Human visual cortex: circuitry for vision and reading

Brian A. Wandell

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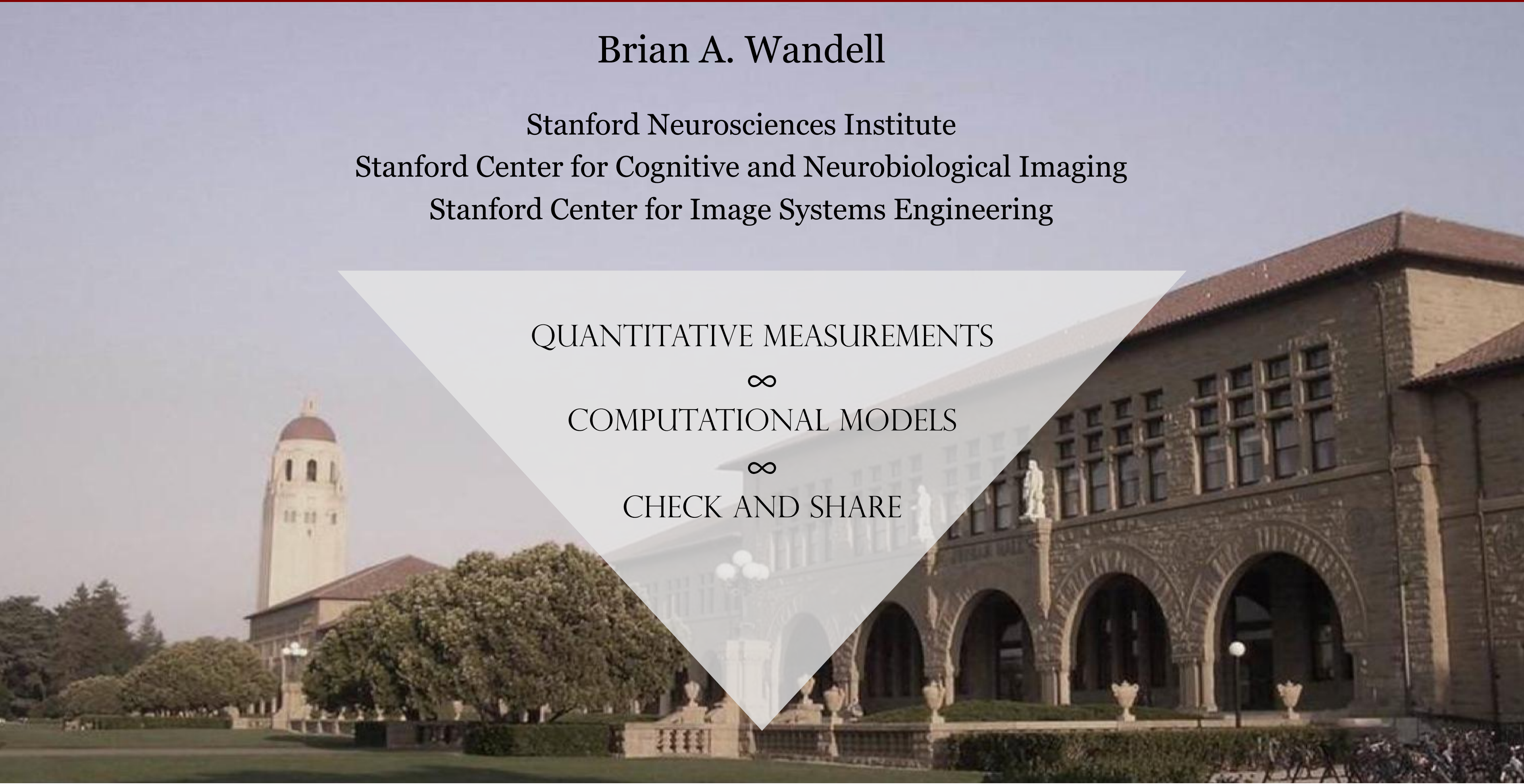


QUANTITATIVE MEASUREMENTS

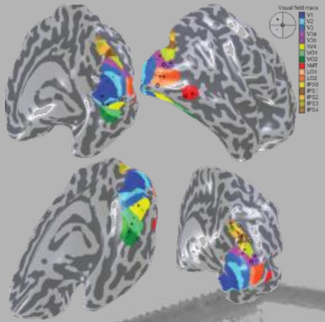
∞

COMPUTATIONAL MODELS

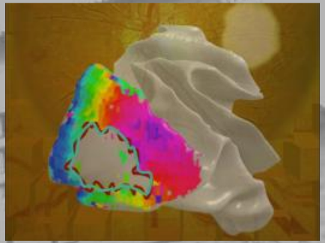
∞

CHECK AND SHARE

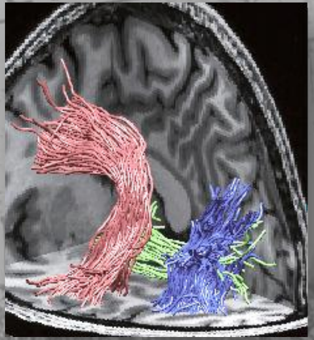
Human visual cortex: circuitry for vision and reading



- Human visual field maps and clusters



- Plasticity and stability of human visual cortex



- Seeing words – connecting vision to cognition

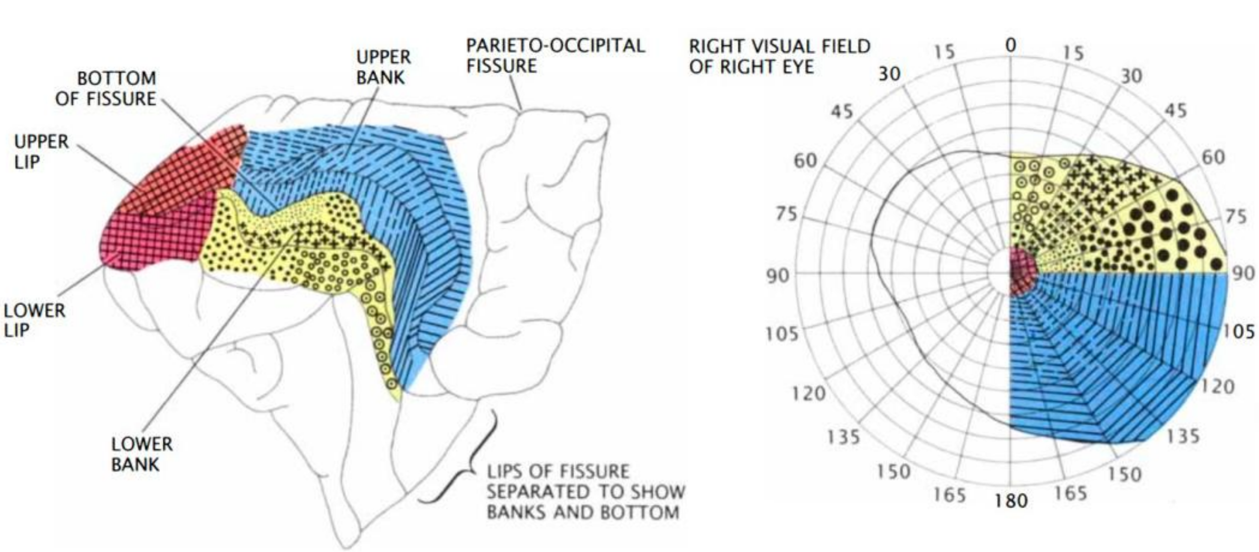
1880-1920 Identifying human V1 and retinotopic mapping

Henschen

Munk

Inouye

Holmes



Glickstein, M. 1988. “The Discovery of the Visual Cortex.” *Scientific American* 259 (3): 118–27.

1940-1990 More maps (or areas) identified in animal models

Distributed Hierarchical Processing in the Primate Cerebral Cortex

Daniel J. Felleman[1] and David C. Van Essen[2]

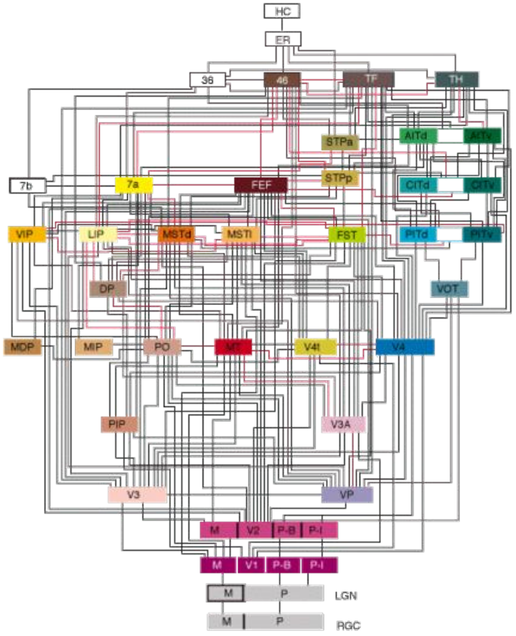
Cerebral Cortex (1991)

QUADRANTIC VISUAL FIELD DEFECTS

A HALLMARK OF LESIONS IN EXTRASTRIATE (V2/V3) CORTEX

by JONATHAN C. HORTON *and* WILLIAM F. HOYT

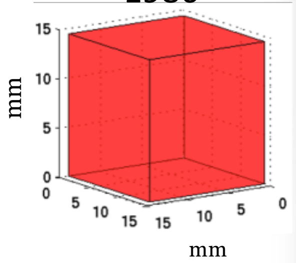
Brain (1991)

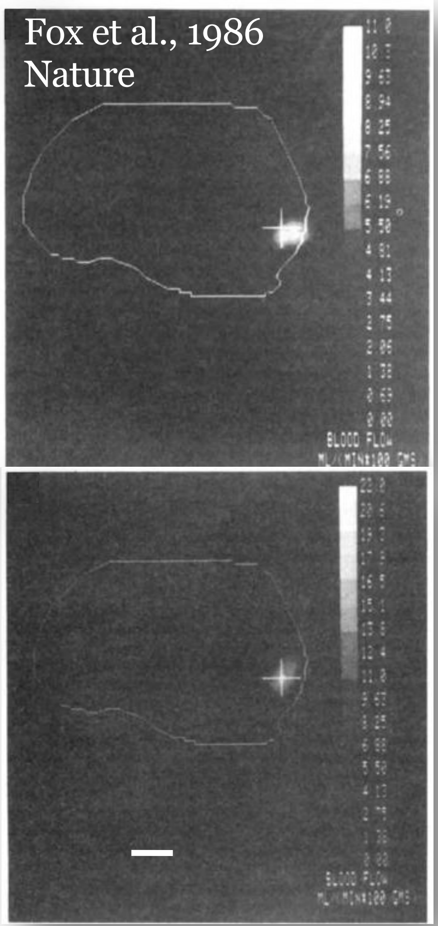


“No information is available about the topography of V2 in human visual cortex. (p 1709)”

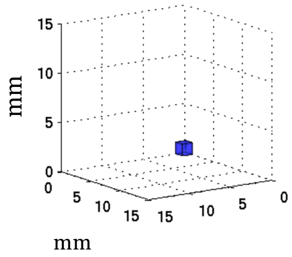
1990-2010 Excellent progress in human measurements

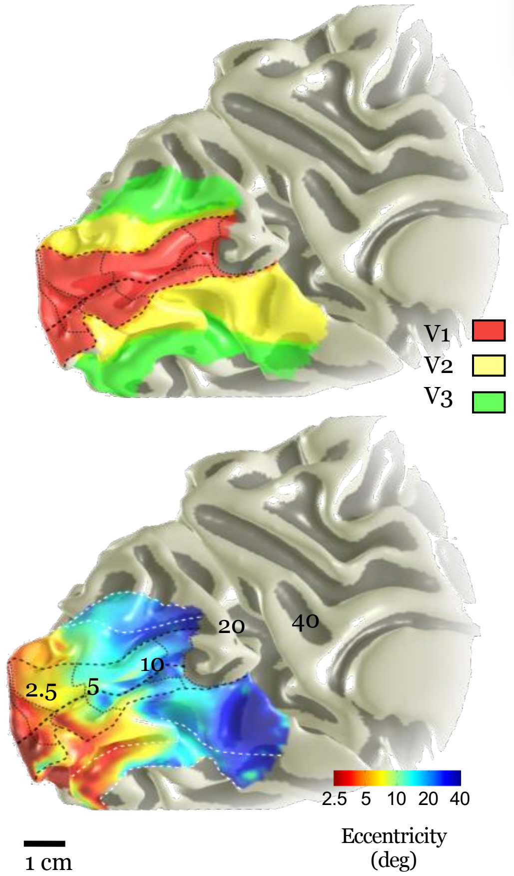
Voxel size
1986





Voxel size
2009



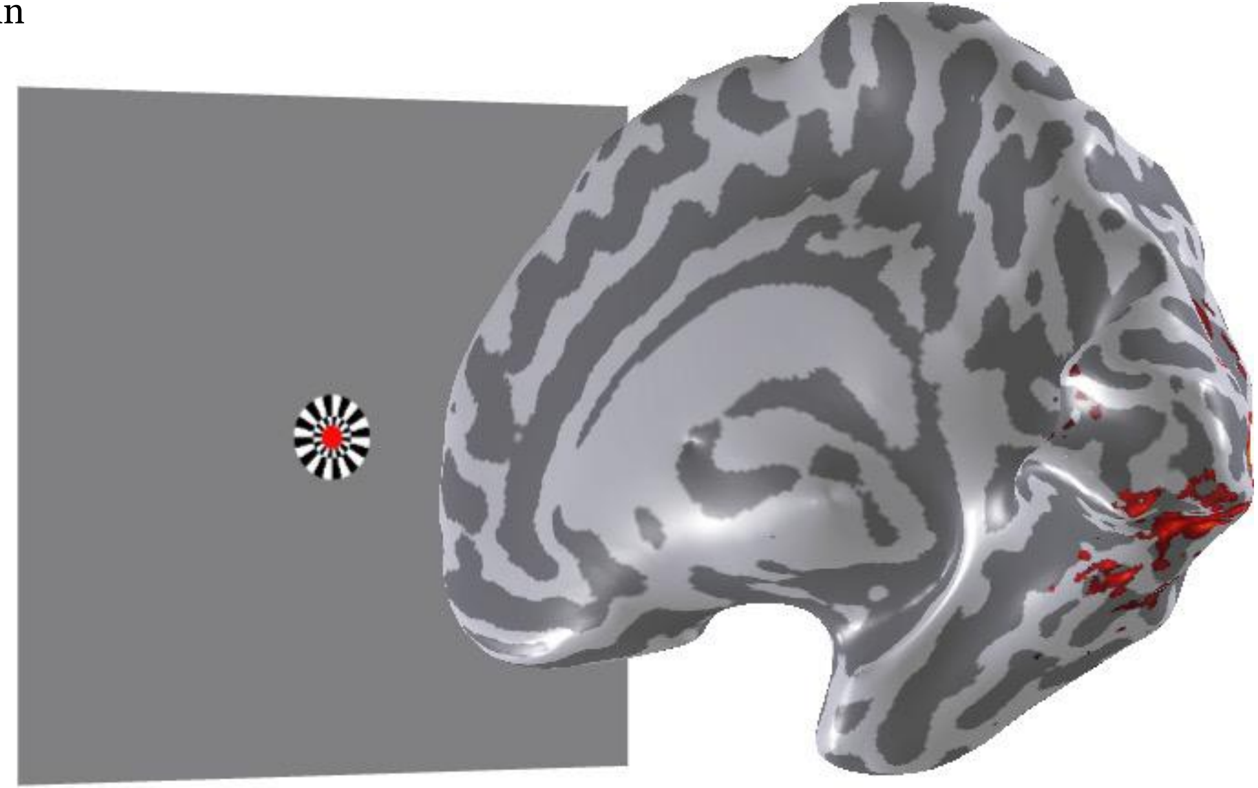


Winawer

Human eccentricity mapping with fMRI

Engel

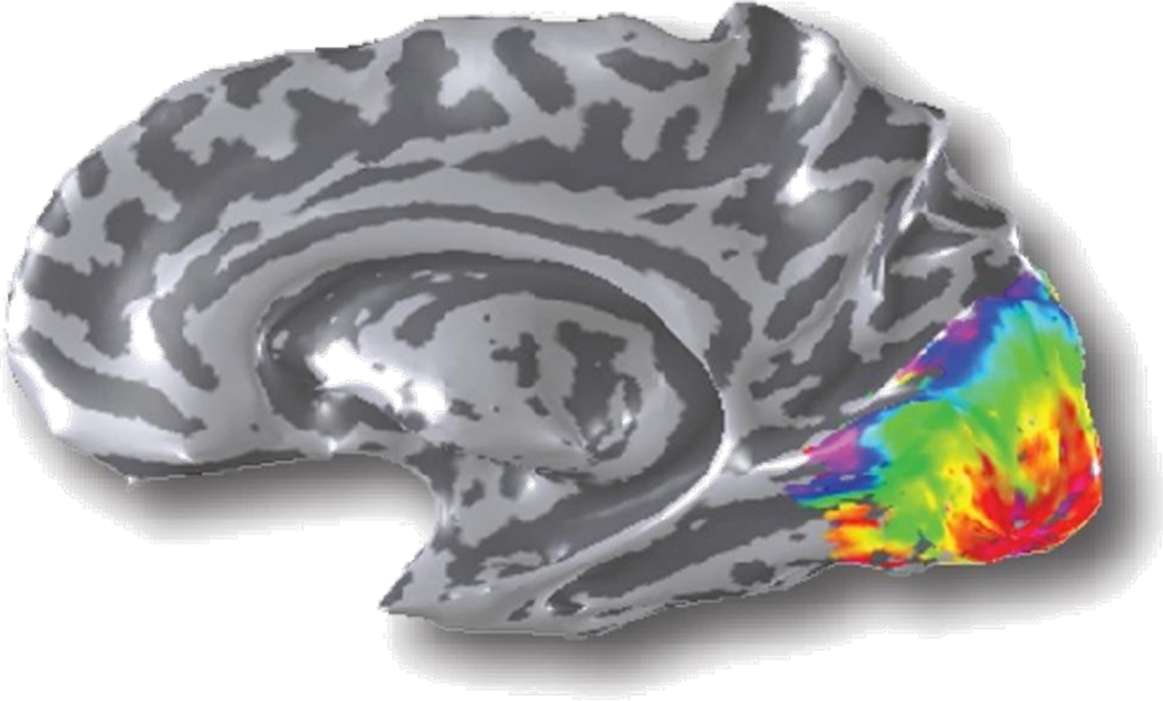
- Segmented brain surface
- Inflated brain
- Gray/white are sulci/gyri



