Artificial Intelligence and Neurotechnologies for Human Augmentation

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Search Wlodzislaw Duch

Frontiers of Artificial Intelligence and Machine Learning, China, 14-16.04.2023

Toruń


Rockall (U.K.)
ORKNEY ISLANDS
HEBRIDES
North Atlantic Ocean
Aberdeen
Glasgow
Edinburgh
UNITED KINGDOM
Belfast
Dublin
IRELAND
Isle of Man (U.K.)
Irish Sea
Leeds
Manchester
Liverpool
Birmingham
Cardiff
London
Celtic Sea
English Channel
Guernsey (U.K.)
Jersey (U.K.)
Bergen
Stavanger
Oslo
Stockholm
ALAND ISLANDS
Tallinn
ESTONIA
RUSSIA
Moscow
North Sea
Skagerrak
Kattegat
Göteborg
Gotland
Riga
LATVIA
Baltic Sea
Öland
LITHUANIA
Vilnius
Vitsyebsk
Smolensk
DENMARK
Copenhagen
Malmö
Bornholm
Kaliningrad
RUSSIA
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Minsk
BELARUS
Gdańsk
Hrodna
Homyel'
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Poznań
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CARPATHIAN MTS.
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ROMANIA
Bay of Biscay
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SWITZ.
ALPS
Ljubljana
SLOVENIA
Zagreb
Bucharest
Constanţa
Black Sea
MASSIF CENTRAL
Lyon
Milan
Venice
Turin
DINARIC ALPS
BOSNIA AND HERZEGOVINA
Belgrade
Varna
Bordeaux
Genoa
CROATIA
SAN MARINO
Serbia
BULGARIA
Bilbao
Toulouse
MONACO
Sarajevo
Sofia
APENNINES
Andorra la Vella
Marseille
Ligurian Sea
Florence
Porto
PYRENEES
ANDORRA
ITALY
Adriatic Sea
Podgorica
Skopje
İstanbul
Zaragoza
Corsica
Rome
F.Y.R.O.M.
Bursa
PORTUGAL
Madrid
Barcelona
VATICAN CITY
Tirana
ALB.
Thessaloniki

Toruń

Nicolaus Copernicus, born in 1473 in Toruń (550 years ago).
Studied in Krakow, Bologna, Padova and Ferrara.

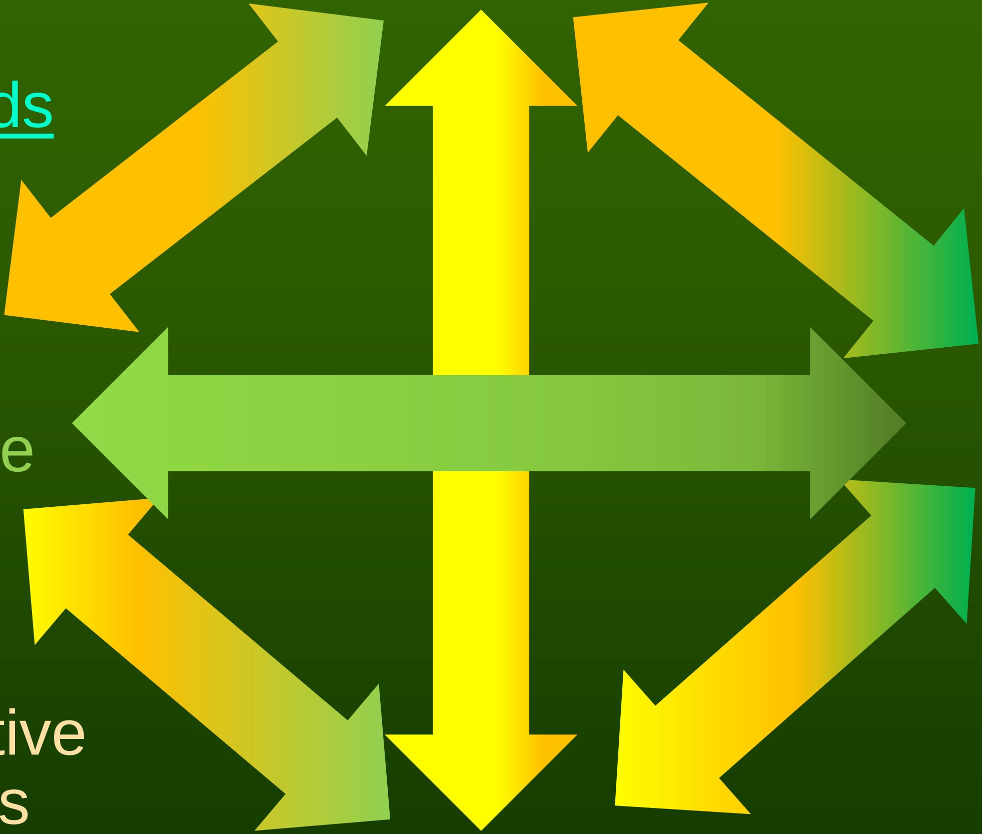
AI ⇔ Brain

AI

- Large Language Models.
- Generative Pretrained Transformers (GPT).
- Attention mechanism and the brain.

Brains

- Human enhancement with **neurocognitive technologies**.
- Closed loop biofeedback.
- Source localization, spectral fingerprinting, recurrence.
- Unrealistic expectations.



Cogni
Cognitive sciences

Biohybrids

Cognitive
Informatics

Brains
Neuroscience

Nano
QuantumTech

Neurocognitive
Informatics

Quantum
Informatics

Info
Artificial/Computational Intelligence,
Machine Learning, Neural Networks

Artificial Intelligence

AGI & BICA

From an engineer's perspective, to understand the brain is to build a working model that exhibits the same functions. Needed: spatial models of phenomena, actions and their causes, real world imagery.

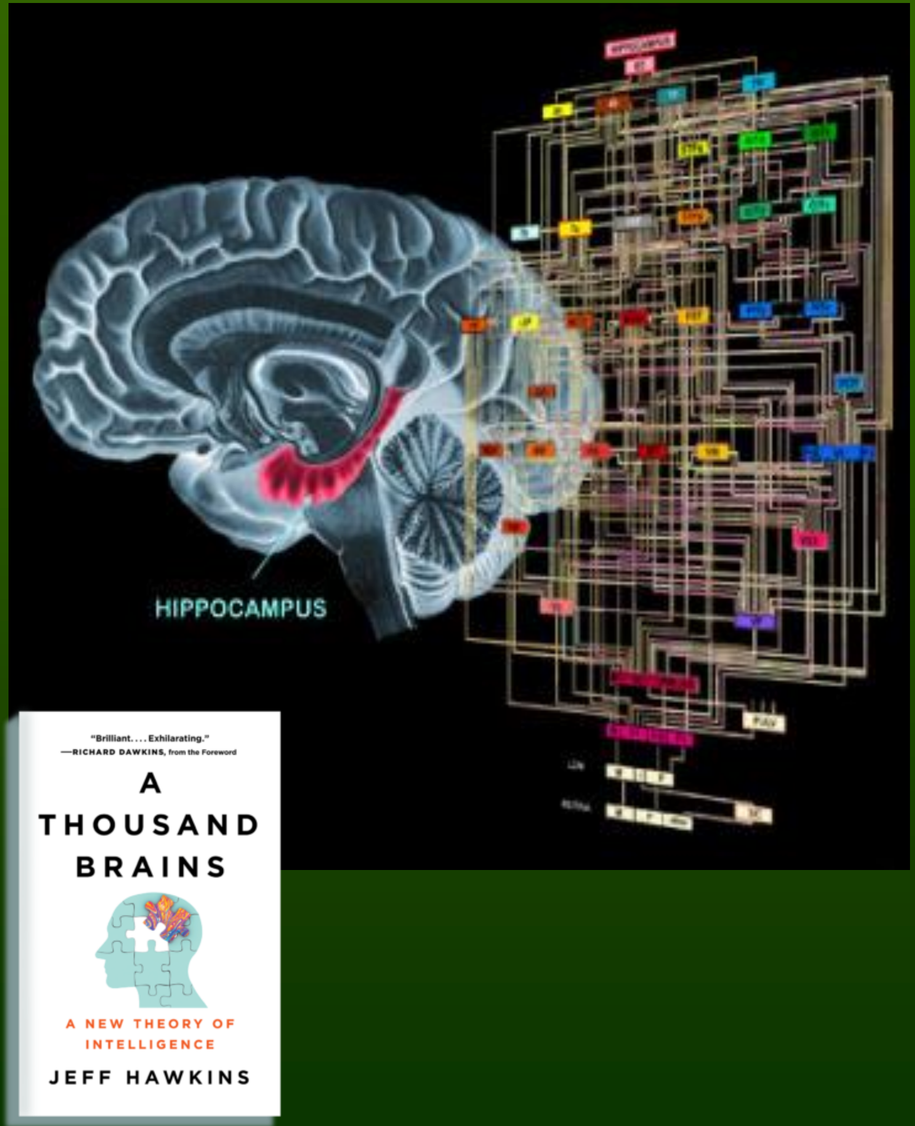
AGI = Artificial General Intelligence, learn many different things.

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).



“Brilliant. . . . Exhilarating.”
—RICHARD DAWKINS, from the Foreword

A THOUSAND BRAINS

A NEW THEORY OF INTELLIGENCE

JEFF HAWKINS

Artificial General Intelligence (AGI), Memphis 2008

2022: DeepMind Gato is a relatively small model, with 1.2 billion parameters. Multi-modal, multi-task, multi-embodiment, learned simultaneously over 600 tasks, games to controlling robots. Small working memory capacity.

Towards Human-like Intelligence

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

2013 IEEE Symposium Series on Computational Intelligence
IEEE SSCI 2013
15 Mon – 19 Fri, April 2013, Singapore
Call for Papers
http://www.ieee-ssci.org/

IEEE SSCI CIHLI 2022 Symposium on Computational Intelligence for Human-like Intelligence, Singapore. In 2023 it will be in Mexico City.

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, 13th Annual Meeting of the BICA Society, Guadalajara, Mexico 2023.

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

Neuroscience ⇔ AI

Hassabis, D., Kumaran, D., Summerfield, C., Botvinick, M. (2017). **Neuroscience-Inspired Artificial Intelligence**. *Neuron*, *95*(2), 245

Affiliations: **Google DeepMind**, Gatsby, ICN, UCL, Oxford.

Attention, awareness models, consciousness, complementary learning systems, various types of memory, reinforcement learning are used in machine learning.

Key concepts from RL inform neuroscience and ML techniques are basic tools for analysis and interpretation of brain neuroimaging data. Ex:

CNN ⇔ interpret neural representations in high-level ventral visual stream of humans and monkeys, finding evidence for deep supervised networks.

LSTM architecture provides key insights for development of working memory, gating-based maintenance of task-relevant information in the prefrontal cortex.

All this will help in development of **neurocognitive technologies**.

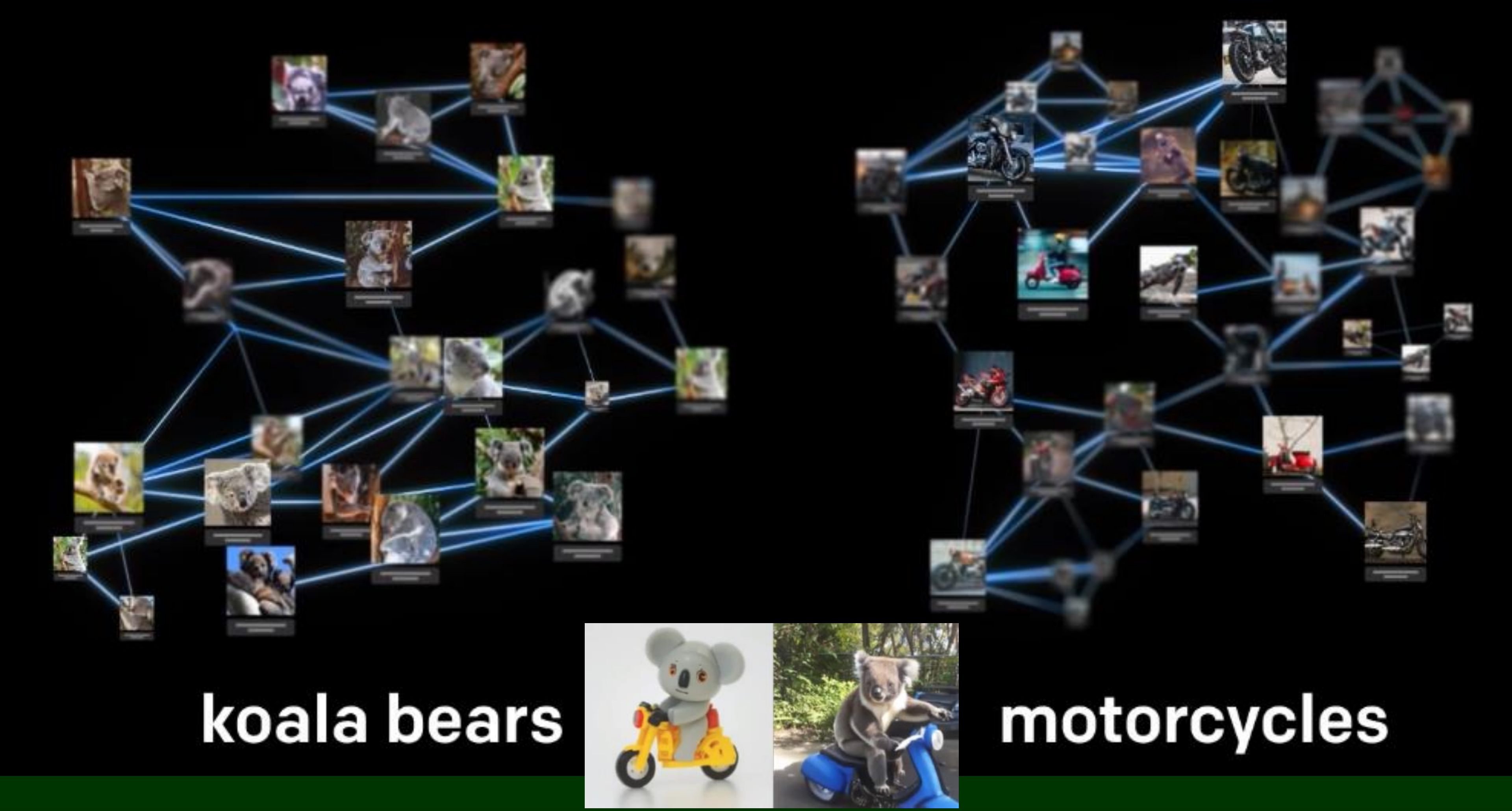
Language algorithms

Language models: relation of words in complex network structures.
In 2018, to gain a general-purpose "language understanding",
Google created BERT, model pre-trained on a very large text corpus.

- **Bidirectional Encoder Representations from Transformers** (**BERT**). Transformer-based machine learning technique for (NLP) pre-training.
- English-language BERT: two networks, smaller 110M parameters, larger model with 340M parameters in 24-layers; trained on the BooksCorpus with 800M words, and Wikipedia with 2,500M words. In 2019 BERT worked already in 70 languages.
- BERT model was then fine-tuned for specific NLP tasks such as question answering or semantic information retrieval. Many smaller pre-trained open software models were published in GitHub repository.
- The network learns to predict masked words (images, signals):
  Input: the man went to the [MASK1]. He bought a [MASK2] of milk.
  Labels: [MASK1] = store; [MASK2] = gallon.

