Neural circuitry for vision and reading

Professor Brian Wandell
Director, Stanford's Center for Cognitive and Neurobiological imaging
Deputy Director, Stanford Neurosciences Institute

- Historical perspective on neuroimaging
- Visual system –Maps, Cluster, Models (fMRI)
- White matter tracts (dMRI)
- Neuroscience for society: Diagnosing reading impairment

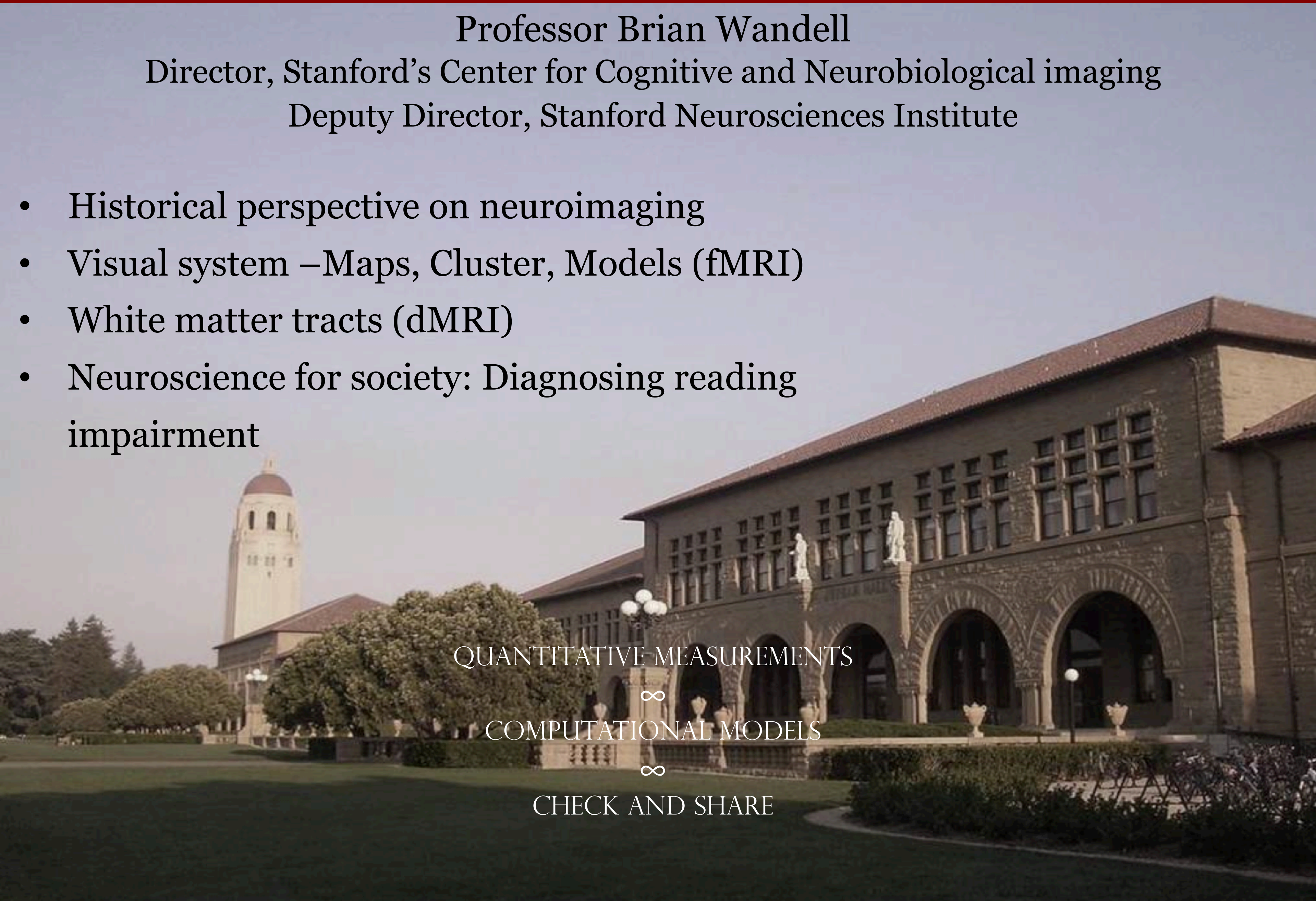
QUANTITATIVE MEASUREMENTS

∞

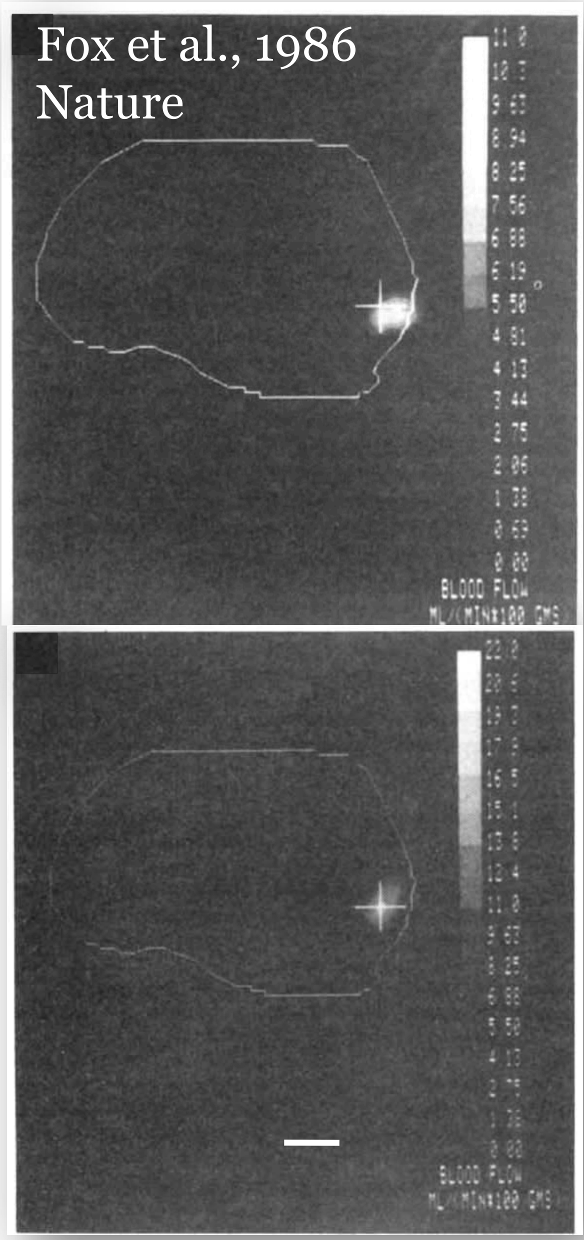
COMPUTATIONAL MODELS

∞

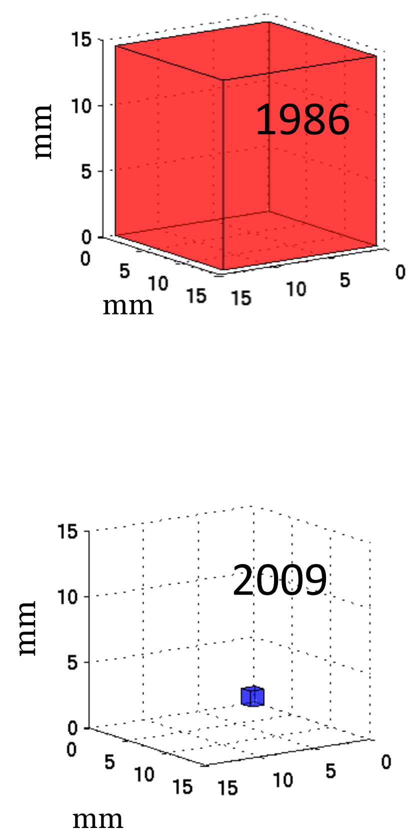
CHECK AND SHARE

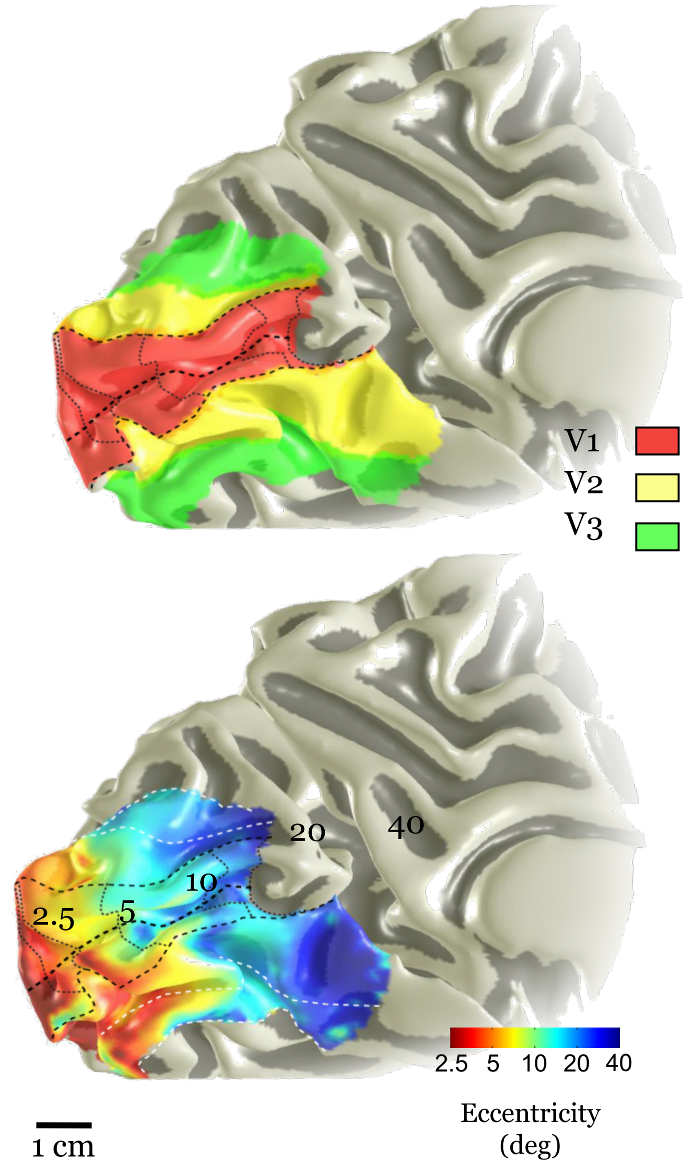


Remarkable progress in 25 years
(Wandell and Winawer, 2011)



Voxel size

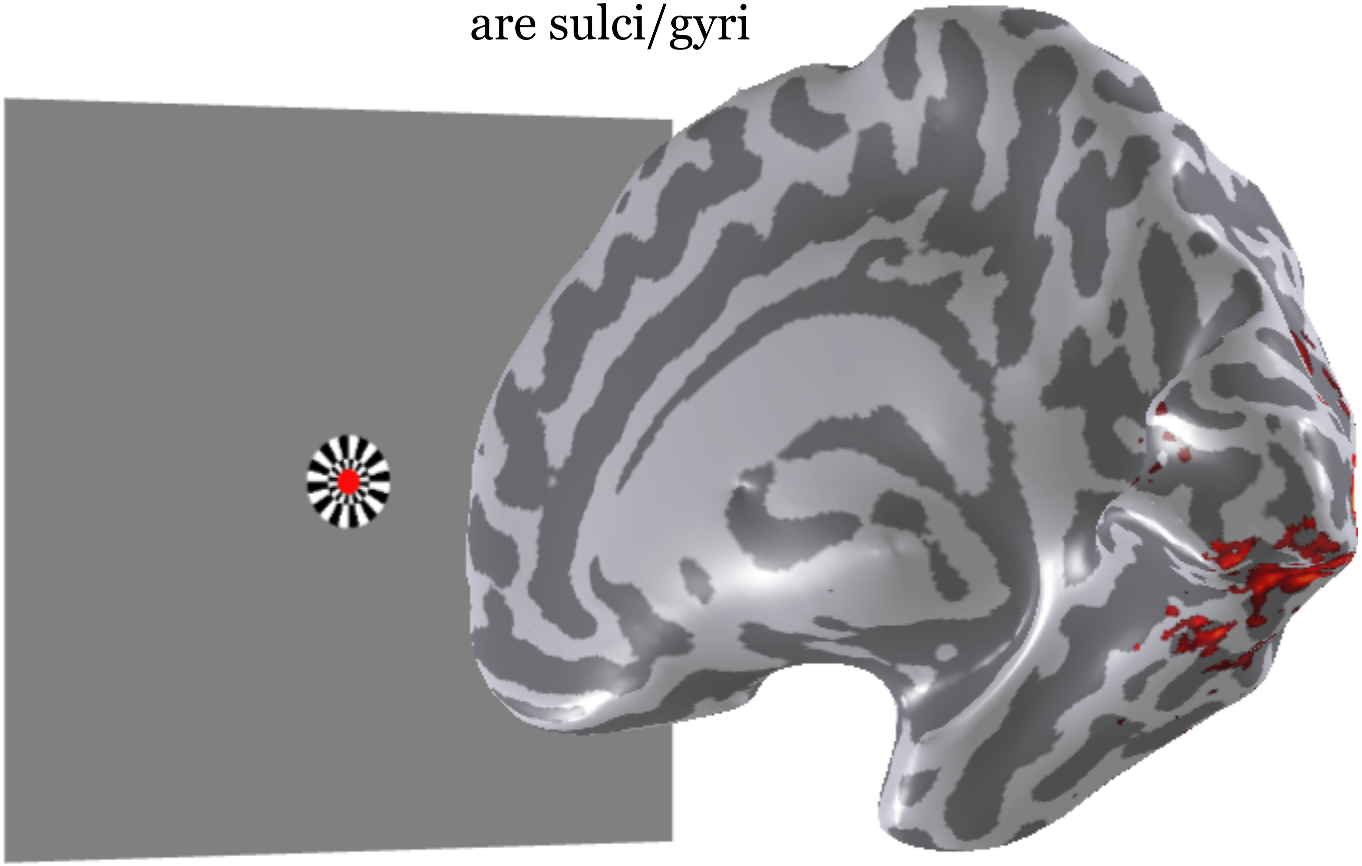




Human eccentricity mapping with fMRI

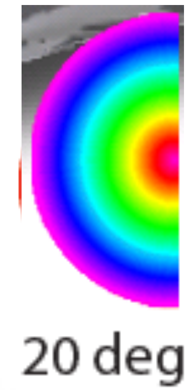
(Engel et al., 1994,1997; Sereno; Tootell, DeYoe; Others)

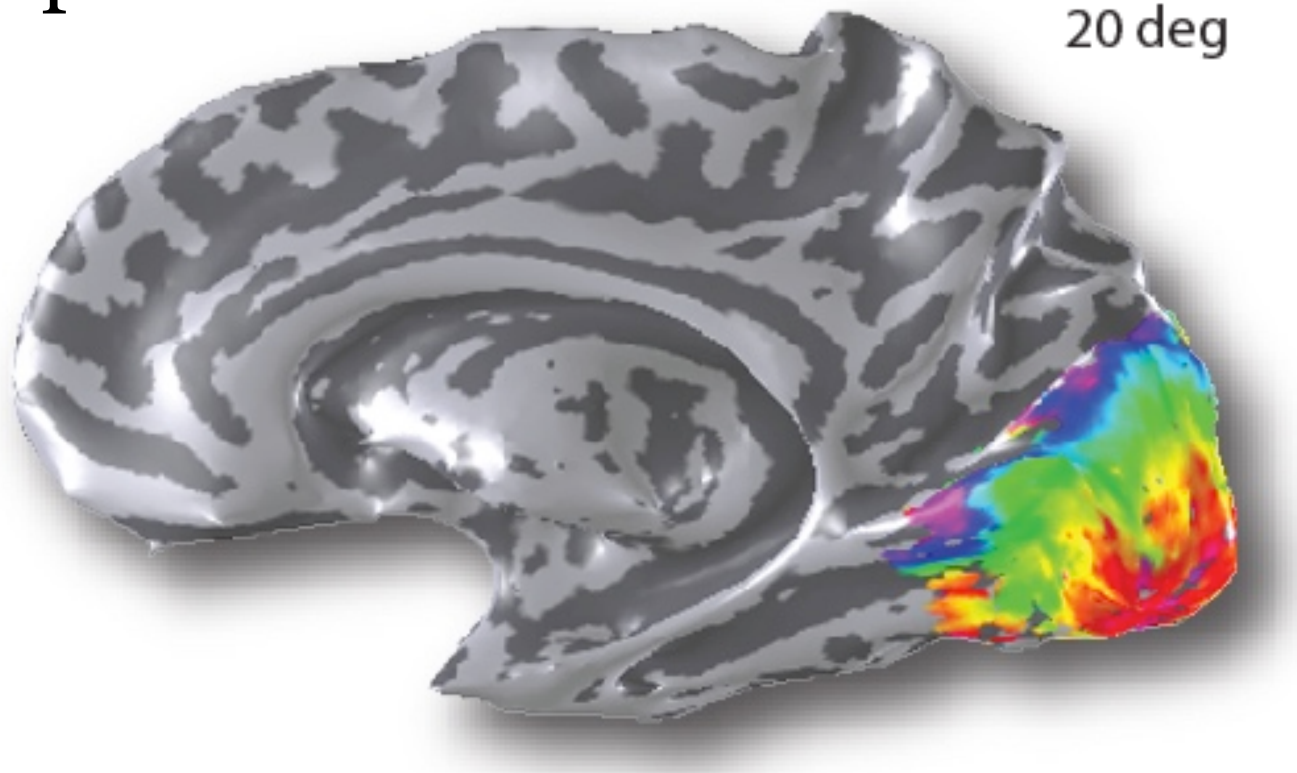
- Inflated brain
- Gray/white are sulci/gyri



Pseudo-color representation of visual field map

- Inflated brain
- Gray/white are sulci/gyri

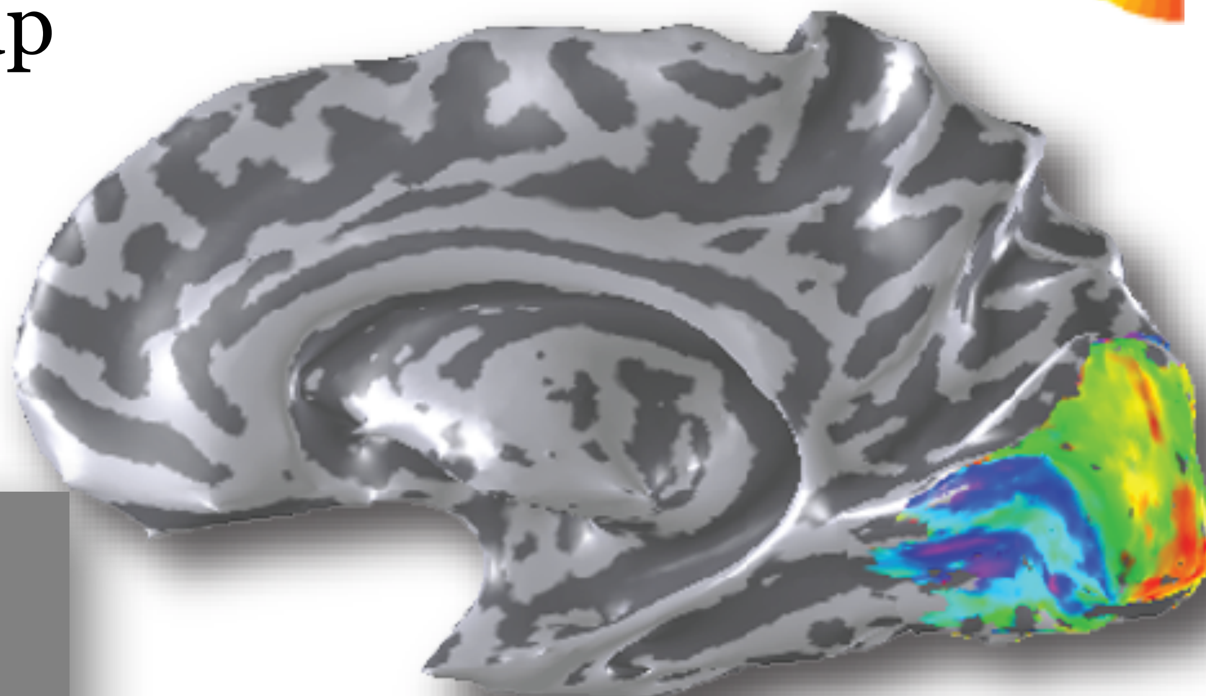


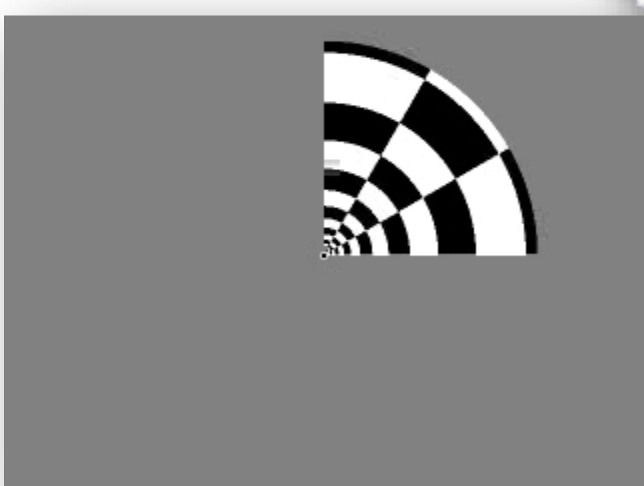


Note: Dougherty;

Angular measurements sharply delineate visual field map boundaries

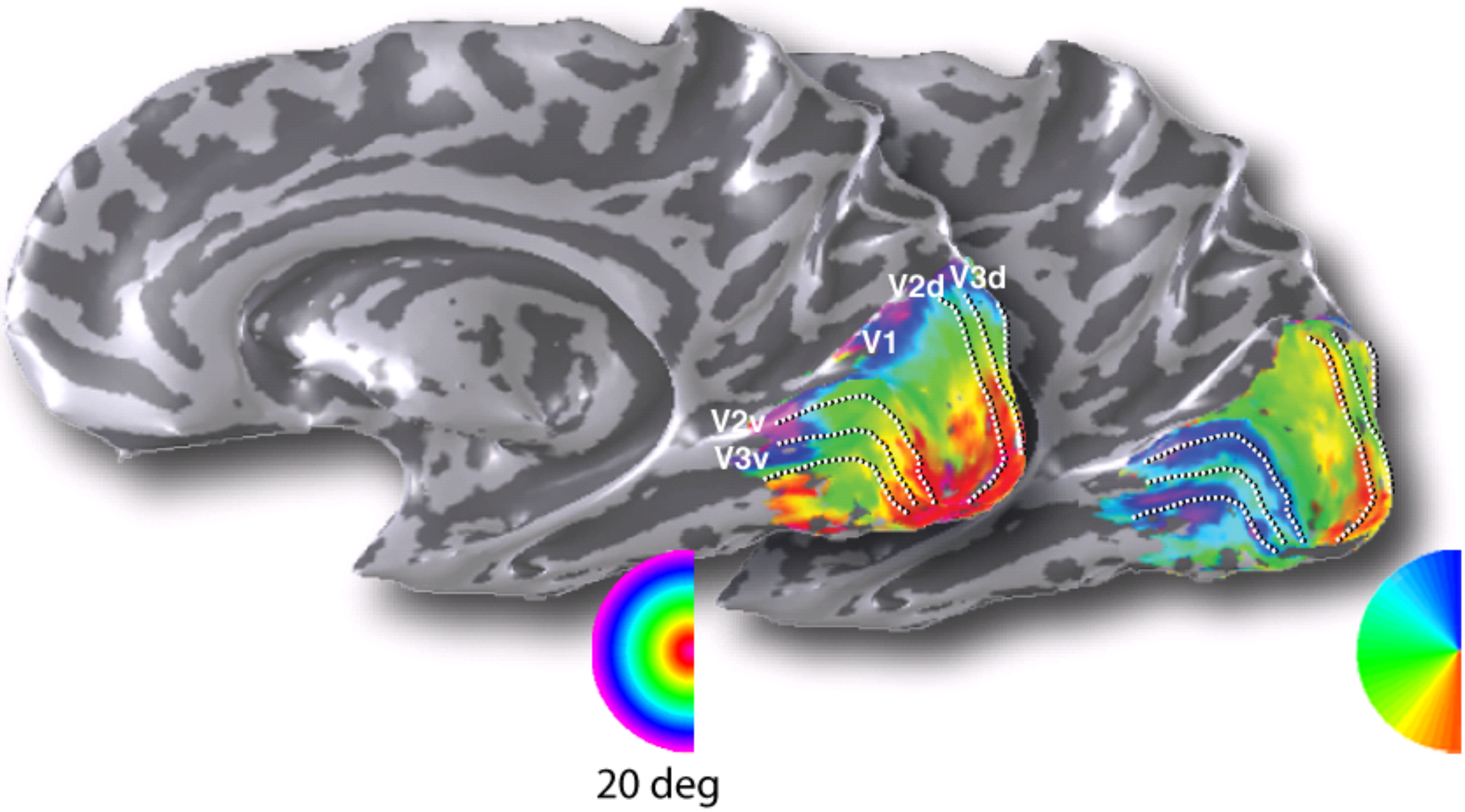
- Inflated brain
- Gray/white are sulci/gyri





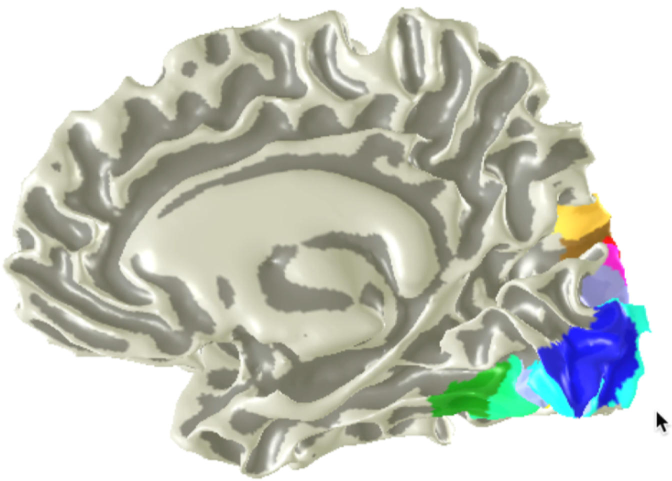
Note: Horton and Hoyt; hV4

Combining eccentricity and angle data yields maps



Note: Benson;

Review articles



- Maps tile the occipital lobe
- Extend into IPS and VOT
- Response properties differ
- Identification from gross anatomy

366 Neuron 56, October 25, 2007

Neuron
Review

Visual Field Maps in Human Cortex

Brian A. Wandell,[1,*] Serge O. Dumoulin,[1] and Alyssa A. Brewer[2]
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DOI 10.1016/j.neuron.2007.10.012

Much of the visual cortex is organized into visual field maps: nearby neurons have receptive fields at nearby locations in the image. Mammalian species generally have multiple visual field maps with each species having similar, but not identical, maps. The introduction of functional magnetic resonance imaging made it possible to identify visual field maps in human cortex, including several near (1) medial occipital (V1,V2,V3), (2) lateral occipital (LO-1,LO-2, hMT+), (3) ventral occipital (hV4, VO-1, VO-2), (4) dorsal occipital (V3A, V3B), and (5) posterior parietal cortex (IPS-0 to IPS-4). Evidence is accumulating for additional maps, including some in the frontal lobe. Cortical maps are arranged into clusters in which several maps have parallel eccentricity representations, while the angular representations within a cluster alternate in visual field sign. Visual field maps have been linked to functional and perceptual properties of the visual system at various spatial scales, ranging from the level of individual maps to map clusters to dorsal-ventral streams. We survey recent measurements of human visual field maps, describe hypotheses about the function and relationships between maps, and consider methods to improve map measurements and characterize the response properties of neurons comprising these maps.