Engel, S. A., D. E. Rumelhart, B. A. Wandell, and A. T. Lee. 1994. “fMRI of Human Visual Cortex.” *Nature*

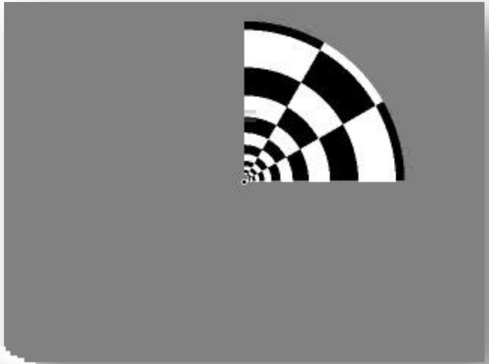
Engel, S. A., G. H. Glover, and B. A. Wandell. 1997. “Retinotopic Organization in Human Visual Cortex and the Spatial Precision of Functional MRI.” *Cerebral Cortex*

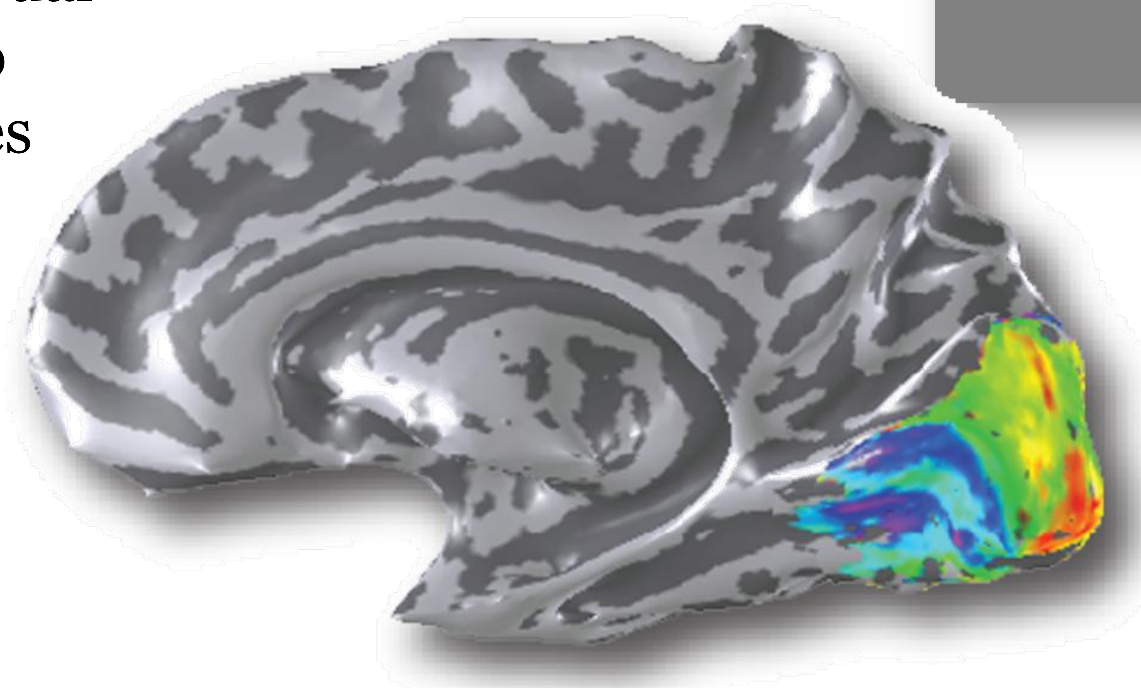
Pseudo-color representation of visual field map



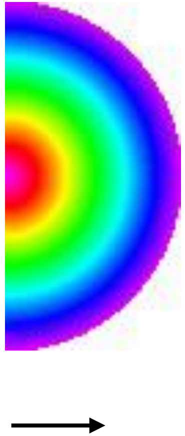
20 deg

Angular measurements delineate visual field map boundaries

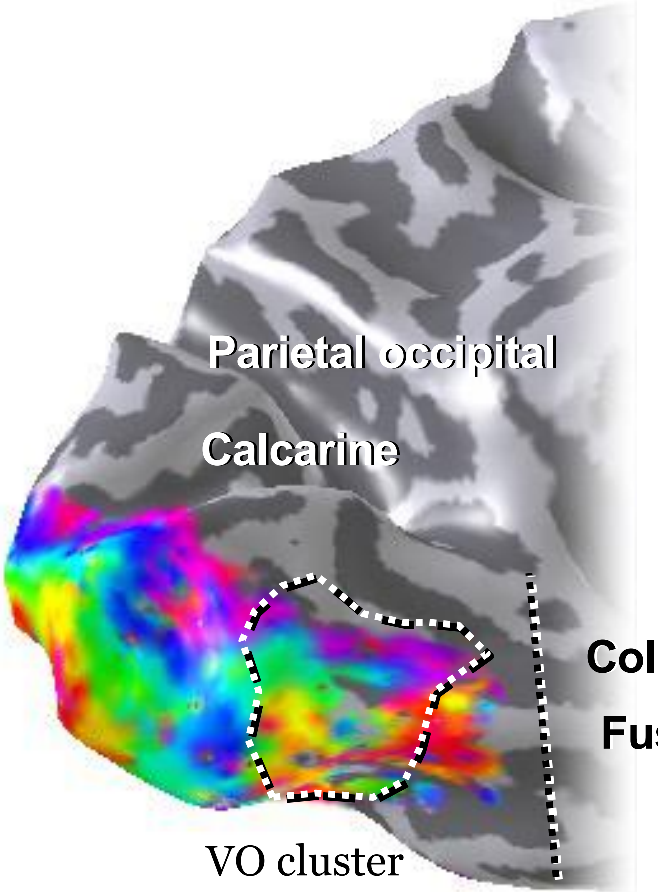




Visual field map clusters



Coherence = 0.25



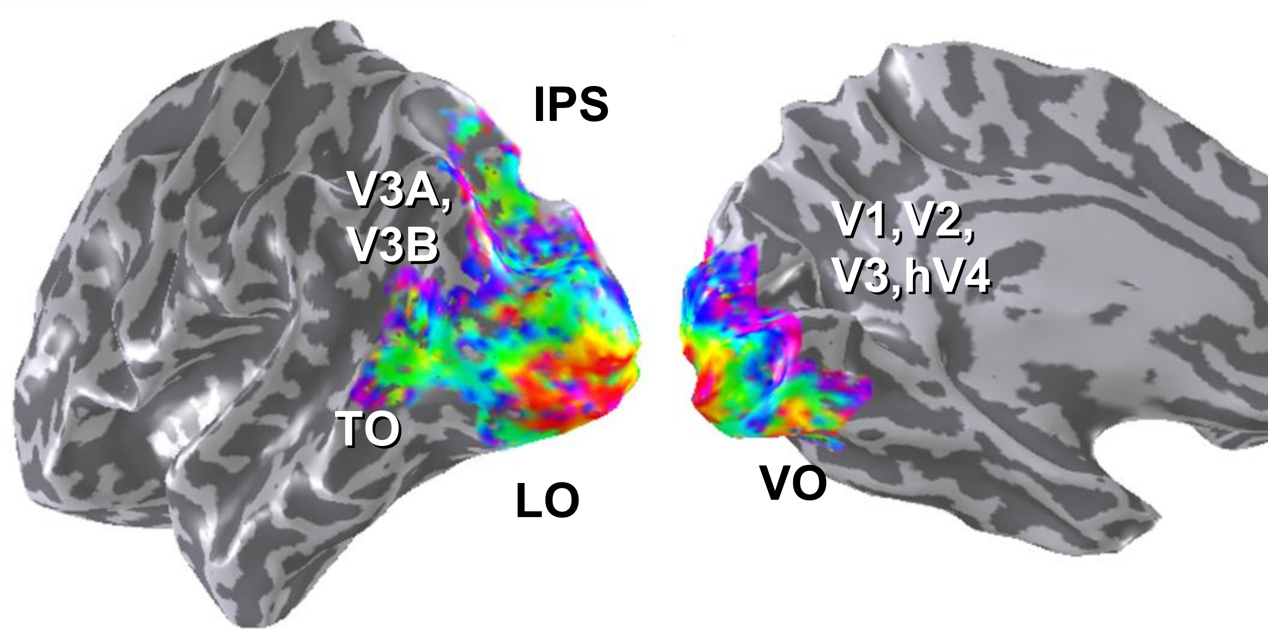
Visual field maps and stimulus selectivity in human ventral occipital cortex
(2005) . A.A. Brewer, J. Liu, A.R. Wade, B.A. Wandell, Nat Neurosci.

Visual field map clusters

Left hemisphere

Lateral view | Medial view

Clusters
Early - V1,V2,V3,hV4
LO - Lateral occipital
VO – Ventral occipital
TO – Temporal occipital
IPS – Intraparietal sulcus

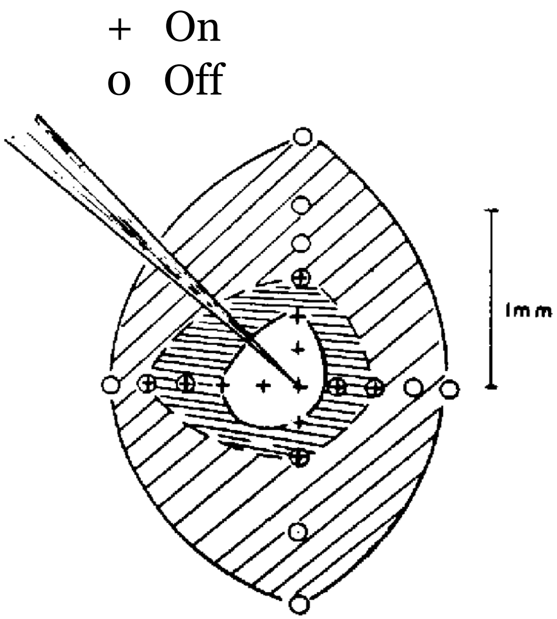


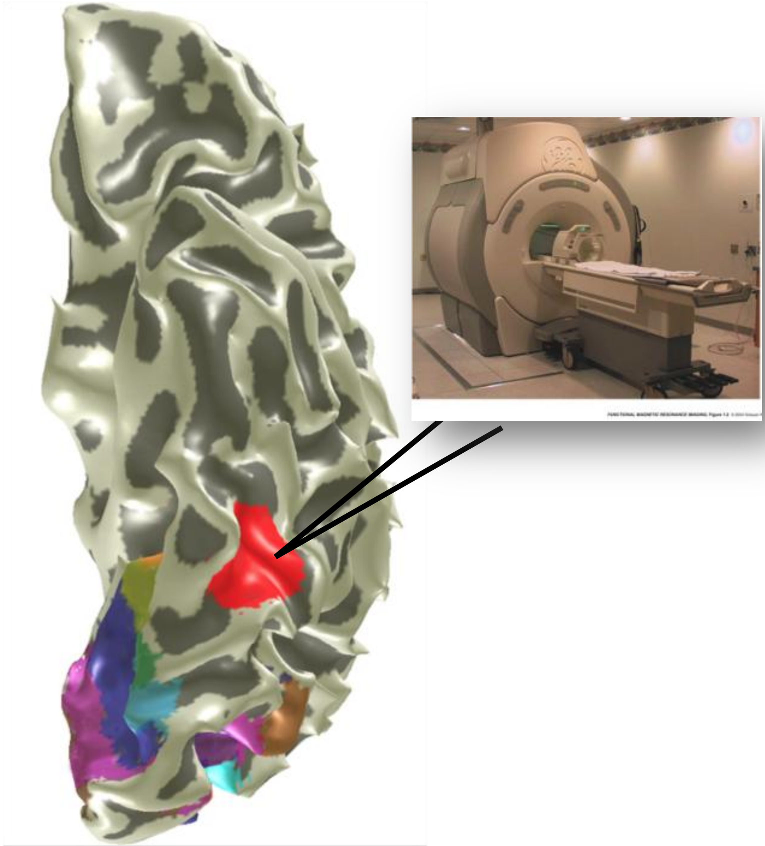
Coherence >= 0.20

Visual Field Map Clusters in Human Cortex (2005). Wandell, Brewer and Dougherty Phil. Trans. of the Royal Society London

Quantitative modeling: the population receptive field (pRF)

‘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)’.



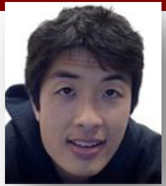


Sherrington, 1910
Kuffler, 1953

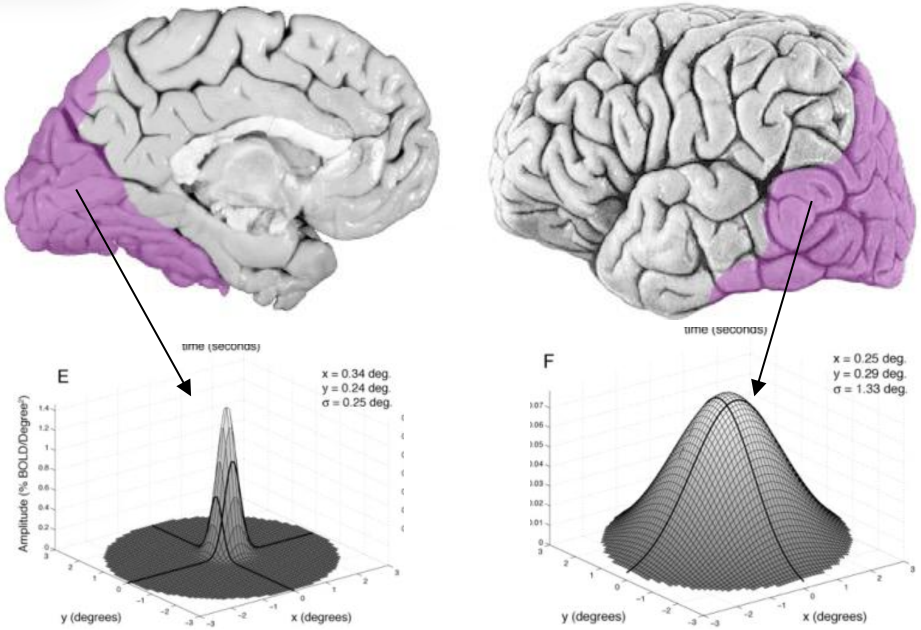
PRF size varies substantially and regularly across visual cortex

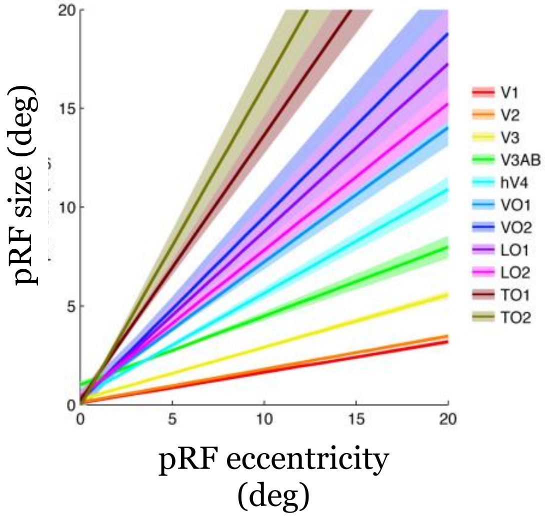
Dumoulin

- PRF size increases with eccentricity for all maps
- At equal eccentricity, different maps have different pRF sizes

