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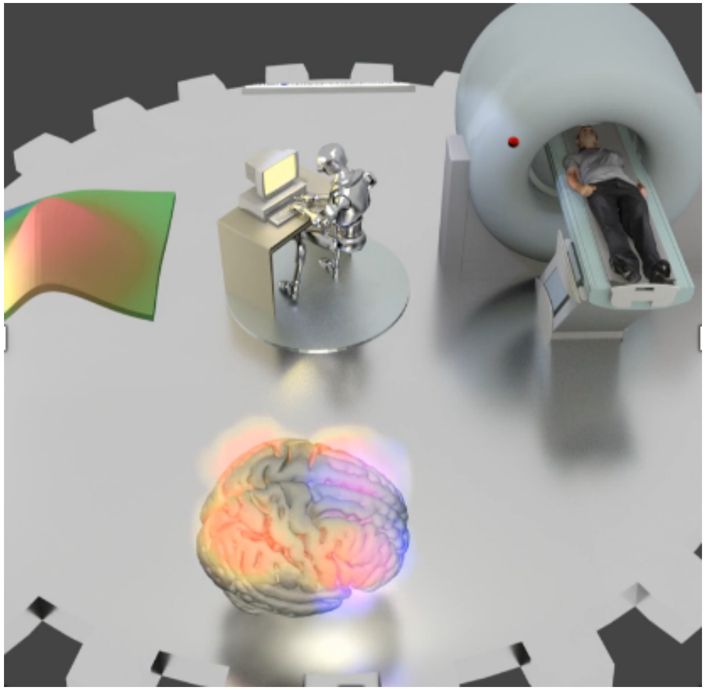
Neuroadaptive Bayesian Optimization

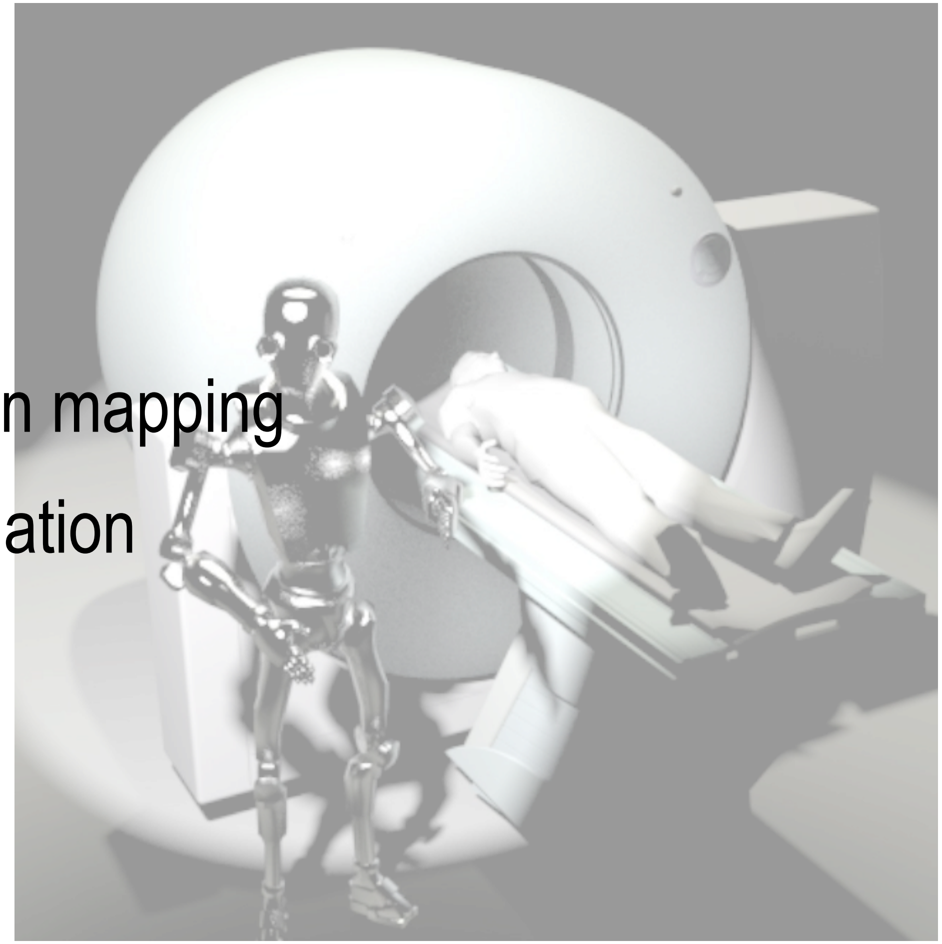
Implications for the Cognitive Sciences



Romy Lorenz

Postdoctoral Research Fellow
Cognitive, Clinical and Computational Neuroimaging Lab
Imperial College London

Overview



1. Motivation
2. The framework
3. Validation study
4. Application 1: Human brain mapping
5. Application 2: Brain stimulation
6. Ongoing work
7. Implications & Discussion

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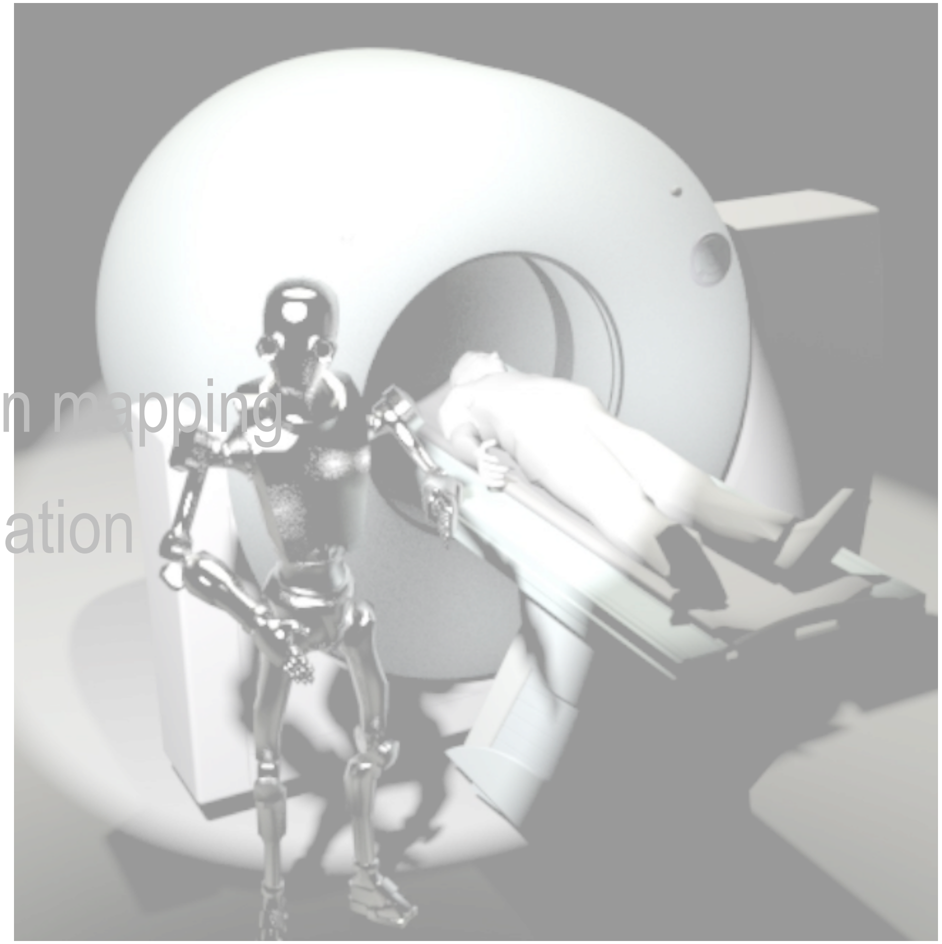
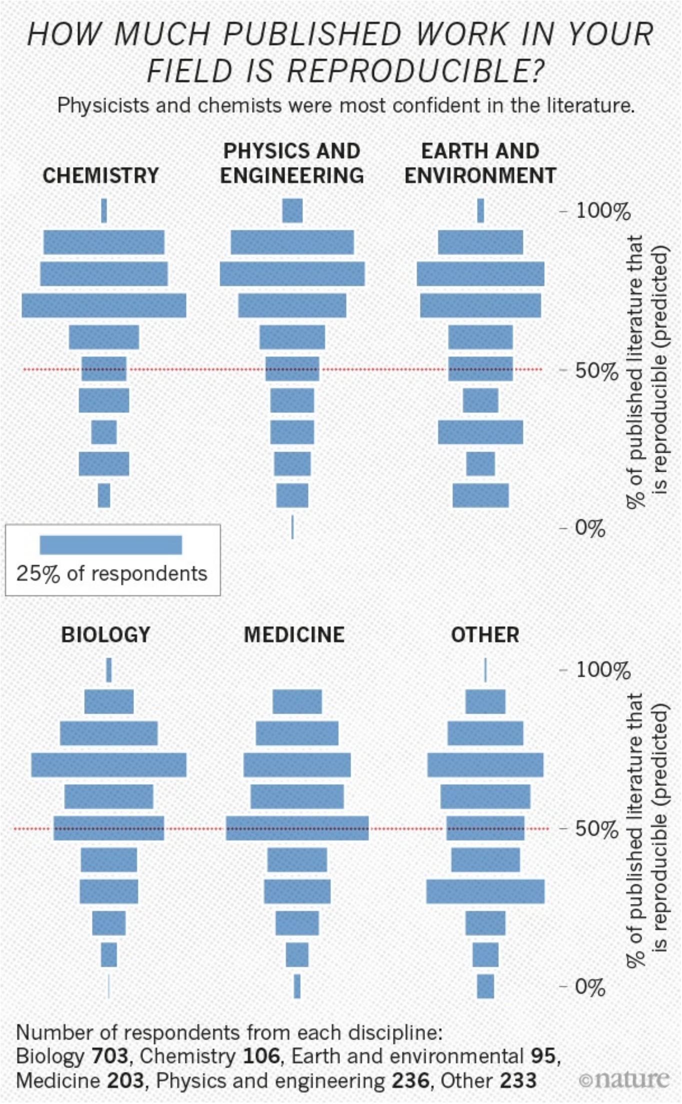
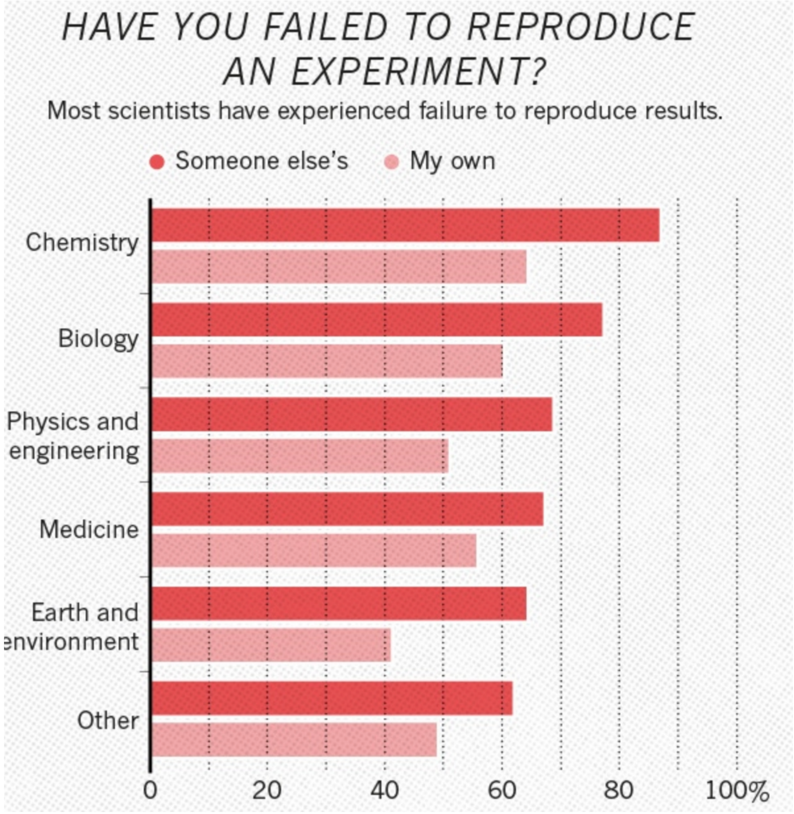


