Modeling fMRI data

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http://cvnlab.net

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Outline

1. My background
2. Thoughts on statistics, analysis, and coding
3. A model-based approach to fMRI
4. What is the value of computational models?
5. Steps in building encoding models
6. Recent work on high-resolution fMRI

Section 1: My background

Who am I?

- Assistant Professor at the
  Center for Magnetic Resonance Research (CMRR)
  at the University of Minnesota
- CMRR specializes in high-field MRI (7T, 10.5T)

http://www.cmrr.umn.edu

Research summary

- **What I work on**
  - Modeling visual processing in the brain
  - Object and form vision
- **Approach**
  - High-field fMRI
  - Data-driven approach
  - Computational modeling
- **Resources**
  - http://cvnlab.net

- Statistics and data analysis
- fMRI methods
- GLMdenoise
- Open science (public data and code)
  (data have been re-used in other publications)

Computing approach

- Pull bits and pieces from:
  - FreeSurfer
  - SPM
  - FSL
- Integrate into MATLAB pipelines
  - Some standalone MATLAB toolboxes (GLMdenoise, analyzePRF, etc.)
- Analysis is done mostly on a large workstation, using cluster computing for parallel analysis of individual voxels

Section 2: Thoughts on statistics, analysis, and coding

Think first, program later

Step 1. Why should we even care?
(neuroscientific theory)

Step 2. What is the proper analysis approach?
(statistics)

Step 3. How do we implement this effectively?
(data science)

There are many ways to analyze data.
Before hacking away, think about the proper way.

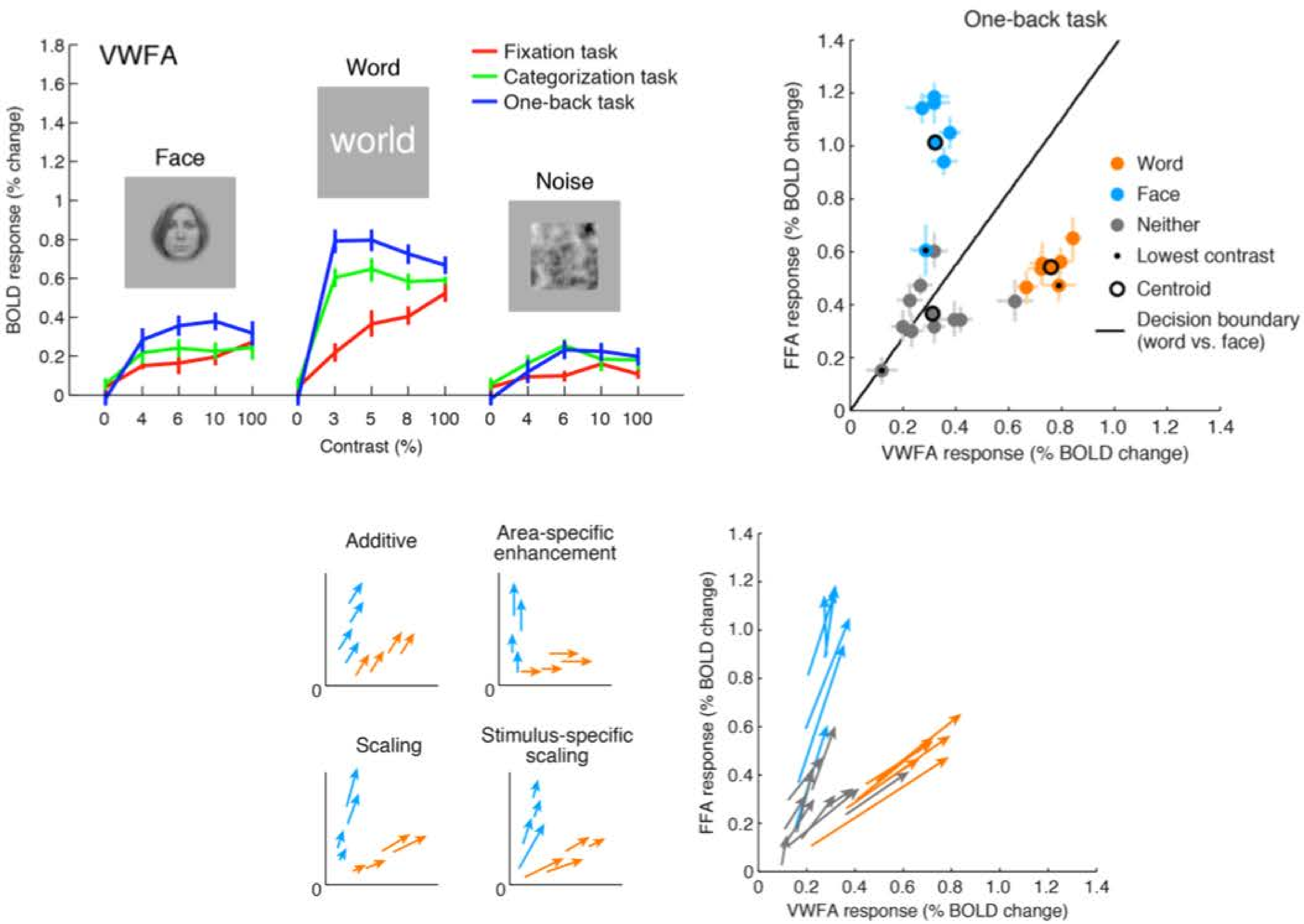
Statistical principles for fMRI denoising:
http://kendrickkay.net/GLMdenoise/

Statistics blog:
http://randomanalyses.blogspot.com

Statistics materials at:
http://kendrickkay.net/psych5007/

Look at your data!

- Good visualization can do wonders.
- This cannot be automated. The brain is still necessary.



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The importance of functions

- Reusable and documented functions are super important. Take time to do it.

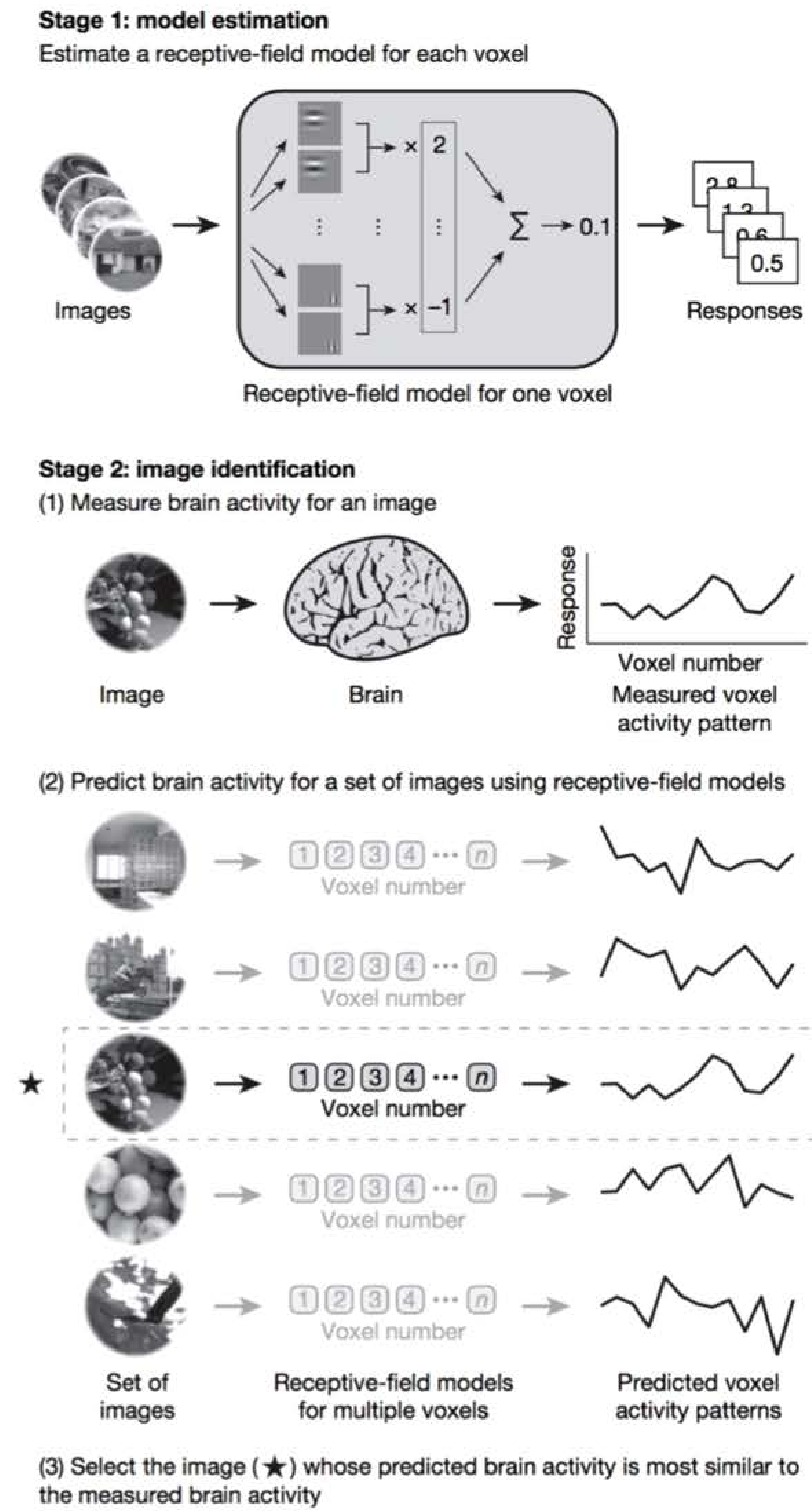
- A function is a promise to your future self.

- Good function documentation is a skill. One must determine the proper amount of detail.
  - No one wants to see computer code in a scientific paper.
  - On the other hand, can you clearly and concisely state exactly what you did to your data?

Section 3: A model-based approach to fMRI

A simple example

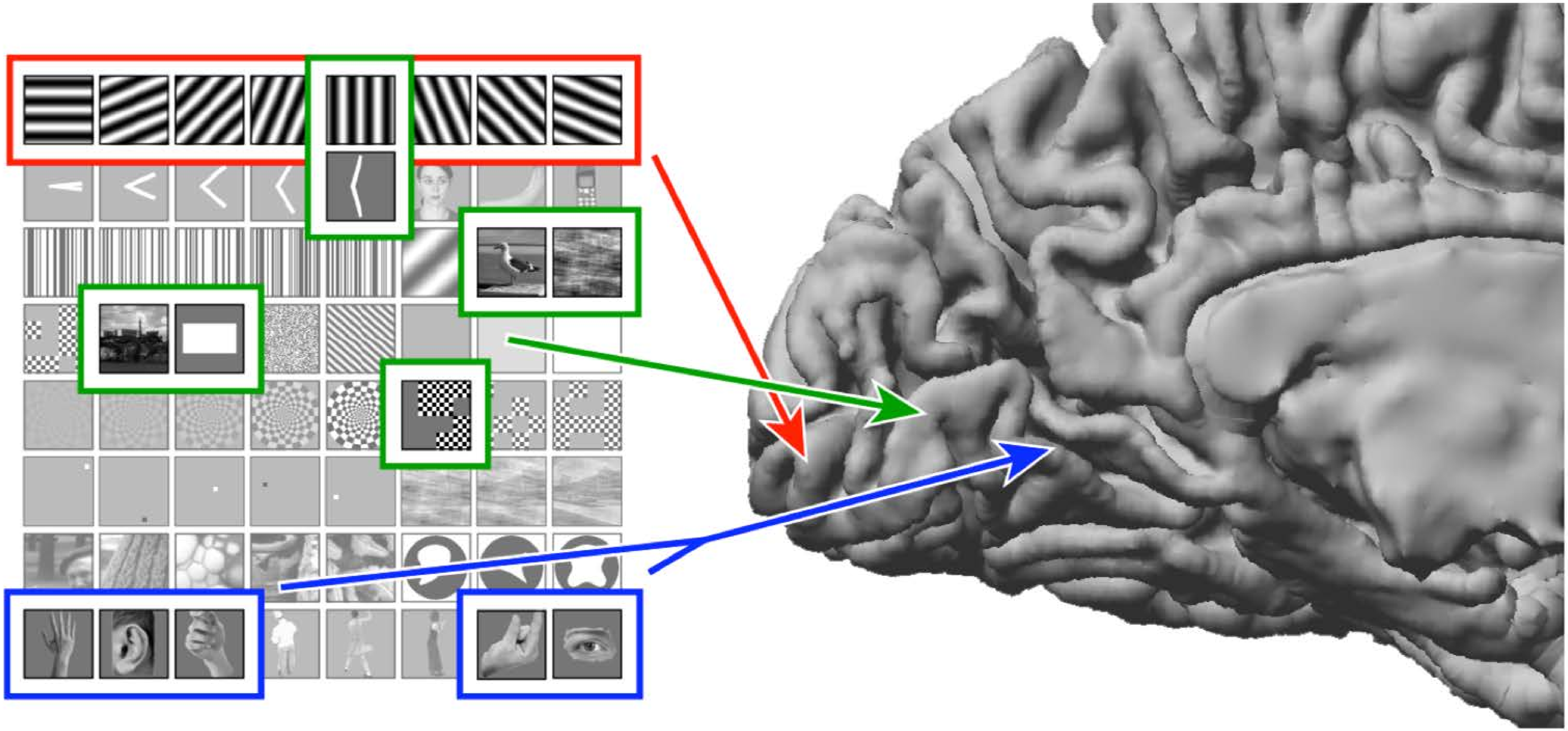
1. Measure brain activity in response to stimuli
2. Build models of how the brain processes the stimuli
3. Use models to infer the stimulus given brain activity



