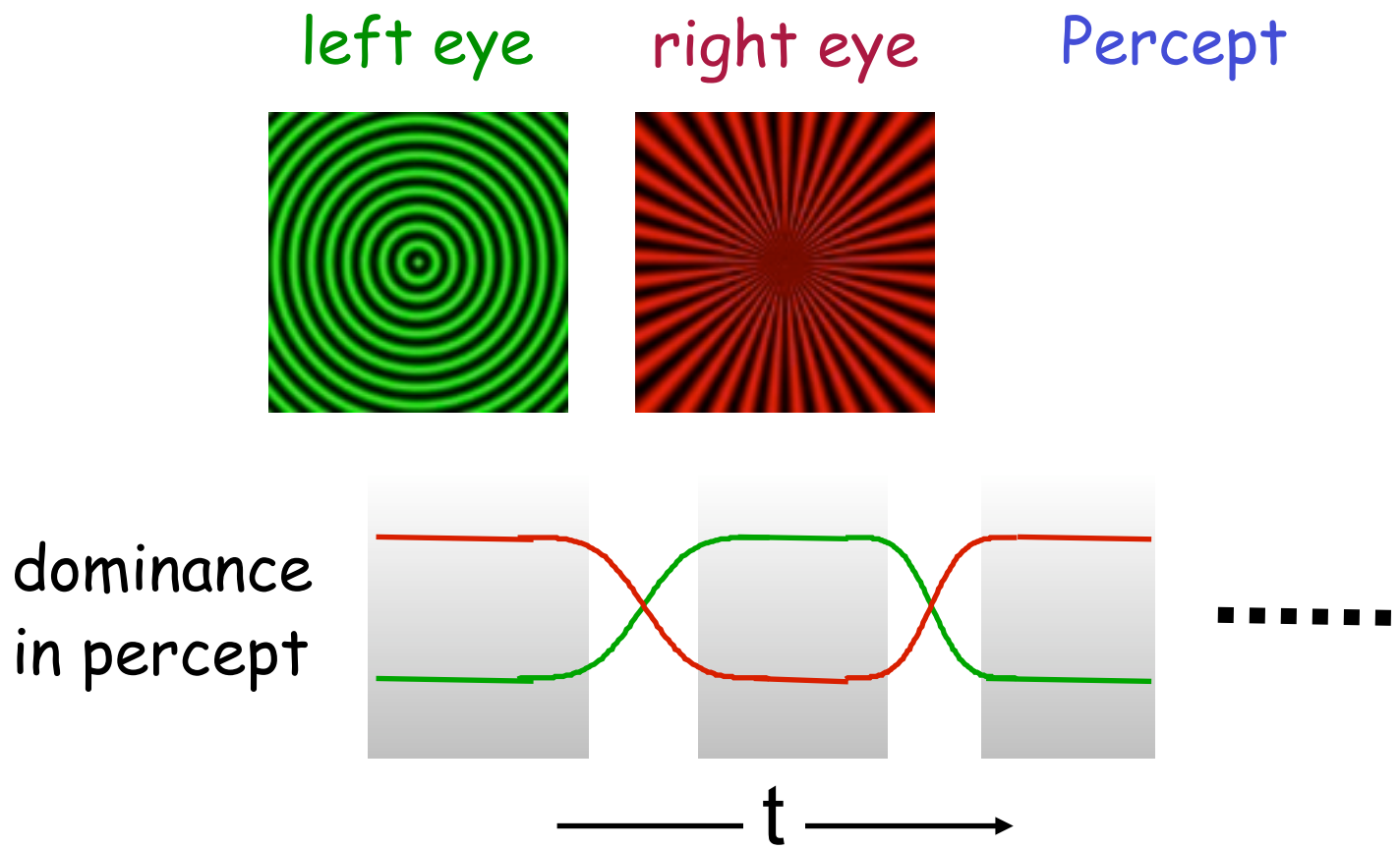
Spatiotemporal dynamics of activity in human visual cortex

David J. Heeger
New York University

Part I: Spatiotemporal dynamics during binocular rivalry



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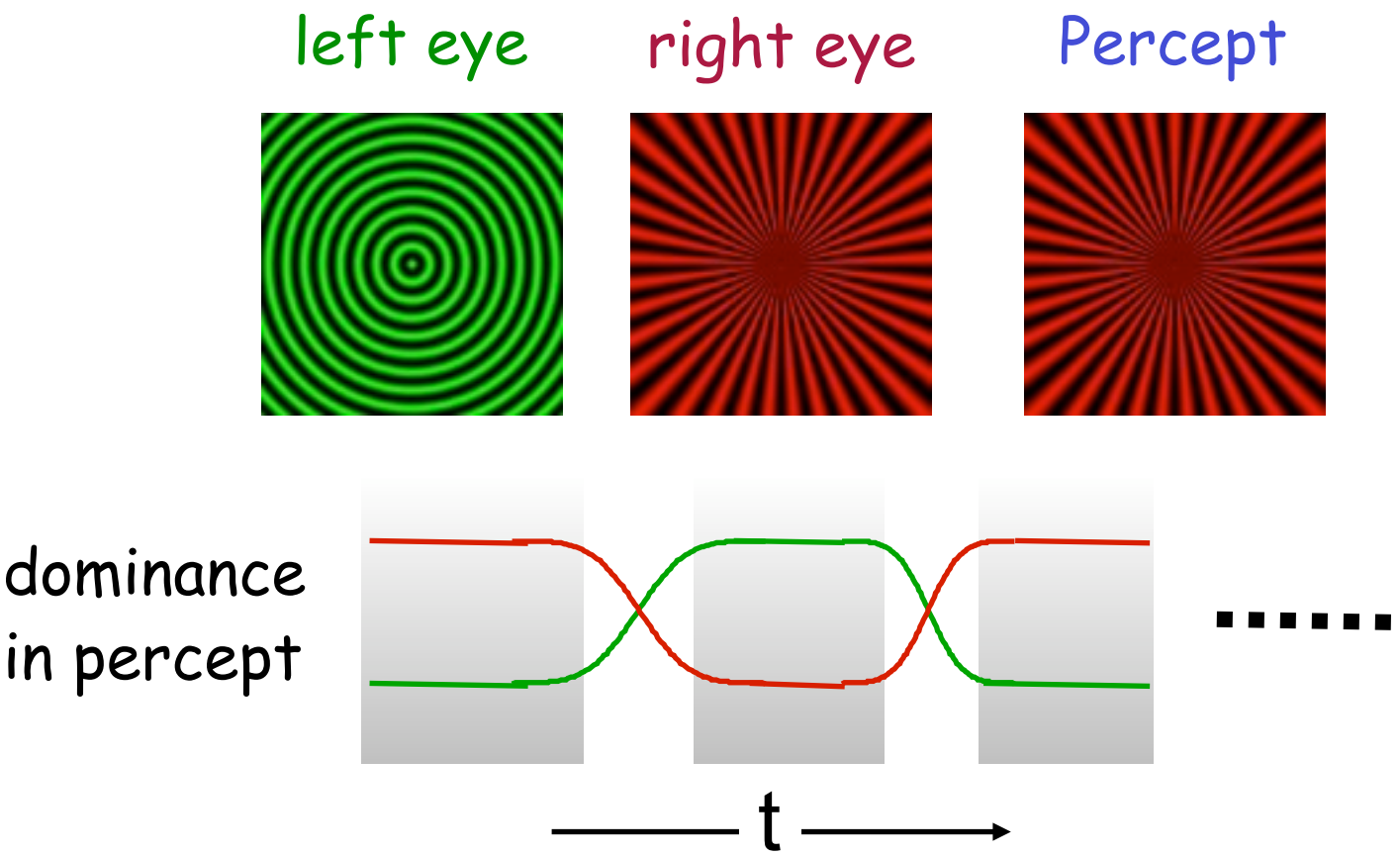

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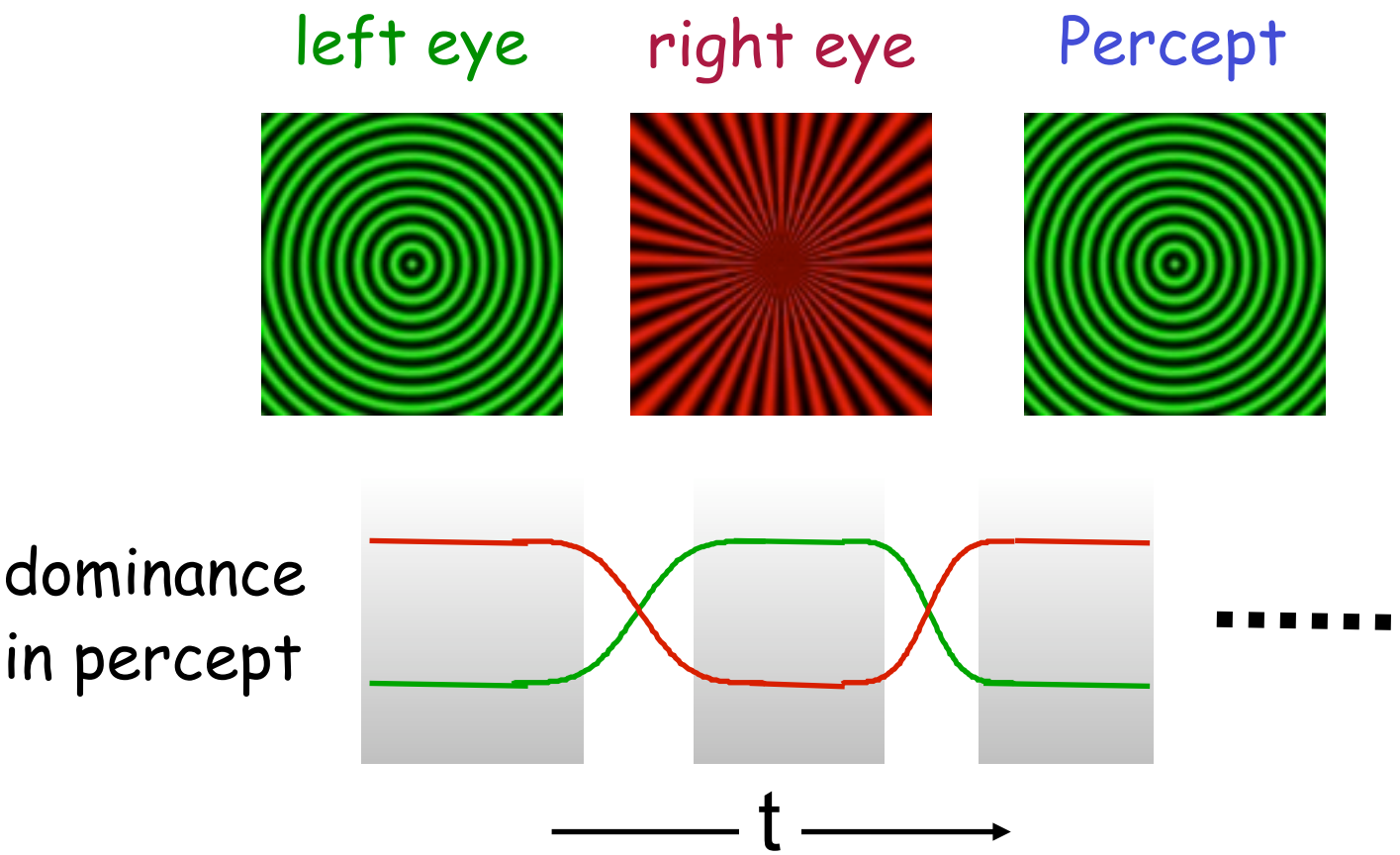

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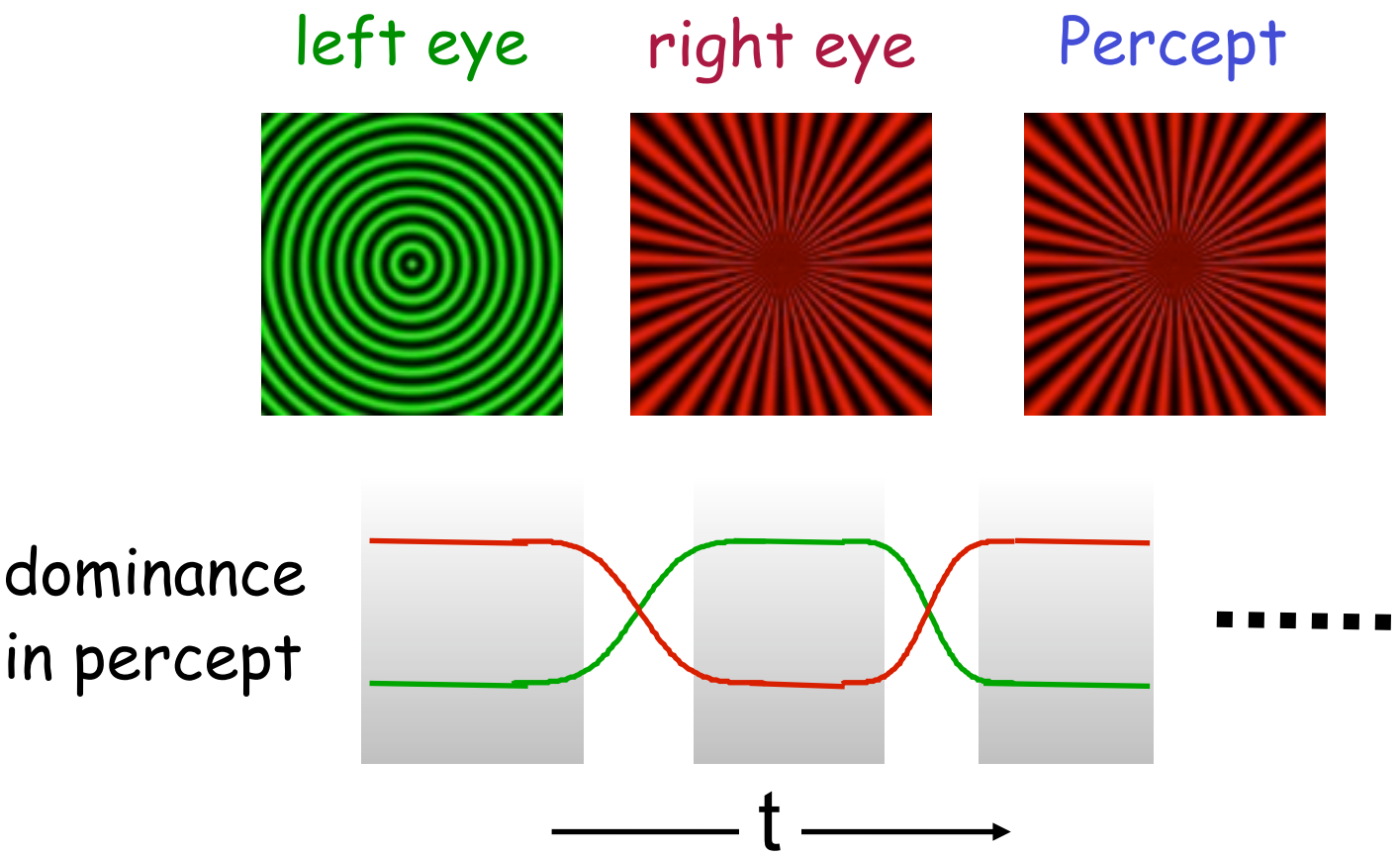

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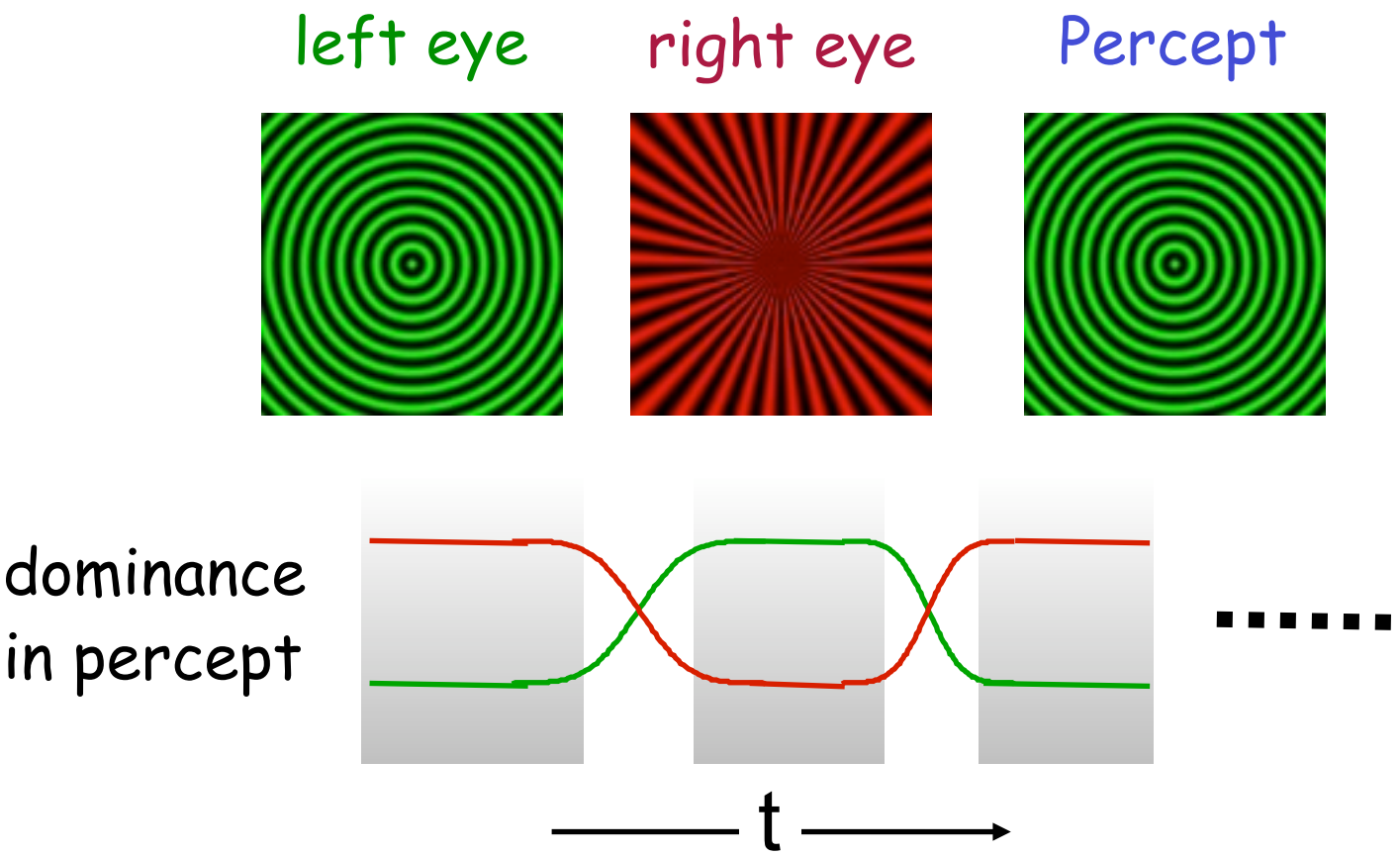

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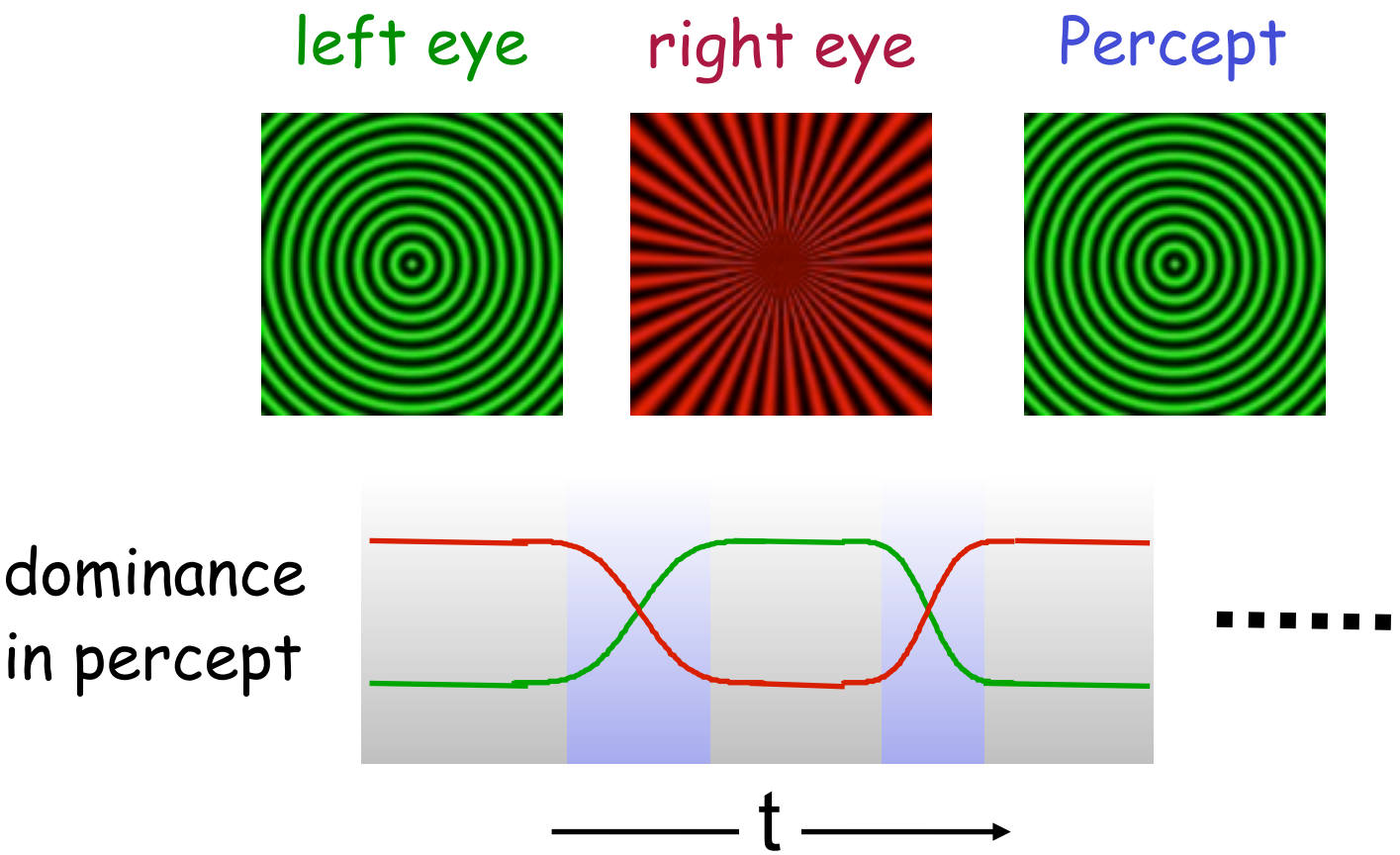

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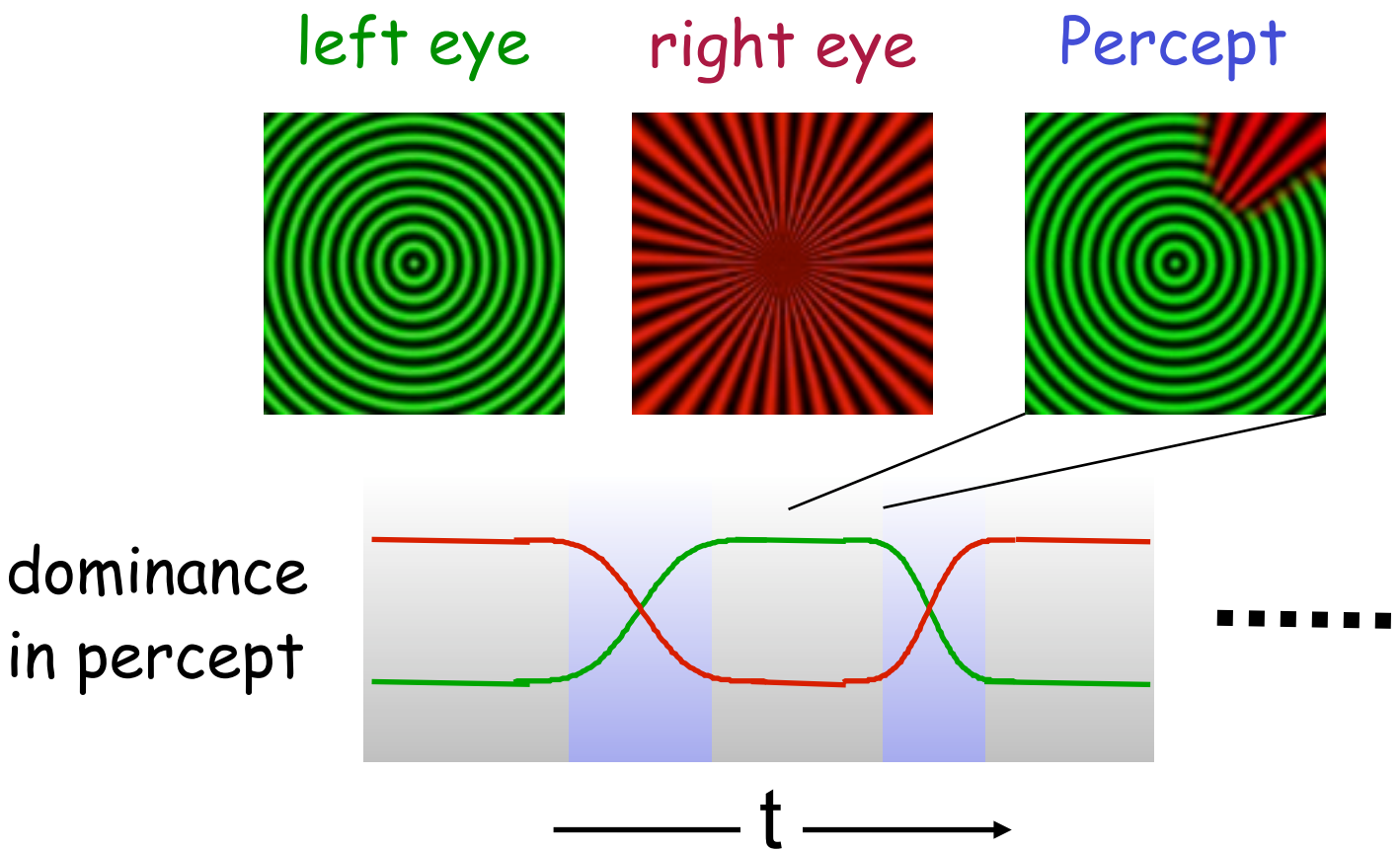