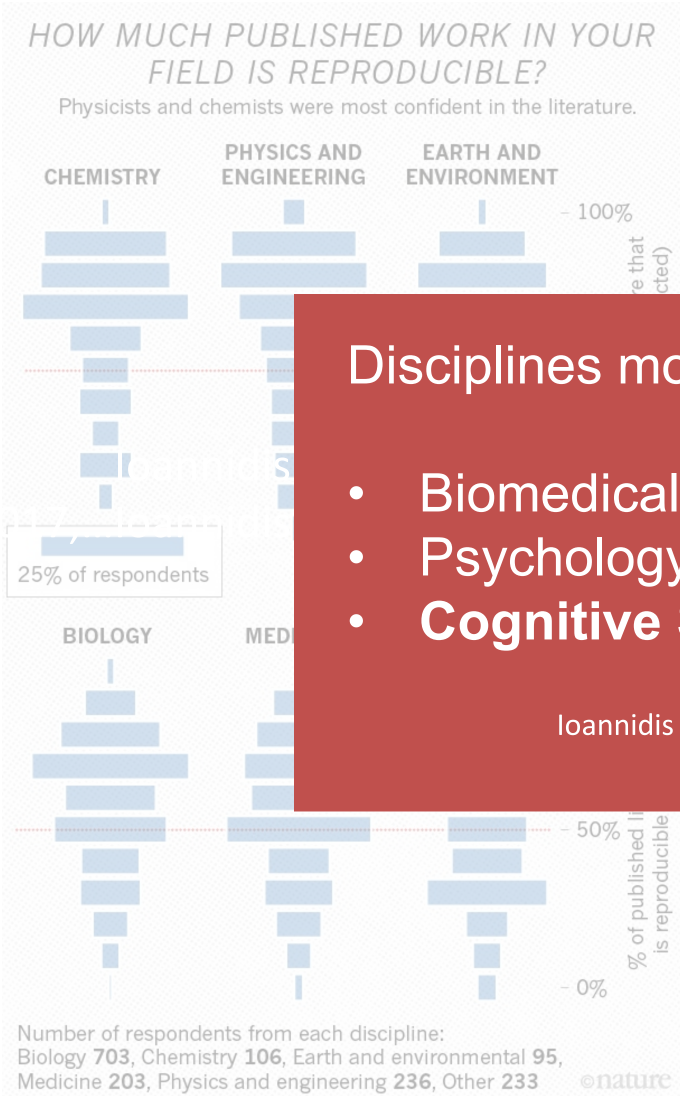
Reproducibility crisis

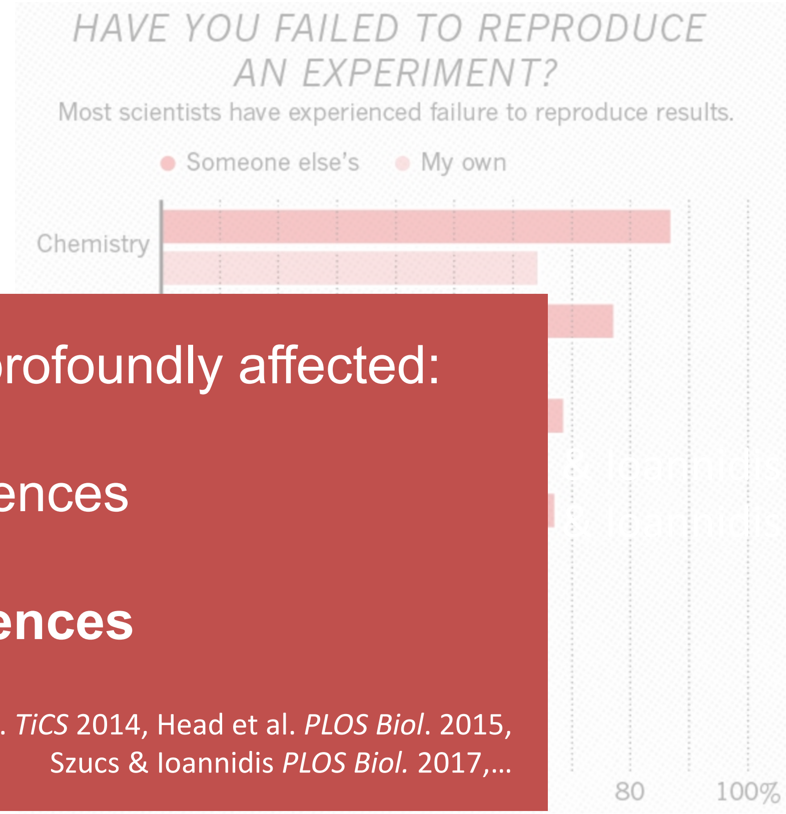




Survey by *Nature* 2016

Reproducibility crisis





Survey by *Nature* 2016

Disciplines most profoundly affected:

- Biomedical sciences
- Psychology
- **Cognitive Sciences**

Ioannidis et et al. *TiCS* 2014, Head et al. *PLOS Biol*. 2015,
Szucs & Ioannidis *PLOS Biol.* 2017,…

Reproducibility crisis in Cognitive Sciences

- Cognitive biases
  - IKEA-effect
  - Texas sharp-shooter effect
- Bad research practices
  - P-hacking
  - HARKing
  - File-drawer effect
- Limitations of methodology
  - Underpowered studies
  - “Narrow” experimental designs

Reproducibility crisis in Cognitive Sciences

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- Limitations of methodology
  - Underpowered studies
  - **“Narrow” experimental designs**

Aims of cognitive neuroscience

Research questions

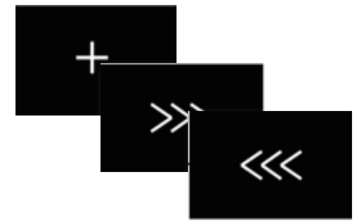
What are the fundamental aspects of cognition?

What are the fundamental roles of distinct networks in the brain?

How can cognitive processes be modulated or enhanced?

Standard approach

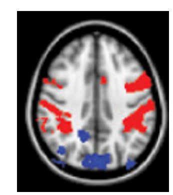
select task



test

> 20

group-level inference



broad ⟷ narrow

Aims of cognitive neuroscience

Human-brain mapping

- Over-specified inferences about functional-anatomical mappings
- Inflated test statistics
  (Westfall et al. *Wellcome Open Research* 2017)

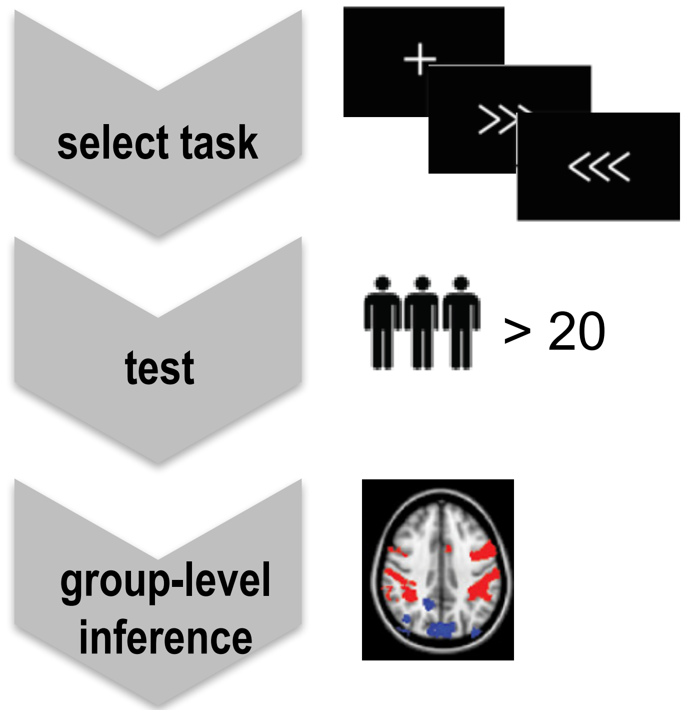
Biomarker discovery

- Which exact task conditions will be sensitive to certain patient group?
  (Sprooten et al. *Human Brain Mapping* 2017)

Non-invasive brain stimulation

- Many *free* parameters, confusion surrounding efficacy

Standard approach



broad ⟷ narrow

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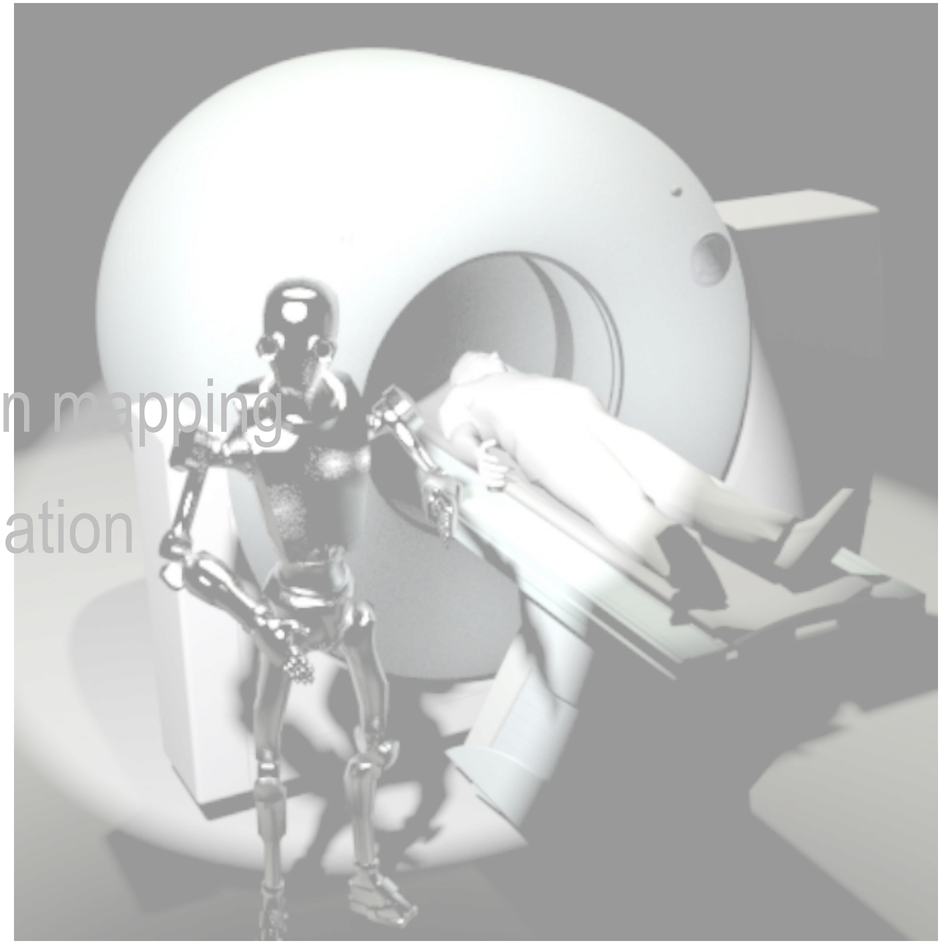
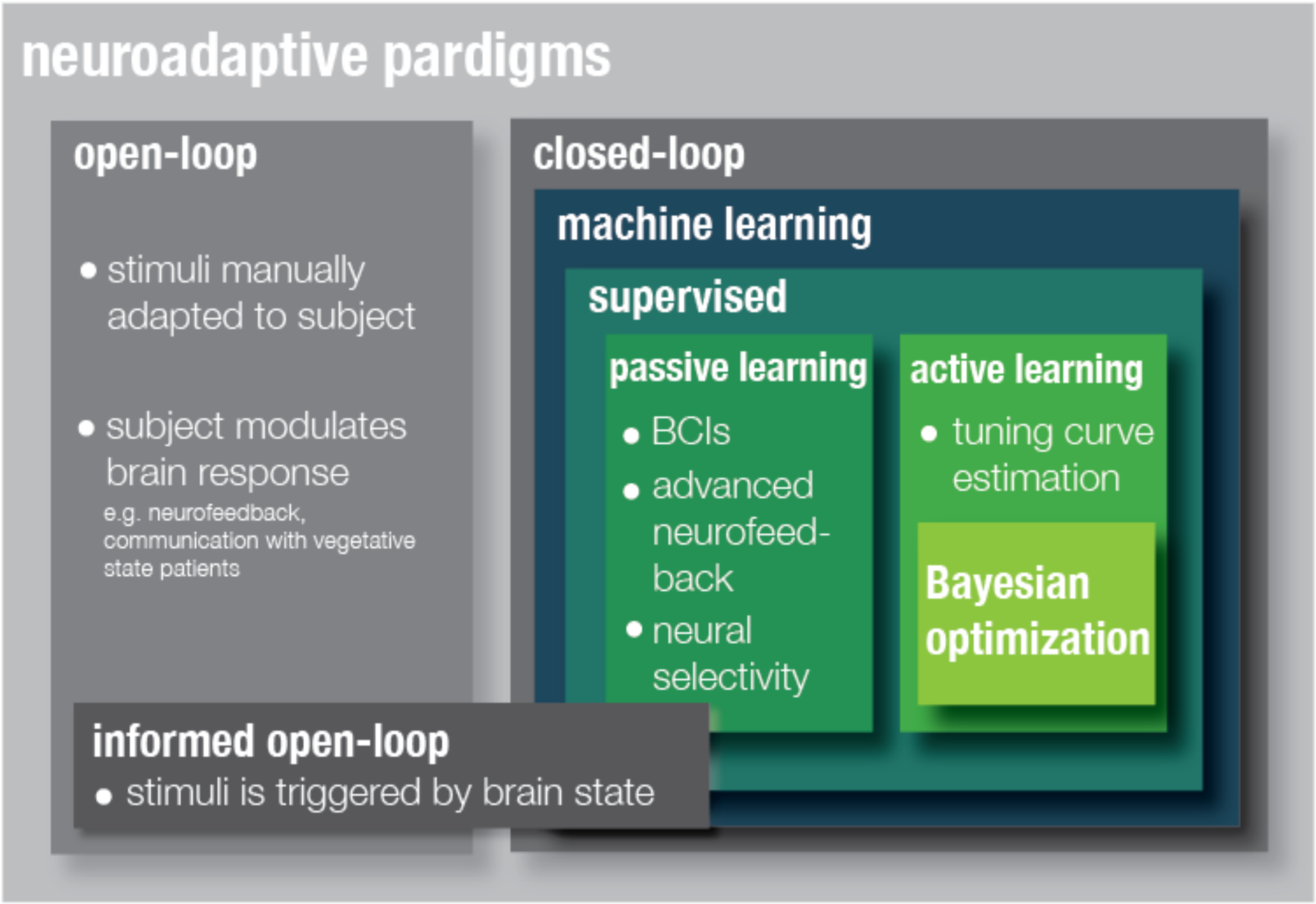
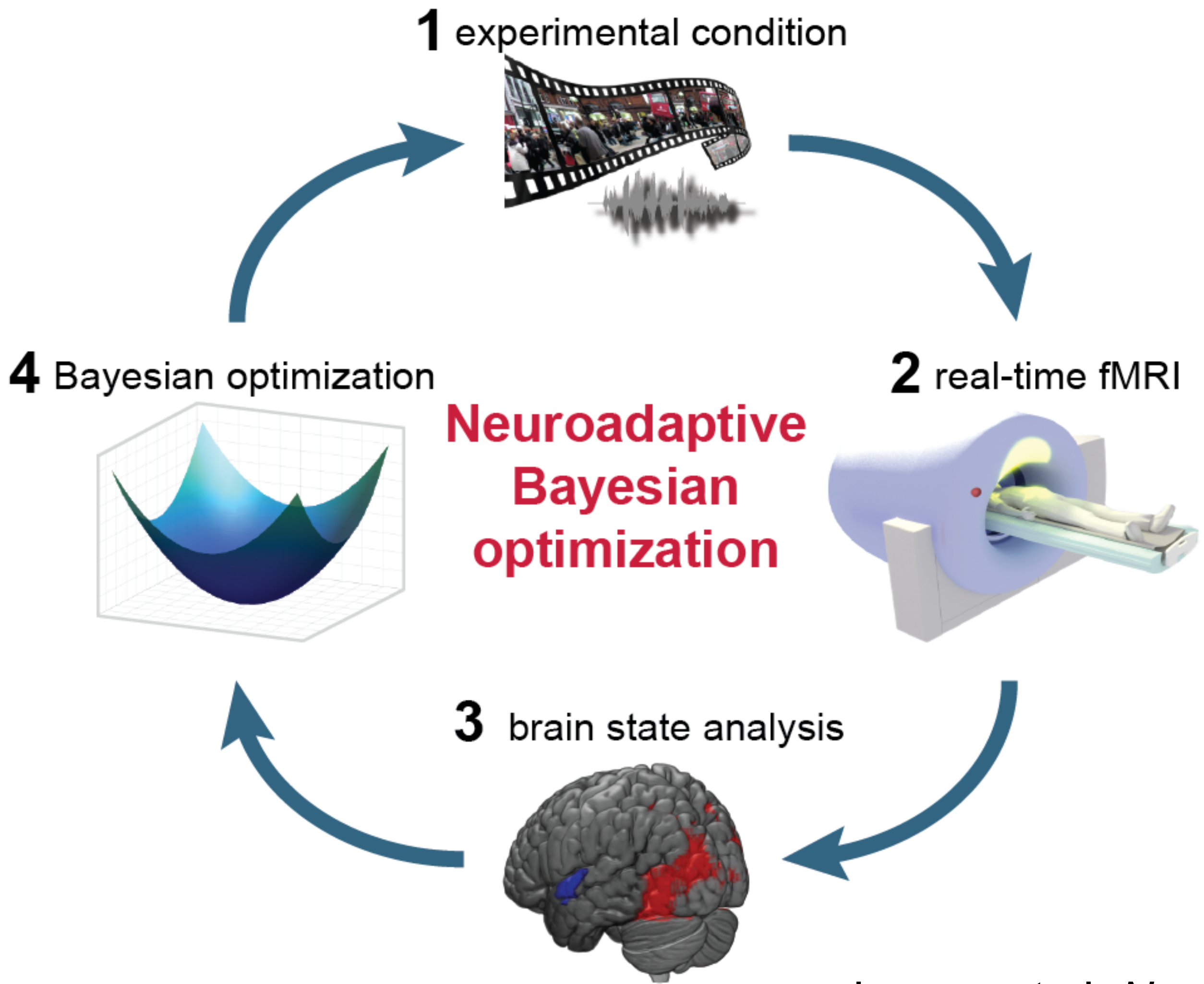


