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

Suliann Ben Hamed, PhD, DR

Neural bases of spatial cognition and action group

Lyon, France

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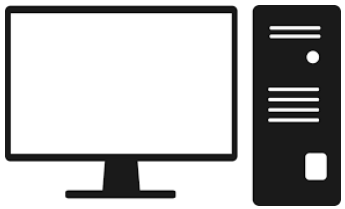
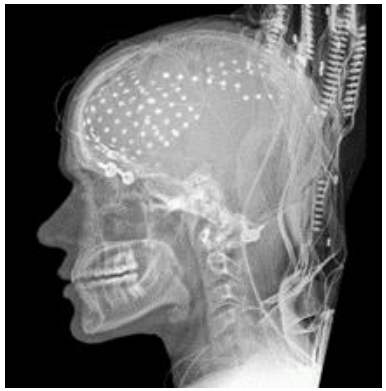
Frontier Research and Artificial Intelligence, ERC, Brussels

Invasive Brain computer interfaces



Identify the neural signature of a specific cortical operation and translate it into a control command ***in real-time***



Motor Brain computer interfaces

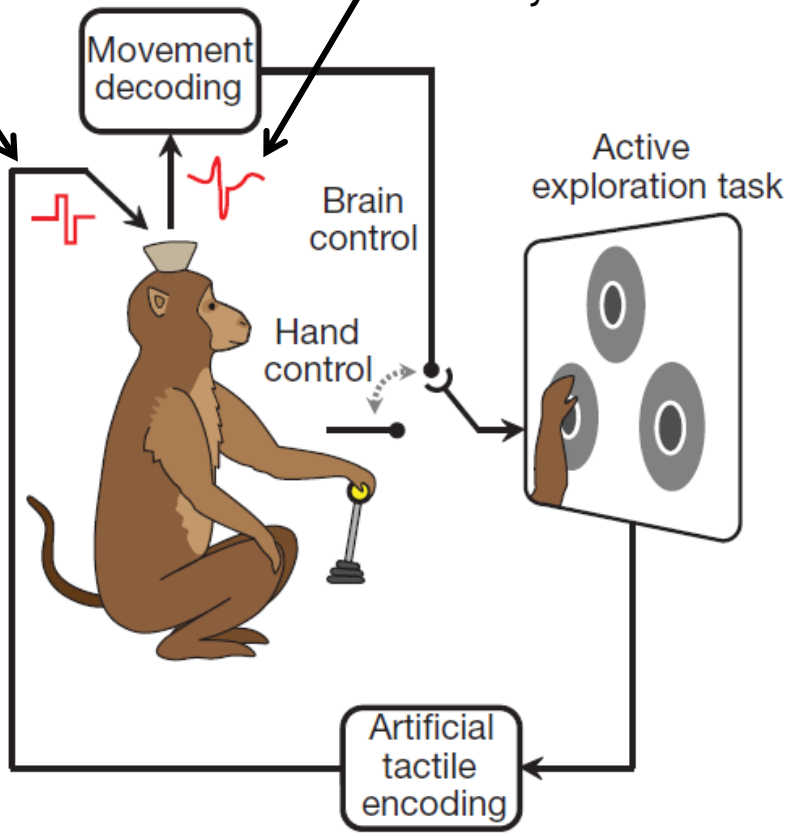
Cathy Hutchinson, ALS patient
Brain gate project, Donoghue Lab, Brown University, Rhode Island, USA

