Cognition, Emotion, Behavior. The brain at work. - Neuroimaging and artificial intelligence

CIBIT
Coimbra Institute for Biomedical Imaging and Translational Research

UNIVERSIDADE D COIMBRA
INSTITUTO DE CIÊNCIAS NUCLEARES APLICADAS À SAÚDE

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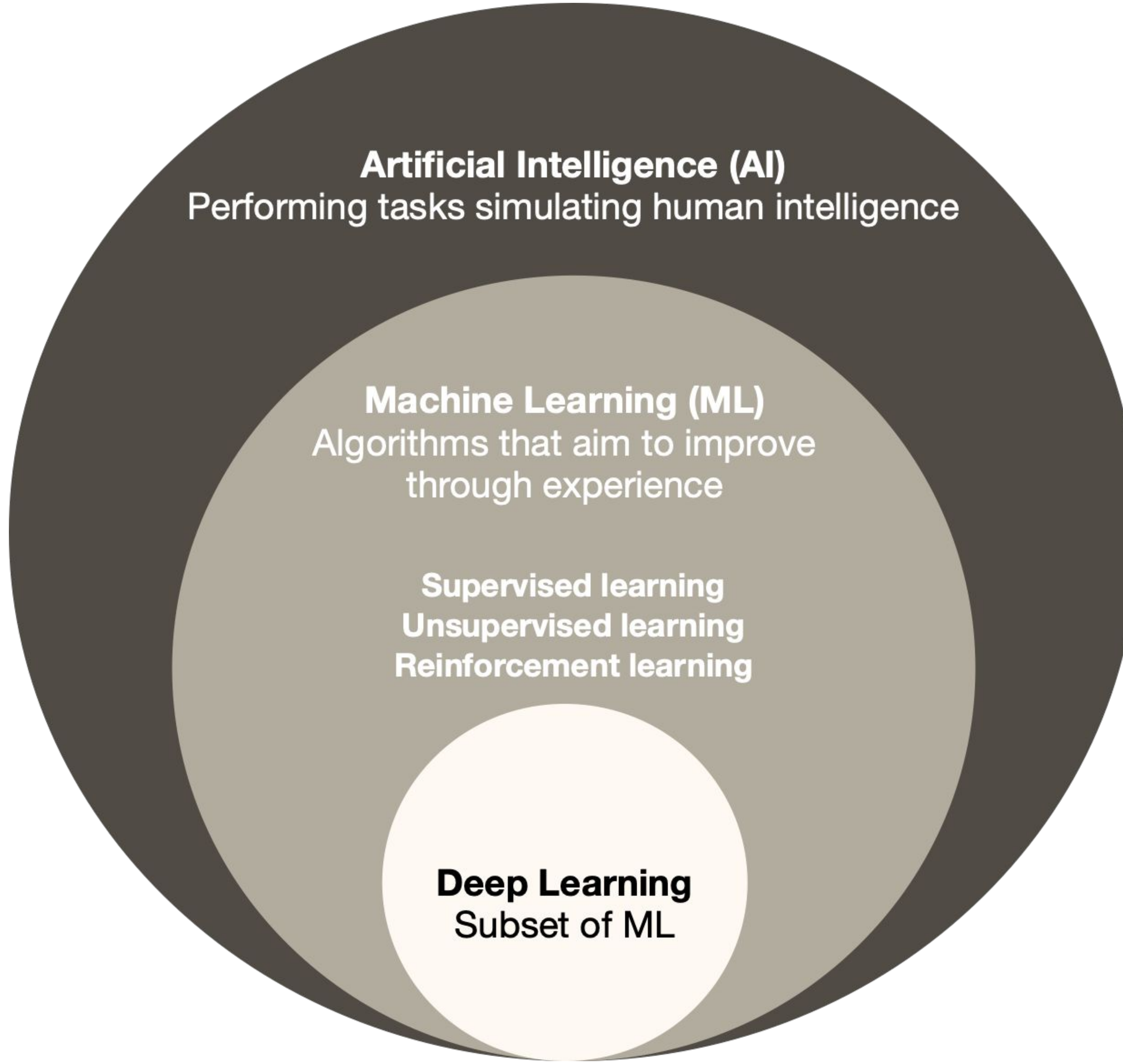
Live updates

- Ter em conta a apresentação do Prof. Nuno Moniz
  - Limitações associadas à aprendizagem
    - Algoritmos
    - Amostragem
      - ‘Overfitting’
  - Muitos dos pontos são análogos aos apresentados pela Prof. Joana Cabral
    - Procura de base para os padrões neuronais de desordens neurodesenvolvimento / psicopatologia

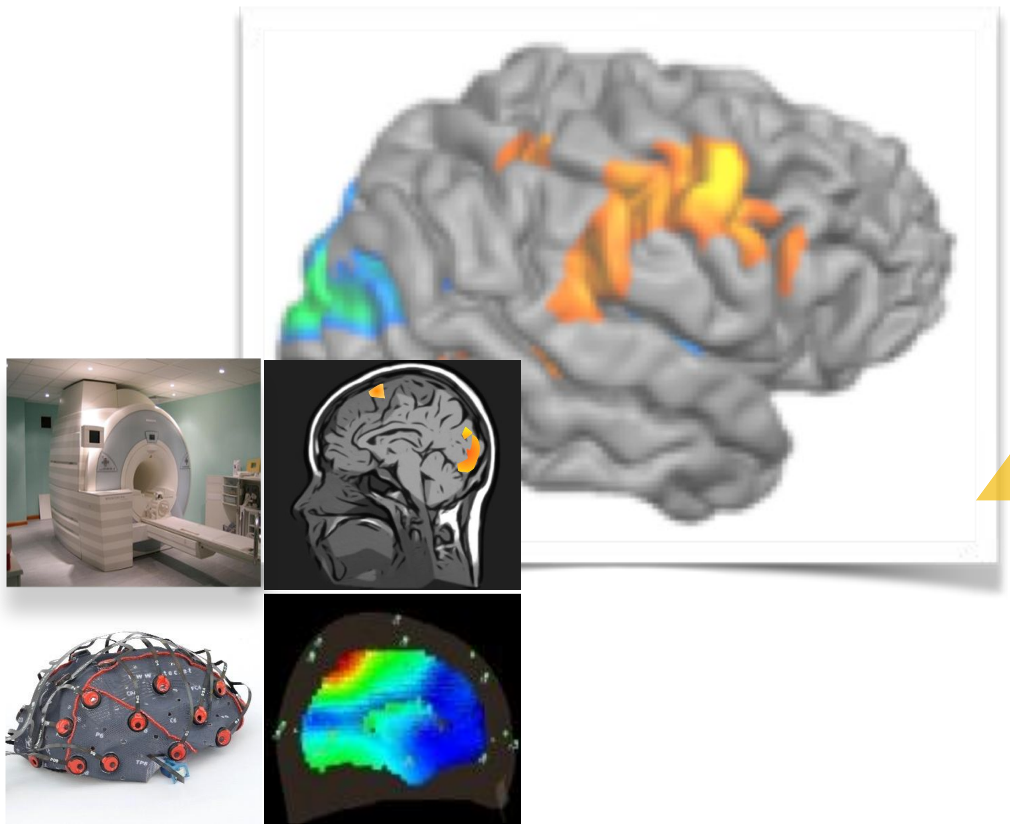
- Artificial Intelligence (computer vision, NLP, Robotics, …)
  - Machine Learning
    - Deep Learning



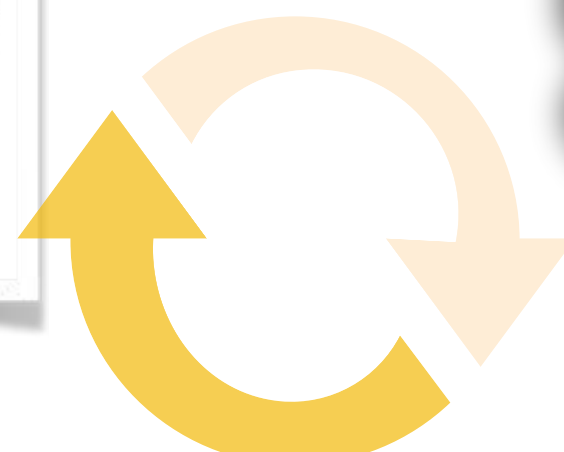
Neuroimaging (cognitive/functional) and **Artificial Intelligence**/Machine Learning

Brain measurements

Behavior descriptors



Magnetic Resonance Imaging (MRI) Scanner
and Electroencephalography (EEG)