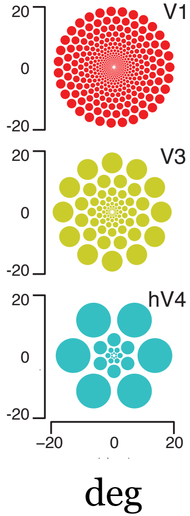


Kay





From J. Freeman



Dumoulin, Serge O., and Brian A. Wandell. 2008. “Population Receptive Field Estimates in Human Visual Cortex.” *NeuroImage*

Wandell, Brian A., and Jonathan Winawer. 2015. “Computational Neuroimaging and Population Receptive Fields.” *Trends in Cognitive Sciences*

Visual field maps and pRF reviews

Winawer Brewer Dumoulin

Neuron 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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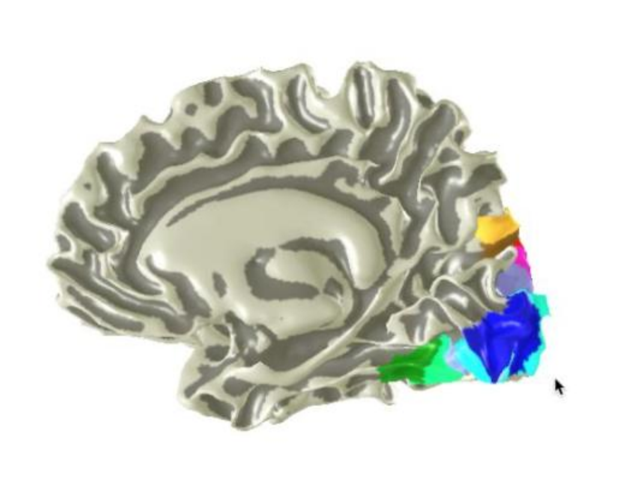
[2]Department of Cognitive Sciences, University of California, Irvine, Irvine, CA 92697, USA
*Correspondence: wandell@stanford.edu
DOI 10.1016/j.neuron.2007.10.012

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 (2011)

Vision Research
journal homepage: www.elsevier.com/locate/visres

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-

Review

Trends in Cognitive Sciences, 2015,

CellPress

Computational neuroimaging and population receptive fields

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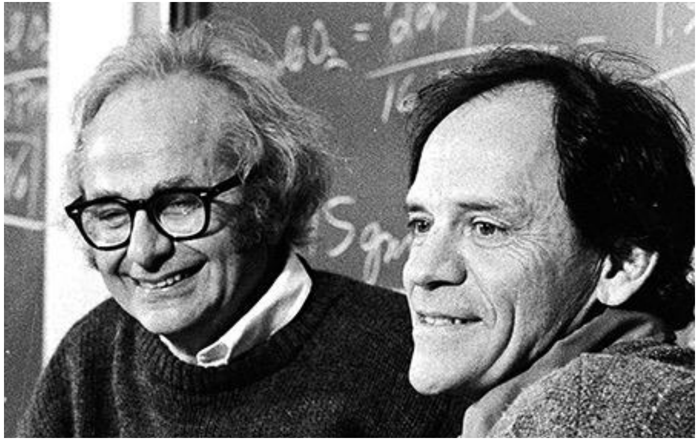
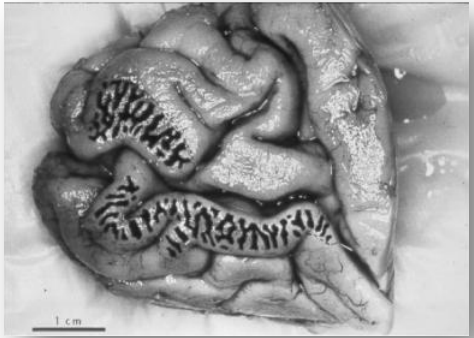
[1]Psychology Department and Neurosciences Institute, Stanford University, Stanford, CA, USA
[2]Psychology Department and Center for Neural Science, New York University, New York, NY, USA

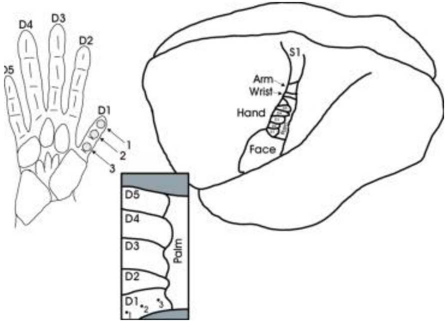
Plasticity and stability in primate cortex



David Hubel　　Torsten Wiesel　　Michael Merzenich　　Jon Kaas



Thanks to Jonathan Horton



Thanks to A. Das (adapted from Kaas 1991)

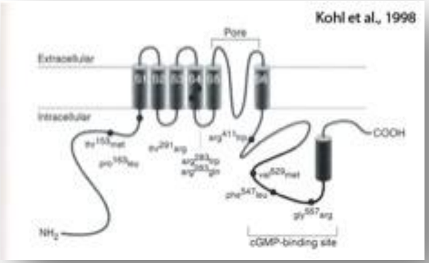
Developmental plasticity

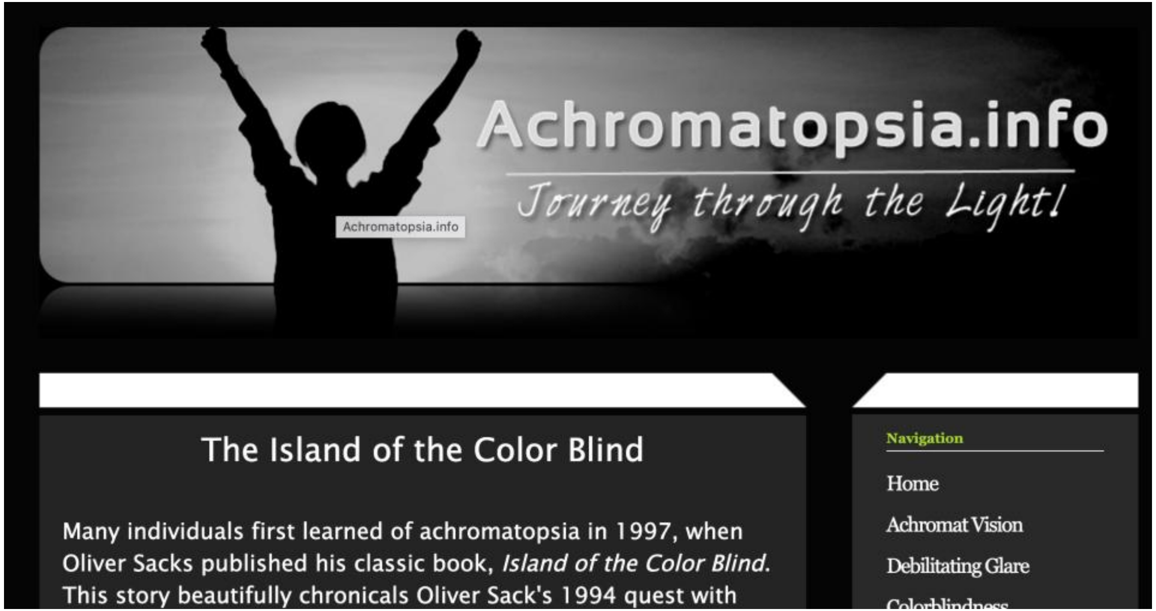
Baseler

Morland

Brewer

Congenital complete achromatopsia (Rod monochromats)

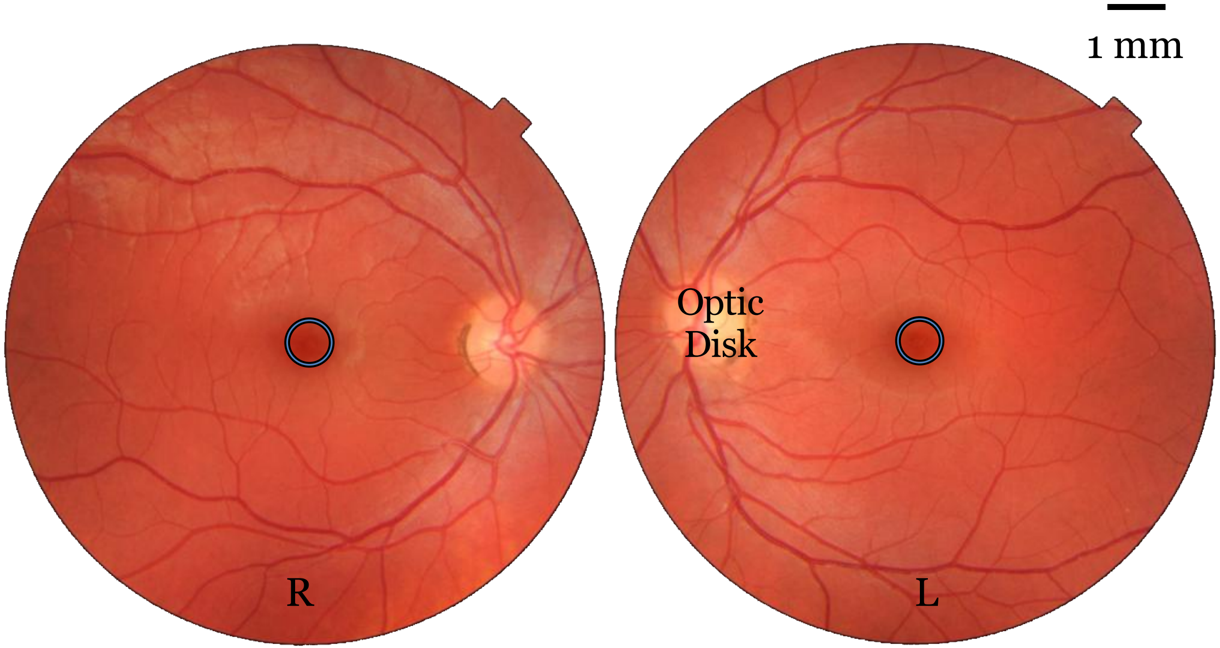




Reorganization of human cortical maps caused by inherited photoreceptor abnormalities (2002). Baseler, Brewer, Sharpe, Jägle and Wandell. Nature Neuroscience

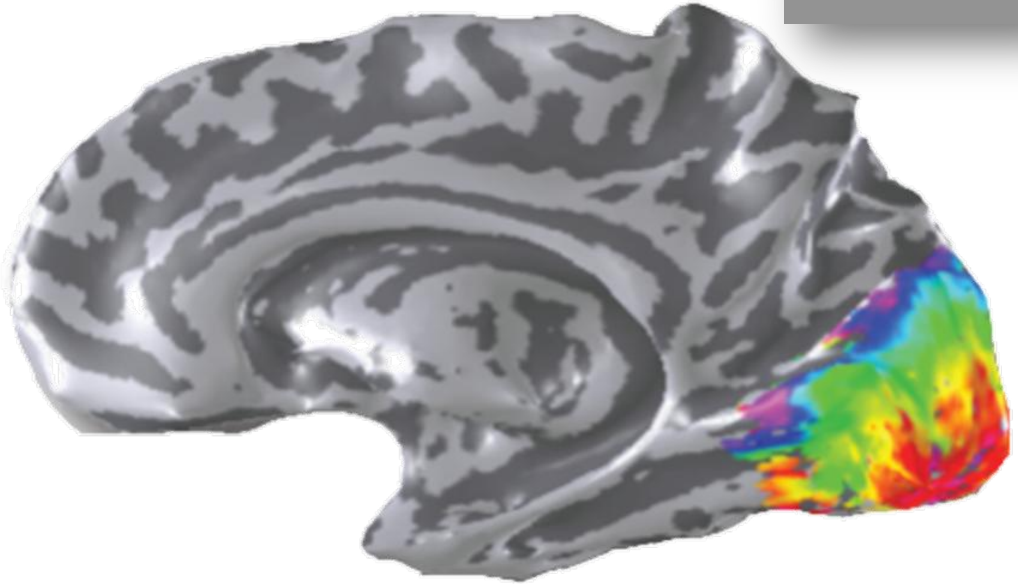
The rod-free zone in the retina

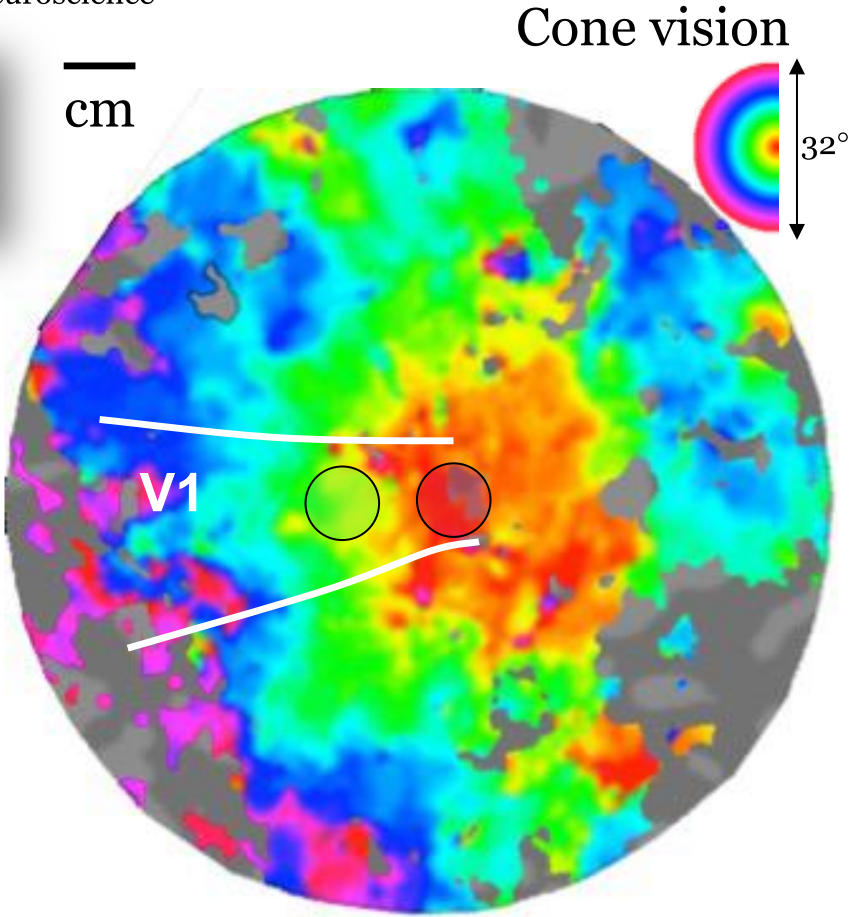
Rod free zone (1.25 deg, ~ 400 um)



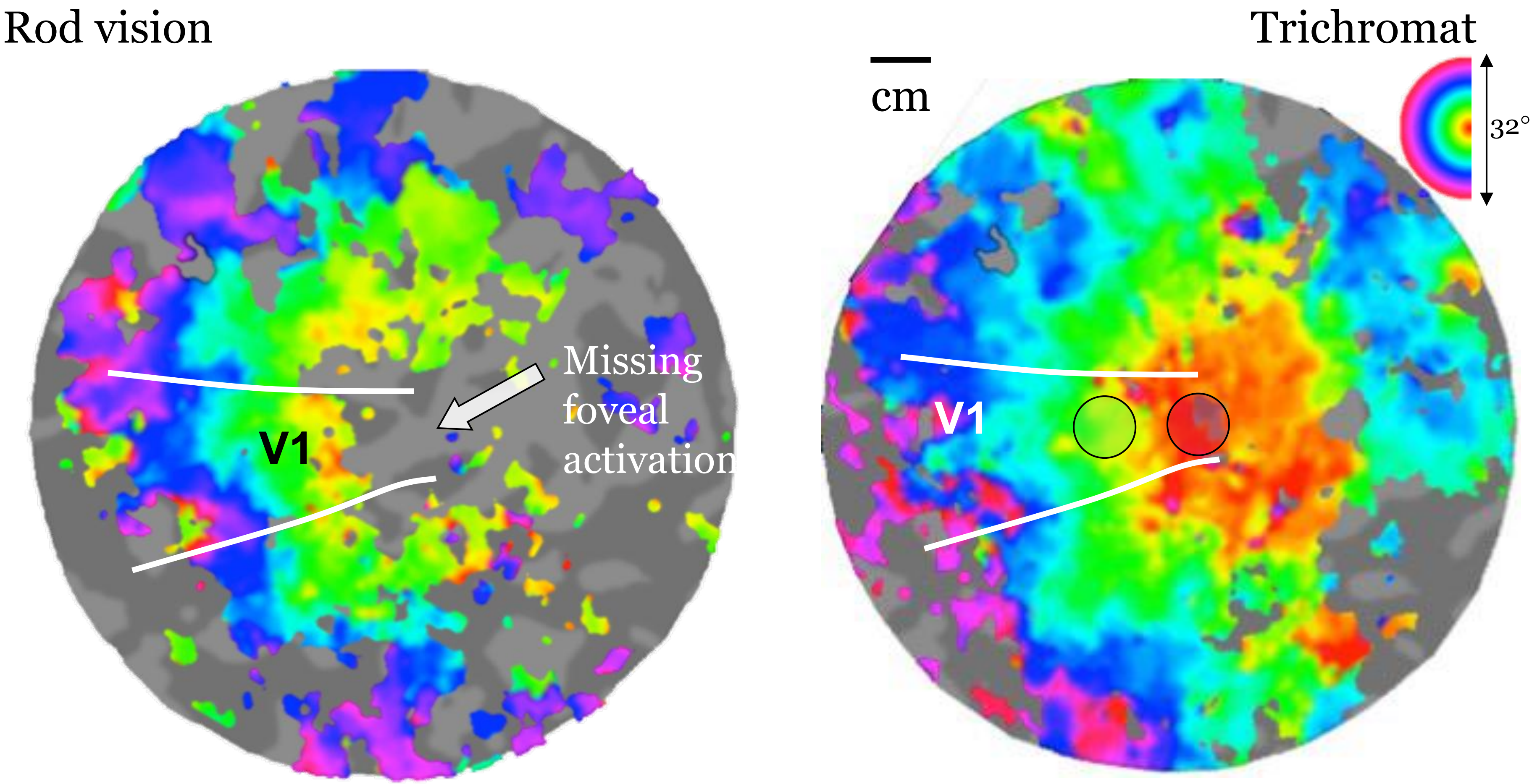
Typical cone-driven to expanding ring stimulus