Vision Research 51 (2011) 718-737

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Review

Imaging retinotopic maps in the human brain

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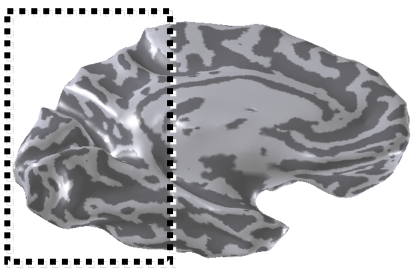
ABSTRACT

A quarter-century ago visual neuroscientists had little information about the number and organization of retinotopic maps in human visual cortex. The advent of functional magnetic resonance imaging (MRI), a non-invasive, spatially-resolved technique for measuring brain activity, provided a wealth of data about human retinotopic maps. Just as there are differences amongst non-human primate maps, the human maps have their own unique properties. Many human maps can be measured reliably in individual sub-

Visual field map clusters

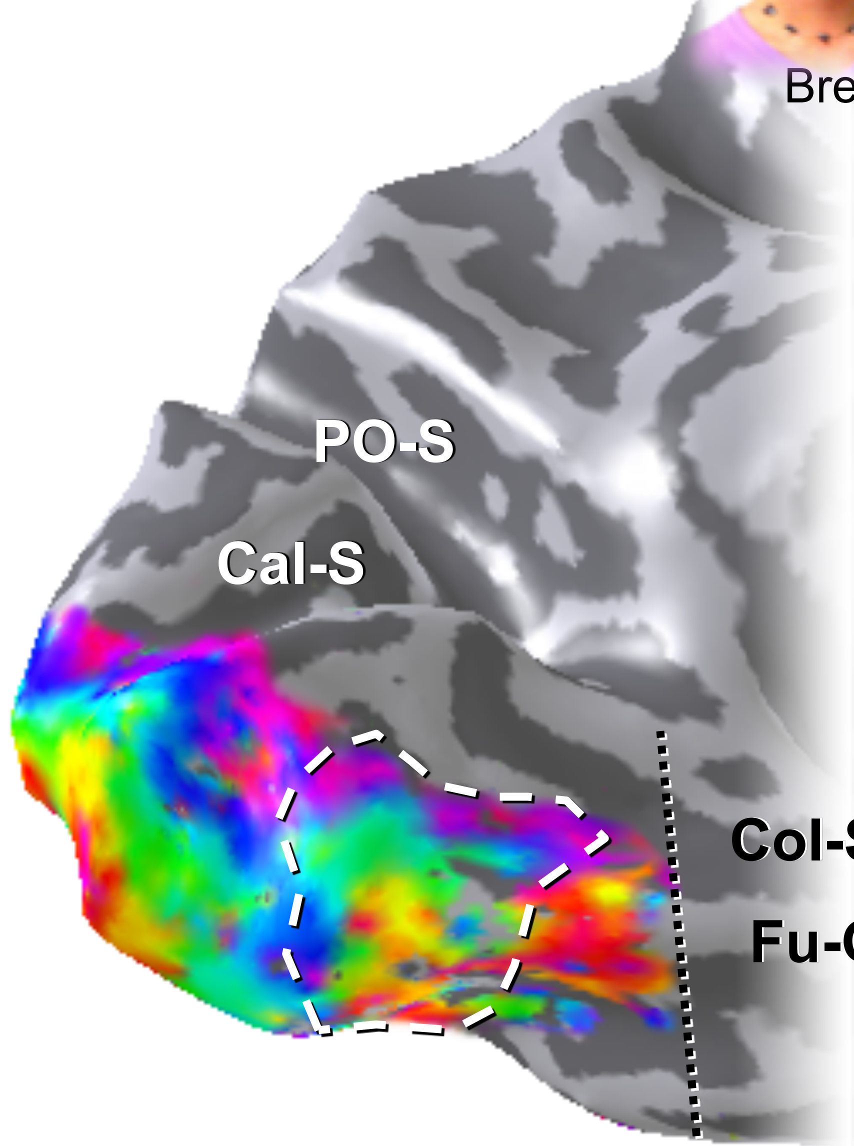
Brewer

Visual field maps and stimulus selectivity in human ventral occipital cortex.
A.A. Brewer, J. Liu, A.R. Wade, B.A. Wandell
Nat Neurosci., vol. 8 no. 8, pp. 1102-9



3° →

Coherence = 0.25

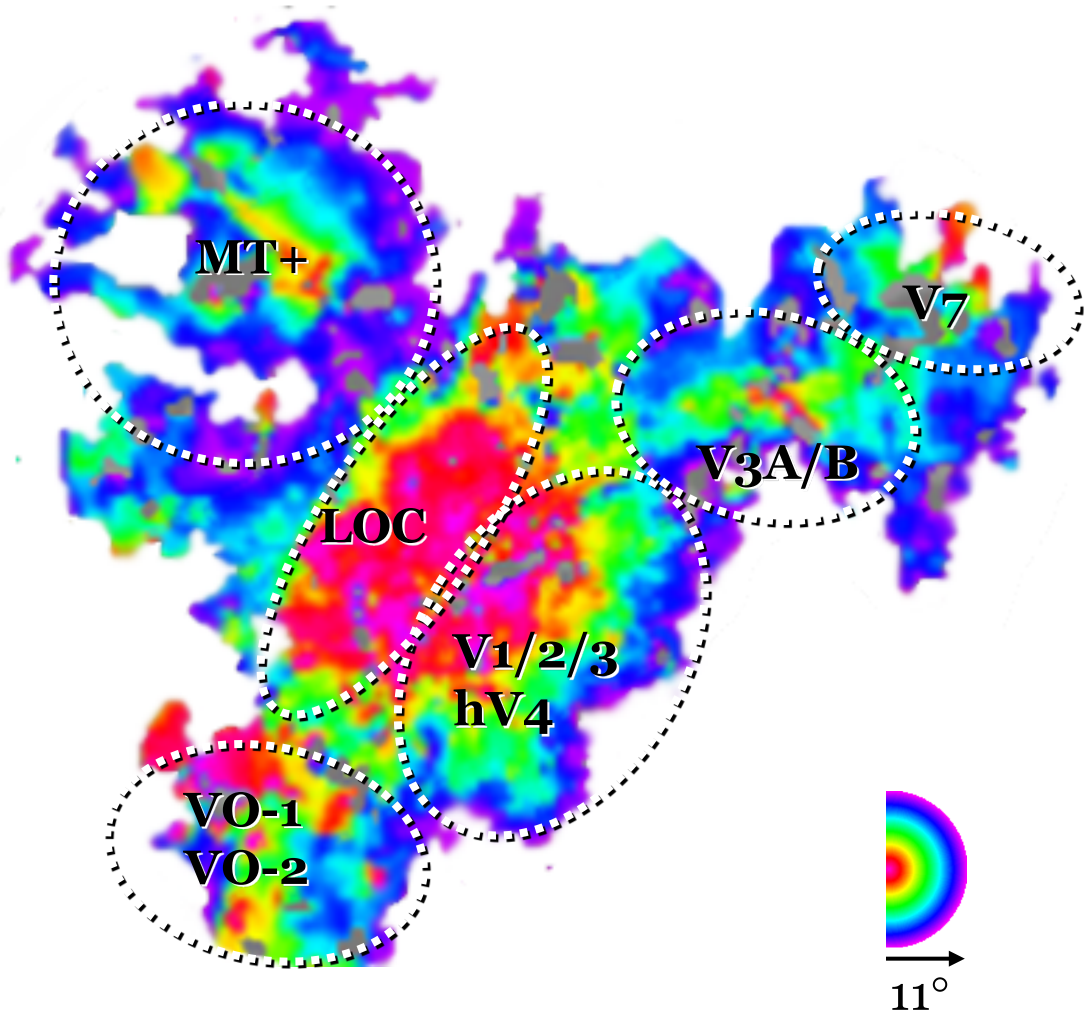


Visual field map clusters

Wandell et al., 2005
Phil Trans Roy Soc

Clusters

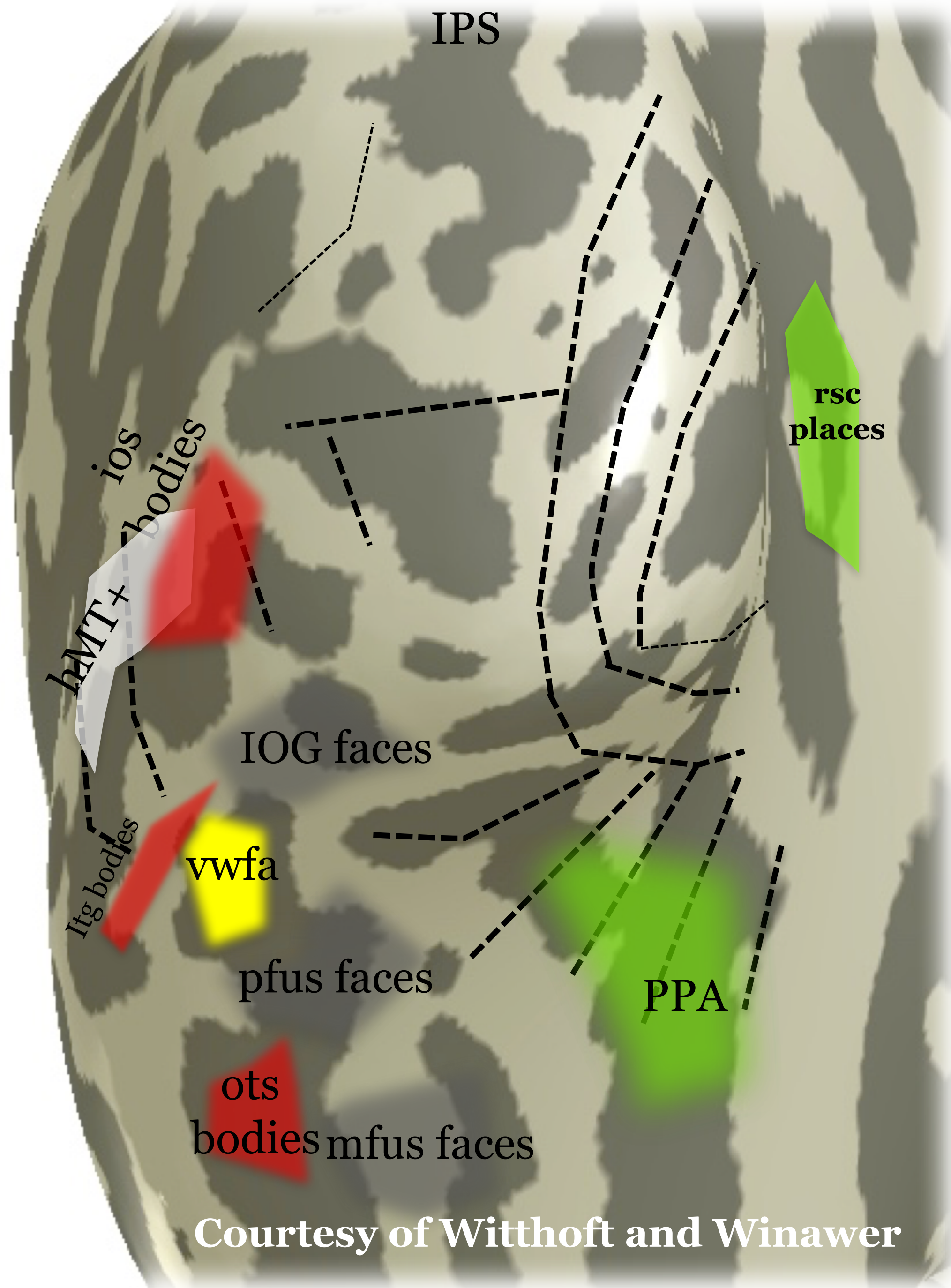
- Share a common circular or semi-circular eccentricity map.
- Contain multiple angle maps within the eccentricity representation.
- May share similar computational resources.



Occipital cortex is tiled by retinotopic maps and object-preferring regions

- 3 face-selective patches
- VWFA– Visual word form area
- PPA – Places
- Body parts

- Some object-preferring regions have retinotopic information as well



Computational neuroimaging

Serge Dumoulin | Kendrick Kay | Jon Winawer



QUANTITATIVE MEASUREMENTS

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COMPUTATIONAL MODELS

∞

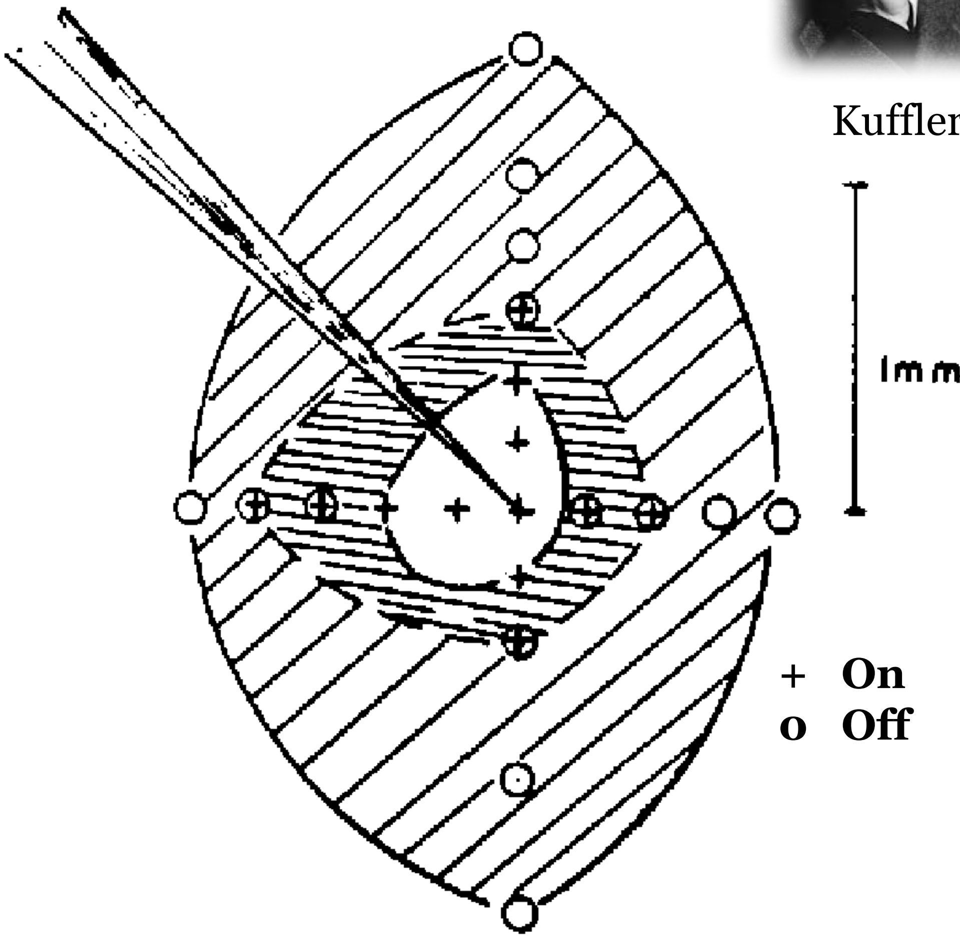
CHECK AND SHARE

The receptive field - a stimulus referred measurement

‘Responses can be obtained in a given optic nerve fiber only upon illumination of a certain restricted region of the retina, termed the receptive field of the fiber (Hartline, 1936)’.

- Functional description
- Stimulus-referred

Kuffler



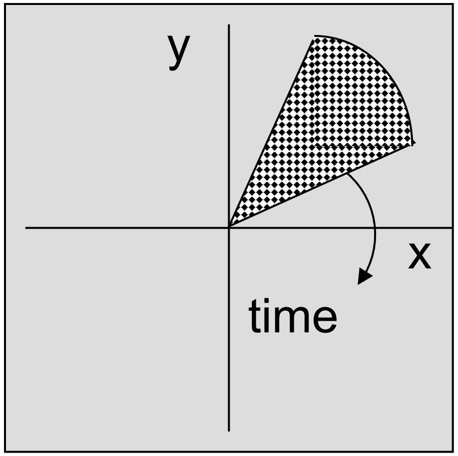
+ **On**
o **Off**

Sherrington, 1910
Kuffler, 1953

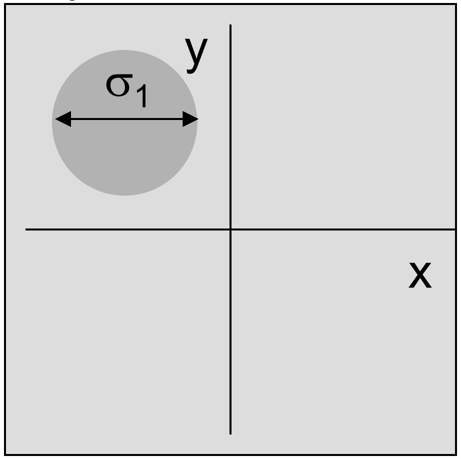
Population RF estimation

Dumoulin and Wandell, 2008
Neuroimage

Stimulus



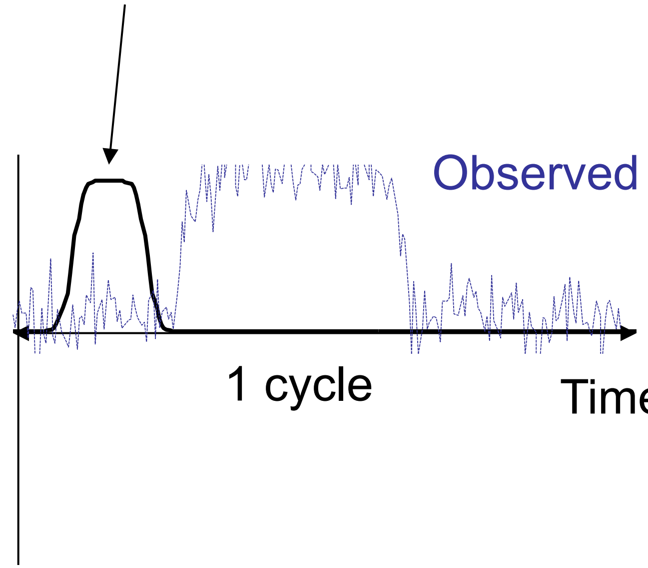
Population RF model



Parameters

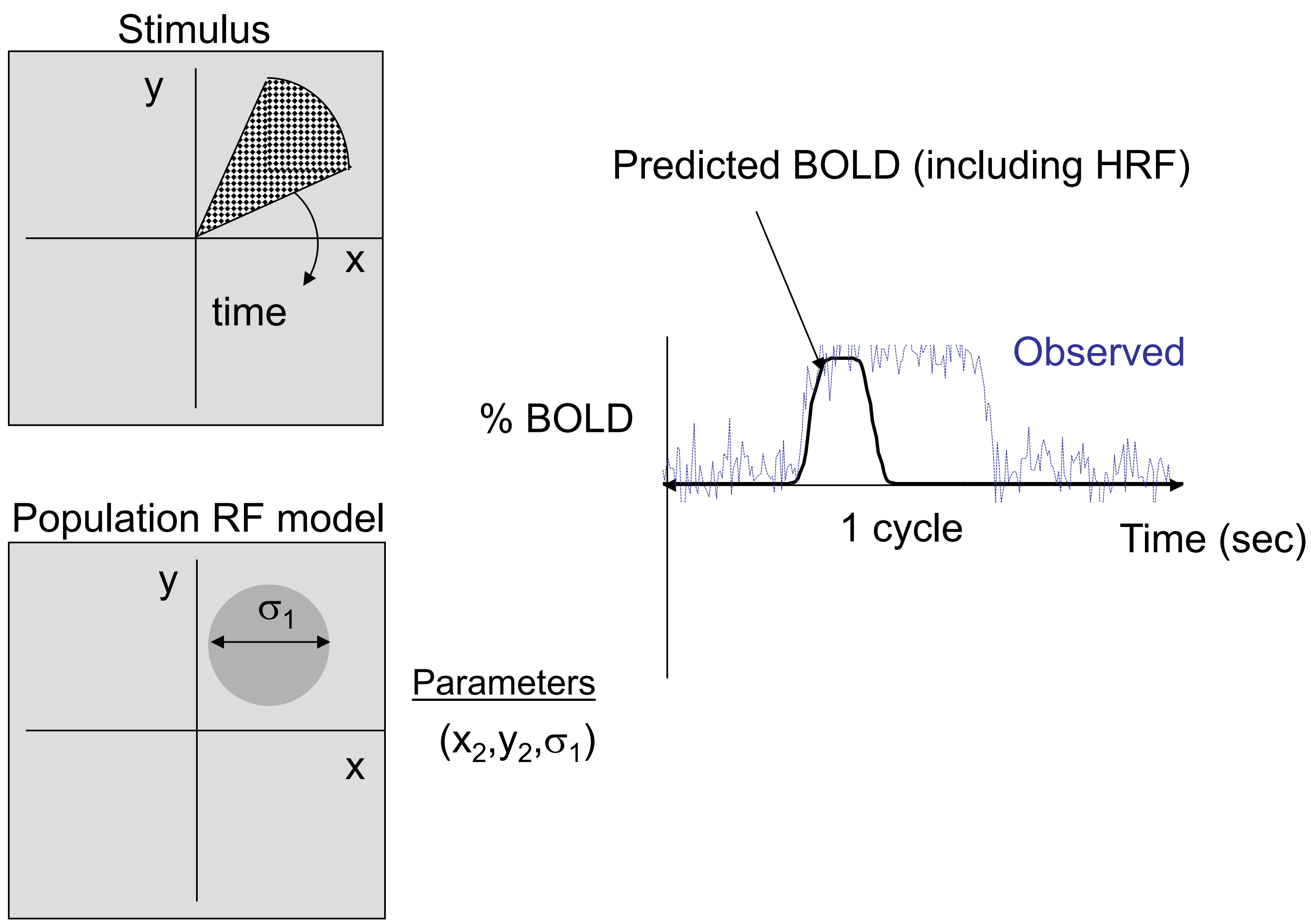
(x_1, y_1, σ_1)

Predicted BOLD (including HRF)



Population RF estimation

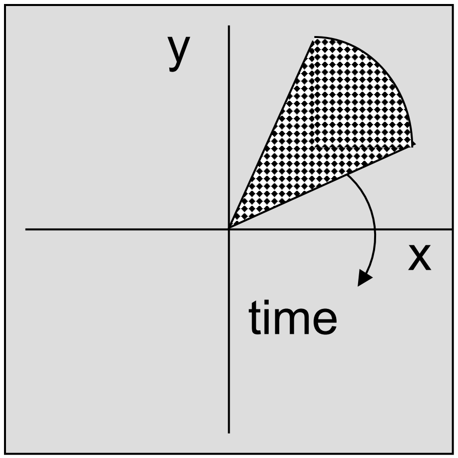
Dumoulin and Wandell, 2008
Neuroimage



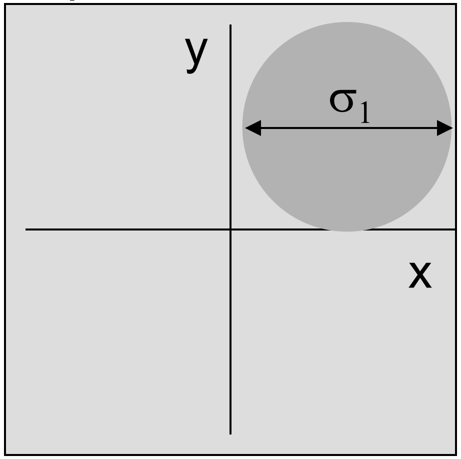
Population RF estimation

Dumoulin and Wandell, 2008
Neuroimage

Stimulus

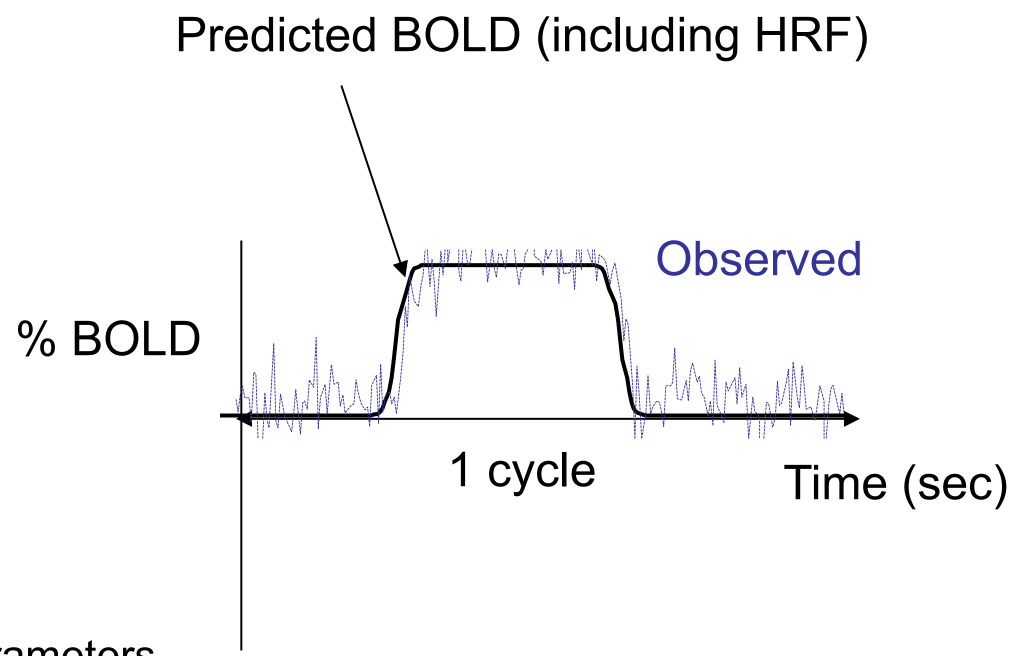


Population RF model



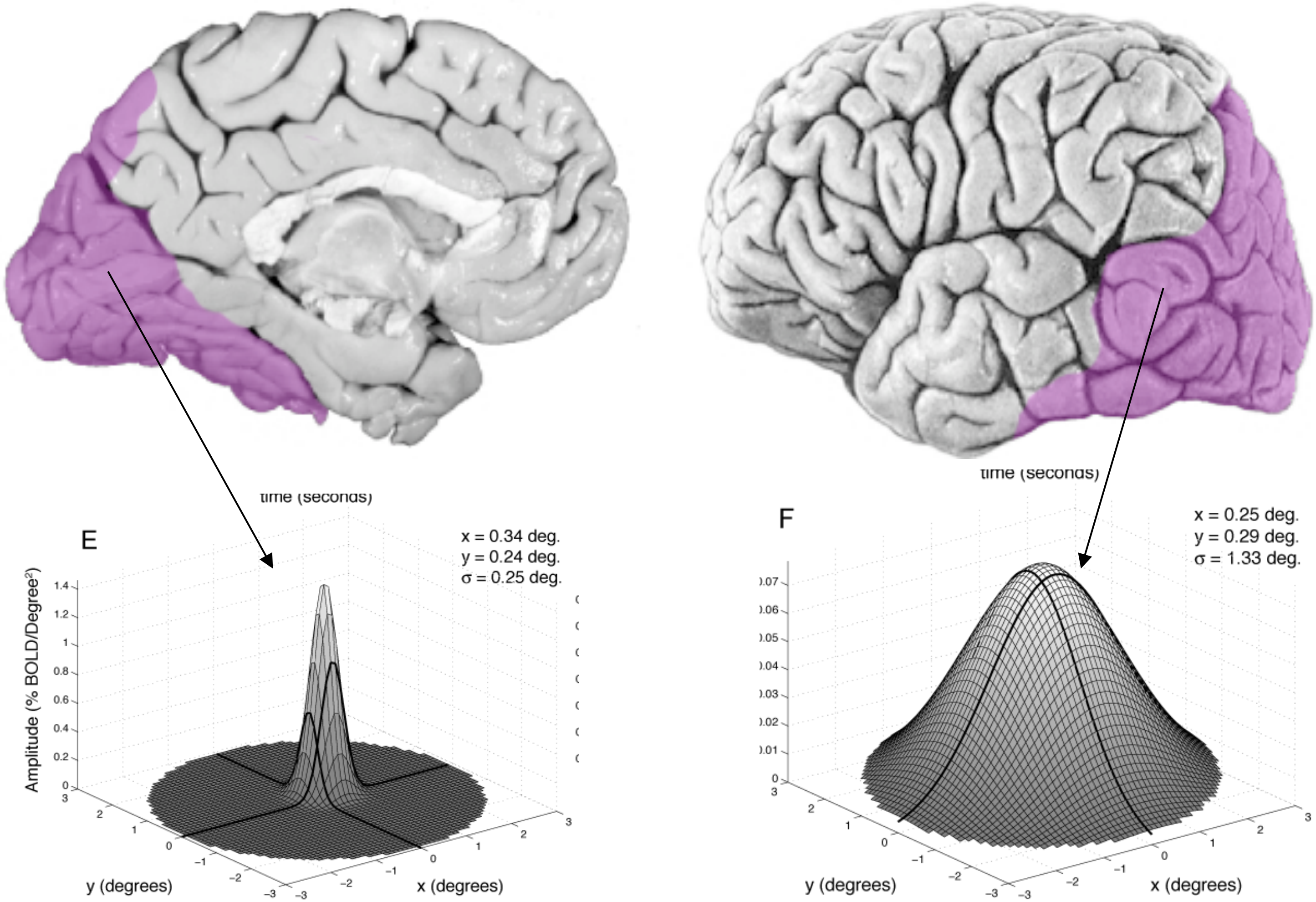
Parameters

(x_2, y_2, σ_1)