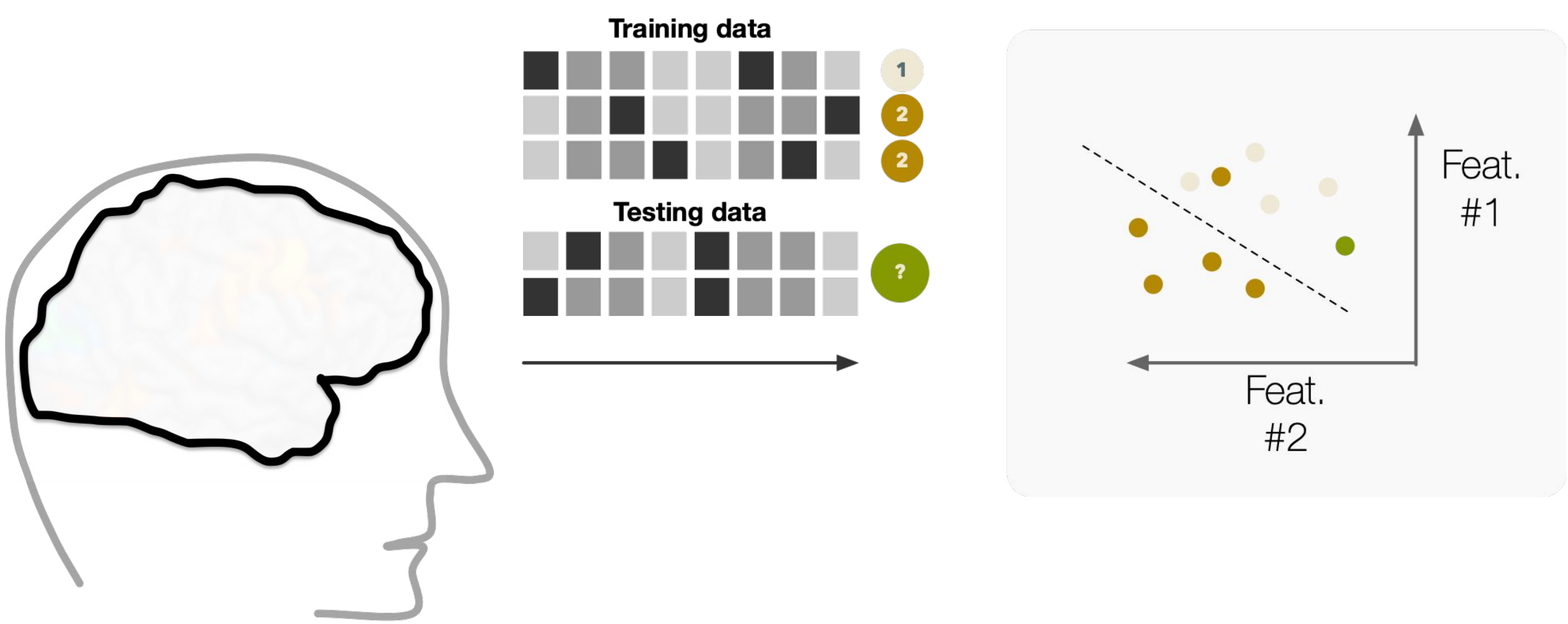


Decoding and Encoding

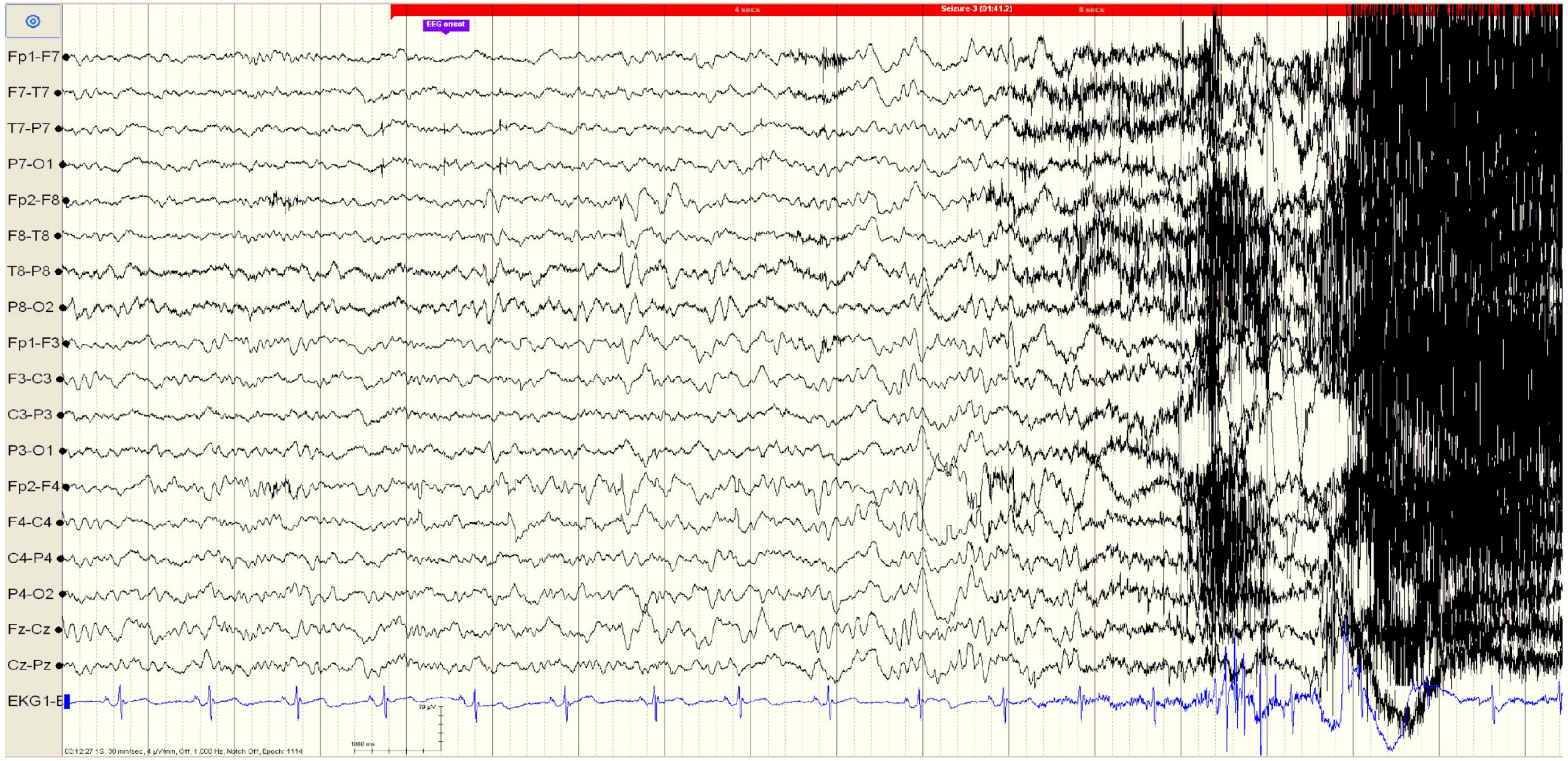
Decoding and Encoding

Decoding

- a.k.a. "Reading the brain"
- Reveals the 'product' but not the mechanisms involved
  - "Black box" correspondence between a pattern and a label



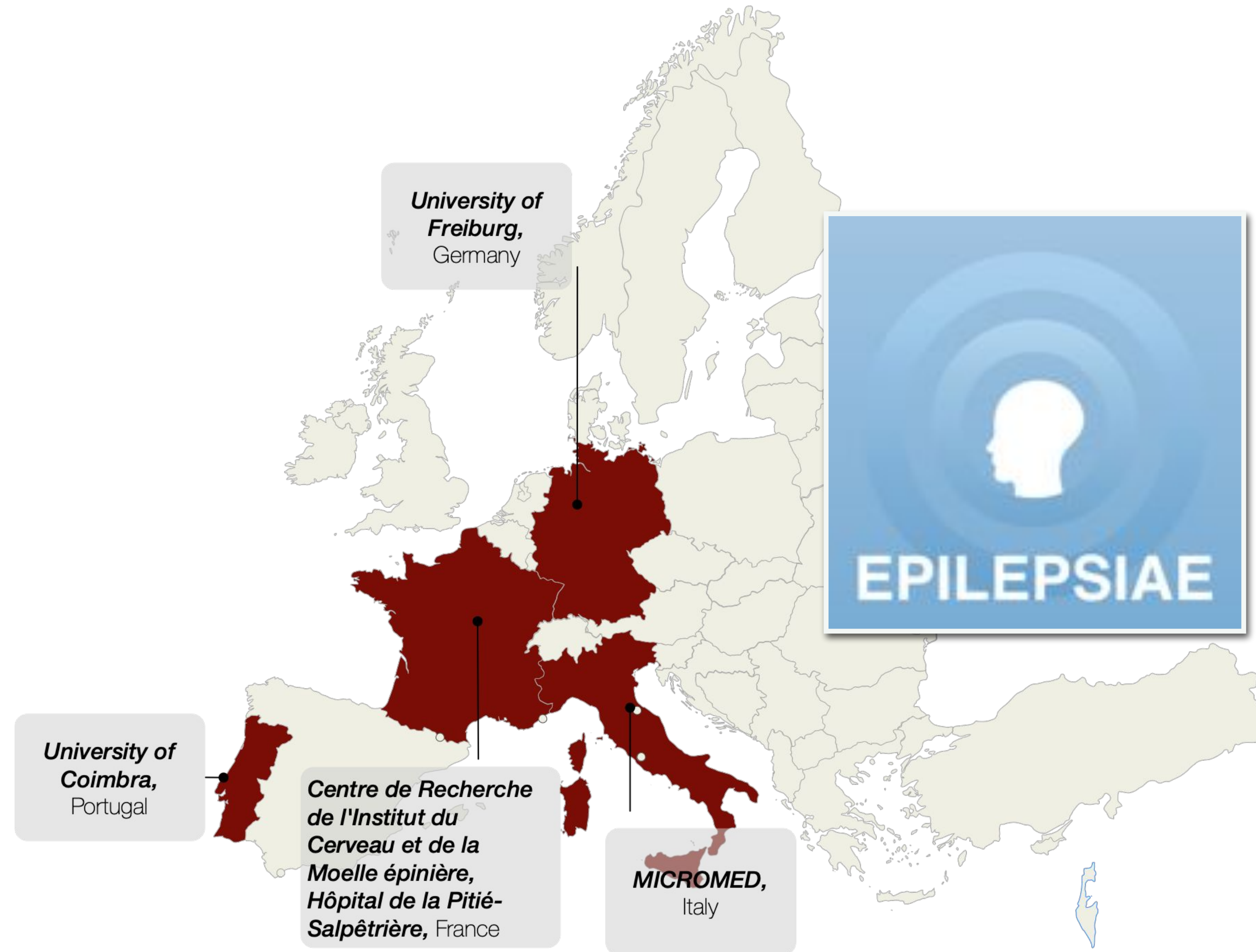
Electroencephalography and epilepsy



https://www.j-epilepsy.org/journal/Figure.php?xn=er-2-1-16-5.xml&id=

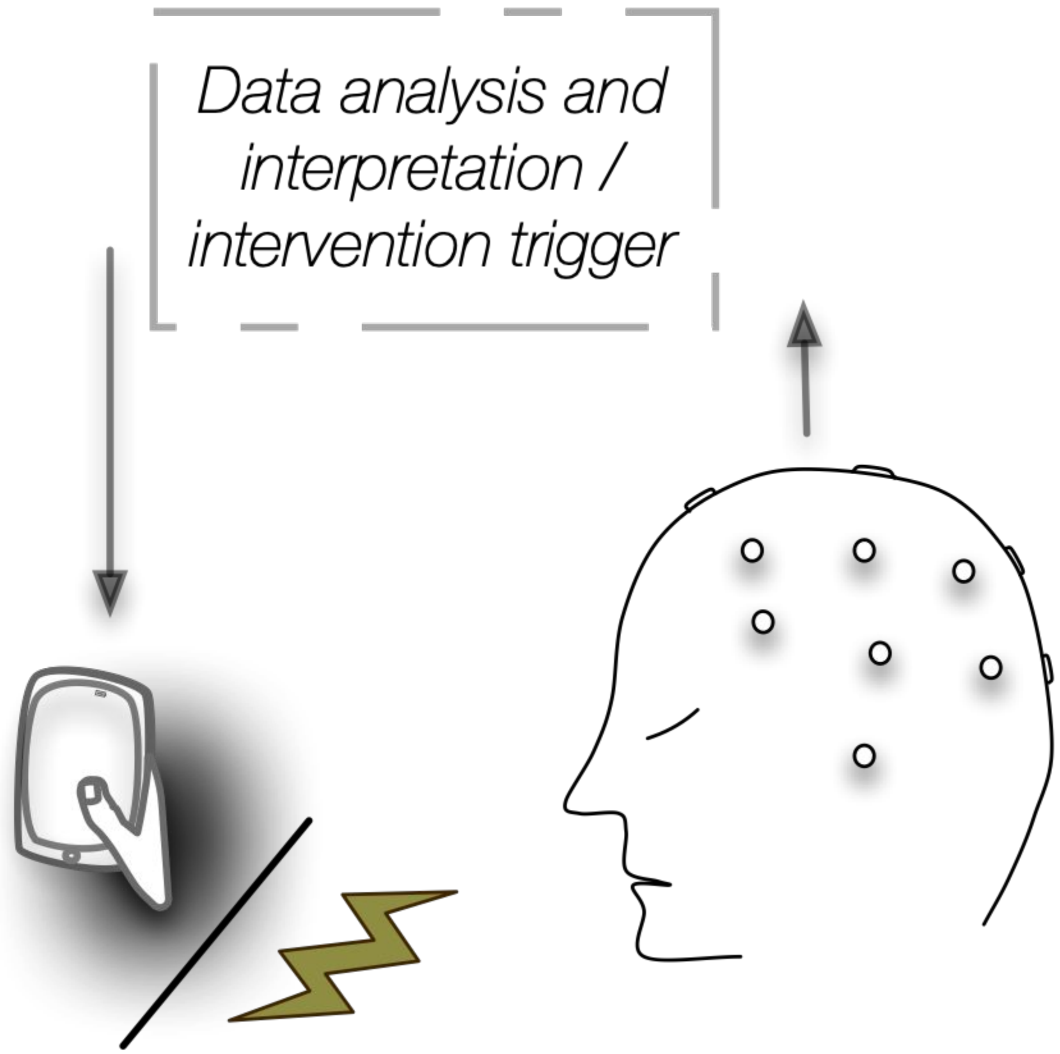
EPILEPSIAE

Aims to explore technology of **brain-computer interaction** to enhance human life and to use **Information and Communication Technologies** to empower the **epileptic patients to monitor their own risks and improve their safety in daily**



partners

EPILEPSIAE - epileptic seizure prediction



Closed-loop strategy

Anti-Epileptic Drugs

Approximately 30% of the patients remain unresponsive

Epilepsy surgery

Low percentage of cases result in seizure free

Seizure intervention devices

Open-loop and Closed-loop

Seizure intervention devices - approach

Open-loop

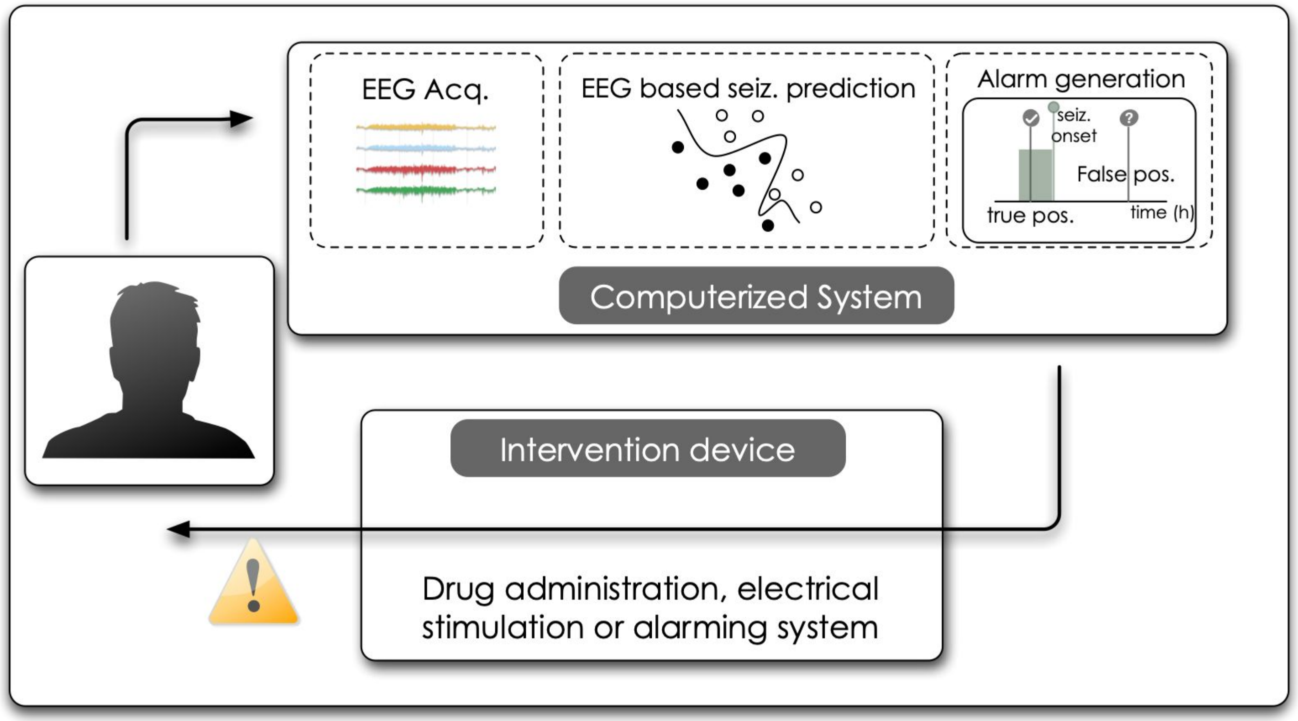
Operate on a predetermined schedule regardless of seizure occurrence and probability

