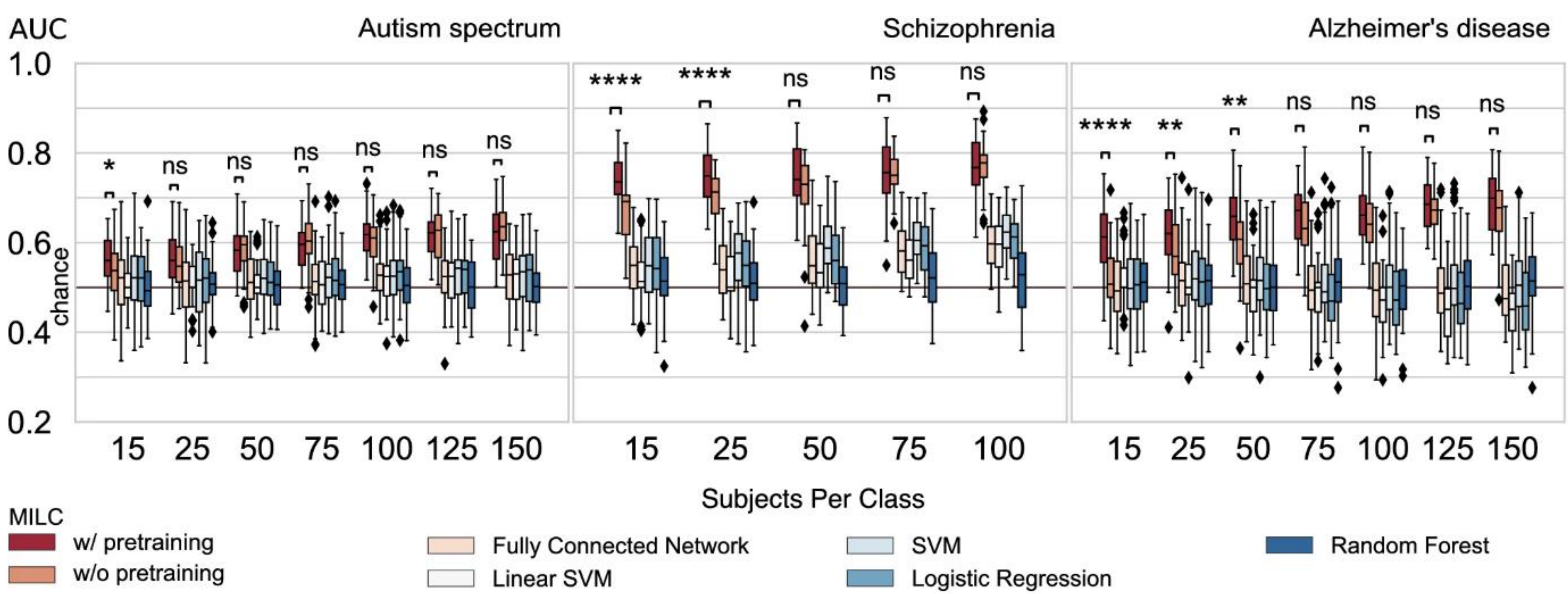
Image as a Foreign Language: BEIT Pretraining for All Vision and Vision-Language Tasks. ArXiv 8/2022 https://aka.ms/beit-3

MILC model

Rahman, … & Plis, S. M. (2022). Interpreting models interpreting brain dynamics. *Scientific Reports*, *12*(1), 12023. Supervised pretraining scheme, which maximizes “Mutual Information Local to (whole) Context” (MILC).



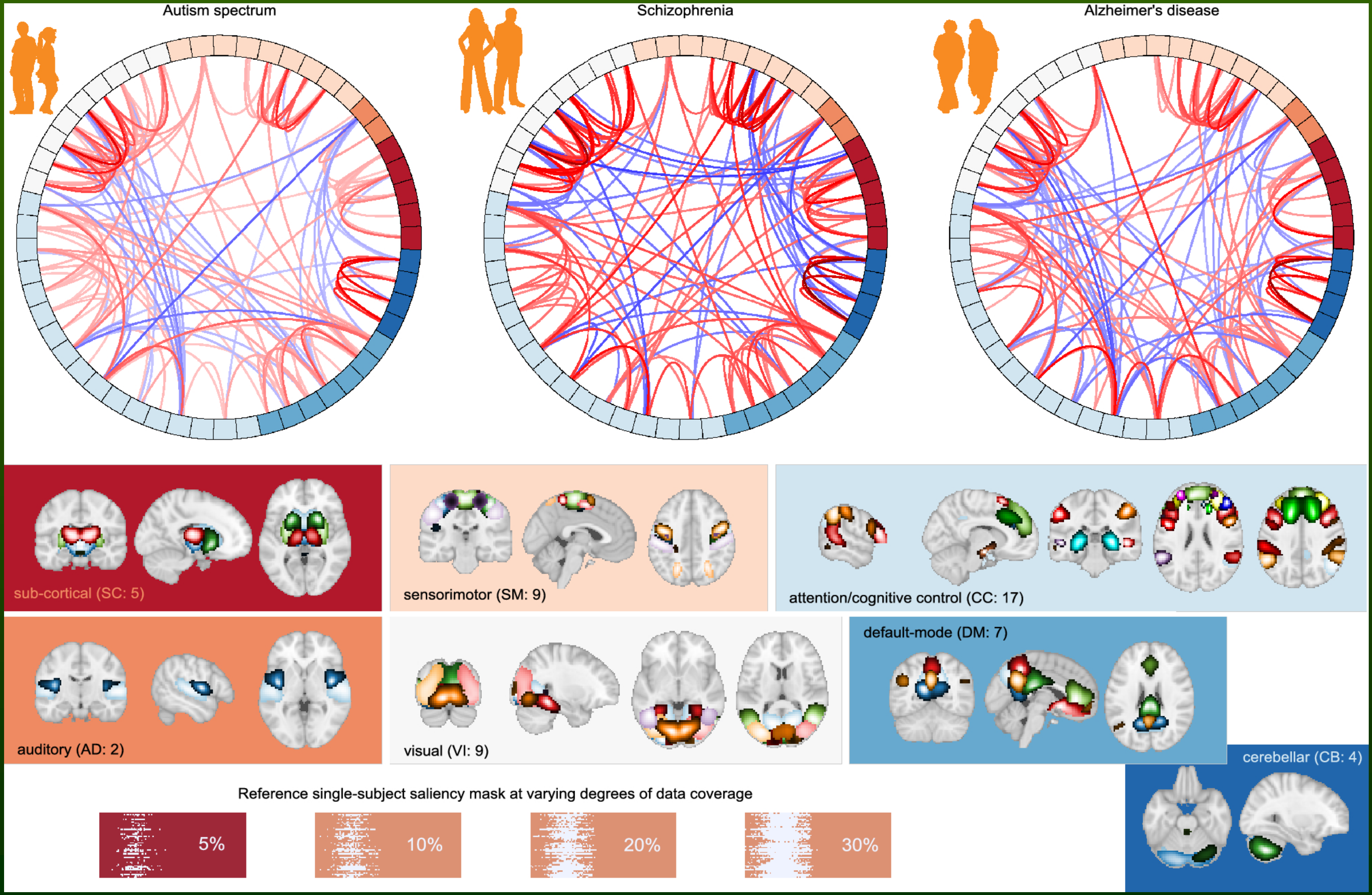
MILC model results



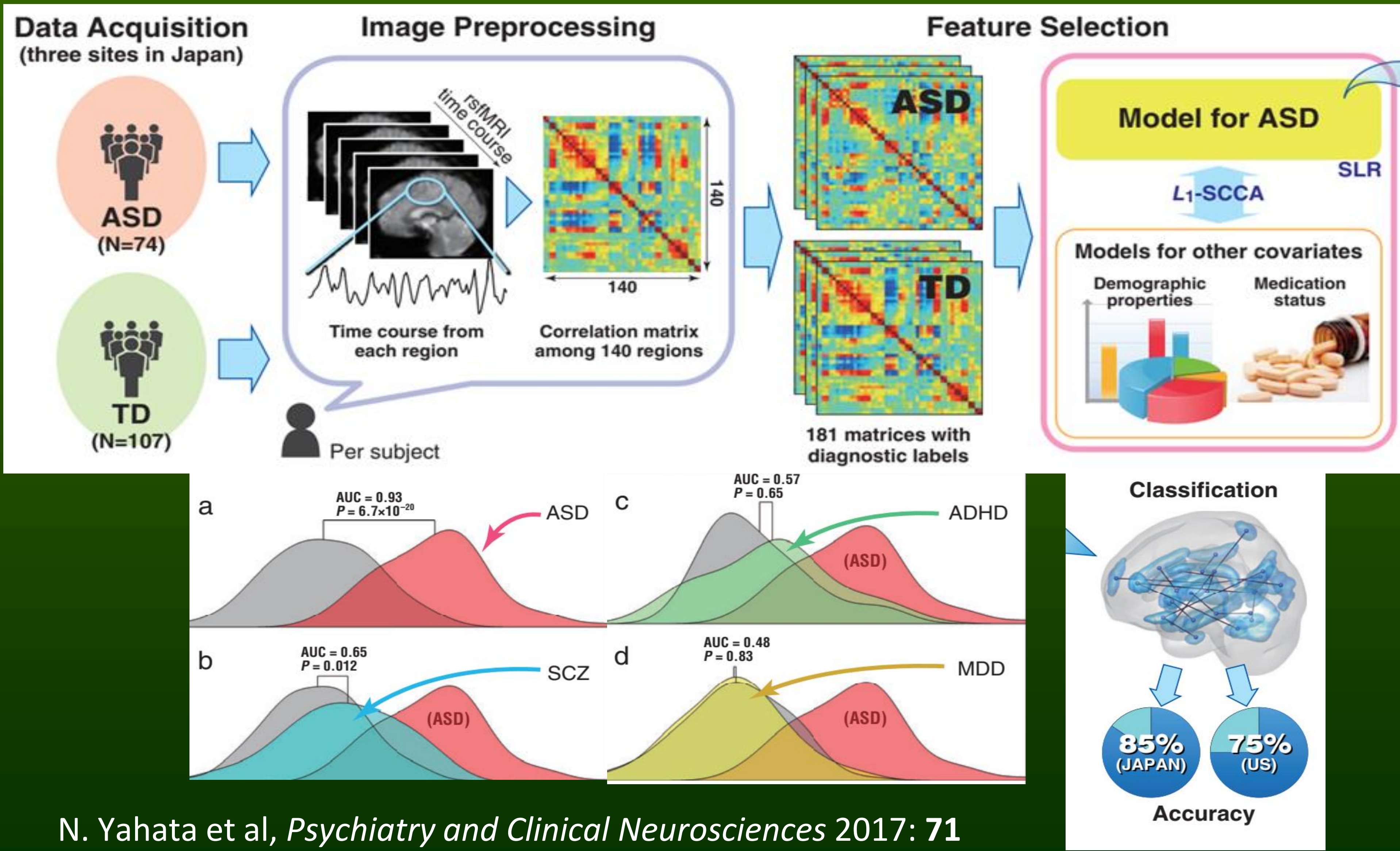
- Deep learning + MILC can learn directly from high-dimensional signal dynamics even in small datasets (15 subjects), after pre-training on large data.
- Mutual information maximization between the whole sequence (context embedding) and local windows (local embedding) from the same sequence.
- FNC (Functional Network Connectivity) was computed as Pearson's correlations between time courses of the components obtained by spatial independent component analysis (sICA).

MILC diagnosis

Top 10% FNC for patients computed using most 5% of the salient data as thresholded using feature attribution maps (saliency maps) for 3 disorders.

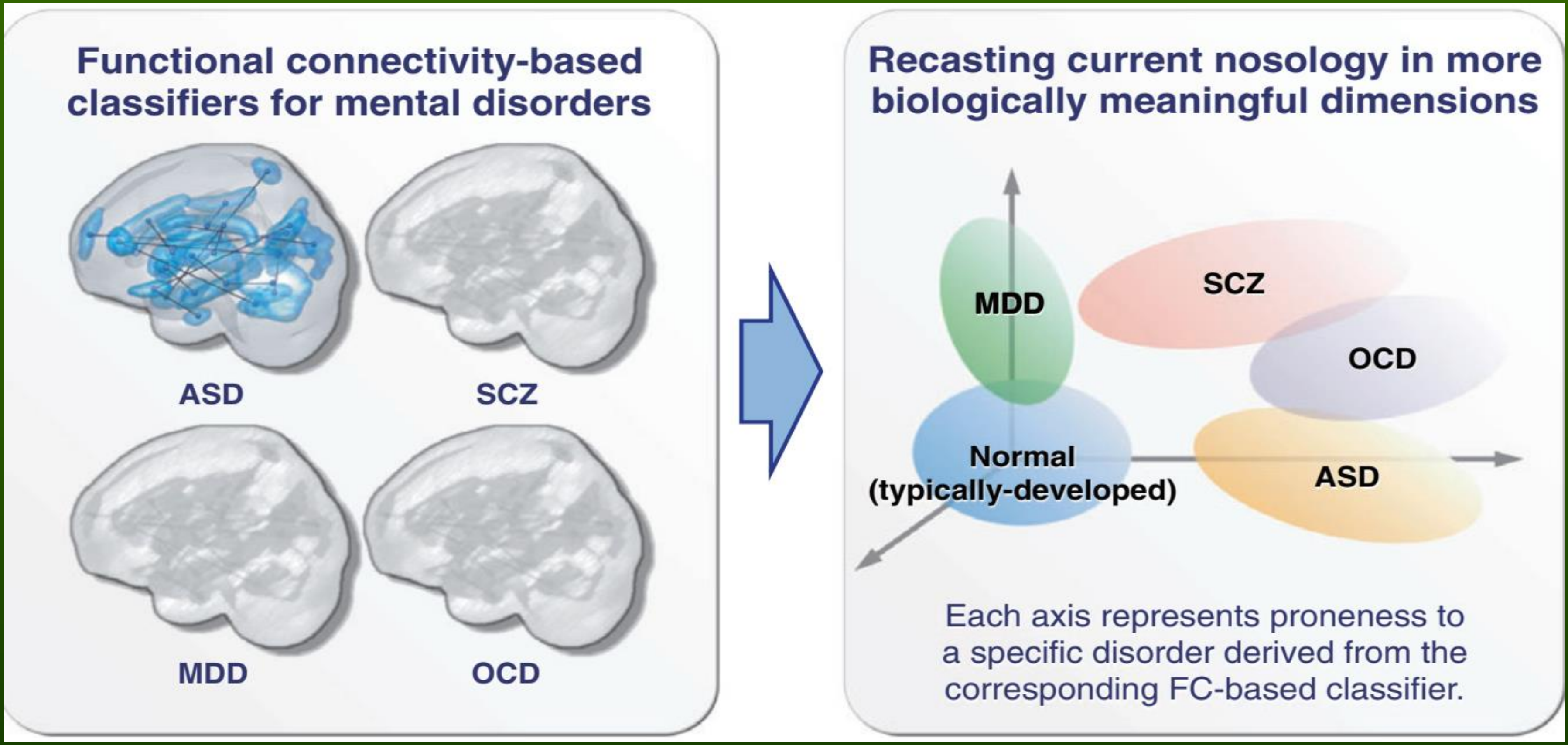


Biomarkers from neuroimaging



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

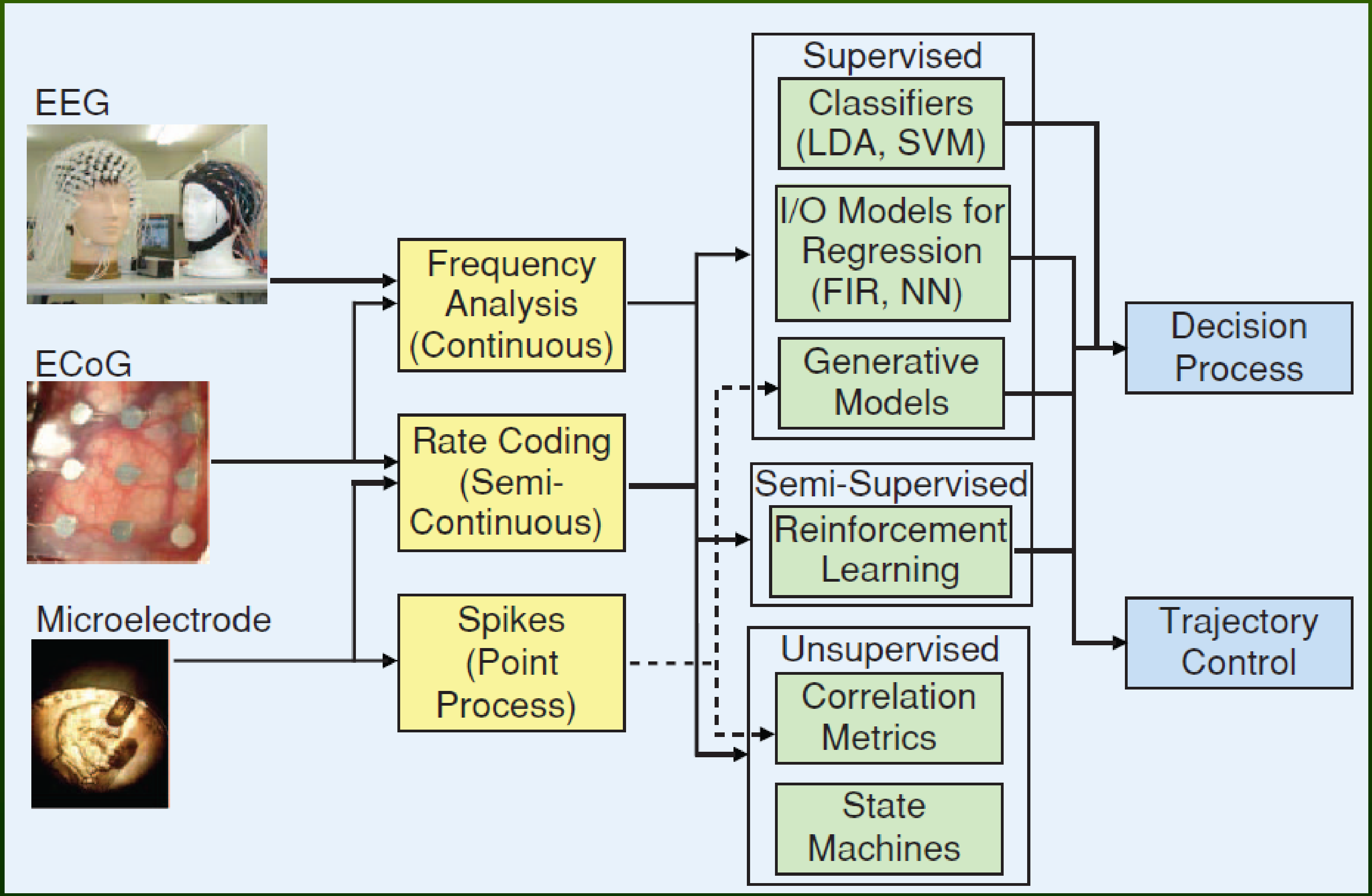
Use it in neurofeedback.

BCI/BMI hardware

BMI: time to connect our brains …

Non-invasive, partially invasive and invasive methods carry increasing amount of information, but are more difficult to implement.

EEG+ML still reigns supreme!



Cyberdyne Hal-5

Ford is using EksoVest exoskeletons,
LG makes CLOi SuitBot, some exoskeletons may lift 100 kg, but without bionic control.

Cyberdyne plans on renting and selling it's robot suit, called Hal-5, or "Wearable Cyborg”.
Sensors attached to the user's skin monitor changes in the body's biosignals.

Anytime you think of what you're going to move, your brain sends a nerve biosignal to your muscles, telling them to carry out the action.

Medical: improving physical functions.

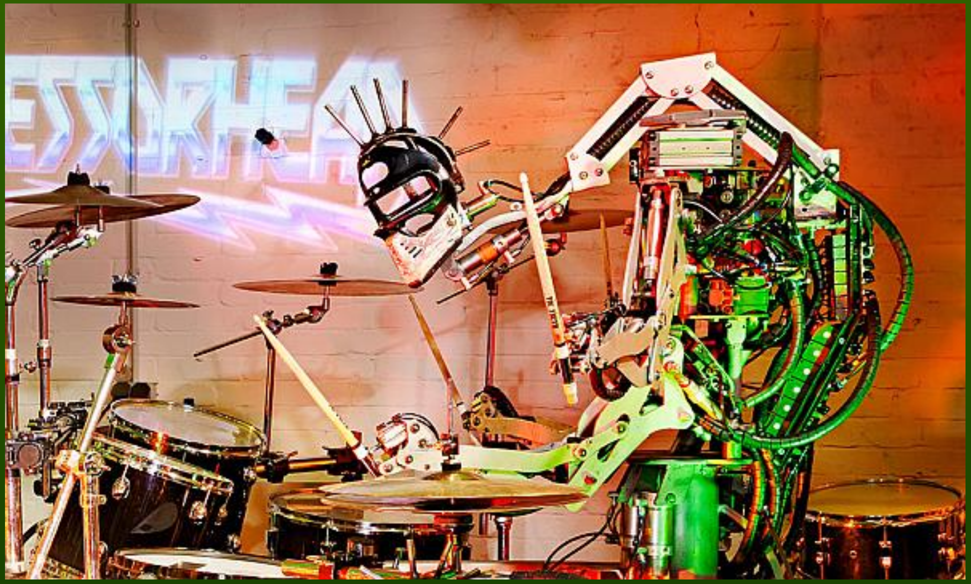
Labor: heavy work support in other workplaces, mitigates risks of the wearer’s back pain.

Supporting recovery activities at disaster sites.

Many military „future soldier programs” …

What could I do with additional hand?

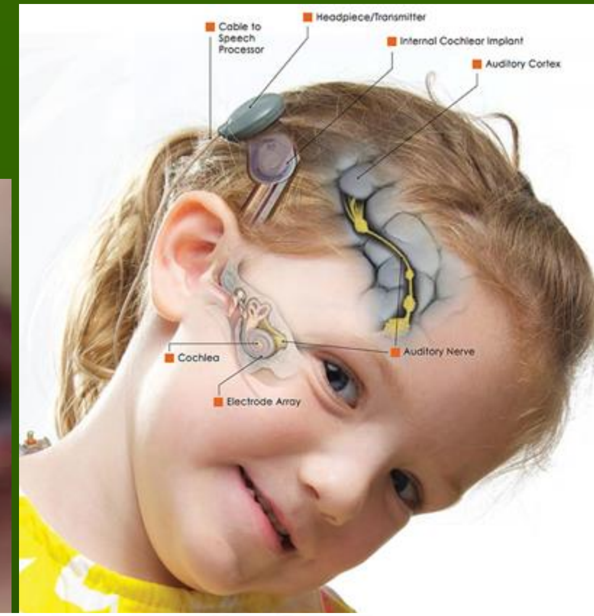
If I was like an octopus ... I would be the best drummer in the world!

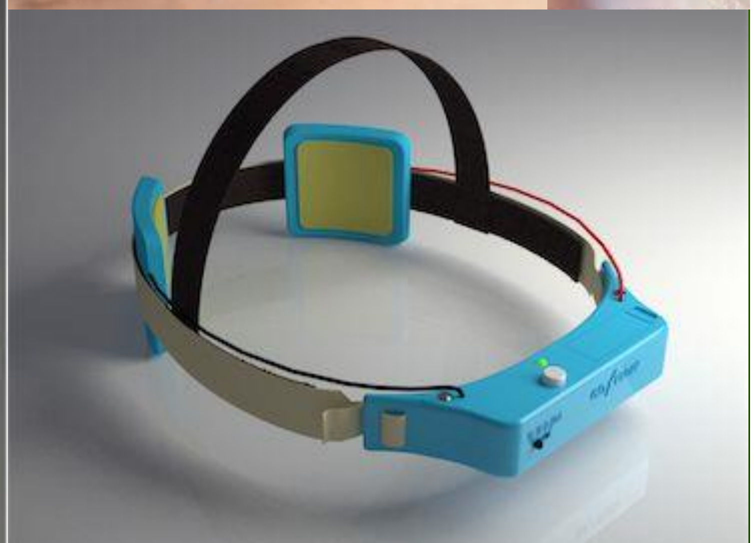


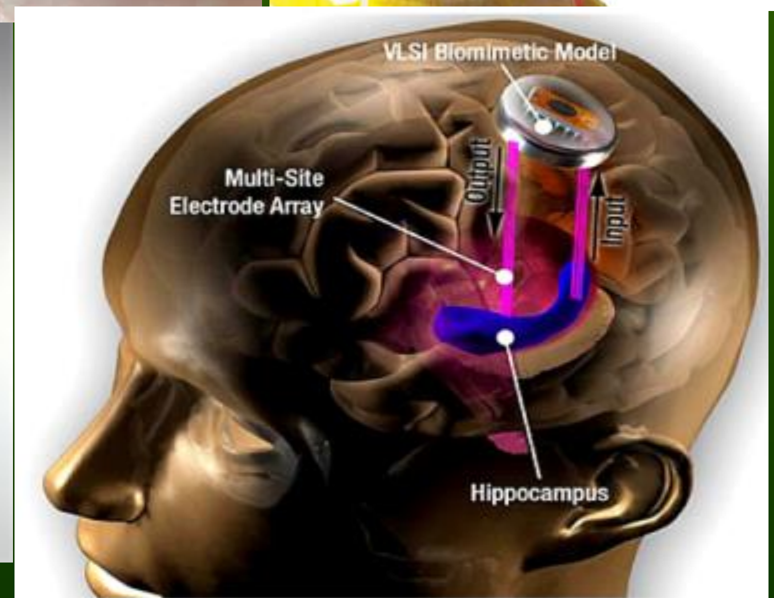
And if I were a robot, I would just play with 4 hands ... YouTube
Animatronic robot band Compressorhead goes on a tour around the world.

4 legs (or hands) better than two!

Amplification







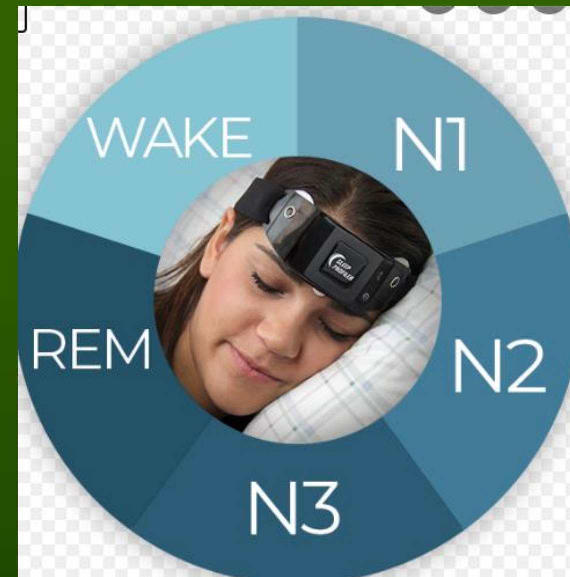
Expansion of the senses: sight, hearing, touch, memory, attention ...
Improving brains by adding new senses (Eagleman, Livewired 2020).

EEG headphones

EEG + music for mood/concentration.

Sleep

Neurosky-Sleep Shepherd Blue; Flowtime; Bittium BrainStatus (for ICU); Kokoon

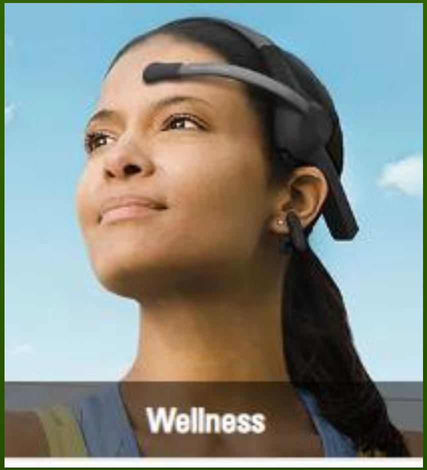


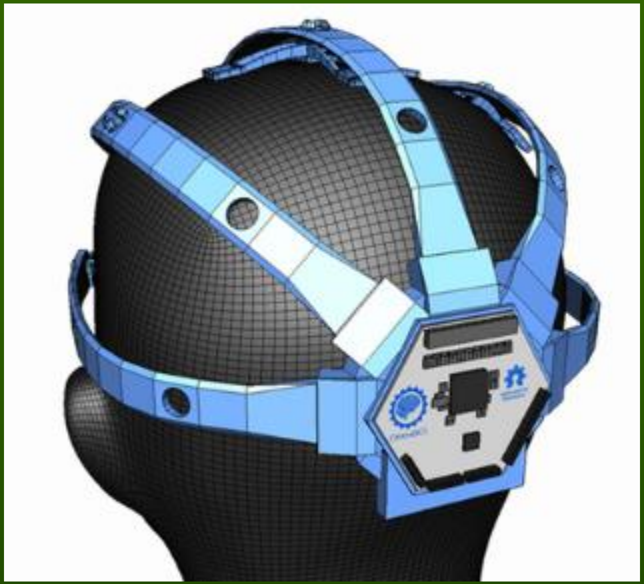
BCI tools

Many inexpensive EEG solutions, but analysis of brain signals is always hard.

Over 30 companies

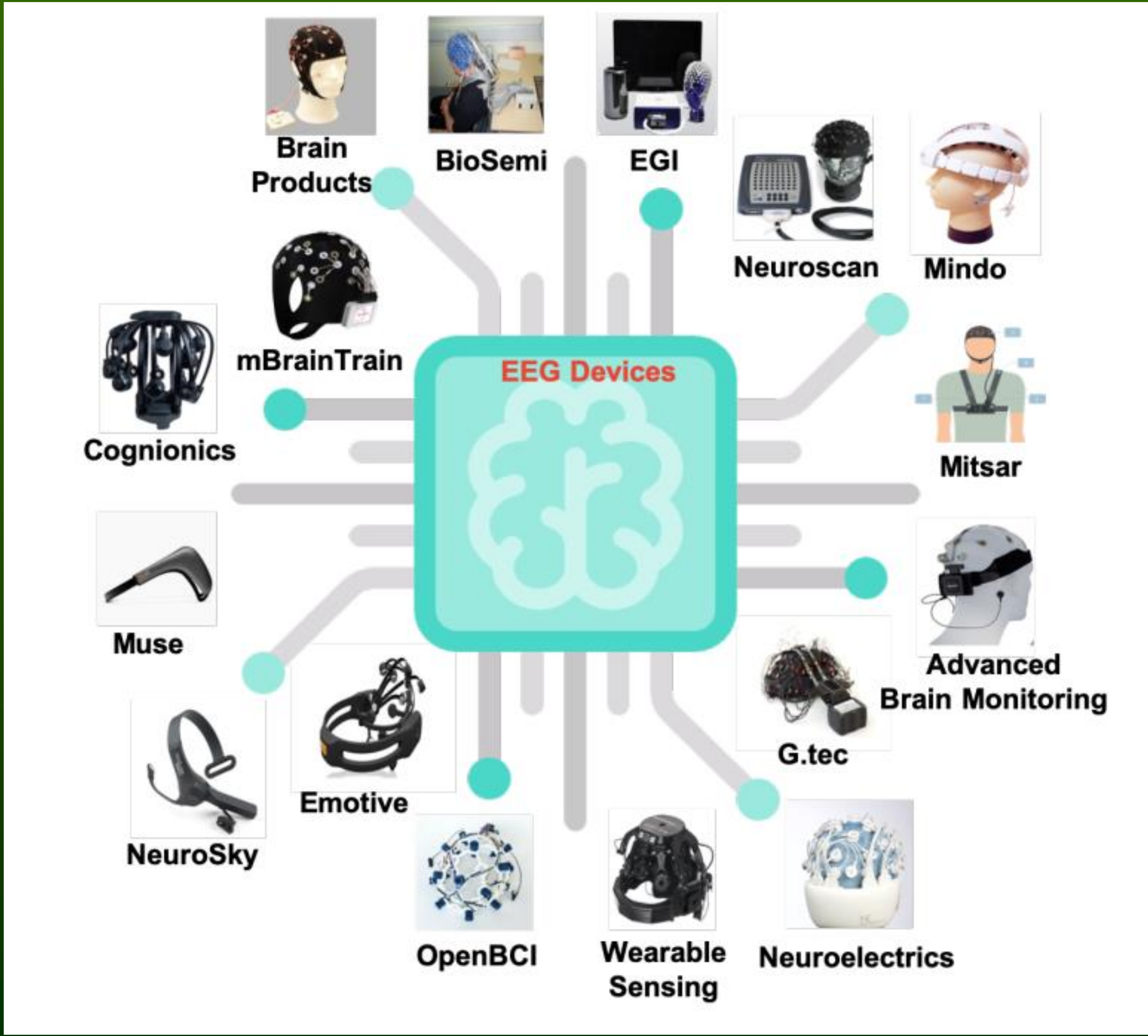
Neurosky-MindWave Mobile 2; G-Tec, OpenBCI, ANT-neuro, Waveguard, Google Wireless EEG …





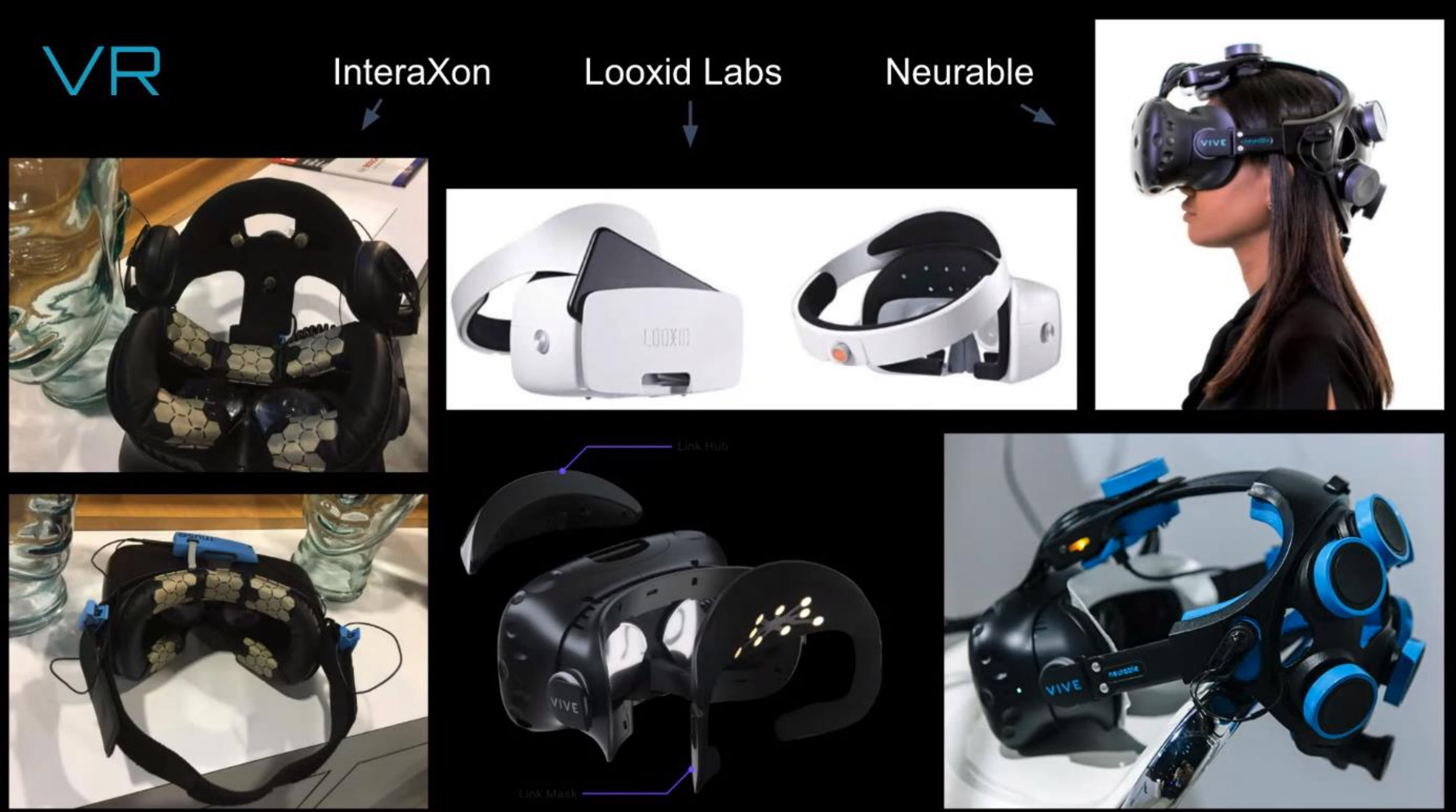
BCI tools

Gu … & Lin, C.-T. (2021).
EEG-Based BCIs: A Survey of Recent ...
IEEE/ACM Transactions on Computational Biology & Bioinformatics, 18(5), 1645–1666.