Baseler et al., (2002) Nature Neuroscience



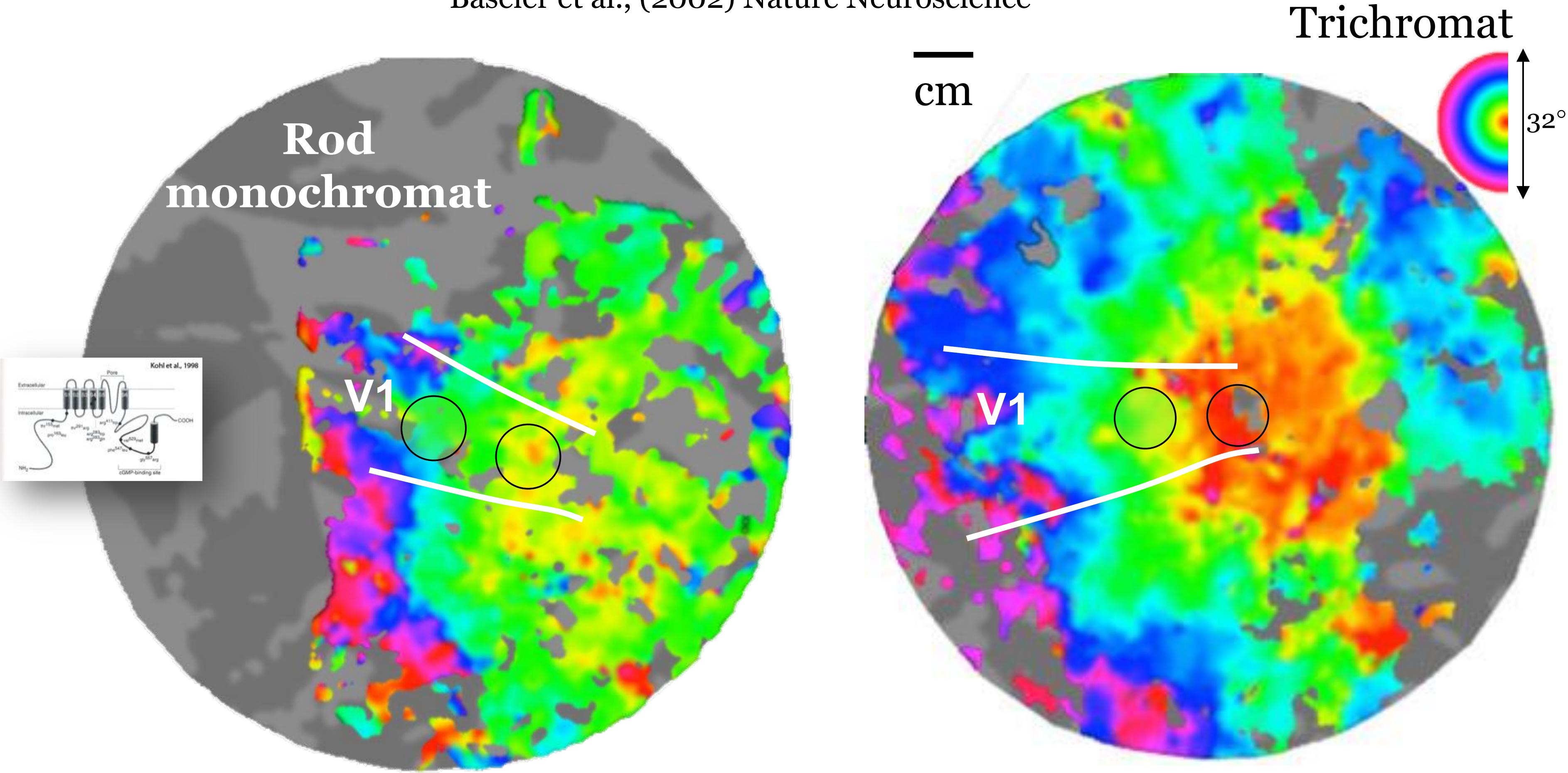


Rod-driven response: missing central representation



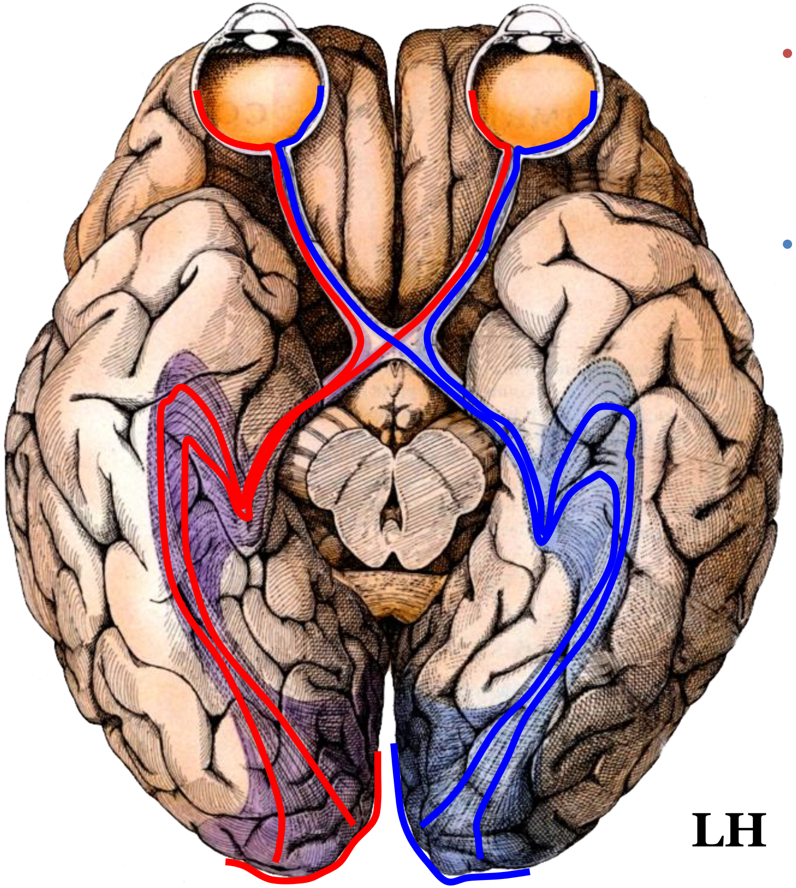
Rod monochromats: a visual response in the central representation

Baseler et al., (2002) Nature Neuroscience



An achiasmic subject: Major projections from retina to V1

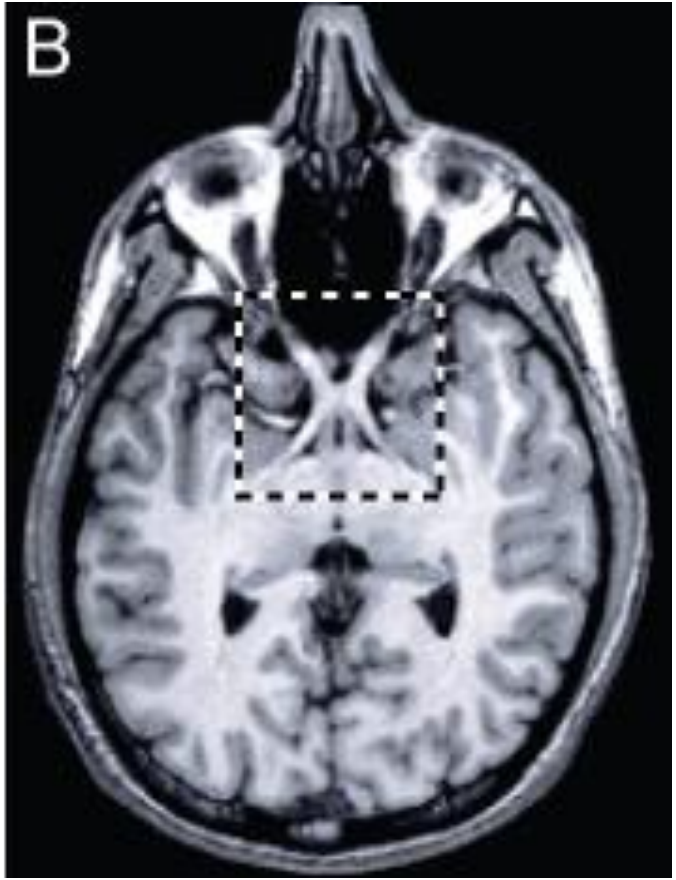
Molecular guidance at chiasm mediated by Ephrin-B2 and EphB1 (Williams et al., 2003, Neuron)



- Right visual field
  - left temporal retina
  - right nasal retina
- Left visual field
  - right temporal retina
  - left nasal retina

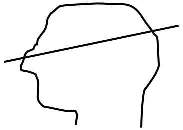
Right visual field
Left visual field

The optic chiasm is easy to see in a T1-weighted MRI

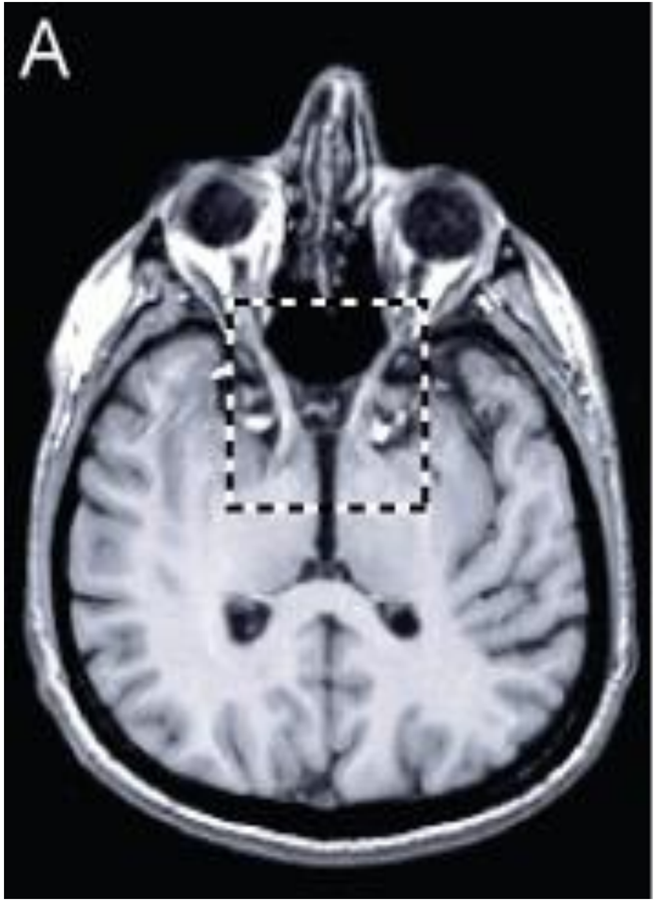


Conventional optic chiasm

Control

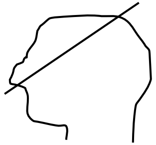


This subject doesn't have an optic chiasm

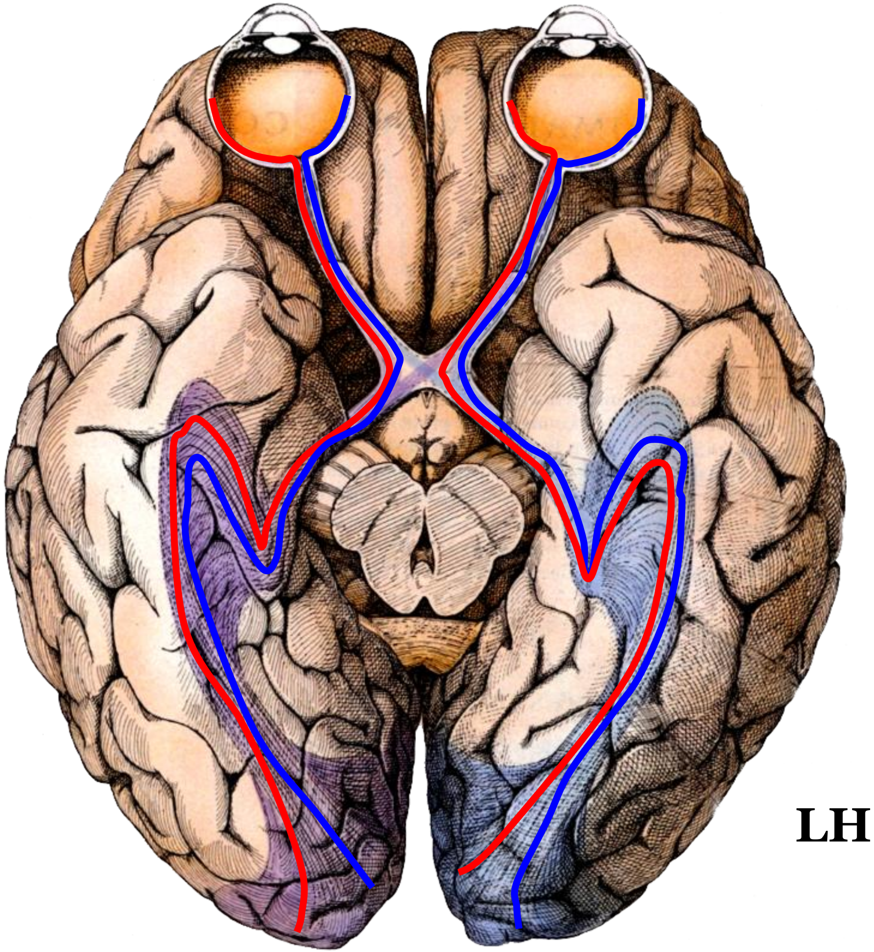


Missing optic chiasm

Achiasma



In the achiasmic subject, each eye maps to ipsilateral cortex

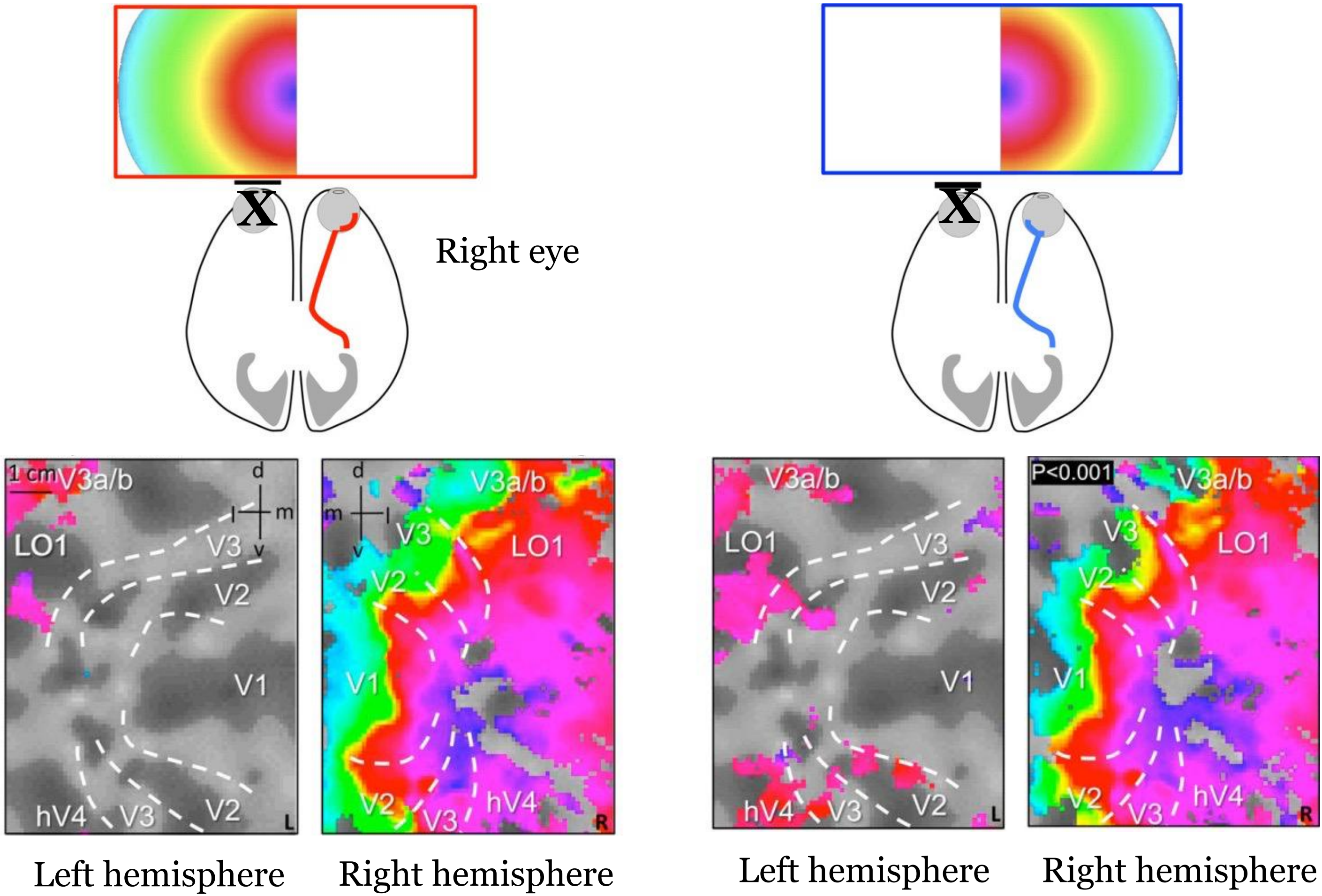


- Right visual field
  - left temporal retina
  - right nasal retina
- Left visual field
  - right temporal retina
  - left nasal retina