Closed-loop

First generation closed-loop based on seizure detection

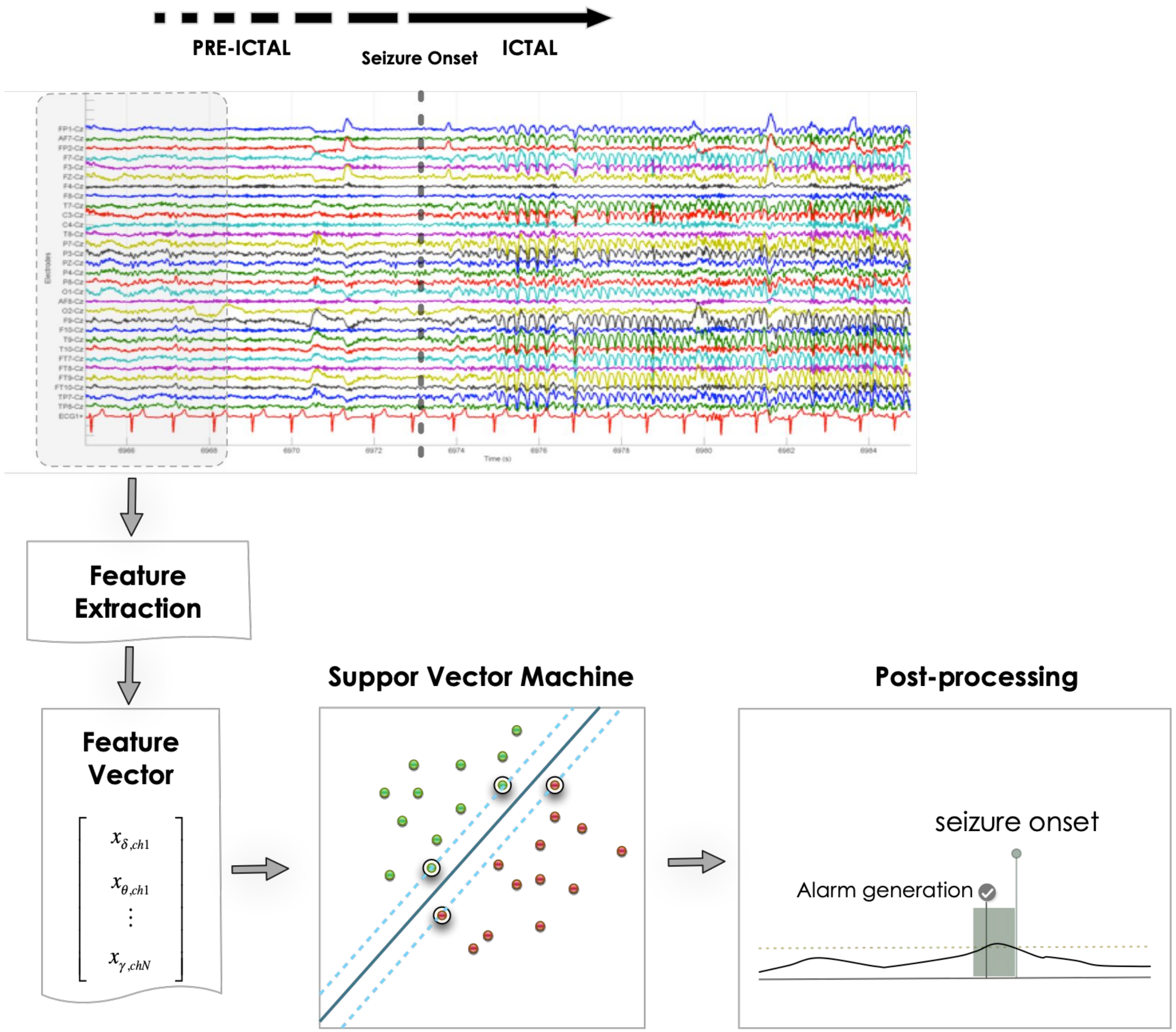
Significant, yet modest antiepileptic efficacy

<u>New approaches based on seizure prediction algorithms</u>



Closed-loop strategy

Overview of the approach*



- Preprocessing
- Feature Extraction

  22 features per channel

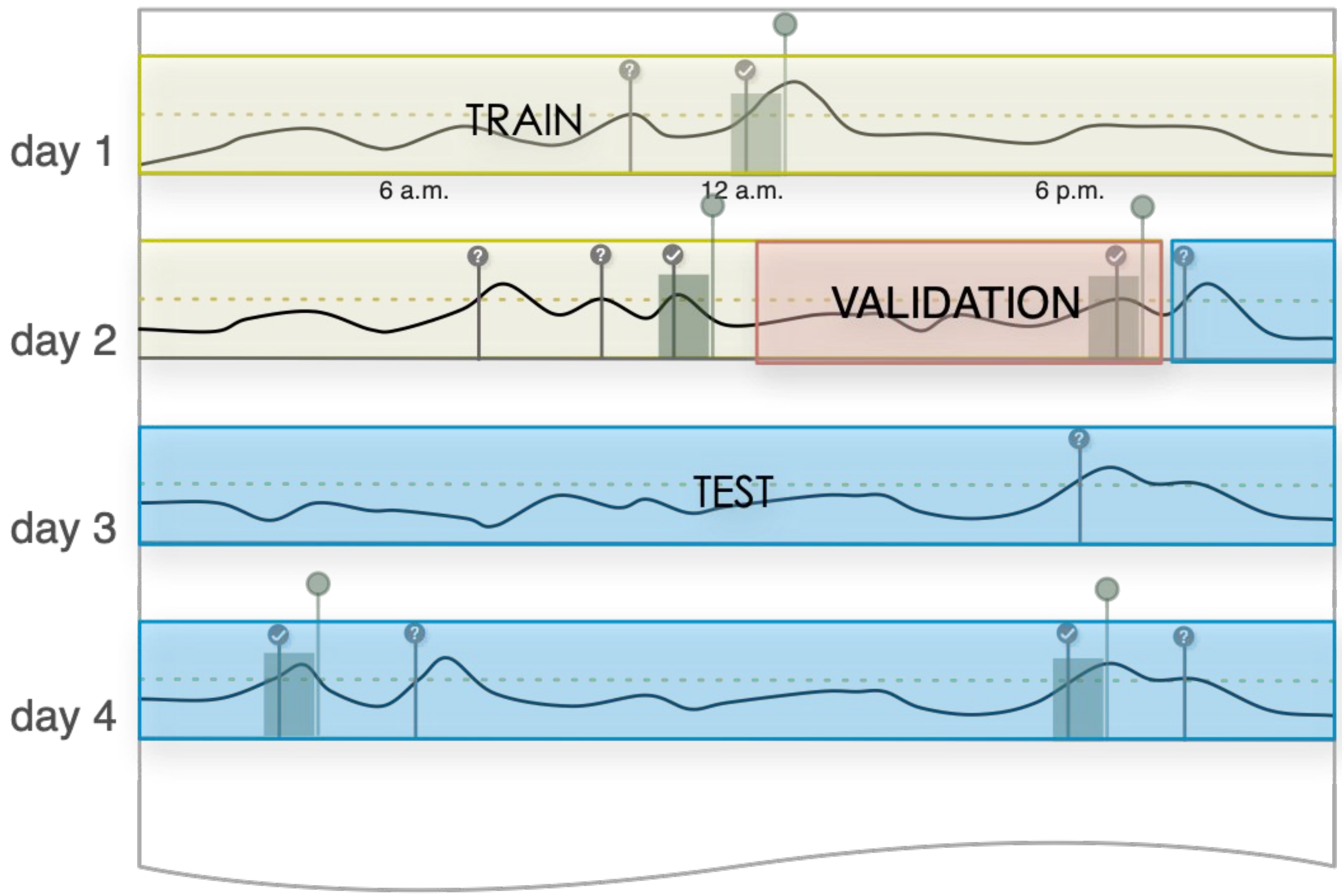
  Sliding window approach
- Multiclass classification

  Support Vector Machines
- Post-processing and alarm generation

  "Firing power"

Direito, B., et al (2017). A Realistic Seizure Prediction Study Based on Multiclass SVM. International Journal of Neural Systems. 27 (3). p.p. 1750006.

Approach overview



TRAIN — *consists of the period necessary to include three seizures - 3-fold cross validation*

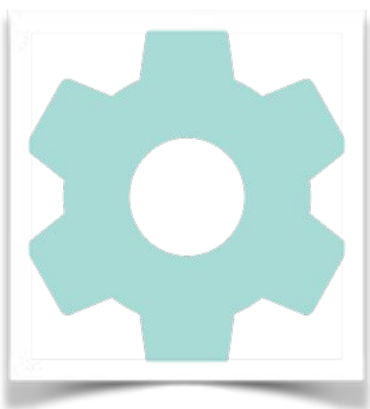
VALIDATION

TEST — *The rest of the data*

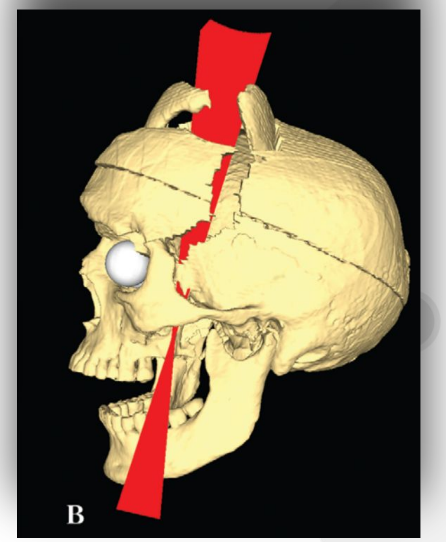
Decoding and Encoding

Encoding

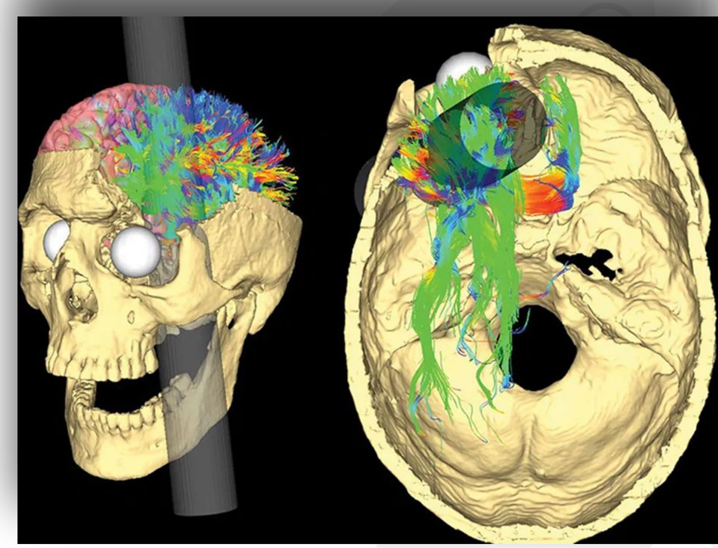
- Objects, emotions, procedures
  - Mapping of *sensory inputs* to internal *representation*



Fundamental principals of organization



“In the past decade functional neuroimaging has been (…) successful in establishing **functional segregation** as a principal of organization (…).
Functional segregation is inferred by the presence of activation foci in change score or statistical parametric maps.”
Friston (1994)



“A notion of cortical function has prevailed in which **different parts specialize in performing particular processing** of the sensory input”.
Zamora-López et al. (2011)

Friston, K. J. (1994). Functional and effective connectivity: A synthesis. Human Brain Mapping, 2, 56–78
Zamora-López, G., Zhou, C., & Kurths, J. (2011). Exploring brain function from anatomical connectivity. Frontiers in Neuroscience, 5, 1–11
van Horn, J. D., et al.(2012). Mapping connectivity damage in the case of phineas gage. PLoS ONE, 7(5). https://doi.org/10.1371/journal.pone.0037454

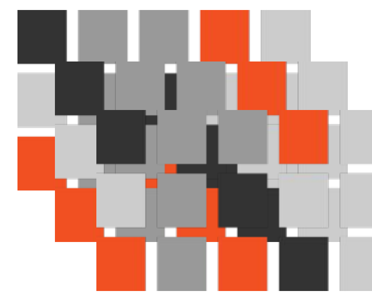
Encoding and the Basis of Neural Activation

