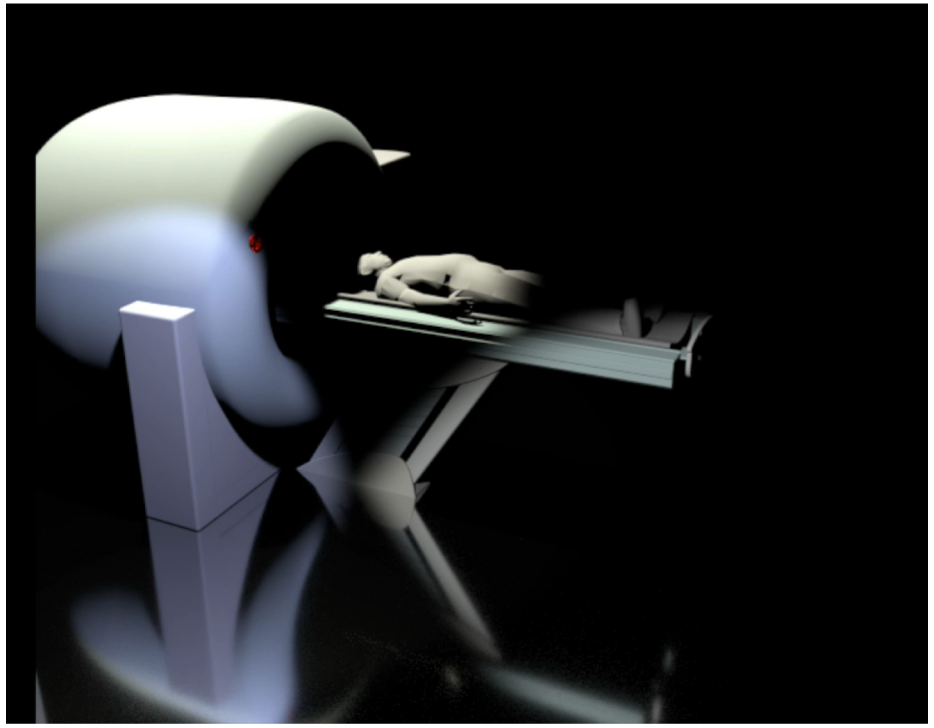
MAX PLANCK INSTITUT FÜR KOGNITIONS- UND NEUROWISSENSCHAFTEN LEIPZIG

UNIVERSITY OF CAMBRIDGE

wellcome

Neuroadaptive Bayesian Optimization

Implications for the Cognitive Sciences



Romy Lorenz

Sir Henry Wellcome Postdoctoral Fellow
University of Cambridge & Max Planck Institute for Human Cognitive and Brain Sciences

Overview

1. Motivation
2. The framework
   - 2.1 Bayesian optimization
   - 2.2 Validation study
3. Application studies
   - 3.1 Human brain mapping
   - 3.2 Non-invasive brain stimulation
   - 3.3 Biomarker discovery
4. Implications & Discussion

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Aims of cognitive neuroscience

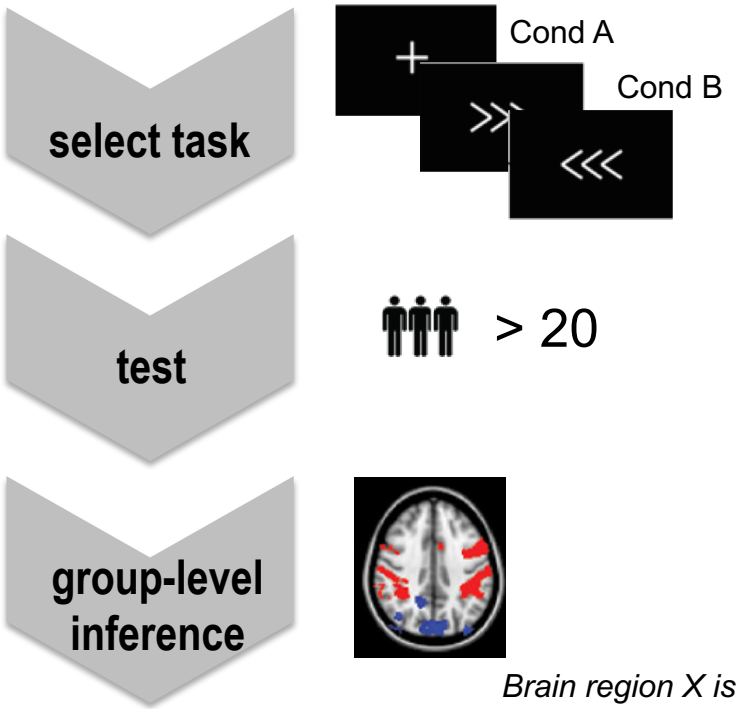
Research questions

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



broad ⟷ narrow

Aims of cognitive neuroscience

Lorenz et al. *TiCS* 2017

Human-brain mapping

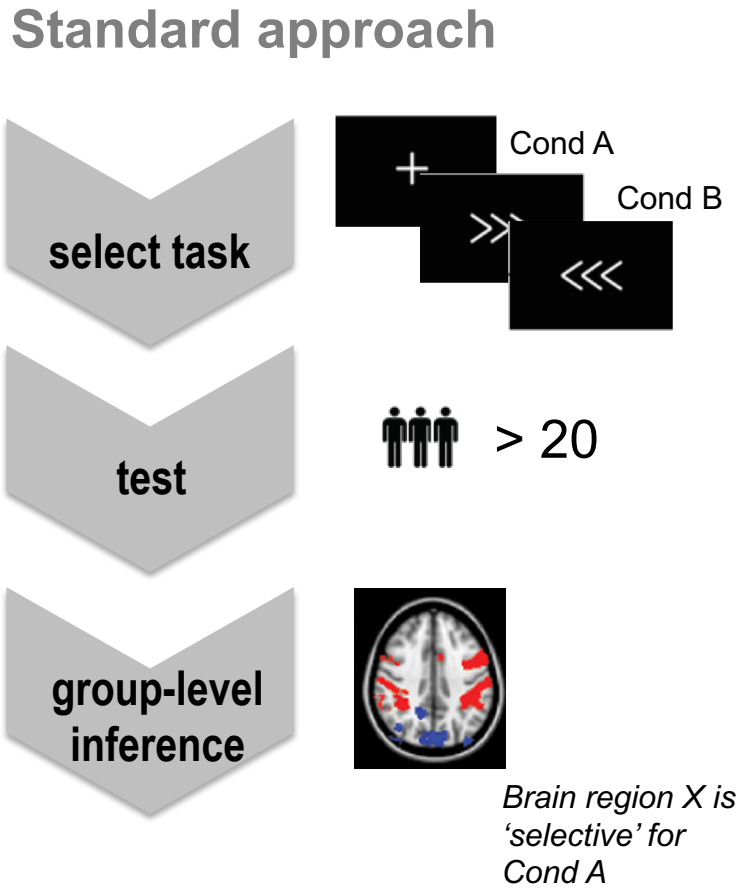
- Over-specified inferences about functional-anatomical mappings
  - right IFG Hampshire & Sharp *TiCS* 2015
  - dACC *Wager et al. PNAS 2016*

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



broad ⟷ narrow

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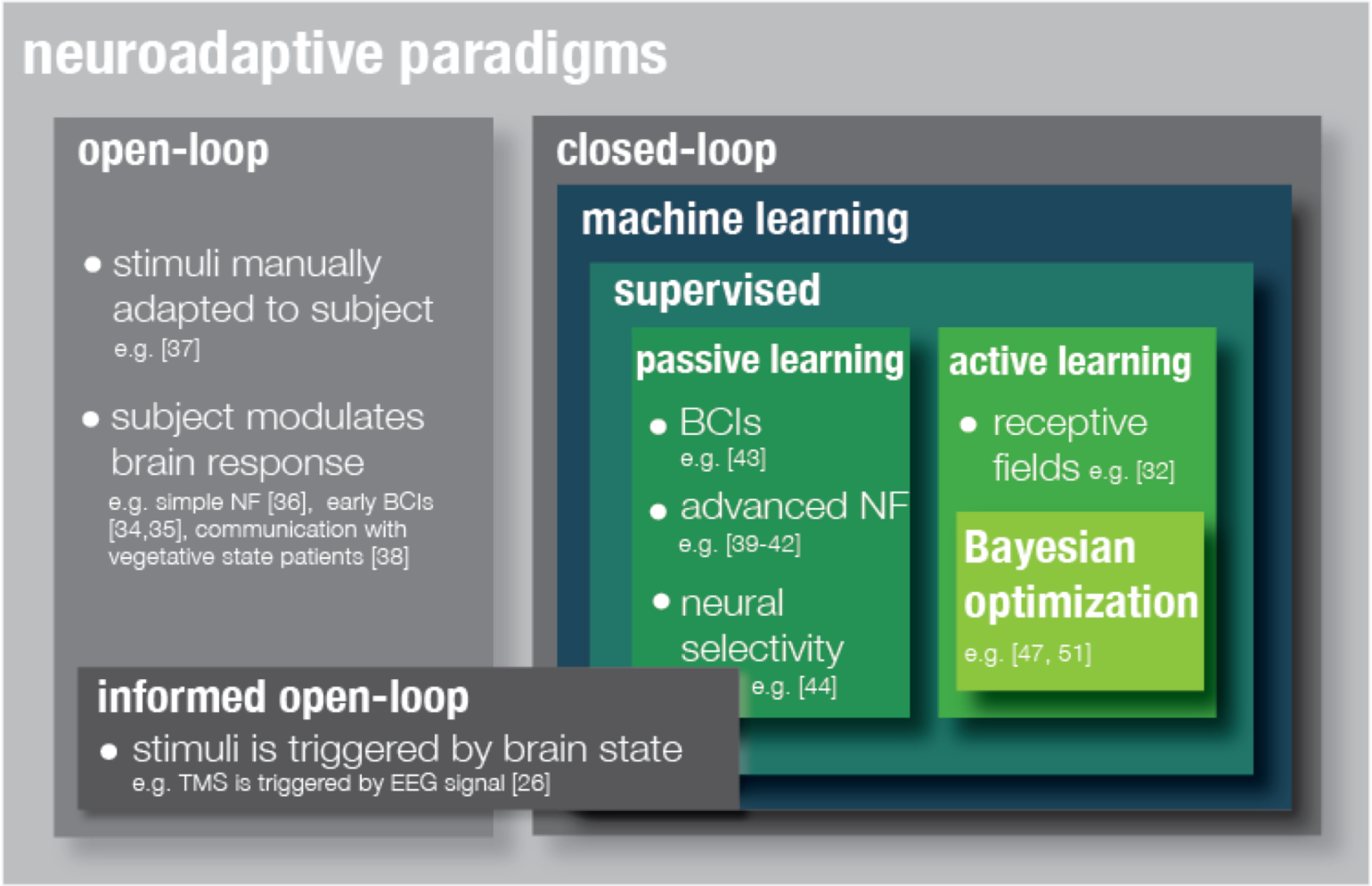
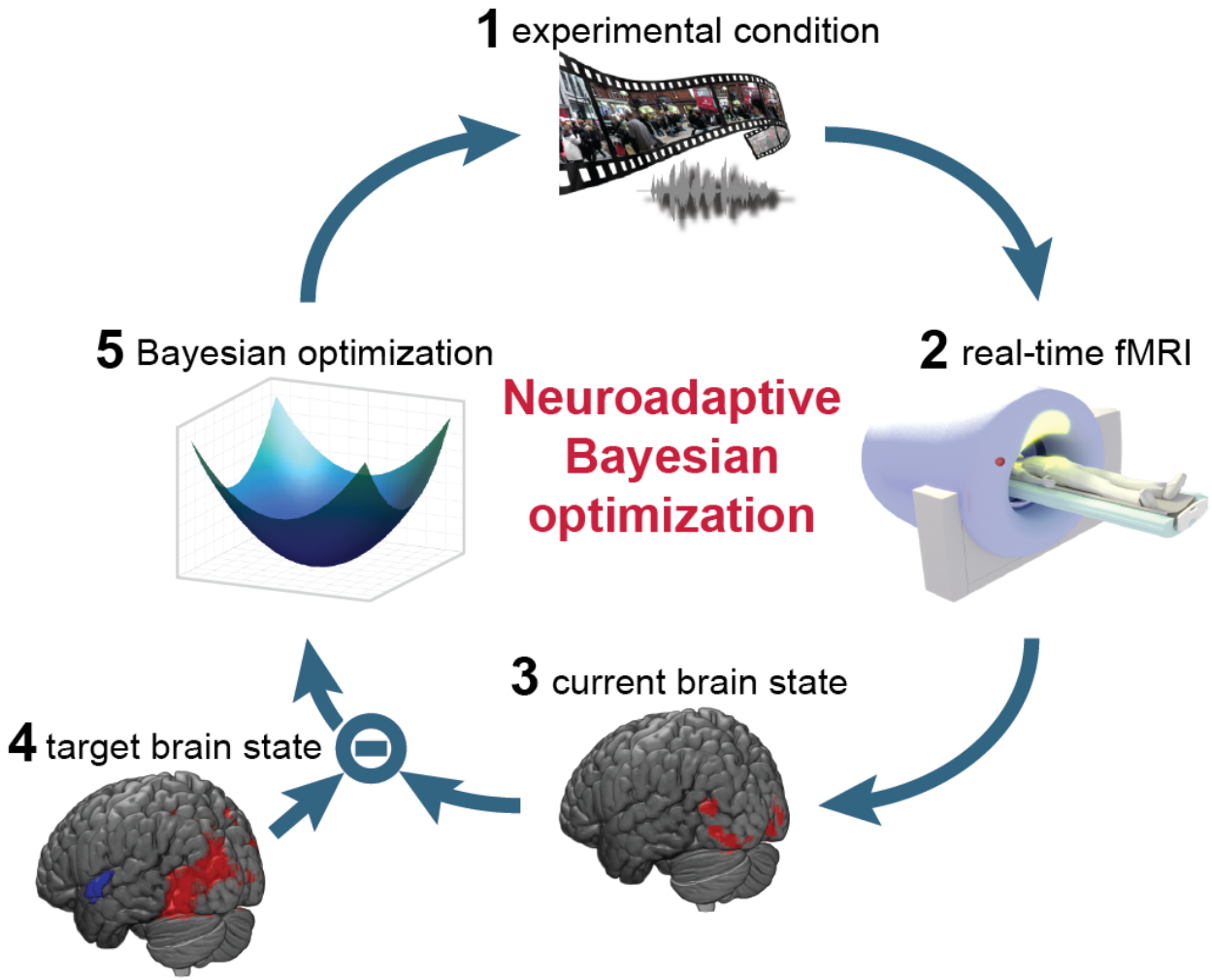
The framework