Right visual field
Left visual field

We confirmed this using fMRI measurements

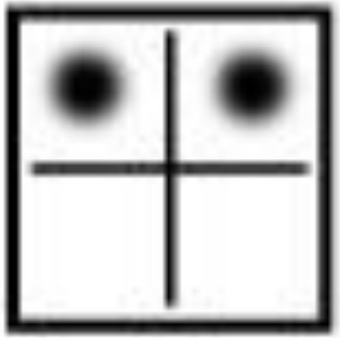
Signals from the right eye stay in the right hemisphere, unlike controls

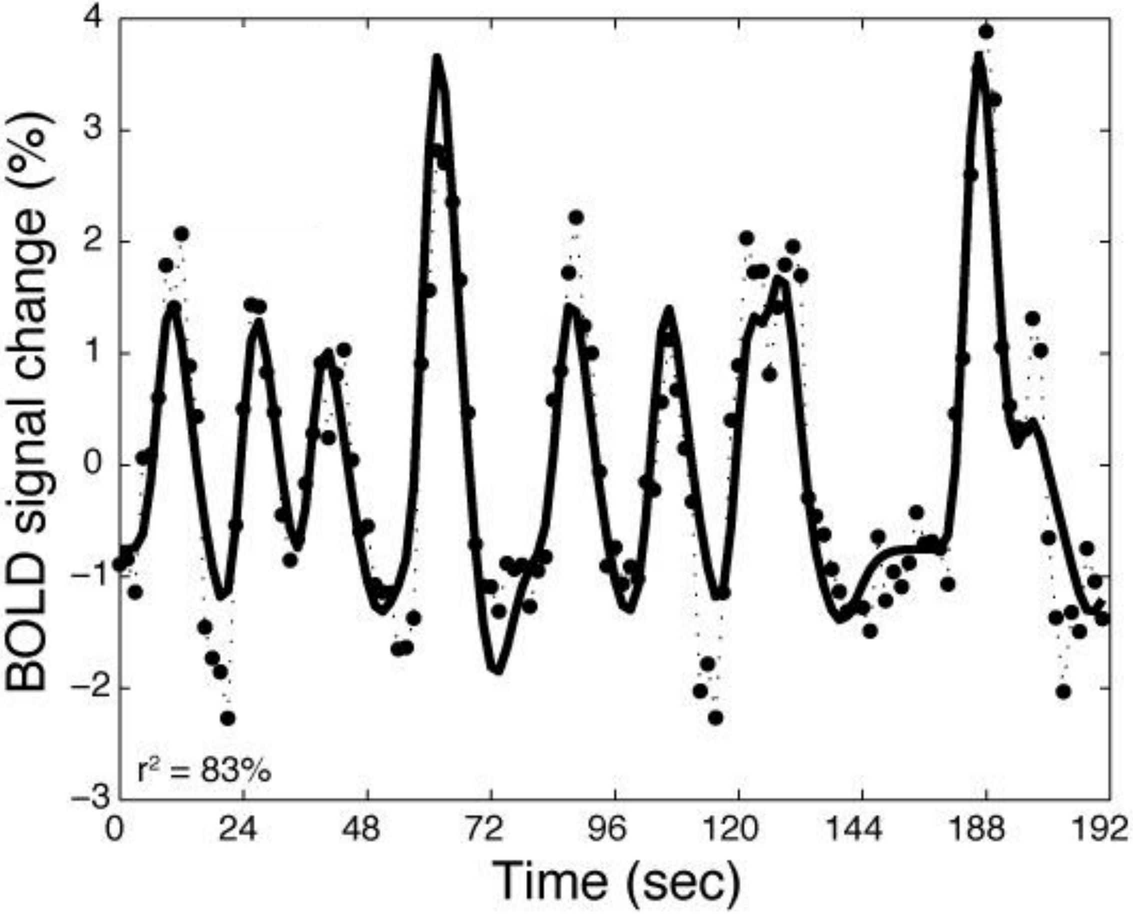


Plasticity and Stability of the Visual System in Human Achiasma. Hoffmann, Michael B., Falko R. Kaule, Netta Levin, Yoichiro Masuda, Anil Kumar, Irene Gottlob, Hiroshi Horiguchi, et al. 2012. Neuron

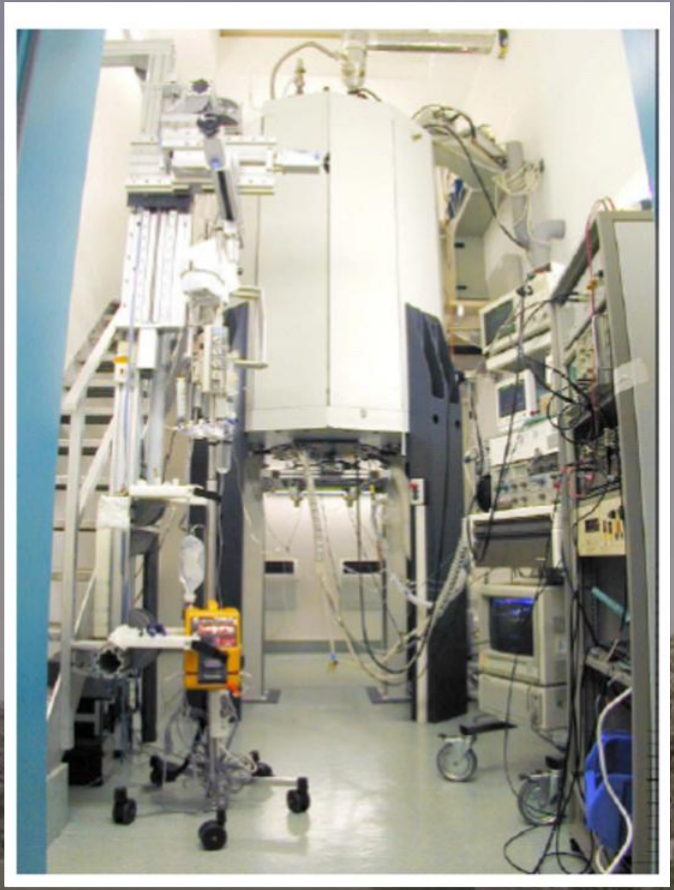
The population receptive fields are symmetric around the midline

Dual pRF model, with regions symmetric across the midline, fit the subject's data





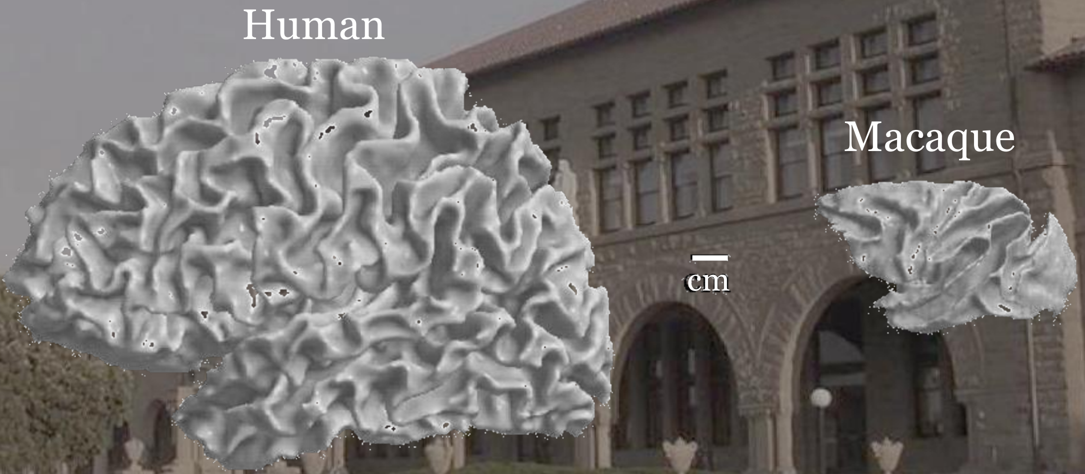
Non-human primate measurements



Potential for molecular and pharmacological studies of cortical plasticity

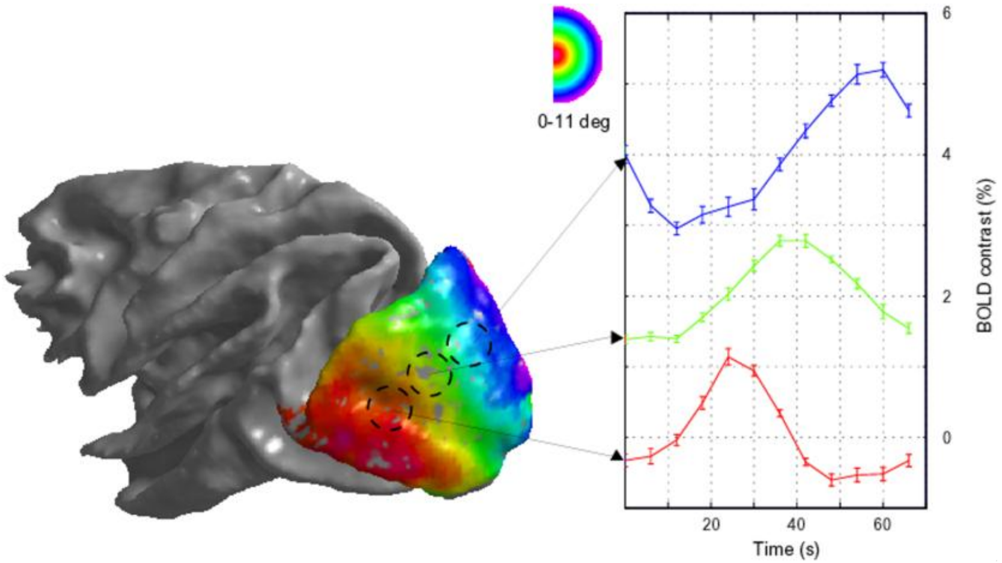
Smirnakis

Logothetis



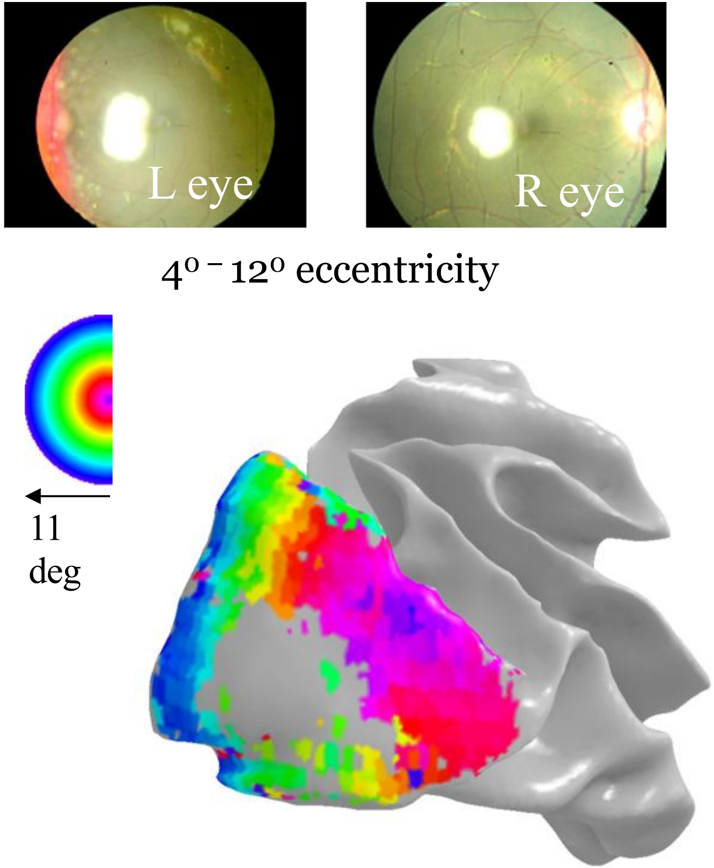
FMRI visual field mapping in macaque

(a)



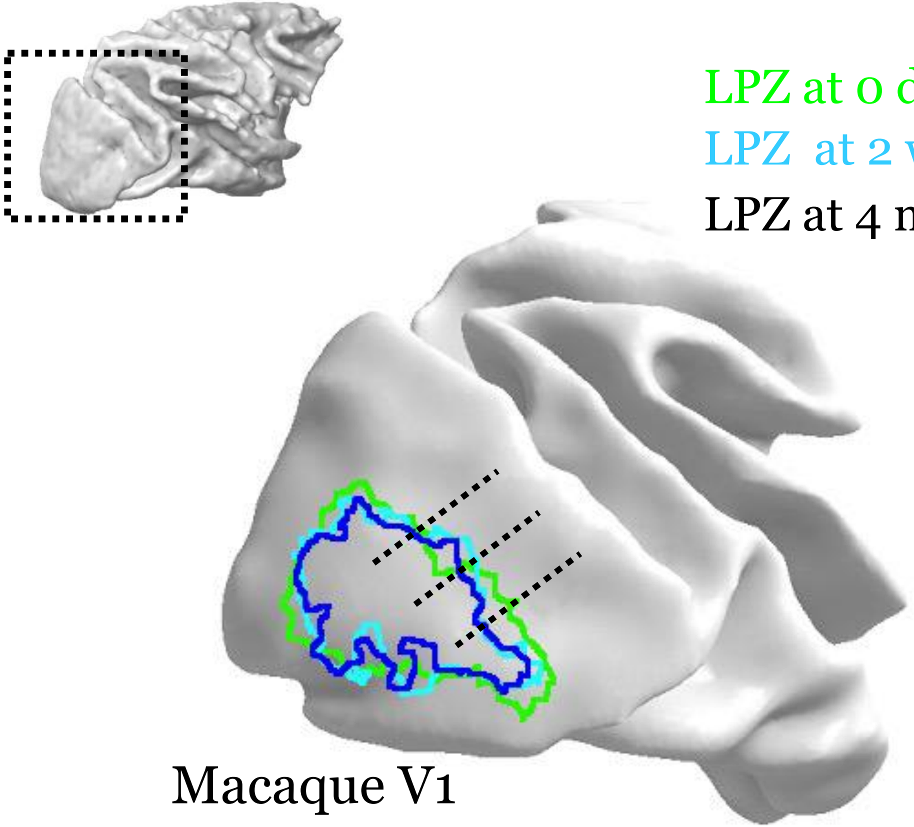
"Visual Areas in Macaque Cortex Measured Using Functional Magnetic Resonance Imaging." Brewer, Alyssa A., William A. Press, Nikos K. Logothetis, and Brian A. Wandell. 2002. *The Journal of Neuroscience*.