Kay, Naselaris, Prenger, Gallant, *Nature*, 2008

Visual representation

- Different stimuli drive different areas



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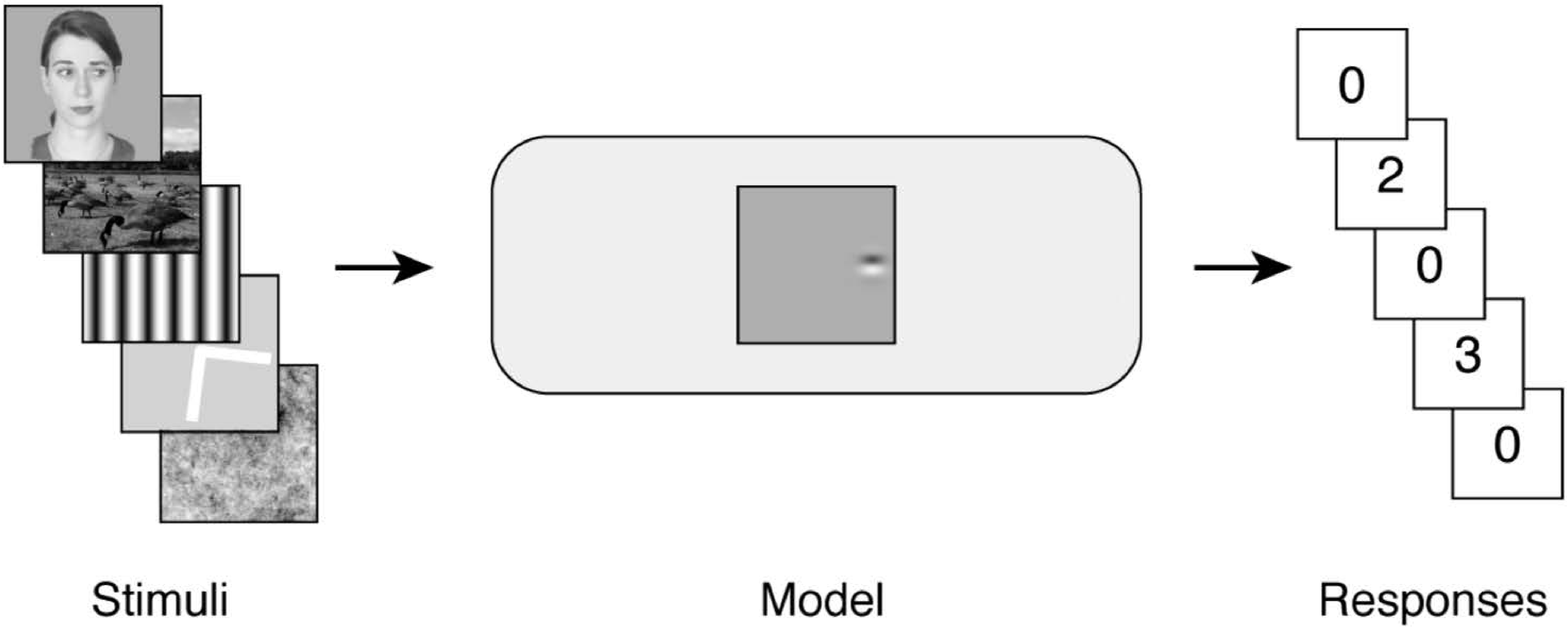
Functional models of the visual system

The general question is:
What information-processing operations does the brain perform?



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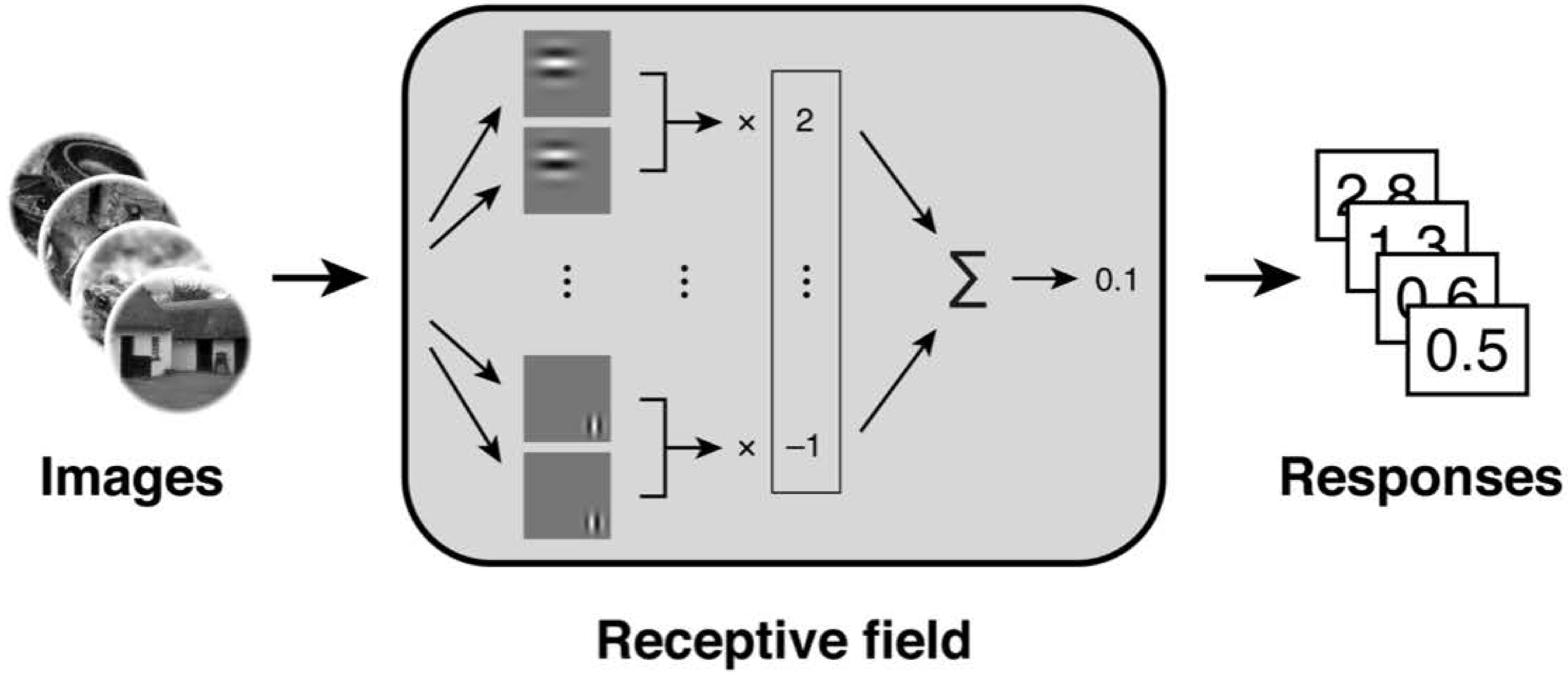
Why model building is a hard problem

- High-dimensional problem
- Small amount of data
- Nonlinear mapping

Static 100 x 100 grayscale images:

$$\mathbb{R}^{10000} \Rightarrow \mathbb{R}$$

Example 1

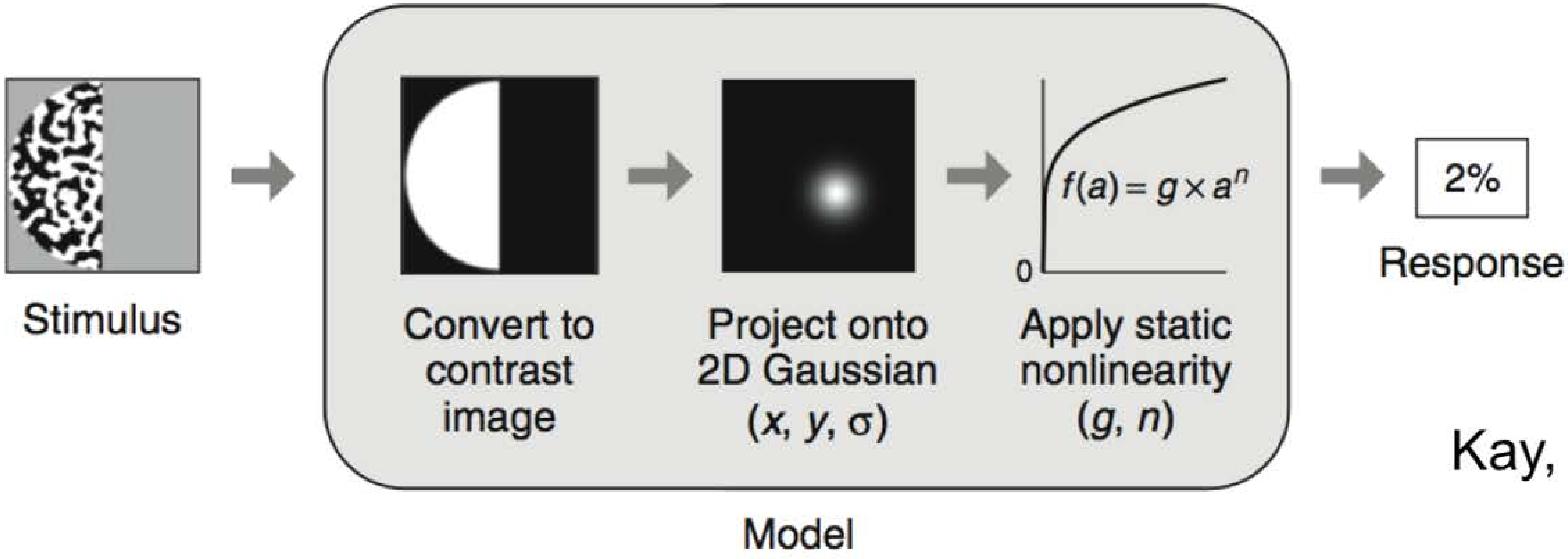


Kay, *Nature*, 2008

- **y = Xh + n**
  (1750 x 1) = (1750 x 2730) (2730 x 1) + (1750 x 1)
- Regularized linear regression (e.g. ridge regression)

