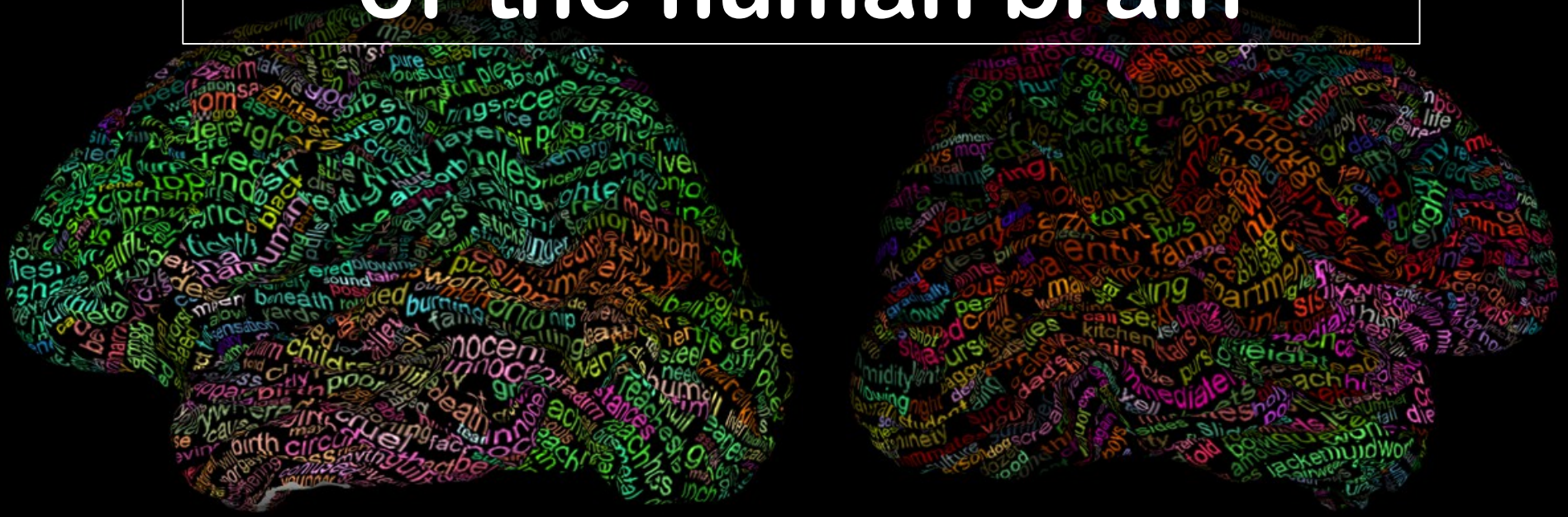
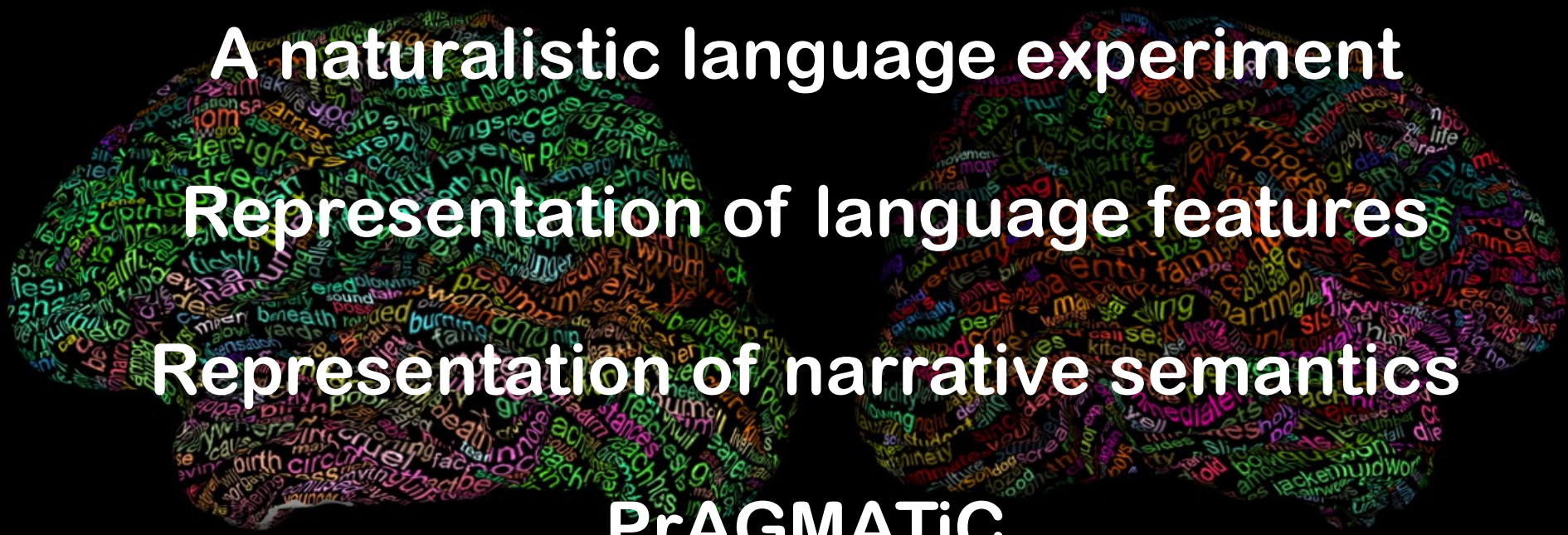
Working toward a complete functional atlas of the human brain



Jack Gallant
Alex Huth, Wendy de Heer, Tom Griffiths, Frederic Theunissen
Fatma Imamoglu, Leila Wehbe, Anwar Nunez-Elizalde
University of California at Berkeley

The pursuit of detailed cortical maps



A naturalistic language experiment

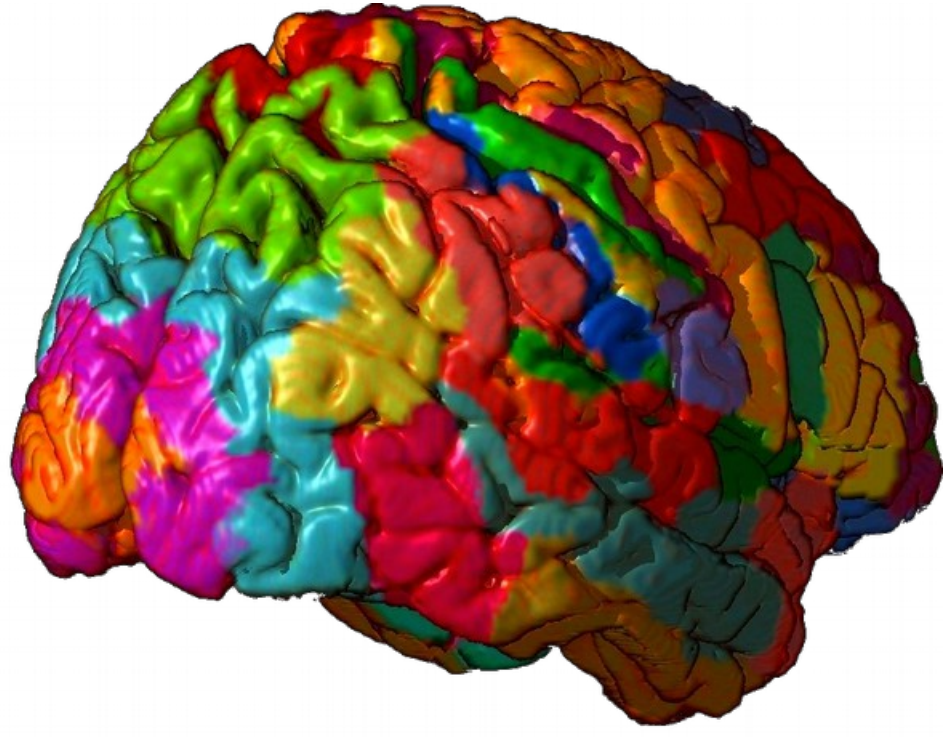
Representation of language features

Representation of narrative semantics

PrAGMATiC

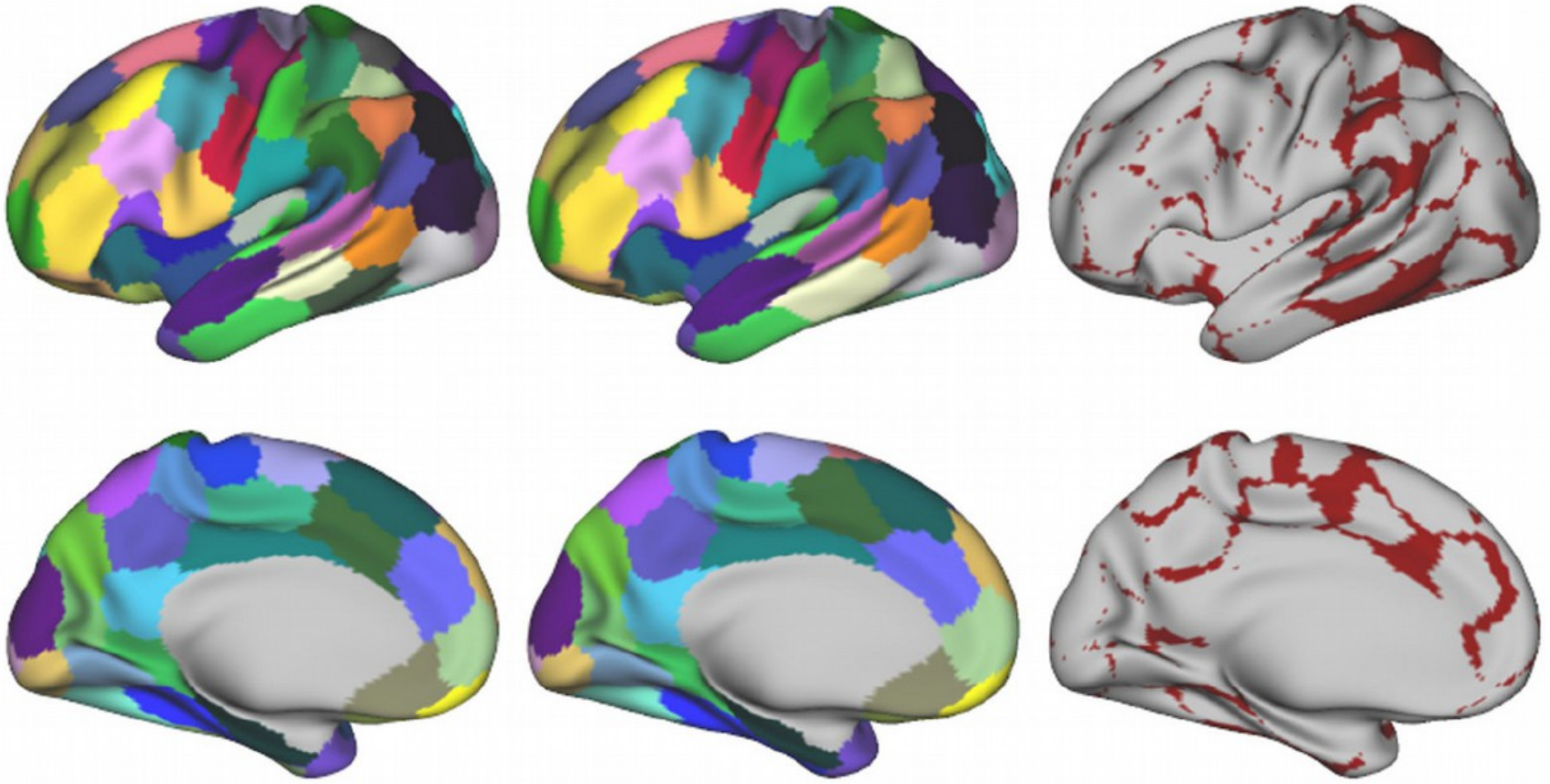
“But what good does this do me?”

Parcellation from histology



After Brodmann, 1868/1918

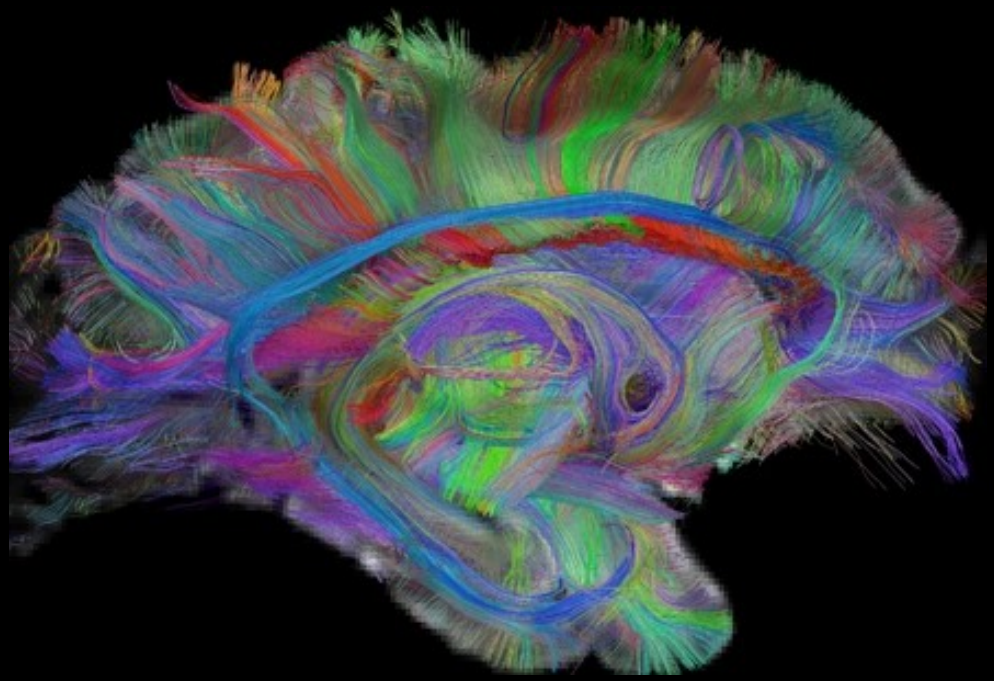
Parcellation from diffusion MRI

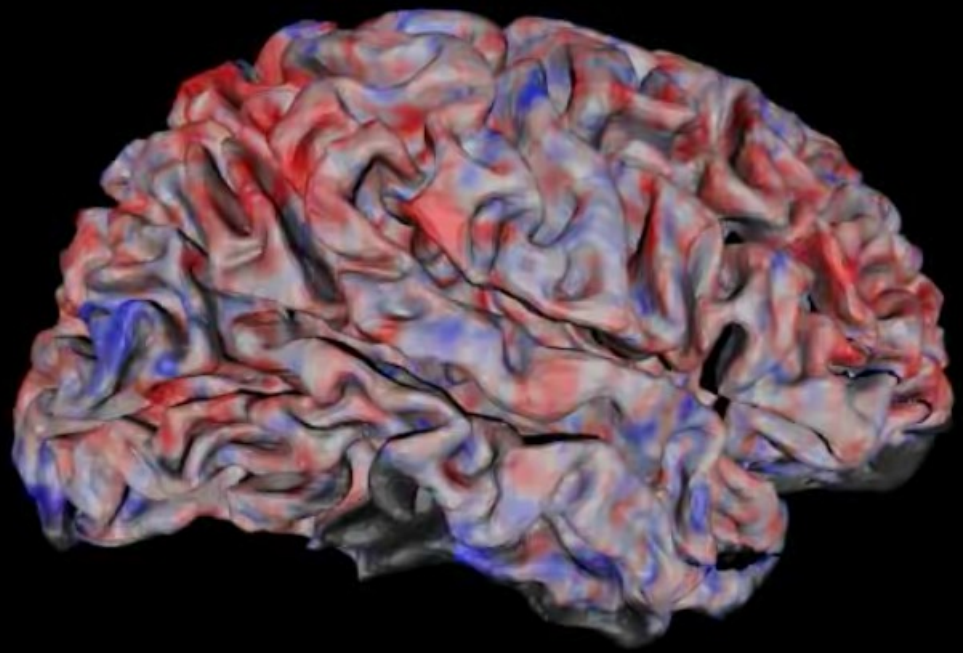


70 Area Parcellation

Parisot, Arslan, Passerat-Palmbach et al., *Inf. Proc. Med. Img.*, 2015

Structure and function are intimately related

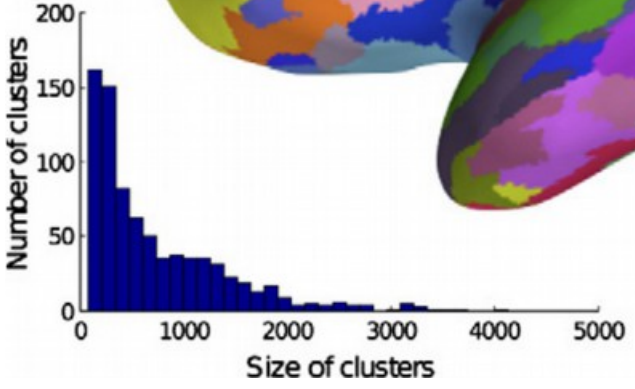




Parcellation from resting state covariances

60 minutes rest

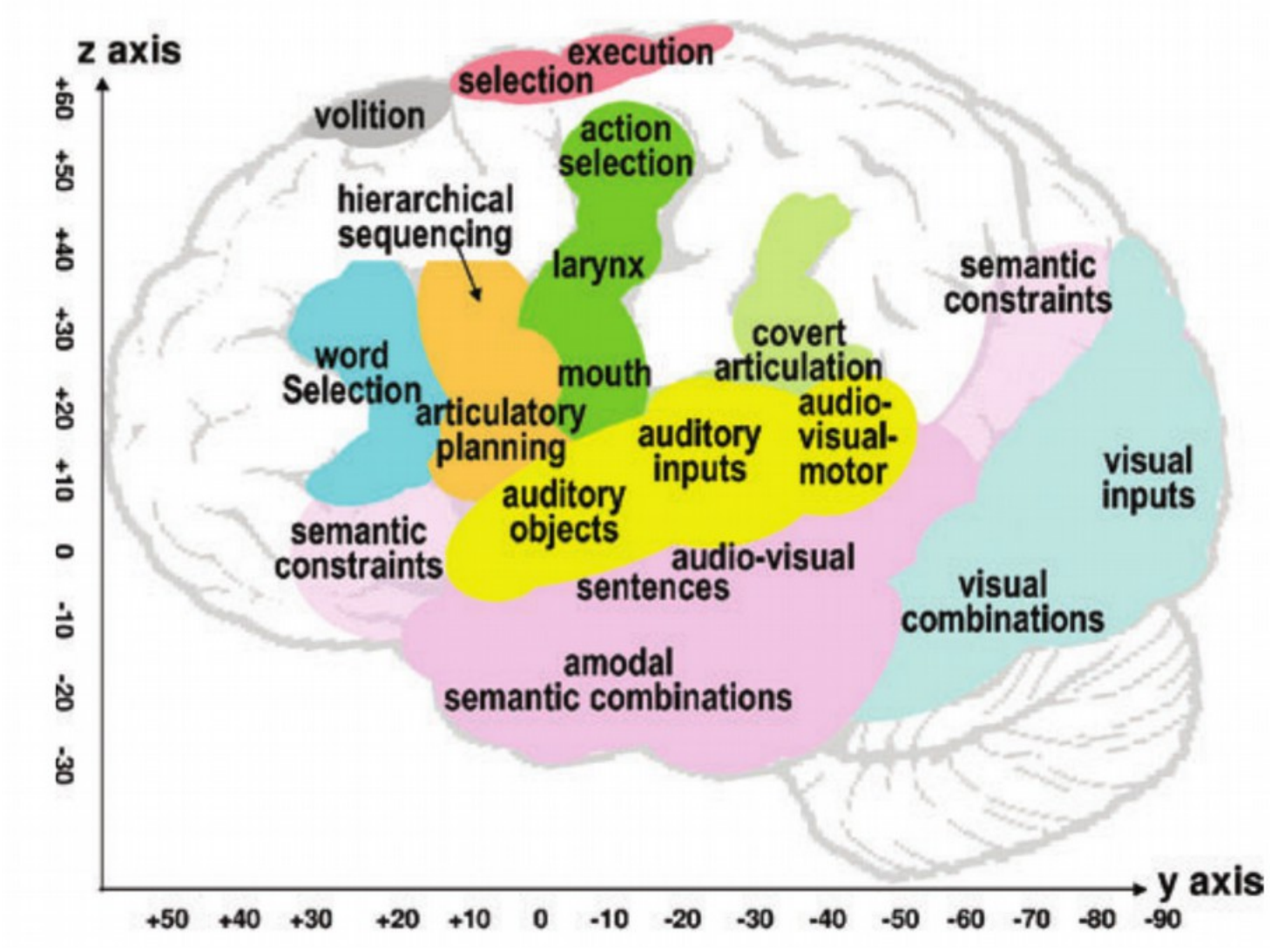
Replication



400 Area Parcellation

Blumensath, Jabaldi, Glasser, et al., *NeuroImage*, 2013

Parcellation from meta-analysis of functional contrasts



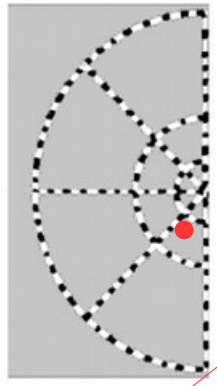
Price, *Ann. NY Accad. Sci.*, 2010

Goals for functional parcellation

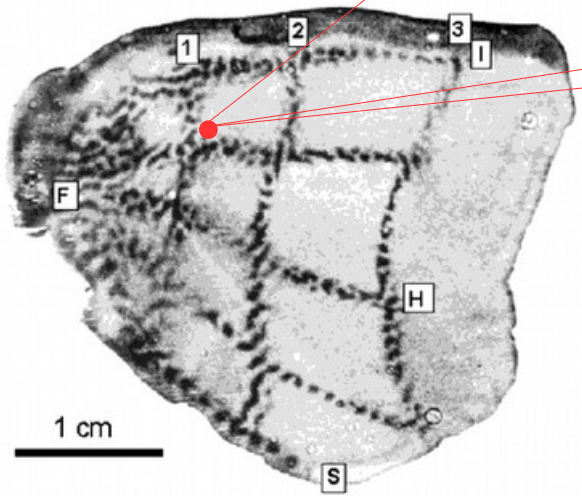
- Obtain a functional parcellation for real stimuli, tasks and responses.
- Account for as broad a range of stimuli, tasks and responses as possible.
- Recover as much of intrinsic tuning space of each parcellated area as possible.
- Account for individual differences in functional parcellation.
- Account for changes in functional parcellation due to task demands.
- Link functional parcellation to anatomical parcellation.

