Understanding Visual Processing with fMRI

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Computational Neuroimaging and Perception (CNaP)

Laboratory of Brian and Cognition

revisiting the classics

What fMRI has taught us about human vision

Susan M Courtney* and Leslie G Ungerleider†

The recent application of functional magnetic resonance imaging (fMRI) to visual studies has begun to elucidate how the human visual system is anatomically and functionally organized. Bottom-up hierarchical processing among visual cortical areas has been revealed in experiments that have correlated brain activations with human perceptual experience. Top-down modulation of activity within visual cortical areas has been demonstrated through studies of higher cognitive processes such as attention and memory.

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Current Opinion in Neurobiology 1997, **7**:554–561

http://biomednet.com/elecref/0959438800700554

Abbreviations

fMRI	functional magnetic resonance imaging
LO	lateral occipital (area)
MT	middle temporal (area)
PET	positron emission tomography
V1	primary visual cortex

results in a localized increase in the fMRI signal in the brain [3–5]. Therefore, fMRI signal intensity is correlated with localized changes in neural activity (typically averaged over 2–6 s and over 1–27 mm^3 of cortex). At least within the primary visual cortex (V1), the fMRI signal increases monotonically with stimulus contrast [6•].

Organization of visual cortical areas in monkeys

Vision is the most richly represented sensory modality in primates. Visual information is processed in over 30 functional cortical areas. In Old World monkeys [7] — our seemingly closest evolutionary ancestors, aside from apes — these cortical areas cover about one-half of the total cortex. Visual cortical areas are organized into two processing pathways, or 'streams', both of which originate in area V1 [8]. The ventral stream, projecting from area V1 through areas V2 and V4 to the inferior temporal cortex, processes the physical attributes of stimuli that are important for object identification, such as color, shape, and pattern. The dorsal stream, projecting from V1 through areas V2 and V3 to the middle temporal area (MT) and thence to additional areas in superior temporal and parietal cortex, processes attributes of stimuli important for localizing objects in space and for the visual guidance of movement towards them, such as the direction and velocity of stimulus motion [9].

Curr Opin Neurobiol, 1997, 554-61

20 years later…what have we learned? what questions remain?

overview

- *why study human vision?*
- *retinotopic mapping*
- *functional specialization*

  orientation
  motion
  color
  objects, faces, and letters

- *bottom-up hierarchical processing within visual cortical areas*
- *top-down influences on visual cortical area*

human brain is best model for…

Neuroscience 296 (2015) 130–137

REVIEW

A CASE FOR HUMAN SYSTEMS NEUROSCIENCE

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Abstract—Can the human brain itself serve as a model for a systems neuroscience approach to understanding the human brain? After all, how the brain is able to create the richness and complexity of human behavior is still largely mysterious. What better choice to study that complexity than to study it in humans? However, measurements of brain activity typically need to be made non-invasively which puts severe constraints on what can be learned about the internal workings of the brain. Our approach has been to use a combination of psychophysics in which we can use human behavioral flexibility to make quantitative measurements of behavior and link those through computational models to measurements of cortical activity through magnetic resonance imaging. In particular, we have tested various computational hypotheses about what neural mechanisms could account for behavioral enhancement with spatial attention (Pestilli et al., 2011). Resting both on quantitative measurements and considerations of what is known through animal models, we concluded that weighting of sensory signals by the magnitude of their response is a neural mechanism for efficient selection of sensory signals and consequent improvements in behavioral performance with attention. While animal models have many technical advantages over studying the brain in humans, we believe that human systems neuroscience should endeavor to validate, replicate and extend basic knowledge learned from animal model systems and thus form a bridge to understanding how the brain creates the complex and rich cognitive capacities of humans.

This article is part of a Special Issue entitled: Contributions From Different Model Organisms to Brain Research.

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INTRODUCTION

A peculiar phenomenon had taken hold of the elevators of the Meyer building when I first arrived as a post-doc at NYU's Center for Neural Science. Students, post-docs and professors all seemed to have a different algorithm for hitting the buttons on the elevator. Some would simply hit the button for their floor and wait. Others, though, would use different cryptic combinations of buttons, stretching their fingers wide to simultaneously press the floor they wanted and the current floor. For some, the order was apparently crucial – hitting first their floor before reaching for the current floor. Others used the exact opposite order. After inquiring around about this curious behavior, I was earnestly informed that these combinations of button presses were required to make the doors of the elevator close more quickly – a matter of great importance to impatient occupants of the building. But, what could explain the diversity of different techniques I had witnessed? After some time in the department, I developed my own (incompletely tested) theory – that the elevator had a time-out of a few seconds, after which *any* button press, or combination thereof, would trigger the doors to close. Thus, the occupants of the building had all learned various completely different behaviors, all of which produced the same reward of a swift start to the elevator ride.

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- *why study human vision?*
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  orientation
  motion
  color
  objects, faces, and letters

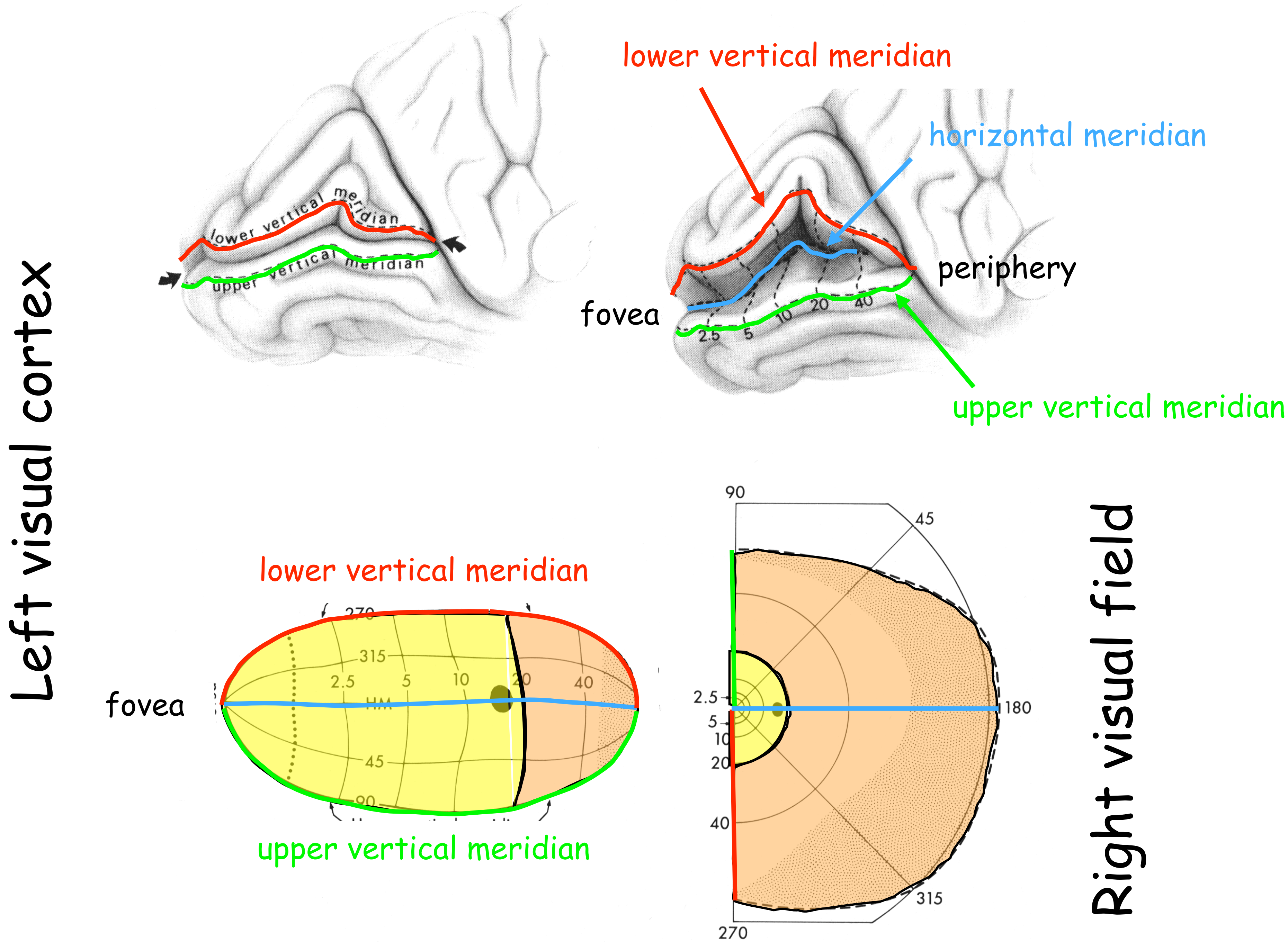
- *bottom-up hierarchical processing within visual cortical areas*
- *top-down influences on visual cortical areas*

what is a visual area?

PhACT

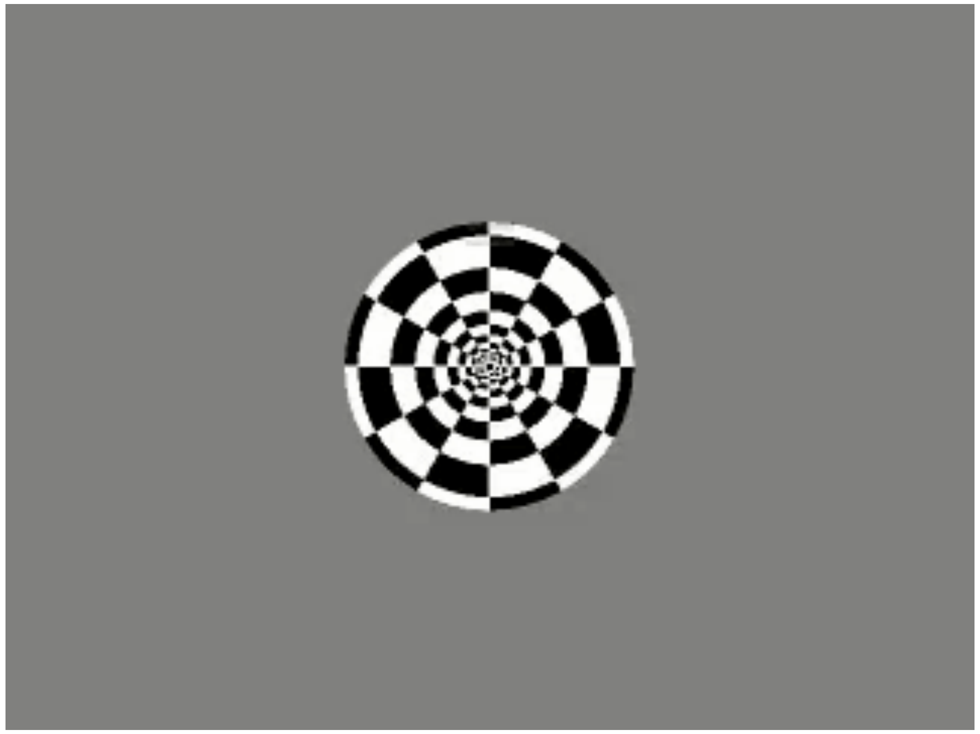
- Physiology
- Architecture
- Connections
- Topography

Topography (human V1)



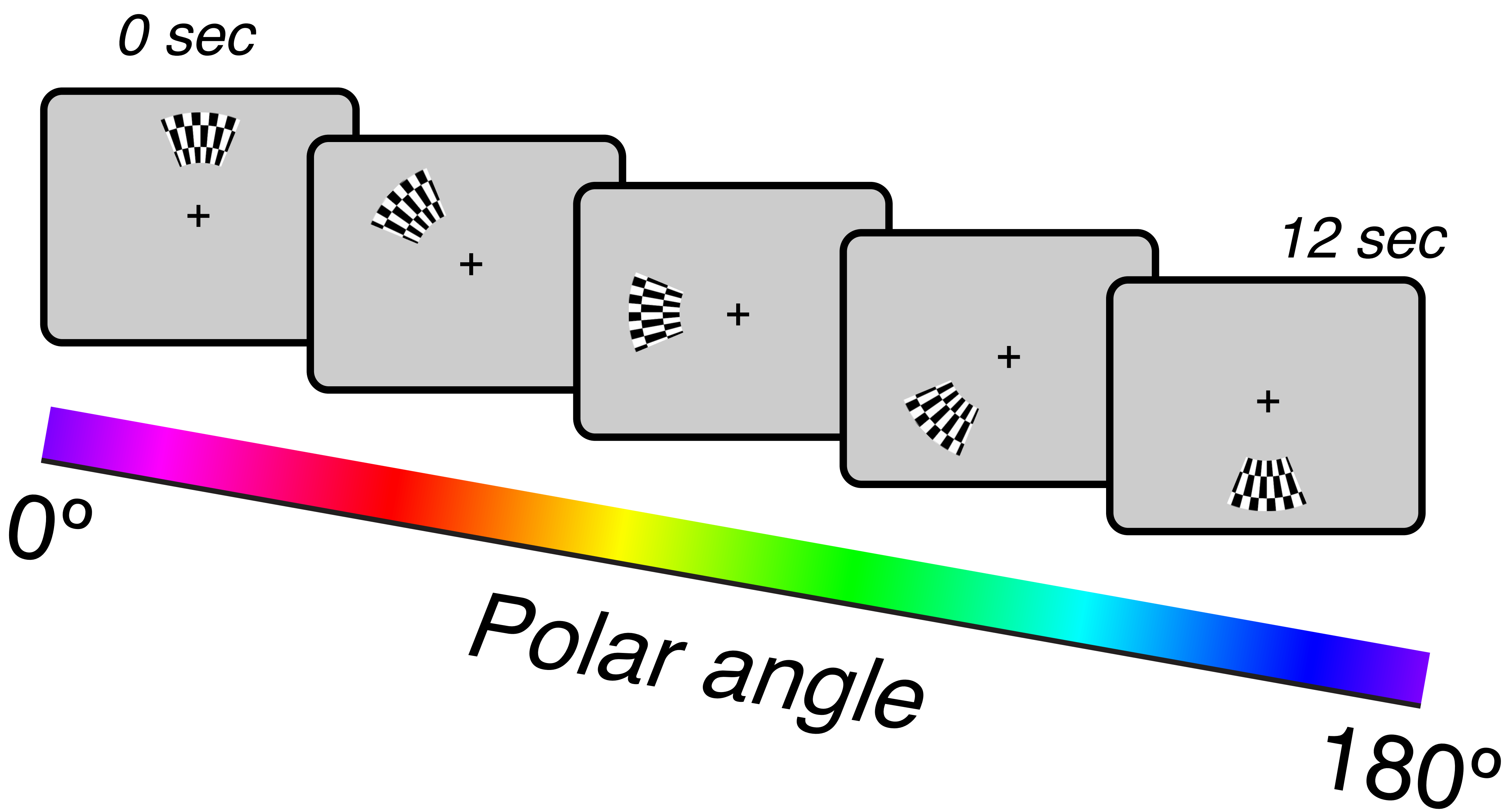
retinotopic mapping stimuli

Radial component



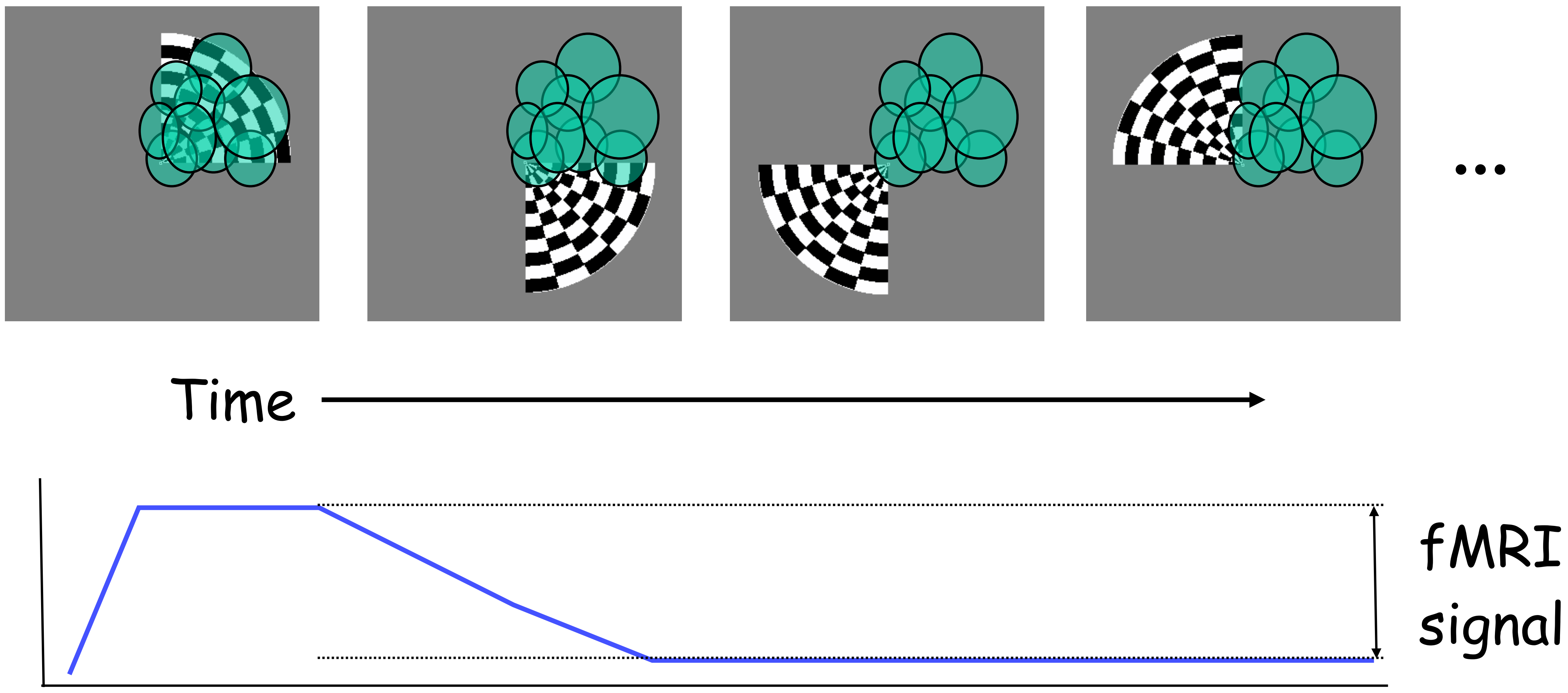
Angular component

retinotopic mapping

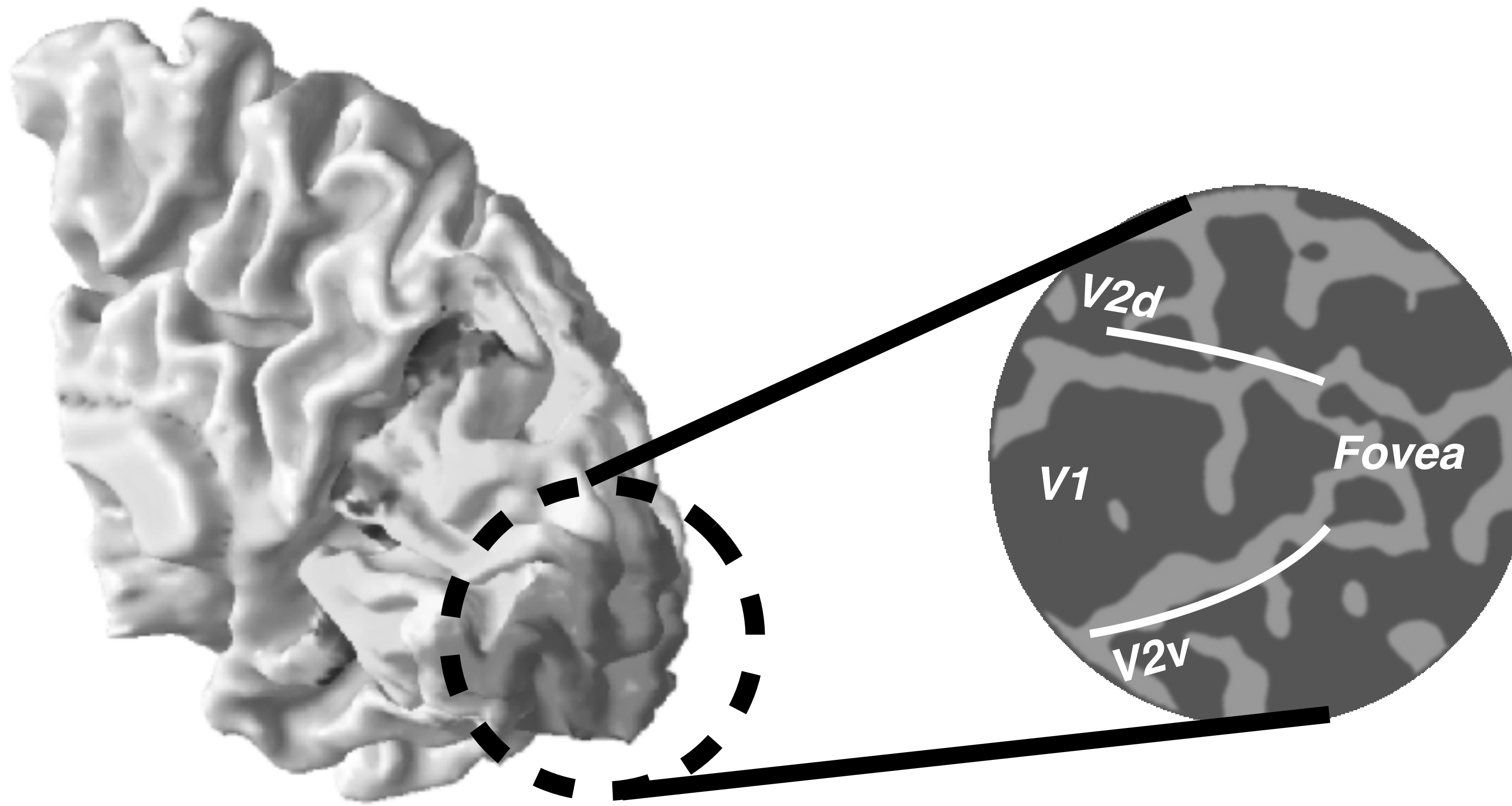


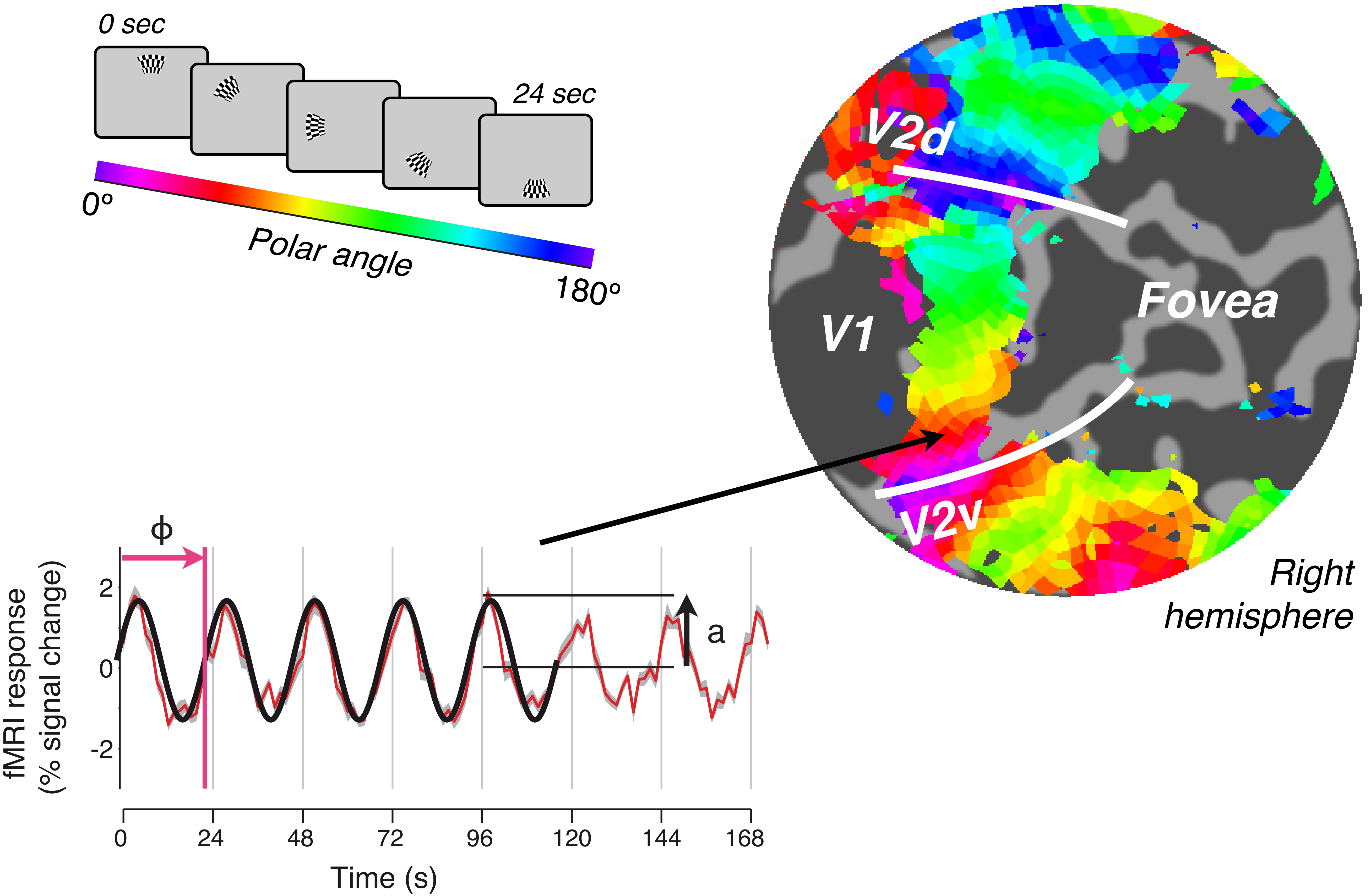
DeYoe et al., 1996
Engel et al., 1997

retinotopic map, timing of activity

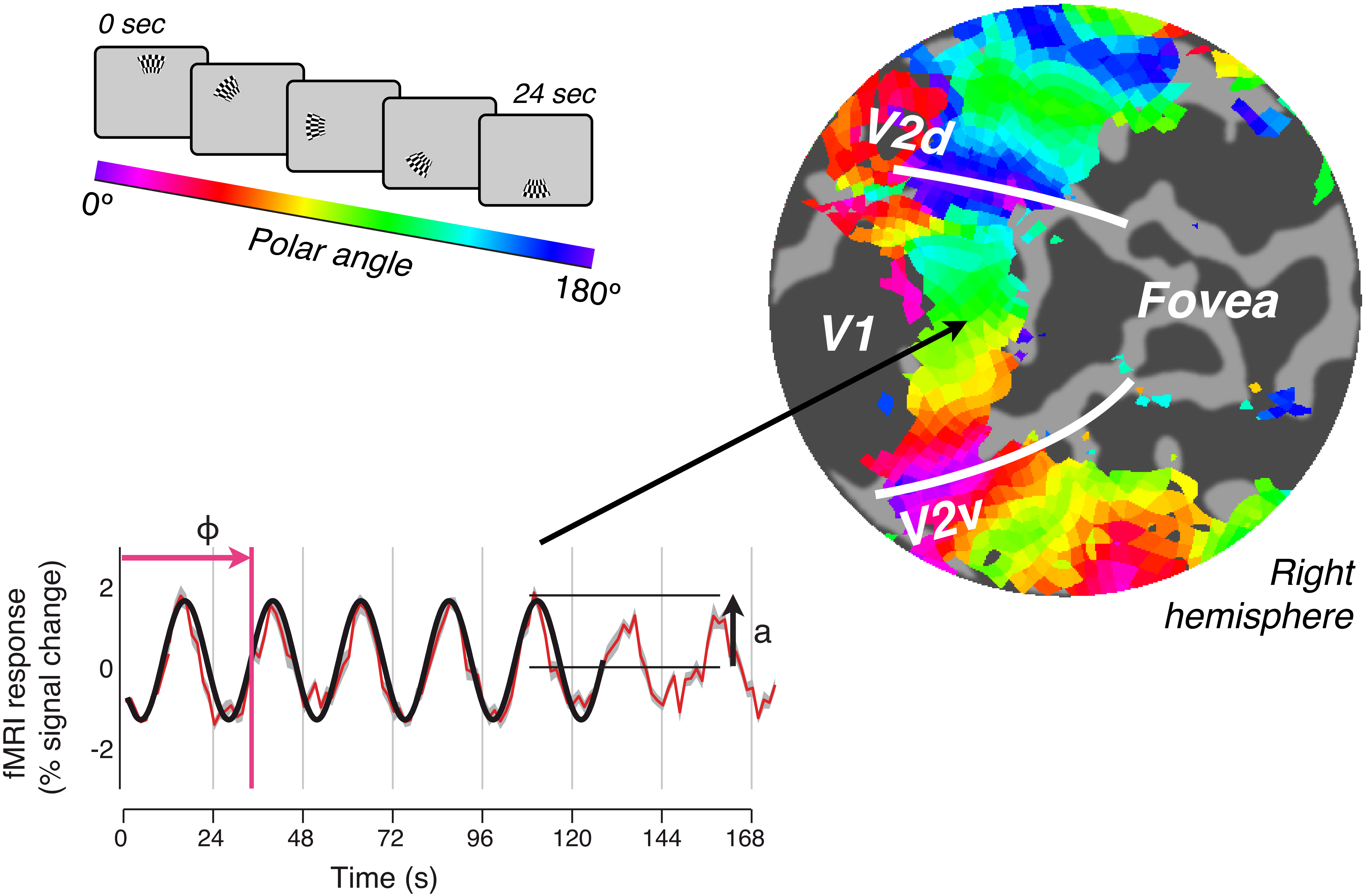


computational flattening





0 sec
24 sec
0°
Polar angle
180°
V2d
V1
Fovea
V2v
Right hemisphere
ϕ
a
fMRI response (% signal change)
2
0
-2
0
24
48
72
96
120
144
168
Time (s)