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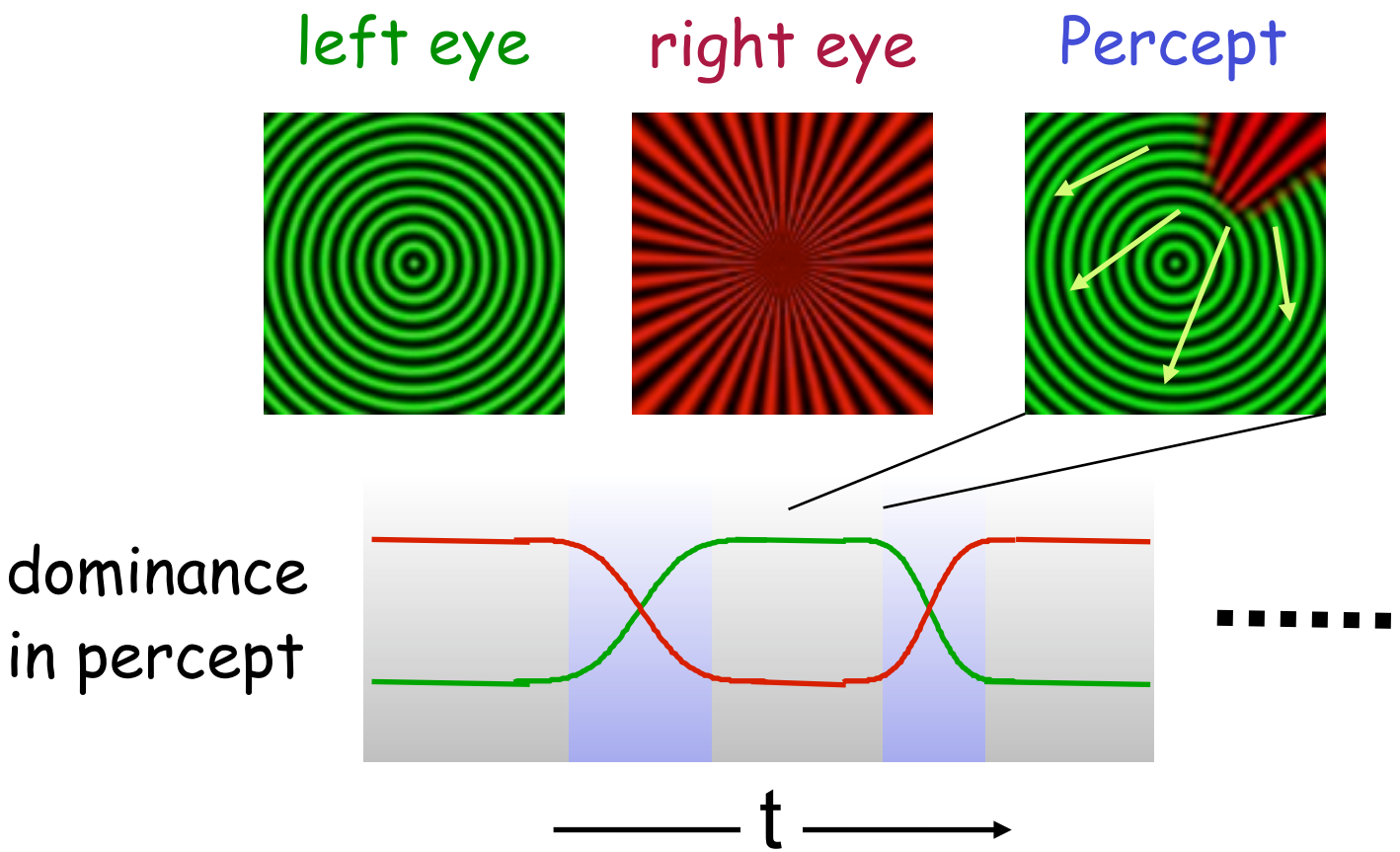

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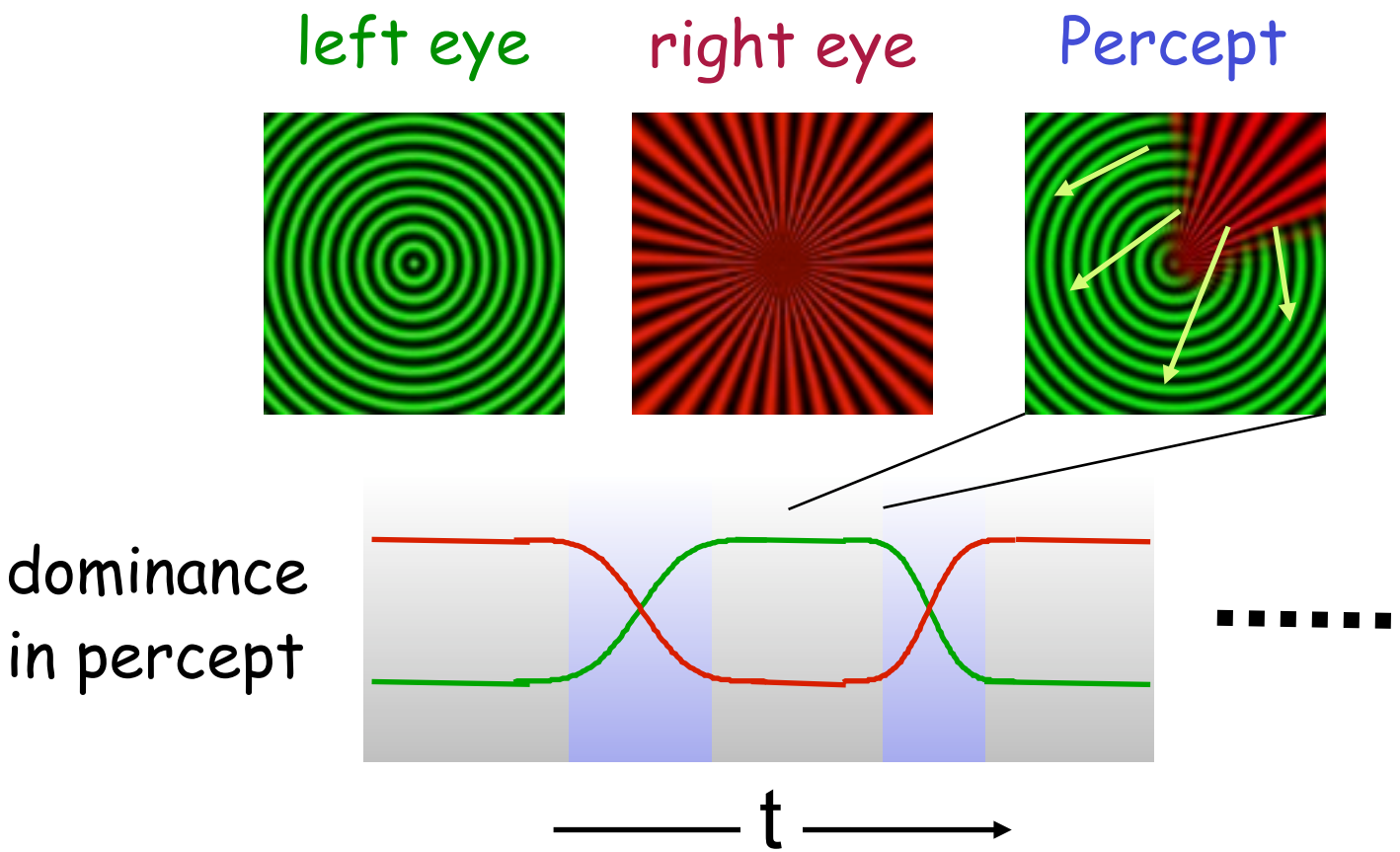

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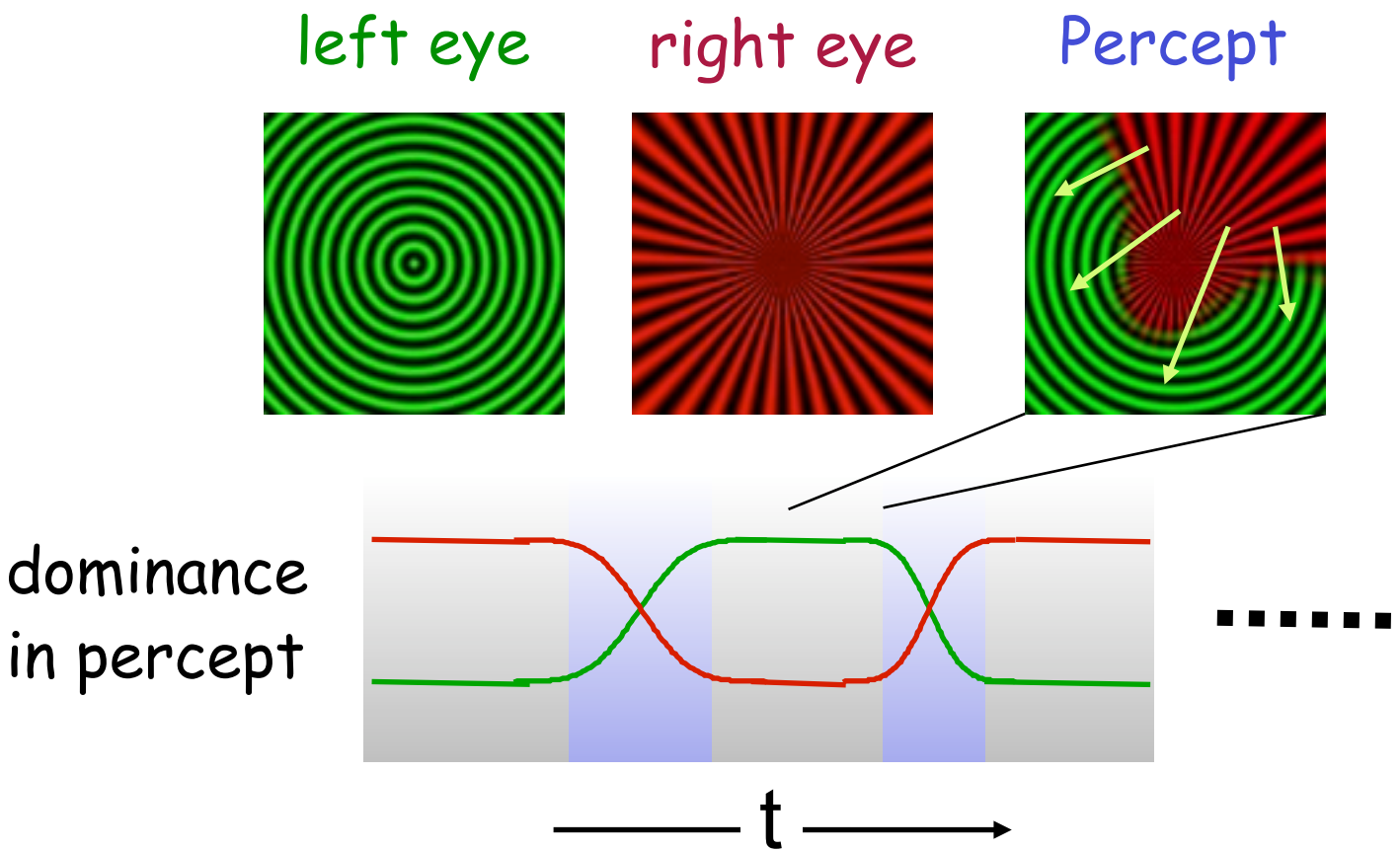

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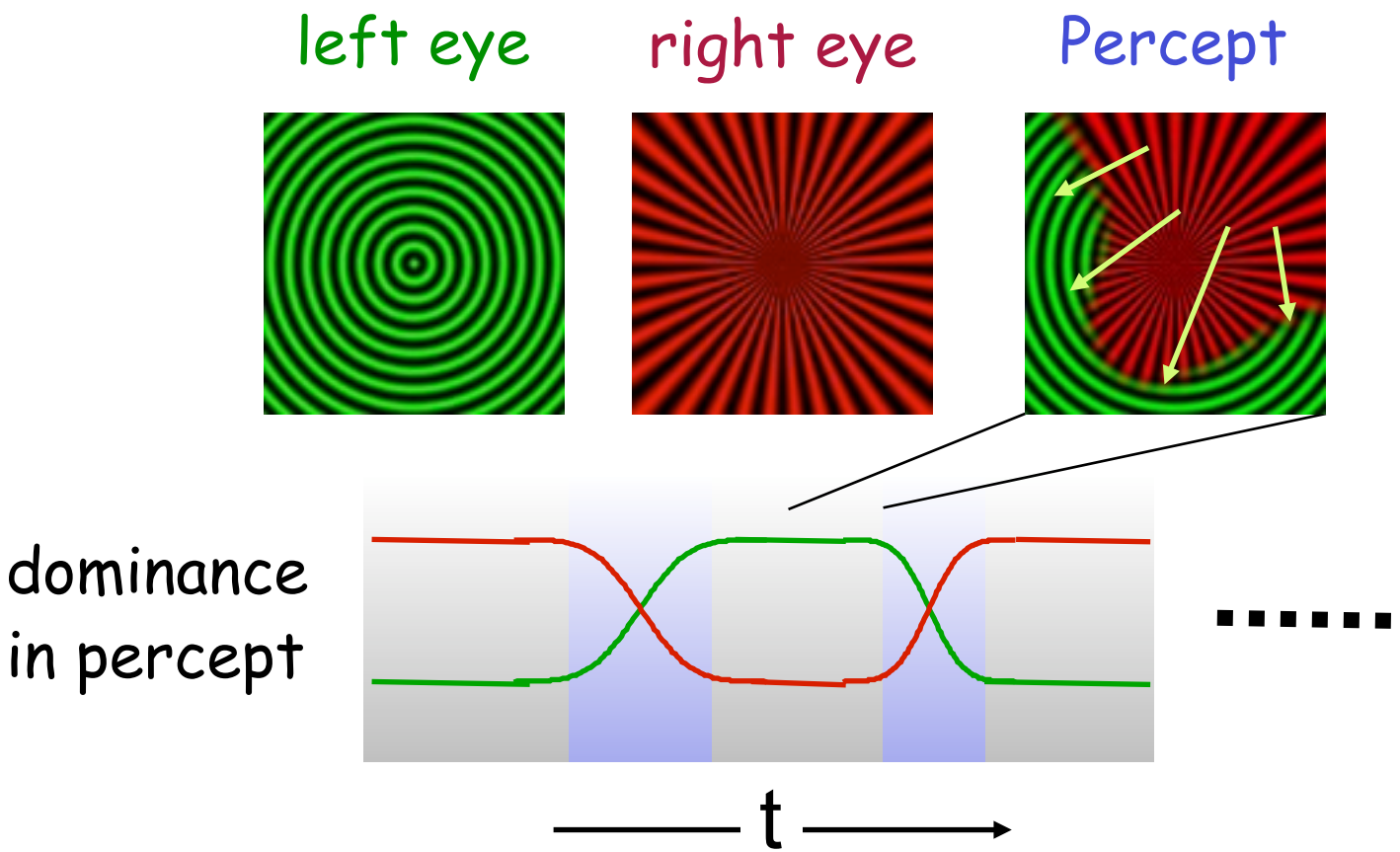

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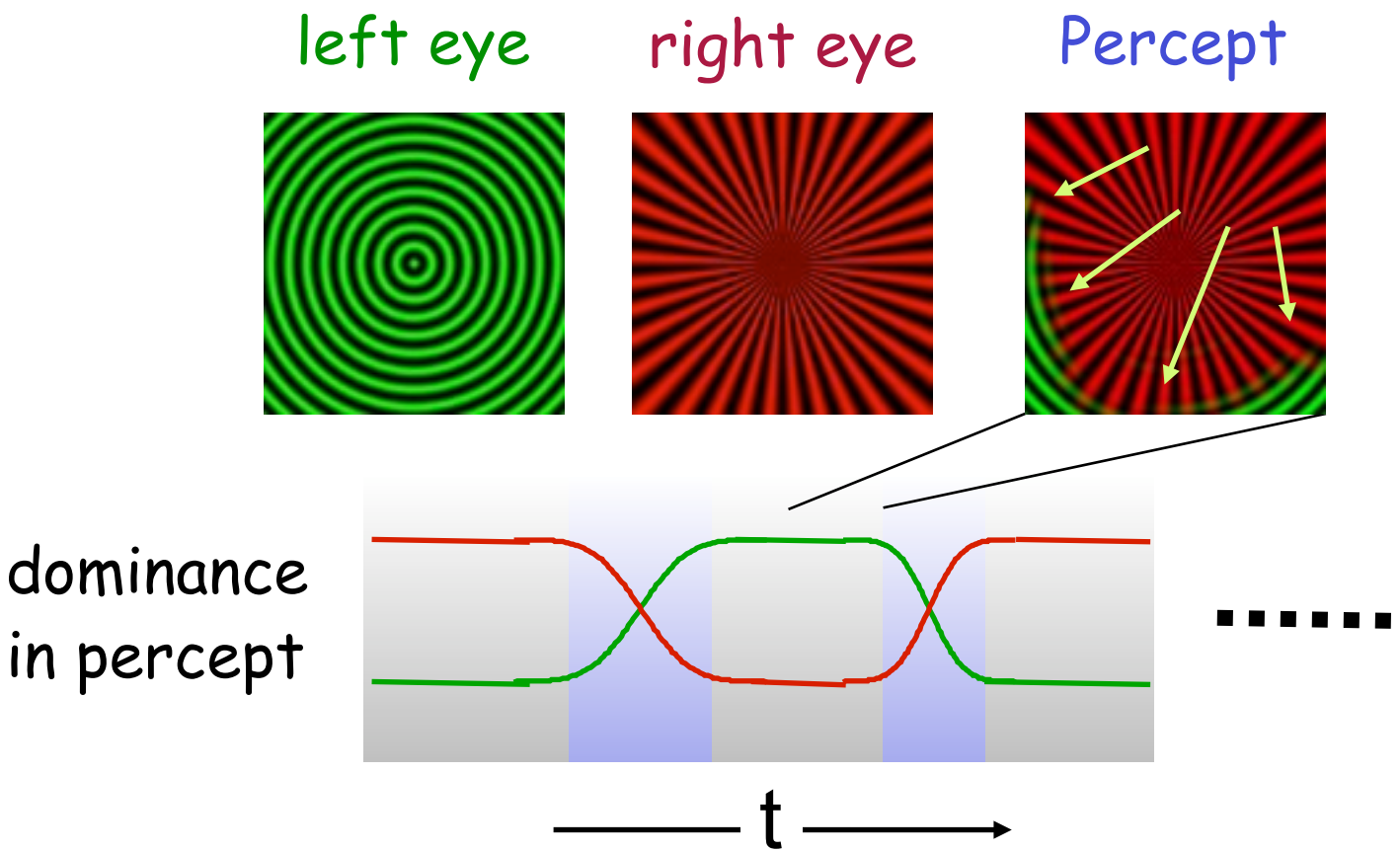

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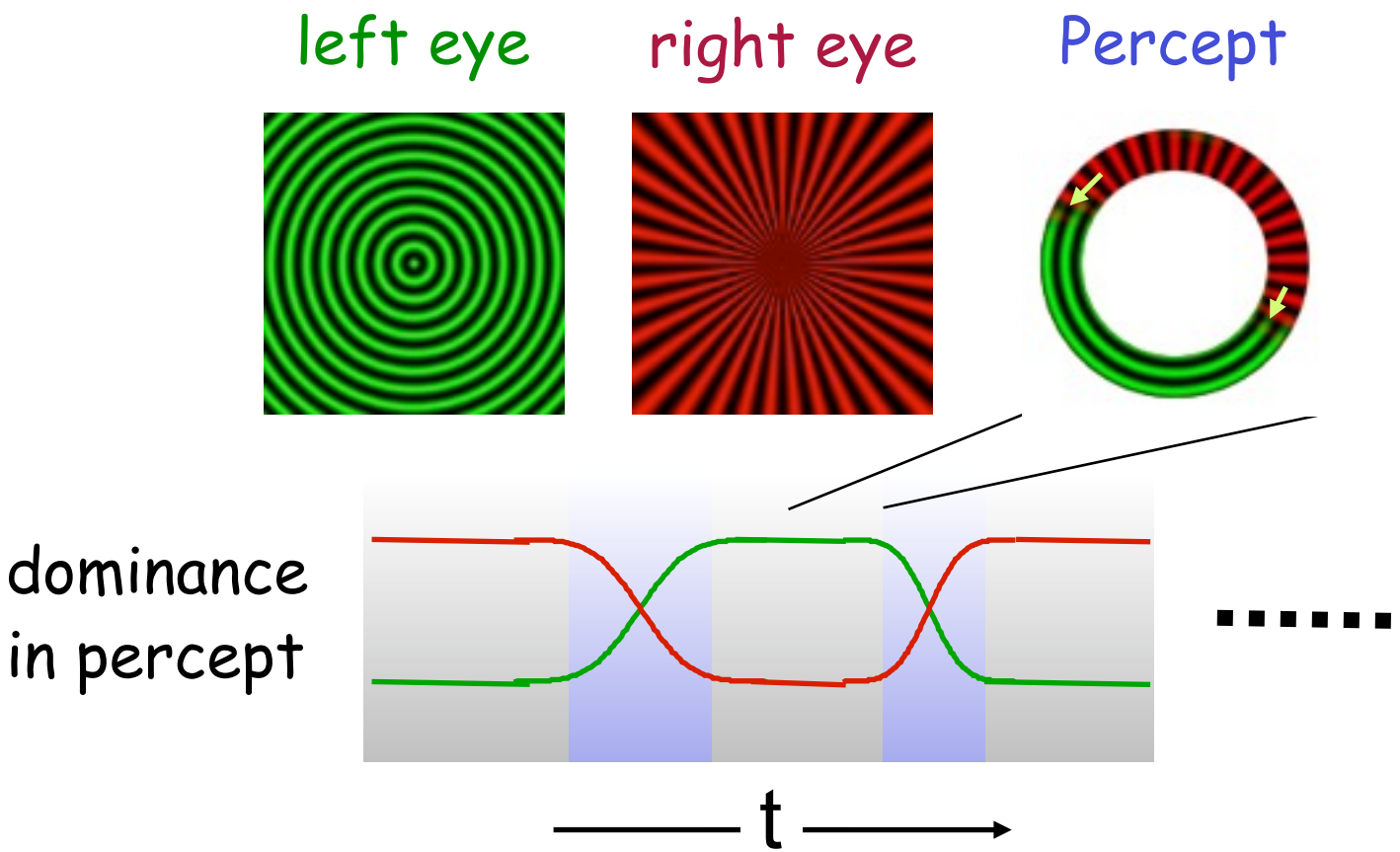
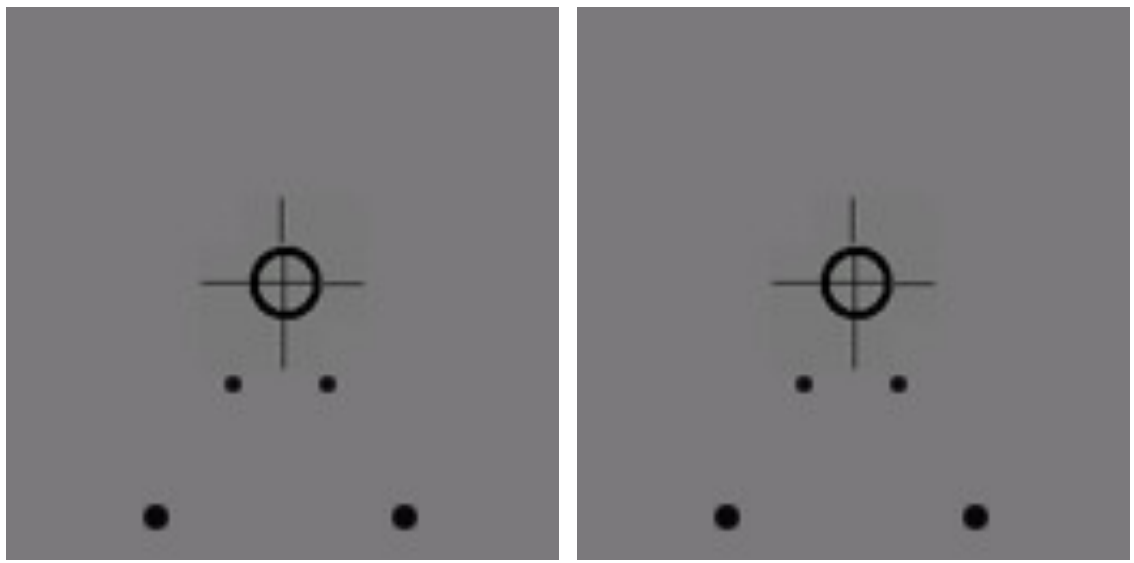