Population receptive fields vary significantly across human visual cortex

Dumoulin and Wandell, 2008
Neuroimage



Trends in Cognitive Sciences, June 2015, Vol. 19, No. 6 349

- Attention
- Stability and Plasticity
- Prosopagnosia
- Development and aging
- Autism
- Alzheimer's disease

Review

CellPress

Computational neuroimaging and population receptive fields

Brian A. Wandell[1] **and Jonathan Winawer**[2]

[1] Psychology Department and Neurosciences Institute, Stanford University, Stanford, CA, USA
[2] Psychology Department and Center for Neural Science, New York University, New York, NY, USA

Functional magnetic resonance imaging (fMRI) noninvasively measures human brain activity at millimeter resolution. Scientists use different approaches to take advantage of the remarkable opportunities presented by fMRI. Here, we describe progress using the computational neuroimaging approach in human visual cortex, which aims to build models that predict the neural responses from the stimulus and task. We focus on a particularly active area of research, the use of population receptive field (pRF) models to characterize human visual cortex responses to a range of stimuli, in a variety of tasks and different subject populations.

Understanding sensory circuits

A mark of understanding a sensory system is the ability to predict how it will respond to stimulation. In the case of human visual cortex, we would like to accurately predict how each part of the system responds to any visual input. Such predictions are beyond current capabilities, but progress has

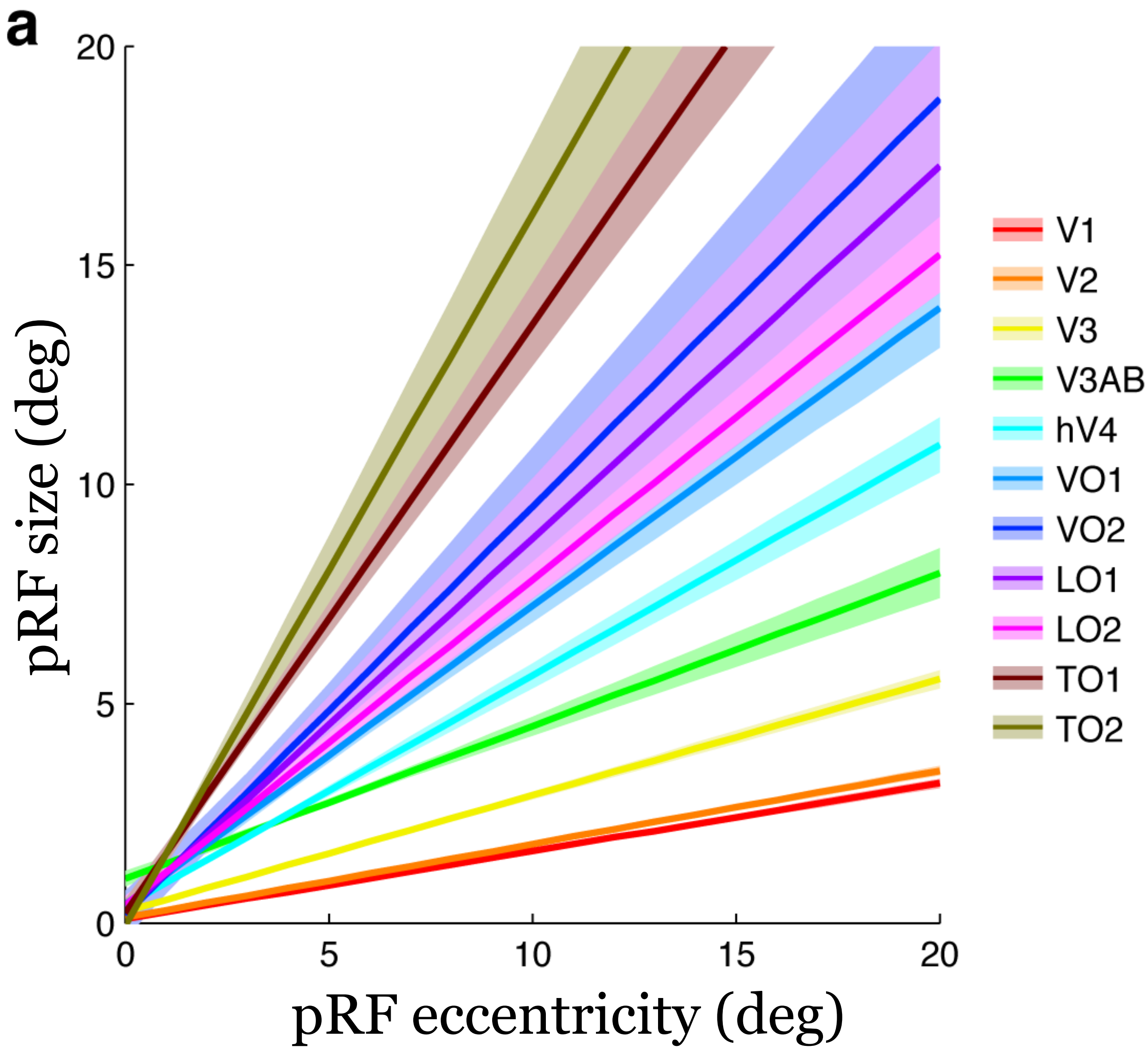
Receptive field models

For more than 75 years, visual neuroscientists have relied on the receptive field concept to make progress in the face of limited knowledge of the neural circuitry [3]. Sherrington [4] coined the phrase 'receptive field' to describe the region of skin from which a scratch reflex could be elicited: 'The "receptive field" may be conveniently applied to designate the total assemblage of receptive points whence by suitable stimuli a particular reflex movement can be evoked' ([4], p. 32). Hartline applied the concept to visual neurons [5]. Hartline's initial definition, similar to Sherrington's, emphasized the spatial extent of the receptive field: 'No description of the optic responses in single fibers would be complete without a description of the region of the retina which must be illuminated in order to obtain a response in any given fiber. This region will be termed the receptive field of the fiber' ([5], p. 410). Over the years, the receptive field concept has expanded to include stimulus features (e.g., orientation, motion, or contrast) and to be based on explicit

Quantifying population RF (pRF) size

Kay et al., 2012
J. Neurophys

- At common eccentricities, different maps have different pRF sizes
- PRF size increases with eccentricity for all maps
- Bands are bootstrap estimates of the standard error

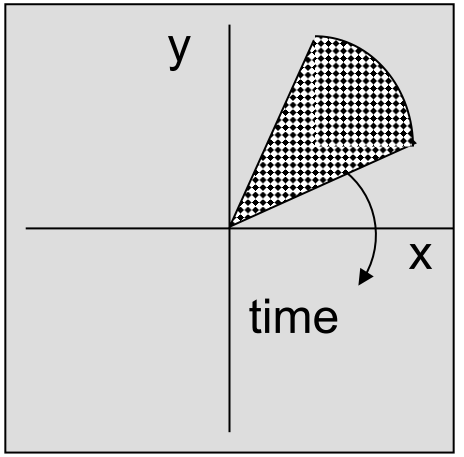


Linear pRF models account well for a narrow range of stimuli

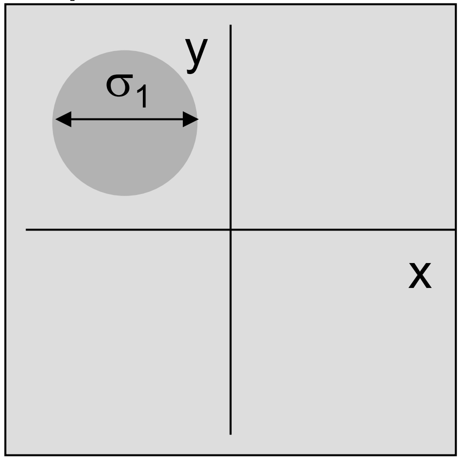
"… all models are wrong, but some are useful "

Box, G. E. P., and Draper, N. R., (1987), *Empirical Model Building and Response Surfaces*, John Wiley & Sons, New York, NY.

Stimulus



Population RF model

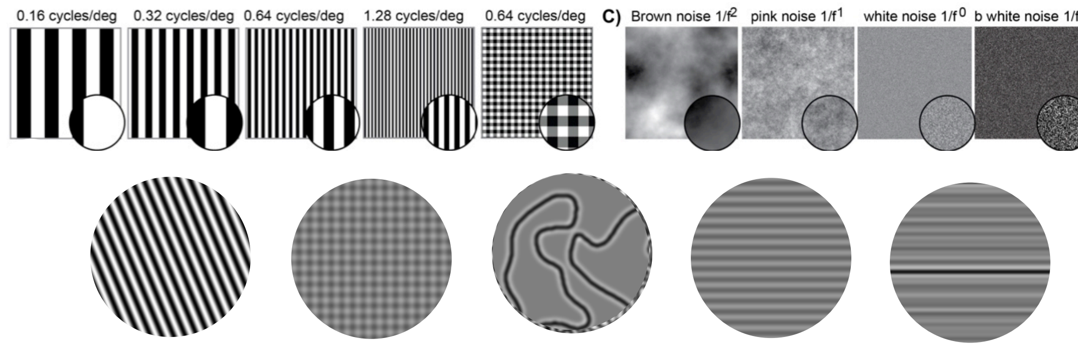


Parameters

(x_1, y_1, σ_1)

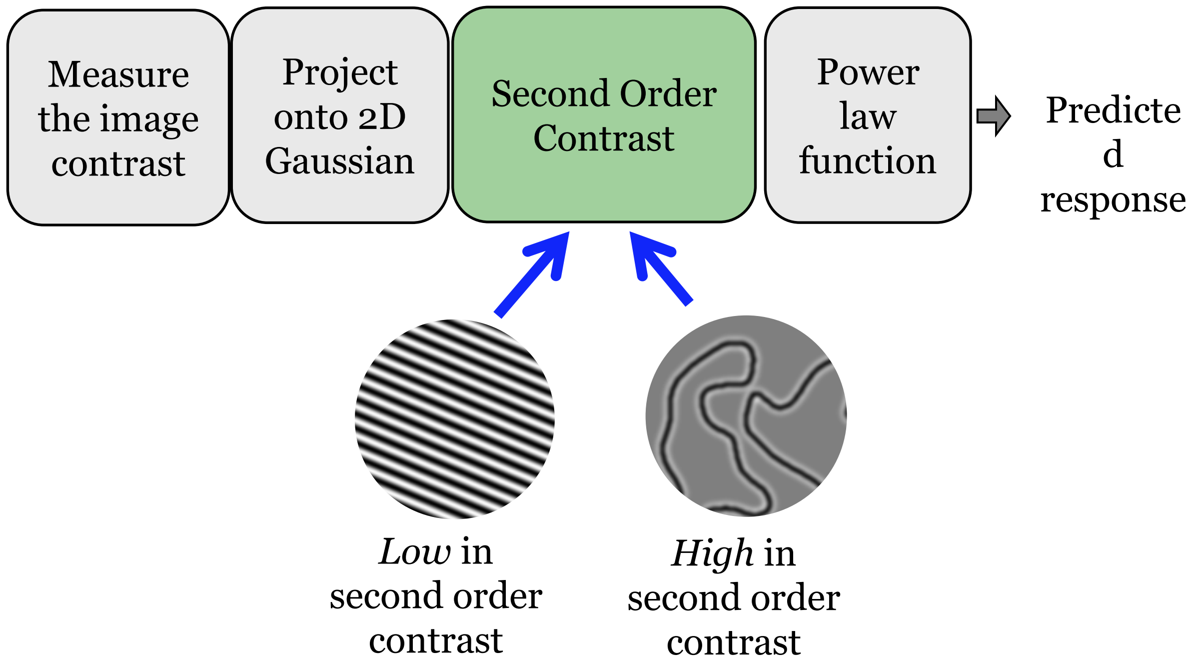
New models account for larger range of stimuli with high accuracy

<u>Greatly extended range of stimuli</u>



- **Prediction**: Start with image and produce BOLD time series

- For achromatic, bandpass stimuli, **the model accounts for about 80-90% of the explainable variance** (cross-validation) in V1, V2,V3, hV4

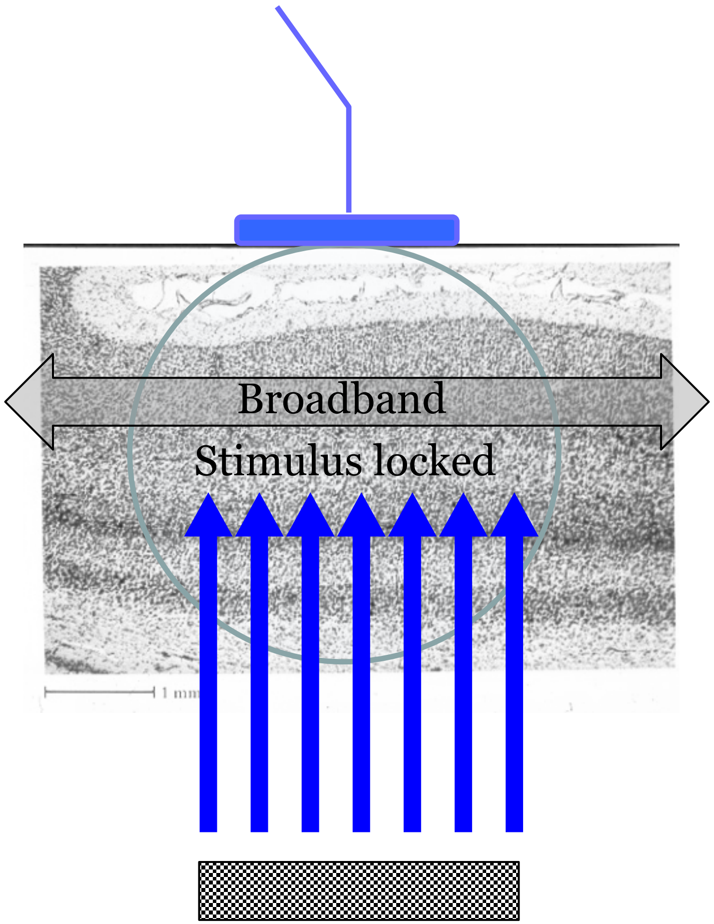


Kay et al., 2013, PLoS Computational Bio

Open-source models integrate data from multiple modalities

- PRF methods applied to BOLD and intracranial electrical recordings (ECoG)
- Showed relationship between BOLD and specific ECoG response components (and not others)

Intracranial implants (ECoG)



Stimulus

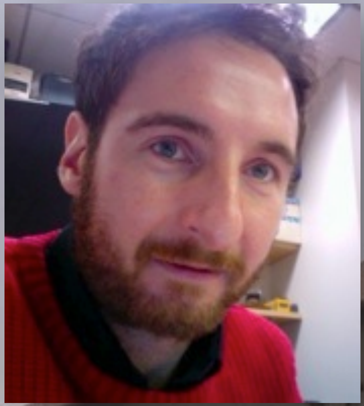
Winawer et al., Current Biology, 2013

Modeling the diffusion signal in a voxel

Ariel Rokem

Aviv Mezer

Franco Pestilli



Hiromasa Takemura

QUANTITATIVE MEASUREMENTS

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COMPUTATIONAL MODELS

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CHECK AND SHARE

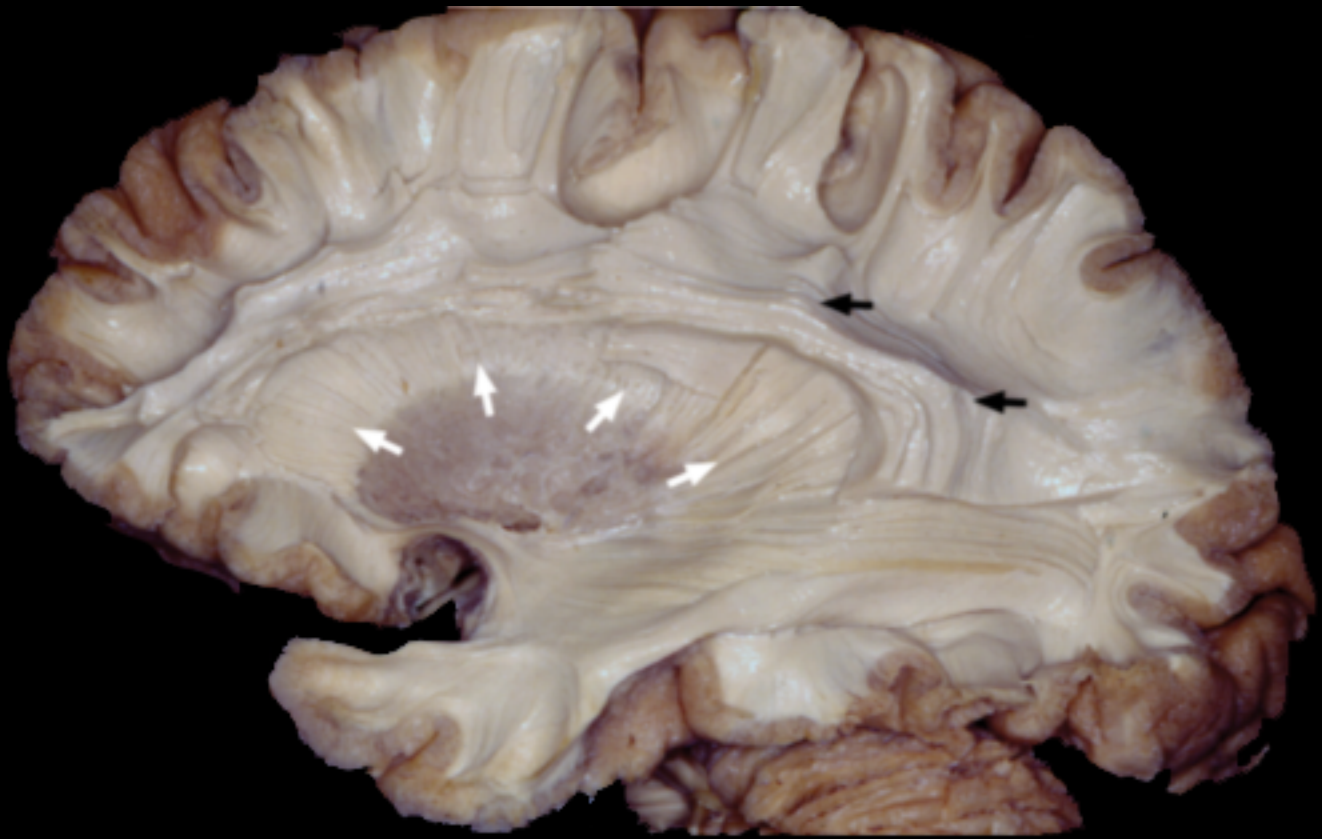
Human fascicles (tracts)

- There are many long-range connections
- These connections are not passive – they change their properties in response to use
- A system with active wires

Courtesy Professor Peggy Mason

Human fascicles (tracts)

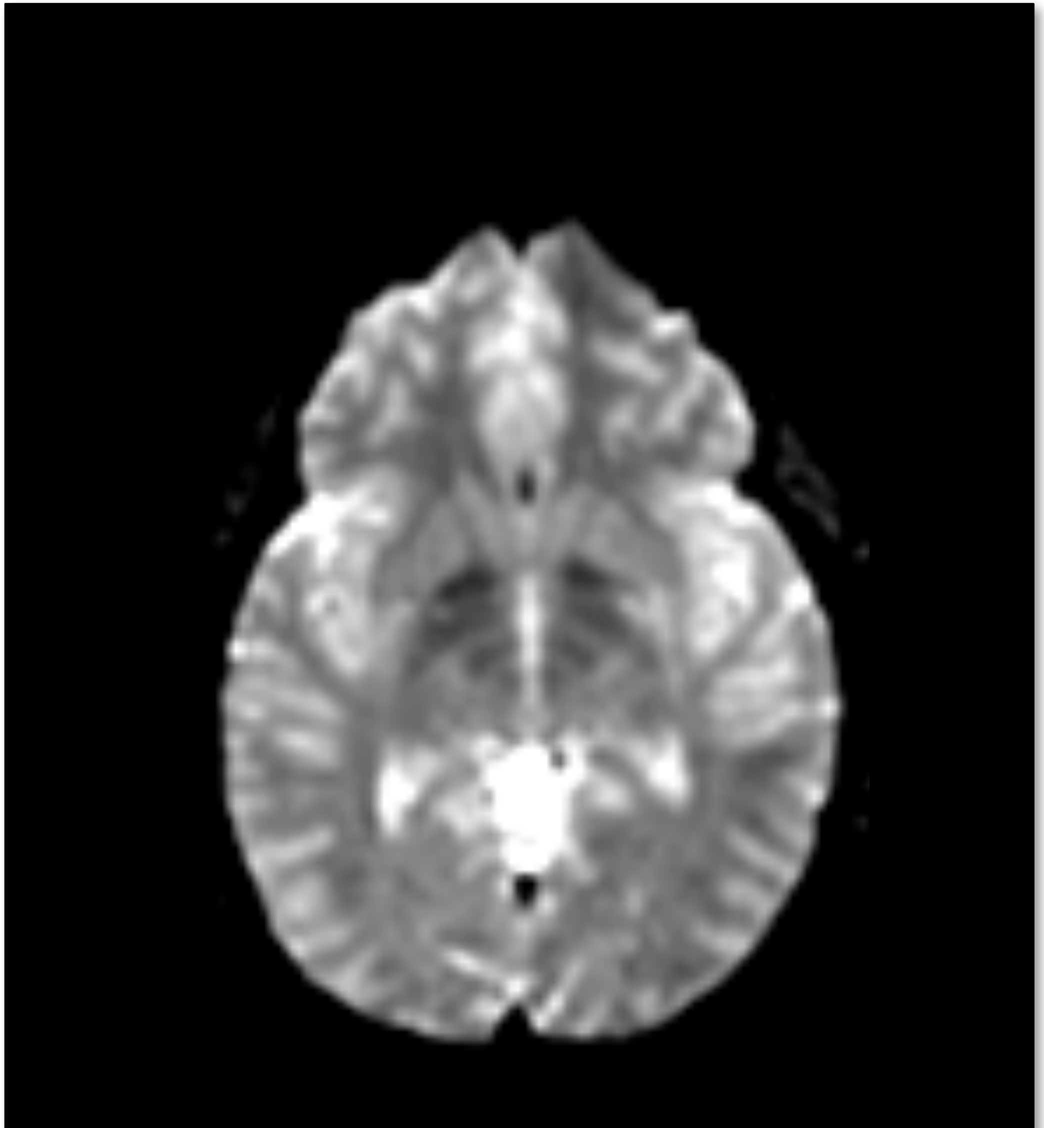
- There are many long-range connections
- These connections are not passive – they change their properties in response to use
- A system with active wires