0 sec
24 sec
0°
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Right hemisphere
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fMRI response (% signal change)
2
0
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0
24
48
72
96
120
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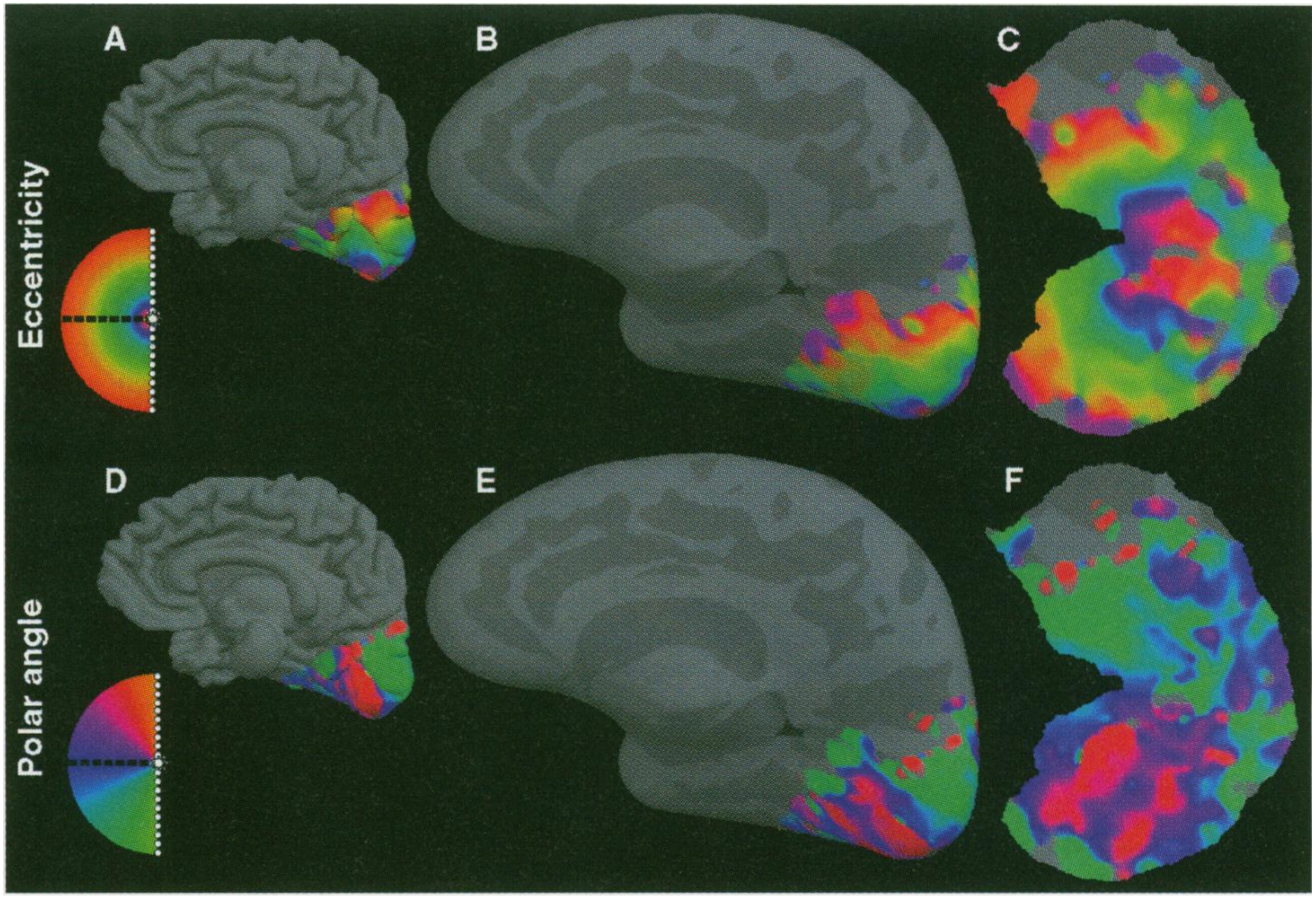
168
Time (s)

visual area boundaries

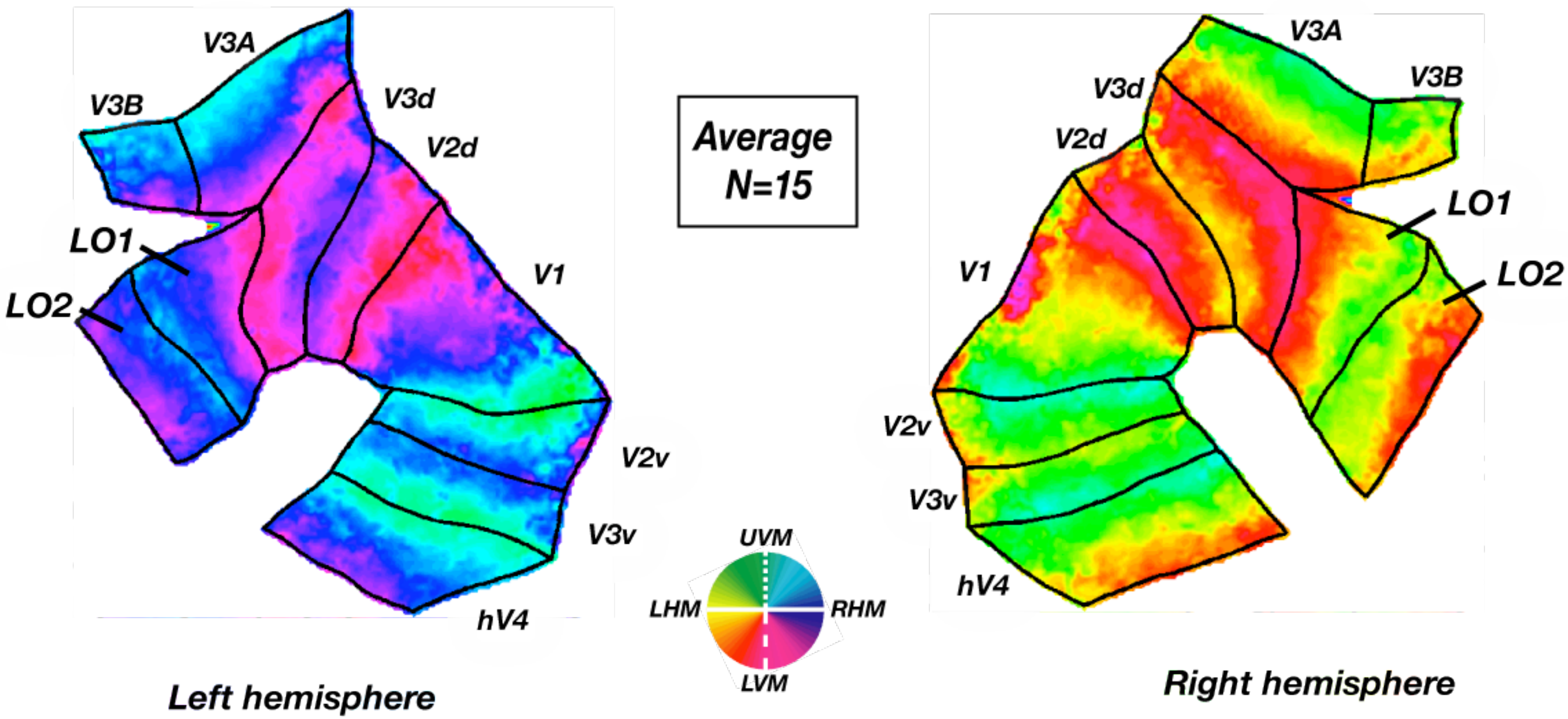


Sereno et al., *Science*, 1995

retinotopic mapping

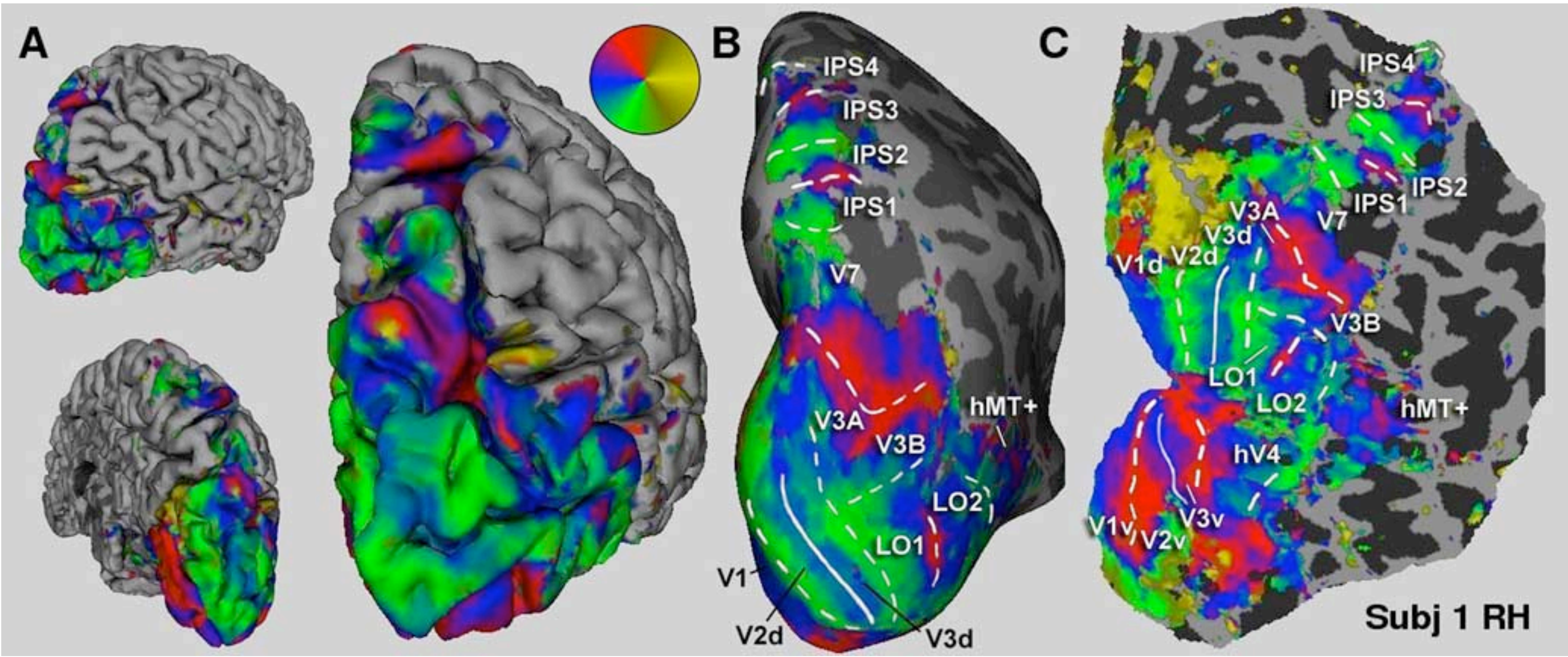
progress and challenges…

additional areas discovered



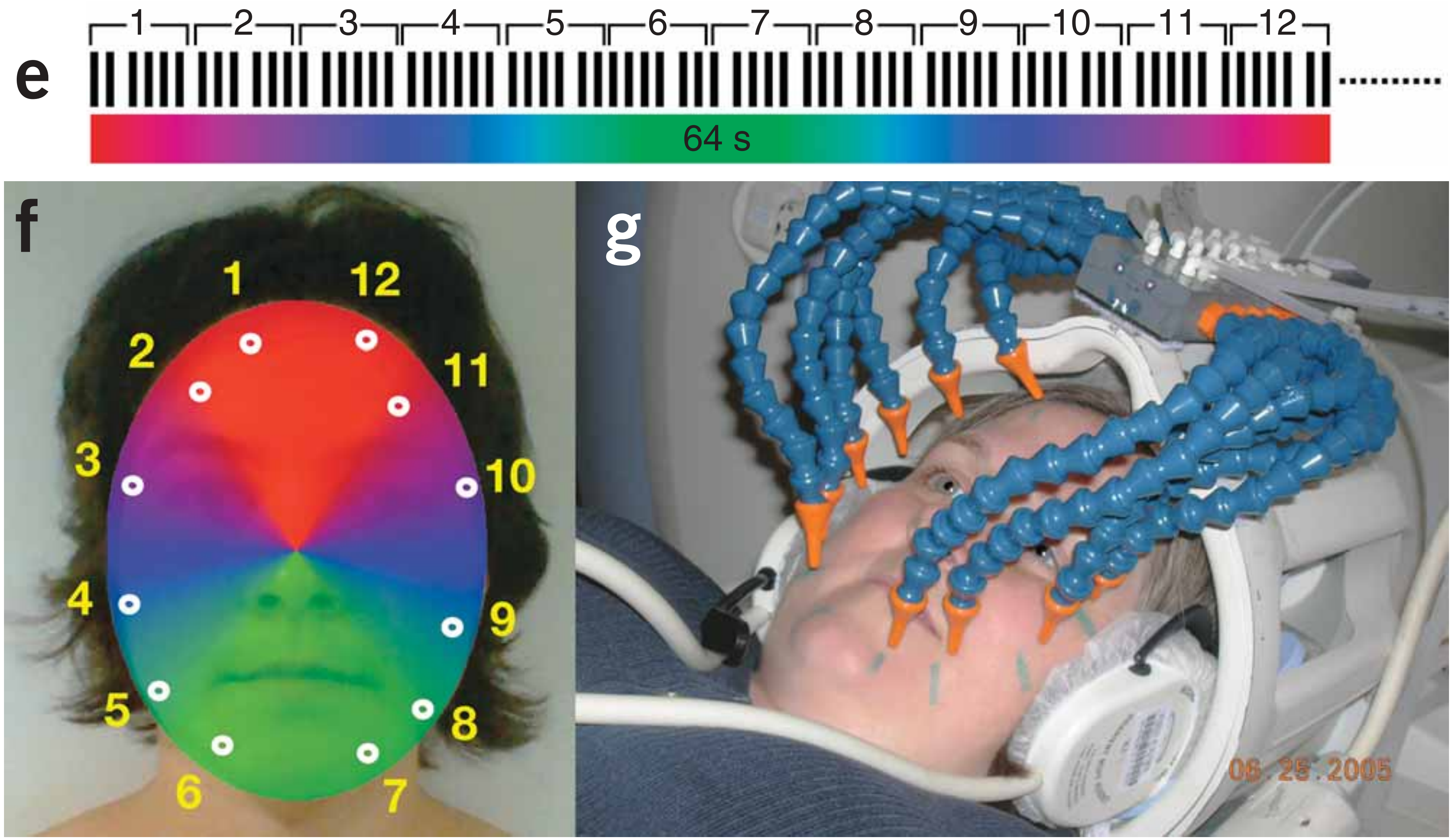
Larson & Heeger, 2006

multiple maps in IPS



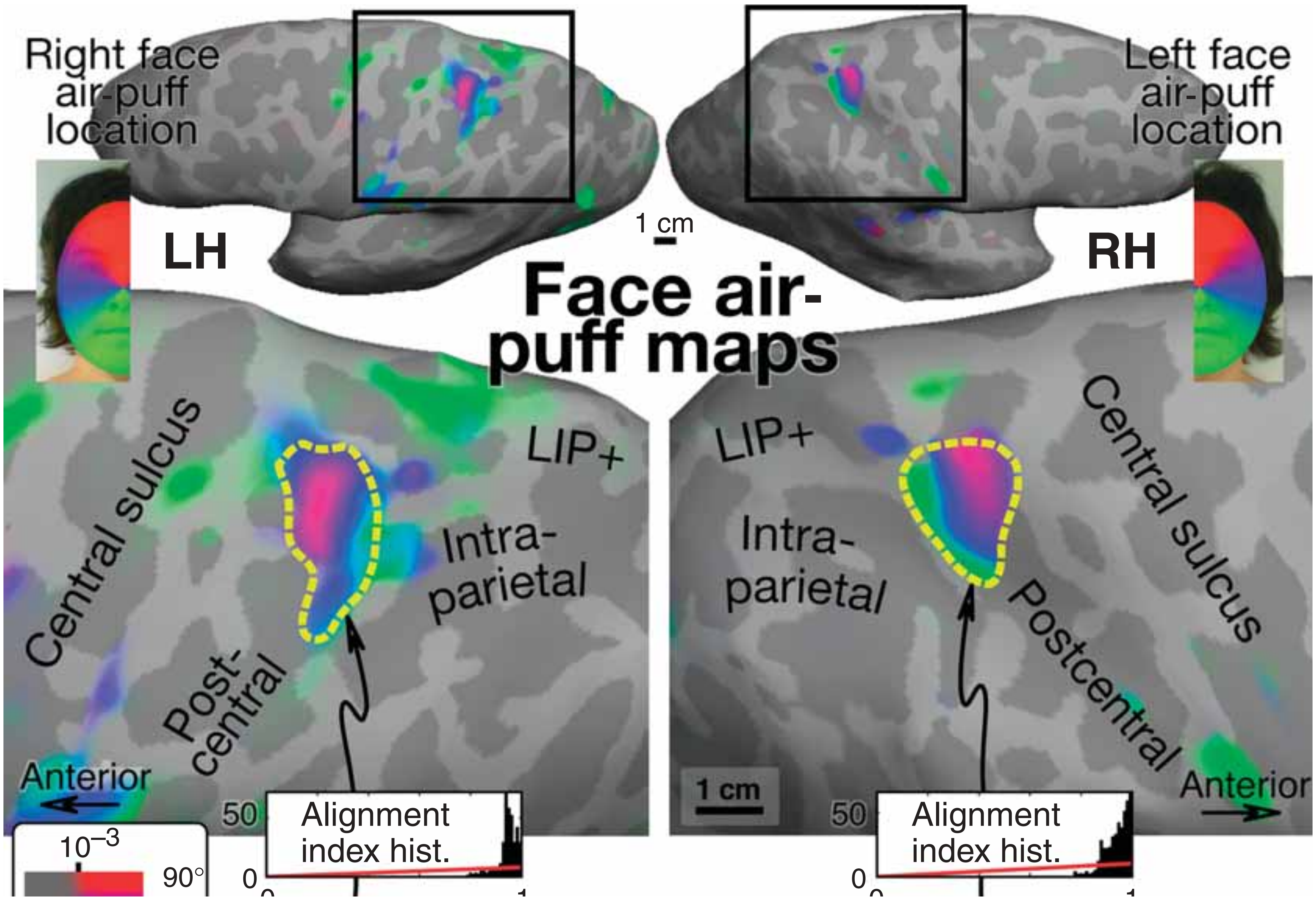
Swisher et al., *J. Neurosci*, 2006

face topography in IPS

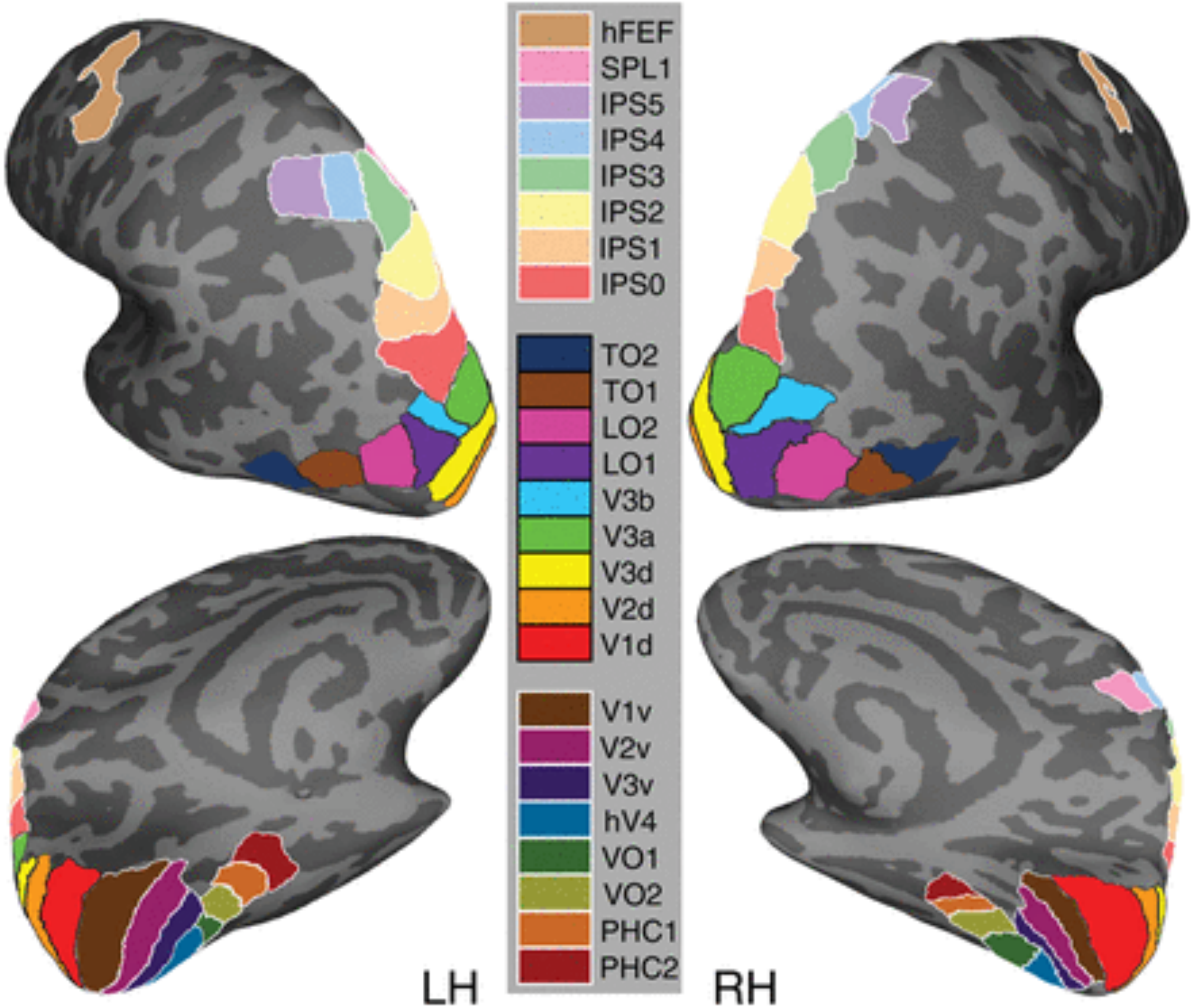


Sereno et al., Nat Neurosci (2006)

face topography in IPS

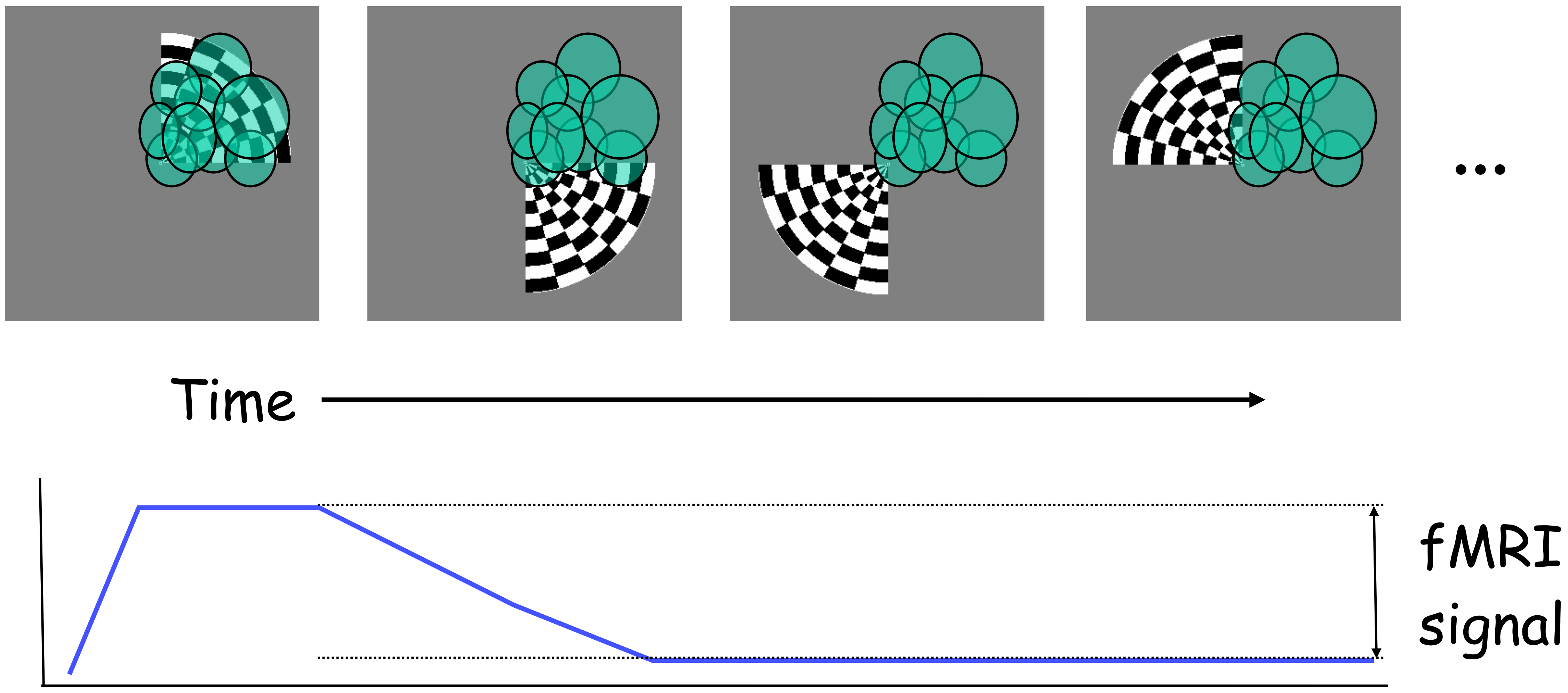


many (>25) visual areas!