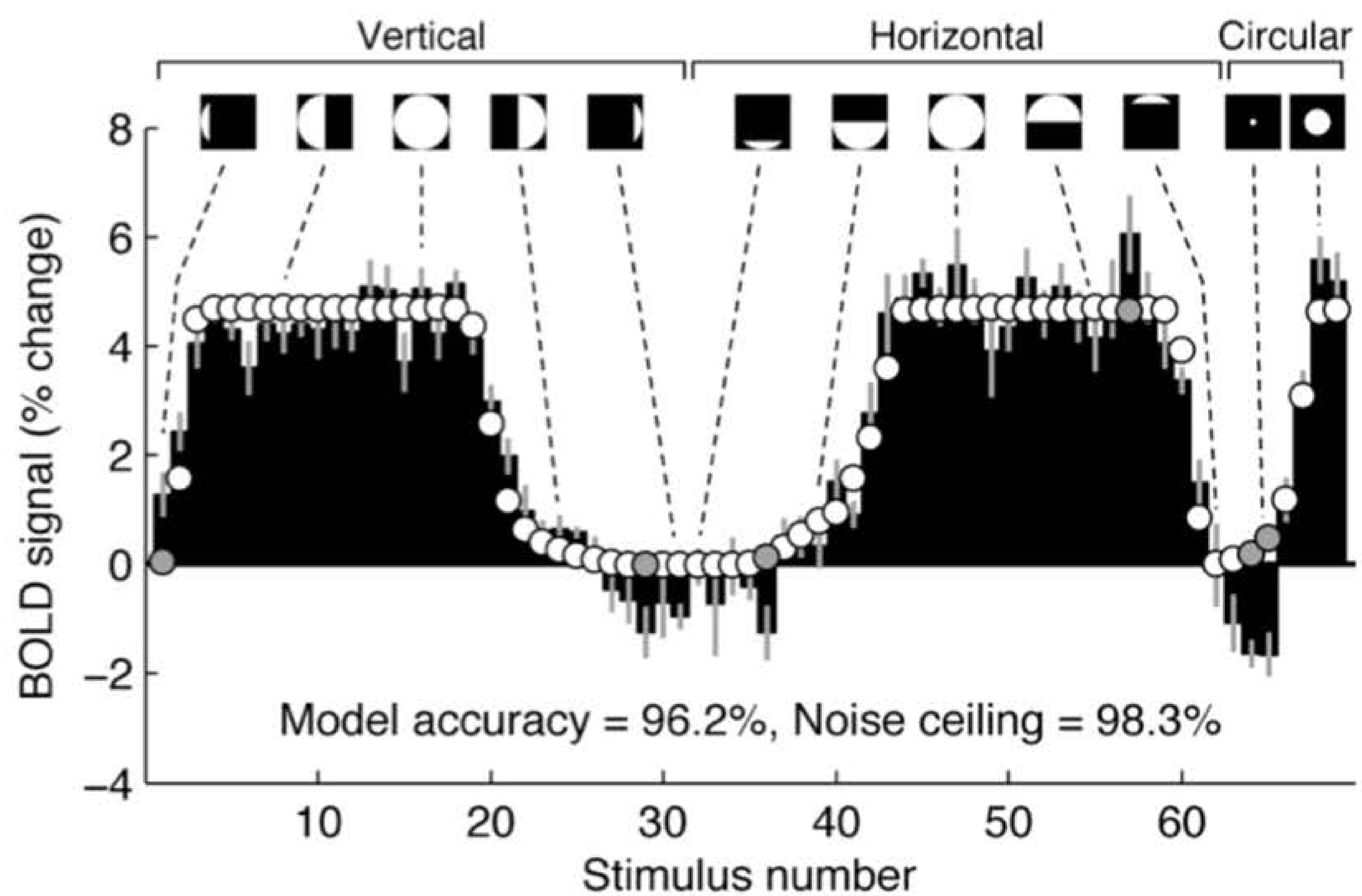
$$\hat{\mathbf{h}} = \underset{\mathbf{h}}{\operatorname{argmin}} \left((\mathbf{y} - \mathbf{X}\mathbf{h})^{\mathrm{T}} (\mathbf{y} - \mathbf{X}\mathbf{h}) + \lambda \sum_i |h_i|^2 \right)$$

Example 2



Kay, *J. Neurophys.*, 2013

- Nonlinear optimization (MATLAB's lsqcurvefit)



Relationship to MVPA

- A lot of fMRI studies use multivariate pattern analysis (MVPA), in which a classifier is trained to distinguish experimental conditions. How does the model-building approach differ?

- That's a longer discussion. For information, see:
  - Naselaris, T. & Kay, K.N. Resolving ambiguities of MVPA using explicit models of representation. Trends in Cognitive Sciences (2015).
  - Naselaris, T., Kay, K.N., Nishimoto, S., & Gallant, J.L. Encoding and decoding in fMRI. NeuroImage (2011).
  - Kay, K.N. Understanding visual representation by developing receptive-field models. In: Visual Population Codes, edited by N. Kriegeskorte & G. Kreiman (2011).

Section 4: What is the value of computational models?

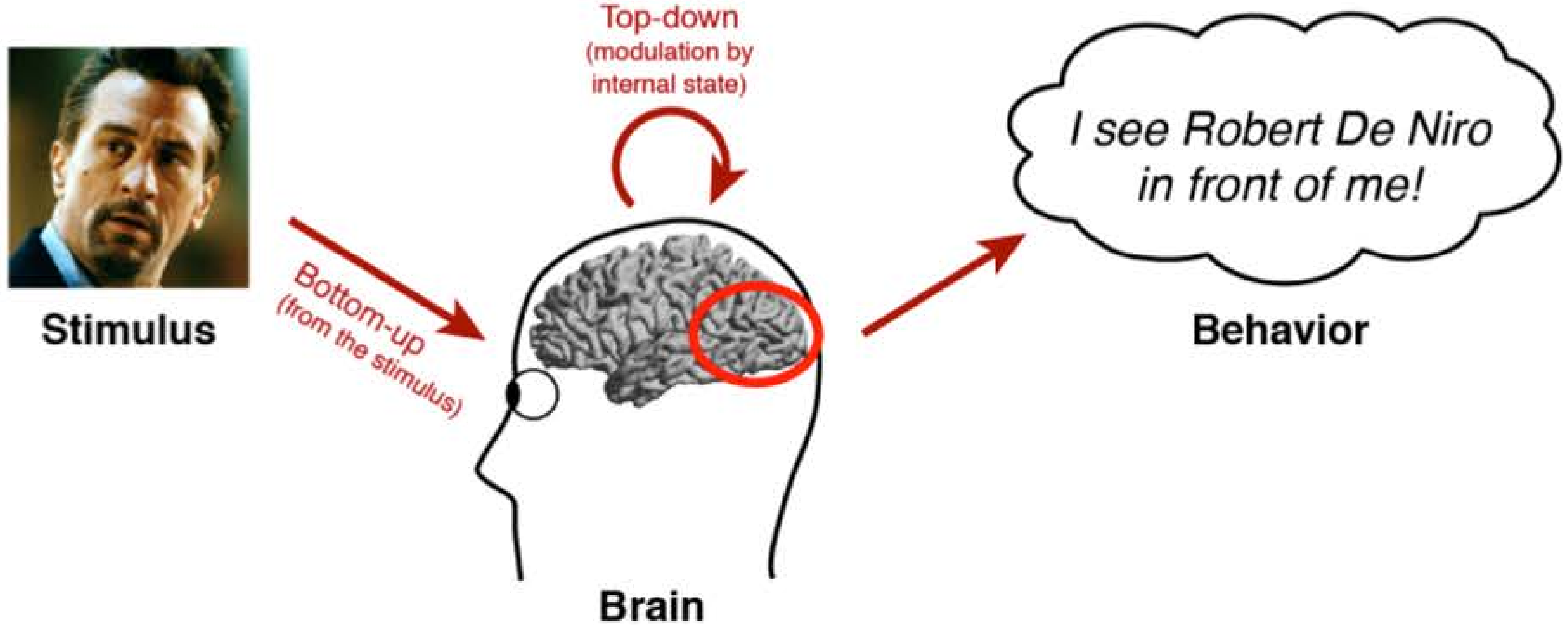
Computation

- Distinction between computational methods and computational models

The brain as a computational device

- The brain represents sensory information
- The brain processes information
- The brain stores information
- The brain uses information to guide motor behavior

We want a model that characterizes the computations that the brain performs.



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What are models good for?

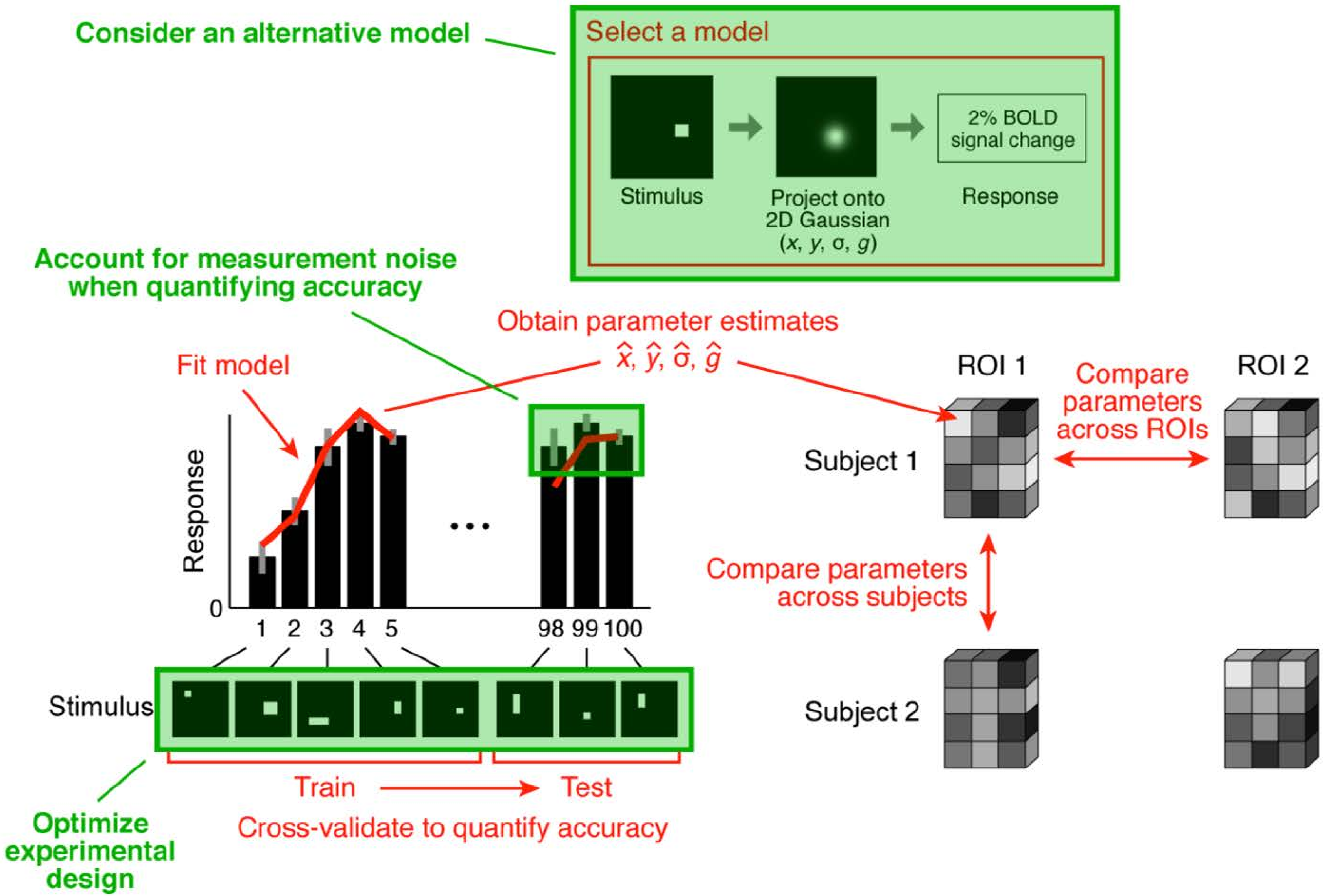
- Describe / summarize
  - Given a big set of data, can we say something?
  - Compact description of a system using a few numbers
- Explain / reduce / uncover mechanism
  - Identify the fundamental operators that give rise to a phenomenon
- Interpret / assign computational function
  - The firing of this neuron achieves an important behavioral goal