fMRI recovers a low-dimensional sub-space of the dimensions represented in an area

Retinotopic Mapping Stimulus

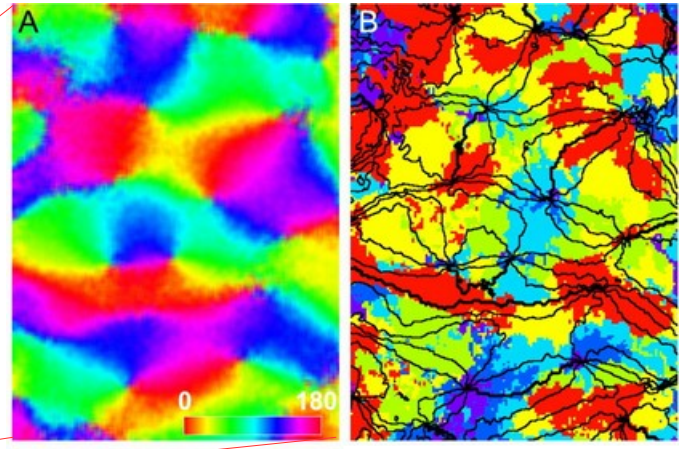


2DG map on flattened Macaque cortex



Orientation

Spatial frequency



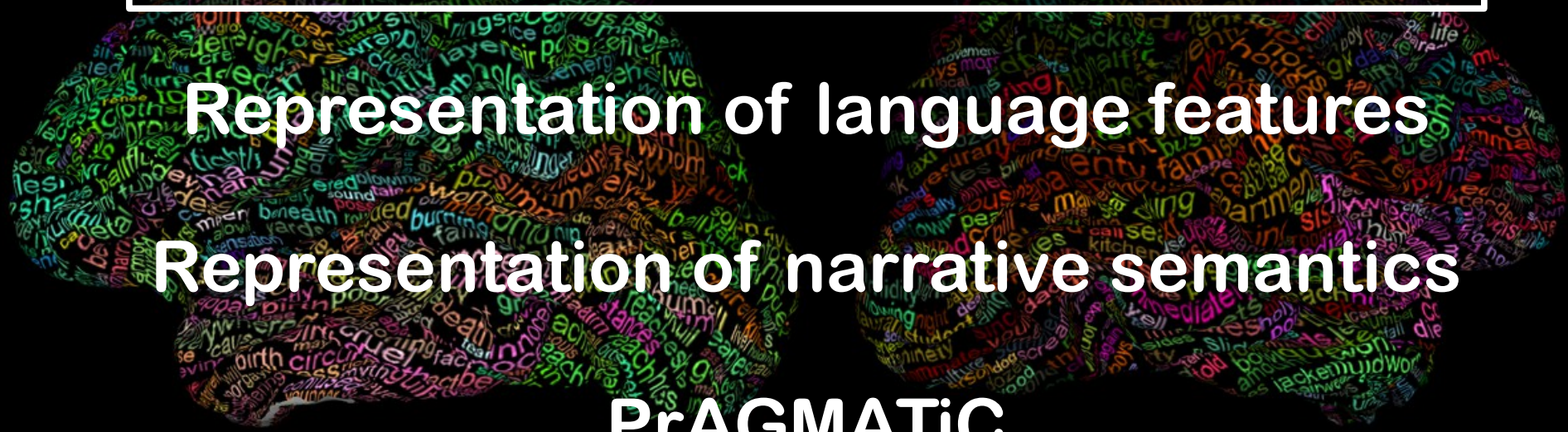
Ocular dom.

Tootel et al., *J. Neurosci* (1988)

Issa, Trepel & Stryker, *J. Neurosci* (2000)

The pursuit of detailed cortical maps

A naturalistic language experiment



Representation of language features

Representation of narrative semantics

PrAGMATiC

“But what good does this do me?”

Comprehension of natural narrative speech

Wendy de Heer

Tom Griffiths

Frederic Theunissen

Alex Huth

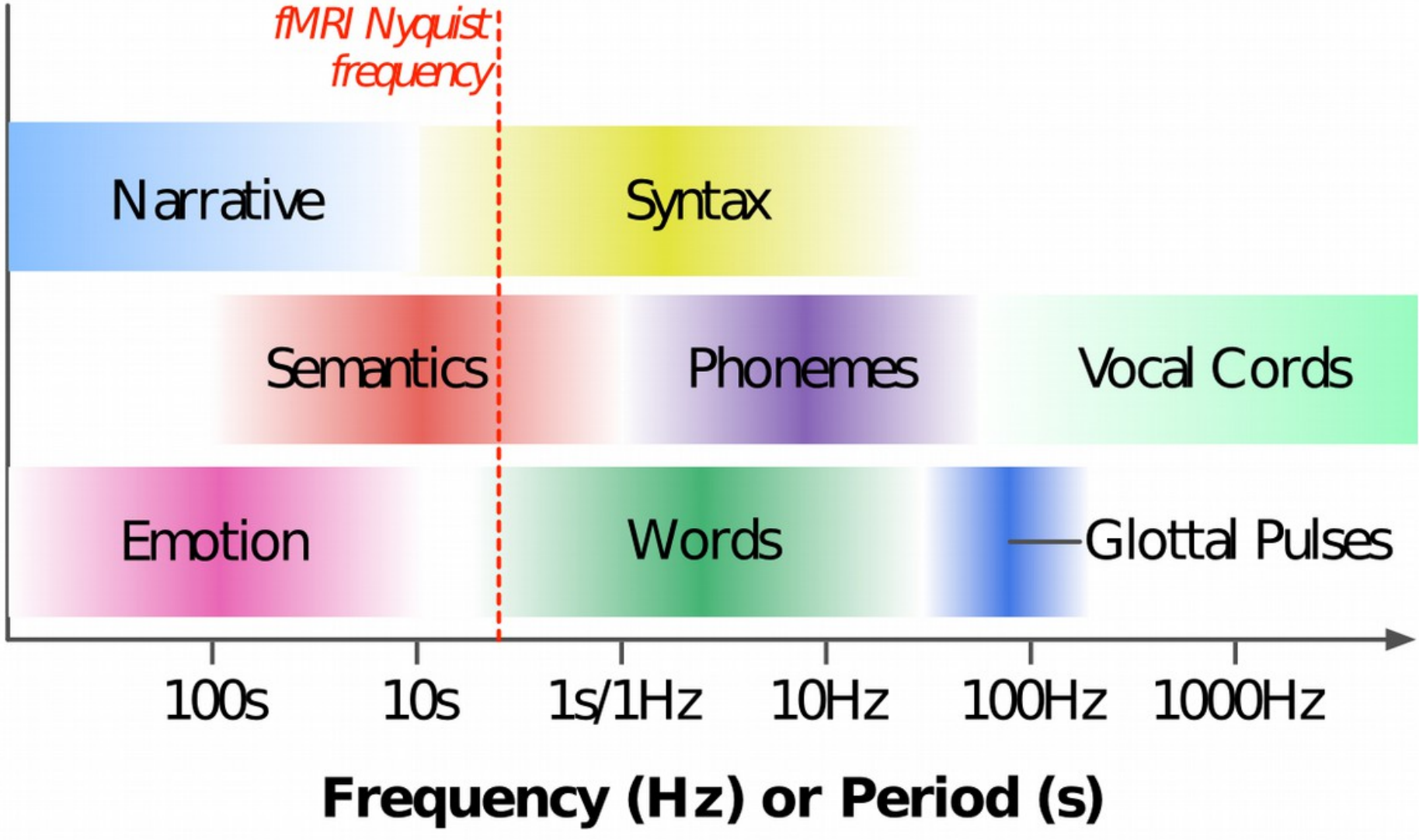
Subjects listen to 2 hours of narrative stories

Whole-brain BOLD recorded using GE-EPI @ 3T

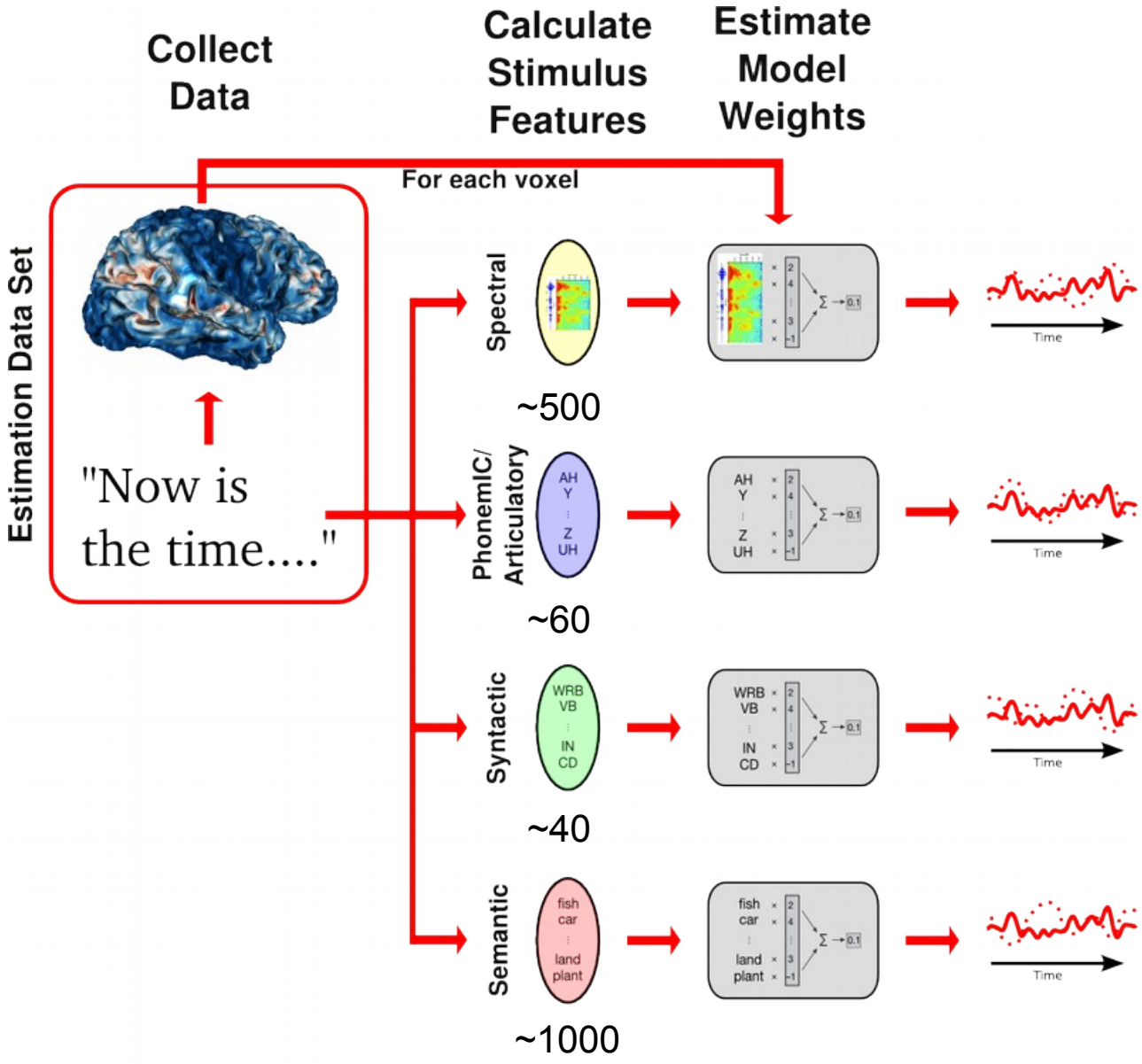
2.24x2.24x4.1 mm voxels

TR 2.0045 s

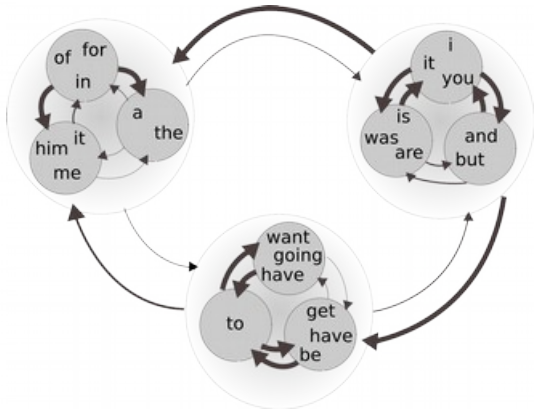
Time scales of linguistic features



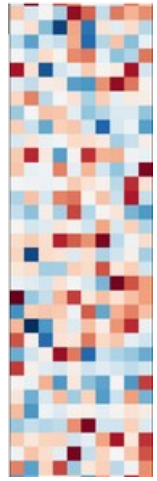
Voxel-wise modeling of narrative stories



Syntactic model: HHMM



Semantic model: ~LSA

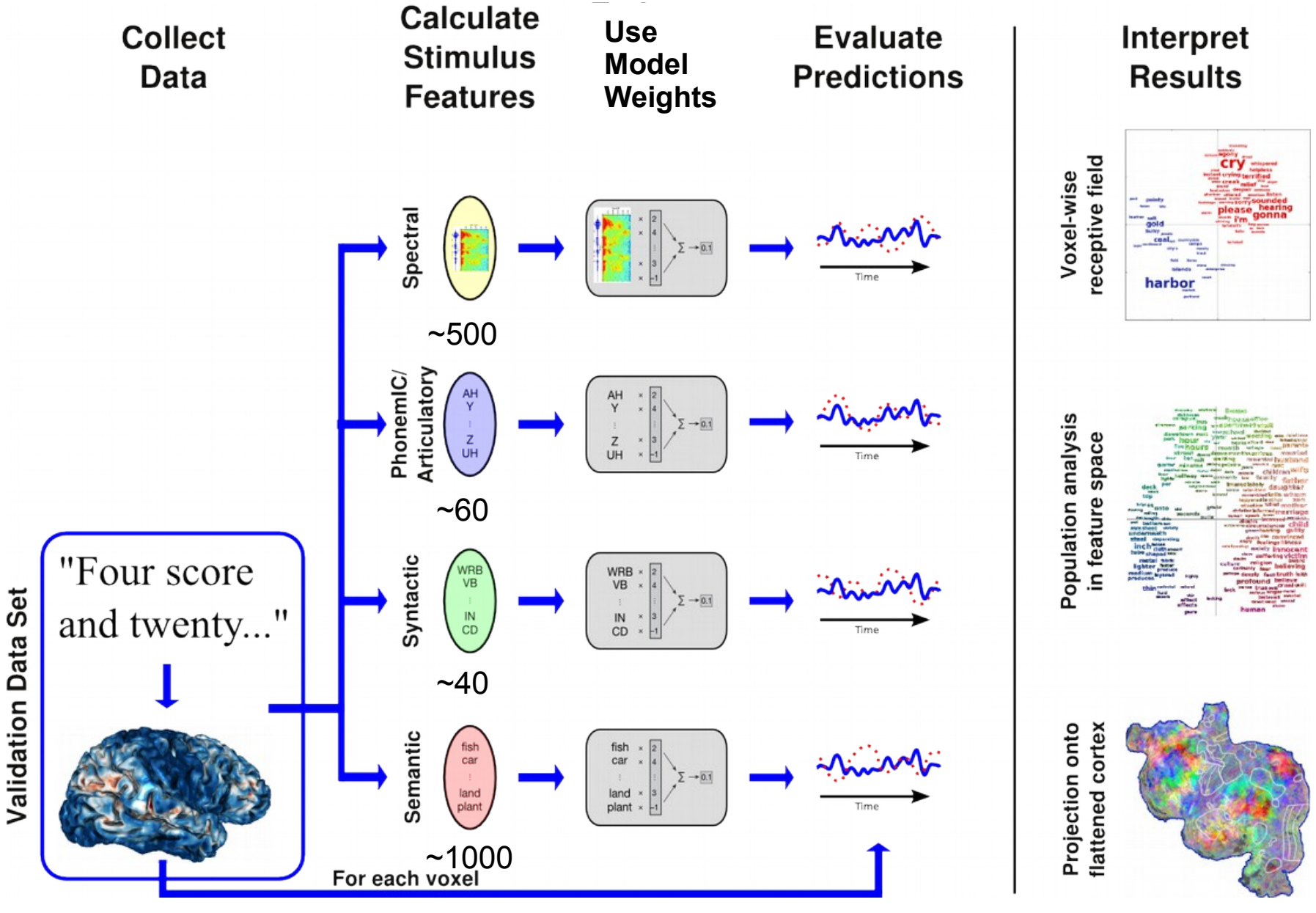


10470 Words in Lexicon

985 Target Words

Other potential feature spaces: Prosody, Narrative

Voxel-wise modeling of narrative stories



The pursuit of detailed cortical maps

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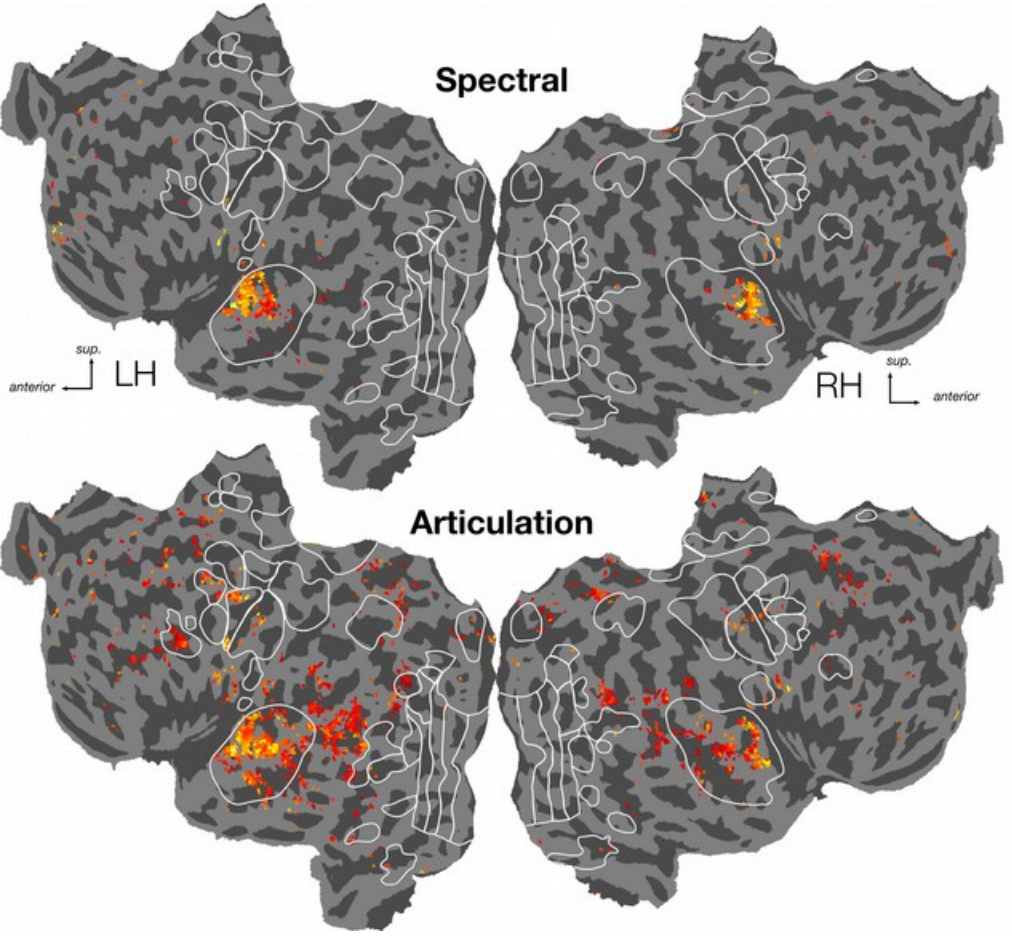
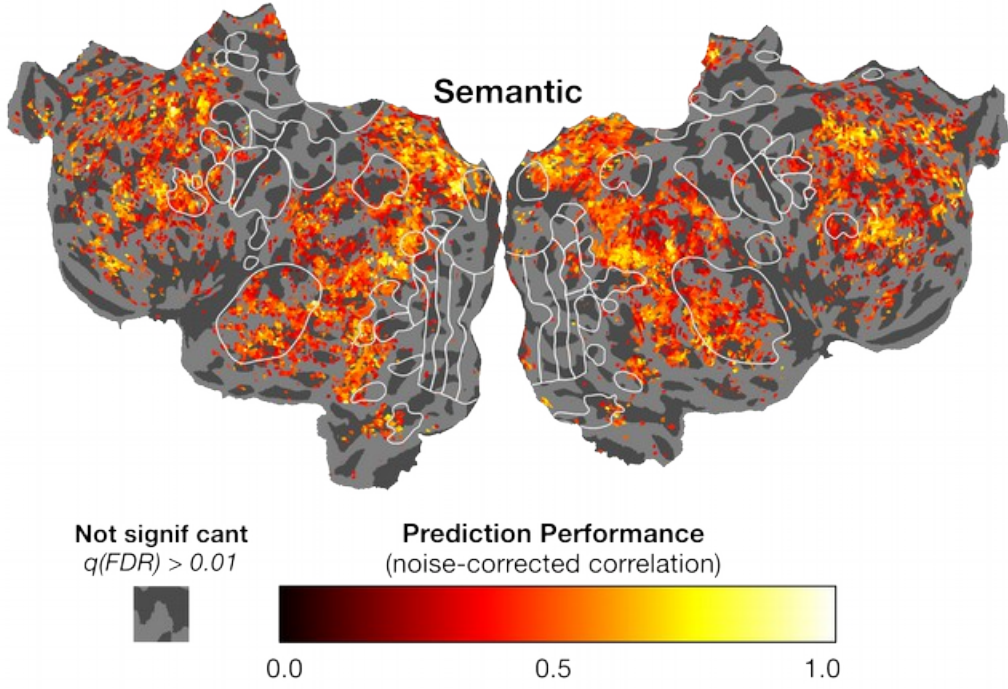
“But what good does this do me?”