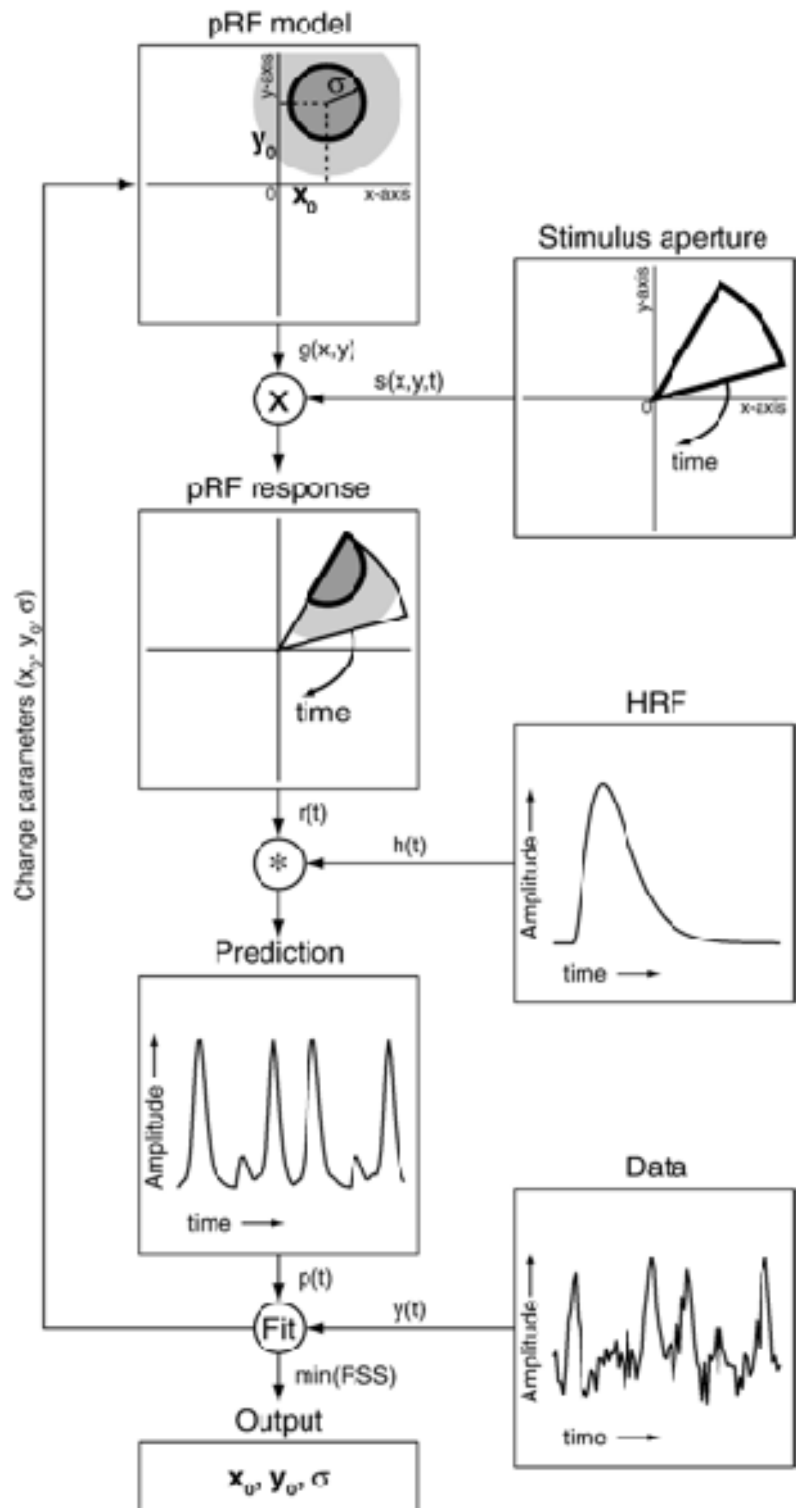


Wang et al., Probabilistic maps of visual topography in human cortex. Cereb Cortex, 2015, 3911-31.

retinotopic map, timing of activity



better mapping methods (pRFs)

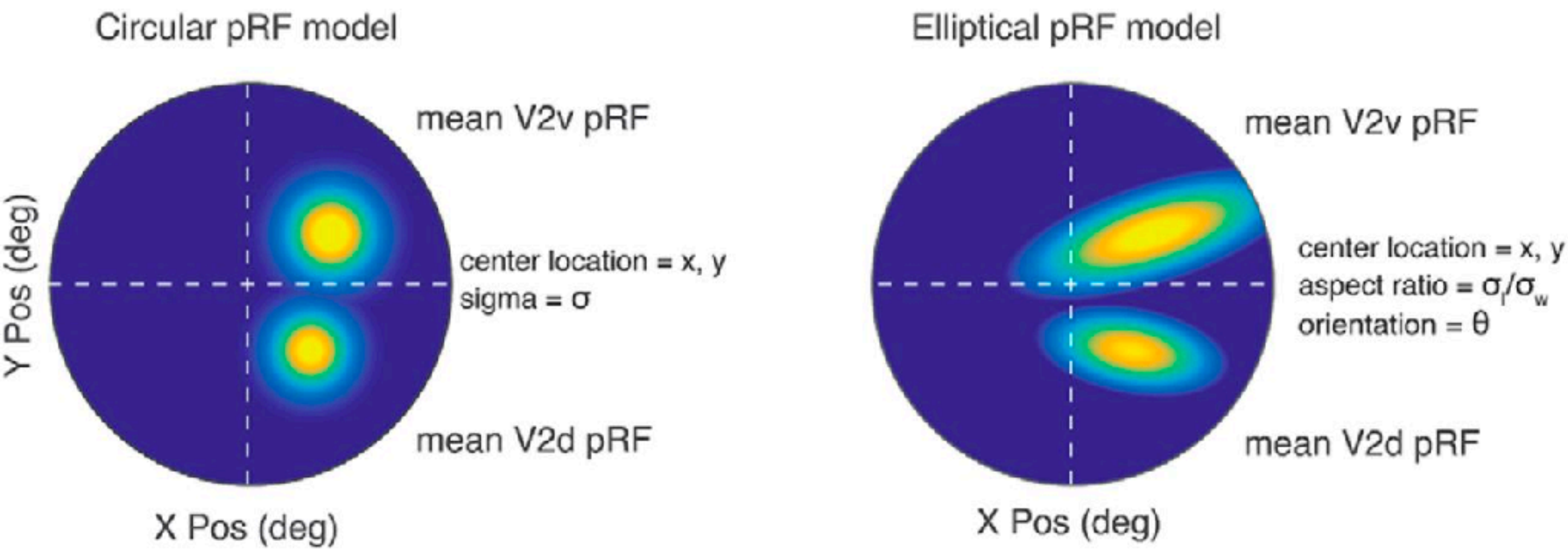


- allows for more flexible stimulus sets
- more full characterization of visual responses (e.g., pRF size)
- richer set of models (surround suppression, non-Gaussian receptive fields)

https://dbirman.github.io/learn/prf/prf.html

after Doumolin & Wandell, 2008

pRFs are elliptical and radially oriented

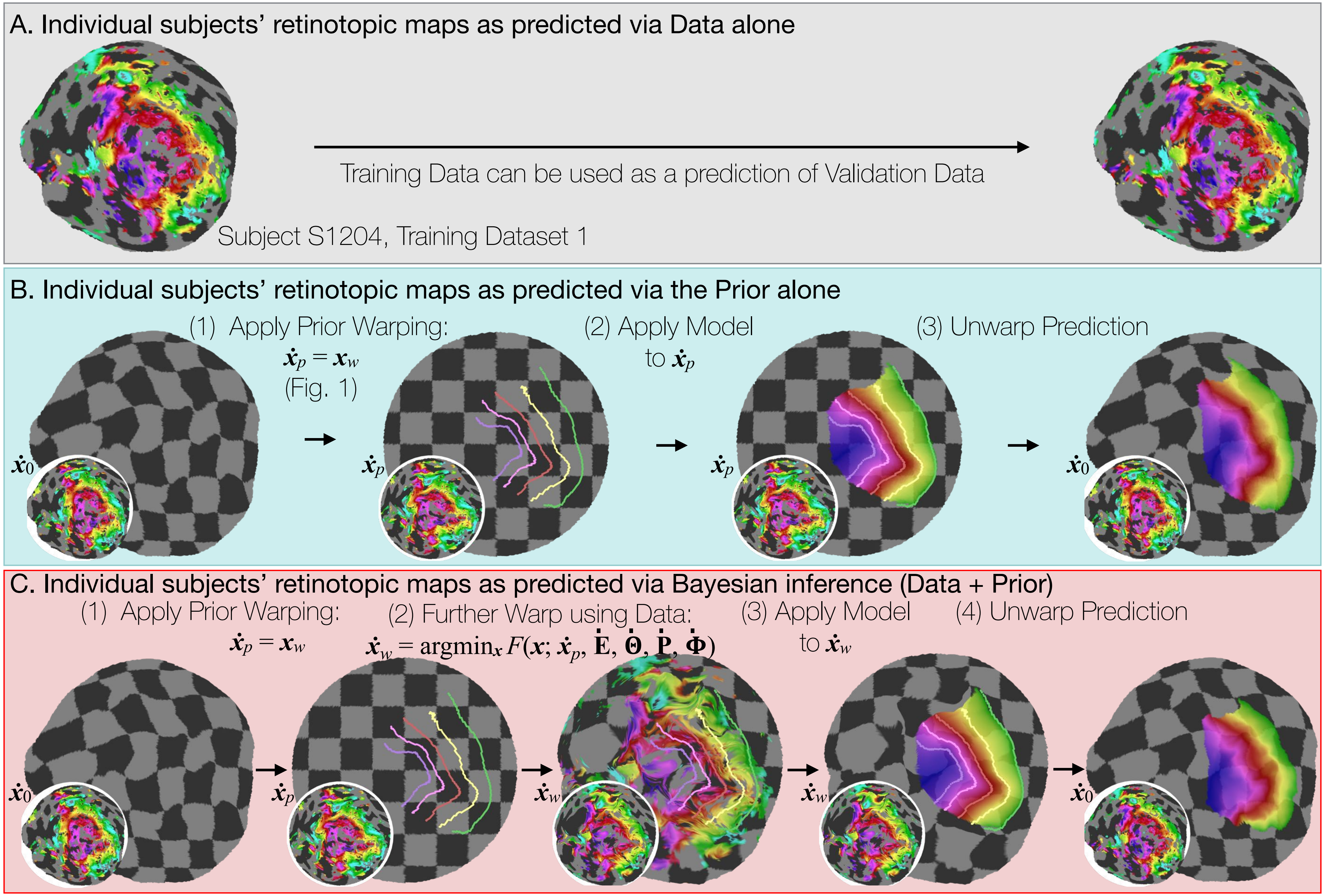


Silson et al., J. Neurosci, 2018

retinotopic mapping

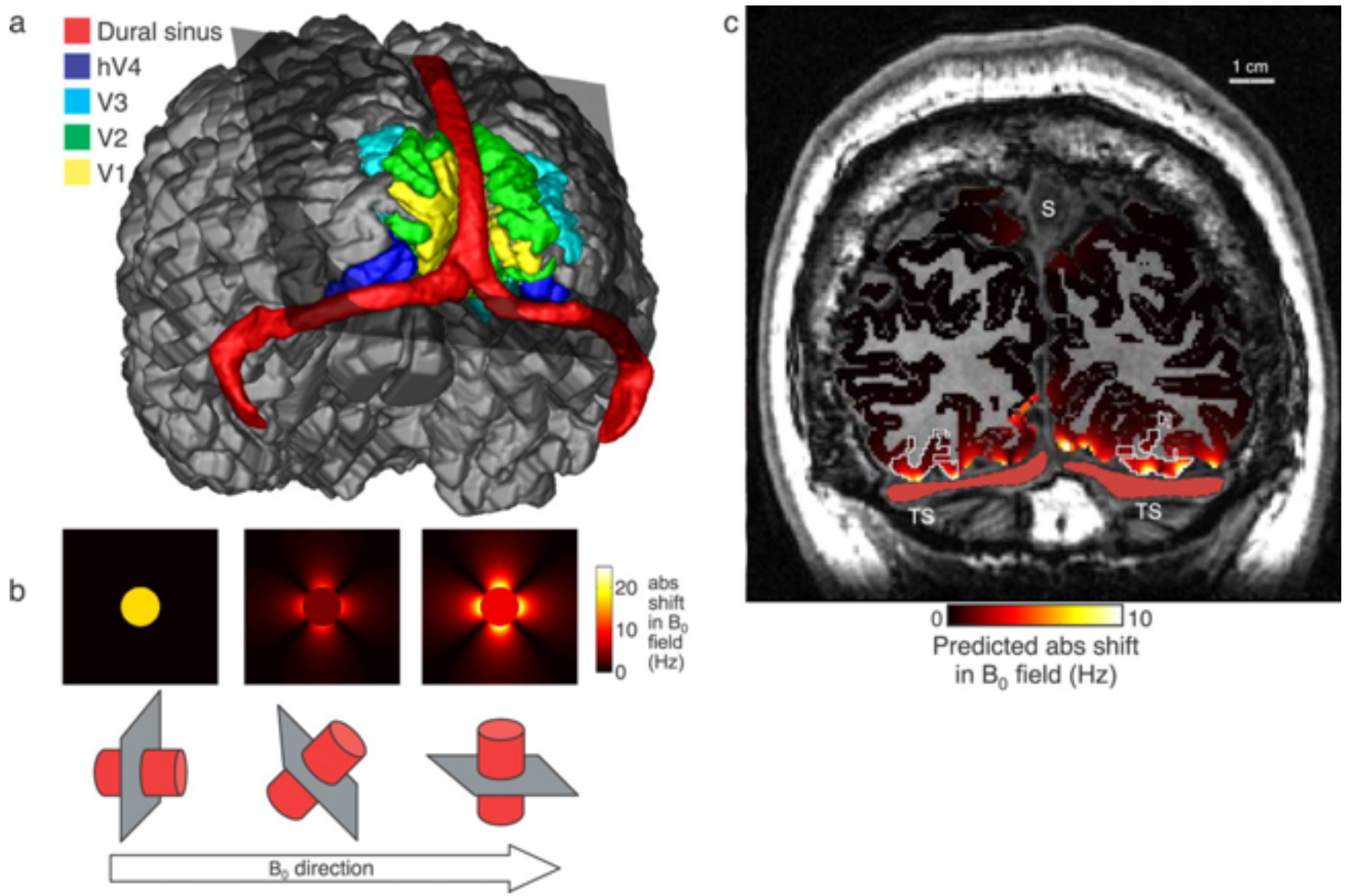
progress and challenges…

but we need better methods



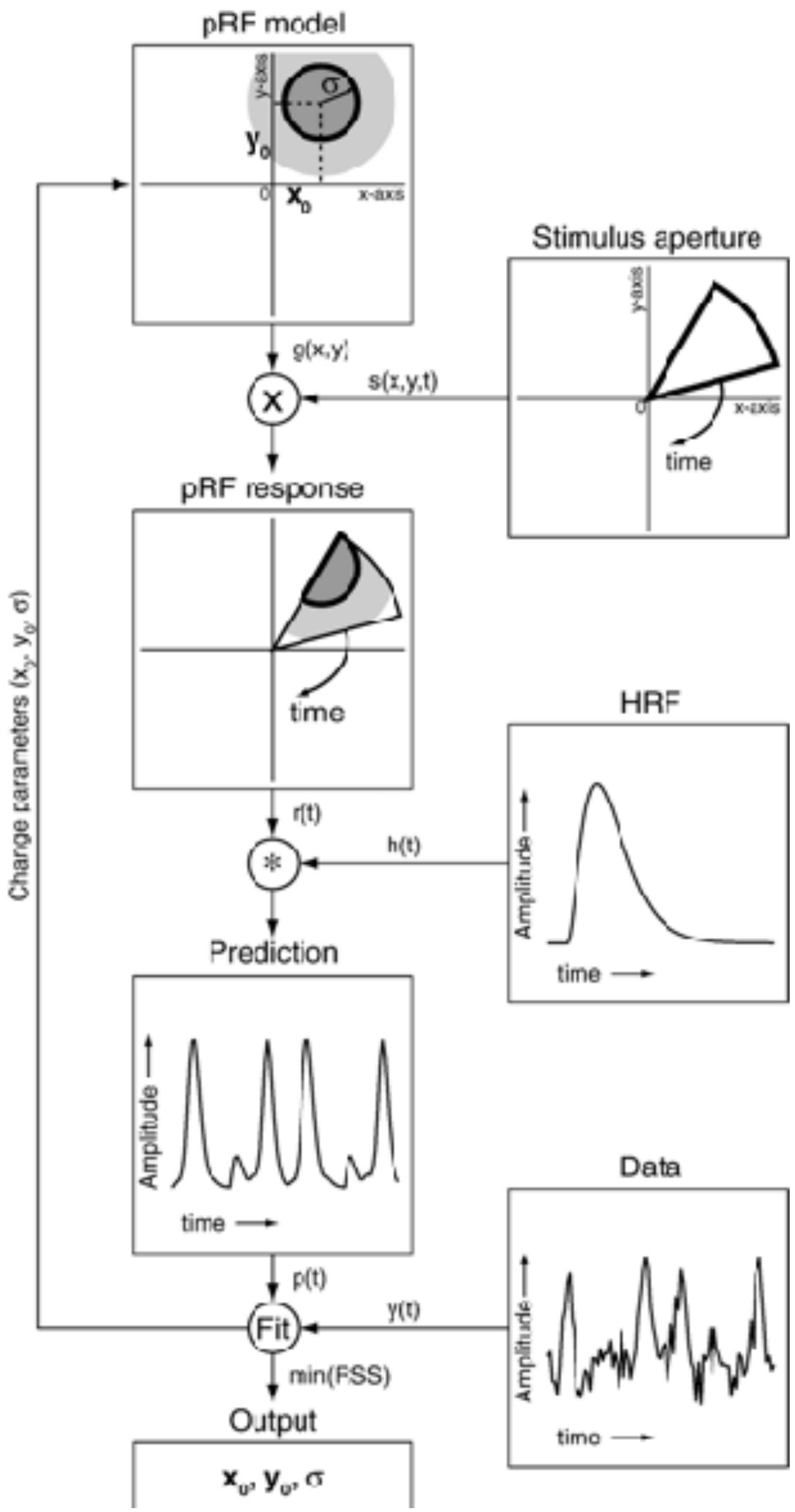
Benson & Winawer, bioRxiv, 2018

the venous eclipse



Winawer et al., 2010

better mapping methods (pRFs)



- allows for more flexible stimulus sets
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- richer set of models (surround suppression, non-Gaussian receptive fields)

after Doumolin & Wandell, 2008

overview

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overview

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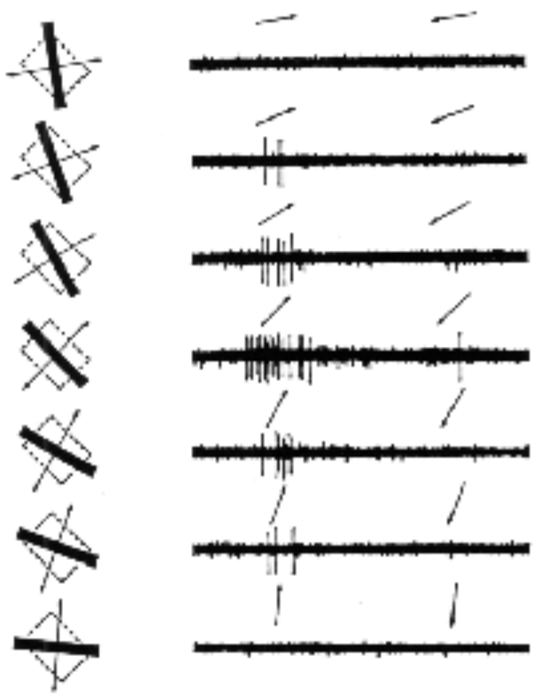
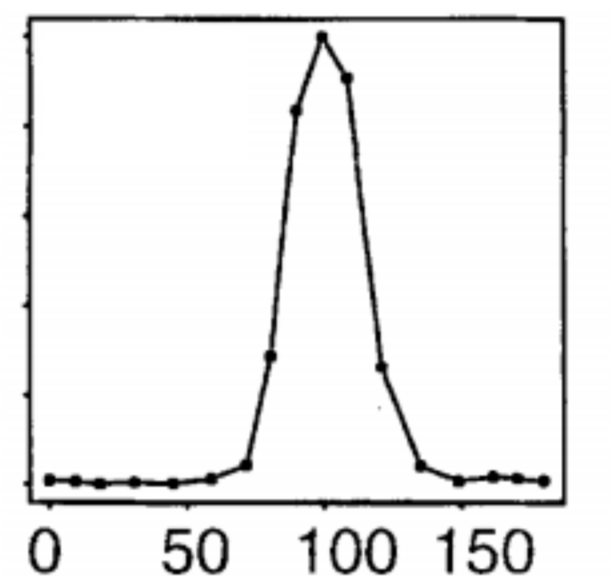
  orientation
  motion
  color
  objects, faces, and letters

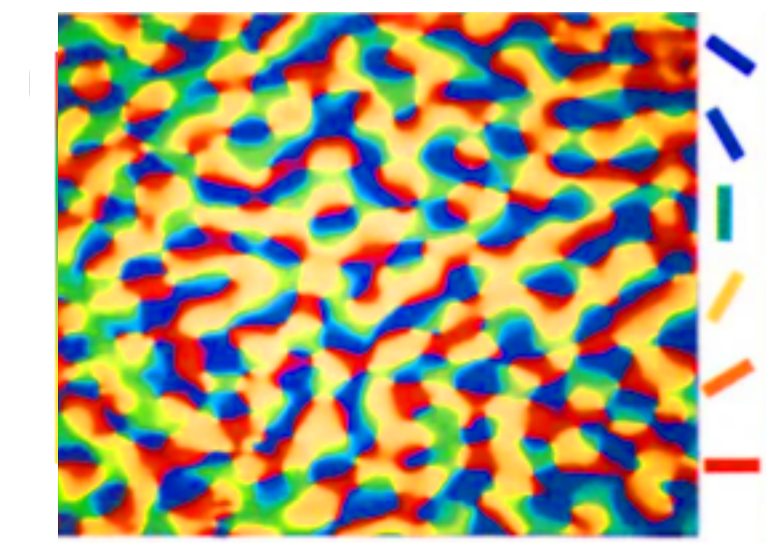
test case: ***<u>orientation selectivity</u>***
can we measure it with fMRI?