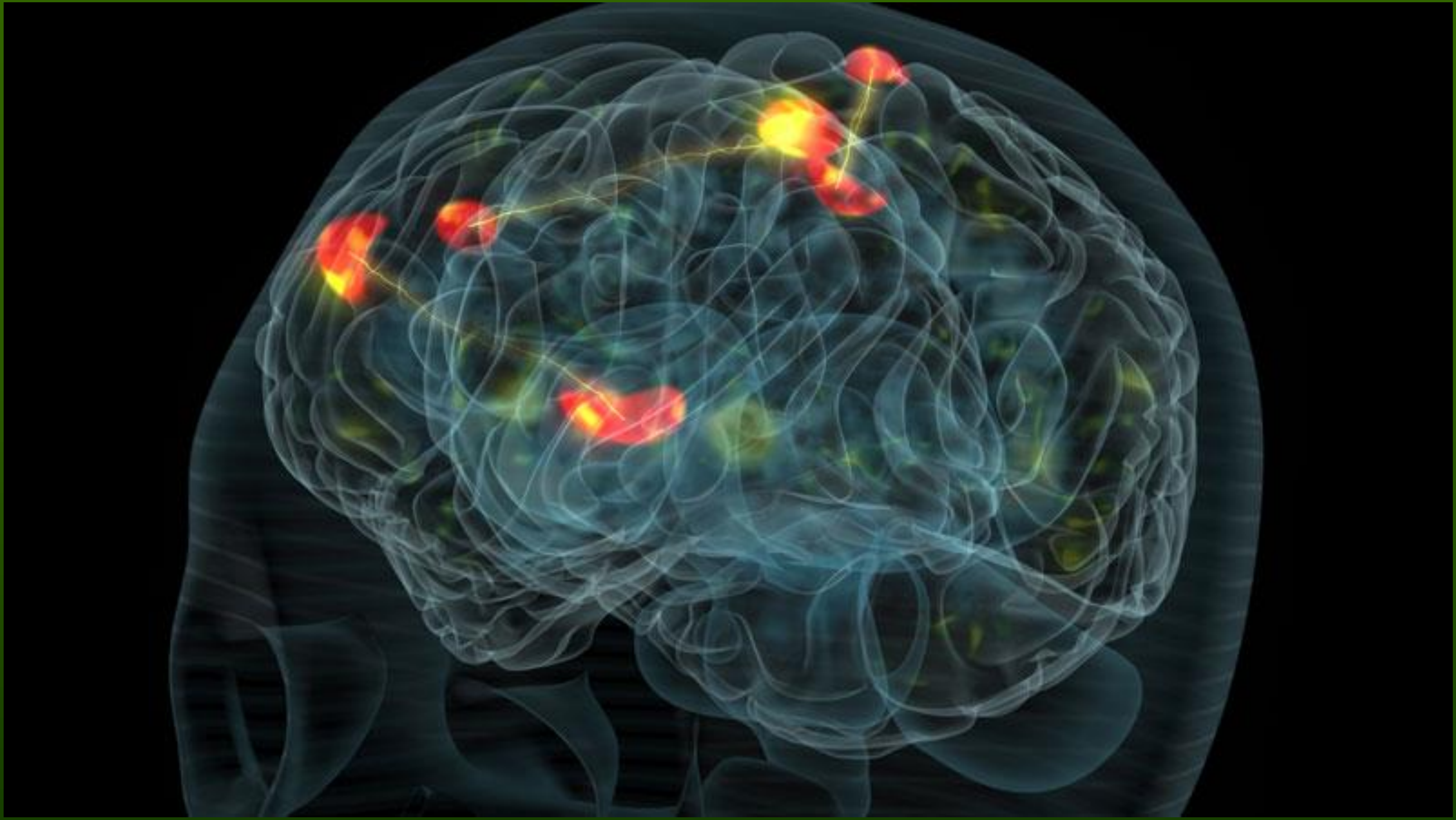
BCI tools

Combination of Virtual Reality with BCI has great potential.



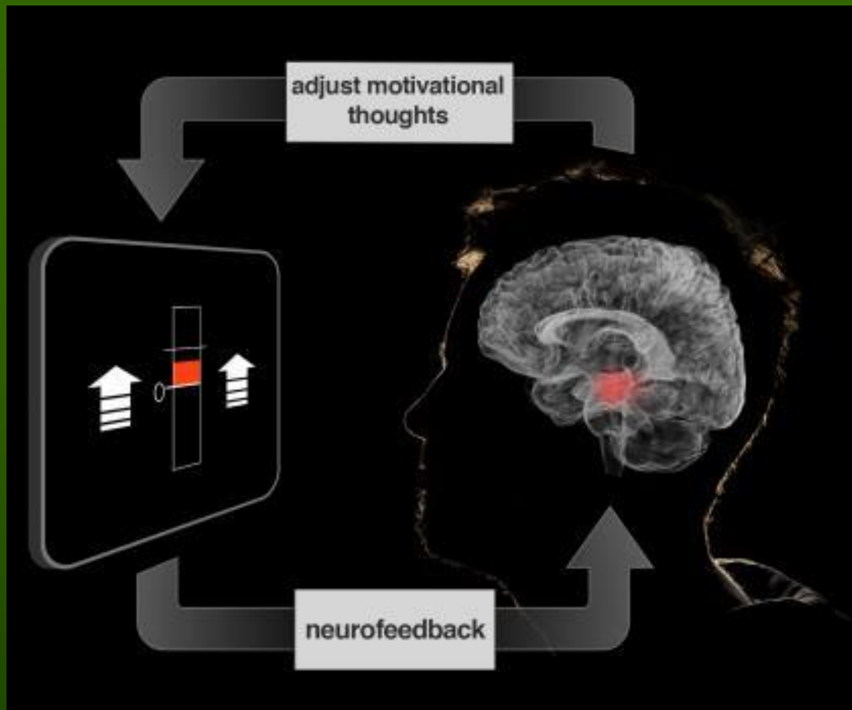
Decoding brain activity

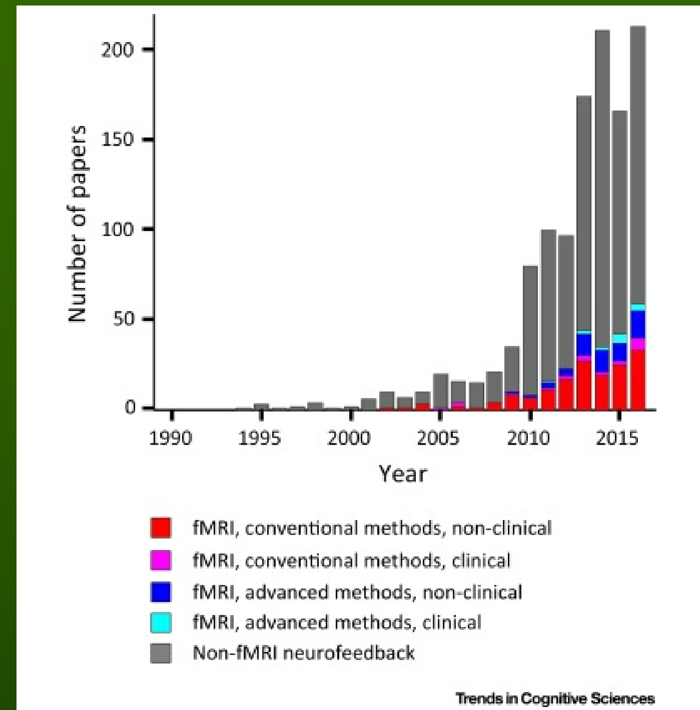
Mental state: strong coherent activation



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 has to be hard.

Neurofeedback: early BMI



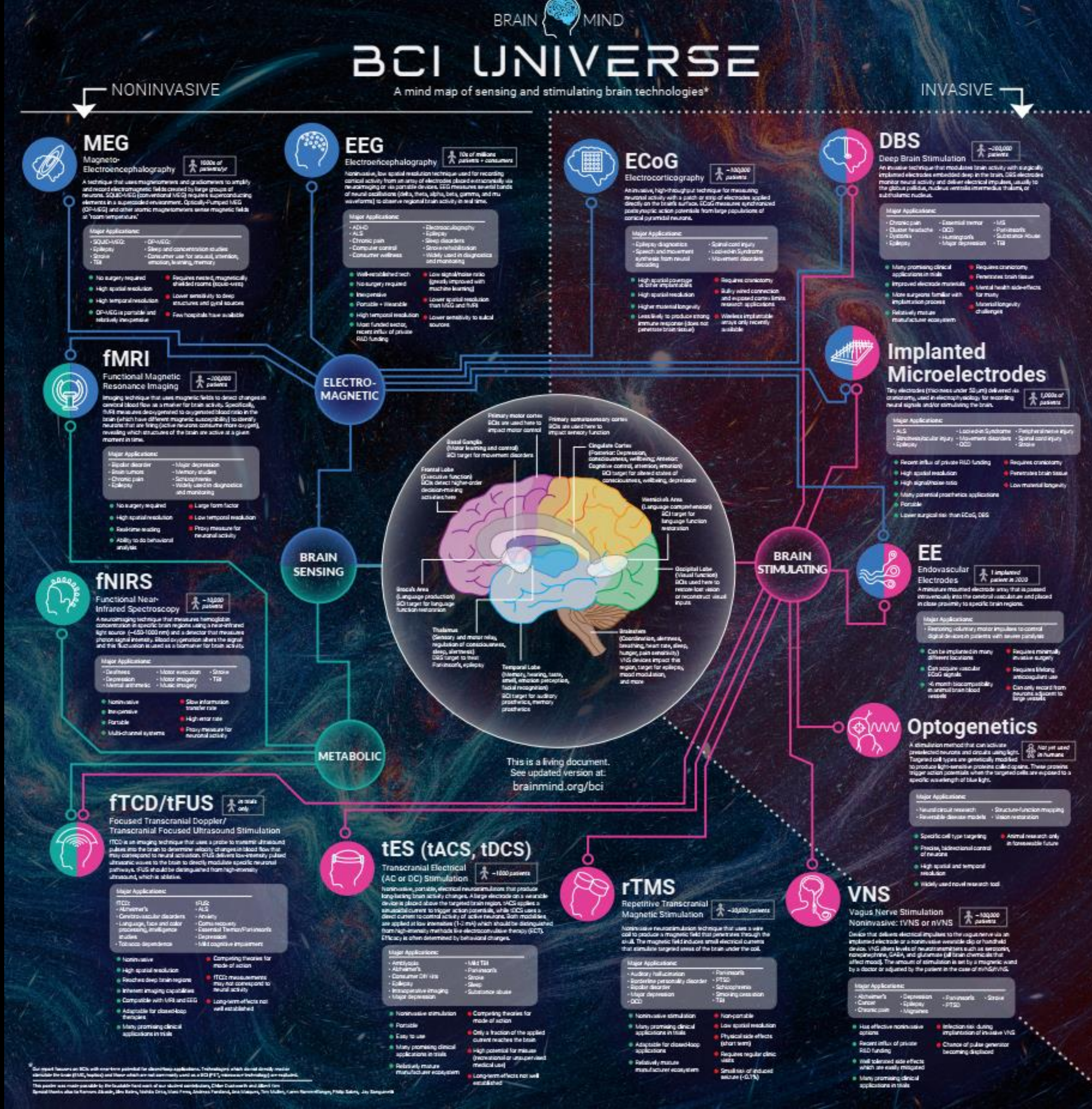


W. Duch, popular art. Stress and electronics, 1978!

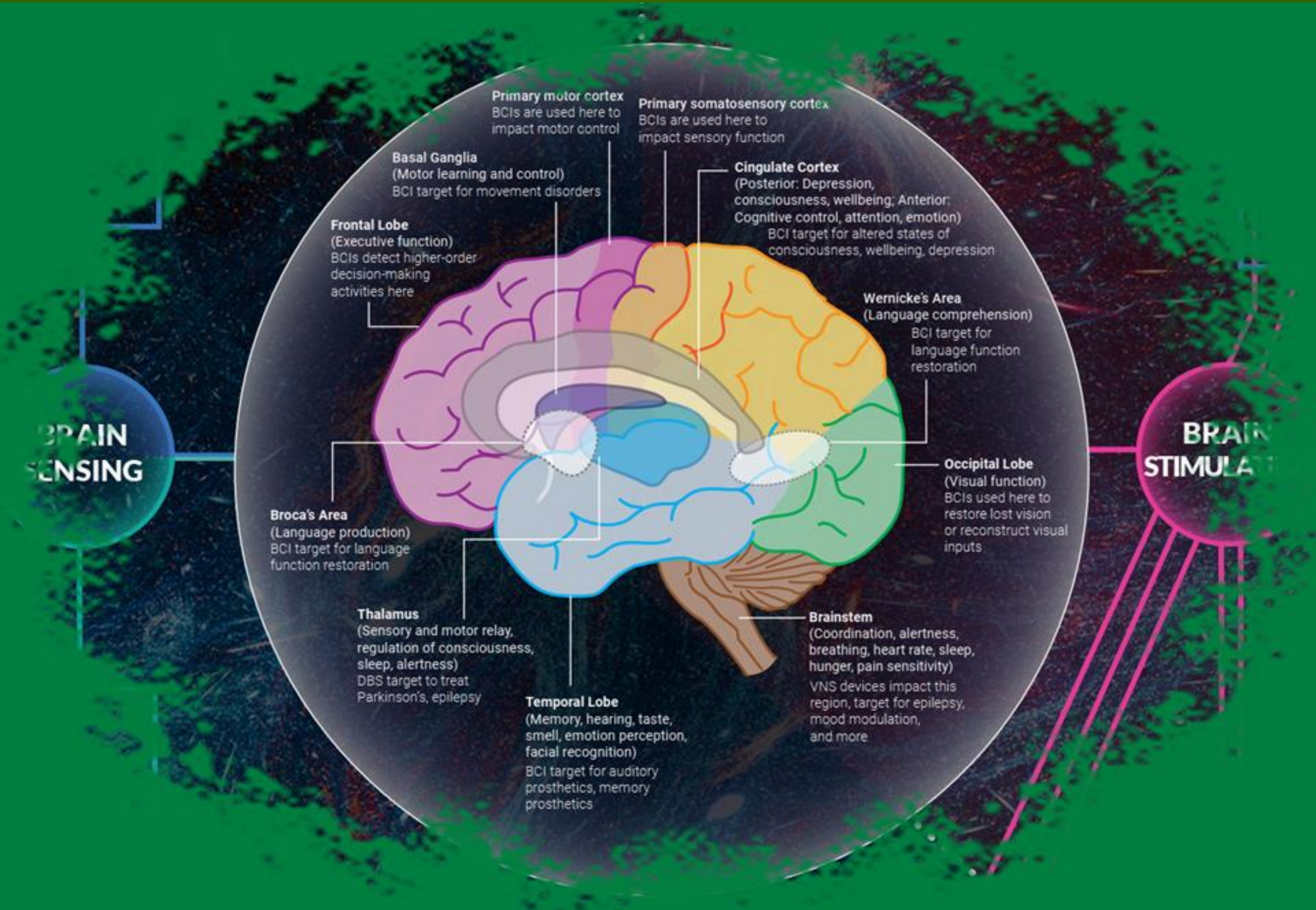
Still used in clinical practice, α/θ rhythms for relaxation.

CHADD classifies EEG neurofeedback as 2/5, or "possibly efficacious".

fMRI more effective, new forms based on the brain fingerprinting are needed.



BRAIN MIND
BCI UNIVERSE
A mind map of sensing and stimulating brain technologies*
NONINVASIVE
INVASIVE
MEG
Magneto-Electroencephalography
EEG
Electroencephalography
ECoG
Electrocorticography
DBS
Deep Brain Stimulation
fMRI
Functional Magnetic Resonance Imaging
ELECTRO-MAGNETIC
Implanted Microelectrodes
BRAIN SENSING
BRAIN STIMULATING
fNIRS
Functional Near-Infrared Spectroscopy
EE
Endovascular Electrodes
METABOLIC
Optogenetics
This is a living document. See updated version at: brainmind.org/bci
fTCD/tFUS
Focused Transcranial Doppler/ Transcranial Focused Ultrasound Stimulation
tES (tACS, tDCS)
Transcranial Electrical (AC or DC) Stimulation
rTMS
Repetitive Transcranial Magnetic Stimulation
VNS
Vagus Nerve Stimulation
Noninvasive: tVNS or nVNS

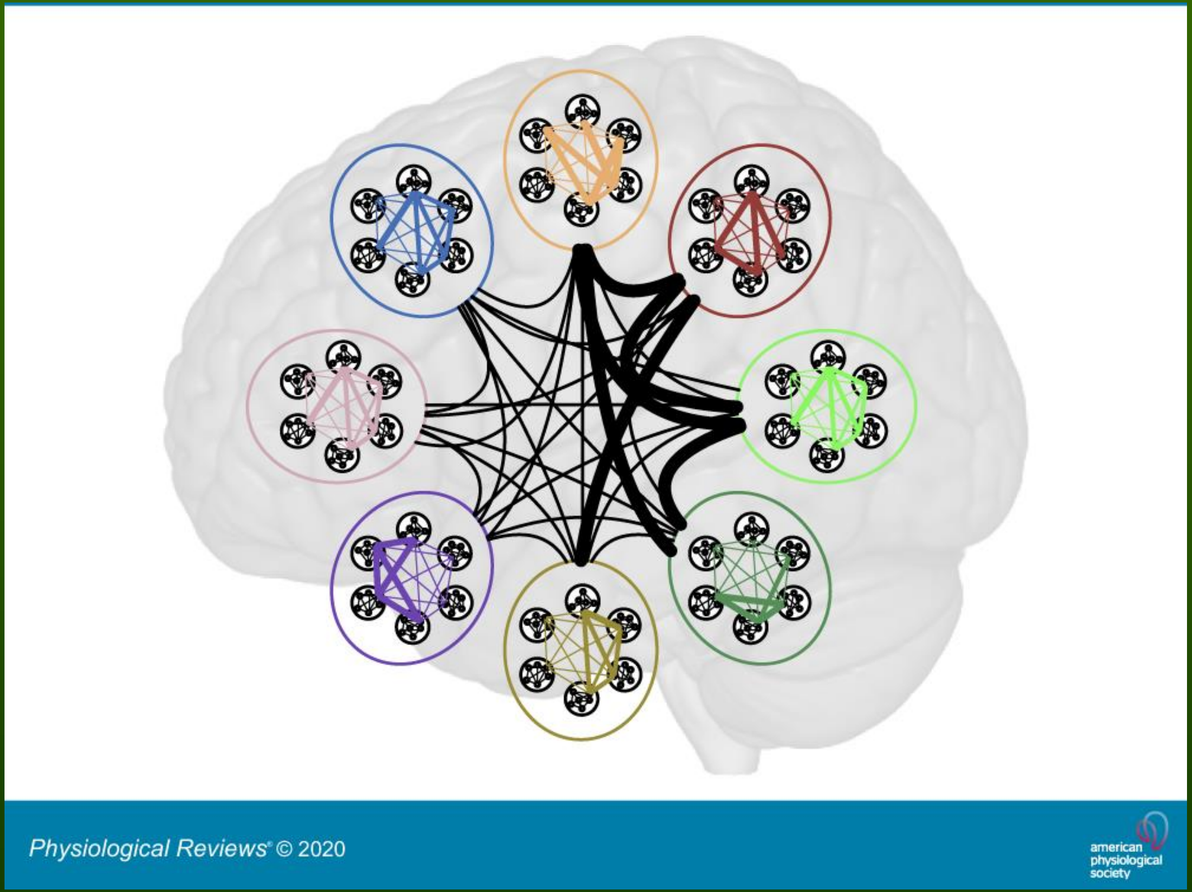

BRAIN SENSING
BRAIN STIMULA
Primary motor cortex
BCIs are used here to impact motor control
Primary somatosensory cortex
BCIs are used here to impact sensory function
Basal Ganglia
(Motor learning and control)
BCI target for movement disorders
Cingulate Cortex
(Posterior: Depression, consciousness, wellbeing; Anterior: Cognitive control, attention, emotion)
BCI target for altered states of consciousness, wellbeing, depression
Frontal Lobe
(Executive function)
BCIs detect higher-order decision-making activities here
Wernicke's Area
(Language comprehension)
BCI target for language function restoration
Occipital Lobe
(Visual function)
BCIs used here to restore lost vision or reconstruct visual inputs
Broca's Area
(Language production)
BCI target for language function restoration
Thalamus
(Sensory and motor relay, regulation of consciousness, sleep, alertness)
DBS target to treat Parkinson's, epilepsy
Temporal Lobe
(Memory, hearing, taste, smell, emotion perception, facial recognition)
BCI target for auditory prosthetics, memory prosthetics
Brainstem
(Coordination, alertness, breathing, heart rate, sleep, hunger, pain sensitivity)
VNS devices impact this region, target for epilepsy, mood modulation, and more

≈ Small worlds architecture

Small world: high levels of clustering, short path lengths, preserved across multiple frequency bands and behavioral tasks.

Local modules are densely connected, extract relevant information from sensory data, salience, memory associations, orchestrate motor actions.

Needs a switchboard?



All complex functions are based on synchronization of activity among brain areas. Memory, personality, or consciousness are processes engaging many functions. Similar to multi-agent systems, the "society of mind", or the Global Workspace Theory. "Deconstruct" psychological constructs, link them to the brain processes.

ELECTRO-MAGNETIC

fMRI

Functional Magnetic Resonance Imaging

~200,000 patients

Imaging technique that uses magnetic fields to detect changes in cerebral blood flow as a marker for brain activity. Specifically, fMRI measures deoxygenated to oxygenated blood ratio in the brain (which have different magnetic susceptibility) to identify neurons that are firing (active neurons consume more oxygen), revealing which structures of the brain are active at a given moment in time.

Major Applications:

- Bipolar disorder
- Brain tumors
- Chronic pain
- Epilepsy
- Major depression
- Memory studies
- Schizophrenia
- Widely used in diagnostics and monitoring

Advantages:
- No surgery required
- High spatial resolution
- Real-time reading
- Ability to do behavioral analysis

Disadvantages:
- Large form factor
- Low temporal resolution
- Proxy measure for neuronal activity

BRAIN SENSING

fNIRS

Functional Near-Infrared Spectroscopy

~10,000 patients

A neuroimaging technique that measures hemoglobin concentration in specific brain regions using a near-infrared light source (~650-1000 nm) and a detector that measures photon signal intensity. Blood oxygenation alters the signal and this fluctuation is used as a biomarker for brain activity.

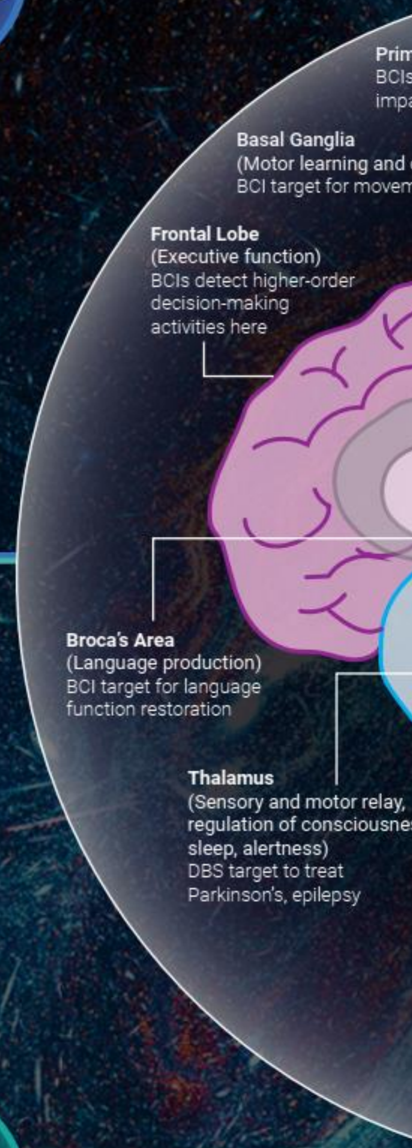
Major Applications:

- Deafness
- Depression
- Mental arithmetic
- Motor execution
- Motor imagery
- Music imagery
- Stroke
- TBI

Advantages:
- Noninvasive
- Inexpensive
- Portable
- Multi-channel systems

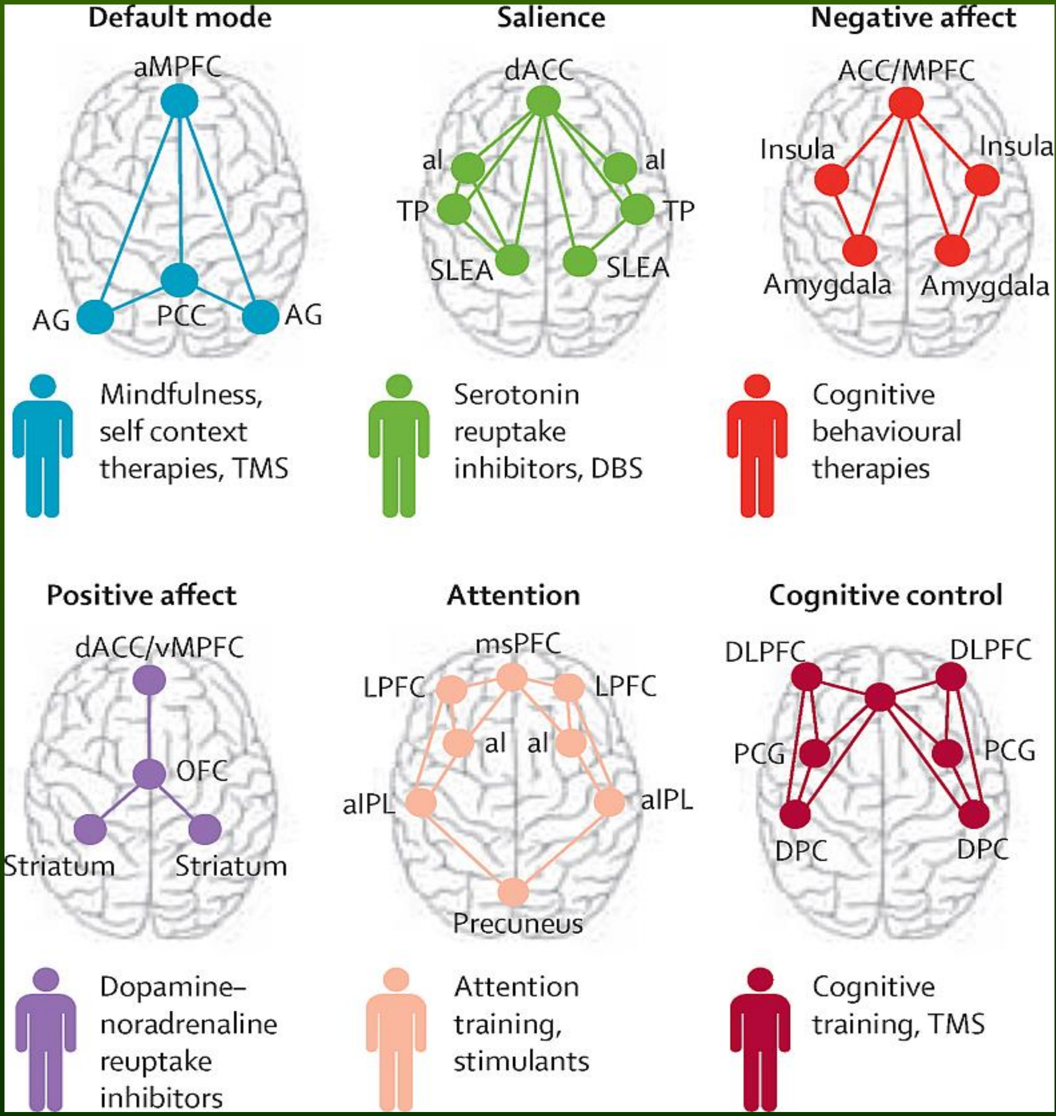
Disadvantages:
- Slow information transfer rate
- High error rate
- Proxy measure for neuronal activity

METABOLIC



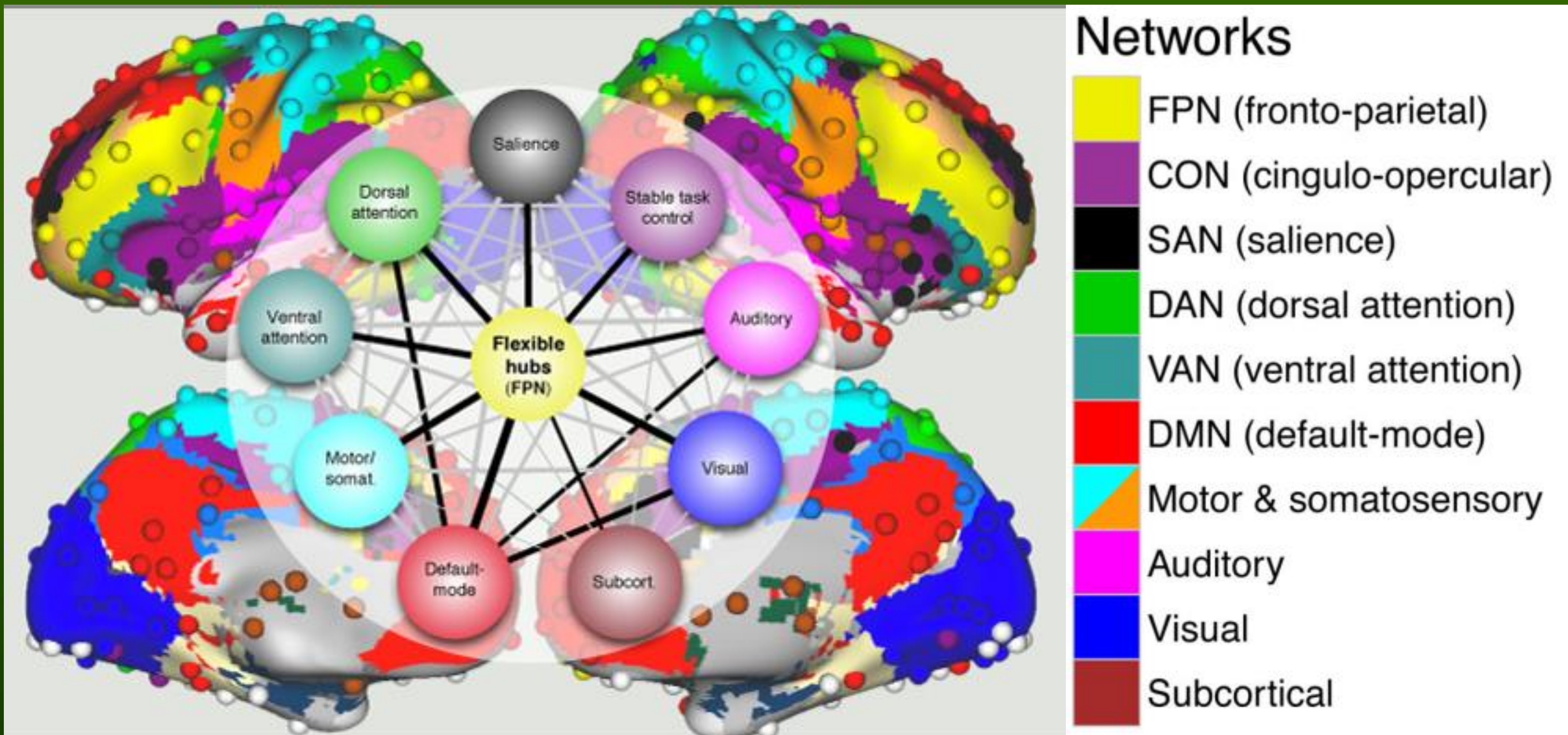
Large-Scale Networks from fMRI

- Large brain systems depend on coordination of activity in many brain regions.
- Decompose neurodynamics into activity of large-scale networks, related to various brain functions.
- LSN or intrinsic brain networks are derived from functional connectivity by statistical analysis of various neuroimaging experiments.
- How many? From 7 to 17 to 120, or much more (3 mln minicolumn)
- Brain networks have specialized functions, dominating frequencies, dynamics, neurotransmitters.



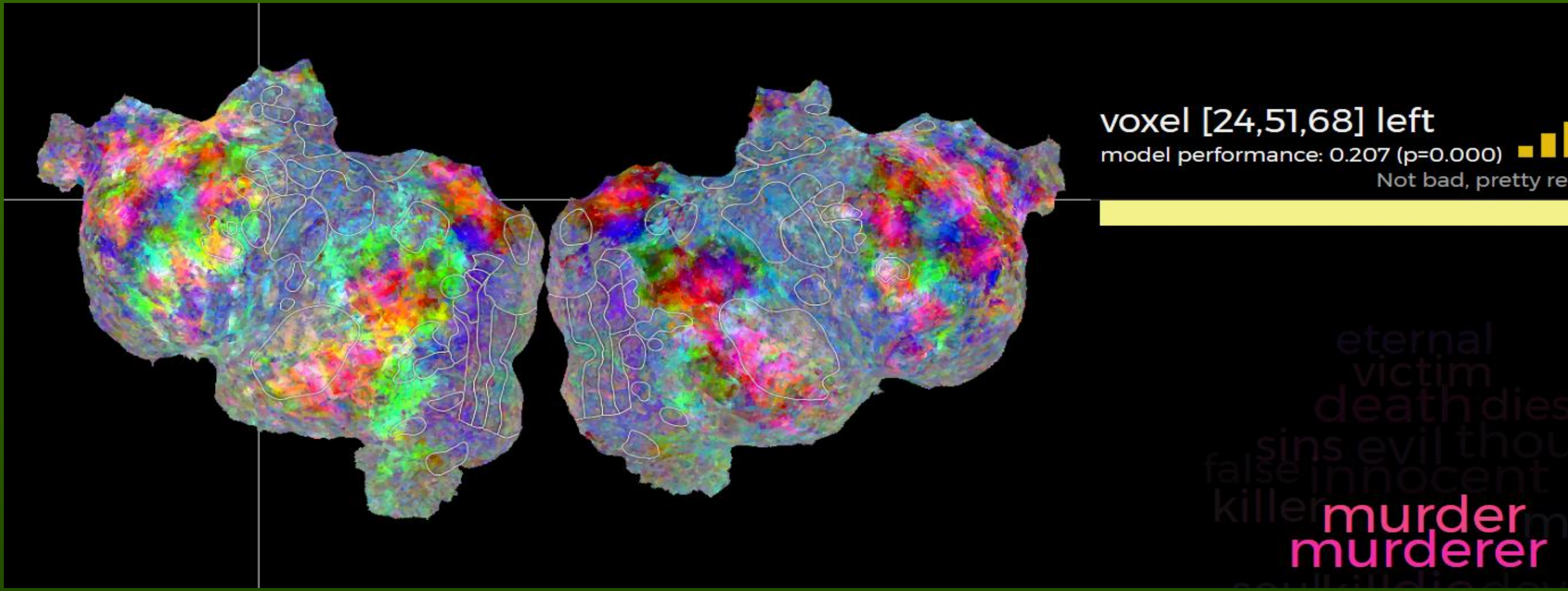
Network science for complex systems.

Neurocognitive Basis of Cognitive Control



Central role of fronto-parietal (FPN) flexible hubs in cognitive control and adaptive implementation of task demands.

Black lines=correlations significantly above network average (Cole et al. 2013).