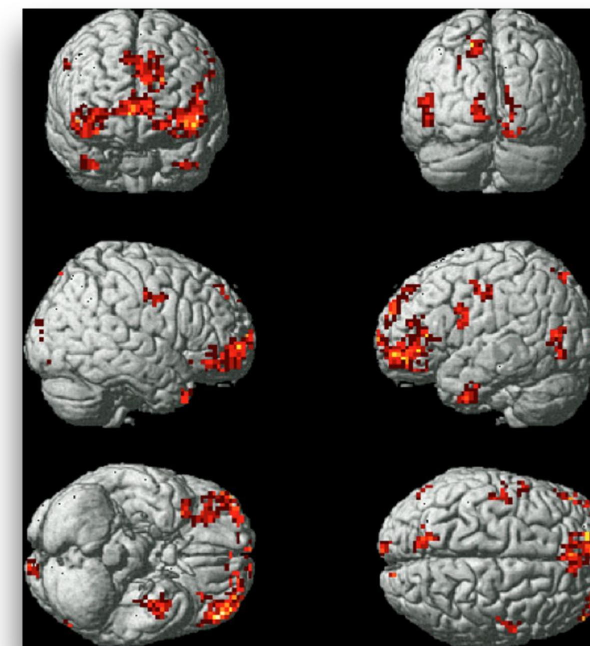
- Are emotions …
  - **Socially or psychologically constructed phenomena,** dependent on learning and high-level cognitive processes
  - Or ***biologically given***?
    - implies a *specific* computational architecture that mediates emotional response
    - **Similarity** between different instantiations at the **neural level**
    - Examine whether patterns of brain activity characteristic of specific emotions exist, and whether these patterns are to some extent common across individuals

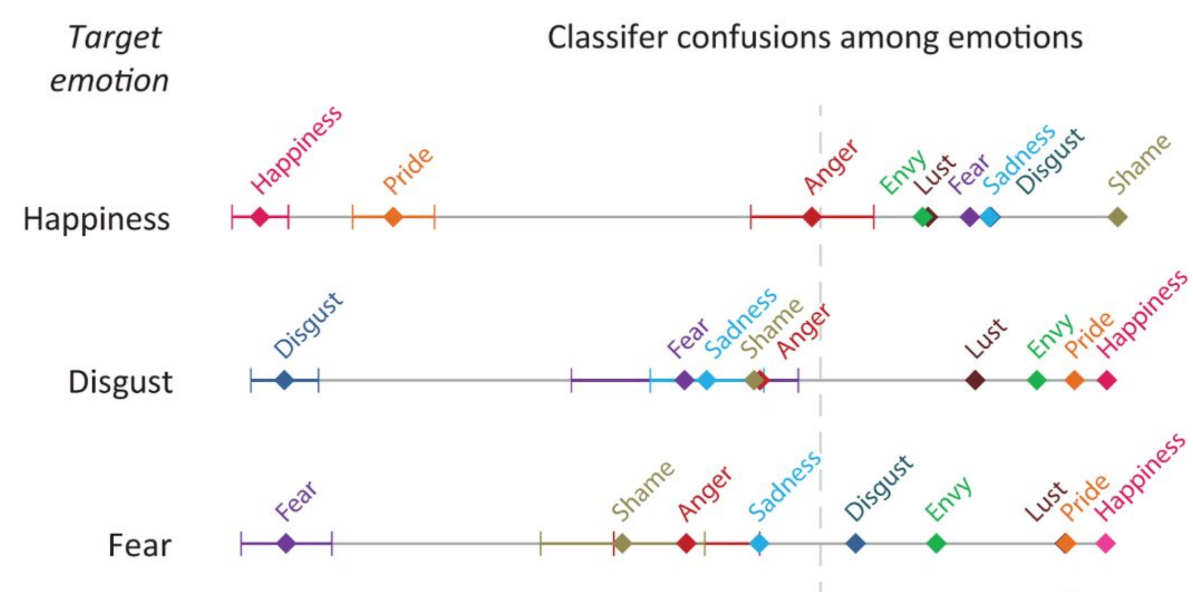
Kassam, K. S., Markey, A. R., Cherkassky, V. L., Loewenstein, G., & Just, M. A. (2013). Identifying Emotions on the Basis of Neural Activation. PLoS ONE, 8(6). https://doi.org/10.1371/journal.pone.0066032

Emotions and the Basis of Neural Activation

- Identifying the ROIs that consistently show specific behaviour
  - Stability measures
- Multivariate pattern analysis (MVPA)
  - Training a classifier on a subset
  - Testing on an independent set







Kassam, K. S., Markey, A. R., Cherkassky, V. L., Loewenstein, G., & Just, M. A. (2013). Identifying Emotions on the Basis of Neural Activation. PLoS ONE, 8(6). https://doi.org/10.1371/journal.pone.0066032

Basis of Neural Activation as a biomarker for ASD

- Identifying the ROIs that consistently show specific behaviour (neural representations of social interactions)
    - Stability measures
- MVPA
    - Training a classifier on a subset
    - Testing on an independent set

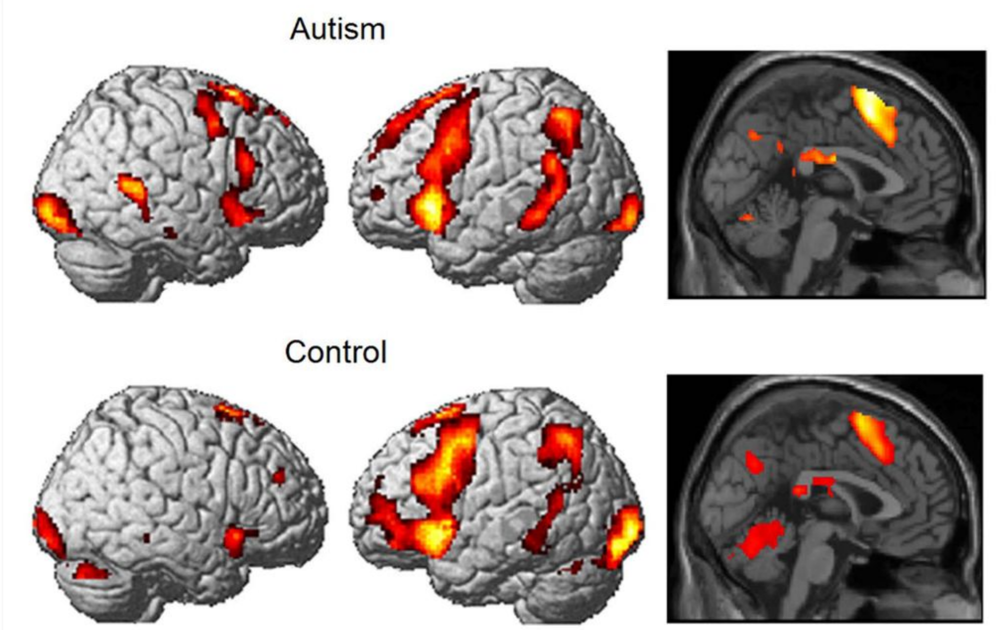
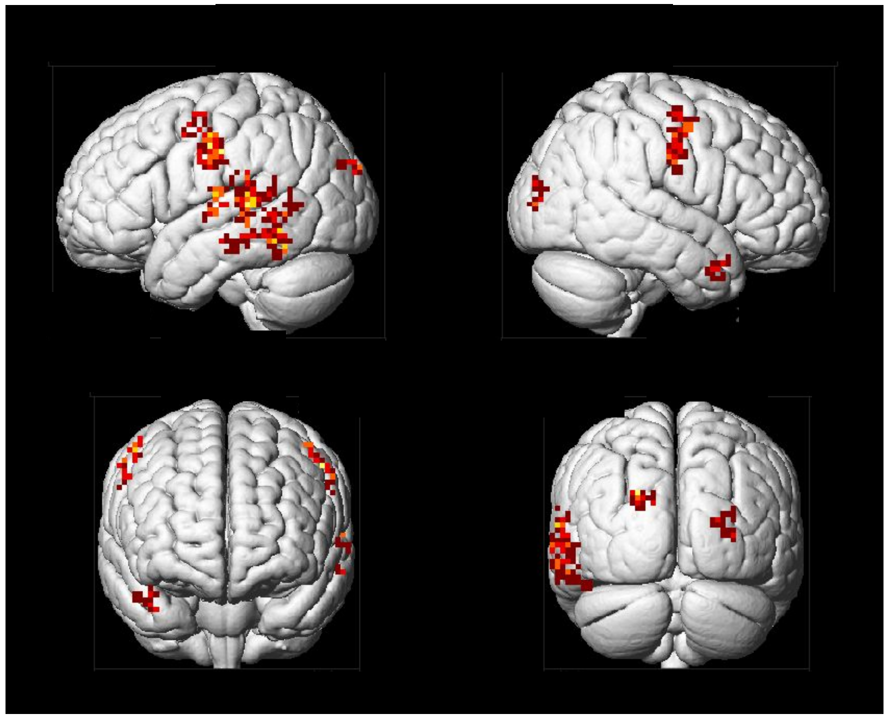


Figure 4. Social Interactions-Fixation contrasts for the two groups. The uncorrected *p*-threshold is 0.001 and the extent threshold is 5 voxels for both groups.

Just, M. A., Cherkassky, V. L., Buchweitz, A., Keller, T. A., & Mitchell, T. M. (2014). Identifying autism from neural representations of social interactions: Neurocognitive markers of autism. PLoS ONE, 9(12), 1–22. https://doi.org/10.1371/journal.pone.0113879

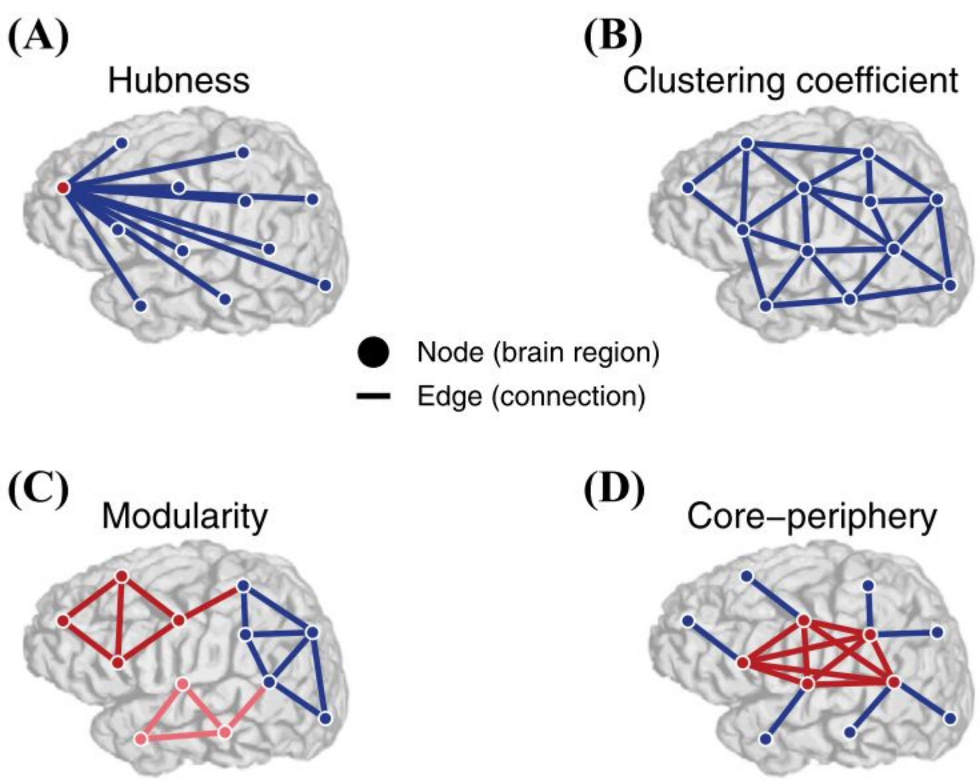
Basis of Neural activation of facial expressions imagery

- Identifying the neural basis of facial expression imagery



Direito et al., in preparation

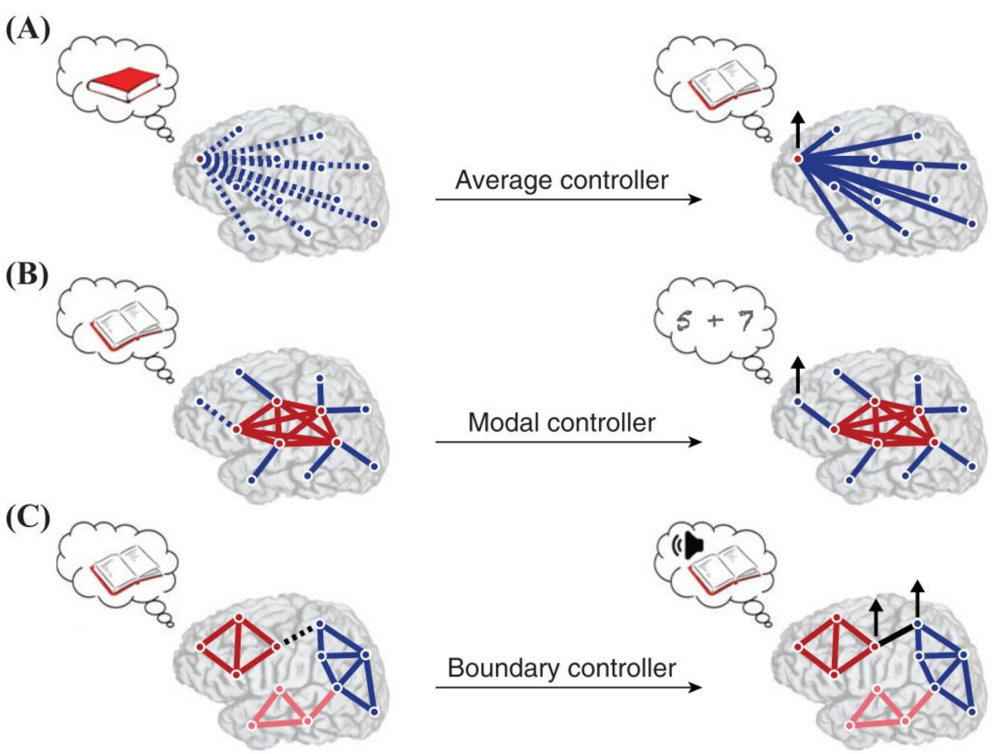
Neurorehabilitation - Fundamental principals of organization



Bassett, D. S., & Khambhati, A. N. (2017). A network engineering perspective on probing and perturbing cognition with neurofeedback. Annals of the New York Academy of Sciences, 1396, 126–143. https://doi.org/10.1111/nyas.13338

Cognitive neuroscience, the potential to use a **perturbative approach like neurofeedback** becomes particularly interesting when viewed in light of the emerging field of **connectomics**.