Vision-language models

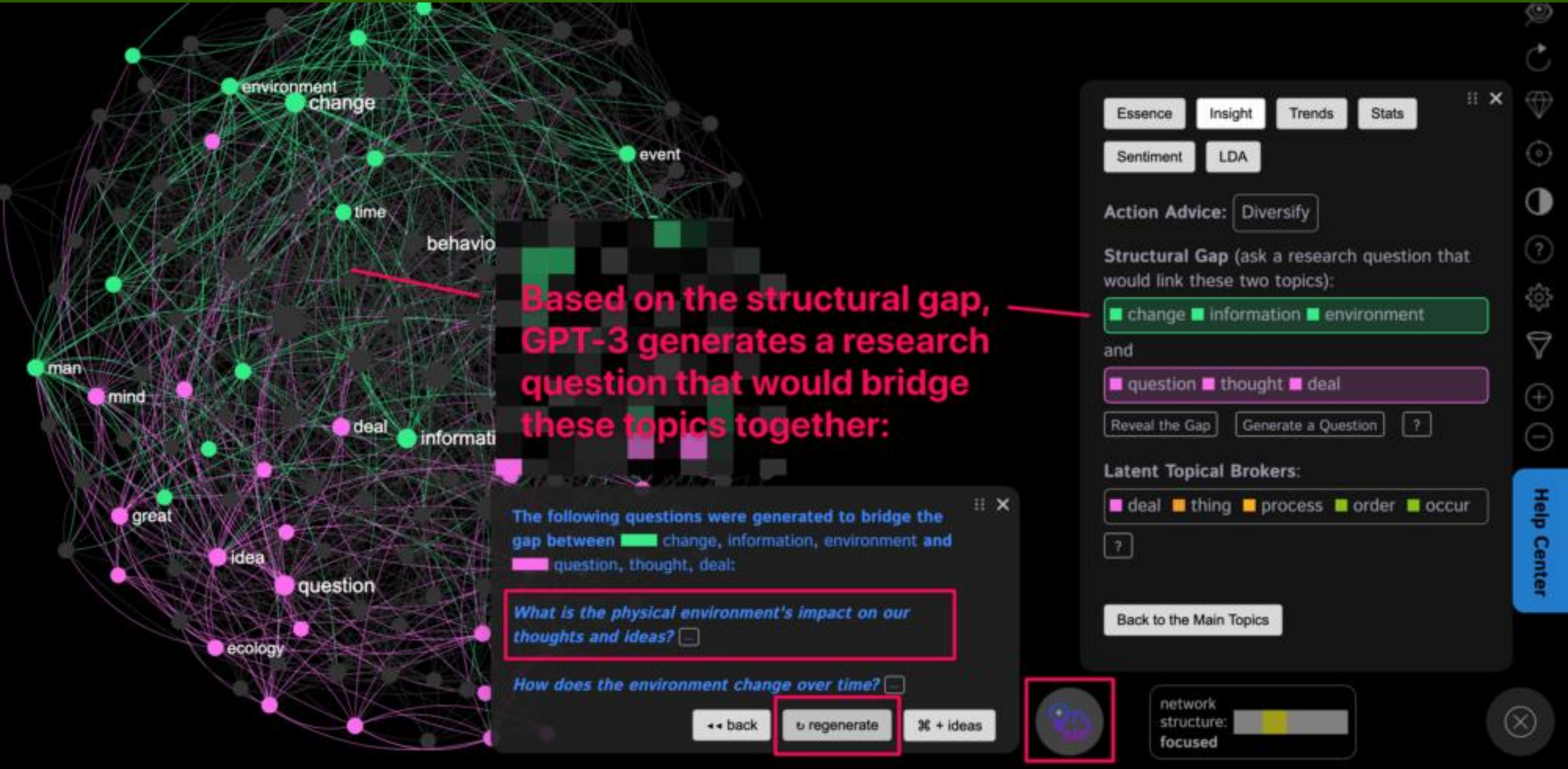
Vision-Language Pre-Trained Models (VL-PTMs), convergence of language, vision, and multimodal pretraining => general-purpose foundation models can handle be easily adapted to multiple diverse tasks with zero-shot learning.



Large language generative models

In the space of trillion parameters many tokens may be linked – such entities as verbal concepts, images, internal body states in robots in Palm-E, BEIT, Gato ... Basic mechanisms involve masking, attention, positional encoding, reflection.

Still why these models work so well is not clear. Priming subnetworks?



Based on the structural gap, GPT-3 generates a research question that would bridge these topics together:

Action Advice: Diversify

Structural Gap (ask a research question that would link these two topics):

🟩 change 🟩 information 🟩 environment

and

🟪 question 🟪 thought 🟪 deal

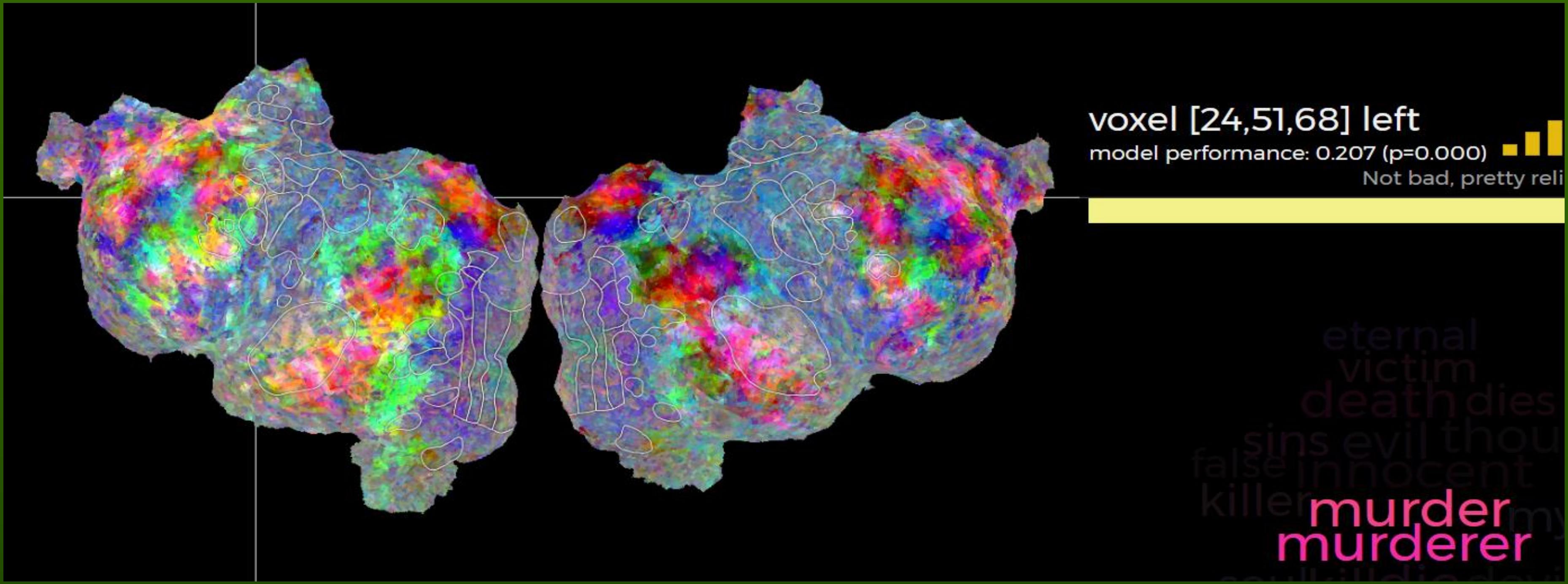
Latent Topical Brokers:

🟪 deal 🟧 thing 🟧 process 🟩 order 🟩 occur

The following questions were generated to bridge the gap between 🟩 change, information, environment **and** 🟪 question, thought, deal:

What is the physical environment's impact on our thoughts and ideas?

How does the environment change over time?



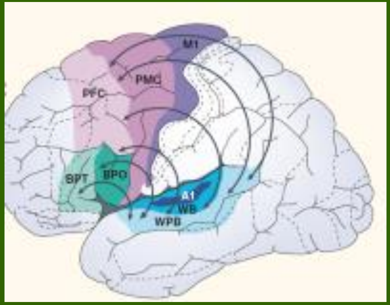
Whole fMRI activity map for the word “murder” shown on the flattened cortex.

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?
Prompts invoke specific activation in LLMs.

Creativity: a simple model



My computational creativity project (2005):
Model inspired by brain process involved in creating new names.

- make a simplest test for creative thinking – invent novel names;
- create interesting new names for products, capturing their characteristics;
- understand newly invented words that are not in the dictionary.

Assumption: a set of keywords (prompts) **primes the trained** cortex subnetwork.

Prompts: ordered strings of phonemes that activate semantic reps of words. Spreading activation => context priming + inhibition in the winner-takes-all process leaves only a few semantically related concepts (word meaning).

Creativity = imagination (activation of pre-trained networks) + filtering (competition, associations to existing states)

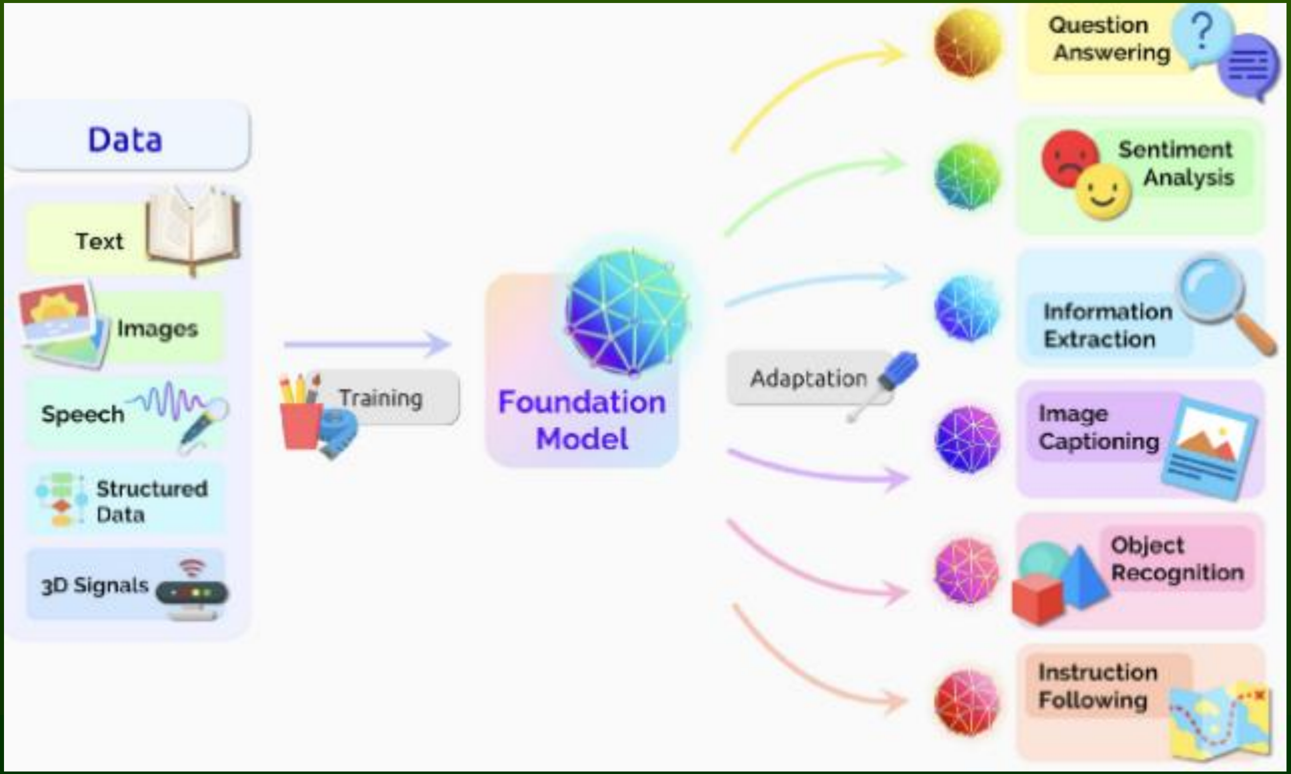
Imagination: many transient patterns of activity arise in parallel, activating both words and non-words, guided by the strength of connections
Filtering: associations, emotions, phonological and semantic density.
Is this what happens in large language models?

Multimodal models

Multimodal 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)



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.

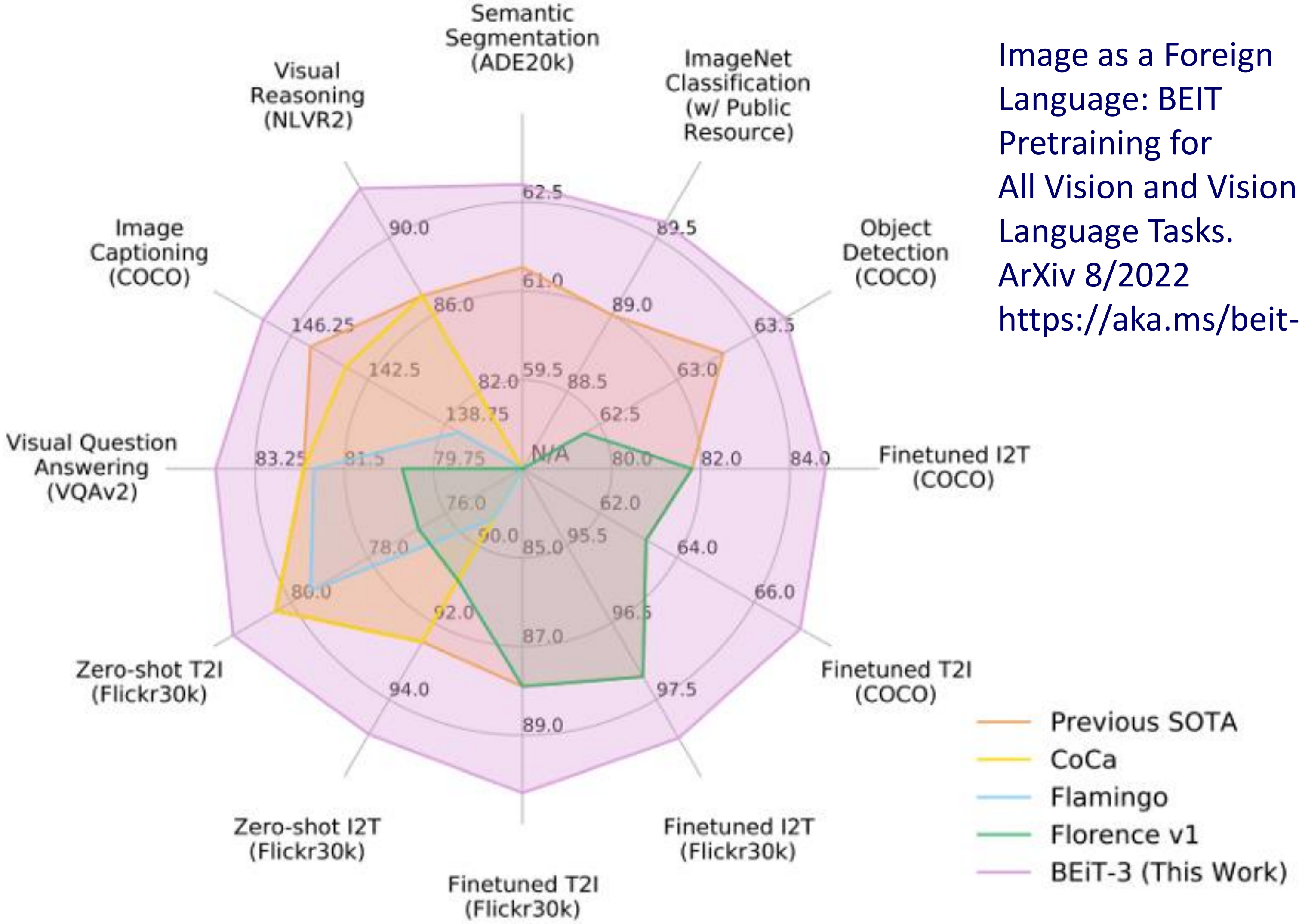


Image as a Foreign Language: BEIT Pretraining for All Vision and Vision-Language Tasks.
ArXiv 8/2022
https://aka.ms/beit-3

Brains

On the threshold of a dream …

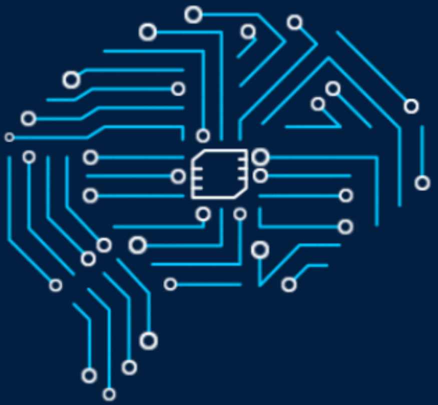
Final goal: optimize brain processes!