Courtesy Professor Ugur Ture

Non-diffusion MR image

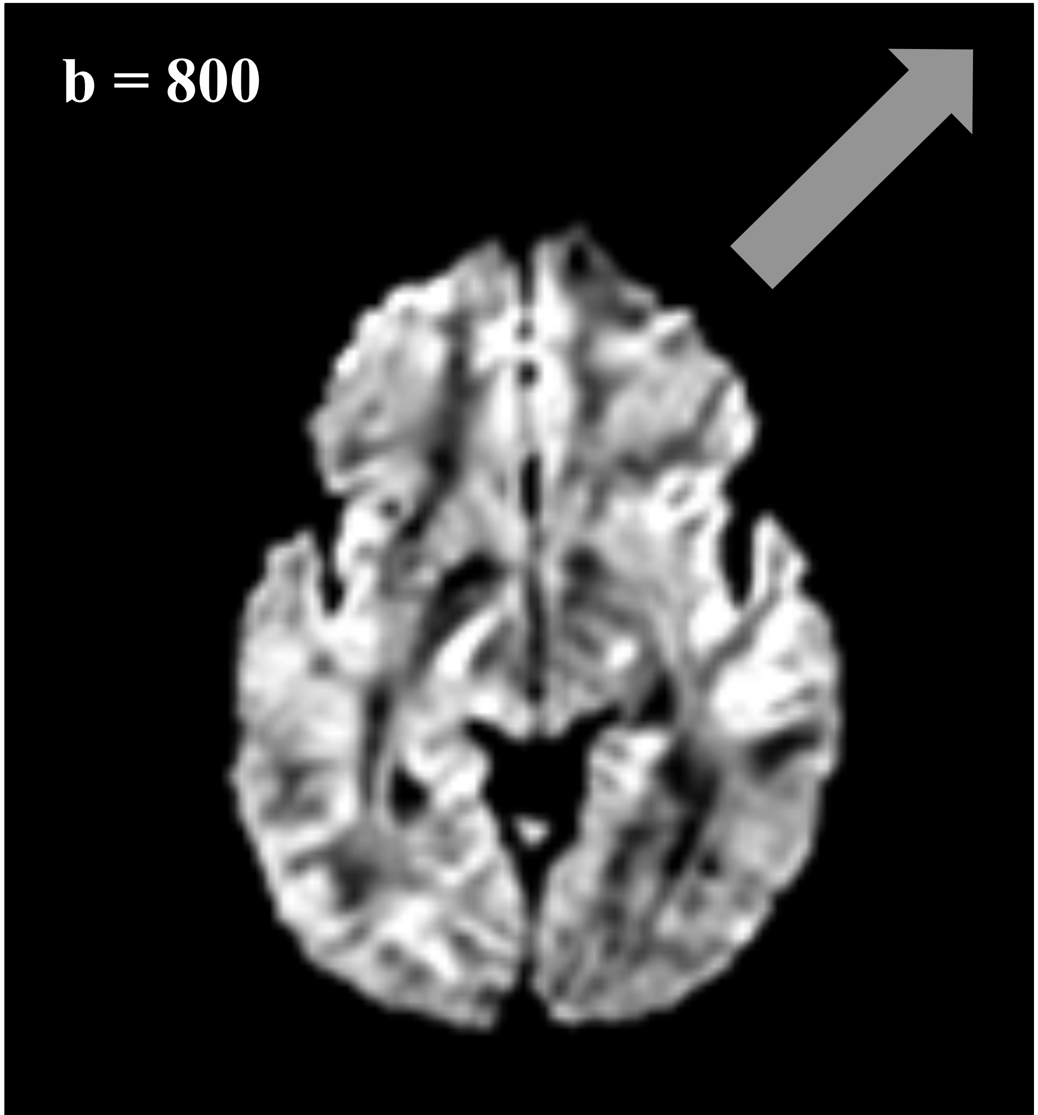
Dark means large signal attenuation
High ADC



Rokem et al., 2015, PLoS One

Diffusion weighting: Directions

Dark means large signal attenuation
High ADC



Rokem et al., 2015, PLoS One

Diffusion weighting: Directions

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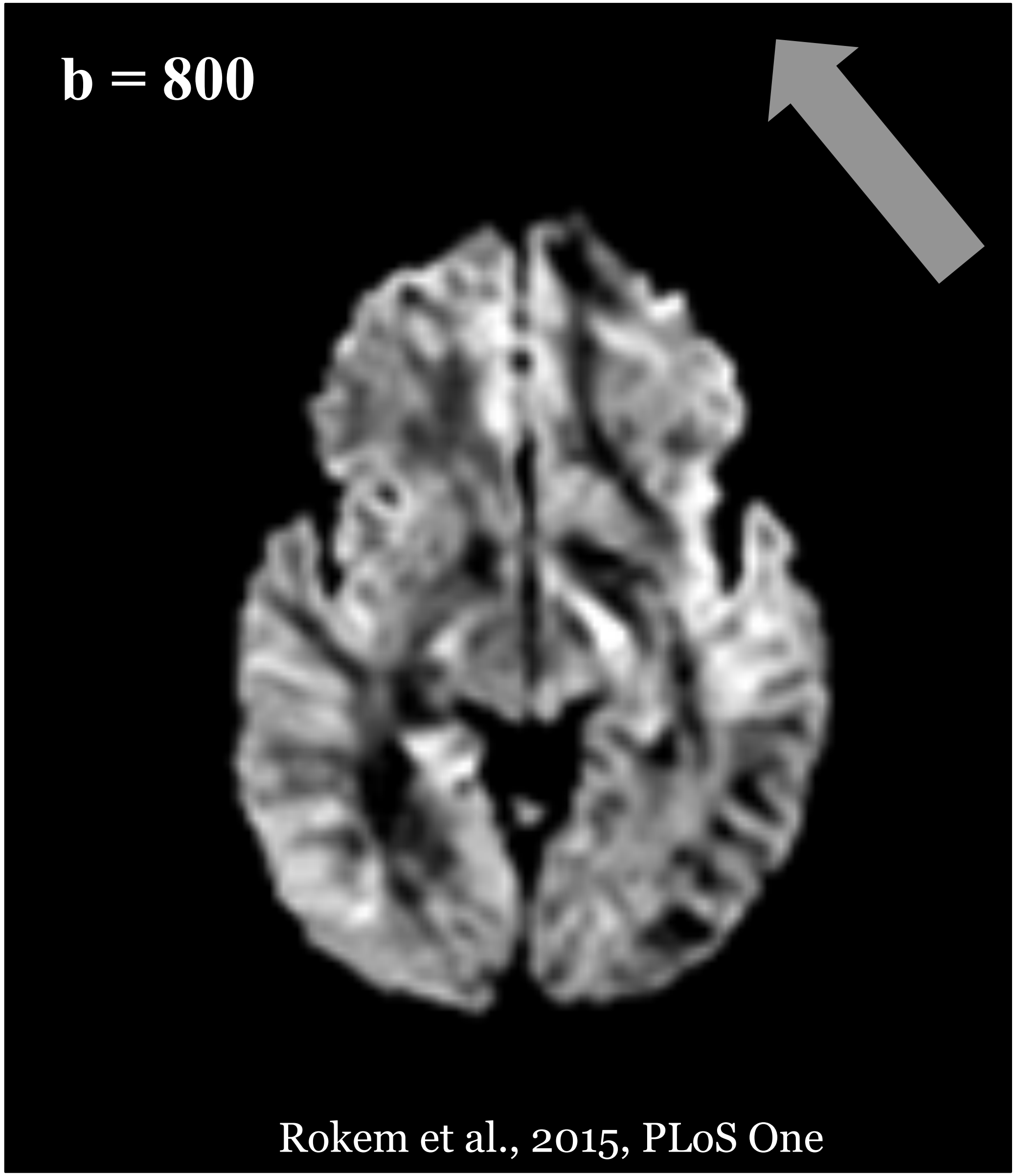


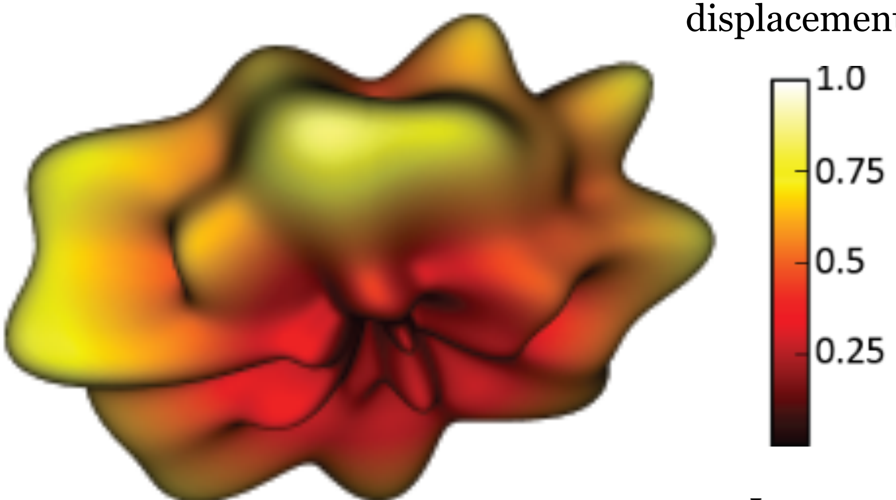
Diffusion signals in different directions

ADC – apparent diffusion coefficient

E. O. Stejskal and J. E. Tanner (1965)

$$S(\theta) = S_0 \, \mathrm{e}^{-bD(\theta)}$$

Small displacement



Large displacement

Signal
Re: b=0

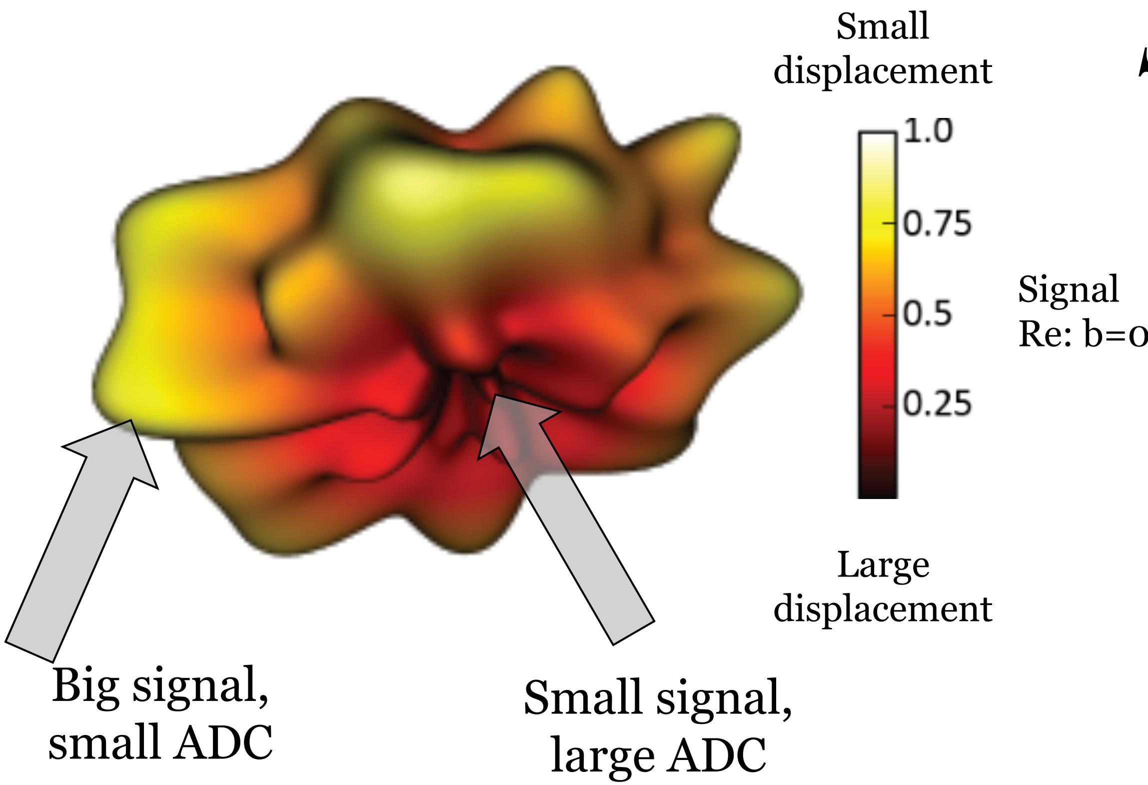
The measured diffusion signal in a direction, θ, is related to the apparent diffusion coefficient in that direction, D(θ)

Diffusion signals in different directions

ADC – apparent diffusion coefficient

E. O. Stejskal and J. E. Tanner (1965)

$$S(\theta) = S_0 \, e^{-bD(\theta)}$$



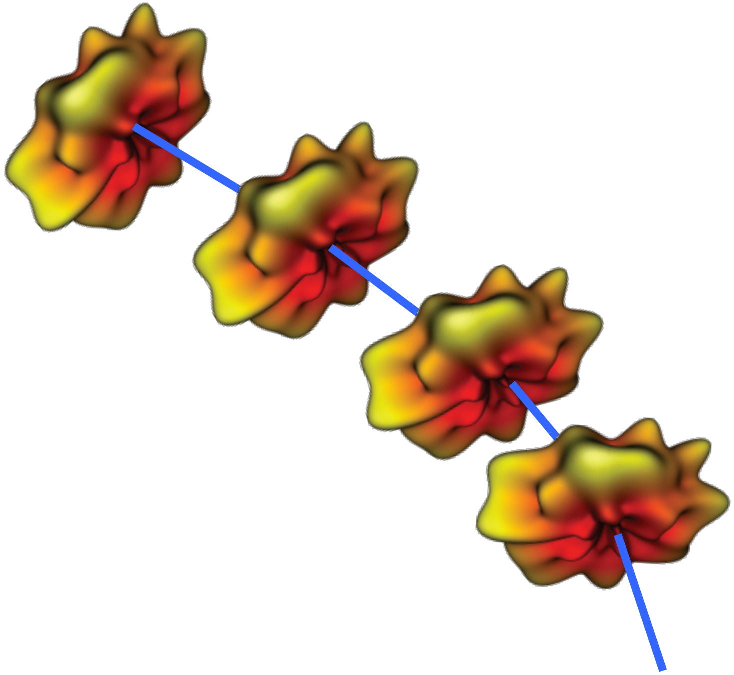
The measured diffusion signal in a direction, θ, is related to the apparent diffusion coefficient in that direction, D(θ)

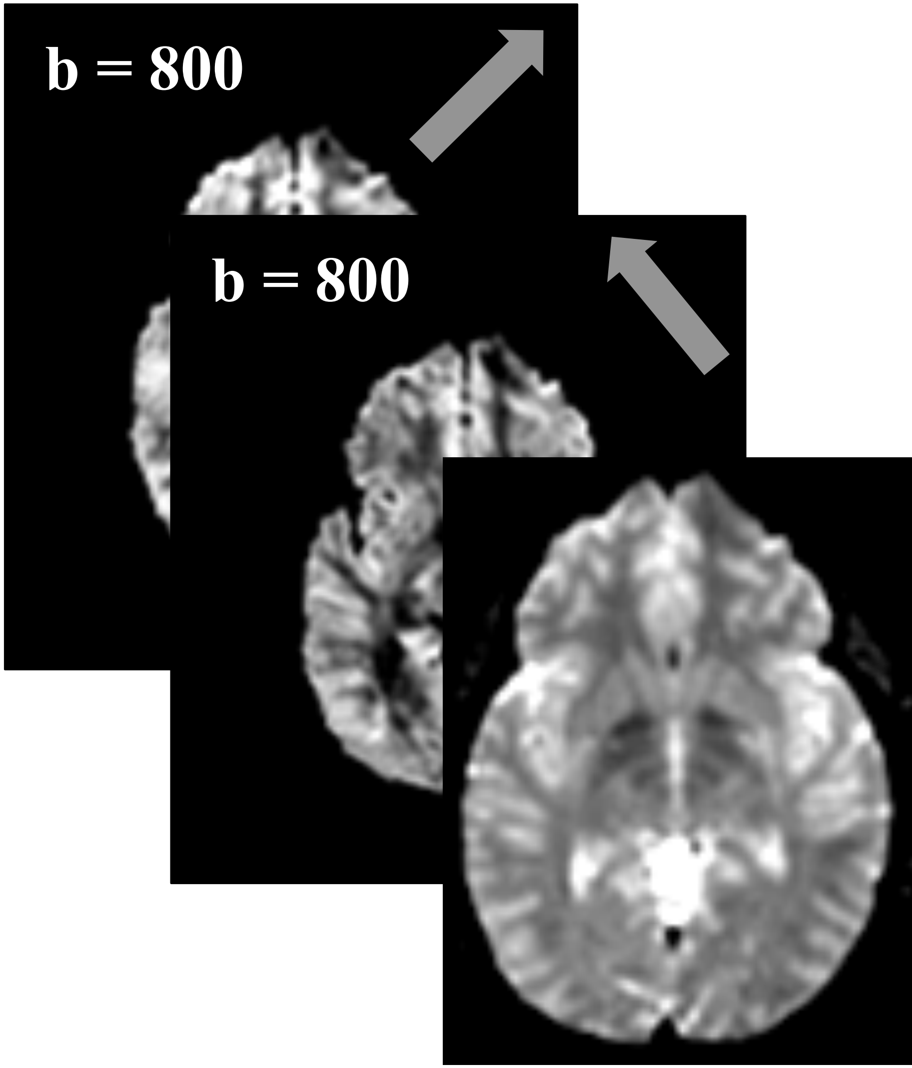
Tractography

Wandell (in press)
Clarifying white matter
Annual Review

Algorithms to combine the local (voxel) diffusion measurements to estimate white matter tracts (streamlines)

Diffusion data are surfaces

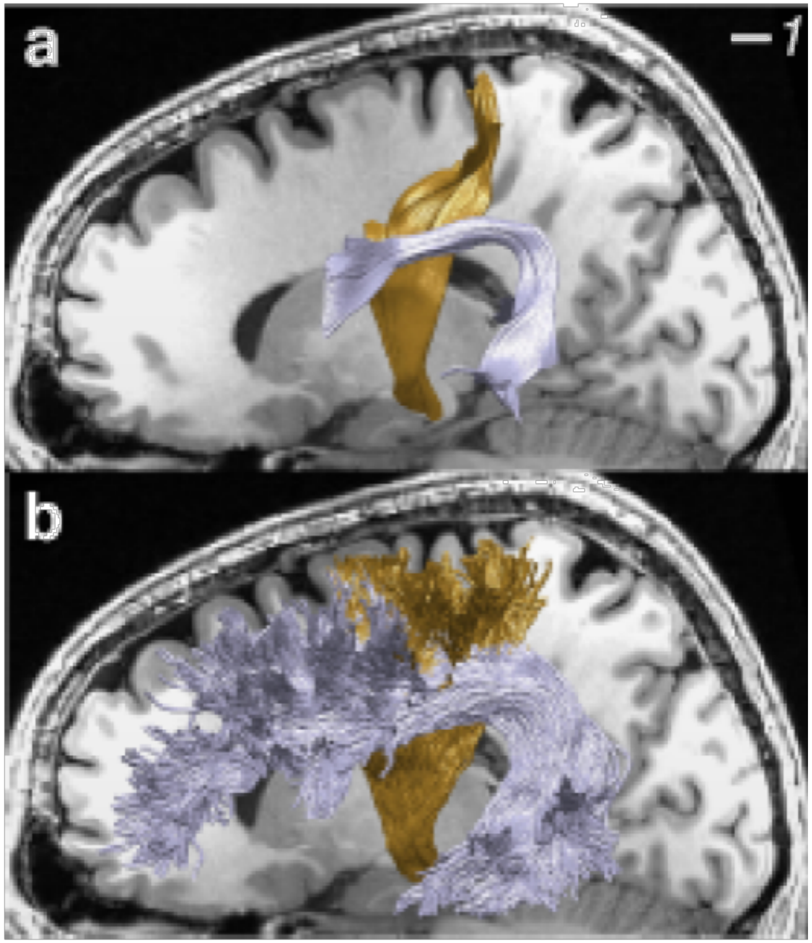


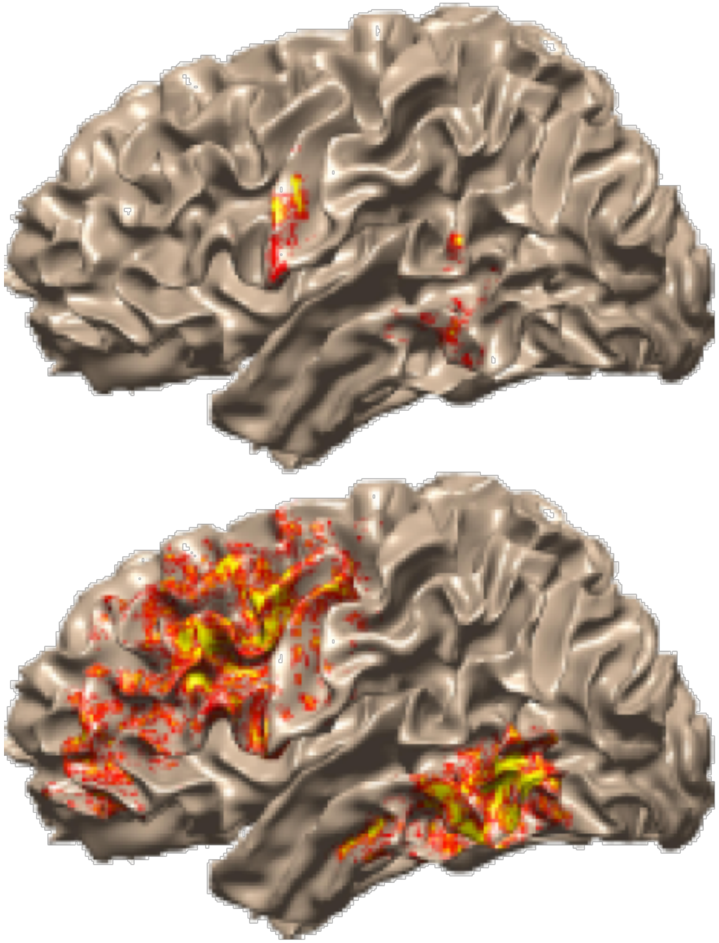


Different methods and parameters make different predictions

A key tractography problem we must solve
– parameter and instrument dependency

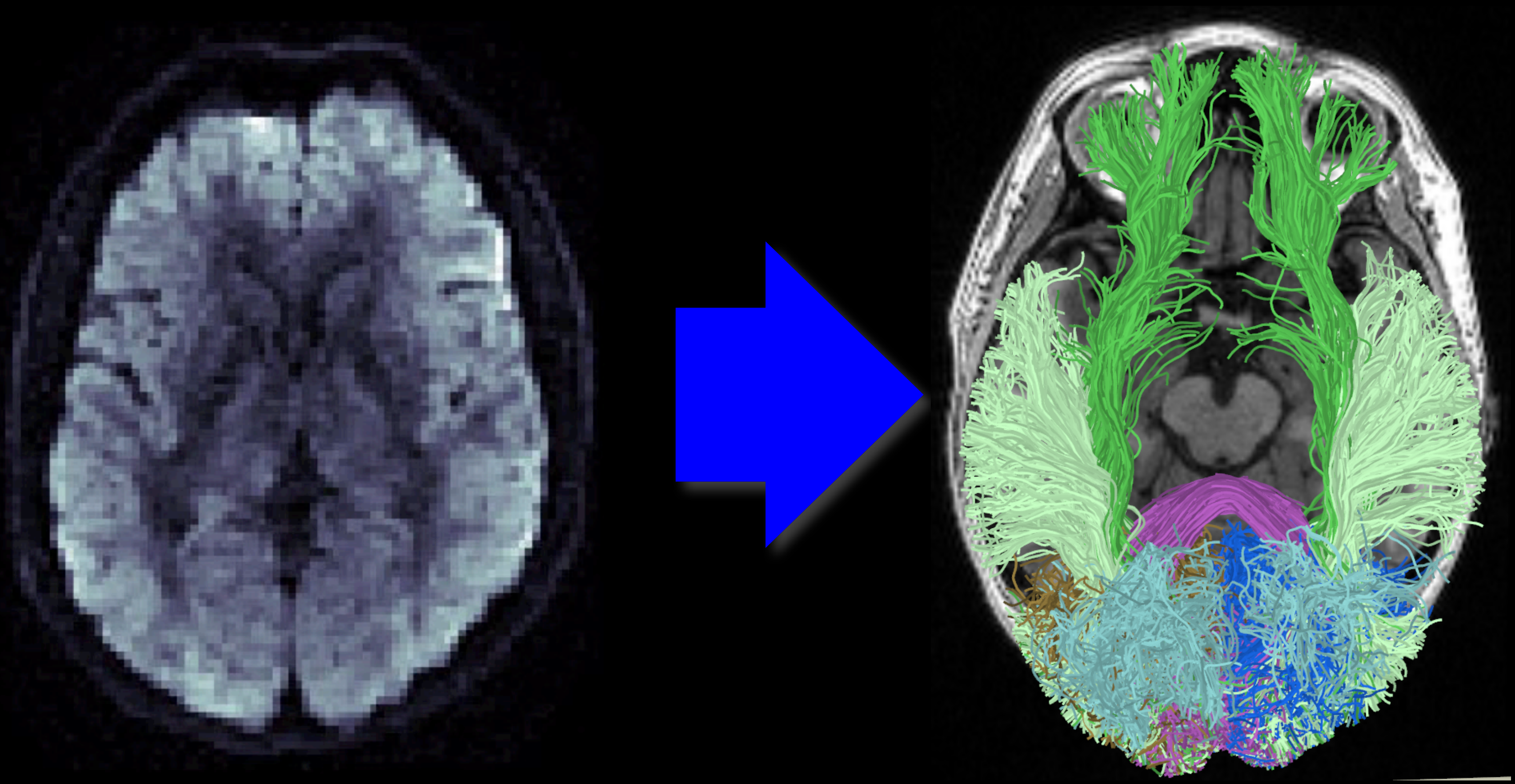
Pestilli et al., 2014, *Nature Methods*





Tractography limitations

We estimate fascicles from diffusion data, but most investigators do not check the model

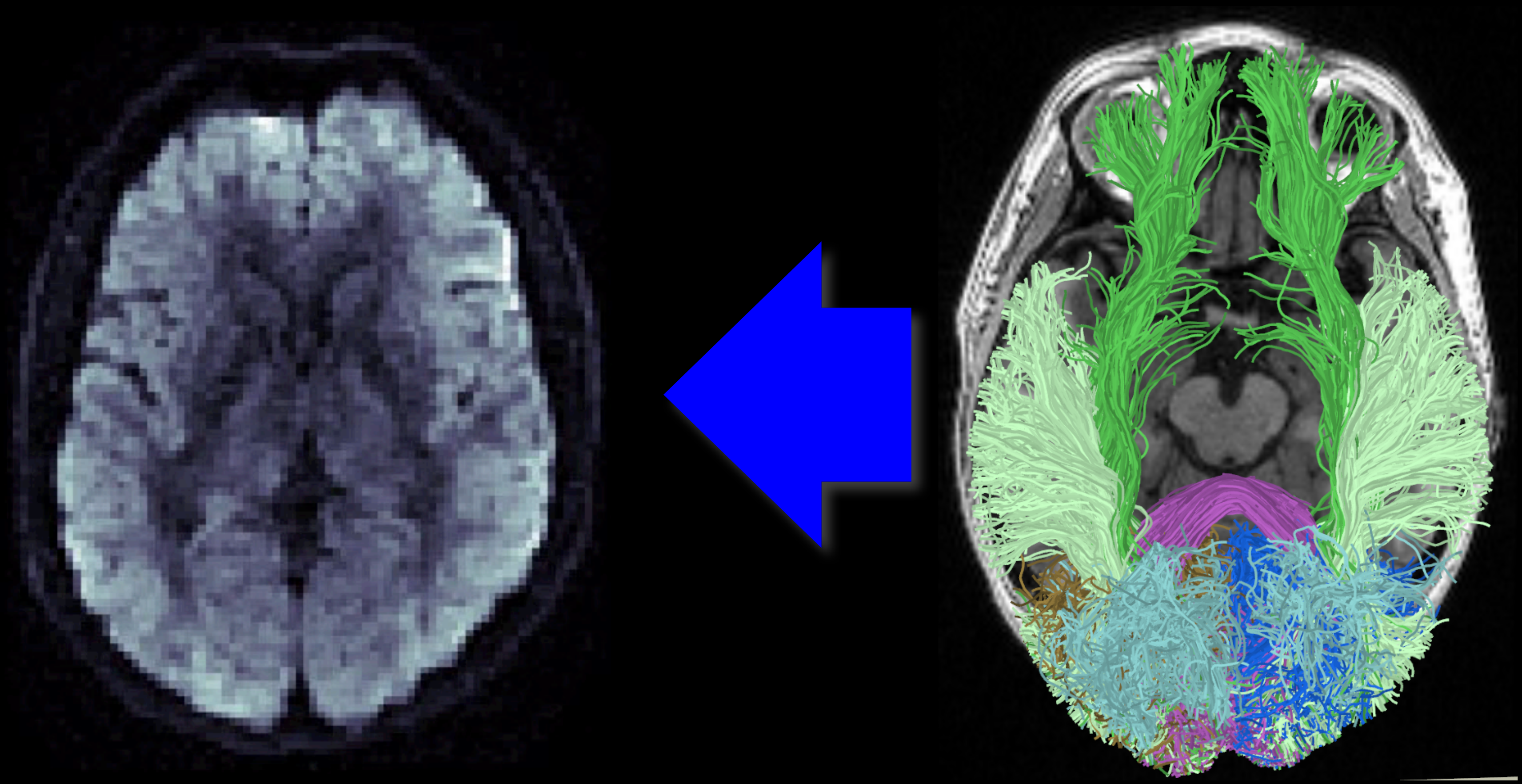


Linear Fascicle Evaluation (LiFE)