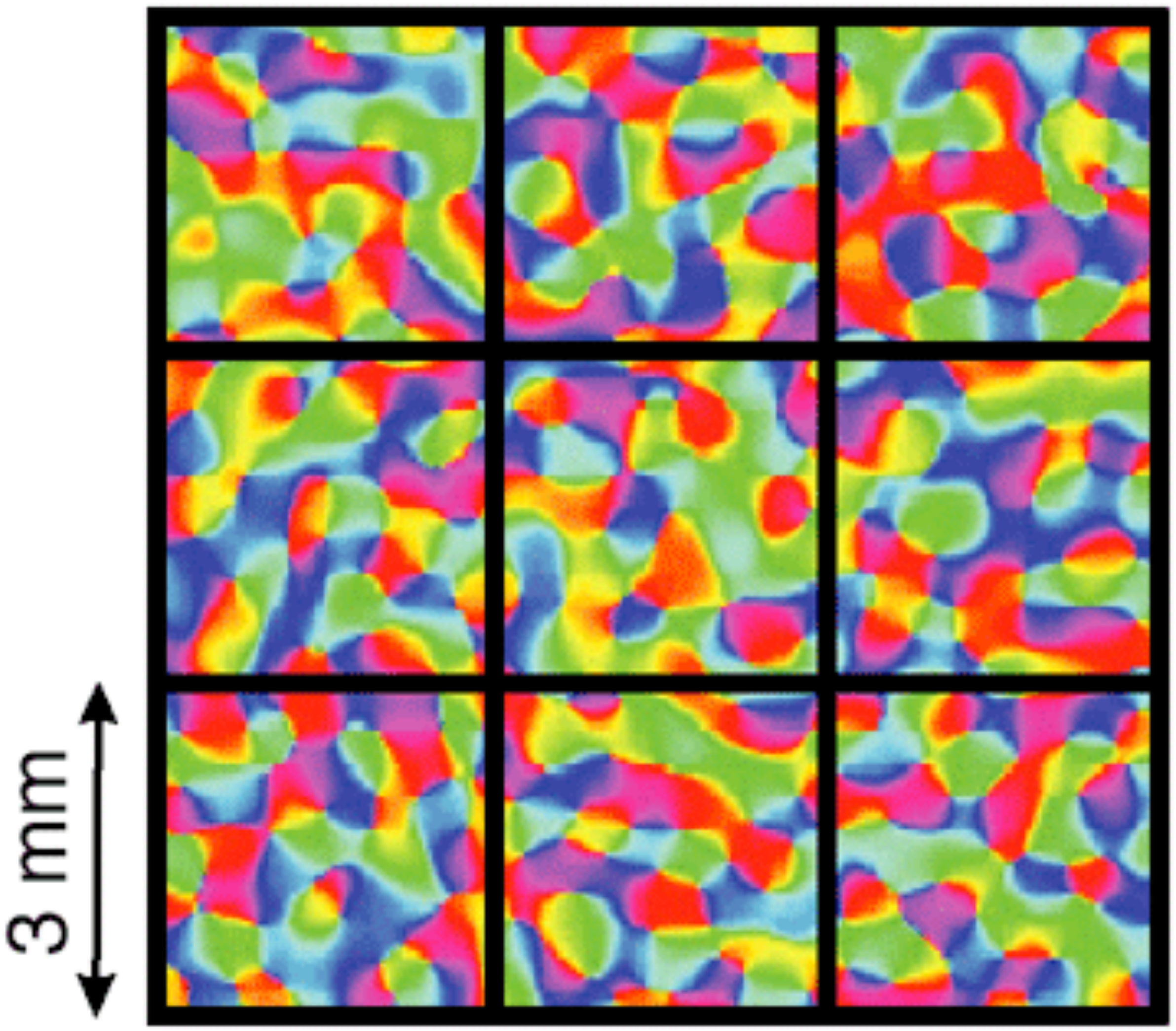
hubel and wiesel, 1962



ringach, hawken, and shapley, 1997

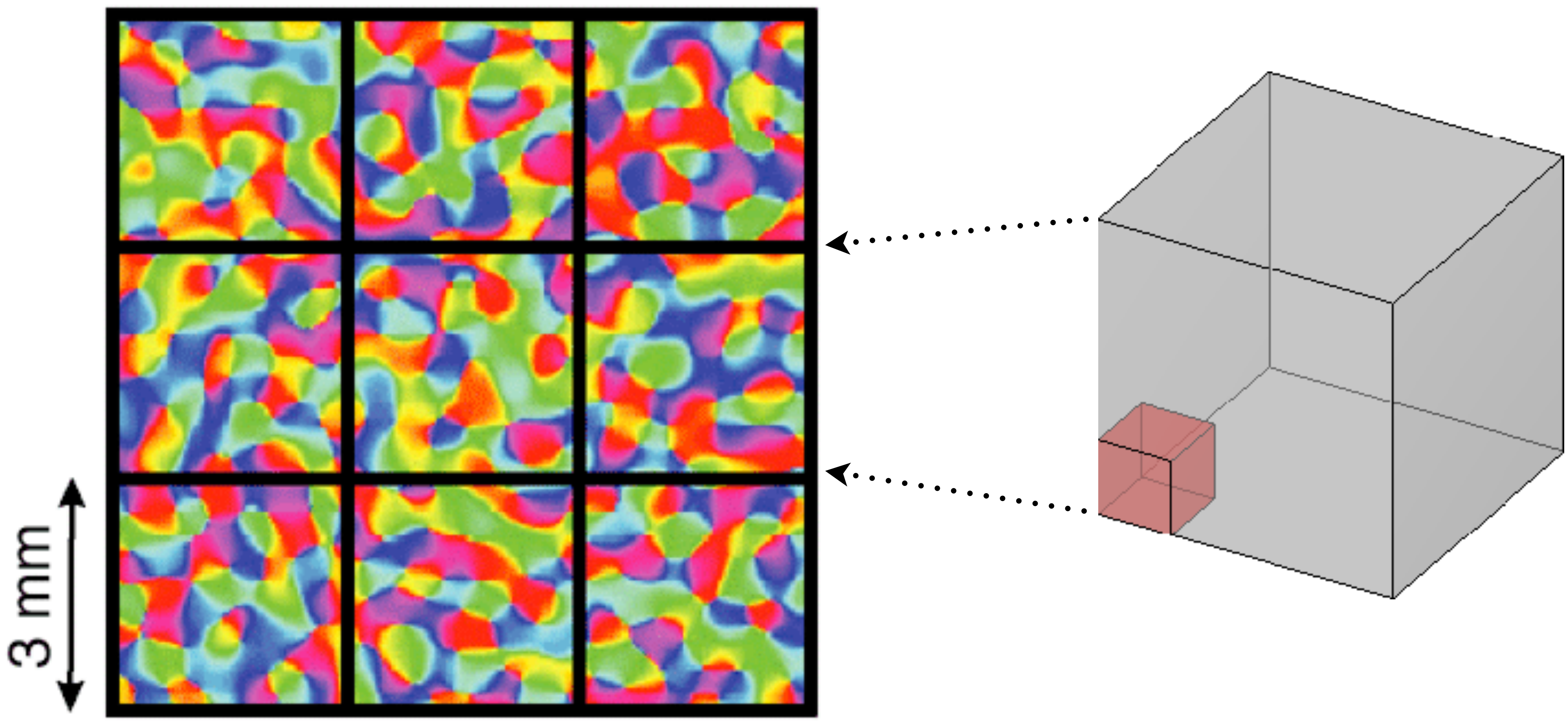


blasdel and salama, 1986

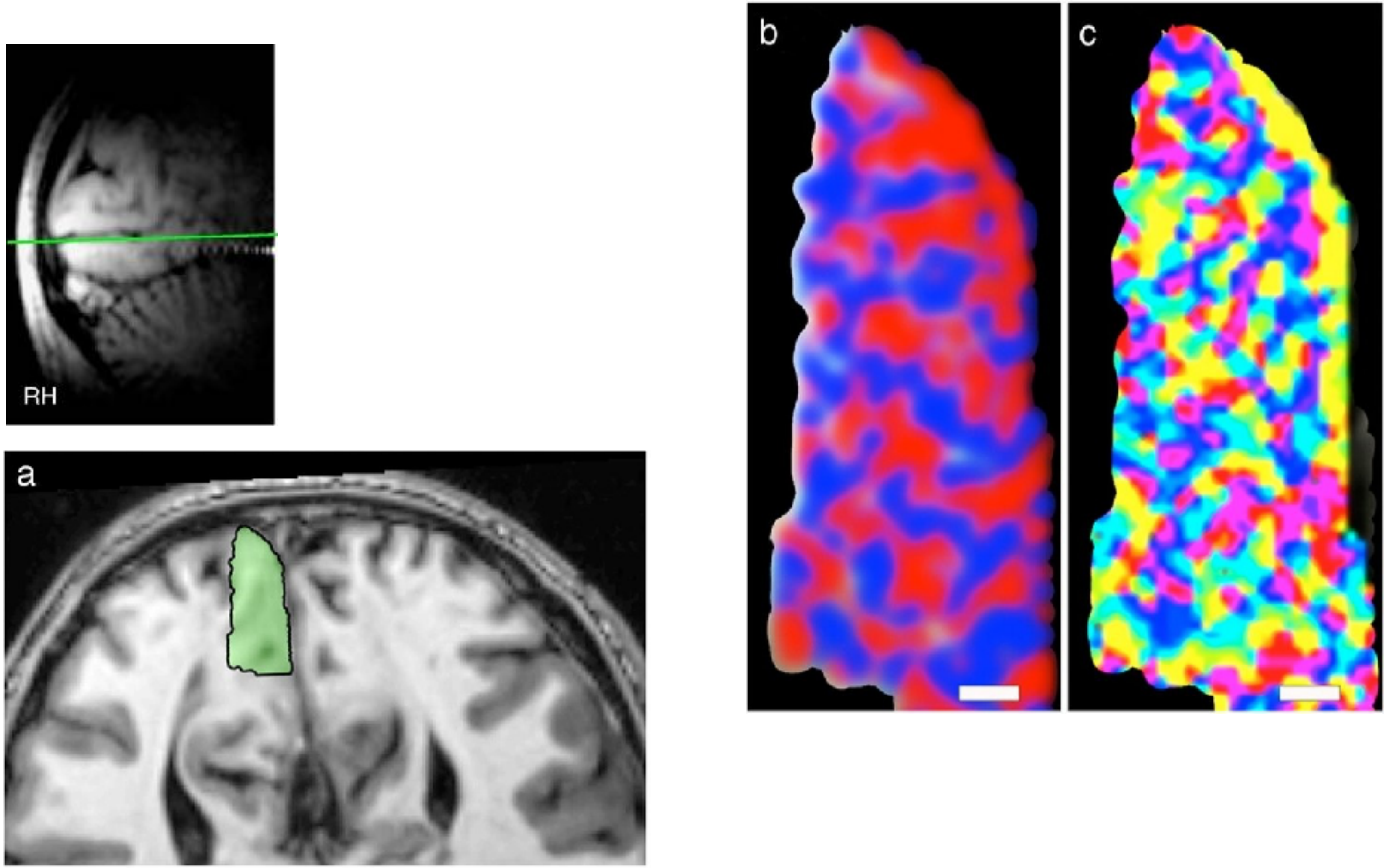


doesn't look good…

solution 1: *high resolution fMRI*



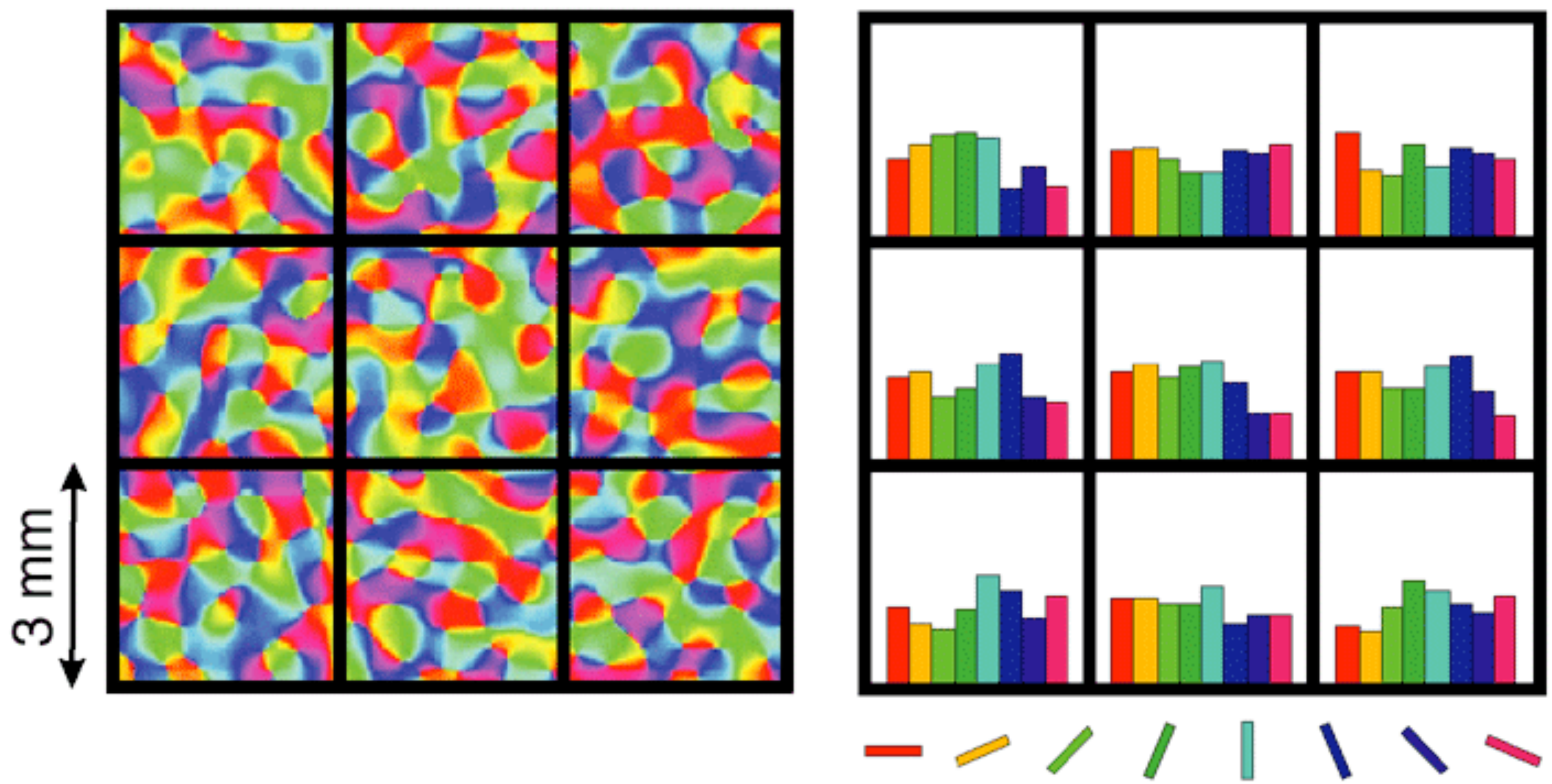
human ocular dominance and orientation columns



yacoub, harel, ugurbil, PNAS (2008)

solution 2: *fMRI decoding (classifiers)*

small biases in fMRI response because voxels sample an irregular underlying columnar architecture



kamitani & tong, 2005
haynes & rees, 2005
boynton, 2005

fMRI decoding: an imager's microelectrode?

fMRI decoding with multi-voxel pattern analysis (MVPA)

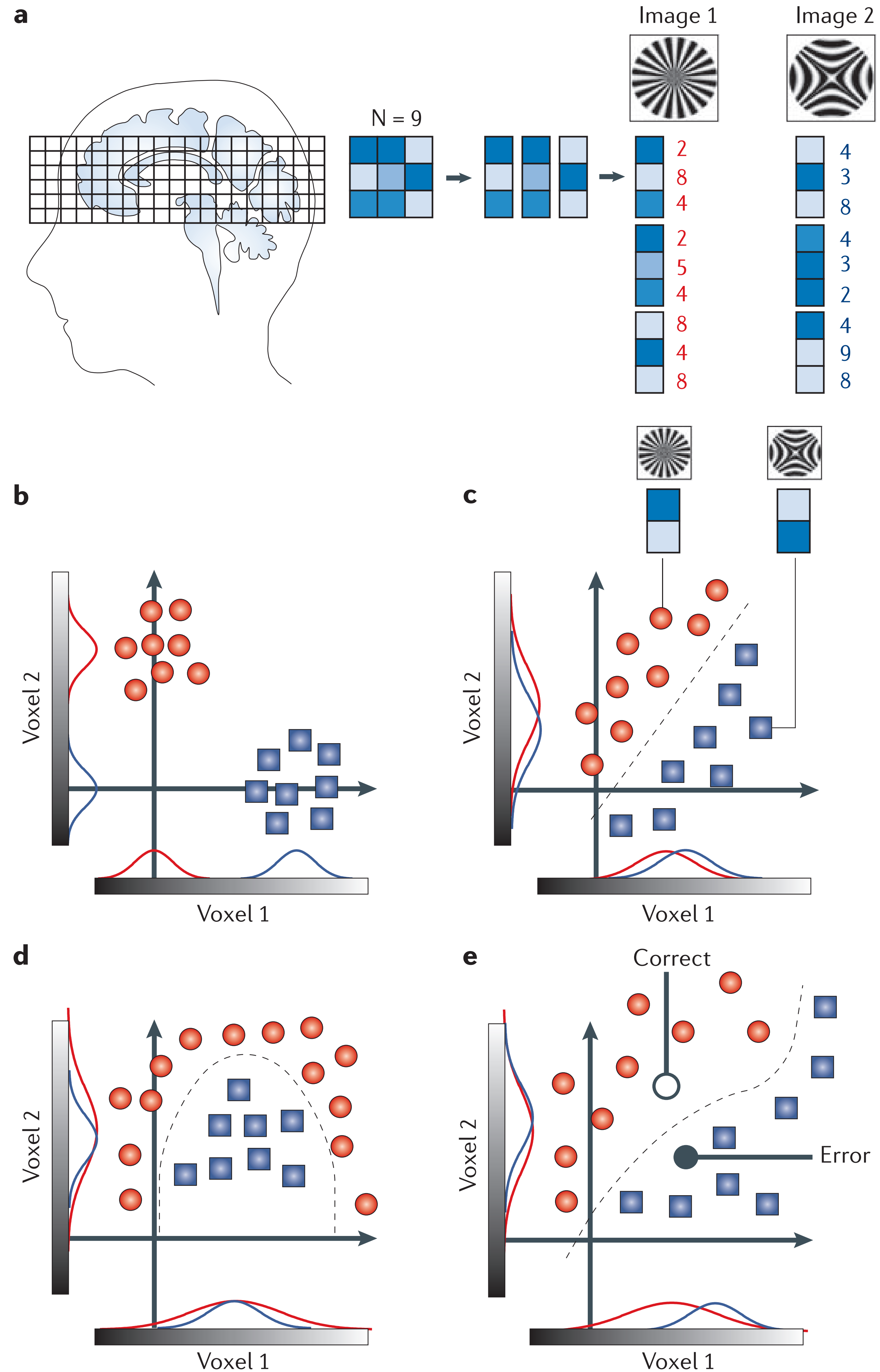
1) train classifier on subset of data

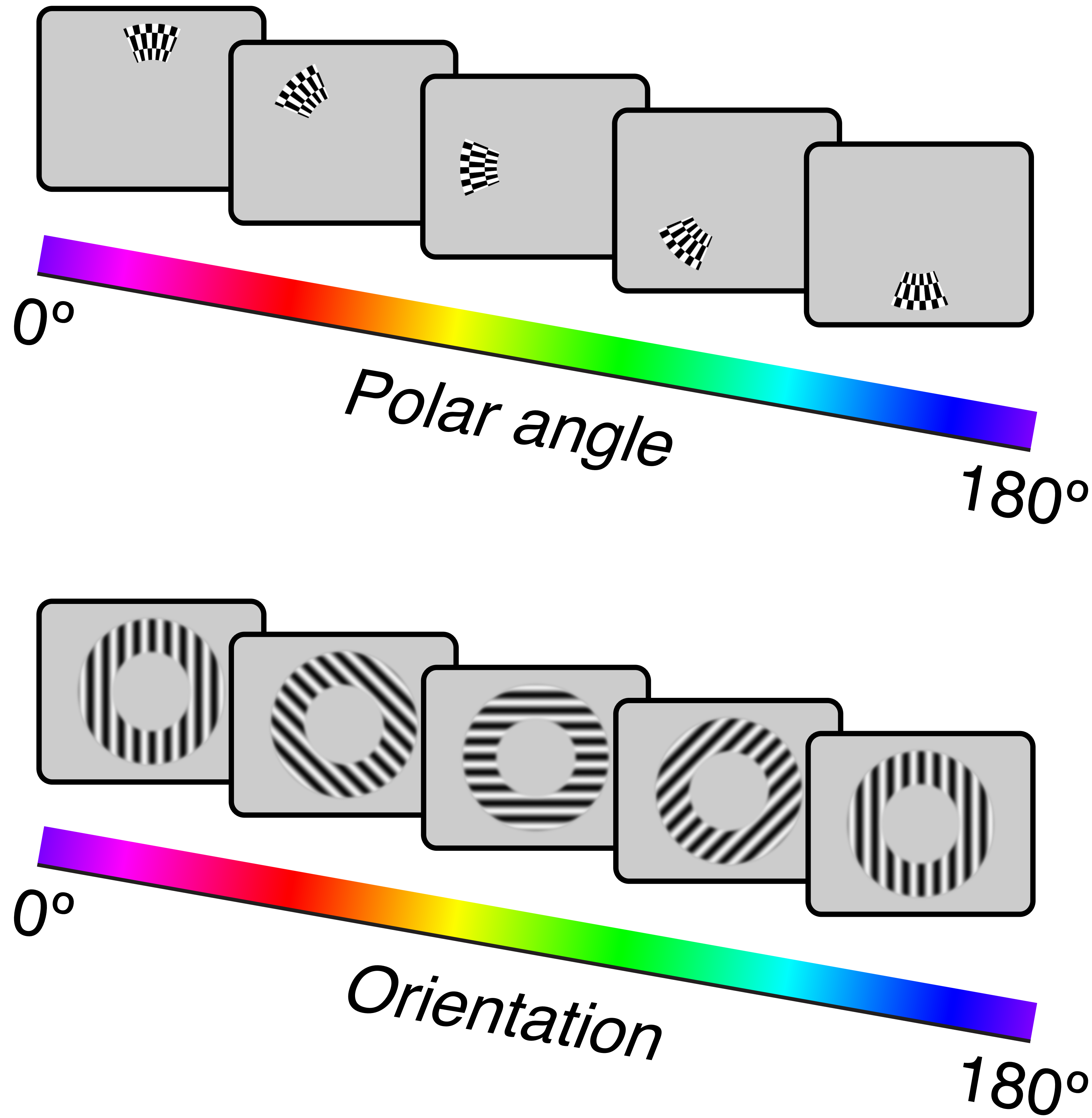
2) test classifier on left-out data

3) get a single number (% correct)

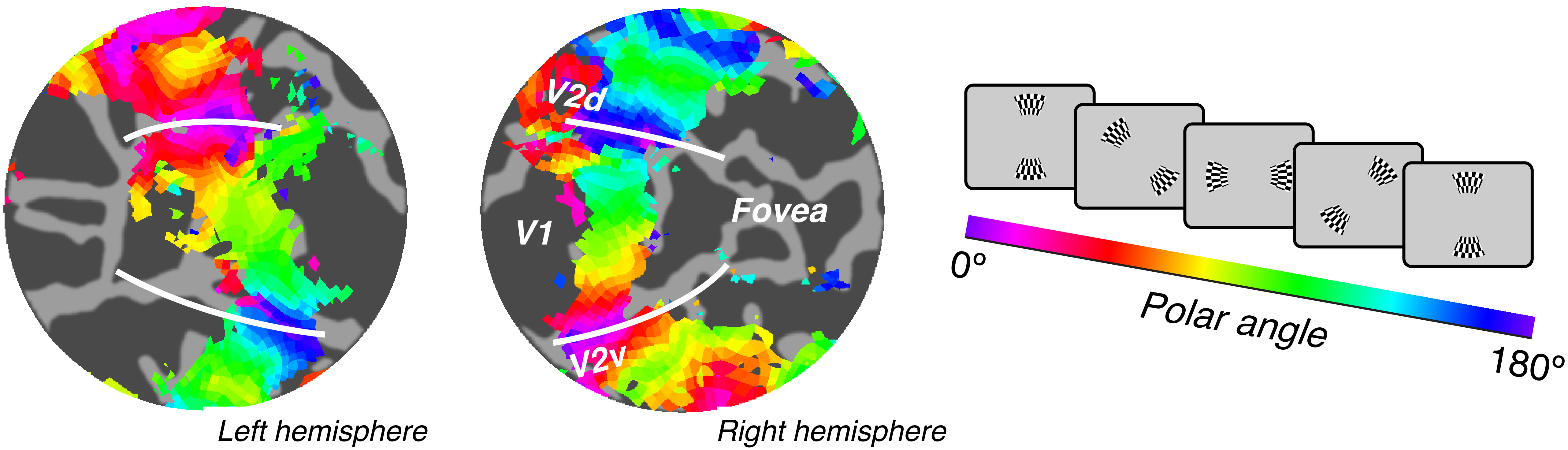
4) compare to 'chance'

