Probing sensory representations with metameric stimuli

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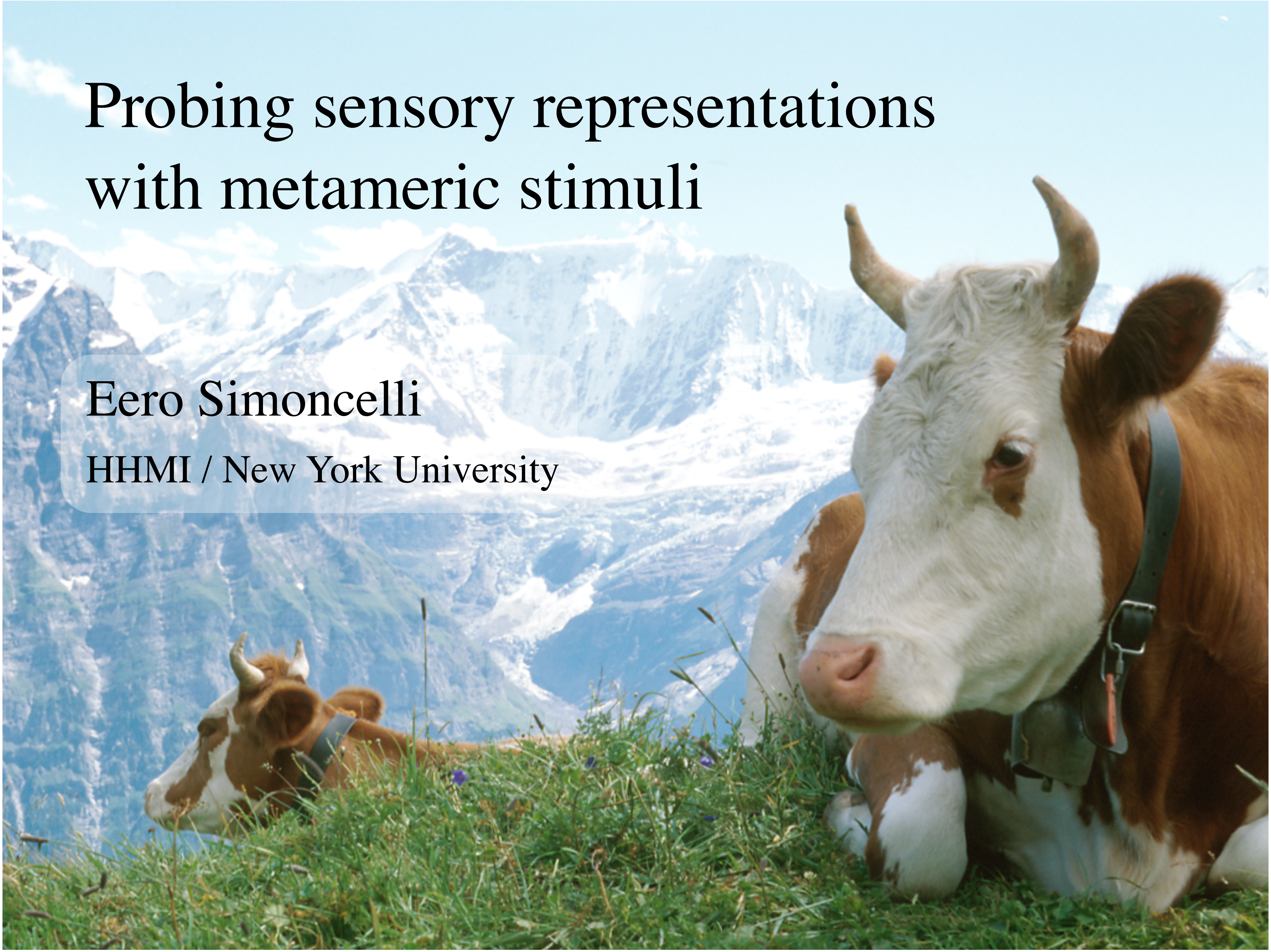
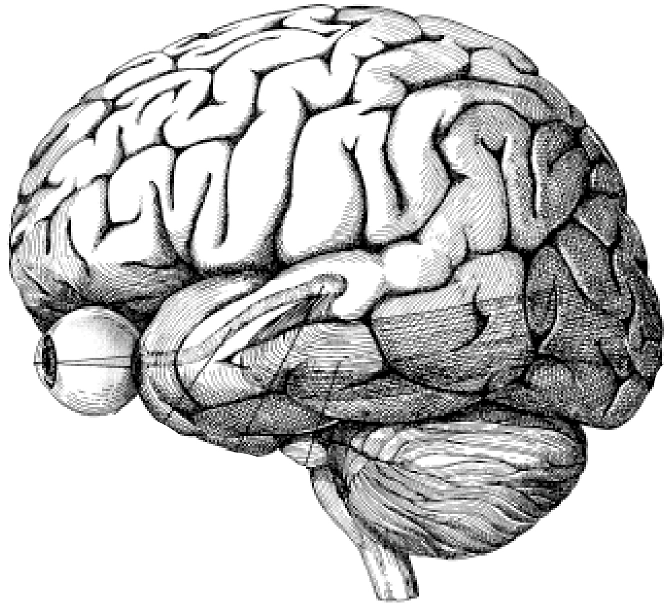
HHMI / New York University