Pestilli et al., 2014, *Nature Methods*

Treat the estimates as a model

Calculate statistical evaluations of model validity



Stages of LiFE: Set up diffusion predictions for each voxel

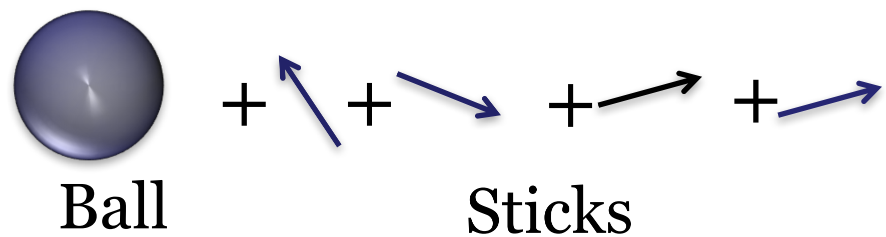
- In each voxel use a conventional fascicle diffusion model to predict the diffusion signal from the candidate connectome
- Each fascicle is assigned a weight to indicate the strength of its contribution to the data

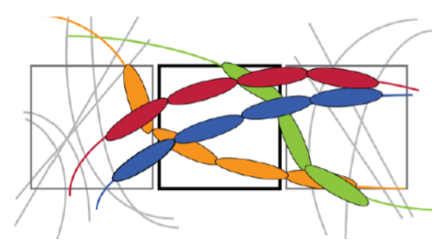
$$S(\theta) = w_0 D_0 + \sum_f w_f e^{-bD_f(\theta)}$$

isotropic

weights

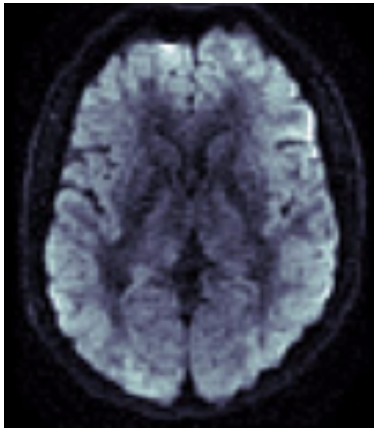
fascicles





Stages of Life: Solve for the fascicle weights

Diffusion signal, $S(\theta)$



$S(\theta)$

v1

v2

vN

=

Each column is the prediction of a fascicle

Each entry is the fascicle contribution for a voxel in a direction

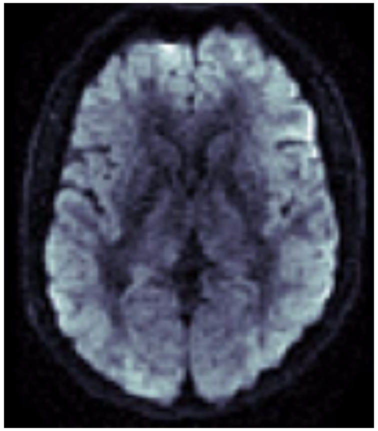
w_f

$10^7 \times 10^6$

Solve for a non-negative weight for each fascicle (least-squares)

Stages of Life: Solve for the fascicle weights

Diffusion signal, S(θ)



S(θ)

v1

v2

vN

=

Each column is the prediction of a fascicle

Each entry is the fascicle contribution for a voxel in a direction

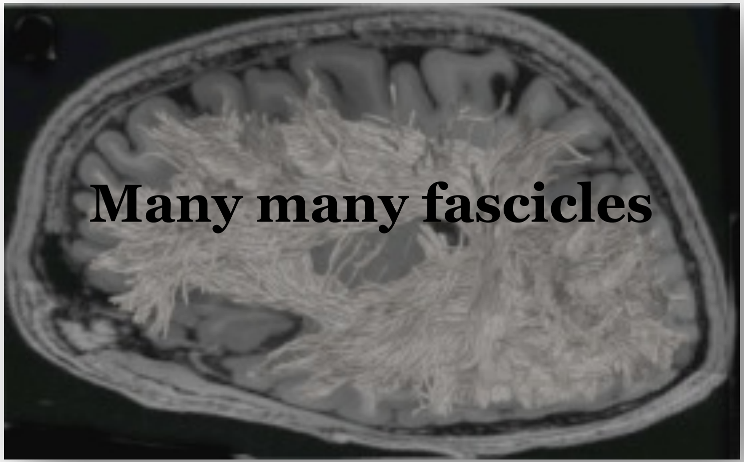
w_f

$10^7 \times 10^6$

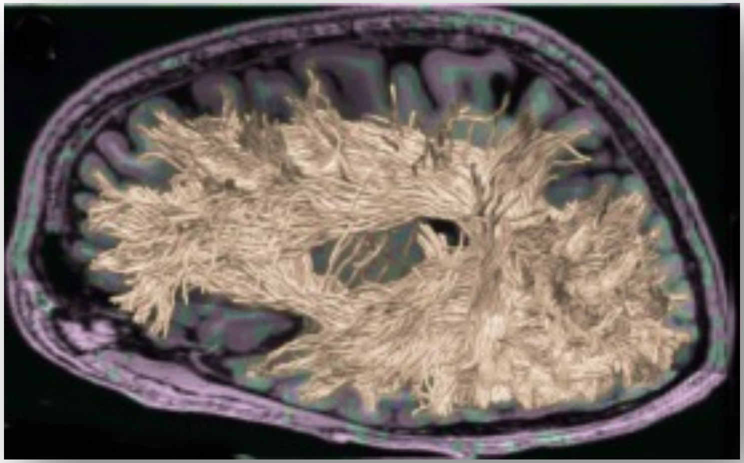
Depending on voxel size, number of directions, and so forth, about 80% of typical tractography weights are zero.

Stages of LiFE: Eliminate zero weight fibers (false alarms)

Candidate connectome



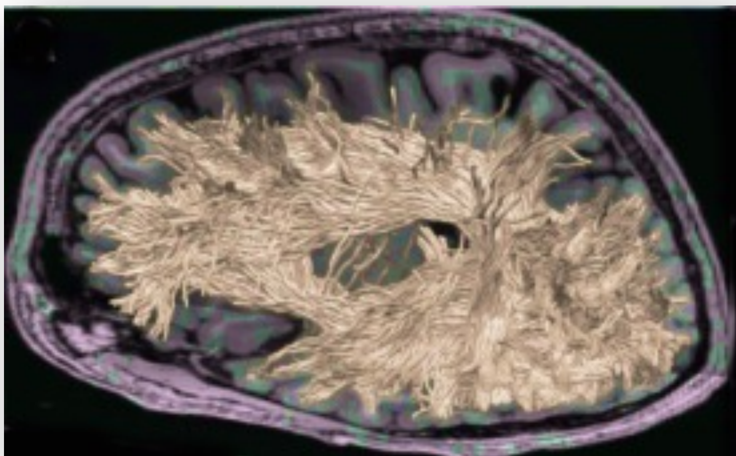
Optimized connectome



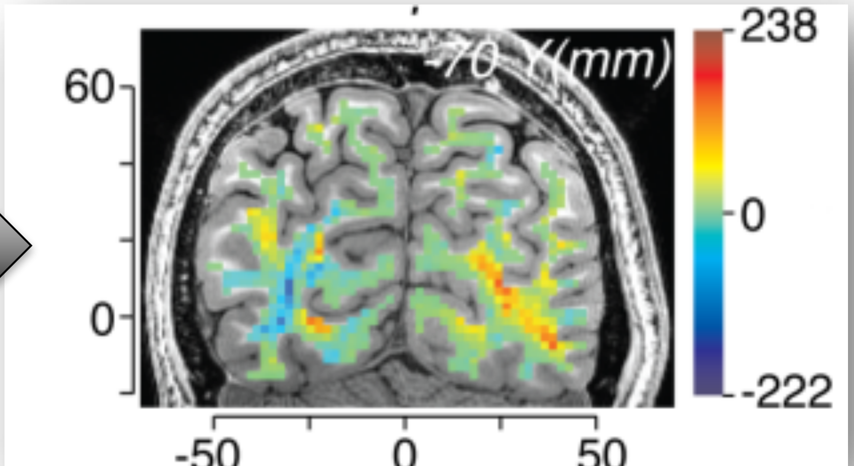
Solving a system of linear equations
(non-negative least-squares)

Stages of LiFE: Predict diffusion signal

Optimized connectome
and weights



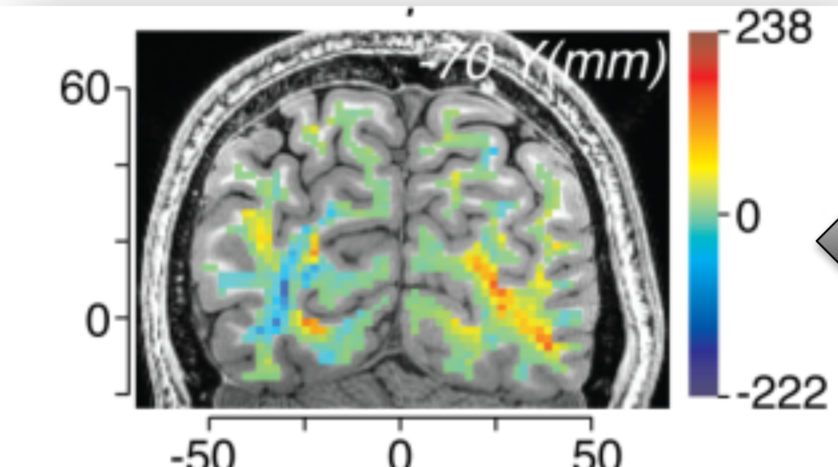
Prediction



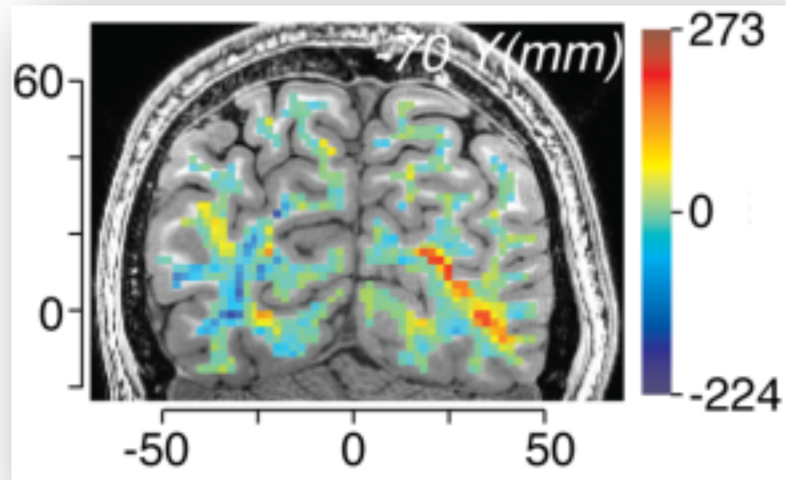
Big matrix multiplication

Stages of LiFE: Cross-validation error

Prediction

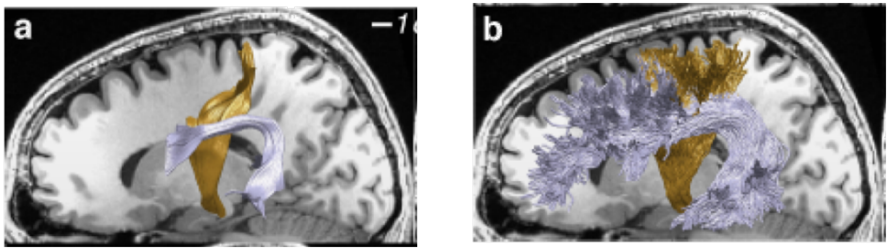


Second data set



Subtraction and root mean square error

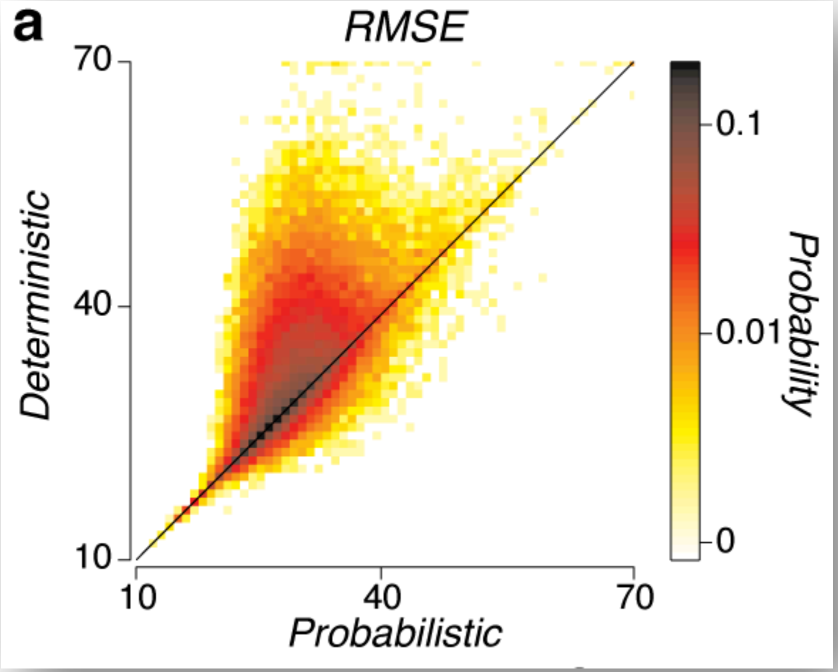
Statistical comparisons of cross-validated model accuracy

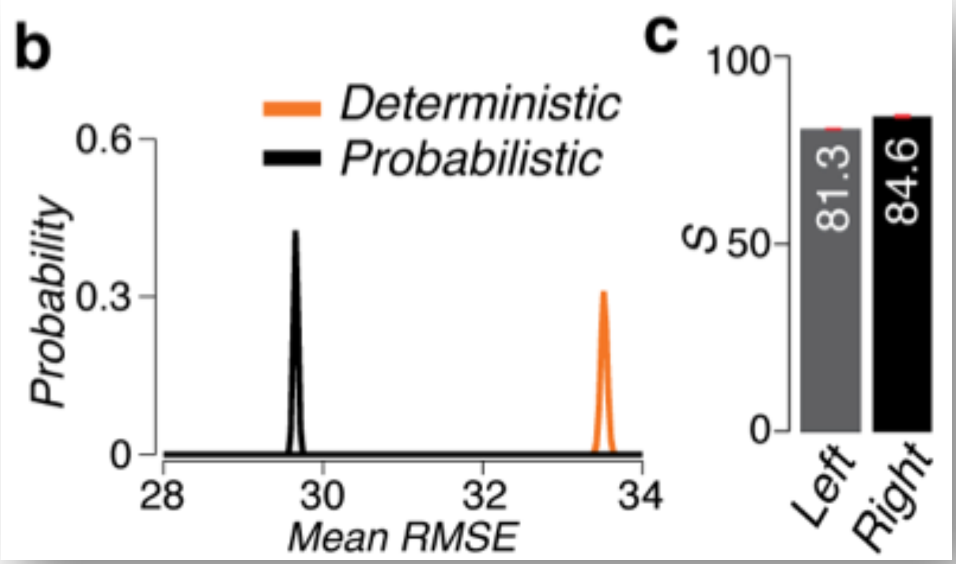


- Different models, or even specific parts of the tractography model, can be compared

- These comparisons provide a means to judge the strength of evidence in support of a particular idea

- These graphs show that the probabilistic model is a much better explanation of the dMRI data





Statistical comparisons of cross-validated model accuracy

- Different models, or even specific parts of the tractography model, can be compared

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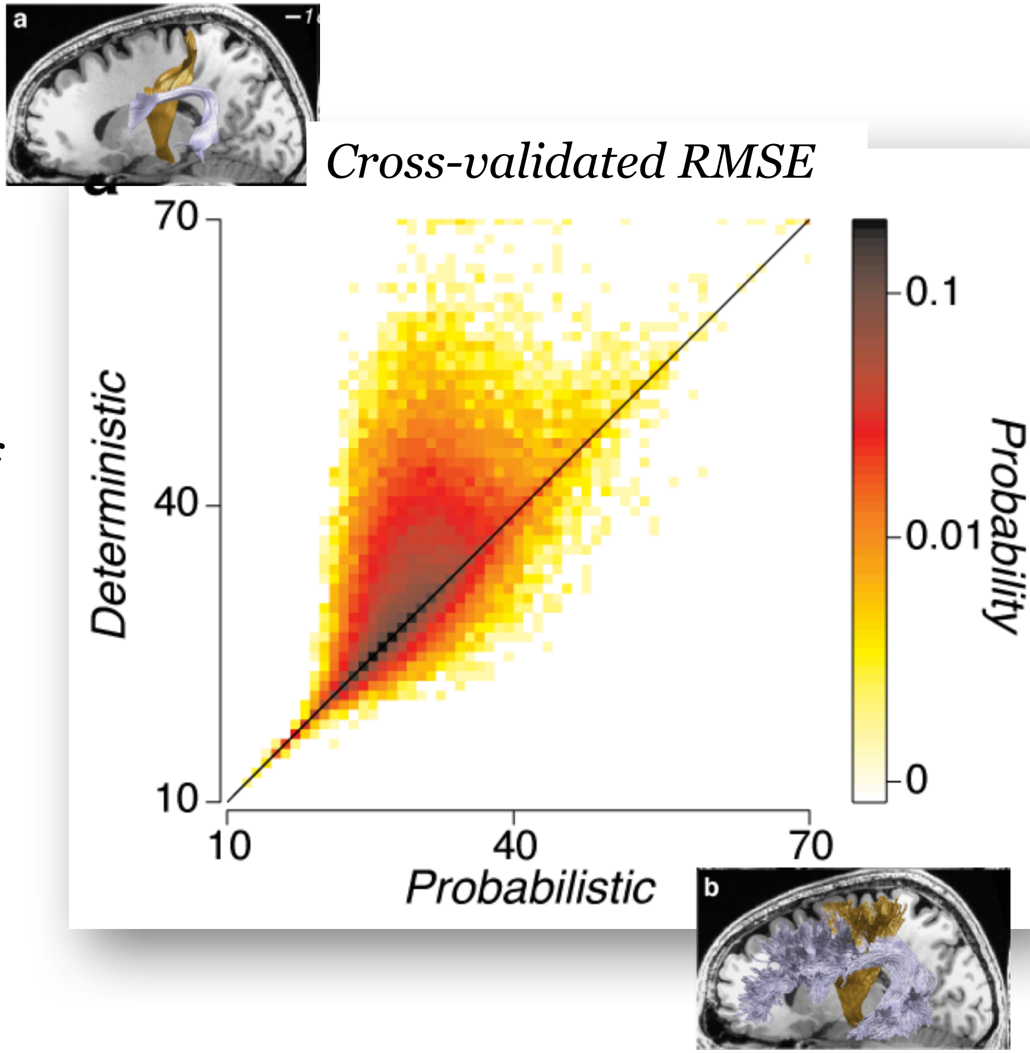
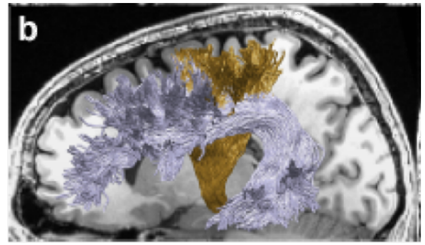
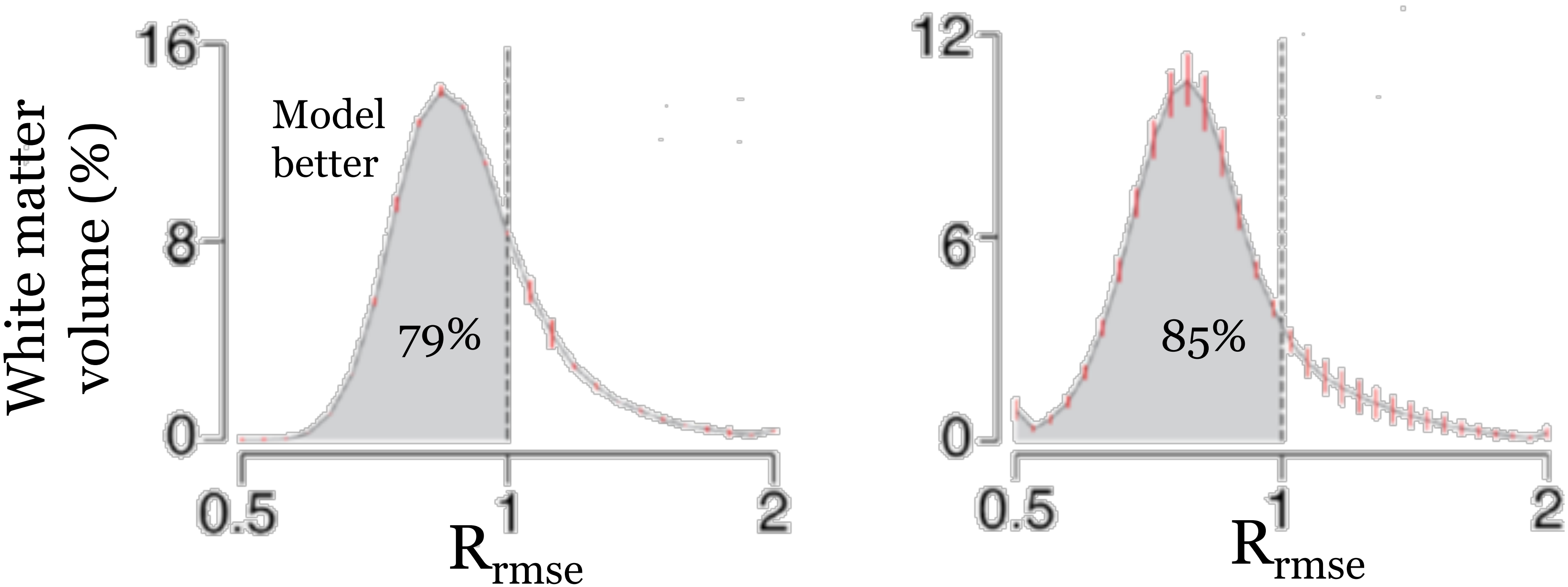
- These graphs show that the probabilistic model is a better explanation of the dMRI data



The optimized connectome predicts diffusion data better than test-retest reliability



150 directions (N=3) | 96 directions (N=6)



R_{rmse} = Ratio of model error to reliability error

Literature

- Explanation of the basic LiFE method
- Extension of the method to manage multiple tractography parameters
- Review of related work, including other global tractography methods (e.g., Daducci, Smith, Riesert)

Feel free to contact us for the code, which is in development and on github

nature methods
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NATURE METHODS | ARTICLE

Evaluation and statistical inference for human connectomes

Franco Pestilli, Jason D Yeatman, Ariel Rokem, Kendrick N Kay & Brian A Wandell

PLOS | COMPUTATIONAL BIOLOGY

OPEN ACCESS PEER-REVIEWED

RESEARCH ARTICLE

Ensemble Tractography

Hiromasa Takemura, Cesar F. Caiafa, Brian A. Wandell, Franco Pestilli

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Clarifying Human White Matter

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Building a model of the circuit for seeing words

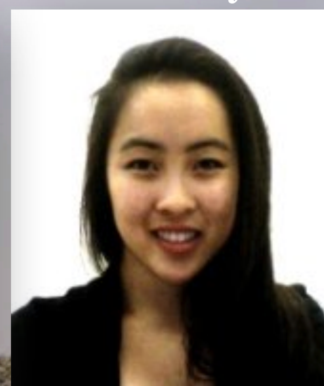
Michal Ben-Shachar

Jason Yeatman

Andreas Rauschecker

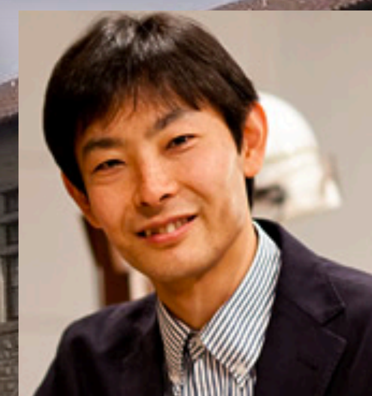
Bob Dougherty

Rosemary Le



Nathan Witthoft

Kaoru Amano



QUANTITATIVE MEASUREMENTS

∞

COMPUTATIONAL MODELS

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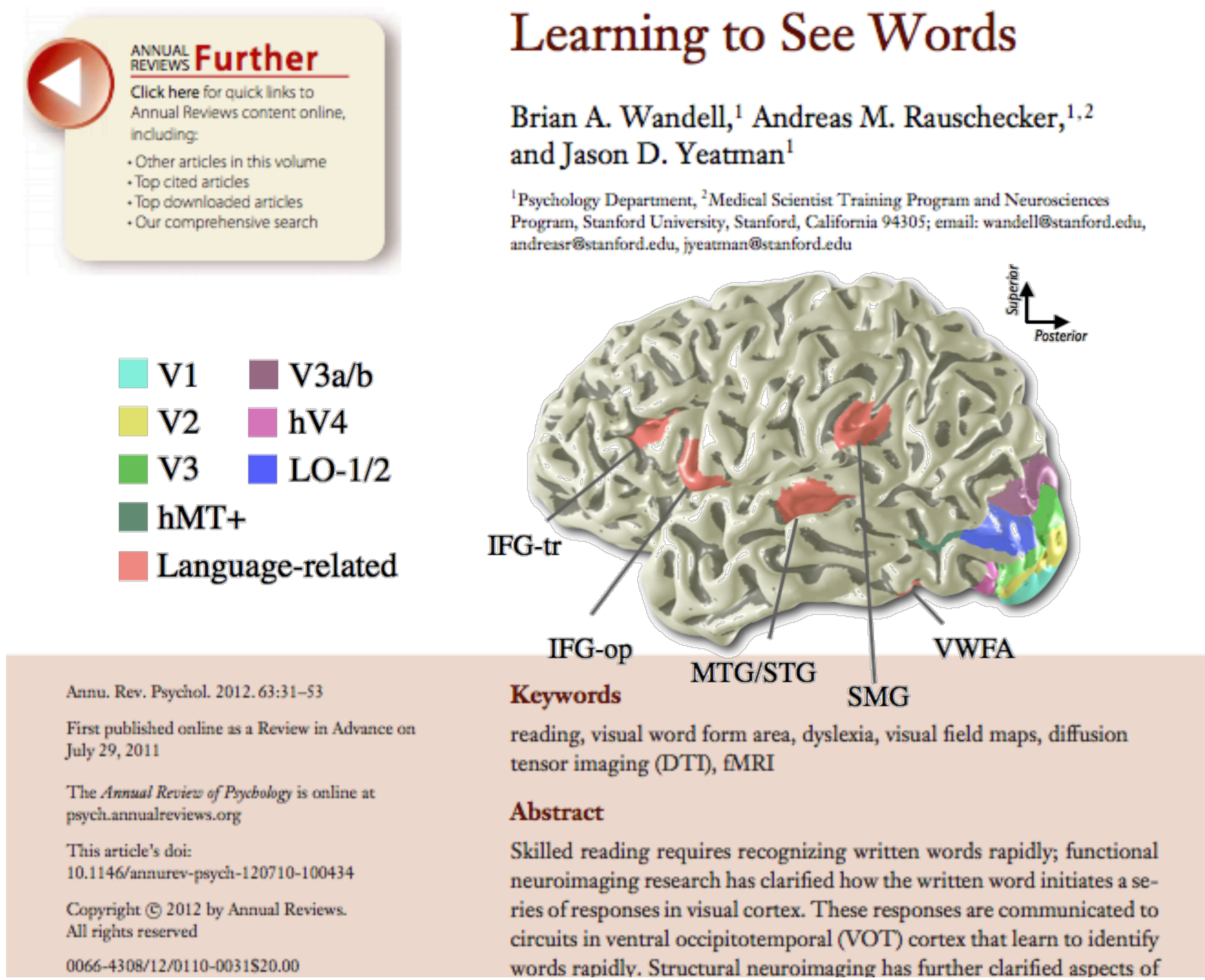
CHECK AND SHARE

The cortical reading network

- Reading and learning disabilities are an important problem in society
- Can we understand the brain networks that are essential for reading and diagnose these disabilities?