Some important issues in modeling

- What type of model is this? (i.e. what are the inputs and outputs?)
- What is the goal of this model? How general is the model?
- Tractability, complexity
- Is the model simple enough to be interpretable?
- Level of biological detail
- Can we get enough experimental data to learn the parameters?
- Which parts of the model are essential? What about other models? Can we do model comparison?
- Does the make make some interesting predictions that we might test in some future experiment?
- How clearly is the model described?
- Can we actually reproduce the model? (software, code)

Section 5: Steps in building encoding models

Steps in building encoding models



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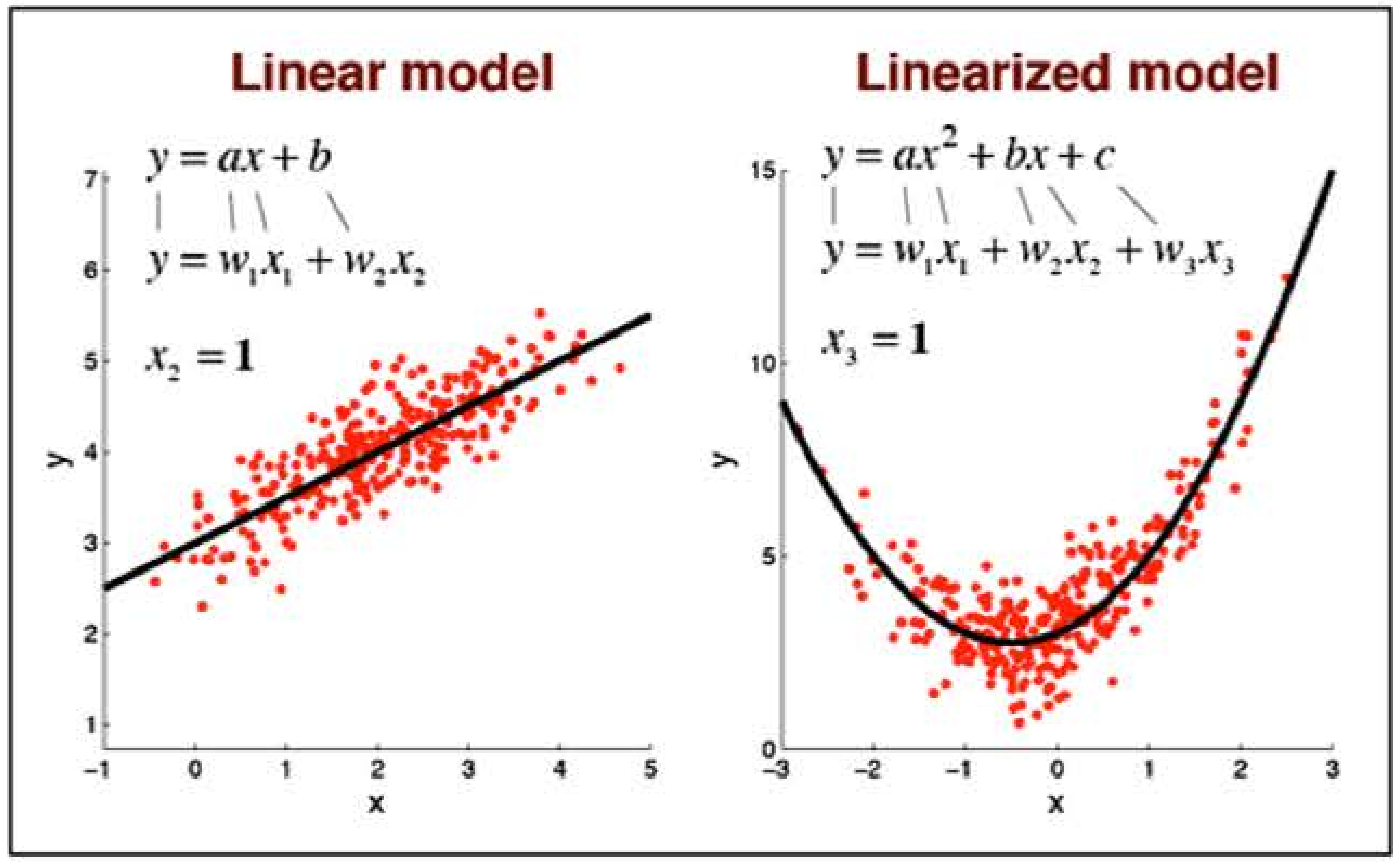
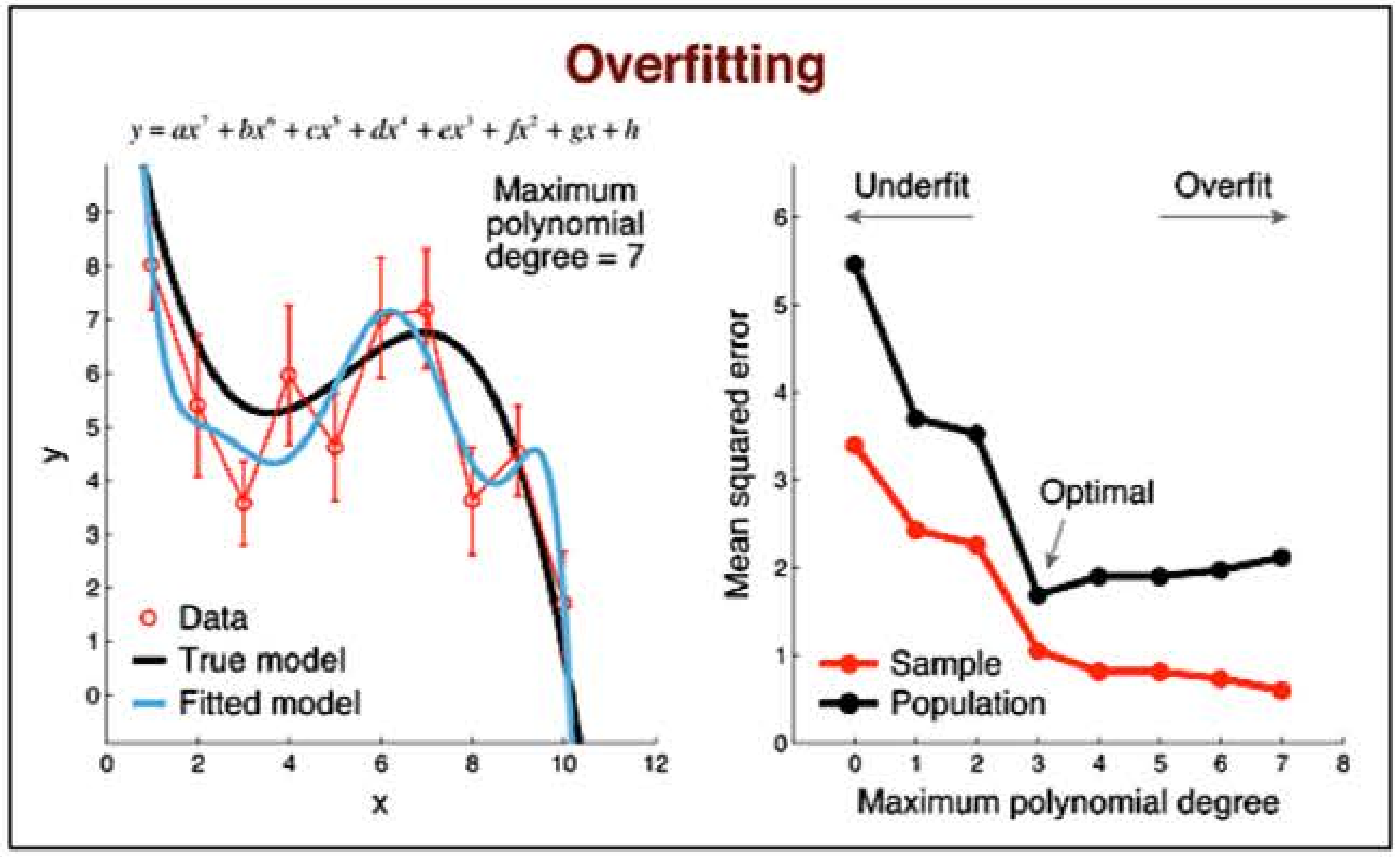
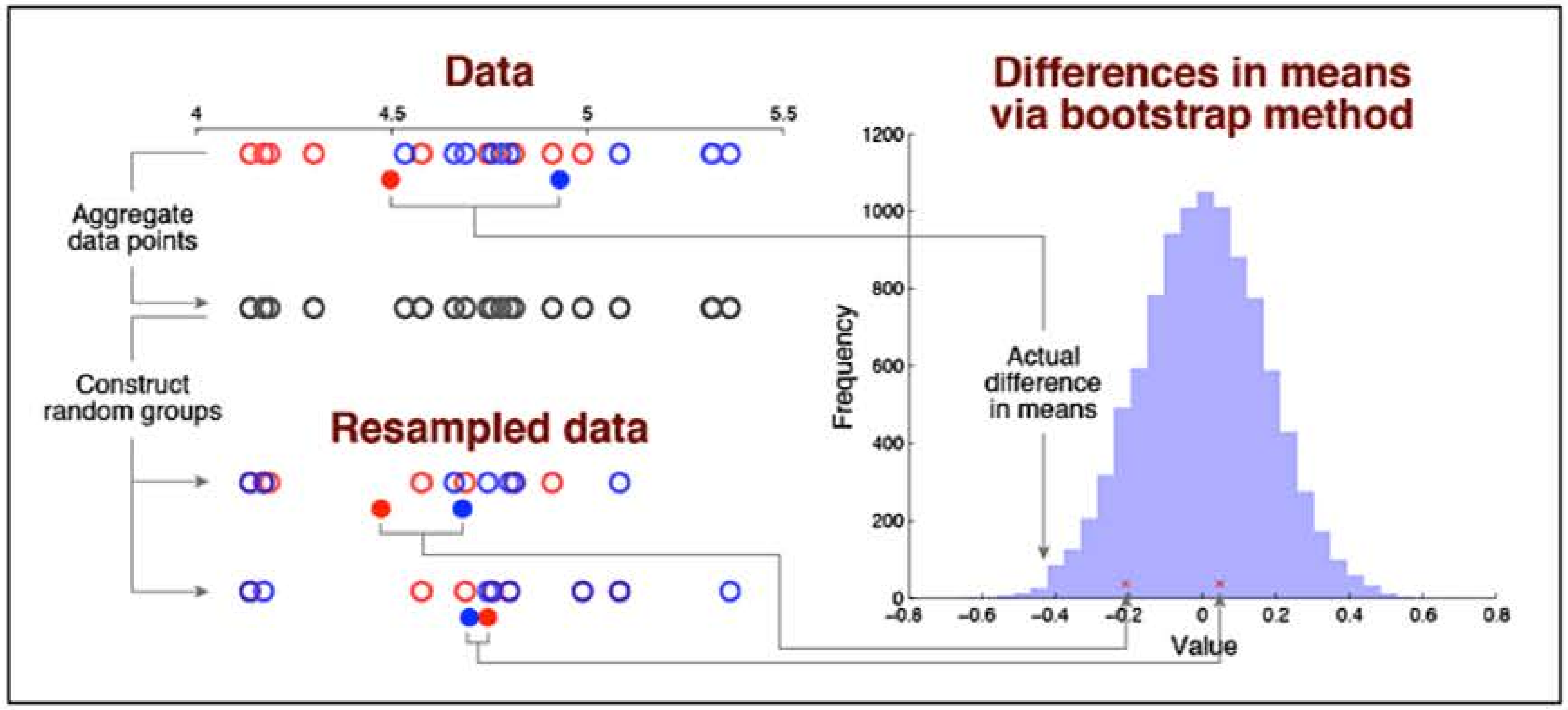
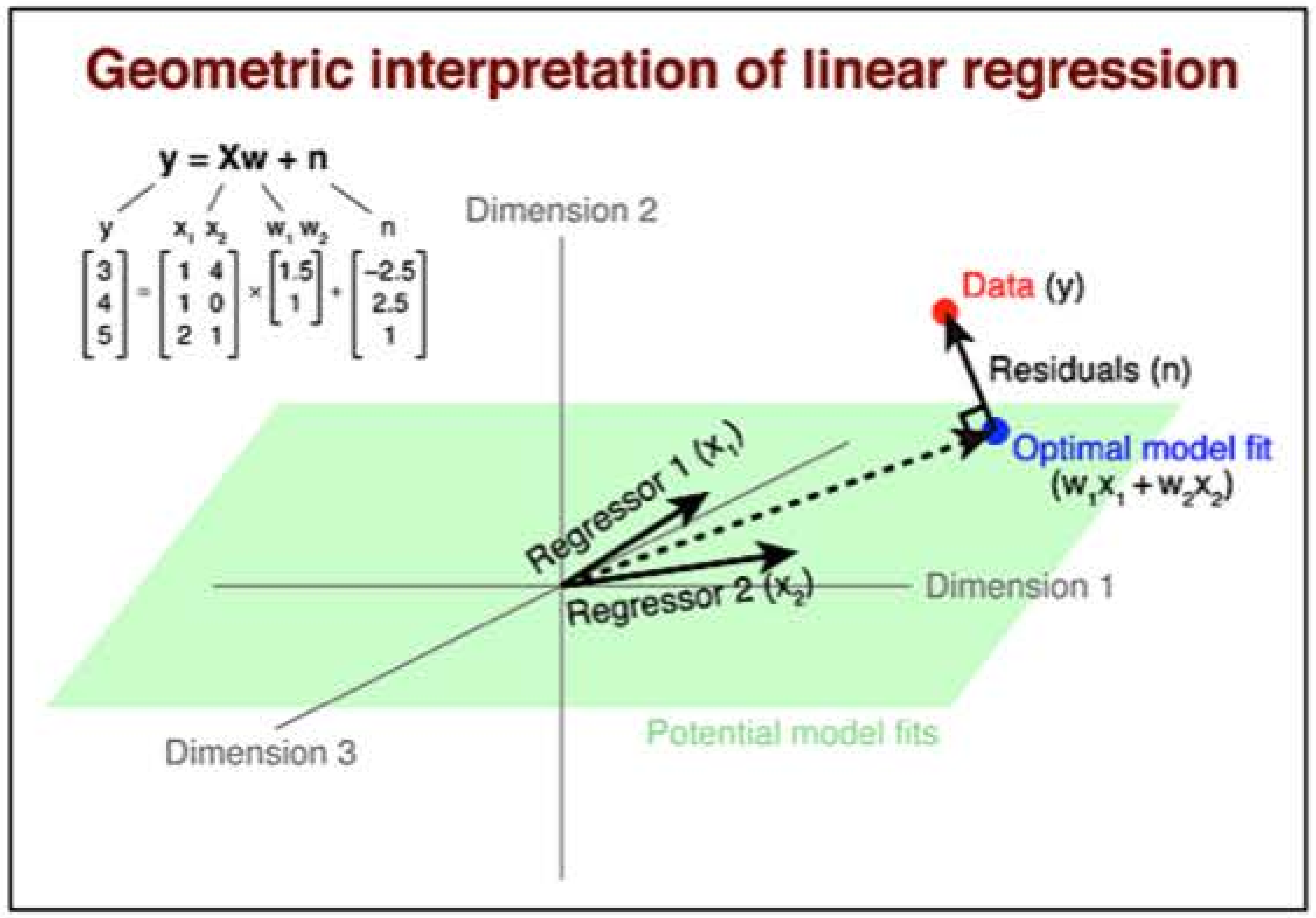
Also see Naselaris and Kay, *TICS*, 2015