Perceptual traveling waves

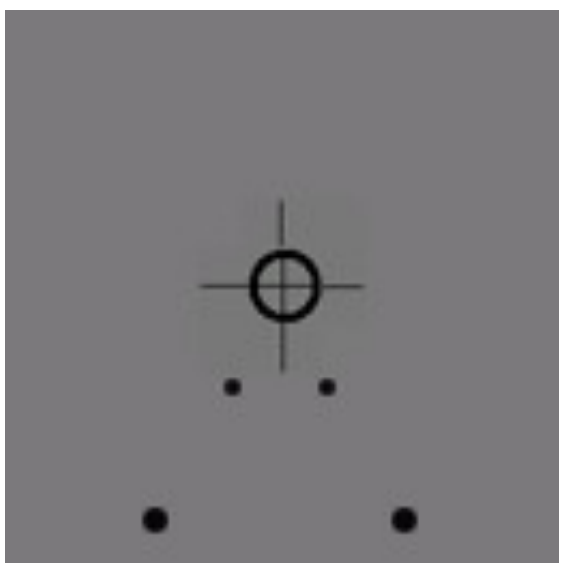
left eye

right eye

Display



Percept



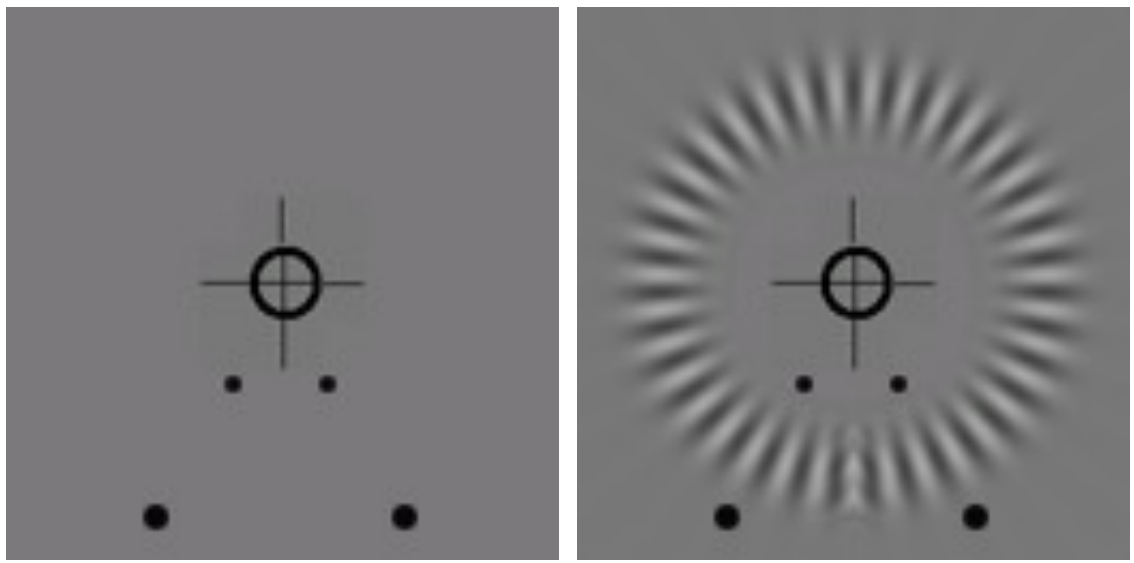
Lee, Blake, & Heeger,
Nature Neurosci (2005)

Perceptual traveling waves

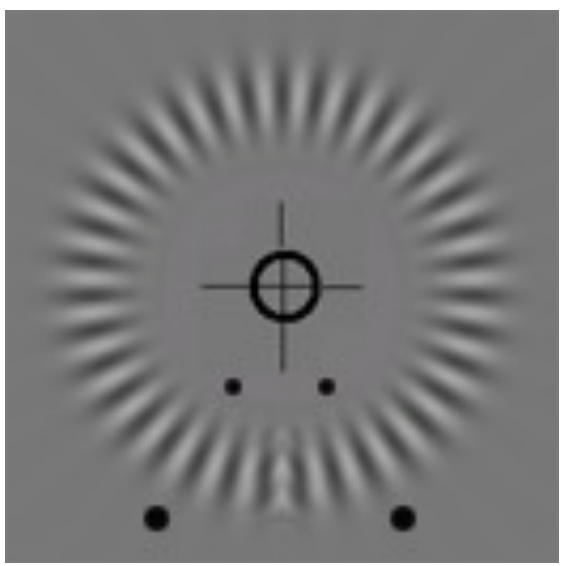
left eye

right eye

Display



Percept



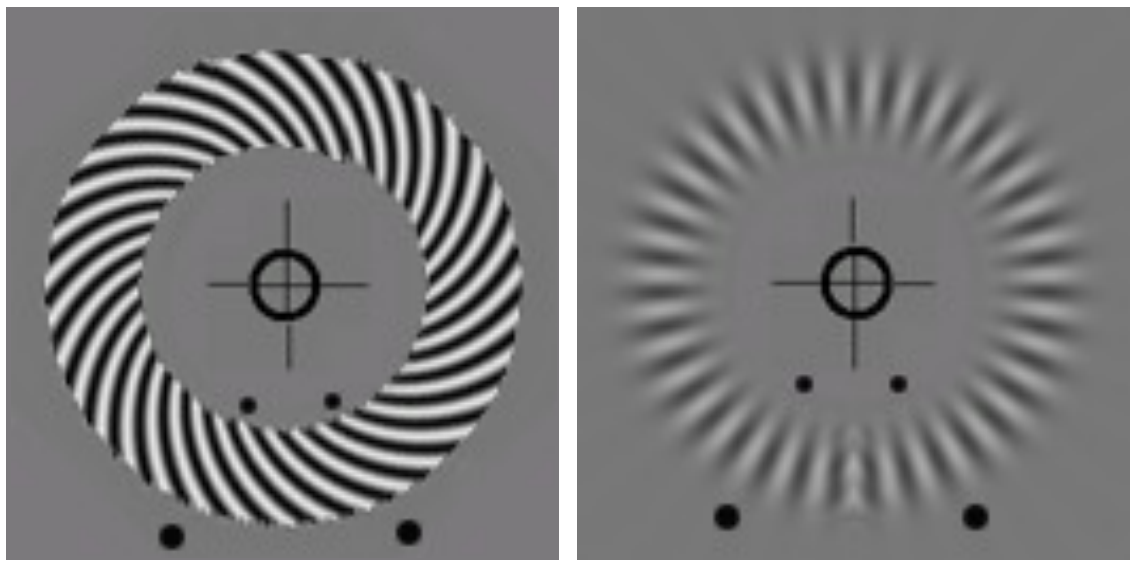
Lee, Blake, & Heeger,
Nature Neurosci (2005)

Perceptual traveling waves

left eye

right eye

Display



Percept

Lee, Blake, & Heeger,
Nature Neurosci (2005)

Perceptual traveling waves

left eye

right eye

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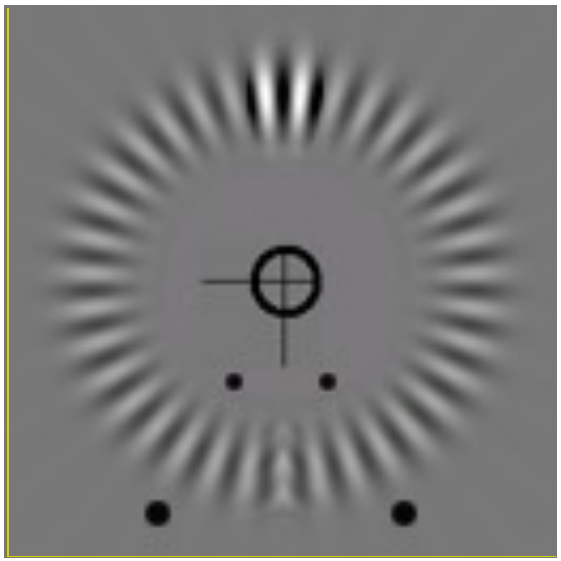

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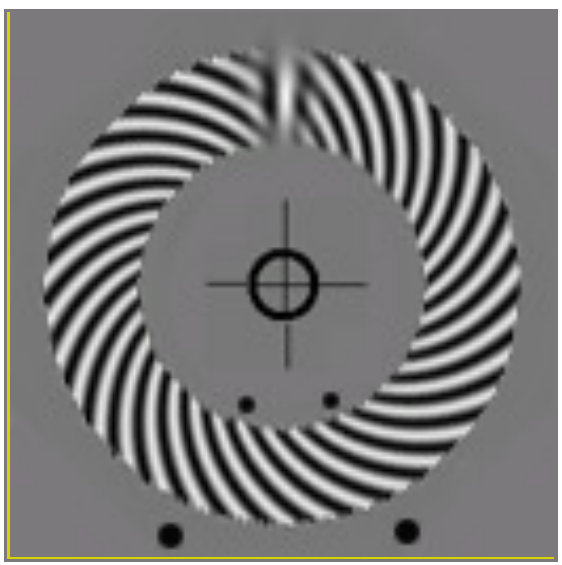

Lee, Blake, & Heeger,
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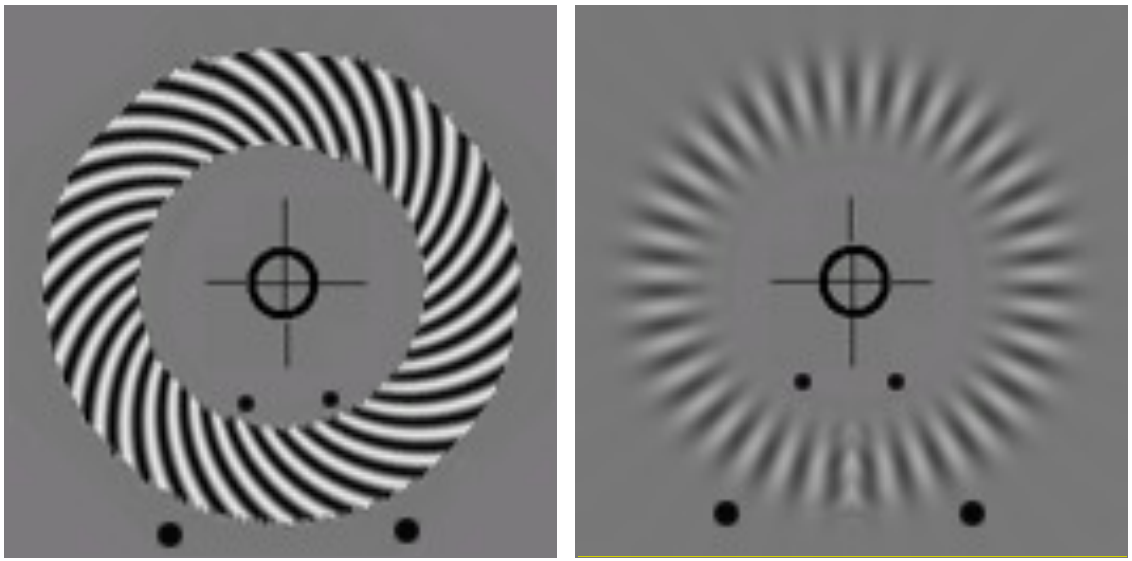
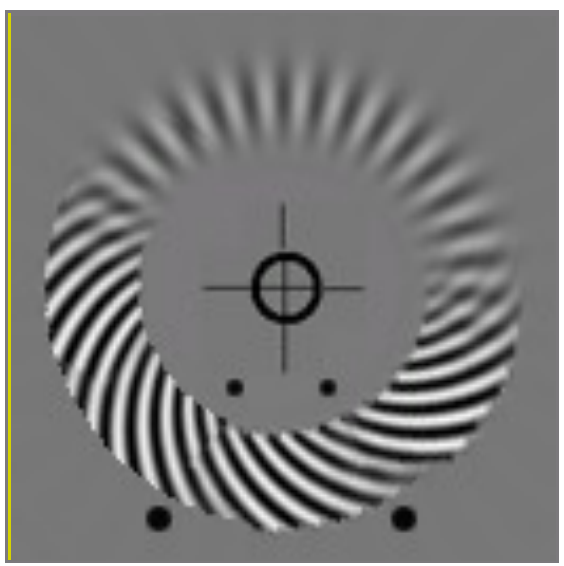


Percept



Lee, Blake, & Heeger,
Nature Neurosci (2005)

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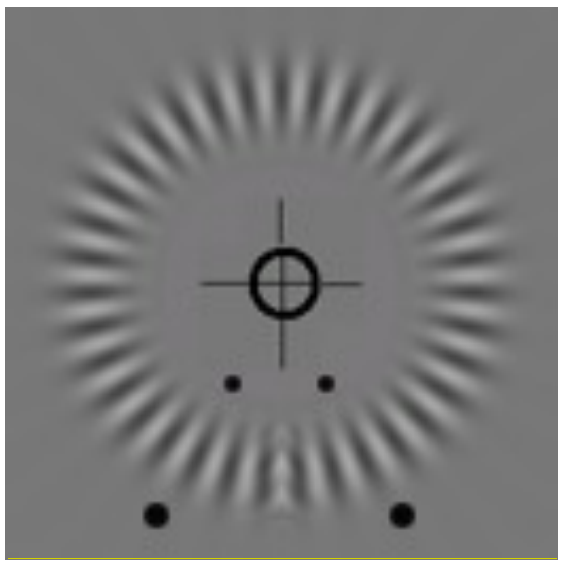
right eye

Display



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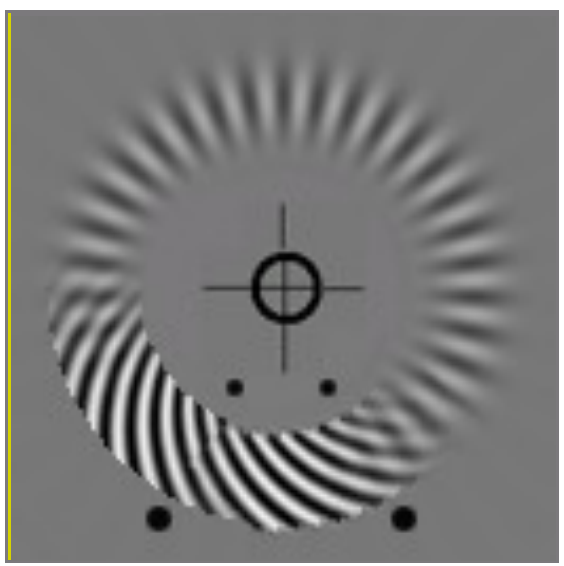


Latency

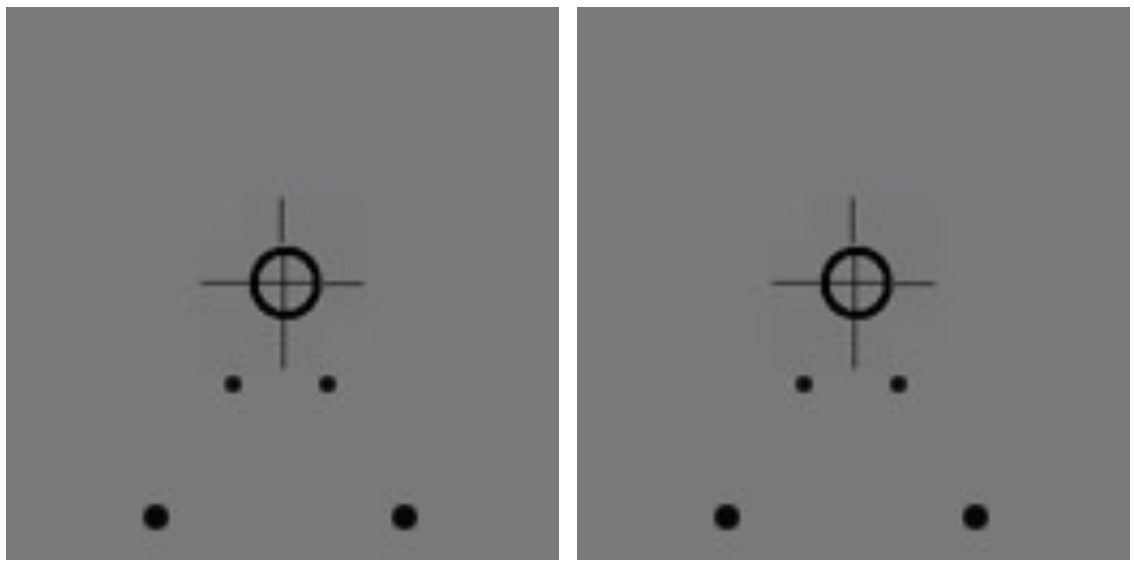
Lee, Blake, & Heeger,
Nature Neurosci (2005)

Perceptual traveling waves

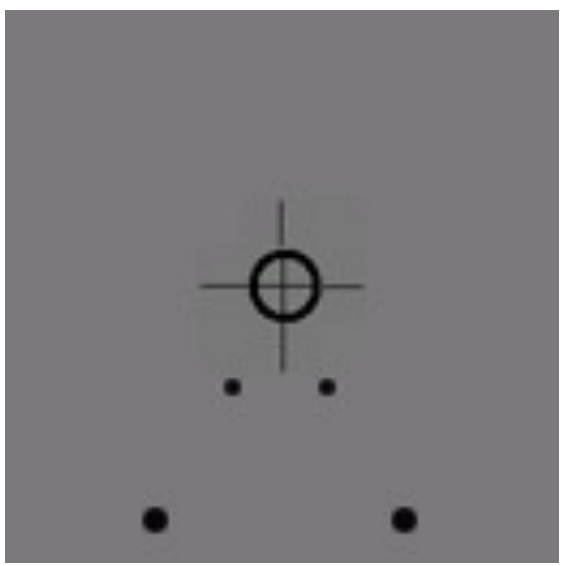
left eye

right eye

Display



Percept

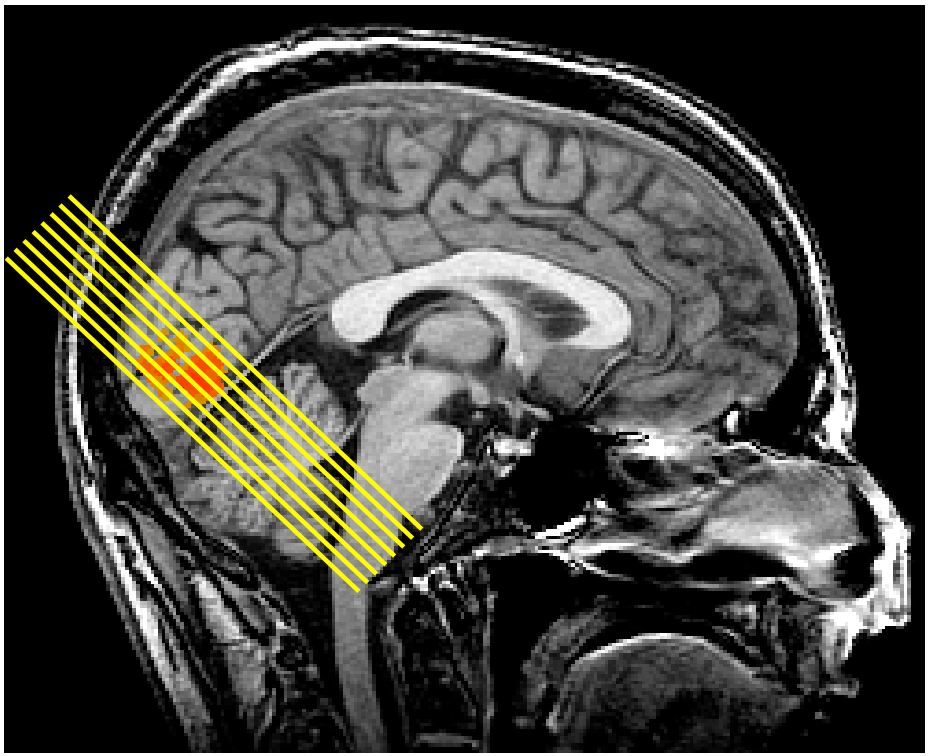


Latency

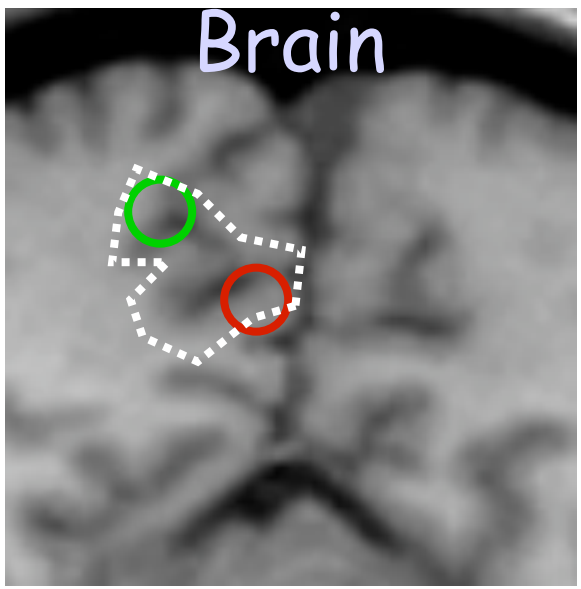
L / R / N

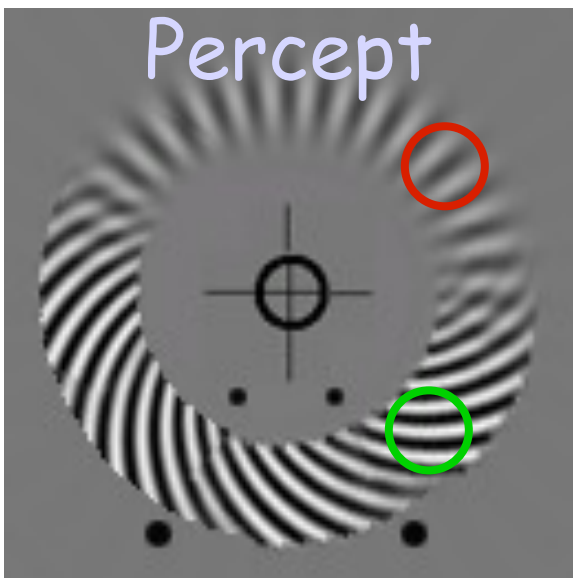
Lee, Blake, & Heeger,
Nature Neurosci (2005)

Functional magnetic resonance imaging



Prediction: traveling waves of cortical activity

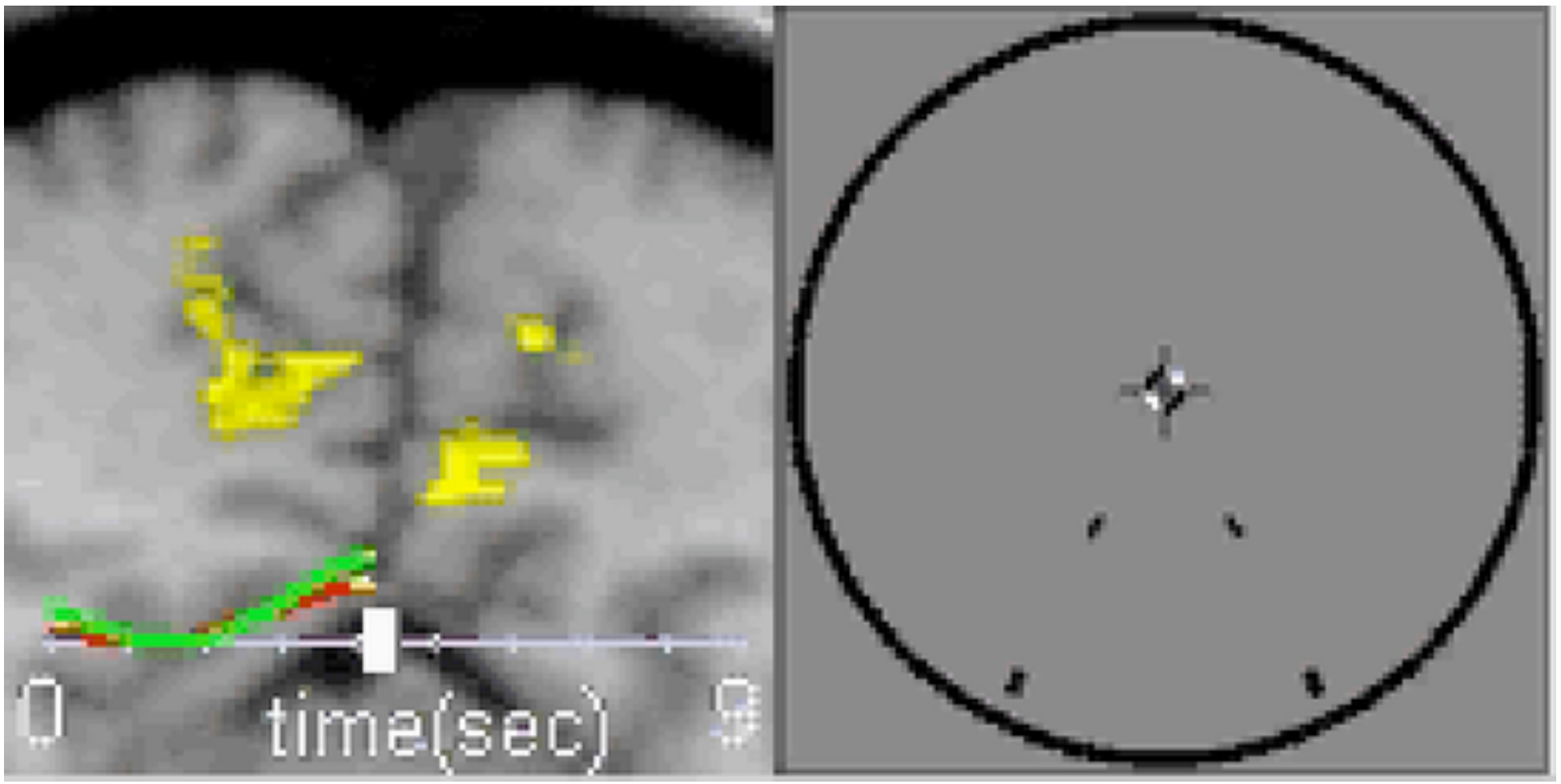




Perceptual and neural traveling waves

Peak fMRI response

Percept



Lee, Blake, & Heeger, Nature Neurosci (2005)