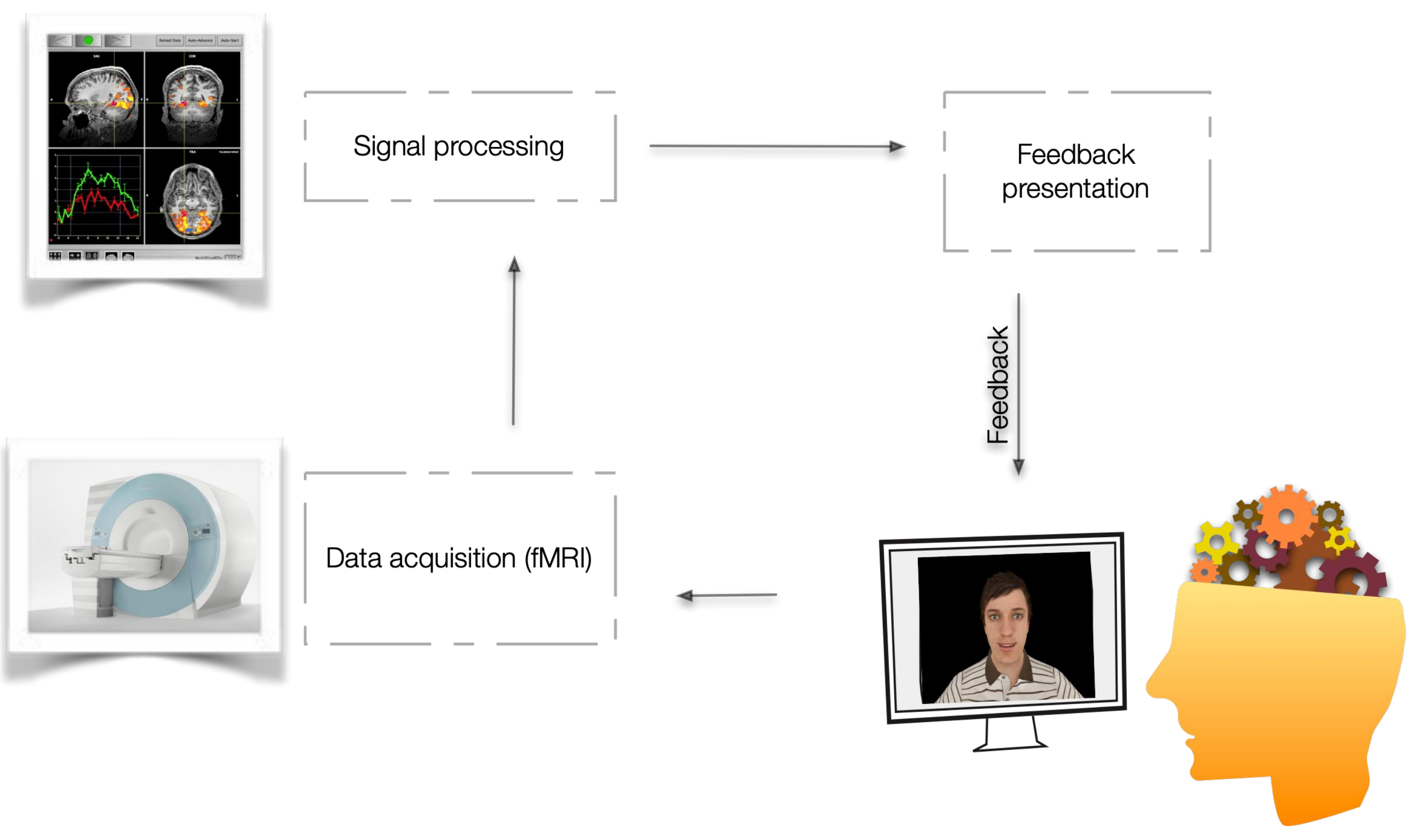
Network control and perturbing cognition with neurofeedback



Bassett, D. S., & Khambhati, A. N. (2017). A network engineering perspective on probing and perturbing cognition with neurofeedback. Annals of the New York Academy of Sciences, 1396, 126–143. https://doi.org/10.1111/nyas.13338

- Definition of the network - neural basis of behavior
- Biomarker of impairment (e.g. ASD)

real-time fMRI neurofeedback

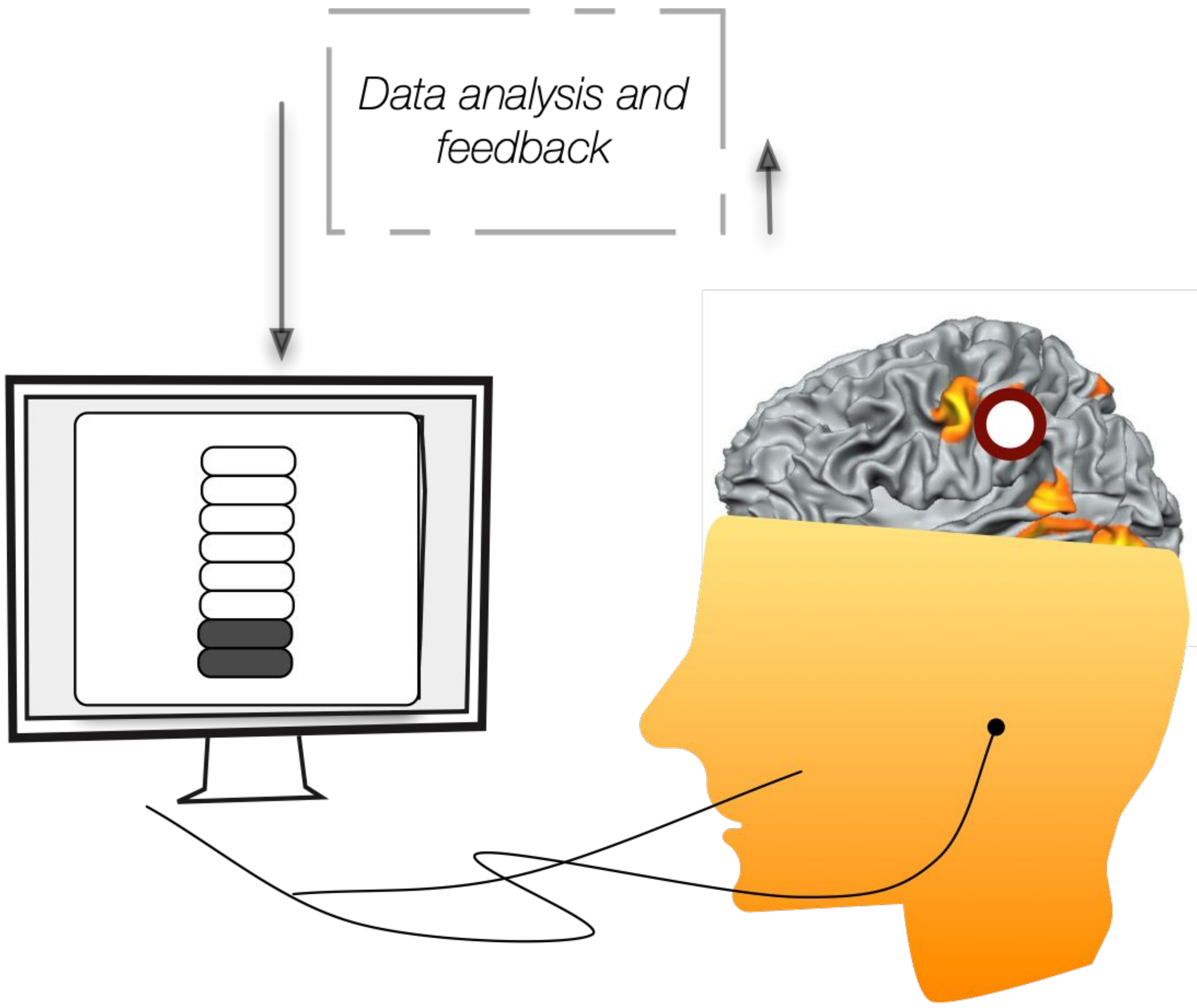


- Uses information from neuroimaging in (pseudo) real-time
  - Allows to present this information to the participant
  - The participants can regulate their own brain activity

Training and self-regulation of brain activity

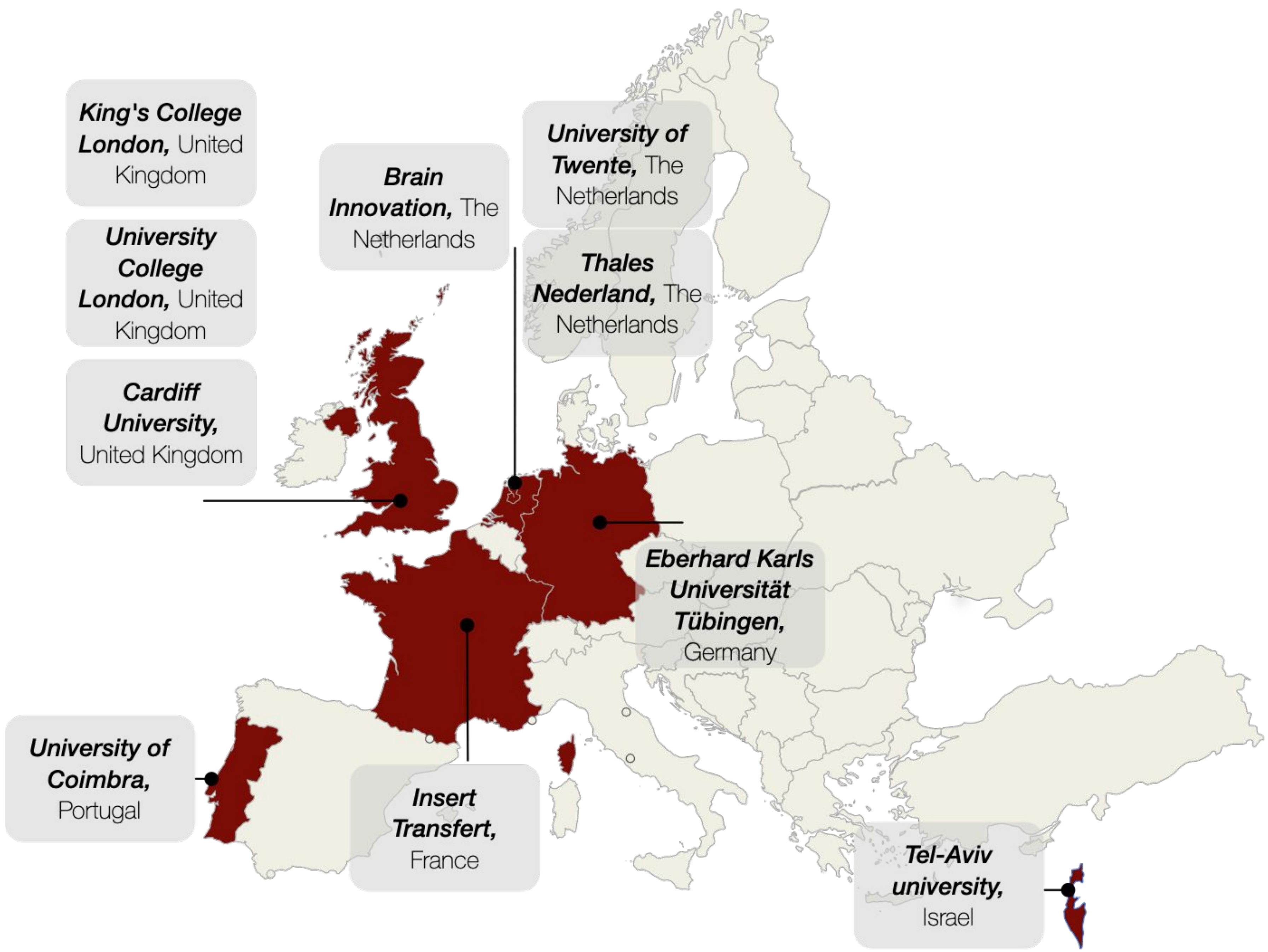
- Modulation of the activity of specific brain regions and/or neural networks
  - Restore function
    - Improve clinical symptoms
  - Induce changes on impaired underlying mechanisms
  - Optimization / functional reorganization
    - Neuroplasticity