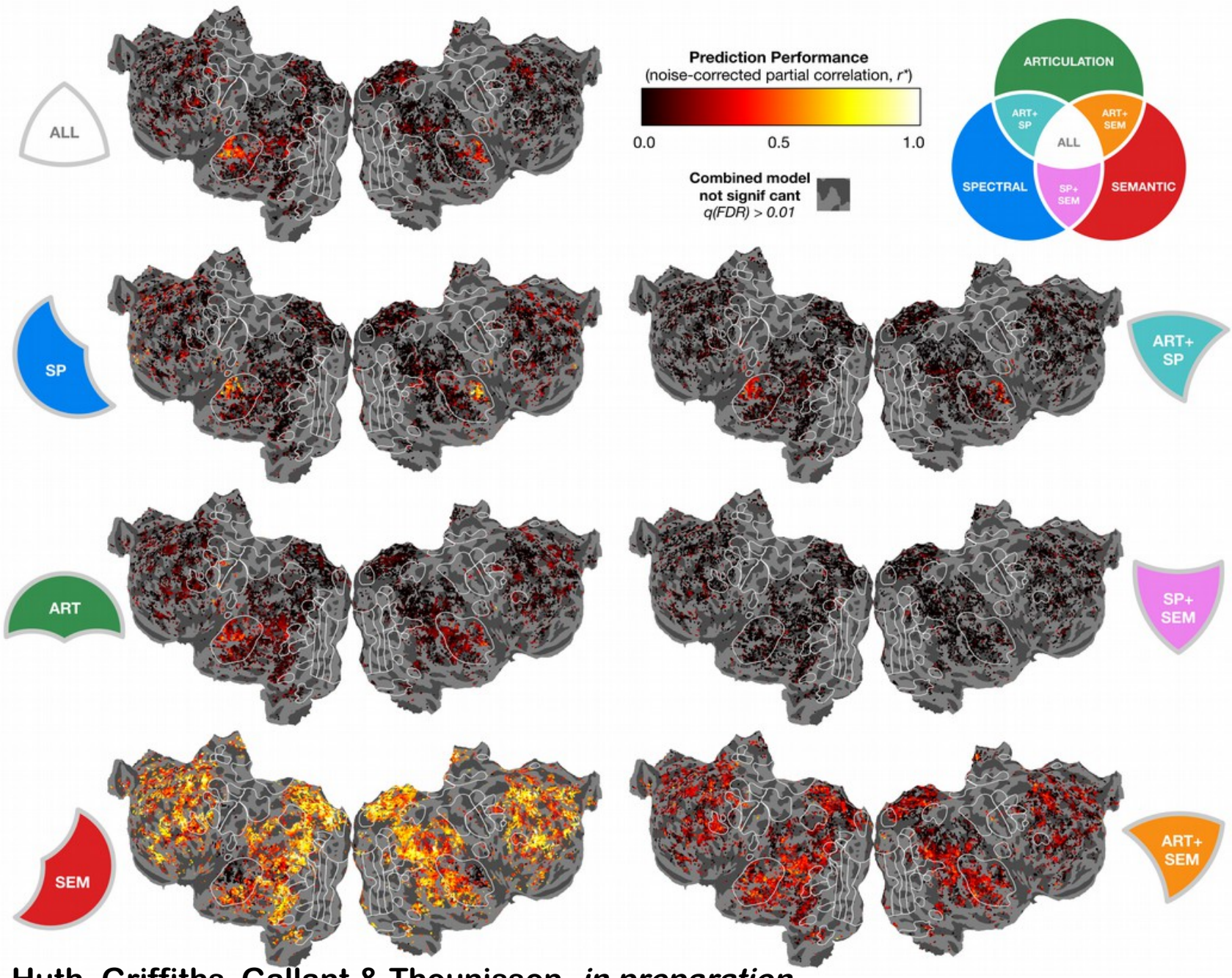
Predictions of spectral, articulatory and semantic models





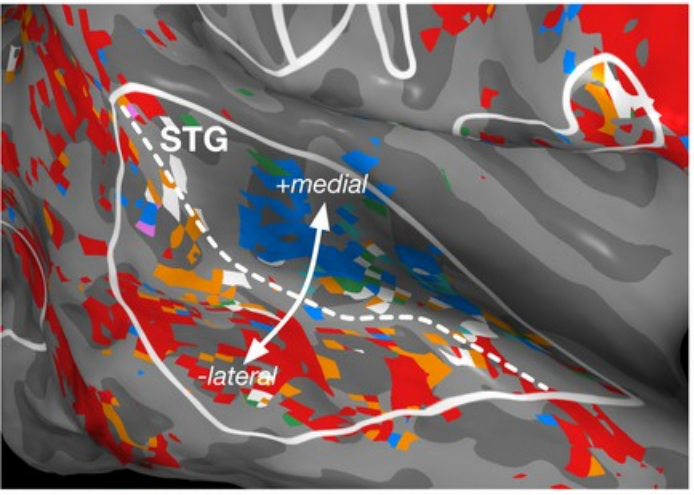
de Heer, Huth, Griffiths, Gallant & Theunissen, *in preparation*

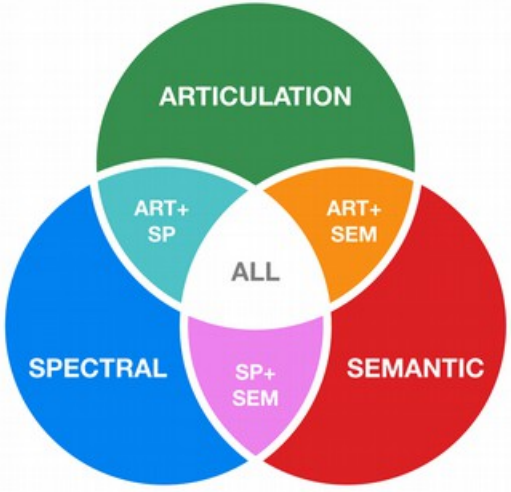
Variance partitioning analysis

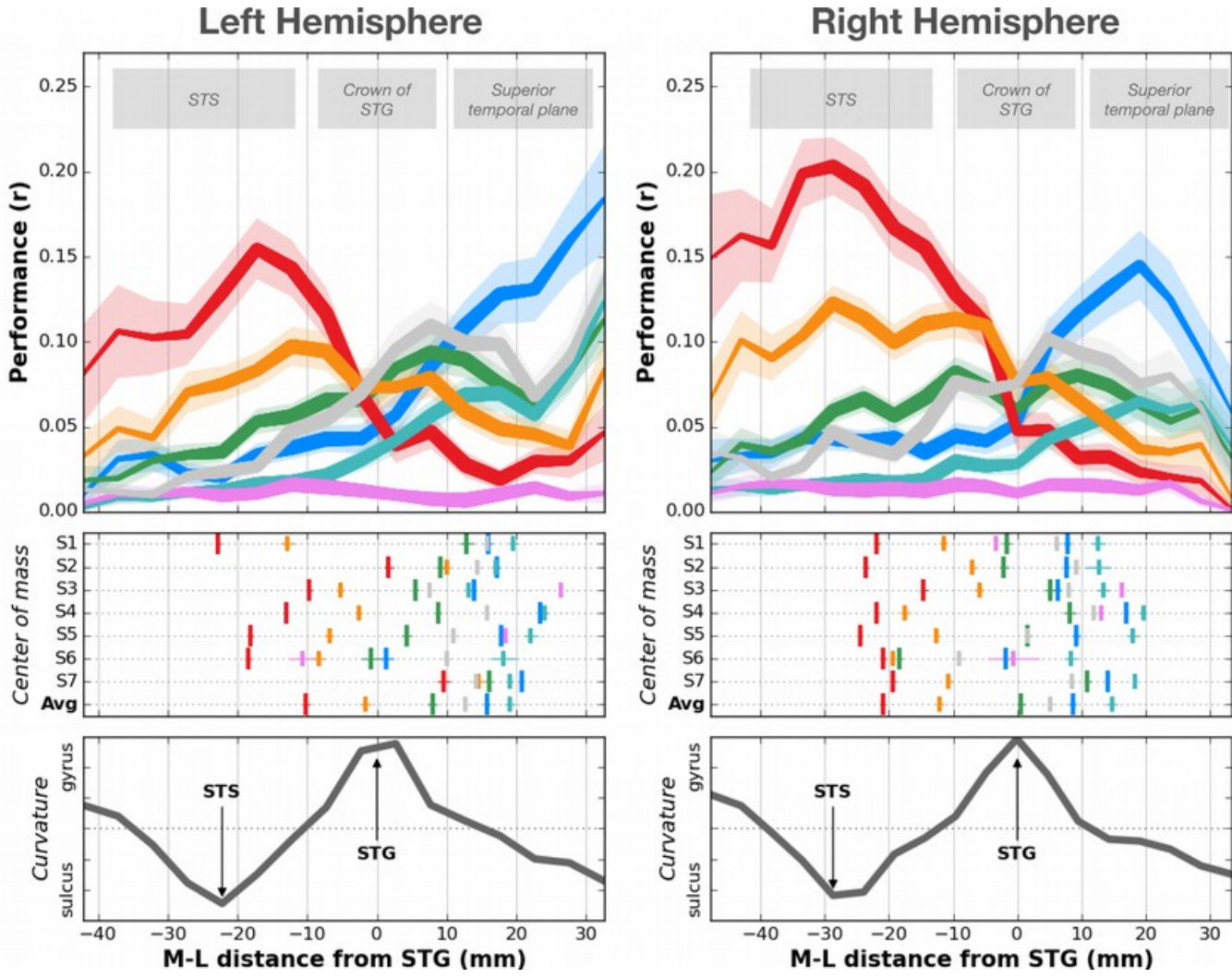


de Heer, Huth, Griffiths, Gallant & Theunissen, *in preparation*

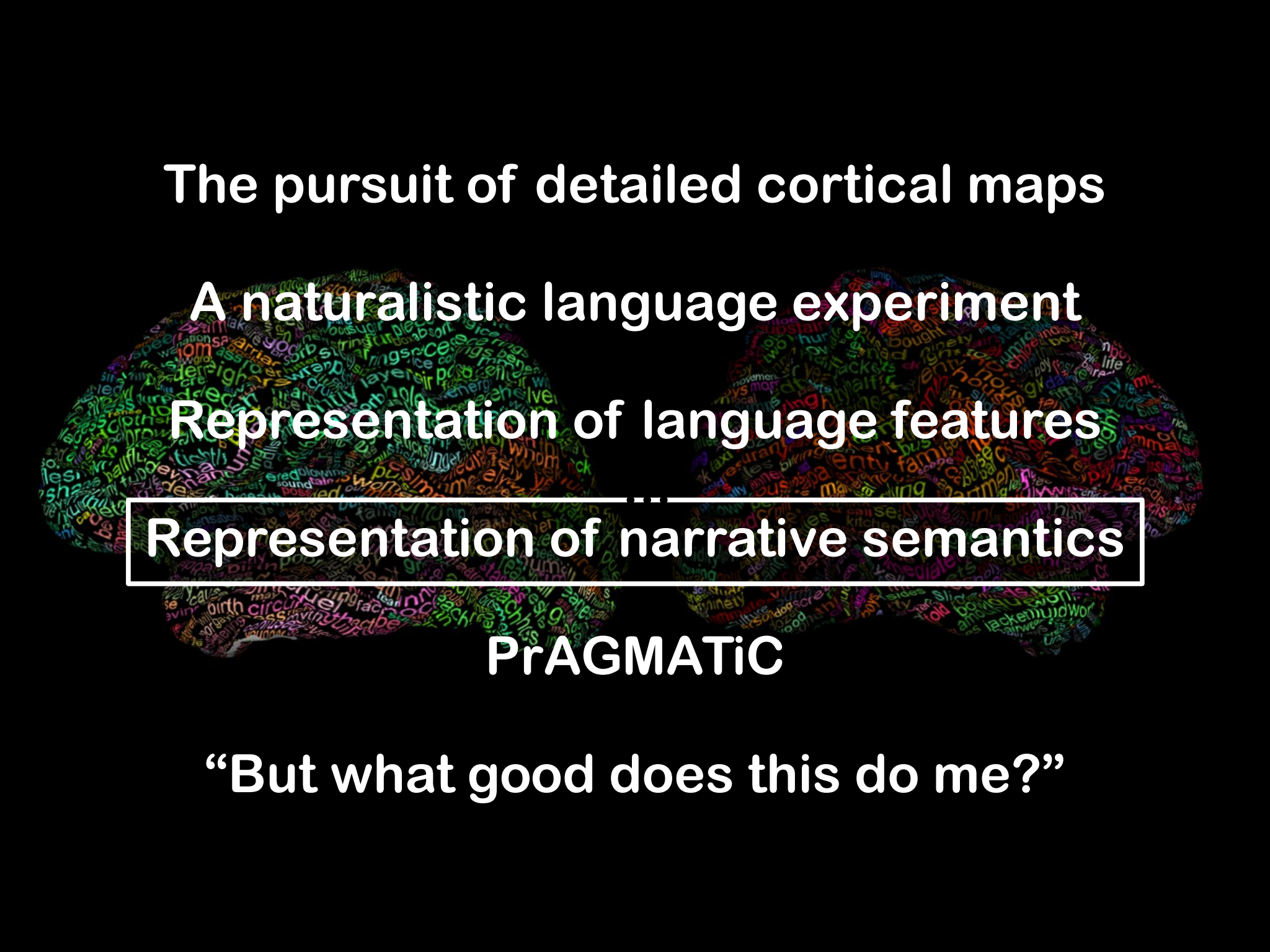
Features represented near STG







de Heer, Huth, Griffiths, Gallant & Theunissen, *in preparation*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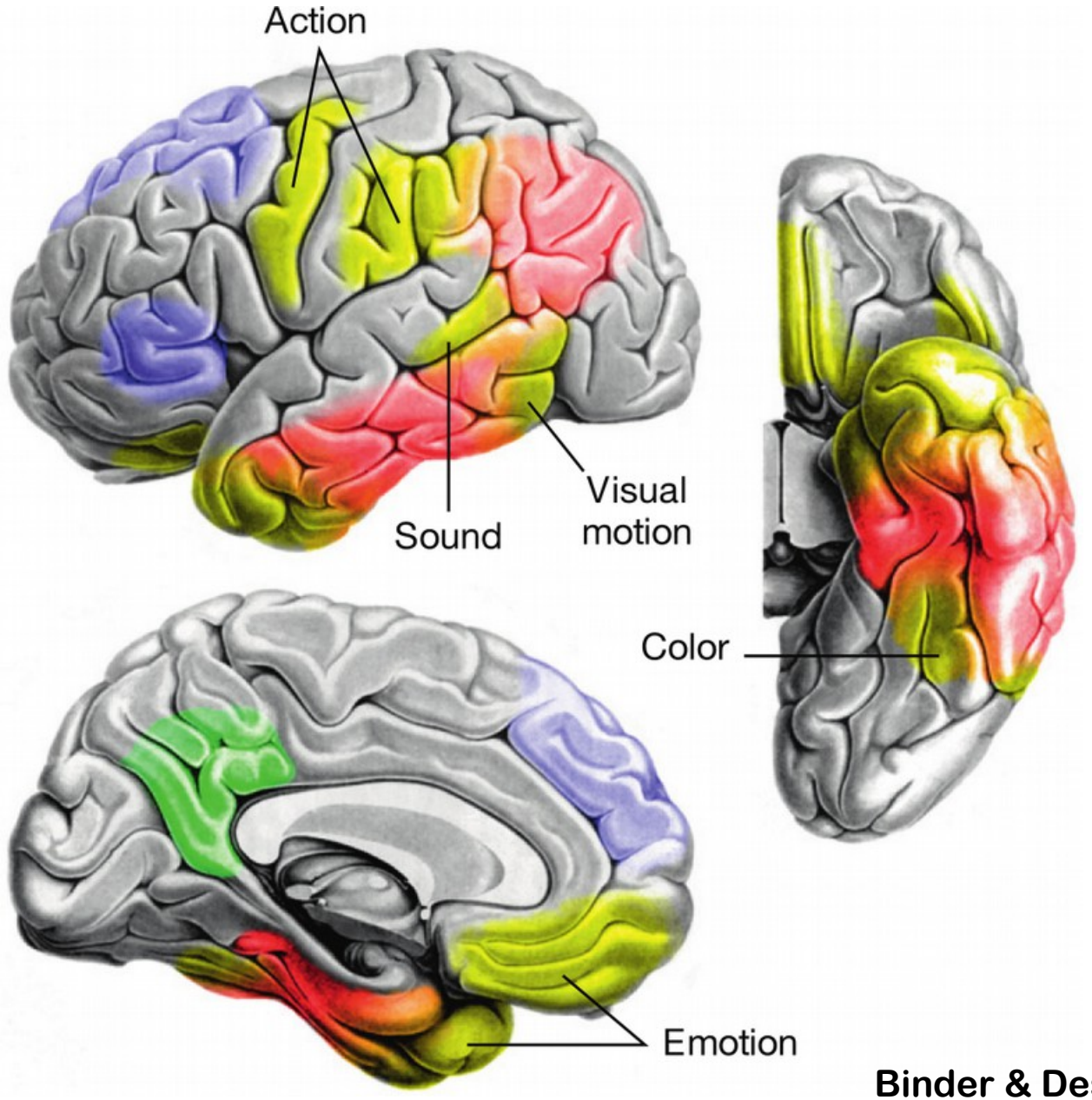
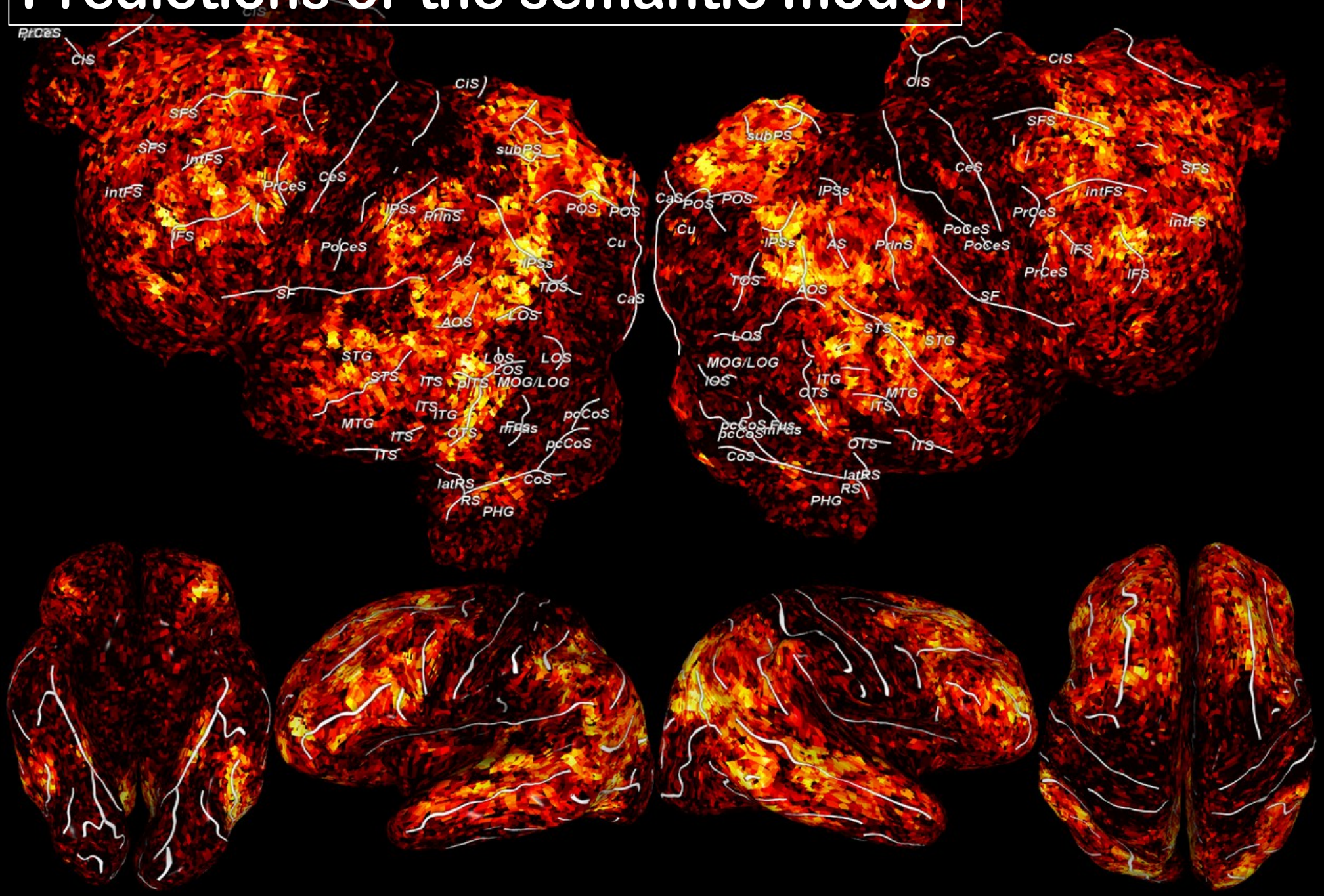


- Modality-specific sensory, motor & emotion systems
- Temporal-Parietal convergence zones
- Semantics/ memory interface
- Goal-directed activation & selection of semantic information.