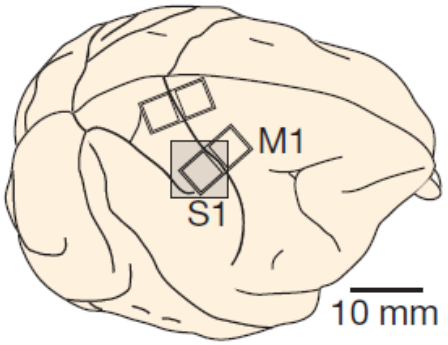
Hochberg et al., Nature, 2012

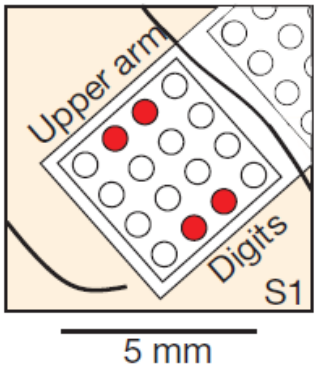
Bidirectional motor Brain computer interfaces

Changing cortical activity

Reading cortical activity







O'Deherty et al., Nature, 2011

Invasive Cognitive Brain computer interfaces : the project

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 …)

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Invasive Cognitive Brain computer interfaces : the project

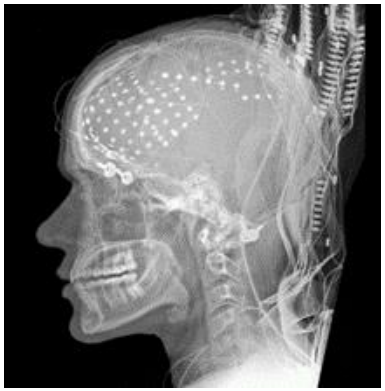
At the interface between Neurosciences and Artifical Intelligence

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



Attention-based Invasive Brain computer interfaces : the project

Covert attention

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

attentional spotlight
- the mind's eyes

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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; of 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 …)

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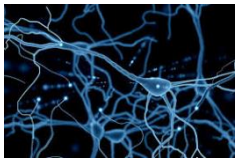
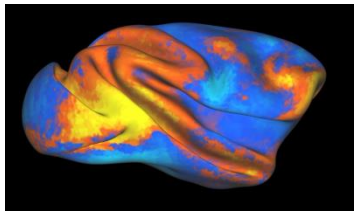
Attention-based Invasive Brain computer interfaces : the project

- Develop attention-based closed-loop neurofeedback designs to
  - **Enhance** attention
  - **Restore** attention
  - **Simulate** attention

- Characterize the associated dynamic reorganization principles

  - microscopic level (neurons)
  - mesoscopic level (area)
  - macroscopic level (network)





- From invasive to non-invasive attention-based closed-loop neurofeedback designs
  - MUA / LFP / ECoG / EEG / fMRI
  - Feasibility ?
  - Reorganization principles
  - From non-human primates to human experiments

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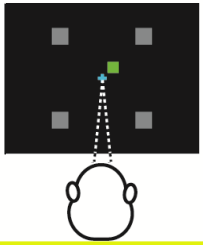
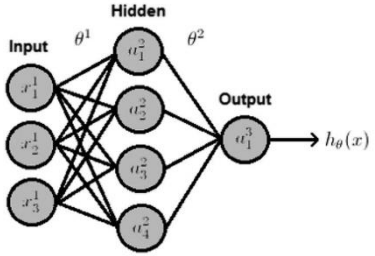
Real-time tracking of the covert attentional spotlight

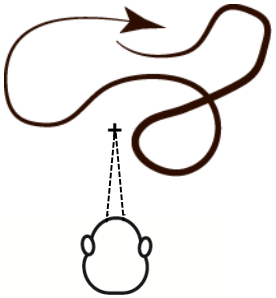
Behaving monkey

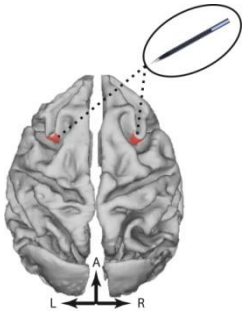
Cued target detection task



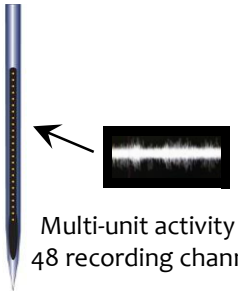


Astrand et al., PLoS ONE, 2014;
Astrand et al., Front. Syst. Neuro., 2014,
Astrand et al., J. Neurosci., 2015
Astrand et al., Curr. Biol., 2016
Astrand et al., BioRxiv, 2018





Neuronal recordings
In the FEF



Multi-unit activity on
48 recording channels

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Real-time tracking of the covert attentional spotlight

Astrand et al., Curr. Biol., 2016
Astrand et al., BioRxiv, 2018

. Correct trials .