haynes & rees, nature neurosci, 2006

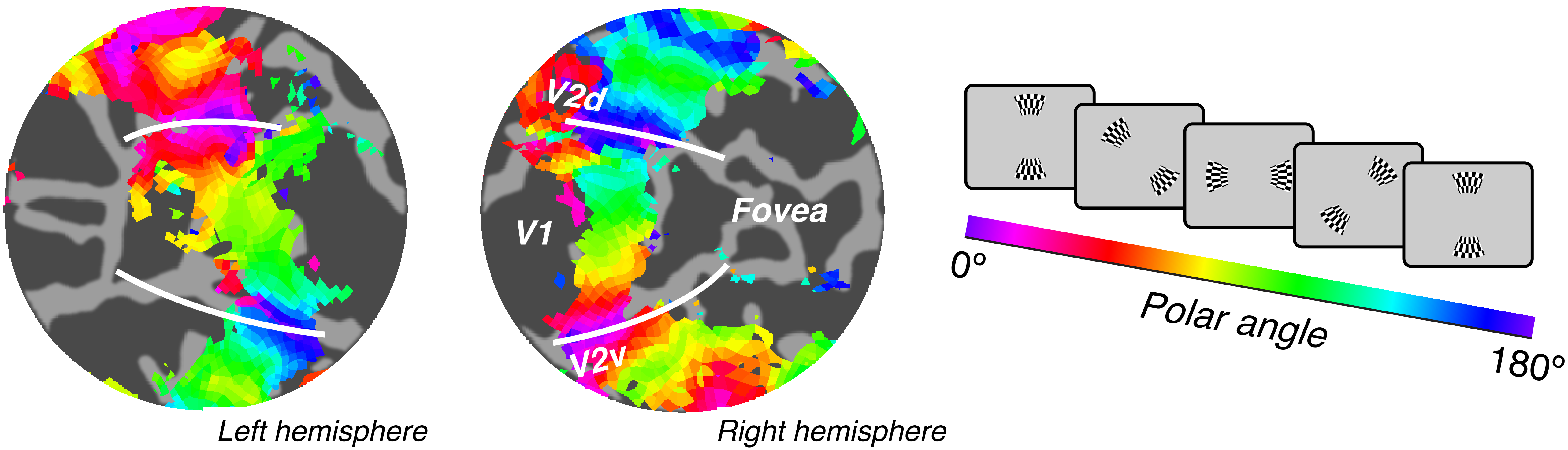


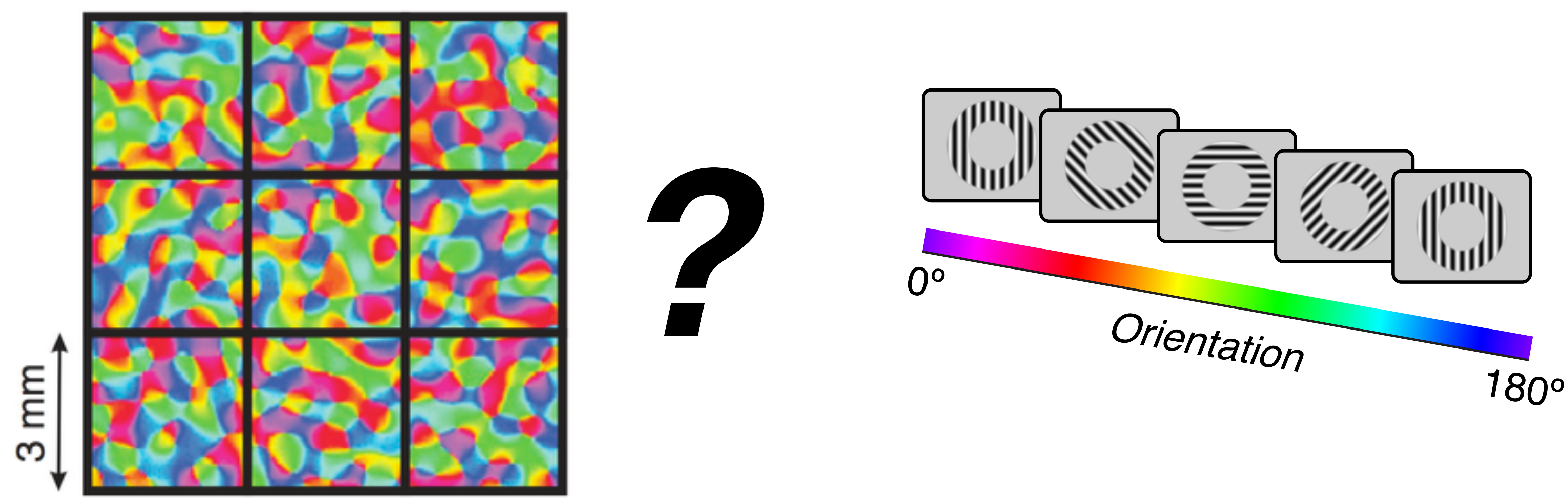

0°
Polar angle
180°
0°
Orientation
180°

retinotopic map

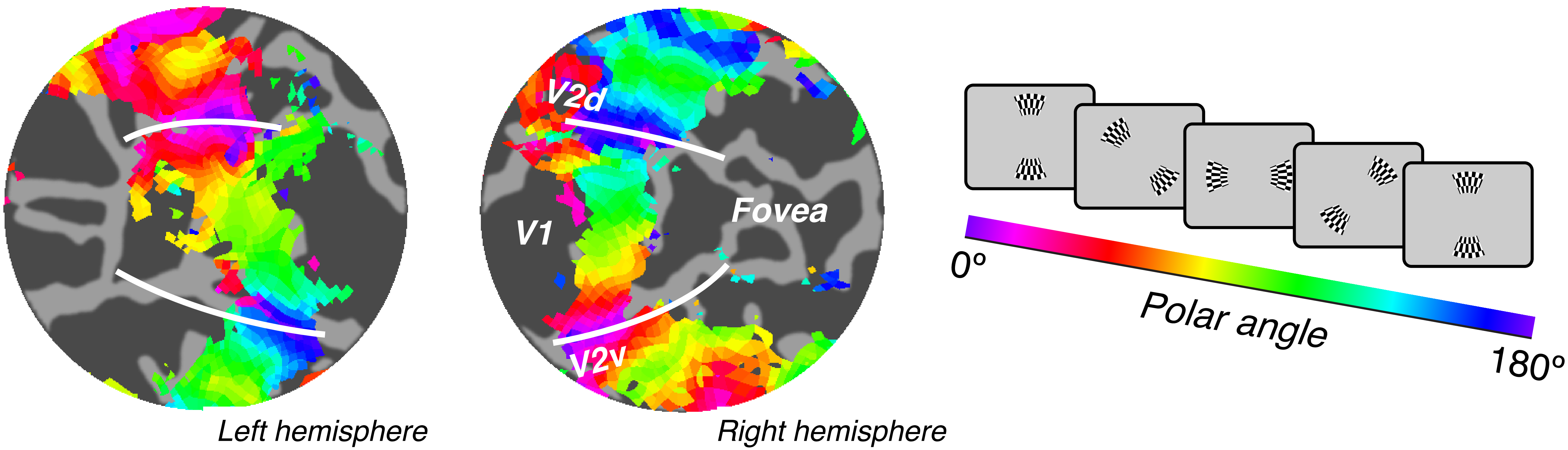


retinotopic map

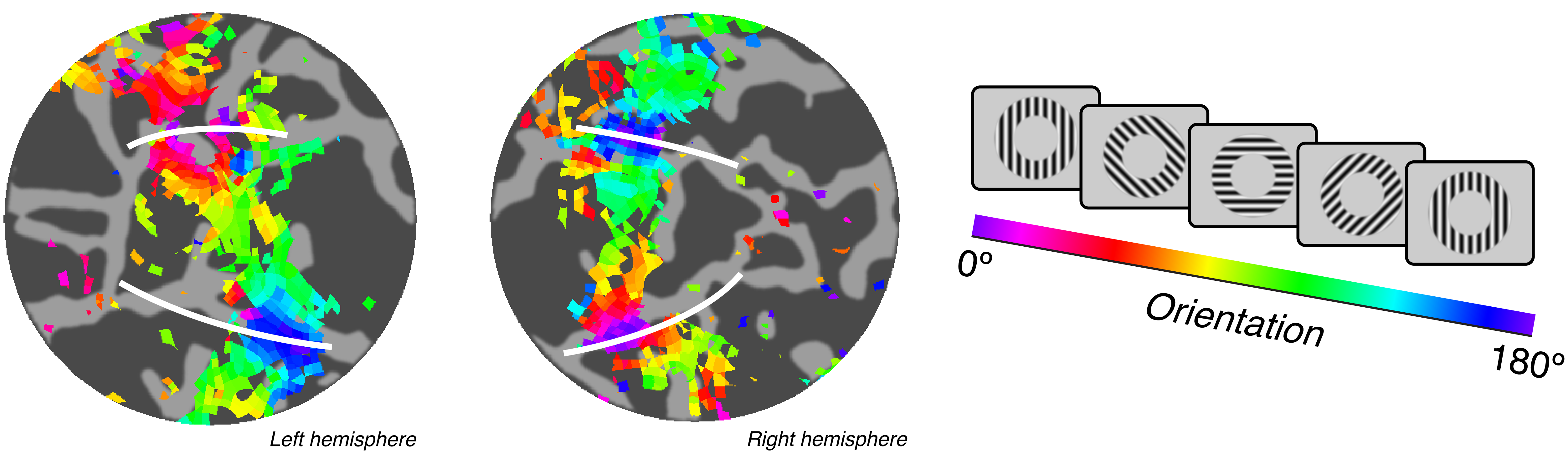




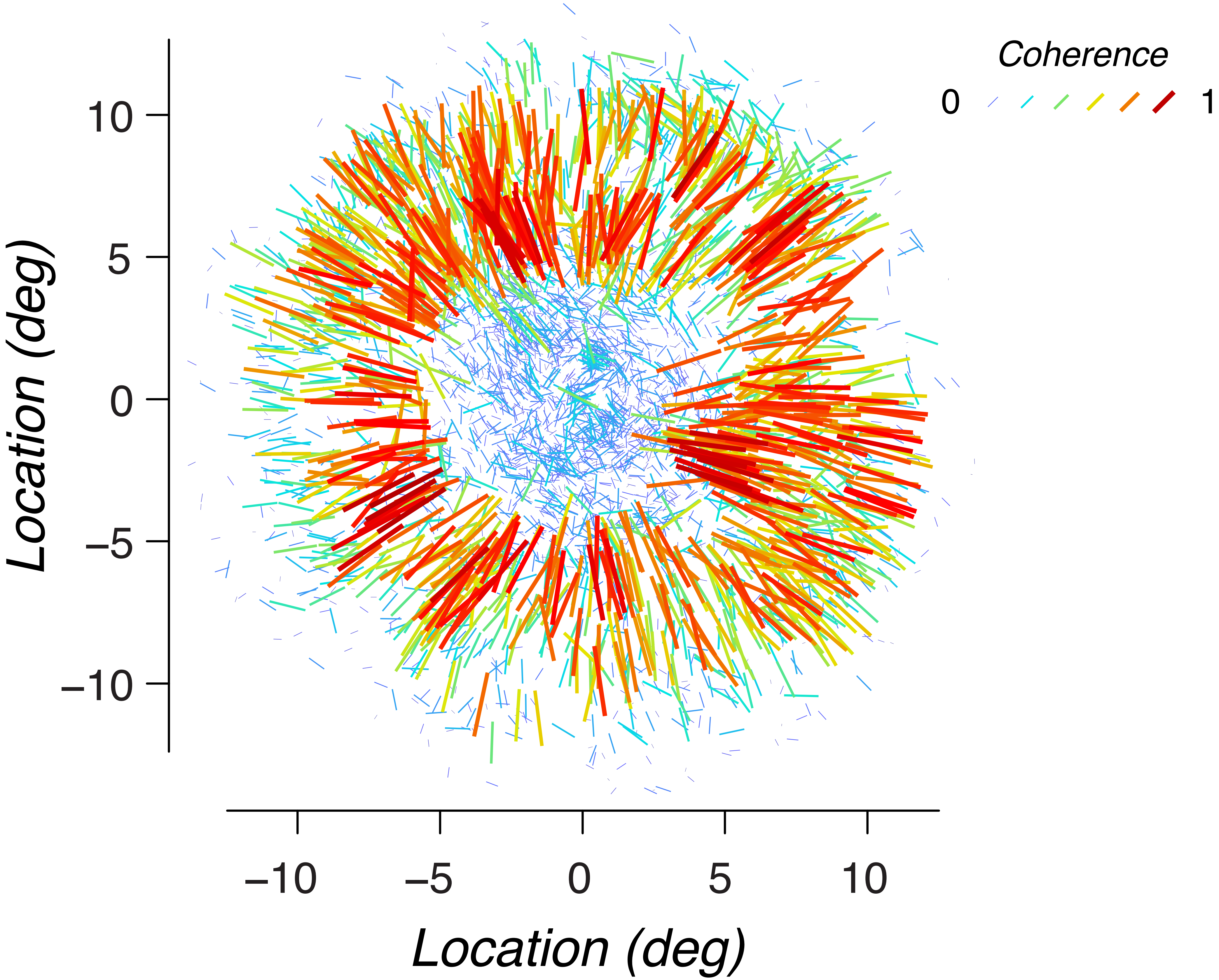
retinotopic map



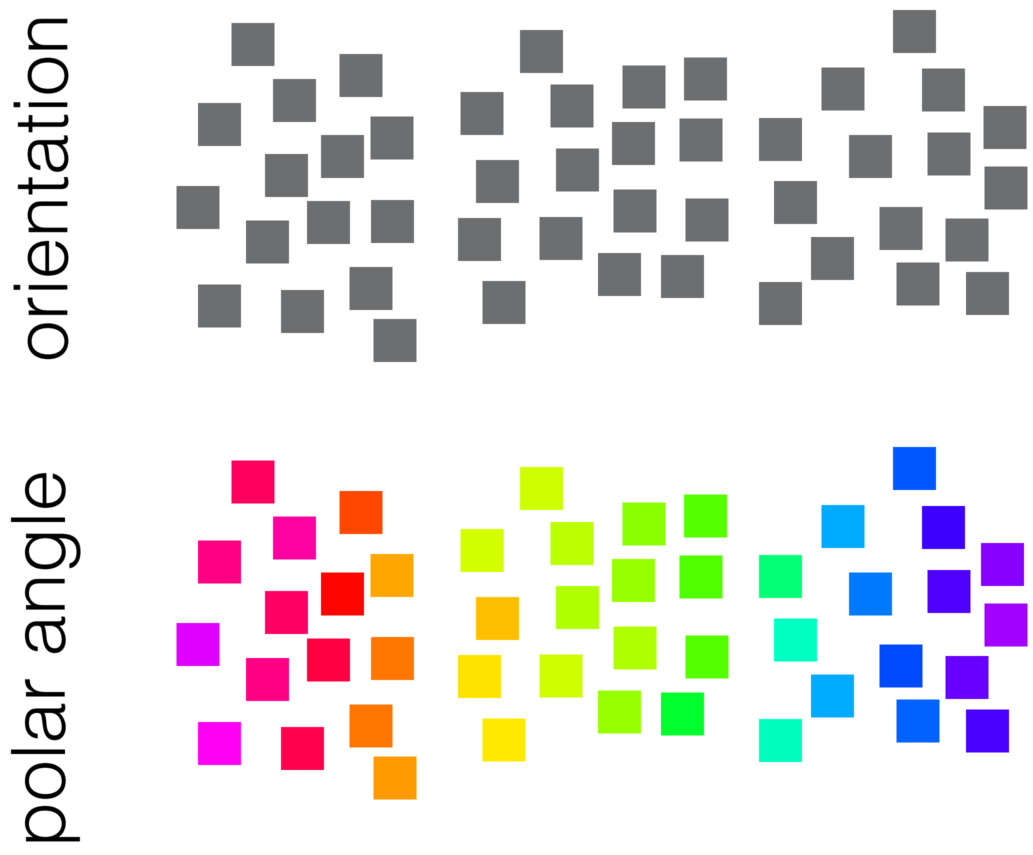
orientation bias map



radial bias

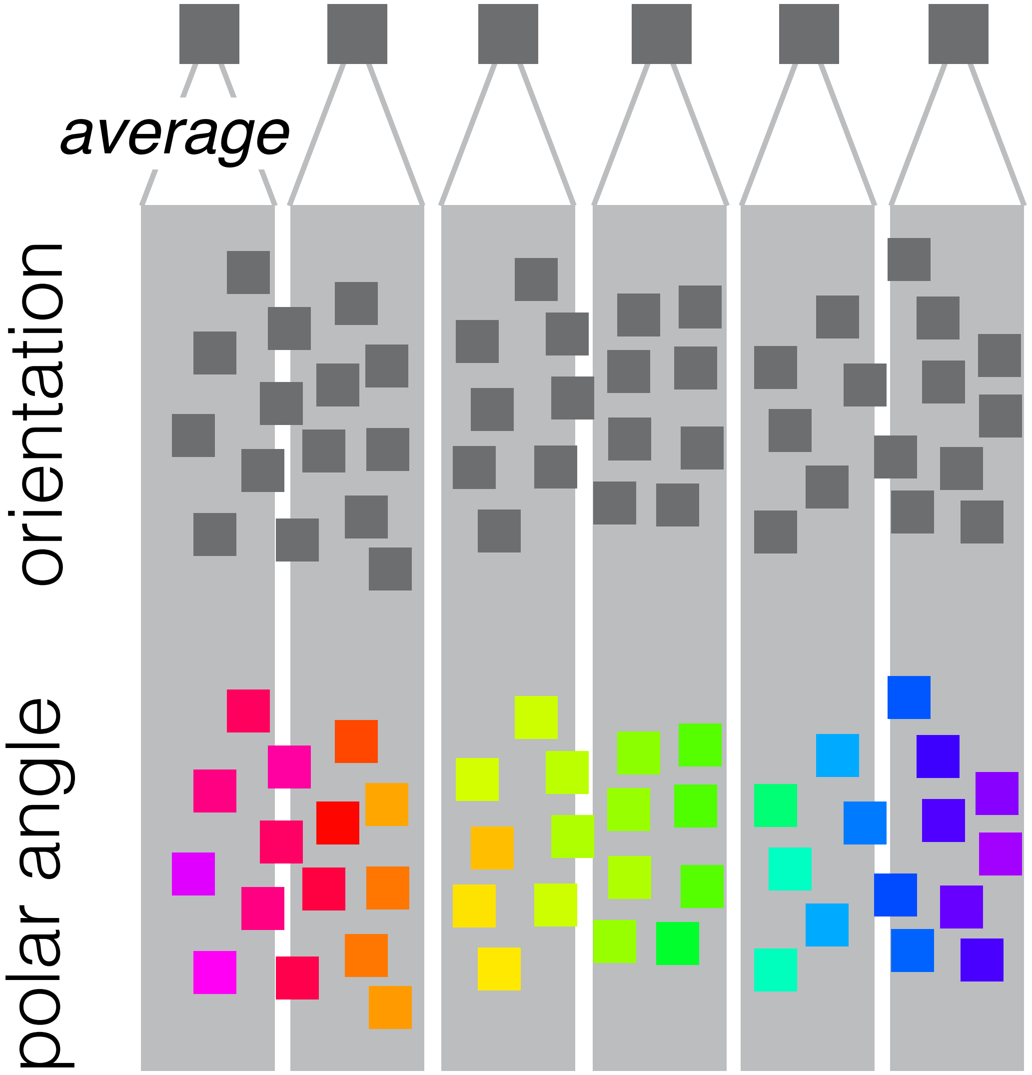


map is ***sufficient*** for decoding



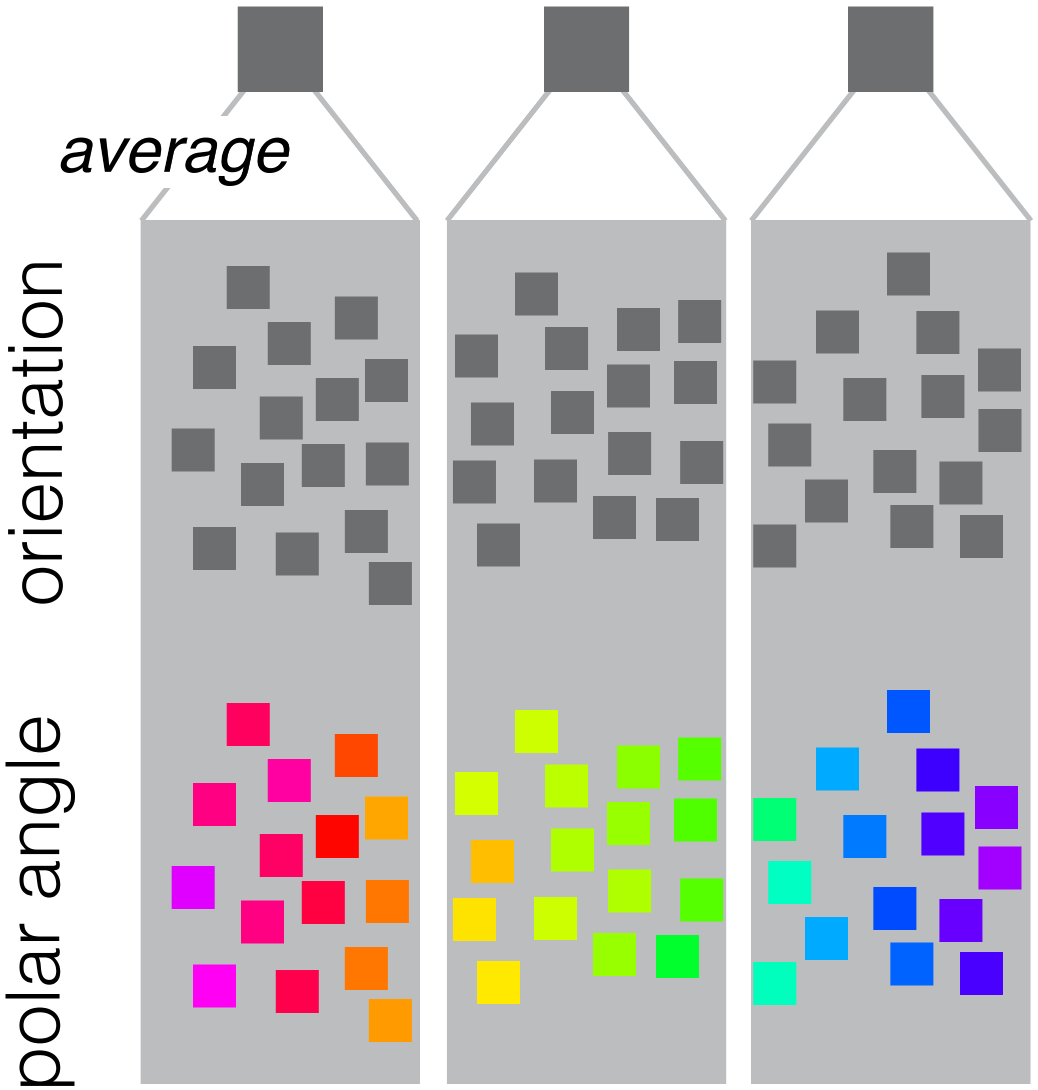
map is ***sufficient*** for decoding

classify averaged responses



map is ***sufficient*** for decoding

classify averaged responses



map is ***sufficient*** for decoding

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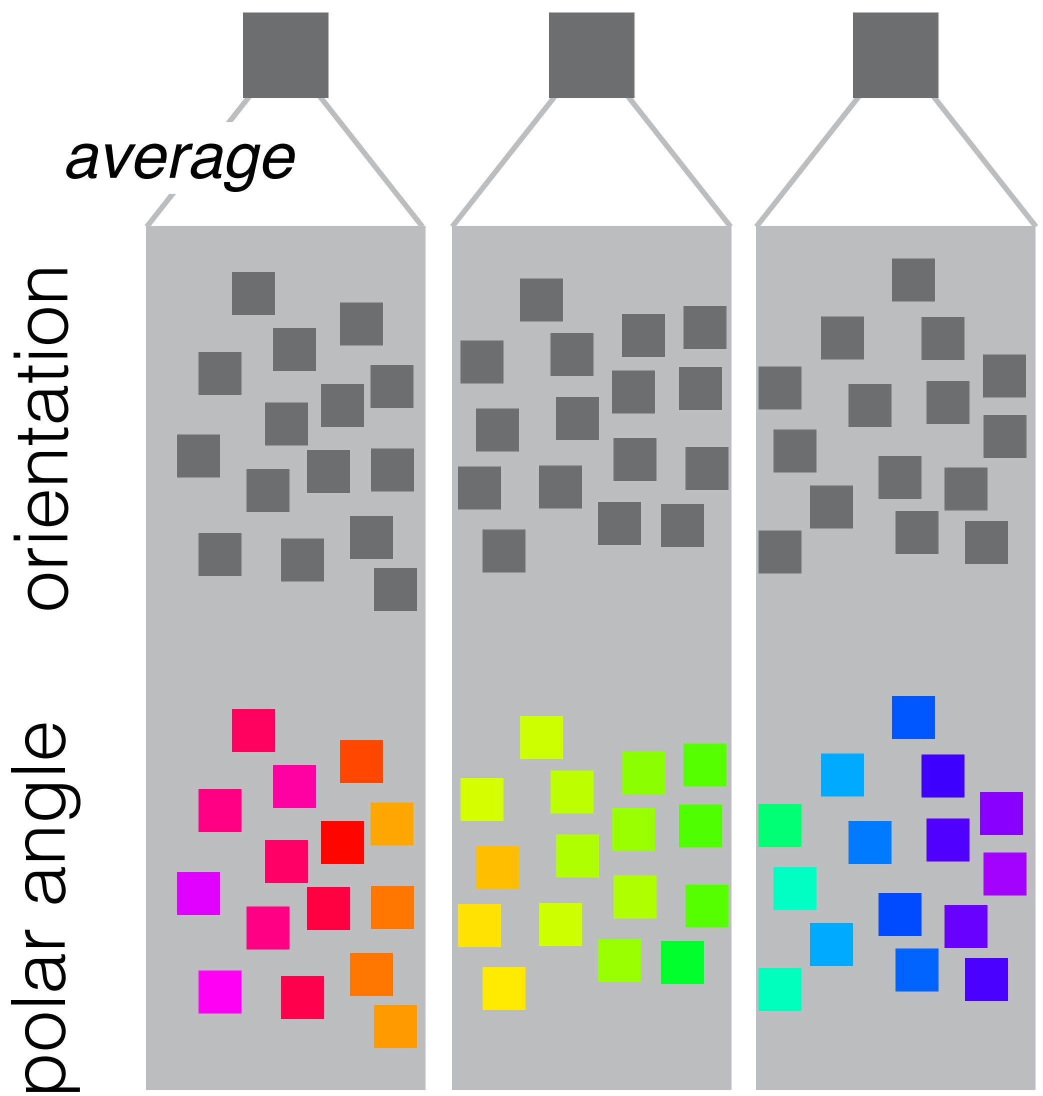
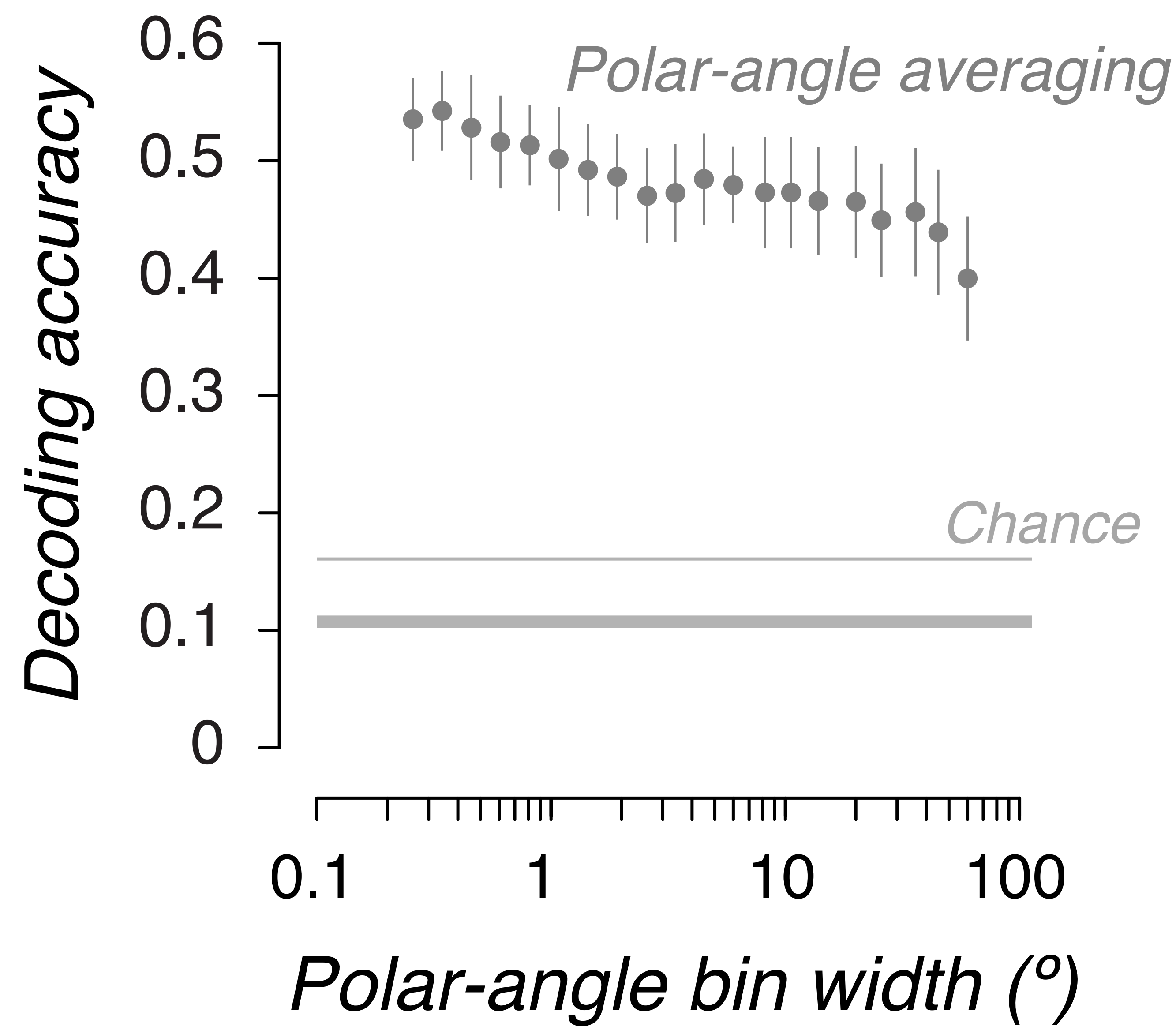
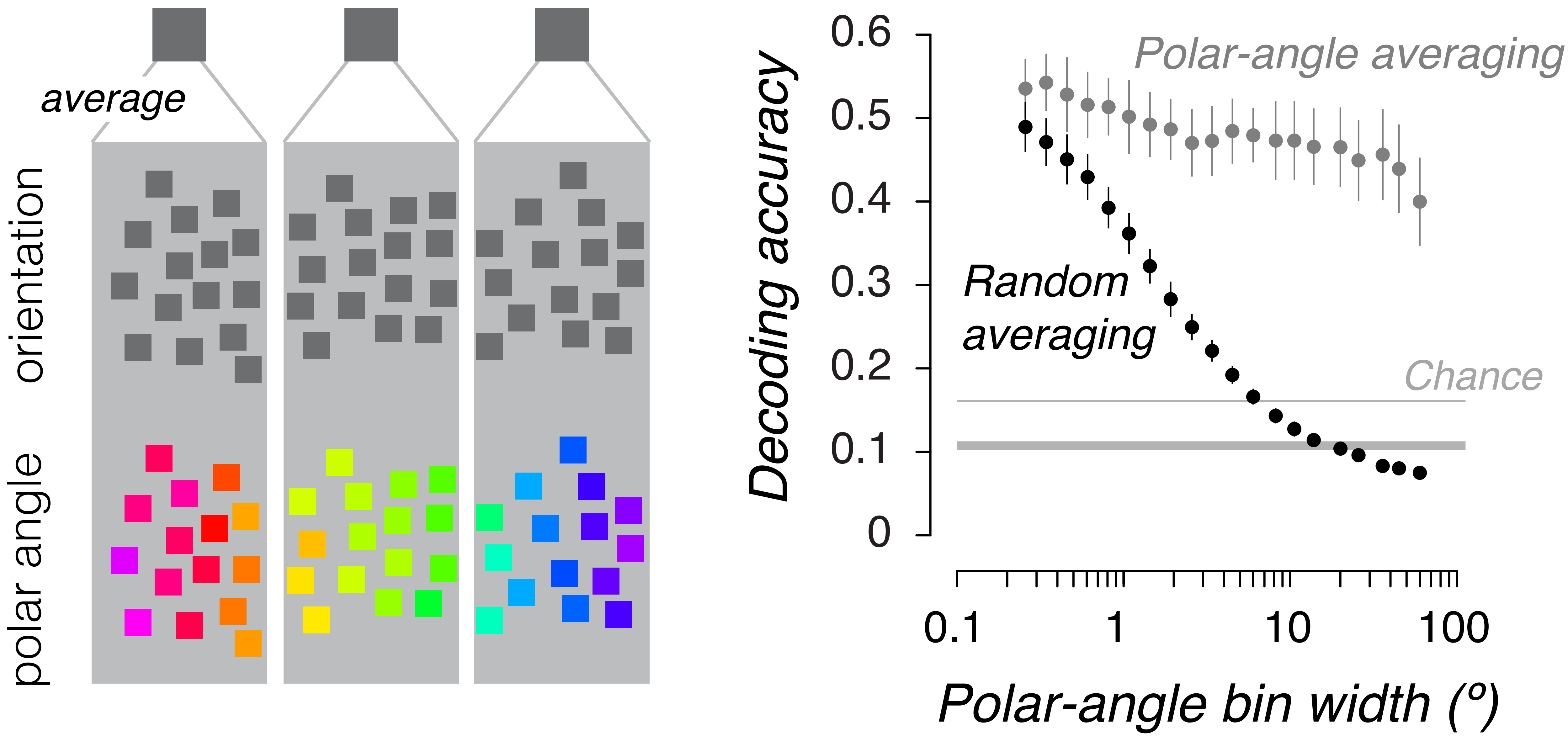