Visual cortical areas

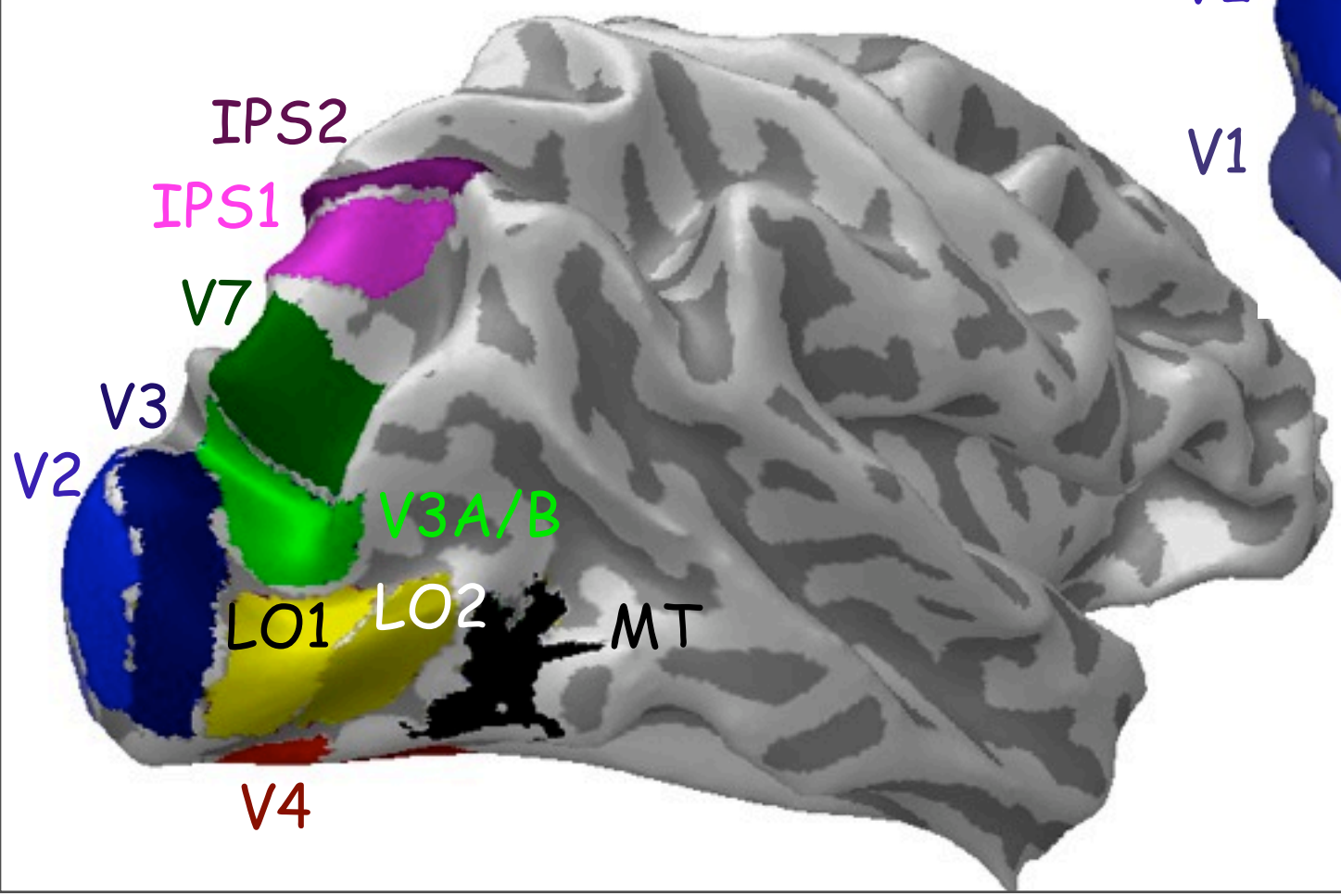
LO1 and LO2:

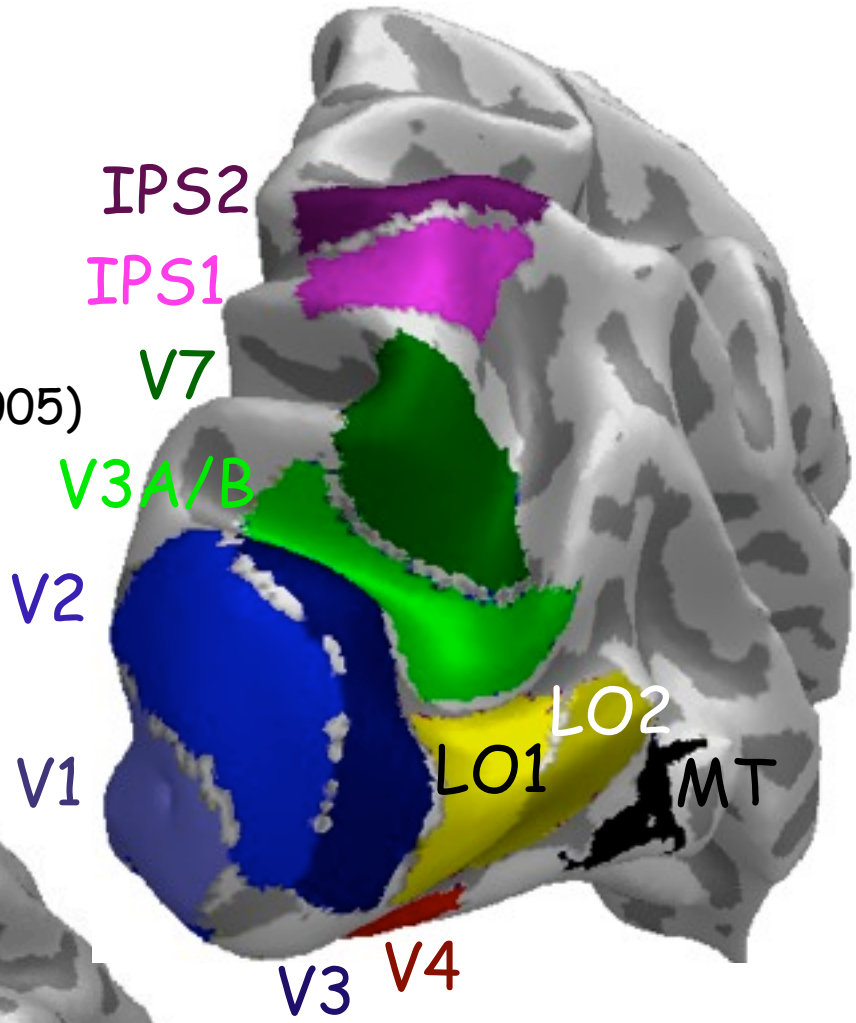
Larsson & Heeger, J Neurosci (2006)

IPS1 and IPS2:

Schluppeck, Glimcher, & Heeger, J Neurophysiol (2005)

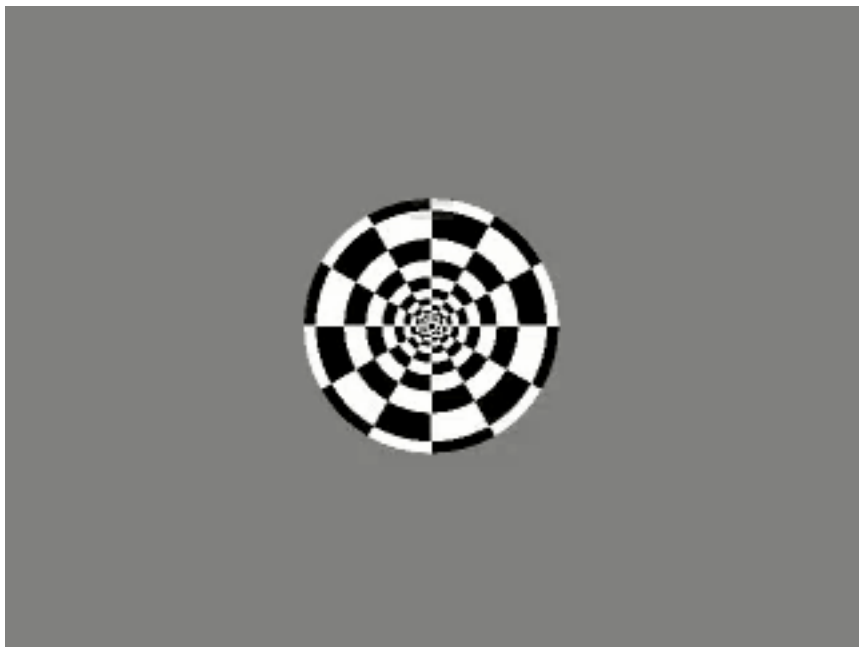
Silver, Ress, & Heeger, J Neurophysiol (2005)



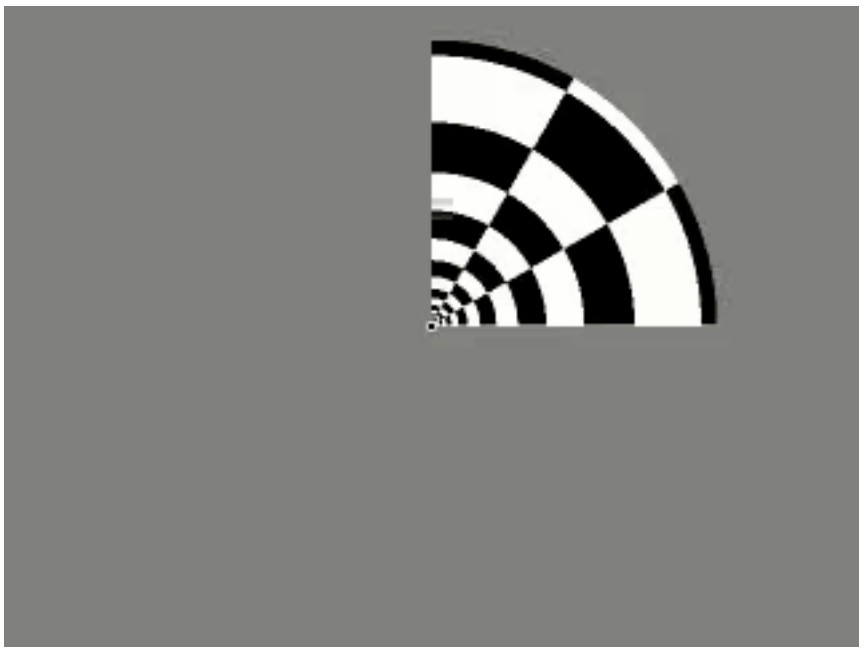


Retinotopy

Radial component

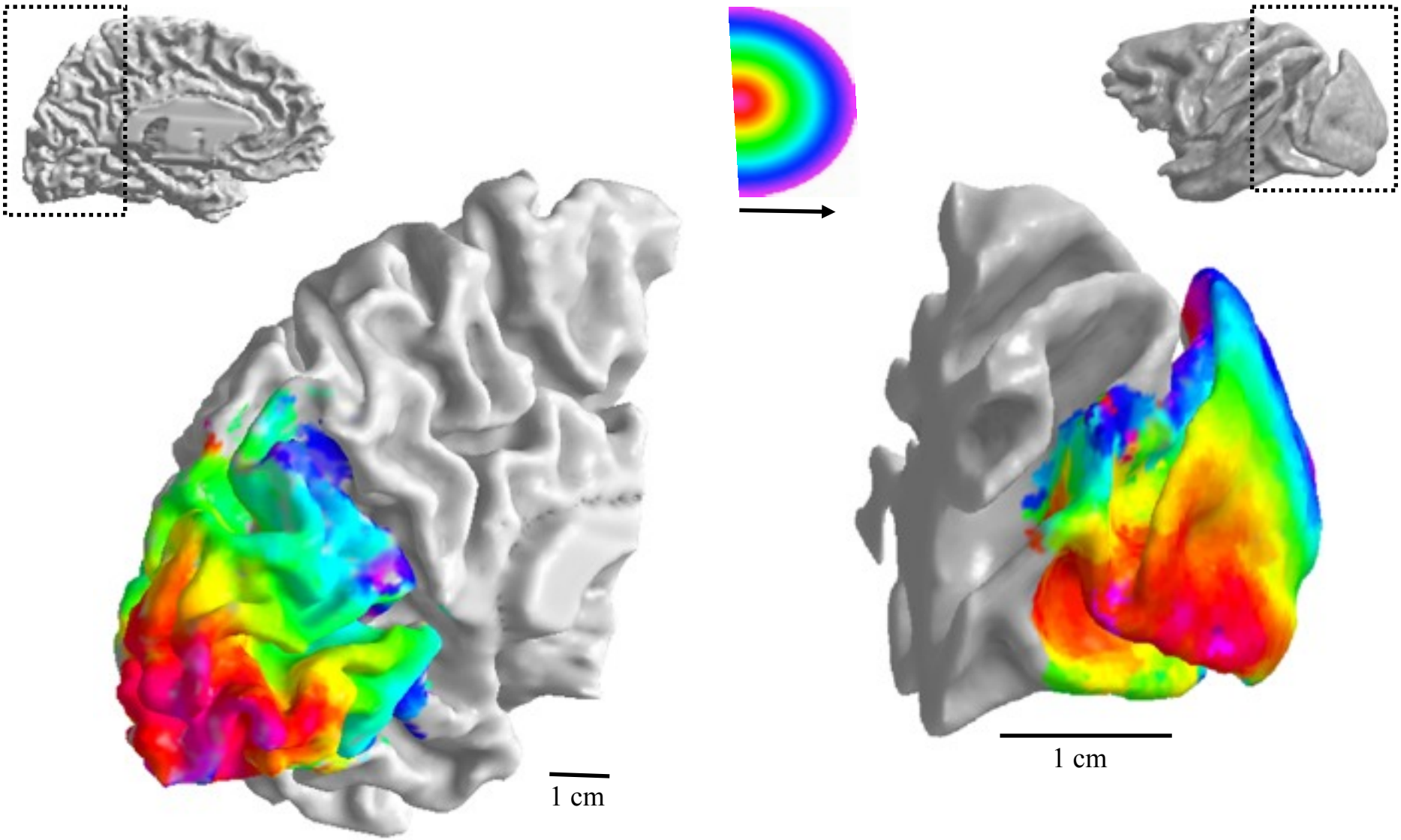


Angular component



Engel et al, Nature (1994)

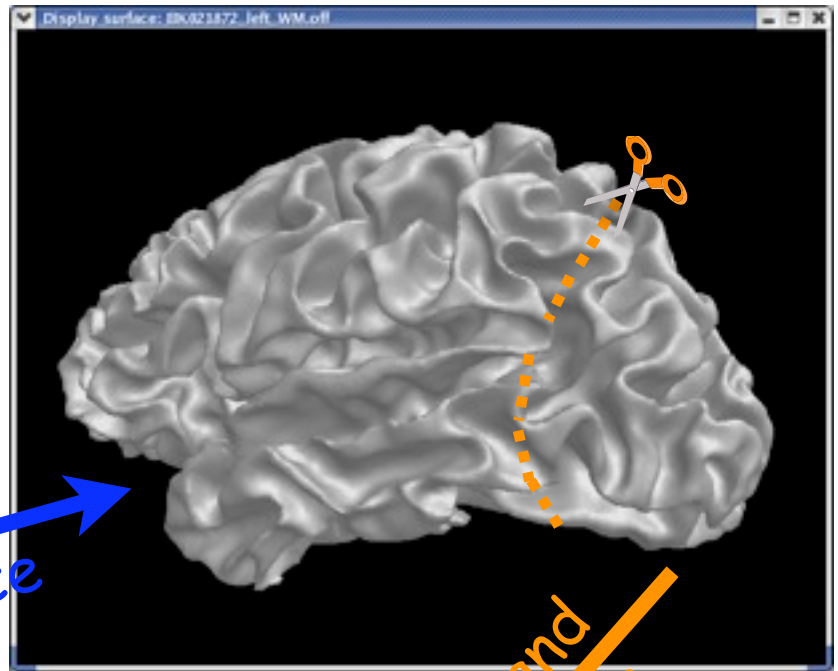
Retinotopy: radial component



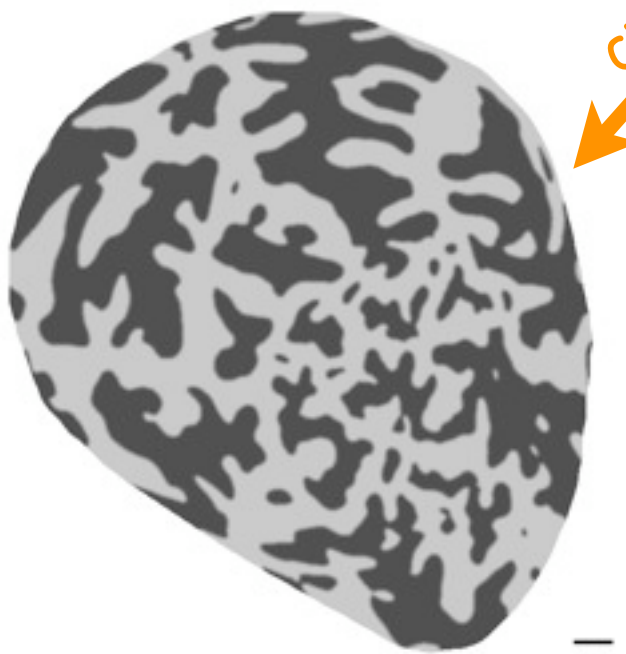
Brewer, Wandell, & Logothetis

Cortical segmentation & flattening

extract cortical surface

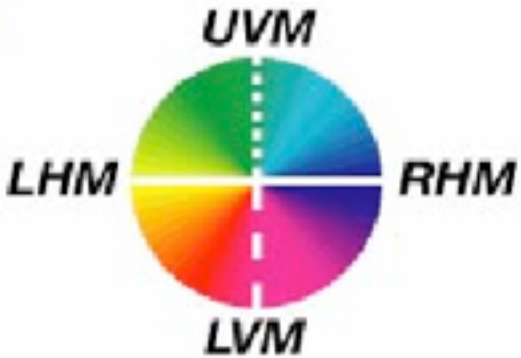


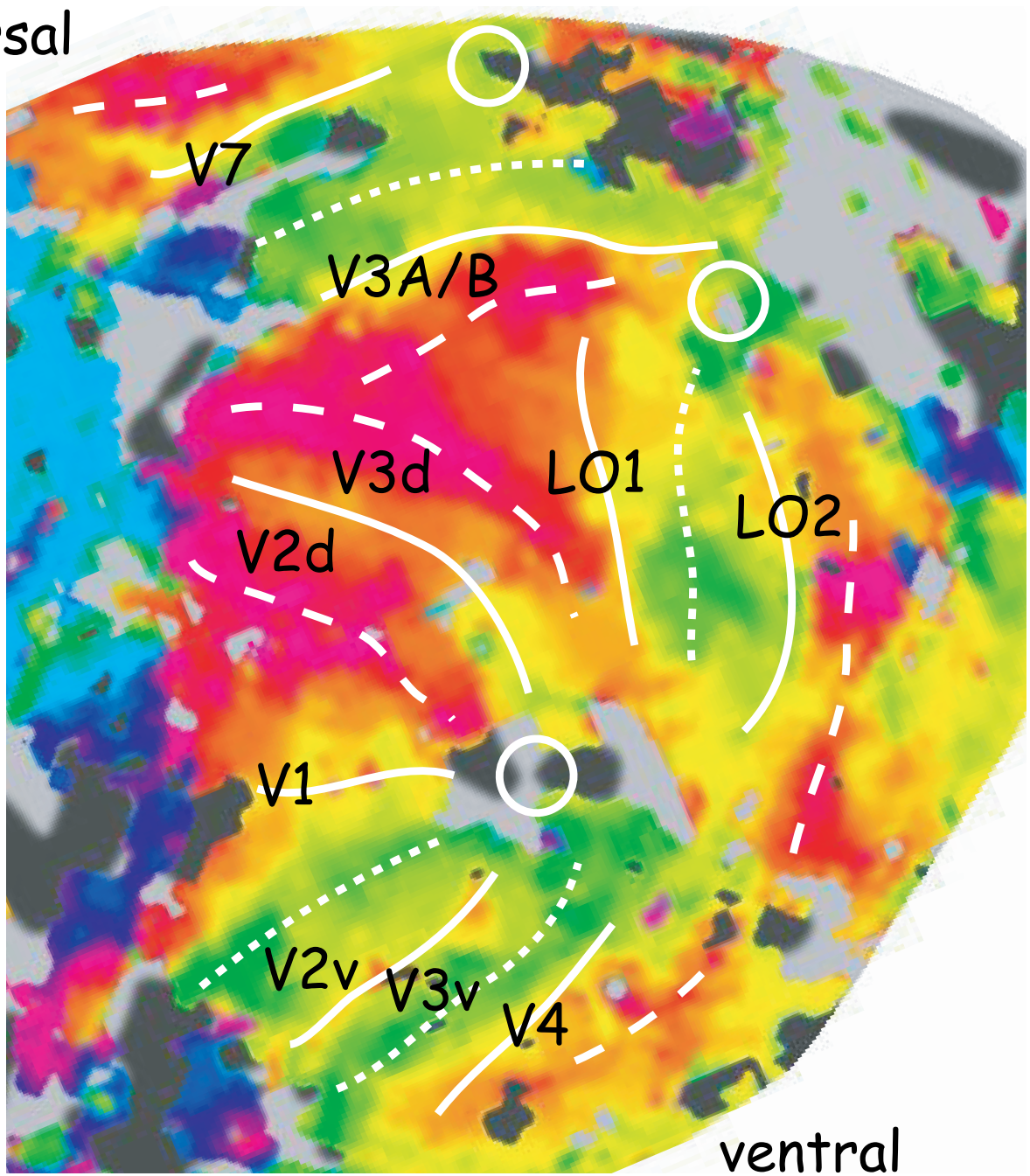
cut and flatten



Jonas Larsson

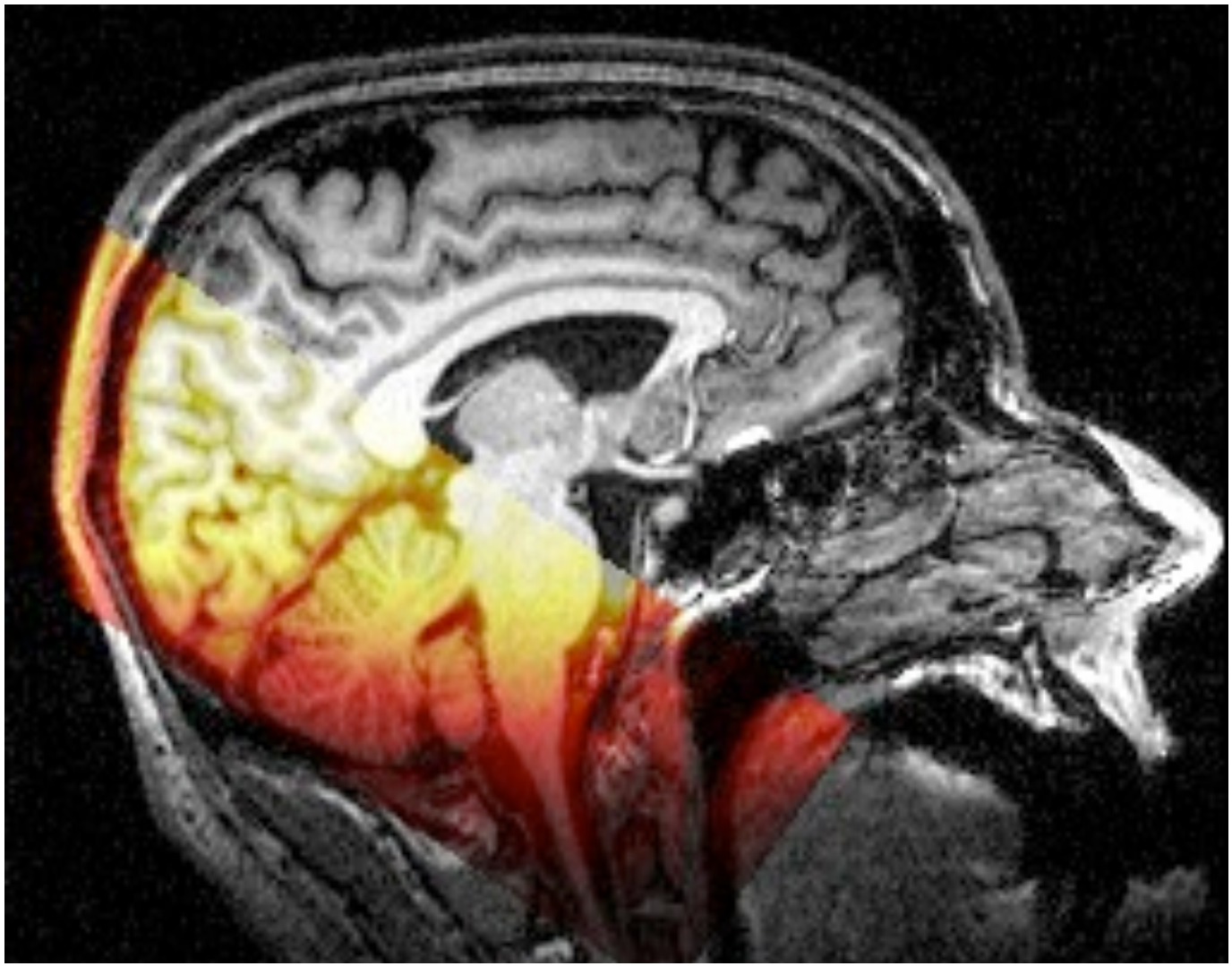
Retinotopy: angular component





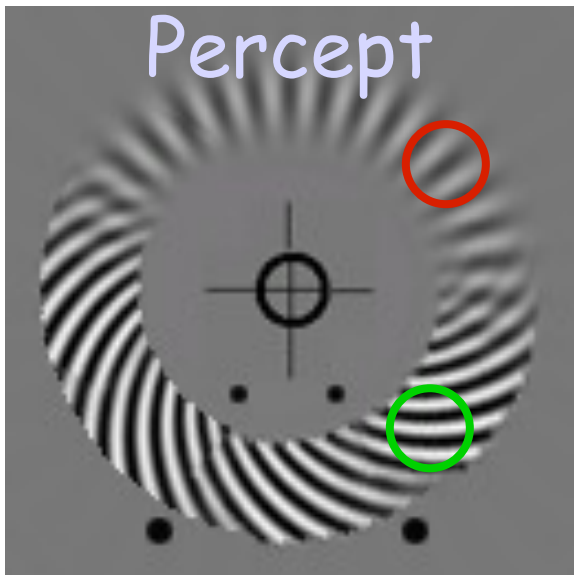
Larsson & Heeger
J Neurosci (2006)