The statistical machinery









Materials at http://kendrickkay.net/psych5007/

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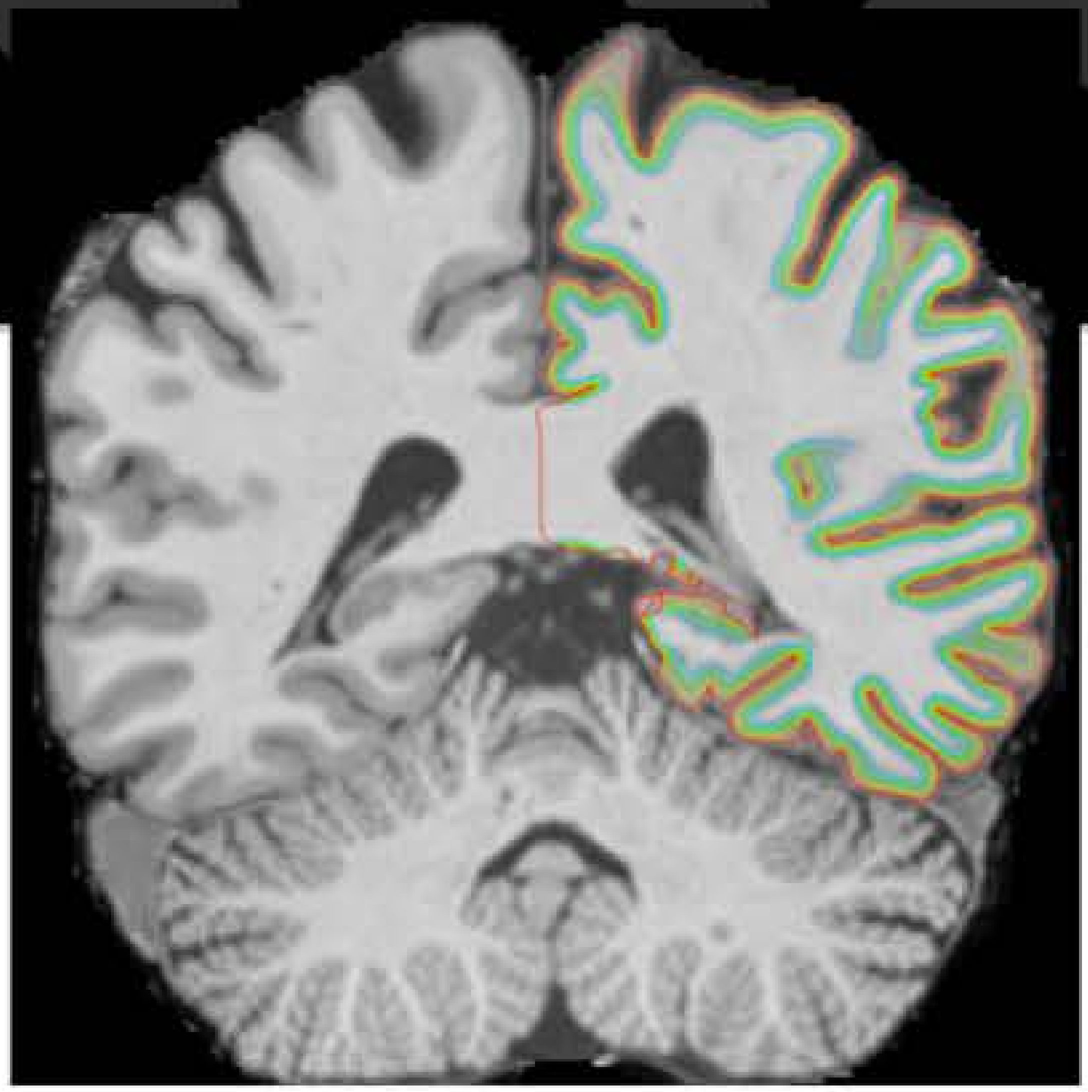
And therein lies a can of worms...

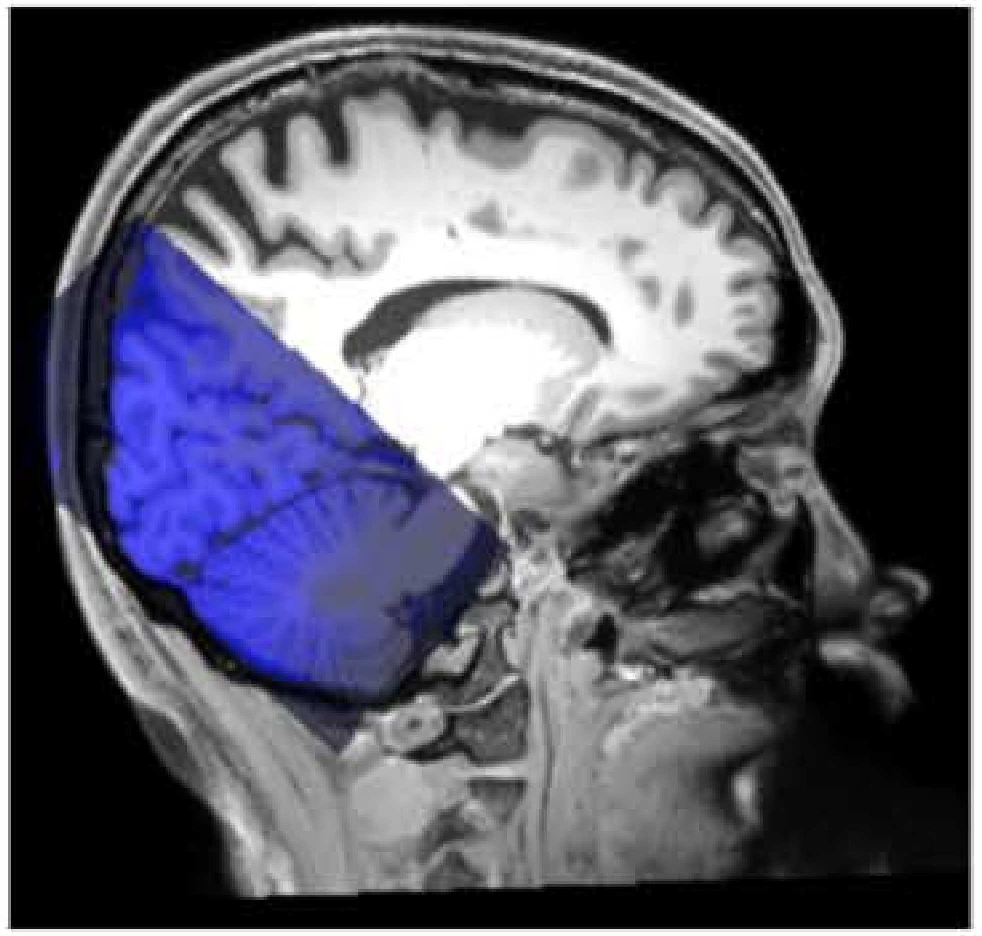
- Noise ceiling
- Experimental design (stimulus sampling)
- Developing better models
- Cross-validation schemes
- Local minima
- Computational time for model fitting
- Model interpretation
- Describing model details clearly