The framework



Lorenz et al. *Trends in Cognitive Sciences* 2017

“The Automatic Neuroscientist”



Lorenz et al. *NeuroImage* 2016

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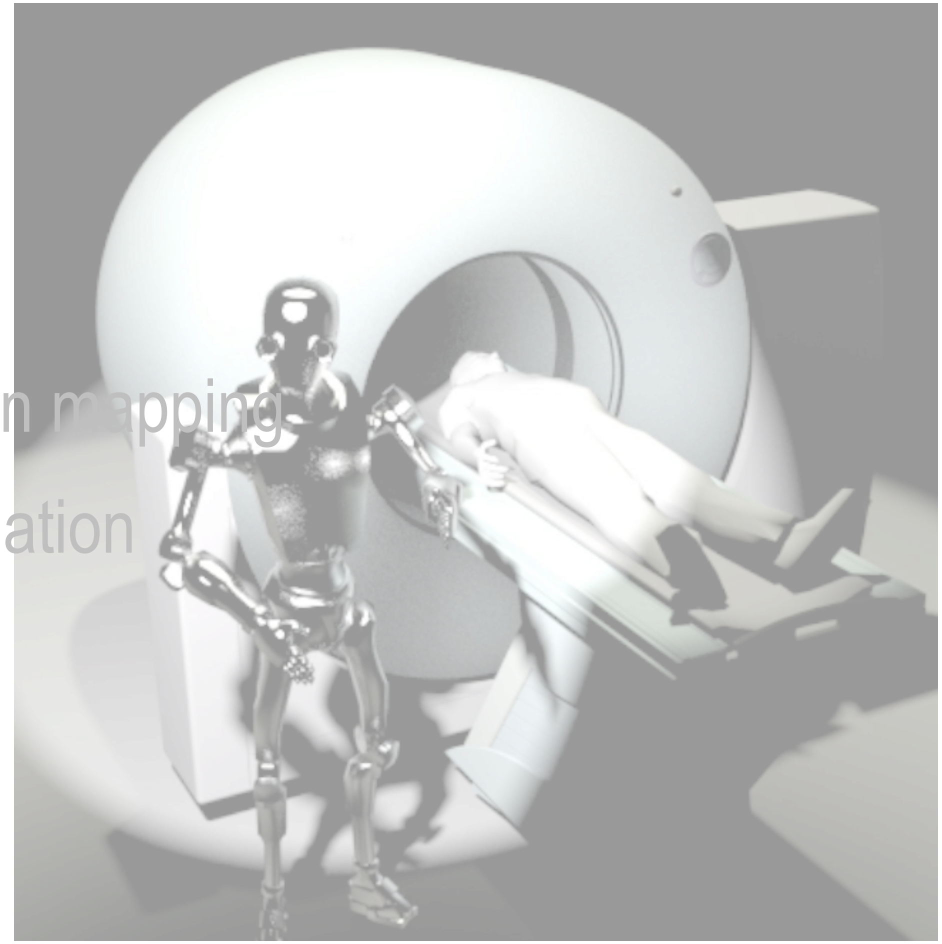
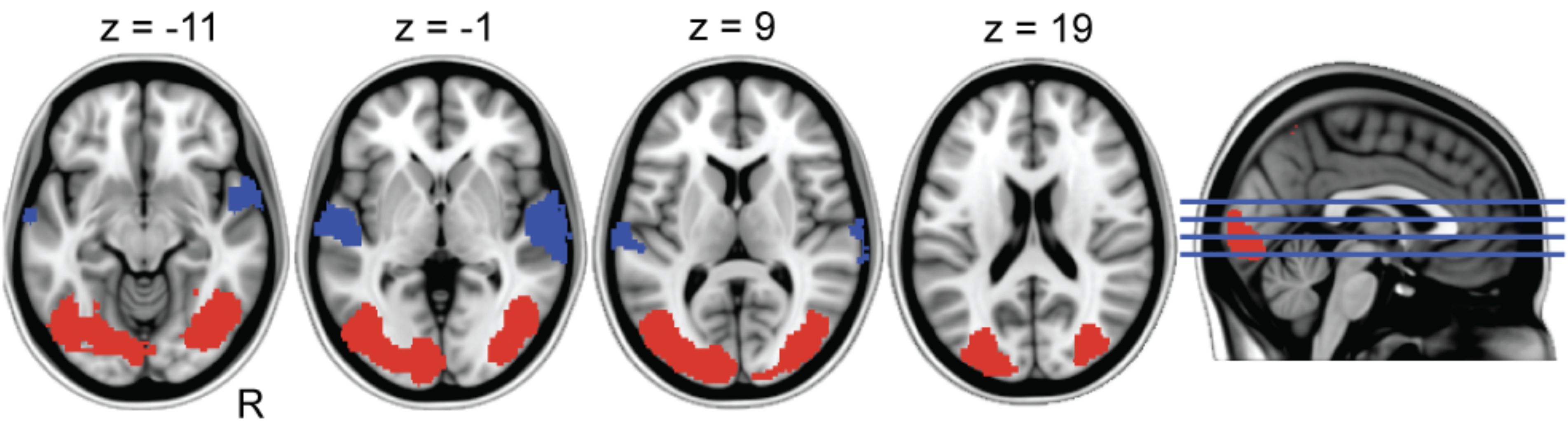


Target brain state

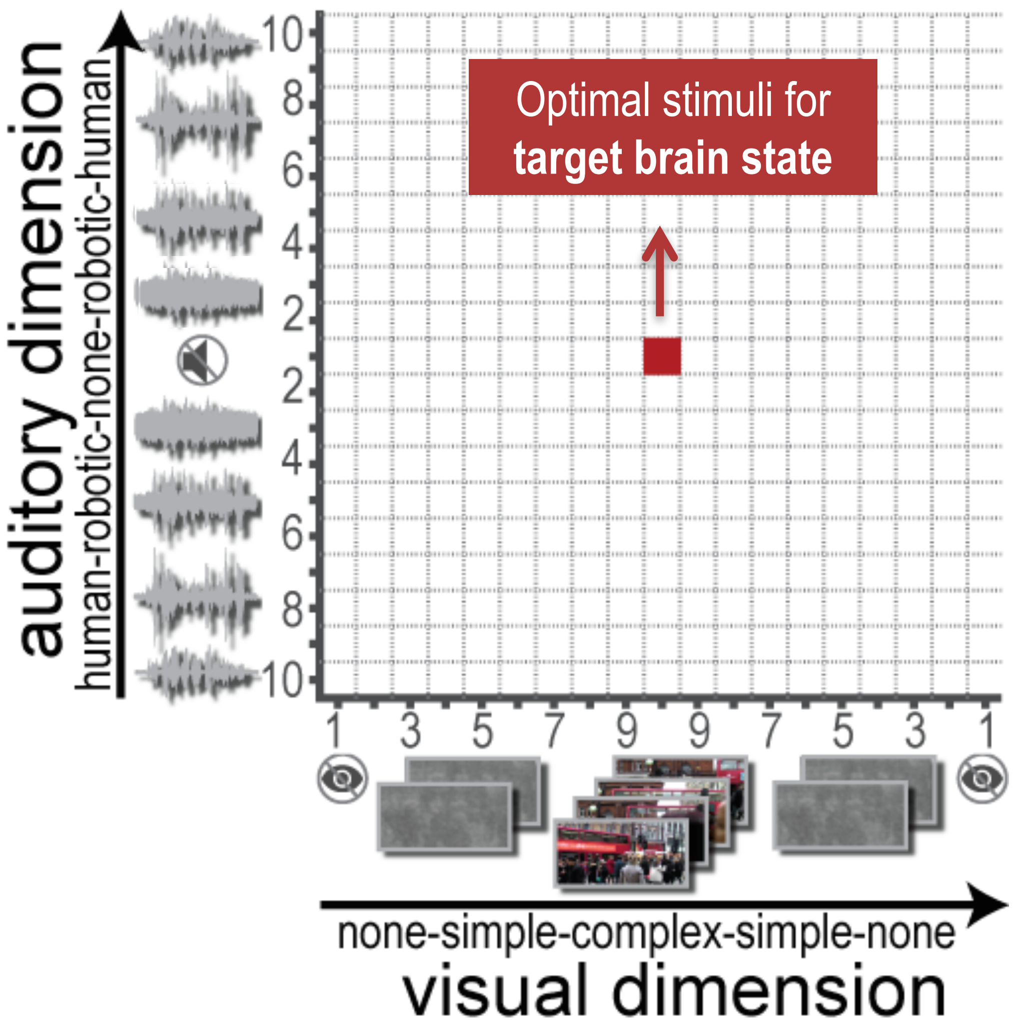


lateral occipital cortex activity ↑

superior temporal cortex activity ↓

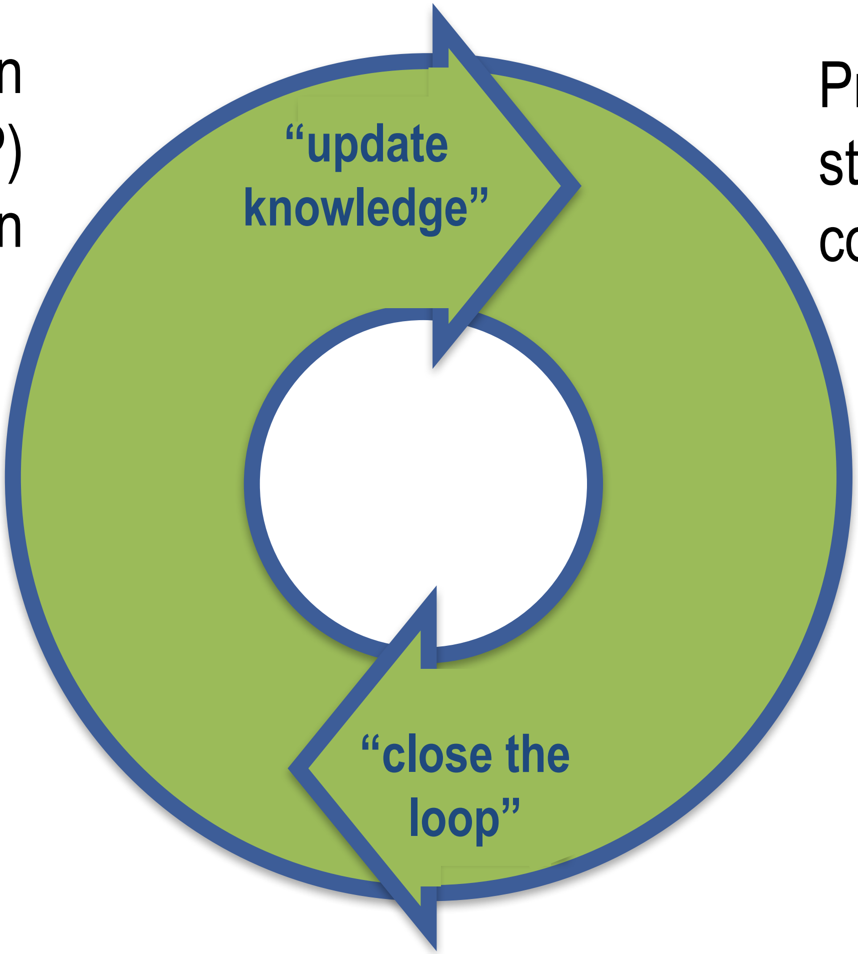
masks derived from
Braga et al. *NeuroImage* 2013