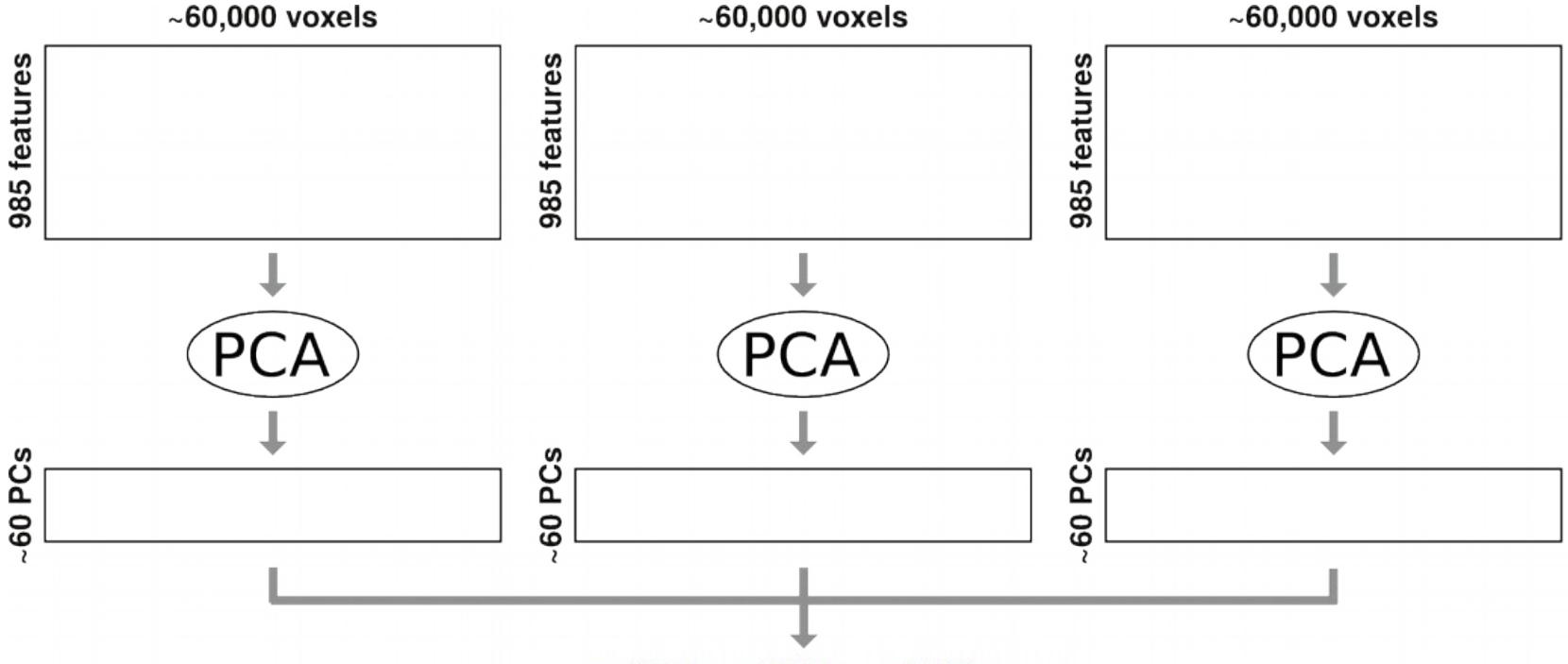
Binder & Desai, *Trends in Cog. Sci.*, 2011

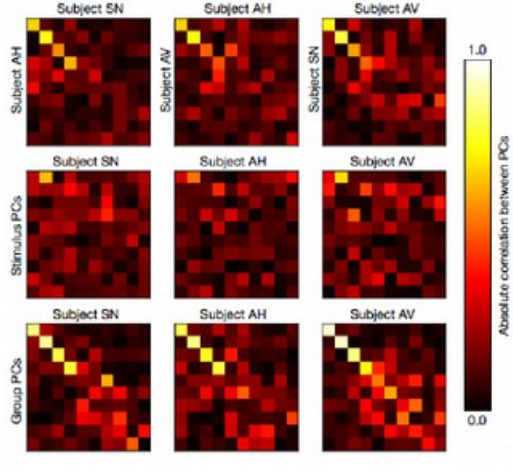
Predictions of the semantic model

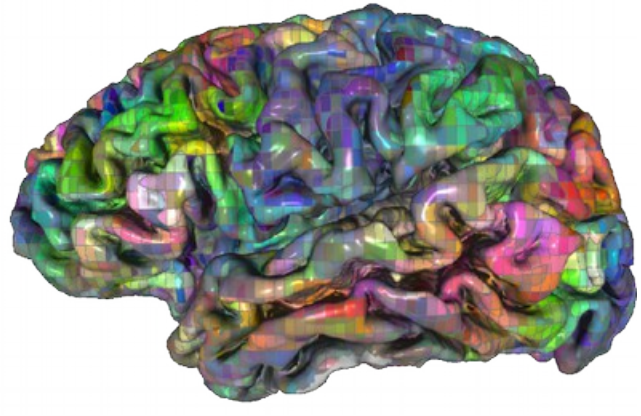


Huth, de Heer, Griffiths, Theunissen & Gallant, *Nature*, in press

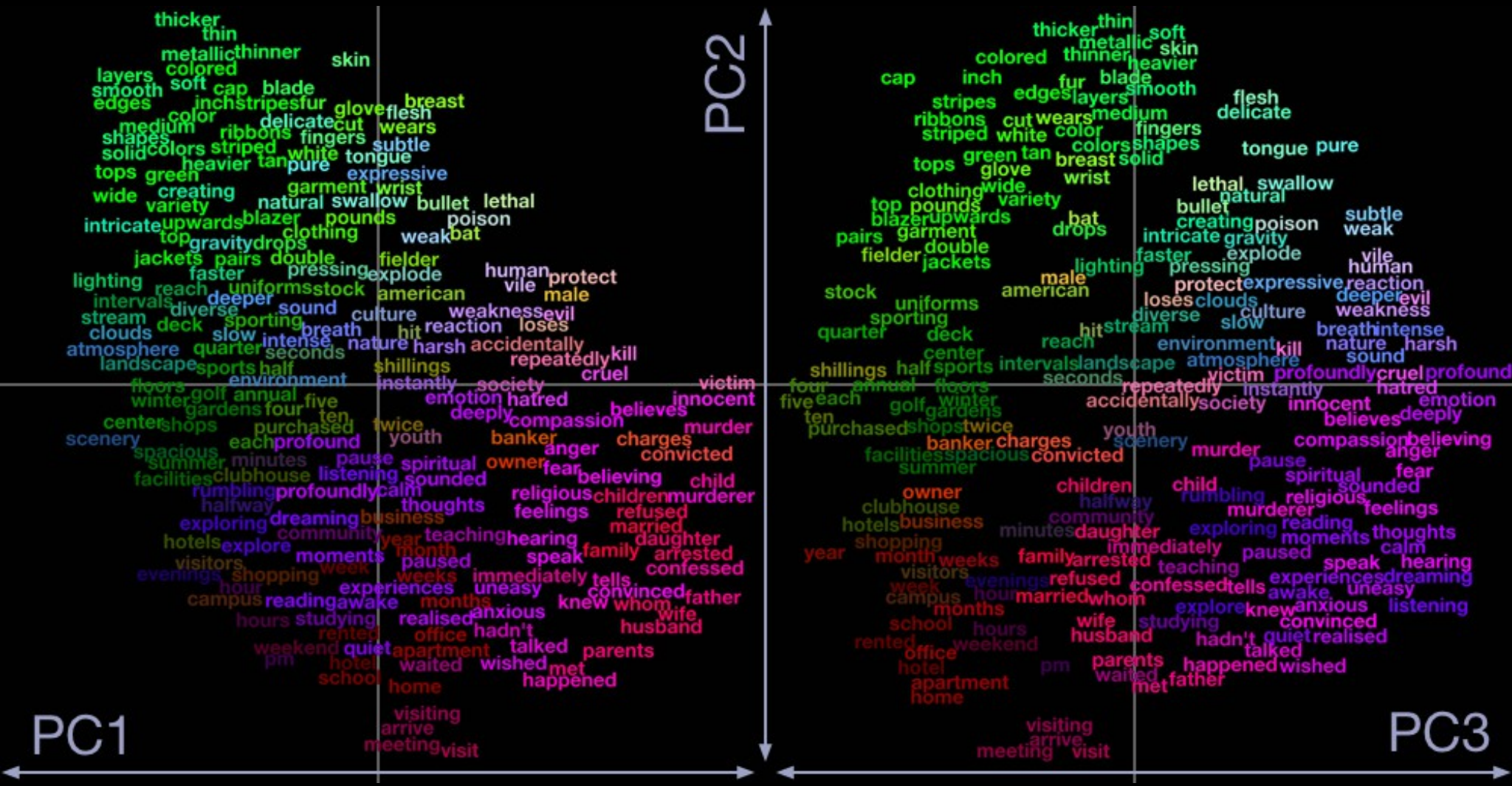
Cross-subject analysis recovers a common semantic space





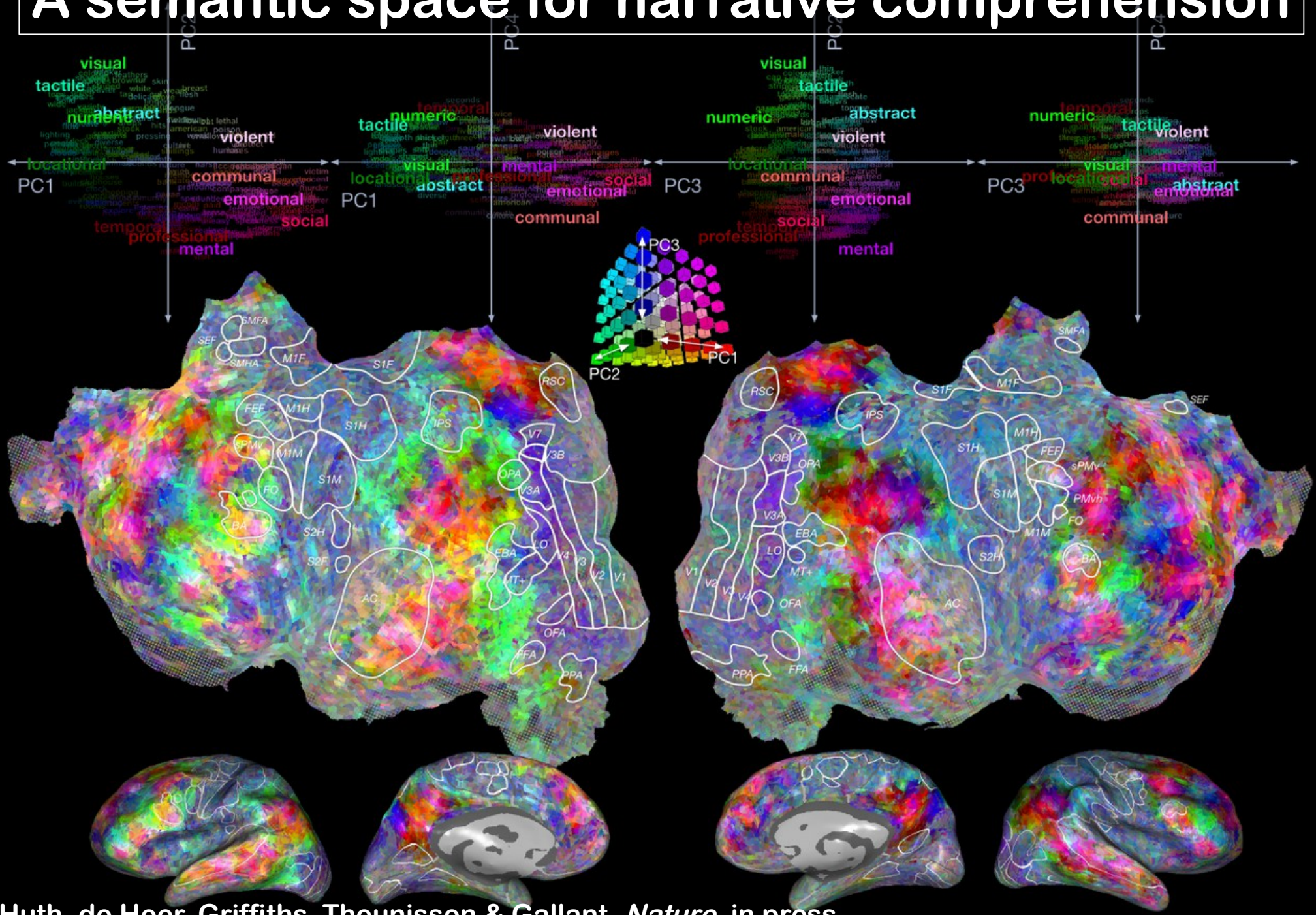


A semantic space for narrative comprehension



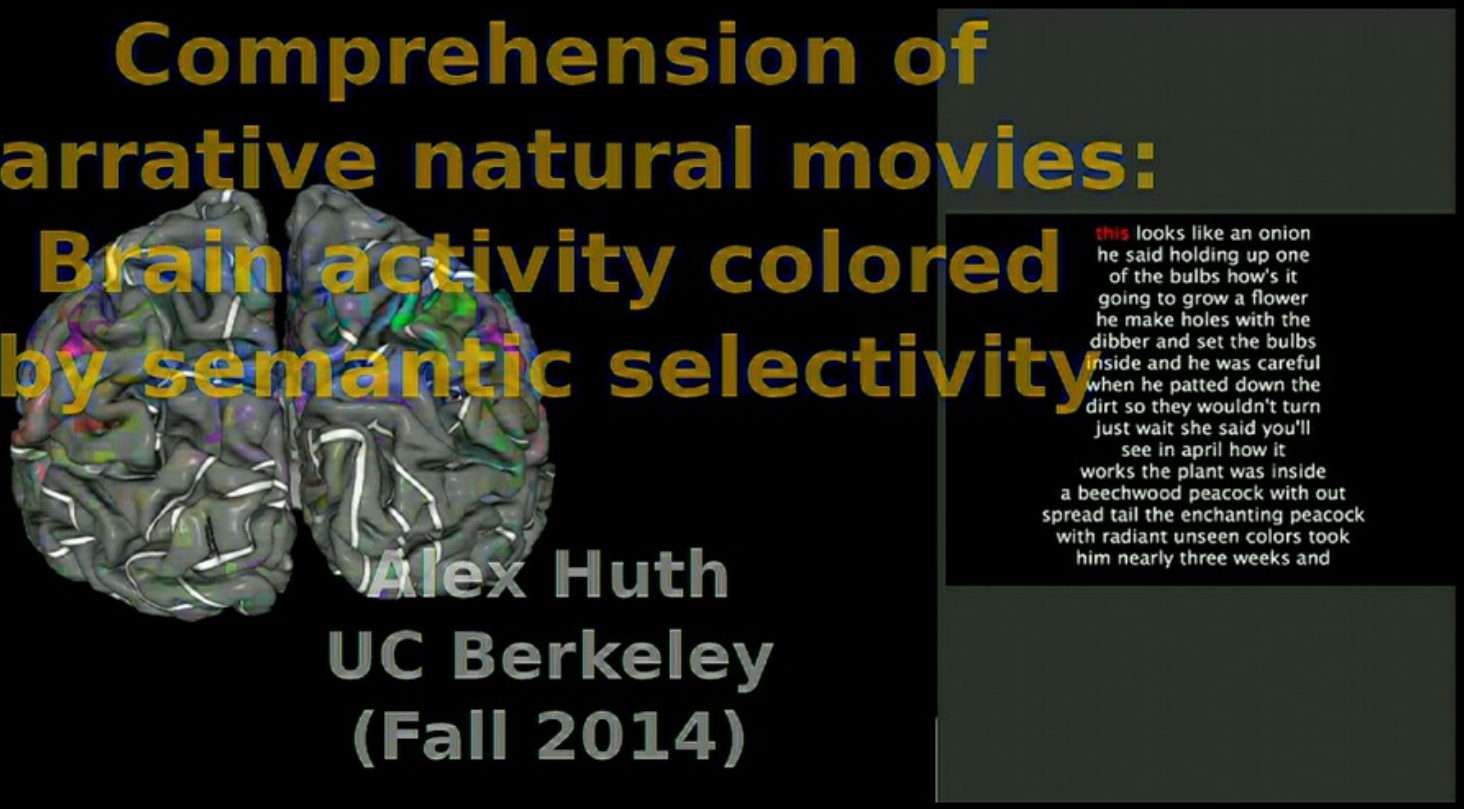
Huth, de Heer, Griffiths, Theunissen & Gallant, *Nature*, in press

A semantic space for narrative comprehension



Huth, de Heer, Griffiths, Theunissen & Gallant, *Nature*, in press

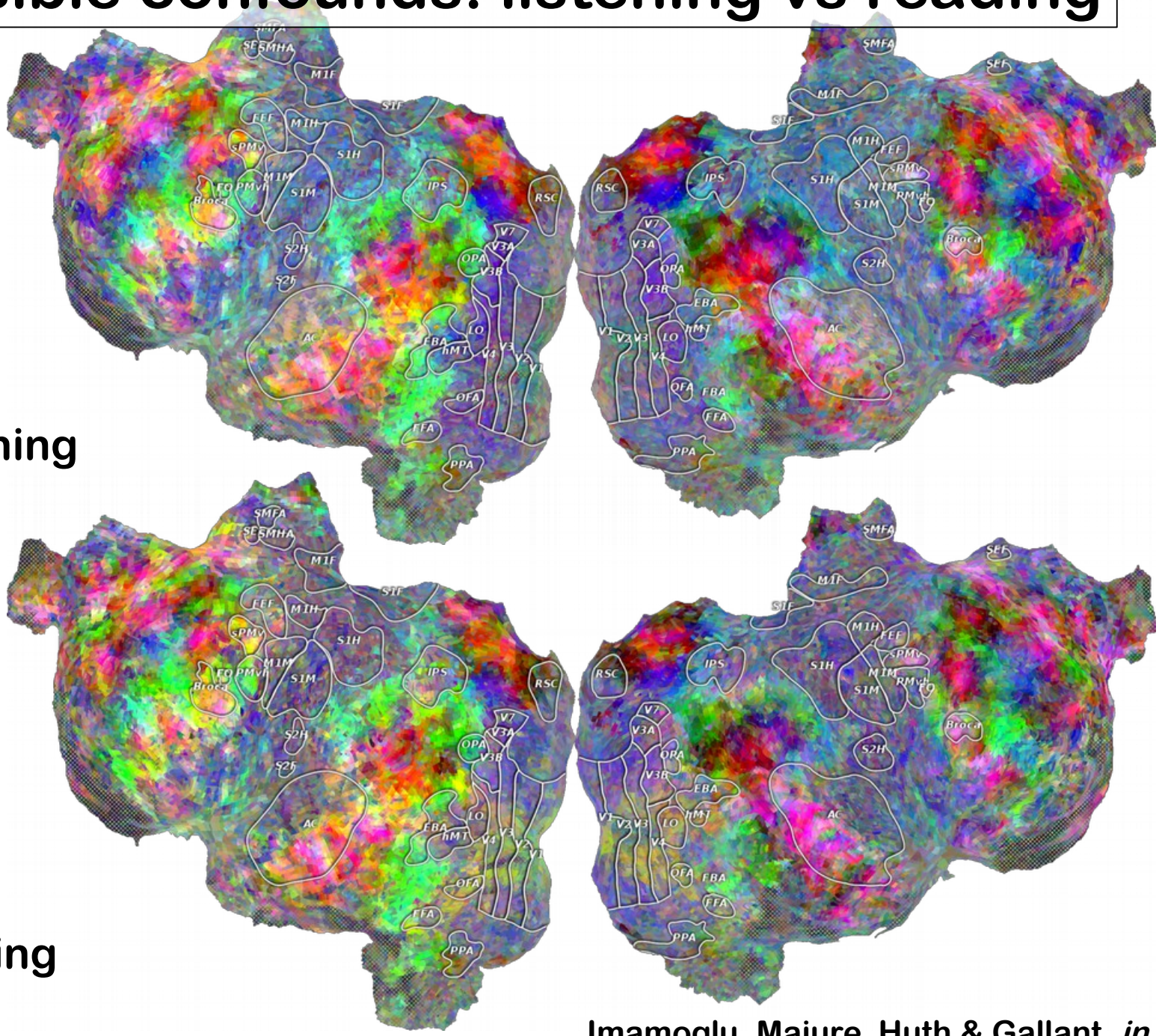
Functional signals and group semantic PCs