Cue
Distractor
Target
Attention

RESPONSE

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Real-time tracking of the covert attentional spotlight

Astrand et al., Curr. Biol., 2016
Astrand et al., BioRxiv, 2018

. Incorrect trials .

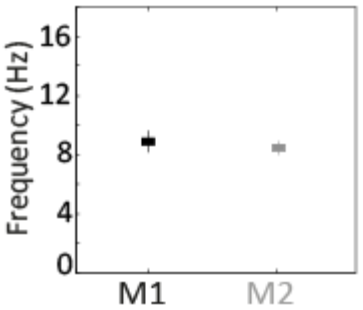
Cue
Distractor
Target
Attention

RESPONSE

Attention in time

Gaillard et al., in preparation

The decoded attentional spotlight oscillates at a specific frequency of 8 Hz, phase locked to the cue

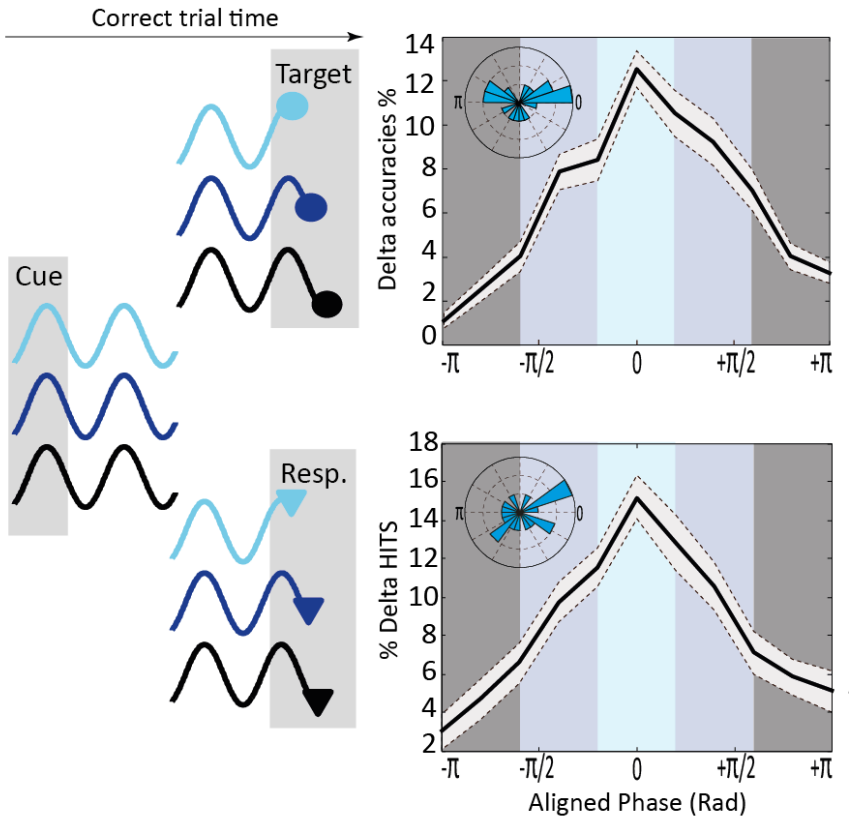


Attention in time

Gaillard et al., in preparation

Prefrontal information about target vary as a function of oscillations of attentional spotlight