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

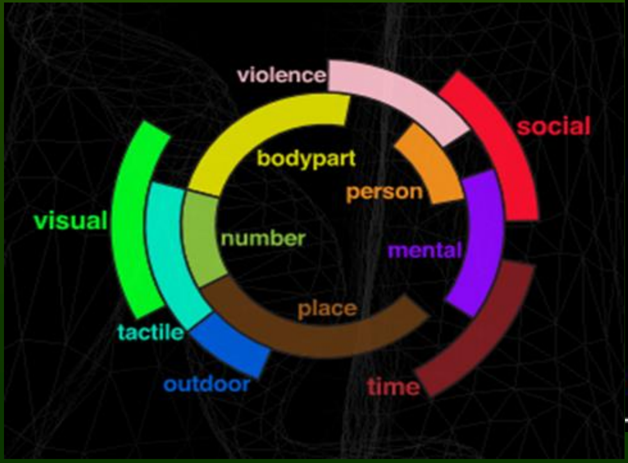
Each word activates a whole map of activity in the brain, depending on sensory features, motor actions and affective components associated with this word.
Why such activity patterns arise? Brain subnetworks connect active areas.

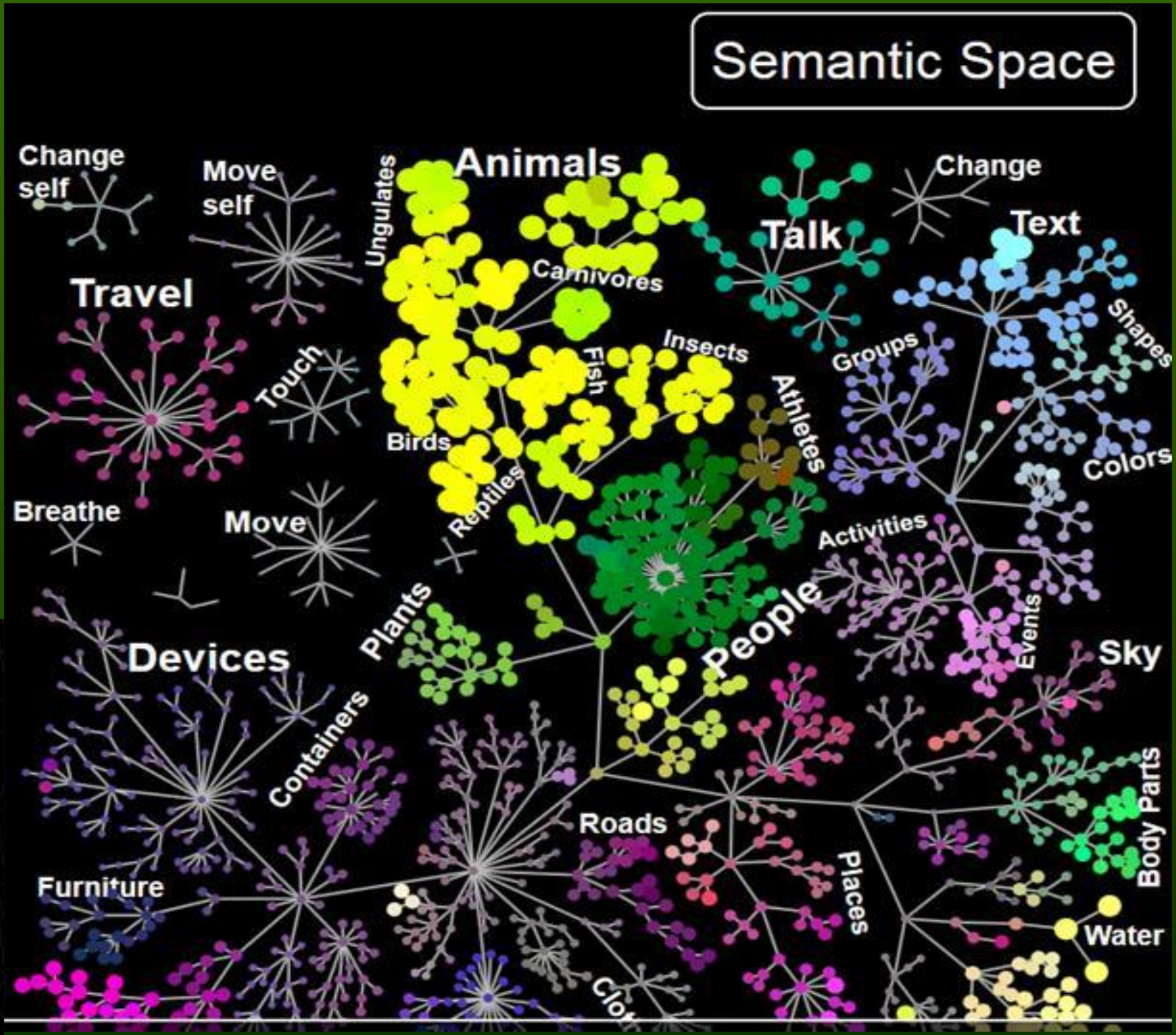
http://gallantlab.org/huth2016/ and short movie intro.

Can one do something like that with EEG or MEG?

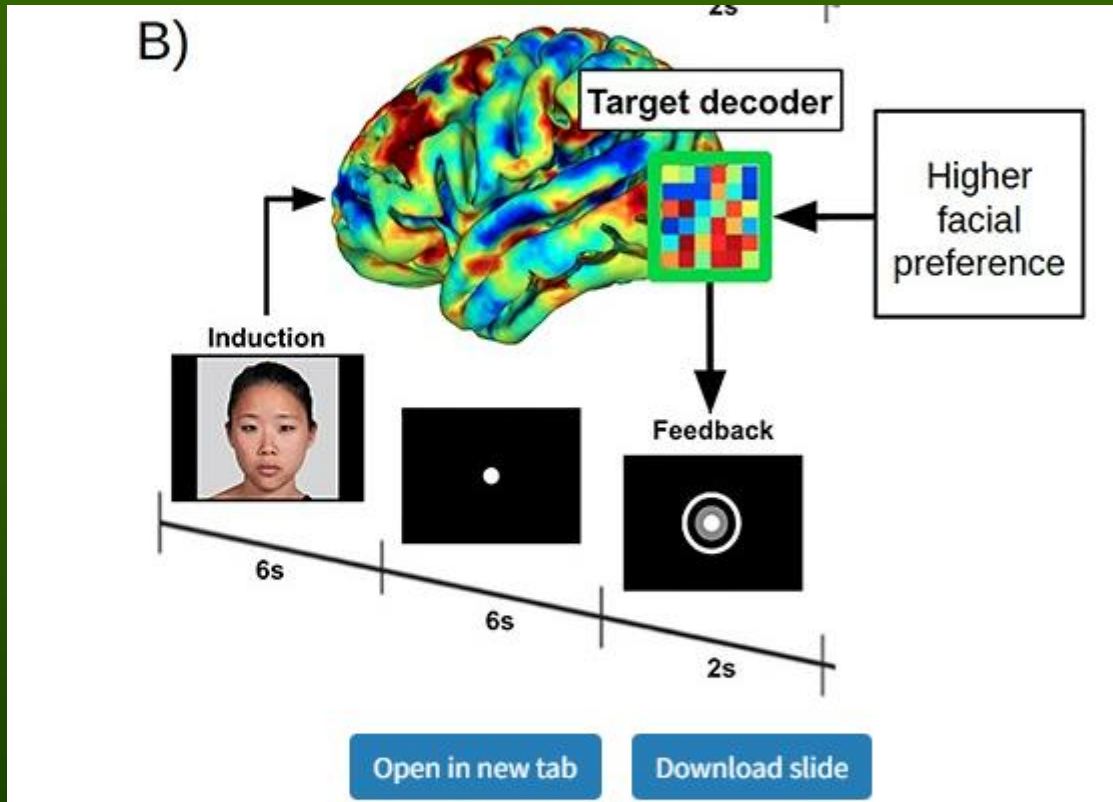
Semantic neuronal space

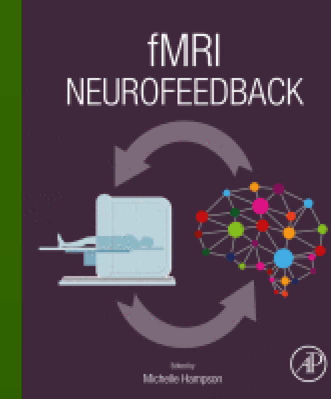
Words in the semantic space are grouped by their similarity.
Words activate specific ROIs, similar words create similar maps (1700 states) of brain activity.
Video or audio stimuli, fMRI 60.000 voxel).
Gallant lab, Berkeley.





fMRI neurofeedback



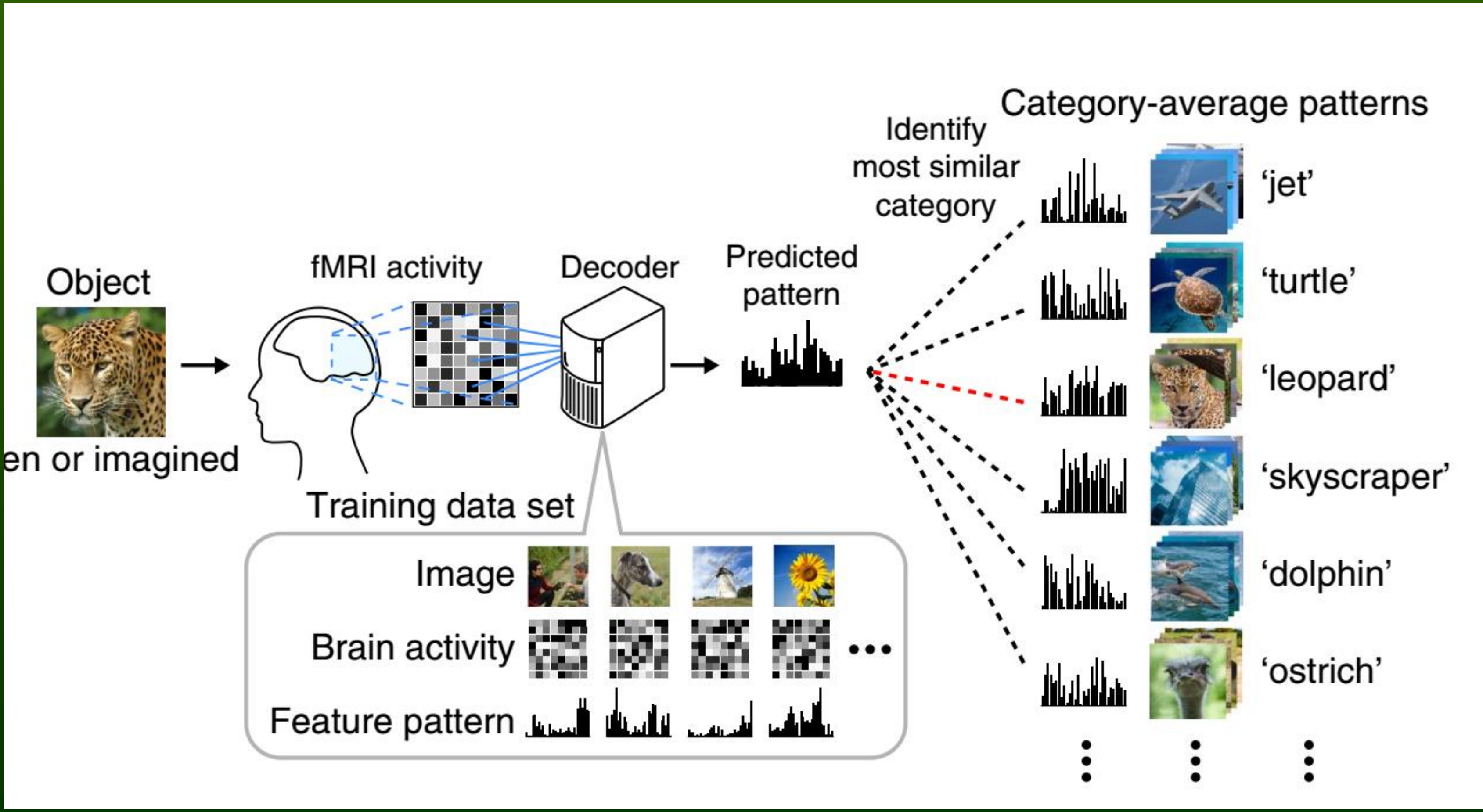


- Decoded Neurofeedback (DecNef).
  Target ROIs or occurrences of specific multivoxel representations.
- Functional Connectivity Neurofeedback (FCNef).

Taschereau-Dumouchel, V., Cortese, A., Lau, H., & Kawato, M. (2021). Conducting decoded neurofeedback studies. *Social Cognitive & Affective Neuroscience 16*, 838–848.

Brain activations ⇔ Mental images

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



Dreams

Decoding Dreams, ATR Kyoto, Kamitani Lab.
fMRI images analyzed during REM sleep or while falling asleep allow for the classification of dreams (~20 categories).
Dreams, thoughts... is it possible to hide what we have seen and experienced?

NONINVASIVE

A mind map of sensing

MEG

Magneto-Electroencephalography

1000s of patients/yr

A technique that uses magnetometers and gradiometers to amplify and record electromagnetic fields created by large groups of neurons. SQUID-MEG (conventional MEG) requires superconducting elements in a supercooled environment. Optically-Pumped MEG (OP-MEG) and other atomic magnetometers sense magnetic fields at "room temperature."

Major Applications:

- SQUID-MEG:
- Epilepsy
- Stroke
- TBI
- OP-MEG:
- Sleep and concentration studies
- Consumer use for arousal, attention, emotion, learning, memory

- ● No surgery required
- ● High spatial resolution
- ● High temporal resolution
- ● OP-MEG is portable and relatively inexpensive

- ● Requires nested, magnetically shielded rooms (SQUID-MEG)
- ● Lower sensitivity to deep structures and gyral sources
- ● Few hospitals have available

EEG

Electroencephalography

10s of millions patients + consumers

Noninvasive, low spatial resolution technique used for recording cortical activity from an array of electrodes placed extracranially via neuroimaging or via portable devices. EEG measures several bands of neural oscillations (delta, theta, alpha, beta, gamma, and mu waveforms) to observe regional brain activity in real time.

Major Applications:

- ADHD
- ALS
- Chronic pain
- Computer control
- Consumer wellness
- Electrooculography
- Epilepsy
- Sleep disorders
- Stroke rehabilitation
- Widely used in diagnostics and monitoring

- ● Well-established tech
- ● No surgery required
- ● Inexpensive
- ● Portable + Wearable
- ● High temporal resolution
- ● Most funded sector, recent influx of private R&D funding

- ● Low signal/noise ratio (greatly improved with machine learning)
- ● Lower spatial resolution than MEG and fMRI
- ● Lower sensitivity to sulcal sources

fMRI

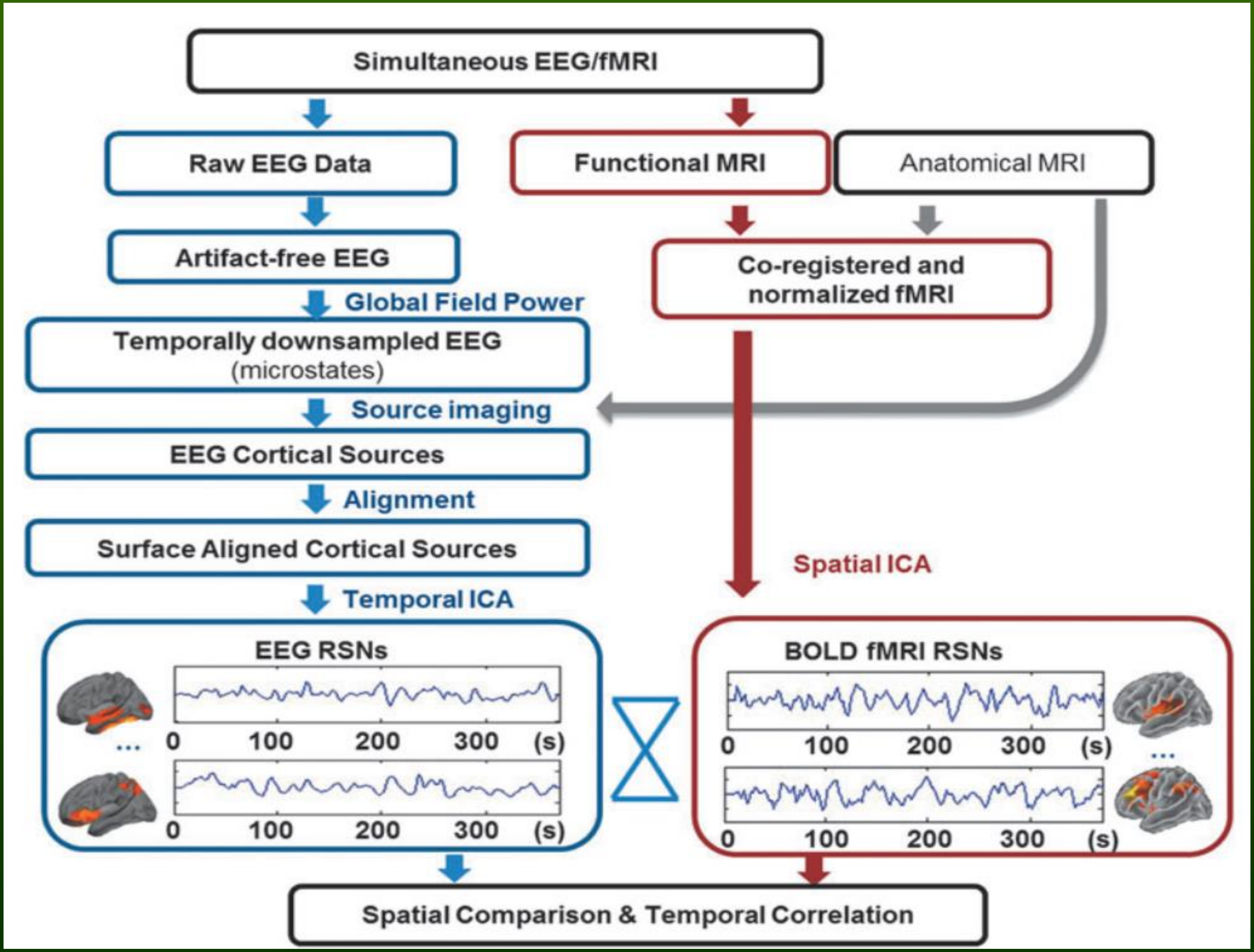
Functional Magnetic Resonance Imaging

~200,000 patients

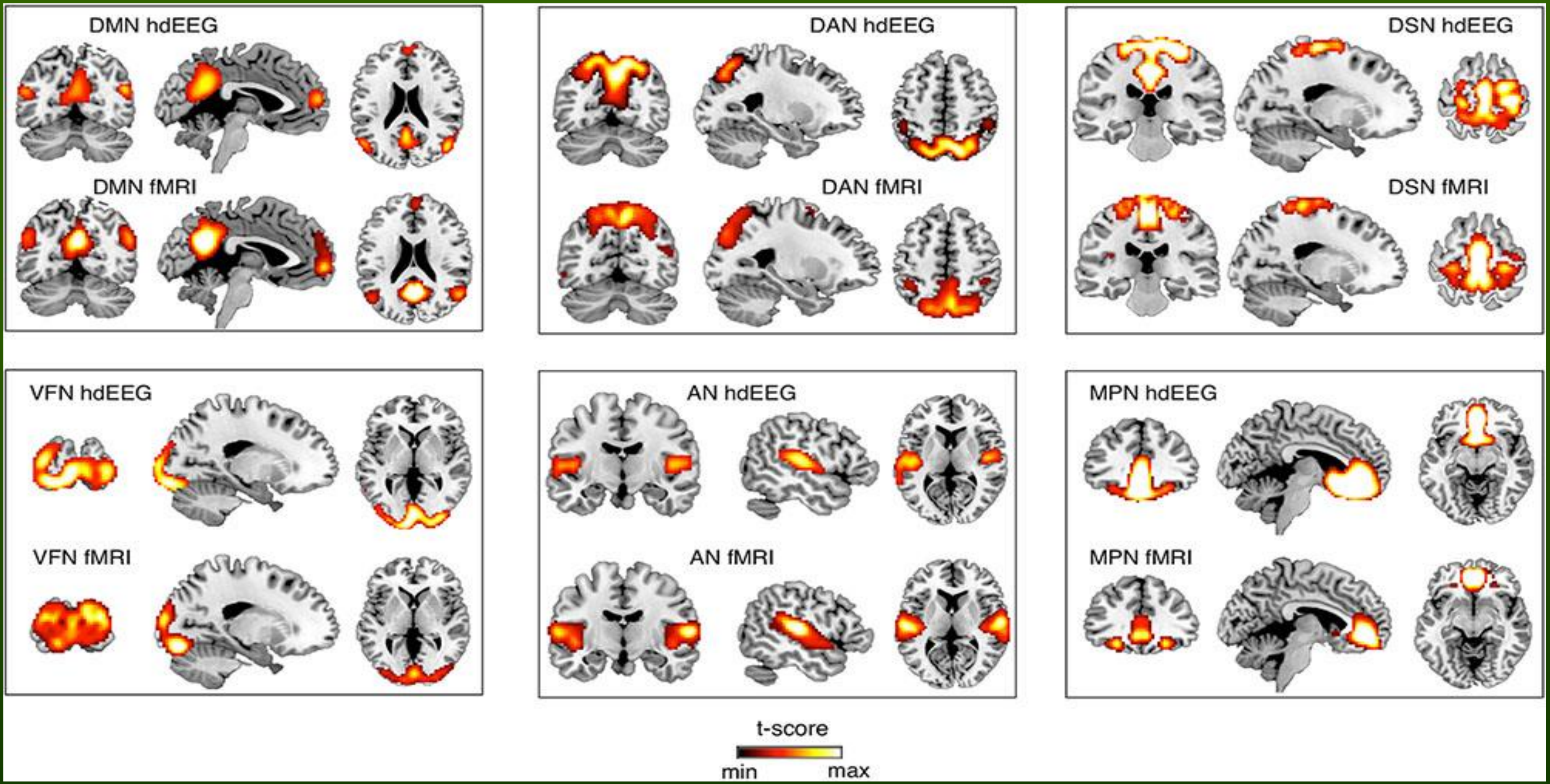
Imaging technique that uses magnetic fields to detect changes in cerebral blood flow as a marker for brain activity. Specifically,

ELECTRO-MAGNETIC

Yuan .. Bodurka, 2015-21



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 (2017; 2018).

- Multi-channel systems
- Proxy measure for neuronal activity

METABOLIC

This is a livin
See updated
brainmin

fTCD/tFUS

in trials only

Focused Transcranial Doppler/ Transcranial Focused Ultrasound Stimulation

fTCD is an imaging technique that uses a probe to transmit ultrasound pulses into the brain to determine velocity changes in blood flow that may correspond to neural activation. tFUS delivers low-intensity pulsed ultrasonic waves to the brain to directly modulate specific neuronal pathways. tFUS should be distinguished from high-intensity ultrasound, which is ablative.

Major Applications:

fTCD:
- Alzheimer's
- Cerebrovascular disorders
- Language, face and color processing, intelligence studies
- Tobacco dependence

tFUS:
- ALS
- Anxiety
- Coma recovery
- Essential Tremor/Parkinson's
- Depression
- Mild cognitive impairment

Advantages:
- Noninvasive
- High spatial resolution
- Reaches deep brain regions
- Inherent imaging capabilities
- Compatible with MRI and EEG
- Adaptable for closed-loop therapies
- Many promising clinical applications in trials

Limitations:
- Competing theories for mode of action
- fTCD: measurements may not correspond to neural activity
- Long-term effects not well established

tES (tACS, tDCS)

Transcranial Electrical (AC or DC) Stimulation

~1000 patients

Noninvasive, portable, electrical neurostimulators that produce long-lasting brain activity changes. A large electrode on a wearable device is placed above the targeted brain region. tACS applies a sinusoidal current to trigger action potentials, while tDCS uses a direct current to control activity of active neurons. Both modalities are applied at low intensities (1-2 mA) which should be distinguished from high-intensity methods like electroconvulsive therapy (ECT). Efficacy is often determined by behavioral changes.

Major Applications:

- Amblyopia
- Alzheimer's
- Consumer DIY kits
- Epilepsy
- Intraoperative imaging
- Major depression
- Mild TBI
- Parkinson's
- Stroke
- Sleep
- Substance abuse

Advantages:
- Noninvasive stimulation
- Portable
- Easy to use
- Many promising clinical applications in trials
- Relatively mature manufacturer ecosystem

Limitations:
- Competing theories for mode of action
- Only a fraction of the applied current reaches the brain
- High potential for misuse (recreational or unsupervised medical use)
- Long-term effects not well established

*Our report focuses on BCIs with near-term potential for closed-loop applications. Technologies which do not directly read or stimulate the brain (EMG, haptics) and those which are not commonly used as a BCI (PET, microwave technology) are excluded.

This poster was made possible by the laudable hard work of our student contributors, Chloe Duckworth and Albert Kim
Special thanks also to Ramses Alcaide, Alex Bates, Nishita Deka, Marc Ferro, Andreas Forsland, Ana Maiques, Tim Mullen, Karen Rommelfanger, Philip Sabes, Jay Sanguinetti

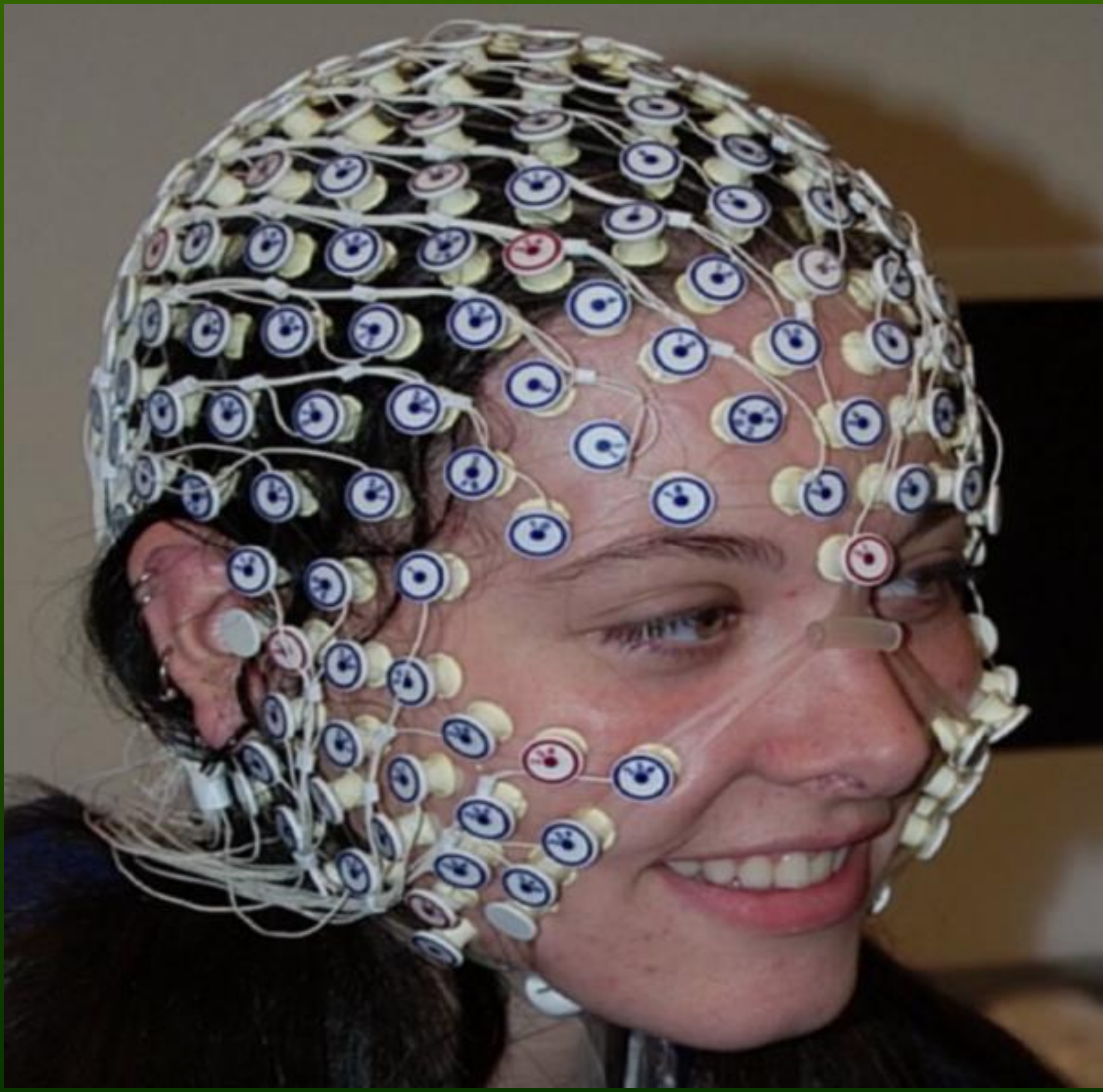
HD DCS for BCBI

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

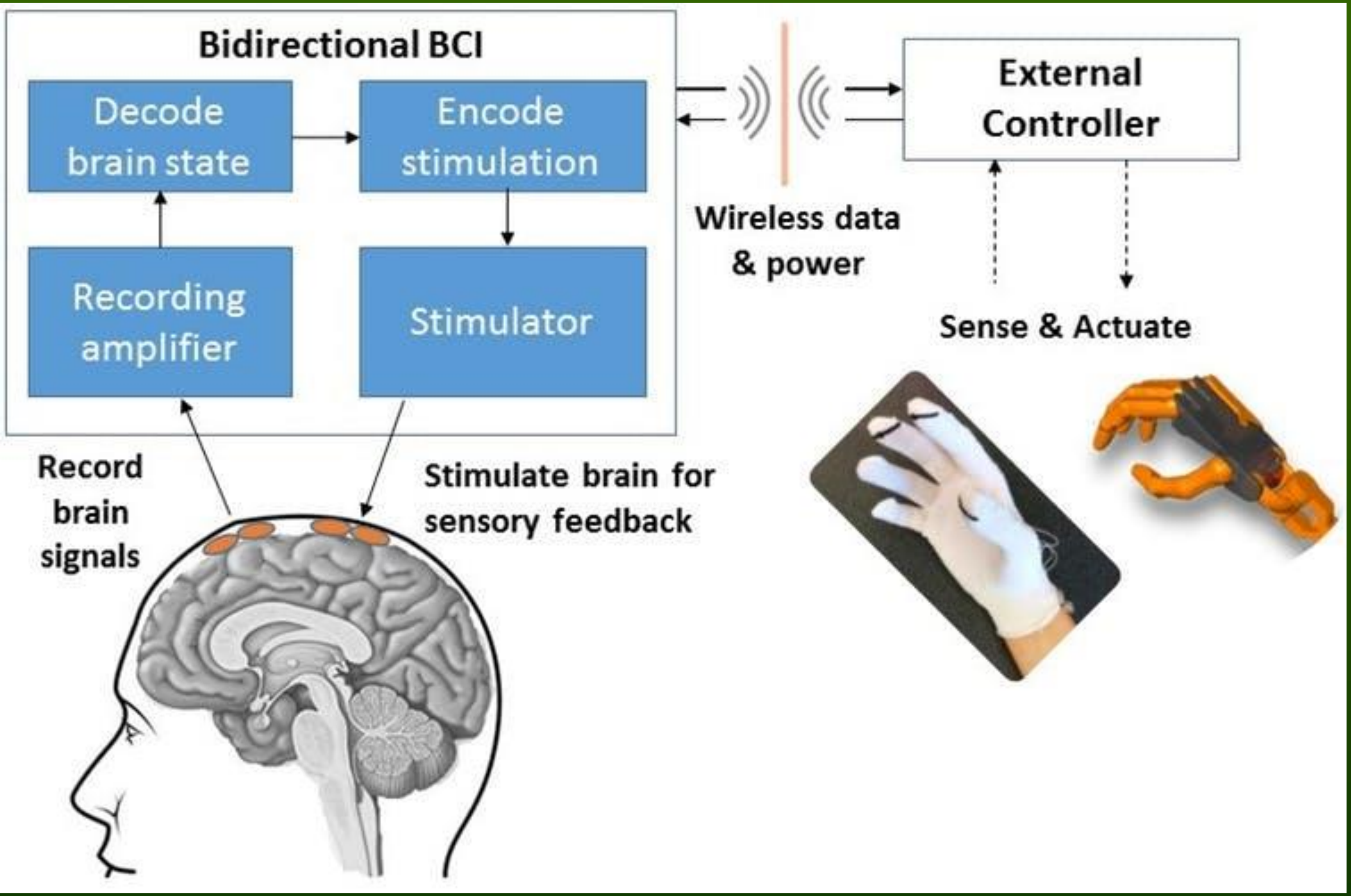
Depression, neuro-plasticity, pain, psychosomatic disorders, teaching!

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

But **no-one really knows** why it works …

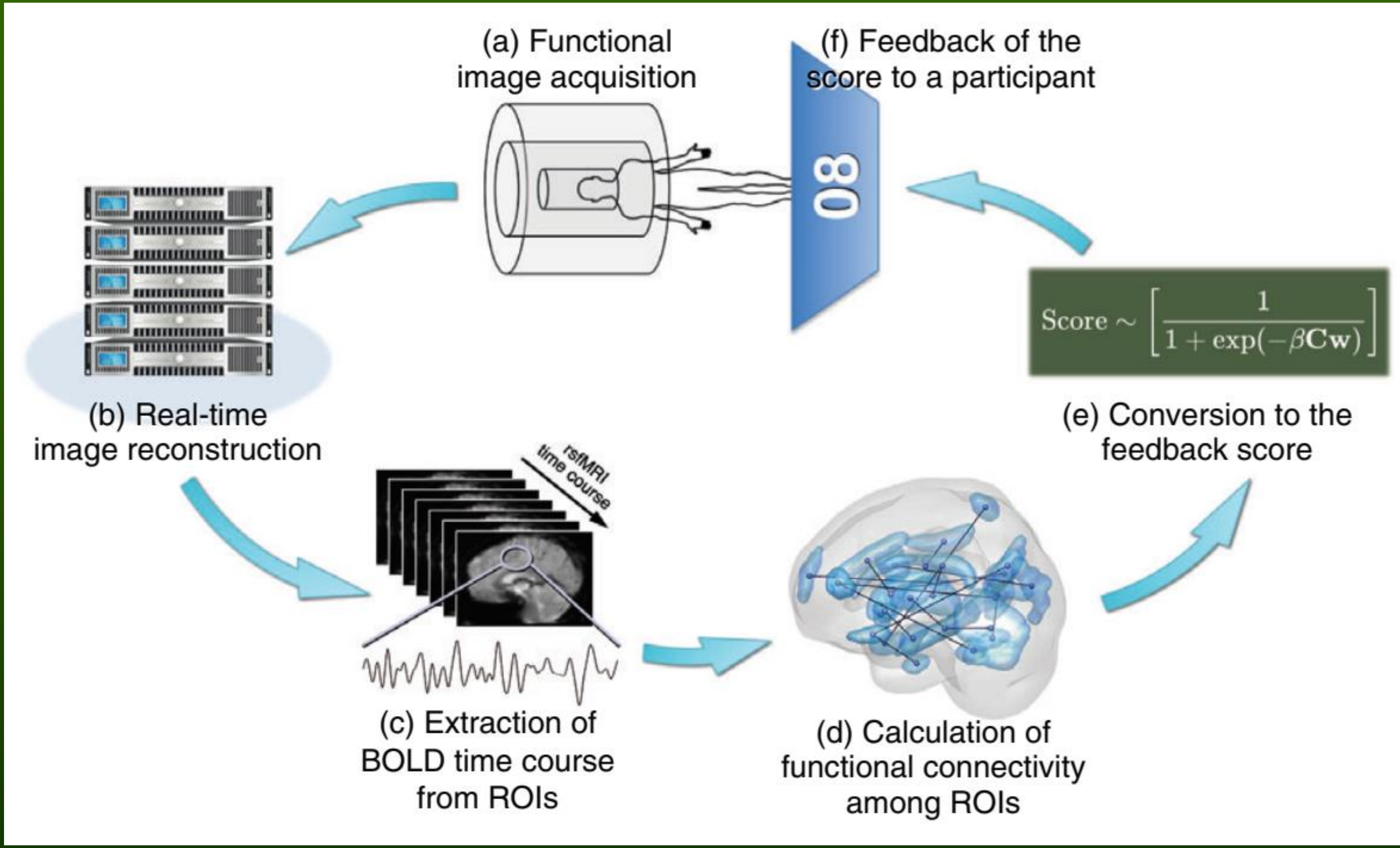


BCBI: Brain-Computer-Brain



BCI + brain stimulation = BCBI – a closed loop through which the brain begins to restructure itself. The body can be replaced by signals in Virtual Reality.