Huth, de Heer, Griffiths, Theunissen & Gallant, *Nature*, in press

Possible confounds: listening vs reading

Fatma Imamoglu

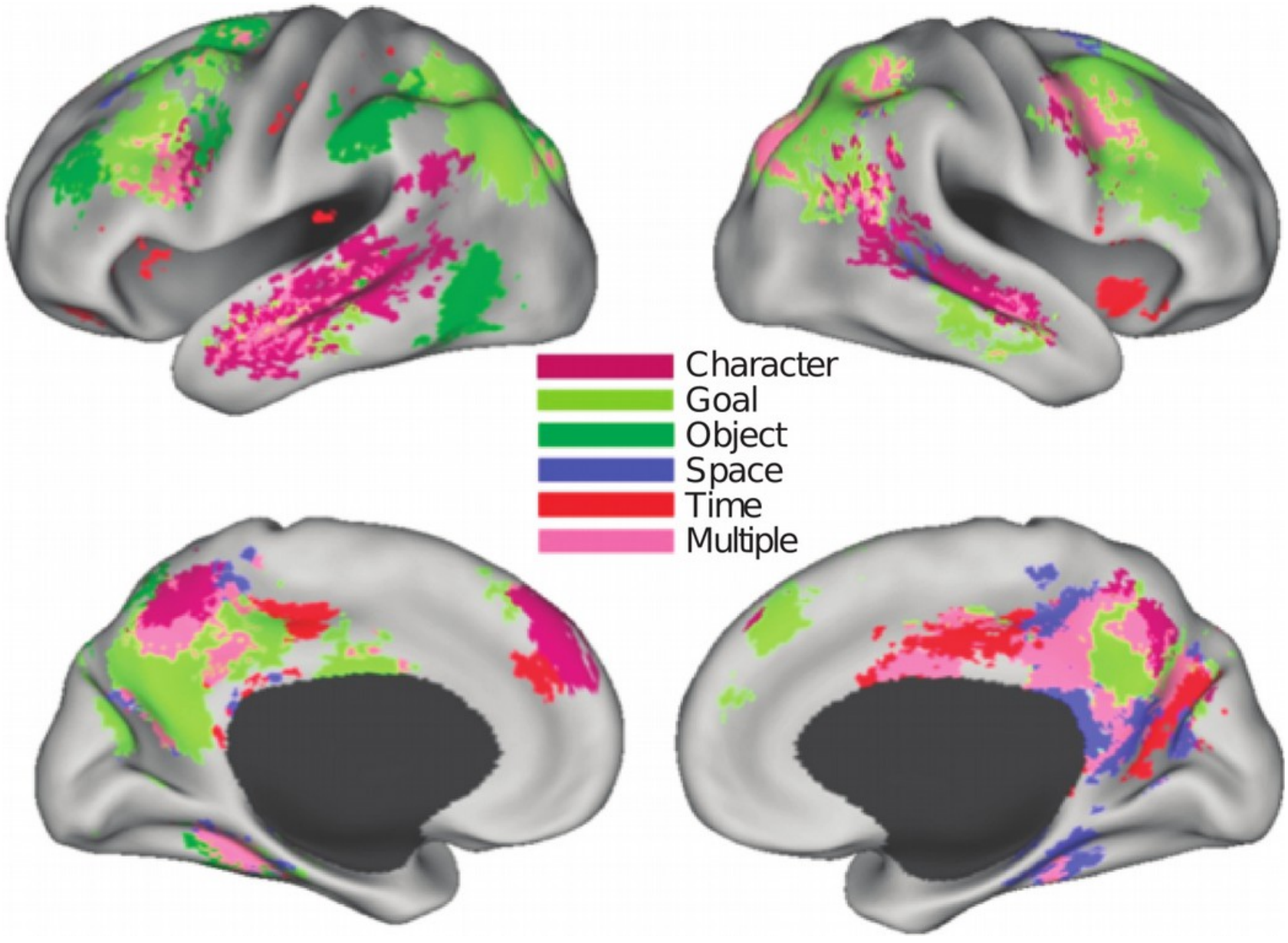


Listening

Reading

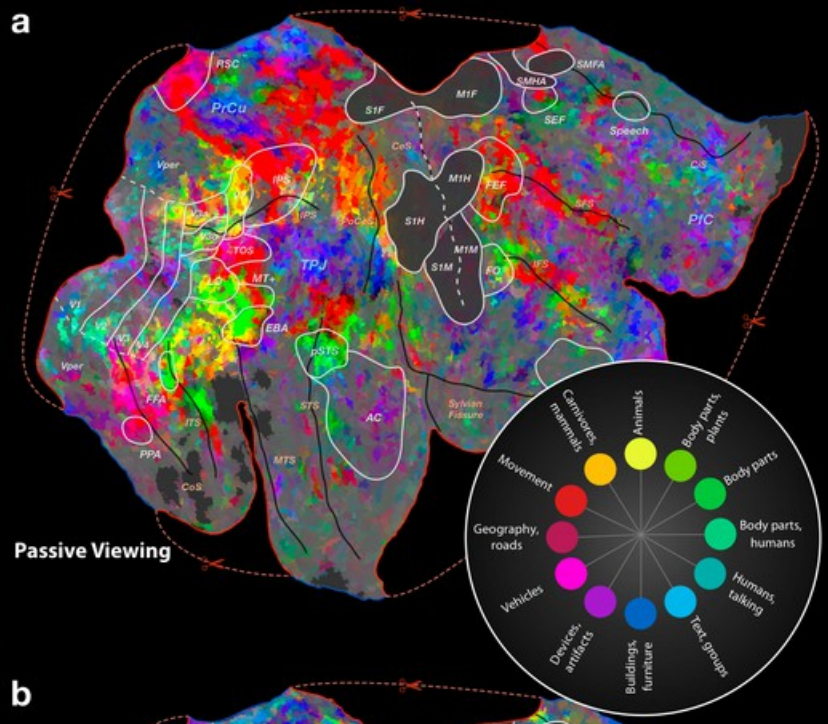
Imamoglu, Majure, Huth & Gallant, *in preparation*

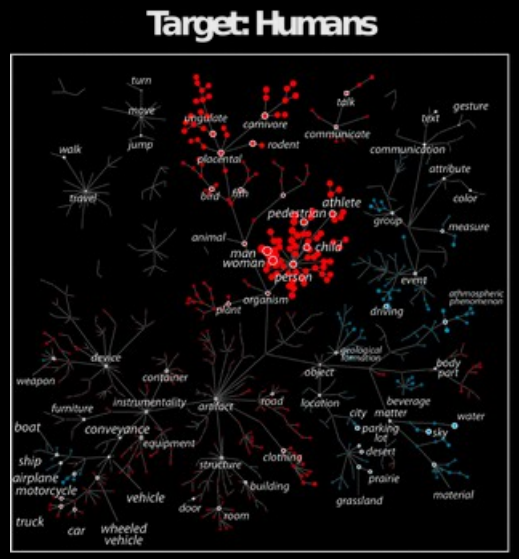
Possible confounds: prosody and narrative

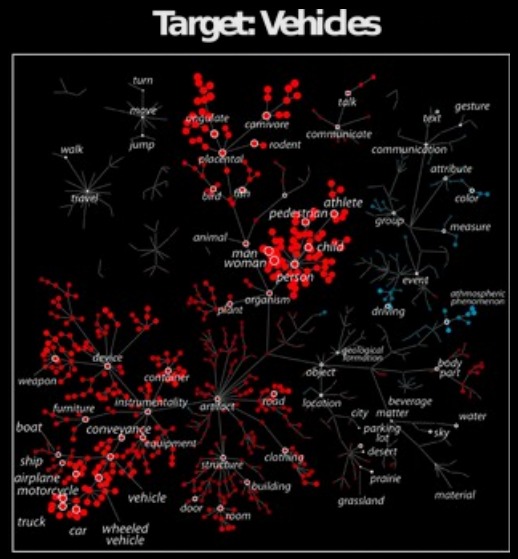


Speer, Reynolds, Swallow & Zacks, *Psych. Sci.*, 2009

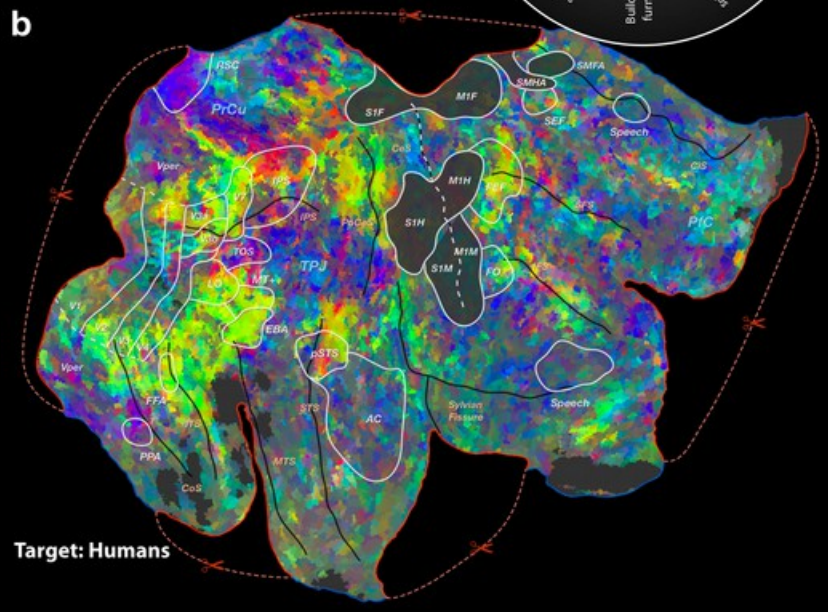
Functional representations depend on task

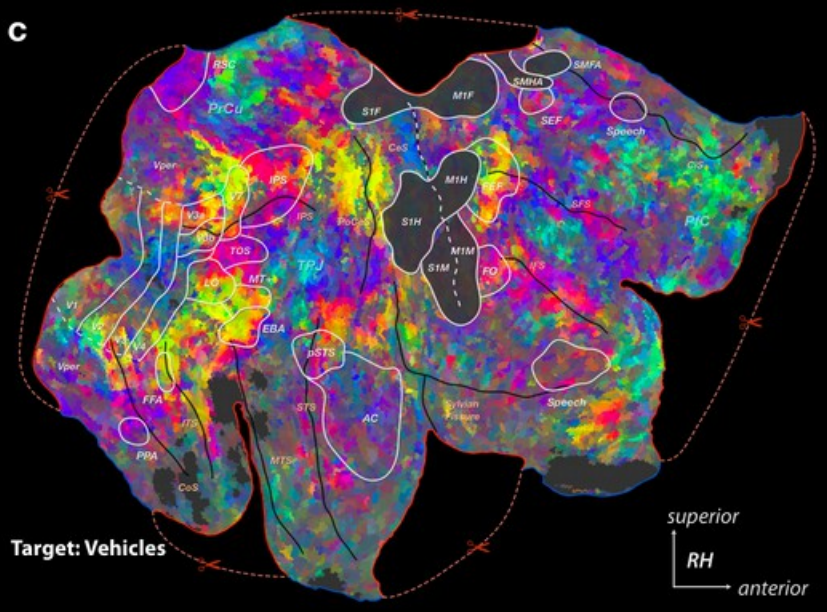






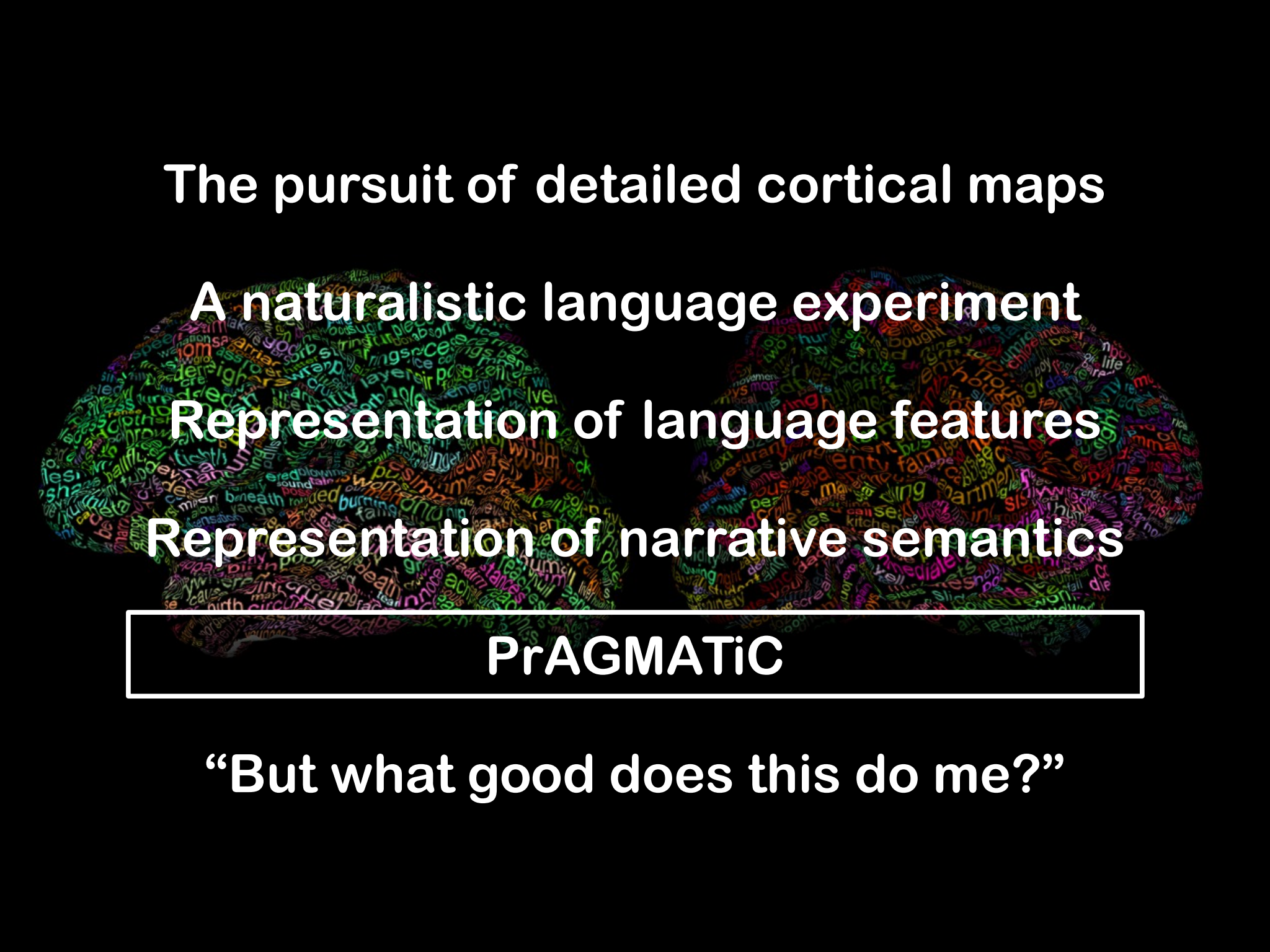
Above Mean — Below Mean ($p < 10^{-6}$)





Tolga Cukur

Cukur, Nishimoto, Huth & Gallant, *Nature Neuroscience*, 2013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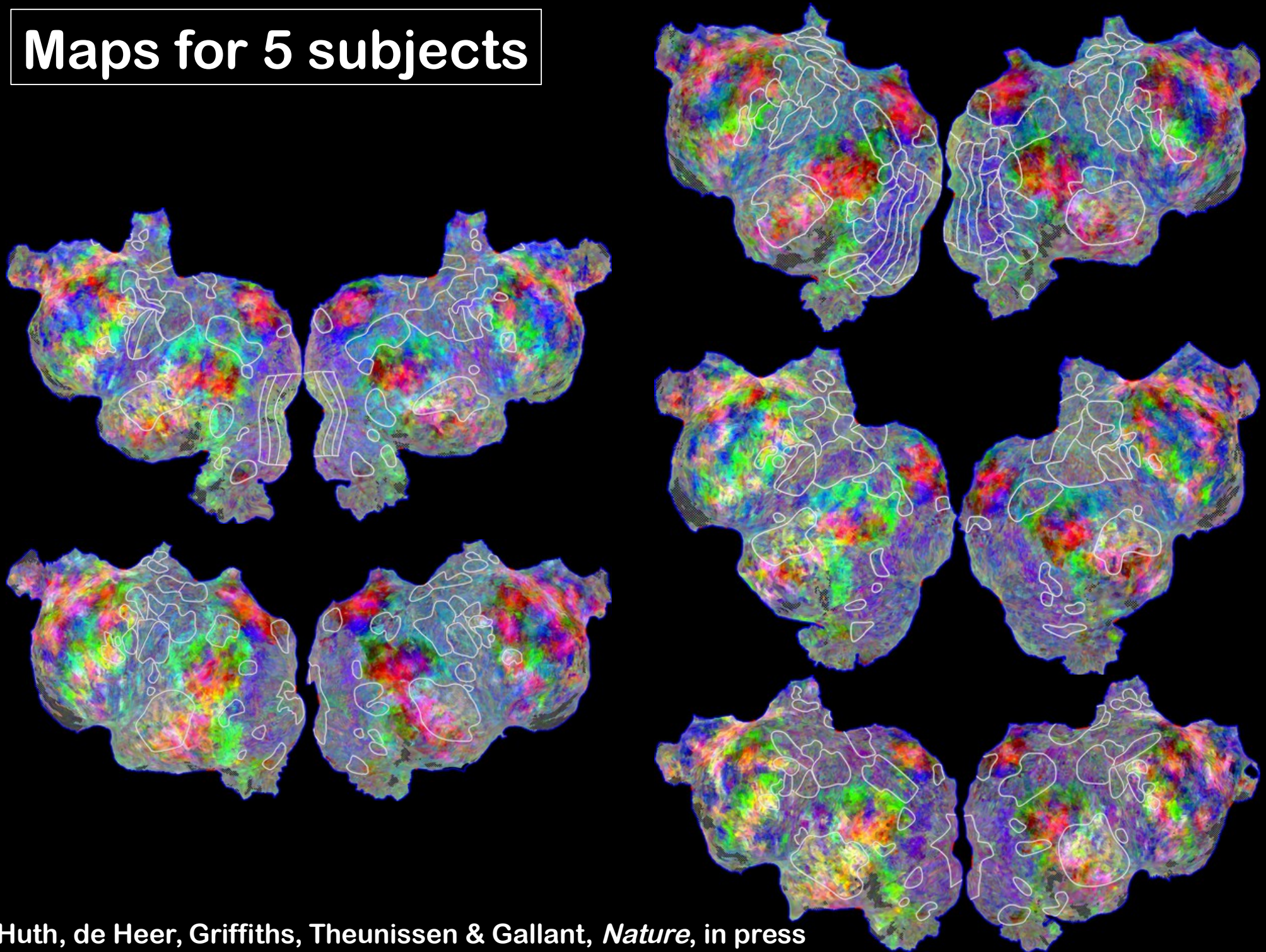
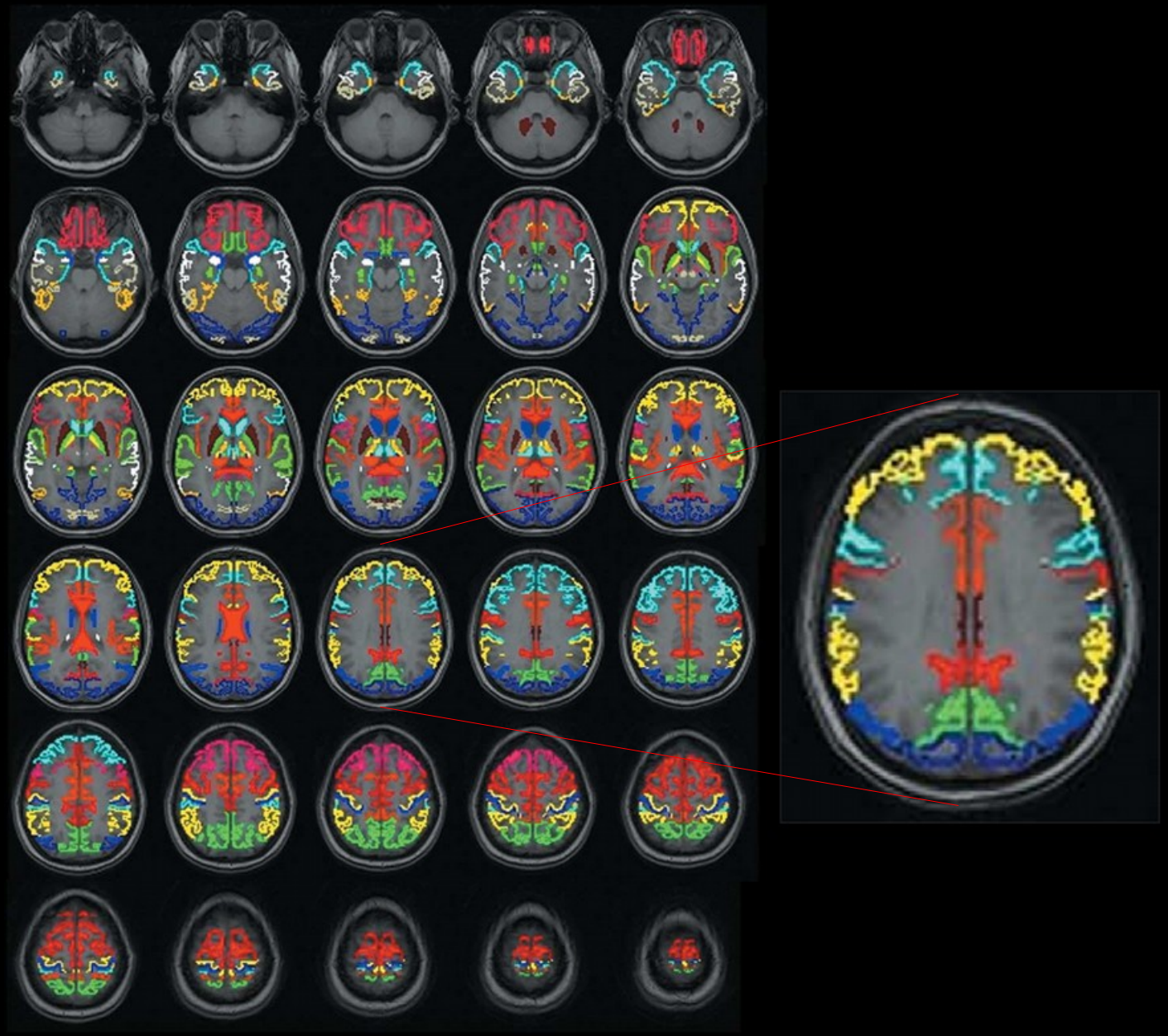
Maps for 5 subjects