(b)



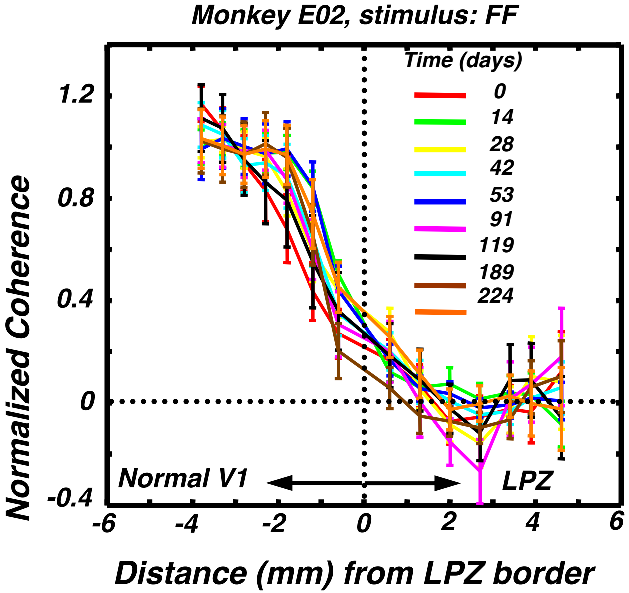
"Lack of Long-Term Cortical Reorganization after Macaque Retinal Lesions." Smirnakis, Stelios M., Alyssa A. Brewer, Michael C. Schmid, Andreas S. Tolias, Almut Schüz, Mark Augath, Werner Inhoffen, Brian A. Wandell, and Nikos K. Logothetis. 2005. *Nature*.

The margins of the LPZ did not change systematically



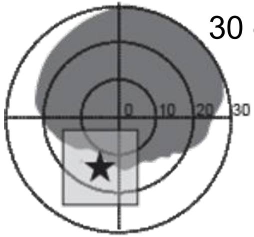
LPZ at 0 days
LPZ at 2 wks
LPZ at 4 months

Macaque V1



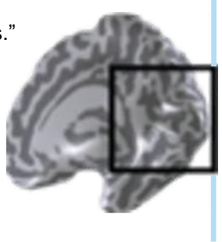
Human adult cortical plasticity in cases of retinal scotomas

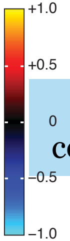
Juvenile Macular Degeneration



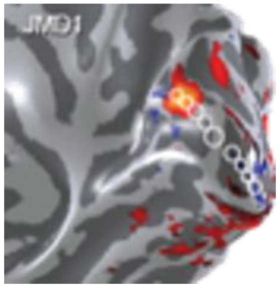
Masuda et al. 2008. "V1 Projection Zone Signals in Human Macular Degeneration Depend on Task, Not Stimulus." *Cerebral Cortex*.

Masuda, et al. 2021. "V1 Projection Zone Signals in Human Macular Degeneration Depend on Task Despite Absence of Visual Stimulus." *Current Biology*.

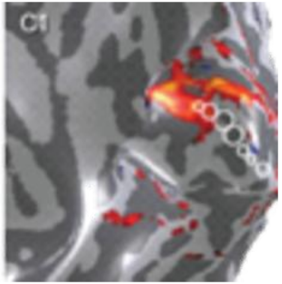




BOLD coherence

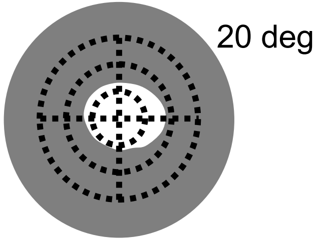


JMD



Control

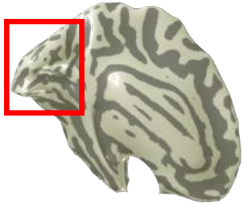
Retinitis Pigmentosa

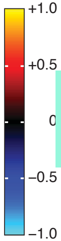


Masuda

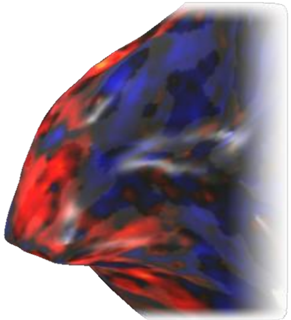
Horiguchi

Masuda, et al. 2010. "Task-Dependent V1 Responses in Human Retinitis Pigmentosa." *IOVS*.

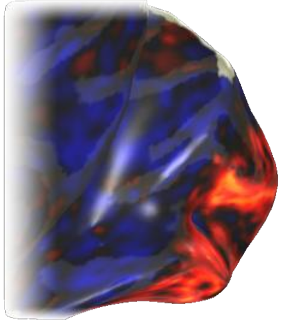




BOLD coherence



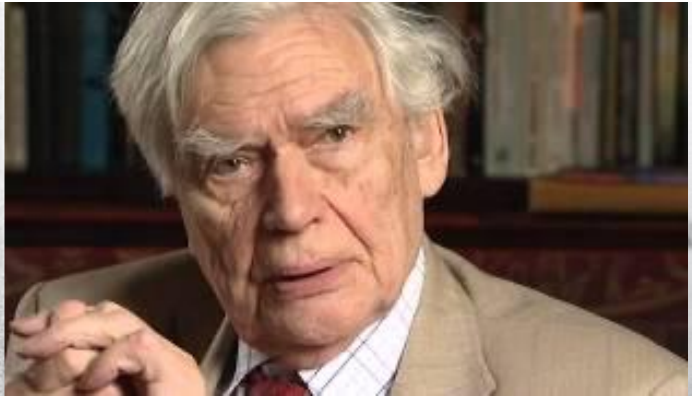
RP



Control

Miracle cures in vision

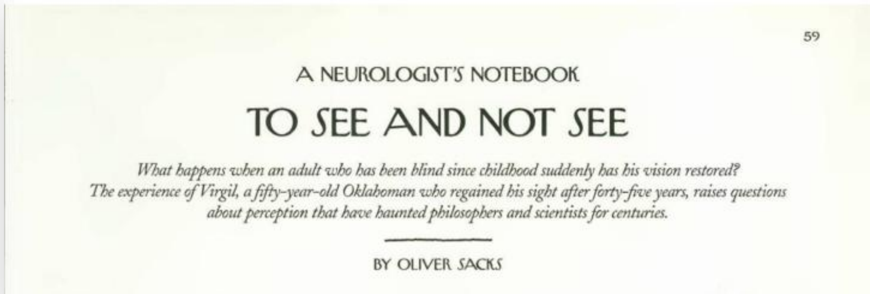
Chesselden, 1728



Gregory, 1960

Sacks, 1990

Alberto
Valvo, 1970



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A NEUROLOGIST'S NOTEBOOK

TO SEE AND NOT SEE

What happens when an adult who has been blind since childhood suddenly has his vision restored? The experience of Virgil, a fifty-year-old Oklahoman who regained his sight after forty-five years, raises questions about perception that have haunted philosophers and scientists for centuries.

BY OLIVER SACKS

Human contrast deprivation from 3-46 years of age

- At three and a half years of age, MM lost one eye and was blinded in the other (chemical and thermal damage to his corneas).
- One unsuccessful corneal replacement in childhood
- For the next 43 years he had some light perception, but no experience of contrast or form; he reports no visual memories or imagery.
- At age 46, MM received a corneal and limbal stem-cell transplant in his right eye; this restored his retinal image

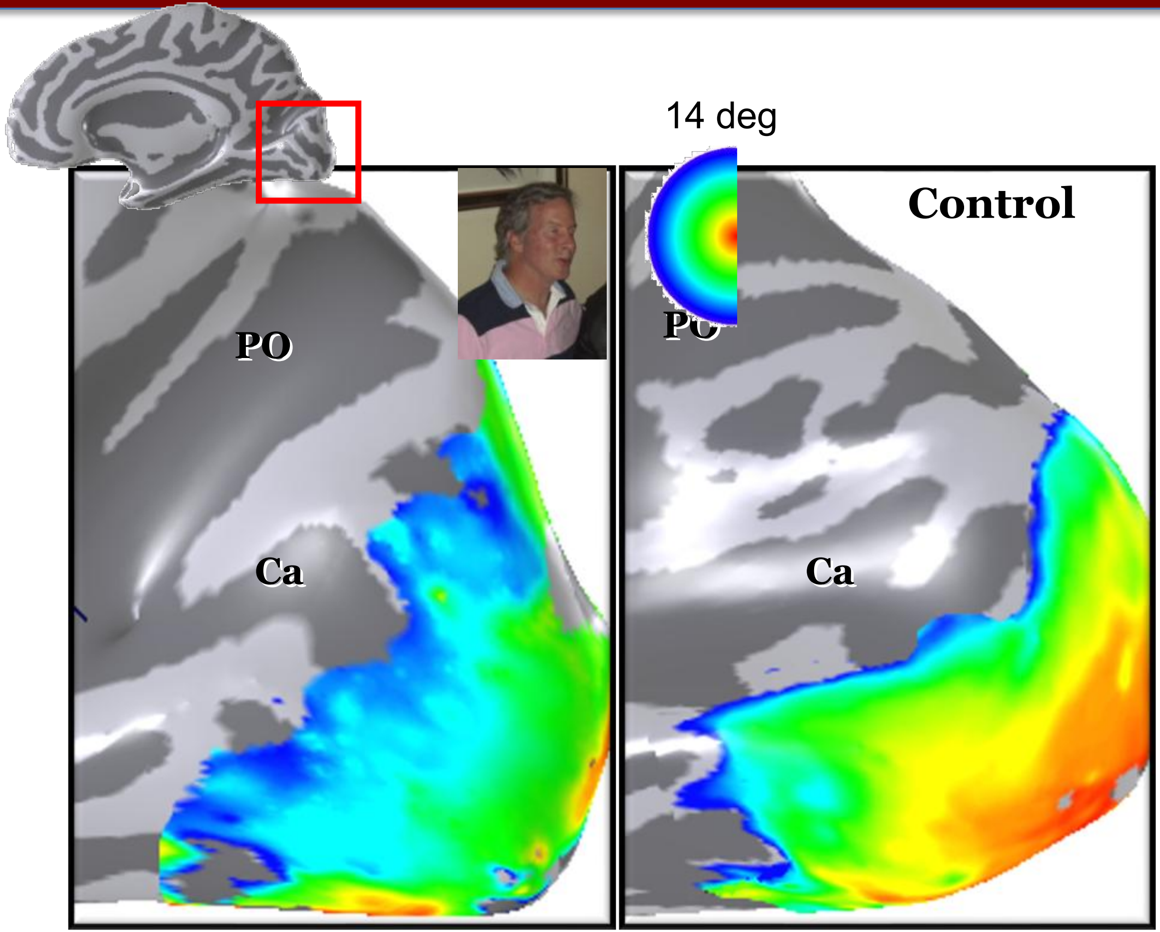
(images courtesy Michael May)

Netta Levin

Ione Fine

Levin, Dumoulin, Winawer, Dougherty, and Wandell. 2010. "Cortical Maps and White Matter Tracts Following Long Period of Visual Deprivation and Retinal Image Restoration." *Neuron* 65 (1): 21–31.

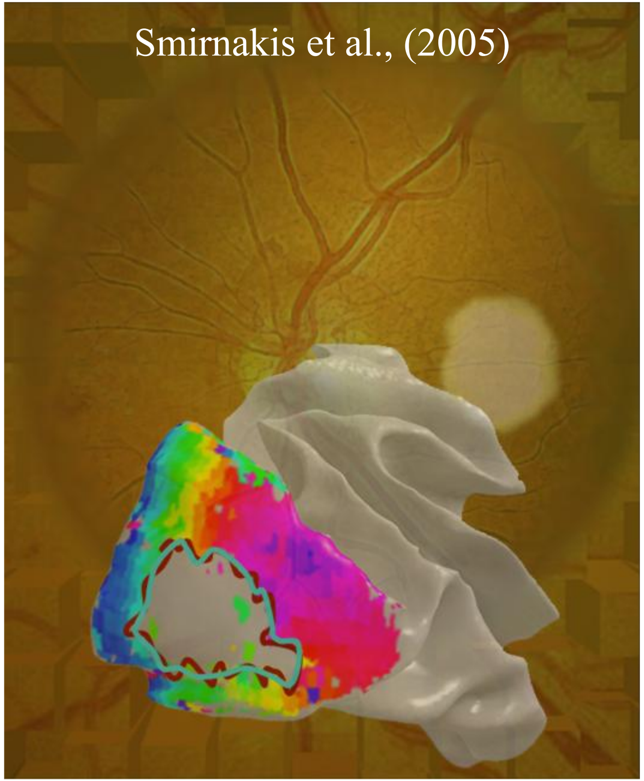
Missing foveal signals in visual cortex



Levin et al., 2010

Summary: Plasticity and stability in early visual cortex

- Plasticity easily demonstrable in development
- In adult early visual cortex, stability is dominant
- Which parts of visual cortex remain plastic to support visual learning, such as **enabling kids to learn to see words rapidly?**



Plasticity and stability of visual field maps in adult primary visual cortex (2009). Wandell and Smirnakis. **Nature Reviews Neuroscience.**

Visual circuits and reading

K. Wernicke

J. Dejerine

N. Geschwind

E. Warrington

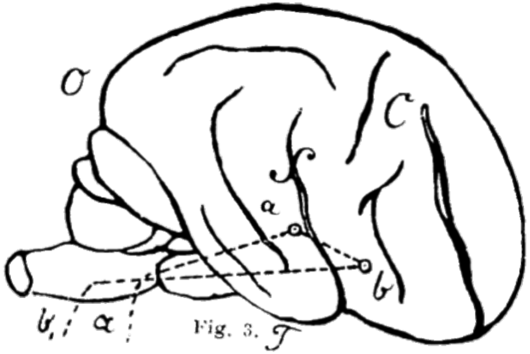
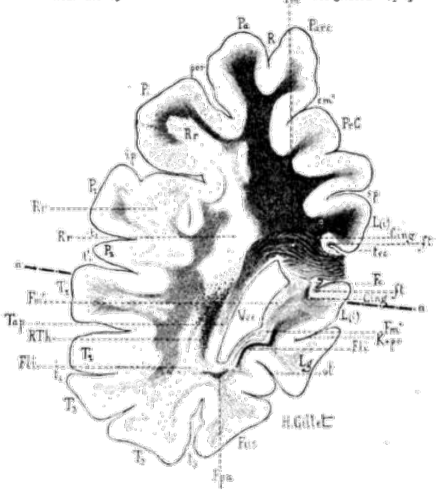
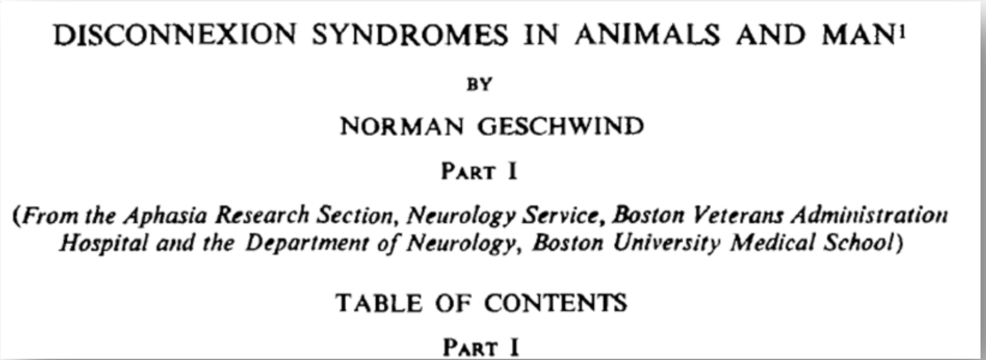


Fig. 3 [The speech areas and their connections. The "a" near the Sylvian fissure should have been designated "a₁".]