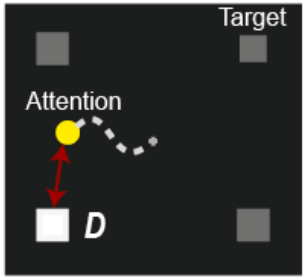
Overt behavior (HITs) vary as a function of oscillations of attentional spotlight

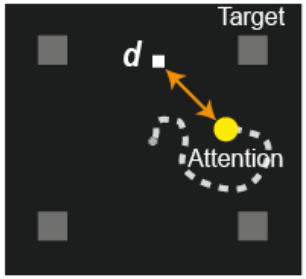


Attention in space

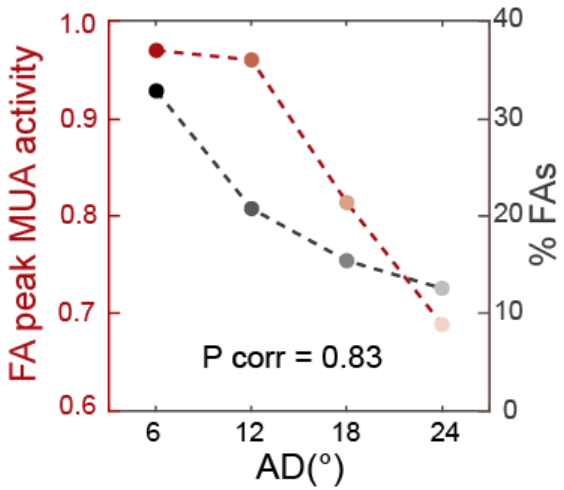
Di Bello et al., in preparation

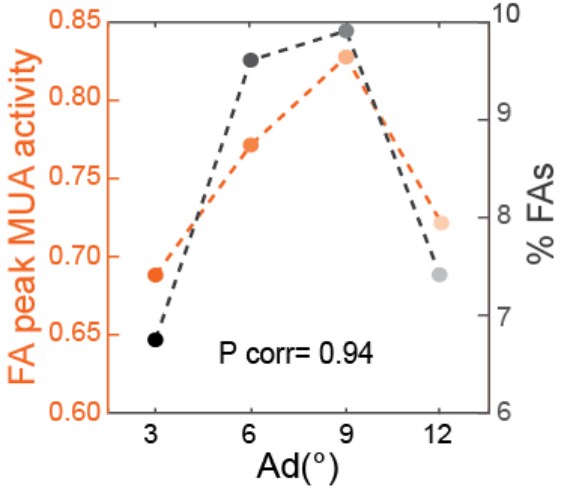
Two different distractor filtering mechanisms