Will neurofeedback repair our brains?



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 to brain

Engagement Skills Trainer (EST), procedures for training American soldiers.

Intific Neuro-EST
a technology that uses EEG analysis and a multi-channel transcranial stimulator (MtCS) to transfer skills between master and student, brain-to-brain.

ory

large vessels

ving document.
ated version at:
ind.org/bci

Optogenetics

Not yet used in humans

A stimulation method that can activate preselected neurons and circuits using light. Targeted cell types are genetically modified to produce light-sensitive proteins called opsins. These proteins trigger action potentials when the targeted cells are exposed to a specific wavelength of blue light.

Major Applications:

- Neural circuit research
- Reversible disease models
- Structure-function mapping
- Vision restoration

Pros:
- Specific cell type targeting
- Precise, bidirectional control of neurons
- High spatial and temporal resolution
- Widely used novel research tool

Cons:
- Animal research only in foreseeable future

rTMS

Repetitive Transcranial Magnetic Stimulation

~30,000 patients

Noninvasive neurostimulation technique that uses a wire coil to produce a magnetic field that penetrates through the skull. The magnetic field induces small electrical currents that stimulate targeted areas of the brain under the coil.

Major Applications:

- Auditory hallucination
- Borderline personality disorder
- Bipolar disorder
- Major depression
- OCD
- Parkinson's
- PTSD
- Schizophrenia
- Smoking cessation
- TBI

Pros:
- Noninvasive stimulation
- Many promising clinical applications in trials
- Adaptable for closed-loop applications
- Relatively mature manufacturer ecosystem

Cons:
- Non-portable
- Low spatial resolution
- Physical side effects (short term)
- Requires regular clinic visits
- Small risk of induced seizure (<0.1%)

VNS

Vagus Nerve Stimulation
Noninvasive: tVNS or nVNS

~100,000 patients

Device that delivers electrical impulses to the vagus nerve via an implanted electrode or a noninvasive wearable clip or handheld device. VNS alters levels of neurotransmitters such as serotonin, norepinephrine, GABA, and glutamate (all brain chemicals that affect mood). The amount of stimulation is set by a magnetic wand by a doctor or adjusted by the patient in the case of nVNS/tVNS.

Major Applications:

- Alzheimer's
- Cancer
- Chronic pain
- Depression
- Epilepsy
- Migraines
- Parkinson's
- PTSD
- Stroke

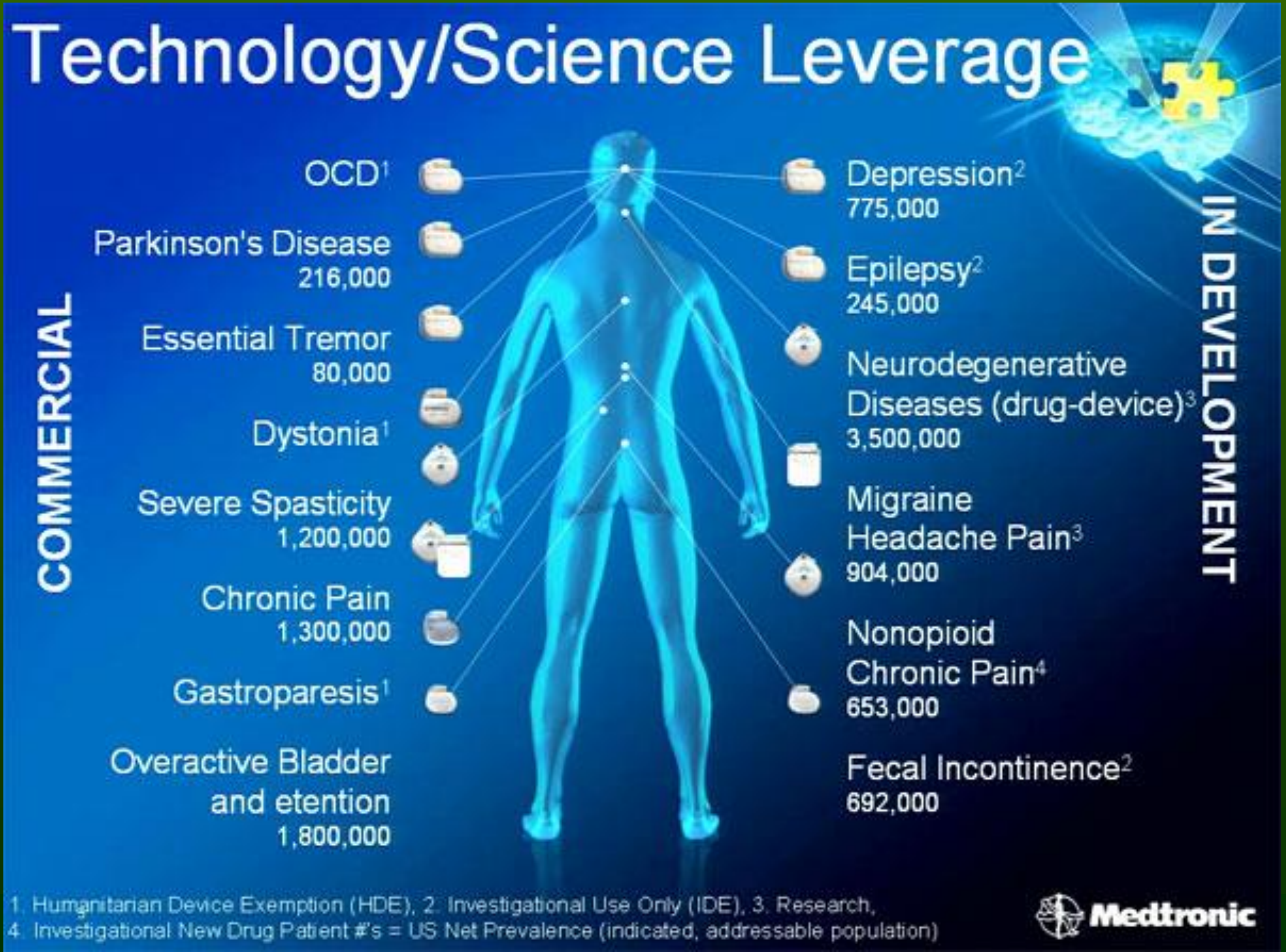
Pros:
- Has effective noninvasive options
- Recent influx of private R&D funding
- Well tolerated side effects which are easily mitigated
- Many promising clinical applications in trials

Cons:
- Infection risk during implantation of invasive VNS
- Chance of pulse generator becoming displaced

Neuromodulation

Cochlear implants are common, deep implants stimulate brain structures, not only for deficits of perception, but to regulate cortical neural processes.

Market:
10B$ (2021),
25B$ in 2027.



stimulating brain technologies*

INVASIVE

ECoG

Electrocorticography

~100,000 patients

An invasive, high-throughput technique for measuring neuronal activity with a patch or strip of electrodes applied directly on the brain's surface. ECoG measures synchronized postsynaptic action potentials from large populations of cortical pyramidal neurons.

Major Applications:

- Epilepsy diagnostics
- Speech and movement synthesis from neural decoding
- Spinal cord injury
- Locked-in Syndrome
- Movement disorders

Pros:
- High spatial coverage vs other implantables
- High spatial resolution
- Higher material longevity
- Less likely to produce strong immune response (does not penetrate brain tissue)

Cons:
- Requires craniotomy
- Bulky wired connection and exposed cortex limits research applications
- Wireless implantable arrays only recently available

DBS

Deep Brain Stimulation

~200,000 patients

An invasive technique that modulates brain activity with surgically implanted electrodes embedded deep in the brain. DBS electrodes monitor neural activity and deliver electrical impulses, usually to the globus pallidus, nucleus ventralis intermedius thalami, or subthalamic nucleus.

Major Applications:

- Chronic pain
- Cluster headache
- Dystonia
- Epilepsy
- Essential tremor
- OCD
- Huntington's
- Major depression
- MS
- Parkinson's
- Substance Abuse
- TBI

Pros:
- Many promising clinical applications in trials
- Improved electrode materials
- More surgeons familiar with implantation process
- Relatively mature manufacturer ecosystem

Cons:
- Requires craniotomy
- Penetrates brain tissue
- Mental health side-effects for many
- Material longevity challenges

Implanted Microelectrodes

Tiny electrodes (thickness under 50 μm) delivered via craniotomy, used in electrophysiology for recording neural signals and/or stimulating the brain.

1,000s of patients

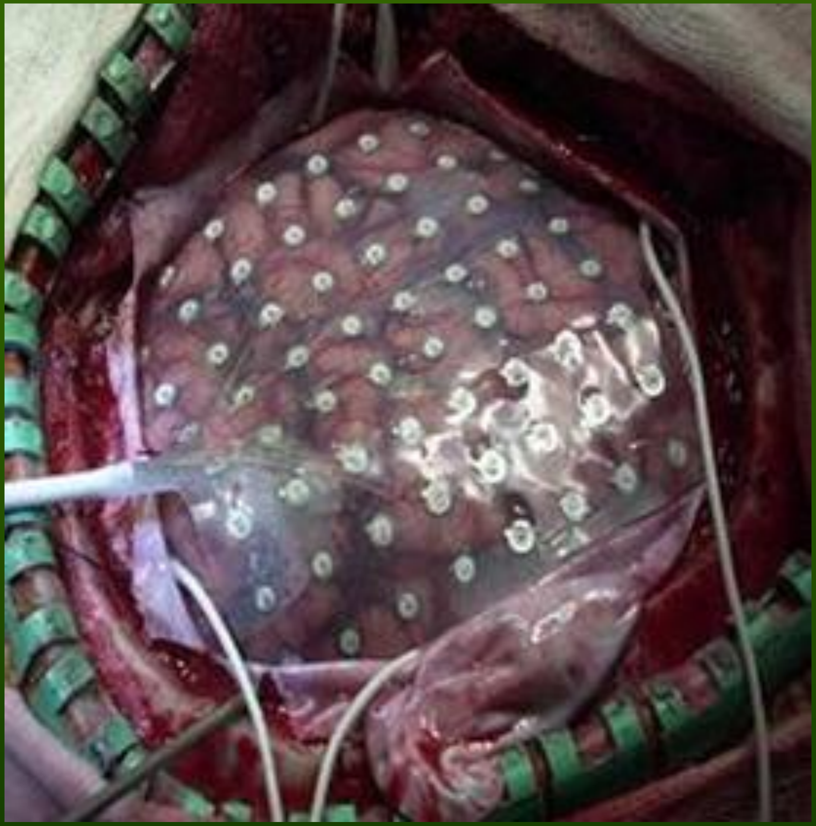
Major Applications:

- ALS
- Blindness/ocular injury
- Epilepsy
- Locked-in Syndrome
- Movement disorders
- OCD
- Peripheral nerve injury
- Spinal cord injury
- Stroke

Primary somatosensory cortex
BCIs are used here to impact sensory function

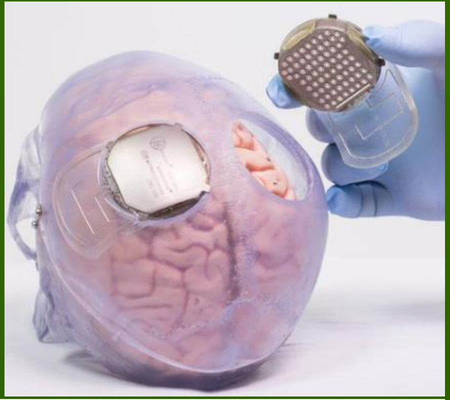
Cingulate Cortex
(Posterior: Depression,

Invasive brain computer interfaces



People with Parkinson's disease or compulsive-obsessive disorder who have pacemakers implanted in their brain can regulate their behavior with an external controller.

Neuroprothesis



Classical BMI: motor control.

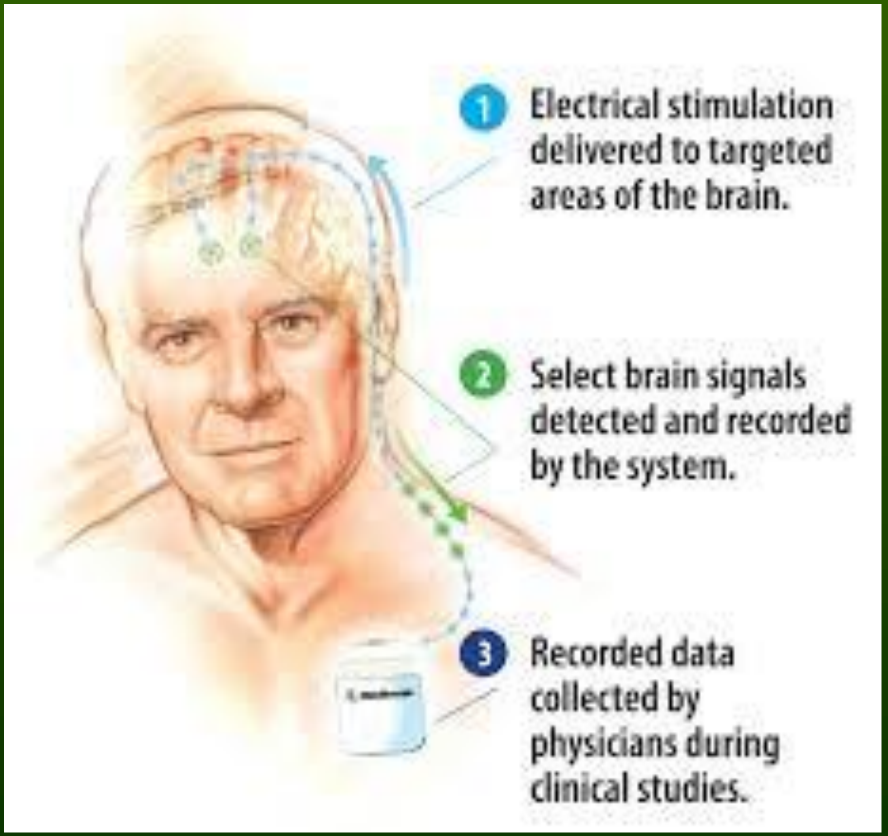
Benabid, A. L… Chabardes, S. (2019).
An exoskeleton controlled by an epidural wireless brain–machine interface in a tetraplegic patient: A proof-of-concept demonstration.
The Lancet Neurology, *18*(12), 1112–1122.

Tetraplegic man walking using a mind-controlled 65kg exoskeleton with two brain implants that read and transmit information
via the patient’s sensorimotor cortex,
which controls motor function.

Amazon introduces neural implant for subconscious shopping (Some News, 12/07/22)

Deep brain stimulation

People suffering from Parkinson's disease or compulsive-obsessive disorder who have electrodes implanted deeply in their brain can regulate their behavior with an external controller.
Let's turn up our brains ... Can I program my brain?

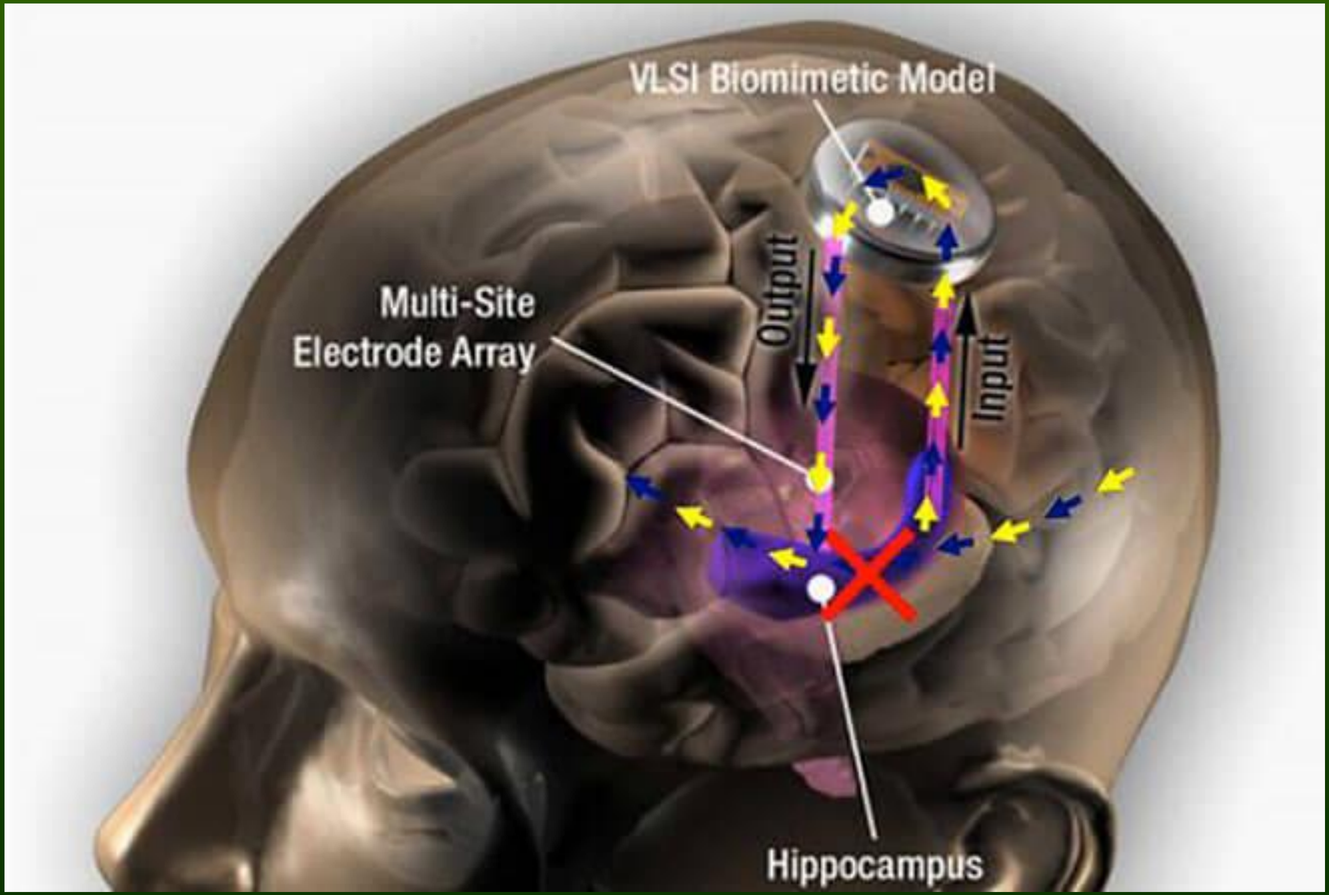


Memory implants

Tests on rats, monkeys, and in 2017 on 20 humans gave an improvement in memory by 30% (on rats by 35%). Ted Berger (USC, Kernel) : There are good reasons to believe that the integration of memory with electronics is possible.

DARPA: Restoring Active Memory (RAM) program, for people with brain damage (TBI), should be non-invasive.

Neurofeedback + closed-loop neurostimulation.



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– **Occipital Lobe**
(Visual function)
BCIs used here to
restore lost vision
or reconstruct visual
inputs

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BRAIN STIMULATING

Implanted Microelectrodes

Tiny electrodes (thickness under 50 μm) delivered via craniotomy, used in electrophysiology for recording neural signals and/or stimulating the brain.

1,000s of patients

Major Applications:

- ALS
- Blindness/ocular injury
- Epilepsy
- Locked-in Syndrome
- Movement disorders
- OCD
- Peripheral nerve injury
- Spinal cord injury
- Stroke

Advantages:
- Recent influx of private R&D funding
- High spatial resolution
- High signal/noise ratio
- Many potential prosthetics applications
- Portable
- Lower surgical risk than ECoG, DBS

Disadvantages:
- Requires craniotomy
- Penetrates brain tissue
- Low material longevity

EE

Endovascular Electrodes

1 implanted patient in 2020

A miniature mounted electrode array that is passed intravenously into the cerebral vasculature and placed in close proximity to specific brain regions.

Major Applications:

- Restoring voluntary motor impulses to control digital devices in patients with severe paralysis

Advantages:
- Can be implanted in many different locations
- Can acquire vascular ECoG signals
- >6 month biocompatibility in animal brain blood vessels

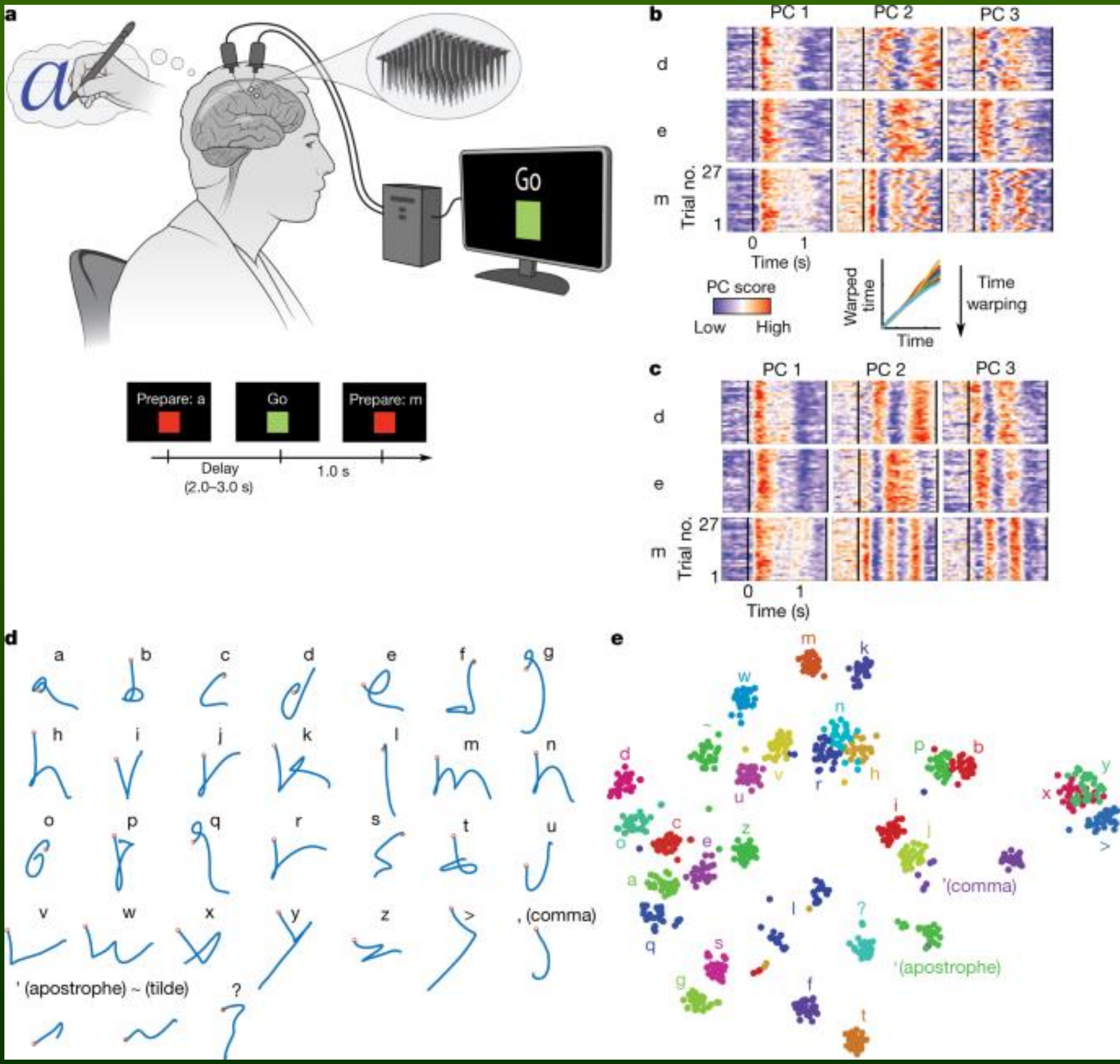
Disadvantages:
- Requires minimally invasive surgery
- Requires lifelong anticoagulant use
- Can only record from neurons adjacent to large vessels

Intracortical array with 192 electrodes.

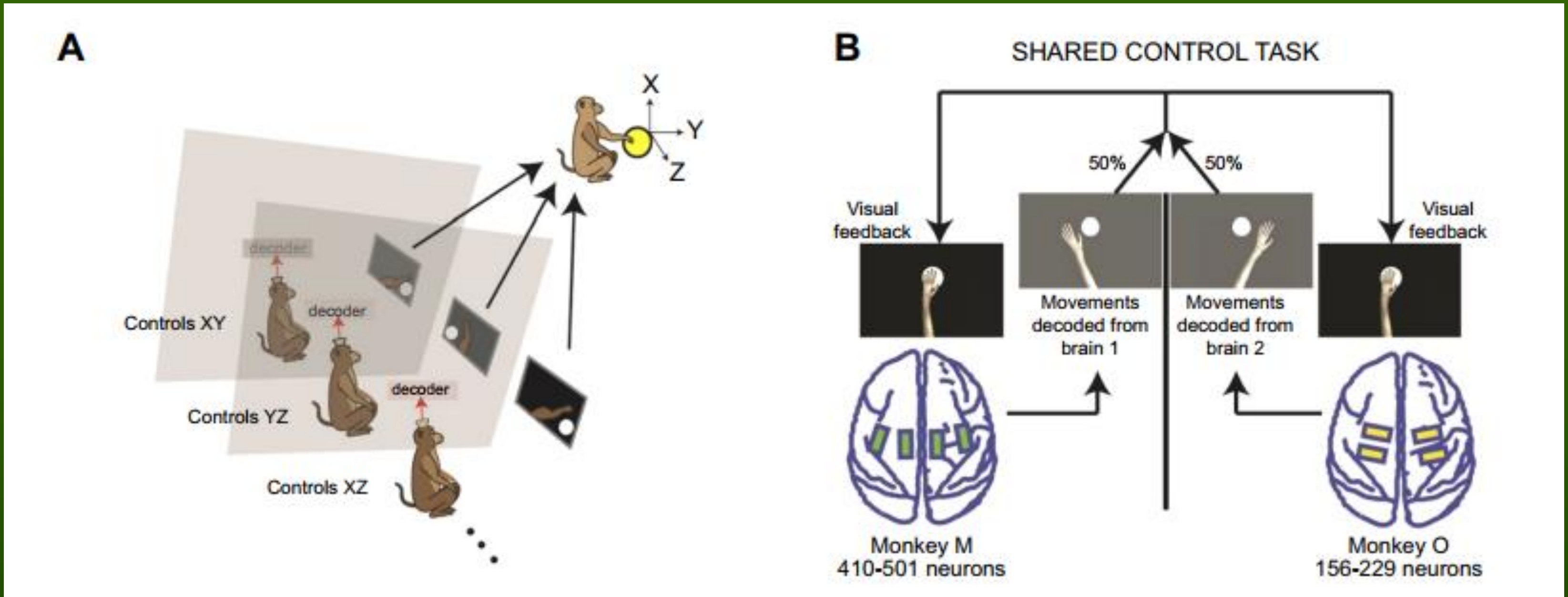
Decoded pen trajectories are shown for all 31 characters.
Time wrapping (shift + scale) is essential for denoising.

Speed: 90 char/min!

Willett, F.R. …. & Shenoy, K.V.(2021) High-performance brain-to-text communication via handwriting. *Nature*, *593*, 249



Brainnets and cBCI



3 monkeys in virtual reality synchronize their brain activity!
Lebedev, M. A., & Nicolelis, M.A.L. (2017). Brain-Machine Interfaces: From Basic Science to Neuroprostheses and Neurorehabilitation. *Physiological Reviews*, *97*(2), 767–837

Bhattacharyya, S., Valeriani, D., Cinel, C., Citi, L., & Poli, R. (2021). Anytime collaborative brain–computer interfaces for enhancing perceptual group decision-making. *Scientific Reports*, *11*(1), Article 1.

Neural screen

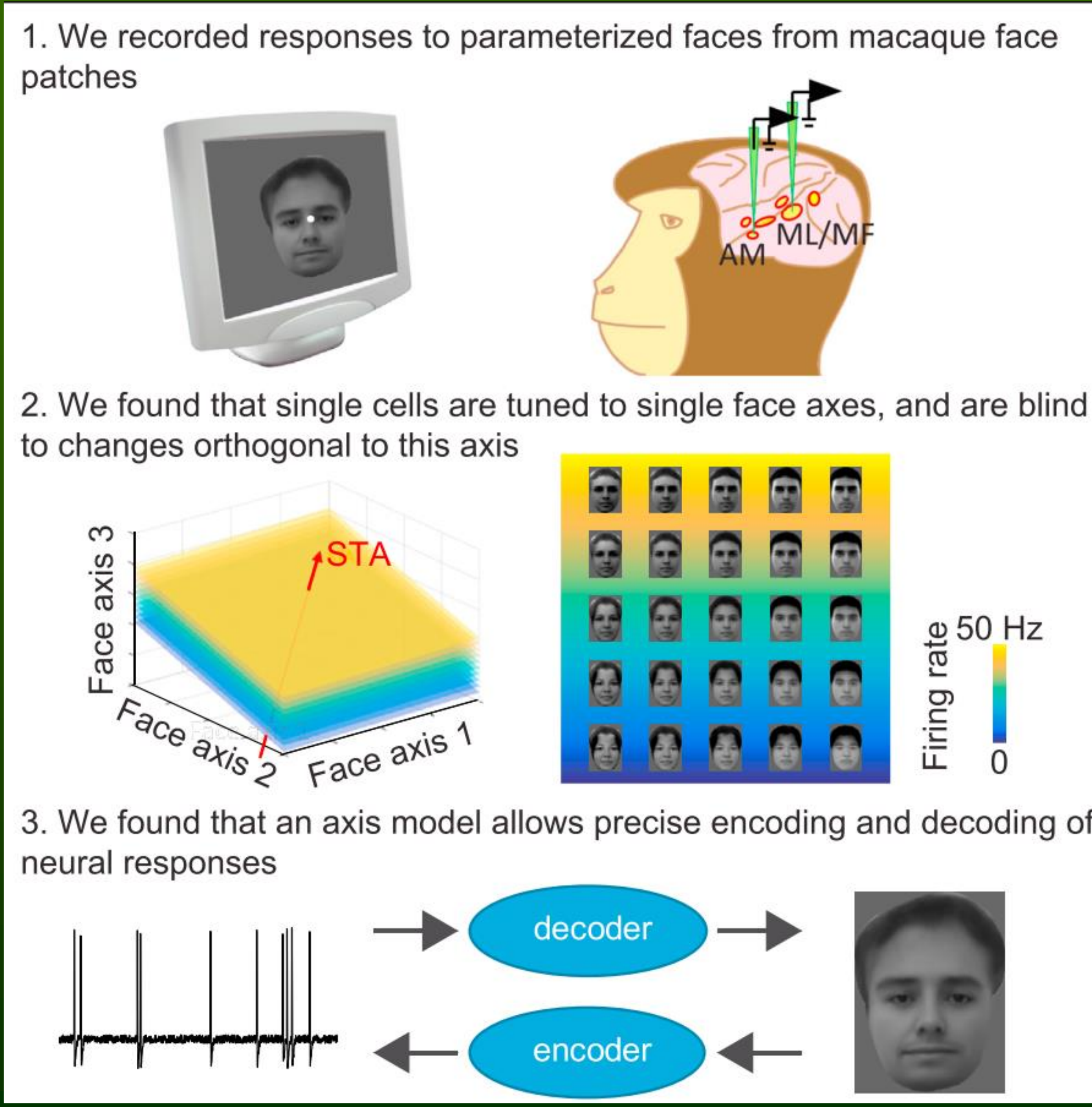
Features of the face image are analyzed and their combination remembered.

This can be decoded from brain signals if we have access to neural spikes.

It took only 205 neurons in several visual cortex areas to reproduce images of the faces from spikes.

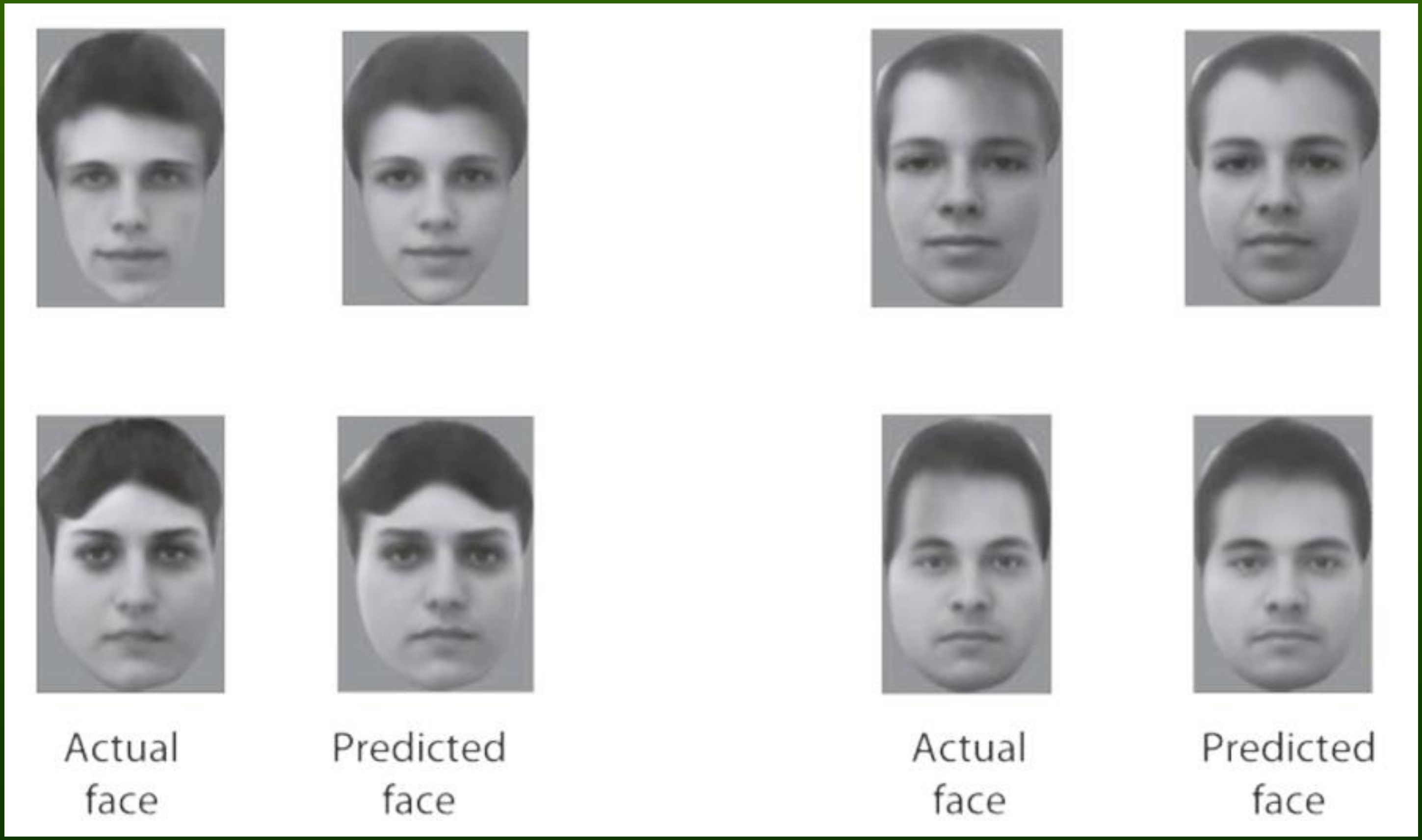
L. Chang and D.Y. Tsao, "**The code for facial identity in the primate brain**" *Cell* 2017

Voice, and even thoughts can be read in a similar way.