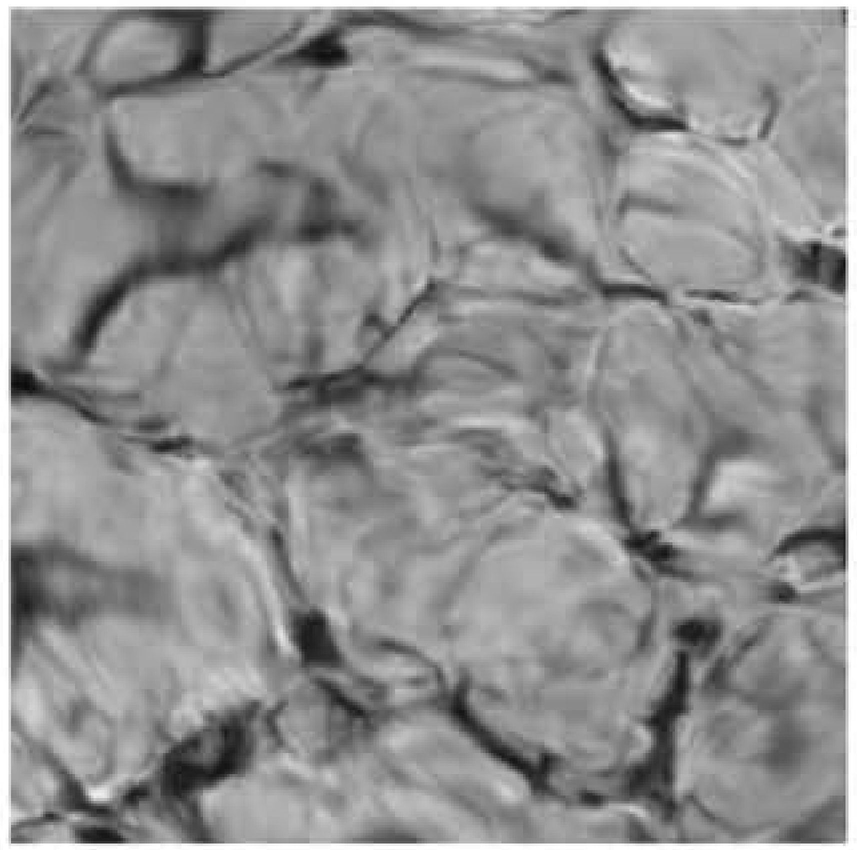
Section 6: Recent work on high-resolution fMRI

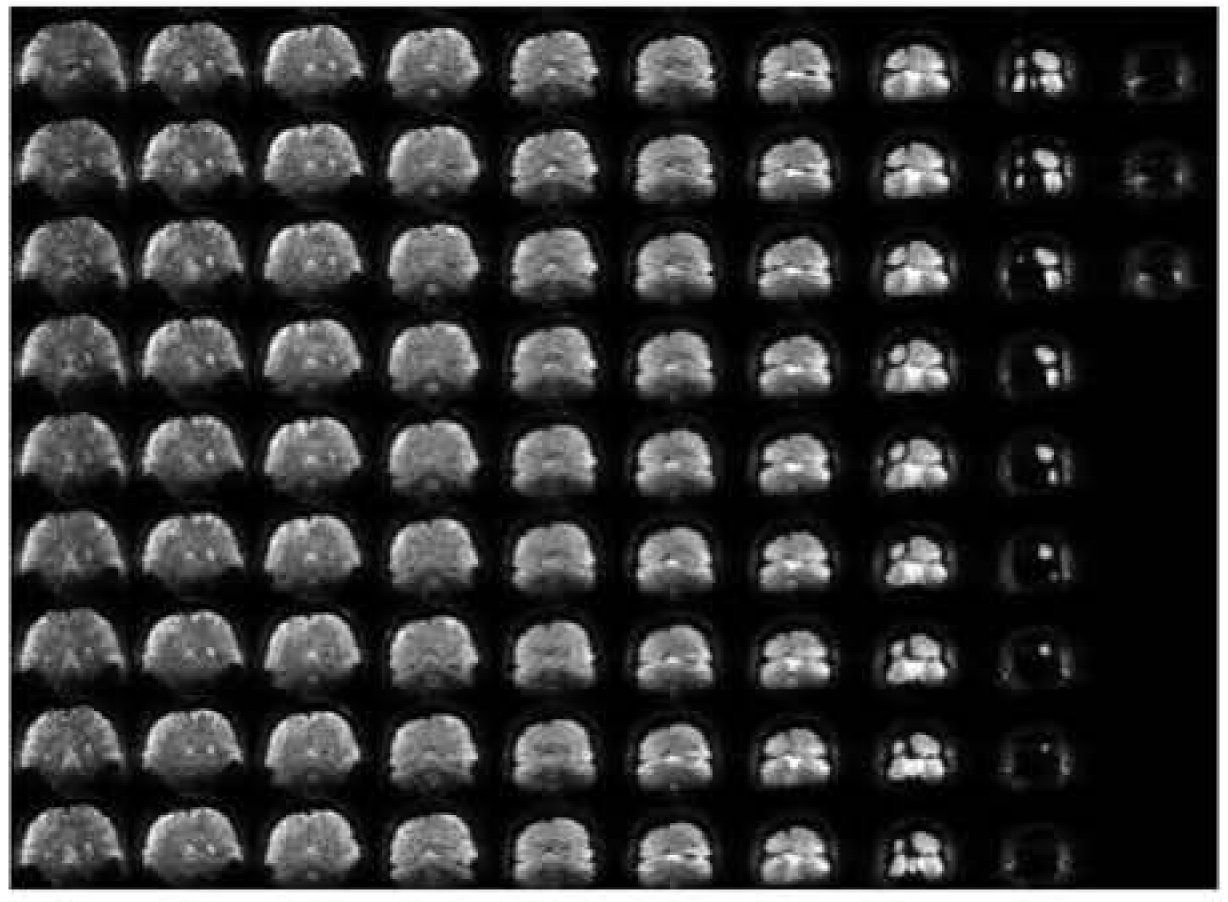
Pre-processing

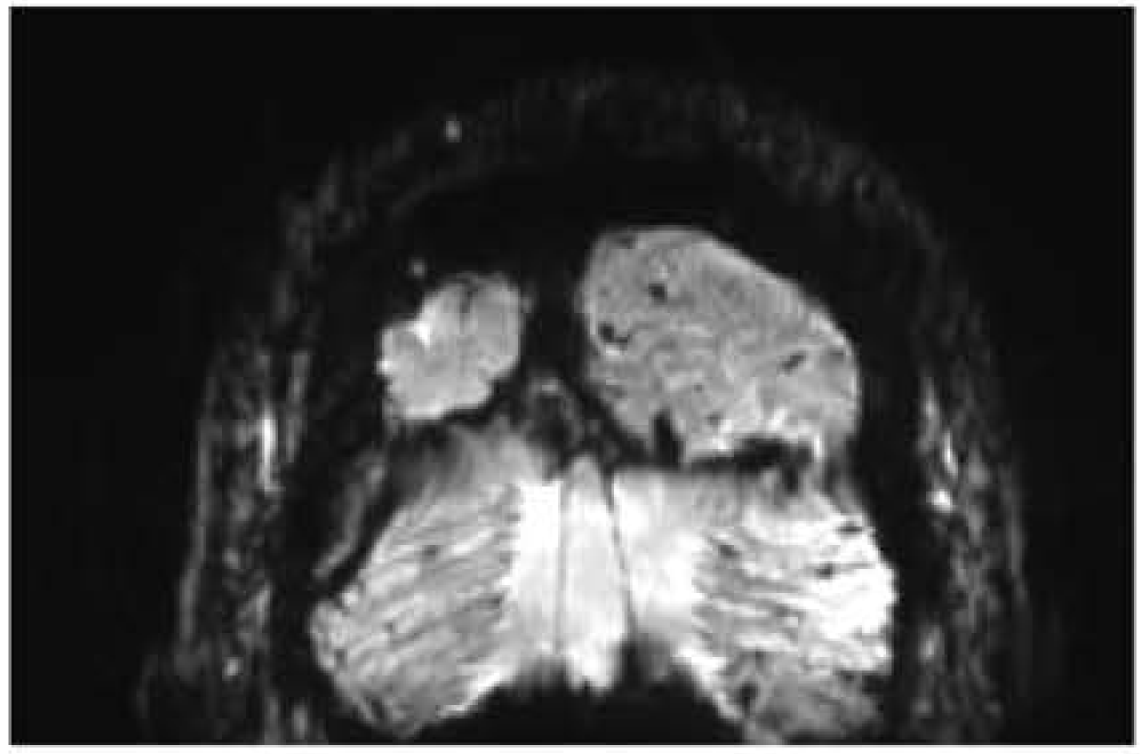
- 8 T1s, 2 T2s (0.8 mm, 3 T)
- 0.8-mm fMRI protocol (7 T, GE-EPI, TR 2.2 s, 84 slices, MB2, IPAT3) + GRE fieldmaps
- FreeSurfer (dense, layer, truncated)
- slice time correction (and temporal upsampling), motion correction, fieldmap undistortion, coregistration to T2
- 1 temporal resampling, 1 spatial resampling