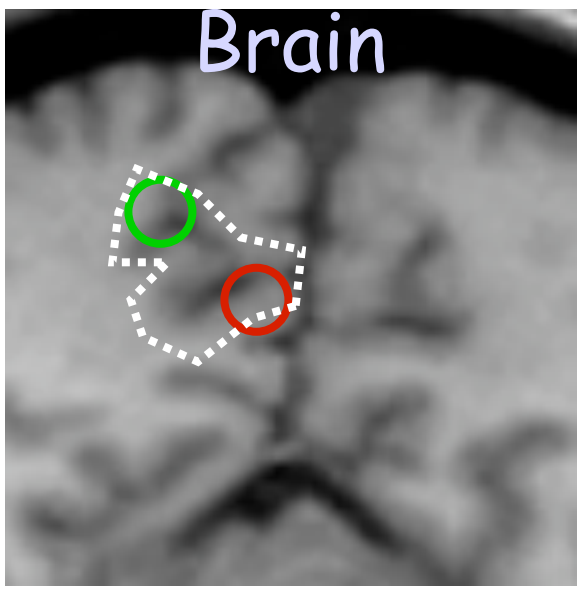
Alignment across scanning sessions

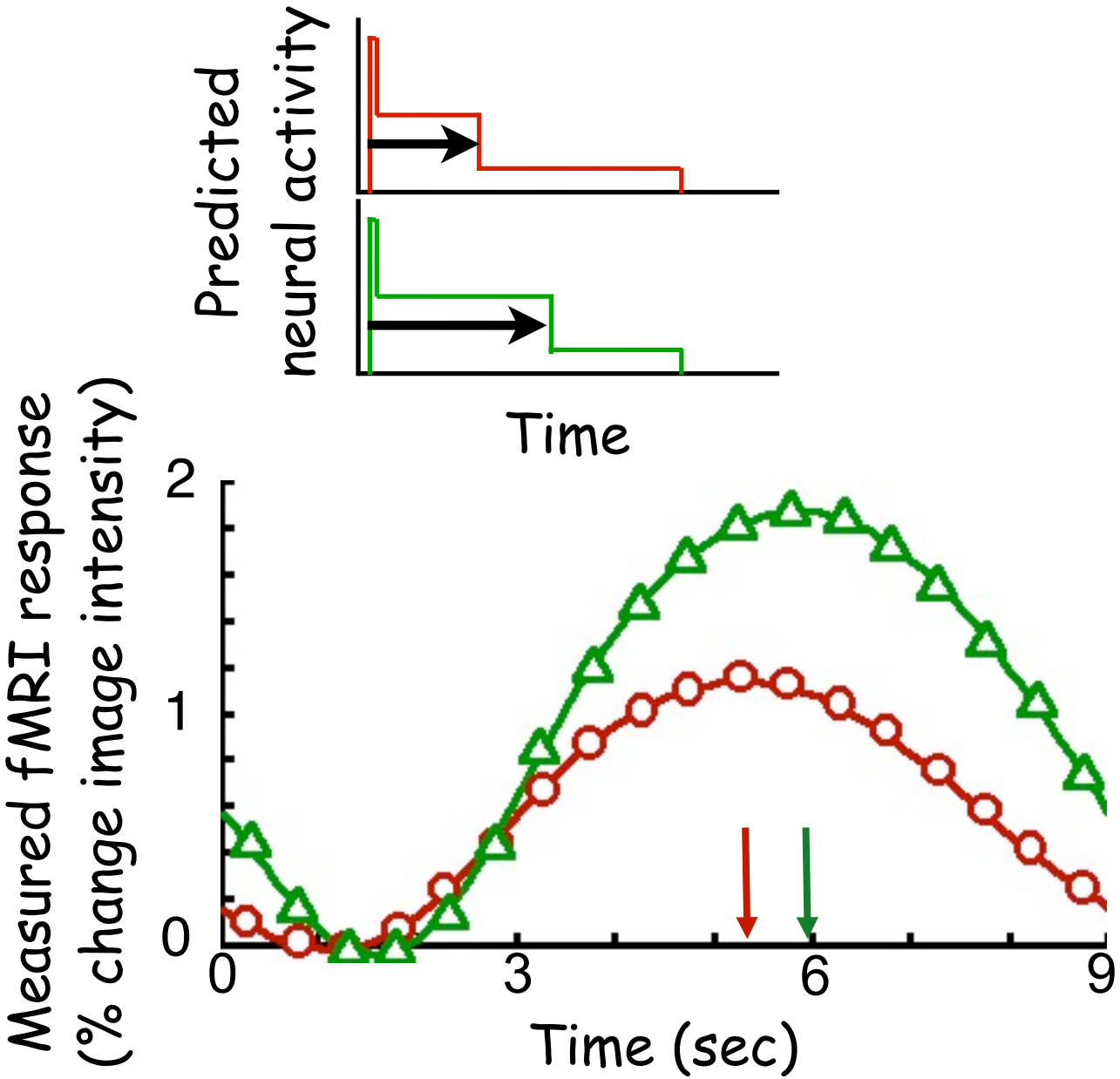


Nestares & Heeger, Magn Reson Med (2000)

Predicted and measured responses

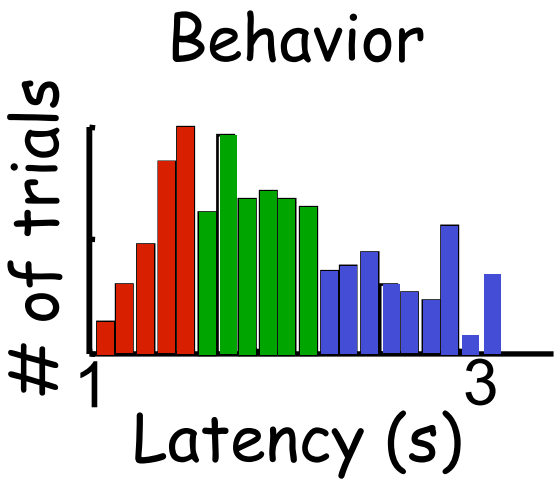


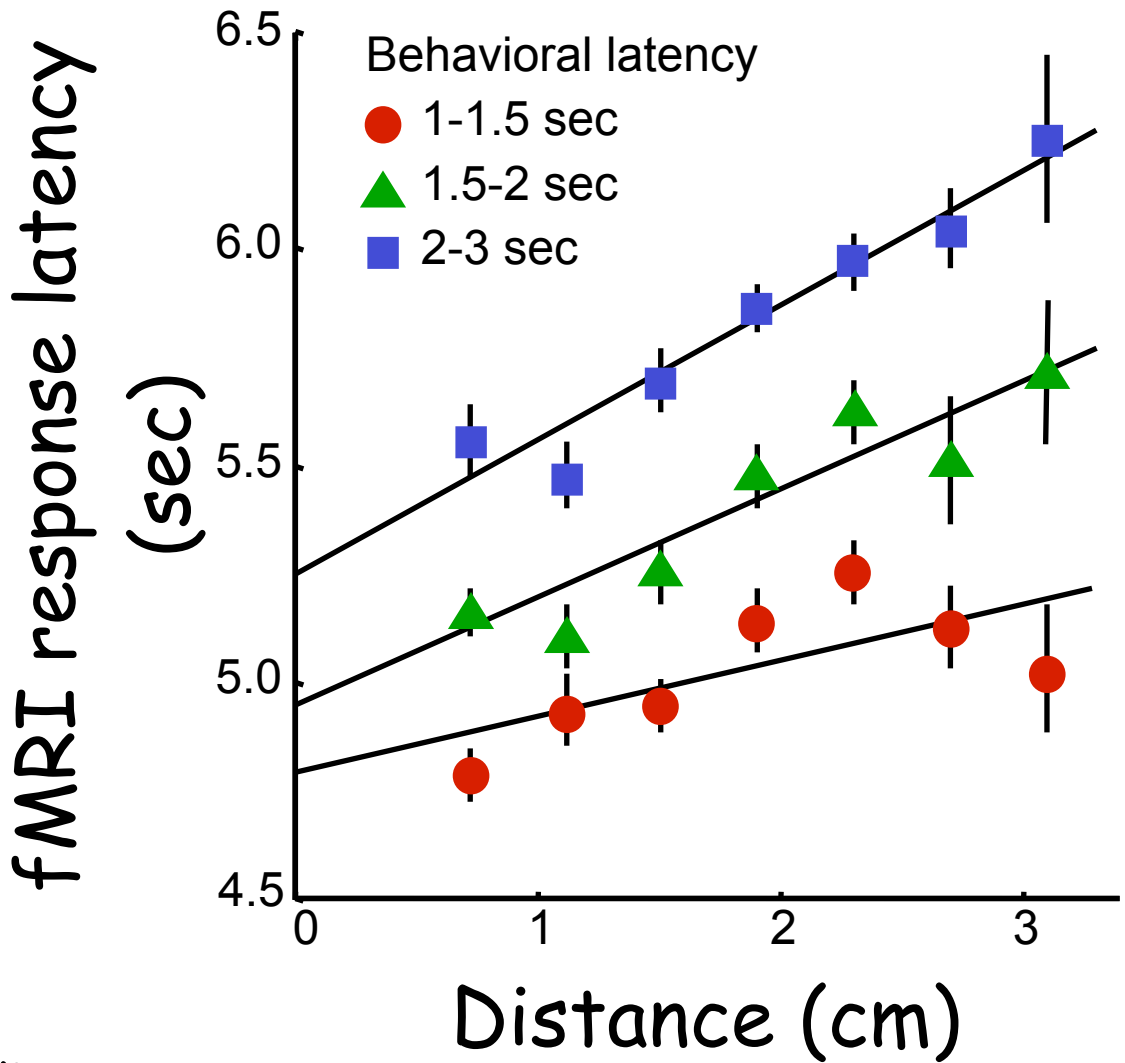




Lee, Blake, & Heeger, Nature Neurosci (2005)

Activity correlates with perceived latency

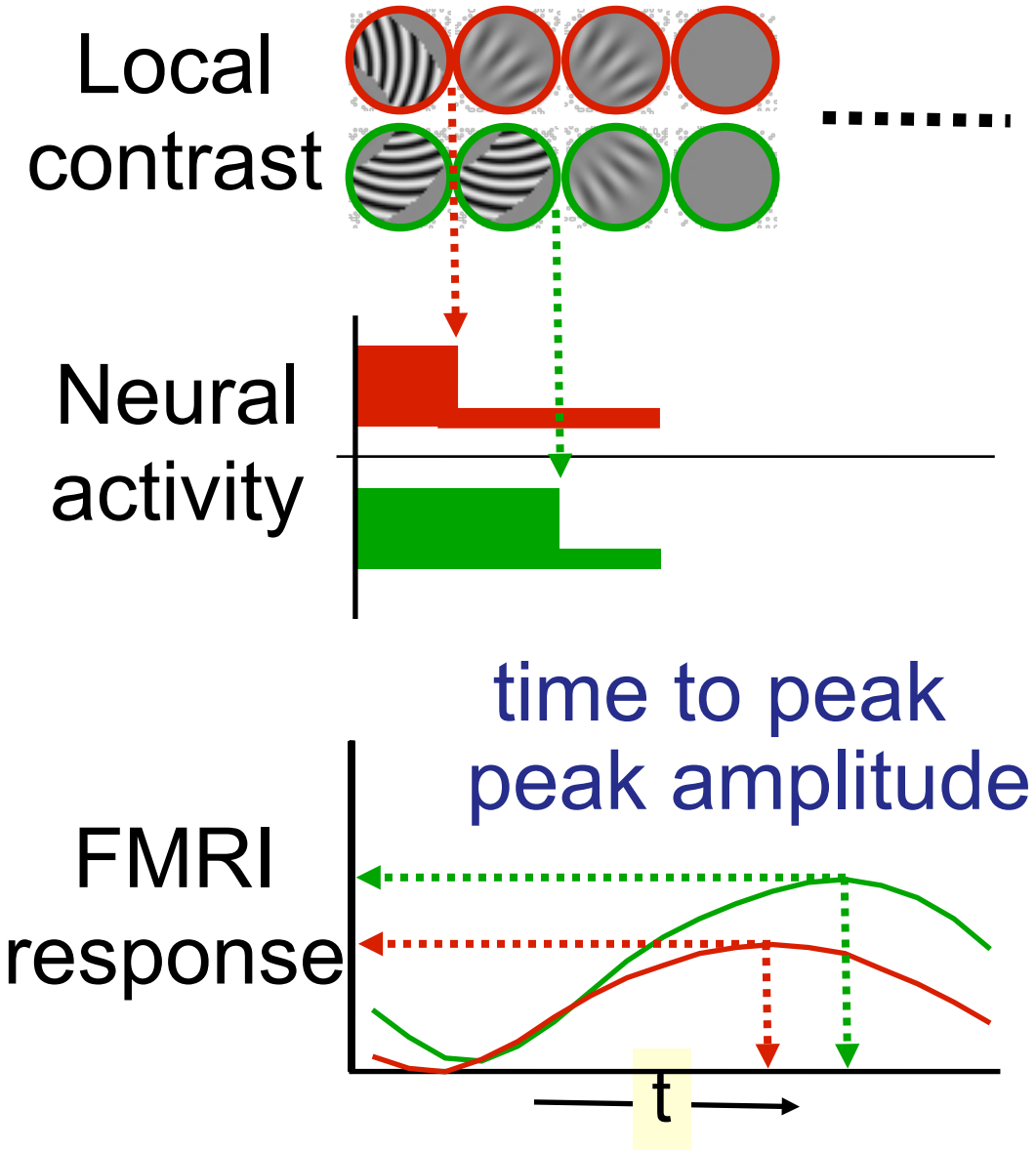




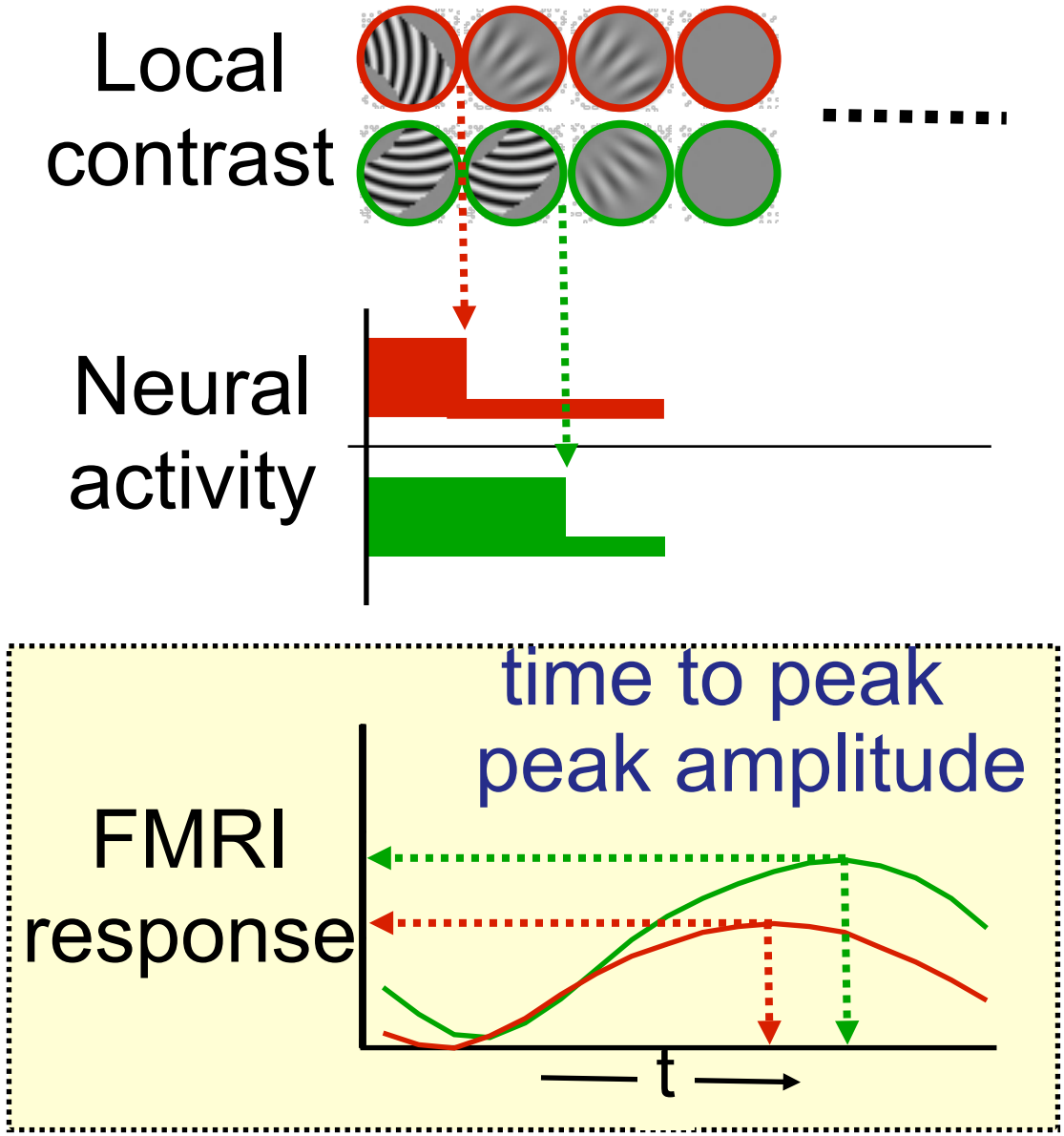
Infer ~115 ms timing difference over ~3.5 mm distance.

Lee, Blake, & Heeger, Nature Neurosci (2005)