Lorenz et al. *TiCS* 2017

The framework



Lorenz et al. *NeuroImage* 2016

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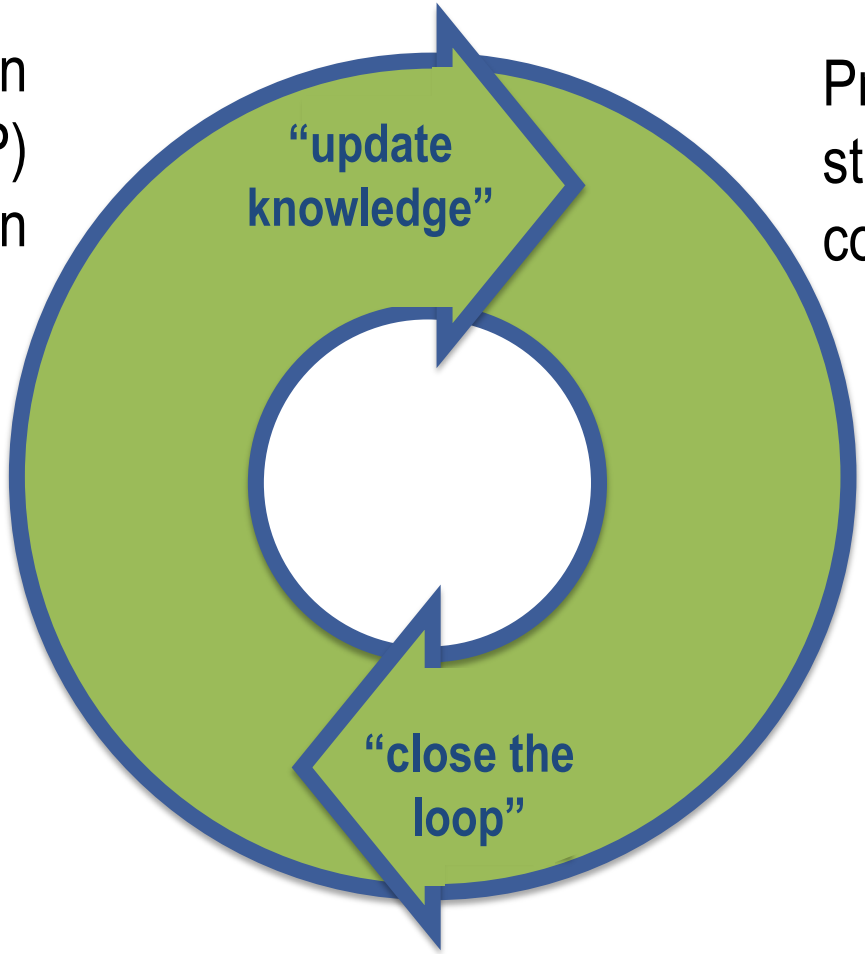
Bayesian optimization

Gaussian process (GP) regression

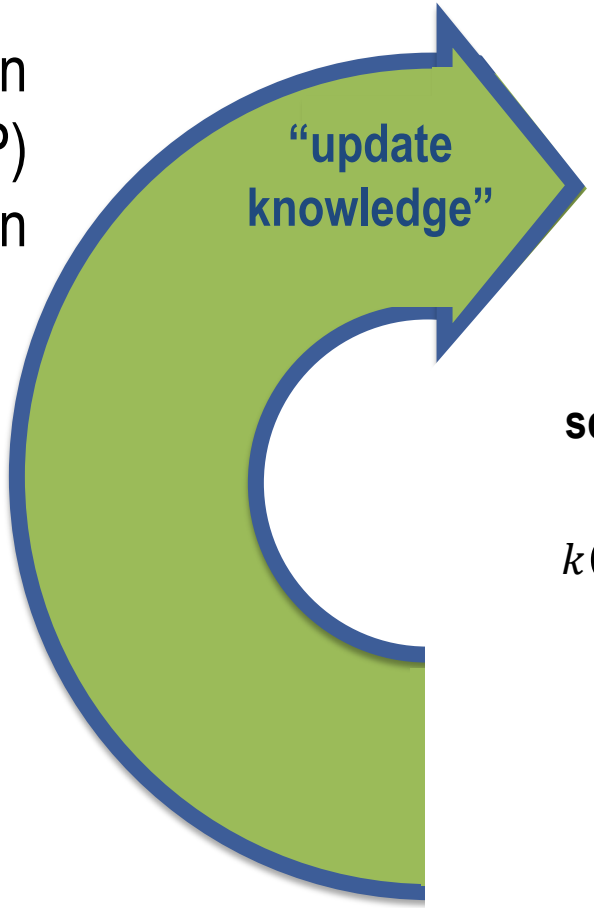


Propose new stimuli combination

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

Bayesian optimization

Gaussian process (GP) regression



choice of covariance function

squared exponential kernel:

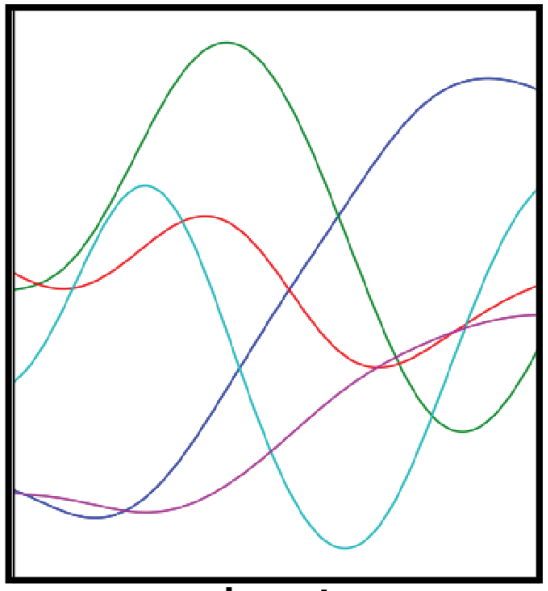
$$k(x,y) = \sigma^2 \exp\left\{-\frac{(x-y)^2}{2\,l^2}\right\}$$

$x, y \in \mathbb{R}^2$	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

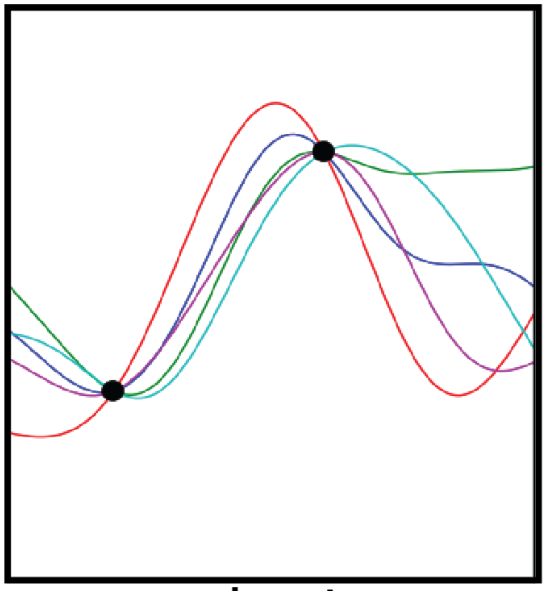
GP regression (1D – example)

prior



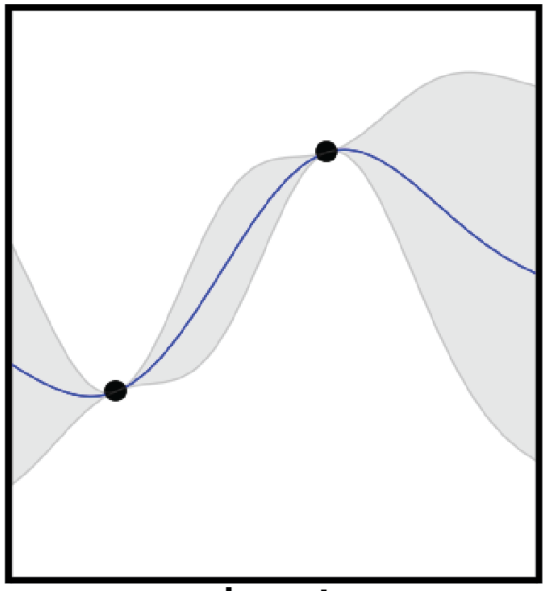
experiment space

posterior



experiment space

prediction



experiment space

Bayesian optimization

Expected improvement acquisition function:

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

$m(x)$: predicted mean

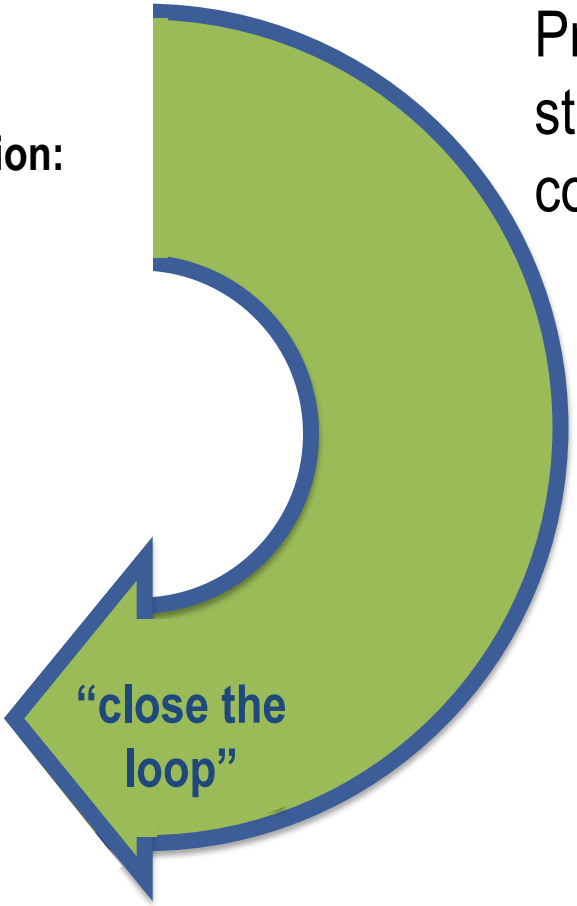
$var(x)$: predicted variance

f_{max}: maximum predicted value

$q()$: cumulative distribution function

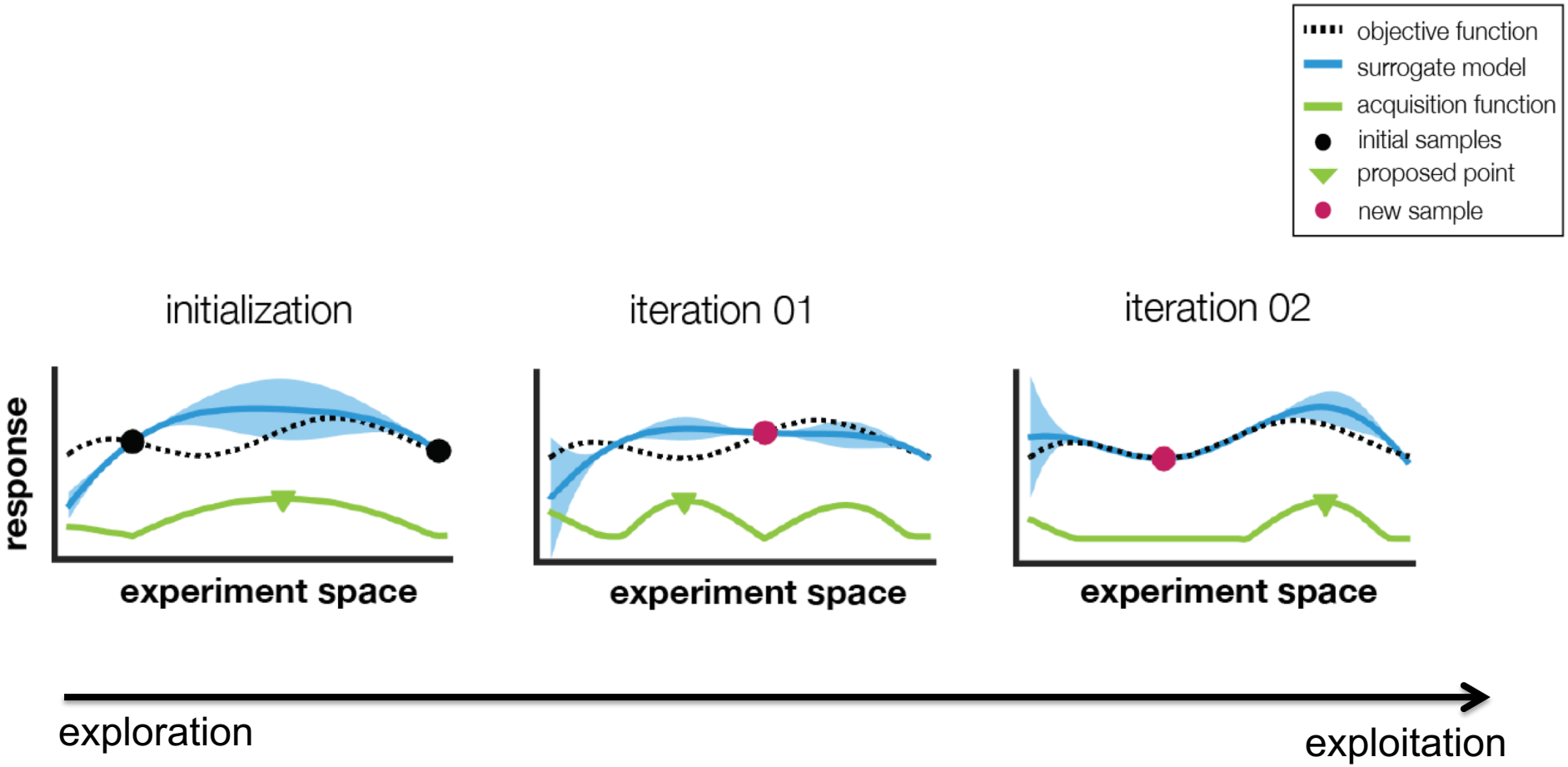
$p()$: probability density function

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



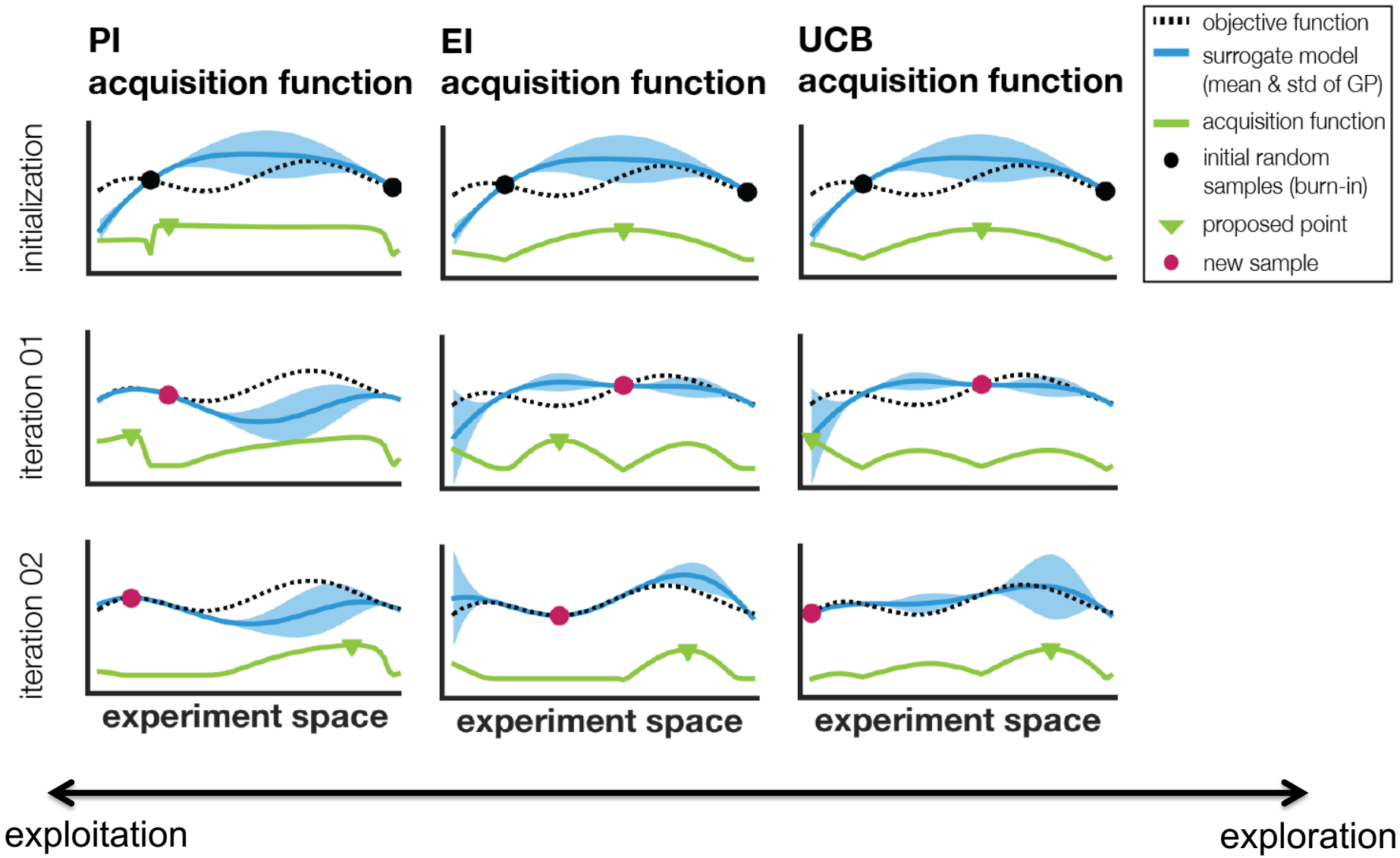
Rasmussen & Williams 2006
Brochu et al. *arXiv* 2010