Learning to See Words

Brian A. Wandell,[1] Andreas M. Rauschecker,[1,2] and Jason D. Yeatman[1]

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Keywords

reading, visual word form area, dyslexia, visual field maps, diffusion tensor imaging (DTI), fMRI

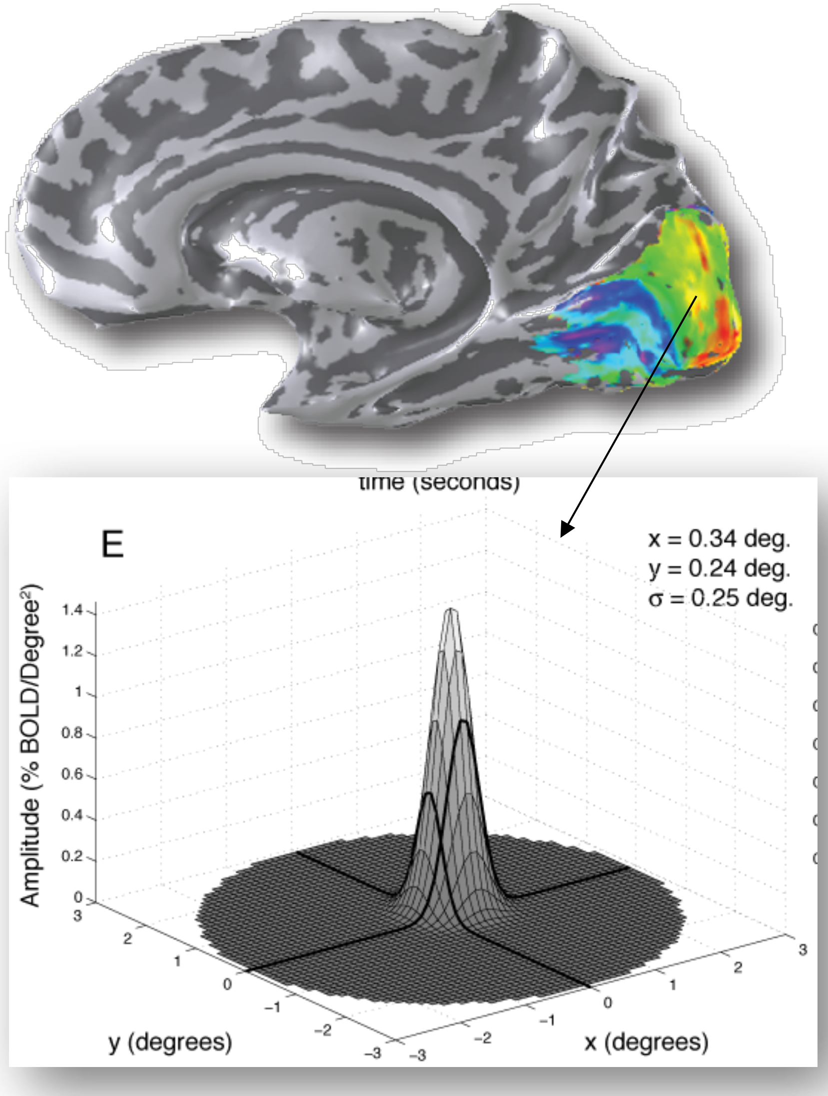
Abstract

Skilled reading requires recognizing written words rapidly; functional neuroimaging research has clarified how the written word initiates a series of responses in visual cortex. These responses are communicated to circuits in ventral occipitotemporal (VOT) cortex that learn to identify words rapidly. Structural neuroimaging has further clarified aspects of

Tracing the signal through the system

Amano et al. 2009

- A single voxel within, say, V1 has a pRF position and size
- Combining the pRFs from the voxels in a region tells us about its field of view
- In early visual field maps, the population receptive fields tile large portions of the visual field



Measuring the field of view of cortical regions

Amano et al. 2009

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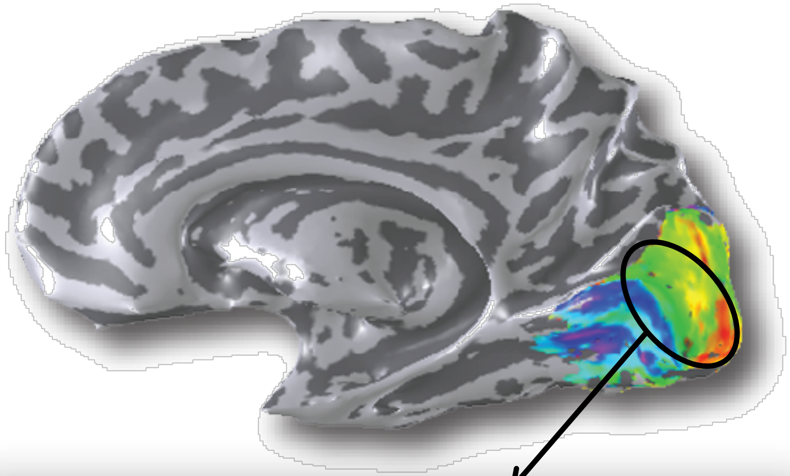

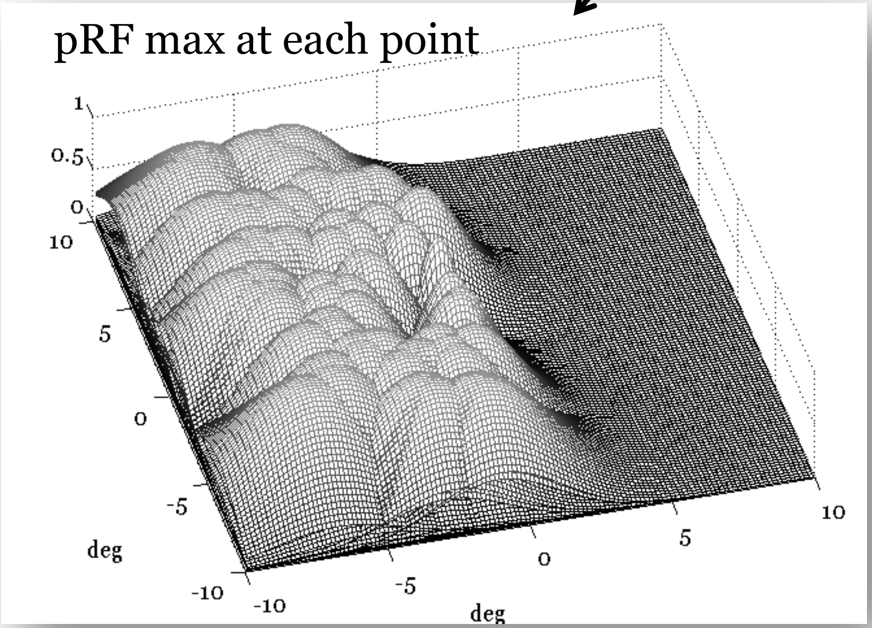

Measuring the field of view of cortical regions

Amano et al. 2009

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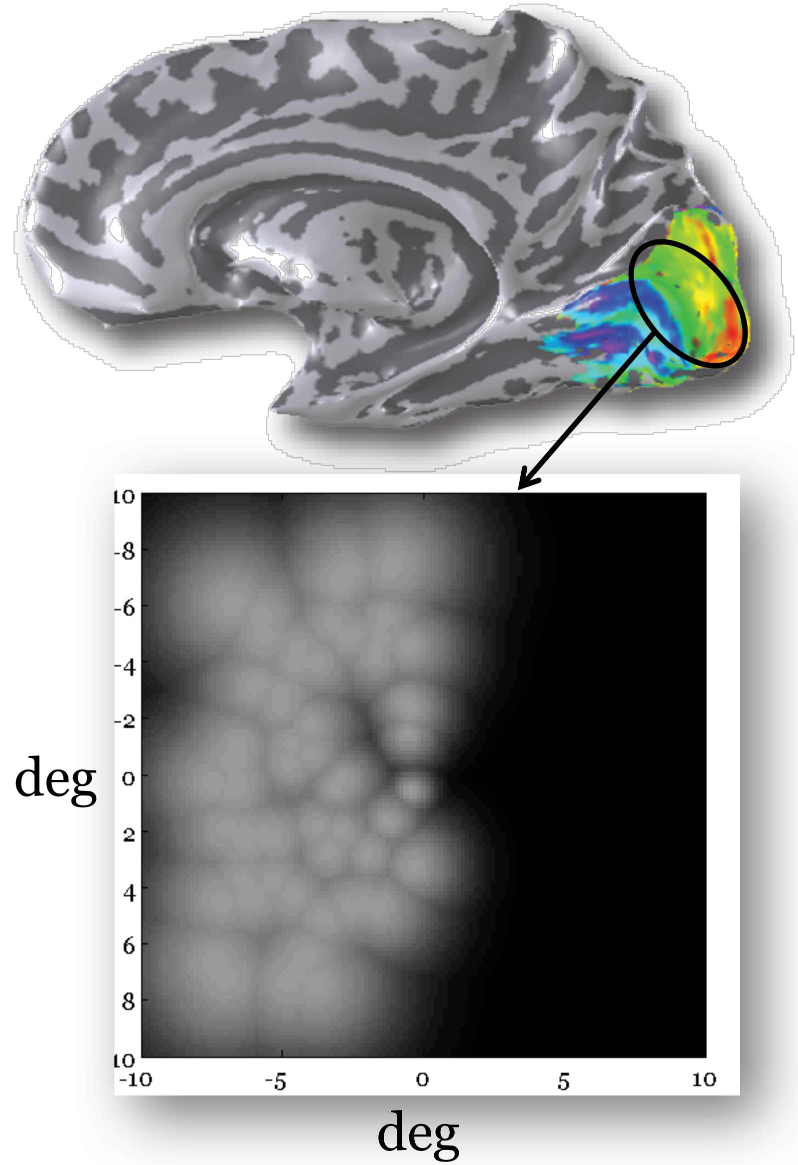
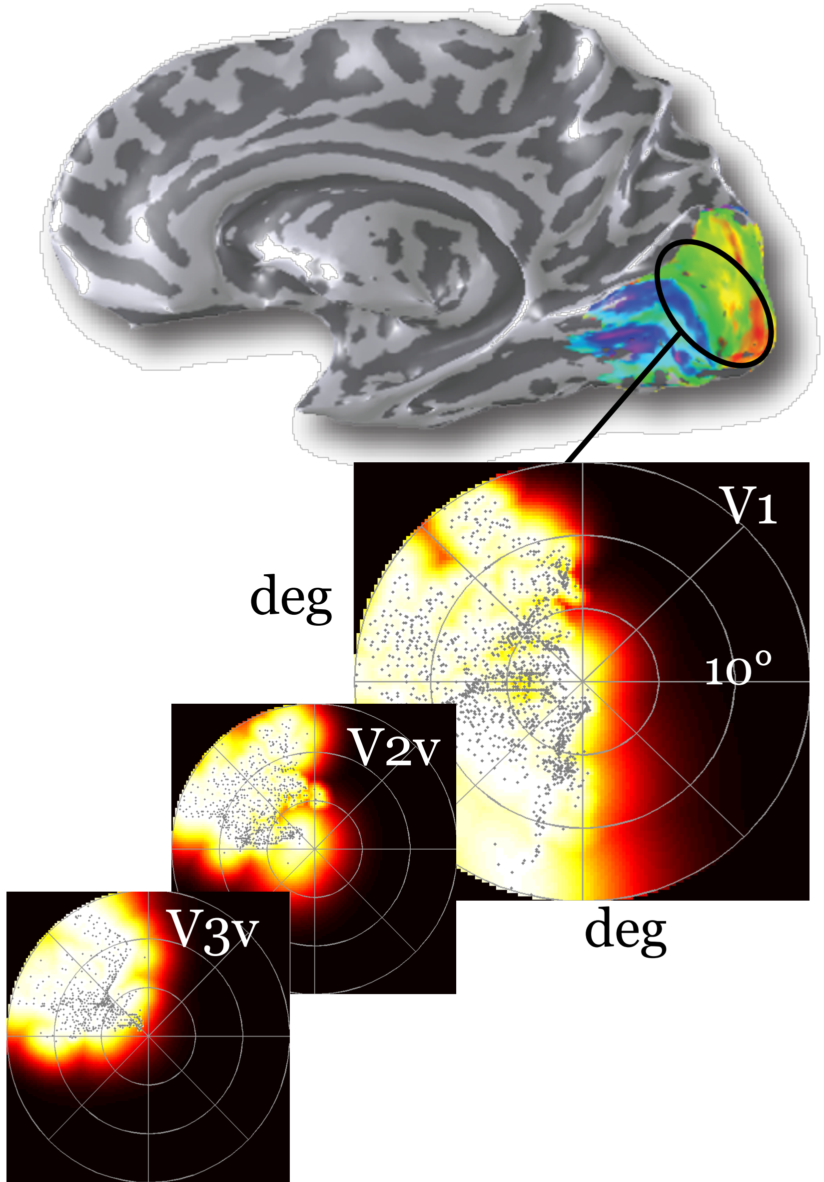


Measuring the field of view of cortical regions

Amano et al. 2009

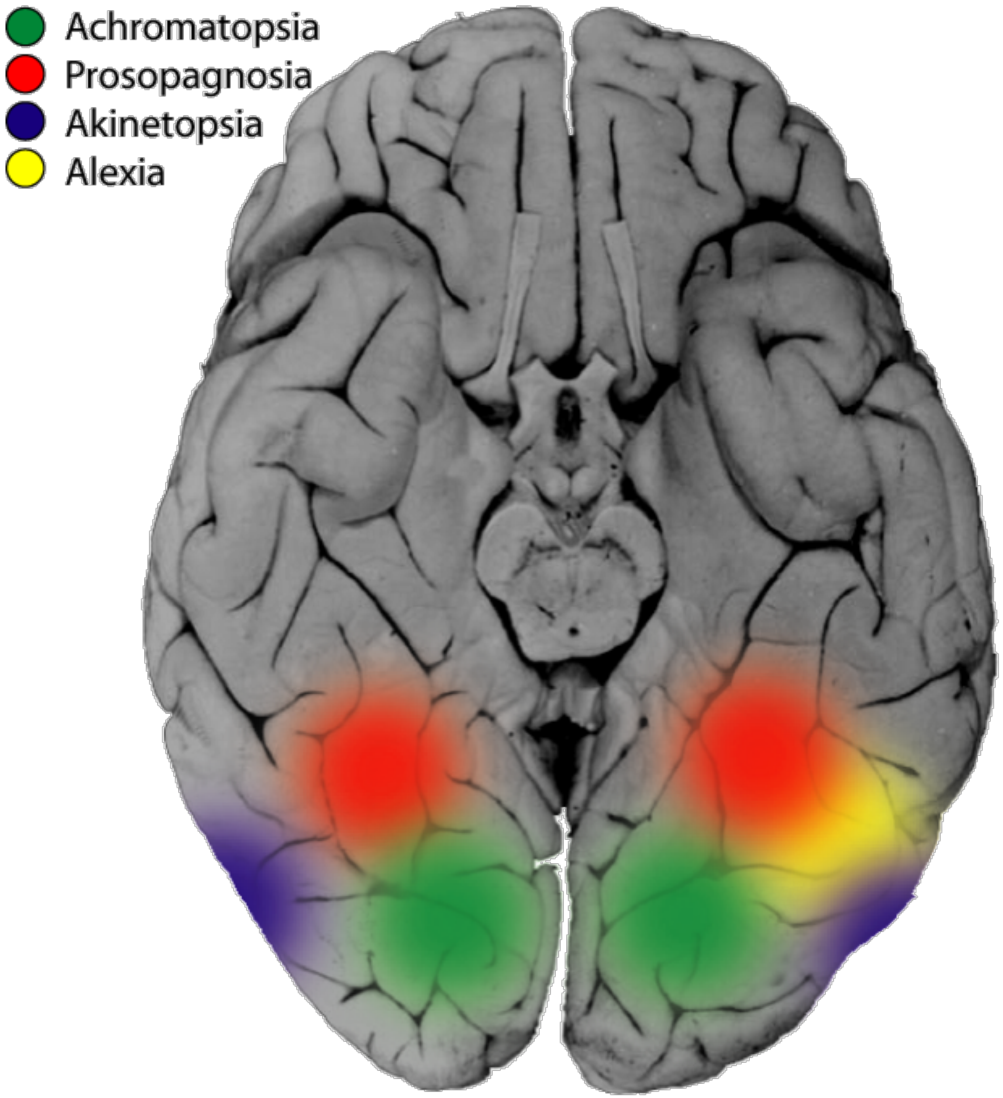
- A single voxel within, say, V1 has a pRF position and size
- Combining the pRFs from the voxels in a region tells us about its field of view
- The early visual field maps, the pRF field of view covers large portions of the visual field



Visual field coverage in face-responsive regions

- Ventral occipito-temporal cortex (VOT) includes many regions that appear to play a special role in visual function

- Neurological studies from the 70s on show that these regions play an essential role in perceiving color, faces, motion, word recognition (Meadows, Zeki, Geschwind, Greenblatt, Nobre, McCarthy, Cohen, Dehaene)

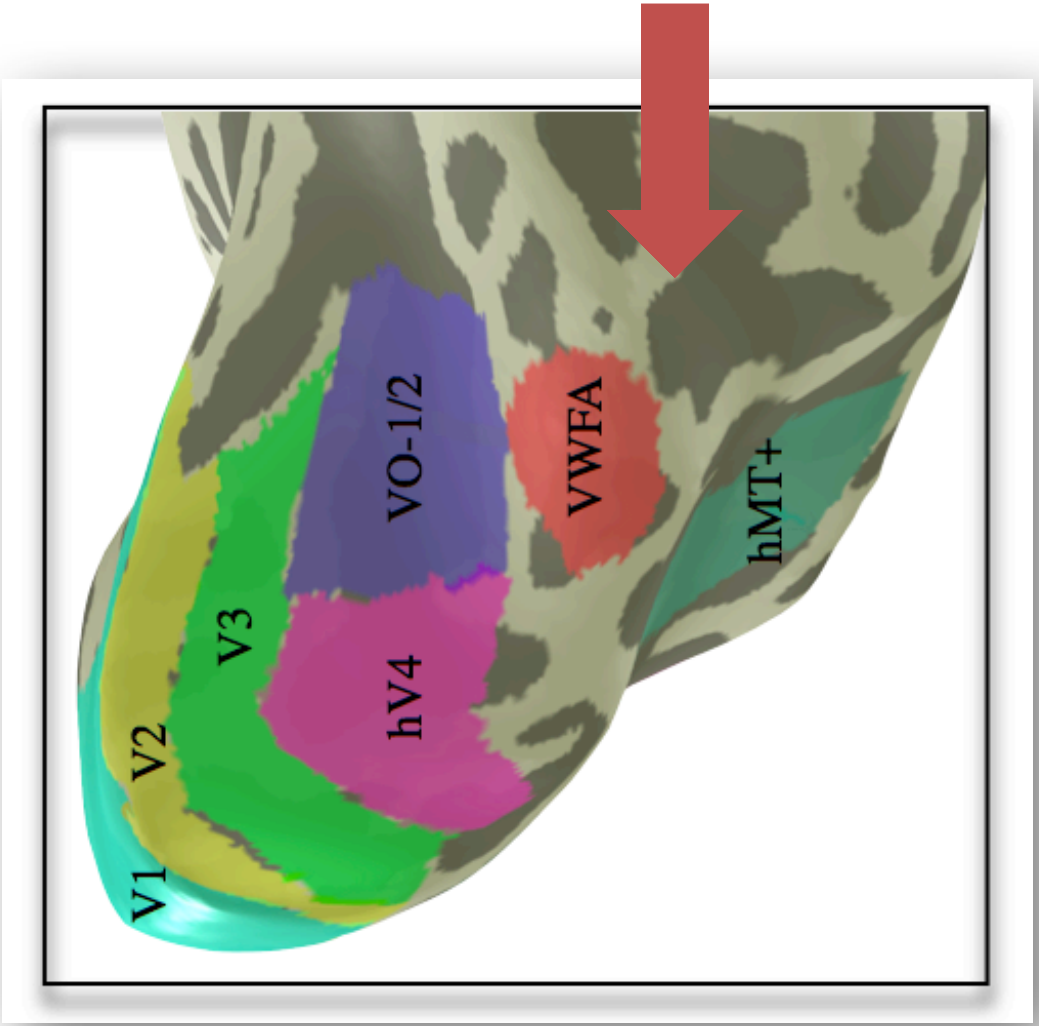


Visual field coverage in VOT

- Ventral occipito-temporal cortex (VOT) includes many regions that appear to play a special role in visual function

- Neurological studies from the 70s on show that these regions play an essential role in perceiving color, faces, motion, word recognition (Meadows, Zeki, Geschwind, Greenblatt, Nobre, McCarthy, Cohen, Dehaene)

- Can we trace the signals and field of view from cortex into VOT, and particularly the reading circuitry?



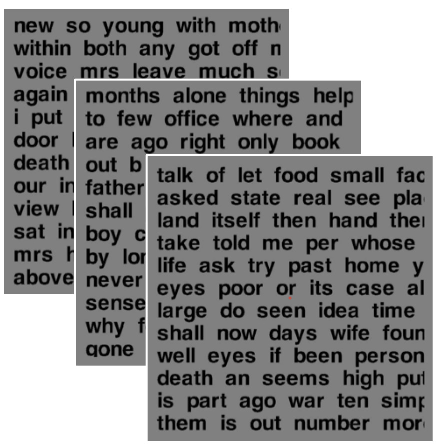
VWFA Localizer

VWFA: voxels within an anatomical region whose amplitude when shown words, exceeded that of phase-scrambled objects and faces.