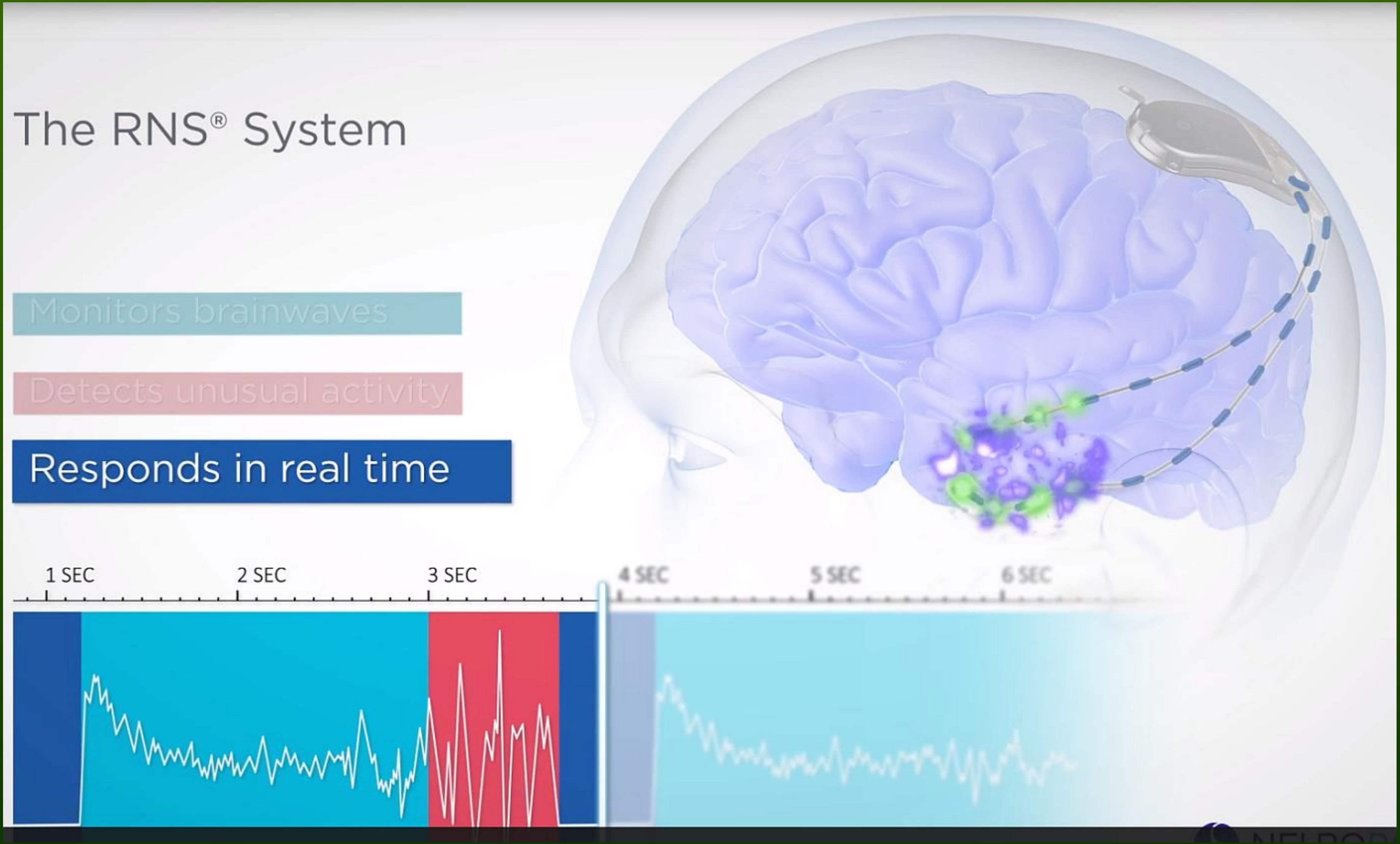
Mental images

The image of the face is encoded using a simple neural code that is based on the ability of neurons to distinguish facial features along specific axes in the facial features space.



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

Epilepsy



The neurostimulator and detector stops attacks of drug-resistant epilepsy before cramps occur. About 1% of people in the world have epilepsy.

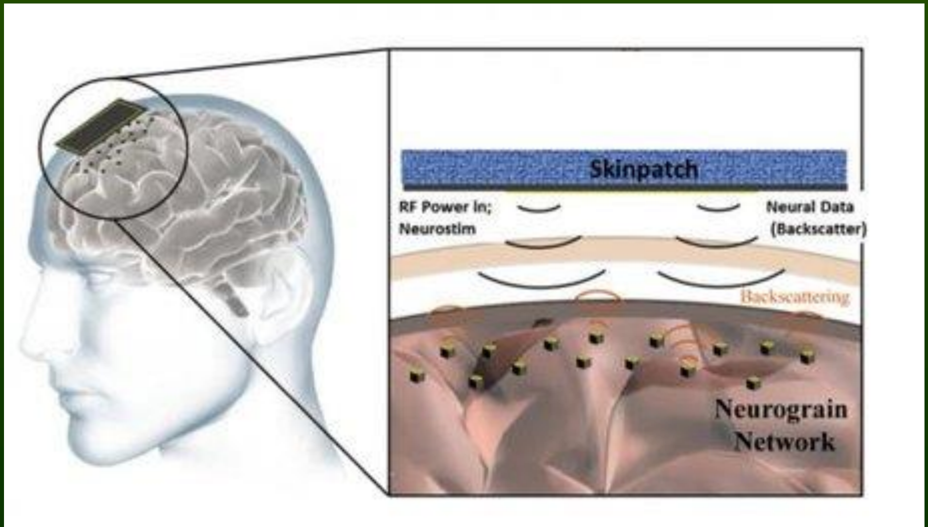
A million nanowires in the brain?

DARPA initiative: **Neural Engineering System Design (NESD)** and other projects.

An interface that reads the impulses of 10^6 neurons, stimulates 10^5 neurons, simultaneously reads and stimulates 10^3 neurons.

DARPA awarded grants to research groups for projects under the program Electrical Prescriptions (ElectRx), whose aim is to develop BCBI systems modulating the activity of peripheral nerves for therapeutic purposes.

Neural dust – microscopic wireless sensors in the brain.
Elon Musk and the much-heralded technology neuralink (neural lace).

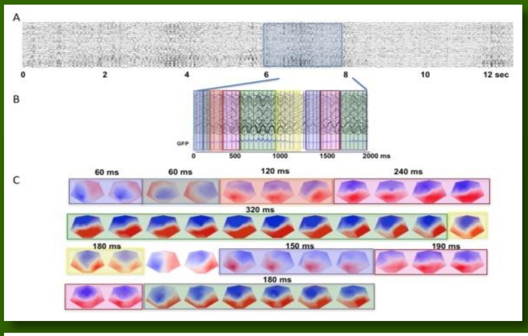


Understanding the brain

Brain fingerprinting

- Find unique patterns of brain activity to identify:
  - brain regions of interest (ROI)
  - active neural networks
  - mental states, tasks, processes.
- **Several approaches:**
- 1. Microstates and their transitions (Michel & Koenig 2018)
- 2. Reconfigurable task-dependent modes (Krienen et al. 2014)
- 3. Contextual Connectivity (Ciric et al. 2018)
- 4. Spectral Fingerprints (Keitel & Gross 2016)
- 5. fMRI networks (Yuan … Bodurka, 2015).
- 6. Recurrence quantification analysis.
- + many more approaches…

1



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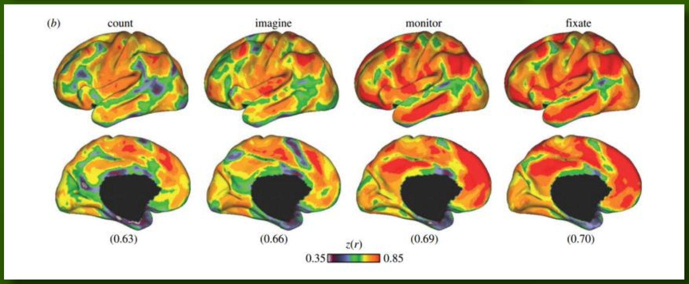

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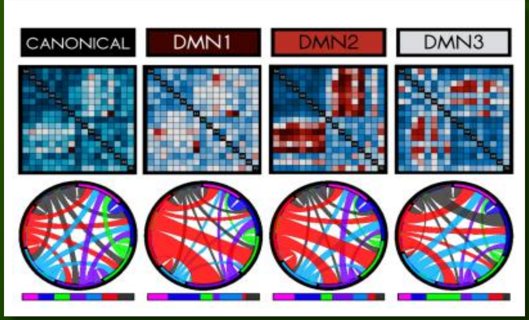

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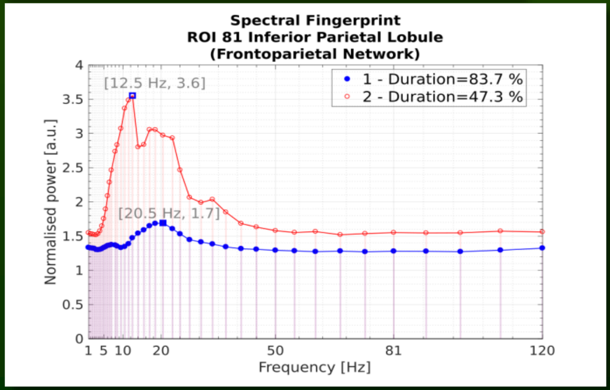
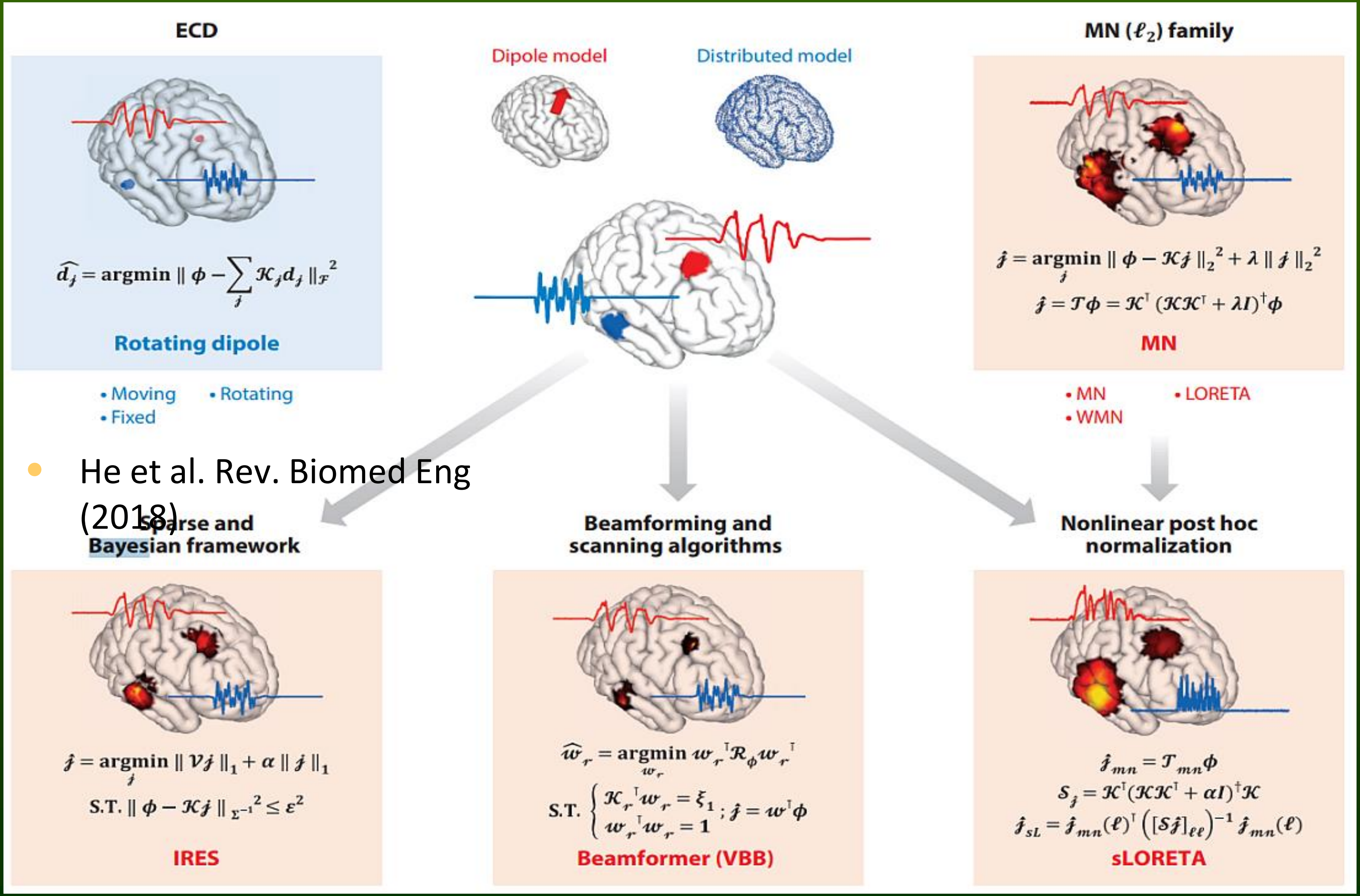


EEG localization and reconstruction

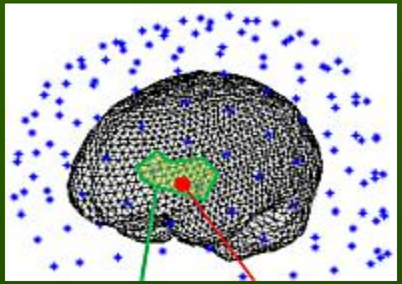


- He et al. Rev. Biomed Eng (2018)

Spatial filters

- LCMV (Linearly Constrained Minimum Variance), classical reconstruction filter is a solution to the following problem:
  K - *lead-field* matrix; θ – dipol positions, *j* – activations; *W* – spatial filter, leadfiled

$$\Phi = K(\theta) j + n,\ j \approx W\Phi,\ WK(\vartheta) \approx \mathrm{I}$$



- LCMV has large error if:
  • sources are correlated,
  • signal to noise ratio (SNR) is low, or
  • forward problem is ill-conditioned.

- Minimum variance pseudo-unbiased reduced-rank, MV-PURE:
  T. Piotrowski, I. Yamada, IEEE Transactions on Signal Processing **56**, 3408-3423, 2008

$$W = \bigcap_{j \in \Upsilon} \arg\min_{\hat{W} \in X_r} \left\| \hat{W} K(\theta) - \mathrm{I}_l \right\|_j^2$$

where X_r is a set of all matrices of rank at most *r*, and set Υ denotes all unitary norms. We use 15000 vertex FreeSurfer brain tessellation together with brain atlases that provide parcellation of the mesh elements into 100-240 cortical patches (ROIs).

SupFunSim

- SupFunSim: our library/Matlab /tollbox, direct models for EEG/MEG, on GitHub.
- Provides many spatial filters for reconstruction of EEG sources: linearly constrained minimum-variance (LCMV), eigenspace LCMV, nulling (NL), minimum-variance pseudo-unbiased reduced-rank (MV-PURE) …
- Source-level directed connectivity analysis: partial directed coherence (PDC), directed transfer function (DTF) measures.
- Works with FieldTrip EEG/ MEG software. Modular, object-oriented, using Jupyter notes, allowing for comments and equations in LaTex.

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

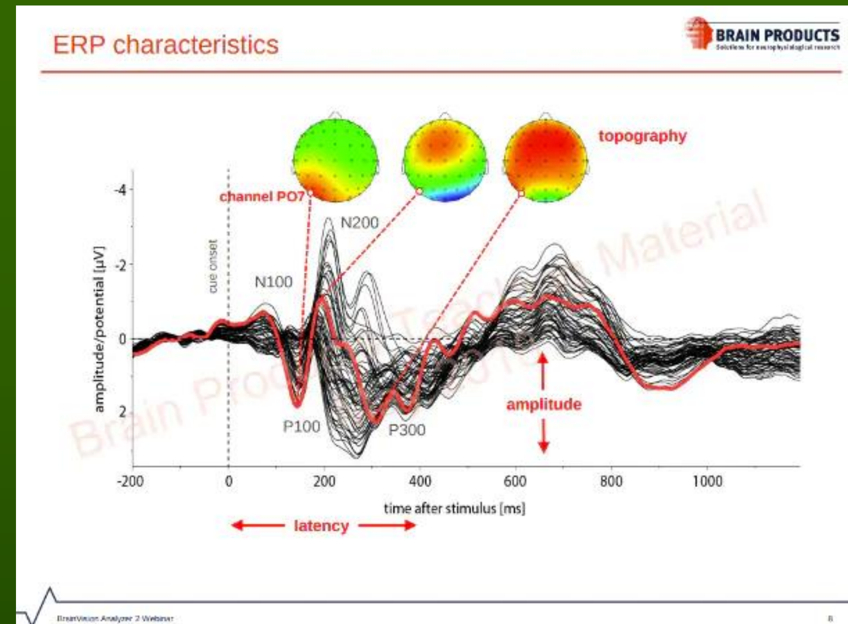
$$B := H_{Src,N} := N^{-1/2} H \quad (35)$$

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

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

- K. Rykaczewski, J. Nikadon, W. Duch, T. Piotrowski, *Neuroinformatics* **19**, 107-125, 2021.

Understanding brains: ERP



What do brain signals tell us?

Evoked potentials:

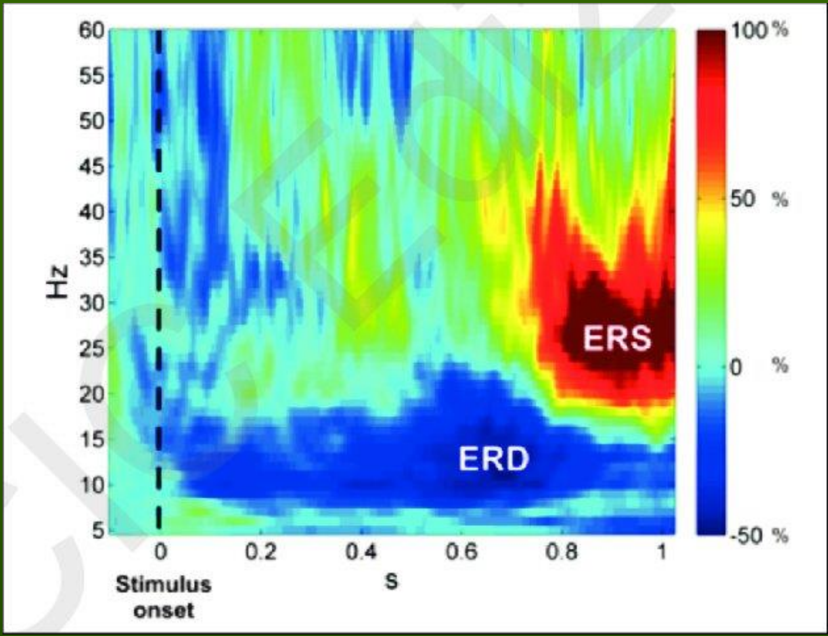
- Visual evoked potential VEP, SSVEP
- Auditory evoked potential AEP
- Somatosensory evoked potential SEP
- Motor evoked potentials MEP

Event-Related Potentials, higher cognitive processing.

ERP – most popular, average of many trials.

- Negativity: N100 • Visual N1 • N170 • N200 • N2pc • N400
- Positivity: P200 • P300 • P3a • P3b • Late positive component • P600
- Contingent negative variation (CNV), Error-related negativity (ERN)
- Mismatch Negativity (MMN), Centro-parietal positivity (CPP)

Understanding brains: ERS/ERD



Event-Related Synchronization (ERS) and Desynchronization (ERD).

- bandpass filtering of each trial, averaging over trials and sample points.
- Sensory, cognitive and motor processing can result in changes of the ongoing EEG in form of ERD or ERS.
- Both phenomena are time-locked but not phase-locked to the event and they are highly frequency-band specific.
- The ERD is correlated with activated cortical area with increased excitability and the ERS in the alpha and lower beta bands can be interpreted, at least under certain circumstances, as a correlate of a deactivated cortical area.
- Spatial mapping of ERD/ERS can be used to study the dynamics of cortical activation patterns. Examples from a movement task are reported.

Understanding brains: microstates

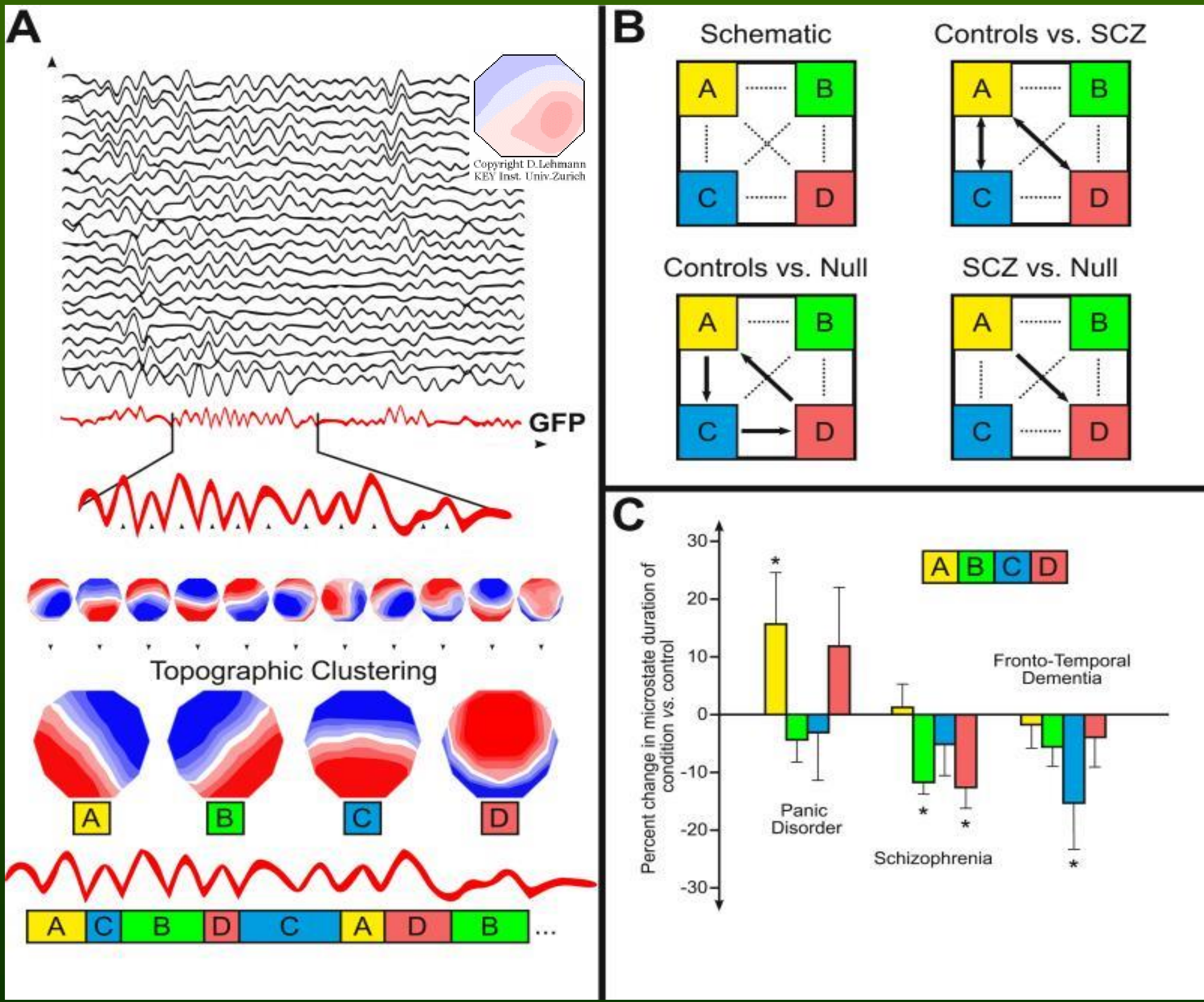
Global EEG Power.
4-7 states, 60-150 ms.

Khanna et al. (2015) Microstates in Resting-State EEG. *Neuroscience and Biobehavioral Reviews*.

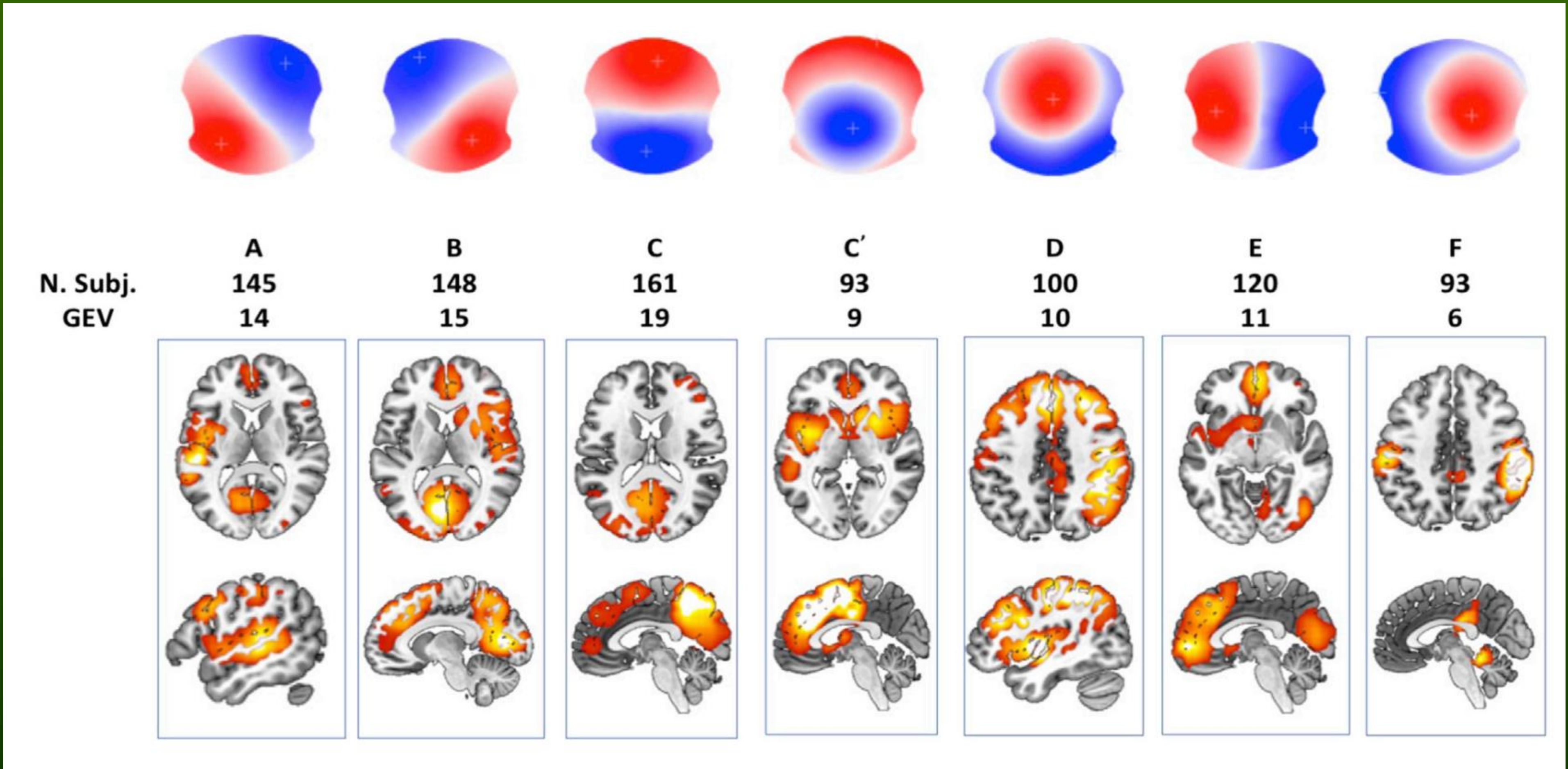
Symbolic dynamics: statistics of A-D symbol strings. Fuzzy Symbolic Dynamics (FSD) + visualizations.

Duch W, Dobosz K. (2011). Cognitive Neurodynamics 5, 145

Dobosz K, Duch W. (2010). Neural Networks, 23(4), 487–496.



Microstates and their 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.

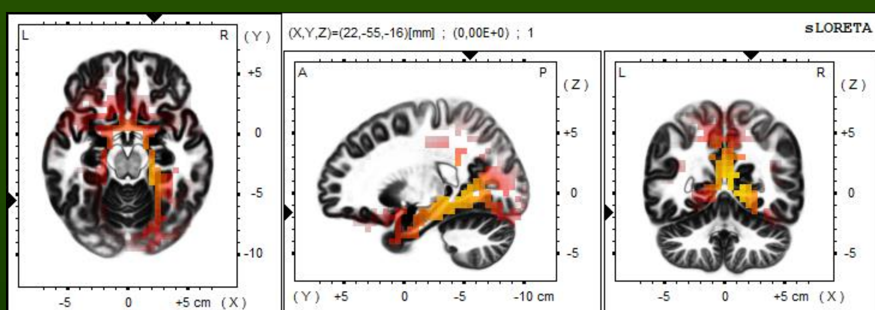
HRV-EEG-feedback

Influence of HRV biofeedback training on microstates and fluent intelligence (PhD of Ewa Ratajczak). Initially:

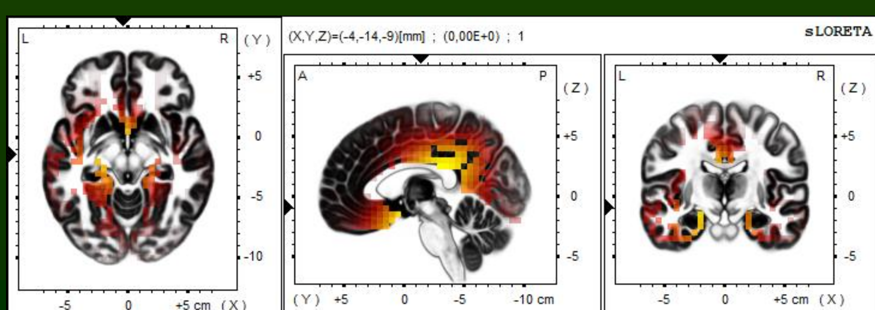
- distinguished 9 microstates during HRV-BFB;
- #5 (G): prefrontal and right temporoparietal areas;
- #9 (E): left hemispheric prefrontal cortex, insular cortex and temporoparietal cortex

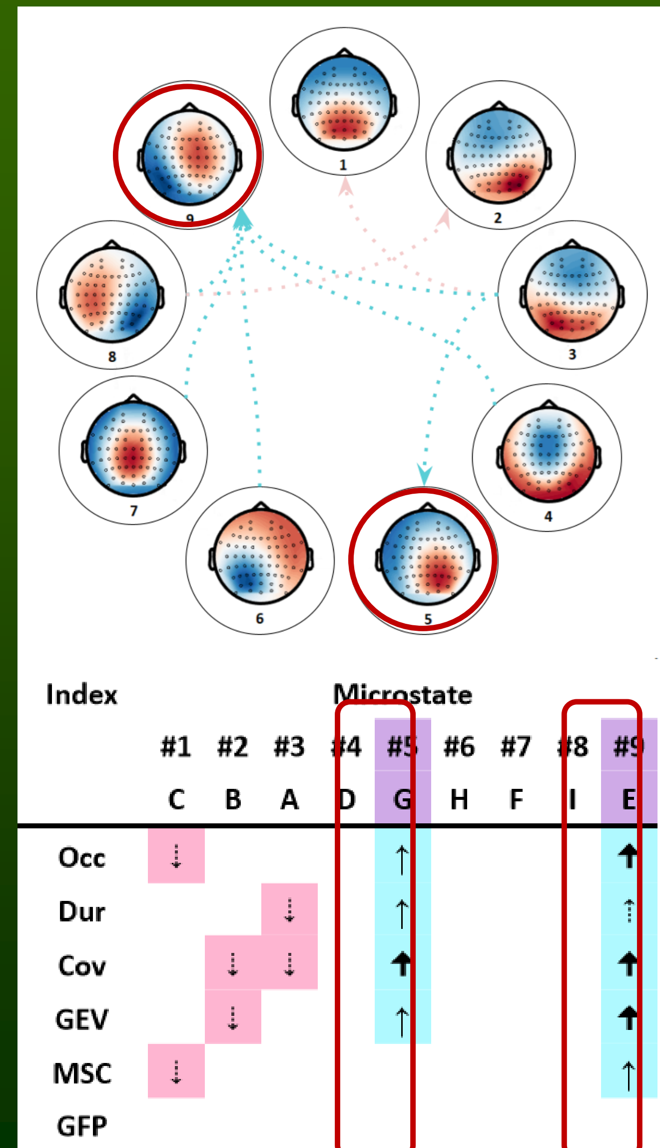
Visually guided somatosensory and affective control.

#5 (G)



#9 (E)

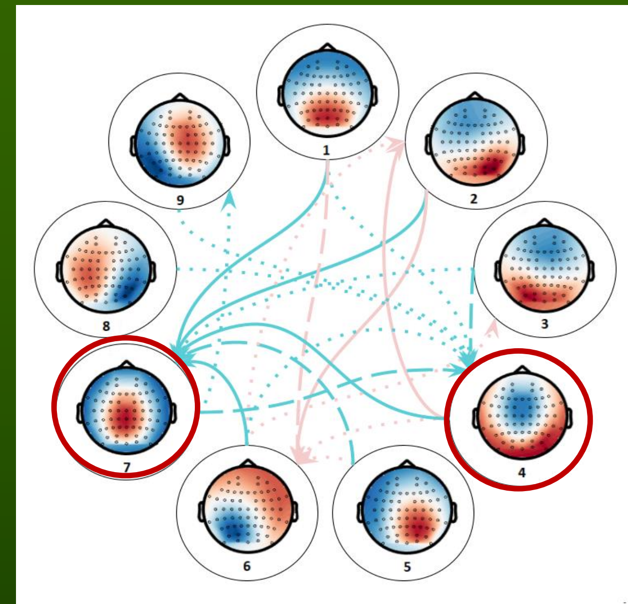




HRV-EEG-training

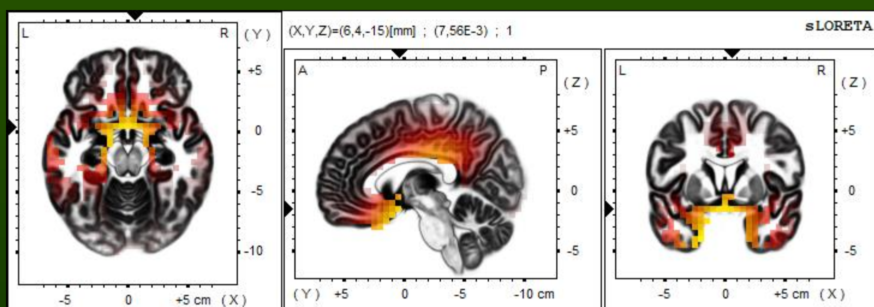
HRV-BFB training increased activation of microstates

- #4 (D): attentional/cognitive control network
- #7 (F): insula/circuit network
- Related to neural activity in EEG θ and δ bands, neuroplasticity.
- Switching between external/internal attention networks, enhanced cognitive control.