BrainTrain

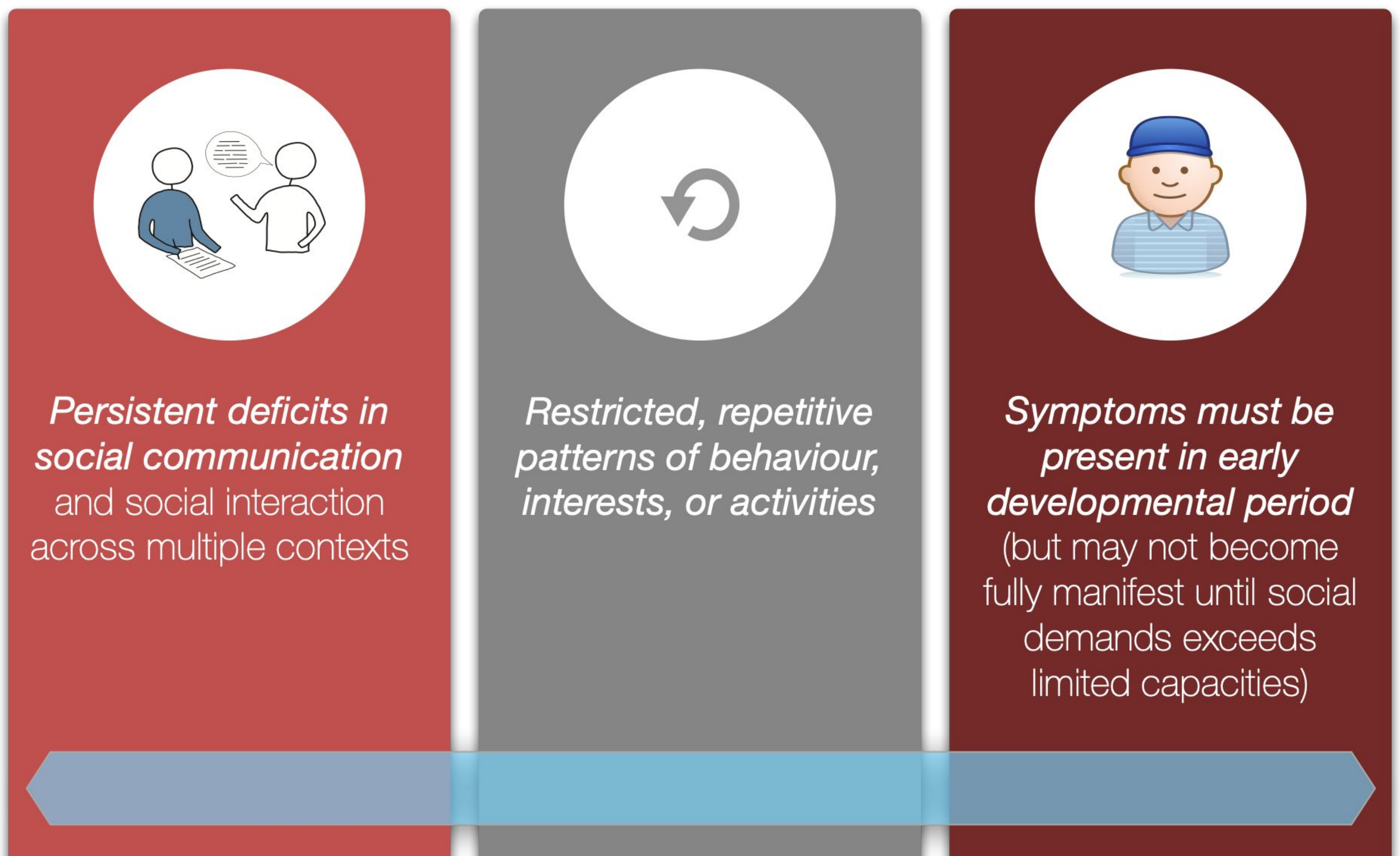


Assess validity of rt-fMRI neurofeedback in autism

BrainTrain Taking imaging into the therapeutic domain: Self-regulation of brain systems for mental disorders



BrainTrain - ASD



main features of ASD

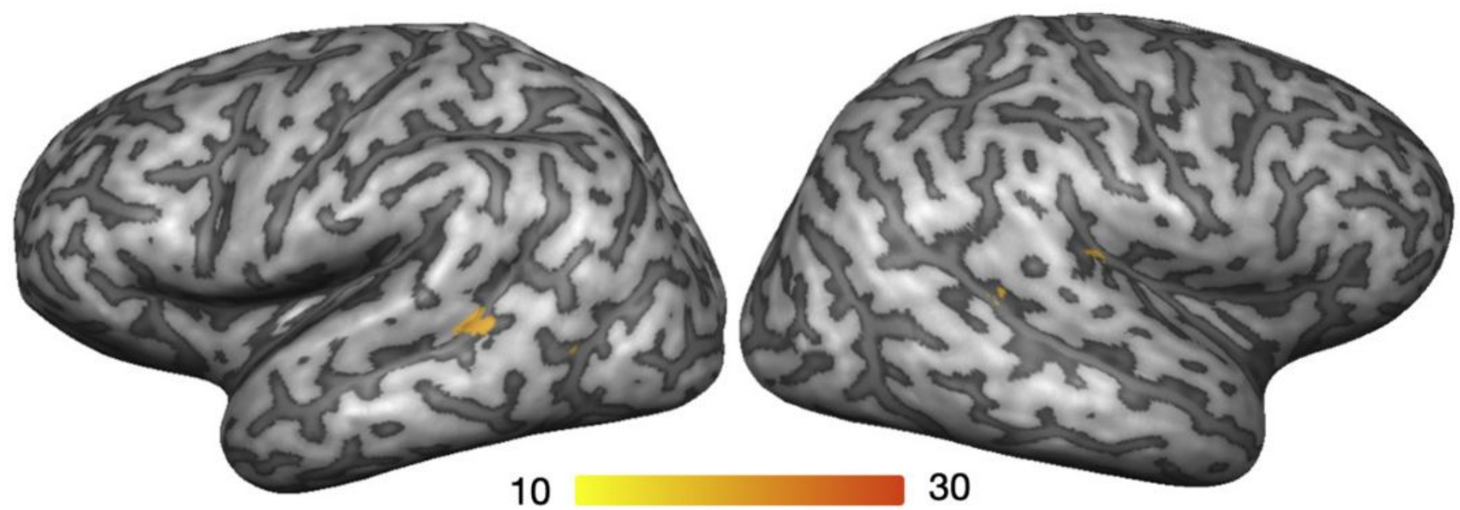
Target brain regions impaired in ASD patients

- face recognition, perception areas (prior work at CIBIT's on social cognition)

  - posterior Superior Temporal Sulcus

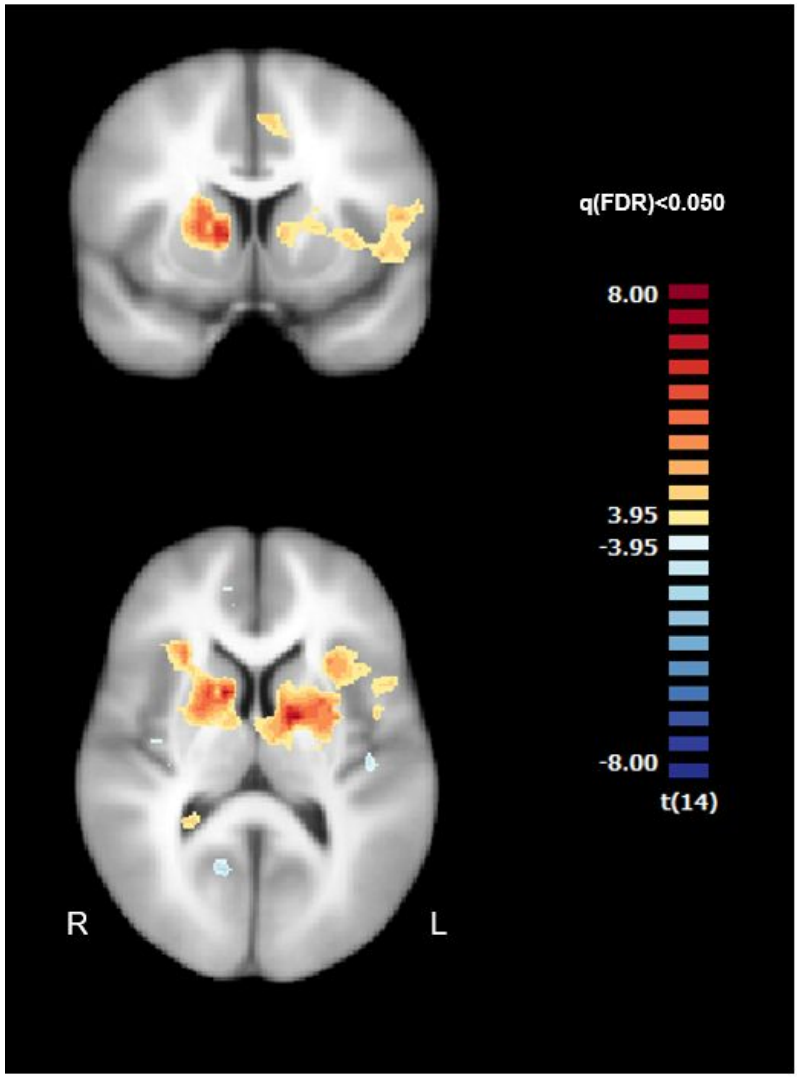
NF-ASD A neurofeedback strategy for the improvement of facial expression recognition/perception in ASD

- Identification, perception and mental imagery of facial expressions
  - Brain activity in areas related to social cognition and facial expression interpretation
    - posterior portion of the superior temporal sulcus (pSTS)



Whole brain analysis of neurofeedback runs

- GLM analysis (15 patients)
  - Active imagery periods vs. baseline
    - Active regions
      - anterior insula
      - caudate,
      - medial prefrontal cortex (MPFC)
      - anterior cingulate cortex (ACC)



RFX-GLM, FDR corrected (p<0.05)

Preliminary conclusions

Data suggest that **ASD patients can modulate pSTS**, however:

- High variability in the clinical group
  - within run, within session, across sessions
  - positive (i.e. as suggested) and inverted modulation

How to optimization of strategy/feedback interface for each participant

- should we introduce a preliminary/exploratory study?

Appropriate evaluation metric?

- achieve modulation during NF? transfer?

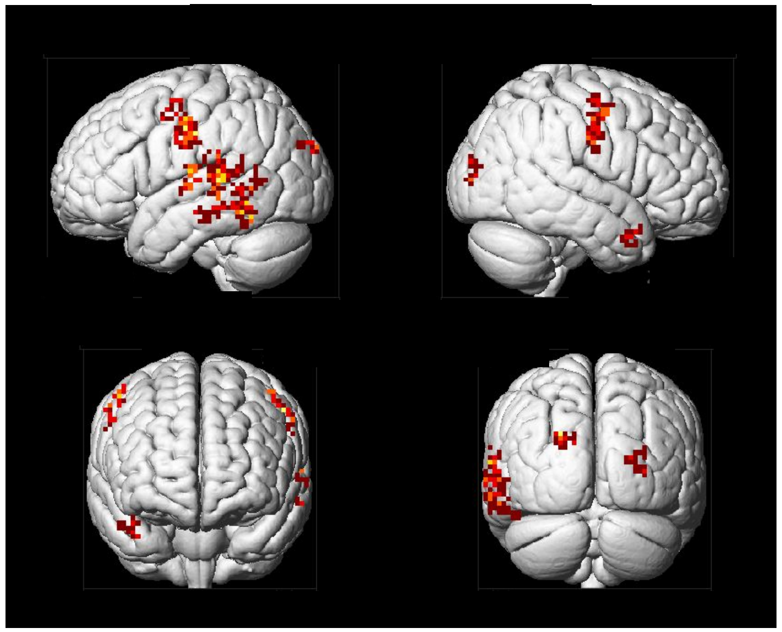
NF depends on a-priori variables?

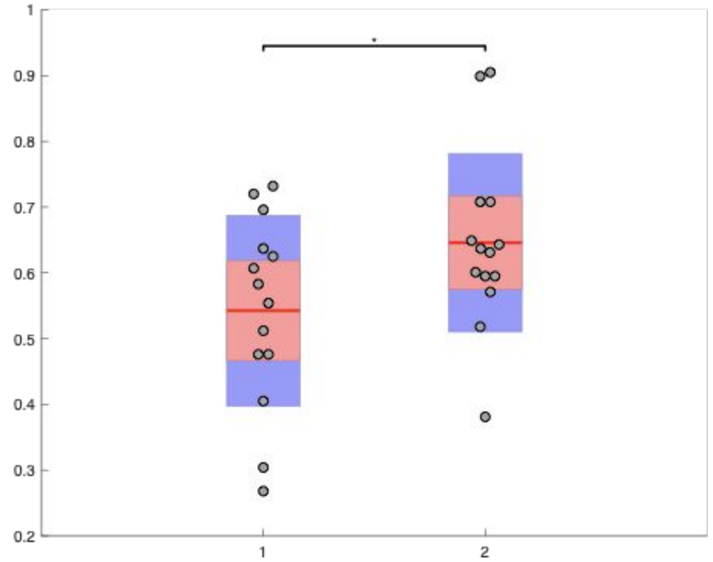
- Maximize metric in the first training run (ceiling effect)

How many sessions to achieve clinical improvements/learning?