DISCONNEXION SYNDROMES IN ANIMALS AND MAN[1]

BY

NORMAN GESCHWIND

PART I

(From the Aphasia Research Section, Neurology Service, Boston Veterans Administration Hospital and the Department of Neurology, Boston University Medical School)

TABLE OF CONTENTS

PART I

Functional specializations in ventral occipital temporal cortex

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

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

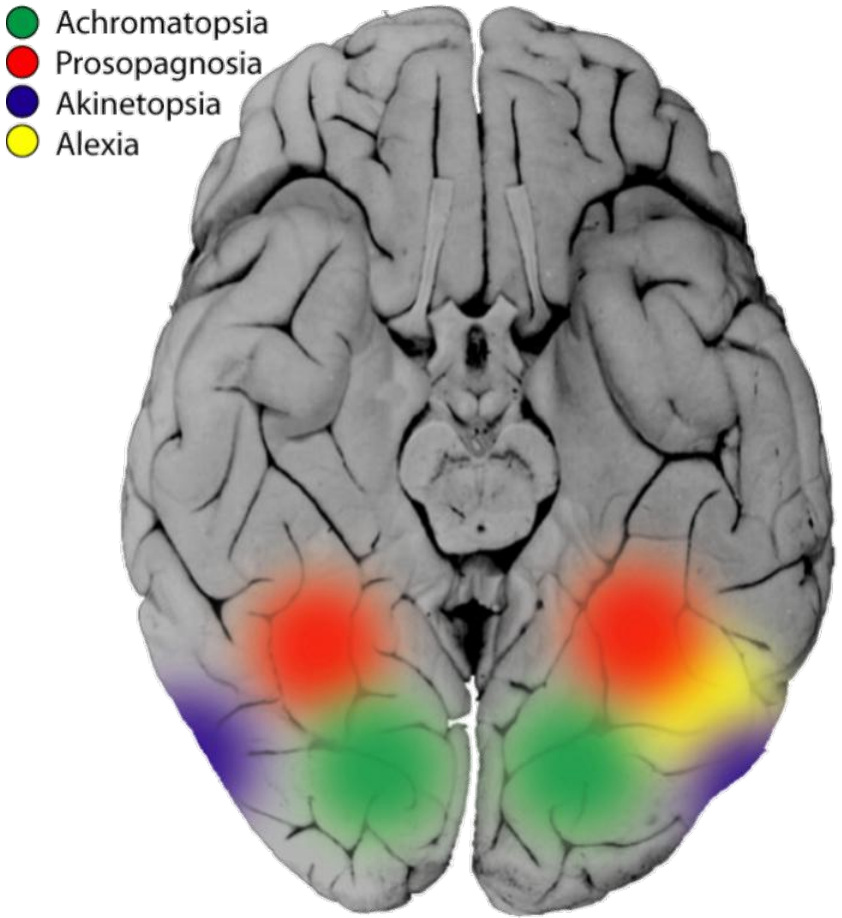


Image courtesy of S. Zeki

Specializations in ventral occipital temporal cortex

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

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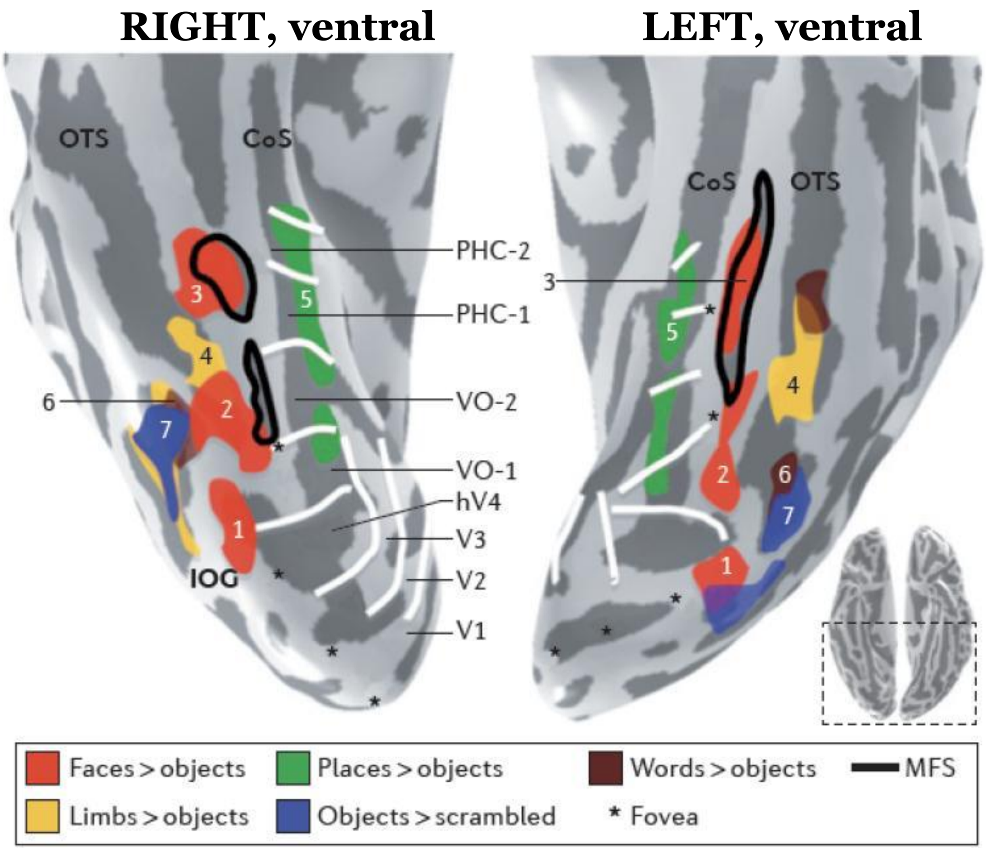
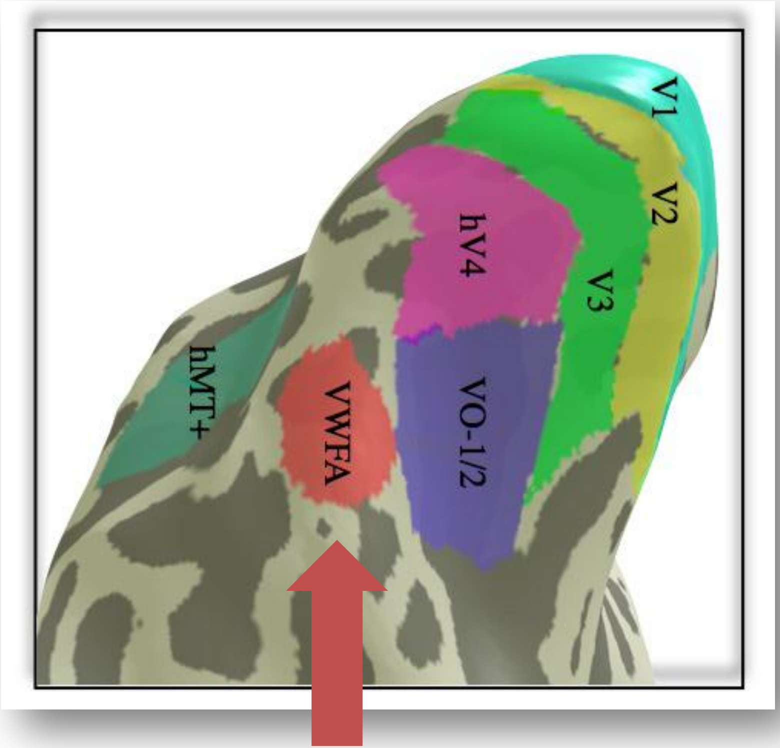


Image from Grill-Spector, Kalanit, and Kevin S. Weiner. 2014. "The Functional Architecture of the Ventral Temporal Cortex and Its Role in Categorization." *Nature Reviews. Neuroscience*

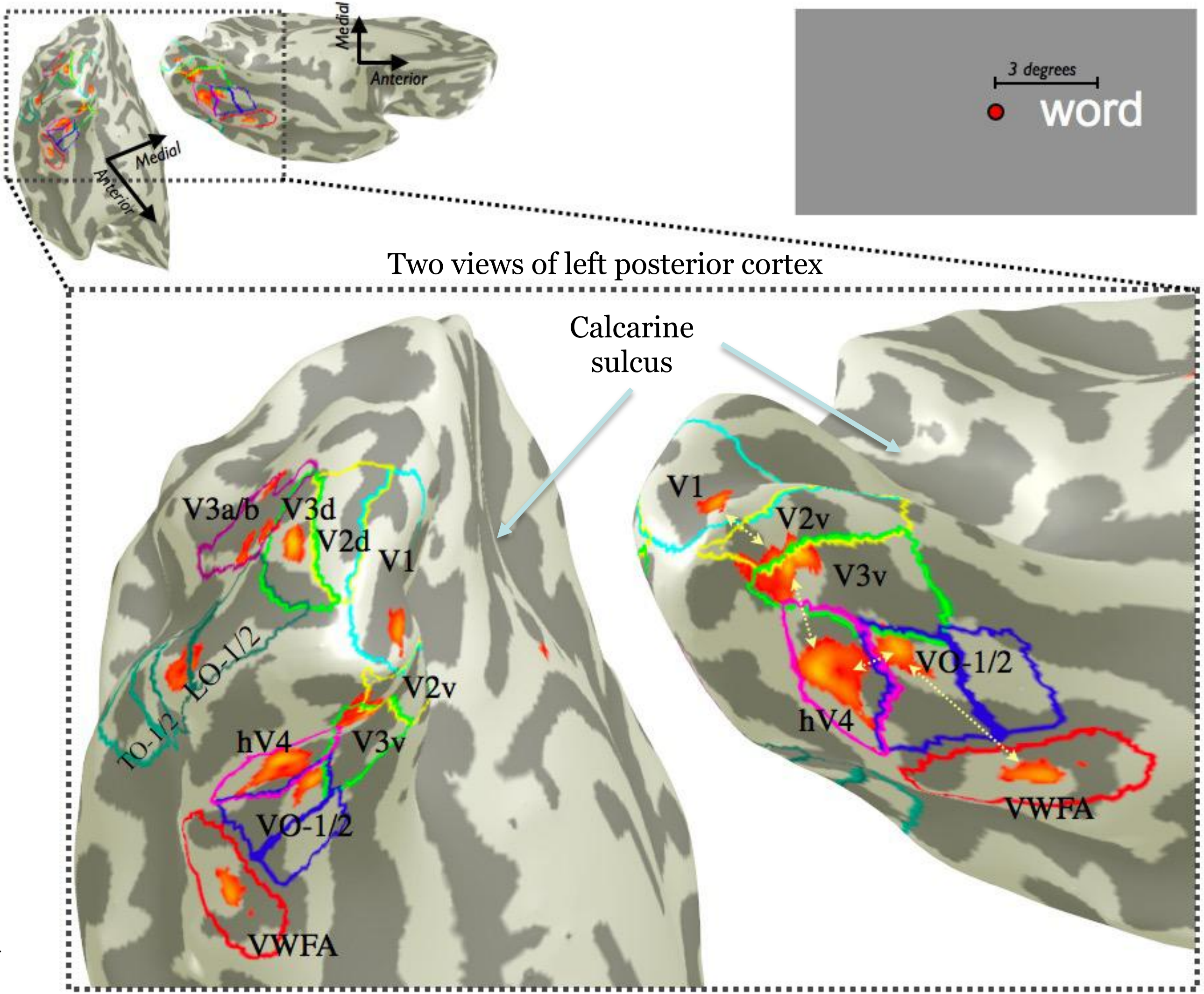
Specializations in ventral occipital temporal cortex

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

Ventral view, posterior left cortex



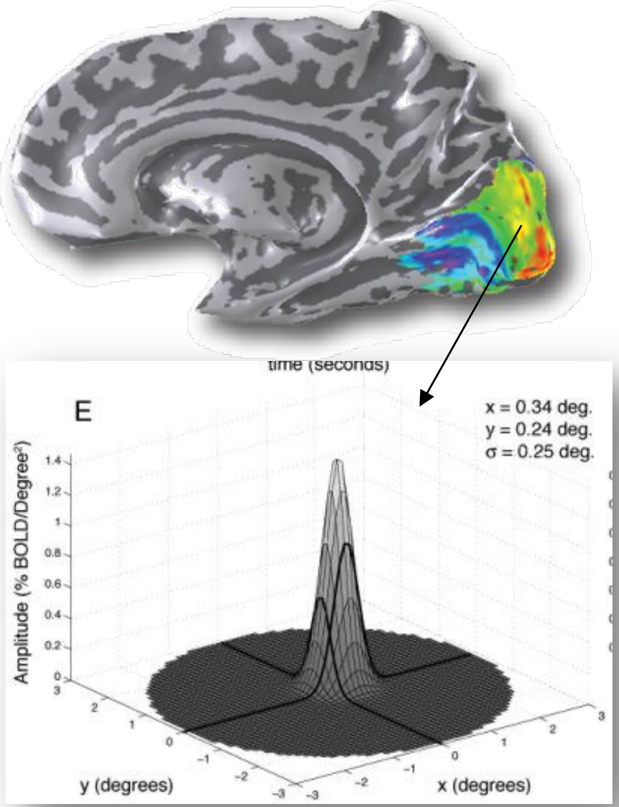
- Comparing a word to just fixation, fMRI measures the activity in the specialized circuitry (VWFA) as well as the visual field maps in individual participants



Wandell, Brian A., Andreas M. Rauschecker, and Jason D. Yeatman. 2012. “Learning to See Words.” *Annual Review of Psychology* 63: 31–53.

Measuring the field of view of a cortical region

- A single voxel within, say V1, responds to a small part of the visual field and thus has a small **field of view**
- 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




Amano


Dumoulin

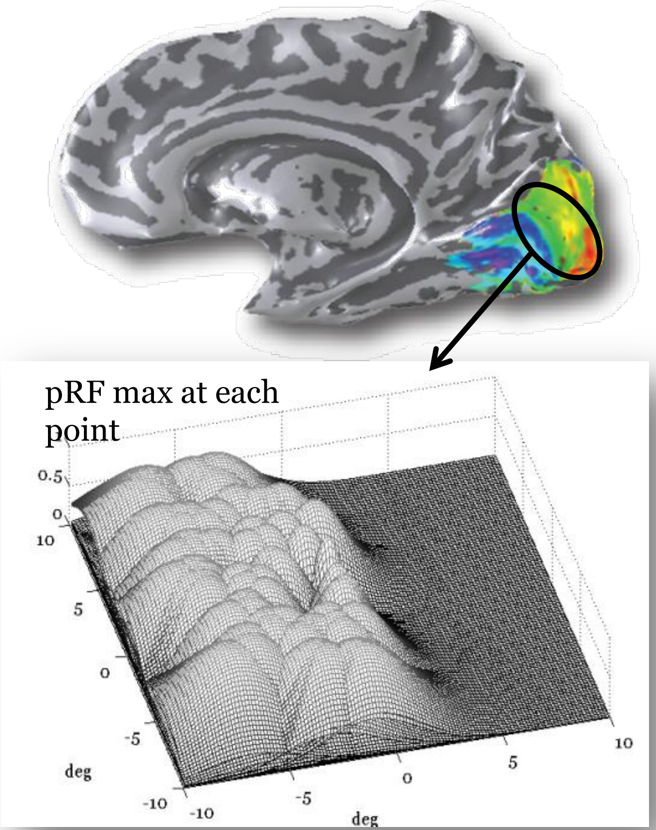
Amano, Kaoru, Brian A. Wandell, and Serge O. Dumoulin. 2009. “Visual Field Maps, Population Receptive Field Sizes, and Visual Field Coverage in the Human MT+ Complex.” *Journal of Neurophysiology*

Measuring the field of view of a cortical region

- A single voxel within, say V1, responds to a small part of the visual field; it has a small **receptive field**

- Combining the field of views from the voxels in a region tells us about the region's **field of view**

- In early visual field maps (V1, V2, …), the field of view covers a large portion of the visual field; by hV4 the coverage is reduced



Measuring the field of view of cortical regions

- A single voxel within, say V1, responds to a small part of the visual field; it has a small **receptive field**