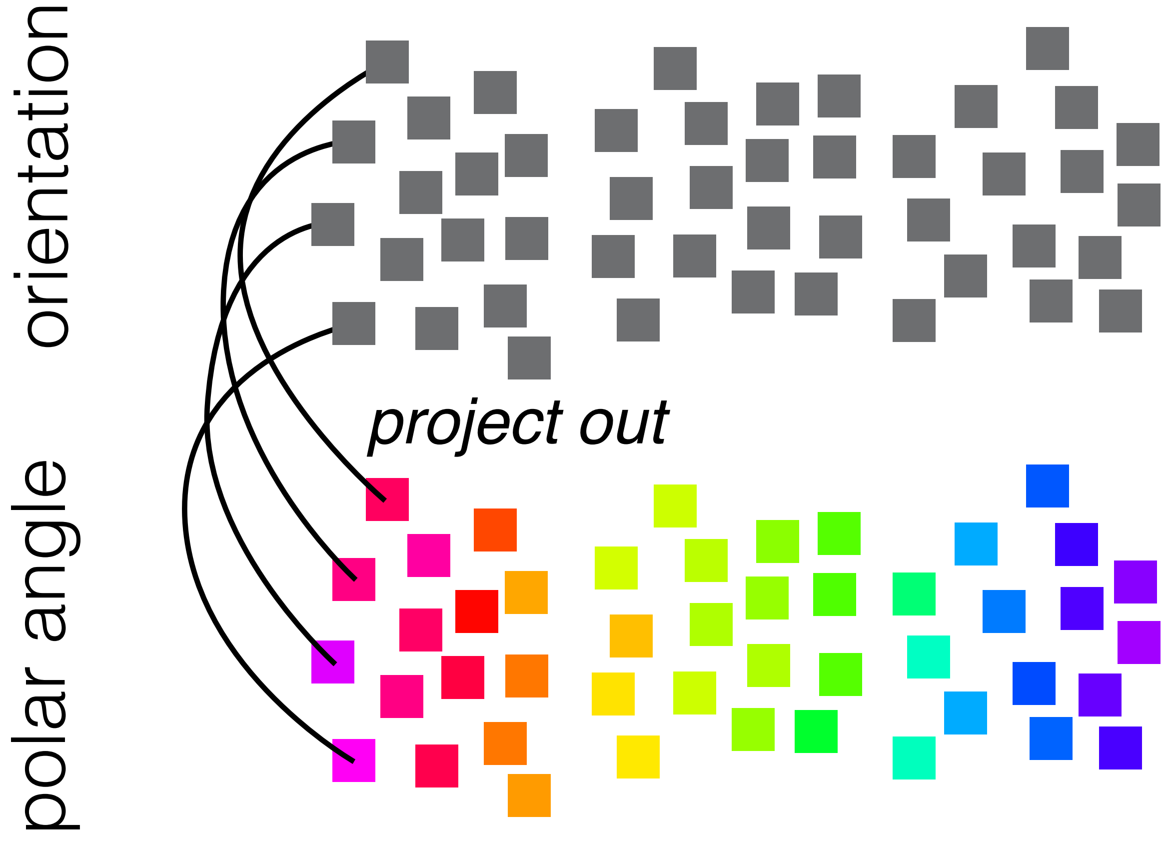
map is ***sufficient*** for decoding

classify averaged responses



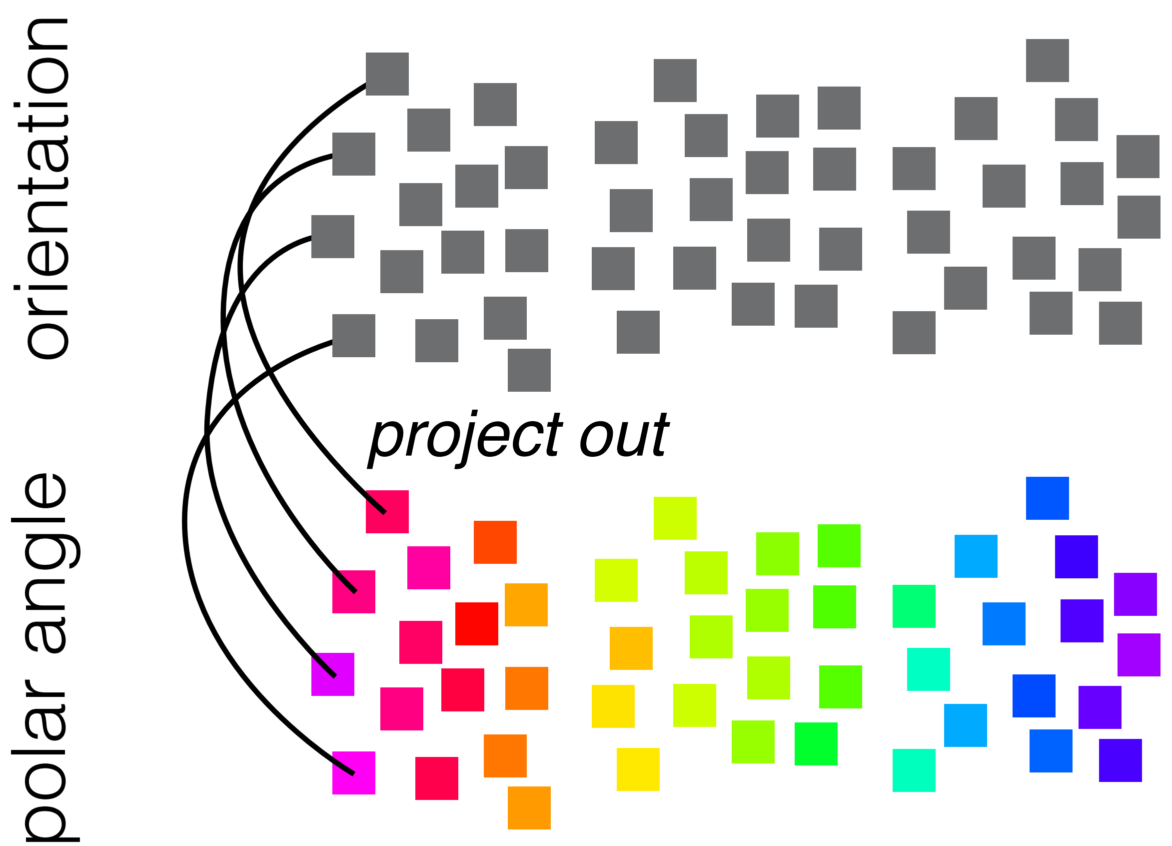
map is ***necessary*** for decoding

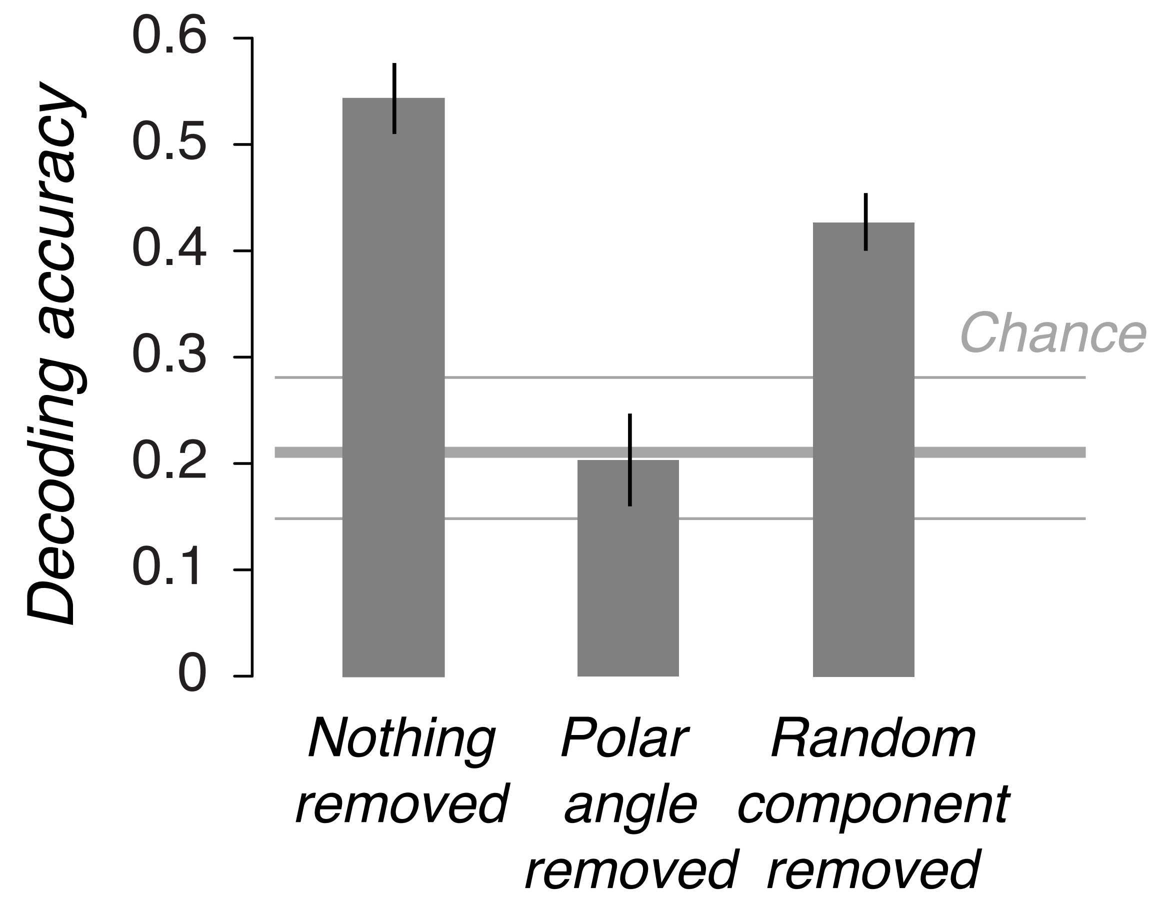
classify residuals after removing response
component predicted by polar angle



map is ***necessary*** for decoding

classify residuals after removing response component predicted by polar angle





overview

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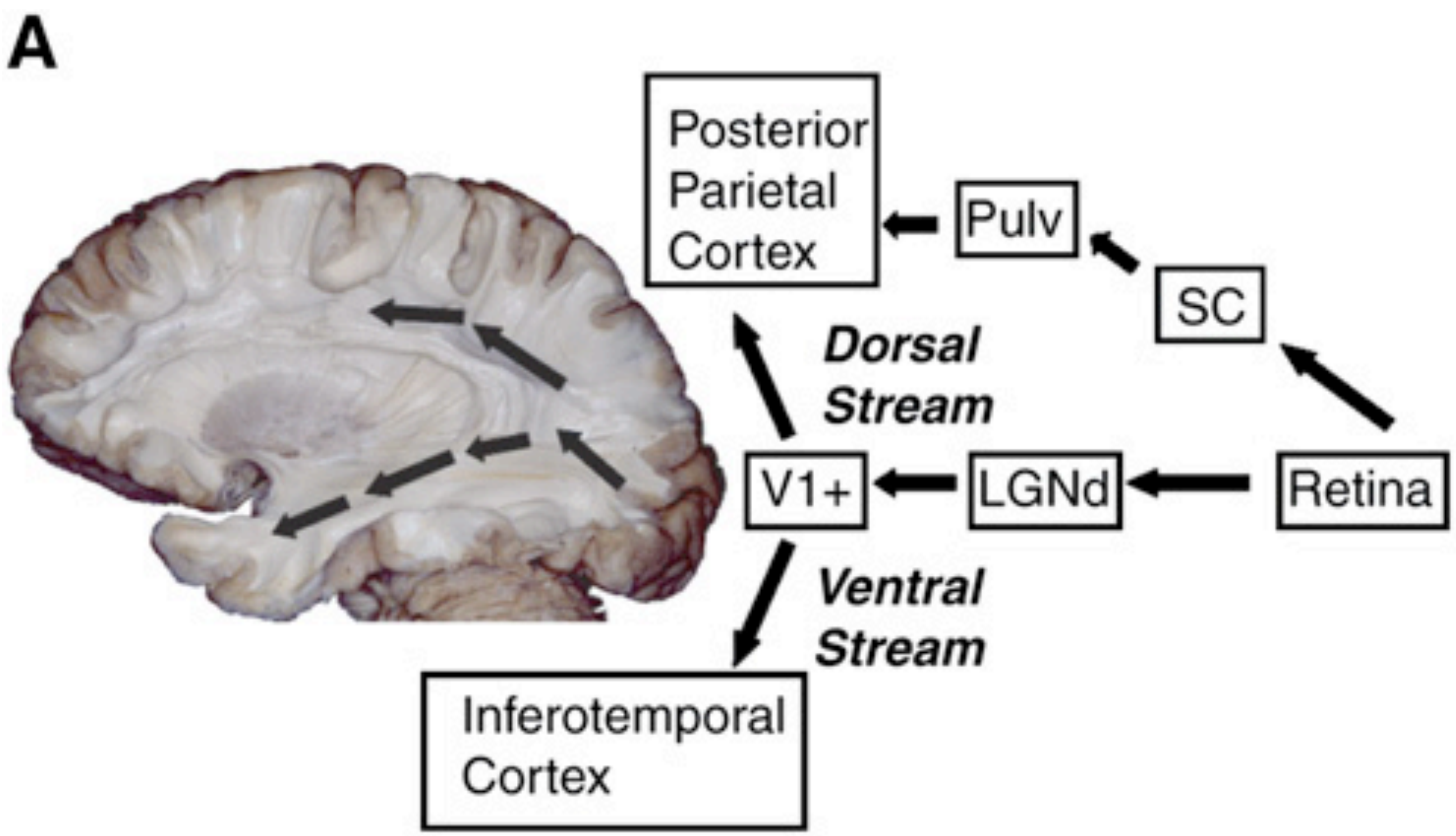
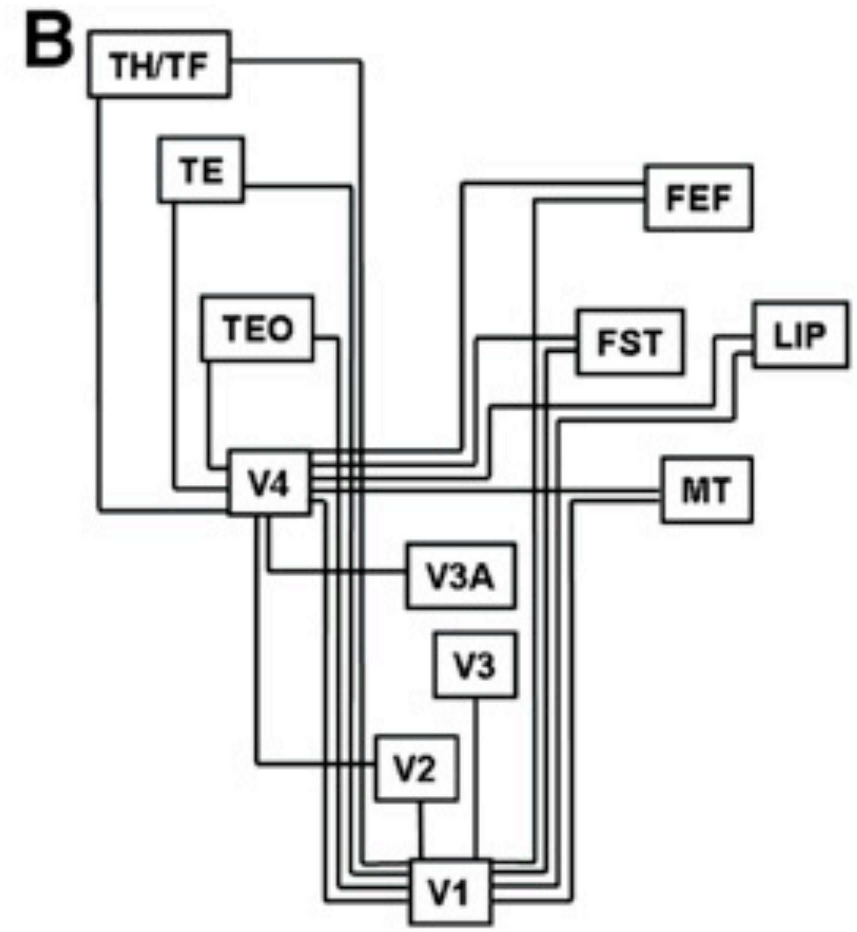
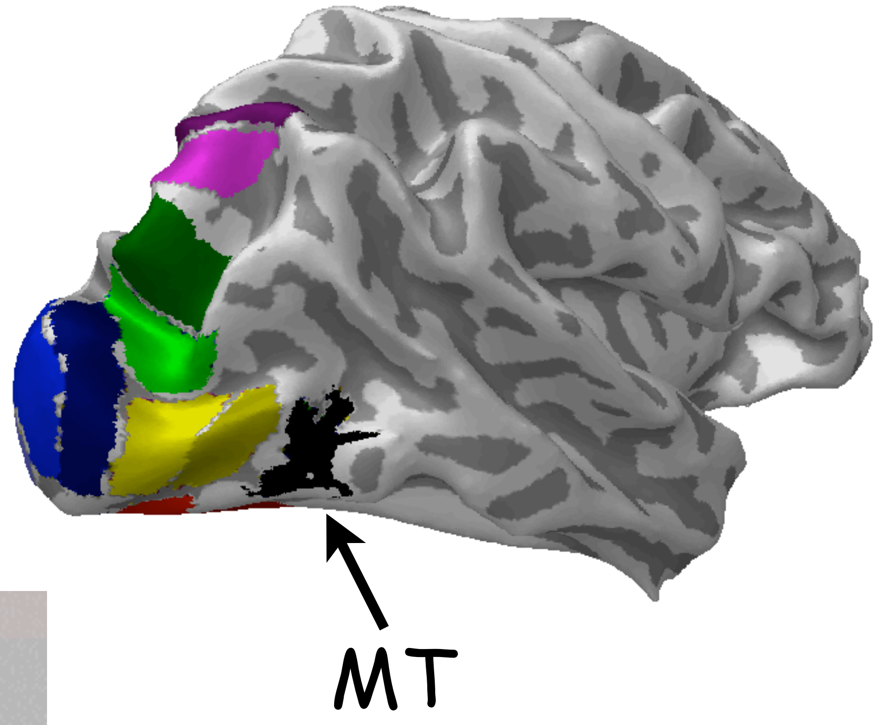
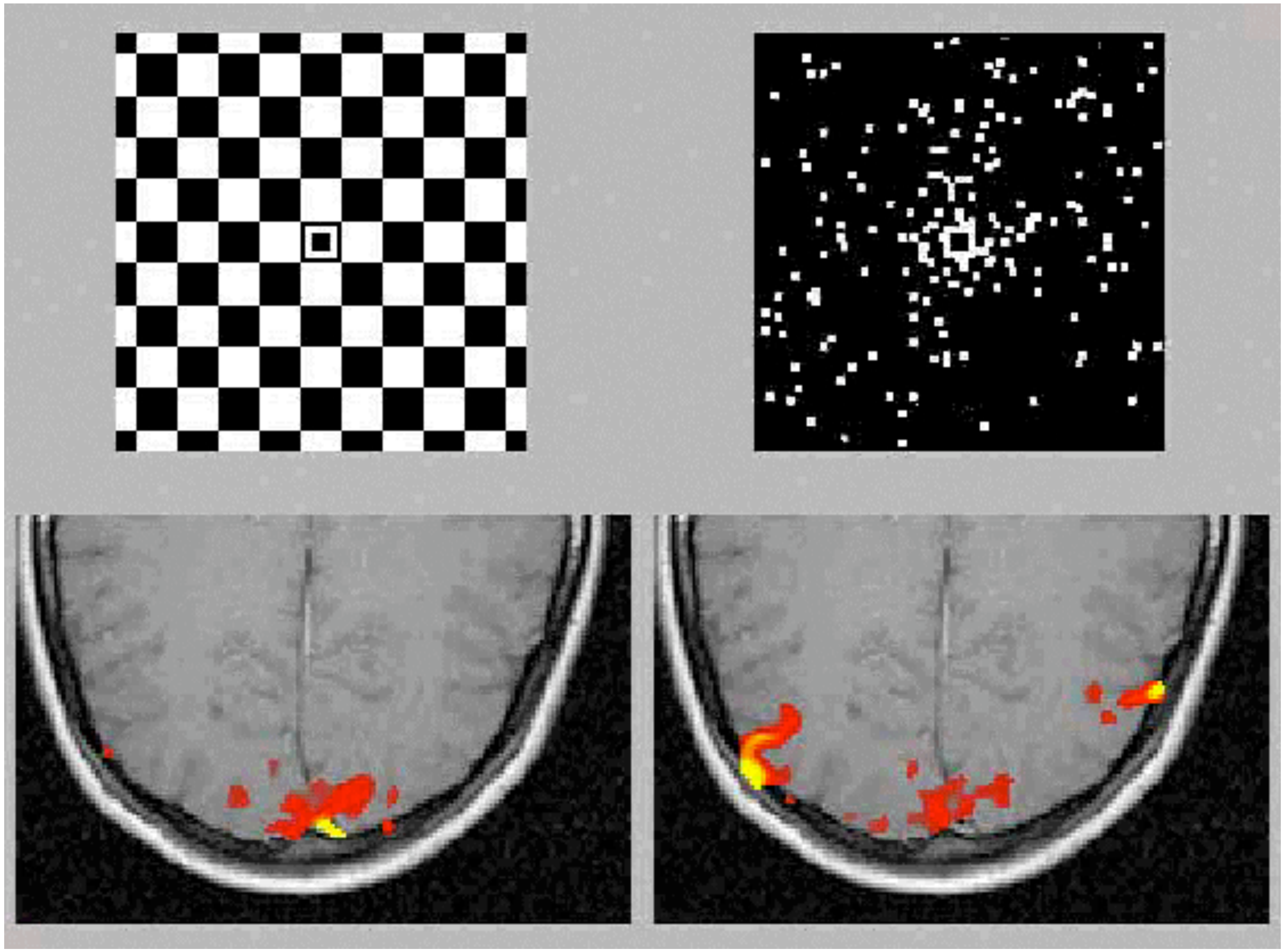
what (ventral) and where (dorsal) pathways