Basis of Neural activation of facial expressions imagery

- Identifying the neural basis of facial expression imagery
  - Accuracy before /after neurofeedback training increased



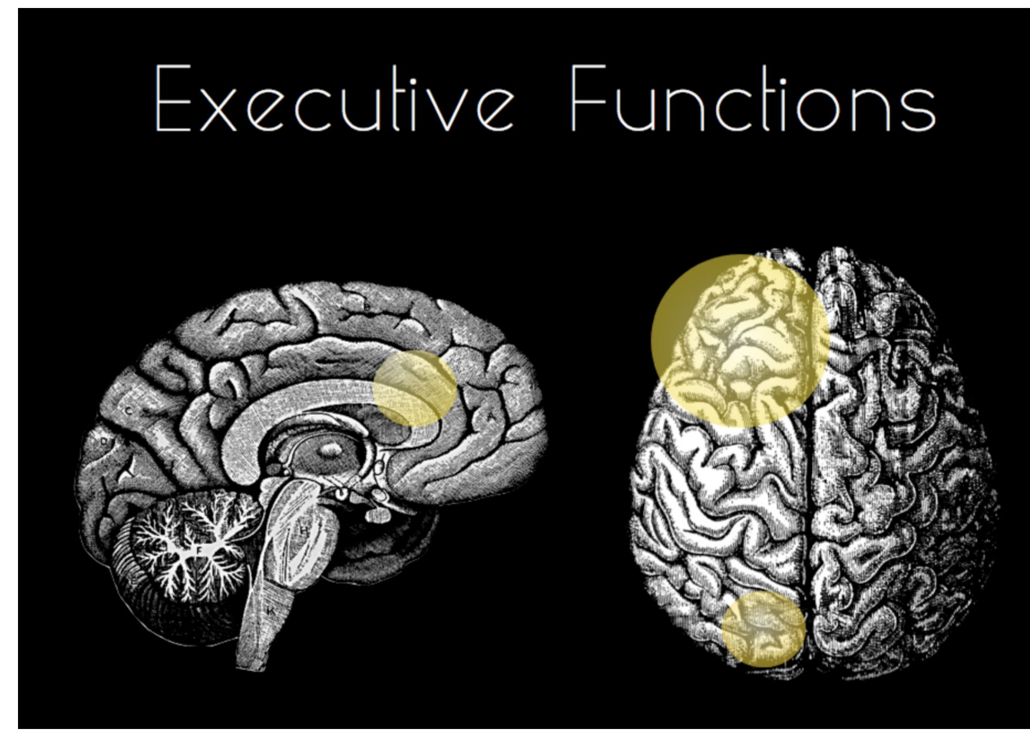


Direito et al., in preparation

Exploring different targets

dlPFC as NF target

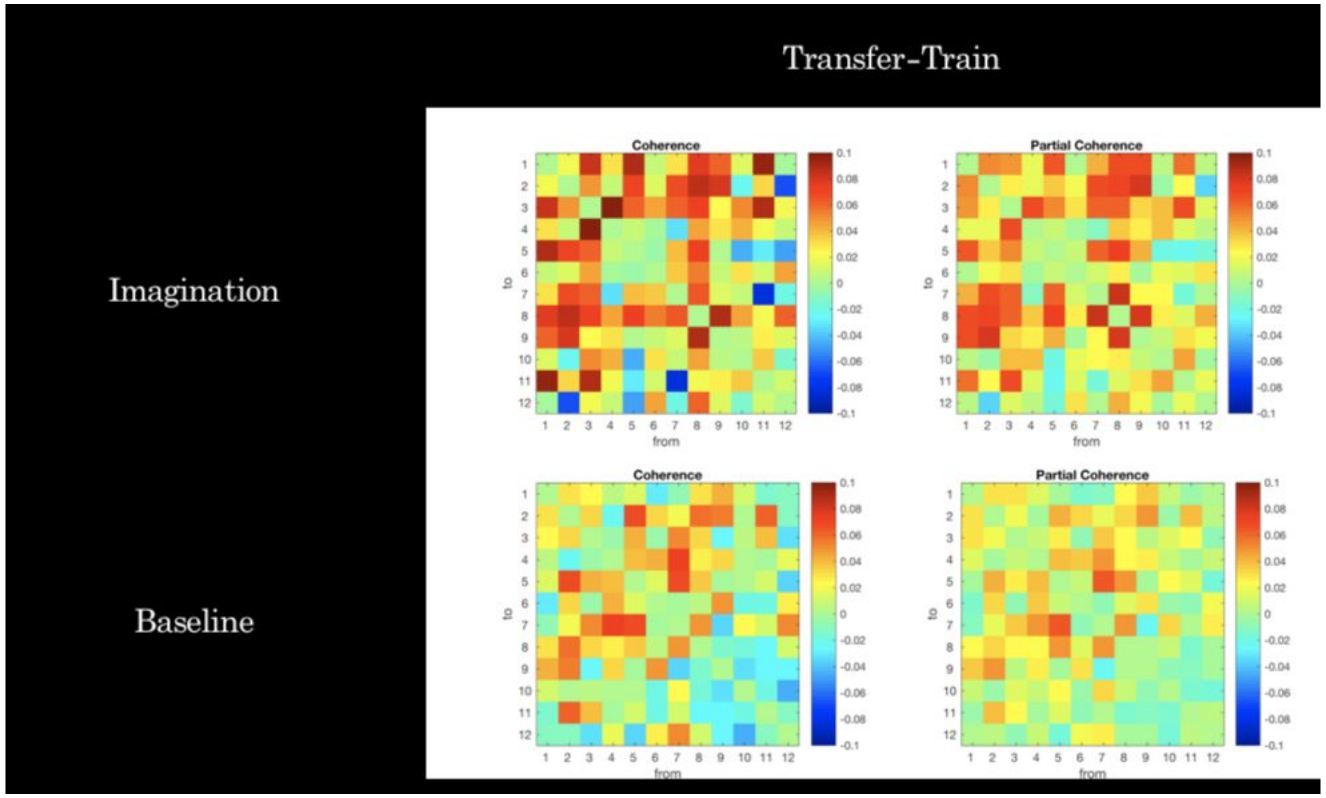
- Neurofeedback-rtfMRI protocol based on the dorsolateral prefrontal cortex (dlPFC), rationale
  - Self-modulation of fronto-parietal network, responsible for Executive Functions (EF)
  - Contribute to improve quality of life in autism, with possible future applications in other mental disorders - EF dysfunction,
- n-back (invert numbers sequence) task
  - EF training in clinical populations
    - Brain region functional impairments and underconnectivity



Pereira, D; Direito, B et al. (in preparation, 2019).

Connectivity analysis

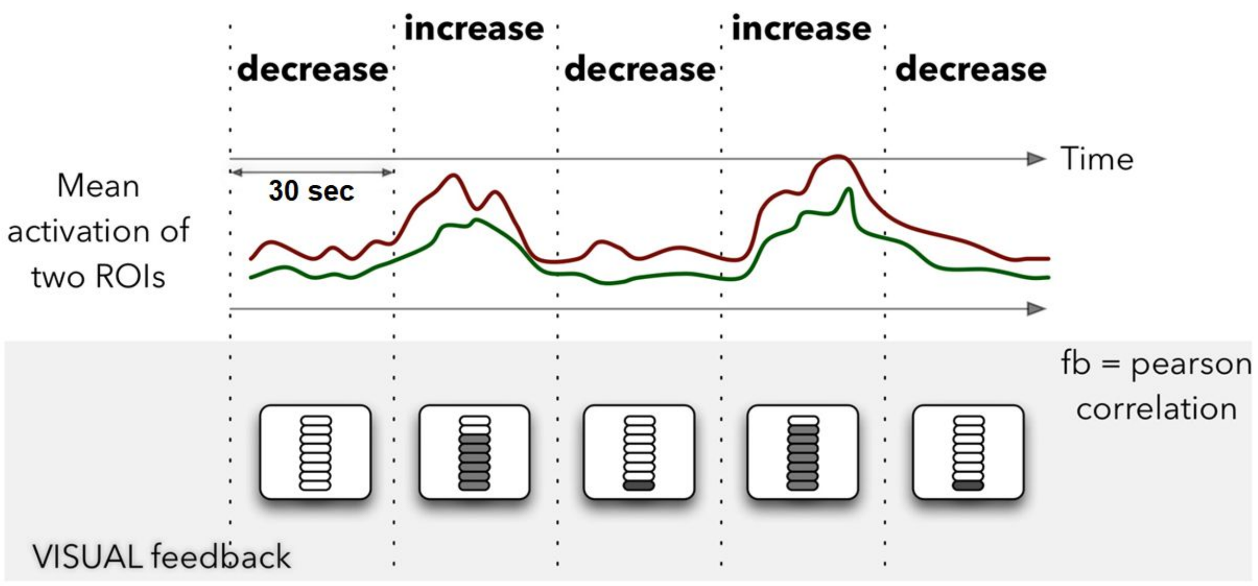
- Connectivity patterns are also quite different in the neurofeedback runs
- Hypothesis: Neurofeedback promotes connectivity



Connectivity matrix between the most important cluster of the EF network during imagination and baseline periods.

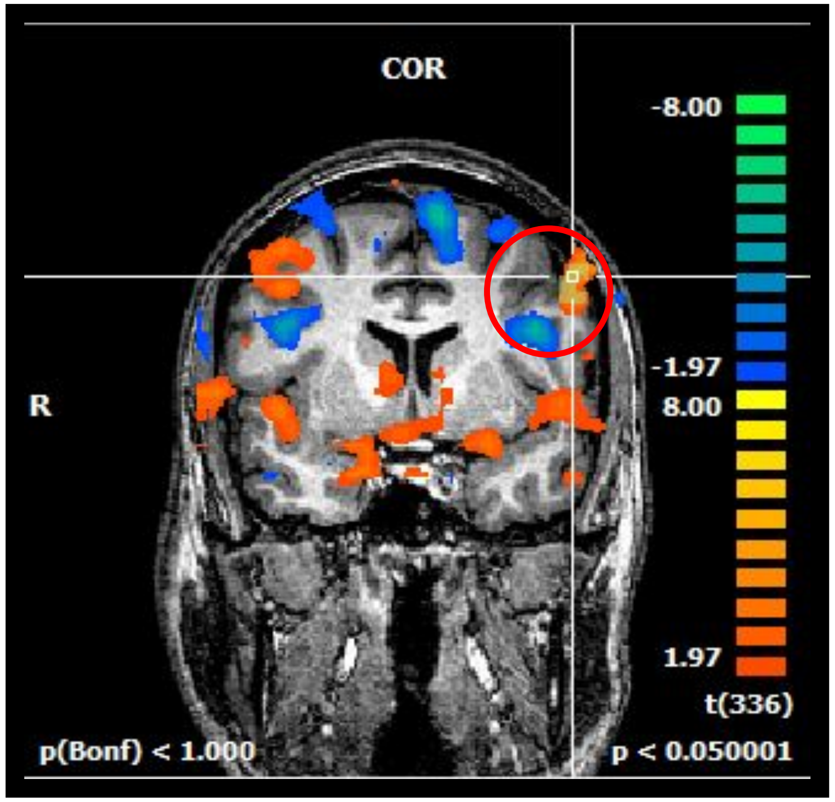
Connectivity neurofeedback

- Can we control not only a region but their connectivity?
  - “Functional connectivity measures (…) are emerging as potential intermediate biomarkers for many diseases”
  - “Functional connectivity markers (…) may indeed provide a valuable tool to enhance and monitor learning within an fMRI neurofeedback setup”

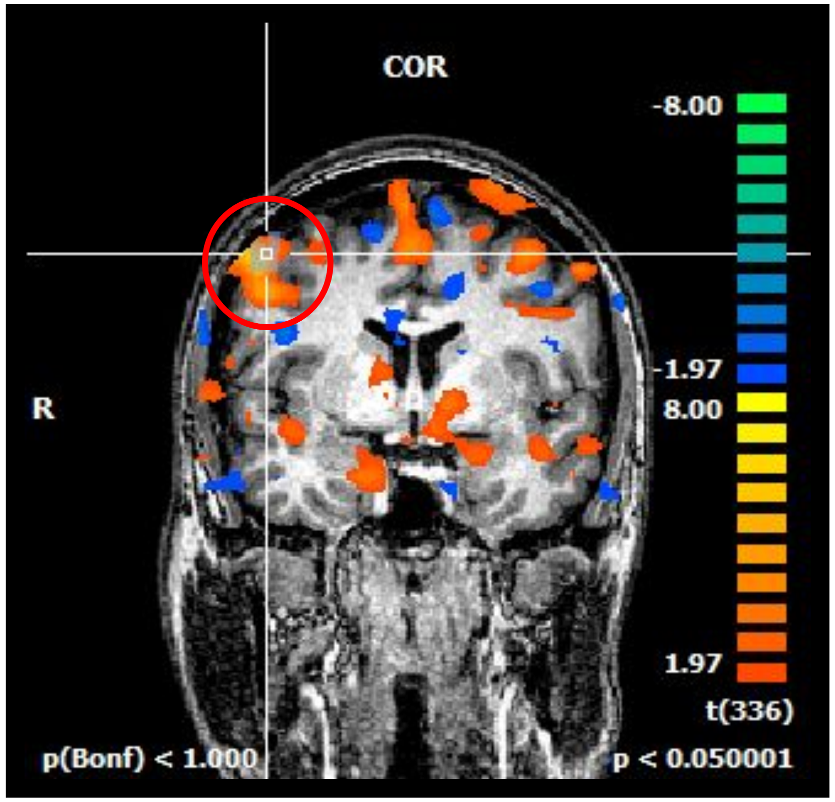


Feedback is based on an 8 point sliding window - Pearson’s Correlation Coefficient