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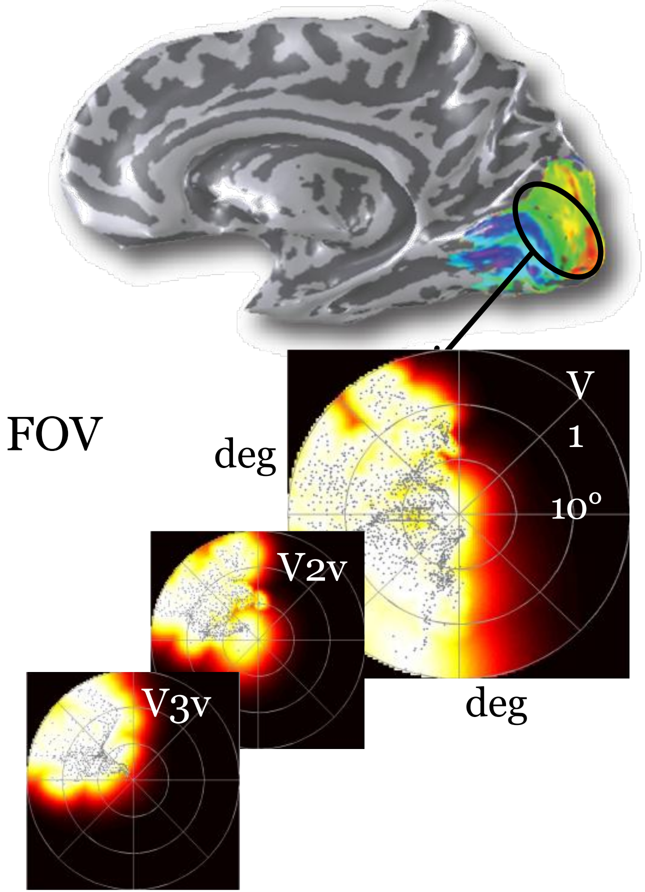
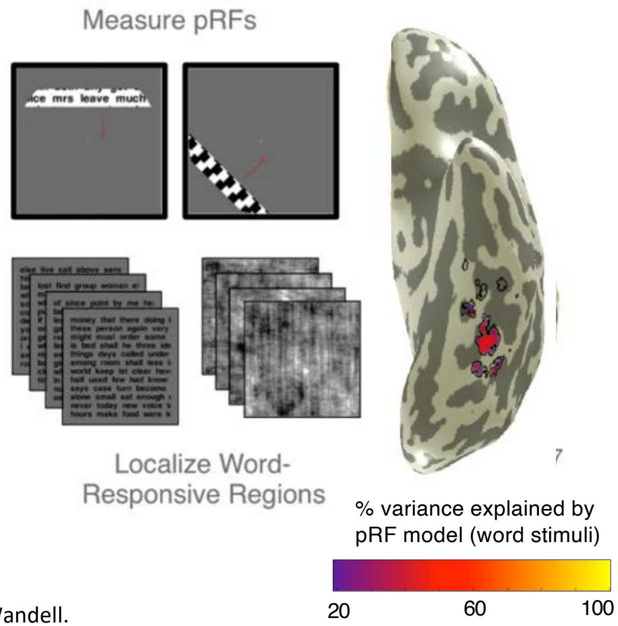
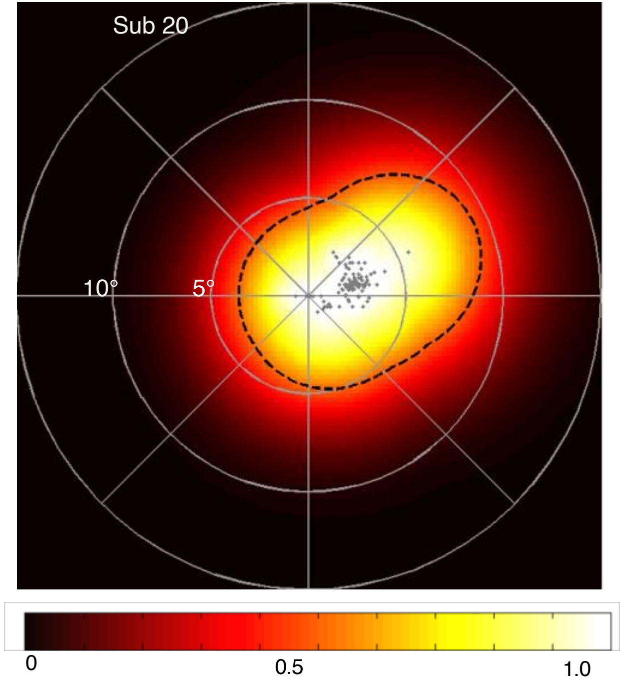


The reading circuitry field of view of a single subject

- In the reading circuitry within the VOT, the field of view is quite small

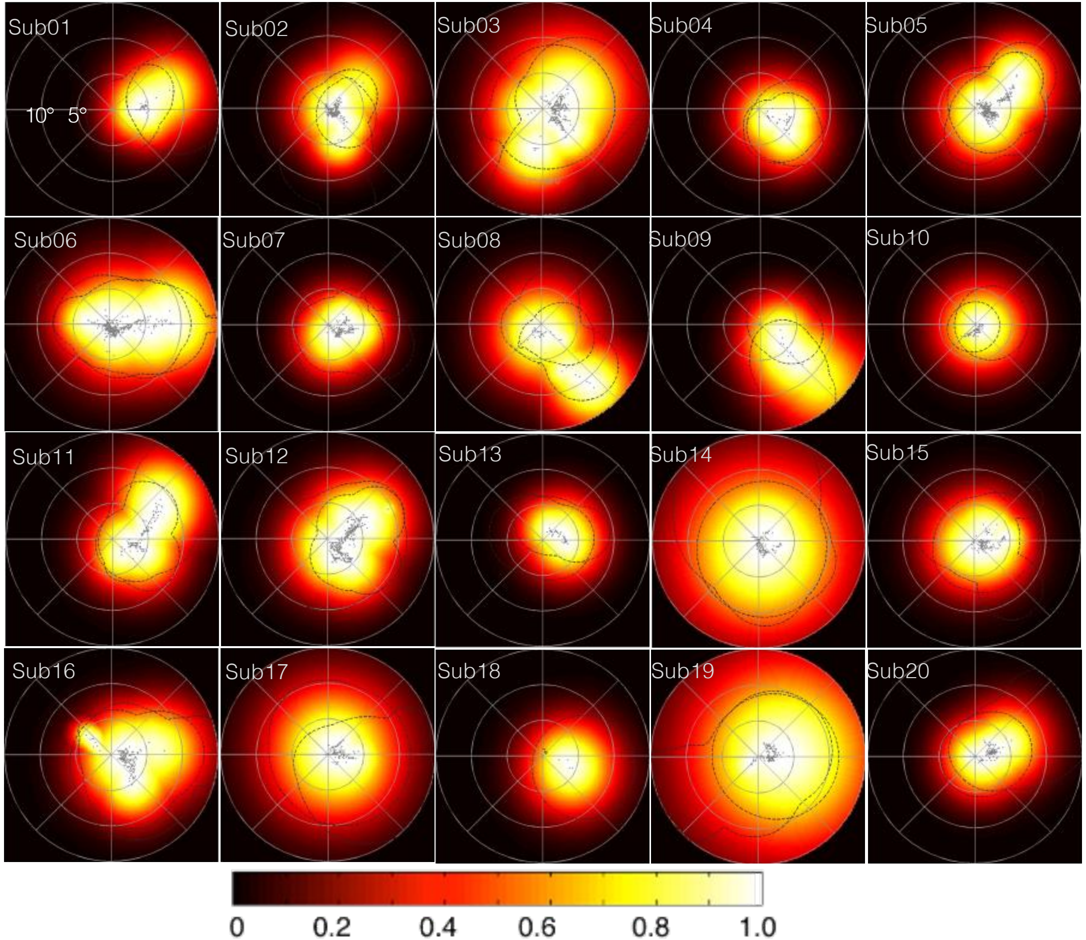




Le, Rosemary, Chen Gafni, Michal Ben-Shachar, and Brian Wandell. 2018. "Stimulus Dependence of Population Receptive Fields within the Visual Field Maps and the Visual Word Form Area." *Journal of Vision*.

Field of view of the VOT reading circuitry

- There are significant differences between individuals
- It remains to show an impact on seeing words, but there is a reported correlations with eye movements measured using texture patterns (Gomez et al., 2018)

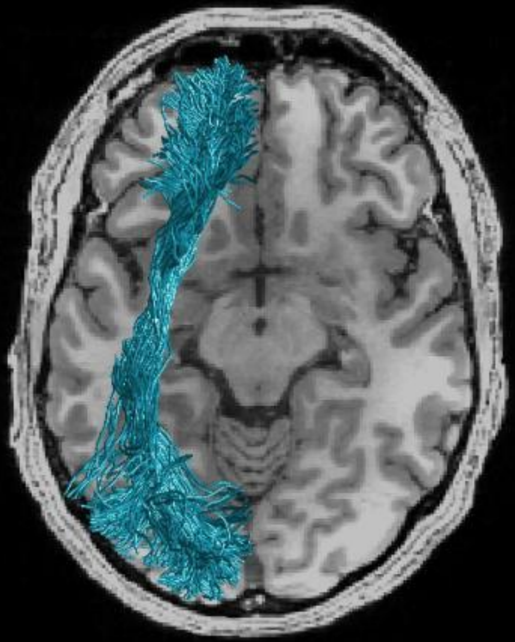


What's Next: Systems modeling


Takemura


Pestilli

Left
IFOF



150 Directions, 2 mm³, B=2000 projected on a 1 mm³ T1 anatomical image

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Evaluation and statistical inference for human connectomes

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

Introduction to LiFE

PLOS | COMPUTATIONAL BIOLOGY

OPEN ACCESS PEER-REVIEWED
RESEARCH ARTICLE

Ensemble Tractography

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

Published: February 4, 2016 • http://dx.doi.org/10.1371/journal.pcbi.1004692

Extension to ensemble method

Annual Review of Neuroscience
Vol. 39: 103-128 (Volume publication date July 2016)

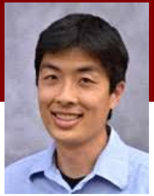
Clarifying Human White Matter

Brian A. Wandell

Department of Psychology and Neurosciences Institute, Stanford University, Stanford, California 94305; email: Wandell@stanford.edu

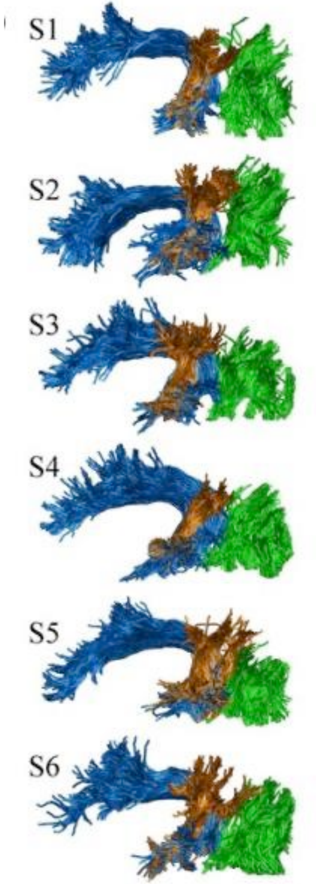
Review of diffusion imaging

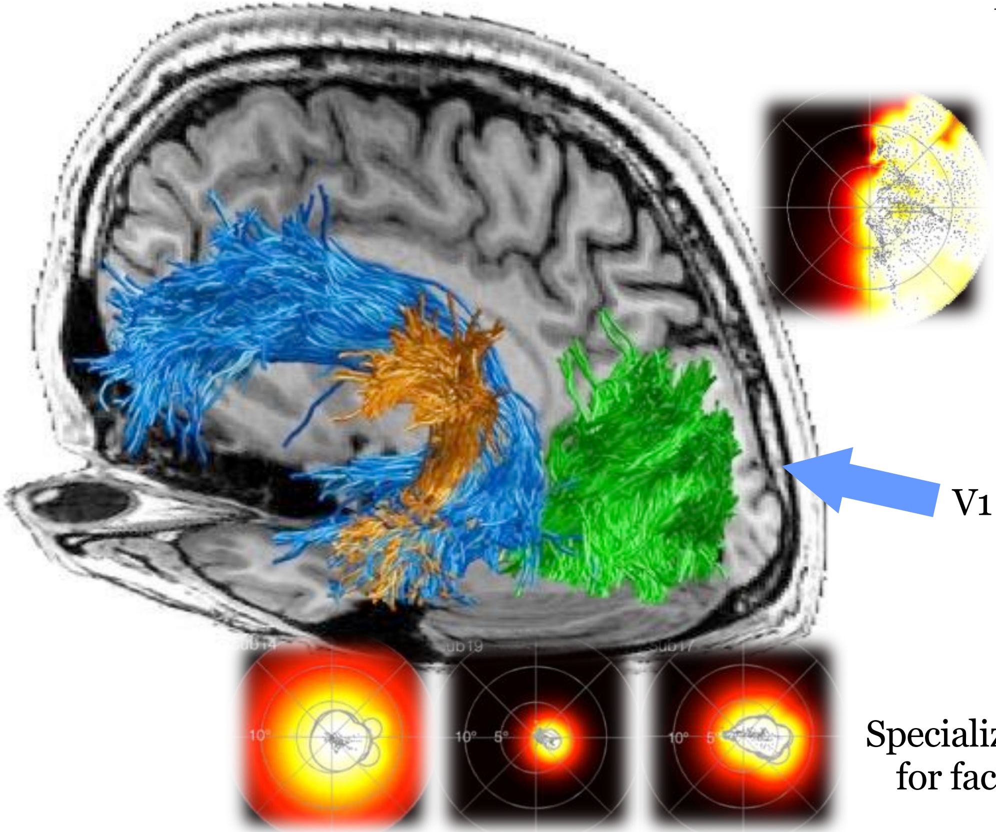
What's next: Systems modeling



Kay

Yeatman





V1 inputs

VOT
Specialized processing
for faces, words, ...

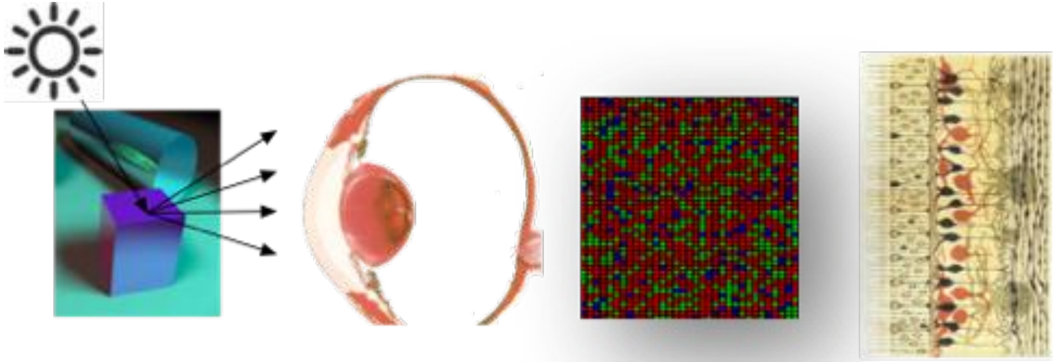
Systems modeling

Brainard

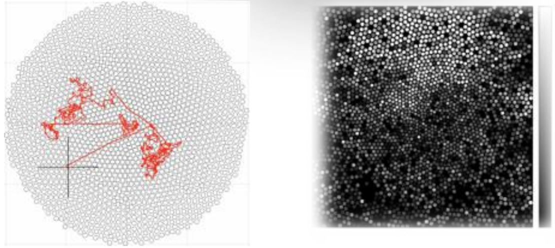
Cottaris

Lian

Image Systems Engineering Tools for Biology (ISETBio)

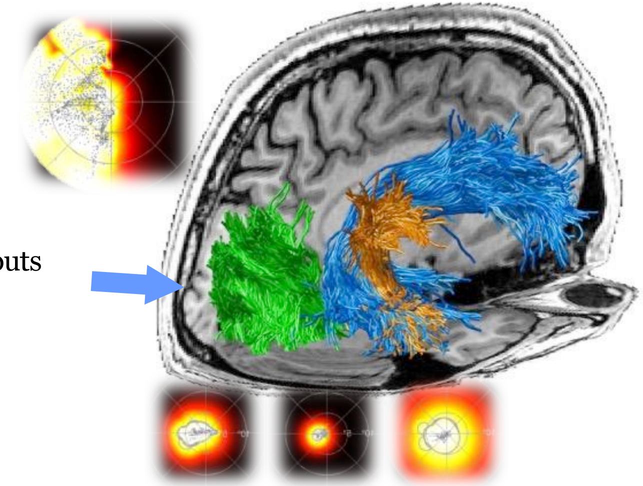


Cottaris, Wandell, Rieke, and Brainard. 2020. “A Computational Observer Model of Spatial Contrast Sensitivity: Effects of Photocurrent Encoding, Fixational Eye Movements, and Inference Engine.” *Journal of Vision*



Lian, MacKenzie, Brainard, Cottaris, and Wandell. 2019. “Ray Tracing 3D Spectral Scenes through Human Optics Models.” *J. Vis.*

V1 inputs



VOT

Specialized processing for faces, words, ...

Thanks to many students and postdocs!

David Brainard

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Tony Morland

Alex Wade

Bill Press

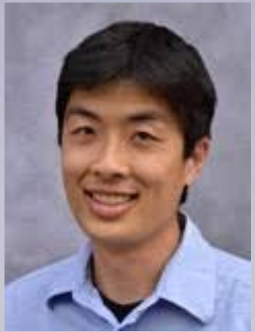
Reno Bowen

Thanks to my many students and postdocs!

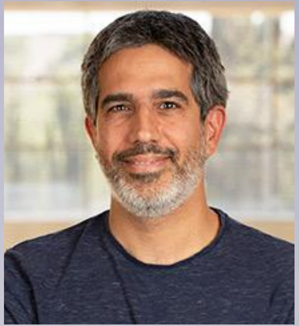
Jon Winawer

Ariel Rokem

Kendrick Kay



Aviv Mezer



A. Rauschecker

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Thanks to my many students and postdocs!

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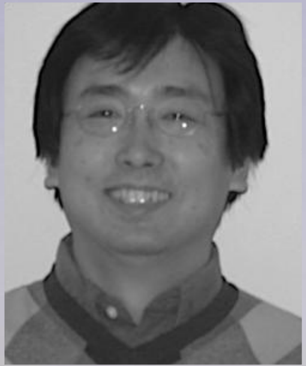
And a special thanks to my ophthalmology collaborators who took career risks to come to the US and work with me!

Satoshi Nakadomari



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Yoichiro Masuda

Shumpei Ogawa