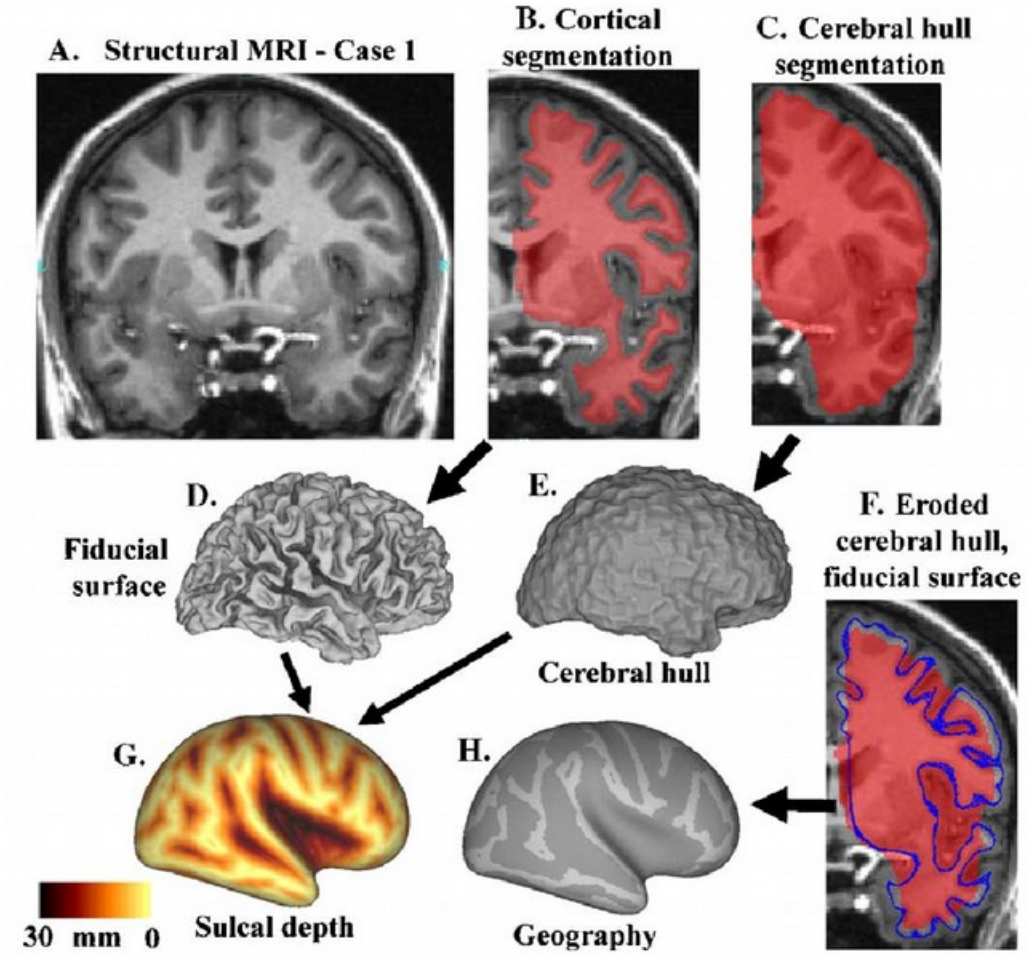
Huth, de Heer, Griffiths, Theunissen & Gallant, *Nature*, in press

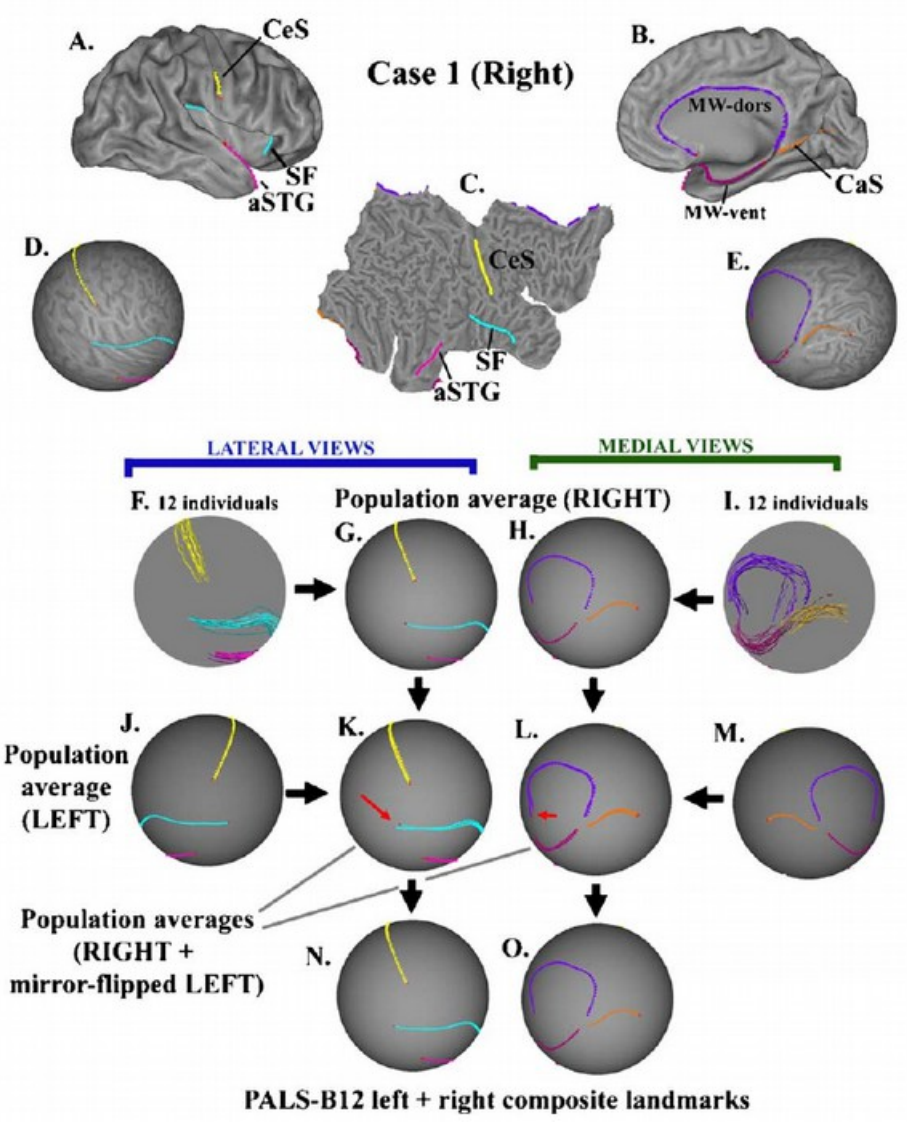
Cross-subject volumetric alignment



Maldjian et. al., *NeuroImage*, 2003

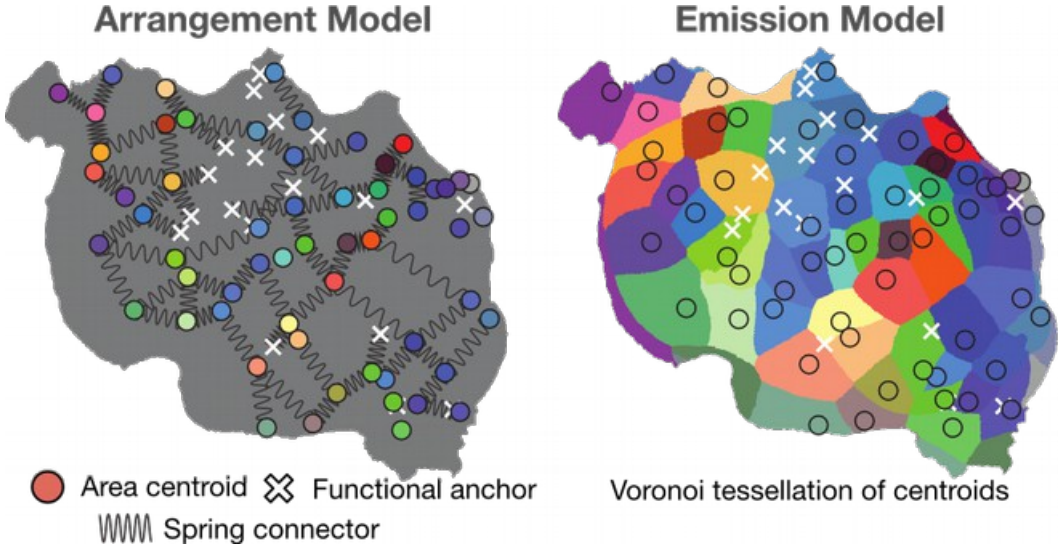
Cross-subject surface alignment





Van Essen et al., NeuroImage, 2005

PrAGMATiC: Probabilistic And Generative Model of Areas Tiling Cortex



PrAGMATiC Parameters

Shared across subjects

- ***L*** - ideal spring lengths
- ***K*** - spring constants
- ***M*** - area functional means

Unique to each subject

- ***H*** - exact centroid locations
- ***V*** - functional values on cortex

$$P(V, H; M, L, K) = P(H; L, K)\, P(V|H; M)$$

total probability = *arrangement probability* * *map probability*

$$P(H; L, K) \propto e^{-E(H;L,K)}$$

$$E(H; L, K) = \sum_{i,j,s} K_{ij}(d_{ijs} - L_{ij})^2$$

distance between centroids i and j in subject s

$$P(V|H; M) \propto e^{-E(V|H;M)}$$

$$E(V|H; M) \propto \sum_{l,s} (M_{H(s,l)} - V_{ls})^2$$

nearest centroid in subject s

Maximum Likelihood Estimation of Parameters

1. *Resample centroid locations*

$$H_j \sim P(H; L, K)$$

2. *Compute likelihood of observed functional values*

$$P(V_{obs}|H_j; M)$$

3. *Compute gradients for **K**, **L**, and **M***

$$\frac{\partial \mathscr{L}(K; V_{obs})}{\partial K} = \left\langle \frac{\partial E_H}{\partial K} \right\rangle_H - \left\langle \frac{\partial E_H}{\partial K} \right\rangle_{V_{obs}|H}$$

$$\frac{\partial \mathscr{L}(L; V_{obs})}{\partial L} = \left\langle \frac{\partial E_H}{\partial L} \right\rangle_H - \left\langle \frac{\partial E_H}{\partial L} \right\rangle_{V_{obs}|H}$$

$$\frac{\partial \mathscr{L}(M; V_{obs})}{\partial M} = -\left\langle \frac{\partial E_V}{\partial M} \right\rangle_{V_{obs}|H}$$

4. *Update parameters*

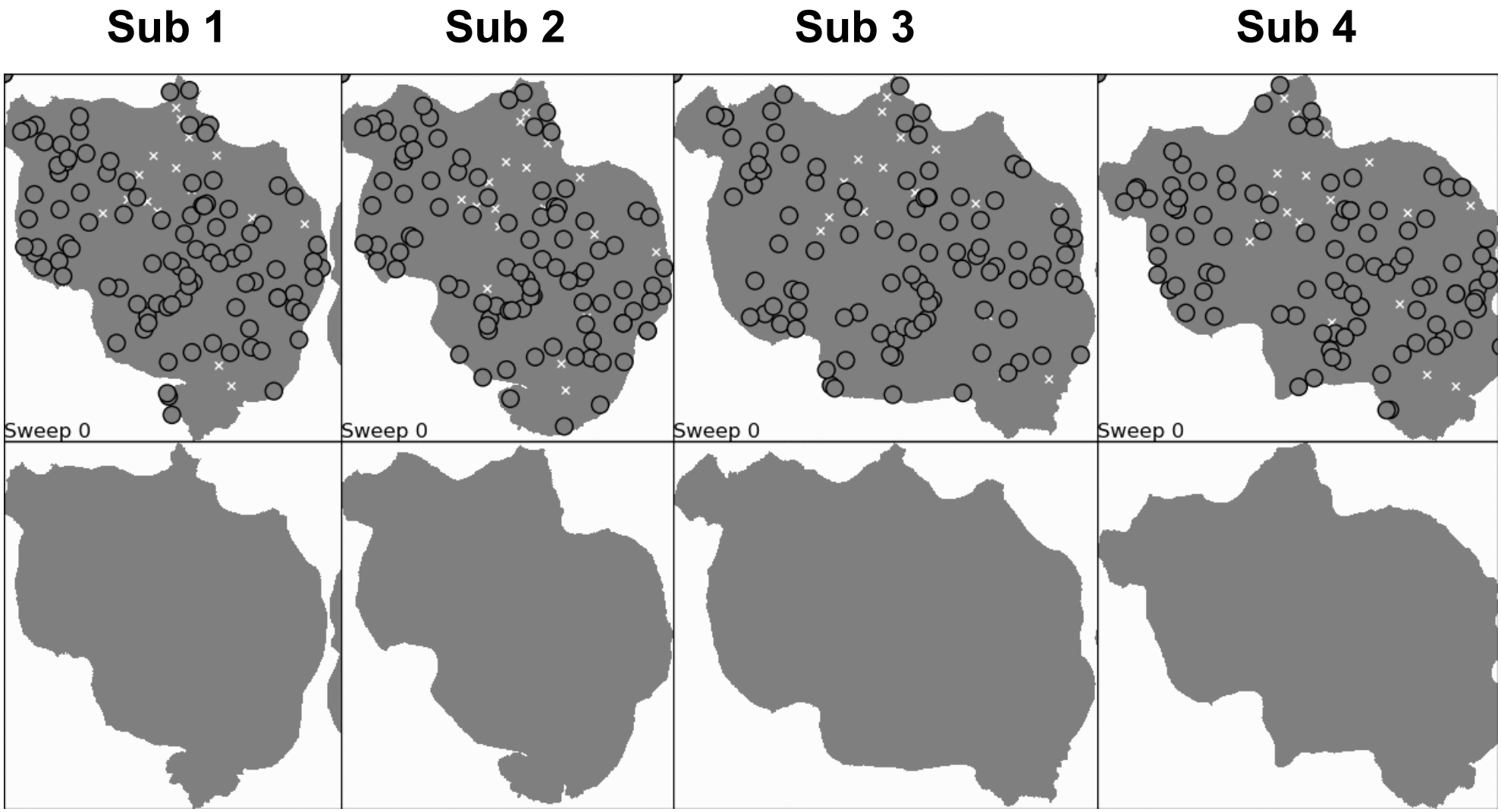
$$K^{t+1} = K^t - \epsilon \frac{\partial \mathscr{L}(K; V_{obs})}{\partial K}$$

$$L^{t+1} = L^t - \epsilon \frac{\partial \mathscr{L}(L; V_{obs})}{\partial L}$$

$$M^{t+1} = M^t - \epsilon \frac{\partial \mathscr{L}(M; V_{obs})}{\partial M}$$

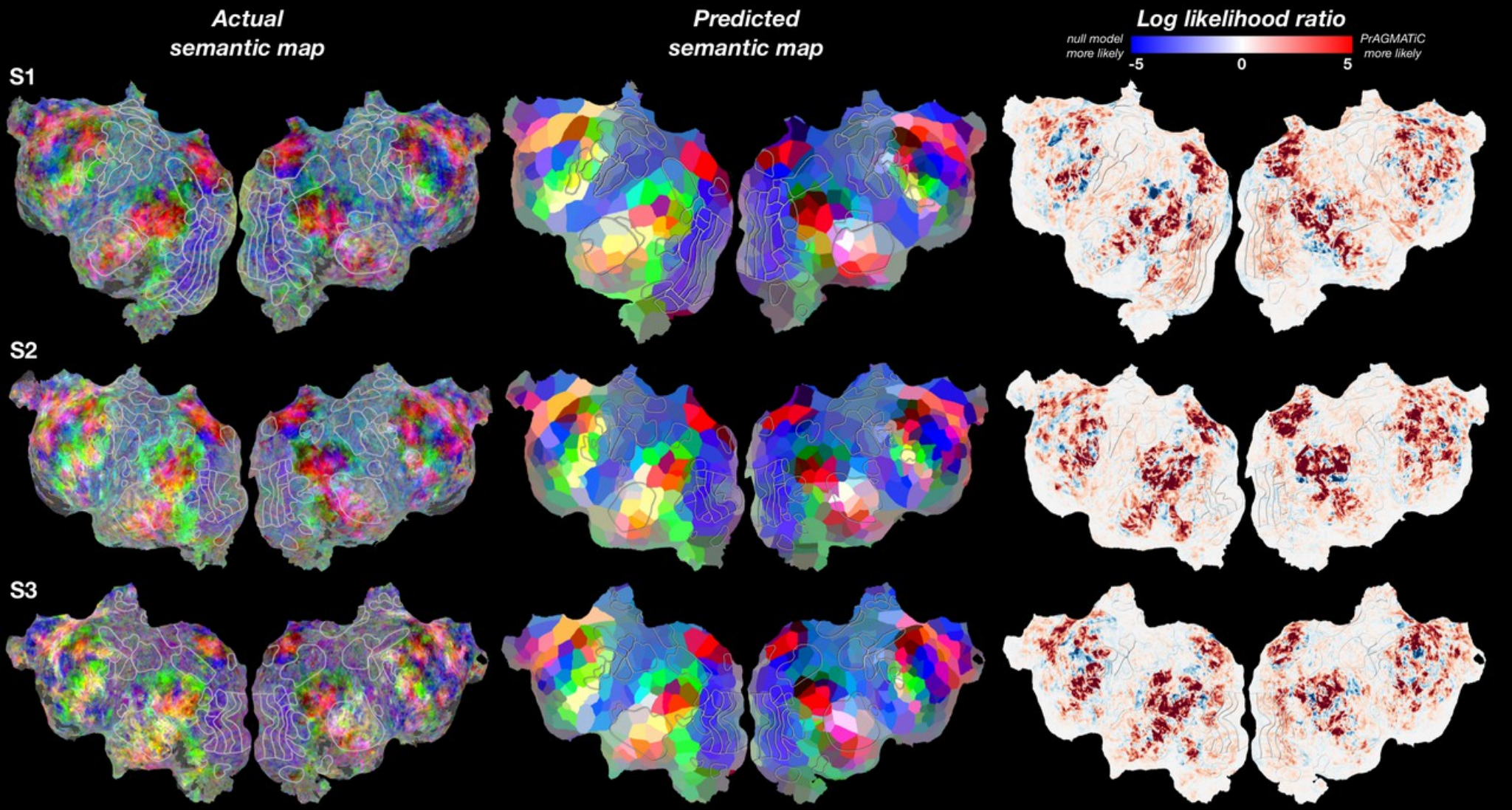
Huth, de Heer, Griffiths, Theunissen & Gallant, *Nature*, in press

Training the PrAGMATiC model



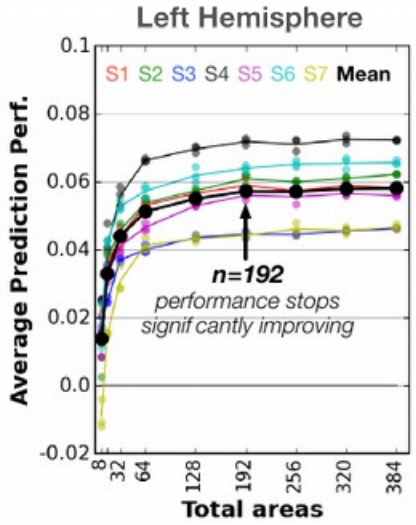
Huth, de Heer, Griffiths, Theunissen & Gallant, *Nature*, in press