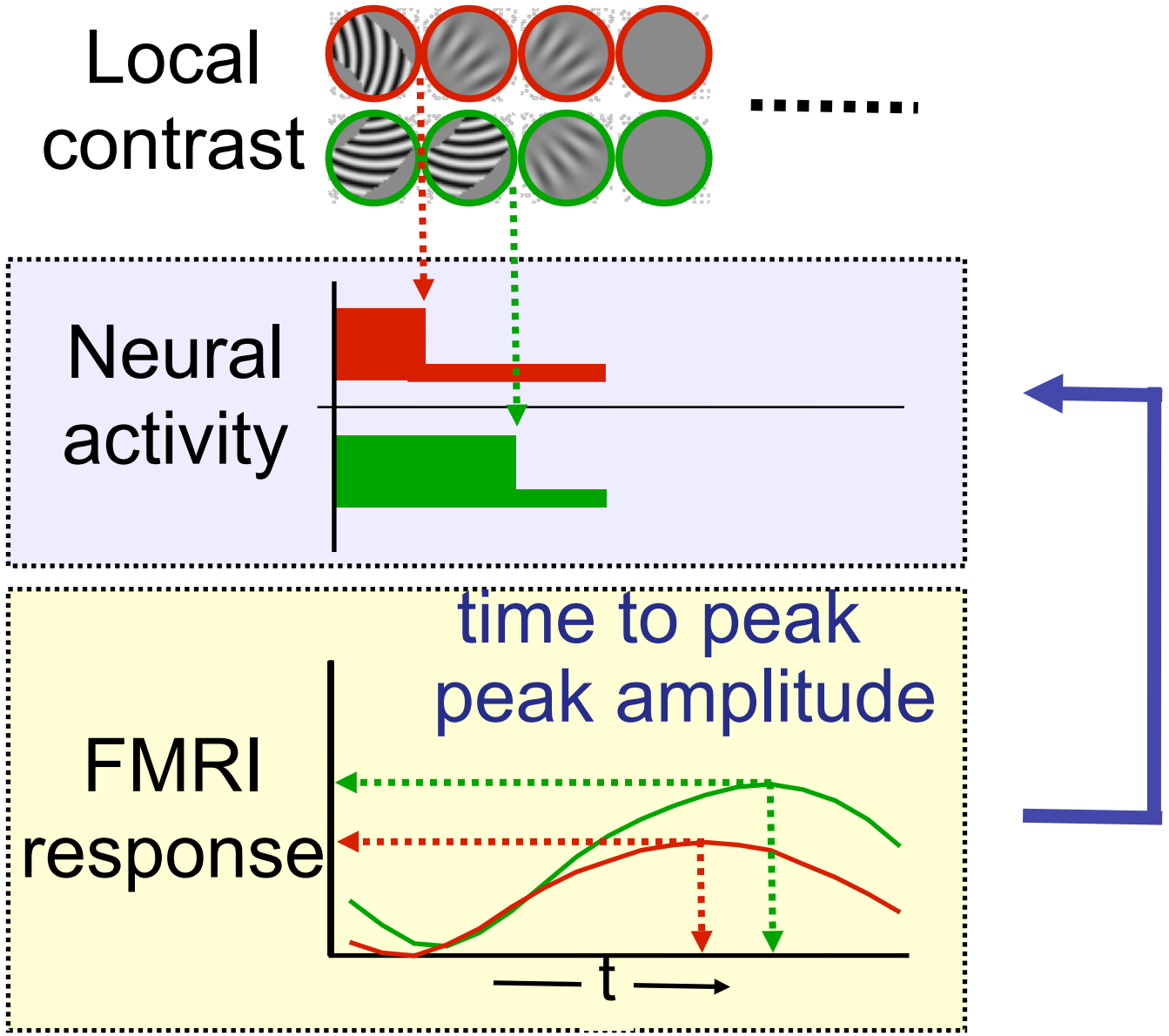
Estimating neural activity



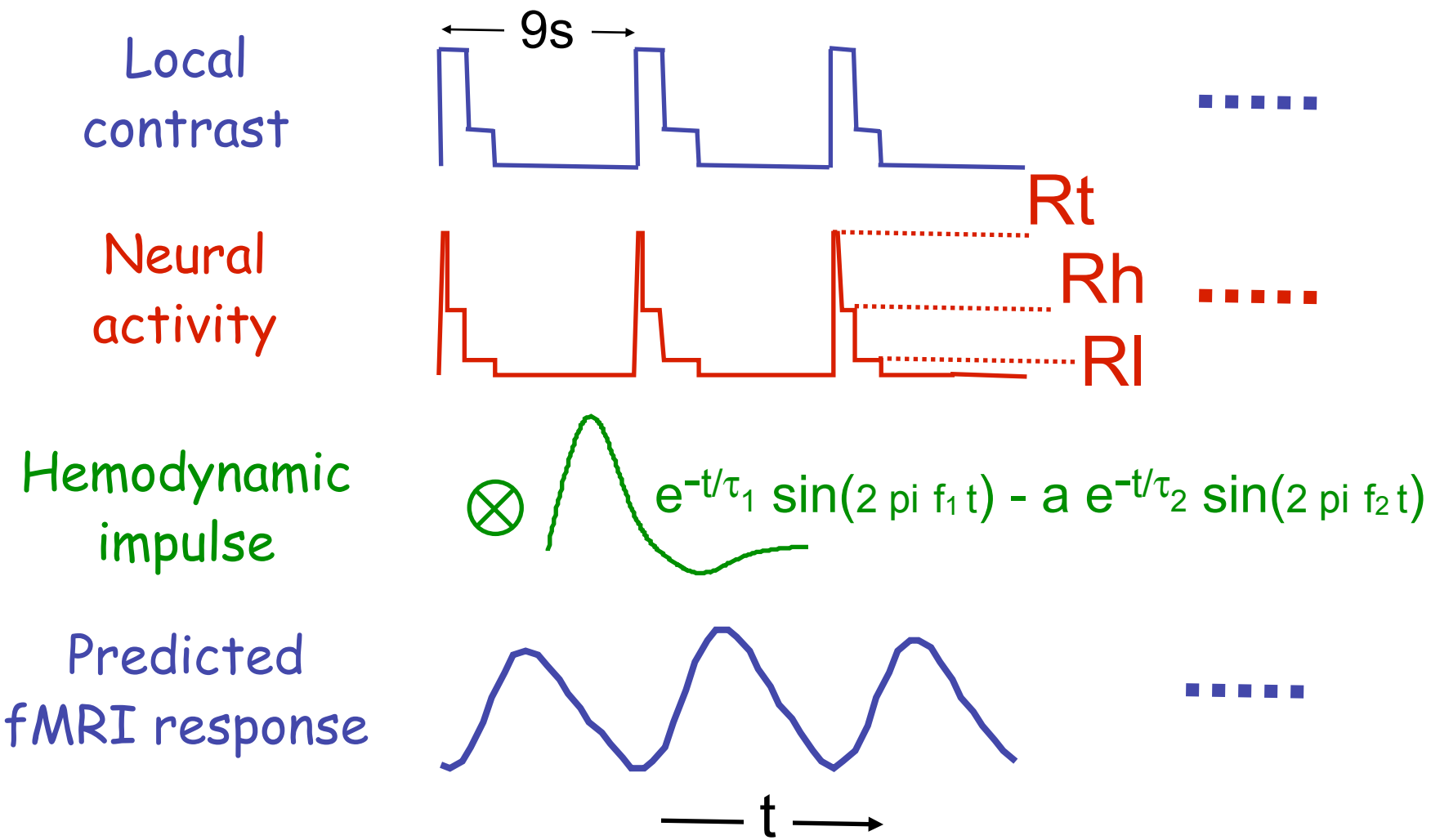
Estimating neural activity



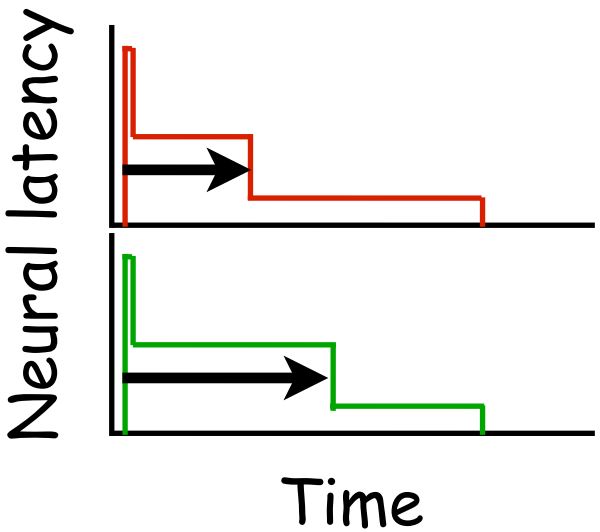
Estimating neural activity

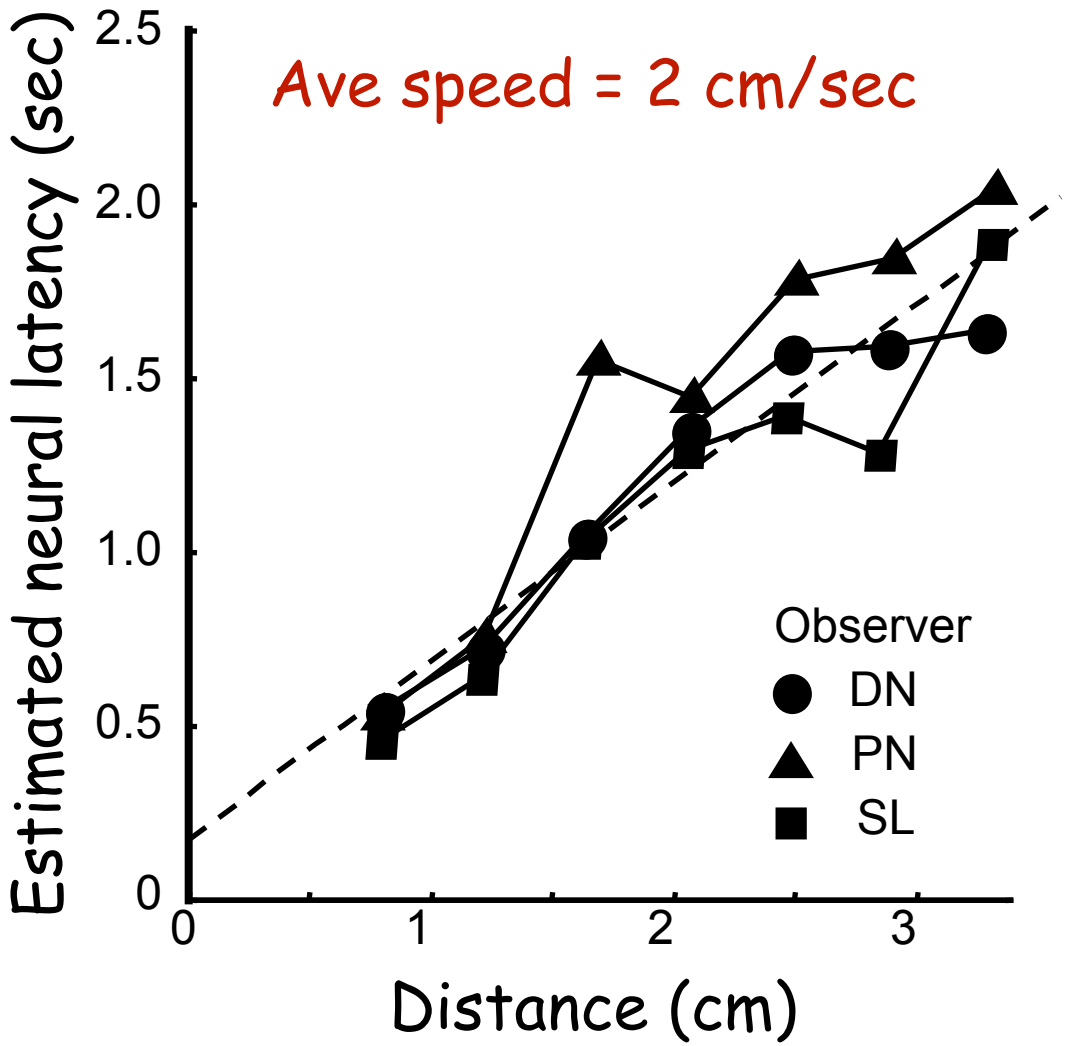


Model of cortical activity & hemodynamic response



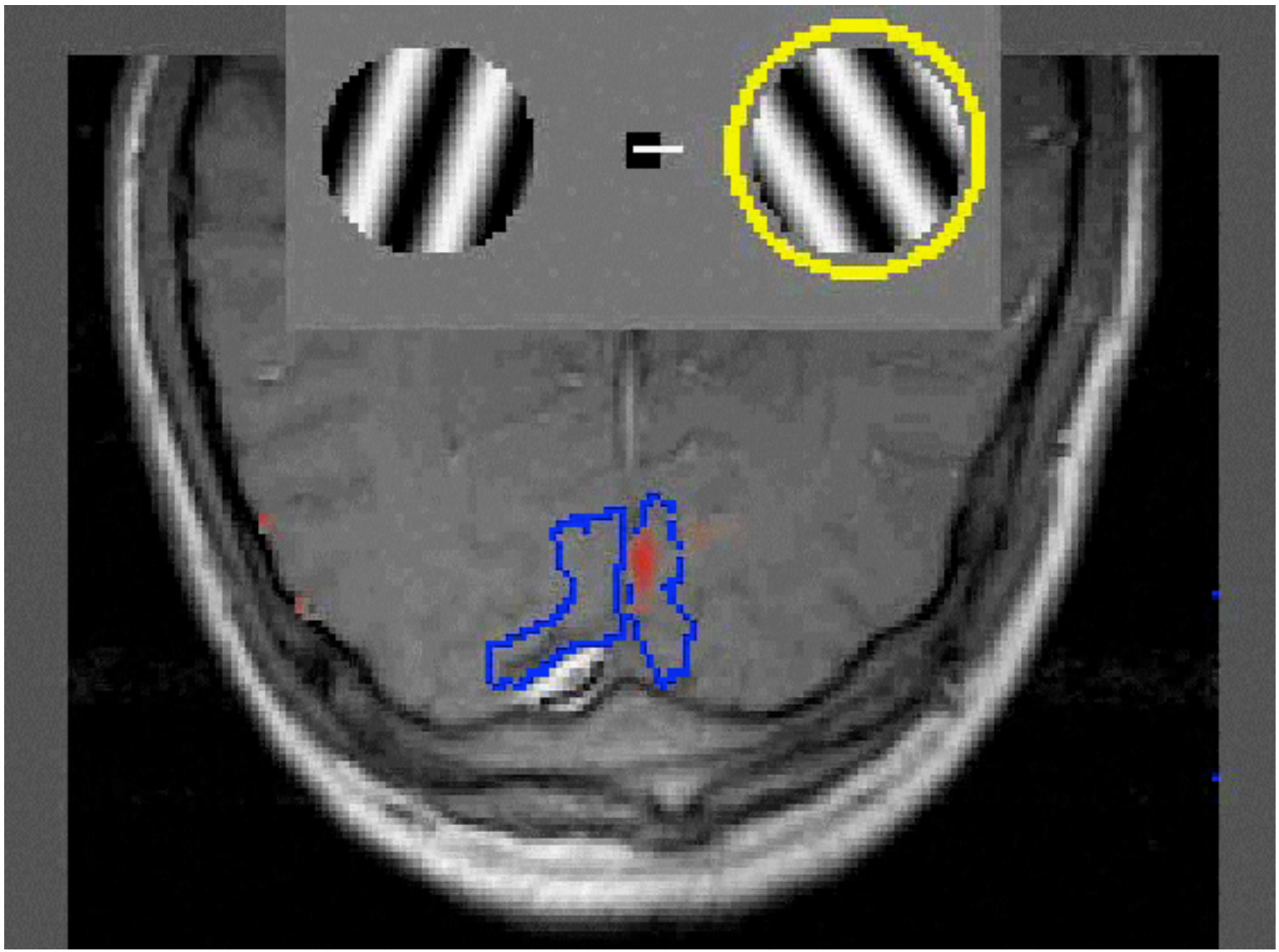
Estimated neural latency





Lee, Blake, & Heeger, Nature Neurosci (2005)

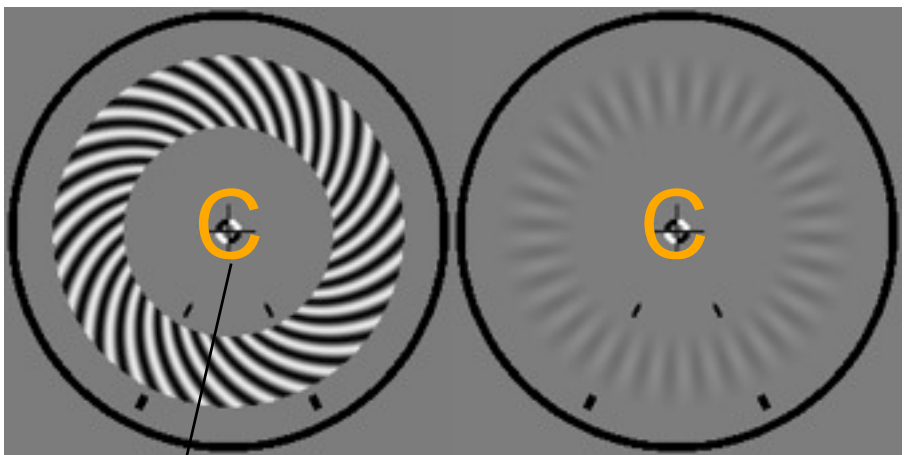
Attention signals in V1



Gandhi, Heeger, & Boynton, PNAS (1999)

Diverted attention

left eye right eye



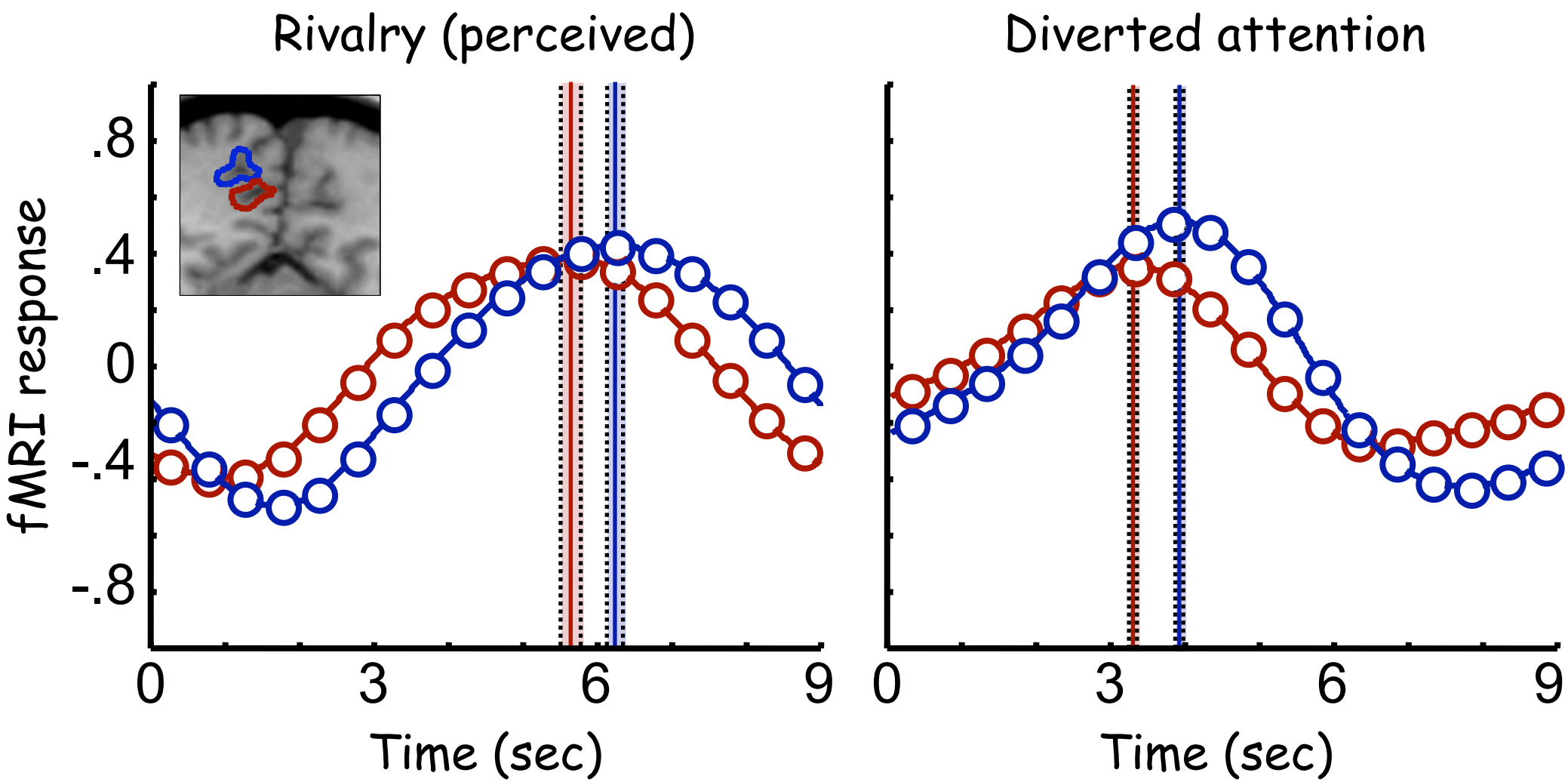
C2DA3B42D...

Time

Detect repetition

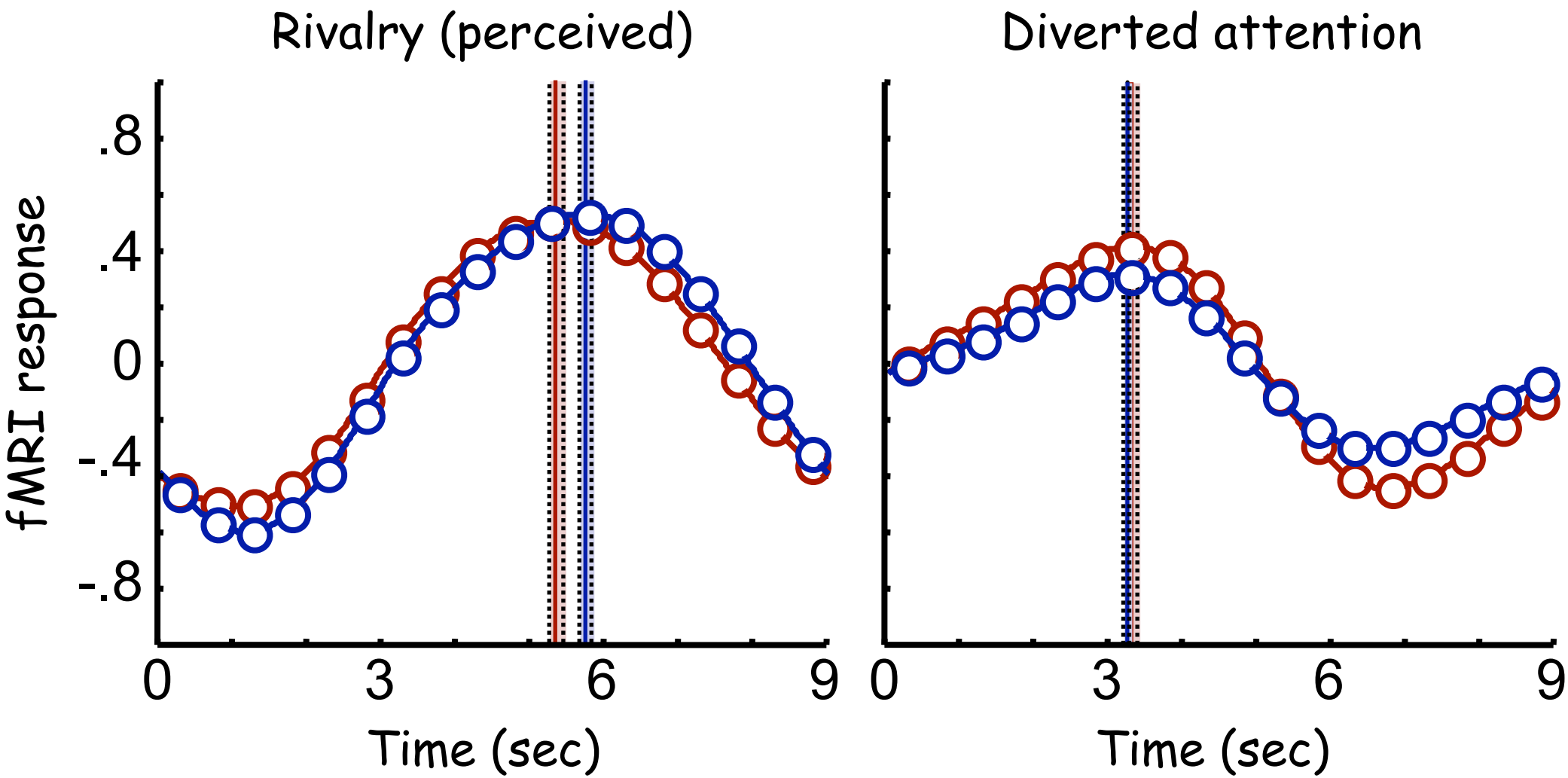
Lee, Blake, & Heeger, Nature Neurosci (2007)

Waves in V1 without attention/perception



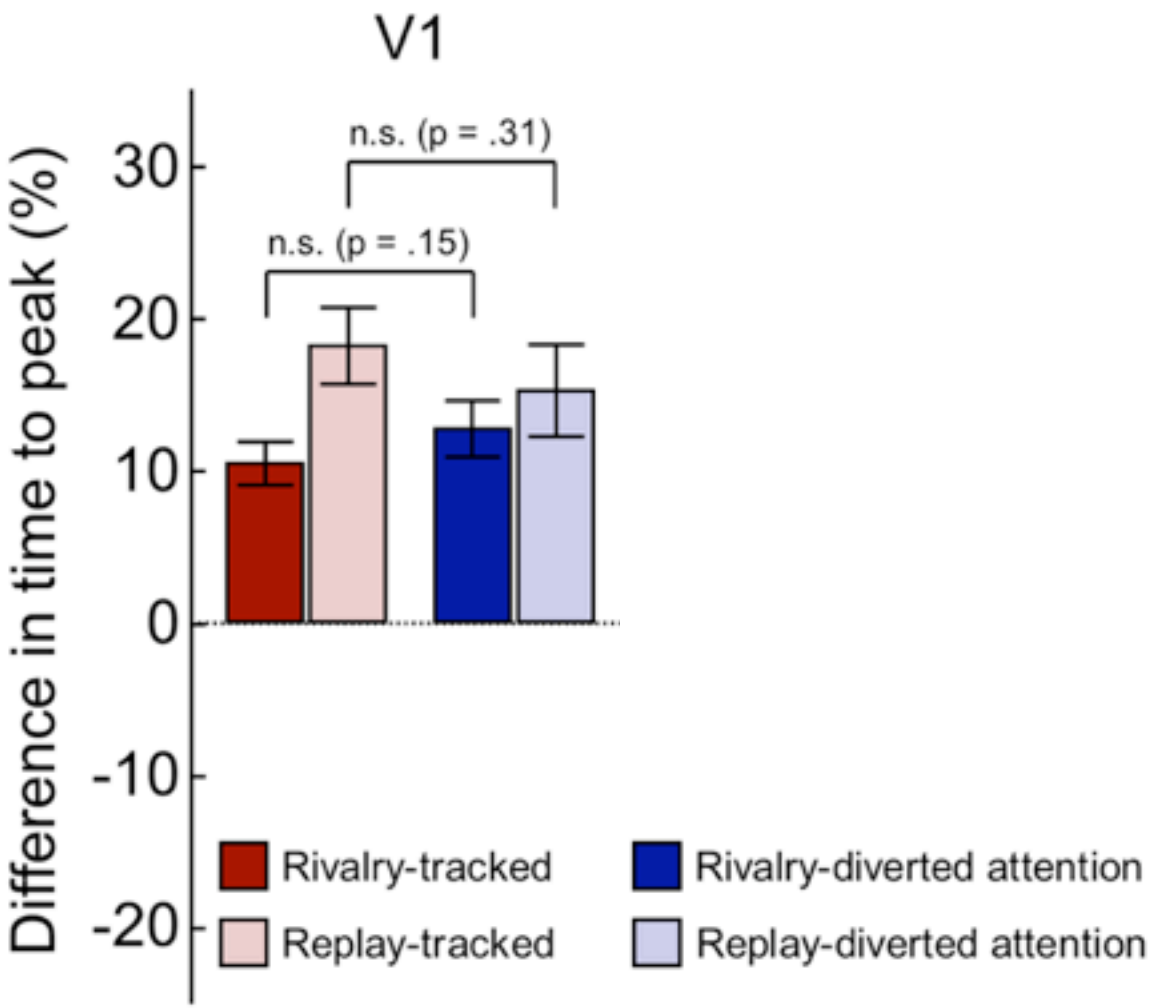
Lee, Blake, & Heeger, Nature Neurosci (2007)

V2



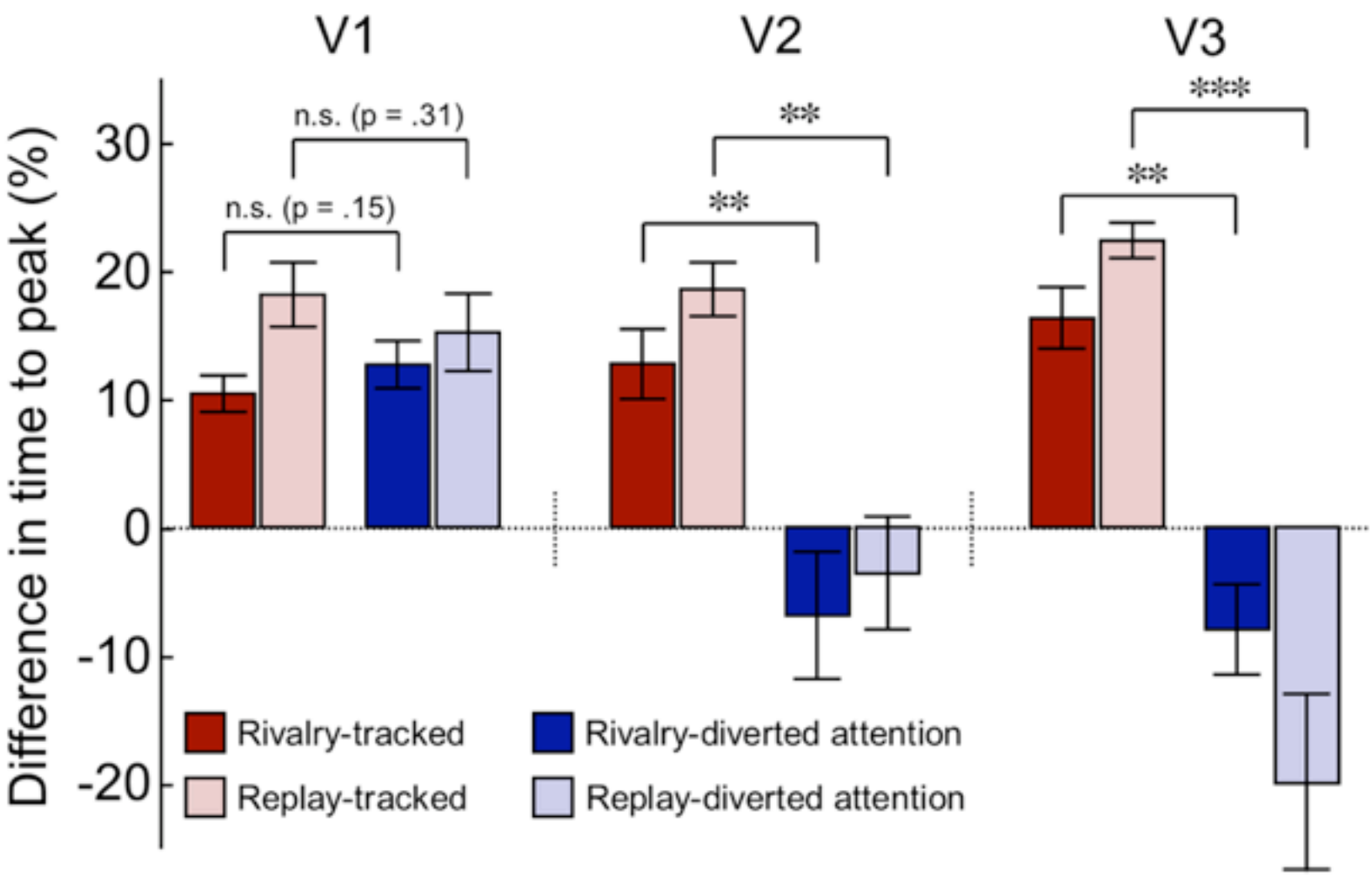
Lee, Blake, & Heeger, Nature Neurosci (2007)

Diverting attention eliminates waves in V2 & V3



Lee, Blake, & Heeger, Nature Neurosci (2007)

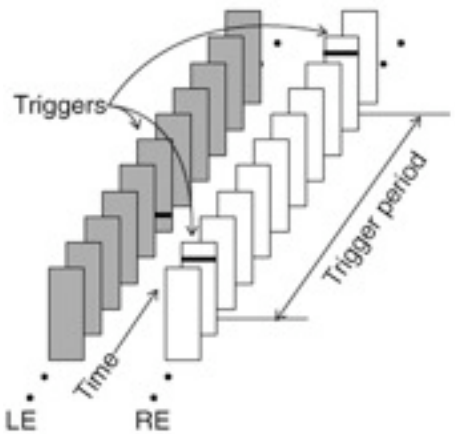
Diverting attention eliminates waves in V2 & V3

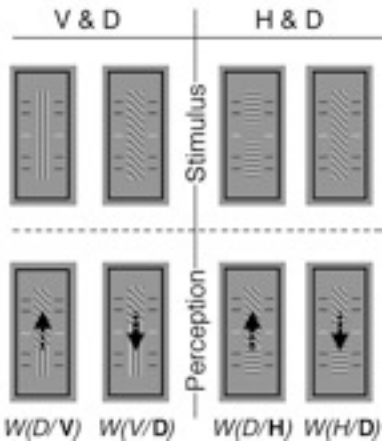


Lee, Blake, & Heeger, Nature Neurosci (2007)