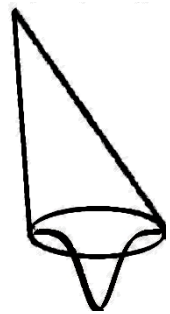


Distractor ***filtered IN***





Distractor ***filtered OUT***

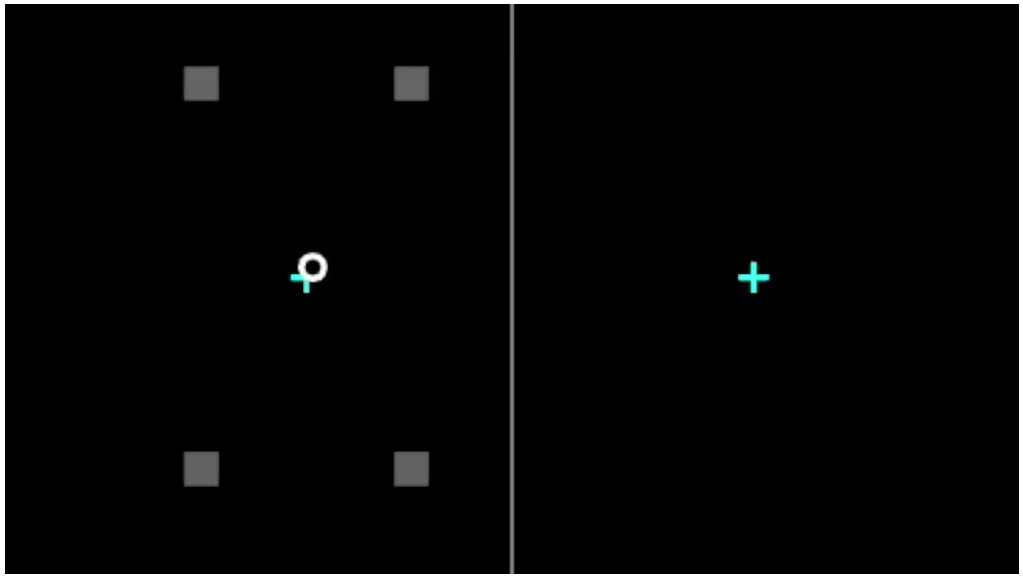


Attention-based closed-loop neurofeedback

Enhancing attention

Astrand, Amengual et al., in preparation

Behavior **Endogenous attention**



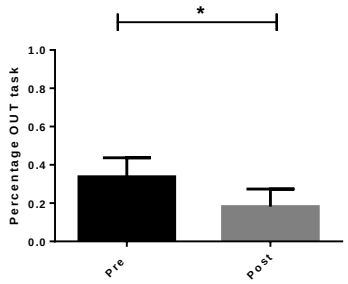
Cue
Attention
Eye position

Reward +
Reward ++
Reward +++
Reward ++++

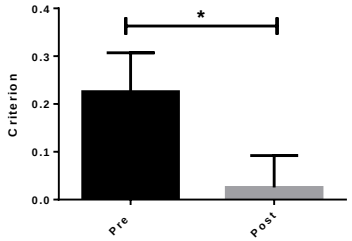
Attention-based closed-loop neurofeedback effects on behavior

Astrand, Amengual et al., in preparation

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.

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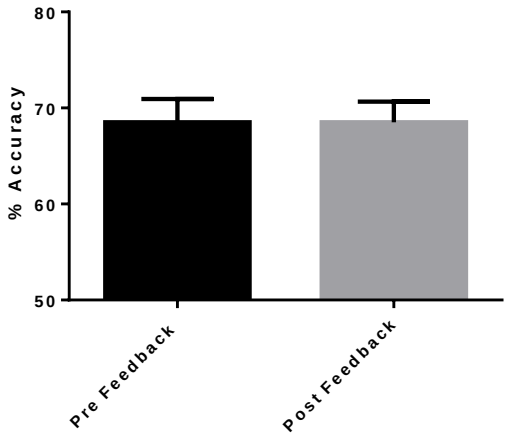
Attention-based closed-loop neurofeedback & neuronal code

Astrand, Amengual et al., in preparation

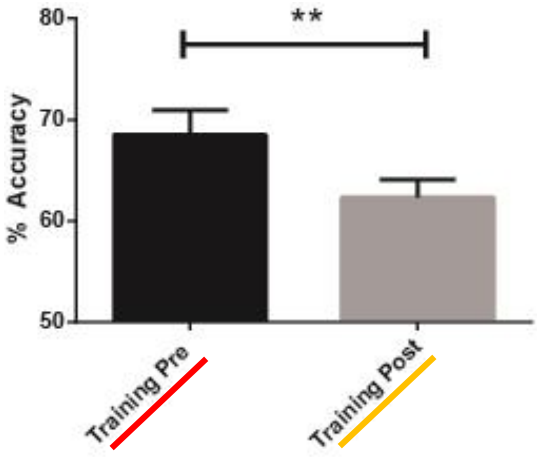
Overall available attention-related information in population does not change with neurofeedback