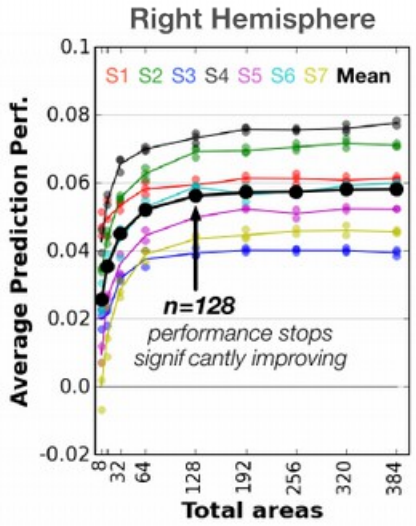
Likelihood tests for PrAGMATiC

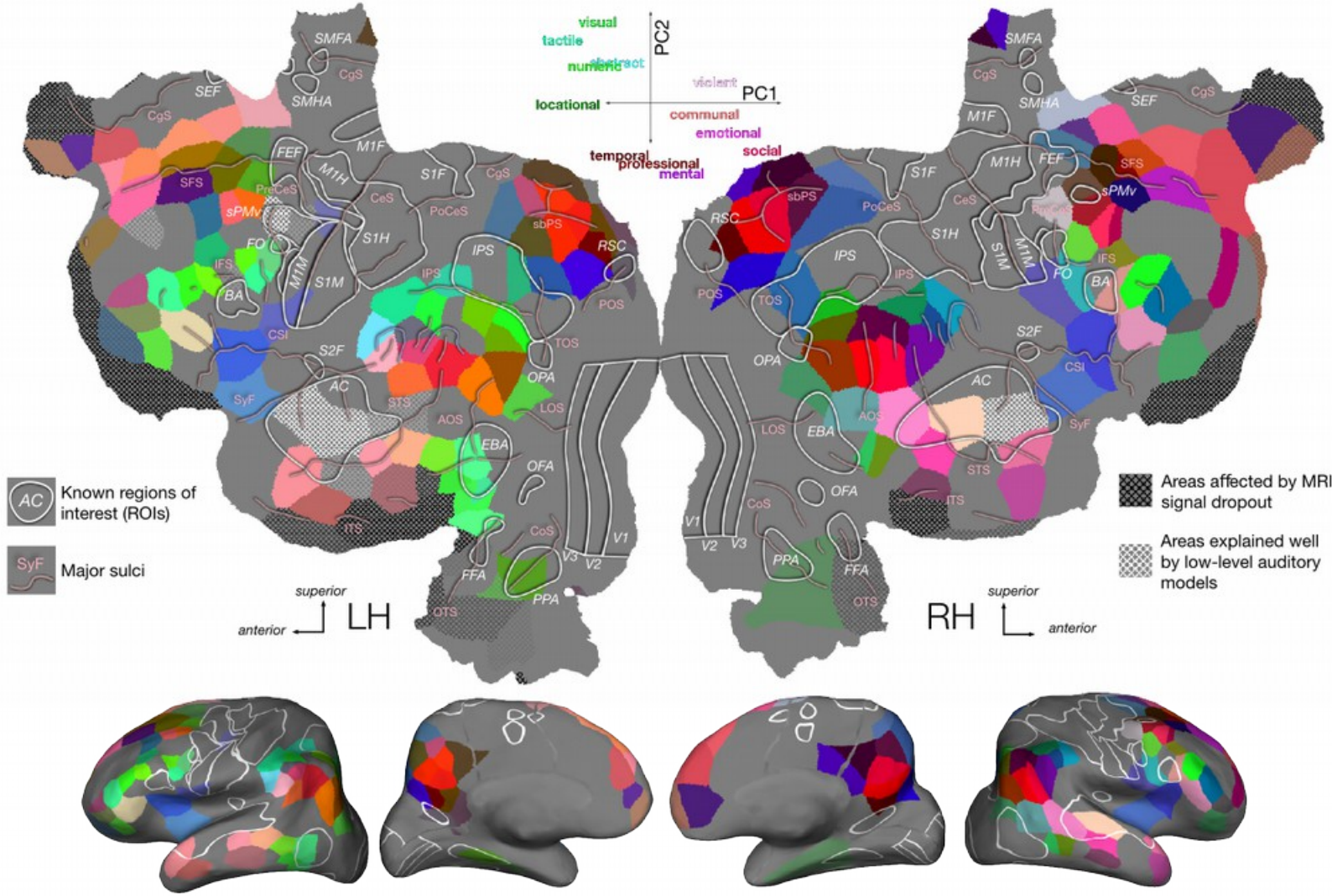


Huth, de Heer, Griffiths, Theunissen & Gallant, *Nature*, in press

Narrative semantic areas by PrAGMATiC

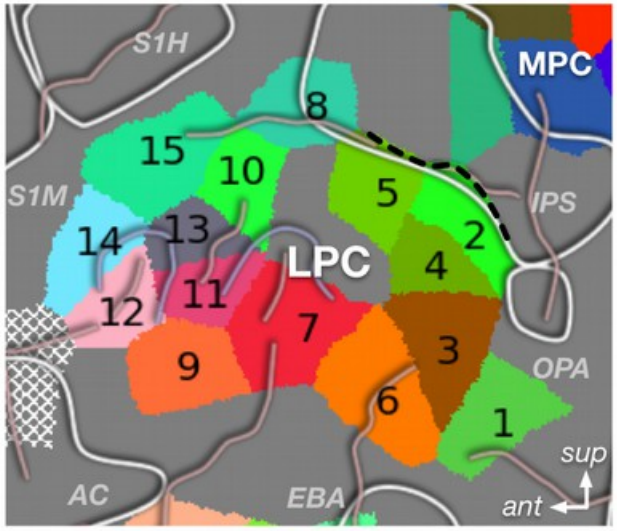


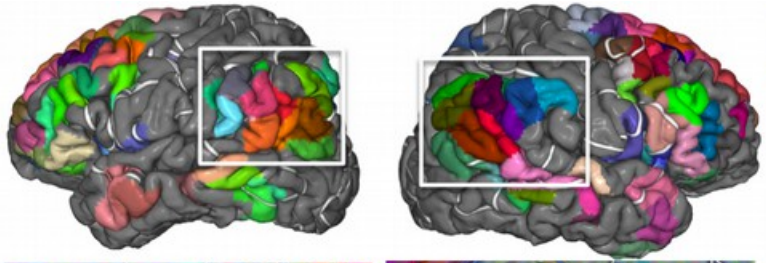


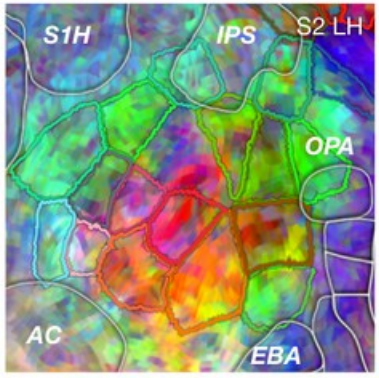


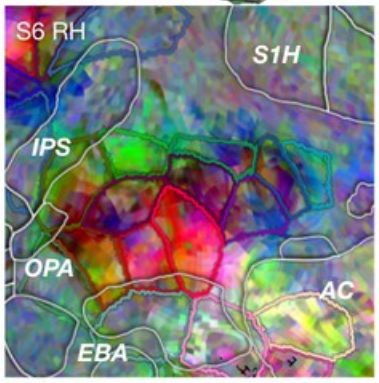
Huth, de Heer, Griffiths, Theunissen & Gallant, *Nature*, in press

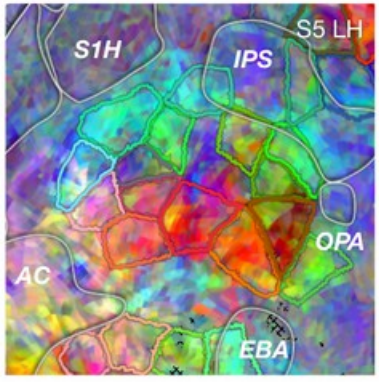
Narrative semantic areas near lateral parietal cortex (LPC)

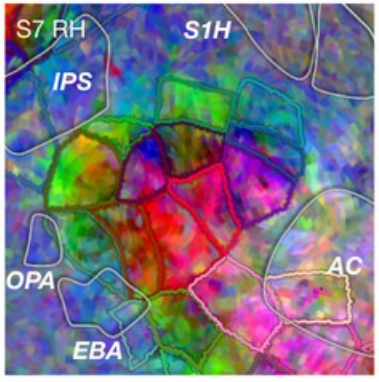


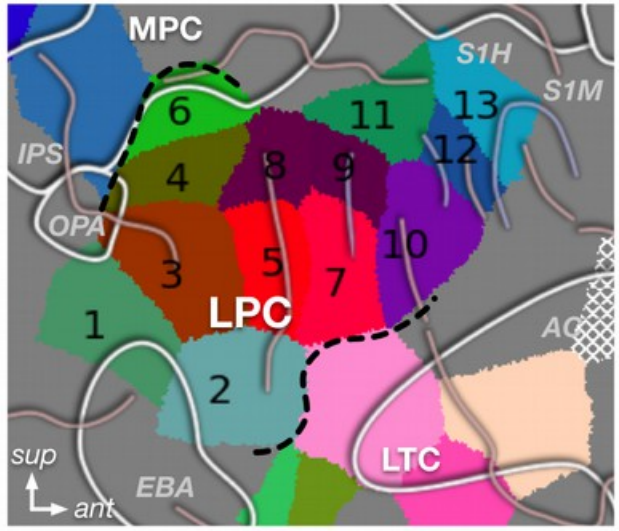


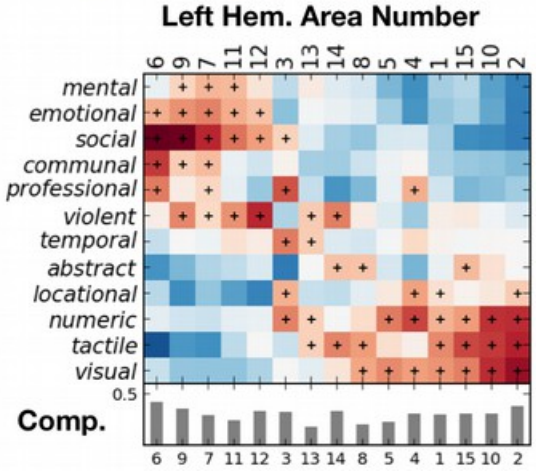


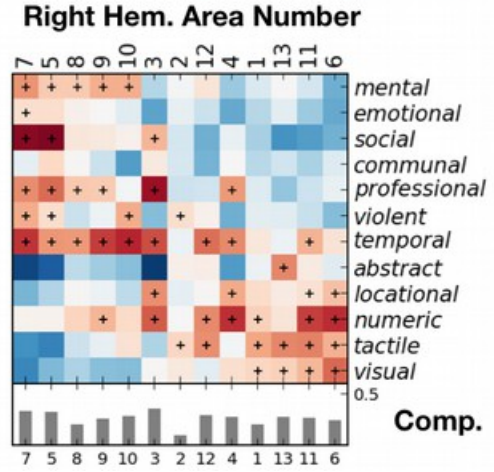






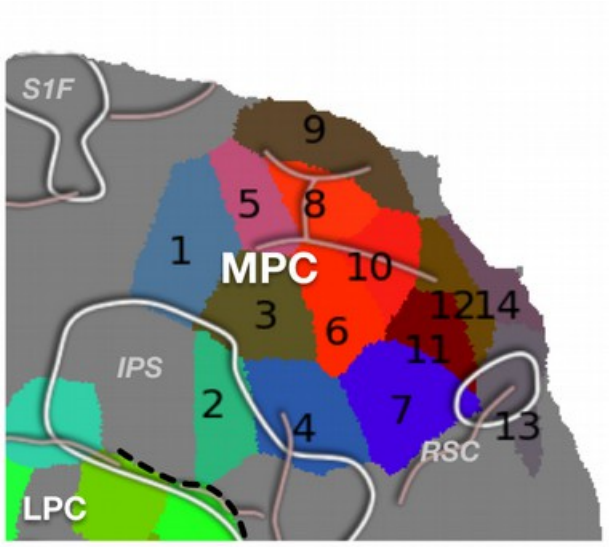


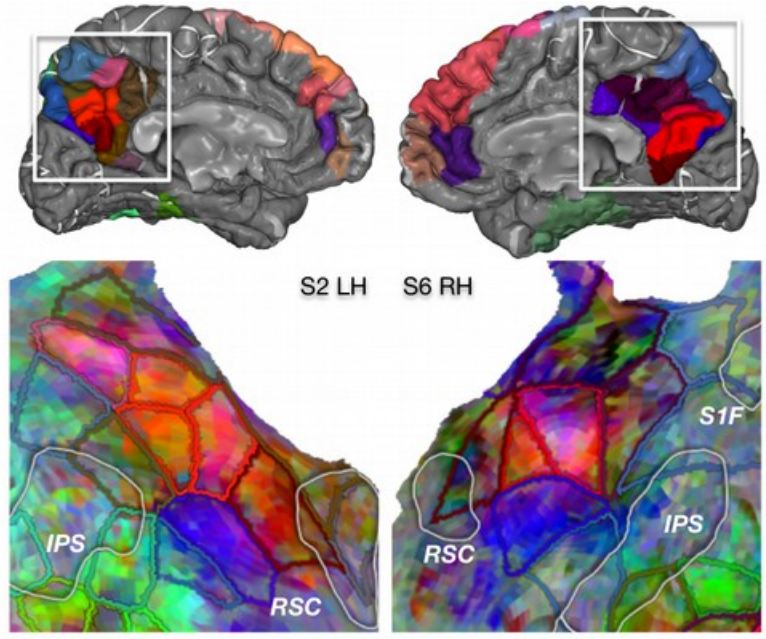


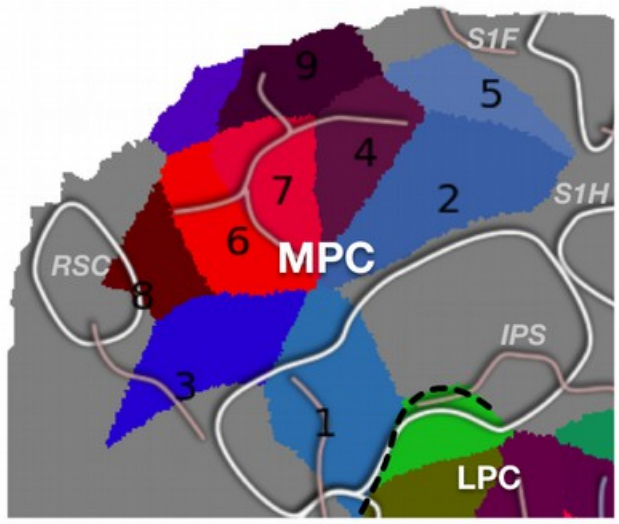


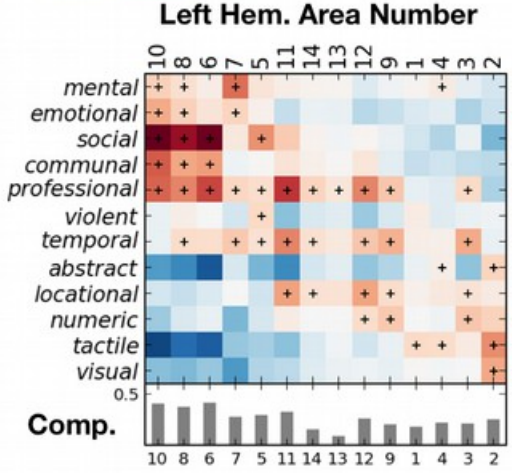
Huth, de Heer, Griffiths, Theunissen & Gallant, *Nature*, in press

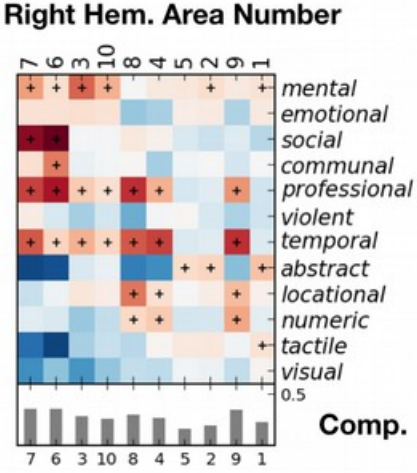
Narrative semantic areas near medial parietal cortex (MPC)





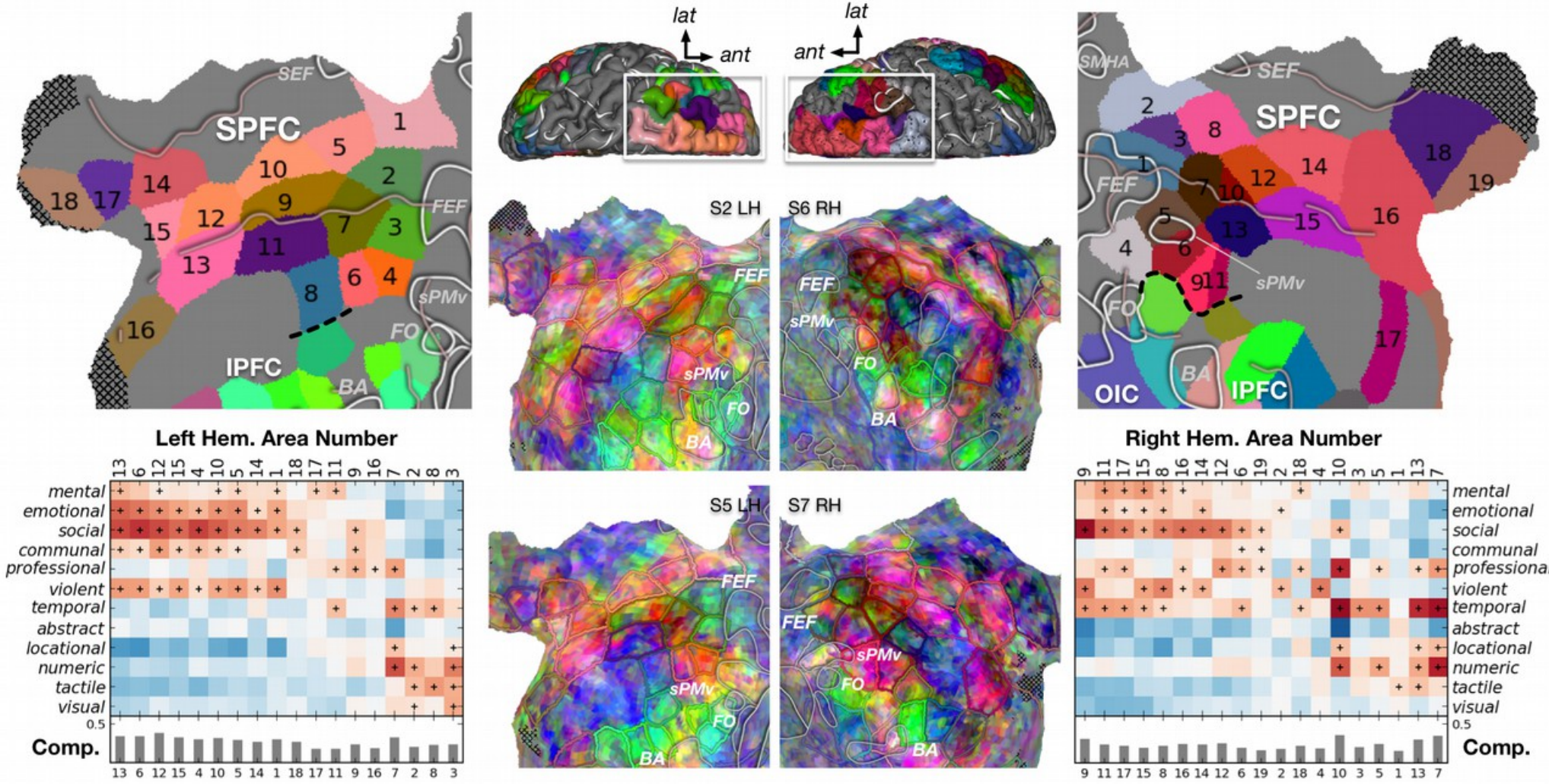






Huth, de Heer, Griffiths, Theunissen & Gallant, *Nature*, in press

Narrative semantic areas near superior prefrontal cortex (SPFC)



