Invasive cognitive brain computer interfaces to enhance and restore attention: proof of concept and underlying cortical mechanisms

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Neural bases of spatial cognition and action group

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Invasive Brain computer interfaces

Identify the neural signature of a specific cortical operation and translate it into a control command in real-time.
Cathy Hutchinson, ALS patient
Brain gate project, Donoghue Lab, Brown University, Rhode Island, USA

Hochberg et al., Nature, 2012
Bidirectional motor Brain computer interfaces

Changing cortical activity

Reading cortical activity

O’Deherty et al., Nature, 2011
Can we achieve what has been done in the field of motor neuroprostheses and apply it to any cognitive function?

The cognitive function
(not categorical, but rich, continuous, high-dimensional ... )
At the interface between Neurosciences and Artificial Intelligence

Identify the neuronal population code that implements the function in real-time?
Invasive Cognitive Brain computer interfaces: the project

Major challenges:

• Subjective content (can only be assessed indirectly by a report of the subject)

• Implemented in cortical regions that simultaneously process several cognitive functions at the same time (e.g. prefrontal cortex multiplex: attention + working memory + planning + decision-making)

• Implemented in cortical regions that are both dynamic & plastic
Covert attention

“Ability to **select** one or several relevant lines of thought or information for further processing while simultaneously **ignoring** other irrelevant sources of information”

attentional spotlight - the mind’s eyes
Attention-based Invasive Brain computer interfaces: the project

- **Essential to most cognitive functions:** working memory, learning, planning, arithmetics, reasoning, language, etc.

- **Acute attentional deficits** (e.g. following cortical parieto-temporal, prefrontal or cingular lesions; or following subcortical basal ganglia or thamalic lesions)

- **Neurodegenerative attentional deficits** (e.g. Alzheimer, Parkinson disease, ...)

- **Developmental attentional deficits** (Attentional deficit and hyperactivity disorder, Autism, Dyslexia ...)

- **Transient attentional deficits** (psychotrops, including mild psychotrops and medication, sleep deprivation, etc ... )
Develop attention-based closed-loop neurofeedback designs to
  o *Enhance* attention
  o *Restore* attention
  o *Simulate* attention

Characterize the associated dynamic reorganization principles
  o microscopic level (neurons)
  o mesoscopic level (area)
  o macroscopic level (network)

From invasive to non-invasive attention-based closed-loop neurofeedback designs
  o MUA / LFP / ECoG / EEG / fMRI
  o Feasibility ?
  o Reorganization principles
  o From non-human primates to human experiments
Real-time tracking of the **covert** attentional spotlight

**Neuronal recordings**

- In the FEF

**Cued target detection task**

- Behaving monkey

**Multi-unit activity**

- On 48 recording channels

**Astrand et al., PLoS ONE, 2014;**

**Astrand et al., Front. Syst. Neuro., 2014,**

**Astrand et al., J. Neurosci., 2015**

**Astrand et al., Curr. Biol., 2016**

**Astrand et al., BioRxiv, 2018**

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Real-time tracking of the **covert** attentional spotlight

. Correct trials .

Astrand et al., BioRxiv, 2018

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Real-time tracking of the **covert** attentional spotlight

Astrand et al., BioRxiv, 2018

. Incorrect trials .

M1 s2tr16
The decoded attentional spotlight oscillates at a specific frequency of 8 Hz, phase locked to the cue.
Prefrontal information about target vary as a function of oscillations of attentional spotlight

Overt behavior (HITs) vary as a function of oscillations of attentional spotlight
Two different distractor filtering mechanisms

Di Bello et al., in preparation
Enhancing attention

Astrand, Amengual et al., in preparation

Behavior

Endogenous attention

- Cue
- Attention
- Eye position

Reward +
Reward ++
Reward +++
Reward ++++
Attention-based closed-loop neurofeedback effects on behavior

After NeuroFeedback:

Subjects spend more time in the task, despite expected fatigue and decreased motivation.

Less conservative responses i.e; change in the decision-making criteria.
Overall available attention-related information in population does not change with neurofeedback.
Attention-based closed-loop neurofeedback & neuronal code

Neurofeedback induced a change in the attentional code

Dynamic co-existence of two codes: ‘old’ + ‘new’ code

Astrand, Amengual et al., in preparation
• The rich content of higher order cognitive functions can be tracked in real-time, very much like motor control signals.

• This direct access to covert cognitive processes provides an unprecedented understanding of their underlying neural and computational bases.

• This direct access to covert cognitive processes can be used in neurofeedback closed loop-BCIs to produce behavioral benefits in normal subjects.

• These behavioral changes are accompanied by complex short-term and long-term re-organizations of the neural codes that remain to be uncovered.
The future of invasive cognitive brain computer interfaces

Neuroscience
- Biocompatible dense electrodes
- Neuromorphic chips
- AI & dynamic system decoding algorithms

Ethics
Psychologists
Neurologists
Robotics

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The future of invasive cognitive brain computer interfaces & AI

• From single-trial neuronal population responses
  • Identify ongoing cognitive state / operation / process
  • Identify multiple ongoing cognitive processes
  • Assign information content to all sources of variability in the signal
  • Predict upcoming signals
  • Predict upcoming behavior

• Robust algorithms (Unsupervised learning / deep learning / dynamic systems)
How does the brain encode multiple processes? How does it dynamically switch from one cortical process to another? Can we externally trigger these switches?

When the brain learns, what happens to the neuronal code? Are there regularities? Can the changes be predicted? Can they be optimized?

Can this knowledge be used to develop optimized closed-loop invasive cognitive BCIs for therapeutic intervention?
Inferring single-trial neural population dynamics using sequential auto-encoders


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• Access the intimate / the subjective self?
• Act onto the intimate / the subjective self?
• Predict the subject’s behavior

• Cognitive restoration: from proof of concept to actual therapeutic applications?
• Cognitive enhancement:
  • Enhanced human beings (transhumanism)
  • Normative cognition
  • Interactions between cognitive skills

• This is an ethical and societal debate that needs to take place ahead of the scientific advances to be
Team members

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