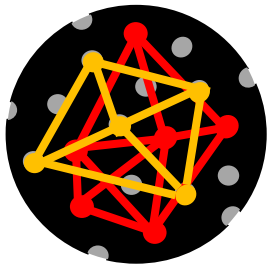


Attention-based closed-loop neurofeedback & neuronal code

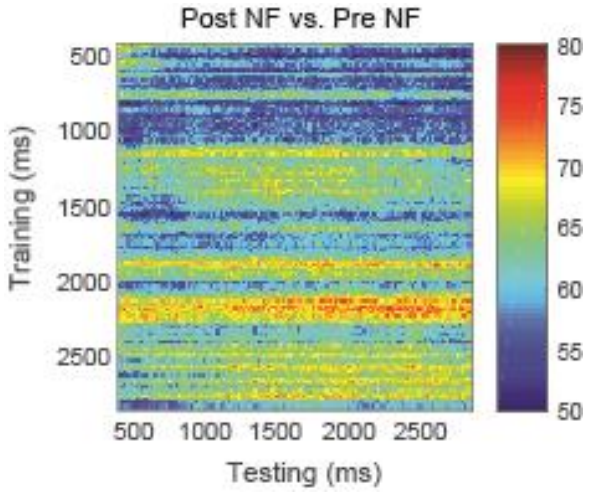
Astrand, Amengual et al., in preparation

Neurofeedback induced a change
in the attentional code





Dynamic co-existance
of two codes: 'old' + 'new' code



Attention-based Brain computer interfaces : recap

- 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

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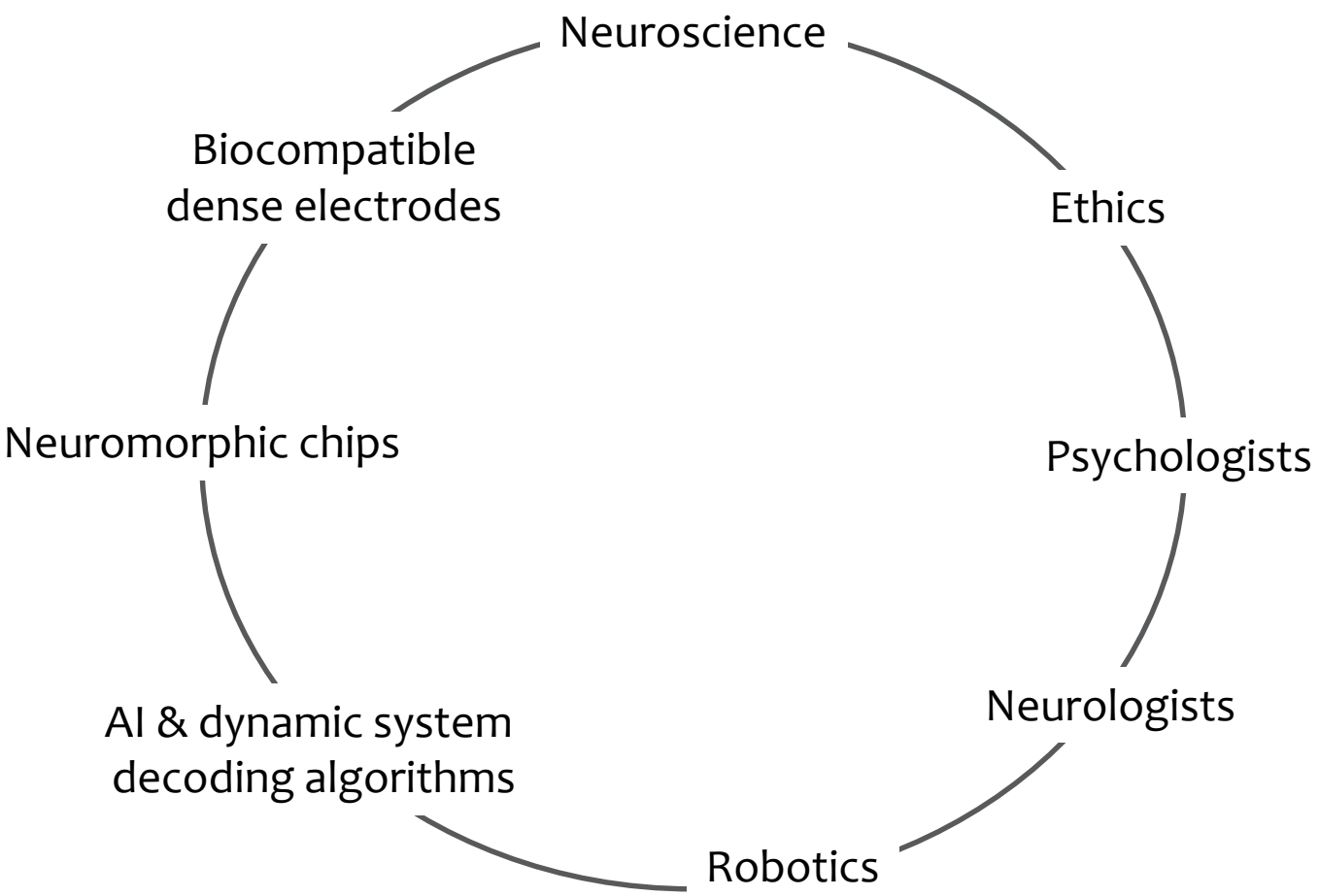
The future of invasive cognitive brain computer interfaces