Huth, de Heer, Griffiths, Theunissen & Gallant, *Nature*, in press

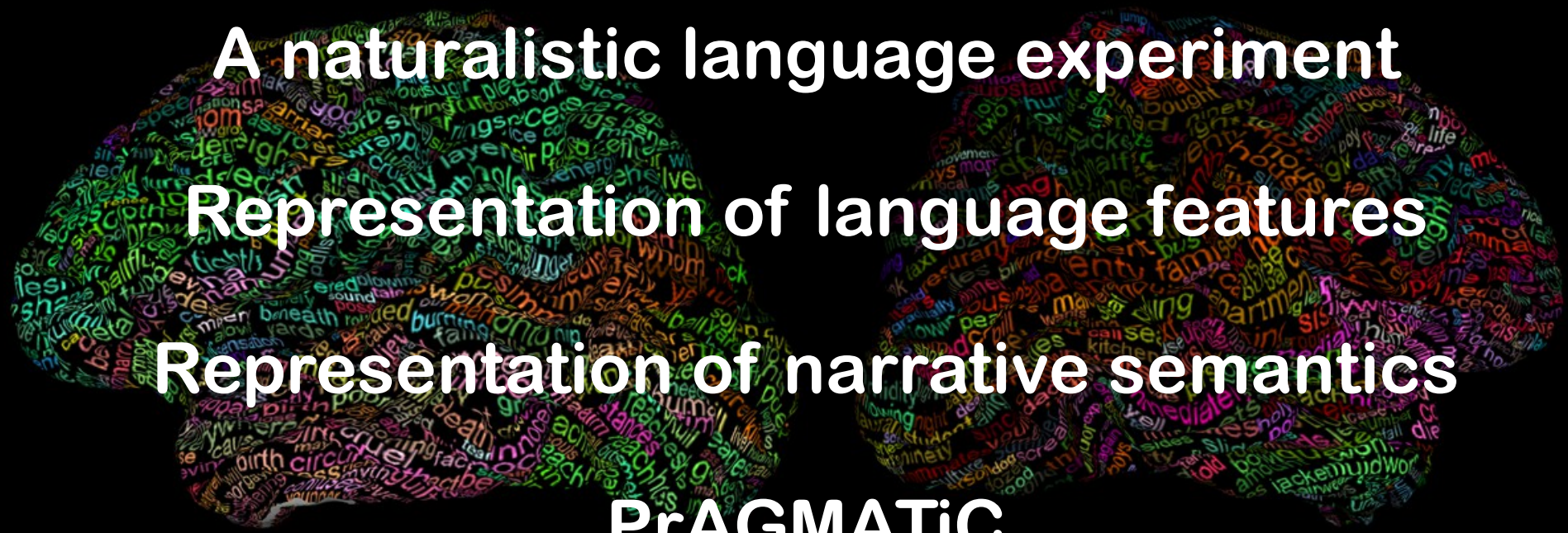
The pursuit of detailed cortical maps

A naturalistic language experiment

Representation of language features

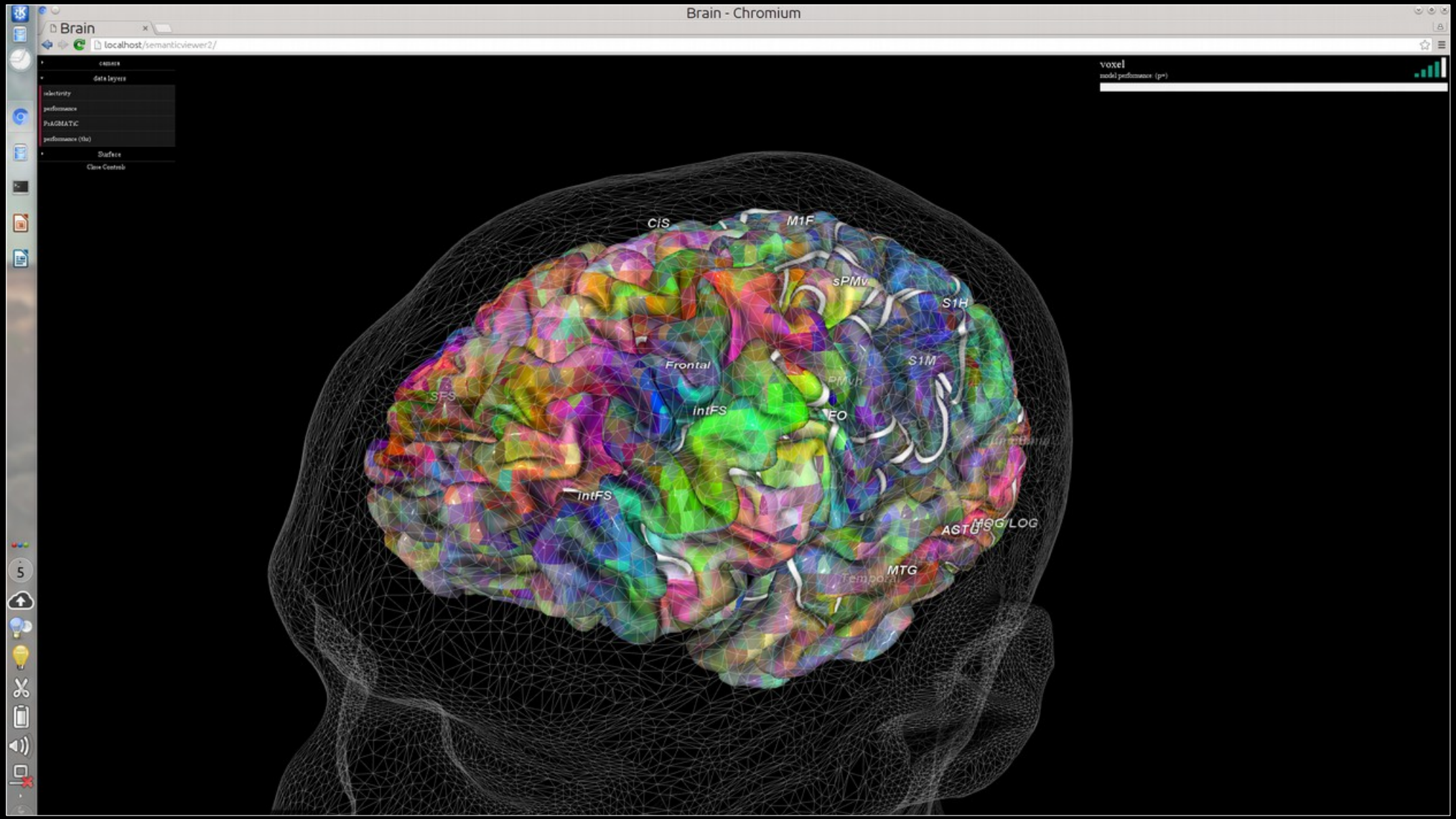
Representation of narrative semantics

PrAGMATiC



"But what good does this do me?"

A brain viewer for semantic representation



http://gallantlab.org/huth2016

Simulated replication of other studies

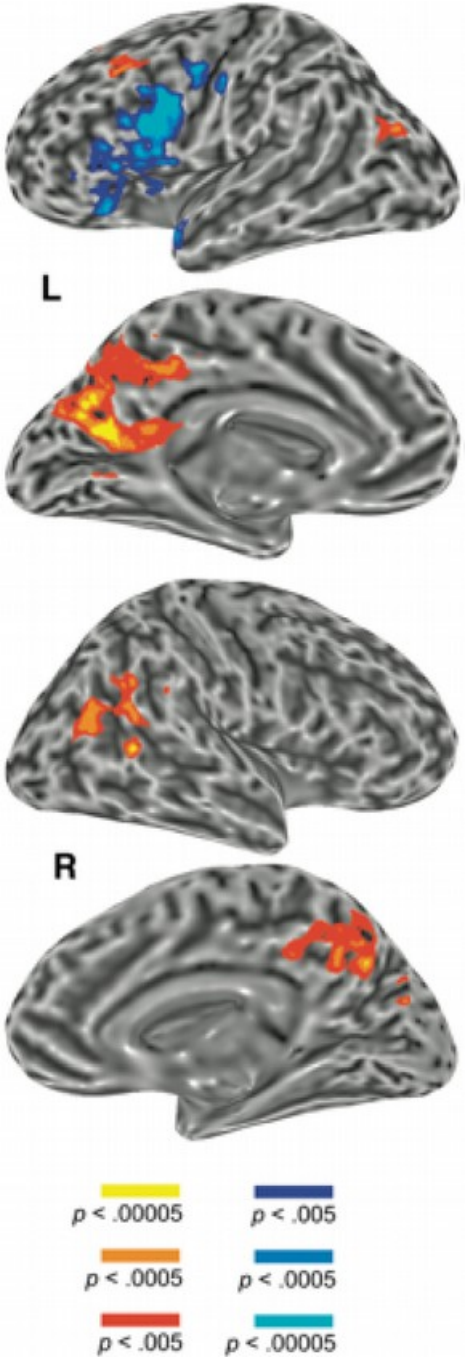
Leila Wehbe

Fatma Imamoglu

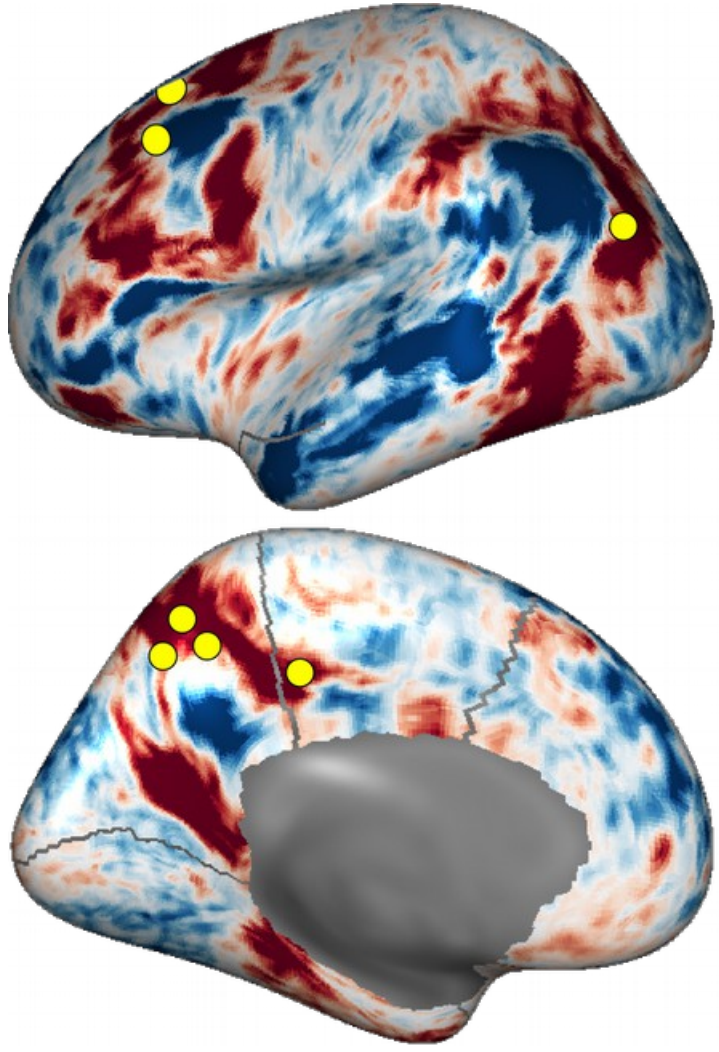
Binder, et al. (2005) “Distinct brain systems for processing concrete and abstract concepts”, J. Cog. Neuro., 17:905-917

```
# First define the stimuli. These are copied from the paper.
concrete_words = “apple, autumn, banana, bridge, cabin, [...]”.split(“, ”)
abstract_words = “advice, affair, aspect, assent, belief, [...]”.split(“,  ”)

# Extract semantic vectors for each word.
concrete_vecs = np.vstack([eng1000[w] for w in concrete_words])
abstract_vecs = np.vstack([eng1000[w] for w in abstract_words])

# Simulate responses to average word vectors
concrete_resp = np.dot(concrete_vecs.mean(0), model_weights)
abstract_resp = np.dot(abstract_vecs.mean(0), model_weights)

# Simulate contrast by subtracting responses
concrete_minus_abstract = concrete_resp - abstract_resp
```

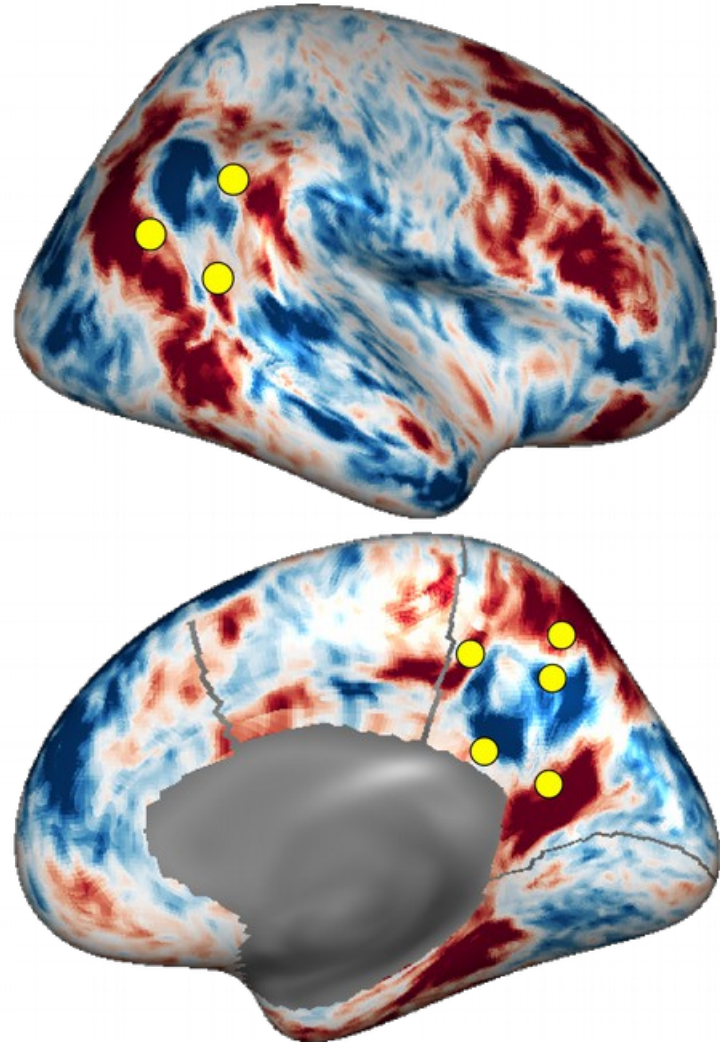
Simulated replication of Binder et al. 2005



Left Hemisphere

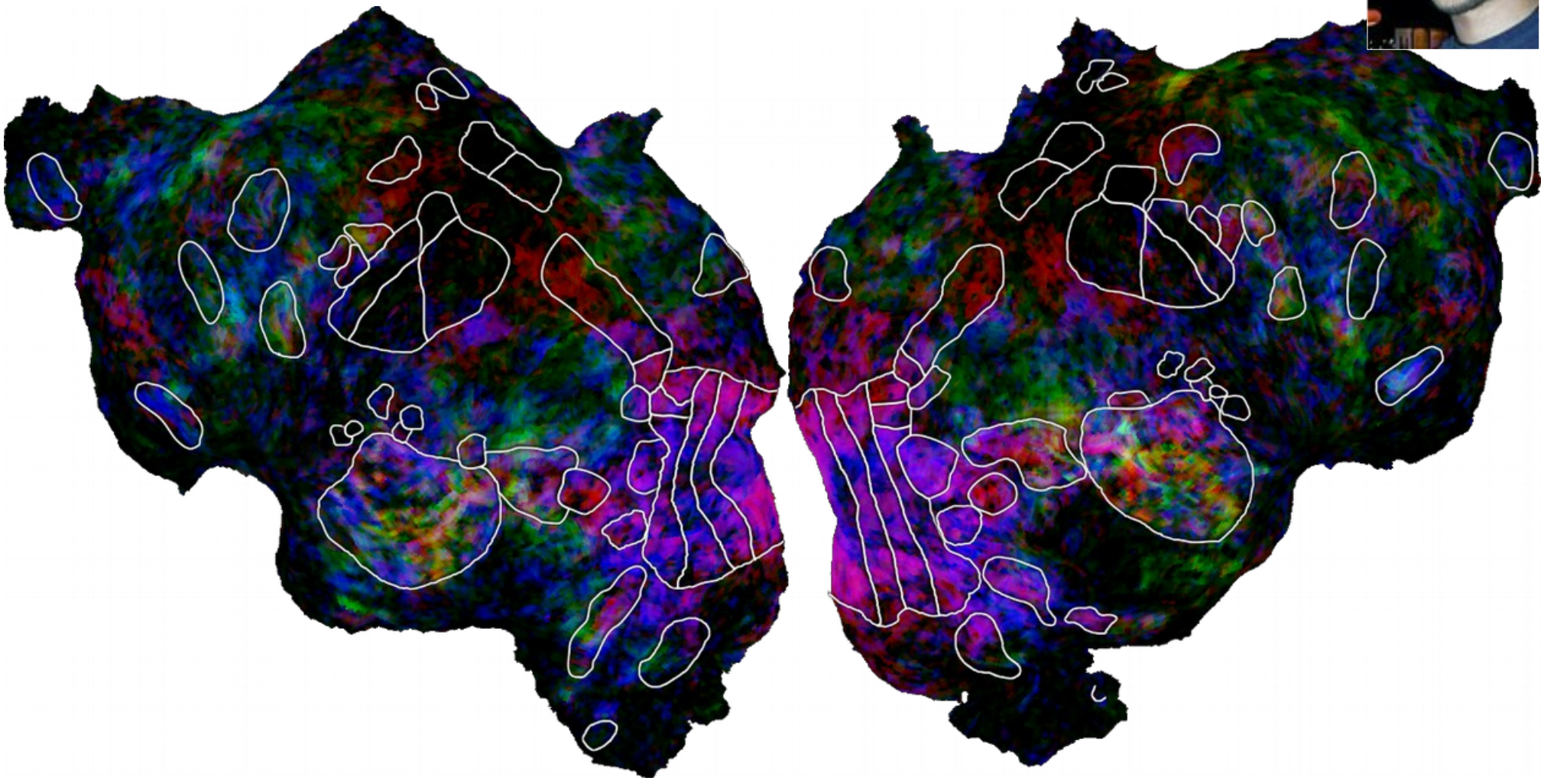


Right Hemisphere



The future: Mapping features across multiple stimulus and task categories

Anwar Nunez-Elizalde



Decision tasks

Narrative stories

Short films

Nunez-Elizalde, Huth & Gallant, *in preparation*

Summary

- Naturalistic experiments, voxel-wise modeling and PrAGMATIC provide an efficient way to generate rich data sets suitable for functional mapping.
- At a coarse level the semantic selectivity we find is consistent with that reported elsewhere. However, our atlas reveals a much richer and more detailed distribution of semantic selectivity than reported in any previous study.
- Each single semantic area represents multiple related but distinct semantic domains. Each semantic domain is represented in multiple semantically-selective areas.
- Our current atlas assumes that areas have uniform tuning. However, PrAGMATiC can be generalized to recover gradients and to model other types of information.

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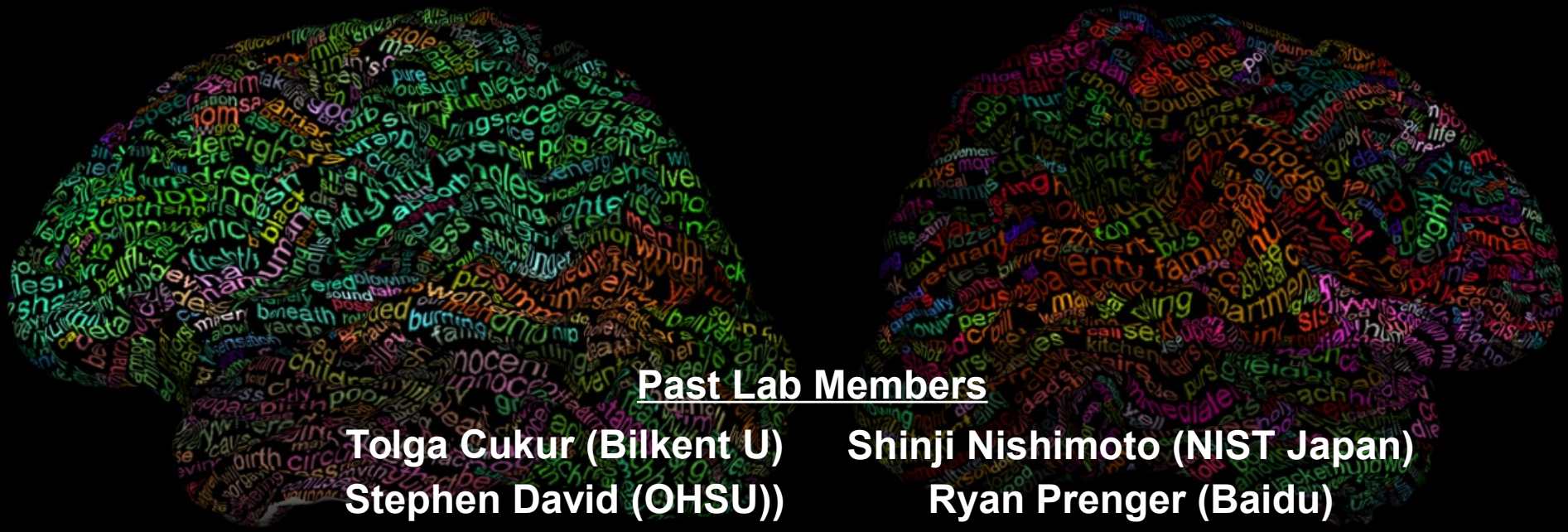
Essa Yacoub, Kamil Ugurbil



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Ben Hayden (U Rochester)
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Shinji Nishimoto (NIST Japan)
Ryan Prenger (Baidu)
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Ben Willmore (Cambridge U)
Bill Vinje (Salk)
An Vu (UCB)
Michael Wu (Lithium)

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