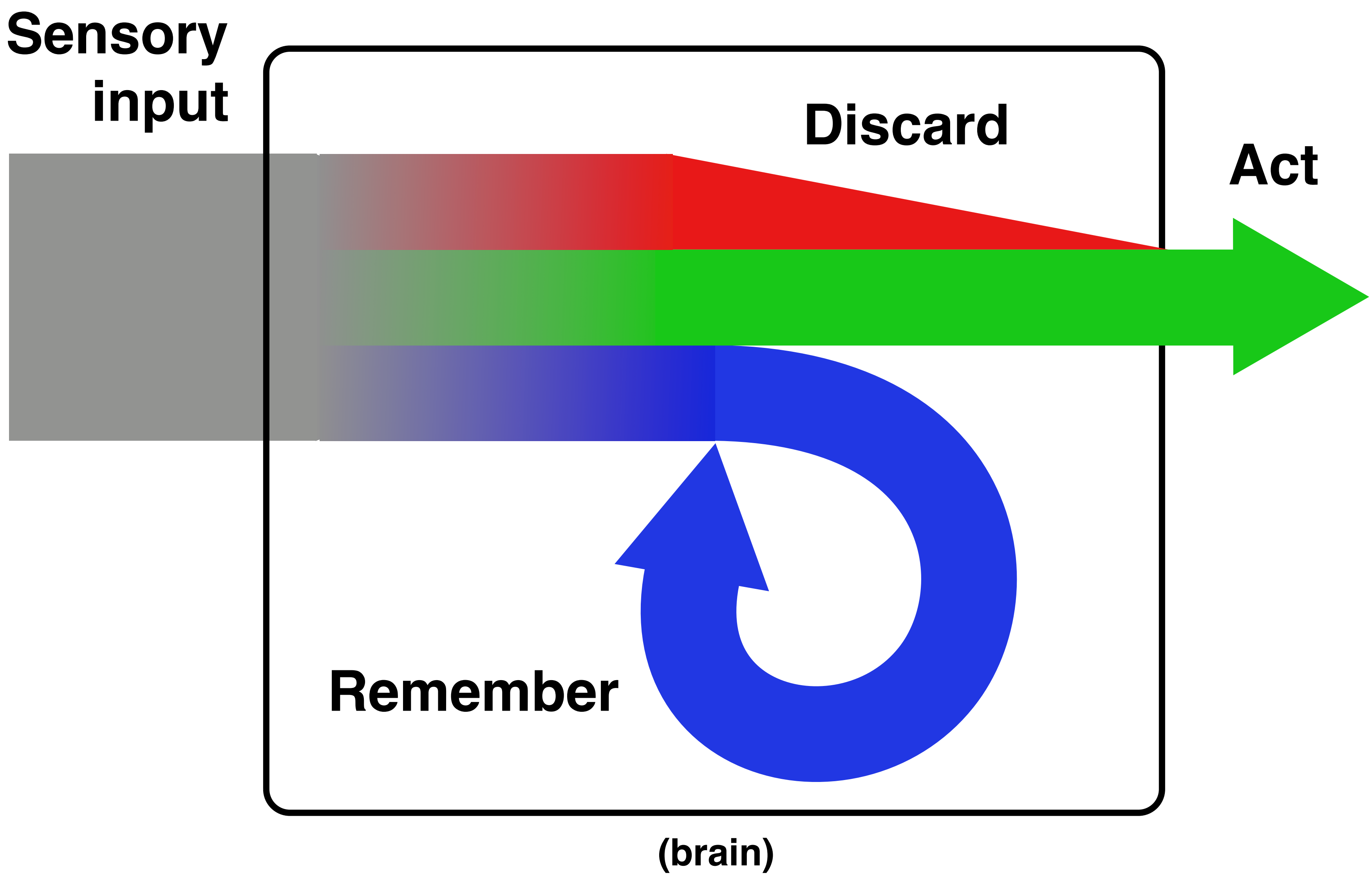




Where does all that visual information go?

[figure: Hubel ‘95]