Although whole brain is always active we are far from achieving full human potential.
Repair damaged brains, increase efficiency of healthy brains! First we need to understand brain processes:

1. Find fingerprints of specific activity of brain structures using new neurotechnologies.
2. Create models of cognitive architectures that help to understand information processing in the brain.
3. Create new diagnostic and therapeutic procedures.
4. Use neurofeedback based on decoding and changes in connectivity to stimulate the brain.
5. Stimulate neuroplasticity by monitoring brain activity and directly stimulating it (TMS, DCS, EM).

G-tec wireless NIRS/EEG on my head.

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

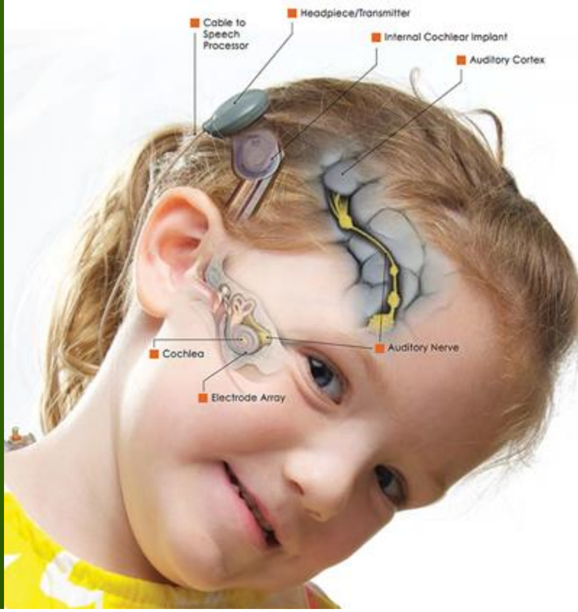
IEEE brain

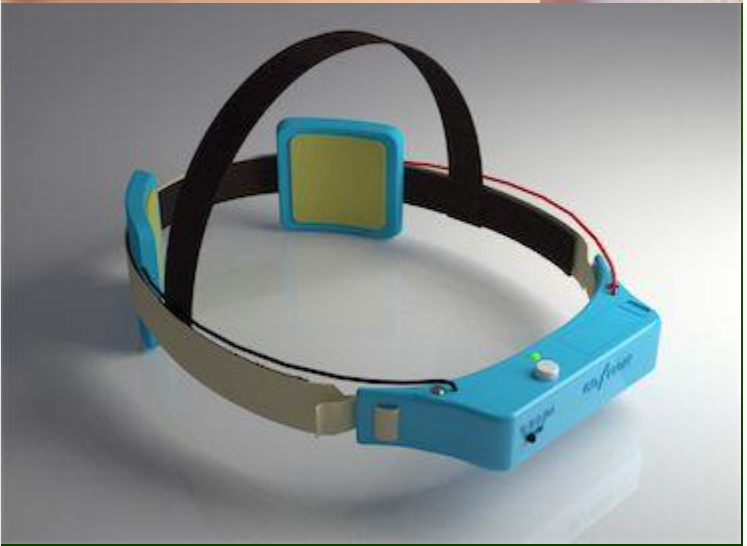
Join the IEEE Brain Community

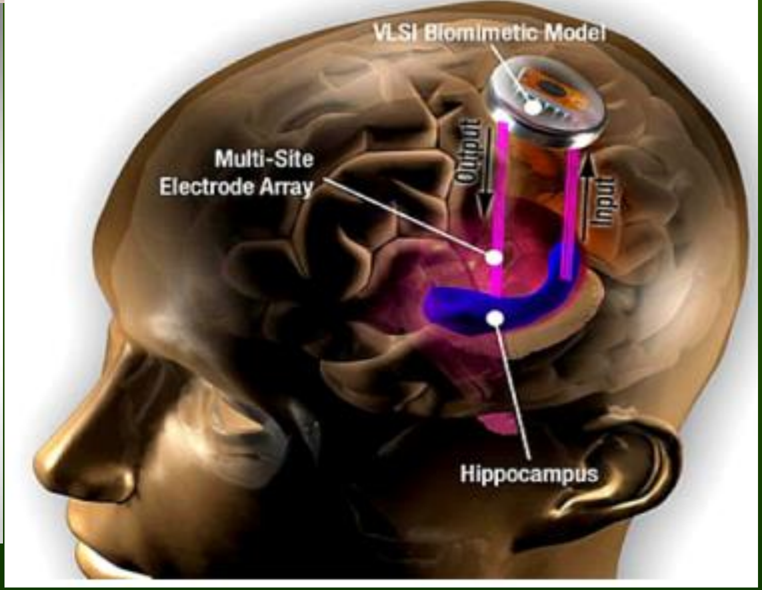
JOIN FREE

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

Amplification

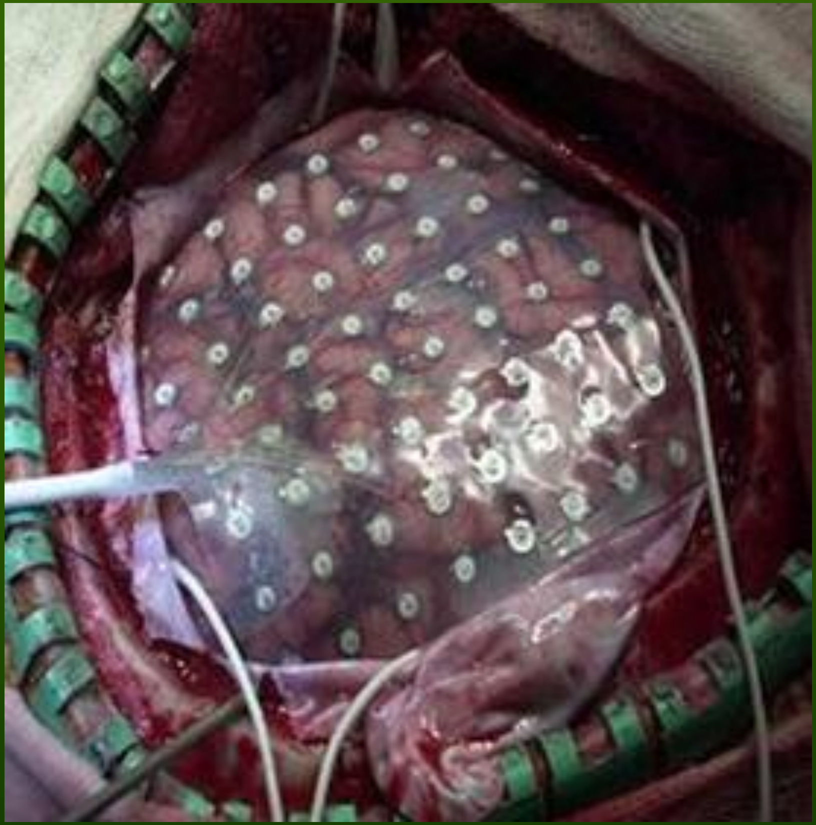






Improvement of our senses: sight, hearing, touch, memory, attention ...
Improving brains by adding new senses (Eagleman, Livewired 2020).

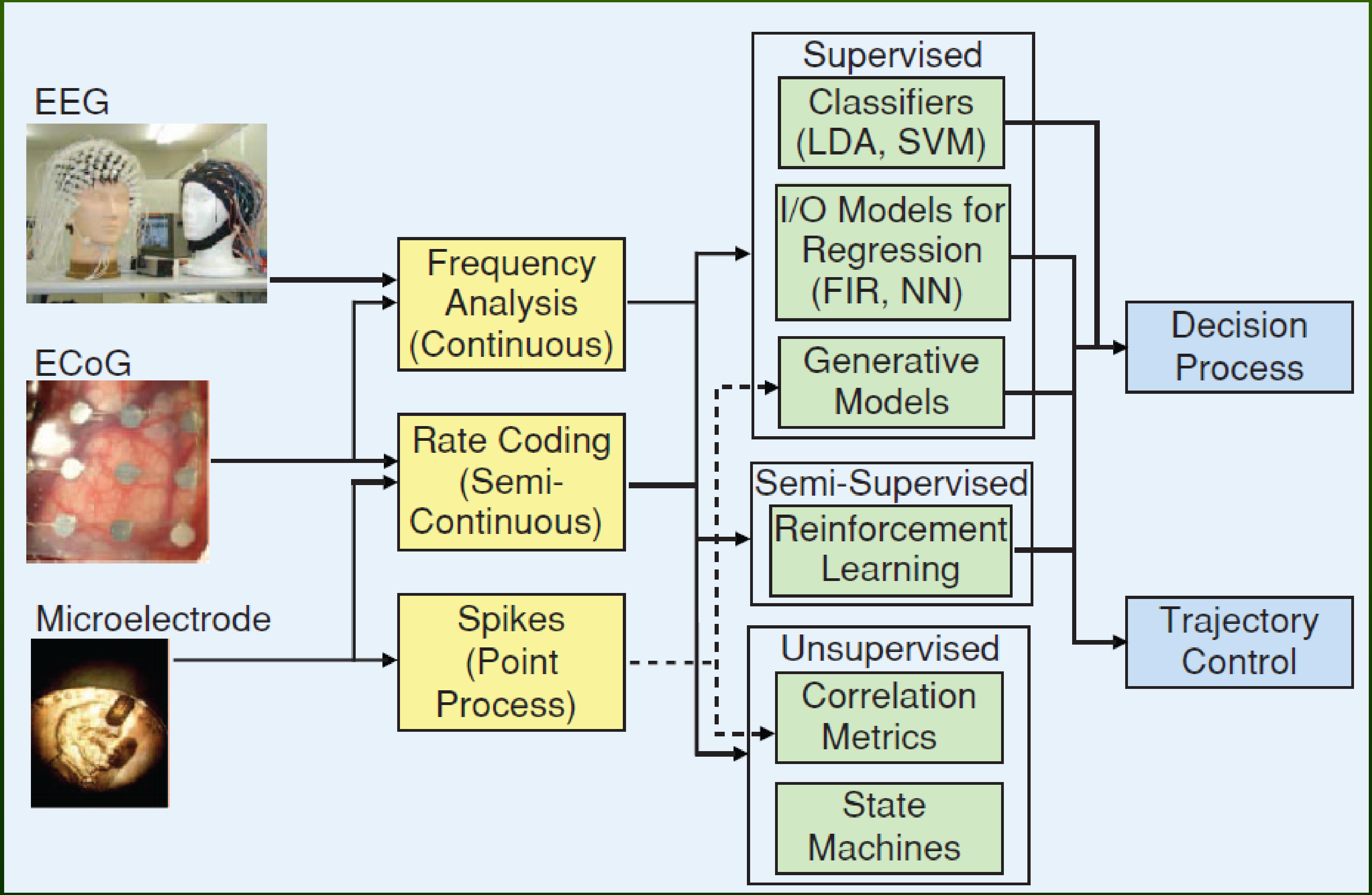
Brain computer interfaces



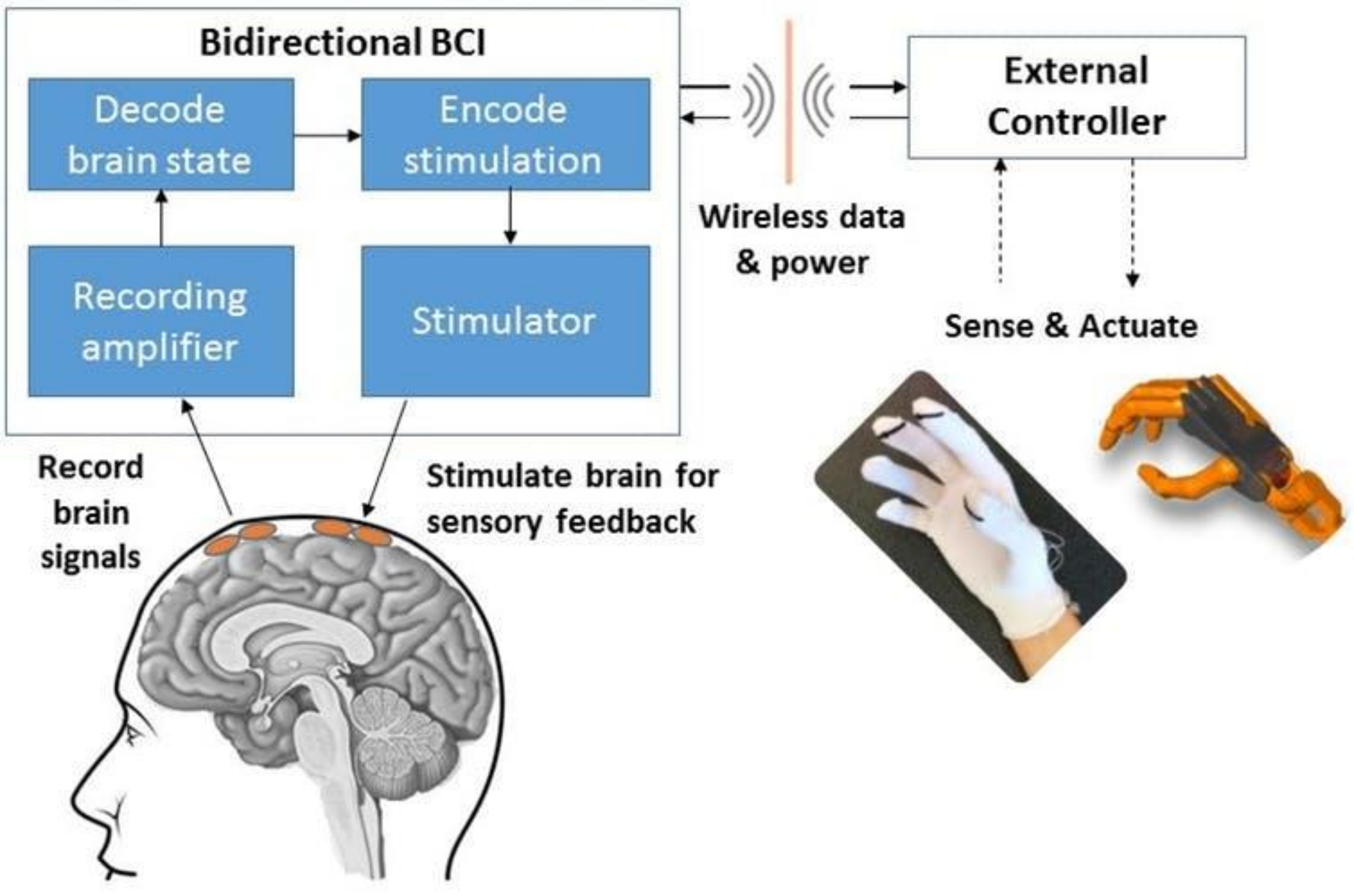
People with Parkinson's disease or compulsive-obsessive disorder who have pacemakers implanted in their brain can regulate their behavior with an external controller.

BCI: time to connect our brains …

Non-invasive, partially invasive and invasive methods carry increasing amount of information, but are also more difficult to implement. EEG+ML still reigns supreme!



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.