Bayesian optimization (1D – example)



Lorenz et al. *TiCS* 2017

Trade off between exploration and exploitation



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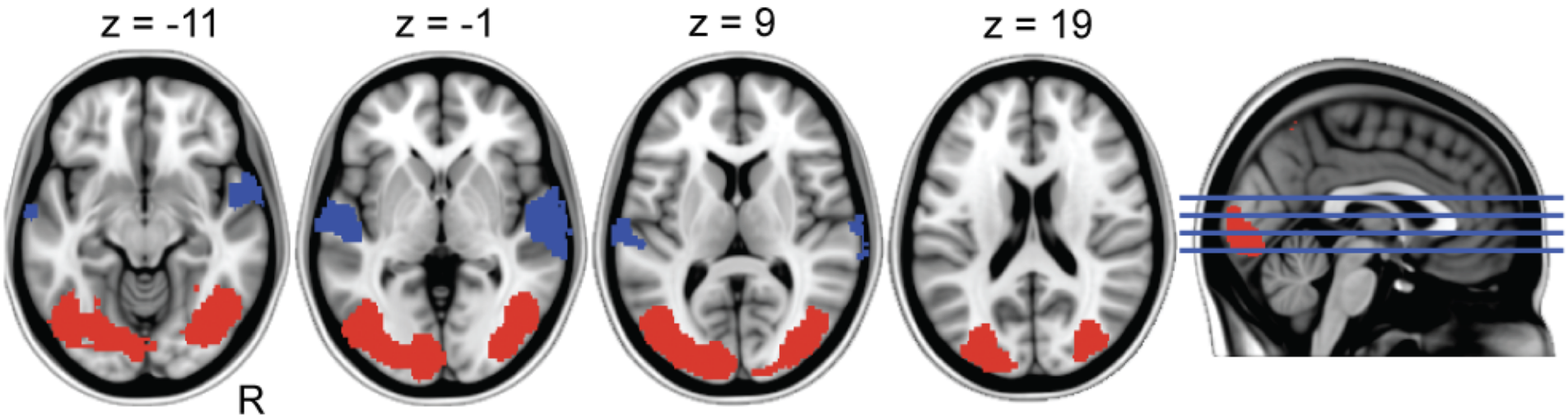
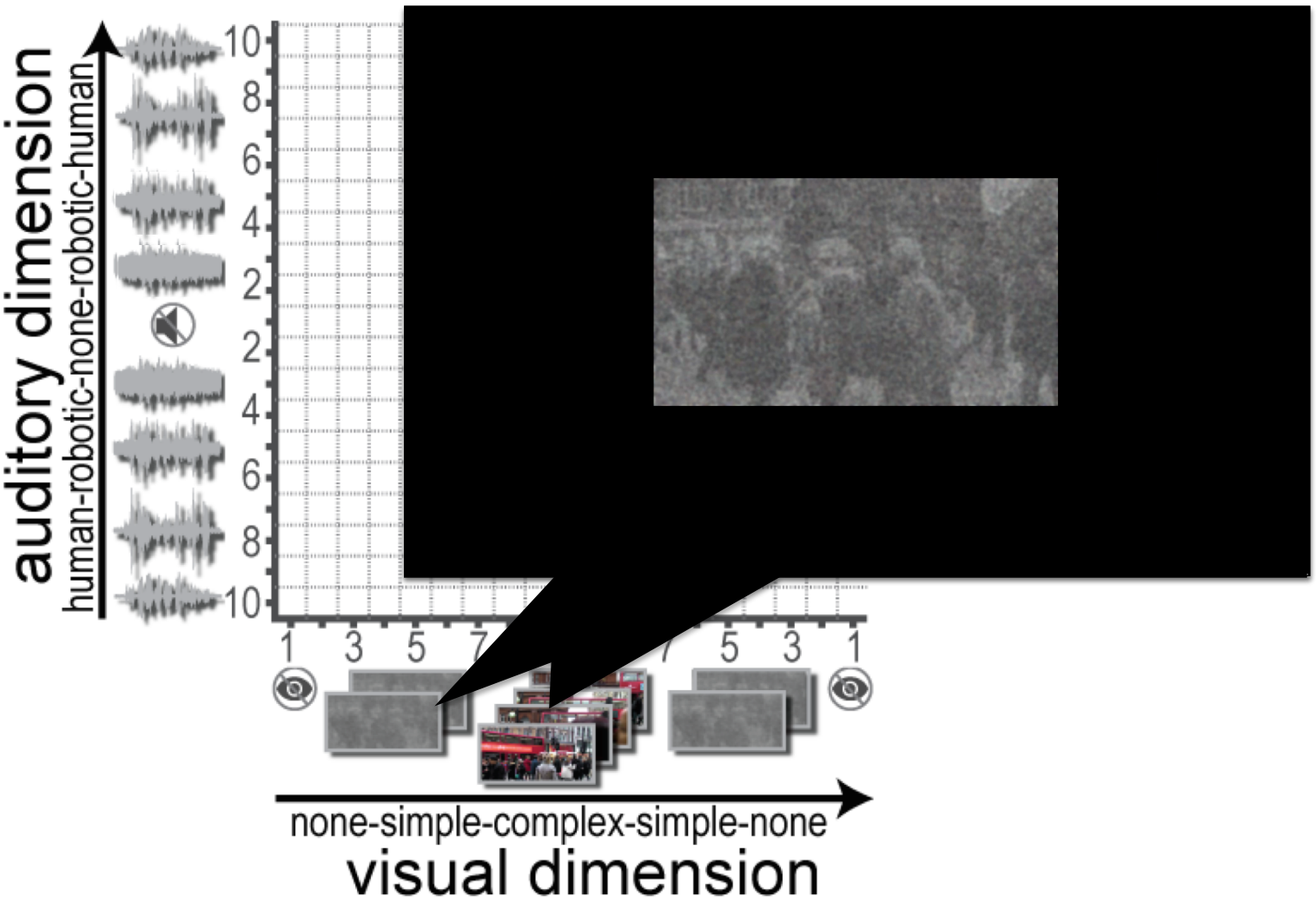
Target brain state



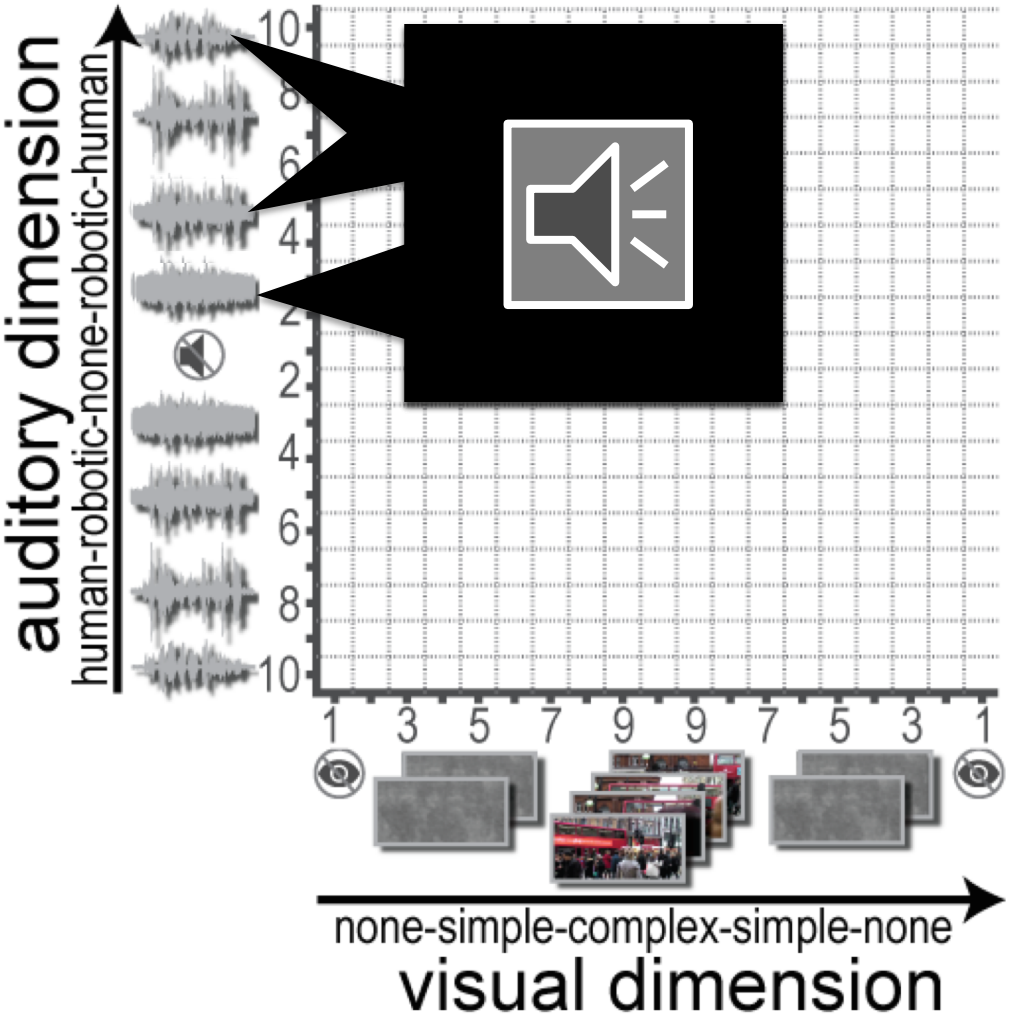
lateral occipital cortex activity ↑ superior temporal cortex activity ↓

masks derived from Braga et al. *NeuroImage* 2013

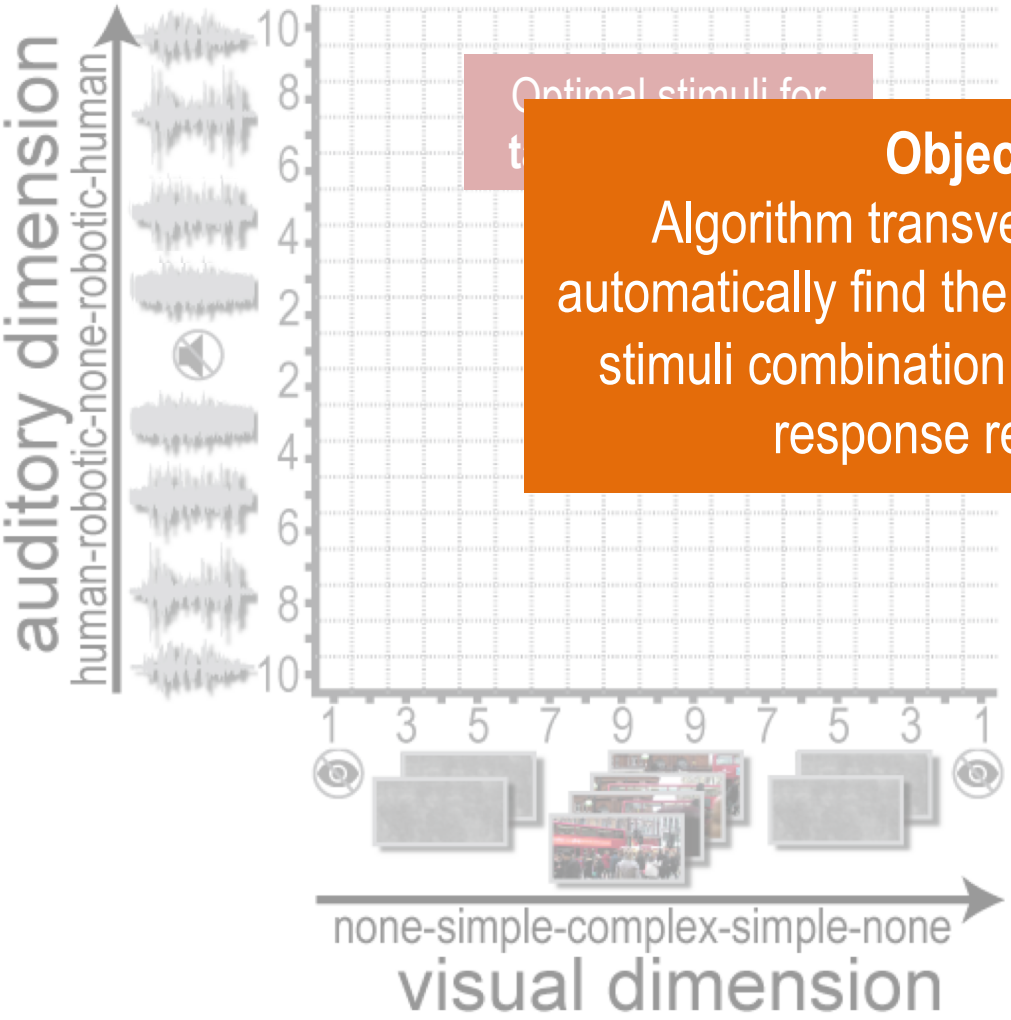
Experiment space



Experiment space

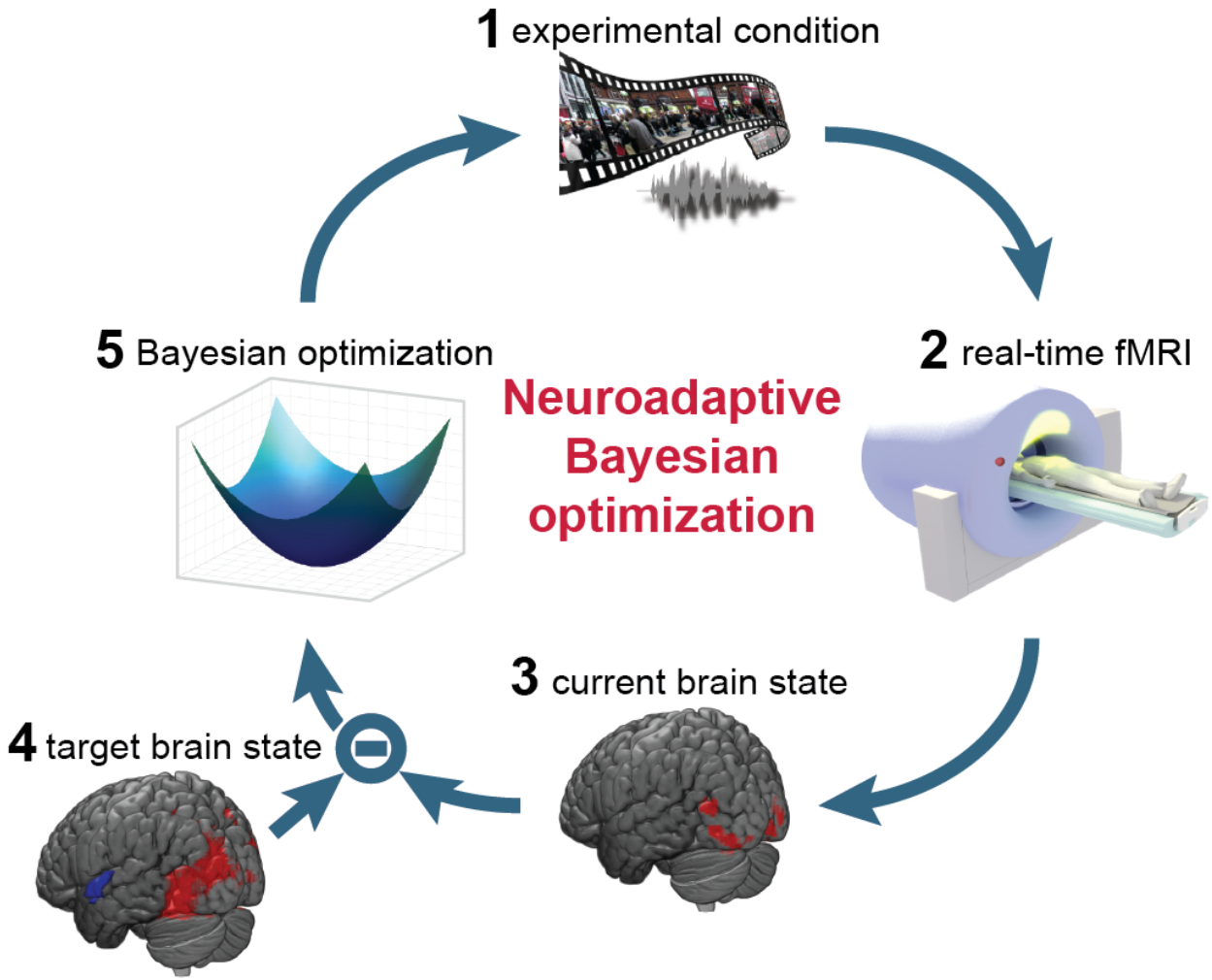


Experiment space



Objective:
Algorithm transverses the space, automatically find the optimal audio-visual stimuli combination & map out stimuli-response relationship