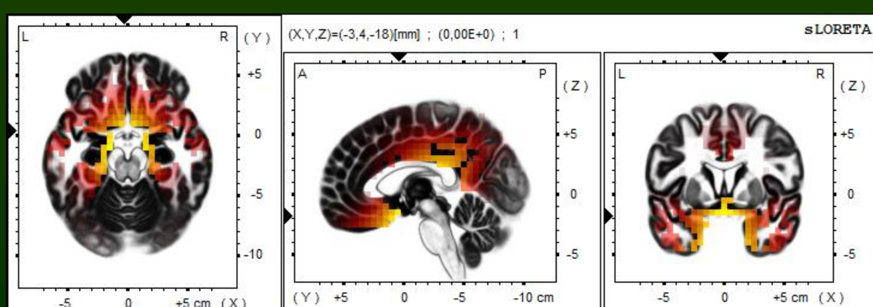


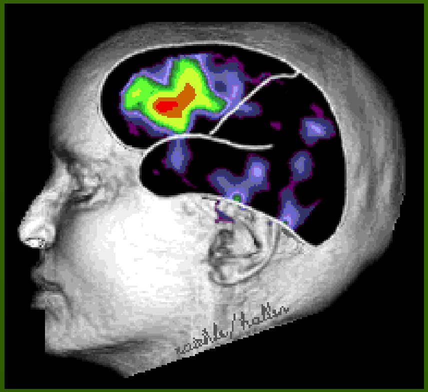
Index	Microstate								
	#1	#2	#3	#4	#5	#6	#7	#8	#9
	C	B	A	D	G	H	F	I	E
Occ		↓	↓	↑		↓	↑		
Dur		↓	↓	↑		↓	↑		
Cov		↓	↓	↑		↓	↑		
GEV		↓		↑		↓	↑		
MSC				↑	↑		↑		↑
GFP									

#4 (D)



#7 (F)

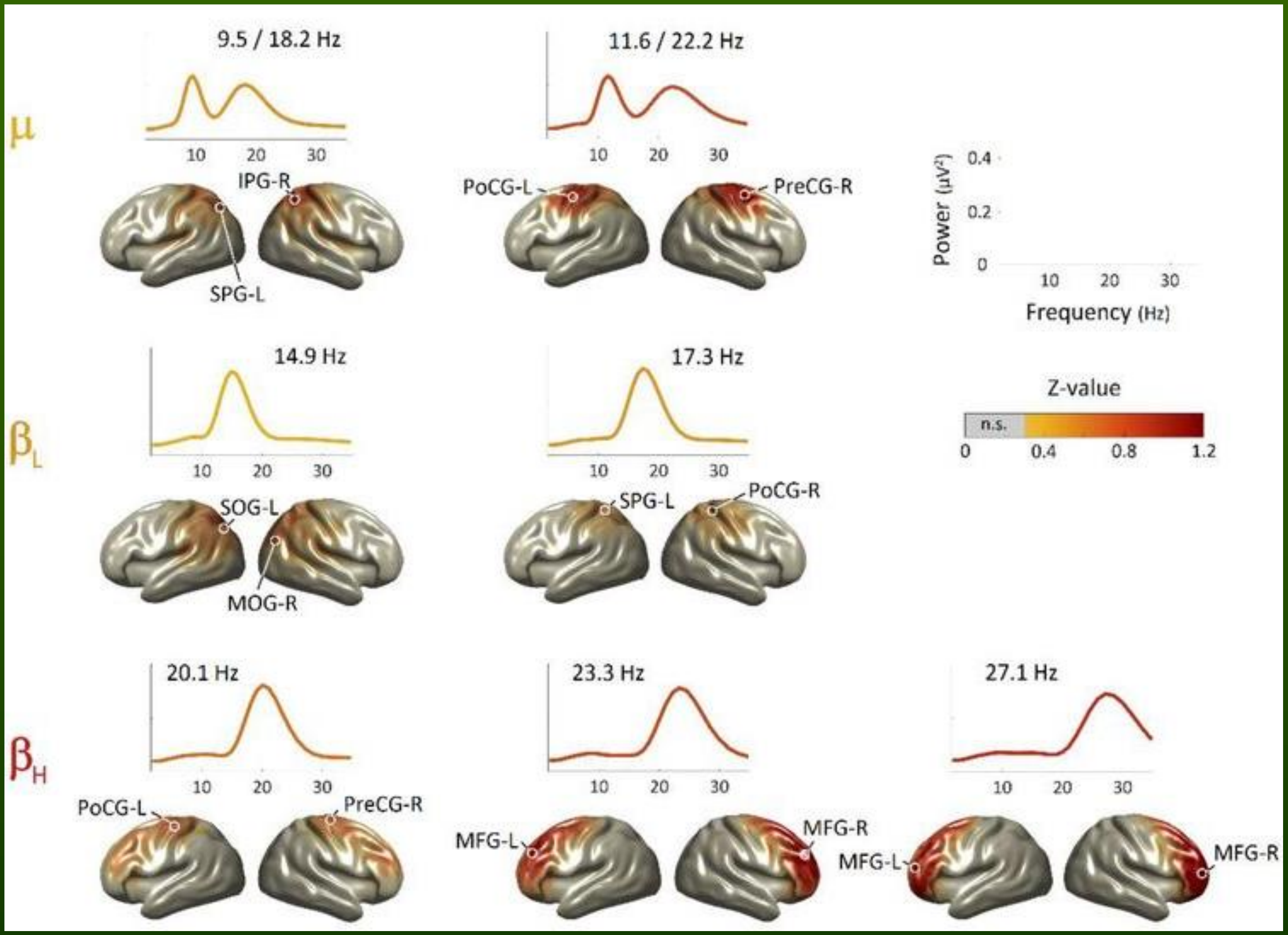




EEG and neurodynamics

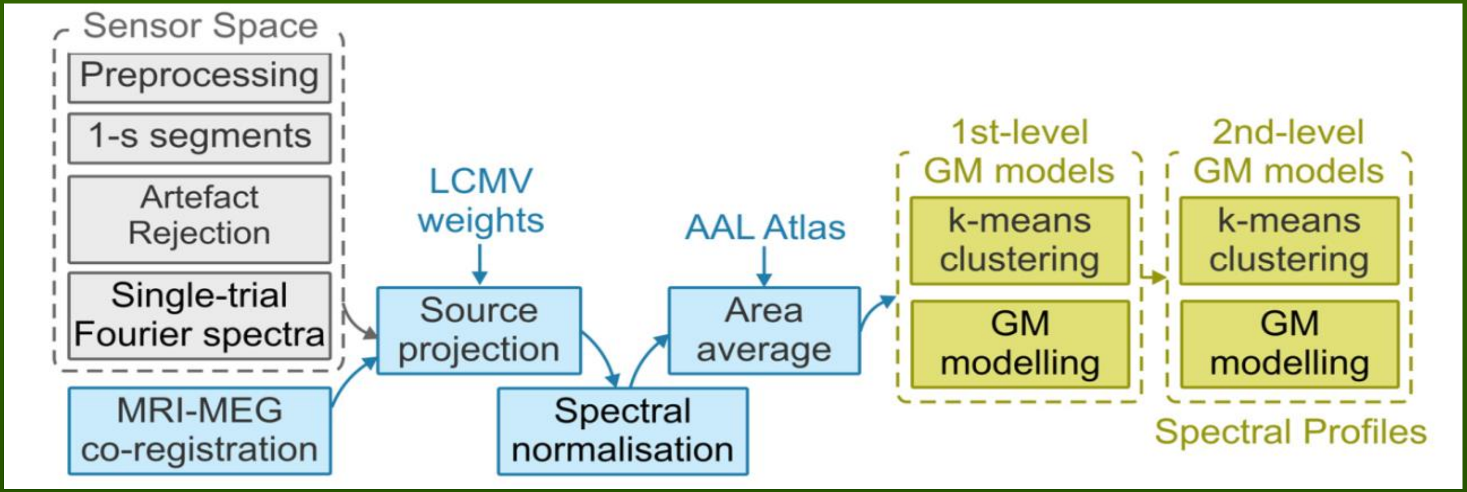
Atlas of the natural frequencies, resting brain

Peak frequencies in selected brain areas observed using MEG in the resting brain.



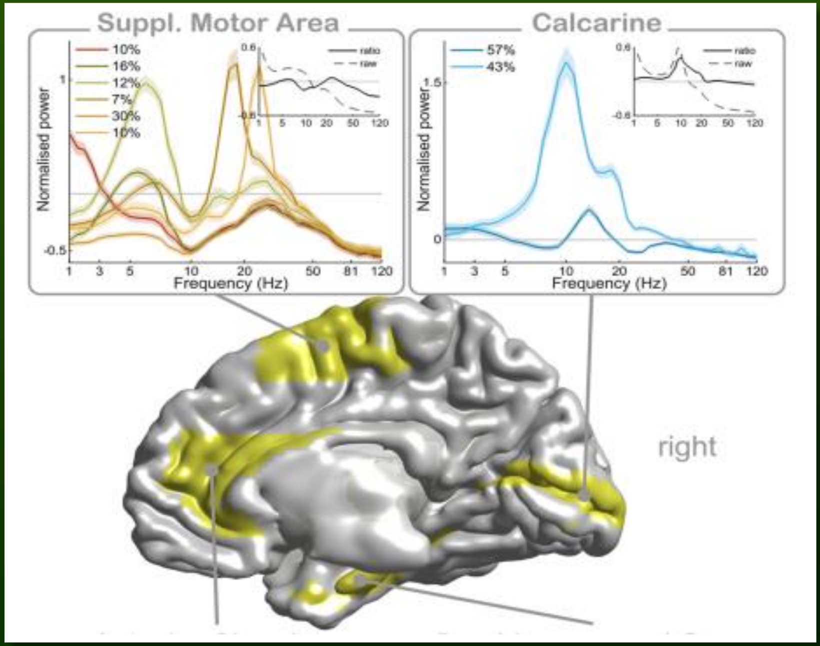
Capilla, A., Arana, L., García-Huéscar, M., Melcón, M., Gross, J., & Campo, P. (2021). *The natural frequencies of the resting human brain: An MEG-based atlas.* BioRxiv 2021 11.17.468973

Spectral analysis

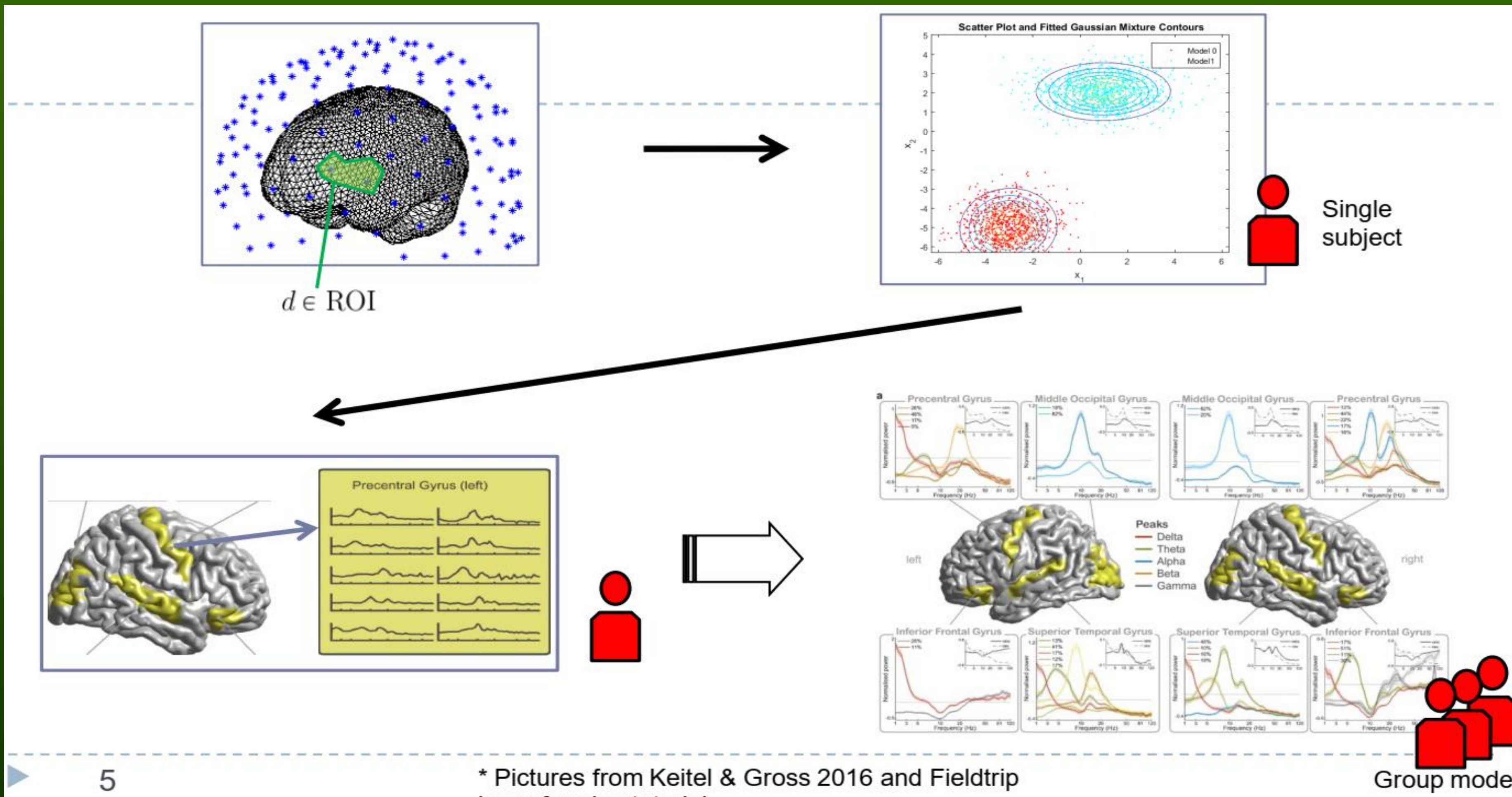


Create spectral fingerprints of ROIs.

- Analyze EEG/MEG power spectra in 1 sec time windows; project them to the source space of ROIs based on brain atlas; clusterize individual/group to create spectra.
- A. Keitel & J. Gross. Individual human brain areas can be identified from their characteristic spectral activation fingerprints. *PLoS Biol* 14, e1002498, 2016



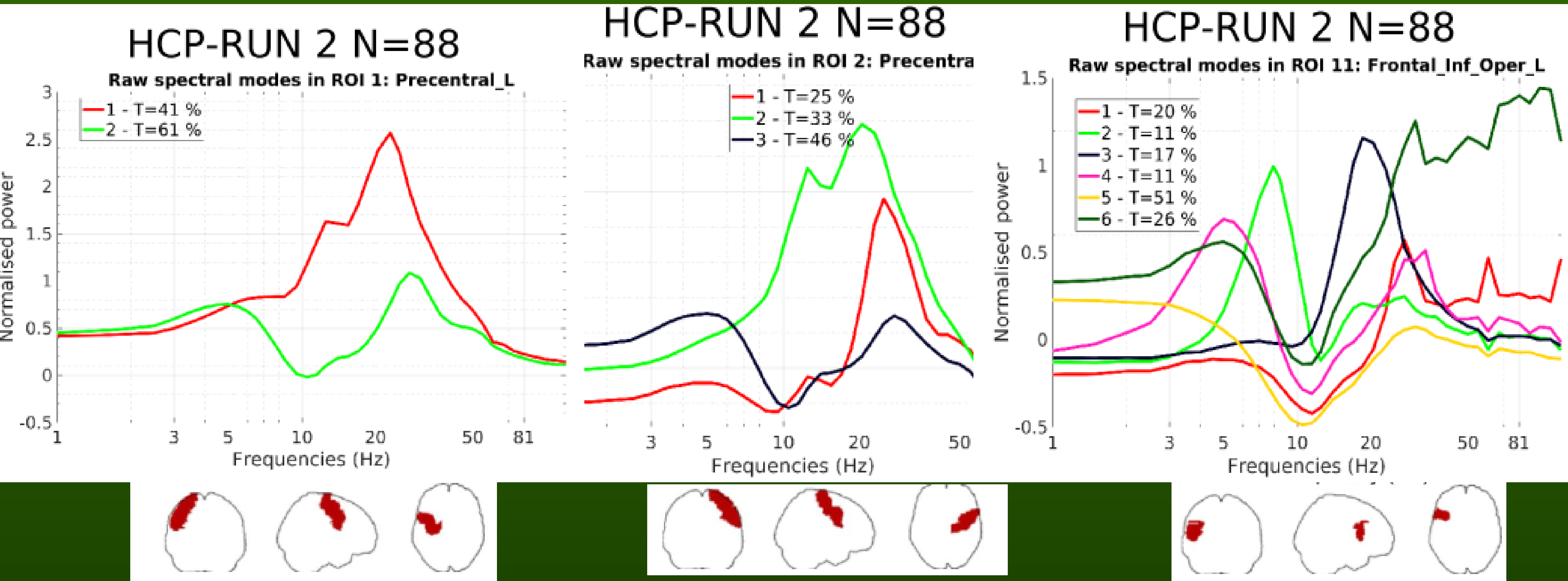
Spectral fingerprints



One ROI, two or more spectra. Static picture showing natural frequencies.

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

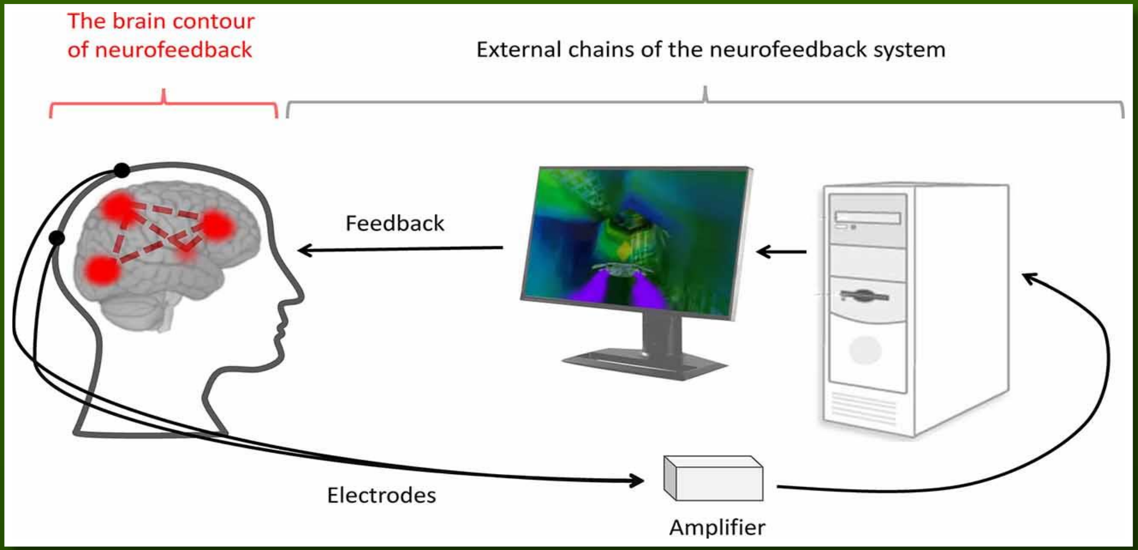
Spectral fingerprints



- Example of spectra showing modes of oscillation characteristic to precentral left and right gyrus, and much more complex opercular part of inferior frontal gyrus. MEG data from the Human Connectome Project (HCP).

Spectral Fingerprint Challenges

Michał Komorowski



Source: O. R. Dobrushina *et al. Front. Hum. Neurosci.* 14, 2020

Method was tested for MEG resting-state data, will it work for EEG recordings?

- Can we extract features that will be useful as biomarkers for brain disorders?
- Can we do it in real time for neurofeedback applications?

M.K. Komorowski, K. … W. Duch (2022)
ToFFi - Toolbox for Frequency-based Fingerprinting of Brain Signals. Neurocomputing (revised + Arxives).

Are linear constraint minimum variance filters (LCMV) sufficient for signal reconstruction?

Spectral fingerprints of cognitive processes

Decompose neurodynamics.
Find subnetworks binding ROIs at specific frequencies.
Oscillations can rapidly change, one ROI is engaged in different subnetworks for short time periods.
This is reflected very crudely in microstates, recurrence plots show more precise information.

Siegel, M., Donner, T. H., & Engel, A. K. (2012). Spectral fingerprints of large-scale neuronal interactions. *Nature Reviews Neuroscience*, *13*(2), 121–134.

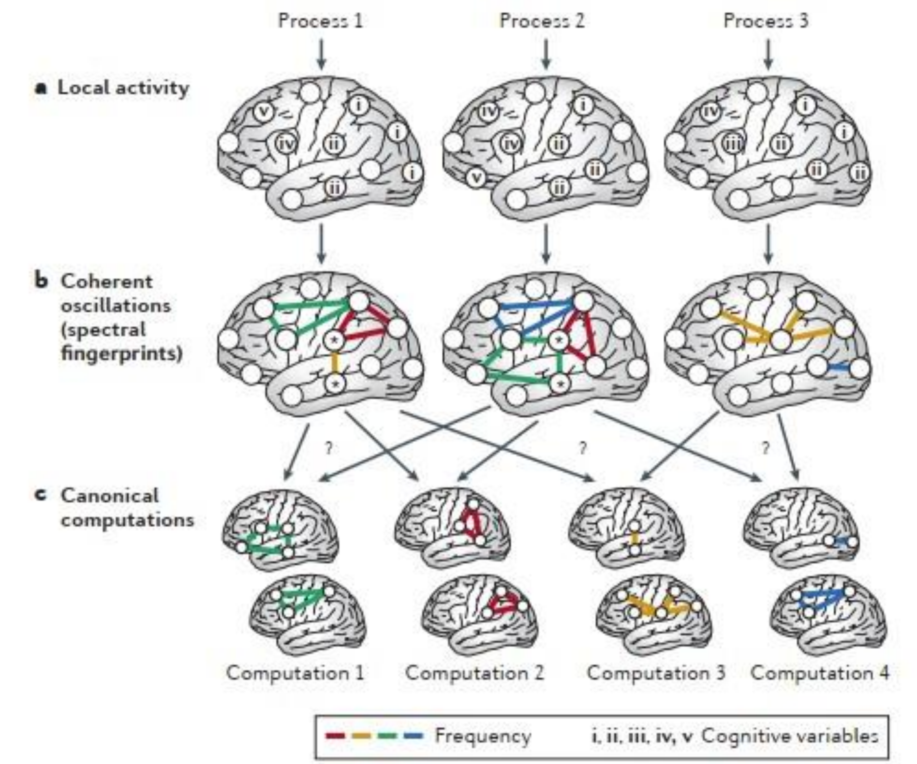


Figure 4 | **Large-scale spectral fingerprints of cognitive processes.** Schematic illustration of how coherent oscillations provide 'spectral fingerprints' for regrouping of cognitive processes 1–3. **a** | Studies of neuronal activity in individual brain regions (circles) elucidate the activation of different regions (bold circles) and the encoding of various cognitive variables (Roman numerals) during different cognitive processes. Several cognitive variables (for example, different sensory features) are simultaneously encoded in each region, but for simplicity only one variable is depicted per region. Note that the pattern of local activity and encoding can be similar between processes. **b** | Coherent oscillations allow for the characterization of the interactions between different brain regions (coloured lines) during different cognitive processes. The frequency of these oscillations (indicated by the colours) allows the corresponding network

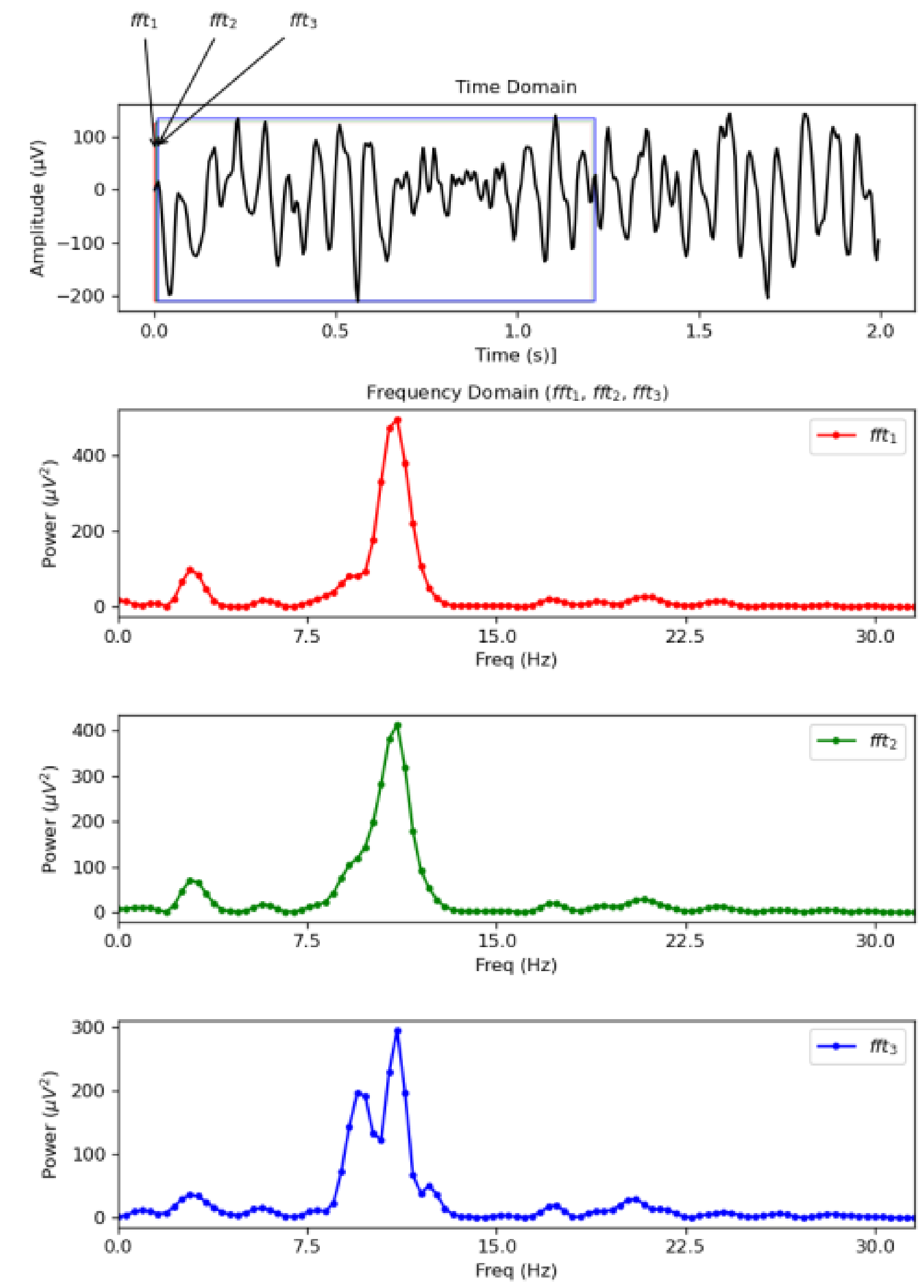
Recurrence analysis

STFT vs. embedding

Takens theorem: attractors are recreated from signals sampled using time-delay embedding, vectors $\mathbf{x}_i = (u_i, u_{i+\tau}, \ldots, u_{i+(m-1)\tau\Delta t})$. Here m is the embedding dimension, and τ is an index enumerating time delays, $\tau\Delta t$.

Alternative representation: STFT, shows power distribution in subsequent time windows. Here changes of spectrum every 100 ms, O1 electrode.

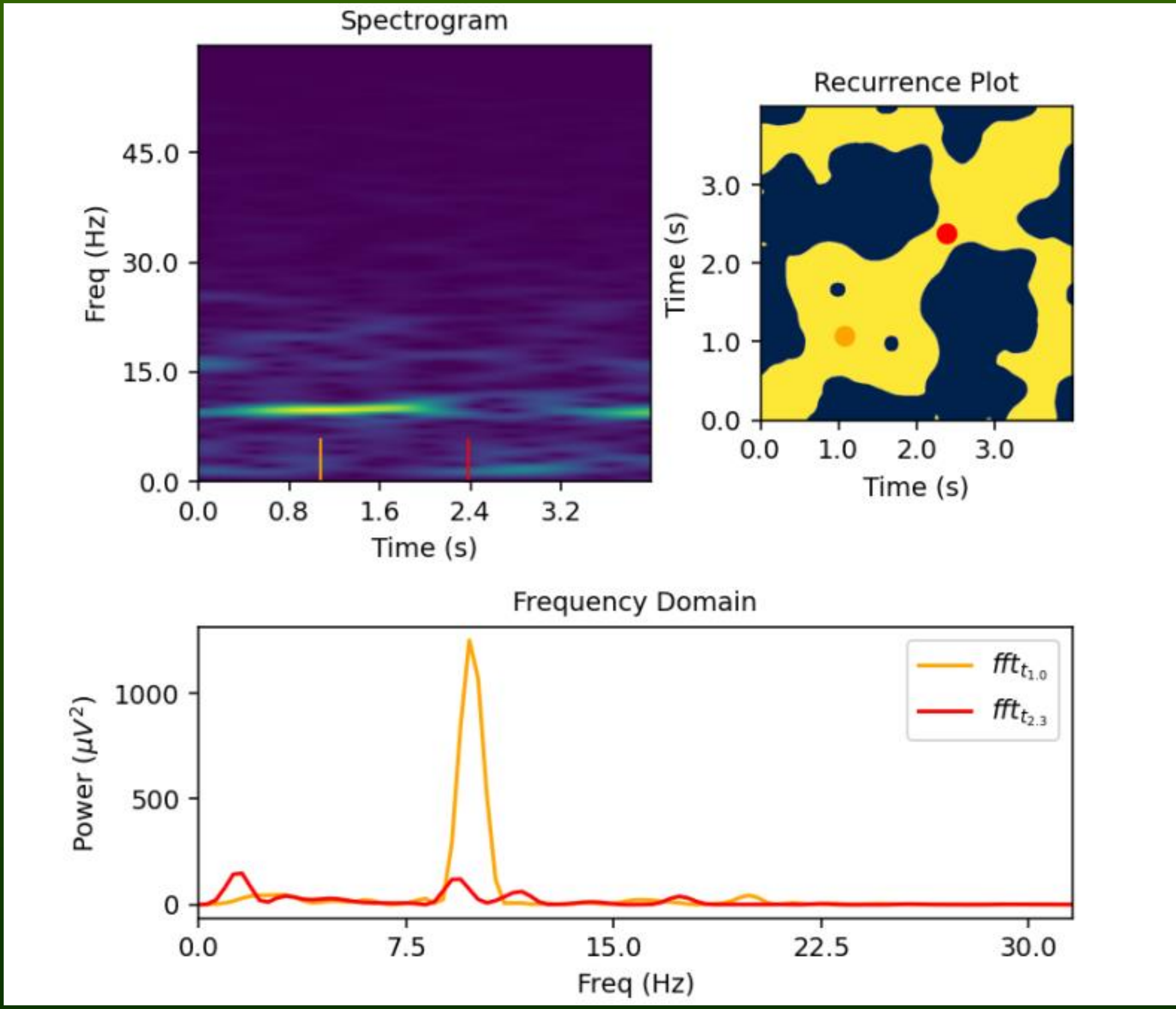
W. Duch, Ł. Furman, K. Tołpa, L. Minati, Short-Time Fourier Transform and Embedding Method for Recurrence Quantification Analysis of EEG Time Series. The European Physical Journal Special Topics (in print).



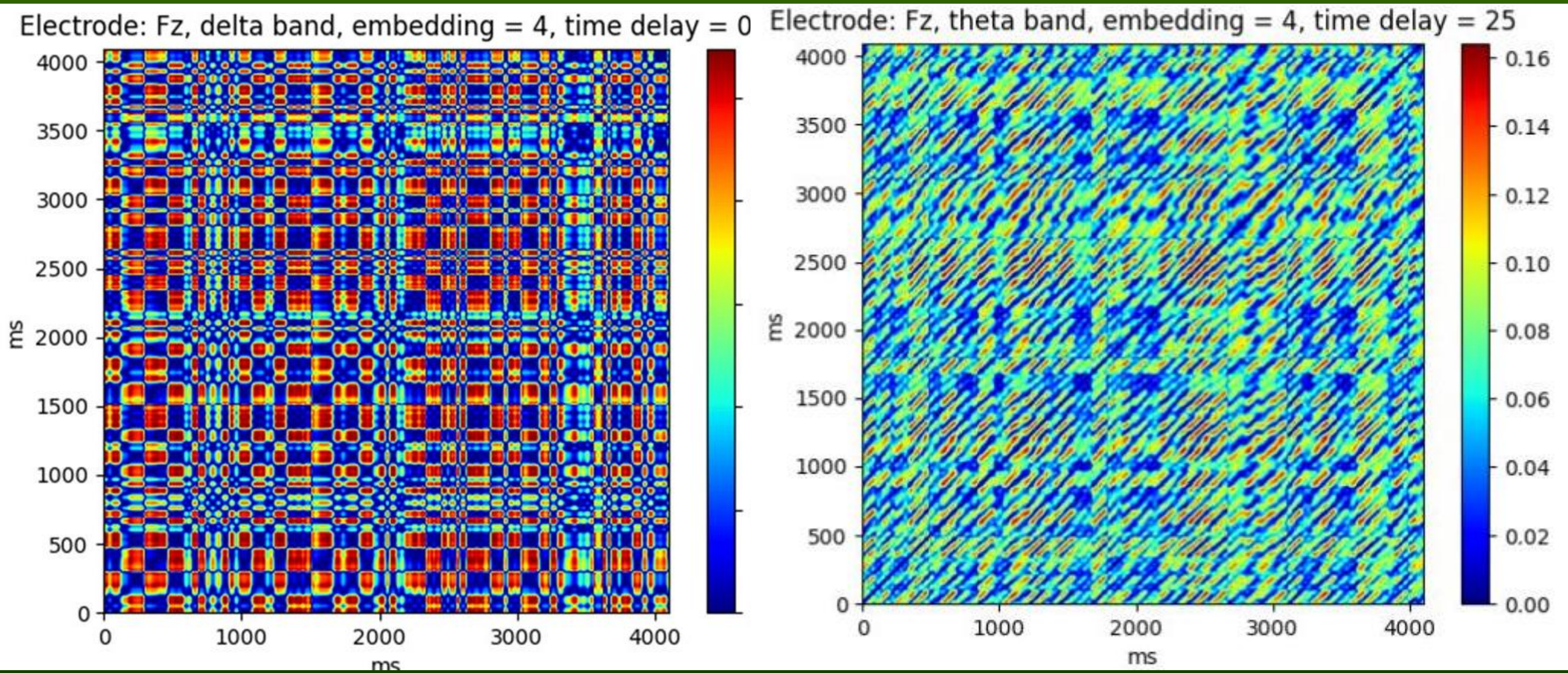
Time/frequency spectrograms & RPs

Information in t/f spectrograms is represented in recurrence plots, that can be analyzed using RQA, recurrence quantification analysis to extract non-linear features characterizing dynamics, see recurrence-plot.tk

Pipelines: raw signal to X (emb) or Y (STFT) to recurrence matrix to non-linear features.
U=>X=>RX=>FX
U=>Y=>RS=>FS.

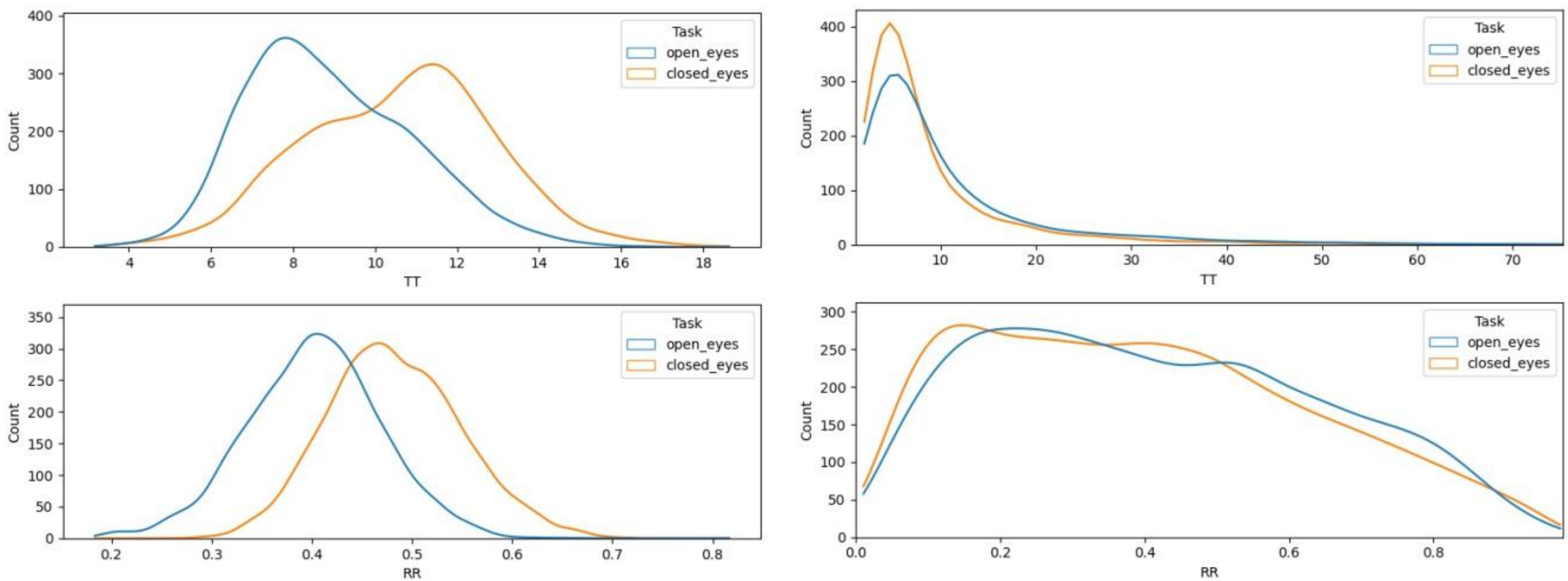


Recurrence plots δ, θ



Unthreshold RPs for delta and theta bands, Fz electrode.
Distance scale changes parameters of the metastable states along diagonal, and influence non-linear parameters. Łukasz Furman builds BrainPulse tools for analysis of RPs. This movie shows changes of t/f spectra, RPs and STFT power spectra.