BRAIN MIND

BCI UNIVERSE

A mind map of sensing and stimulating brain technologies*

NONINVASIVE

INVASIVE

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

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

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

- 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

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

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

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

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

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

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/vascular injury
- Epilepsy
- Locked-in Syndrome
- Movement disorders
- OCD
- Peripheral nerve injury
- Spinal cord injury
- Stroke

- 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

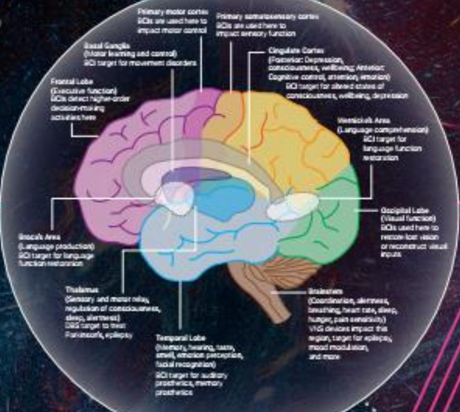
- Requires craniotomy
- Penetrates brain tissue
- Low material longevity

ELECTRO-MAGNETIC

BRAIN SENSING

METABOLIC

BRAIN STIMULATING



This is a living document.
See updated version at:
brainmind.org/bci

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

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

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

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

- Noninvasive
- Inexpensive
- Portable
- Multi-channel systems

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

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

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

- Animal research only in foreseeable future

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

- 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

- 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

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

- 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

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

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

- 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

- 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

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

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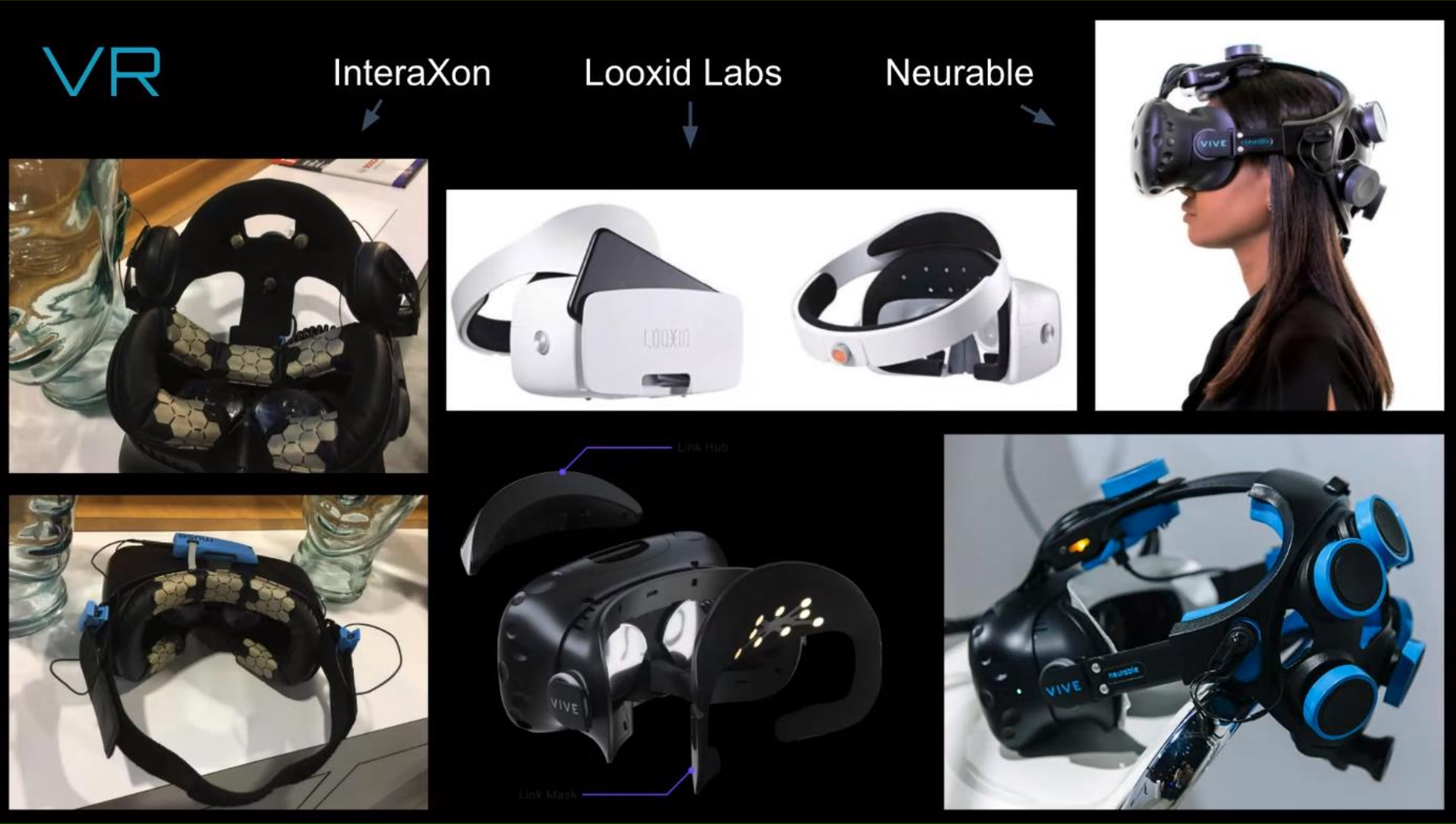
*Our report focuses on BCIs with near-term potential for closed-loop applications. Technologies which do not directly read or stimulate the brain (EMG, haptics) and those which are not commonly used as a BCI (PET, microscopy technology) are excluded.

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, Jim Bahr, [illegible], [illegible], Andreas Forsland, Ana Maiques, Tim Mullen, Karen Rommelfanger, Philip Sabes, Jay Sanguinetti

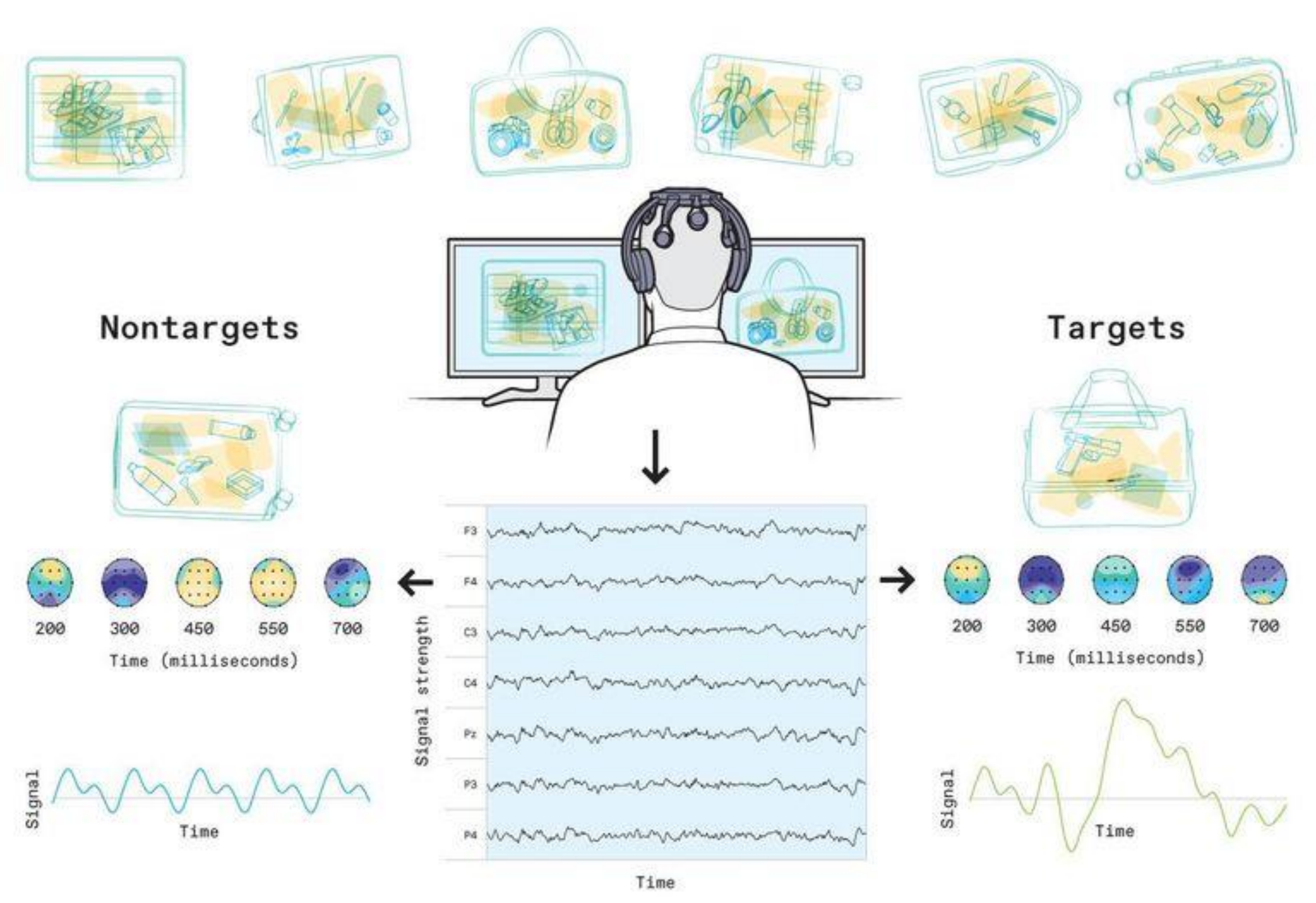
BCI tools

Combination of Virtual Reality with BCI has great potential.



InnerEye

Simple DCS will let you analyze 3-10 images per second for hours …
Your brain is smarter than you!

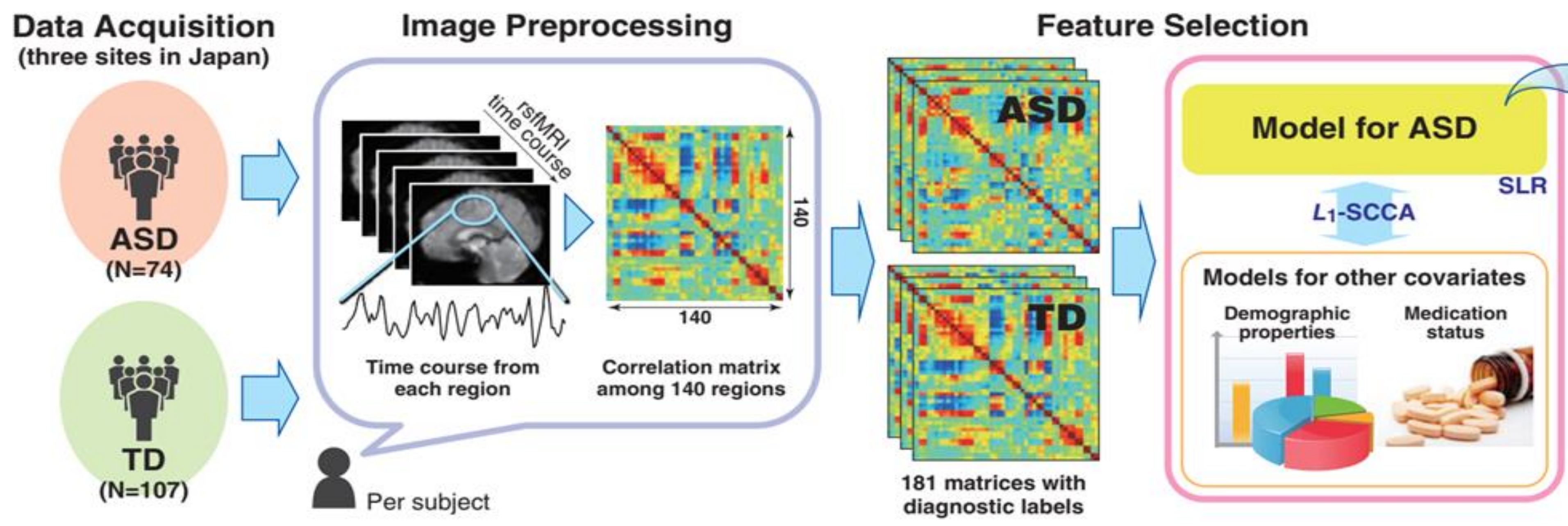


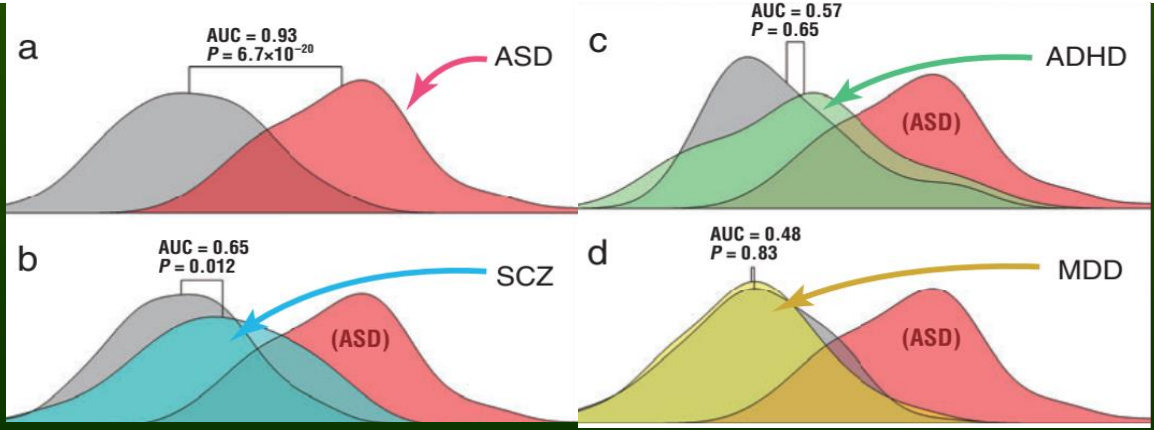
Private Information in BCIs

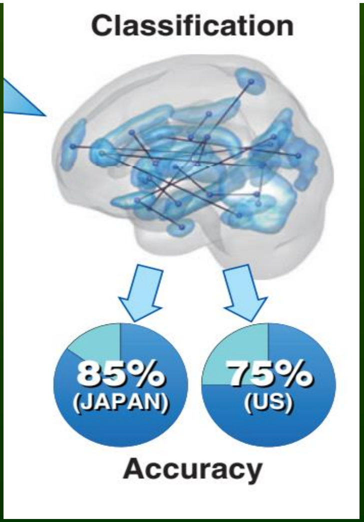
- Private Information
  - Personal Account
    - Identity
    - PIN
    - Bank Account
  - Personal Preference
    - Belief
    - Opinion
    - Prejudice
  - Physical State
    - Age Group
    - Disorders
    - Memory
  - Commercial Models
    - Parameters
    - Architecture
    - Algorithm