Method



Lorenz et al. *NeuroImage* 2016

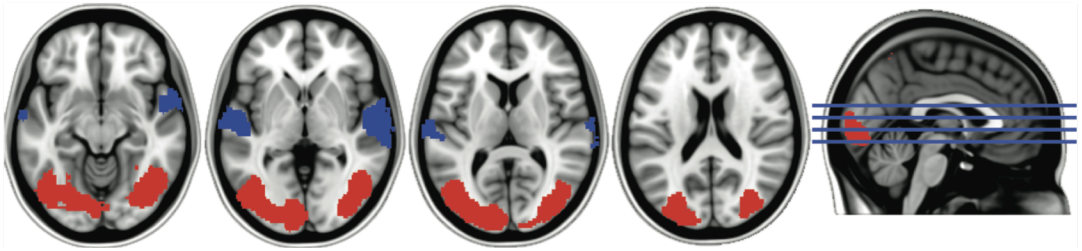
Real-time fMRI pipeline

raw 3D EPI image

Siemens Verio 3T
TR = 2 sec

pre-processing
- motion correction
- smoothing (5 mm)

target brain regions



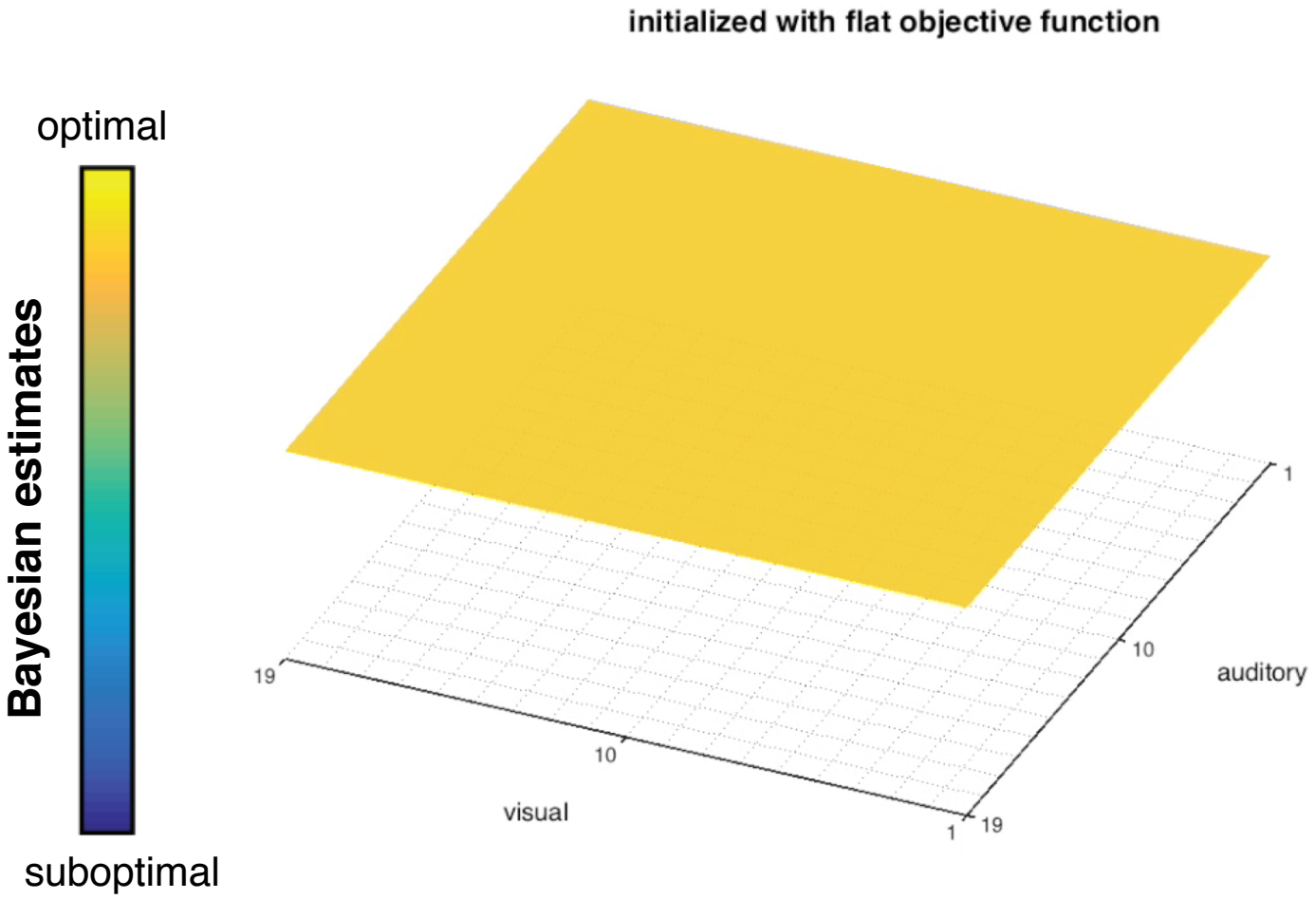
timecourse extraction of target brain masks

post-processsing
- de-trending (exponential moving average)*
- de-spiking (modified Kalman filter)*

General linear model contrast

* both algorithms obtained from Koush et al. *NeuroImage* 2012

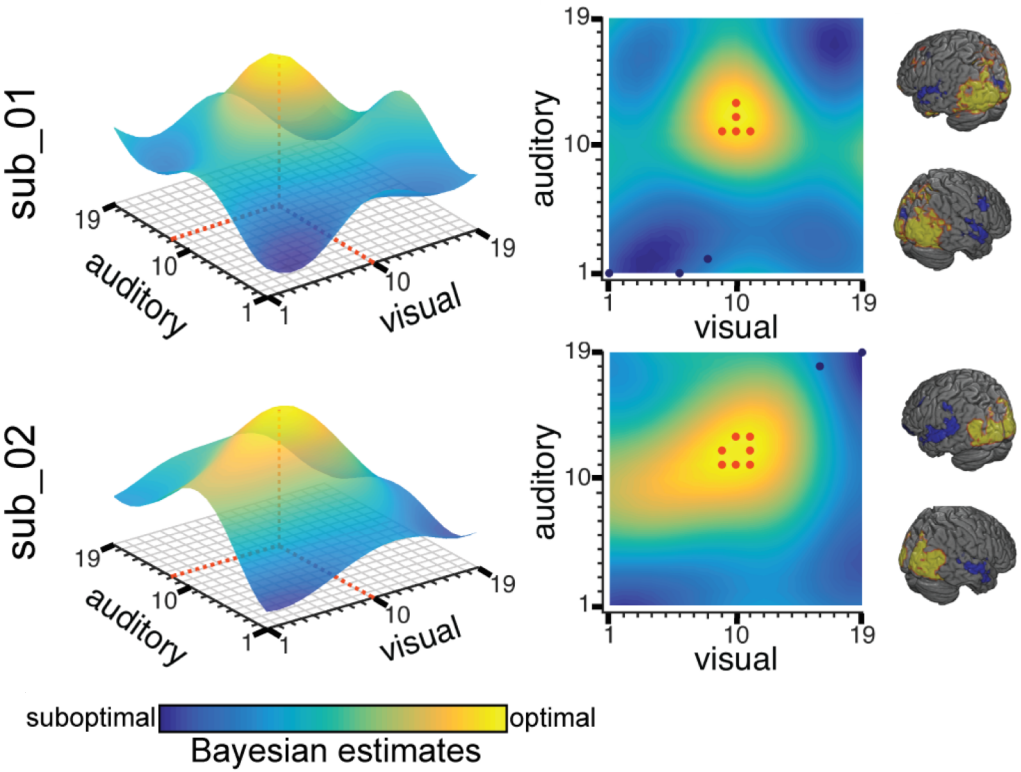
Example of one subject

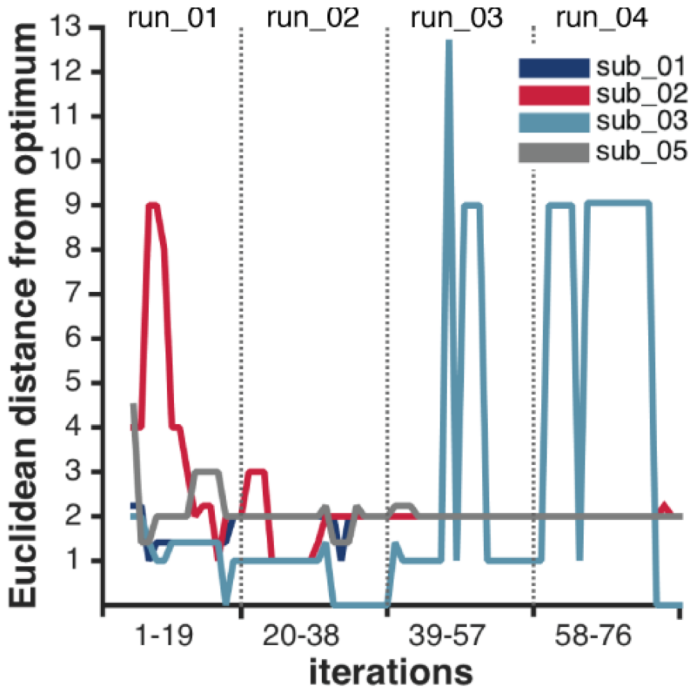


Lorenz et al. *NeuroImage* 2016

Results

= 5





Lorenz et al. *NeuroImage* 2016

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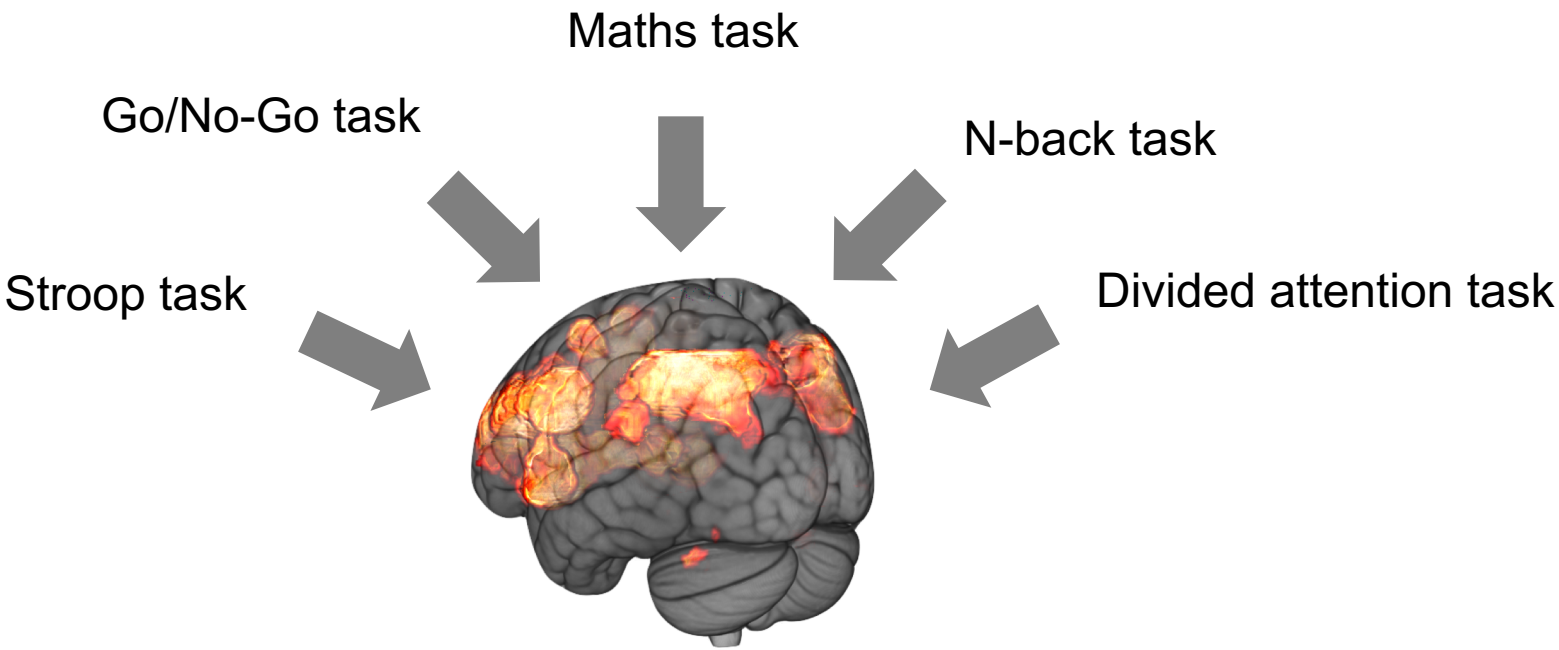
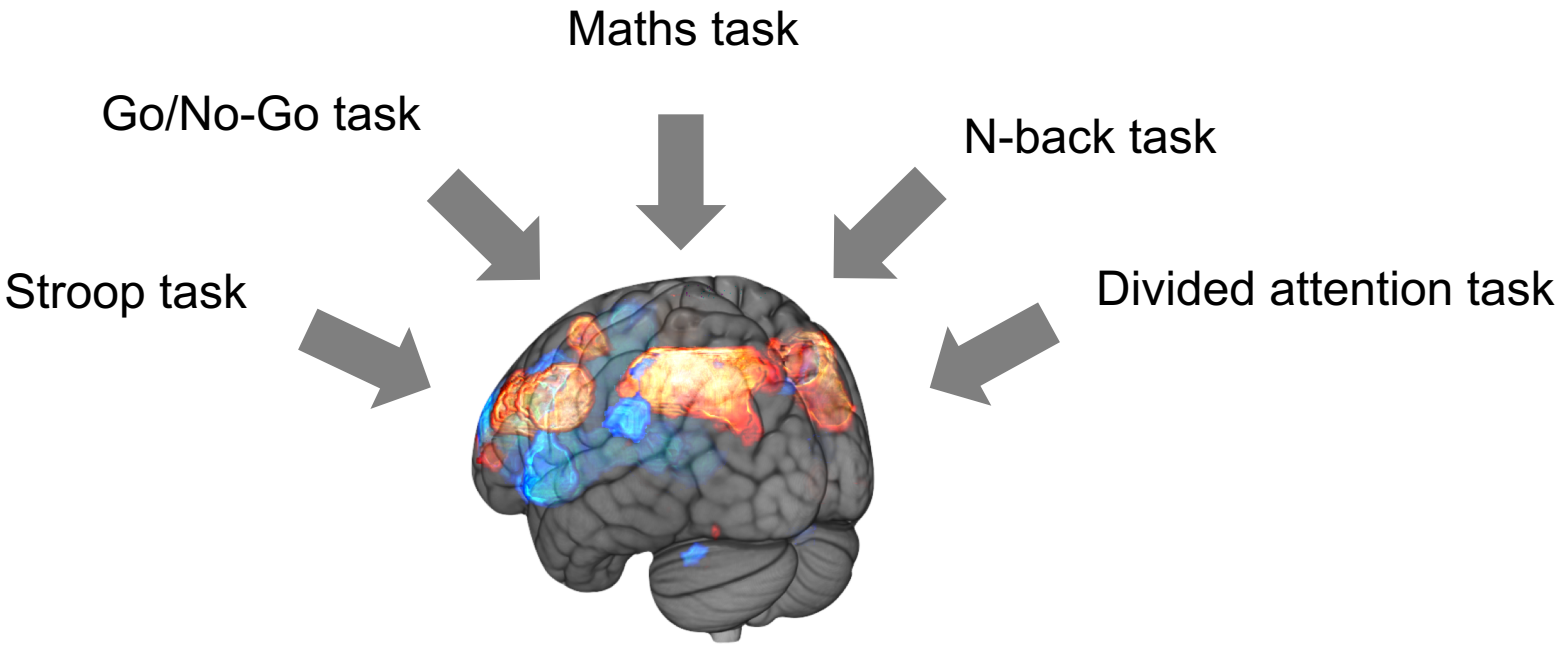
Many-to-many mapping problem