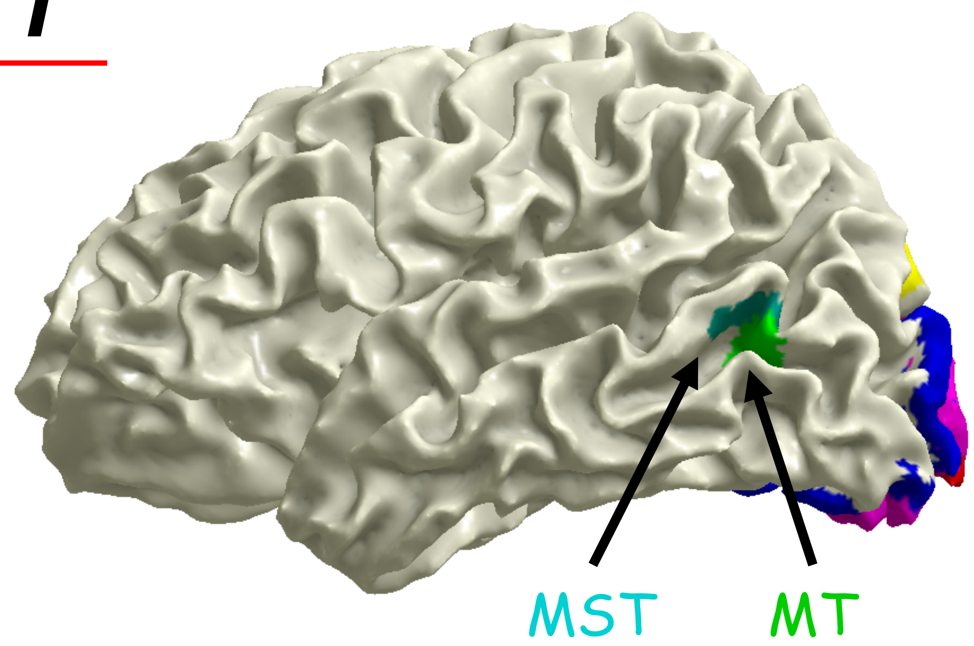


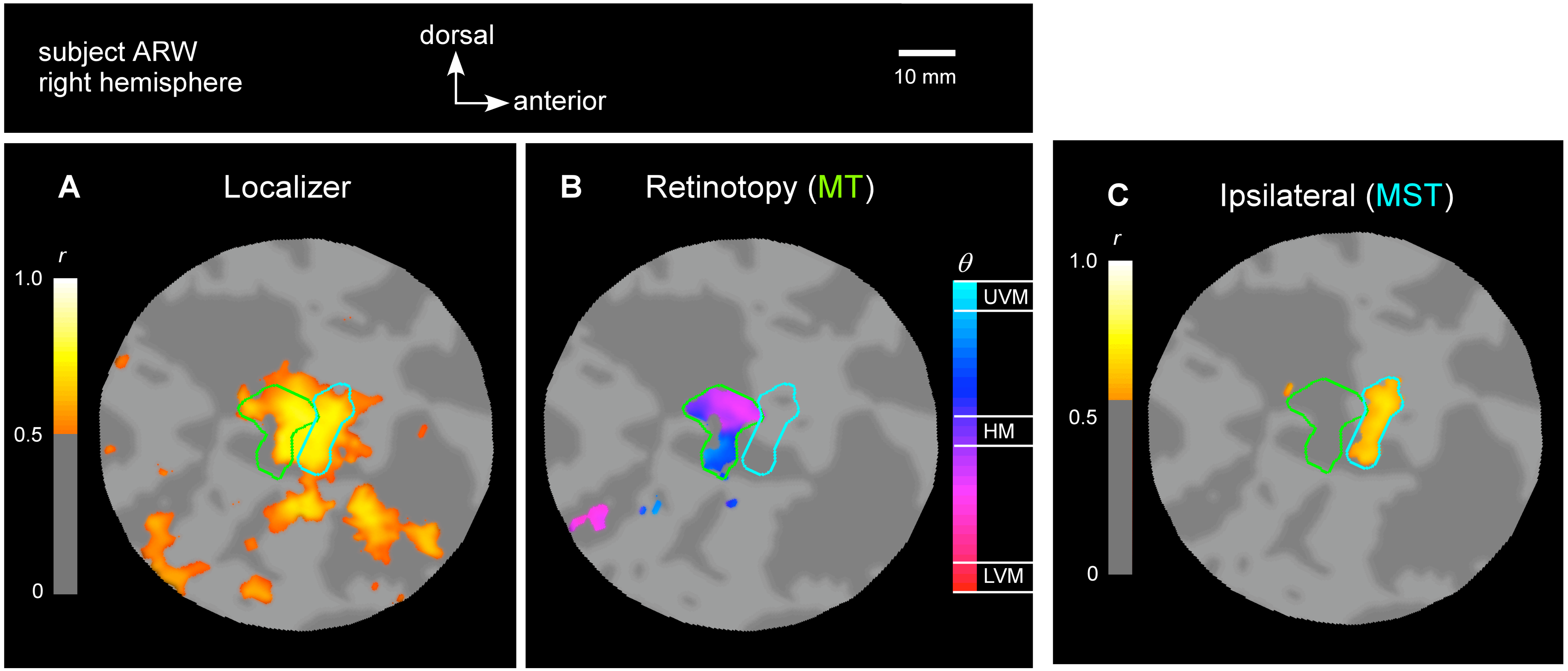
human MT





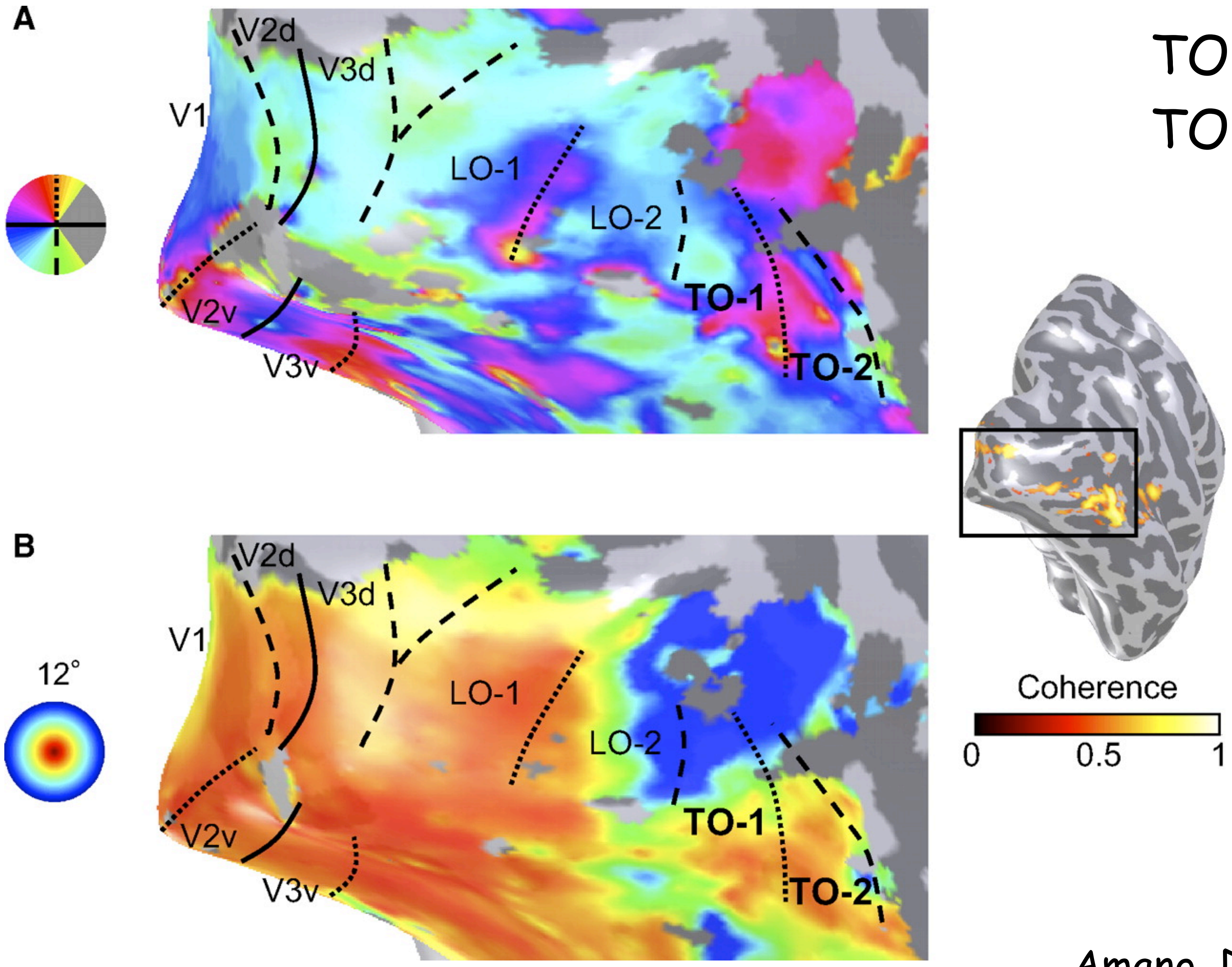
topography in human MT





Huk, Dougherty, & Heeger (2002)

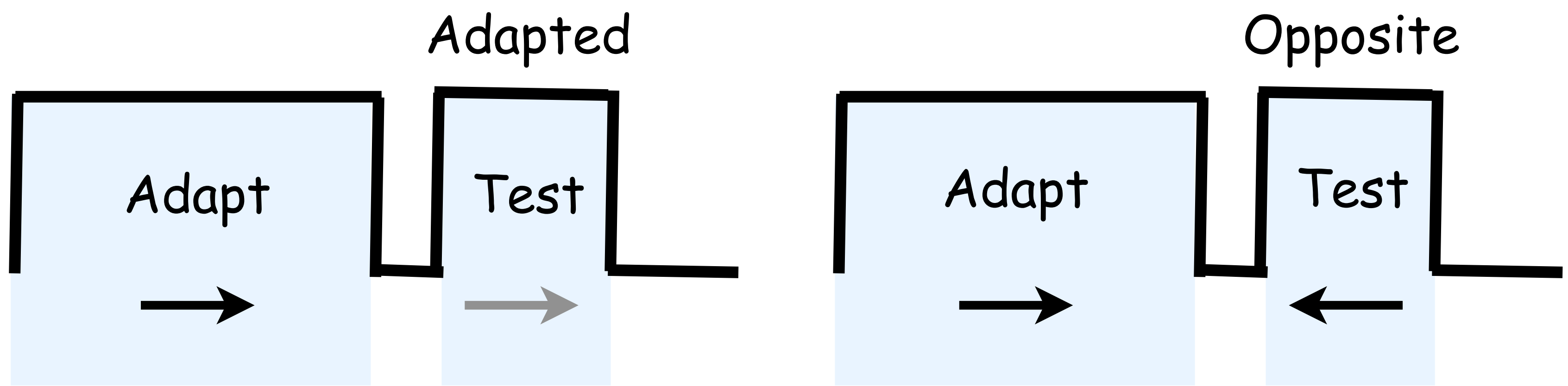
topography in human MT

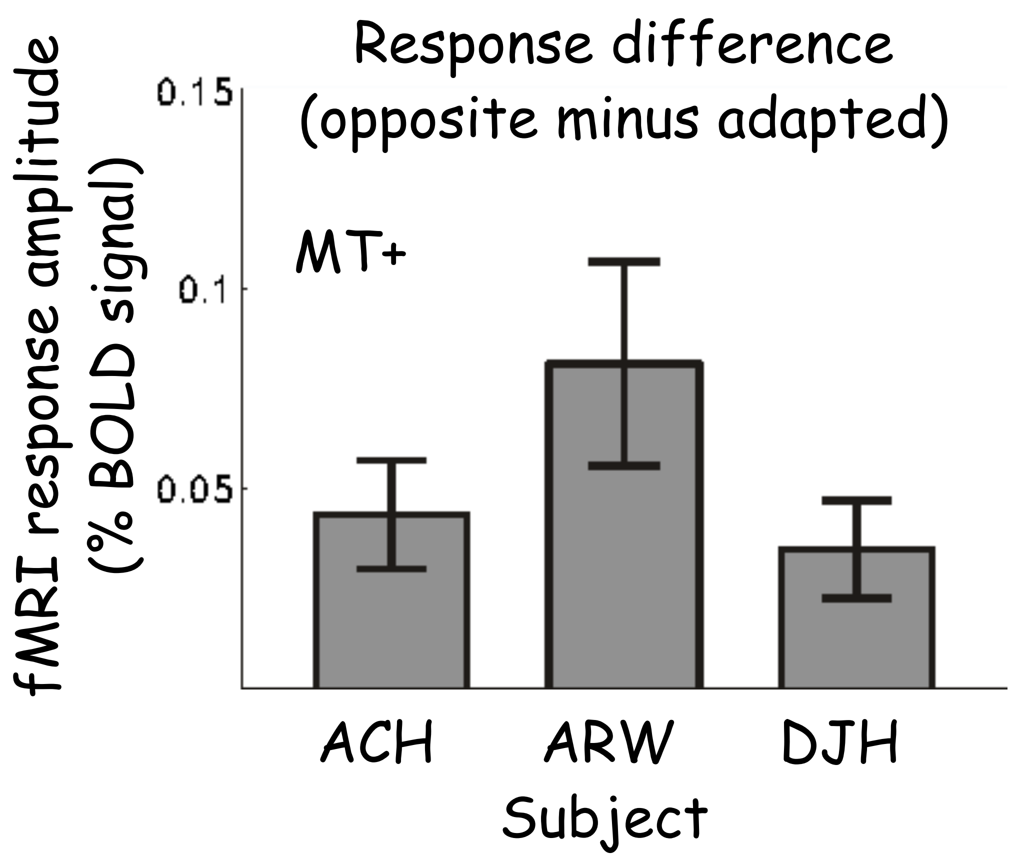


TO-1 = MT
TO-2 = MST

Amano, Dumoulin, & Wandell,
J Neuophysiol (2009)

direction selective adaptation in human MT





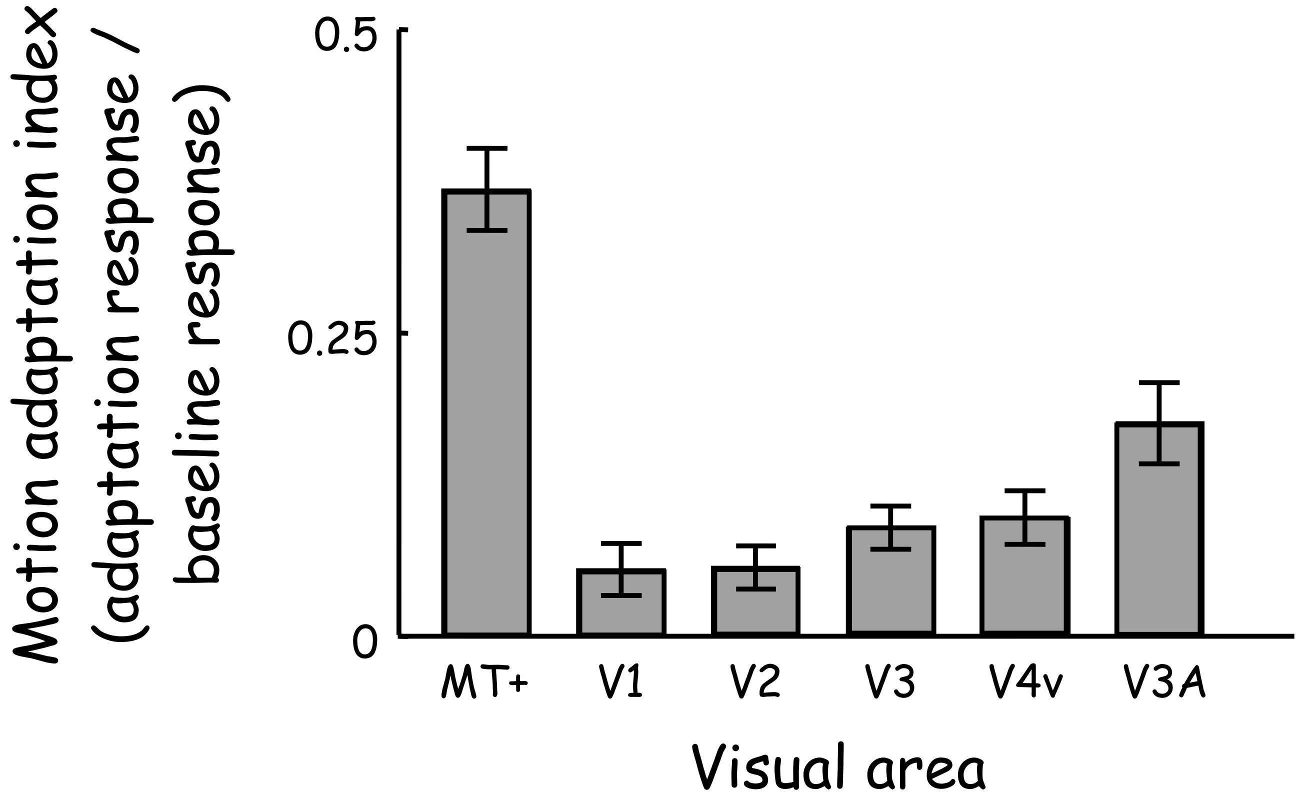
Adaptation improves
speed discrimination thresholds

	Subject		
	ACH	ARW	DJH
Adapted	4.3	7.3	6.6
Opposite	6.9	9.1	9.3

(% speed increment)

Huk, Ress, & Heeger (2001)

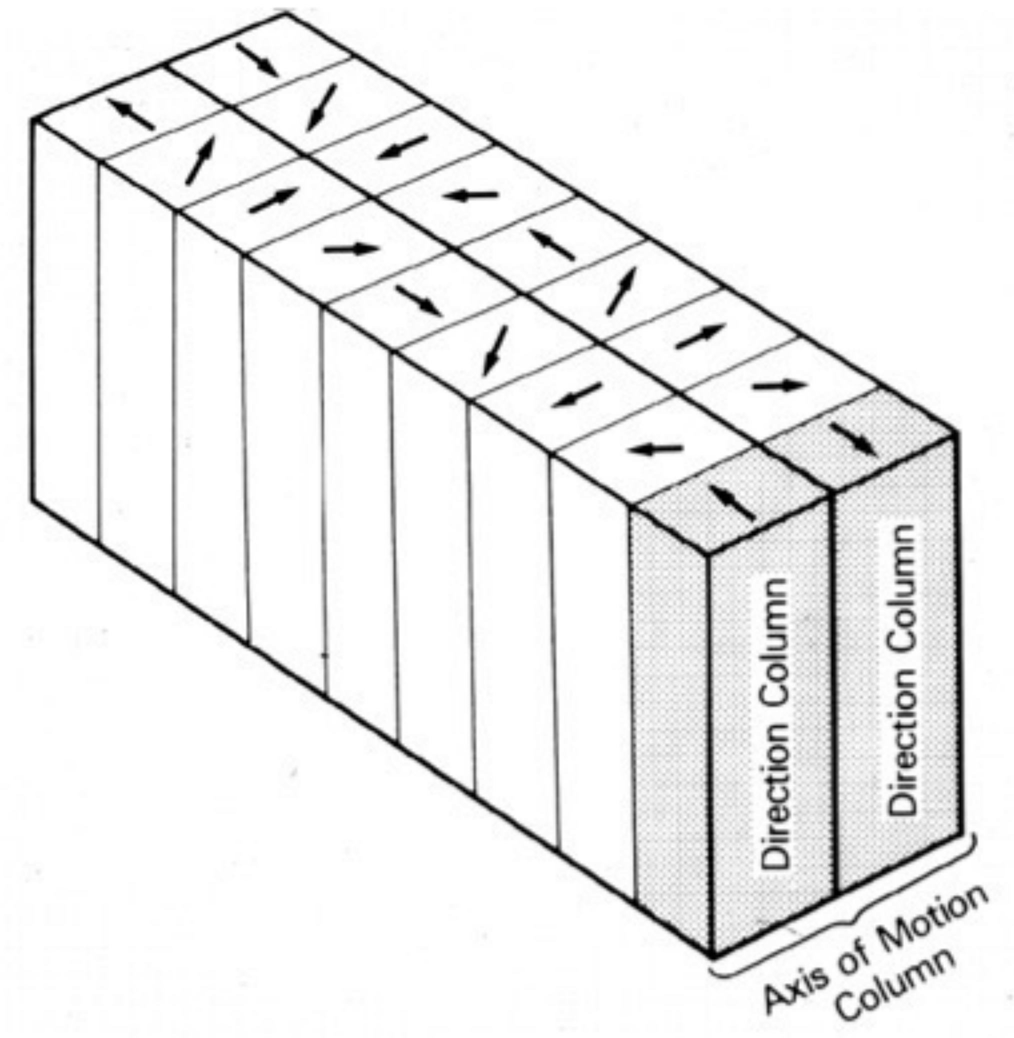
direction selectivity across visual areas



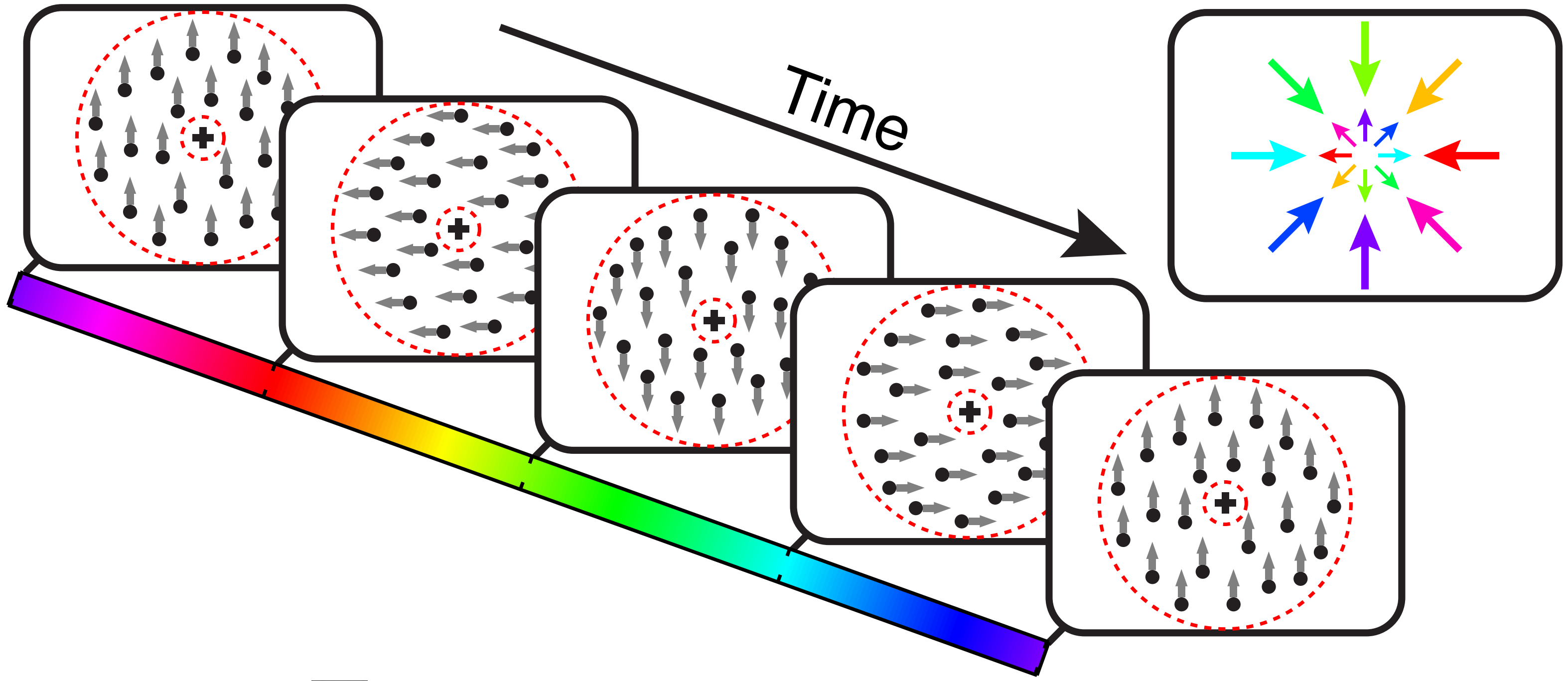
Huk, Ress, & Heeger (2001)

direction selective columns?

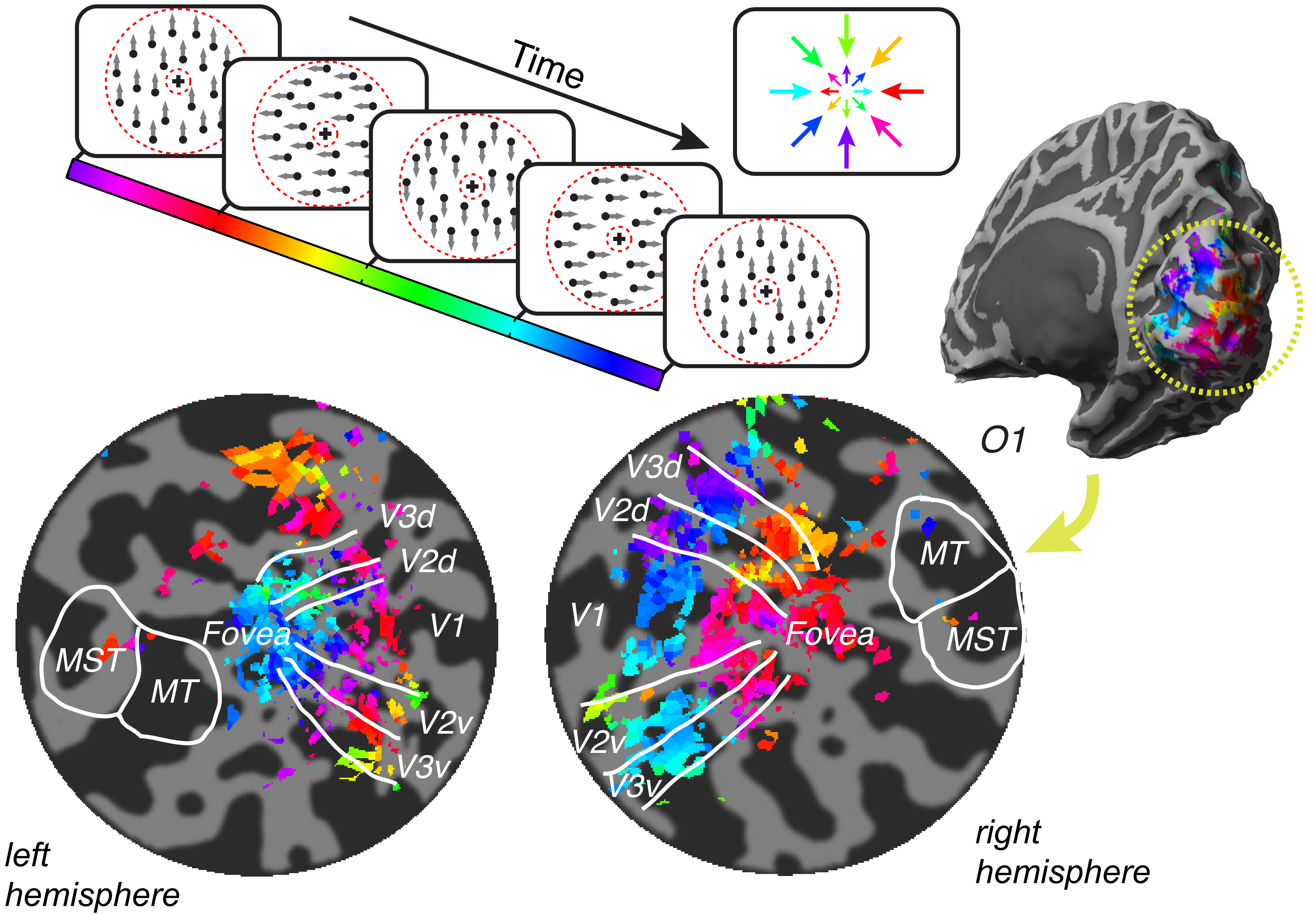
columnar architecture for motion direction in MT