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

Biomarkers from neuroimaging

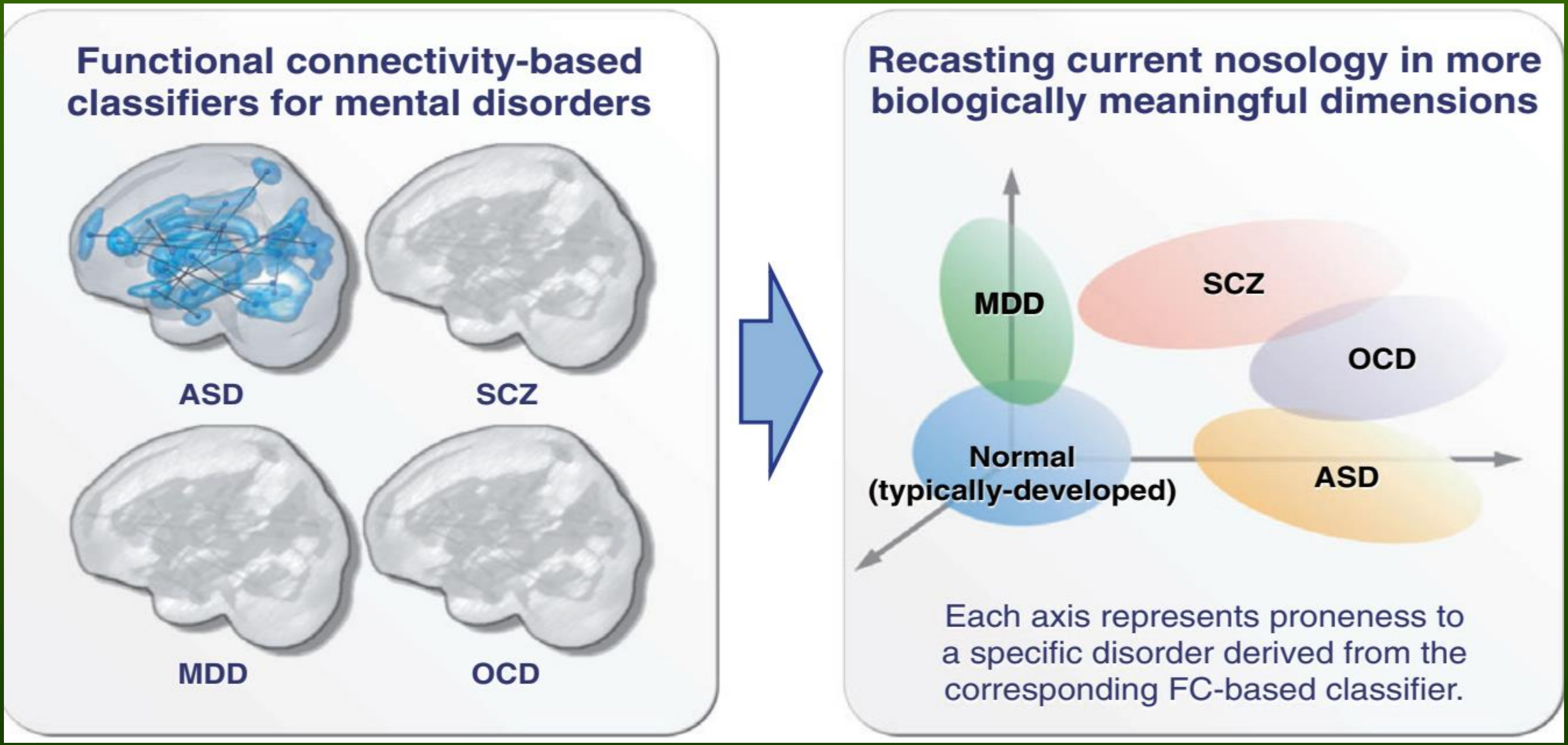






N. Yahata et al, *Psychiatry and Clinical Neurosciences* 2017: **71**

Biomarkers of mental disorders



Functional connectivity-based classifiers for mental disorders

Recasting current nosology in more biologically meaningful dimensions

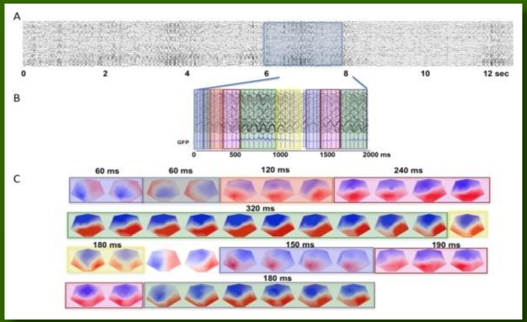
Each axis represents proneness to a specific disorder derived from the corresponding FC-based classifier.

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.

Brain fingerprinting

- Find unique patterns of brain activity, 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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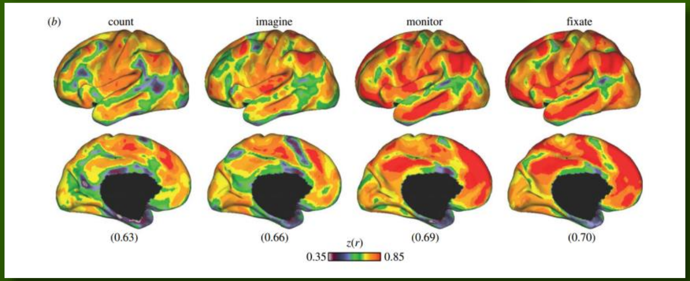

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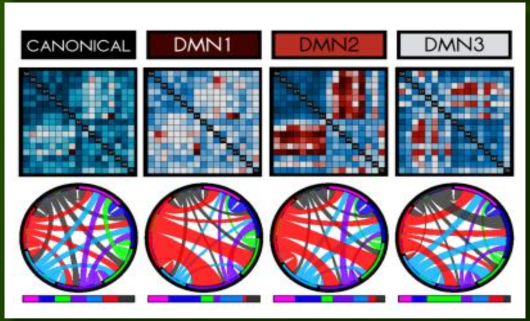

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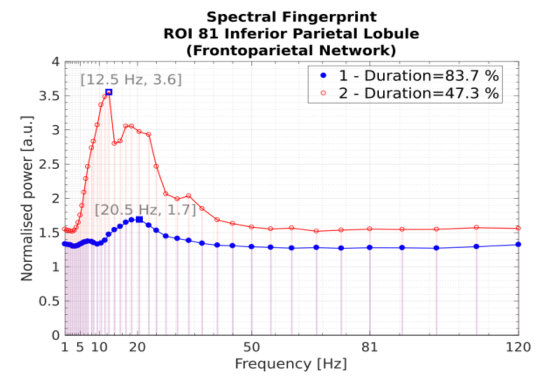


Understanding brains: microstates

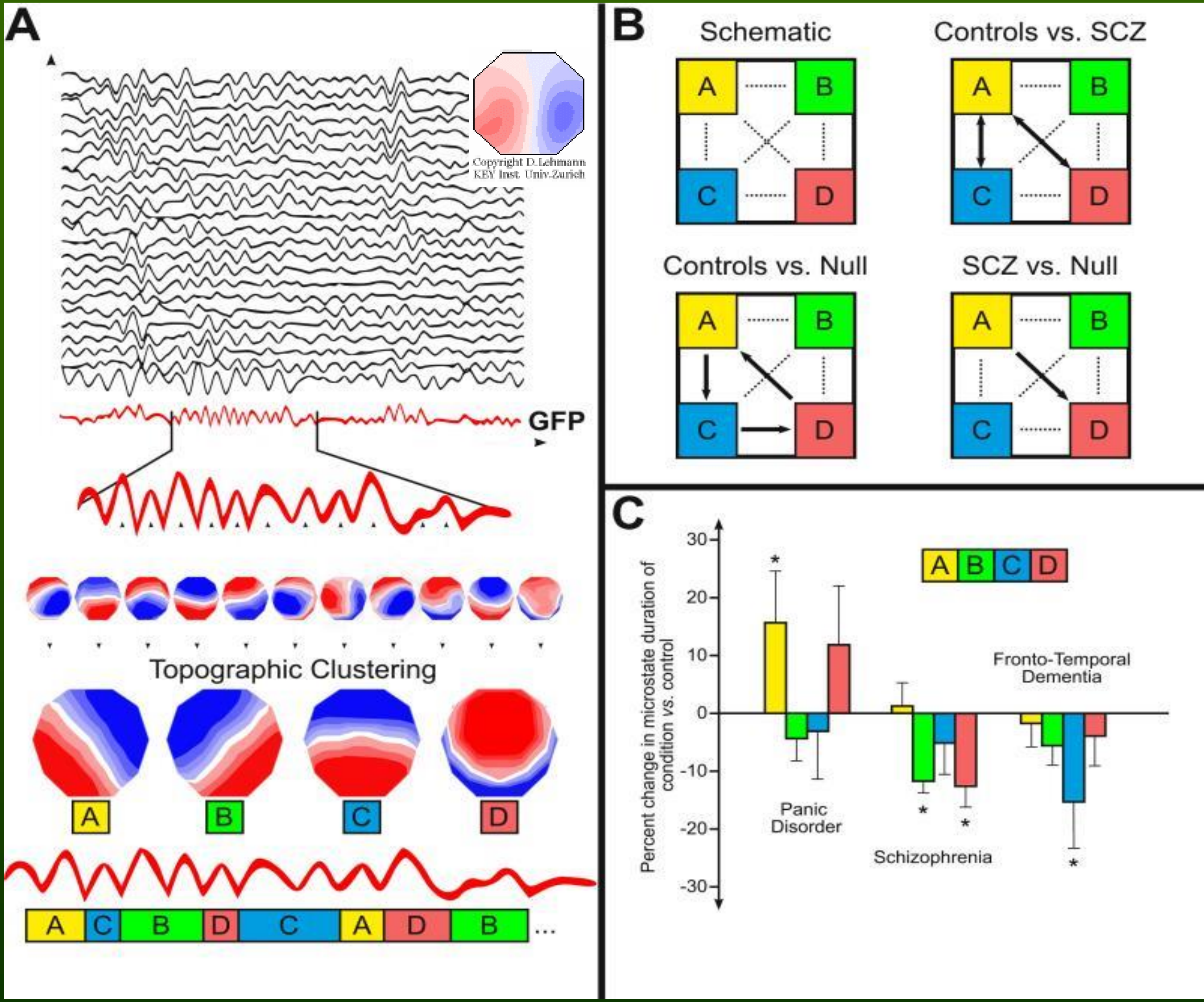
Global Field Power.
4-7 states, 60-150 ms.

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

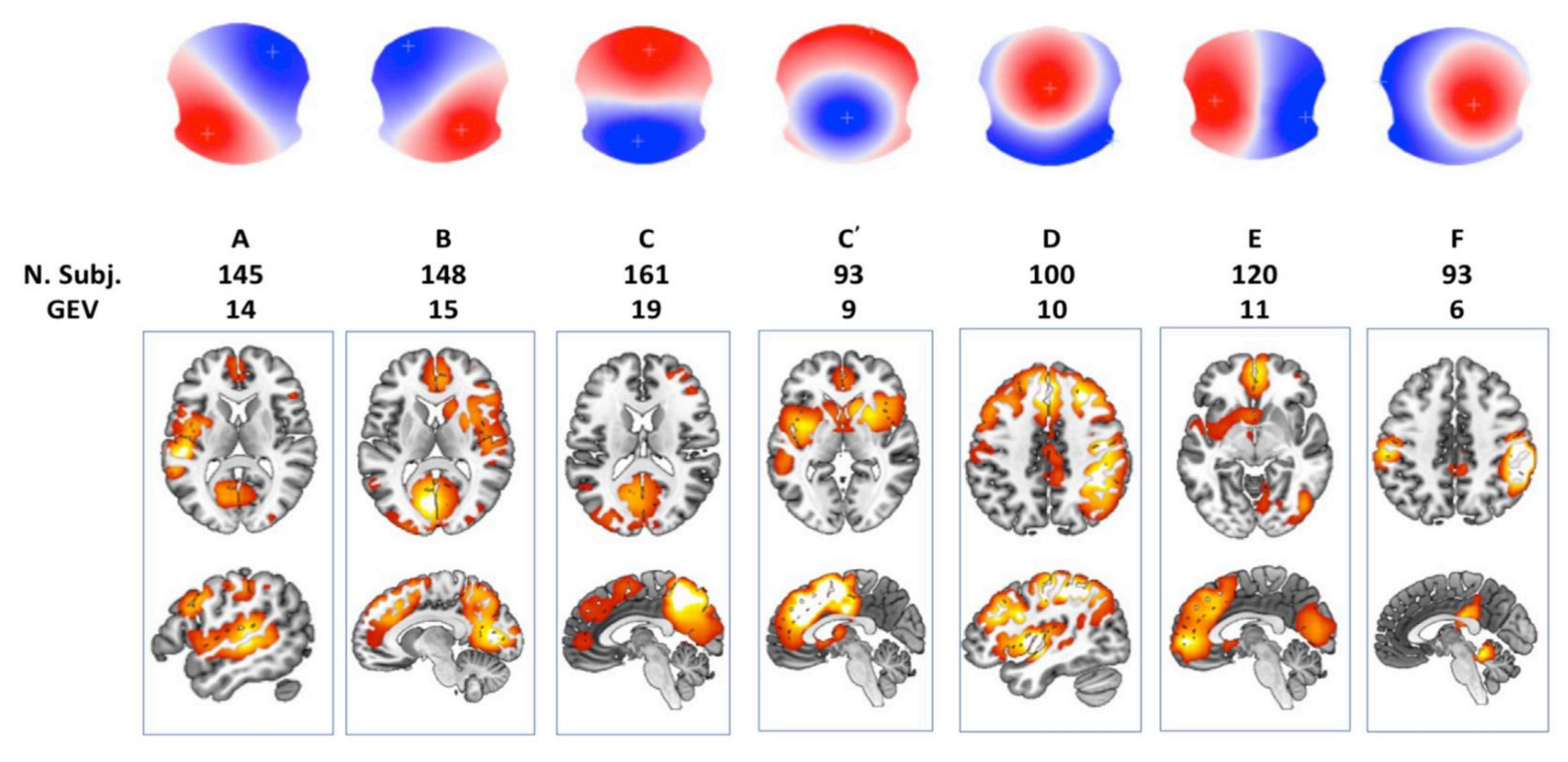
Symbolic dynamics: statistics of A-D symbol strings. Fuzzy Symbolic Dynamics (FSD) + visualizations.

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

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



Microstates and their sources



	A	B	C	C′	D	E	F
N. Subj.	145	148	161	93	100	120	93
GEV	14	15	19	9	10	11	6

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.
Ewa Ratajczak, PhD thesis "Microstate neurodynamics in HRV biofeedback“ (2022)

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.

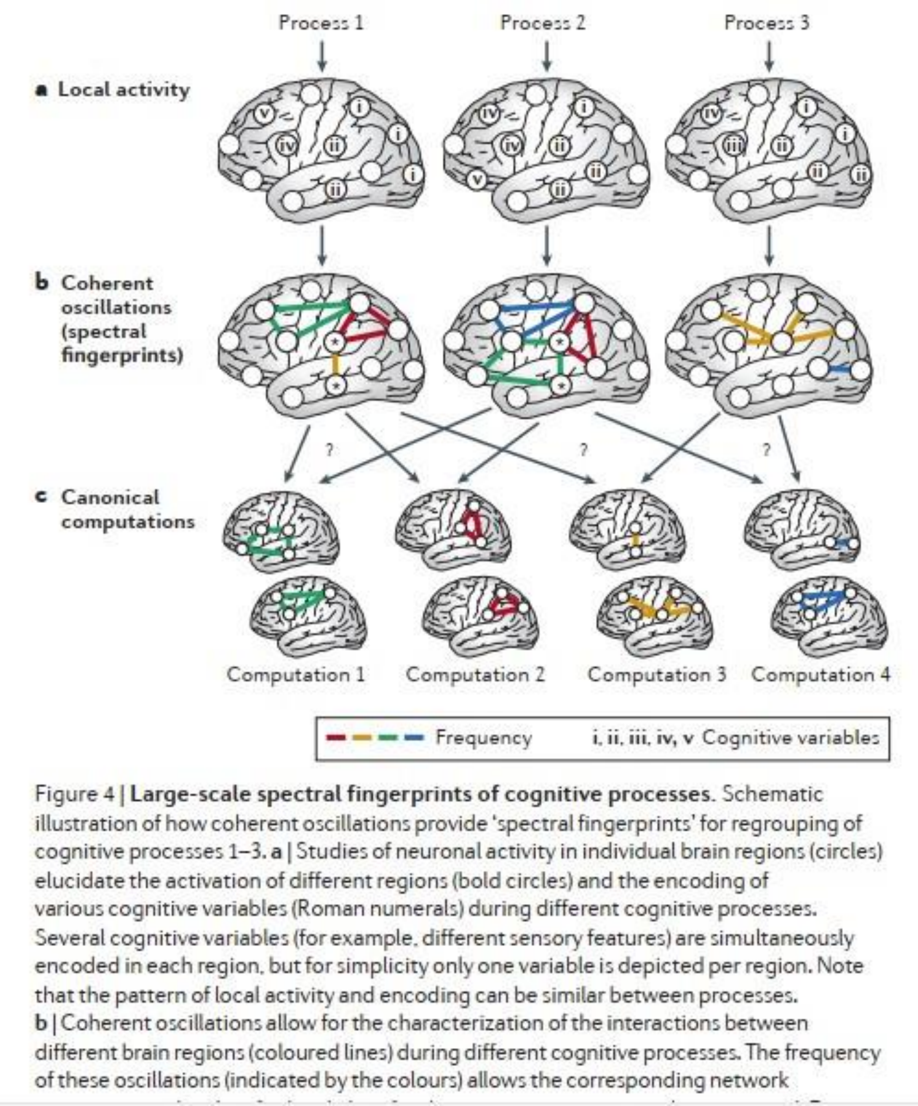
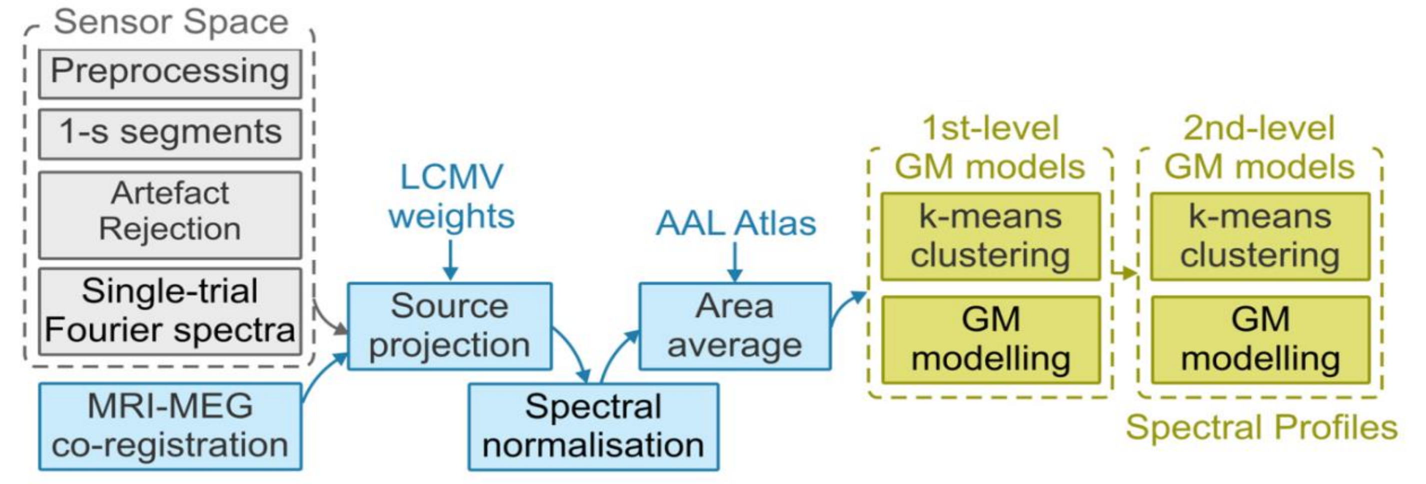