Connectivity neurofeedback

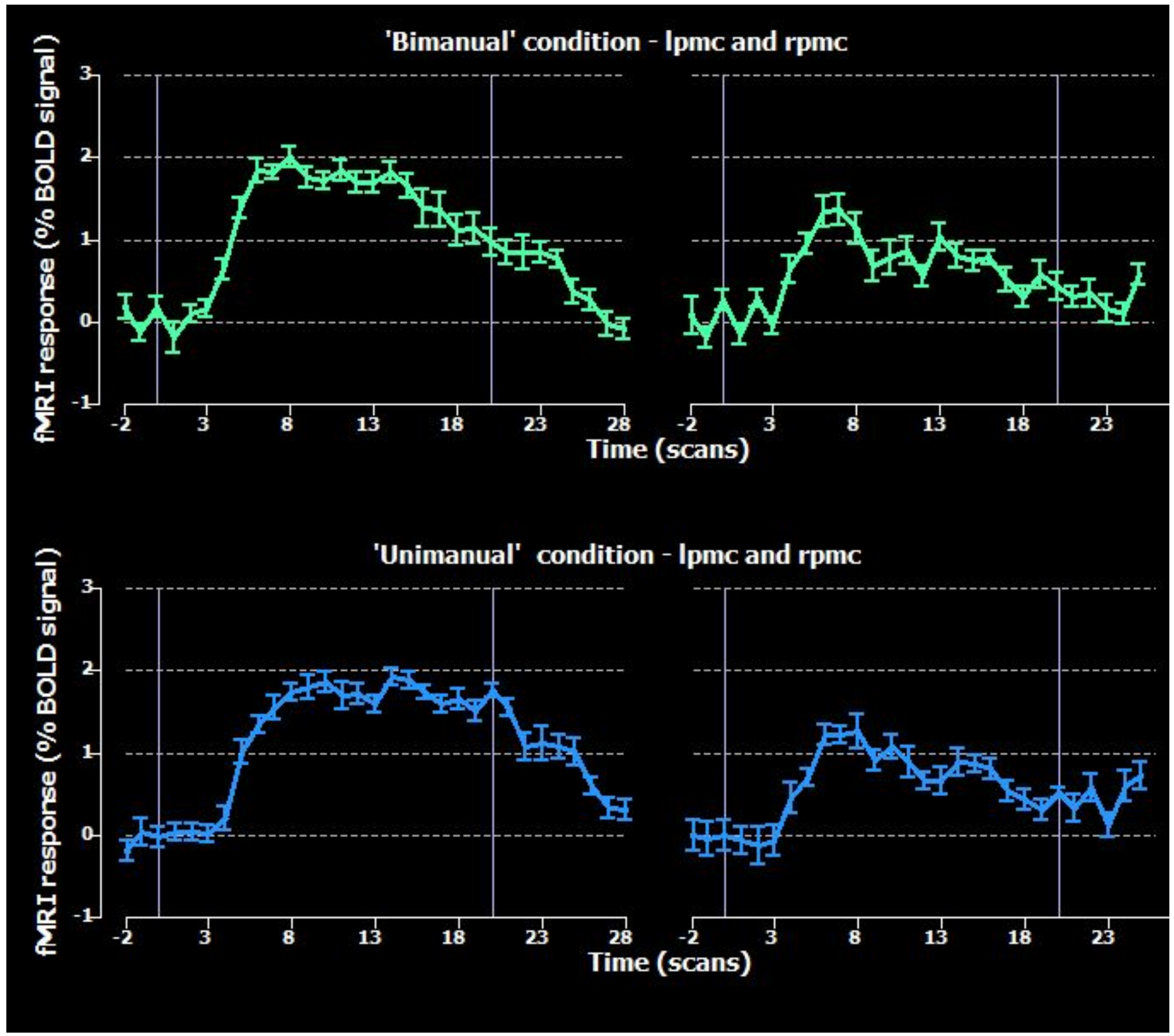


Left Premotor
Cortex (lPMC)



Right Premotor
Cortex (rPMC)

Connectivity neurofeedback



Pereira, J., Direito, B., Sayal, A., Ferreira, C., & Castelo-Branco, M. (2019). Self-Modulation of Premotor Cortex Interhemispheric Connectivity in a Real-Time Functional Magnetic Resonance Imaging Neurofeedback Study Using an Adaptive Approach. Brain Connectivity, 9(9), 662–672. https://doi.org/10.1089/brain.2019.0697

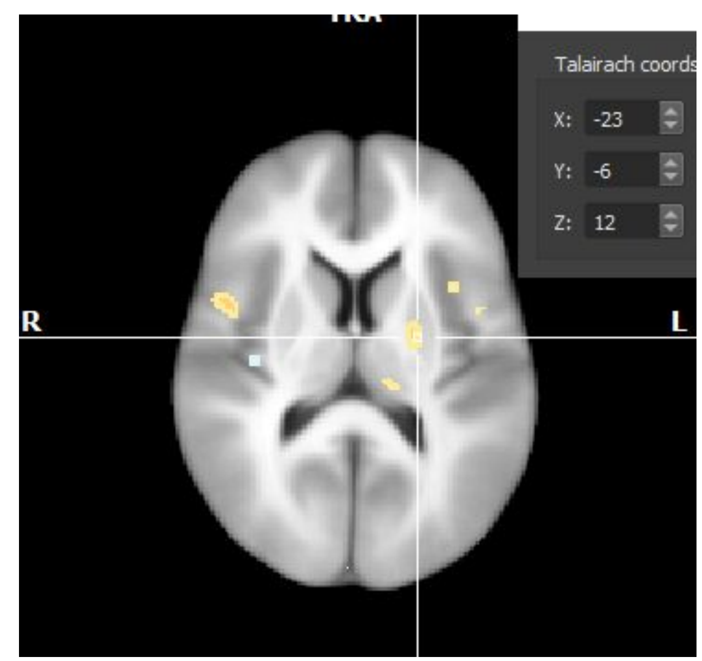
Exploring reward

Exploring success mechanisms and reward

- Overall success rate in neurofeedback is under 50%
- Important regions for neurofeedback success?
  - How to characterize them?
  - What can we learn from them?
  - How to adapt the difficulty level?

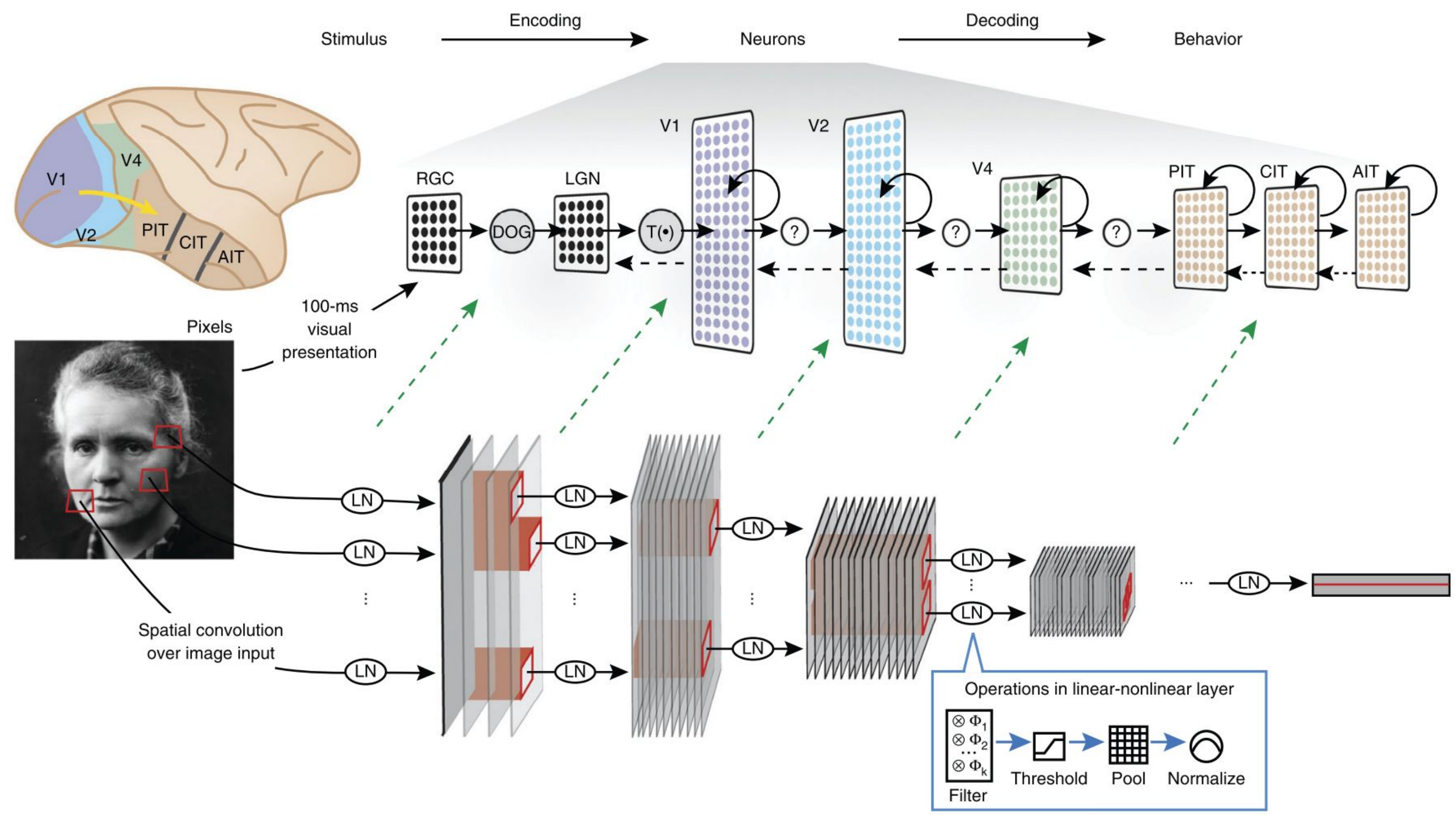
Exploring reward

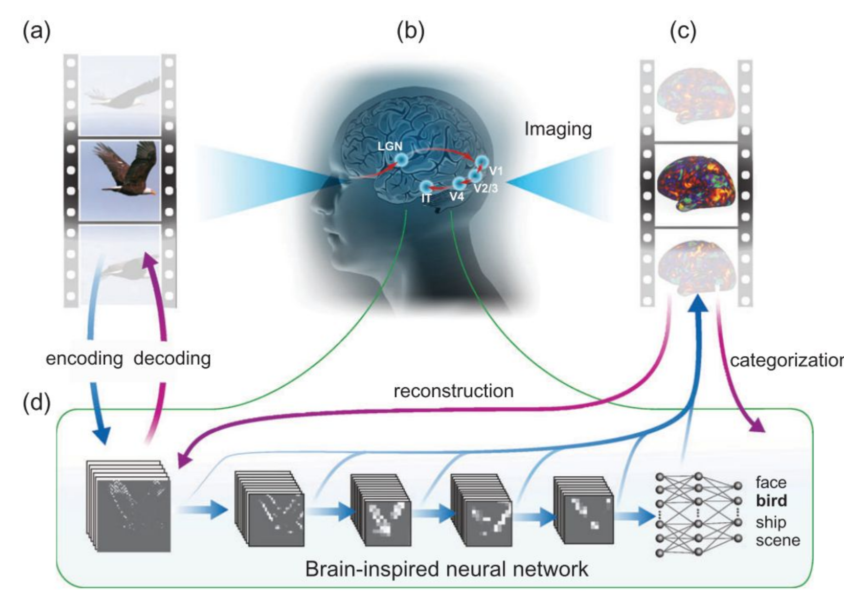
- Exploratory analysis (considered the same paradigm as three-level control - defined specific time points for feedback)
  - Neurofeedback runs
    - Whole-brain
    - 10 participants, 2-runs each
      - (RFX, p< 0.01)
      - Contrast (+) mov vs. (-) static



Encoding and Decoding with deep Learning (Visual system)

- Comparing the Visual System and Deep Convolutional Neural Networks





Wen, H., Shi, J., Zhang, Y., Lu, K., Cao, J., & Liu, Z. (2018). Neural Encoding and Decoding with Deep Learning for Dynamic Natural Vision. Cerebral Cortex, 28, 4136–4160. https://doi.org/10.1093/cercor/bhx268

Yang, G. R., & Wang, X.-J. (2020). Artificial neural networks for neuroscientists: A primer. Neuron, 107(6), 1048–1070. https://doi.org/10.1016/j.neuron.2020.09.005

What’s next

- Neurofeedback - Define ‘learning’ or success
- Connectivity analysis
- Modeling the interaction between nodes - bottom-up vs. top-down - which region is ‘driving’ the system on neurofeedback experiments
  - DCM, GC, etc.
- Data-driven analysis of the data - machine learning (we have focused on the target region, what else?)
- How to “drive” the system towards a particular state? TMS? Visual stimulation?

Team members

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