Models and testing them

Periodic perturbation



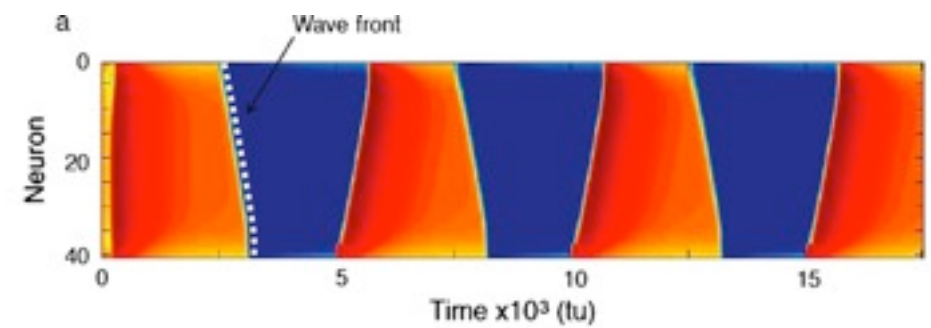


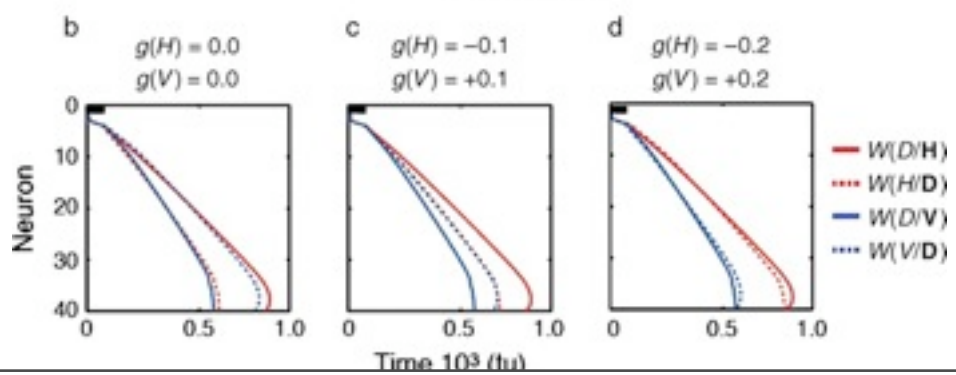
$$\tau_E \partial_t E_{Aij} = -E_{Aij} + \frac{[P_{Aij}]^2}{(10 + H_{Aij})^2 + [P_{Aij}]^2}, \quad (1)$$

$$P_{Aij} = S_{Aij} - \eta_I \sum_{k=1}^{N} \varphi_{Bjk} I_{Bik} + \eta_E \sum_{k=1}^{N} \varepsilon_{Ajk} E_{Aik}, \quad (2)$$

$$\varphi_{Ajk} = \exp\left(\frac{-(k-j)^2}{4\sigma_\varphi^2}\right), \quad (3)$$

Simulations





$$\varepsilon_{Ajk}(X) = \exp\left(\frac{-(k-j)^2}{4\sigma_\varepsilon(X)}\right) (k \neq j) \text{ in which } X \text{ is the stimulus pattern}, \quad (4)$$

$$\tau_I \partial_t I_{Aij} = -I_{Aij} + E_{Aij}, \quad (5)$$

$$\tau_H \partial_t H_{Aij} = -H_{Aij} + \eta_H \gamma_{AH} E_{Aij}, \quad (6)$$

$$\gamma_{AH} = 1 + g(X) \text{ in which } X \text{ is the stimulus pattern.} \quad (7)$$

Kang, Lee, Kim, Heeger, Blake, J Vis, 2010

Part I summary

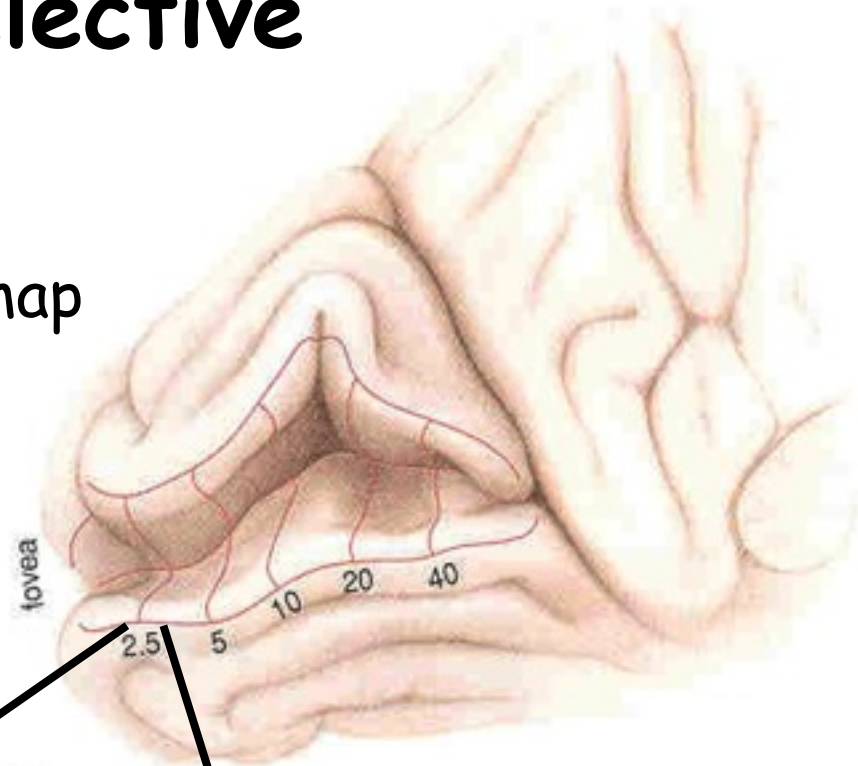
- V1 activity correlated with spatio-temporal dynamics of perceptual waves during binocular rivalry.
- The velocity of neural waves in V1 matched the latency of perceptual waves.
- Neural waves in V1 were still present when attention was diverted, but weaker in amplitude and faster in velocity.
- V2 and V3 exhibited cortical waves of activity during rivalry but the waves were eliminated when attention was diverted.

Implications

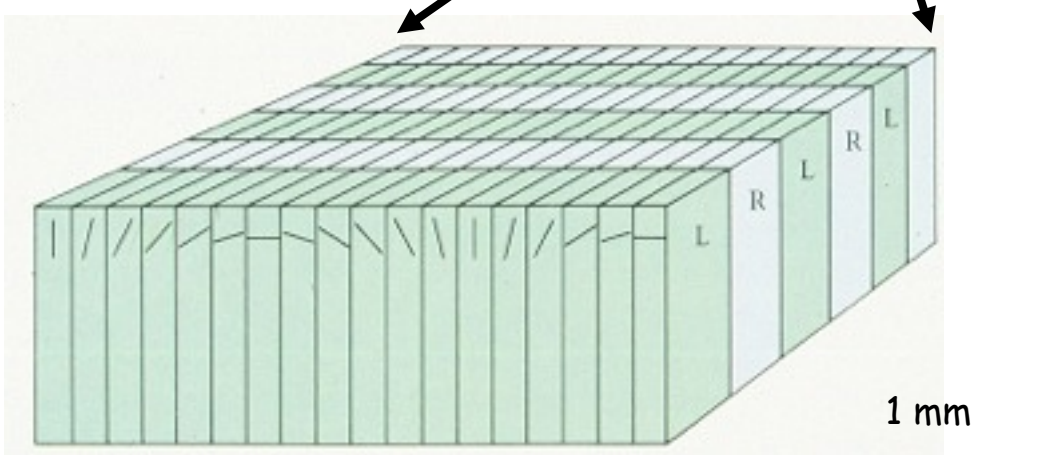
- Neural wave propagation is intrinsic to V1.
- Constrains models of processing and circuitry in V1 (waves are slow relative to action potential propagation and synaptic transmission).

Part II: Spatial resolution & measuring activity in selective subpopulations

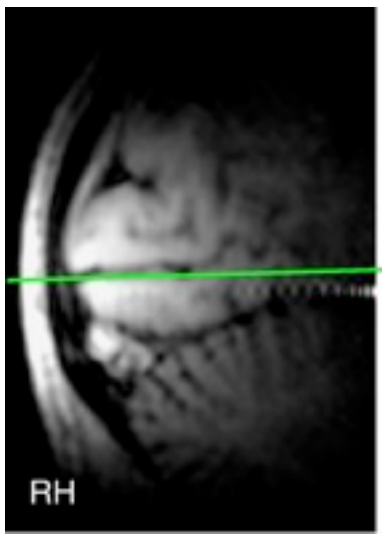
Retinotopic map

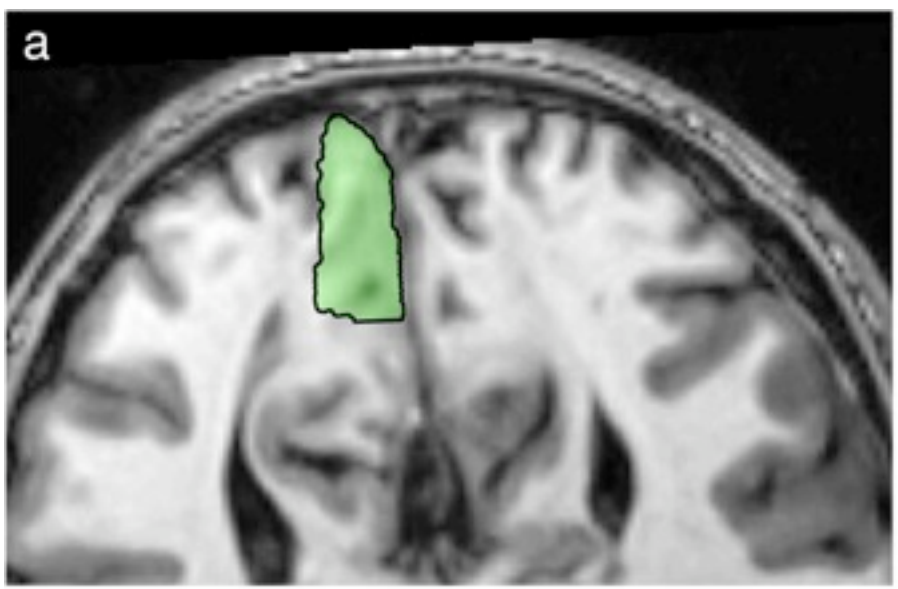


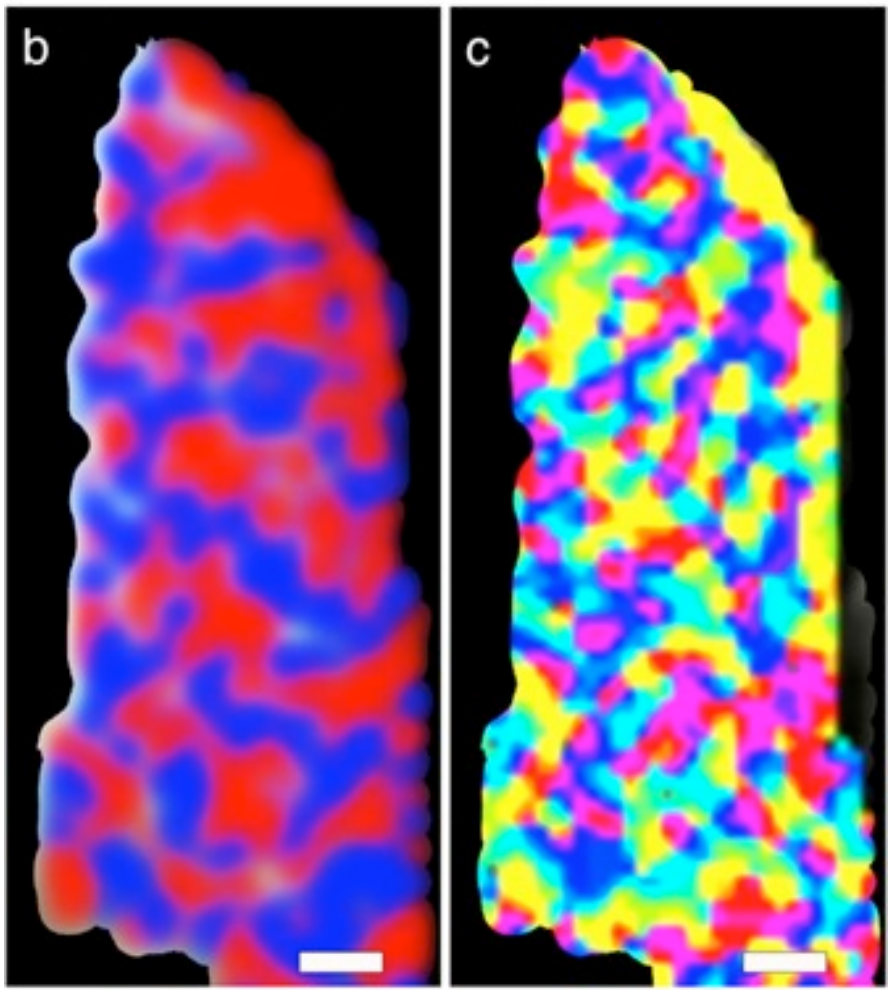
Columnar architecture



Human ocular dominance and orientation columns

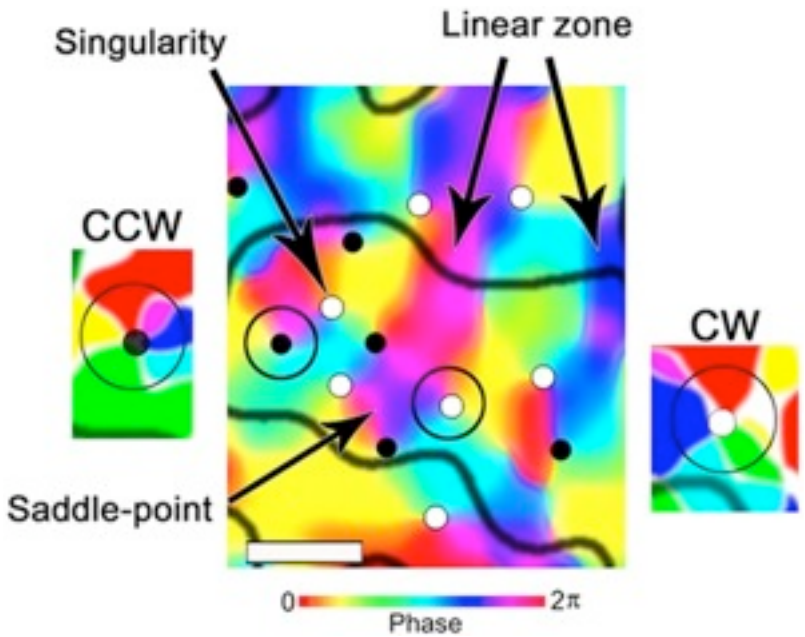


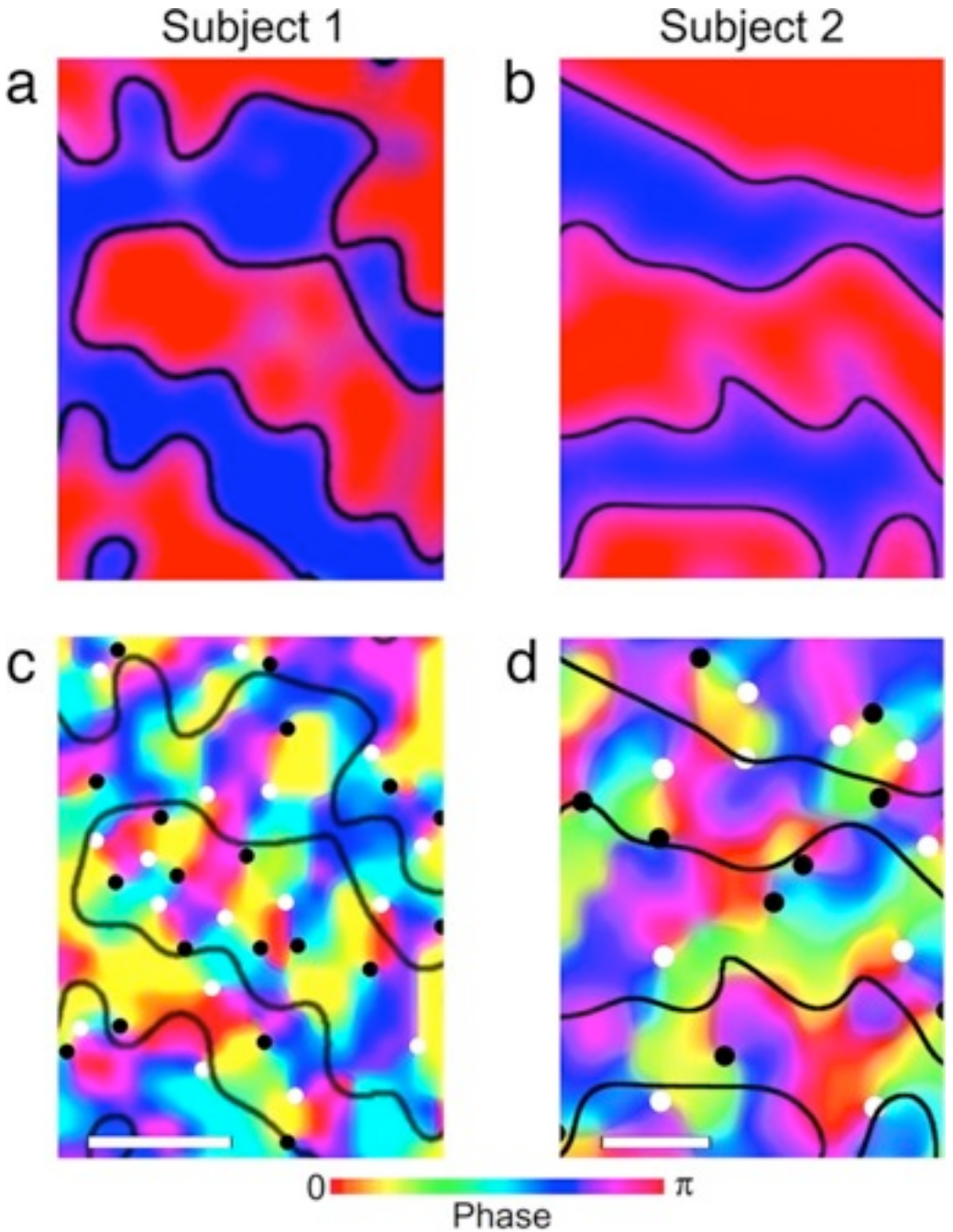




Yacoub, Harel, Ugurbil, PNAS (2008)

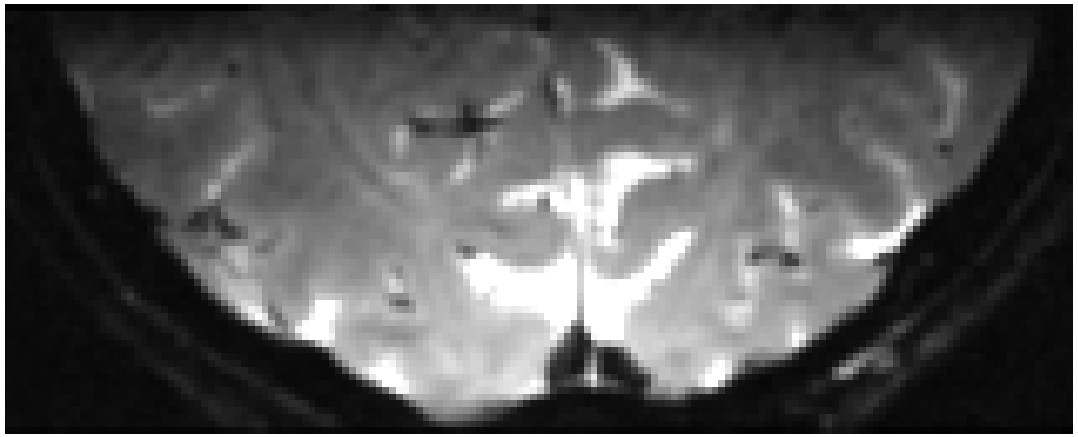
Human ocular dominance and orientation columns



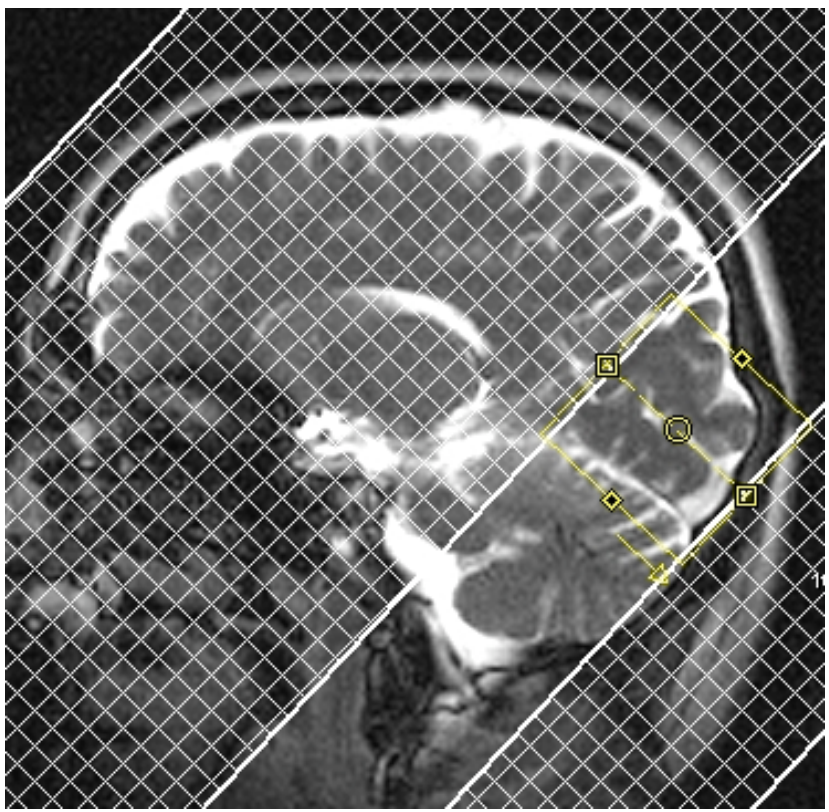


Yacoub, Harel, Ugurbil, PNAS (2008)

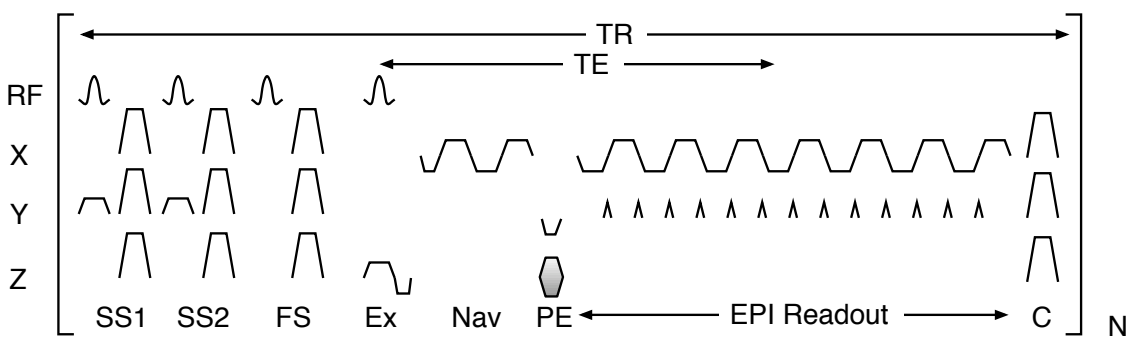
High resolution fMRI acquisition



0.75 x 0.75 x 0.75 mm

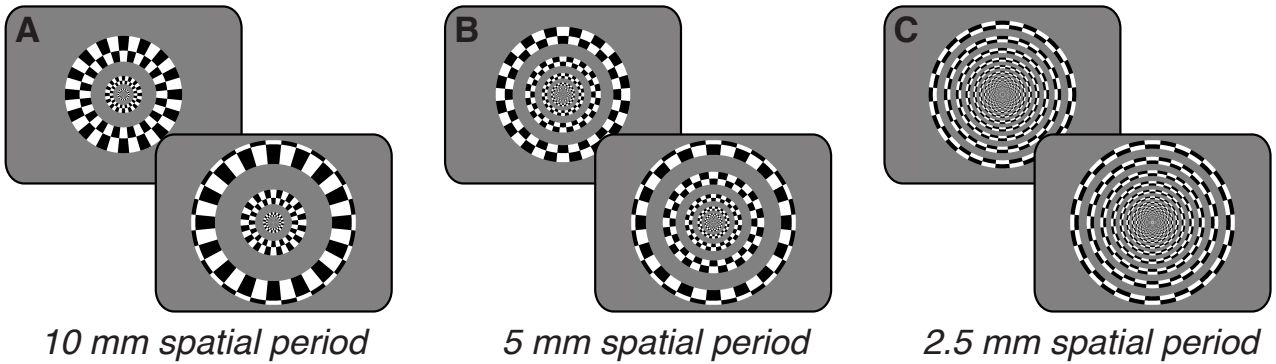


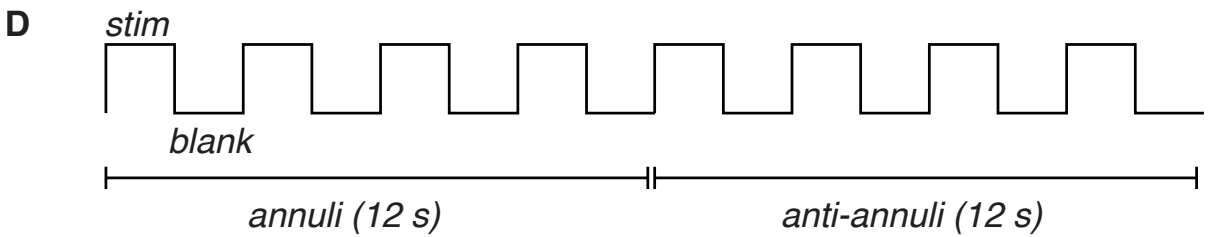
Gradient-recalled echo (GRE) pulse sequence with outer volume suppression.