Experiment space



Bayesian optimization

Gaussian process (GP) regression

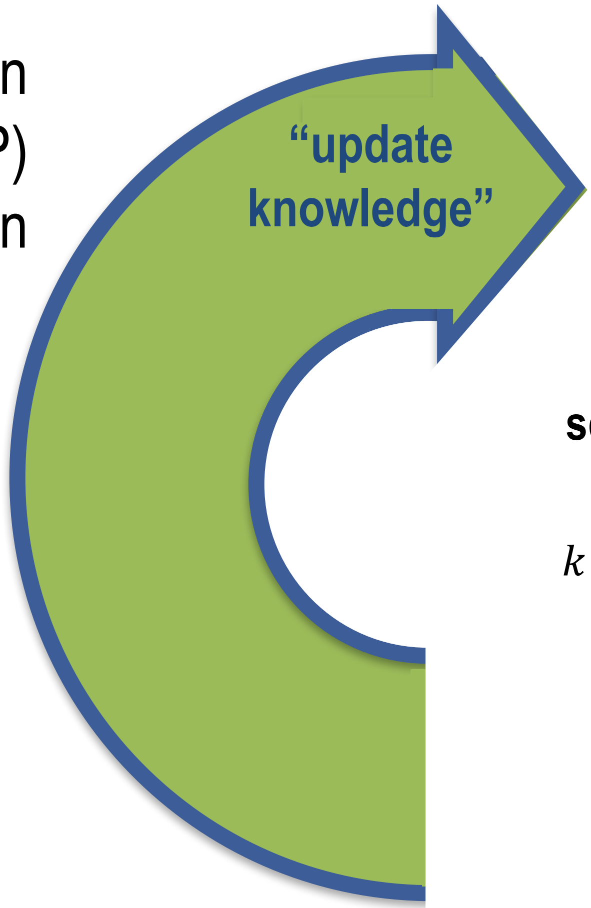


Propose new stimuli combination

Rasmussen & Williams 2006
Brochu et al. *arXiv* 2010

Bayesian optimization

Gaussian process (GP) regression



choice of covariance function

squared exponential kernel:

$$k(x,y) = \sigma^2 \exp\left\{-\frac{(x-y)^2}{2\, l^2}\right\}$$

$x, y \in \mathbb{R}^2$	audio-visual stimulus
$\sigma^2 \in \mathbb{R}$	variance of covariance kernel
$l \in \mathbb{R}$	length of covariance kernel

Rasmussen & Williams 2006
Brochu et al. *arXiv* 2010

Bayesian optimization

Expected improvement acquisition function:

$$EI(x) = (m(x) - f_{max})q(z) + var(x)p(z)$$

$m(x)$: predicted mean

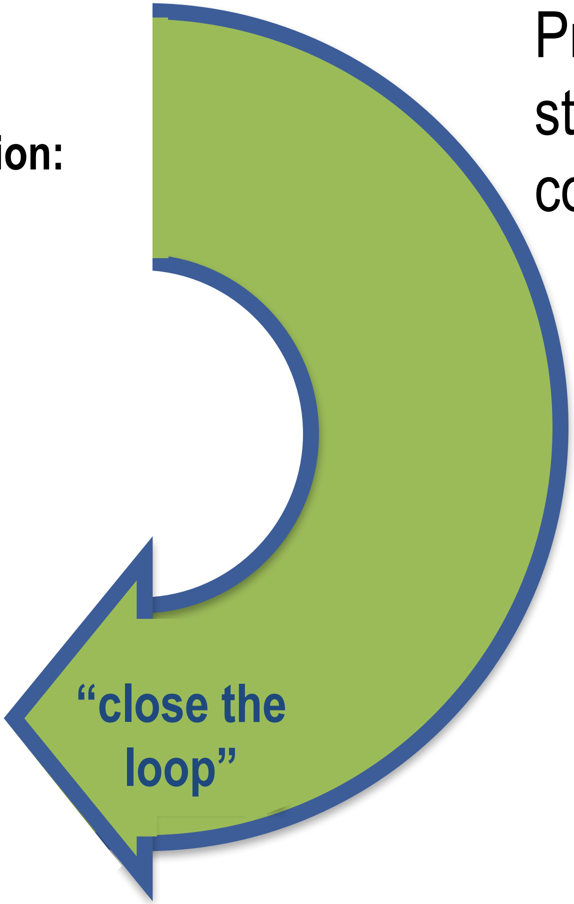
$var(x)$: predicted variance

f_{max}: maximum predicted value

$q()$: cumulative distribution function

$p()$: probability density function

$$z = \frac{m(x) - f_{max}}{var(x)}$$



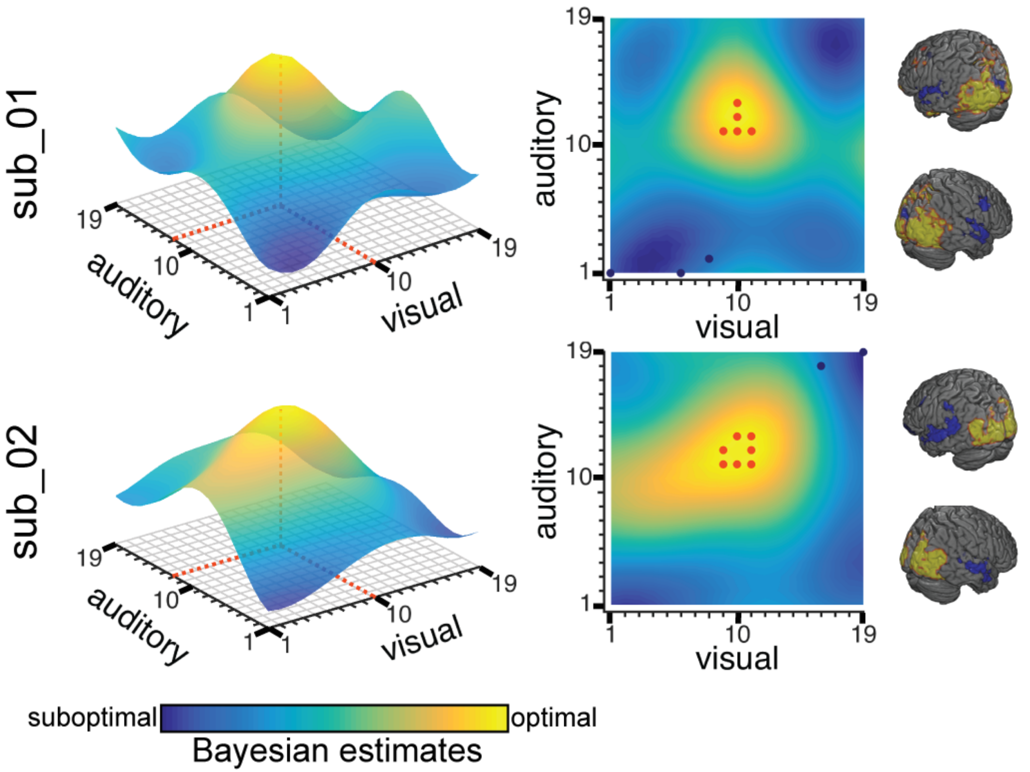
Propose new stimuli combination

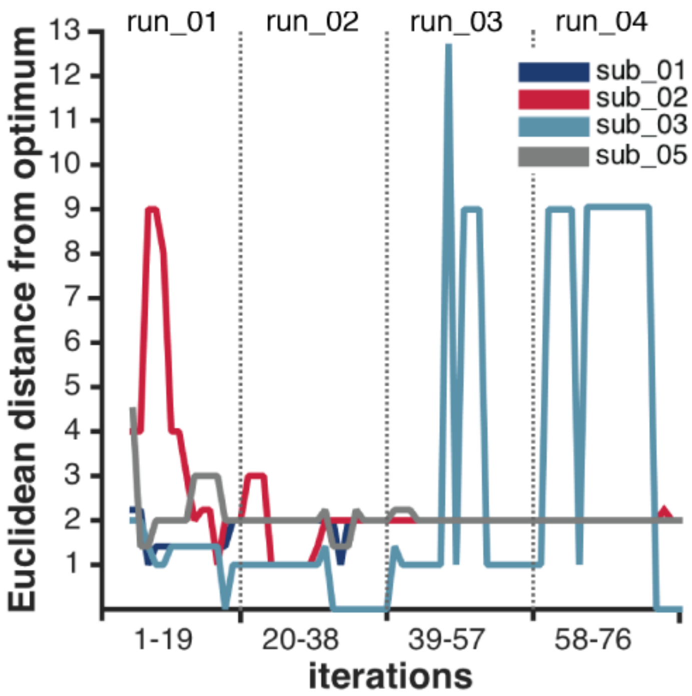
choice of acquisition function

Rasmussen & Williams 2006
Brochu et al. *arXiv* 2010

Results

= 5





Lorenz et al. *NeuroImage* 2016

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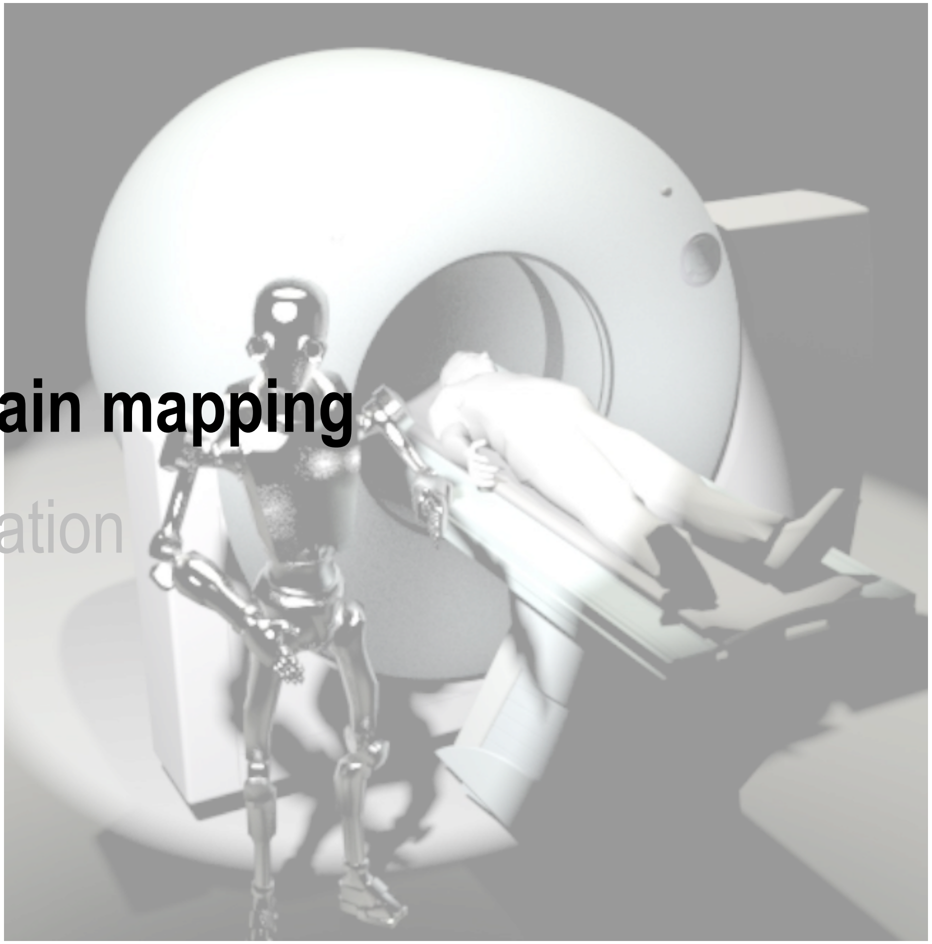
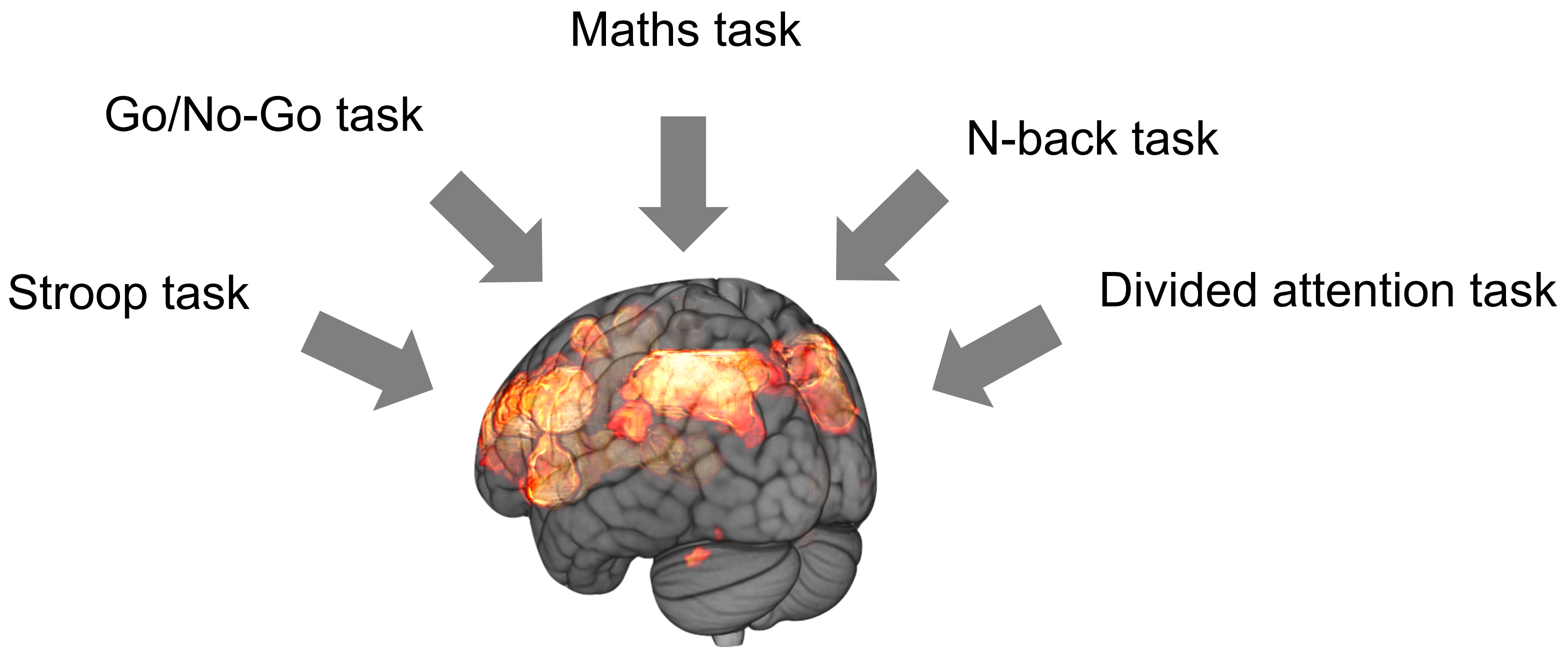


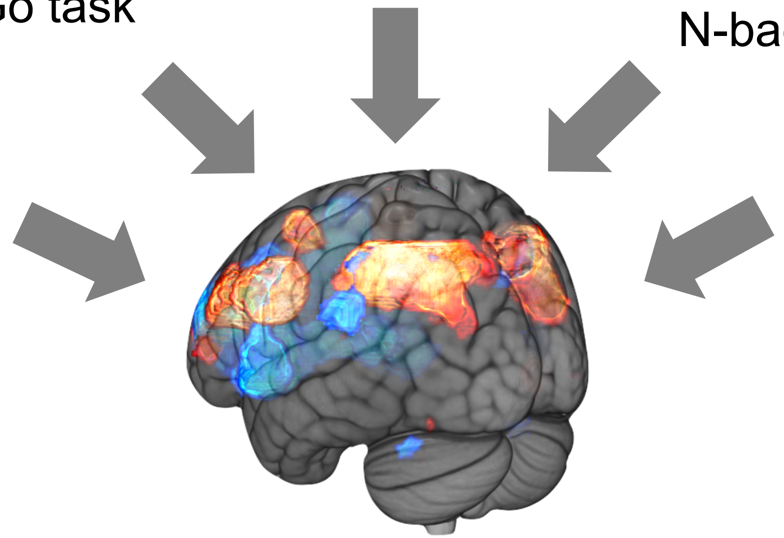
Motivation



frontoparietal networks (FPNs)

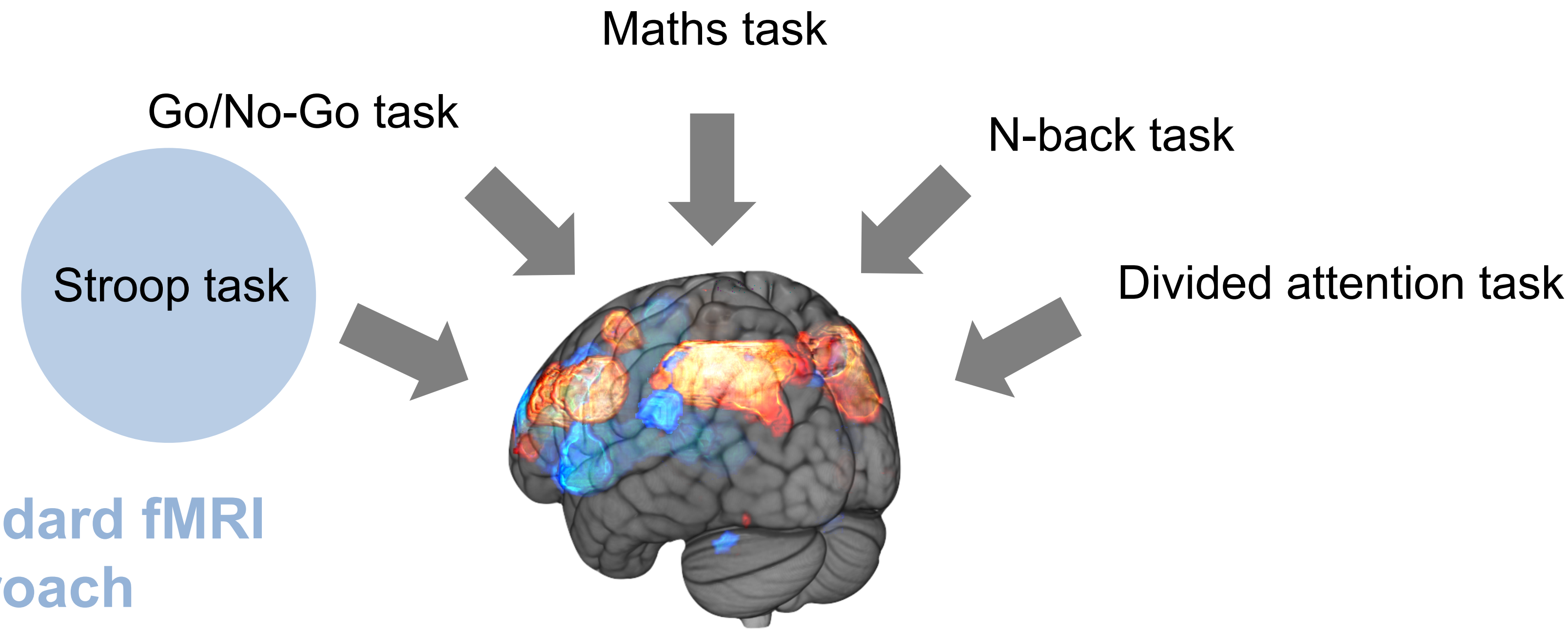
Duncan & Owen *TiNS* 2000
Fedorenko et al. *PNAS* 2013

Motivation



Hampshire et al. *Neuron* 2012

Motivation

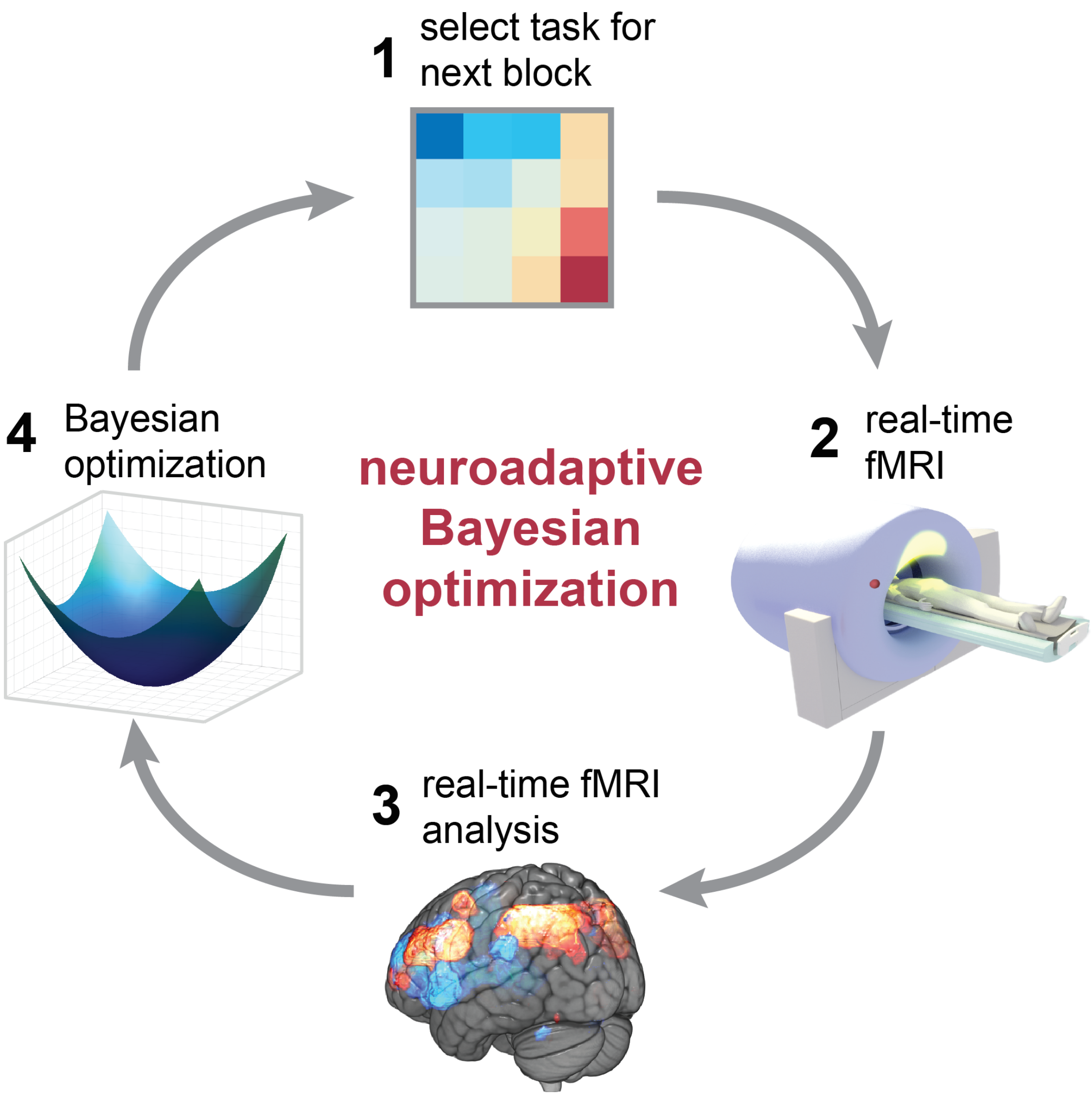


Standard fMRI approach

- **Limited generalizability**
- **Limited reproducibility**

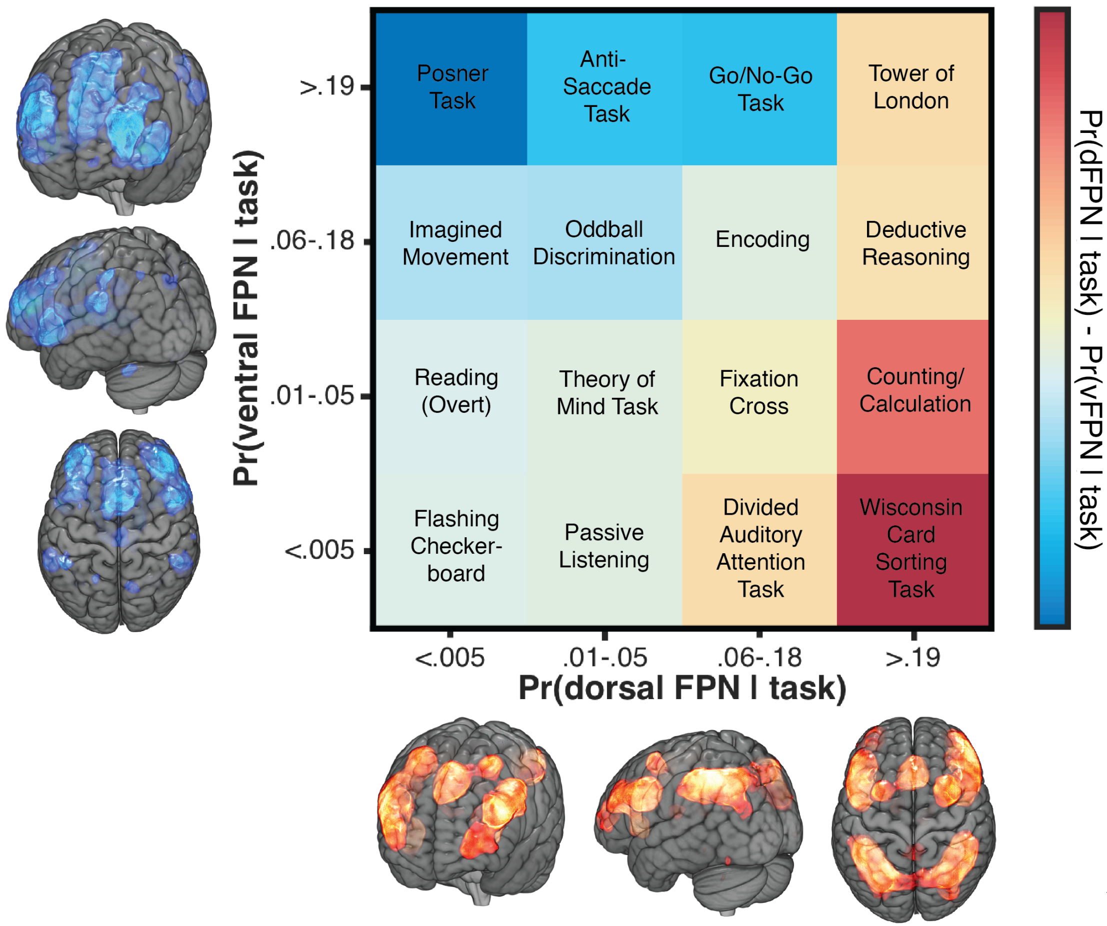
Lorenz et al. *Trends in Cognitive Sciences* 2017
Westfall et al. *Wellcome Open Research* 2017