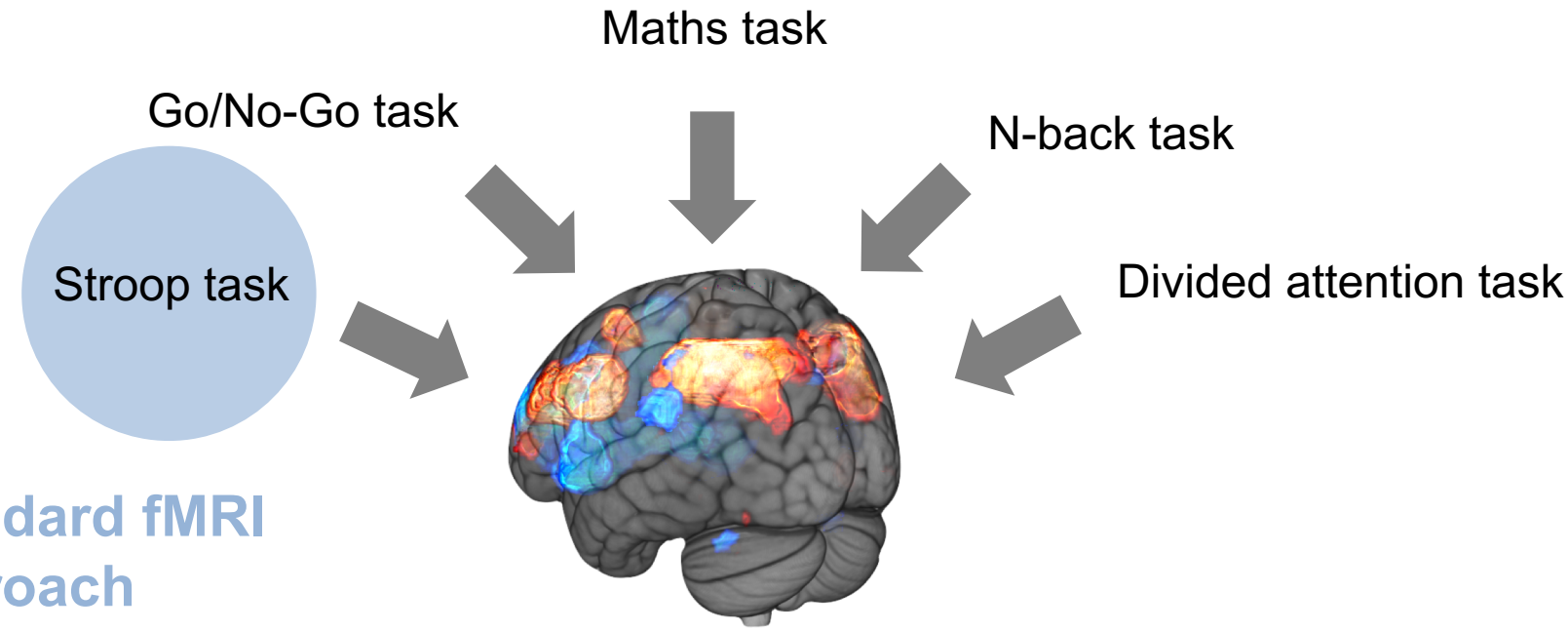
Duncan & Owen *TiNS* 2000
Fedorenko et al. *PNAS* 2013

Many-to-many mapping problem



Hampshire et al. *Neuron* 2012

Motivation

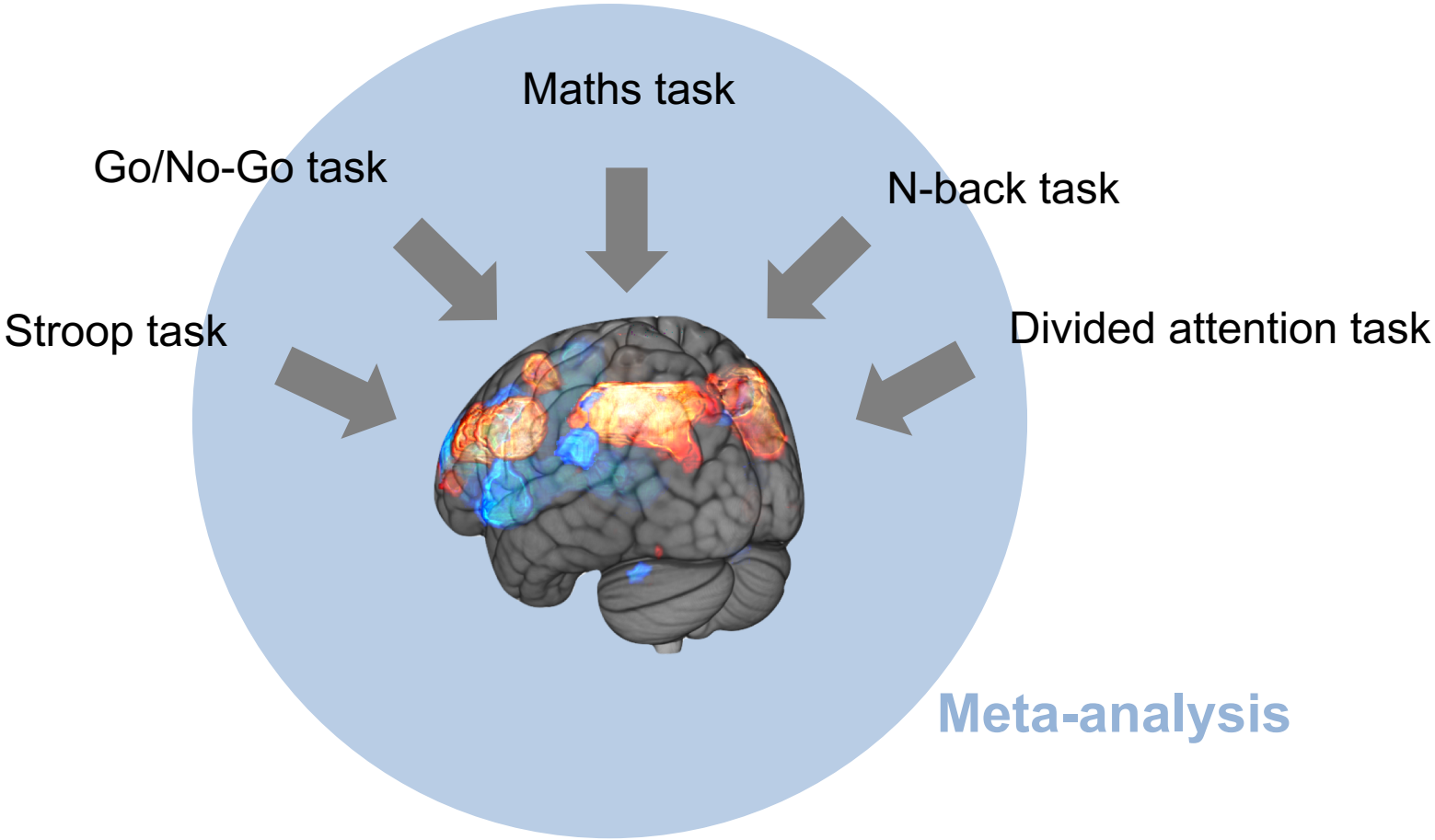


Standard fMRI approach

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

Lorenz et al. *TiCS* 2017
Westfall et al. *Wellcome Open Research* 2017

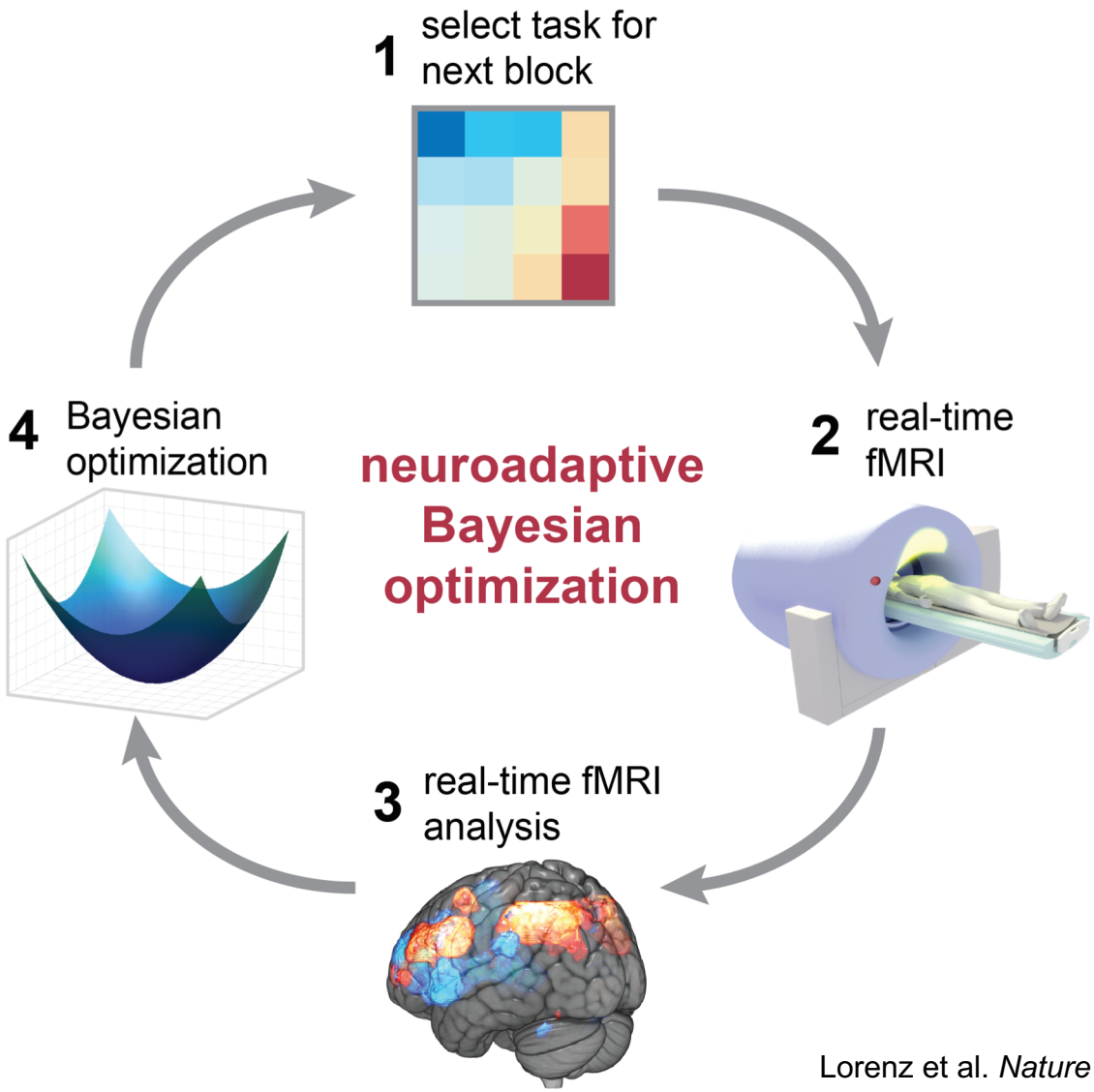
Motivation



- **Broad approximation**
- **Prone to biases**

Yarkoni et al. *Nature Methods* 2011
Poldrack & Yarkoni *Annual Review of Psychology* 2016