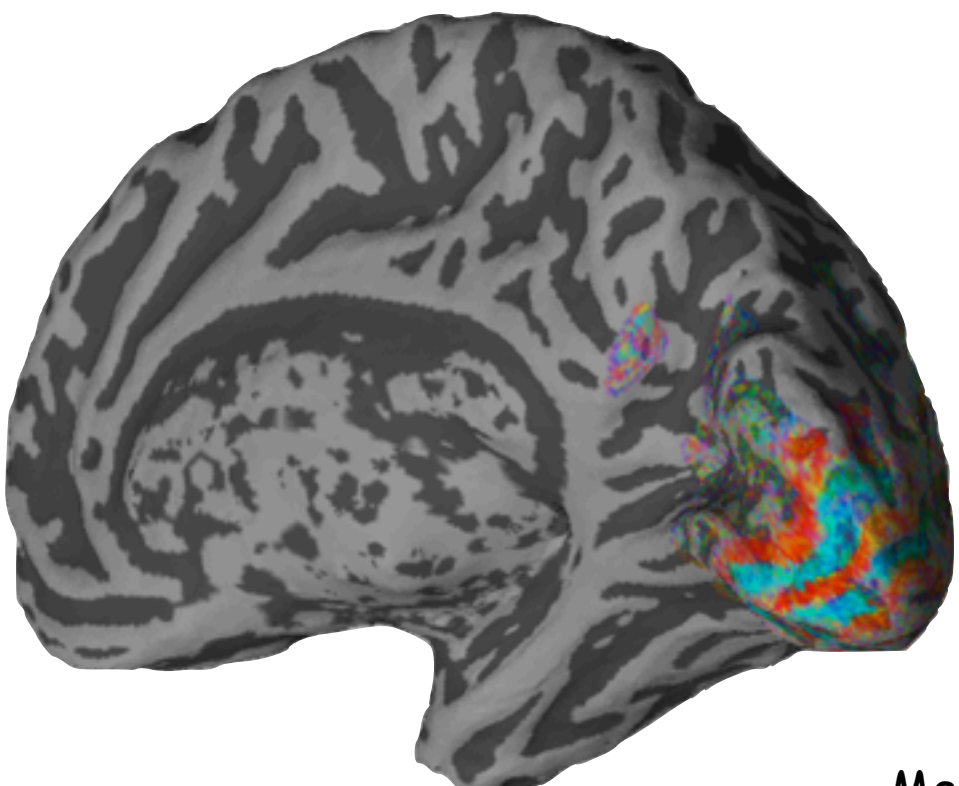


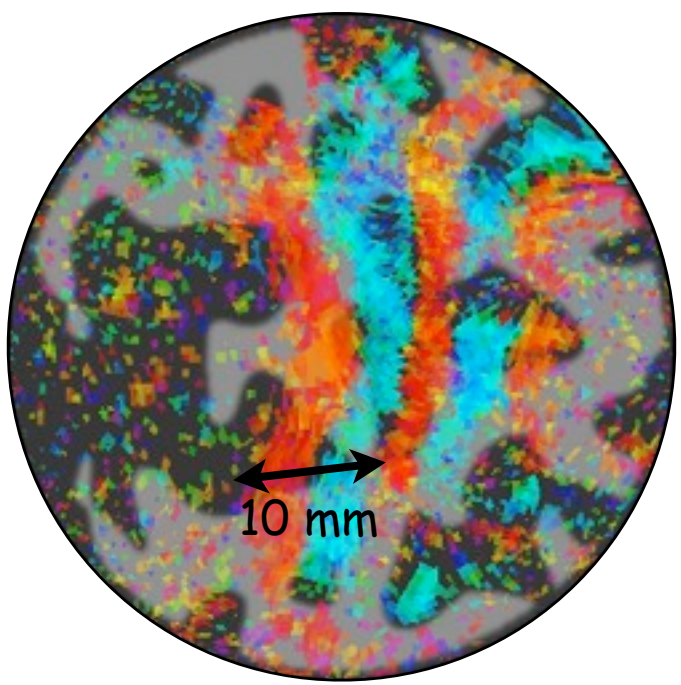
Merriam, Schluppeck, Heeger, et al, SfN (2010)

Spatial resolution protocol



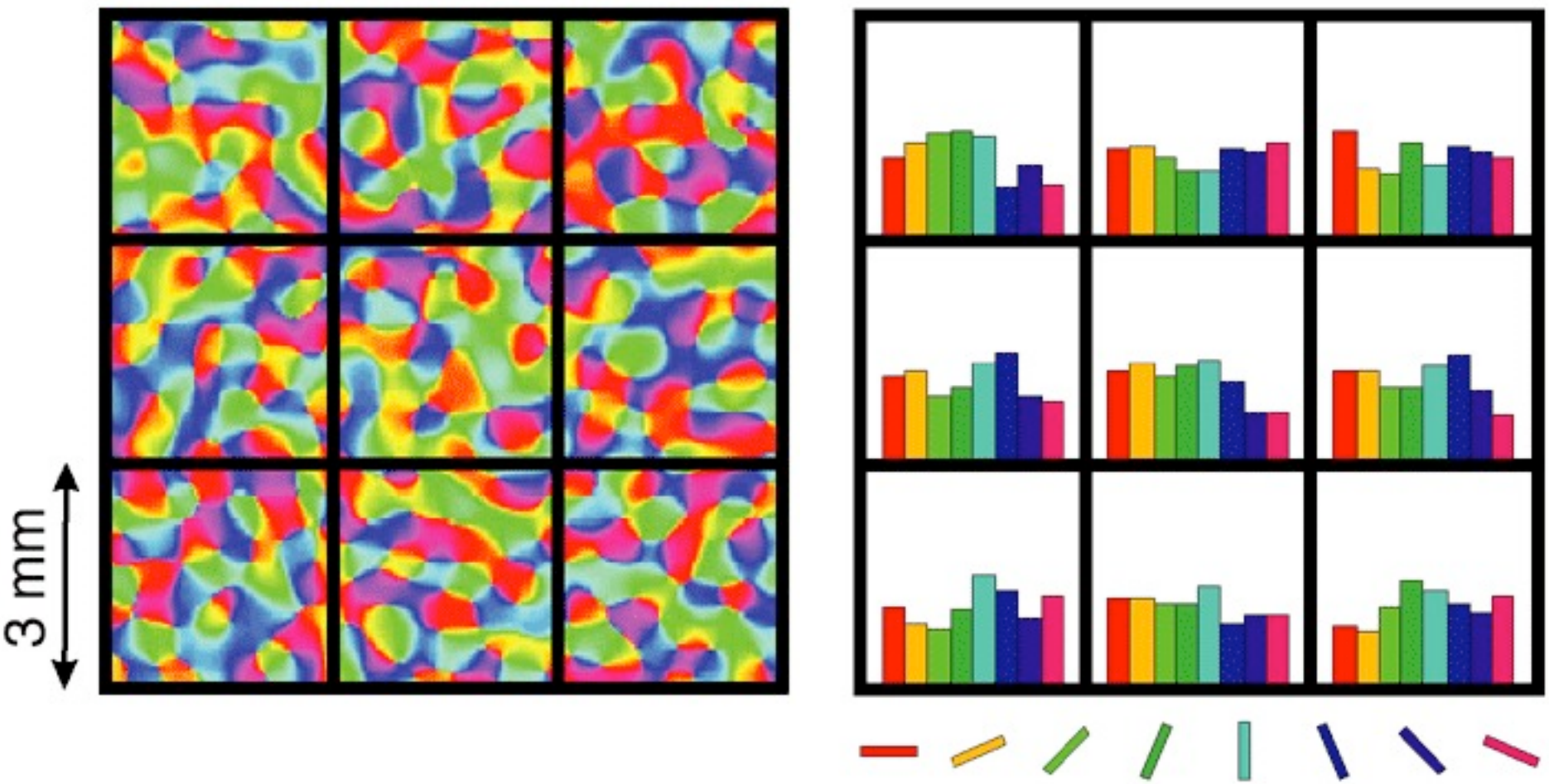






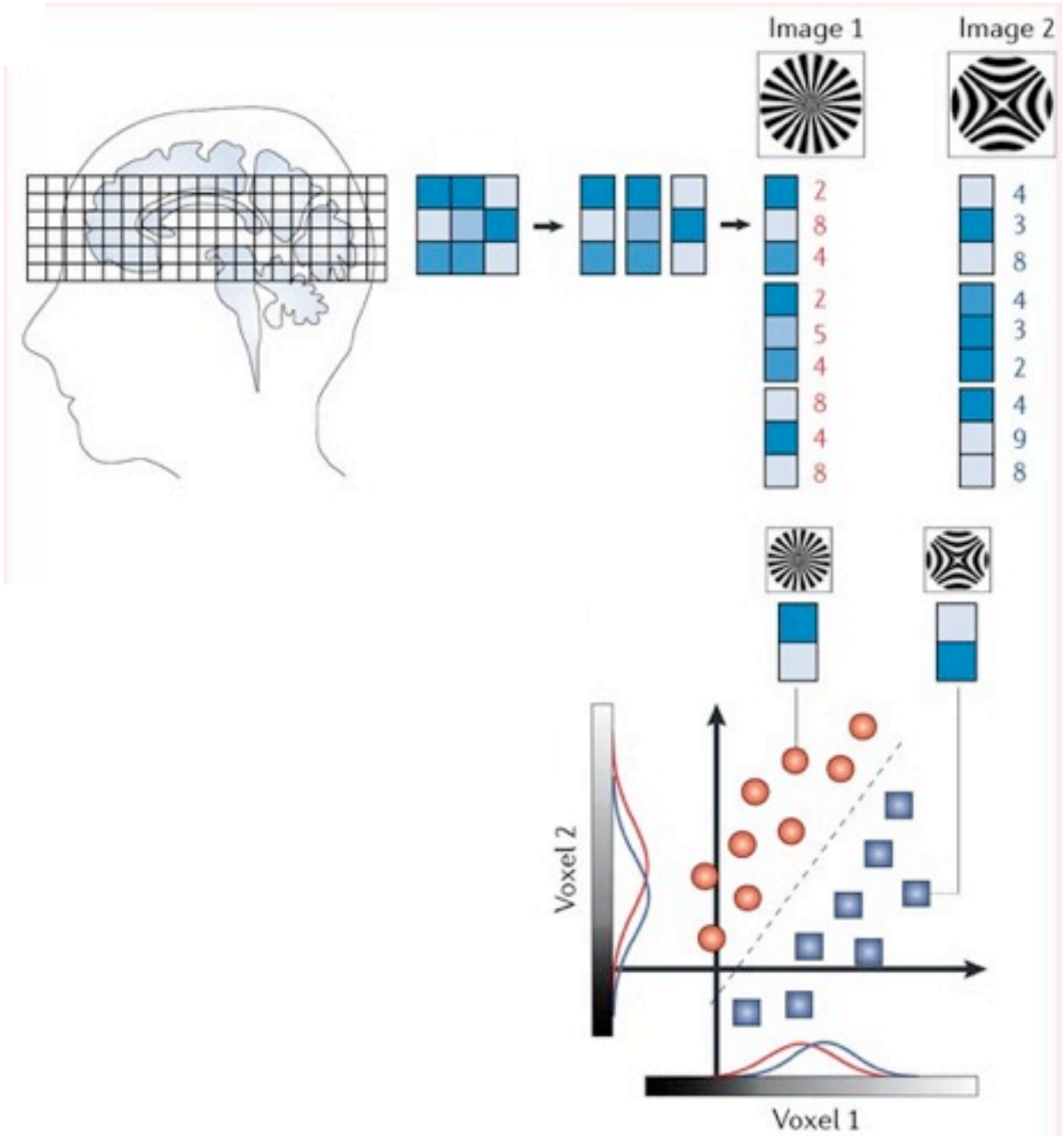
Merriam, Schluppeck, Heeger, et al, SfN (2010)

Orientation decoding

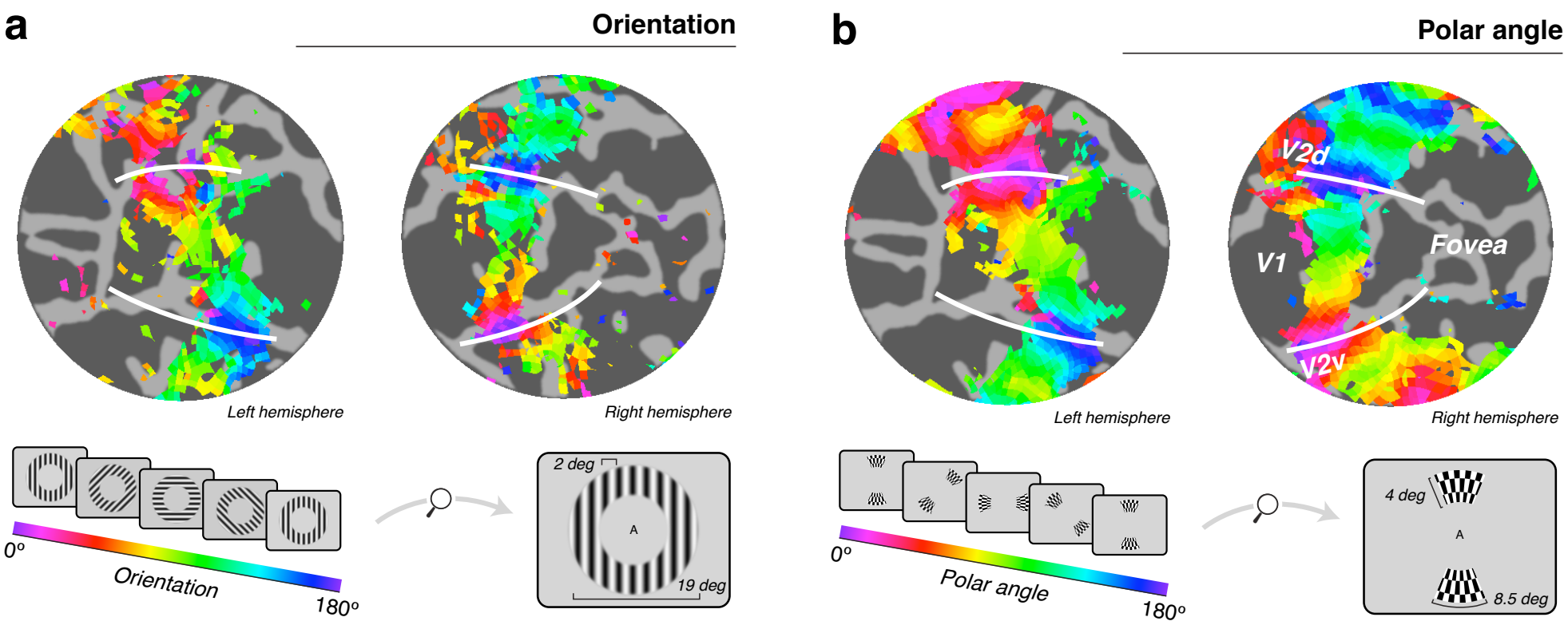


Boynton, Nat Neurosci (2008)
following Kamitani & Tong, Nat Neurosci (2008)

Linear discriminant analysis

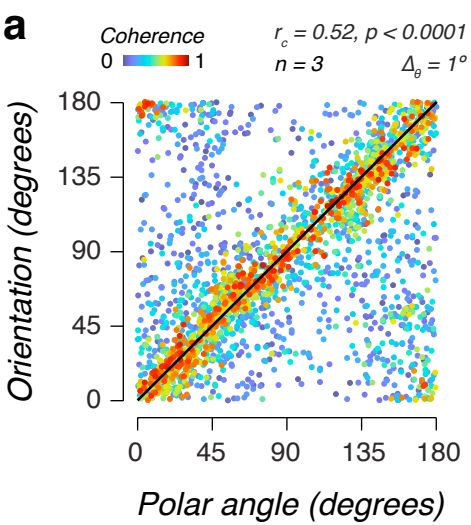


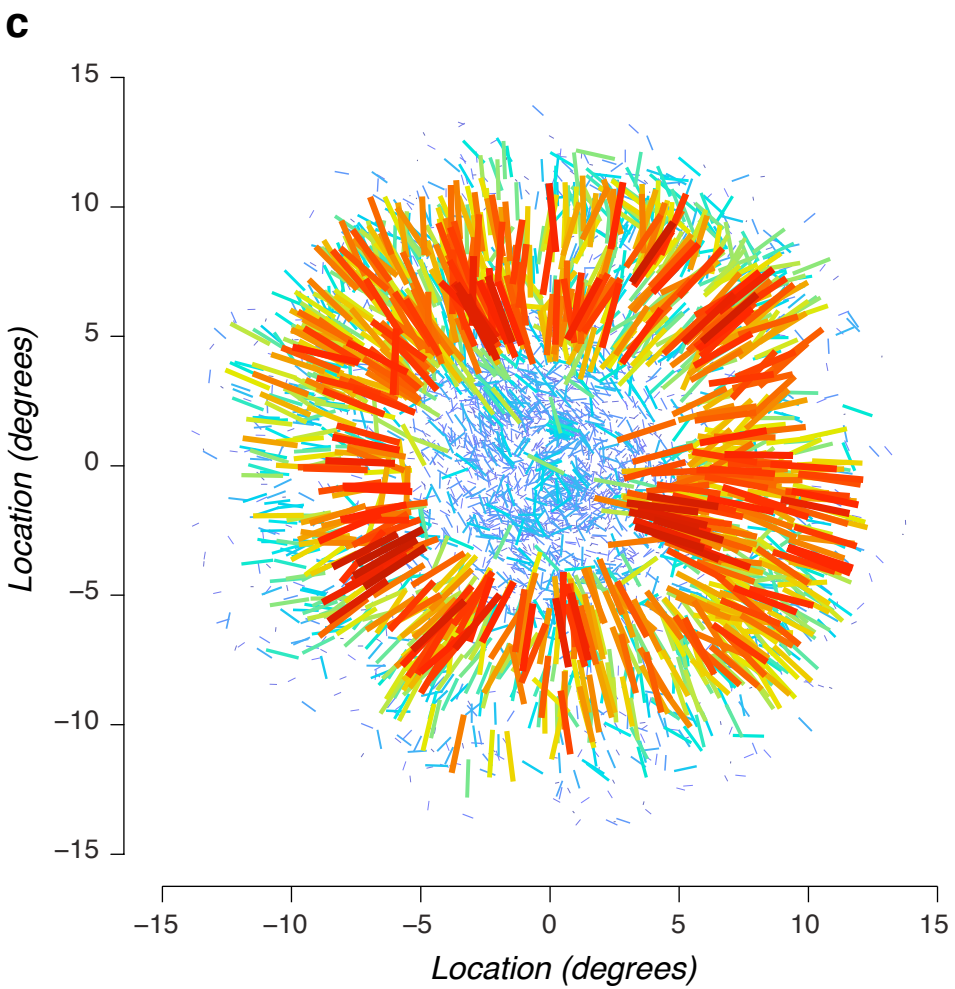
Orientation map matches polar-angle map



Freeman, Brouwer, Heeger, Merriam, SfN (2010)

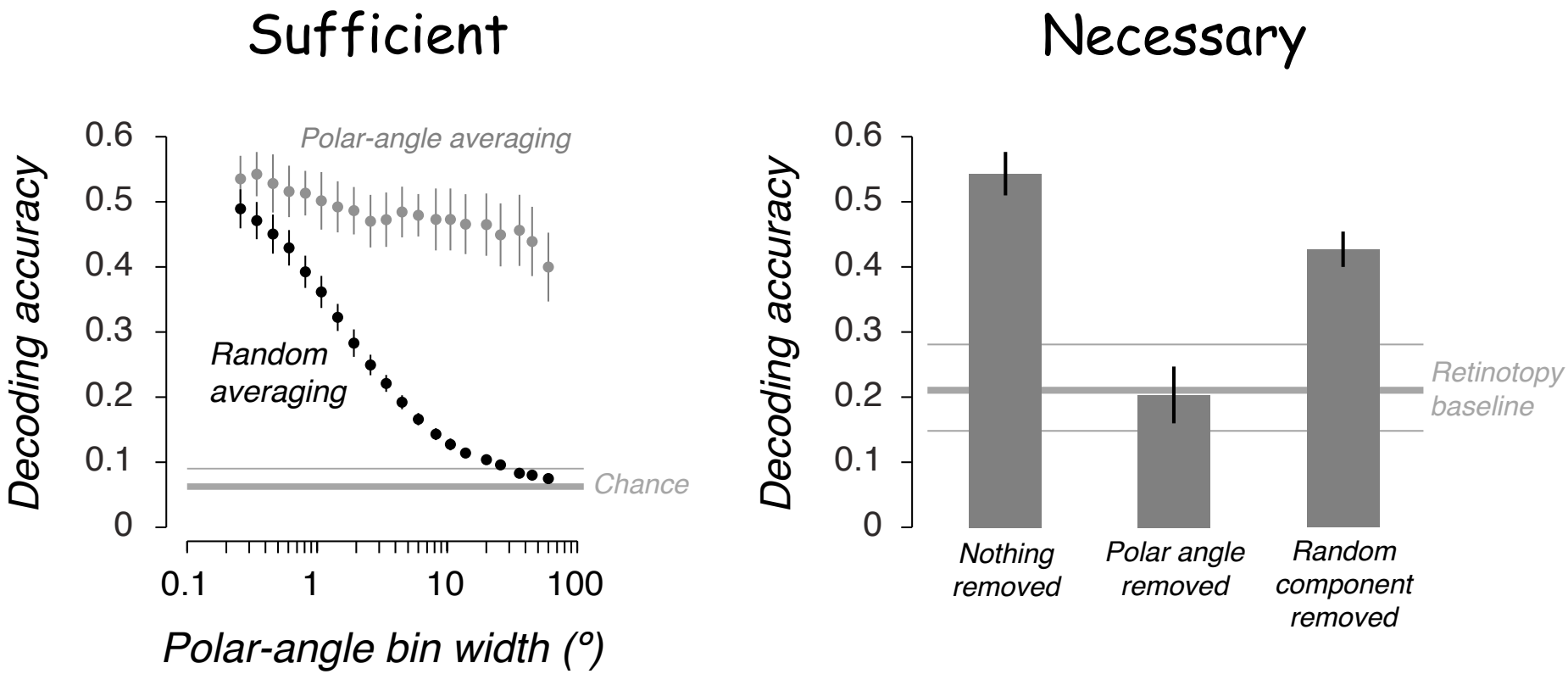
Orientation map matches polar-angle map





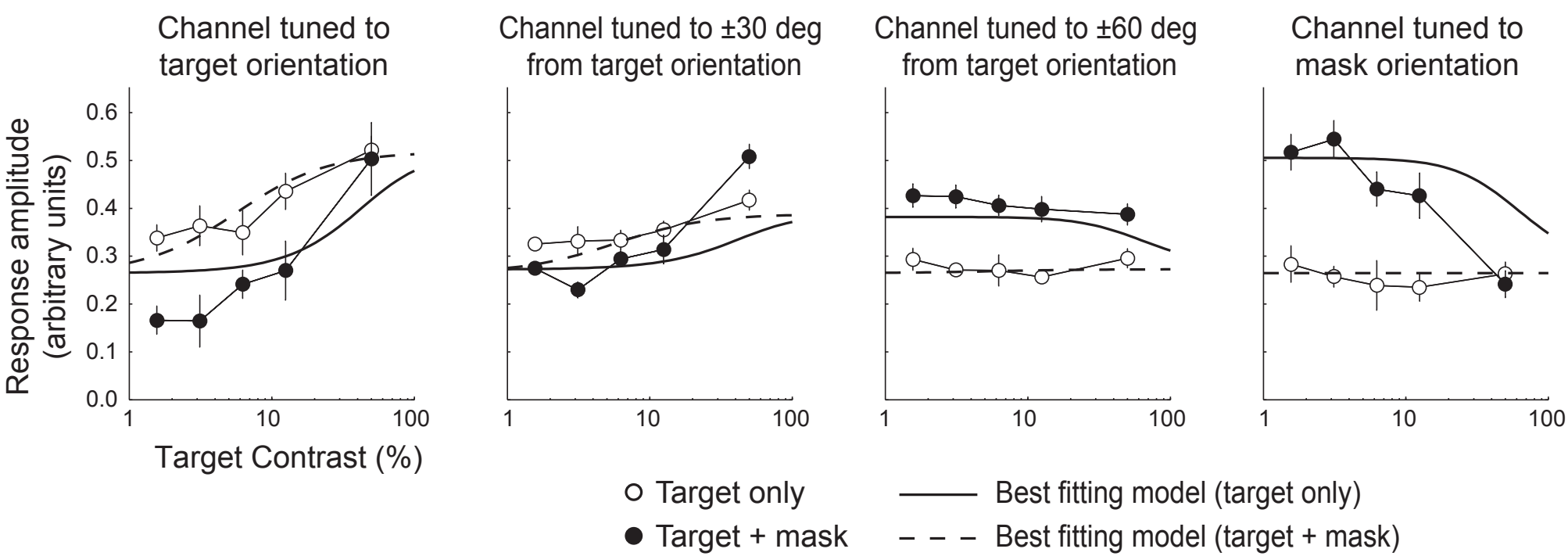
Freeman, Brouwer, Heeger, Merriam, SfN (2010)

Orientation map is necessary and sufficient for decoding



Freeman, Brouwer, Heeger, Merriam, SfN (2010)

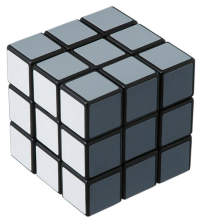
Normalization in human V1



Brouwer & Heeger, Cosyne (2010)

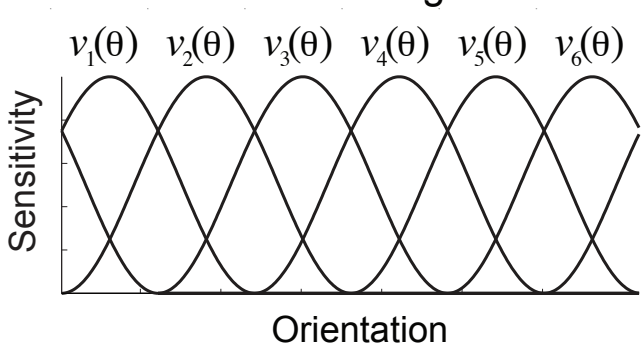
Forward model

Voxel responses



$$y_j = \sum_i w_{ij} x_i$$

Orientation tuning model



$$\mathbf{Y} = \mathbf{W}\,\mathbf{X}$$

Measure weight matrix using full-contrast oriented gratings:

Then for main expt, use inverse of $\mathbf{W}$ to estimate $\mathbf{X}$ from $\mathbf{Y}$.

Brouwer & Heeger, Cosyne (2010)

Part II summary

Goal: measure activity in separate subpopulations of neurons that respond selectively to different features.

- Columnar scale spatial resolution is achievable but not routine.
- Coarse scale radial bias explains orientation decoding/ classification, not random sampling of fine-scale columnar architecture.
- Forward model and regression transforms voxel responses to selective "channel" responses.

Collaborators

Randolph Blake (Vanderbilt University)
Gijs Brouwer (NYU)
Jeremy Freeman (NYU)
Jonas Larrson (Royal Holloway University of London)
Sang-Hun Lee (Seoul National University)
Eli Merriam (NYU)
Denis Schluppeck (University of Nottingham)
Eyal Seidemann (UT Austin)
Zhiyong Yang (Medical College of Georgia)