Searching across cognitive tasks



Task space based on meta-analysis

Study 1 → Study 2 → Study 3

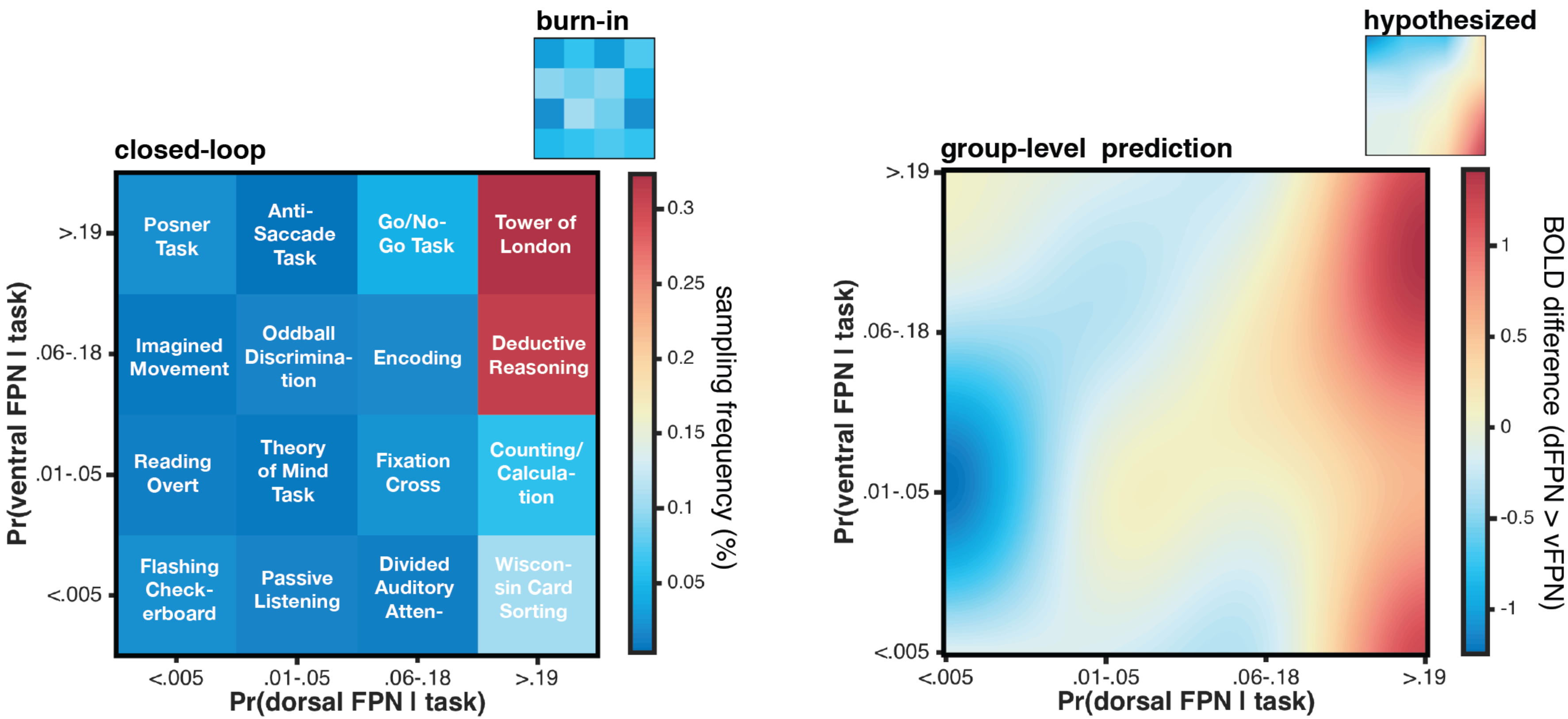


Yeo et al. *Cerebral Cortex* 2015

Find optimal tasks

Study 1 | Study 2 | Study 3

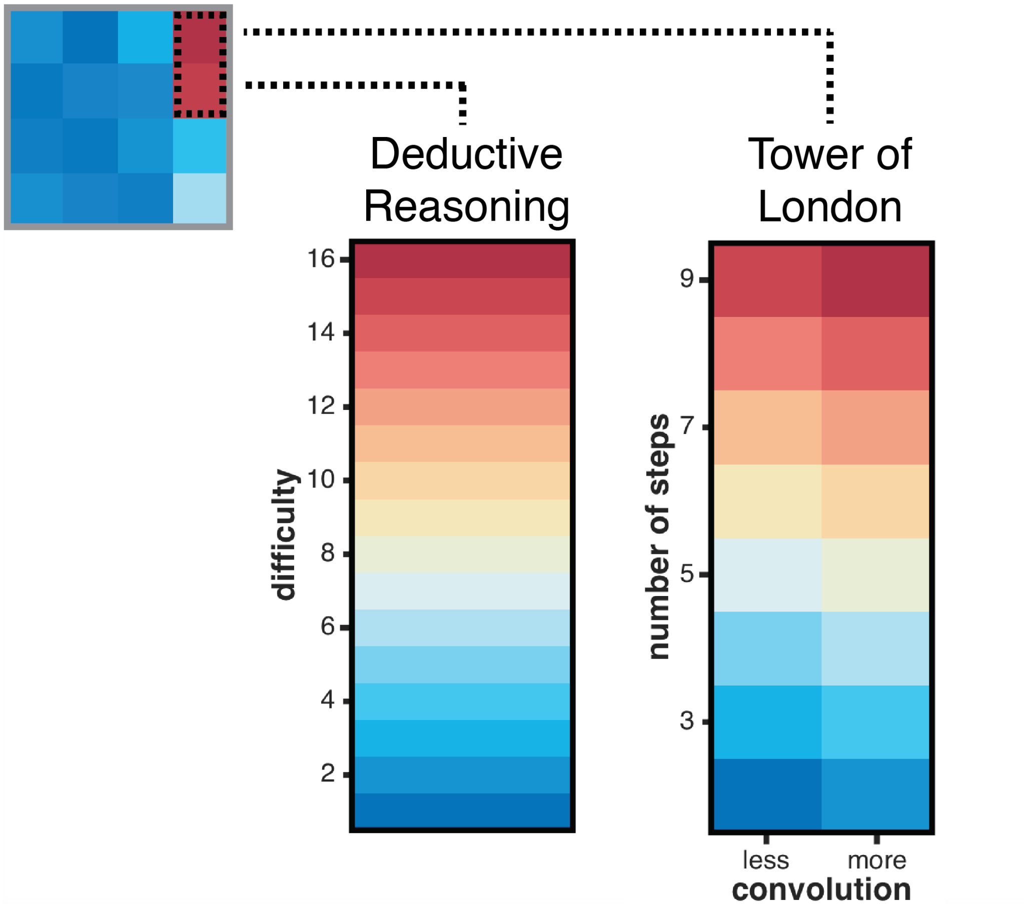
= 10



Tower of London & Deductive Reasoning tasks maximally dissociate FPNs

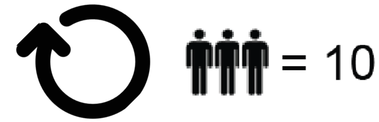
Zoom in task space and fine-tune tasks

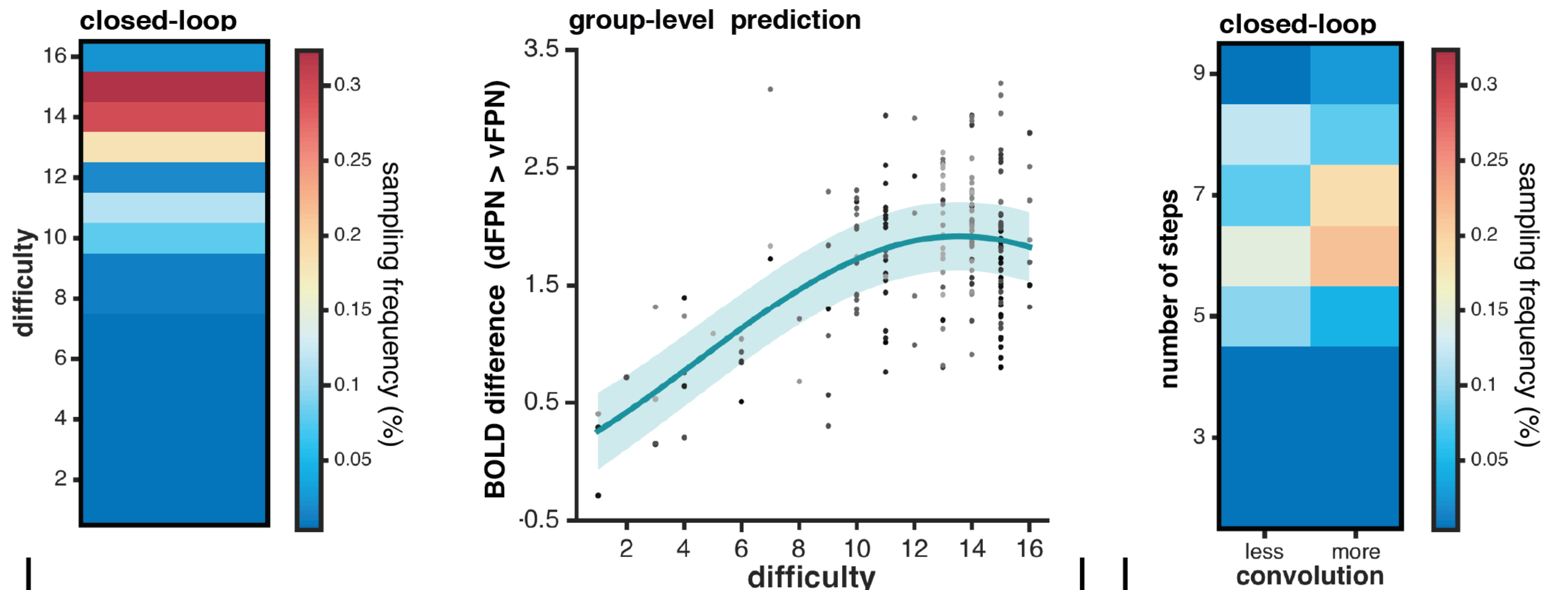
Study 1 | **Study 2** | Study 3



Find optimal task parameters

Study 1 | **Study 2** | Study 3





Deductive Reasoning

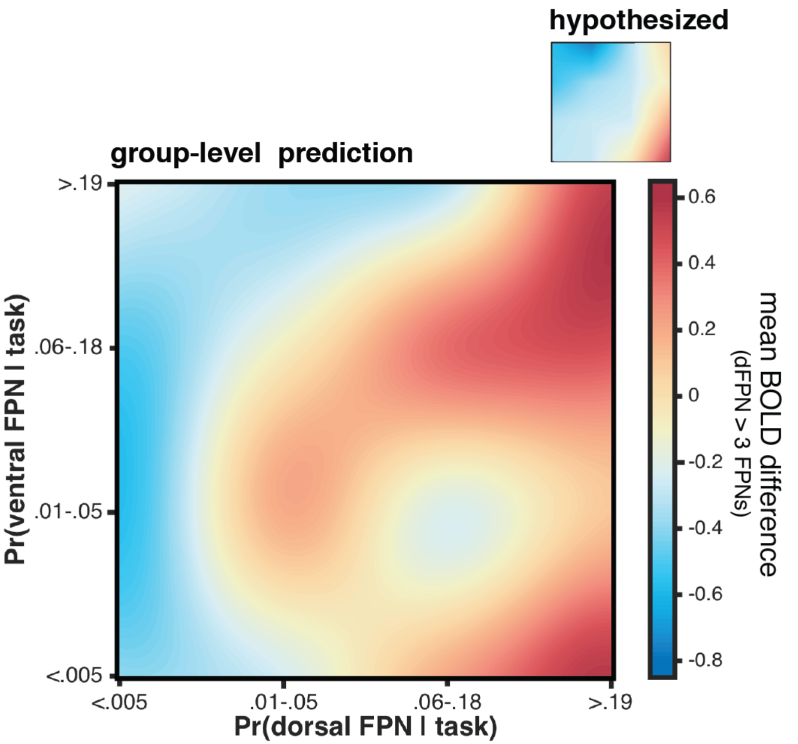
Tower of London

Find *unique* functional profile

Study 1 | Study 2 | **Study 3**

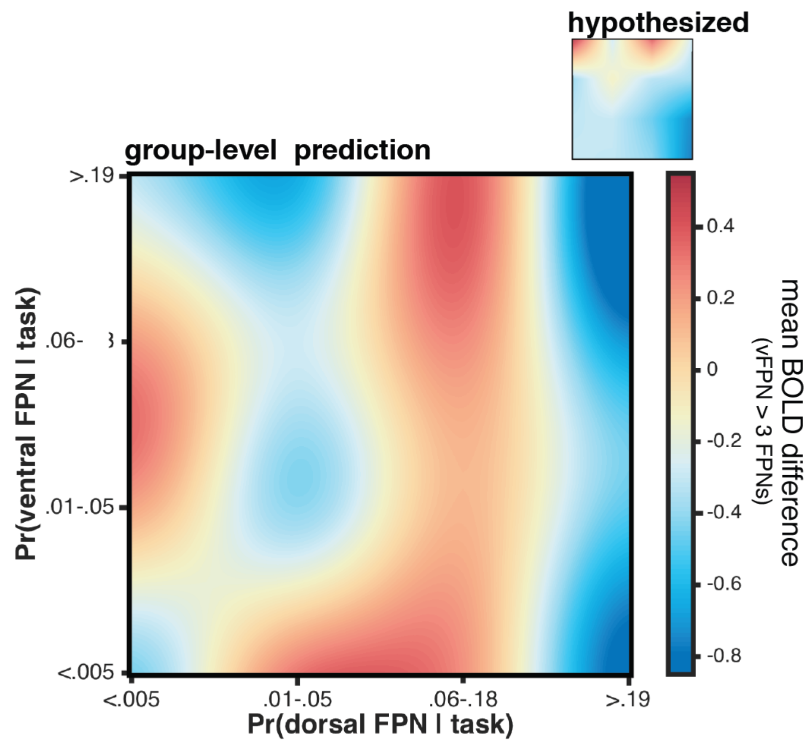
= 10

dorsal FPN > 3 other FPNs



Tower of London, Deductive Reasoning, Encoding & Wisconsin Card Sorting tasks

ventral FPN > 3 other FPNs



Go/No-Go, Divided Auditory Attention, Passive Listening & Reading tasks

Summary

- High inter-subject reliability
- Functional profile across many tasks is unique to each FPN
