Grand challenges in human cognitive neuroscience

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The brain as a computer....

**Designed**
- Functional units known
- Hardware & software independent

**Evolved**
- Functional units unclear
- Hardware constrains software
Reverse-engineering the brain

What kind of data do we need to reverse-engineer? What method should we use to collect these data? How do we interpret and model the results? How can we apply our knowledge?
The brain is organized at multiple scales

Neurons

Columns

Maps

Areas

Cajal, 1891

Oberlaender et al 2012

Ohki et al., 2006

Brodmann 1909
Mammalian vision as a model system

- Dozens of distinct areas.
- Areas arranged in a hierarchical, parallel network.
- Transformations between areas are nonlinear.
- Areas contain systematic, high-dimensional maps.
- Each area represents different visual information.

383 areas

Modha & Singh, *PNAS*, 2010

Felleman and Van Essen, *Cerebral Cortex*, 1992
How is the human cortex organized?
How do functional areas tile the cortical surface?

How is information mapped (represented) in each area?
Reverse-engineering the brain

What kind of data do we need to reverse-engineer?
What method should we use to collect these data?
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How can we apply our knowledge?
Methods for cognitive neuroscience

**Invasive**

- ECOG
- PET

**Non-Invasive**

- EEG
- MEG
- fMRI
- fNIRS

**Neural/metabolic source**
- Neural/metabolic source
- Invasive/Litigious
- PET poor time & space

**Neural source**
- Neural source
- Good time
- Poor space
- Cheap and simple

**Hemodynamic**
- Hemodynamic
- Good space
- Poor time
- fMRI Complicated
The importance of spatial information

We can map function across cortex with fMRI
MRI can recover some functional maps

Retinotopic map in macaque V1 using radioactive tracer (Tootel et al., 1988)

Retinotopic map in Human V1-V3 using functional MRI (Sereno et al., 1995)
Reverse-engineering the brain

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Functional MRI can produce rich data

Less activity  Average activity  More activity

Nishimoto et al., *Current Biology*, 2011; Huth et al., *Neuron*, 2012;
Data visualization by James Gao’s pyCortex (http://pycortex.org)
Online visualization available at http://gallantlab.org
An area can be viewed as a feature space
Voxel-wise modeling (VM)

Data collection

Voxel-wise modeling

Interpretation/visualization

Find functional areas

Decode information

Collect BOLD data
- Select hypothesis domain
- Select stimulus set
- Select behavioral task
- Optimize fMRI acquisition parameters
- Collect BOLD fMRI data

Pre-process BOLD data
- Correct for motion artifacts
- Align brains across sessions
- Remove drift and sphere data

Specify model framework
- Select feature space
- Project stimuli/task into features
- Select fitting algorithm

Fit model to each voxel
- Split data into estimation and validation sets
- Use estimation set to fit models
- Use validation set to evaluate significance
- Use evaluation set to test predictions

Visualize data within subjects
- Use statistical threshold to select voxels
- Use prediction quality to select models
- Visualize RFs of single voxels
- Visualize voxel RFs in feature space
- Visualize voxel RFs on cortical flat maps

Visualize data across subjects
- Find common space across subjects
- Visualize feature space
- Visualize flat maps
- Discover areas/gradients on flat maps
- Visualize canonical flat maps

Decode (identify, reconstruct)
- Obtain prior distribution
- Process prior with encoding models
- Aggregate posterior likelihoods
- Project features into original space
- Display MAP or AHP
A semantic object and action model

Huth, Nishimoto, Vu & Gallant, *Neuron*, 2012

Video clips labeled every 1s

Labels:
- dog
- canine
- animal
- manually assigned label
- woman
- adult
- person
- inferred labels

2 hours of labeled natural movies

Presence of category

<table>
<thead>
<tr>
<th>Dog</th>
<th>Canine</th>
<th>Animal</th>
<th>Tree</th>
<th>Plant</th>
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</tbody>
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Regression