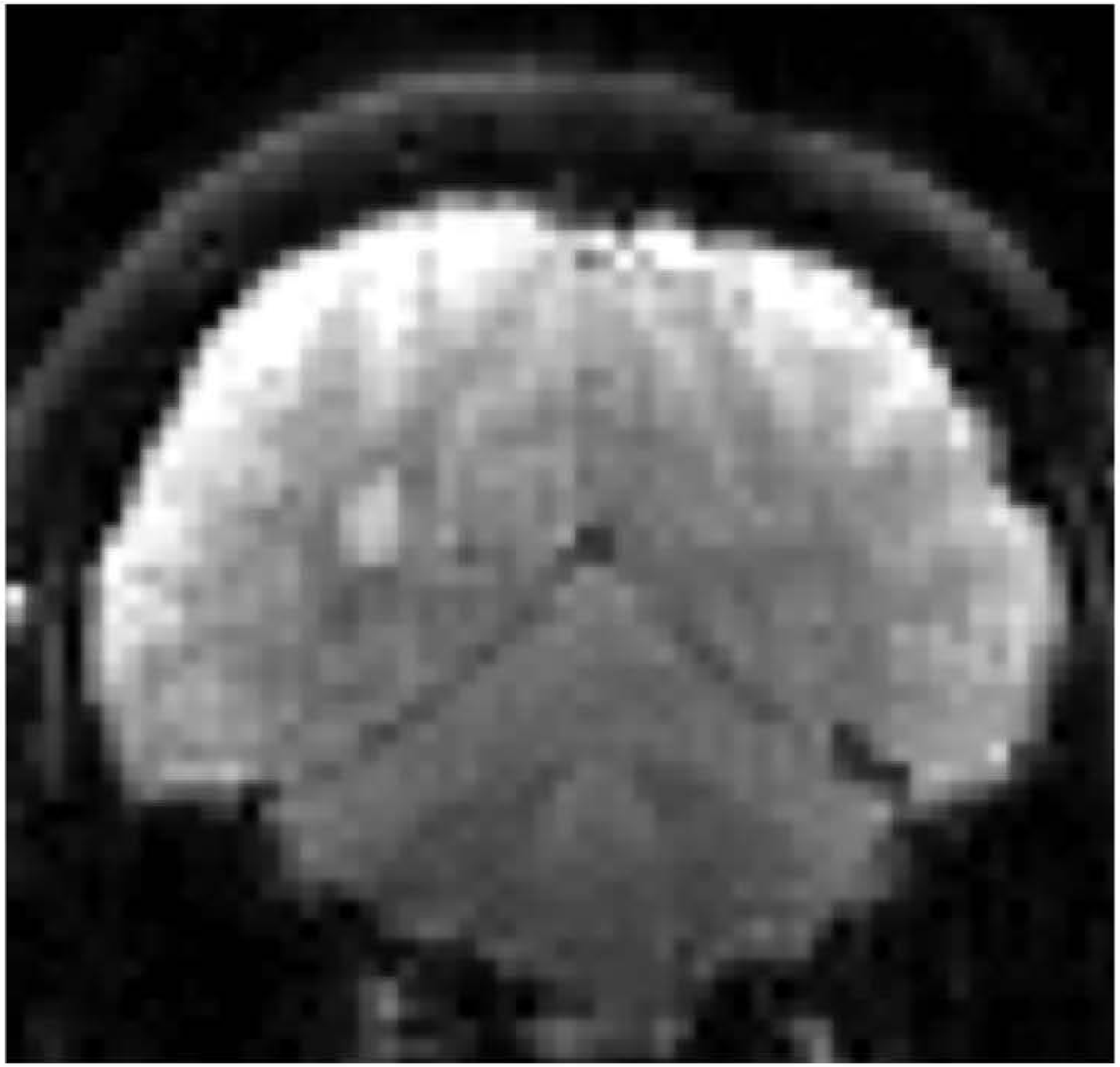




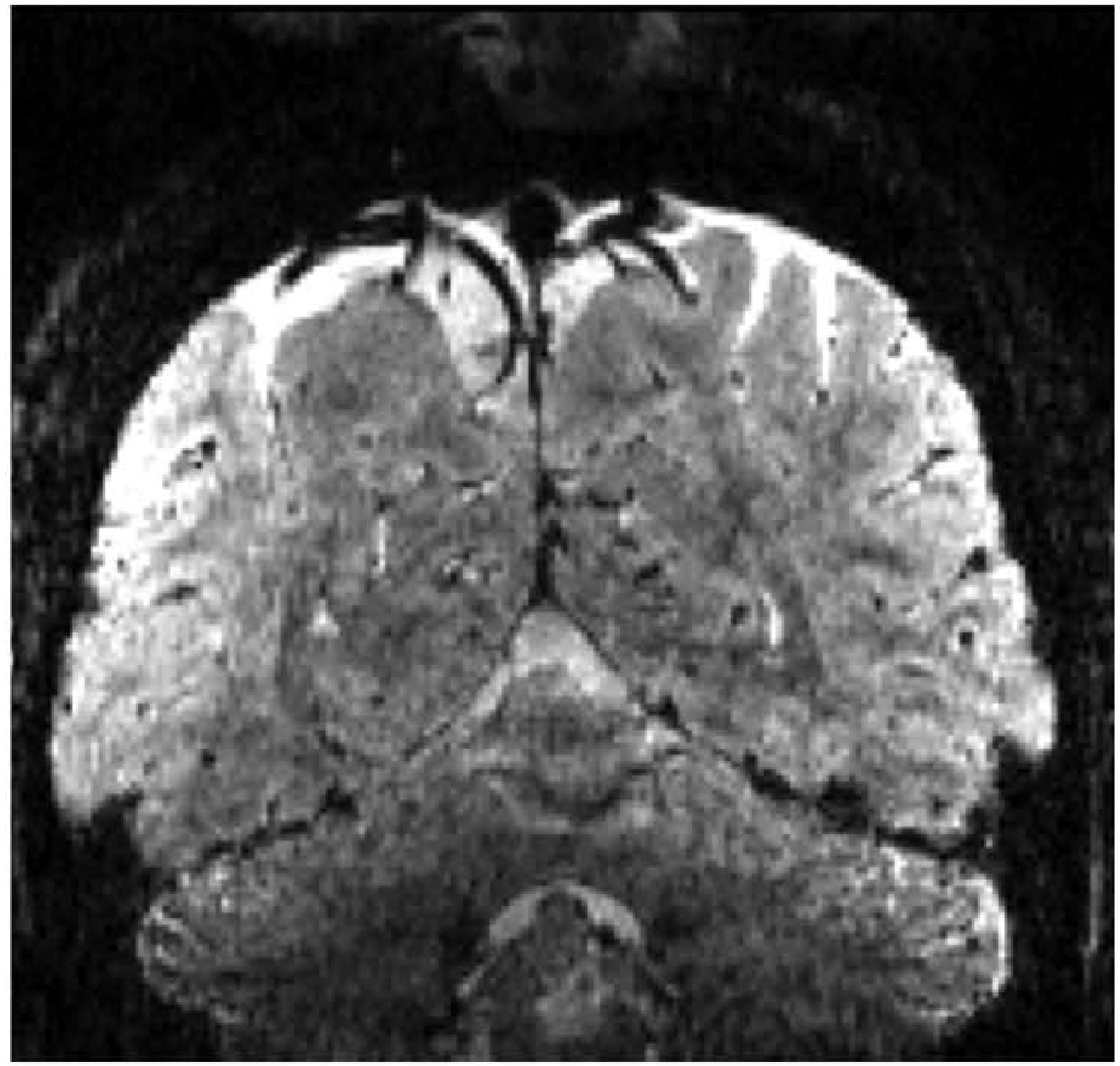


Improvements in spatial resolution

2.5 mm (3 T)



0.8 mm (7 T)



GE-EPI, 2.2-s TR, MB2, IPAT3

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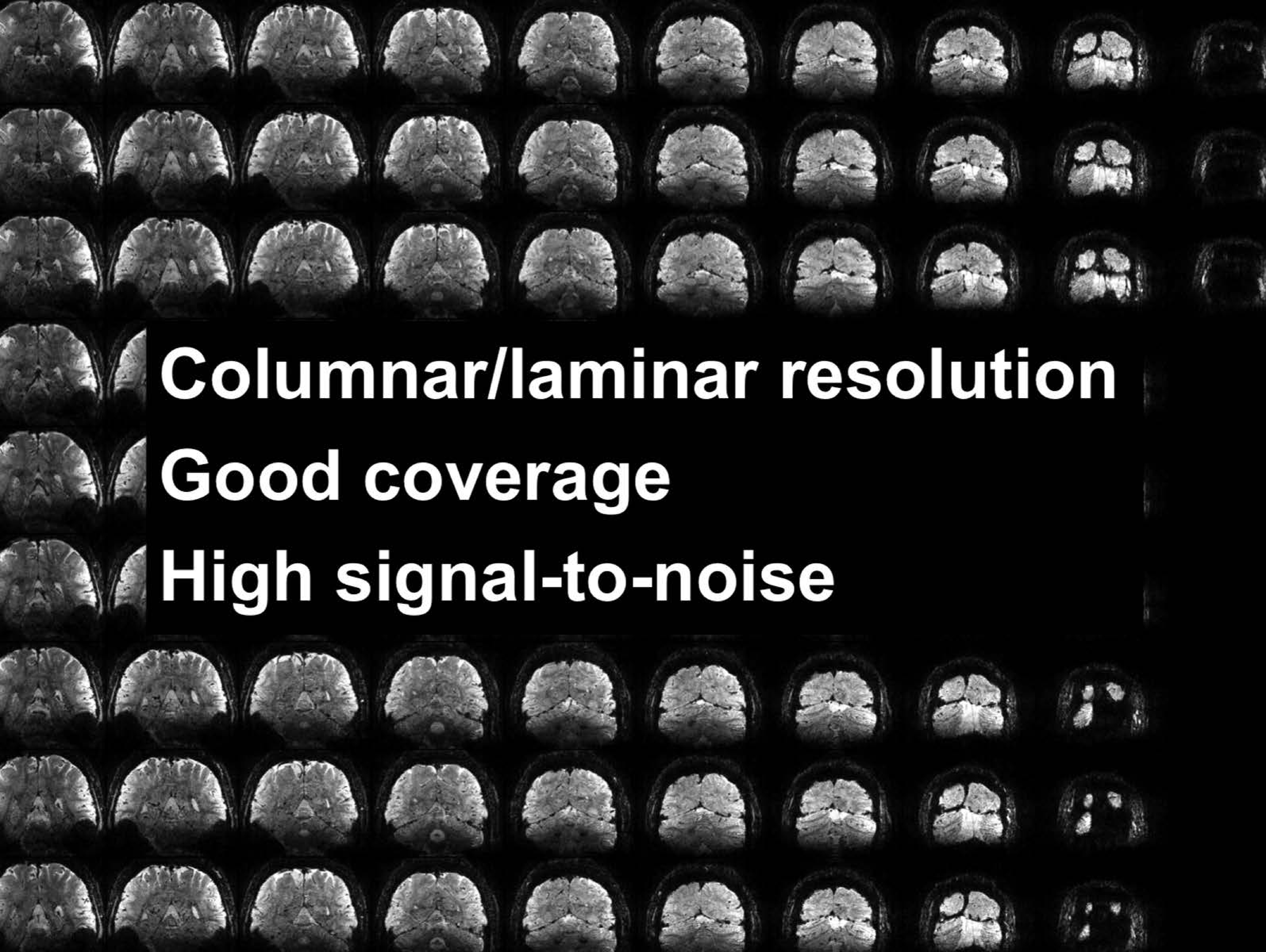
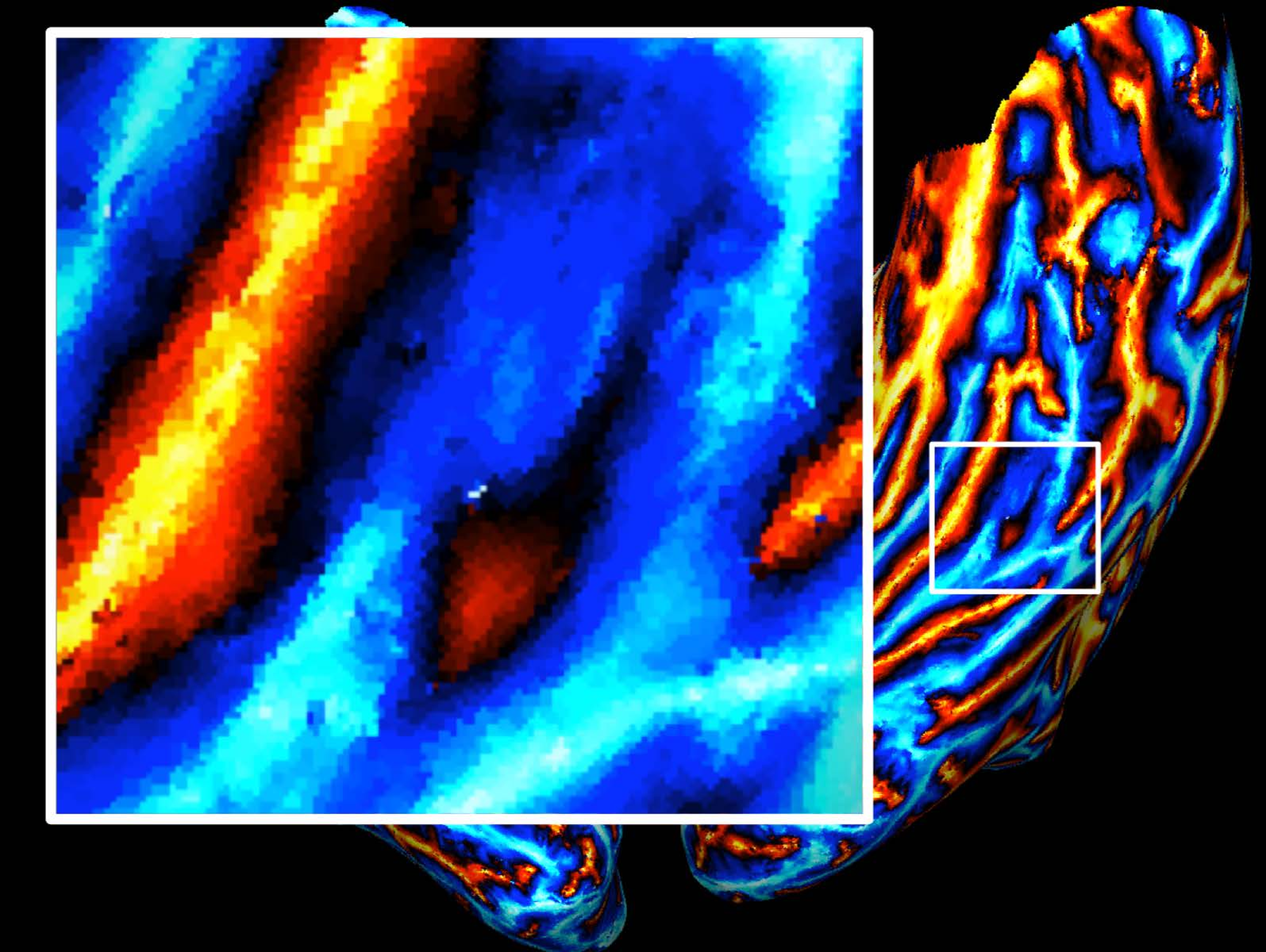
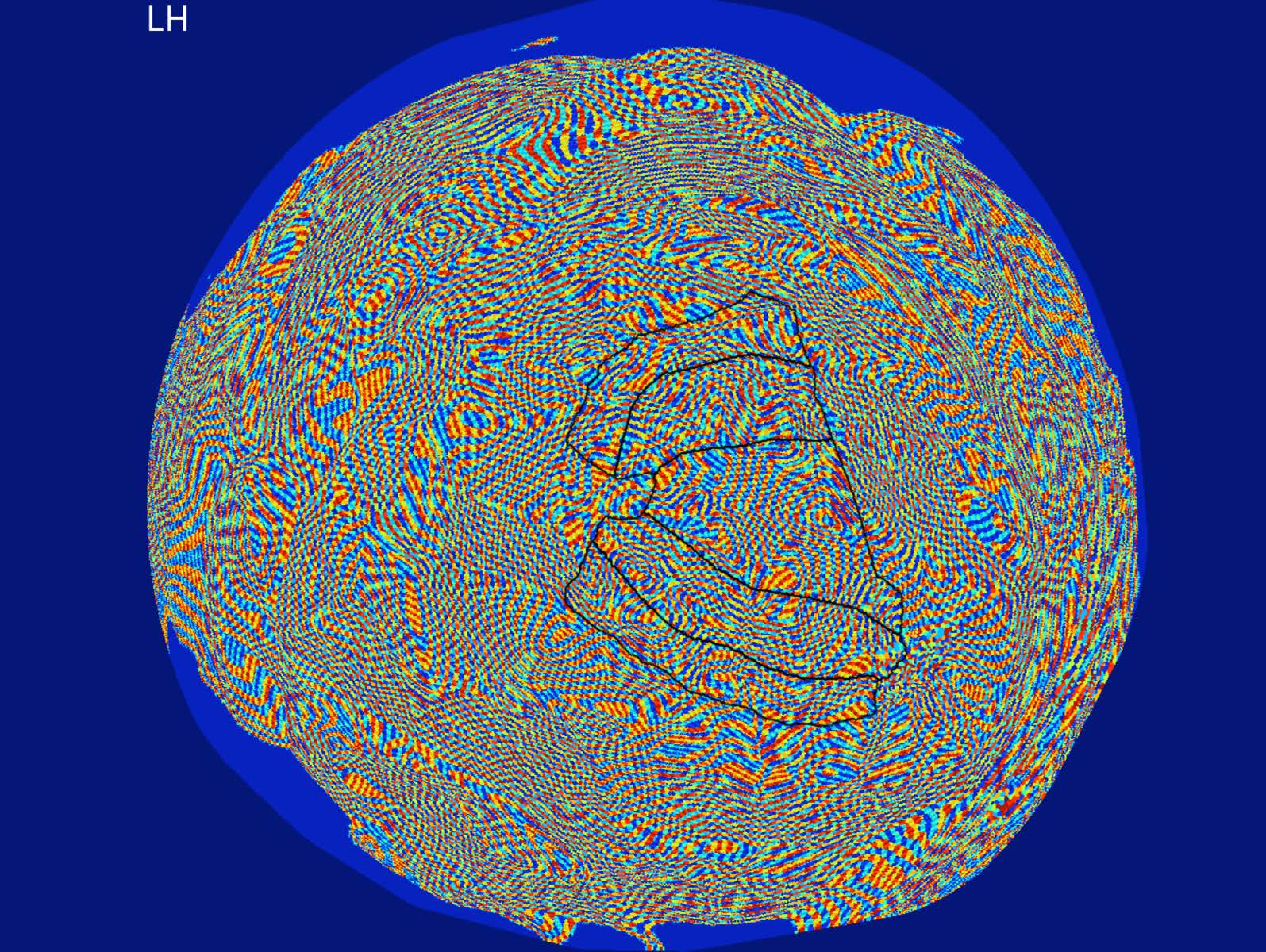