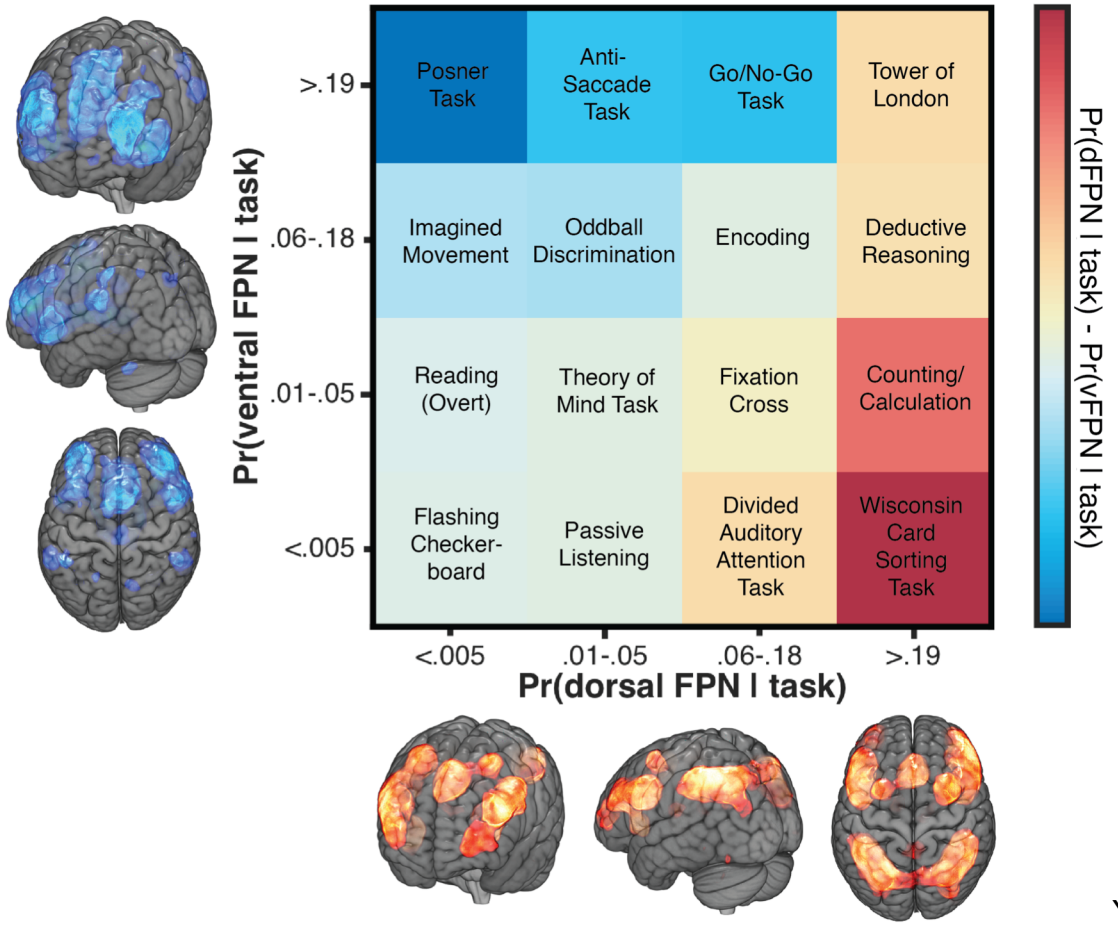
Searching across cognitive tasks



Lorenz et al. *Nature Communications* 2018

Task space based on meta-analysis

Study 1 | Study 2 | Study 3

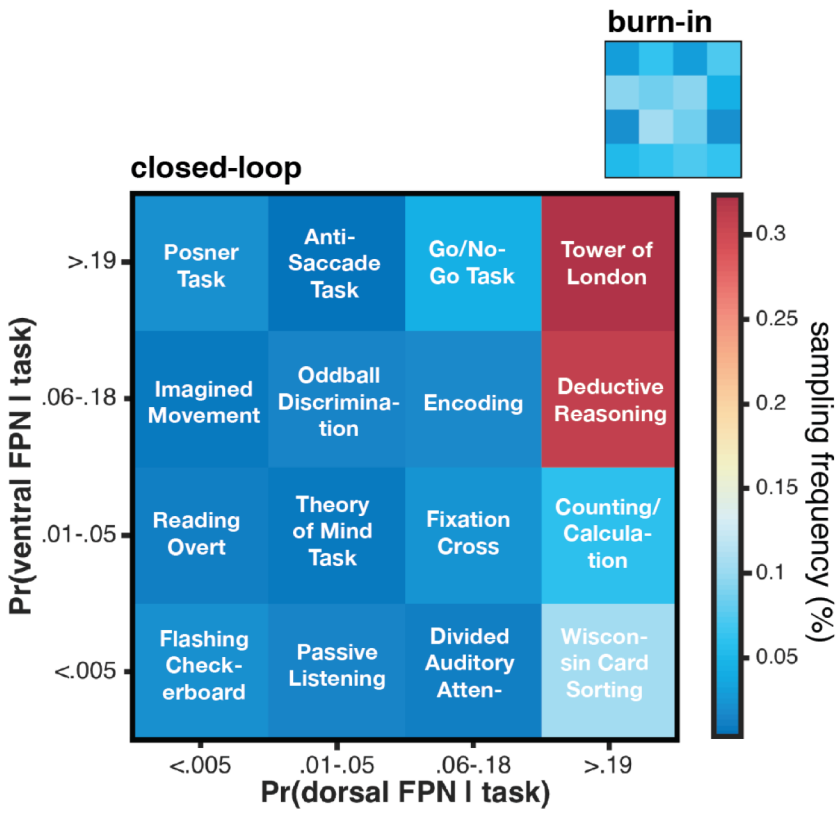


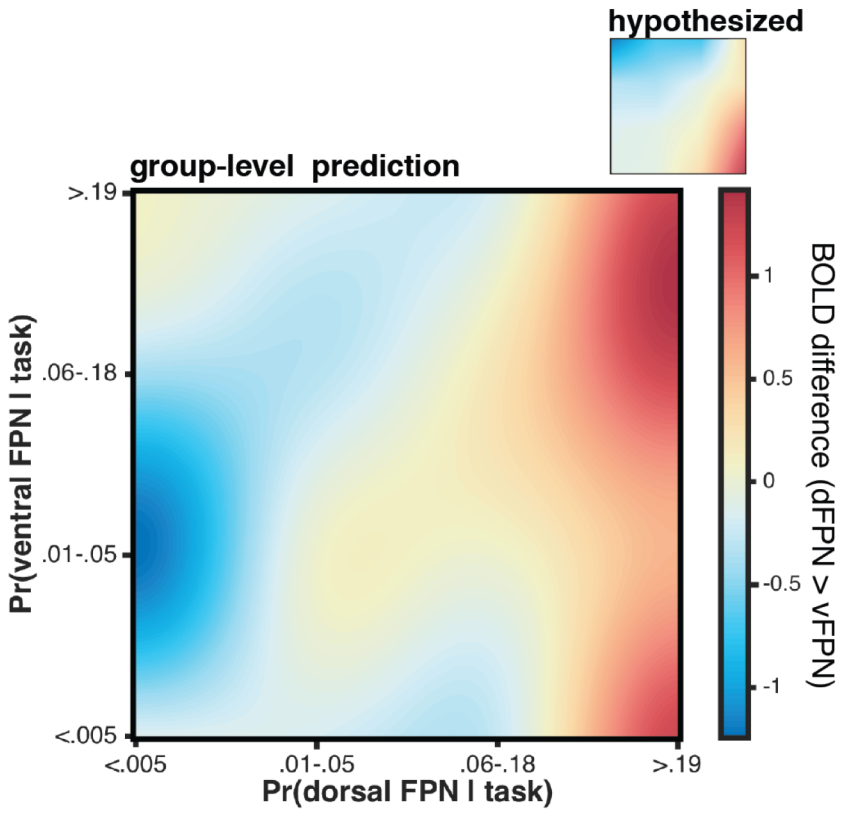
maps & space from
Yeo et al. *Cerebral Cortex* 2015

Find optimal tasks

Study 1 → Study 2 → Study 3

= 10

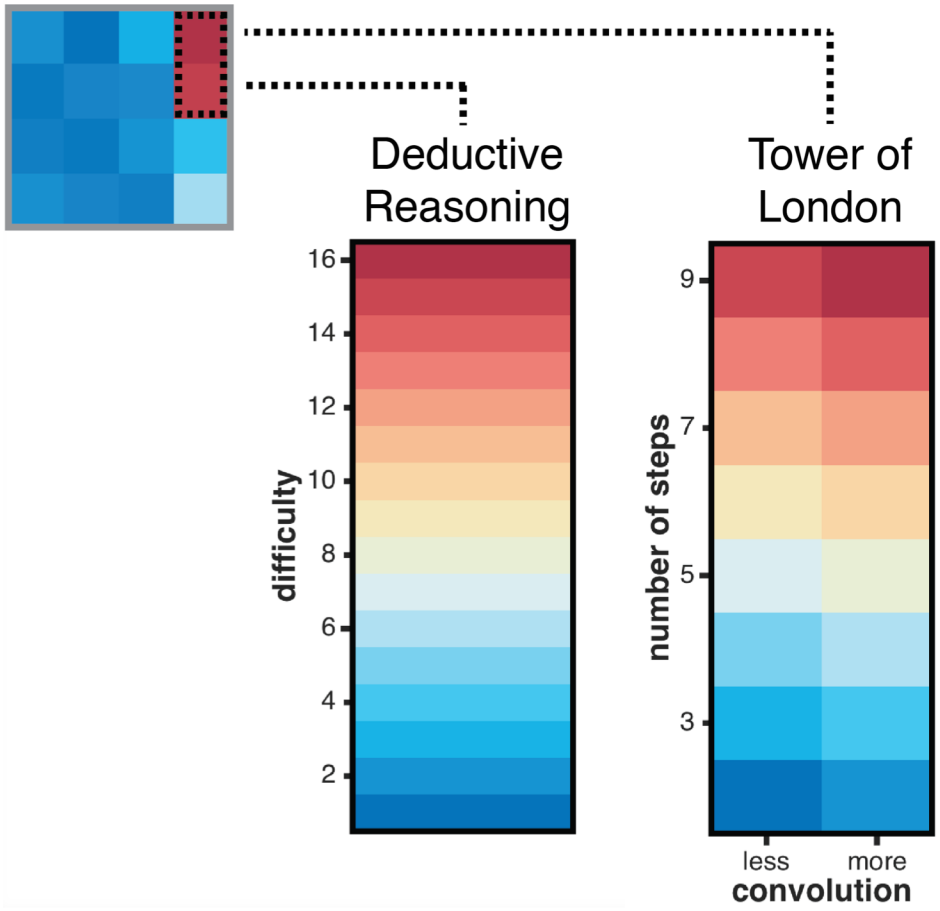




Tower of London & Deductive Reasoning tasks maximally dissociate FPNs

Zoom in task space and fine-tune tasks

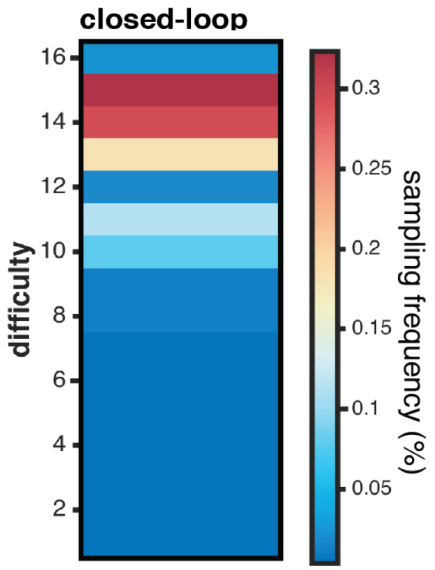
Study 1 | **Study 2** | Study 3

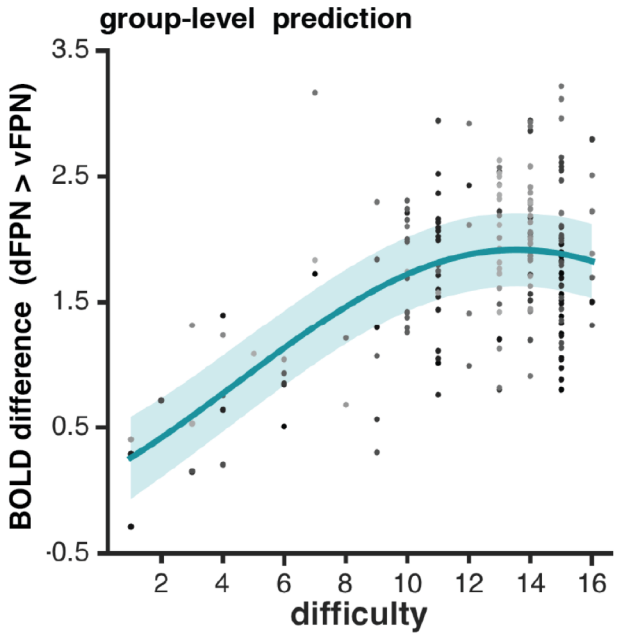


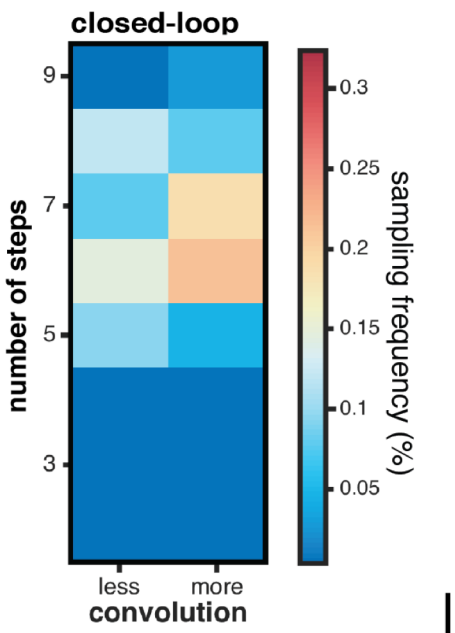
Find optimal task parameters

Study 1 | Study 2 | Study 3

= 10







Deductive Reasoning

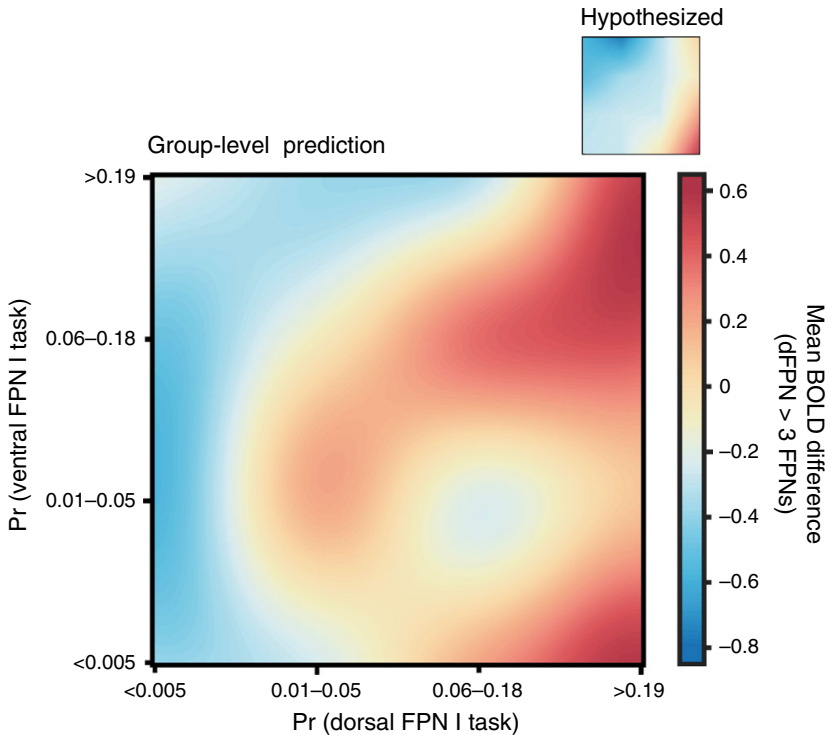
Tower of London

Find *unique* functional activation profile

Study 1 → Study 2 → **Study 3**

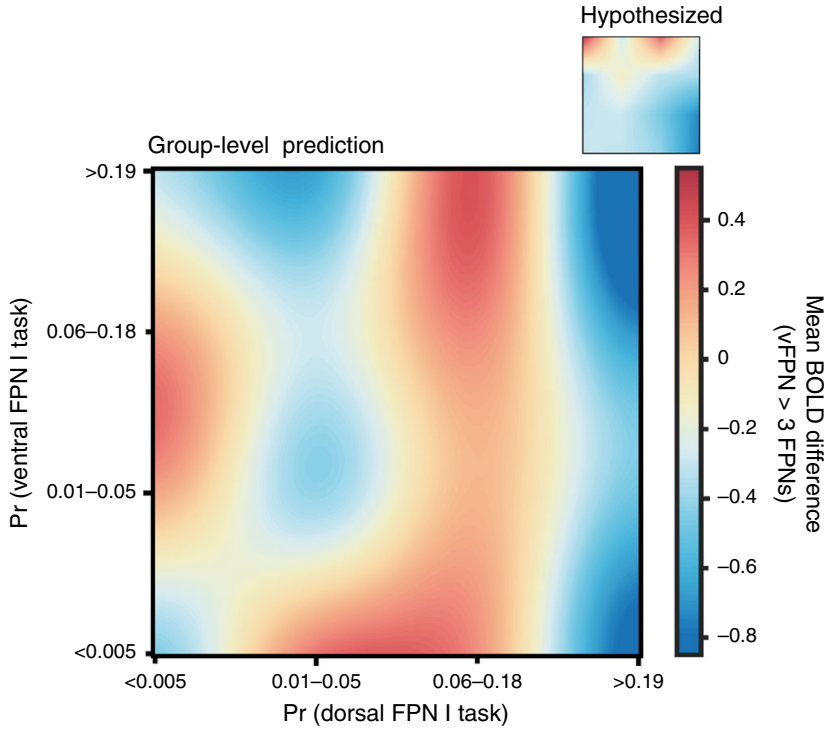
= 10

dorsal FPN > 3 other FPNs



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

ventral FPN > 3 other FPNs



Go/No-Go, Divided Auditory Attention, Imagined Movement, Passive Listening & Overt Reading

Summary

- High intra- and inter-subject reliability (subject-level results)
- Results deviate from previous meta-analyses and hypothesized functional labels for these FPNs
- FPNs should be functionally defined according to unique functional activity profile across multivariate task space
- Starting point for neurobiologically-derived cognitive taxonomy