Response to dog
- Delay (TR)

Response to tree
- Delay (TR)

- (1703 other features)
A common ~4 dimensional semantic space

Huth, Nishimoto, Vu & Gallant, *Neuron*, 2012
Concept representation in the semantic space

Huth, Nishimoto, Vu & Gallant, *Neuron*, 2012
Cortical maps of semantic space

Huth, Nishimoto, Vu & Gallant, *Neuron*, 2012
Attention changes cortical maps

Cukur, Nishimoto, Huth & Gallant, *Nature Neuroscience*, 2013
Maps differ across individuals

Huth, Griffiths & Gallant, *in preparation*
Conventional cross-subject surface alignment

Van Essen, NeuroImage, 2005
Areal vs LSA PC models (provisional)

Areal map predicted from generative model & anatomy

Functional map obtained from semantic model

Huth, Griffiths & Gallant, *in preparation*
Reverse-engineering the brain

What kind of data do we need to reverse-engineer? What method should we use to collect these data? How do we interpret and model the results? How can we apply our knowledge?
Using encoding models to decode the brain

\[ P(f(S)|R) \propto P(R|f(S))P(f(S)) \]
Structural & semantic decoding (all vision)

Naselaris, Kay, Prenger, Oliver and Gallant, *Neuron*, 2009
### LDA scene decoding (higher vision)

<table>
<thead>
<tr>
<th>Image</th>
<th>Likely Scene</th>
<th>Likely Objects</th>
<th>Image</th>
<th>Likely Scene</th>
<th>Likely Objects</th>
</tr>
</thead>
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| ![Image](image1.png) | land animals  
few people  
food  
fields  
water animals | man  
woman  
person  
head  
animal | ![Image](image2.png) | urban areas  
large crowds  
lecture hall | sky  
car  
building  
road  
people |
| ![Image](image3.png) | sporting event  
large crowds  
few people  
lecture hall  
fields | athlete  
people  
man  
woman  
person | ![Image](image4.png) | fields  
fenced areas  
large crowds  
birds  
living area | grass  
trees  
fence  
field  
ground |
| ![Image](image5.png) | signs/text | text  
sign  
washbowl  
beverage  
background | ![Image](image6.png) | food  
few people  
human indoors | food  
fruit  
vegetables  
vegetable  
container |

Stansbury, Naselaris and Gallant, *Neuron*, 2013
Motion-energy decoding (early vision)

Nishimoto, Vu, Naselaris, Benjamini, Yu and Gallant, *Current Biology*, 2011
WordNet decoding (higher vision)

Movie

Likely Objects and Actions

Huth, Lee, Nishimoto & Gallant, in preparation
Structural & semantic decoding (all vision)

Naselaris, Kay, Prenger, Oliver and Gallant 2009

Naselaris, Nishimoto and Gallant, in preparation
Factors limiting brain decoding

- Quality of brain activity measurements.
- Accuracy of brain models.
- Computer power.
Grand challenges: Higher spatial resolution

Grand challenge: Measure neurons!

- **BOLD**
- **Indirect**
- **Coarse**
- **Slow**
Grand challenges: Longer data sets

Oliver & Gallant, in preparation
Grand challenges: Measure connections

Van Wedeen, Science, 2012
Grand challenges: Measure cognitive states

Gao & Gallant, in preparation
Grand challenges: Portable measurement

White & Culver, *NeuroImage*, 2010
Grand challenge

MEASUREMENT!
Natalia Bilenko
Tolga Cukur
James Gao
Alex Huth
Fatma Imamoglu

Mark Lescroart
Anwar Nunez
Michael Oliver
Dustin Stansbury

Stephen David (OHSU))
Kate Gustavsen (UTVM)
Kathleen Hansen (NIH)
Ben Hayden (URochester)
Kendrick Kay (Stanford)
James Mazer (Yale)

This work was supported by NEI, NIMH and NSF