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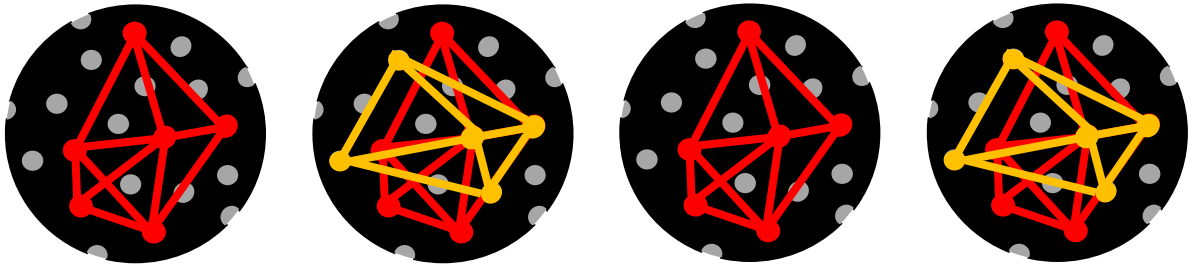
The future of invasive cognitive brain computer interfaces & AI

- 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)

The future of invasive cognitive brain computer interfaces & AI

- How does the brain encode multiple processes? How does it dynamically switches 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 otpimized closed-loope invasive cognitive BCIs for therapeutic intervention

nature methods

ARTICLES

https://doi.org/10.1038/s41592-018-0109-9

Inferring single-trial neural population dynamics using sequential auto-encoders

Chethan Pandarinath[1,2,3,4,5*], Daniel J. O'Shea[4,6], Jasmine Collins[7,20], Rafal Jozefowicz[7,21], Sergey D. Stavisky[3,4,5,6], Jonathan C. Kao[4,8], Eric M. Trautmann[6], Matthew T. Kaufman[6,22], Stephen I. Ryu[4,9], Leigh R. Hochberg[10,11,12], Jaimie M. Henderson[3,5], Krishna V. Shenoy[4,5,13,14,15,16], L. F. Abbott[17,18,19] and David Sussillo[4,5,7*]

NATURE METHODS | VOL 15 | OCTOBER 2018 | 805–815 | www.nature.com/naturemethods

Invasive cognitive Brain computer interfaces & ethics

- 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

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Thank you for your … attention

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