- Set of optimal tasks only partially corresponds to meta-analysis and previous functional labels
- Neurally-derived cognitive taxonomy needed
- **Powerful synergy between neuroadaptive Bayesian optimization and meta-analyses**

Lorenz et al. *under revision* (bioRxiv:**128678**)

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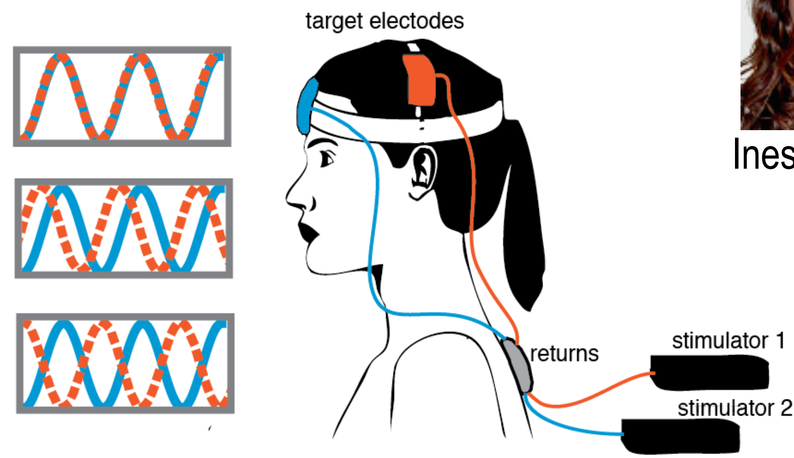
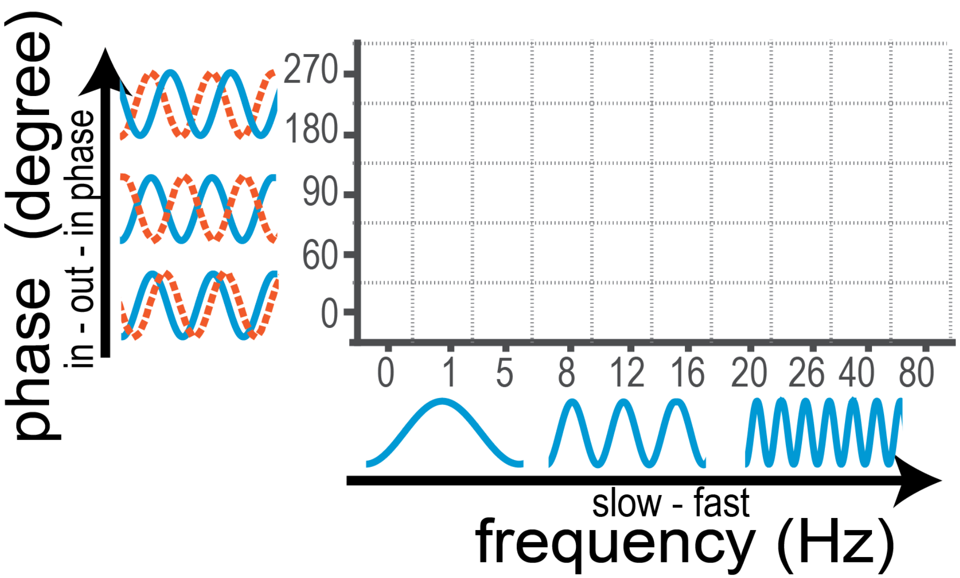
Transcranial alternating current stimulation (tACS)

- **Status Quo**
  - Ad hoc definition of frequency and phase
  - Cohort testing

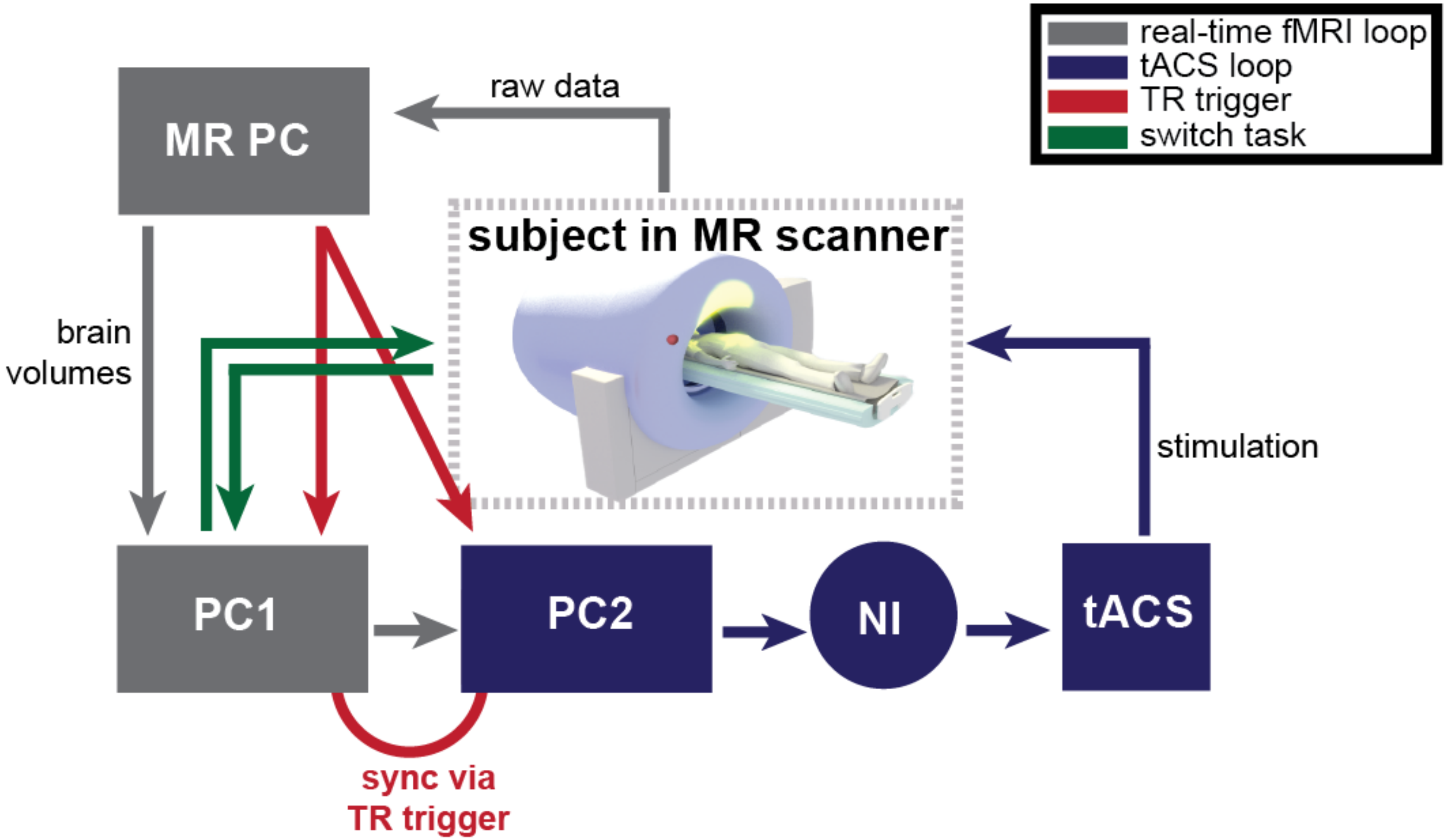


Ines Violante



- **Limitation**
  1. How to choose frequency and phase?
  2. Stimulation parameters may vary due to anatomy or pathology

Concurrent real-time fMRI/tACS

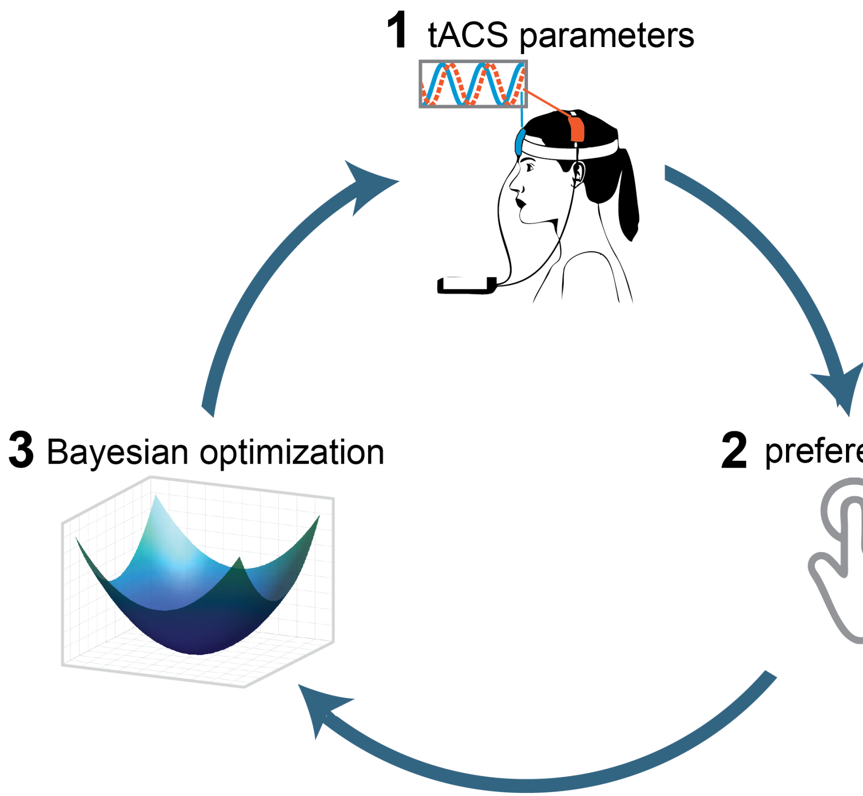


Ines Violante

Lorenz et al. *PRNI* 2016
Lorenz et al. *in preparation*

Phosphene perception

- *Phosphenes* = flash-like percepts during brain stimulation
- Major experimental challenge (neuromodulation, altertness)



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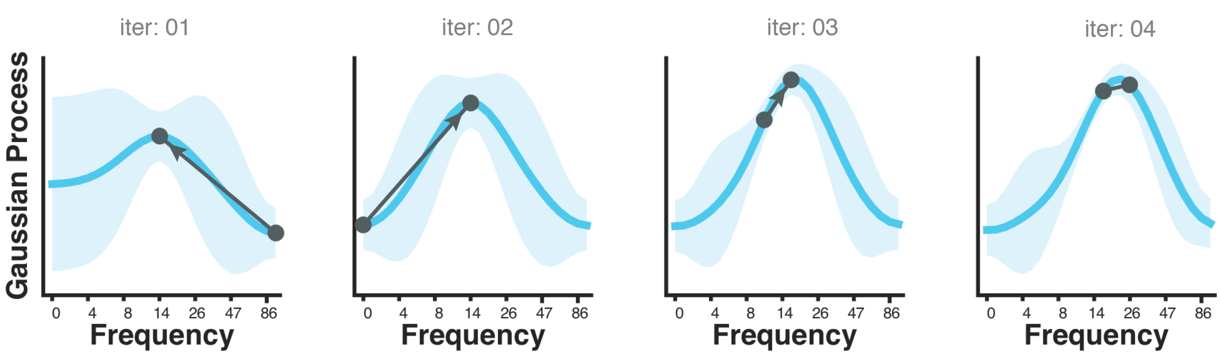