Lorenz et al. *Nature Communications* 2018

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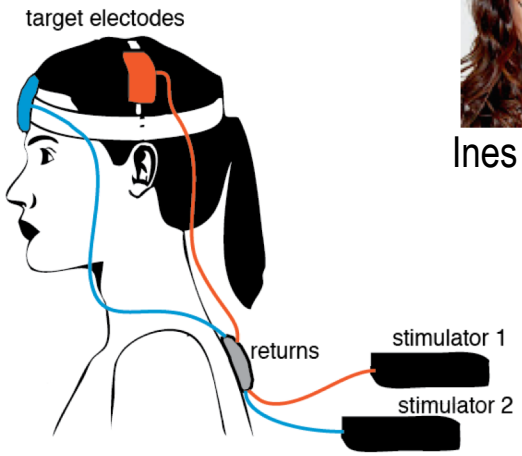
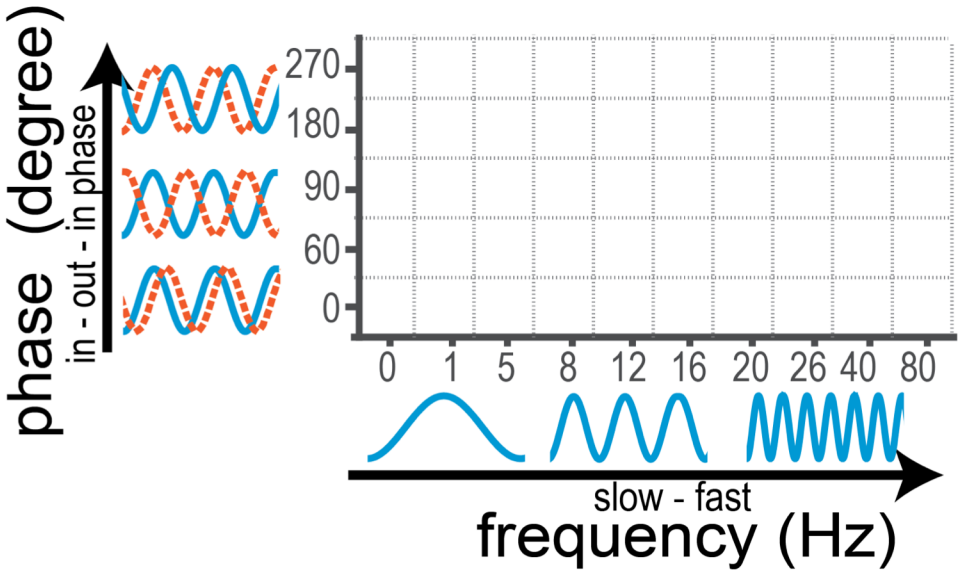
Transcranial alternating current stimulation (tACS)

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



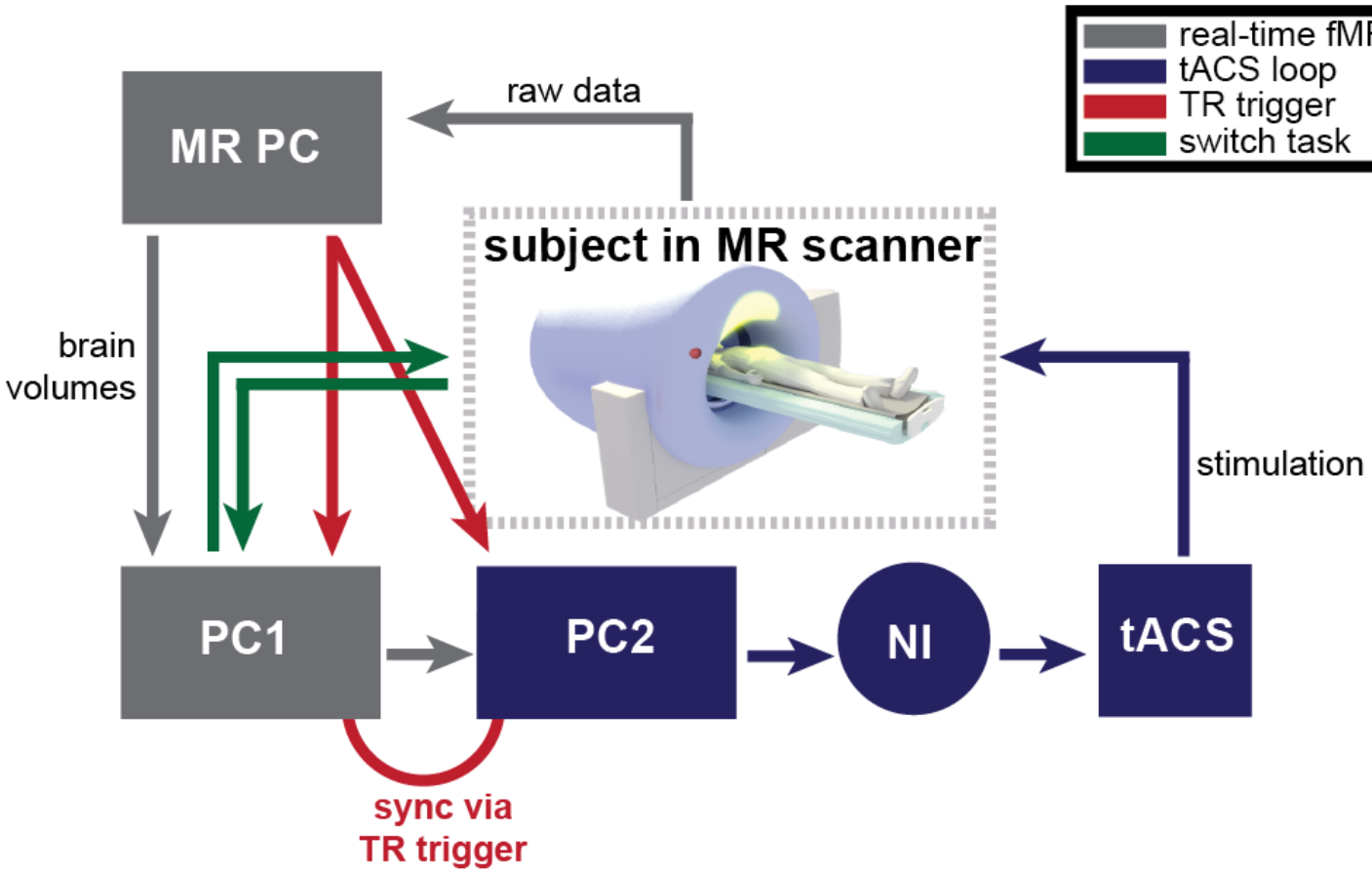
Ines Violante



- **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

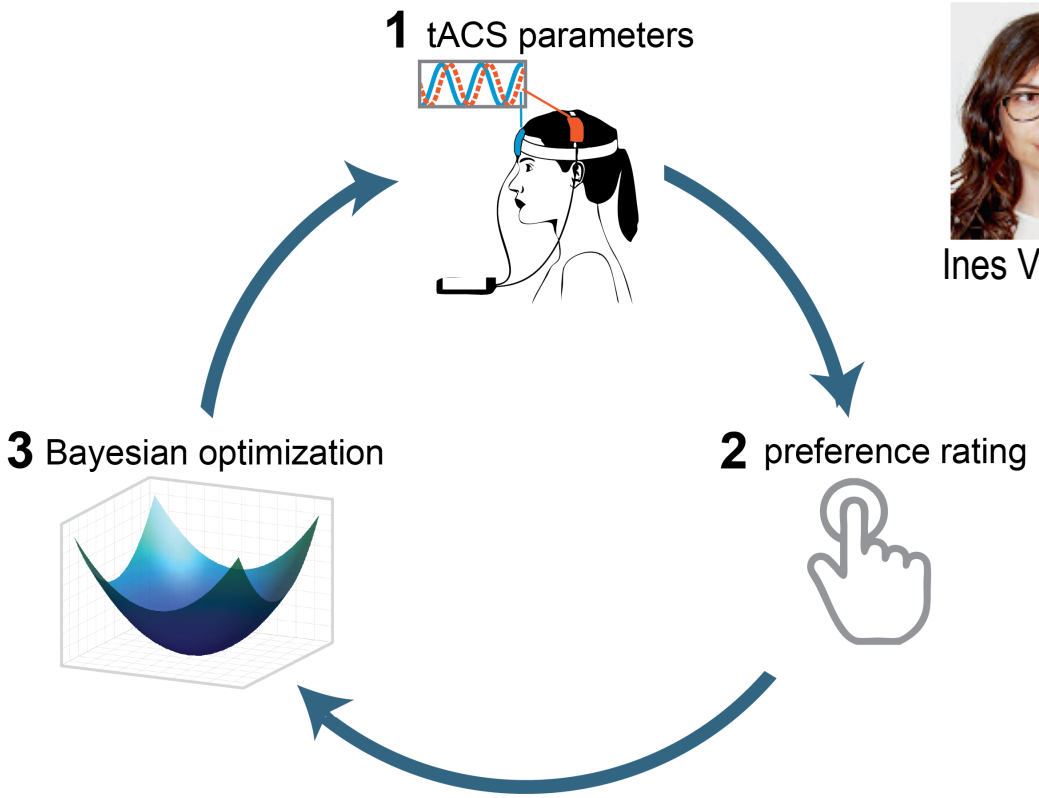


Lorenz et al. *PRNI* 2016
Lorenz et al. *in preparation*

Phosphene perception

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

Schutter et al. *NeuroImage* 2016



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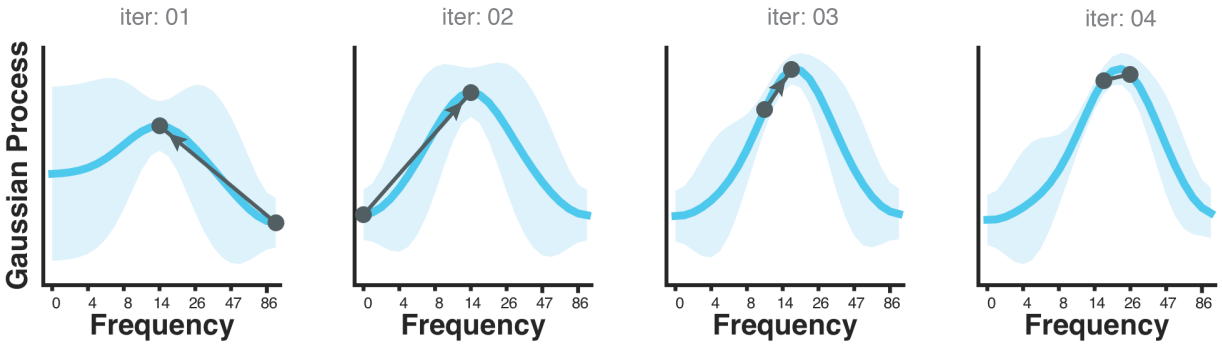
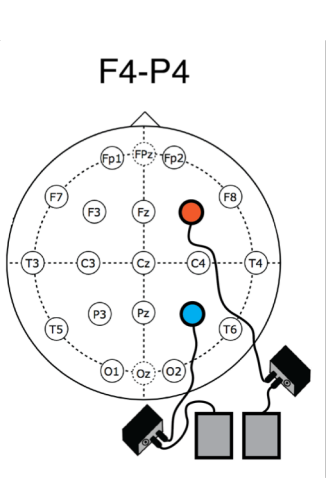
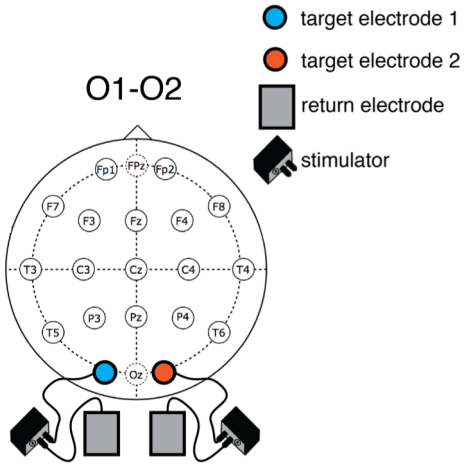


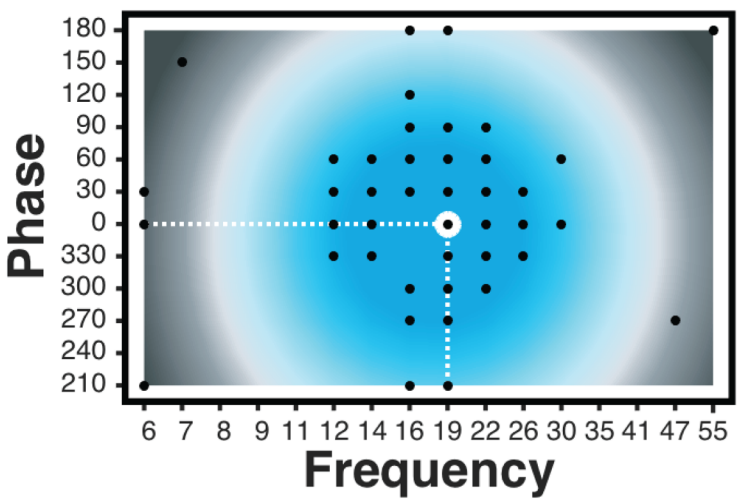
Lorenz et al. *in submission*
(preprint on bioRxiv:**150086**)