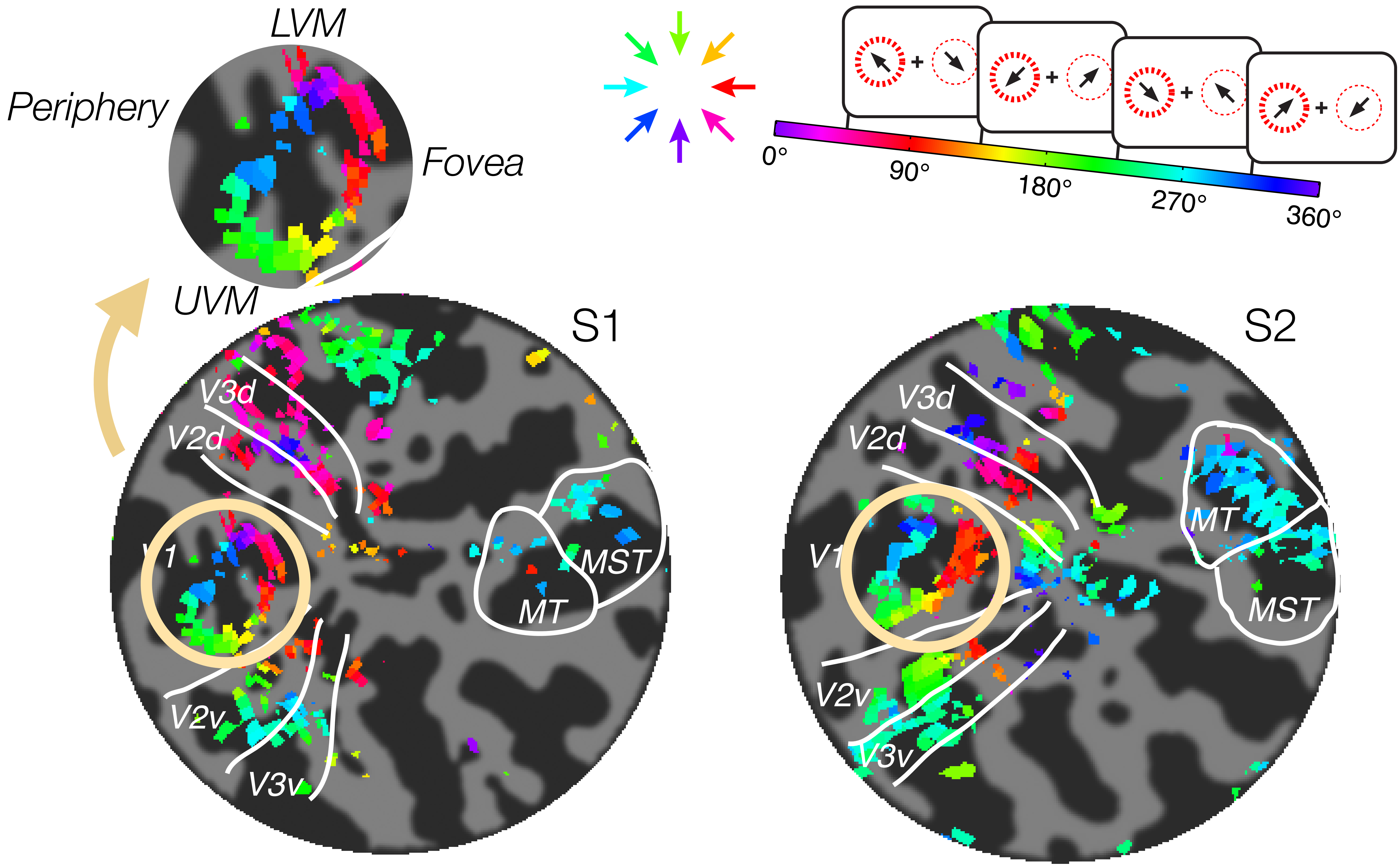
motion direction bias



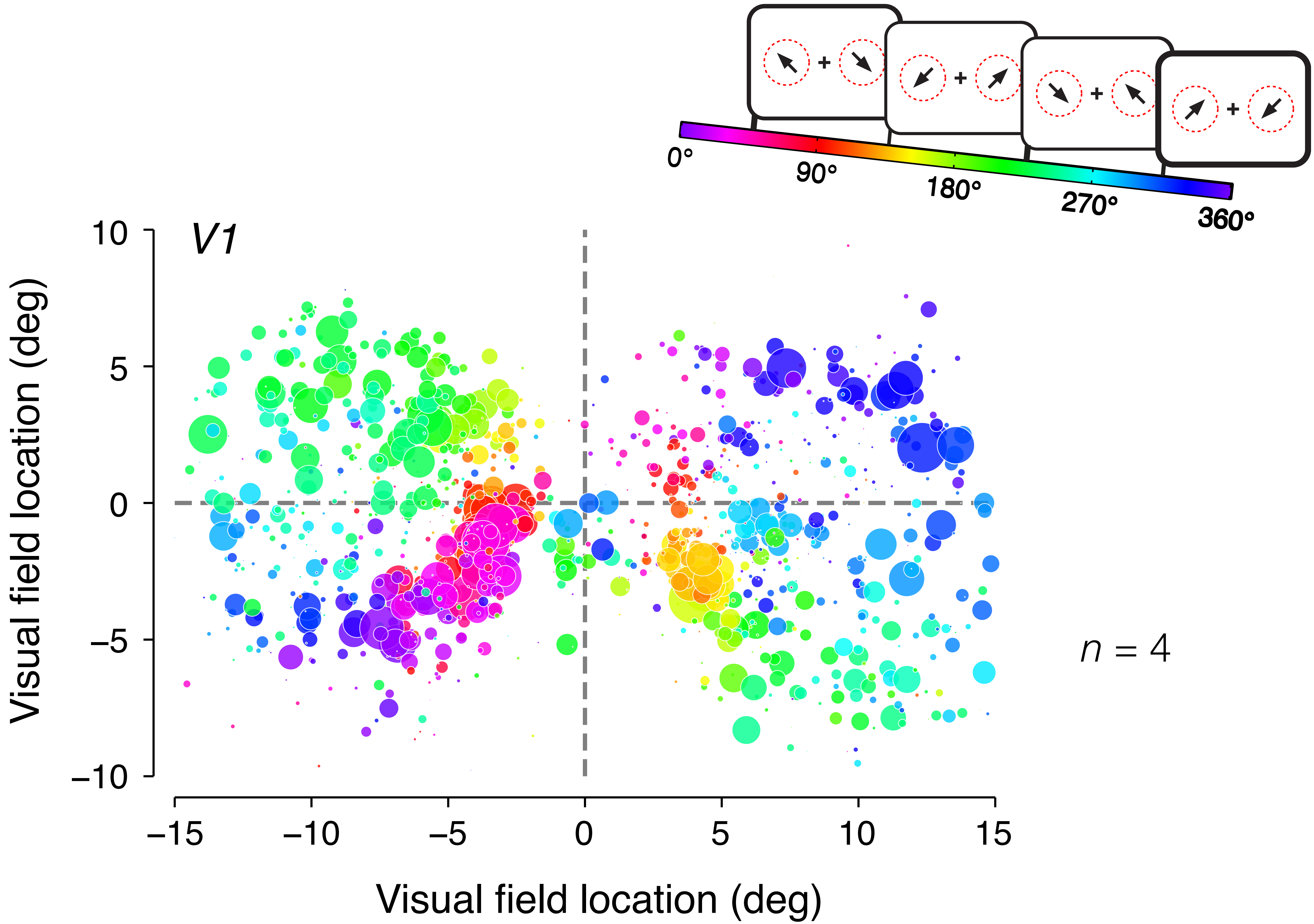
motion direction bias



direction bias depends on aperture



direction bias depends on aperture



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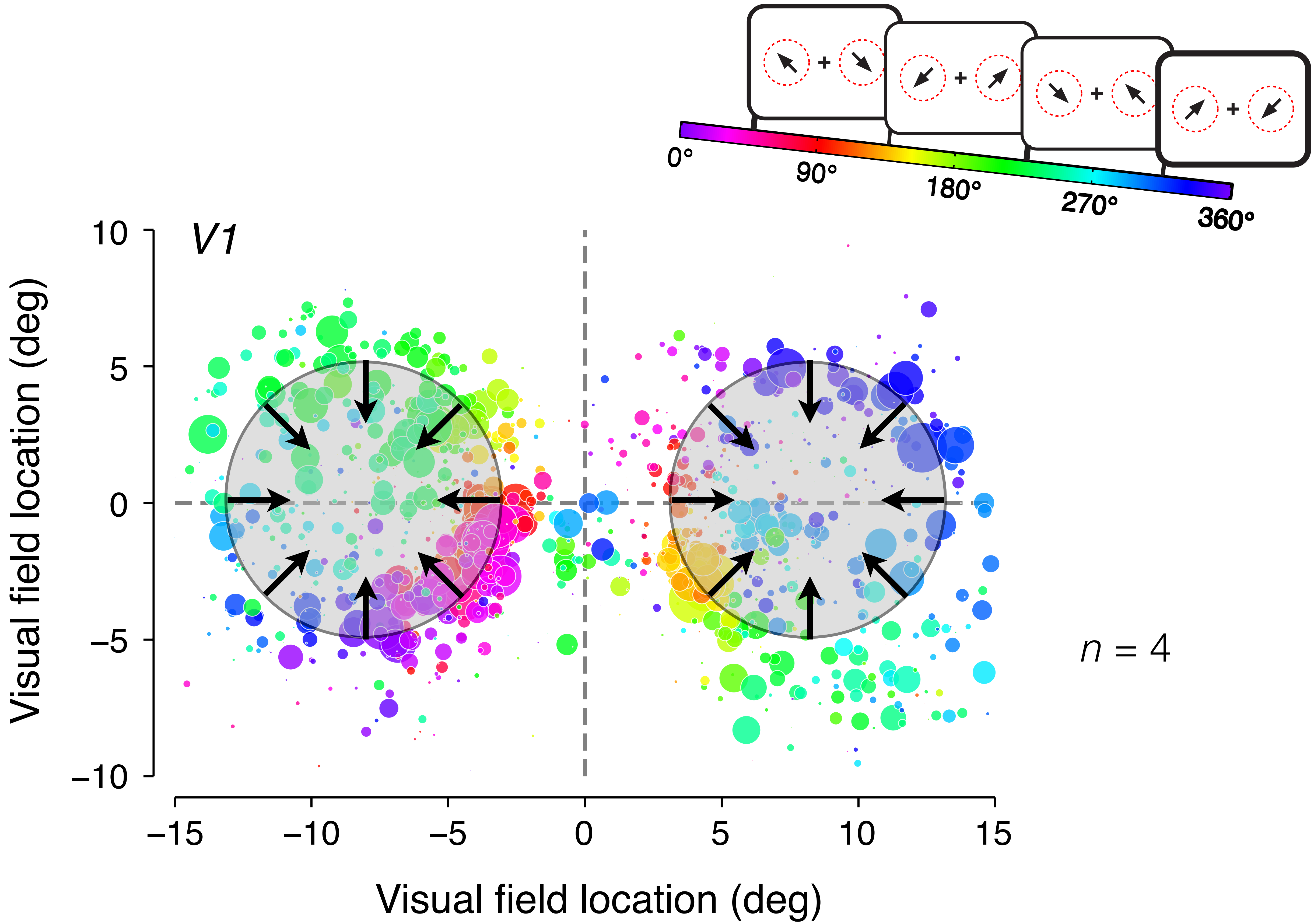
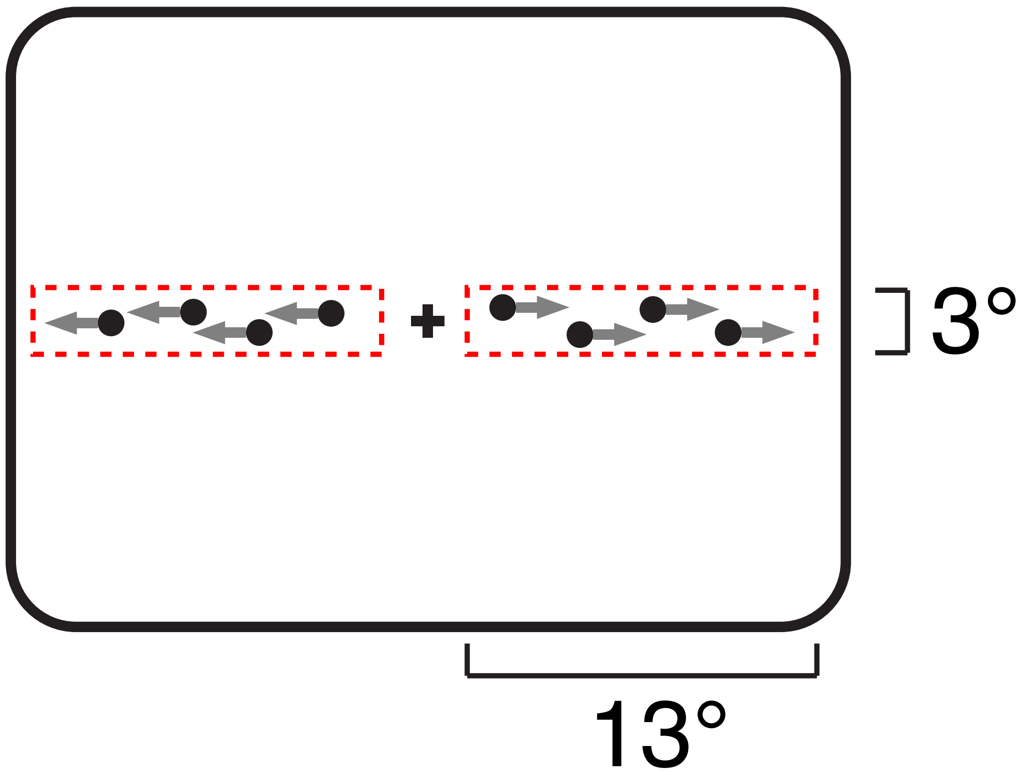
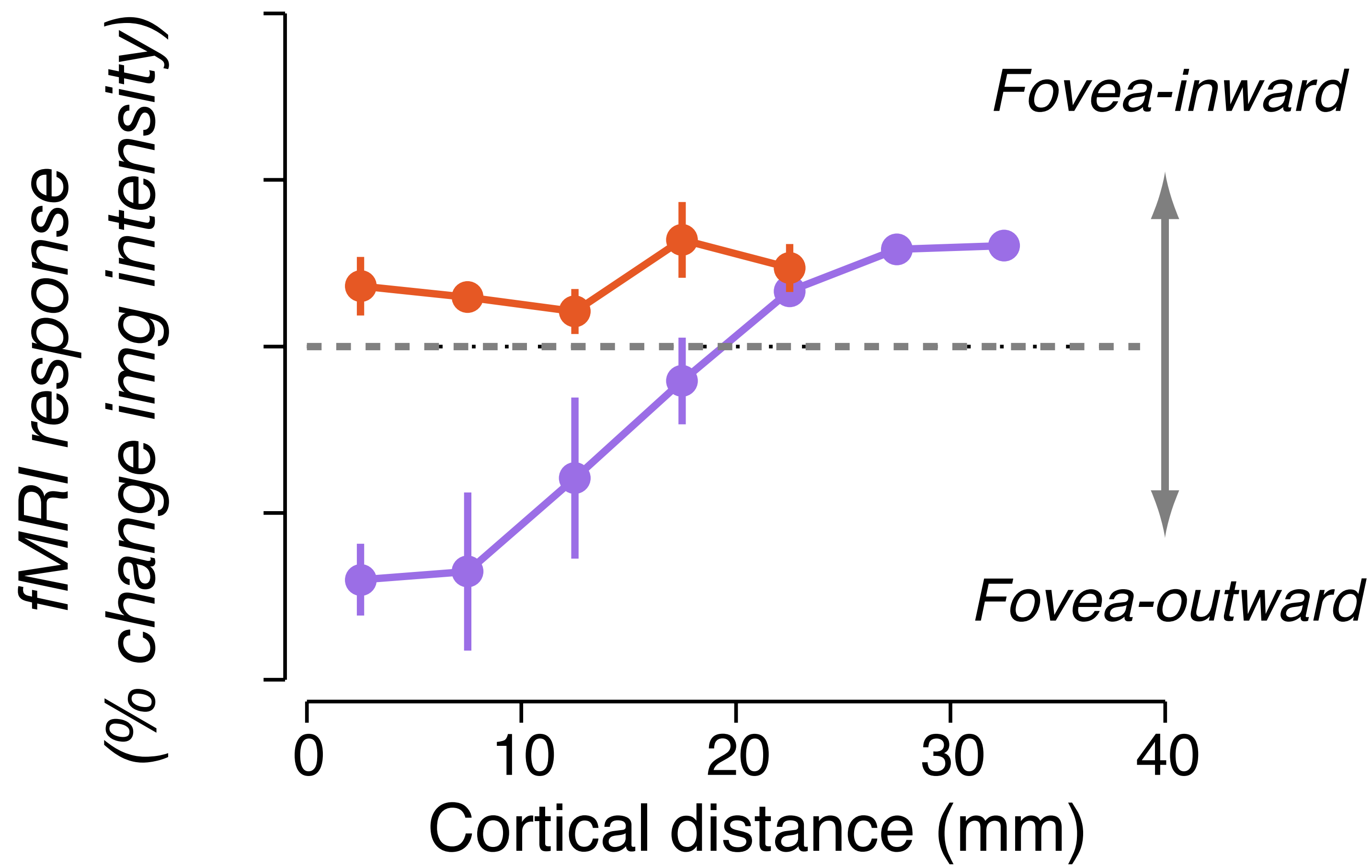


suppression along path of motion





overview

- *why study human vision?*
- *retinotopic mapping*
- *functional specialization*

    orientation
    motion
    color
    objects, faces, and letters

fMRI good for measuring coarse-scale patterns of activity

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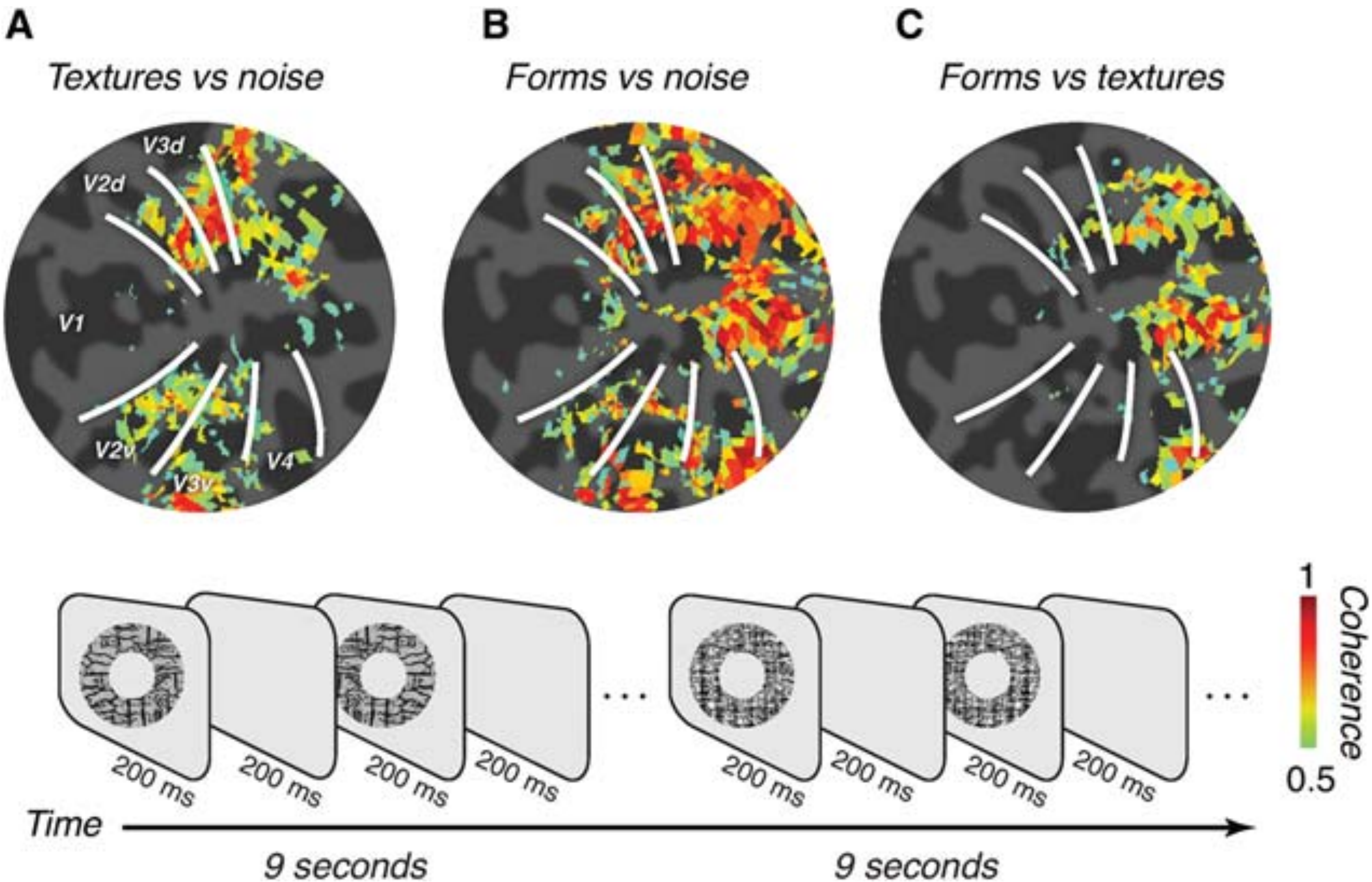
- *bottom-up hierarchical processing within visual cortical areas*
- *top-down influences on visual cortical area*

hierarchical processing in visual cortex



Movshon lab, unpublished

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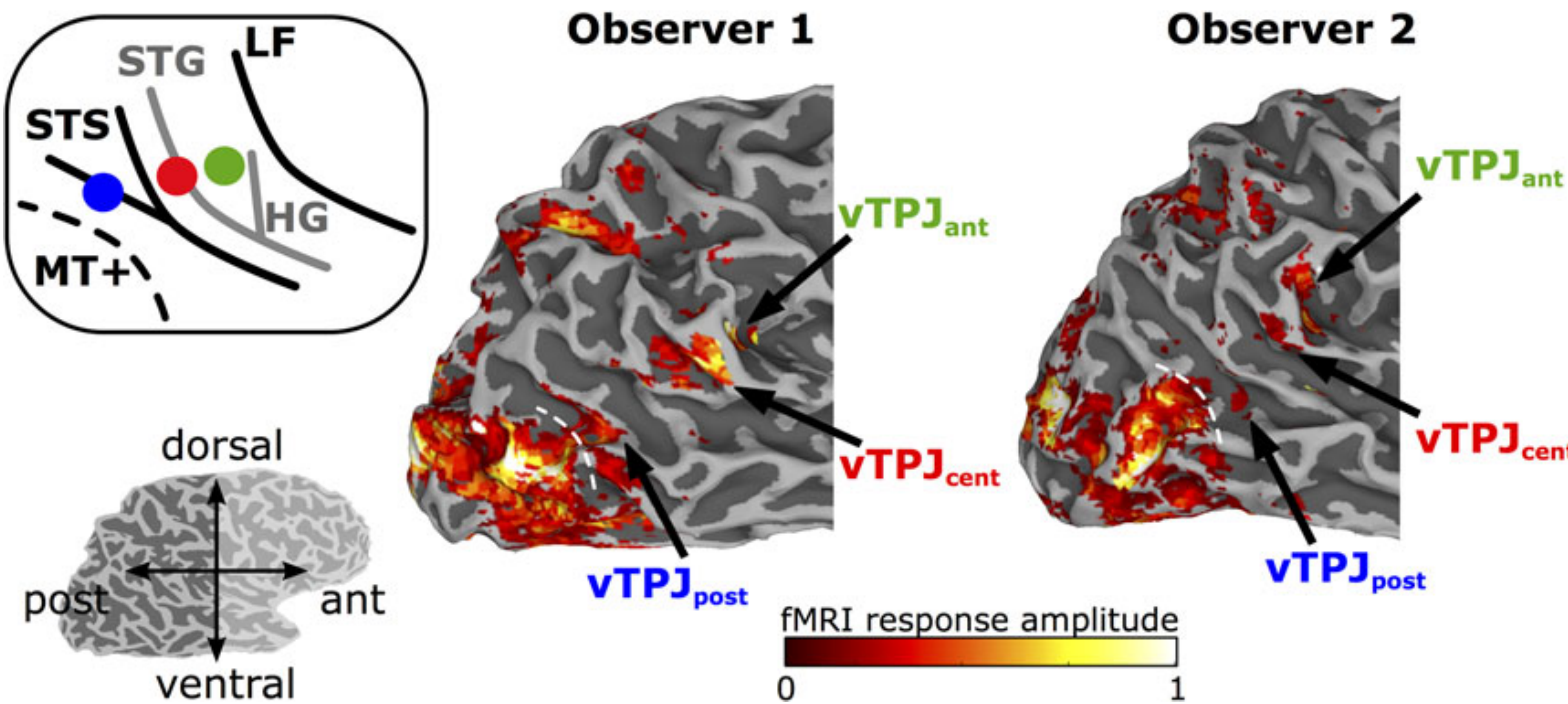
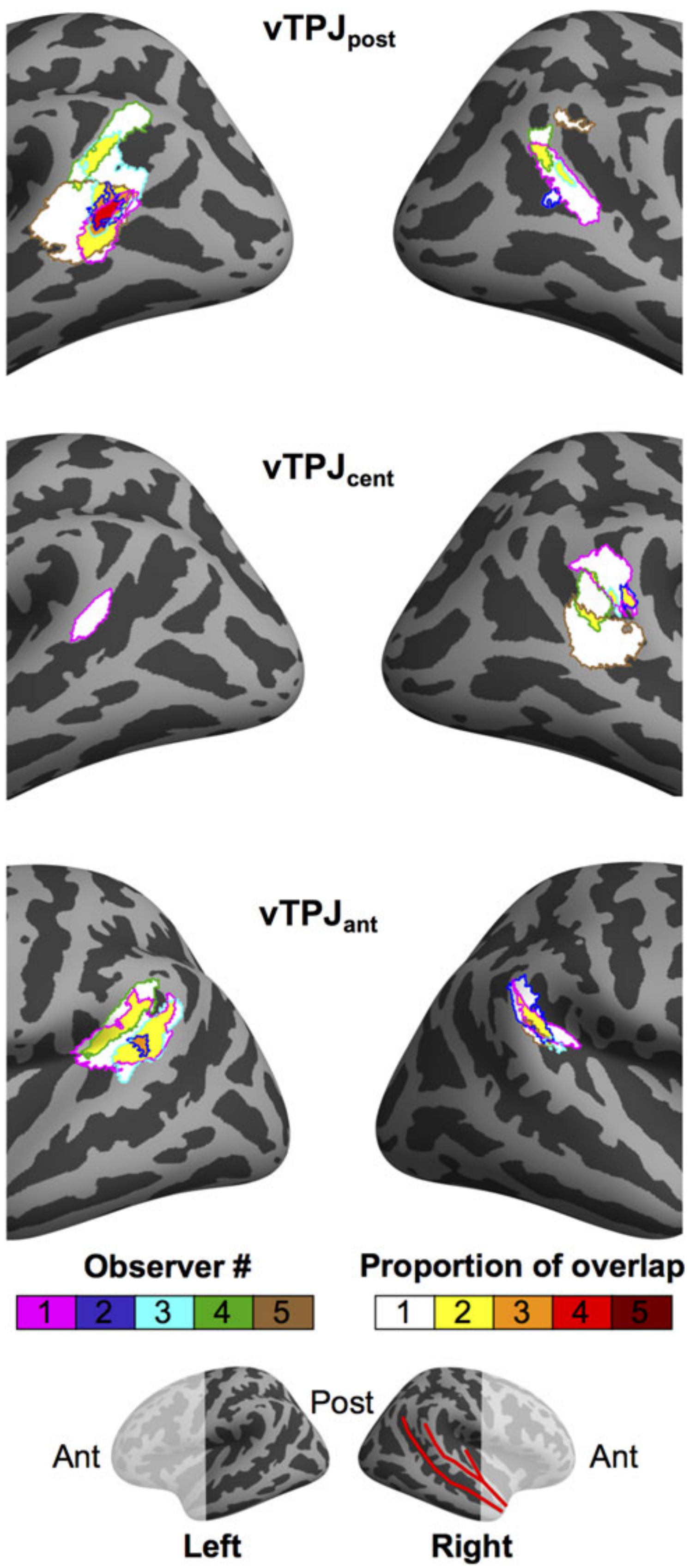
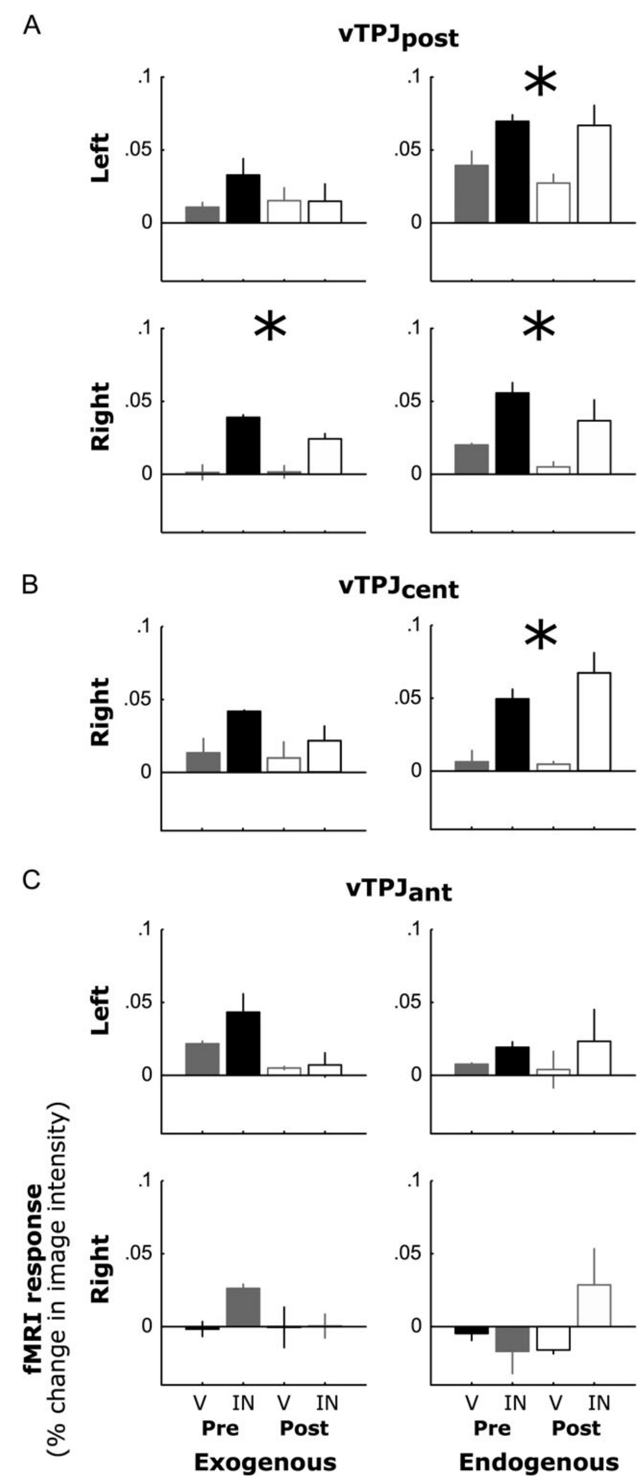
source of top-down modulation



Dugue, Merriam, etc al., 2018

source of top-down modulation





Dugue, Merriam, et al., 2018

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The future is layer fMRI!!

thank you!