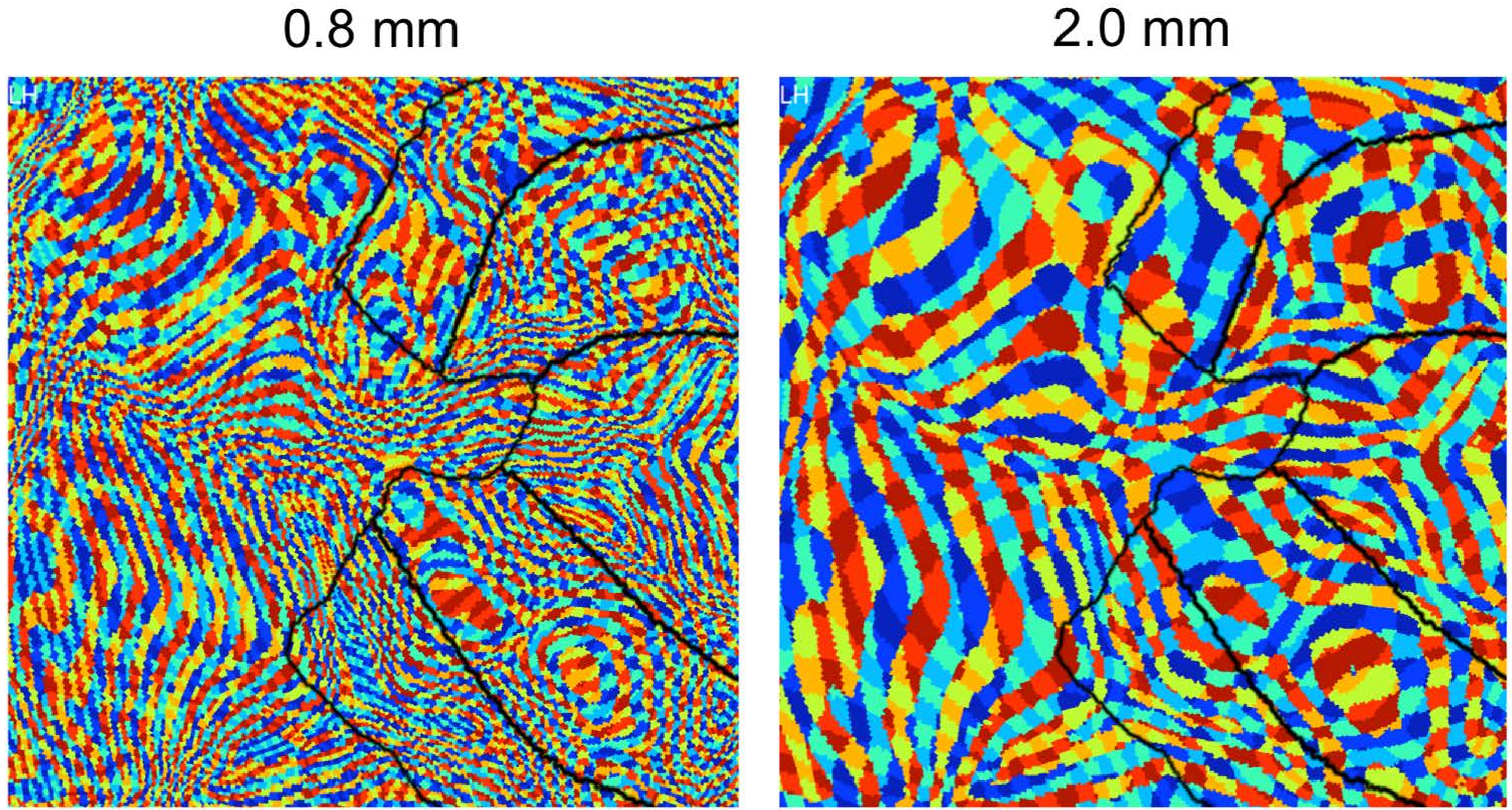
Columnar/laminar resolution

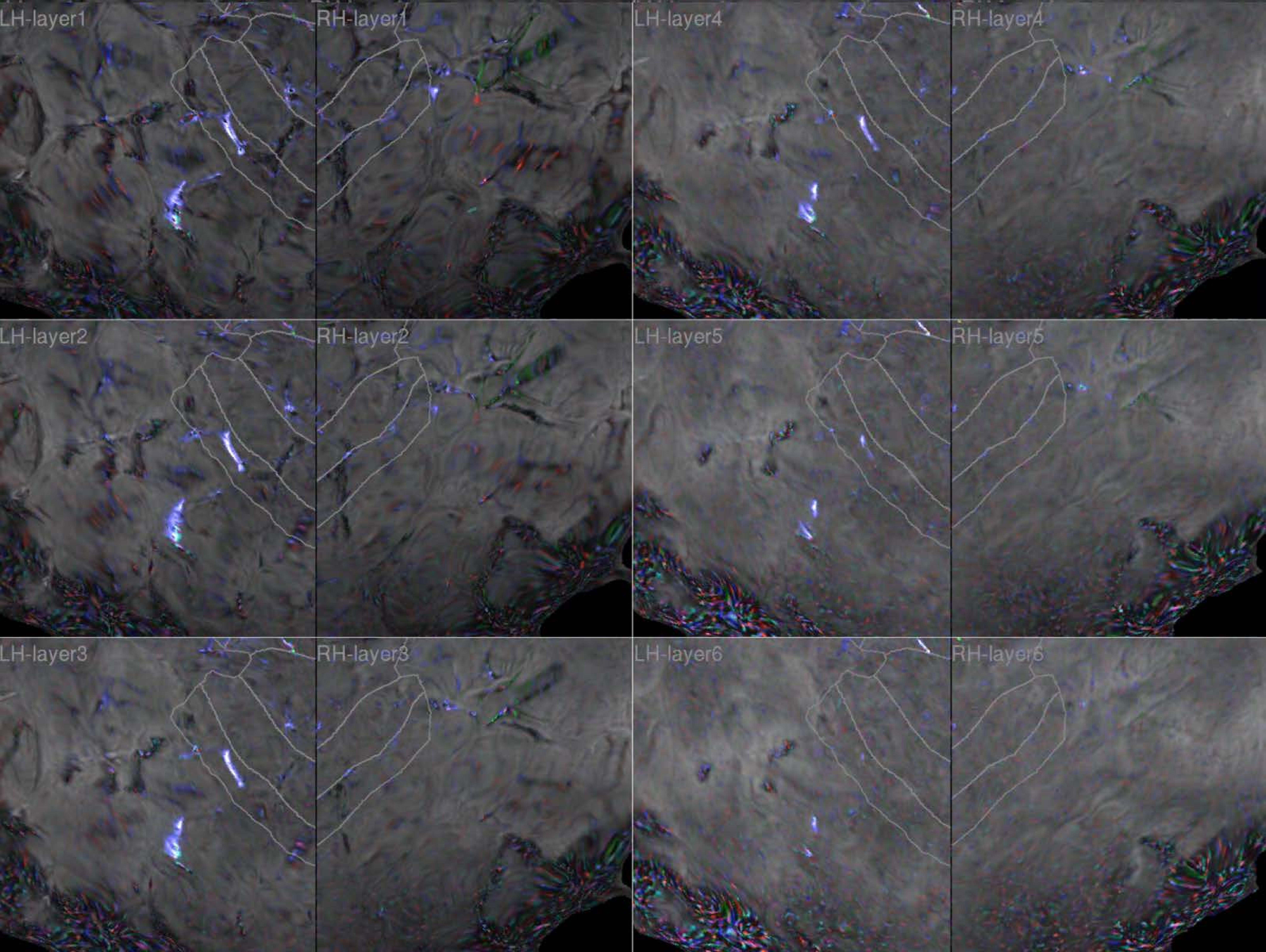
Good coverage

High signal-to-noise




LH


0.8 mm
2.0 mm
LH
LH



LH-layer1
RH-layer1
LH-layer4
RH-layer4
LH-layer2
RH-layer2
LH-layer5
RH-layer5
LH-layer3
RH-layer3
LH-layer6
RH-layer6

Challenges in high-resolution fMRI

- Signal-to-noise ratio
- Veins and neurovascular issues
- A lot of data to look at!
- Memory, computational time, disk space