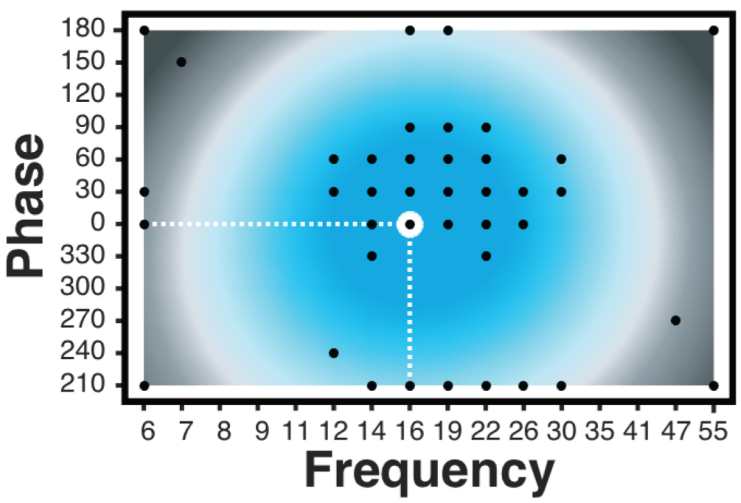
Phosphene perception

Ines Violante









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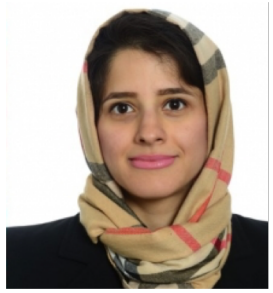
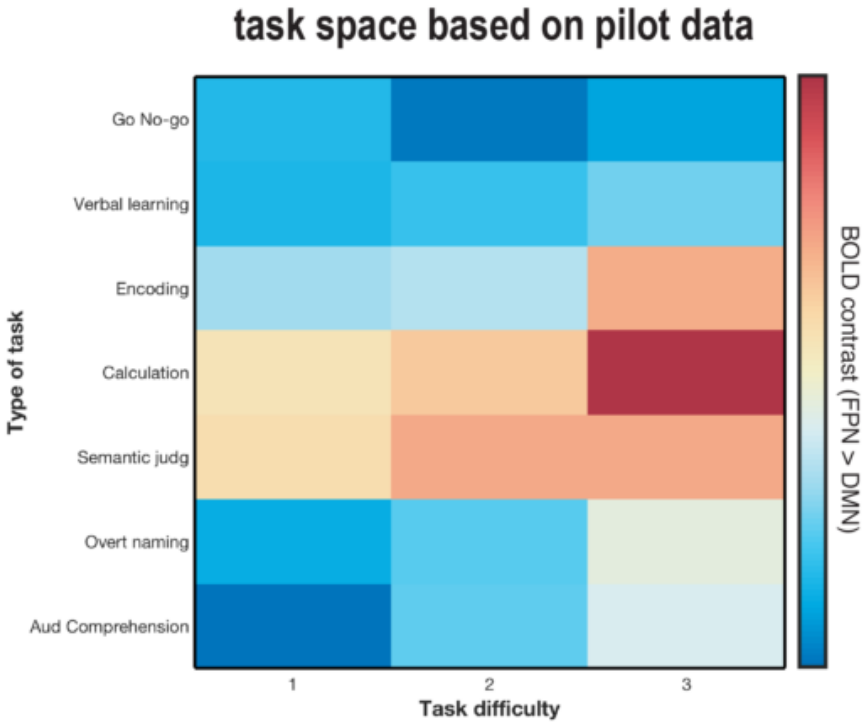
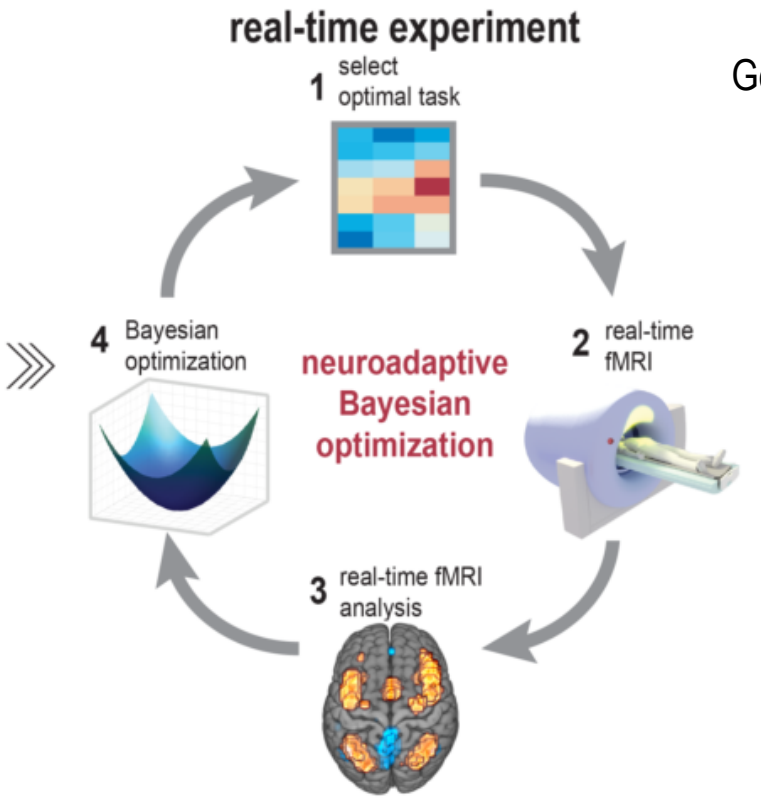
Biomarker discovery

14 stroke patients + 14 controls



Fatemeh Geranmayeh





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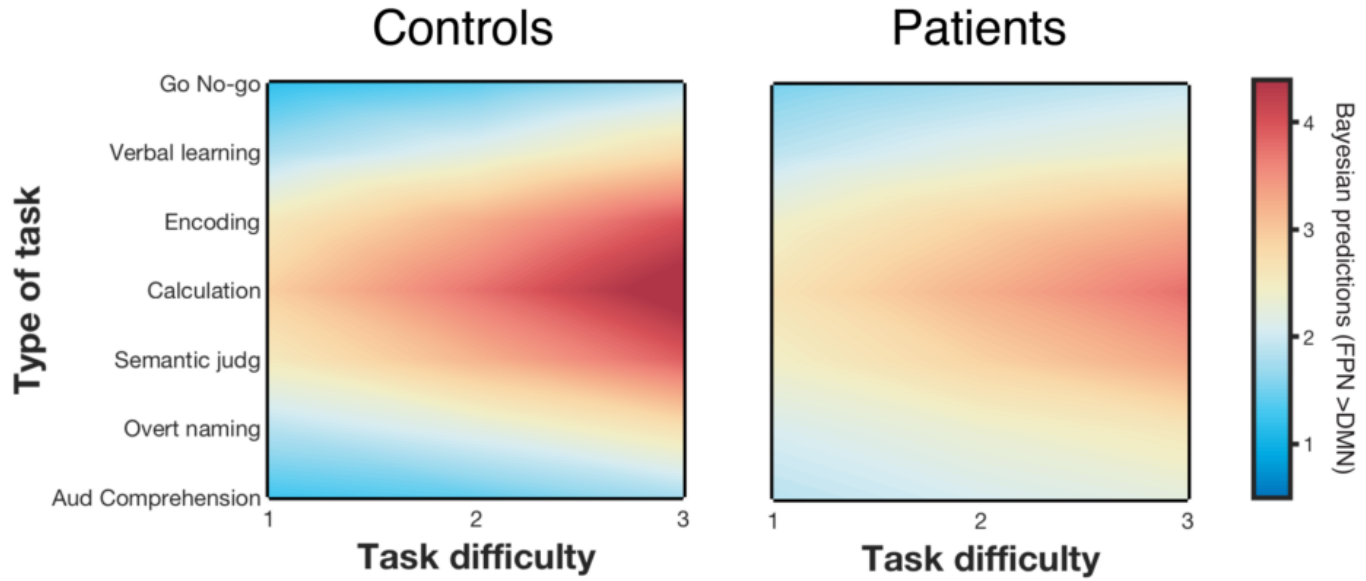
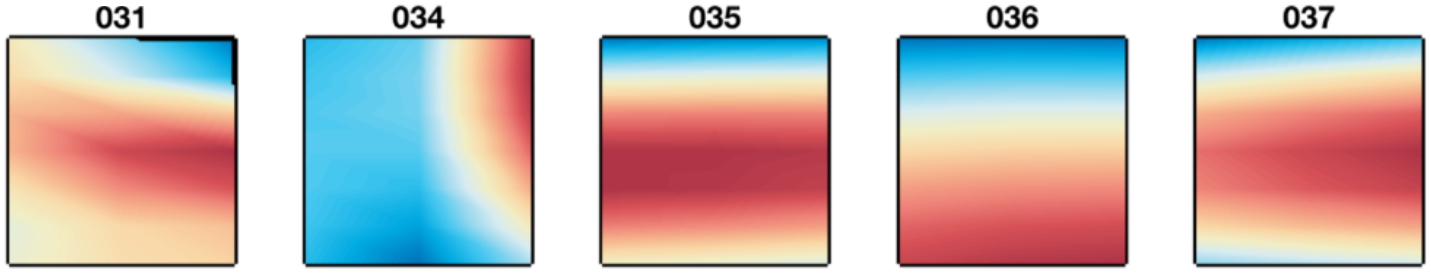
Biomarker discovery

Group results



Fatemeh Geranmayeh

Subject results



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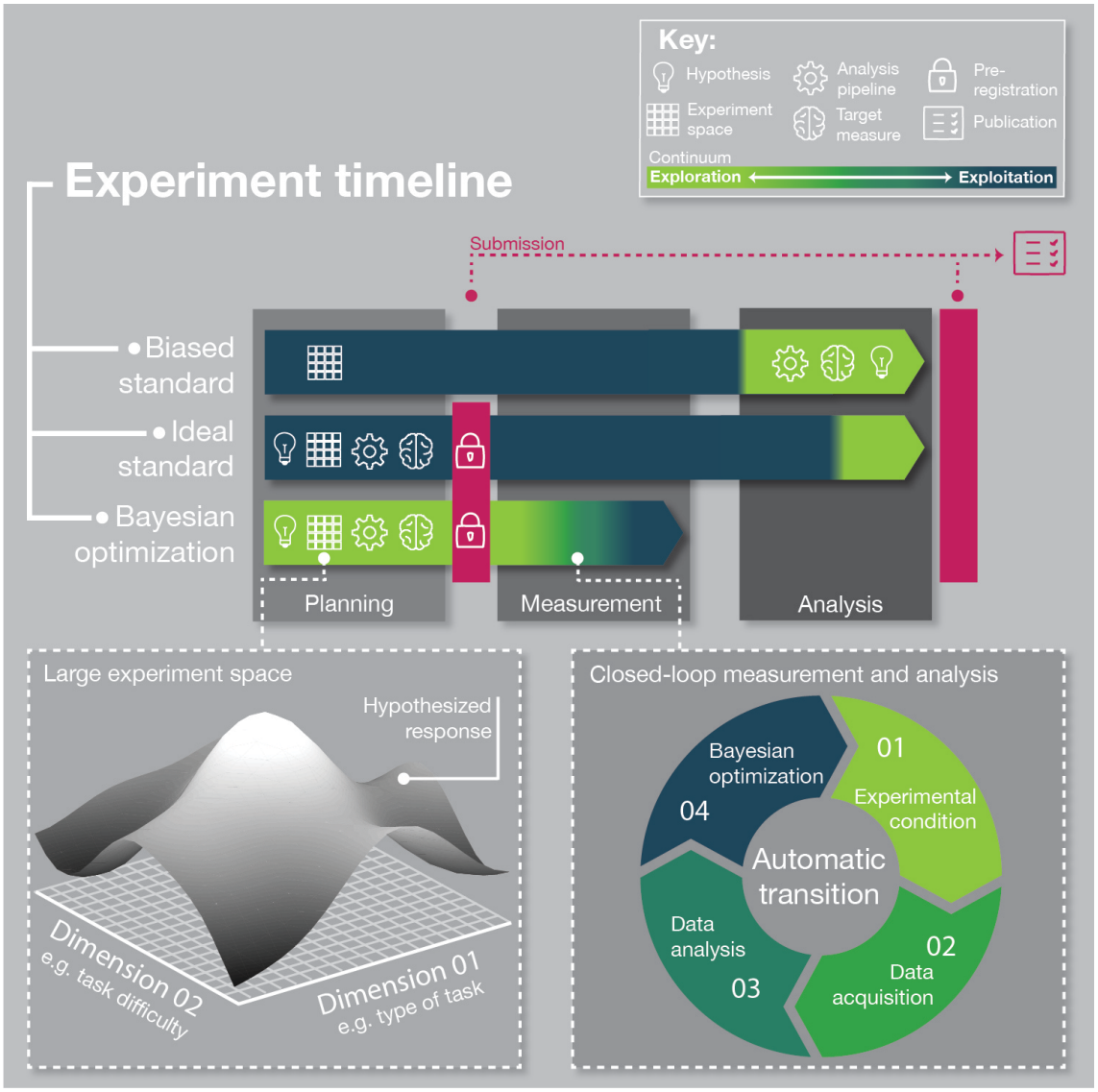
Overview

1. Motivation
2. The framework
   - 2.1 Bayesian optimization
   - 2.2 Validation study
3. Application studies
   - 3.1 Human brain mapping
   - 3.2 Non-invasive brain stimulation
   - 3.3 Biomarker discovery
4. **Implications & Discussion**

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

Registered Reports Special Initiative at NeuroImage

Guidelines for Authors:

Deadline: 19th March 2019

"In place of conventional hypothetico-deductive methods, authors are welcome to propose more innovative analytic approaches such as integration of Bayesian optimisation and hypothesis testing."

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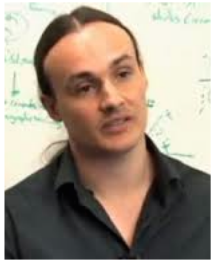
Gatsby Computational Neuroscience Unit

Ricardo P. Monti


Rob


Adam


Ines


Ricardo

Resources

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

- Publications

Lorenz R, Violante IR, Monti RP, Montana G, Hampshire A, Leech R (2018). **Dissociating frontoparietal networks with neuroadaptive Bayesian optimization**. *Nature Communications,* 9:1227.

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

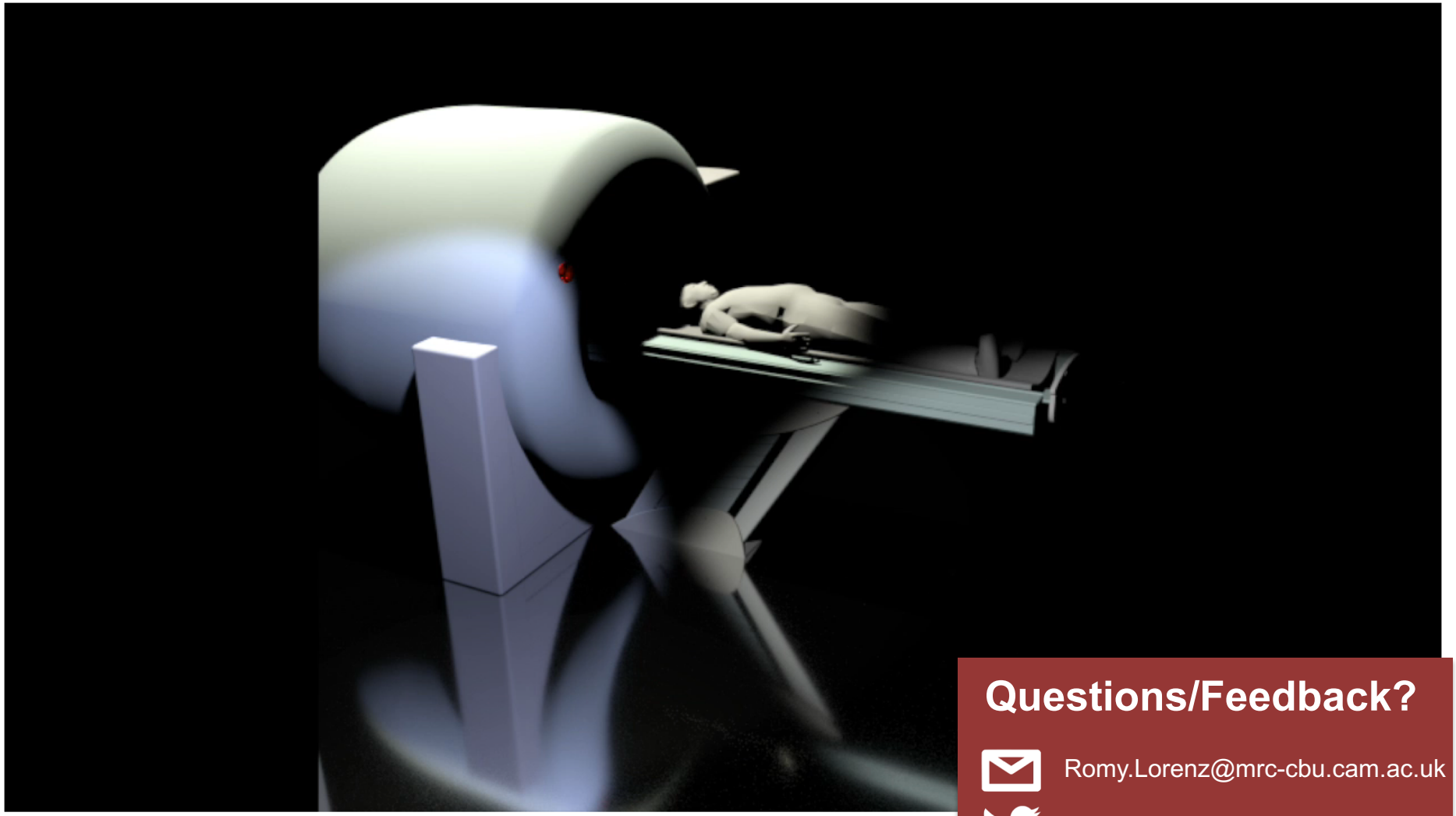
Lorenz R*, Monti RP*, Hampshire A, Koush Y, Anagnostopoulos C, Faisal A, Sharp D, Montana G, Leech R, Violante IR (2016b**. Towards tailoring non-invasive brain stimulation using real-time fMRI and Bayesian optimization**), In *6th International Workshop on Pattern Recognition in Neuroimaging* (free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

Lorenz R, Johal M, Dick F, Hampshire A, Leech R, Geranmayeh F. **Identifying individual functional profiles for a frontoparietal network in aphasic stroke patients**. *In preparation*

Questions



Questions/Feedback?

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