Lorenz et al. *under revision* (bioRxiv:**150086**)

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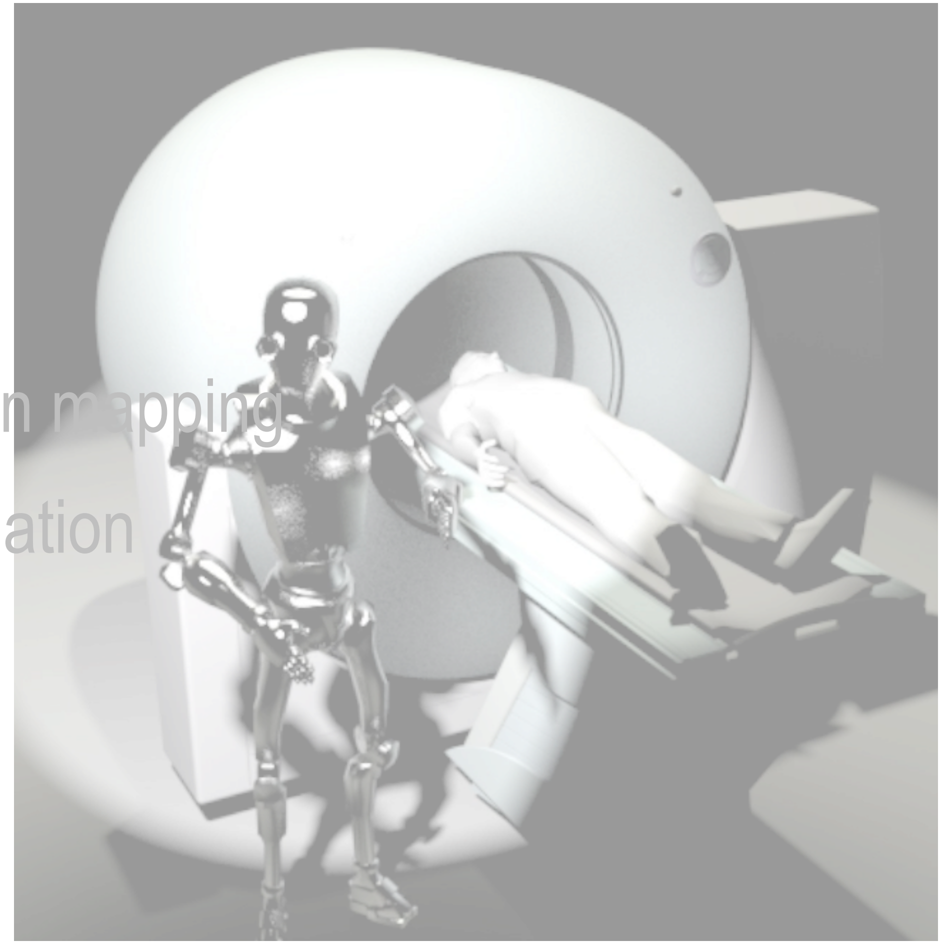
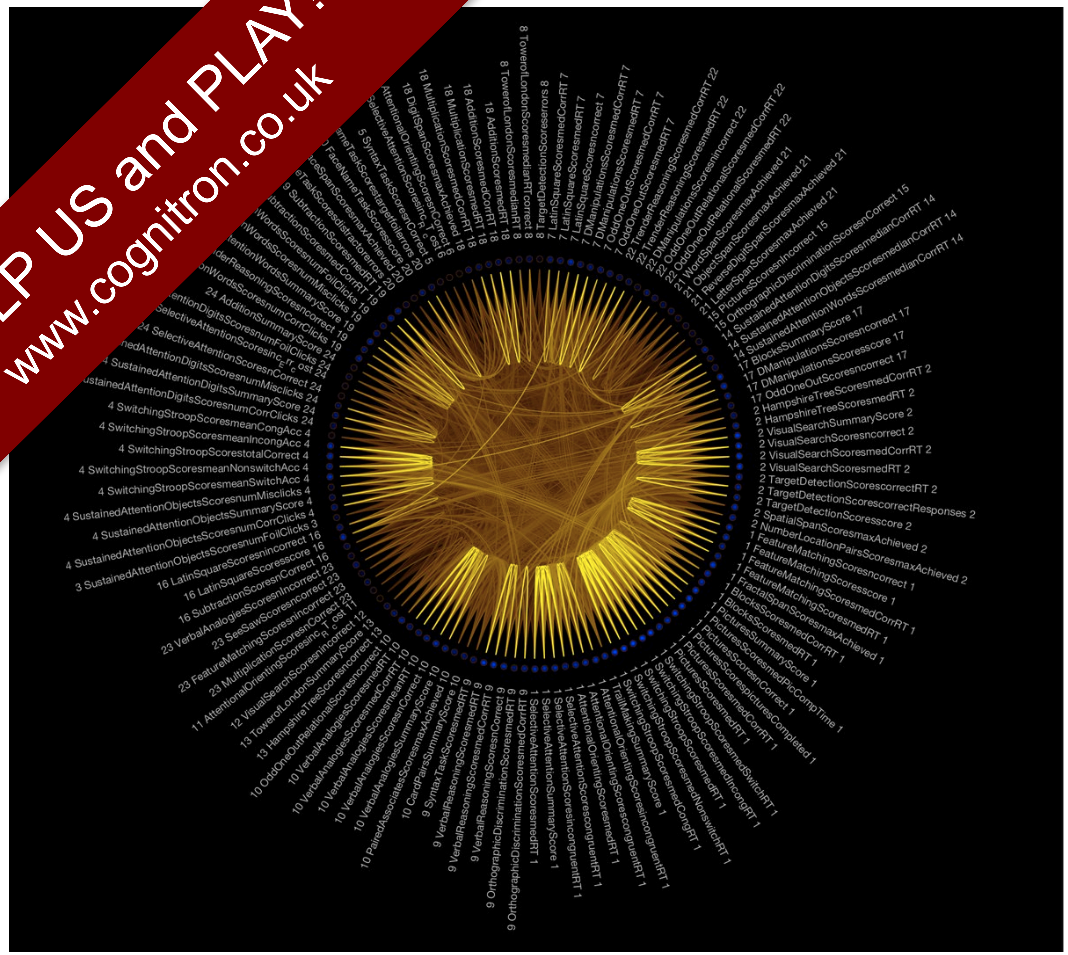


COGNITRON AI-web server to dissect human intelligence

HELP US and PLAY!
www.cognitron.co.uk



Adam Hampshire

N > 15,000

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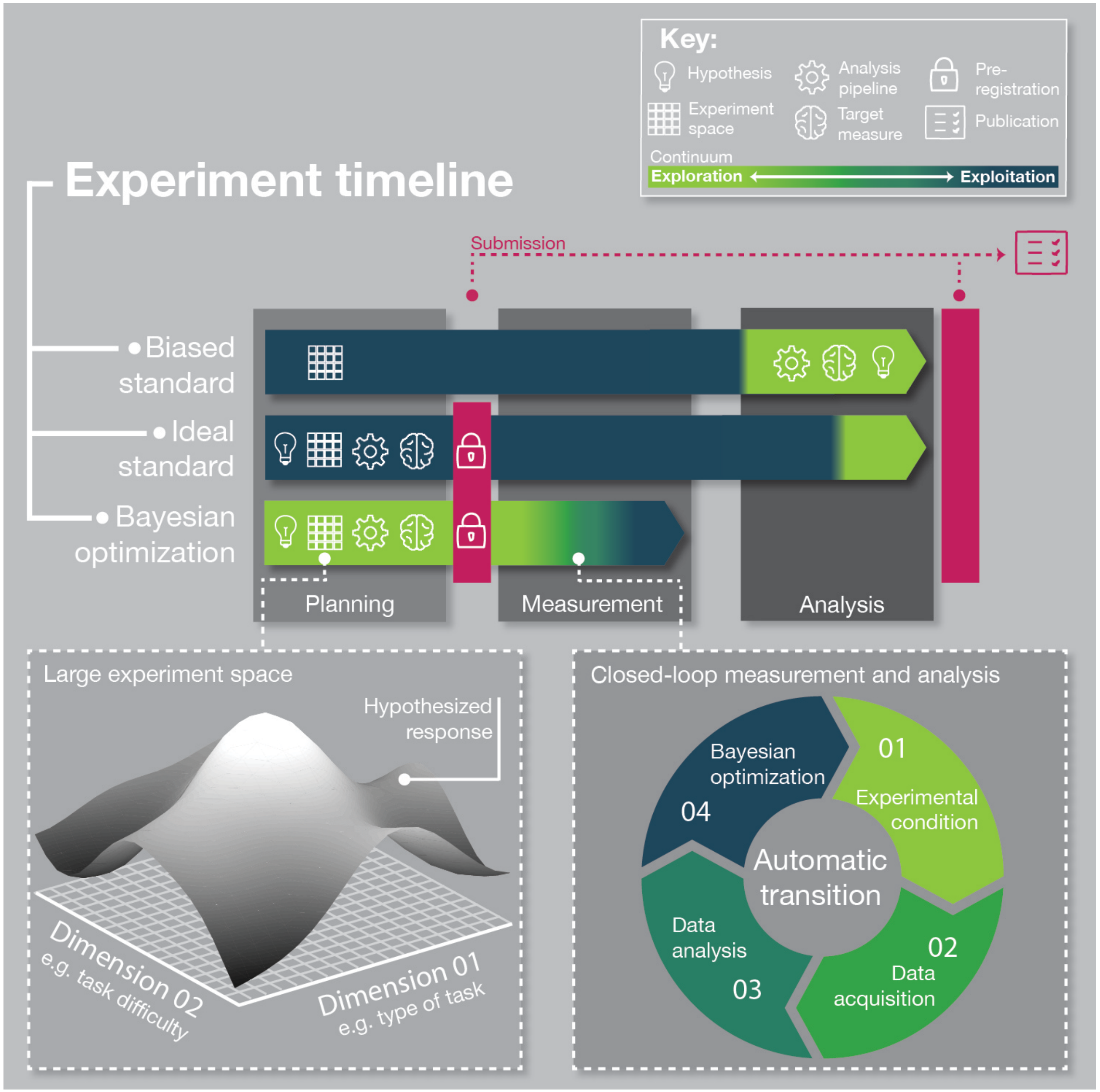
Implications for improving reproducibility



- More **flexible hypothesis** possible (exploration)
- Improved **specifity** & **generalizability** of research findings
- Can be combined with **pre-registration**

Lorenz et al. *TiCS* 2017

Future work – need for method development

- Addressing small effect sizes
  - Hierarchical optimization protocol
- Diagnosis: biomarker discovery
  - Novel acquisition functions
- Therapy: tuning to individual patient
  - Statistical inference on objective function/sampling trajectory
- General:
  - Sopping criteria
  - Non-stationarity in time (habituation)

Acknowledgement

Funding

EPSRC
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Imperial College London

Cognitive, Clinical and Computational Neuroimaging Laboratory C3NL

Robert Leech
Adam Hampshire
Ines R. Violante

UCL

Gatsby Computational Neuroscience Unit

Ricardo P. Monti

Rob

Adam

Ines

Ricardo

Resources

Questions/Feedback?

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- Code
  - GP regression: http://github.com/SheffieldML/GPy
  - Acquisition functions: http://github.com/romylorenz/AcquisitionFunction

- Publications

general

Lorenz R, Hampshire A, Leech R (2017). **Neuroadaptive Bayesian optimization and hypothesis testing**. *Trends in Cognitive Sciences*, 21(3): 155-167

Lorenz R, Monti RP, Violante IR, Anagnostopoulos C, Faisal AA, Montana G, Leech R (2016a). **The Automatic Neuroscientist: A framework for optimizing experimental design with closed-loop real-time fMRI**. *NeuroImage*, 129: 320-334

cognition

Lorenz R, Violante IR, Monti RP, Montana G, Hampshire A, Leech R. **Dissociating frontoparietal networks with neuroadaptive Bayesian optimization**. *Under revision* (preprint available on bioRxiv:**128678**)

brain stimulation

Lorenz R*, Monti RP*, Hampshire A, Koush Y, Anagnostopoulos C, Faisal A, Sharp D, Montana G, Leech R, Violante IR (2016b**. Towards tailoring non-invasive brain stimulation using real-time fMRI and Bayesian optimization**), In *6th International Workshop on Pattern Recognition in Neuroimaging* (free version available on arXiv:**1605.01270**)

Lorenz R, Simmons L, Monti RP, Arthur J, Limal S, Leech R, Violante IR. **Assessing tACS-induced phosphene perception using adaptive Bayesian optimization**. *Under revision* (preprint available on bioRxiv: **150086**)

Lorenz R, Monti RP, Koush Y, Sharp D, Montana G, Hampshire A, Leech R, Violante IR. **Towards tailoring non-invasive stimulation using neuroadaptive Bayesian optimization**. *In preparation.*