Features for classification

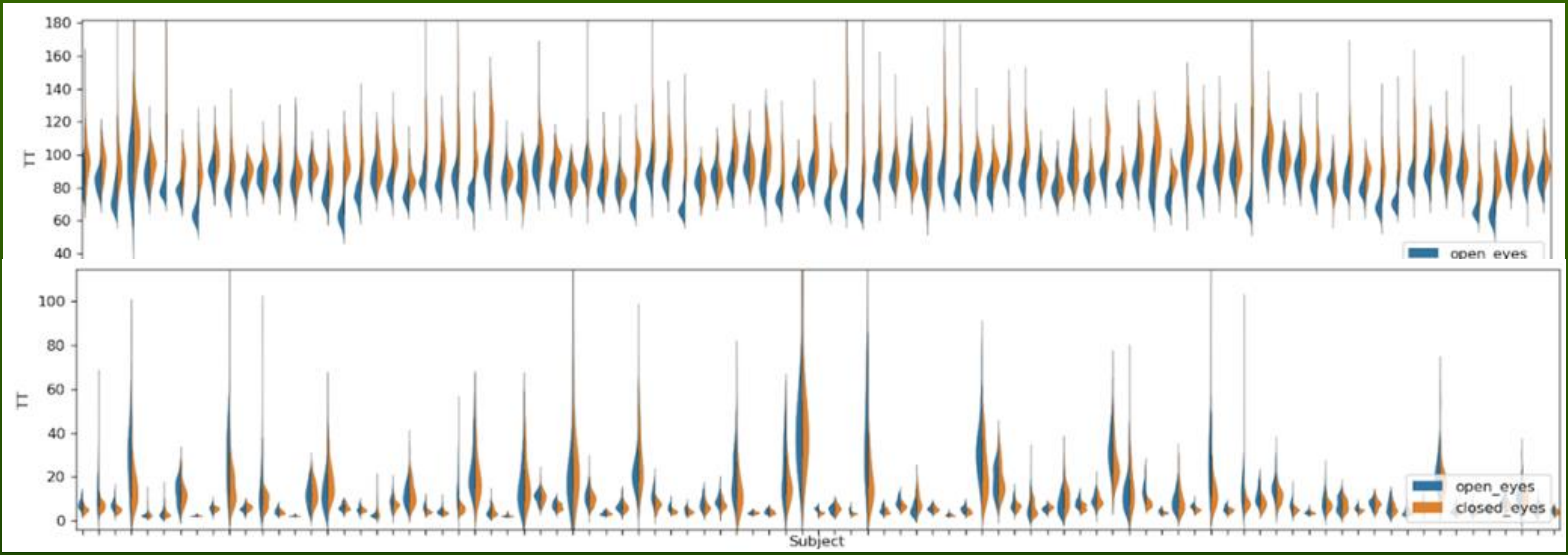


Example of distribution of values of trapping time (TT) and recurrence rate (RR), calculated from 31 seconds of EEG, each containing about 5000 samples per channel, 90 people, in two conditions: eyes closed and open.

Left side: STFT representation, right side embedding with *d*=2, τ=9.

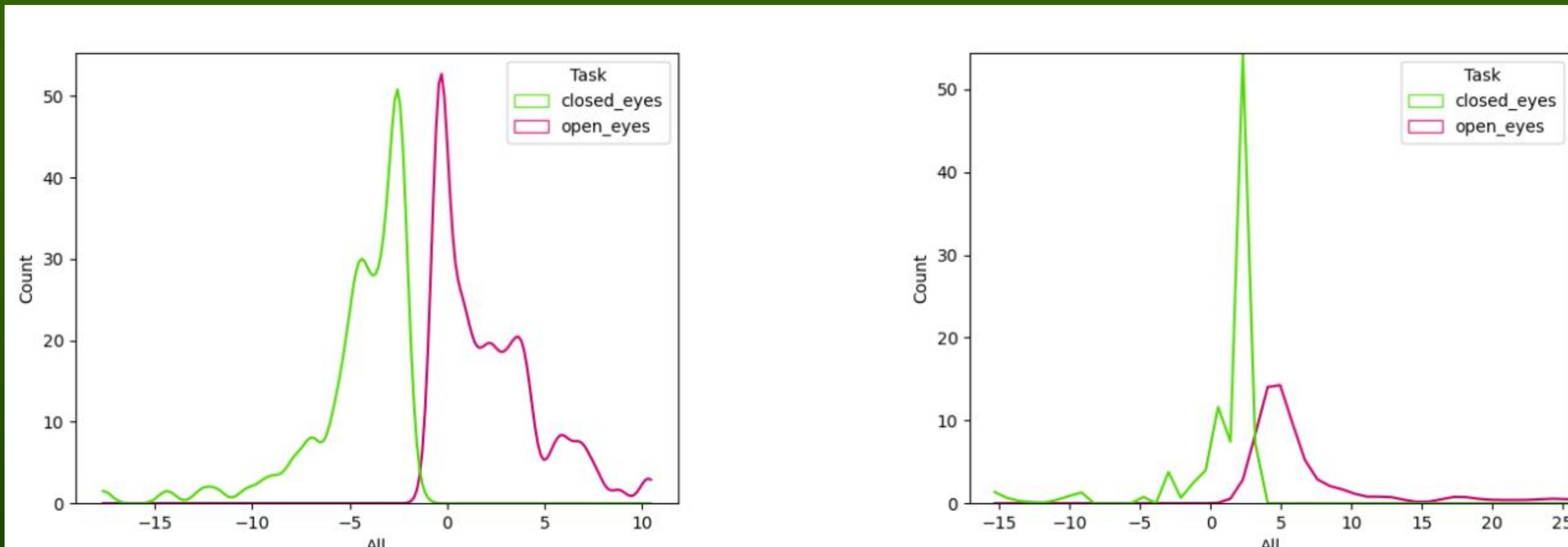
We have used 6 out of 12 non-linear RQA features for classification.

RQA features for 64 electrodes



Distribution of trapping time values for 64 electrodes shown for all 90 subjects.
Top: STFT, bottom: optimized embedding.
For some people STFT allows for easy separation of the two conditions using a single RQA feature. Variance is very different, depending on the person.
Linear SVM provides weights for (feature, electrode), facilitating selection of relevant combinations and reducing number of EEG channels.

LSVM classification



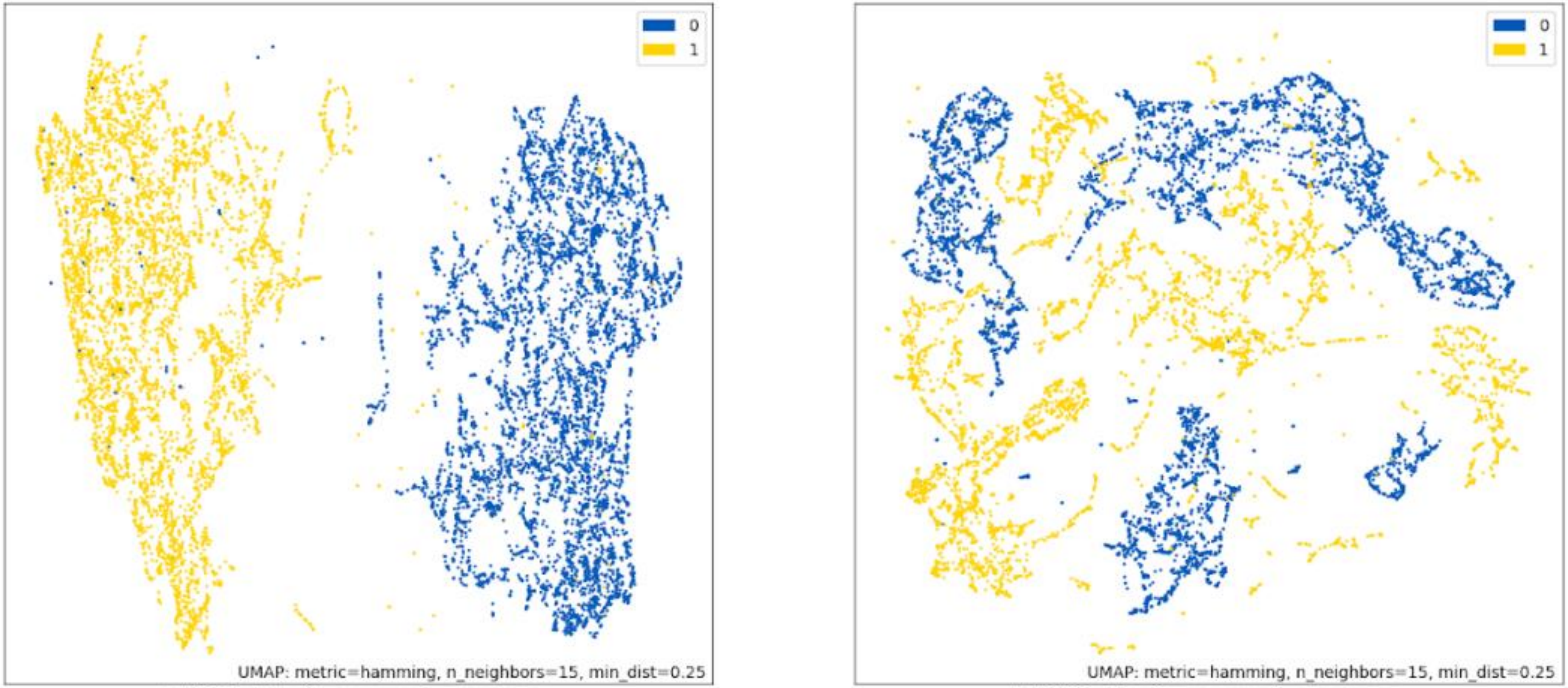
Projection in the direction perpendicular to the LSVM hyperplane, for all data for 90 subjects.

Input has 384 features = 6 RQA features x 64 electrodes.

Left - STFT, window 240 samples (6.2 ms each), test accuracy 90% (open 80%, closed 100%).

Right - embedding dim=2, delay = 9, test accuracy 61% (open 67%, closed 55%).

UMAP distribution



(a) RS. Condition 0 - open eyes, 1 - closed eyes

(b) RX. Condition 0 - open eyes, 1 - closed eyes

UMAP Visualization of 6 features. 5760 points = 64 electrodes x 90 subjects,
Left: STFT representation. Right: signal embedding.

Labeling states

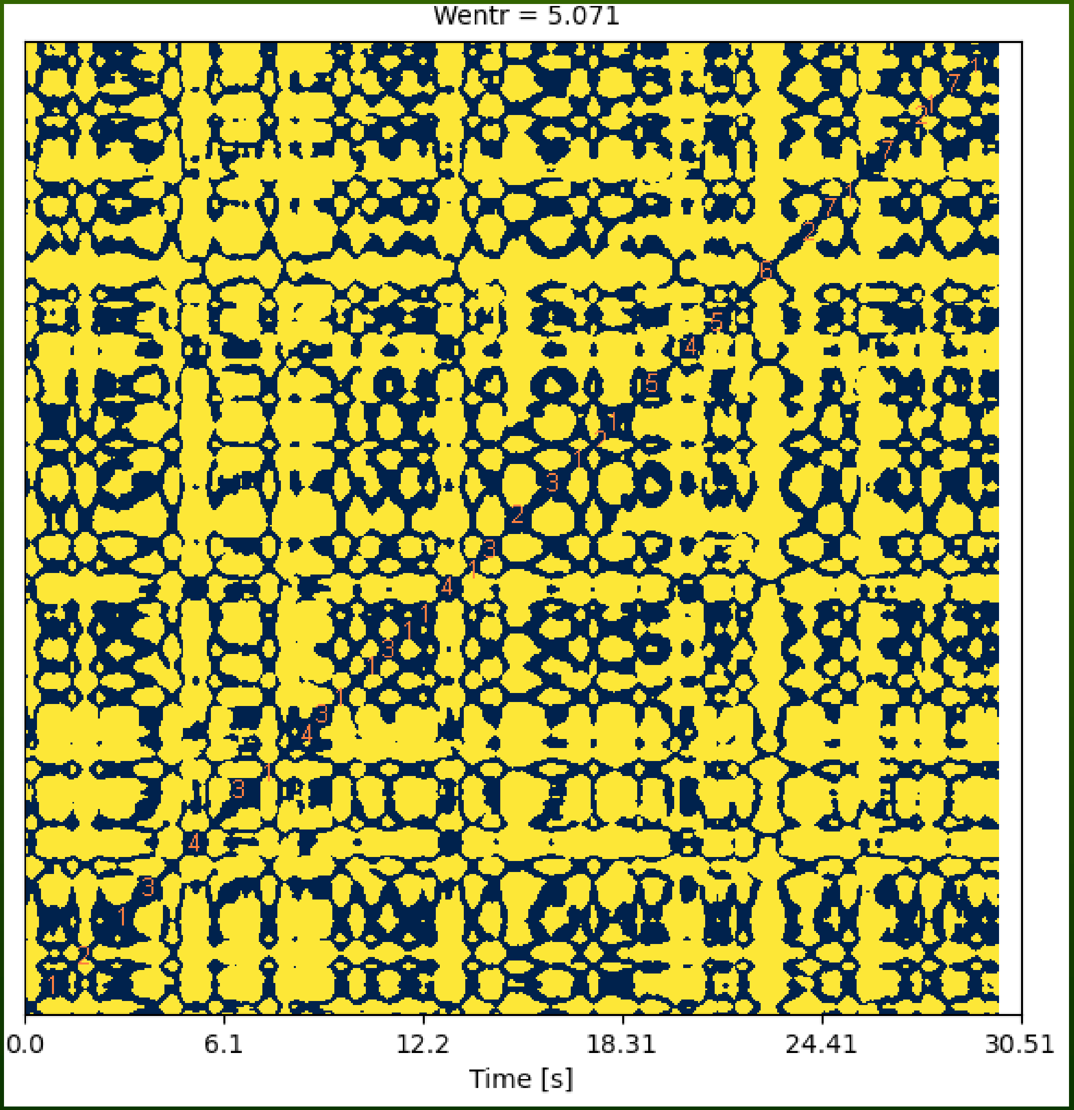
Automatic labeling of states and estimation of their recurrence may be important for biofeedback.

Metabolic costs of transitions between states may be important.

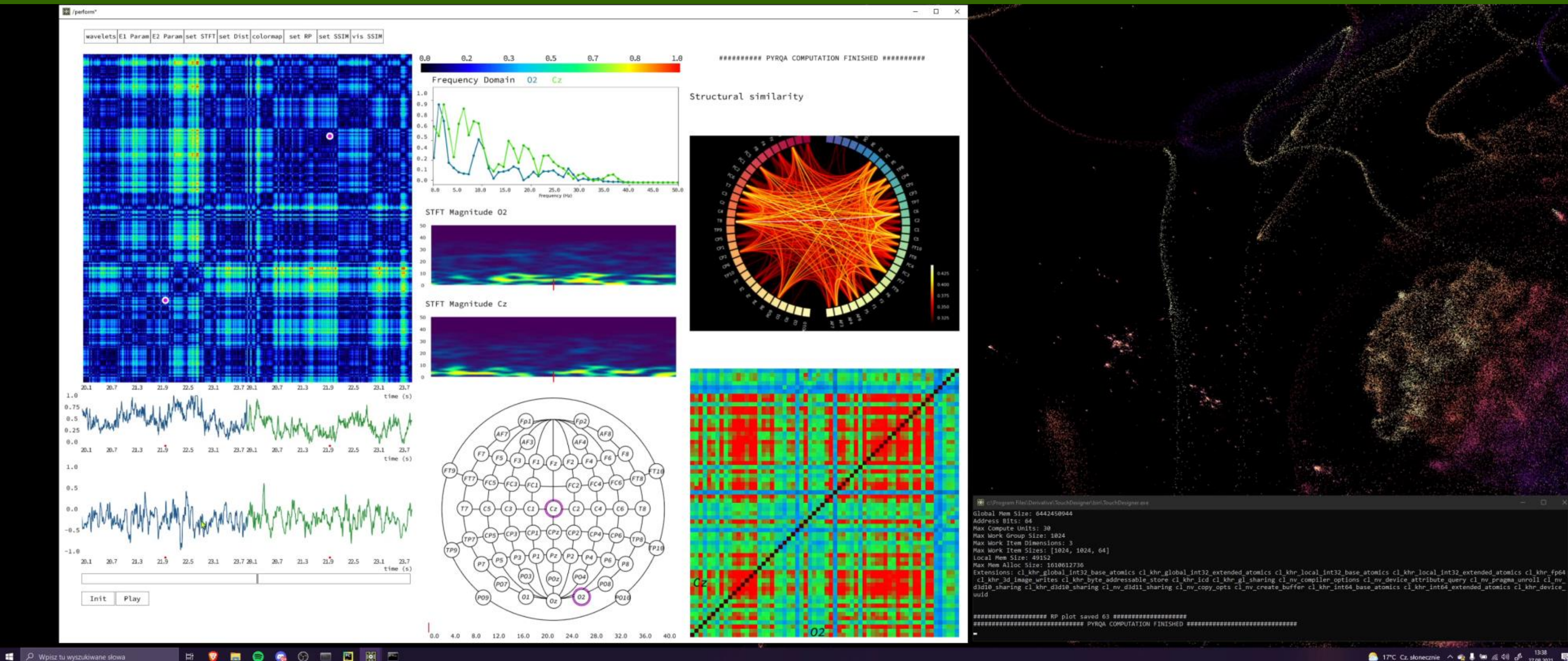
Ruminations? Pain states? How external stimuli influence this dynamics?

Needs automatic method for recognition of metastable, multivariate states.

More precise than micorstates.



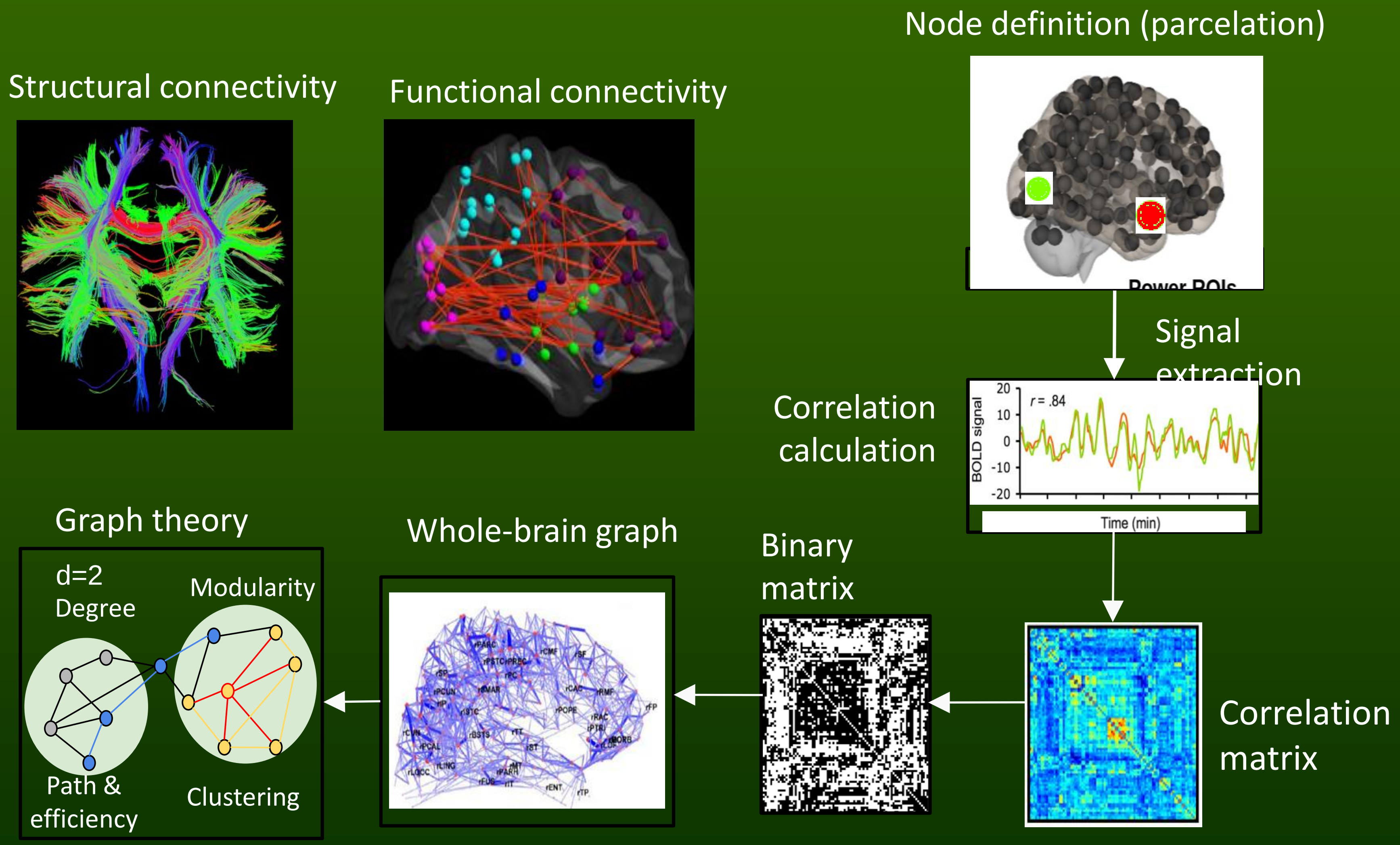
EEG analysis



- EEG data, 128 channels, recursion graphs, power spectrum for two electrodes, information flow and correlations between brain regions (Łukasz Furman).

fMRI and neurodynamics

Human connectome and MRI/fMRI

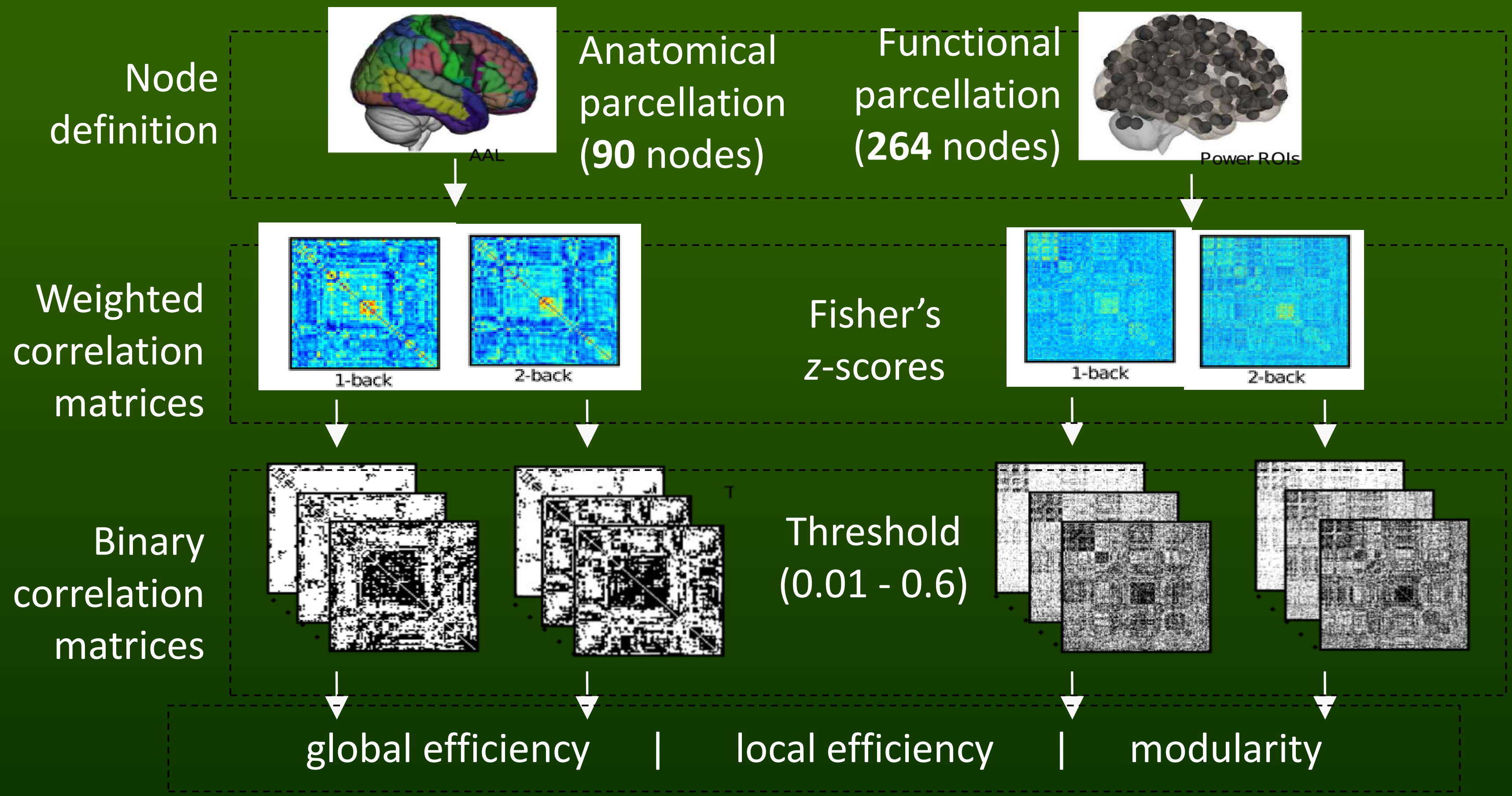


Many toolboxes available for such analysis.

Bullmore & Sporns (2009)

Effects of load and training.

Two experimental conditions: 1-back, 2-back, 35 subjects, letter N-back.



Finc, Bonna, Lewandowska, Wolak, Nikadon, Dreszer, Duch, Kühn. Transition of the functional brain network related to increasing cognitive demands. Human Brain Mapping 38, 3659–3674, 2017.

Brain modules and cognitive processes

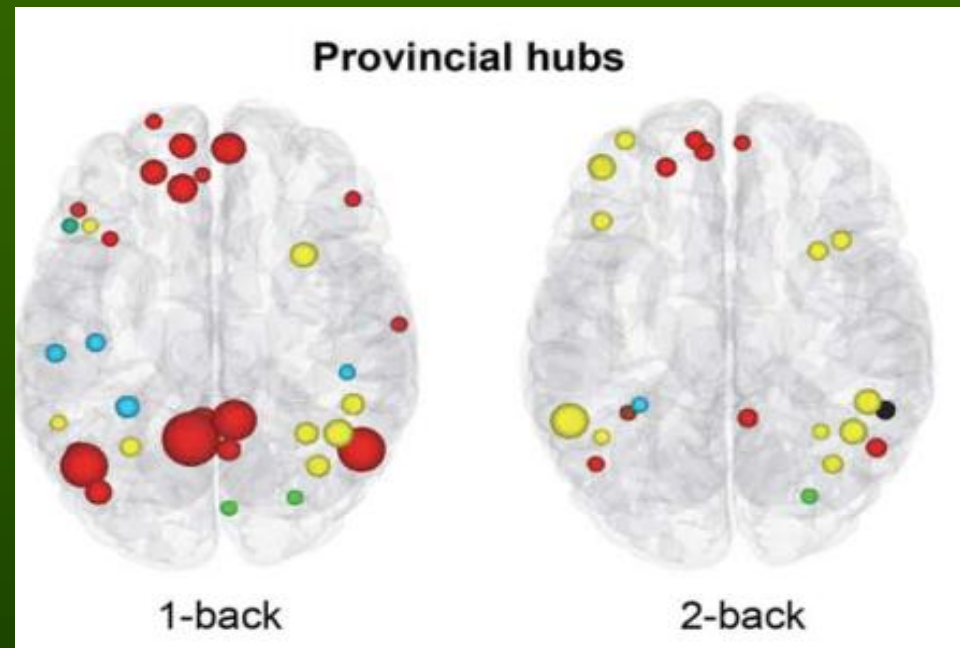
- Simple and more difficult tasks, requiring the whole-brain network reorganization.

Left: 1-back local hubs

Right: 2-back local hubs

Average over 35 *participants.*

Dynamical change of the landscape of attractors, depending on the cognitive load. Less local (especially in DMN), more global binding (especially in PFC).



K. Finc, et al. Transition of the functional brain … Human Brain Mapping 38, 3659–3674, 2017.

Effect of cognitive load on info flow

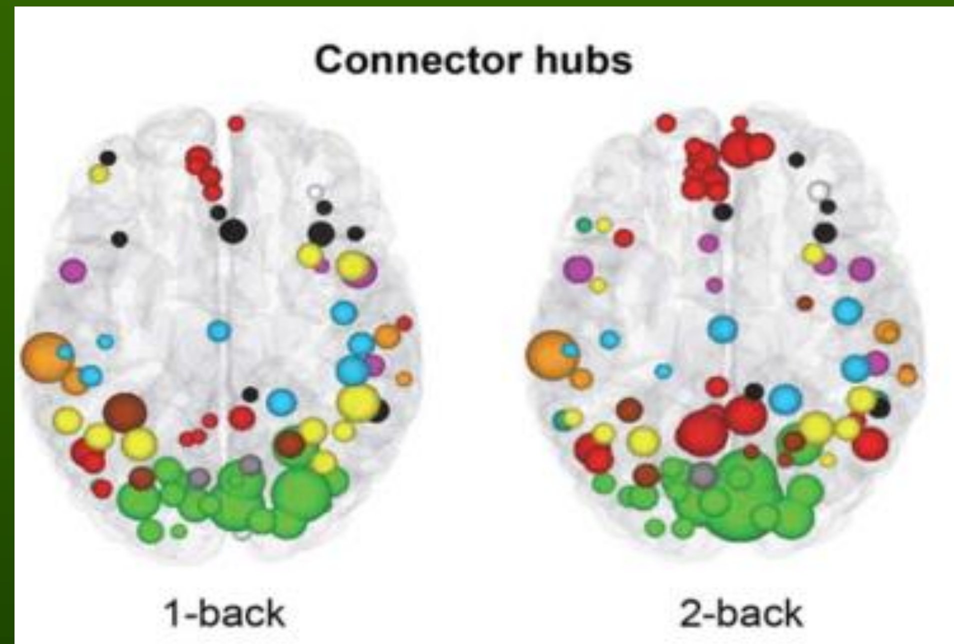
- Simple and more difficult tasks, requiring the whole-brain network reorganization.

Left: 1-back connector hubs

Right: 2-back connector hubs

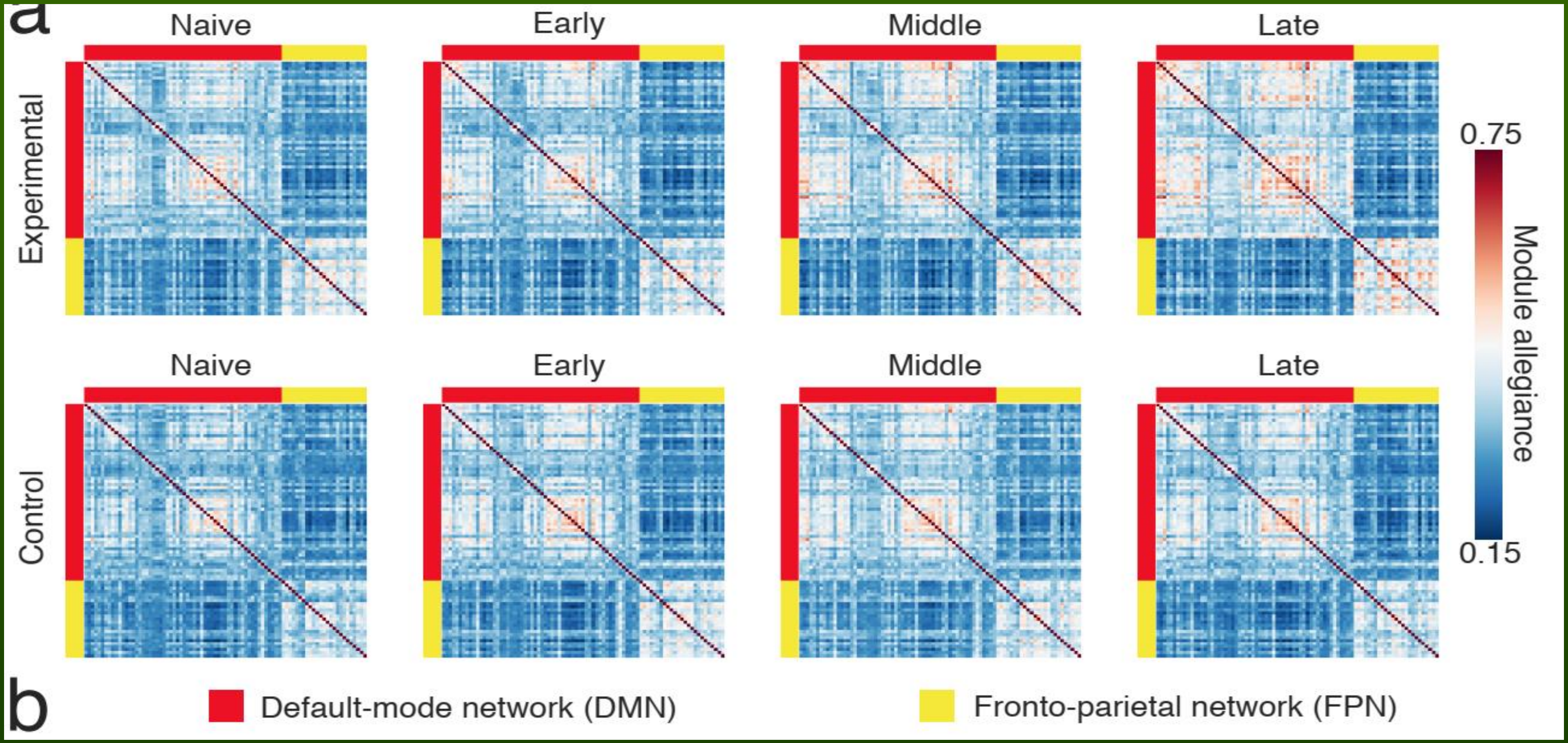
Average over 35 *participants.*

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



K. Finc, et al. Transition of the functional brain … Human Brain Mapping 38, 3659–3674, 2017.

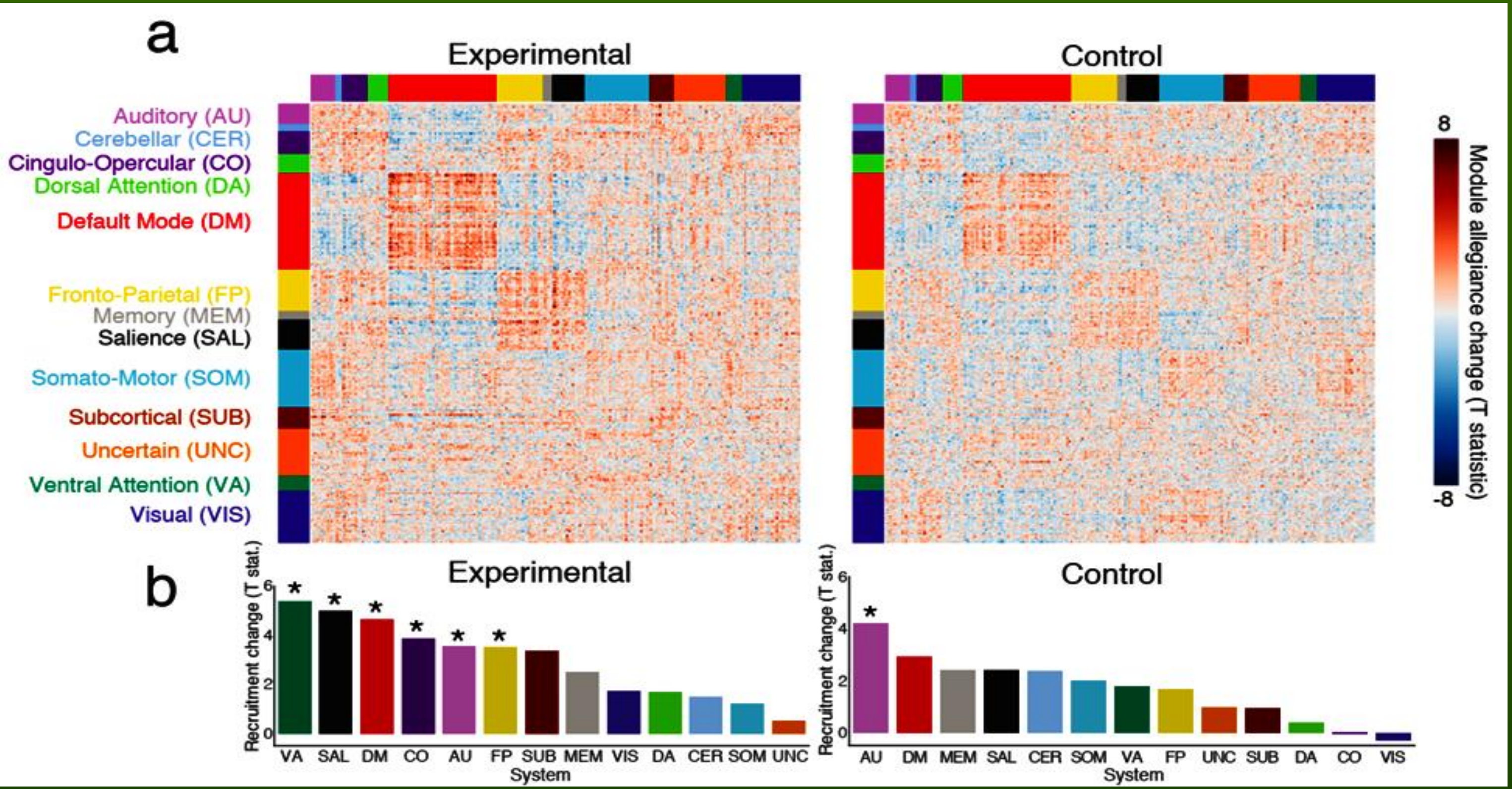
Working memory training



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

Segregation of task-relevant DMN and FPN regions is a result of training and complex task automation, i.e. from conscious to automated processing.