Figure 4 | **Large-scale spectral fingerprints of cognitive processes.** Schematic illustration of how coherent oscillations provide 'spectral fingerprints' for regrouping of cognitive processes 1–3. **a** | Studies of neuronal activity in individual brain regions (circles) elucidate the activation of 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

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

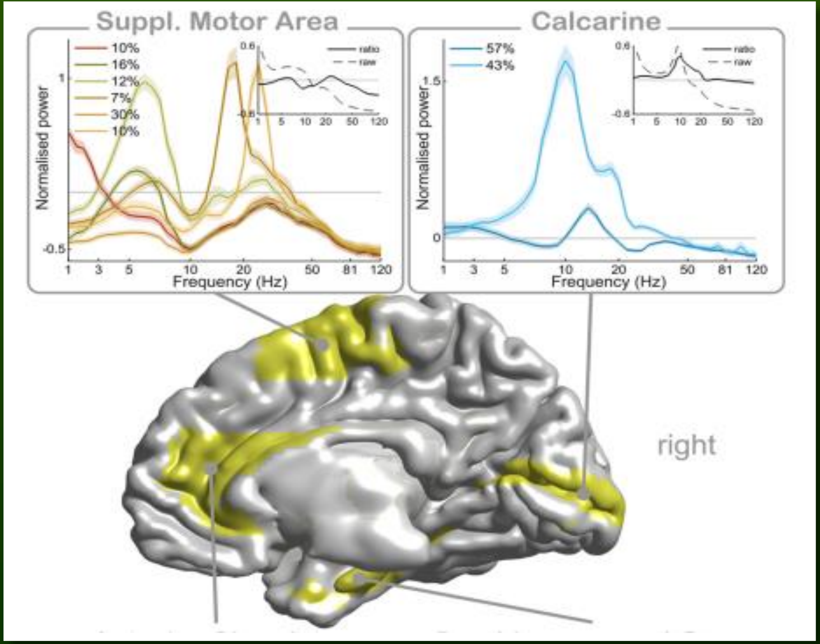
Spectral analysis



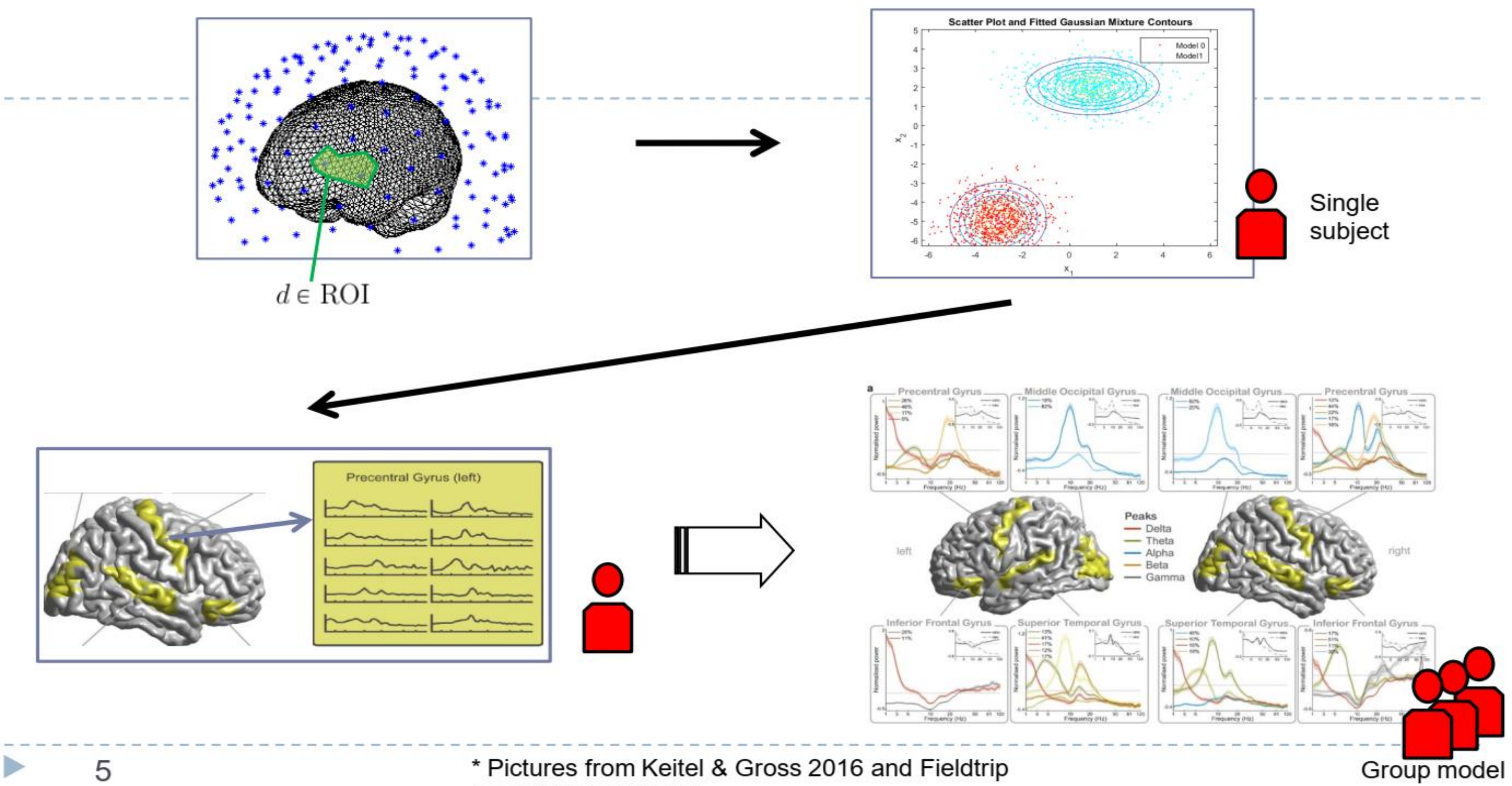
Create spectral fingerprints of ROIs.

- 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



$d \in \mathrm{ROI}$

Single subject

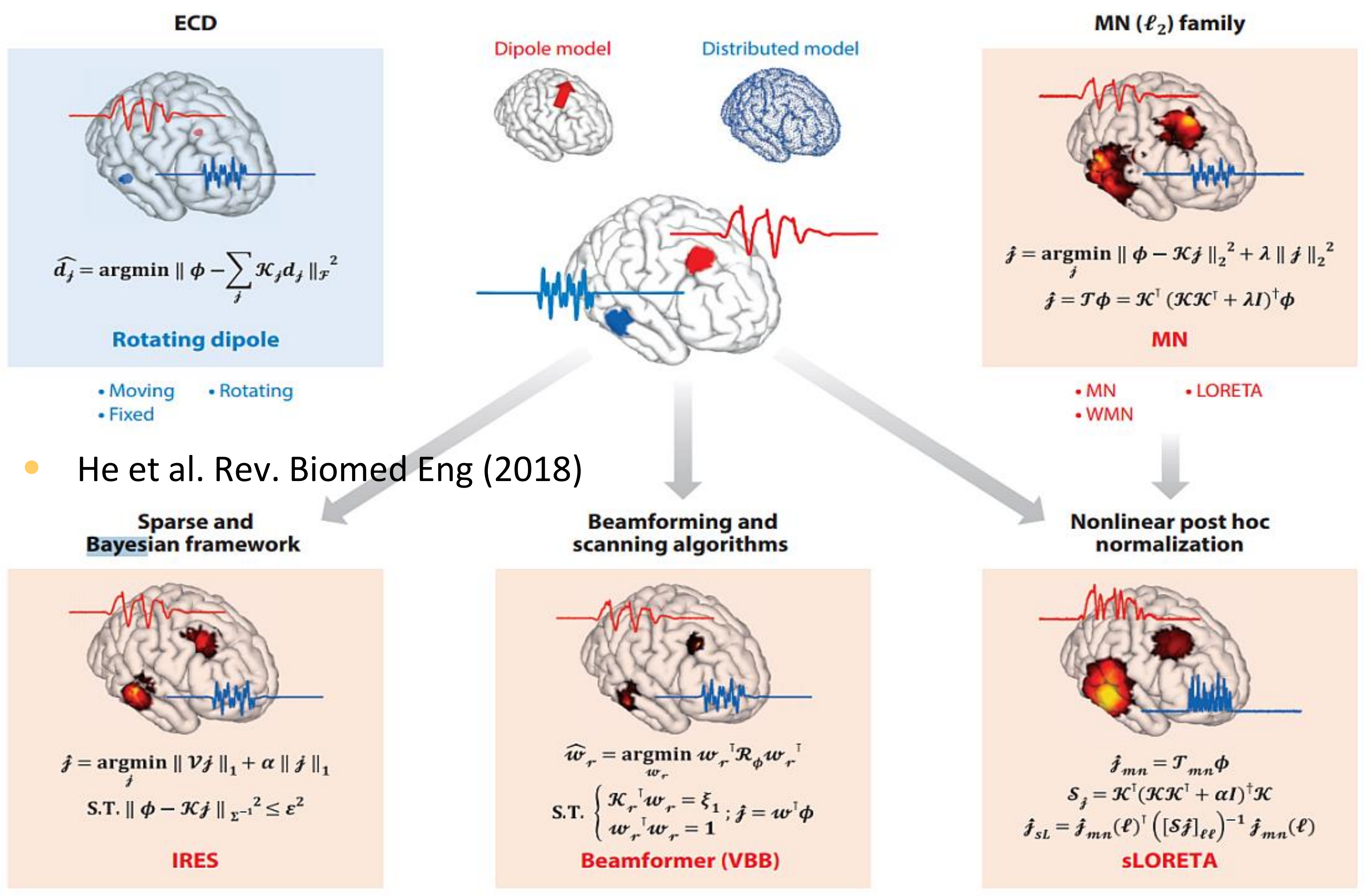
Group model

5

* Pictures from Keitel & Gross 2016 and Fieldtrip beamforming tutorial

One ROI, two or more spectra. Static picture showing natural frequencies. Michał Komorowski PhD "Locally specific human brain dynamics automatically modeled using spectral features of MEG/EEG signals”, 2022. ToFFi toolbox.