Anatomical region: Anterior of hV4, posterior of mid-fusiform sulcus, lateral of collateral sulcus, medial of middle temporal sulcus

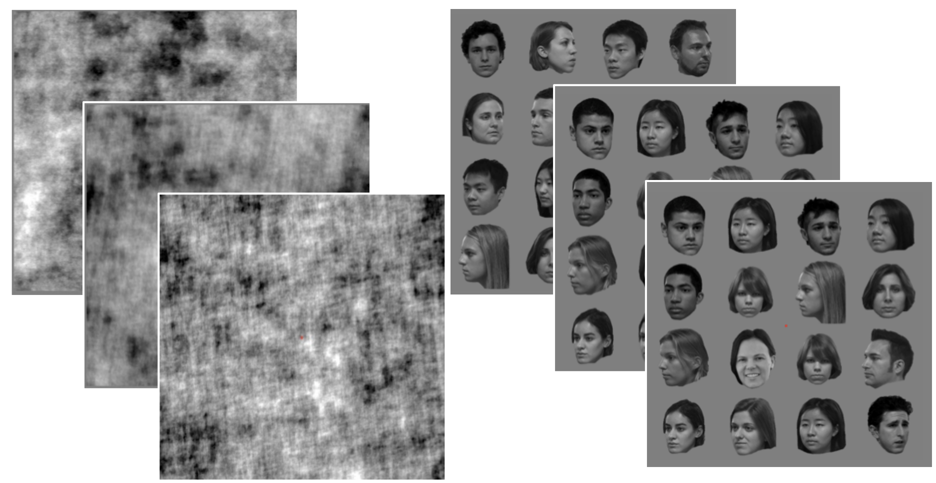
Words

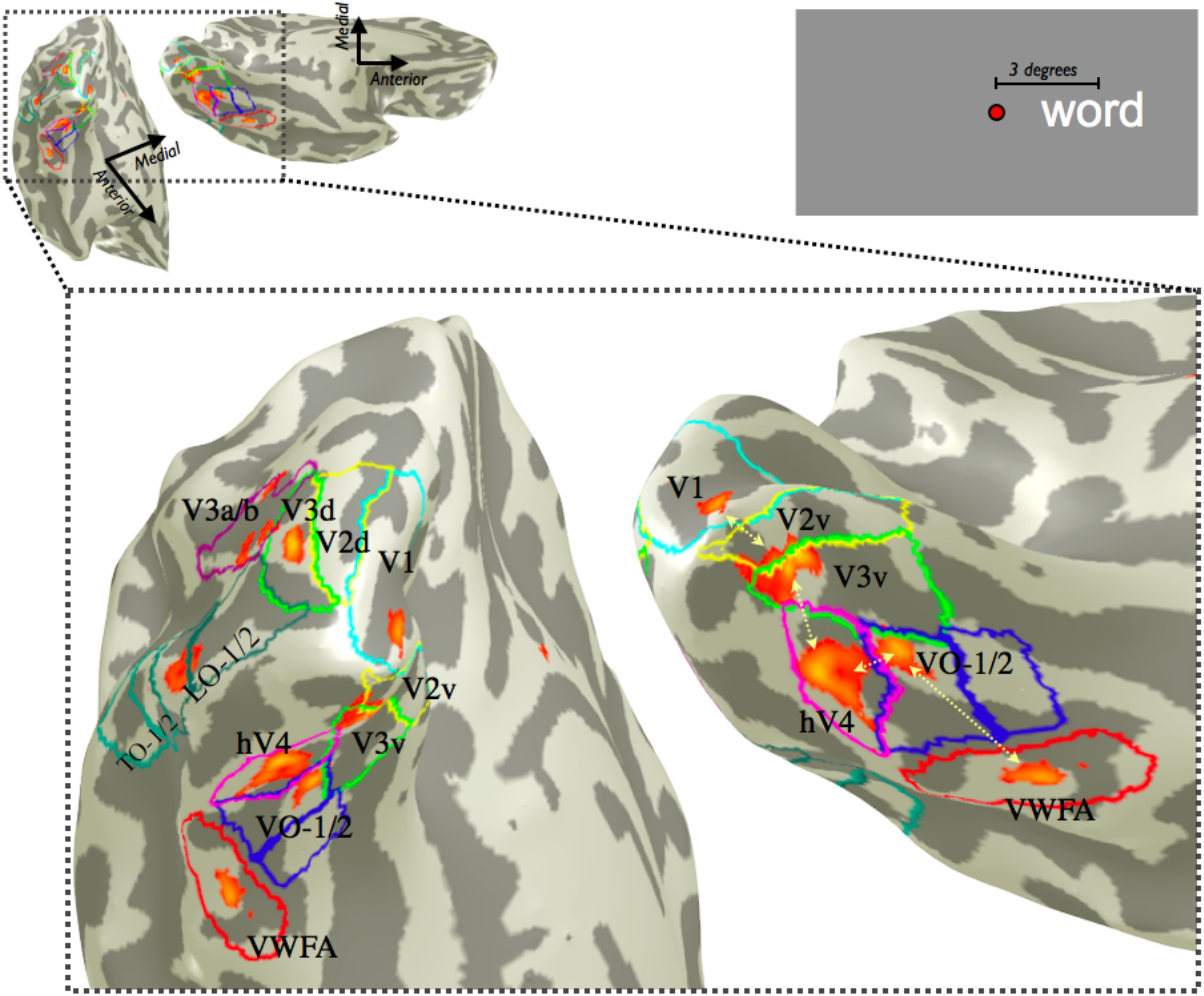
8 sec, 2hz



versus

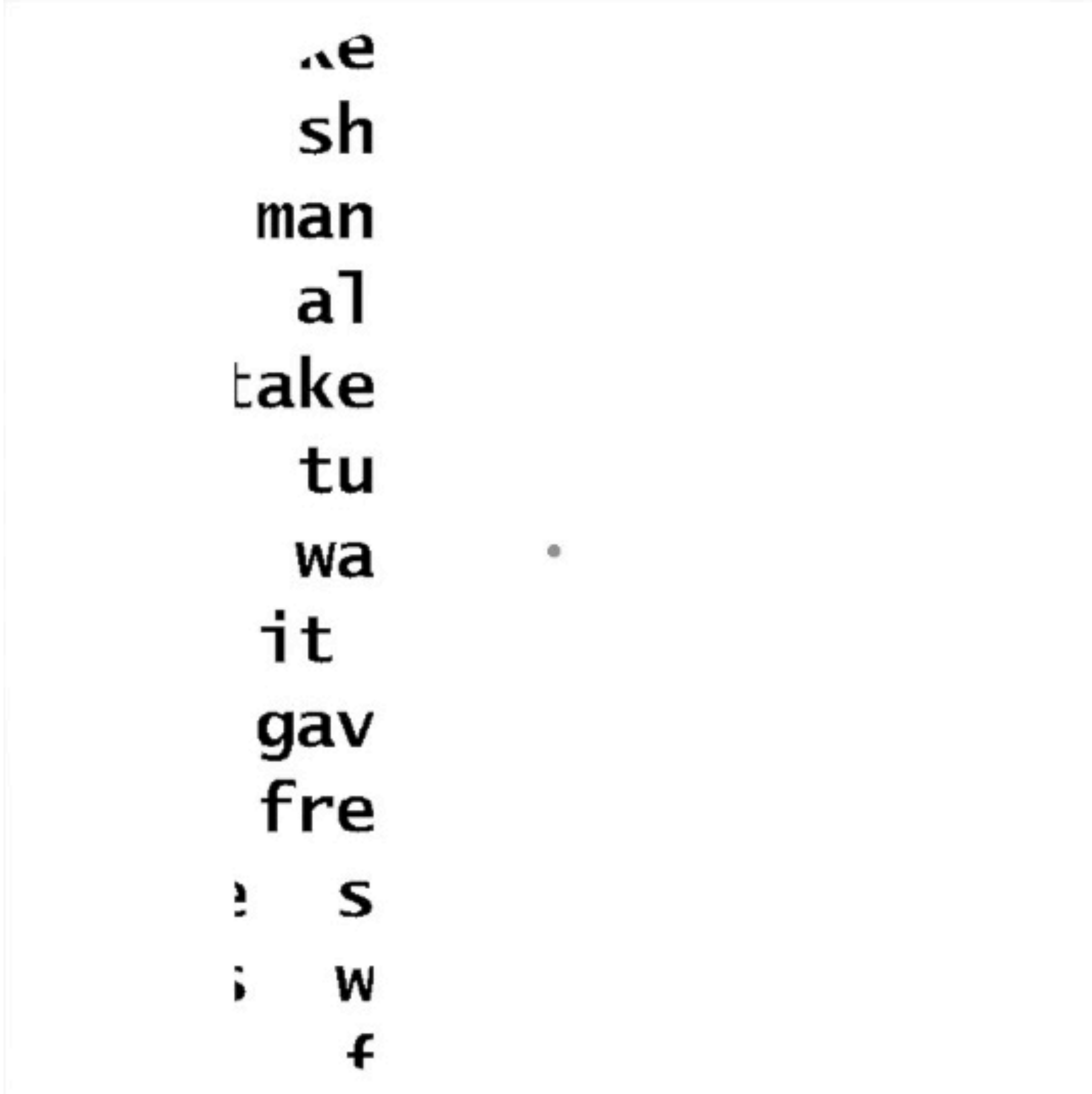
Textures and Faces





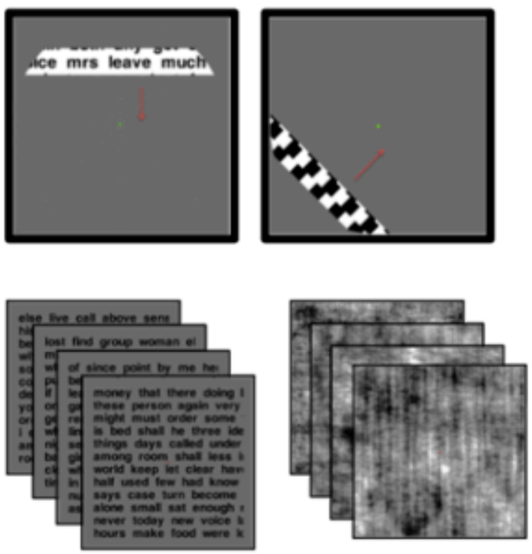
Medial
Anterior
Medial
Anterior
3 degrees
word
V3a/b
V3d
V2d
V1
LO-1/2
TO-1/2
V2v
V3v
hV4
VO-1/2
VWFA
V1
V2v
V3v
VO-1/2
hV4
VWFA

The word-bar stimulus



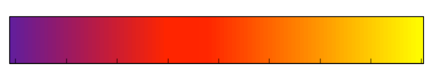
Field of view in reading circuitry of a single subject

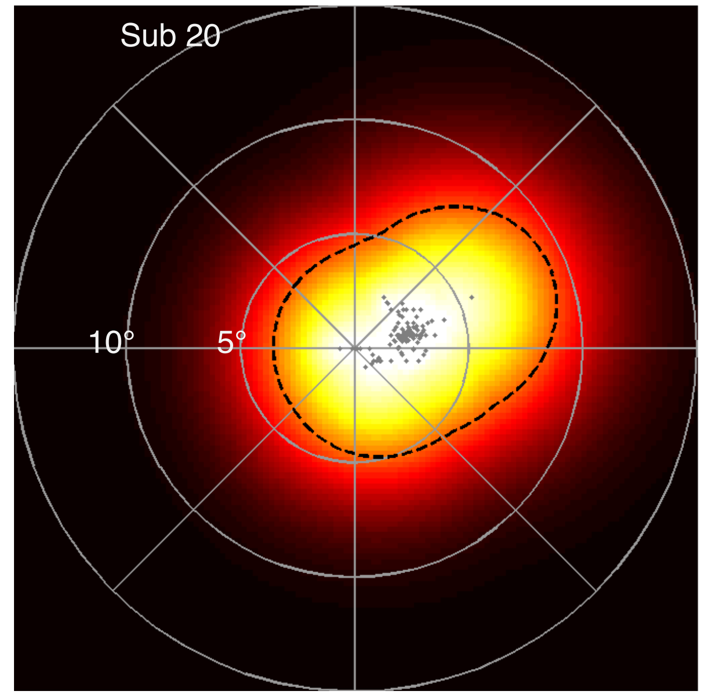
Measure pRFs

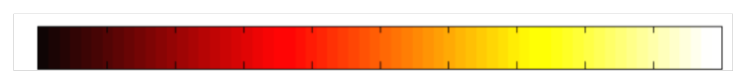


Localize Word-Responsive Regions

% variance explained by pRF model (word stimuli)

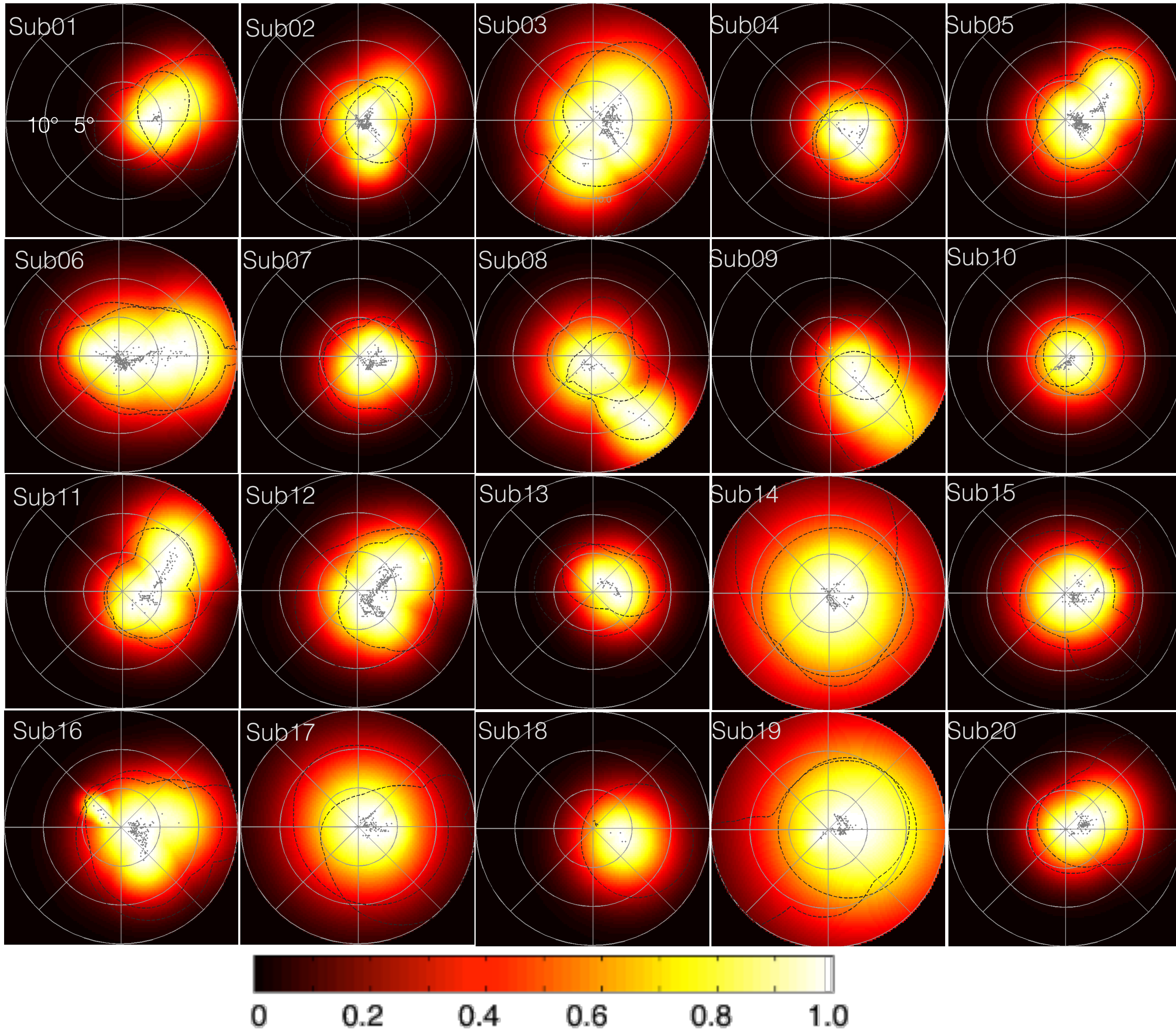






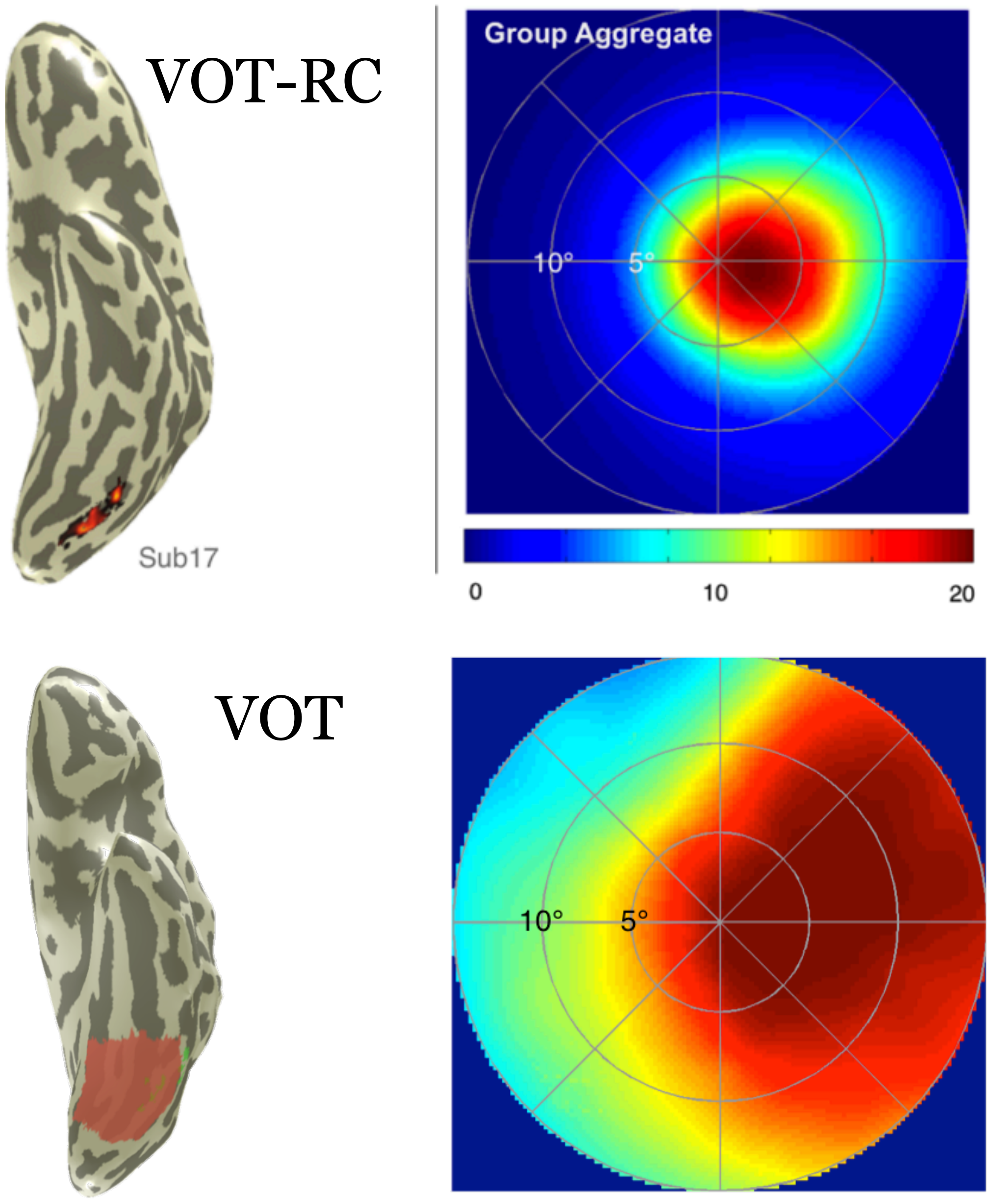
Field of view of the VOT reading reading circuitry

- There are significant differences between subjects
- Yes, we are correlating these differences with measures of word recognition
- FOV value: relative effectiveness in evoking a response in ROI

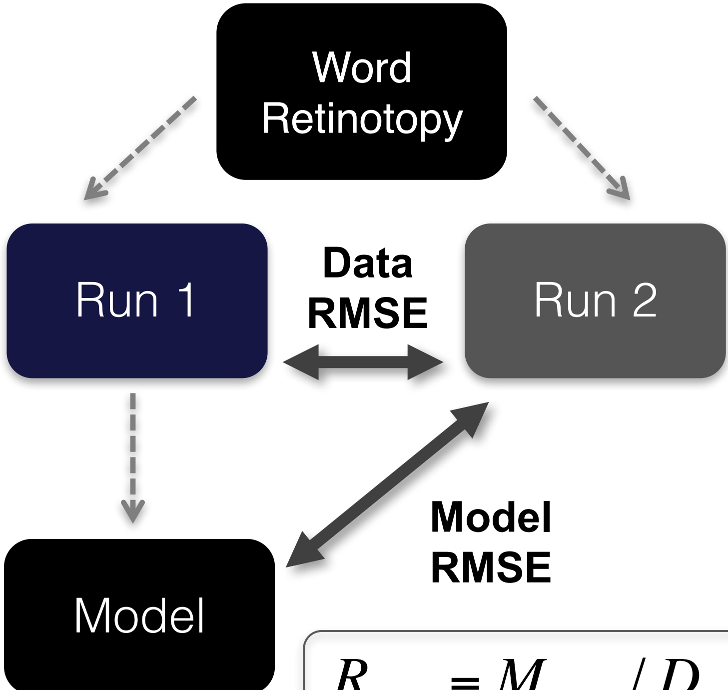


Reading circuitry FOV is more foveal than VOT

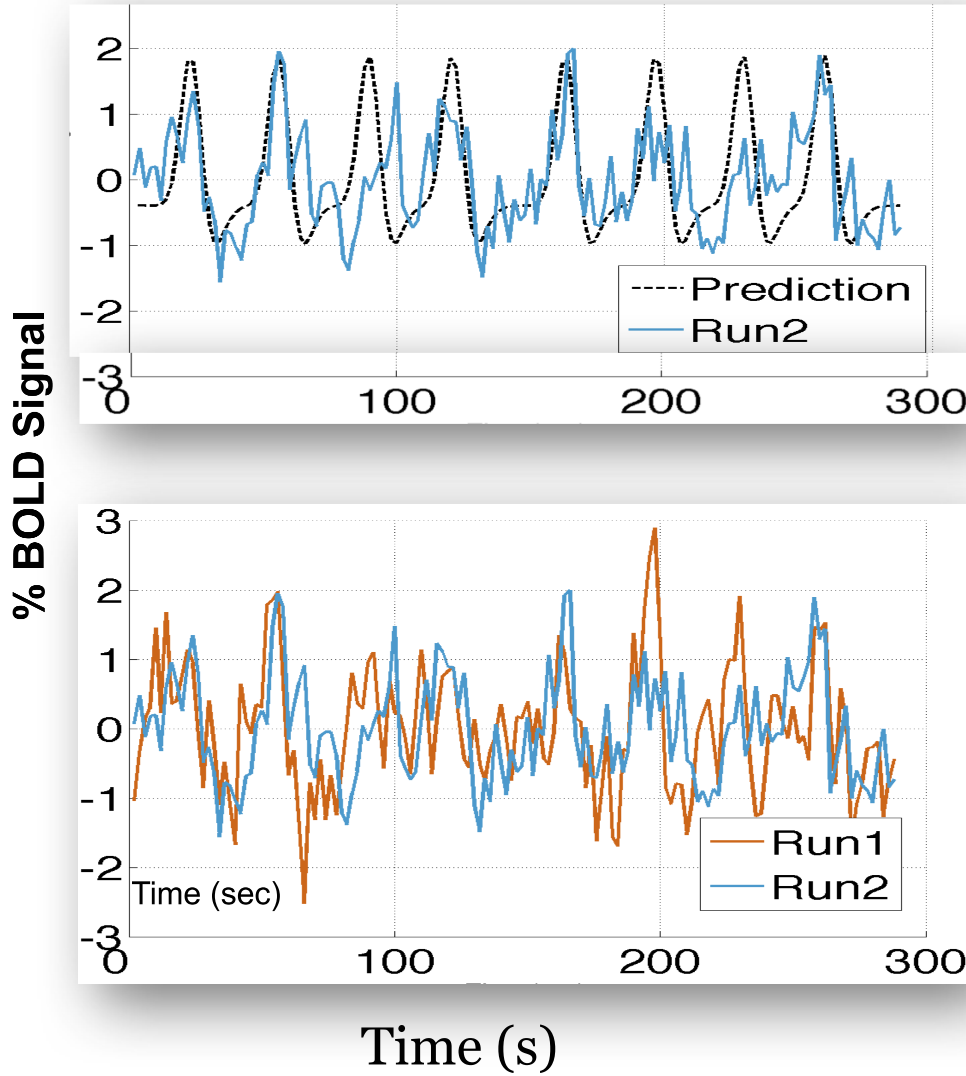
- The VOT field of view covers a larger portion of the field than the portion specialized for seeing words (cf. Levy, Hasson, Malach)



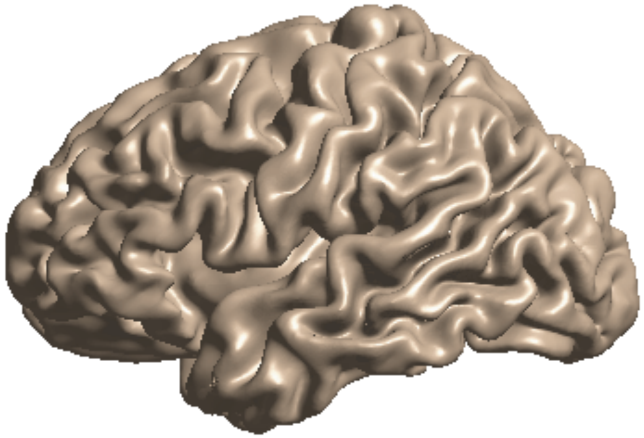
pRF model cross-validates better than test-retest

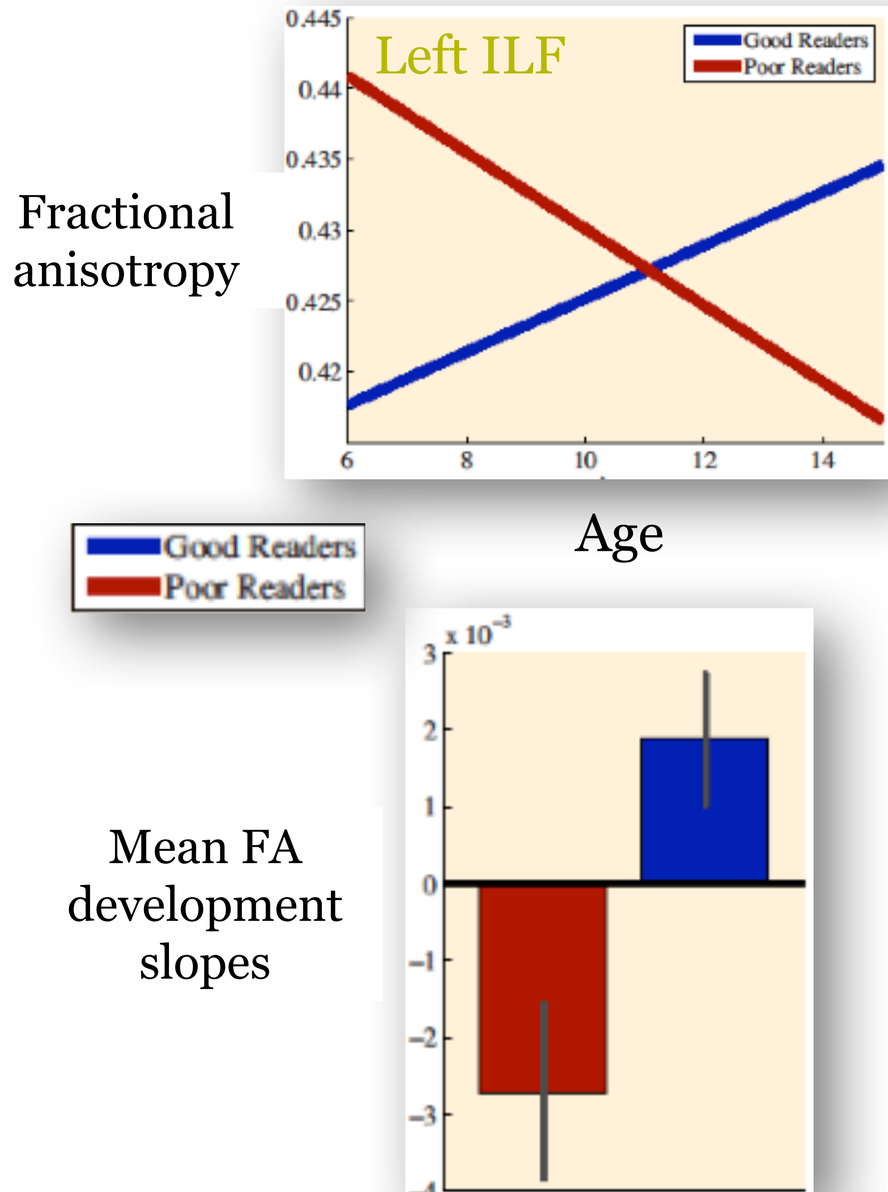


$$R_{rmse} = M_{rmse} / D_{rmse}$$



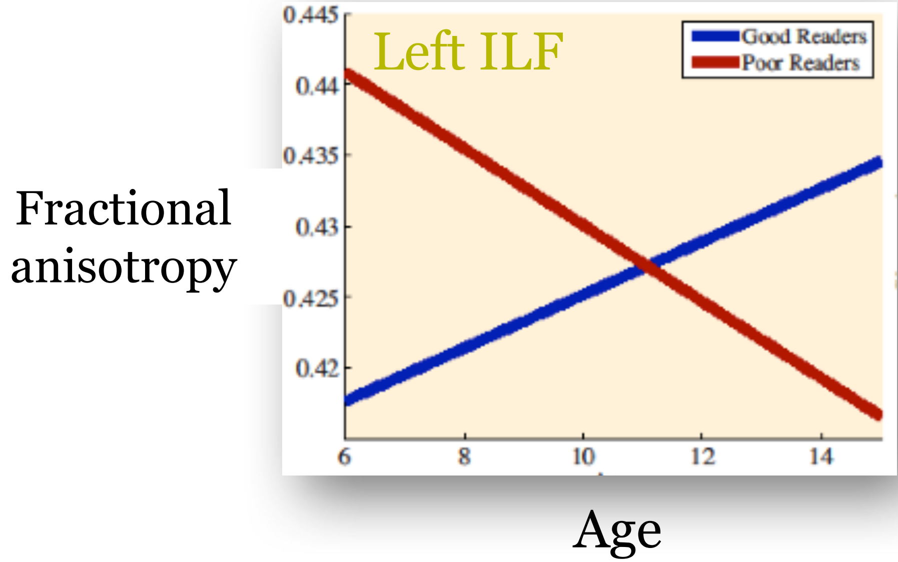
Diffusion (FA) changes differs between good and poor readers