Working memory training

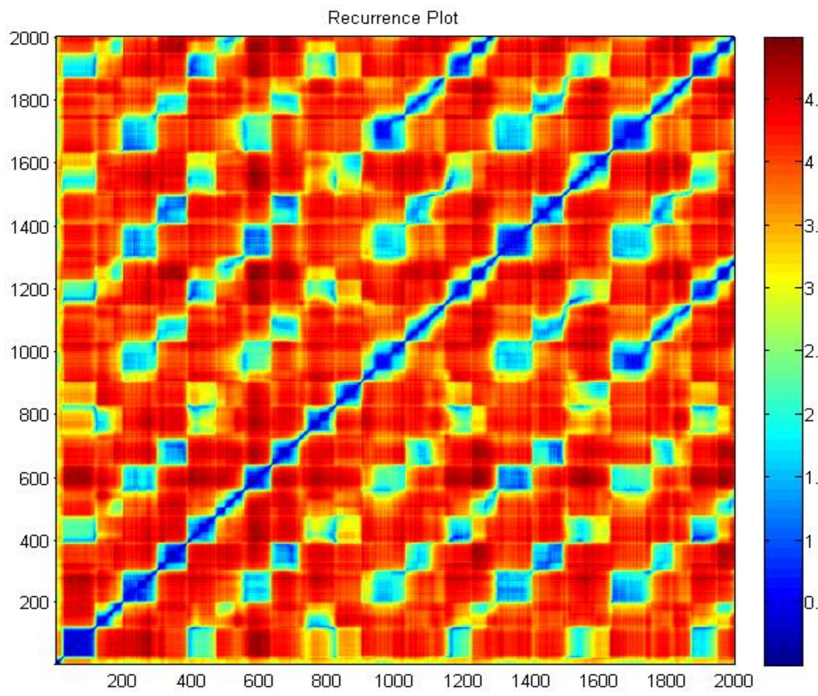


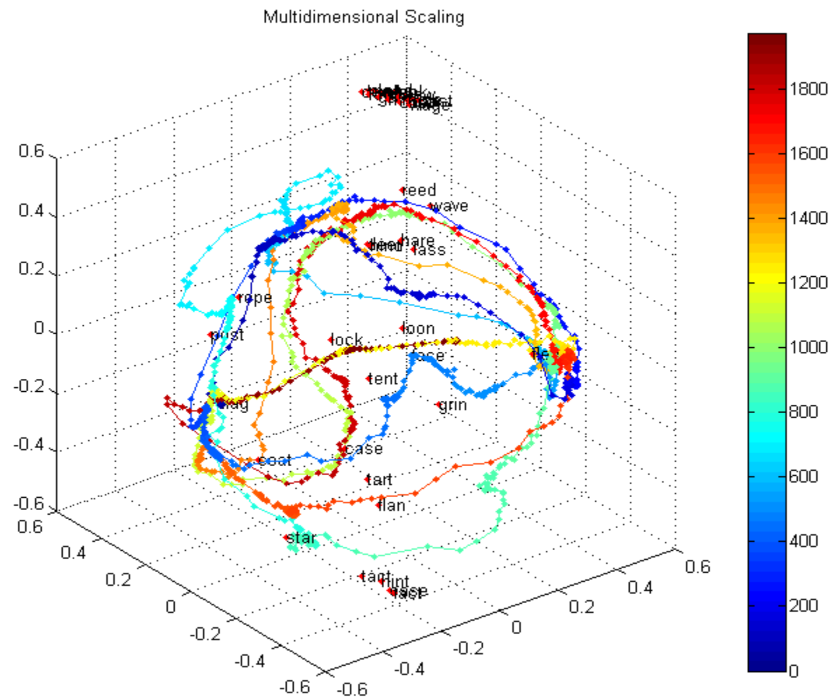
Whole-brain changes in module allegiance between the start and after 6-week of working memory training. (a) Changes in node allegiance as reflected in the two-tailed *t*-test. (b) Significant increase * in the default mode DM, fronto-parietal ventral attention VA, salience SAL, cingulo-opercular CO, and auditory systems AU recruitment.

Finc, Bonna, He, Lydon-Staley, Kühn, Duch, Bassett, Dynamic reconfiguration of functional brain networks during working memory training. Nature Communications 11 (2020).

Simulations of neurodynamics

Trajectory visualization





Recurrence plots and MDS visualization of trajectories of the brain activity.
Here evolution of 140-dim semantic layer activity during spontaneous associations in the 40-words microdomain is presented, starting with the word "flag".
Trajectories may be displayed using tSNE, UMAP, MDS or our FSD visualization.

Identify metastable states, calculate trapping times, recurrence rates, entropy ...

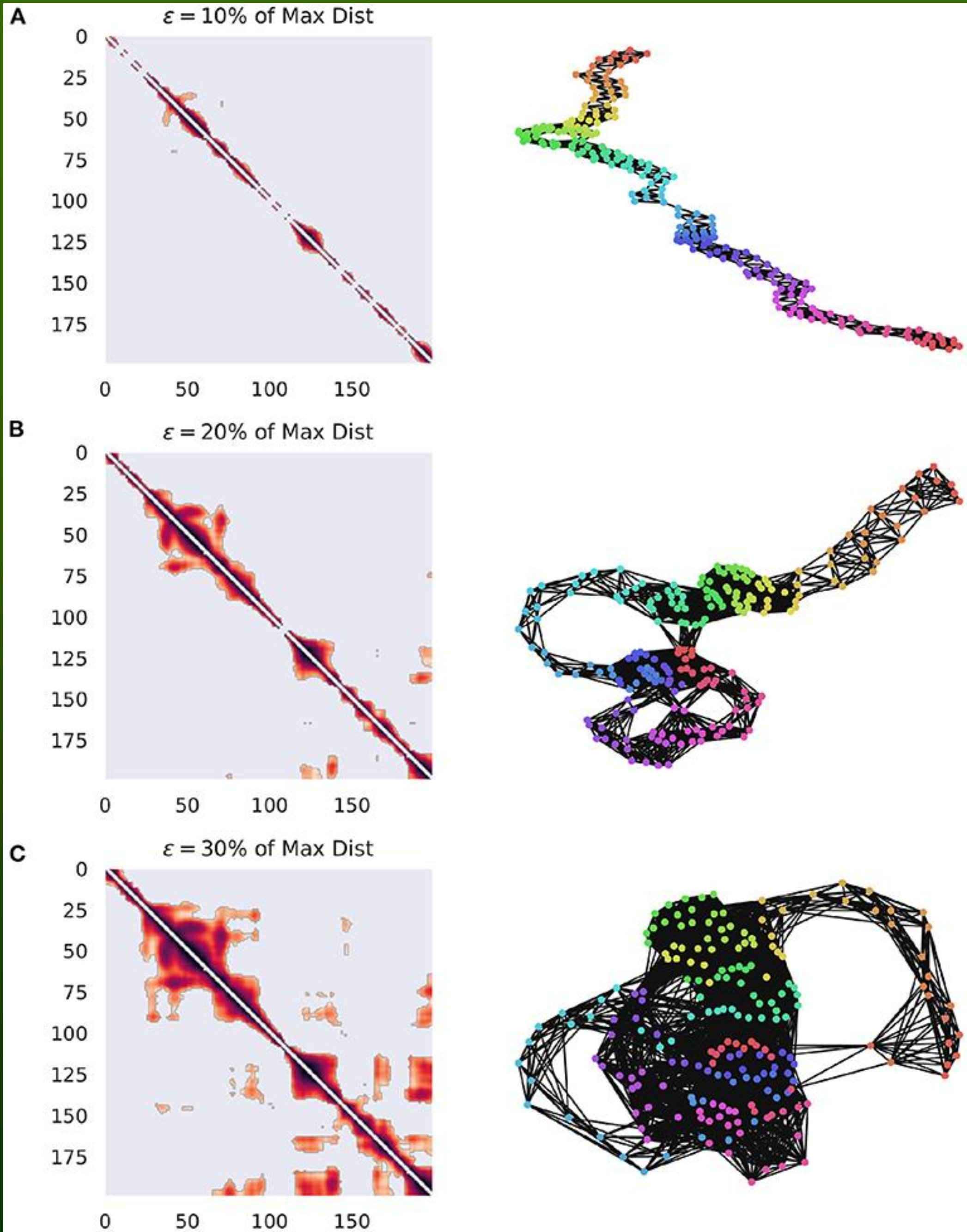
Recurrence network

Real brains, ECoG data: recurrence plots depend on the similarity threshold ε, cosine distance, Takens embedding of oscillatory data with dimension *d* and lag τ, .

Varley, T. F., & Sporns, O. (2022). Network Analysis of Time Series: Novel Approaches to Network Neuroscience. *Frontiers in Neuroscience*, *15*. 10.3389/fnins.2021.787068

For mathematically inclined:

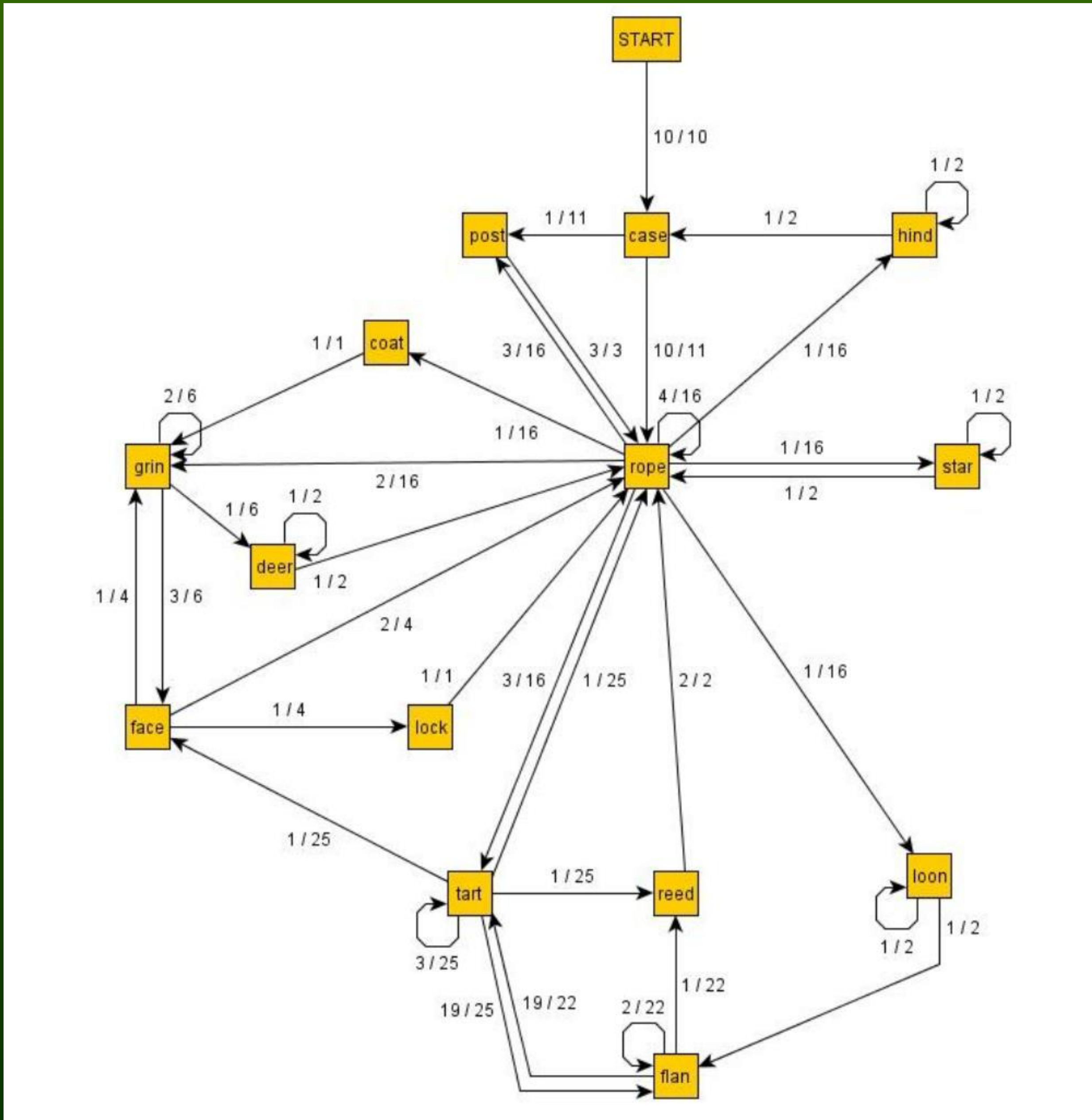
Caputi, L., Pidnebesna, A., & Hlinka, J. (2021). Promises and pitfalls of topological data analysis for brain connectivity analysis. *NeuroImage*, *238*, 118245.



Multiple starts from the same word lead to different trajectories. Calculate transition probabilities between metastable states from frequency of transitions.

Why such transitions?

Linked state have patterns sharing few features, that recruit less active, but strongly connected neurons, and relax those currently active, making the previous state inaccessible for some time (refractory period).



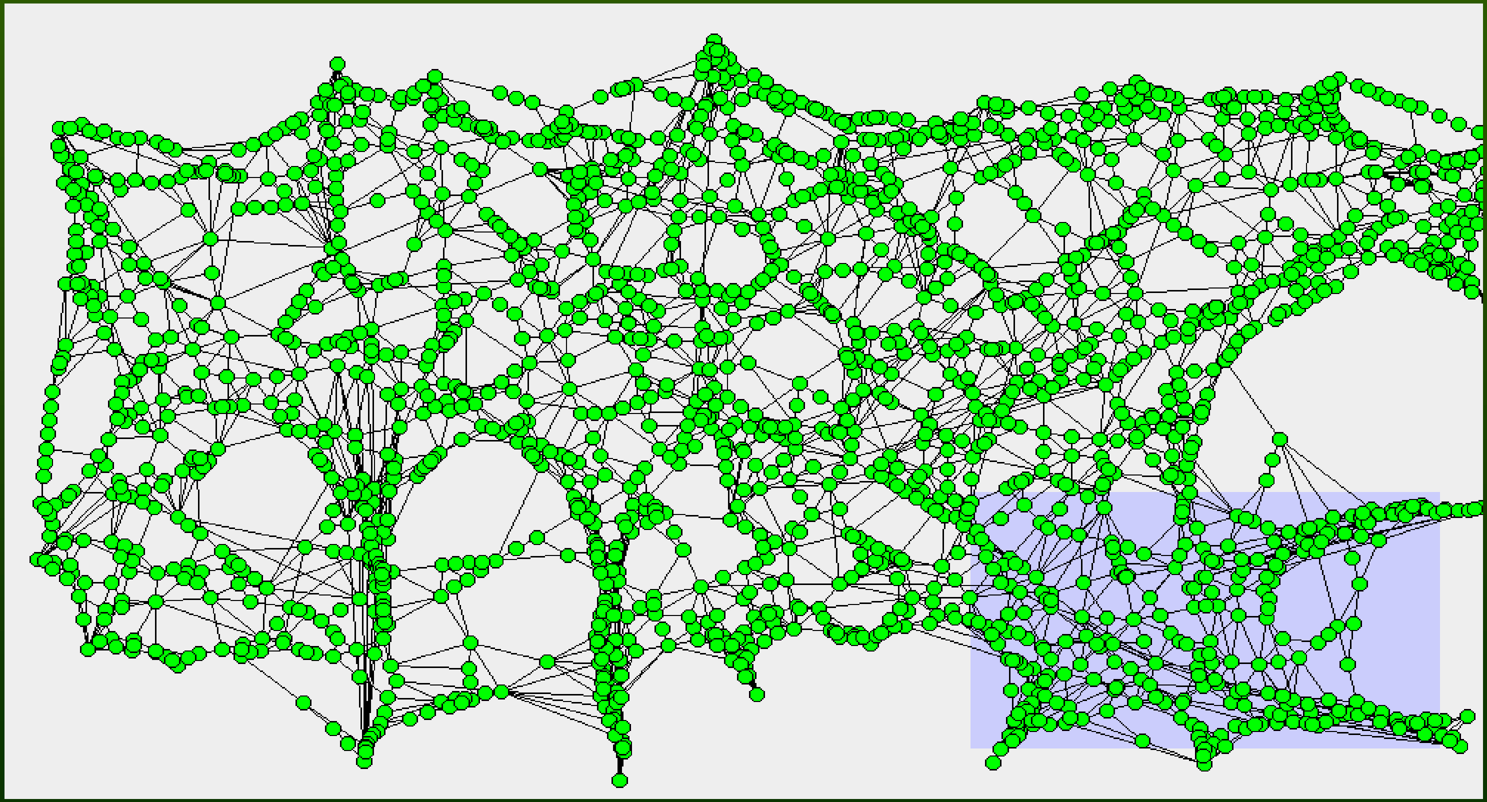
Learning in real situations

Learning complex information creates conceptual grid, each node = metastable brain state, links = associations, thinking = transitions between states, following associations.

Conceptual grid approximates environmental states, but **rapid learning distorts relations**.

Strong emotions increase neuroplasticity, but may lead to accidental associations, save mental energy, creating „sinks" that attract many unrelated episodic memory states.

Growing Neural Gas model, trained on blue patches.

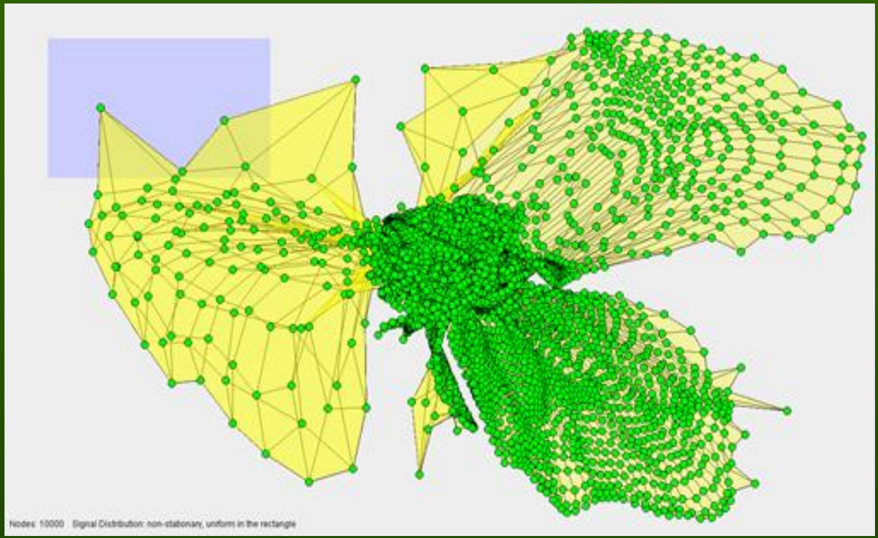


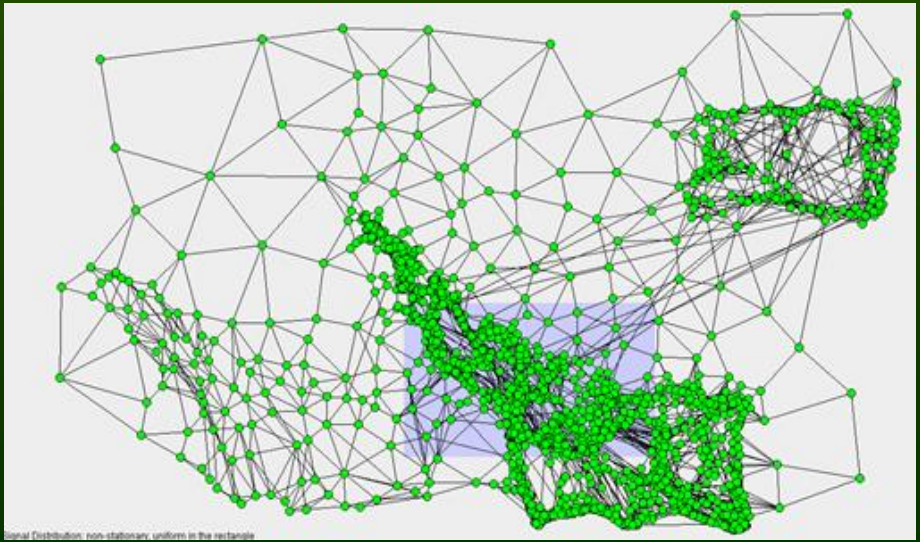
Memoids …

In extreme cases everything is associated with one great idea or cause.
"A lie that is repeated a thousand times becomes truth".

World view is totally distorted, mind states form one big memplex …

- Extraterrestials, politics, Nazis, religion, apocalypse, vaccines, 5G … anything.
- Simplifies dynamics, saves energy.





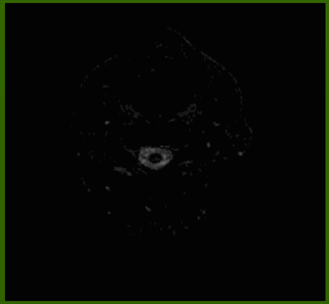
The rapid freezing of high neuroplasticity (RFHN) model. Overtraining => inhibition of alternatives!

Duch W. (2021) Memetics and Neural Models of Conspiracy Theories. Patterns. Cell Press.

Private Information in BCIs

K. Xia, W. Duch, Y. Sun, K. Xu, W. Fang, H. Luo, Y. Zhang, D. Sang, D. Wu, X. Xu, F-Y Wang, Privacy-Preserving Brain-Computer Interfaces: A Systematic Review, IEEE Trans. on Computational Social Systems, 2022

Conclusions



- Neurodynamics is the key to understanding mental states. BMI has now hundreds of applications, medical, entertainment, but does not use cognitive architectures to build better models.
- Simulations show how attractor networks create metastable states, behavioral trajectories, test hypothesis (autism, ADHD, belief formation).
- Brain networks have fluid nature: dynamic, change due to priming, history, refraction, cognitive load, memory training, emotional arousal, aging.
- Many brain fingerprinting methods exists; we have focused on microstates, spectral fingerprinting and recurrence analysis.
- Neurocognitive technologies may help to diagnose, repair and optimize brain processes, improve AI algorithms. Develop close-loop systems based on DecNef and FCNef approaches.

Neurocognitive technologies will profoundly change ourselves.
The integration of brains with AI becomes feasible. Memory implants?
Brain synchronization? Metaverse? Impossible yesterday common tomorrow.

BMI perspectives

- BMI has now hundreds of applications, from medical to entertainment.
- Neuroprothesis and neurorehabilitation are coming of age.
- ECoG and intracortical recordings show what is possible with direct access to cortex.
- Hippocampal memory prothesis is a step towards deep future.
- Medical diagnostics and closed loop systems for therapy of brain disorders are the driving forces.
- DecNef and FCNef approaches used by rt-FMRI should be converted to EEG
- AI development, especially foundational models, should help in creation of more accurate models, enable transfer learning.
- Neurocognitive technologies will profoundly change our selves.
  The integration of brains with AI becomes feasible.
- Metaverse? Brain synch?
- What was impossible yesterday tomorrow will be common.
  The singularity may come faster than we think!

Towards Human-like Intelligence

IEEE Computational Intelligence Society Task Force (Mandziuk, Duch, M. Woźniak), **Towards Human-like Intelligence**

IEEE SSCI CIHLI 2022 Symposium on Computational Intelligence for Human-like Intelligence, Singapore.

AGI: conference, Journal of Artificial General Intelligence comments on Cognitive Architectures and Autonomy: A Comparative Review (eds. Tan, Franklin, Duch).

BICA: Annual International Conf. on Biologically Inspired Cognitive Architectures, 11th Annual Meeting of the BICA Society, Natal, Brazil, 2020.

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

In search of sources of brain's cognitive activity

Project „Symfonia", NCN, Kraków, 18.07.2016

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VIRTUAL BR41N.IO HACKATHON
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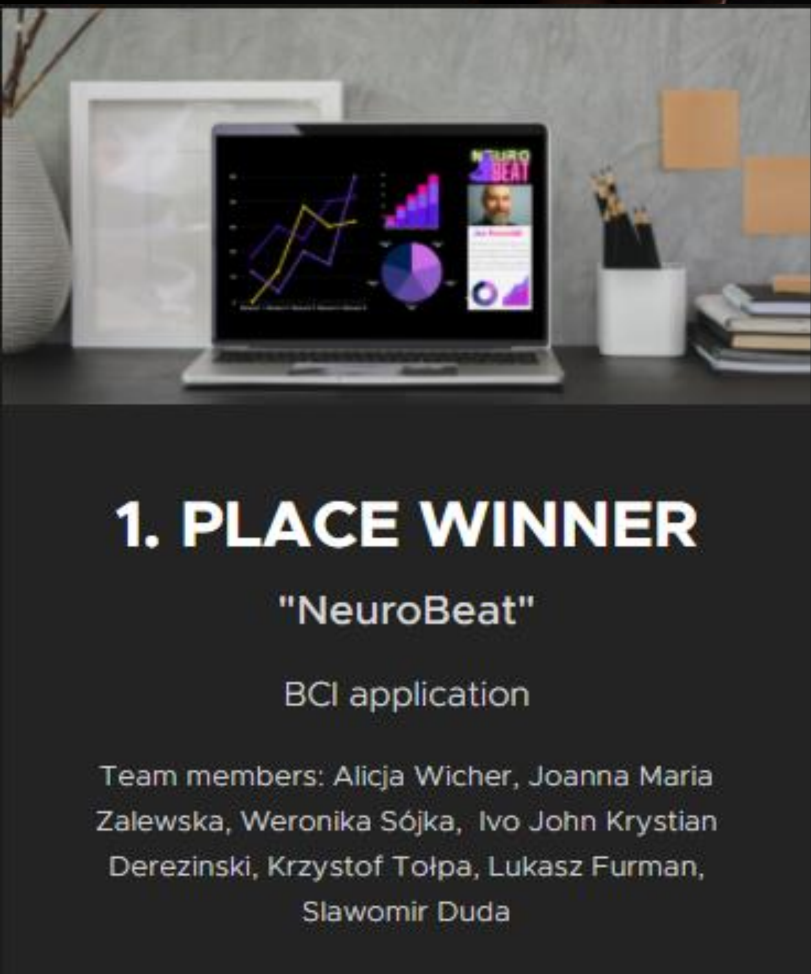
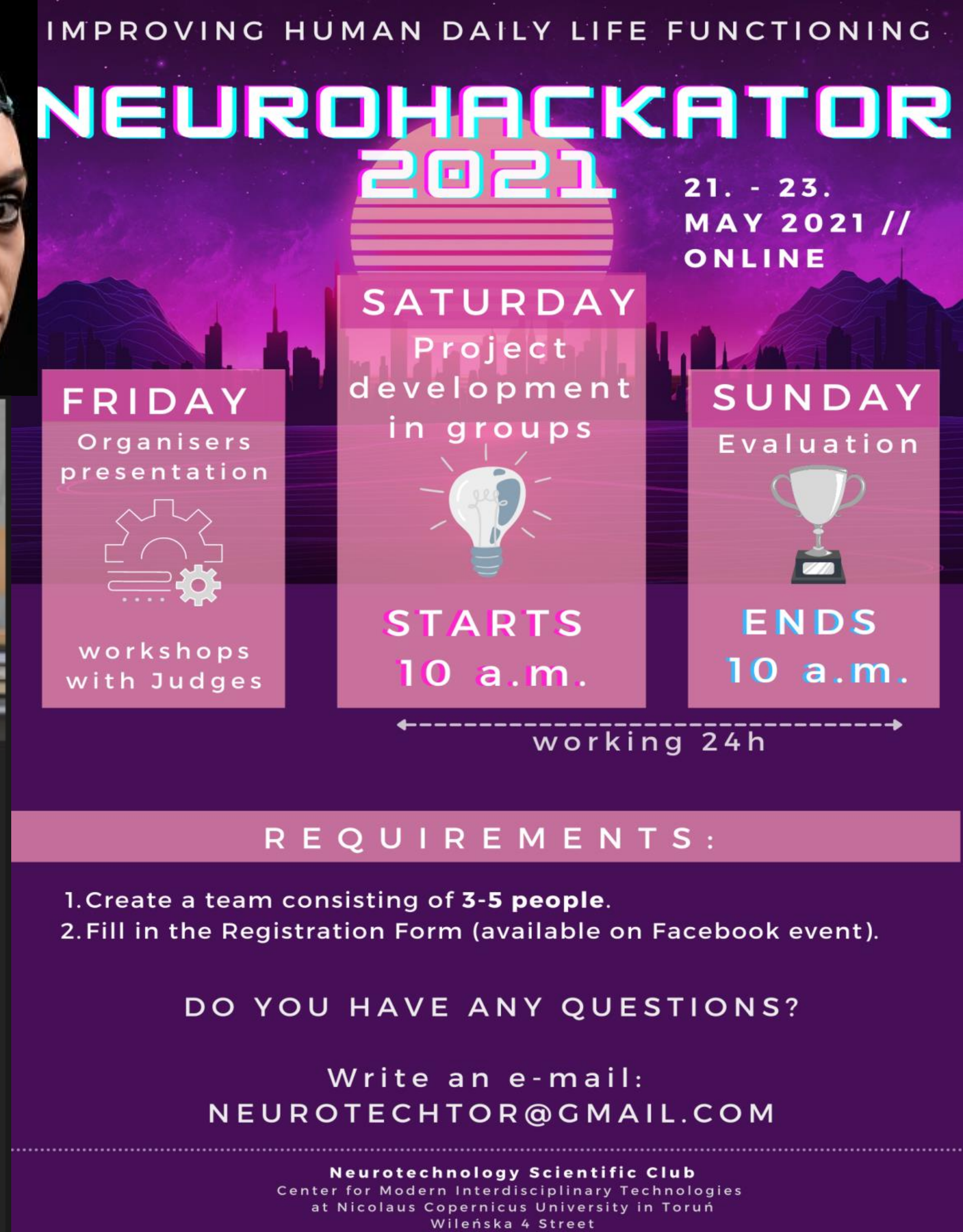
*BR41N.IO and Spring School 2021 are part of g.tec's Teaching Plan 2021 with more than 140 hours of online courses and lectures.


1. PLACE WINNER
"NeuroBeat"
BCI application
Team members: Alicja Wicher, Joanna Maria Zalewska, Weronika Sójka, Ivo John Krystian Derezinski, Krzystof Tołpa, Lukasz Furman, Slawomir Duda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SATURDAY
Project development in groups
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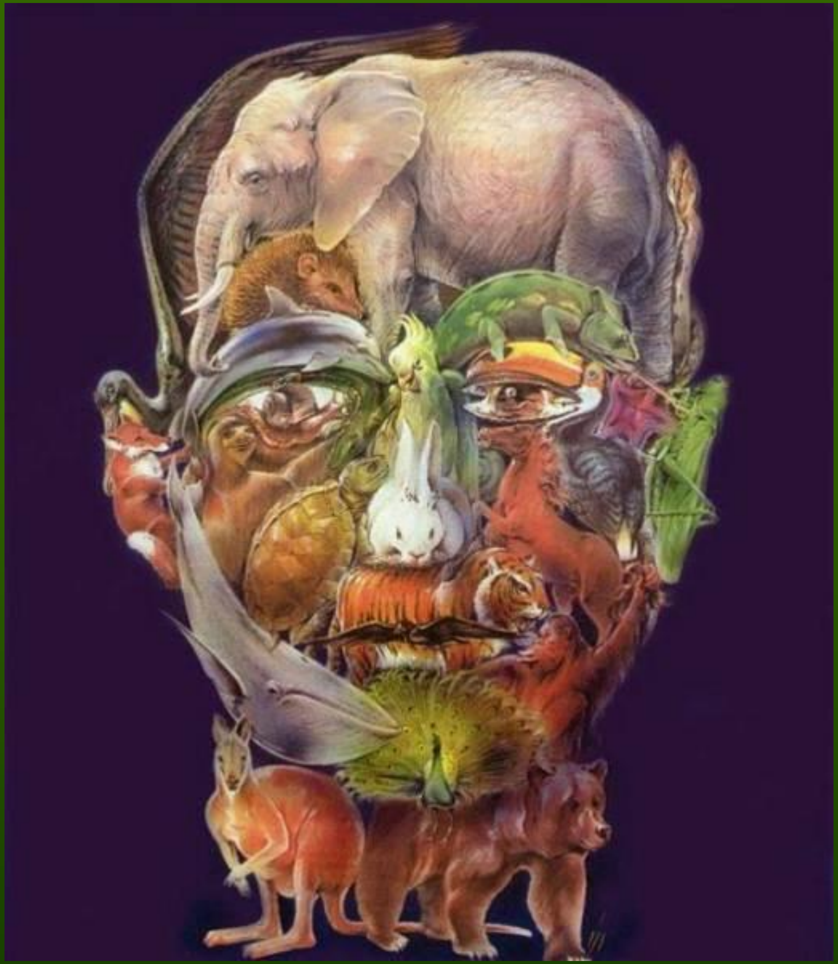
Intelligence?



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