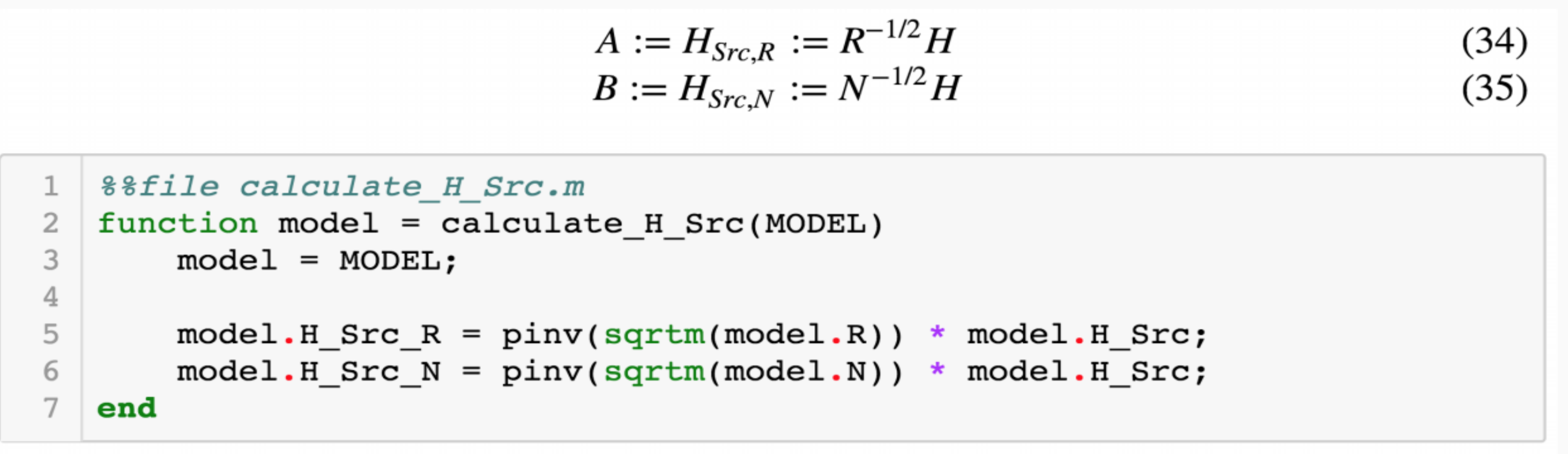
EEG localization and reconstruction



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

SupFunSim

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



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

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

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

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

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

STFT vs. embedding

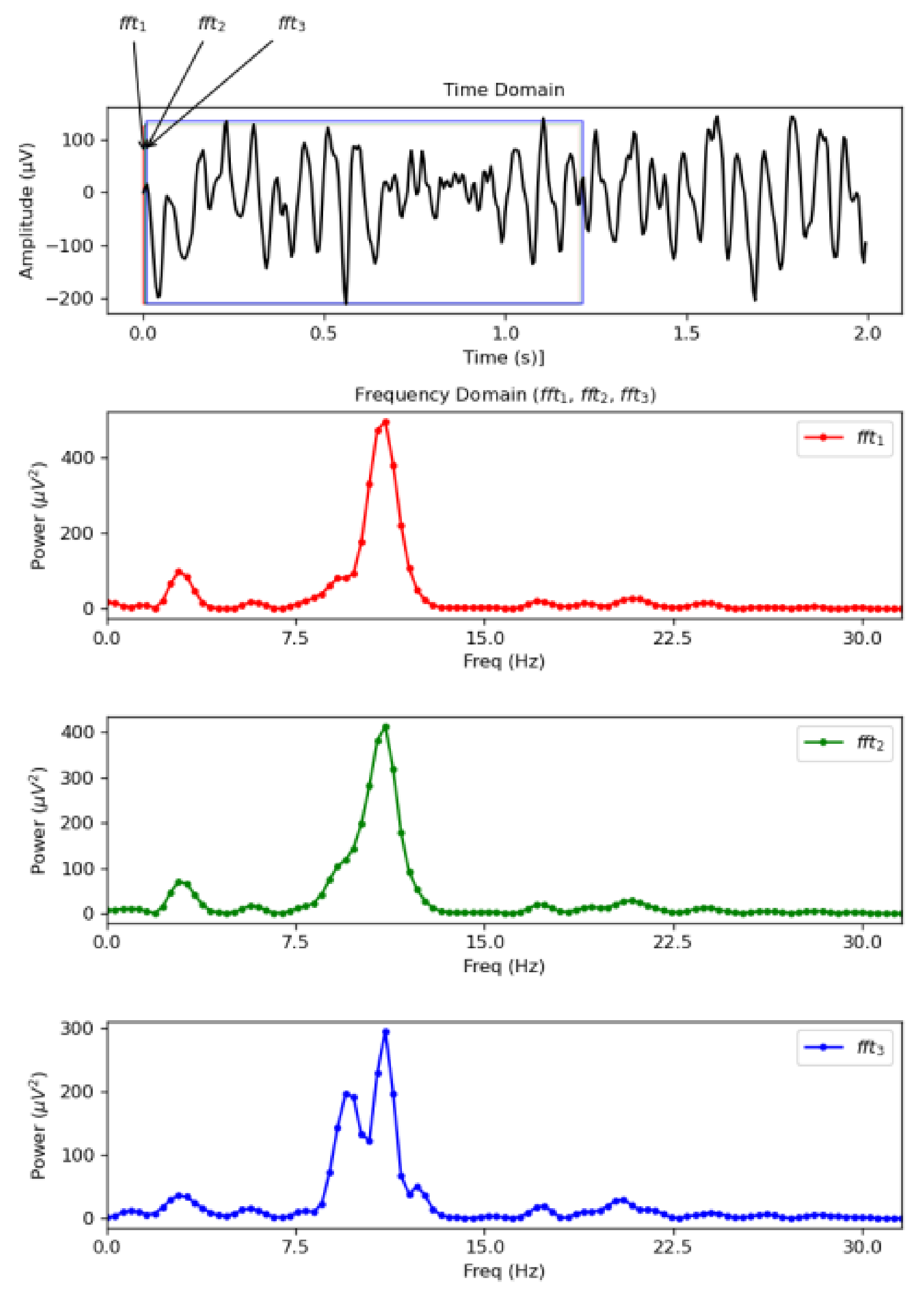
Takens theorem: attractors are recreated from signals sampled using time-delay embedding, vectors

$\boldsymbol{x}_i = (u_i, u_{i+\tau}, \ldots, u_{i+(m-1)\tau\Delta t})$.

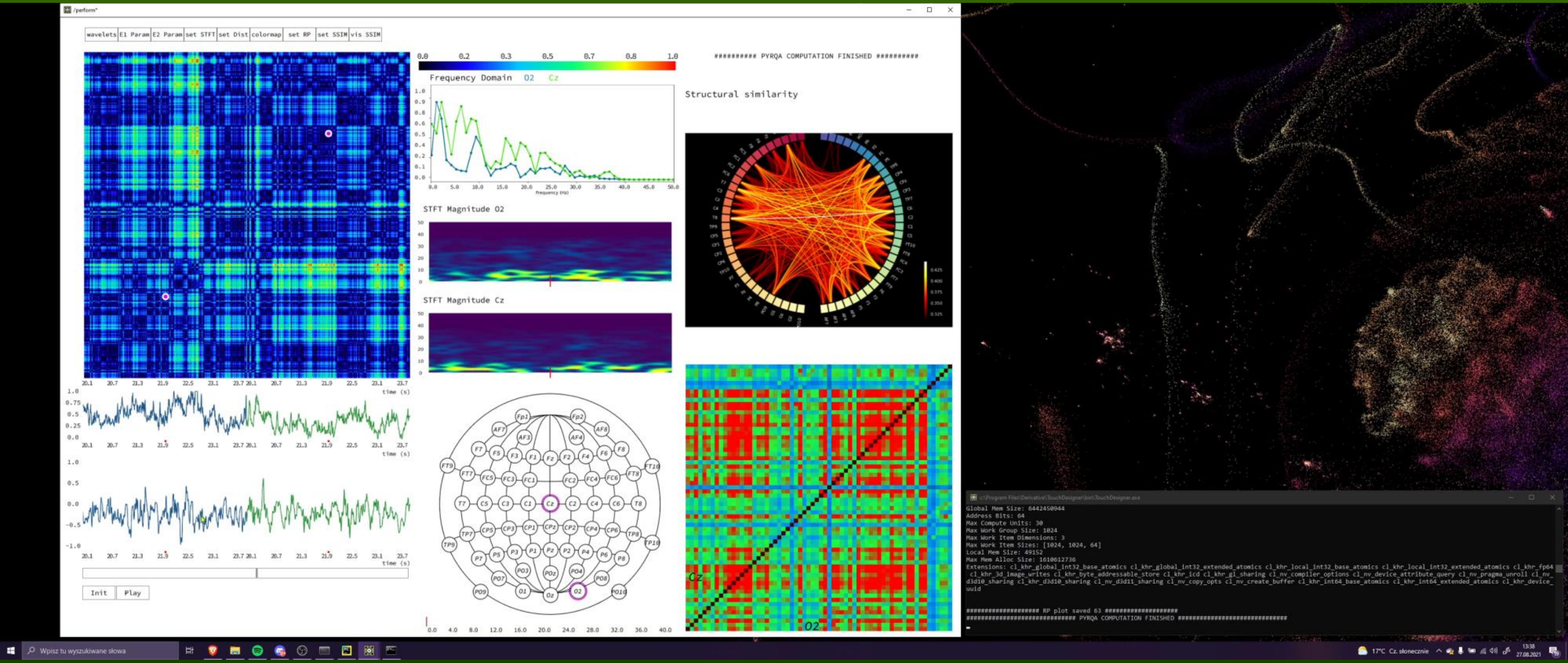
Here m is the embedding dimension, and τ is an index enumerating time delays, $\tau\Delta t$.

Alternative representation:
STFT, shows power distribution in subsequent time windows. Here changes of spectrum every 100 ms, O_1 electrode.

Ł. Furman, W. Duch, L. Minati, K. Tołpa, Short-Time Fourier Transform and Embedding Method for Recurrence Quantification Analysis of EEG Time Series. The European Physical Journal Special Topics (2022, p. 1-15).



STFT EEG in real time



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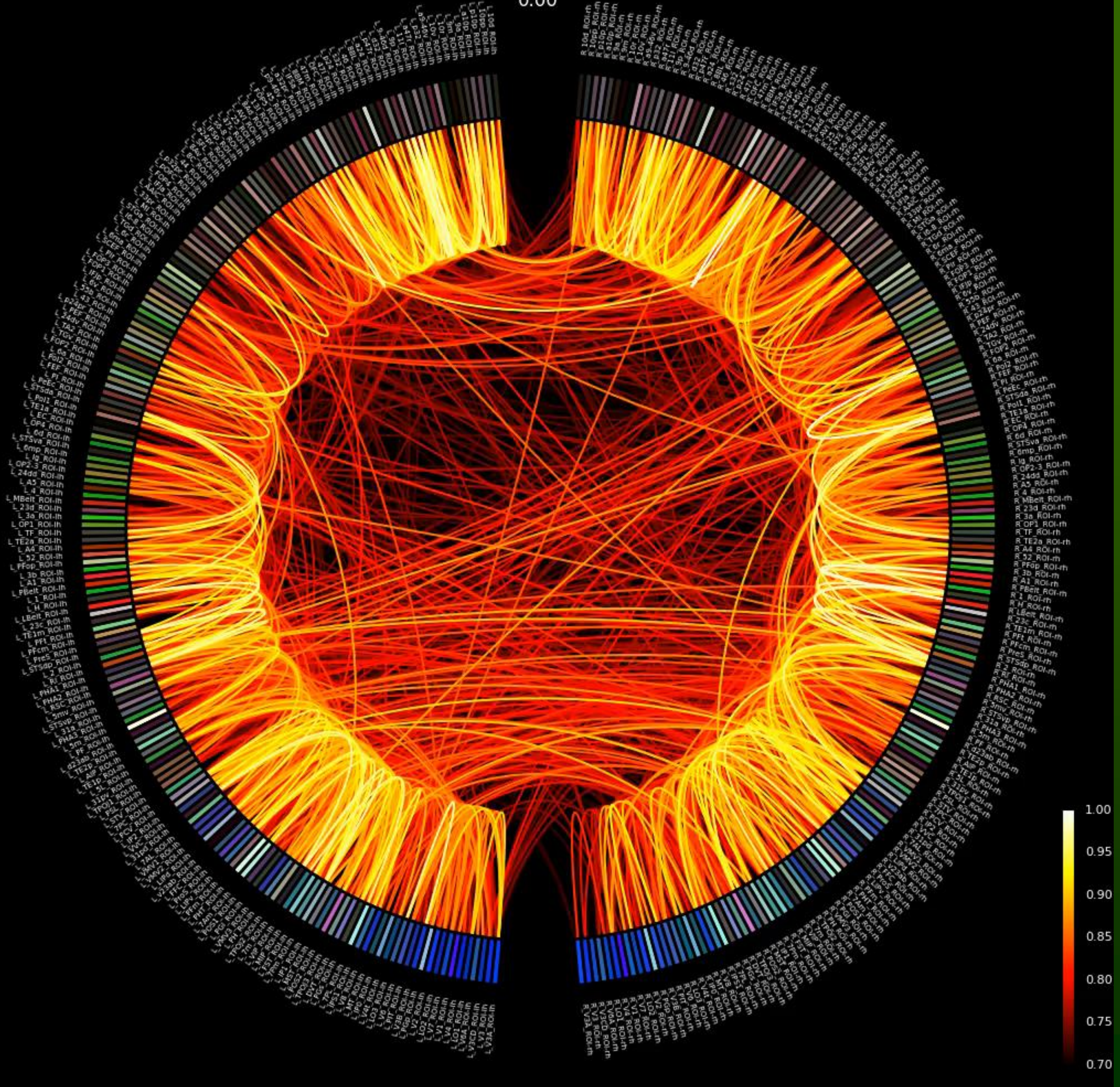
Address Bits: 64
Max Compute Units: 30
Max Work Group Size: 1024
Max Work Item Dimensions: 3
Max Work Item Sizes: [1024, 1024, 64]
Local Mem Size: 49152
Max Mem Alloc Size: 1610612736
Extensions: cl_khr_global_int32_base_atomics cl_khr_global_int32_extended_atomics cl_khr_local_int32_base_atomics cl_khr_local_int32_extended_atomics cl_khr_fp64
 cl_khr_3d_image_writes cl_khr_byte_addressable_store cl_khr_icd cl_khr_gl_sharing cl_nv_compiler_options cl_nv_device_attribute_query cl_nv_pragma_unroll cl_nv_
d3d10_sharing cl_khr_d3d10_sharing cl_nv_d3d11_sharing cl_nv_copy_opts cl_nv_create_buffer cl_khr_int64_base_atomics cl_khr_int64_extended_atomics cl_khr_device_
uuid