- Measured brain and behavior at 4 time points **(data management!)**
- The first measurements predict reading over the next few years
- The rate and direction of FA development differs between good and poor readers in both the Arcuate and the ILF

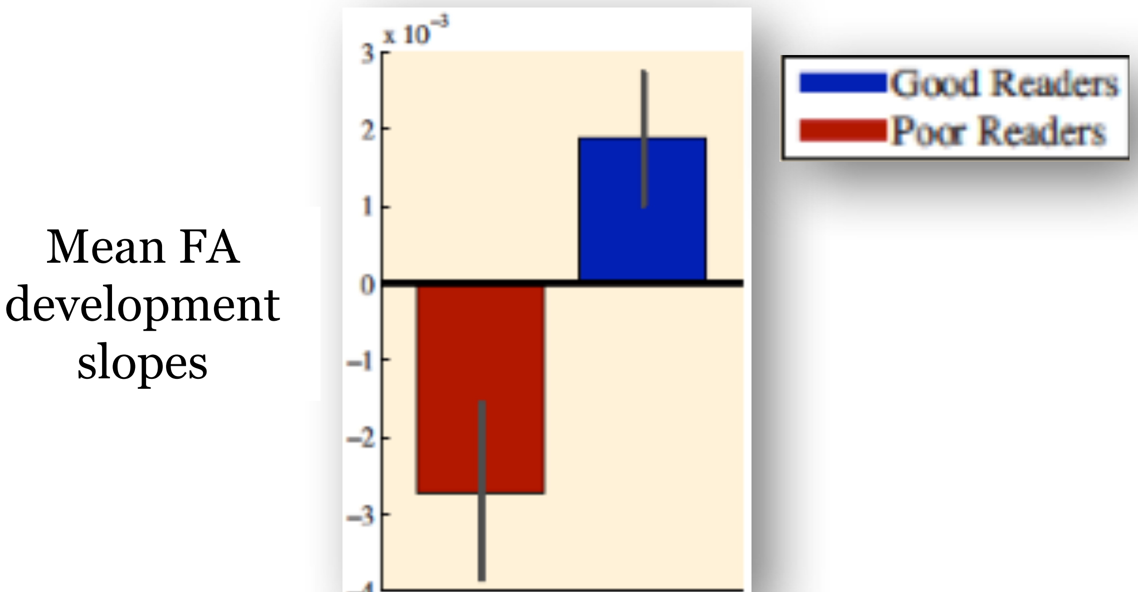
Diffusion (FA) changes differs between good and poor readers



- FA in the ILF increases for good readers (6 – 14 years)

- Over the same ages, the FA declines for poor readers

- The FA development, not the FA level, matters

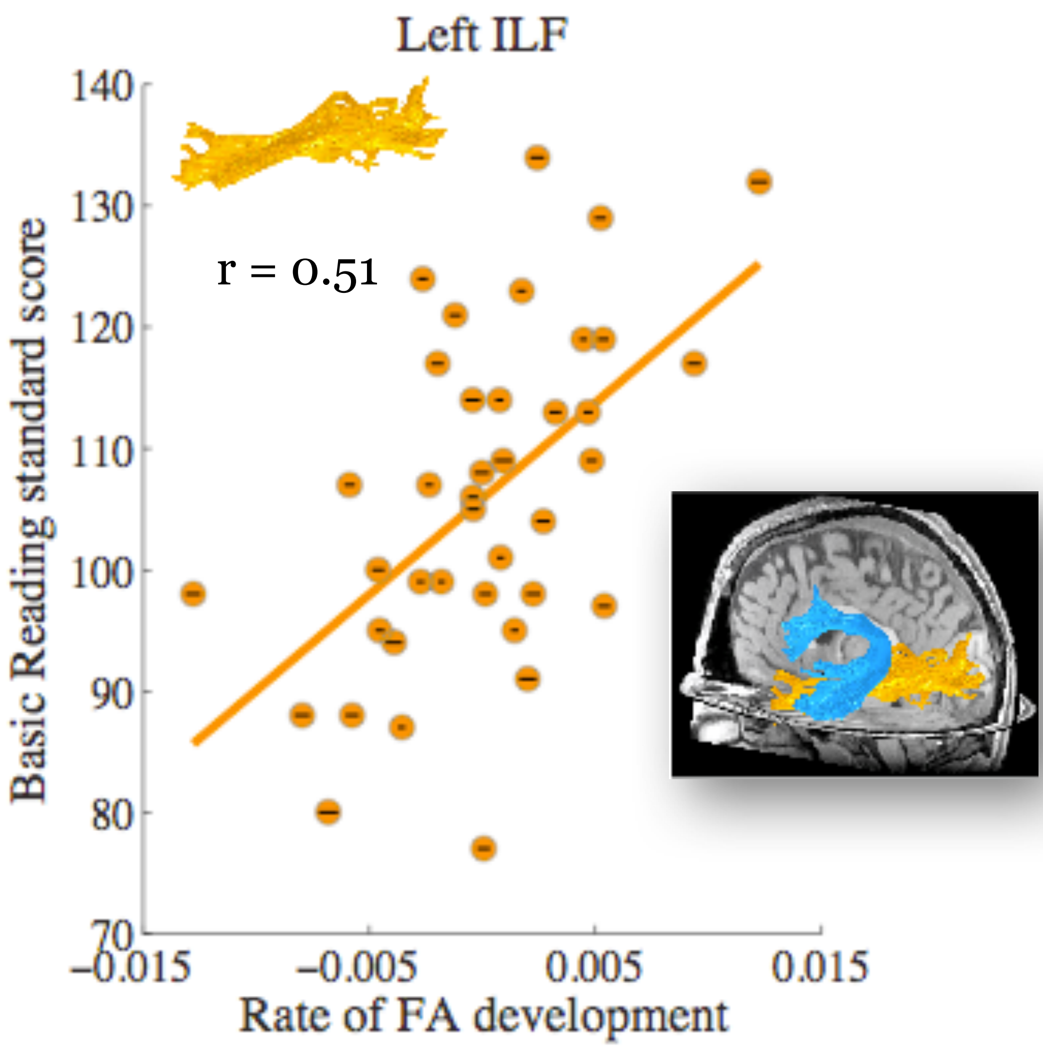


Correlations between tract diffusion change and seeing words

(Yeatman et al., 2012, *PNAS*)

- Development measured by dMRI in the ILF and Arcuate, but not others tracts, correlates with the ability to rapidly see words

- This is one reason we think that the wires are active, changing in response to learning and memory

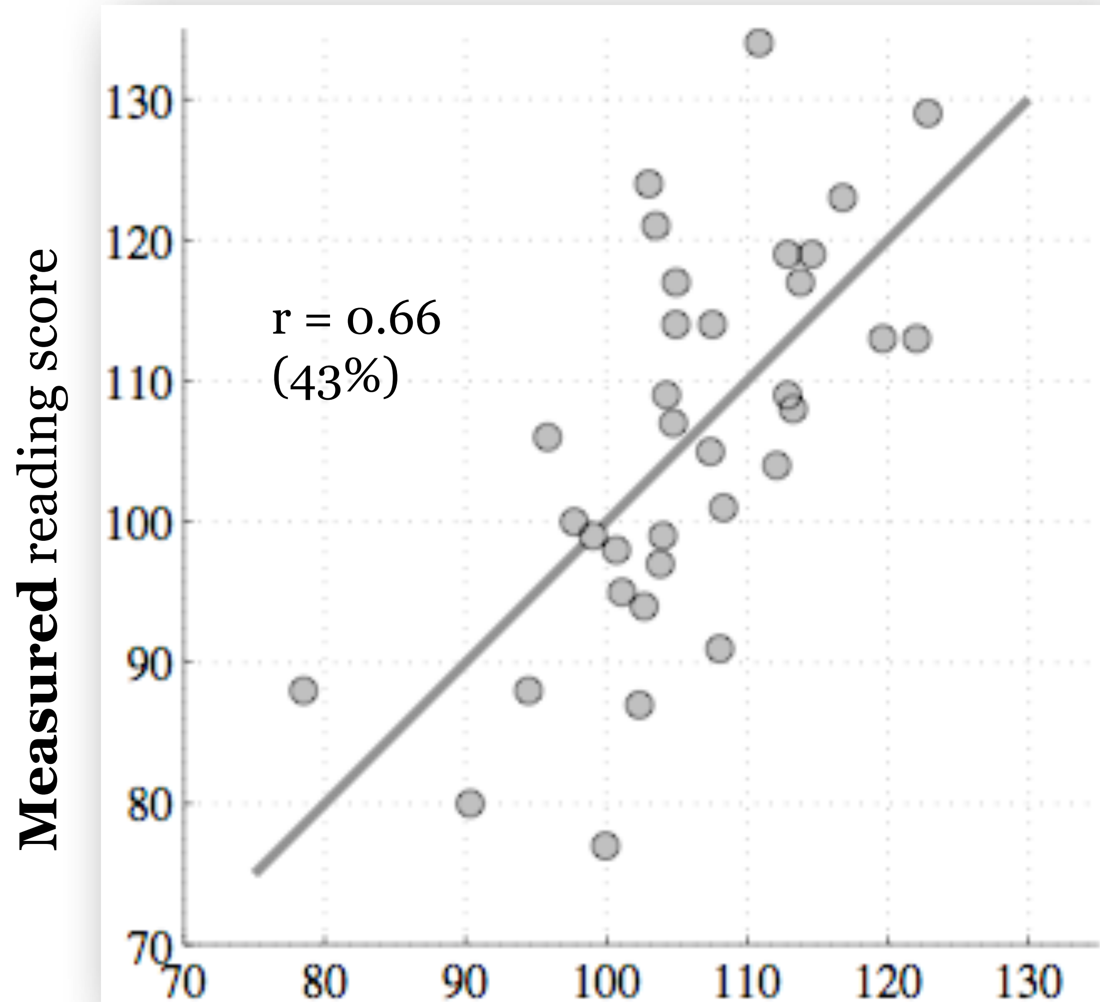


Neuroprognosis

Yeatman et al., (2012)
PNAS

- Combining FA measurements of the two tracts (ILF and AF) predicts reading skill

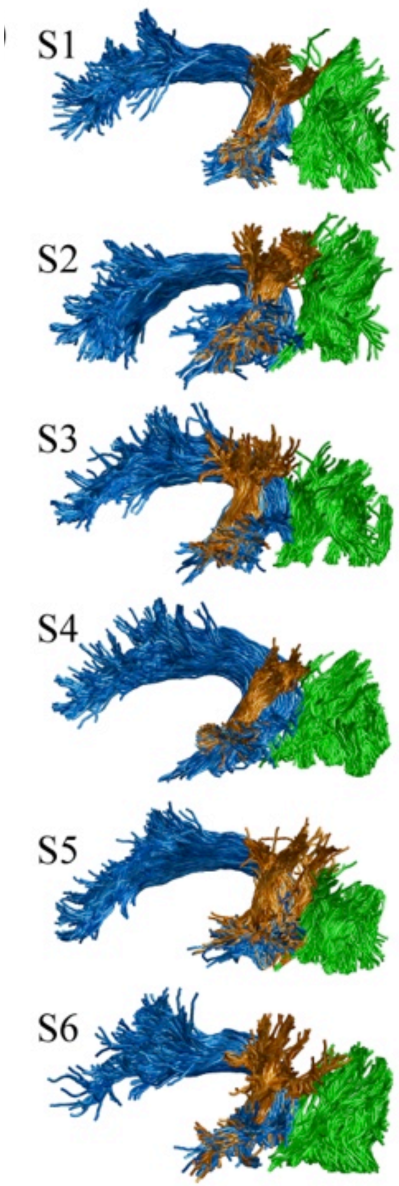
- The predictions are not yet useful; they are statistically reliable

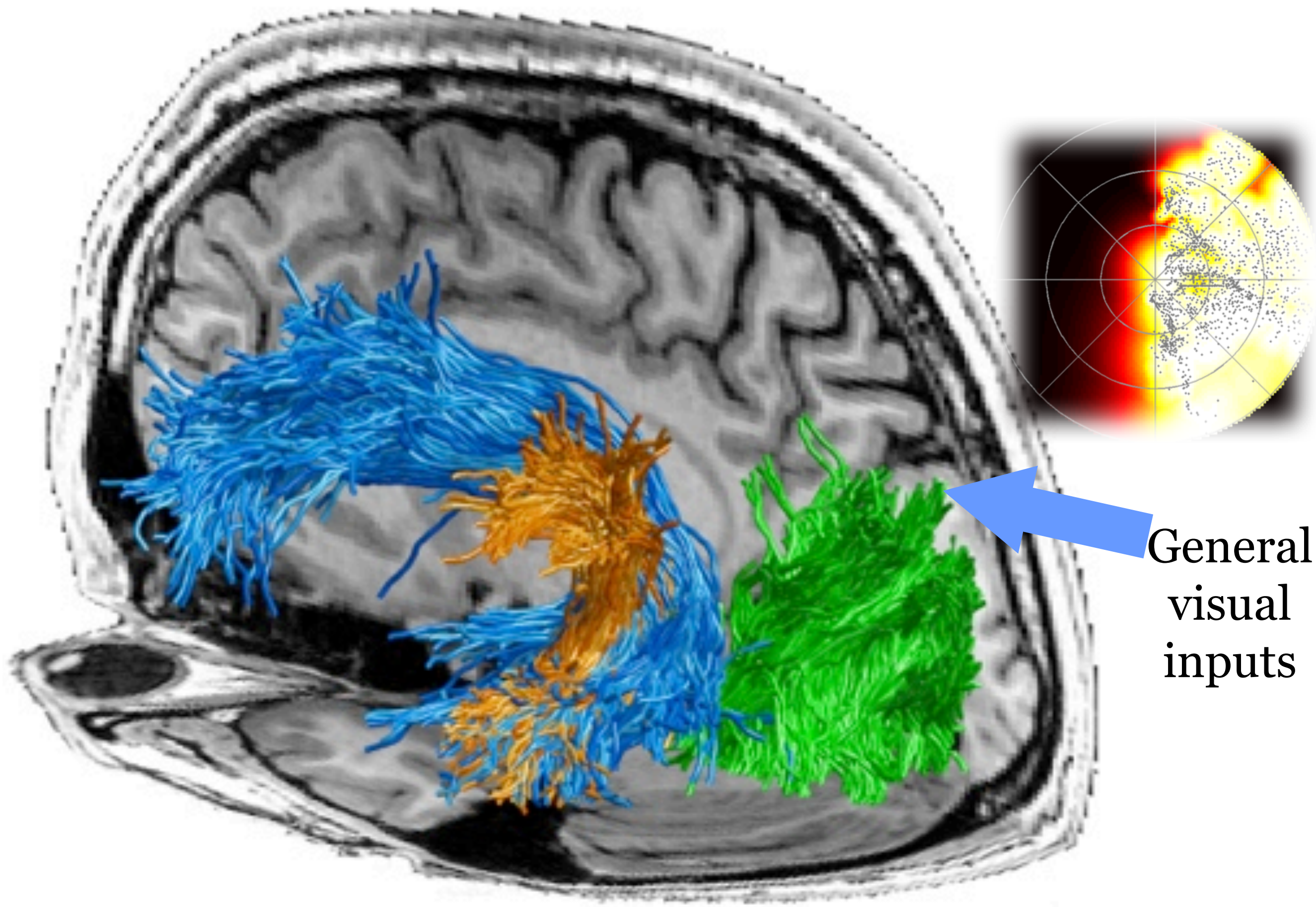


$$w_1 F_{ilf} + w_2 F_{arc}$$

Predicted reading score
(weighted sum of ILF and AF FA)

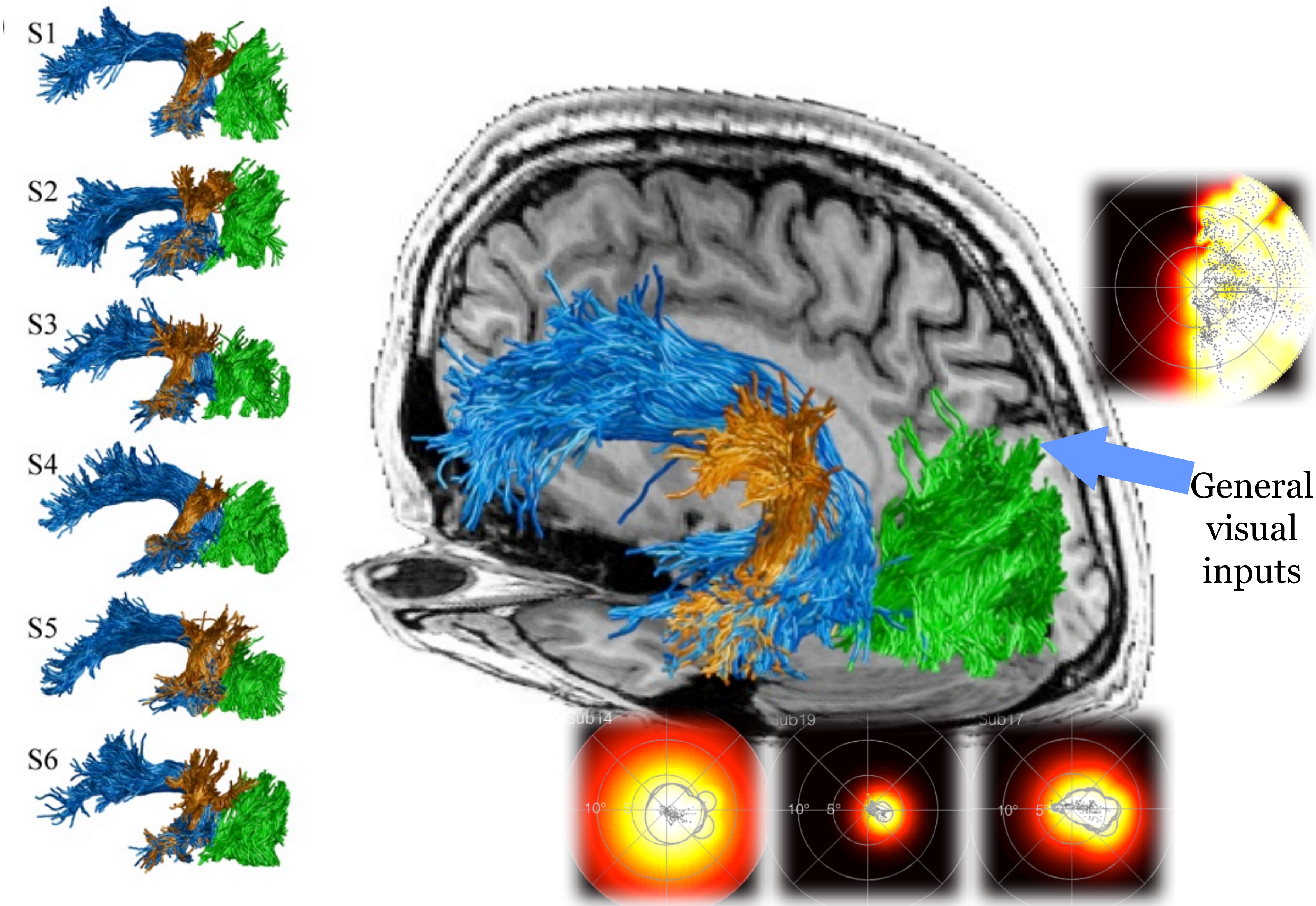
Connectionism: Mismatch hypothesis





VOT
Specialized processing for faces, words, other things

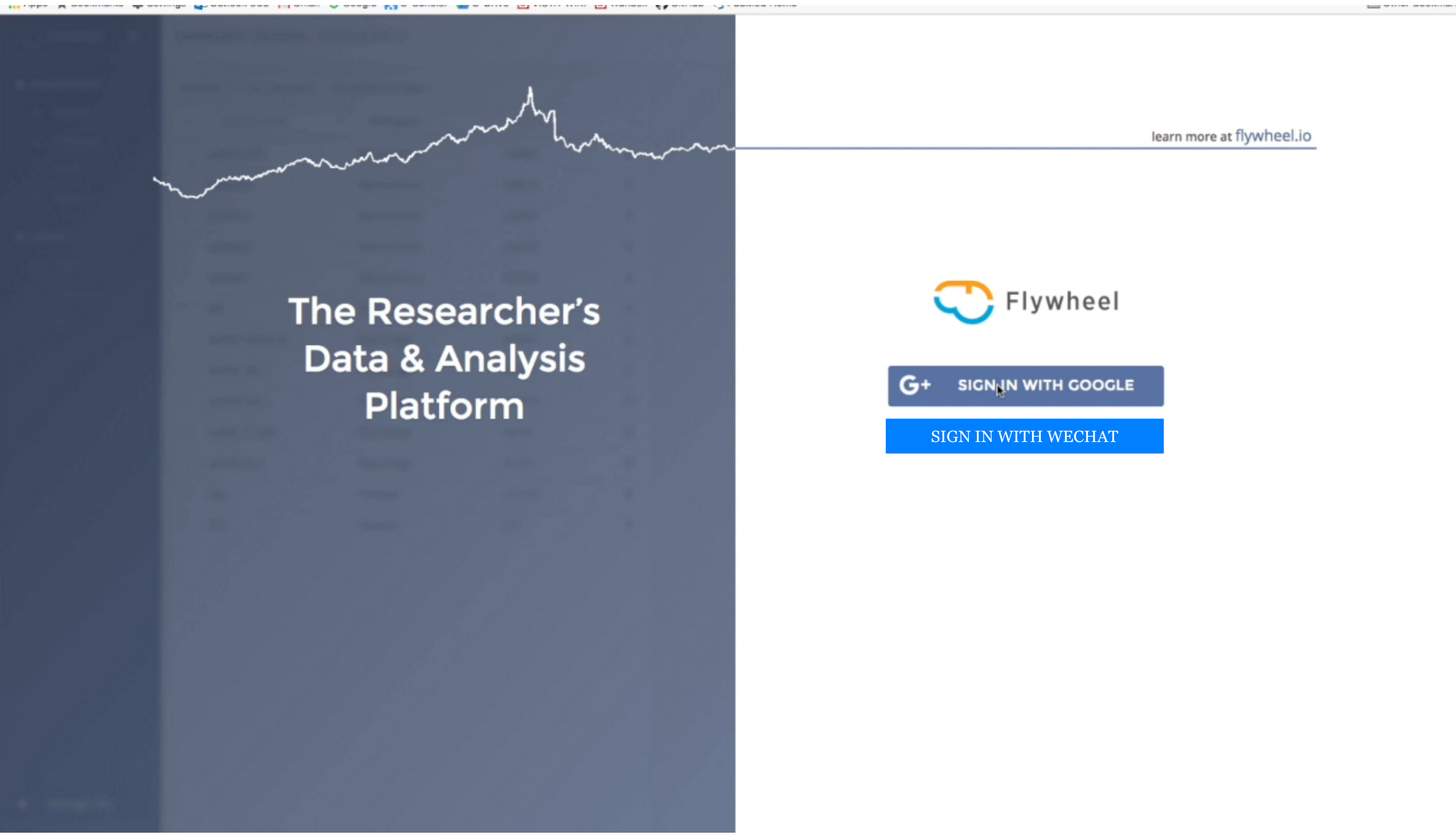
Connectionism: Mismatch hypothesis



Data management and analysis tools

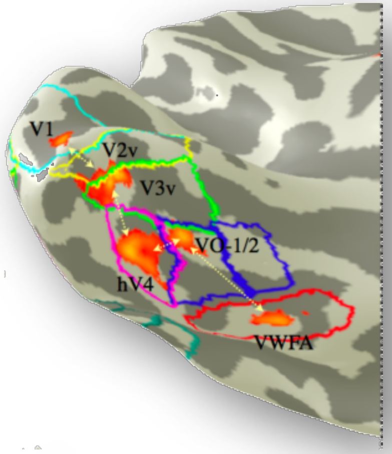
Prof. JH Gao, PKU

Disclosure: Flywheel.io

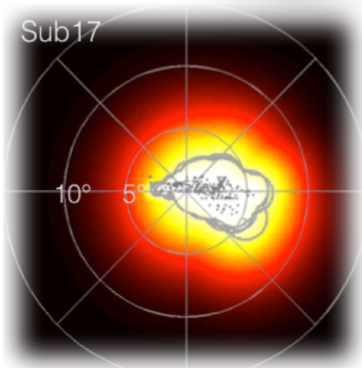


Computational neuroimaging: Reading circuitry

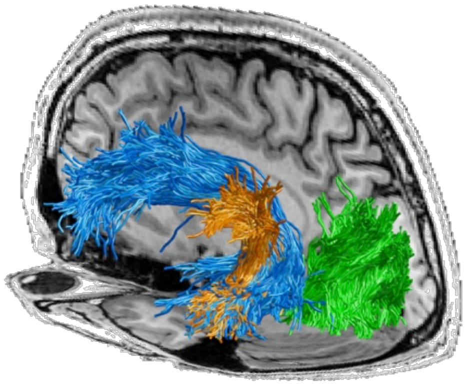
- We made progress in computational neuroimaging methods (fMRI), so that we have visual field maps and computational methods to quantify response properties (pRF)



- We made progress with dMRI to identify the major tracts that carry critical signals for reading between regions of cortex that learn to see words



- These neuroimaging measures correlate with behavior and offer a chance to diagnose the biological reasons for success and failure of the reading circuitry in each child



- To use the science in practice will require technology for data and computational sharing and incentives to support people who do this work

Thanks to NIH, NSF as well as the Simons, Weston-Havens, and Wallenberg Foundations

Alyssa Brewer

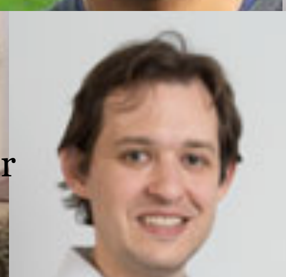
Michal Ben-Shachar

Serge Dumoulin

Bob Dougherty

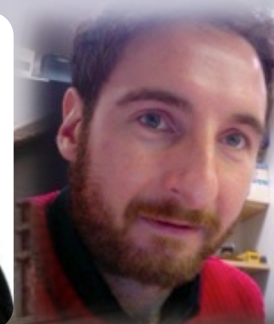
Aviv Mezer

Andreas Rauschecker



Rosemary Le

Franco Pestilli



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