#################### RP plot saved 63 ####################
############################## PYRQA COMPUTATION FINISHED ##############################
```

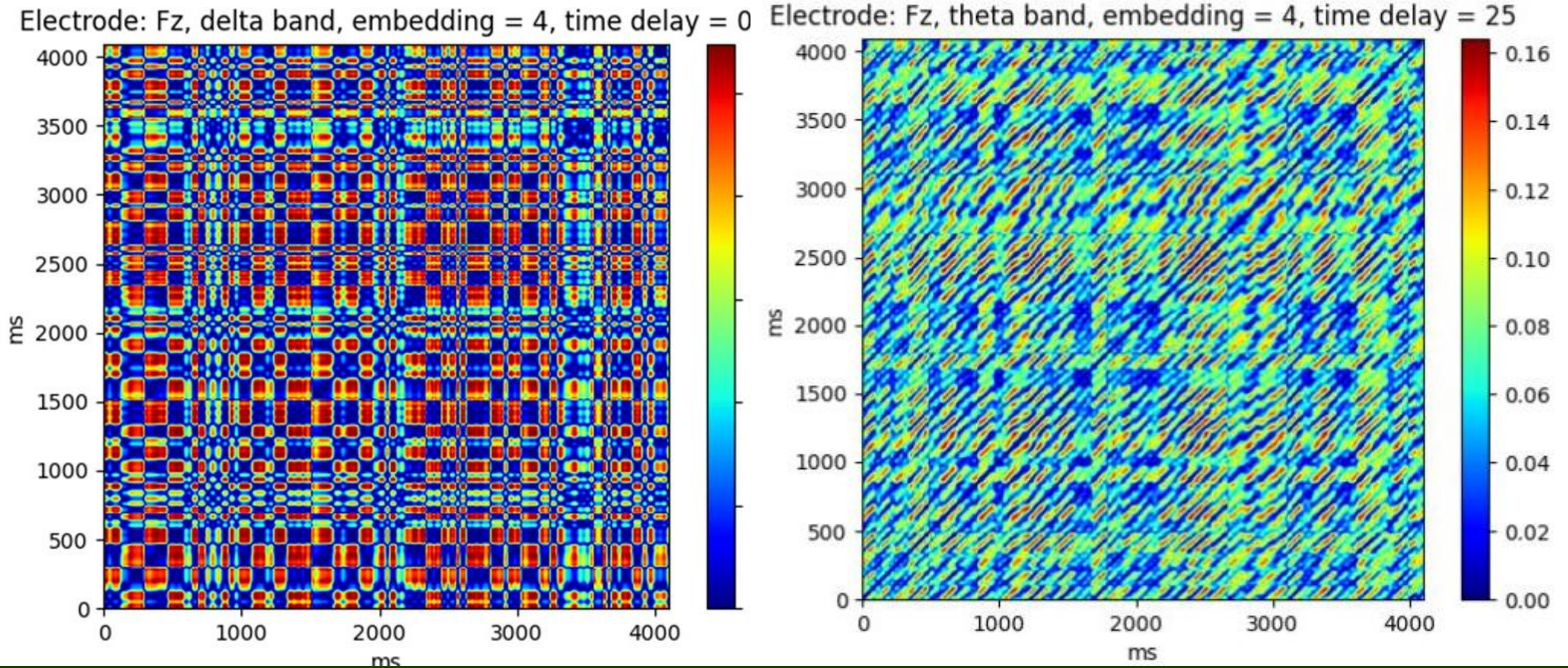
EEG data, 128 channels, recursion graphs, power spectrum for two electrodes, information flow and correlations between brain regions.
BrainPulse (in development, Łukasz Furman).

PAC_IMtest_inverse_circle_coh_8.0-12.0hz_vmin0.7

0.00



Recurrence plots δ, θ



Recurrence Plots showing STFT similarity for delta and theta bands, Fz electrode. Distance scale changes parameters of the metastable states along diagonal, and influence non-linear parameters. BrainPulse tools helps to analyze changes of the t/f spectra, RPs and STFT power spectra.

Labeling states

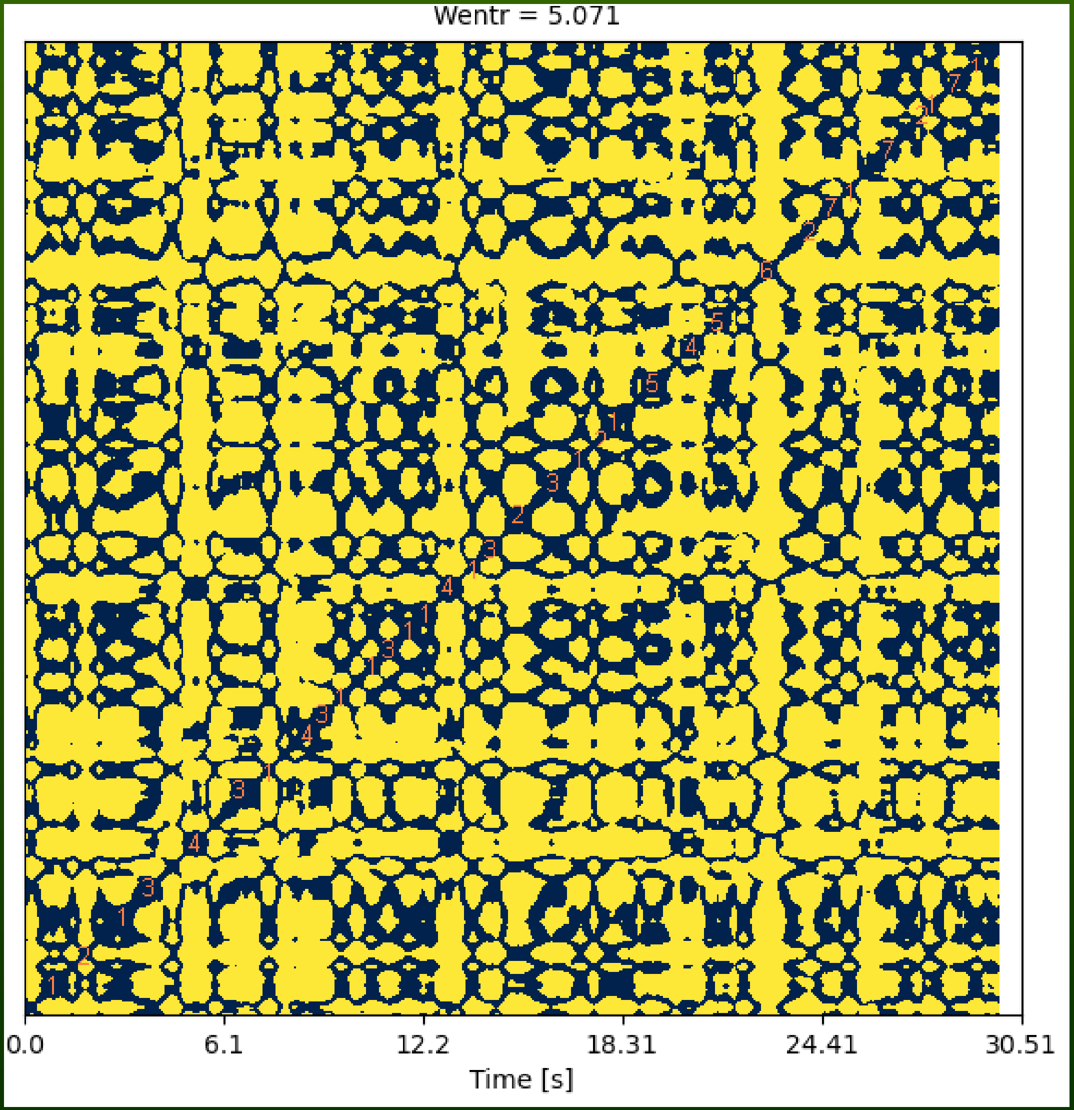
Automatic labeling of states and estimation of their recurrence may be important for biofeedback.

Metabolic costs of transitions between states may be important.

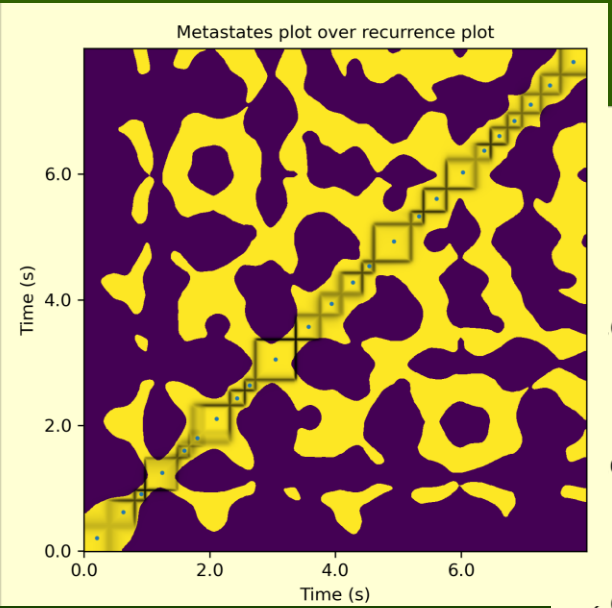
Ruminations? Pain states? How external stimuli influence this dynamics?

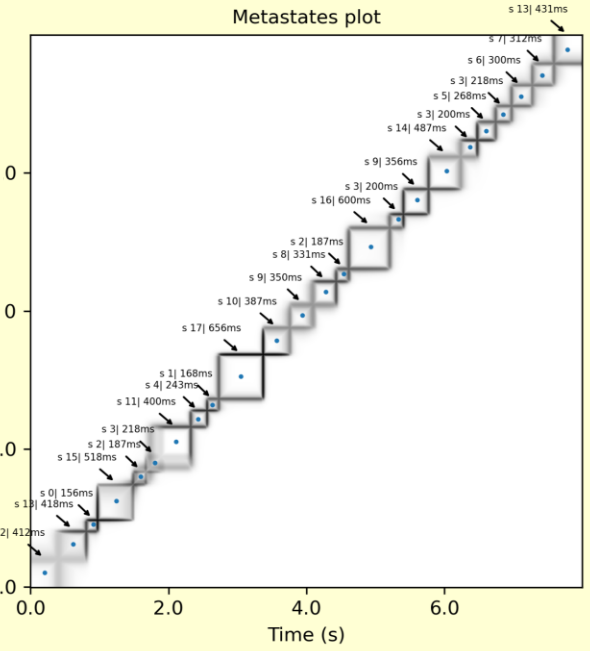
Needs automatic method for recognition of metastable, multivariate states.

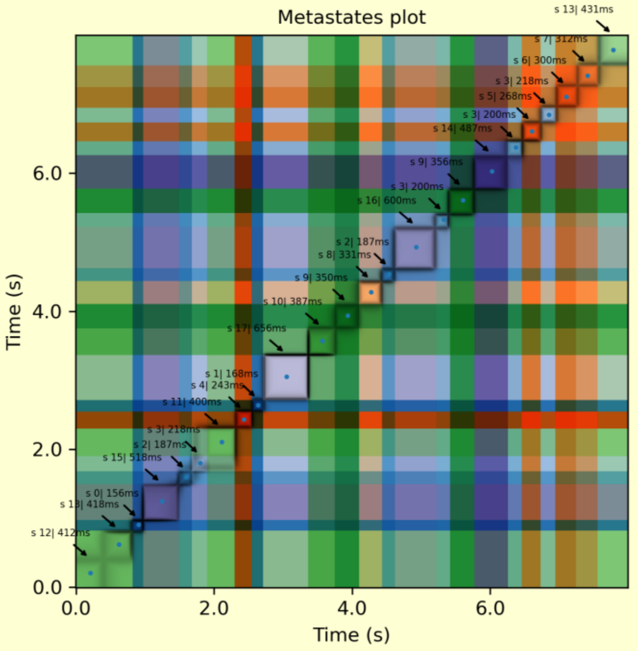
More precise than microstates.



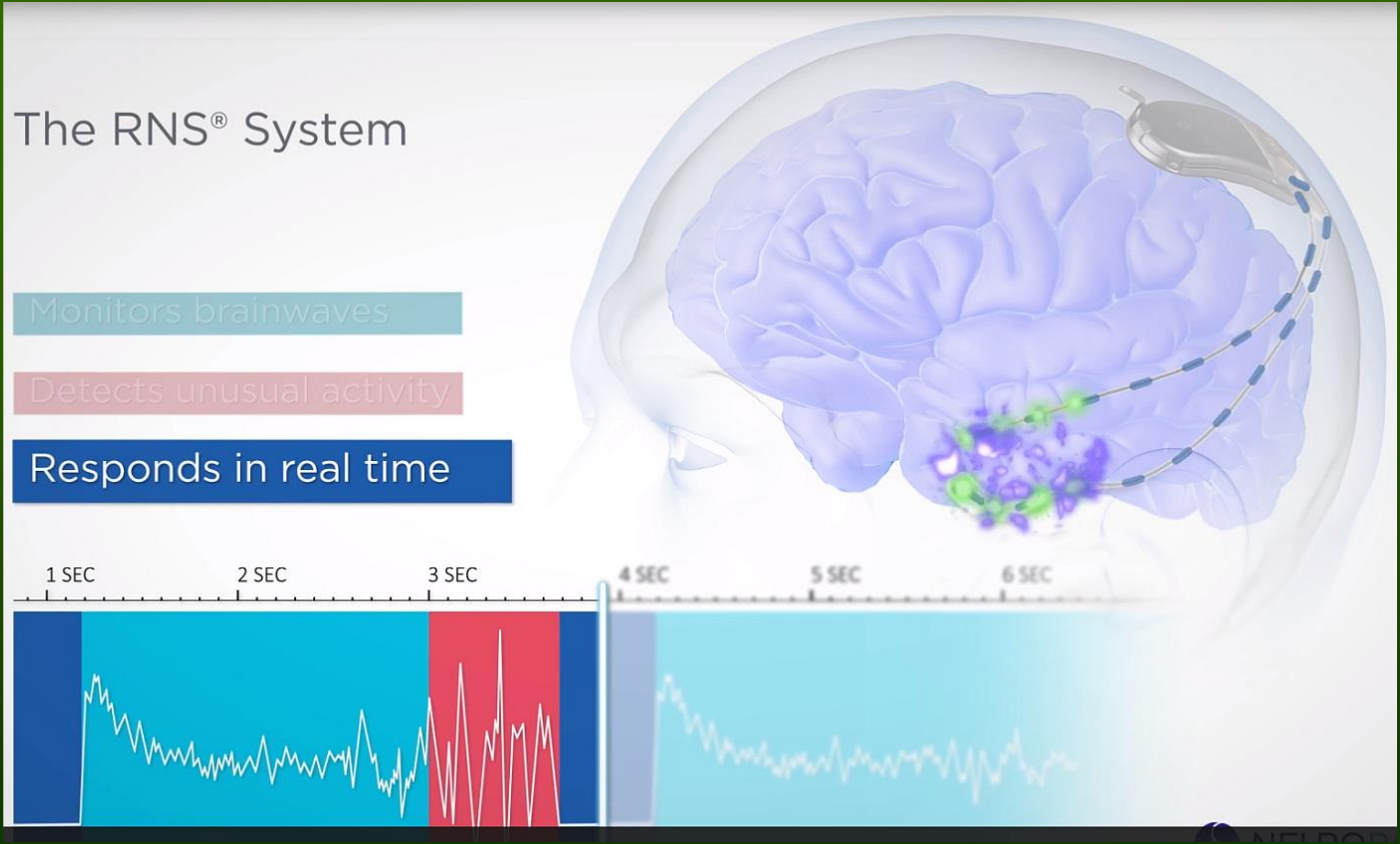
Segmentation of states







Epilepsy



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

Brain Robotic Interface

- Australia, UTS: VR to control robotic dogs using EEG.
  Dry graphene sensors, not as accurate as wet. Can it be useful?

.RICO

ROBOTIC & AUTONOMOUS SYSTEMS
IMPLEMENTATION & COORDINATION OFFICE

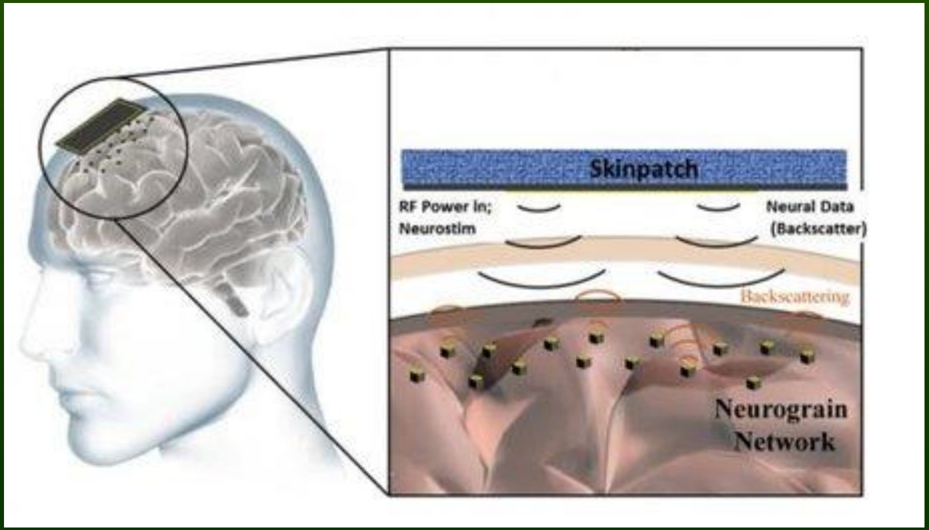
A million nanowires in the brain?

DARPA initiatives: **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 promised neuralink (neural lace). FDA refuses human trials.

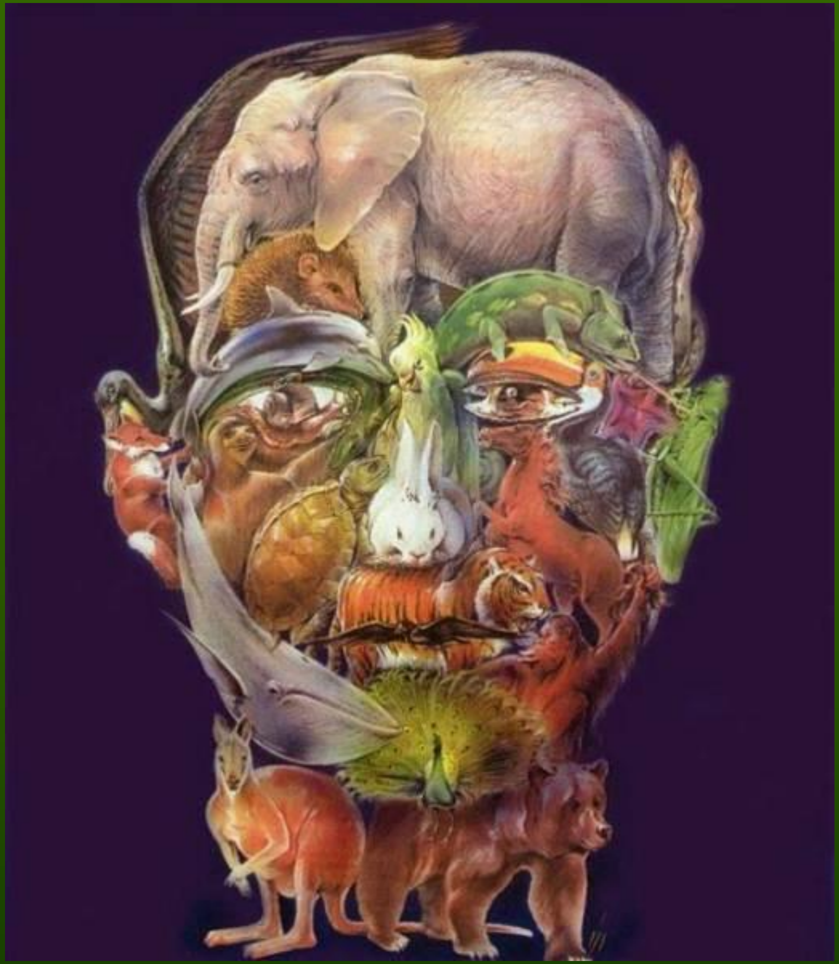


Perspectives

- AI is changing everything, including the way science is done.
- Large language models can do much more than generate language and images.
- AutoGTP can plan and recruit many tools, performing complex tasks.
- Such techniques have a chance to improve brain signal processing, but we still need better methods for understanding brain activity.
- Neurocognitive technologies will profoundly change ourselves, ultimately restoring normal functions and optimizing normal brain processes, but there is a lot of hype in the BCI field.
- Optimization of brain processes is the biggest challenge!

Caution! Singularity may come faster than we think!

Intelligence?



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