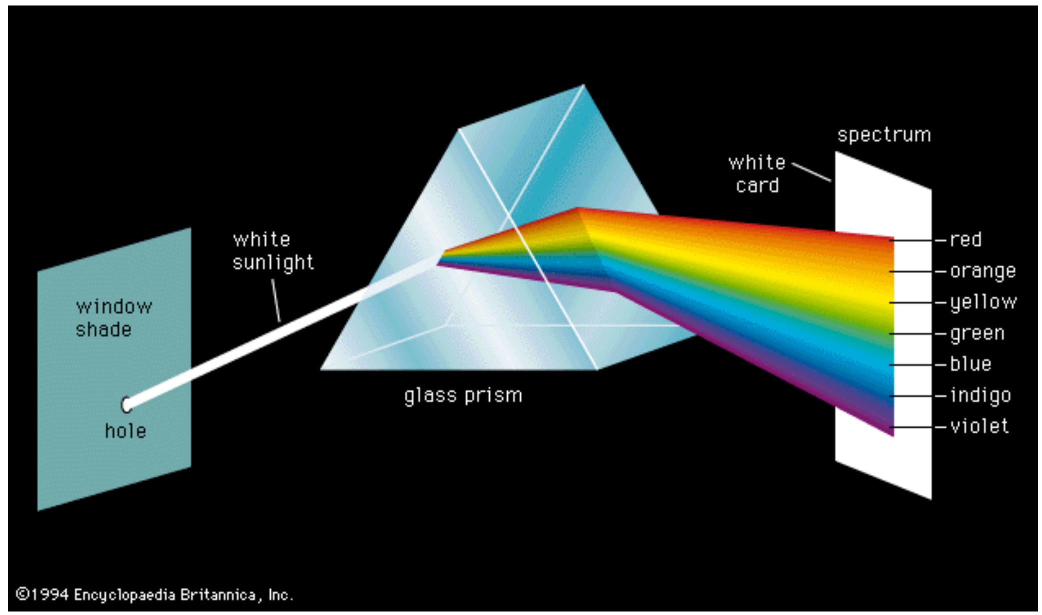
Destiny of sensory information



Metamers

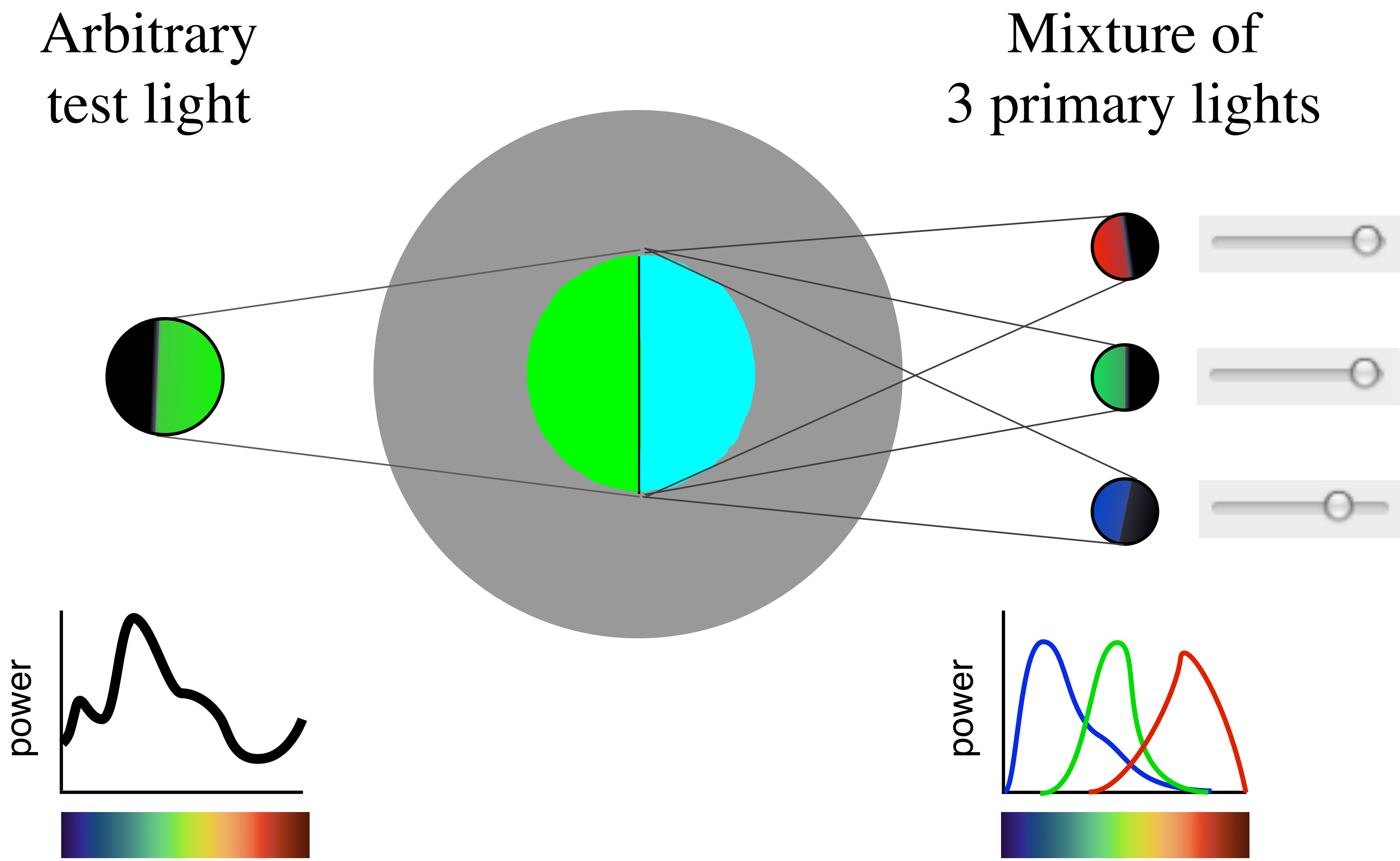
- Two stimuli that are physically different, but appear the same to a human observer
- Classic example: trichromatic color perception
- Another example: texture perception

Spectral nature of light



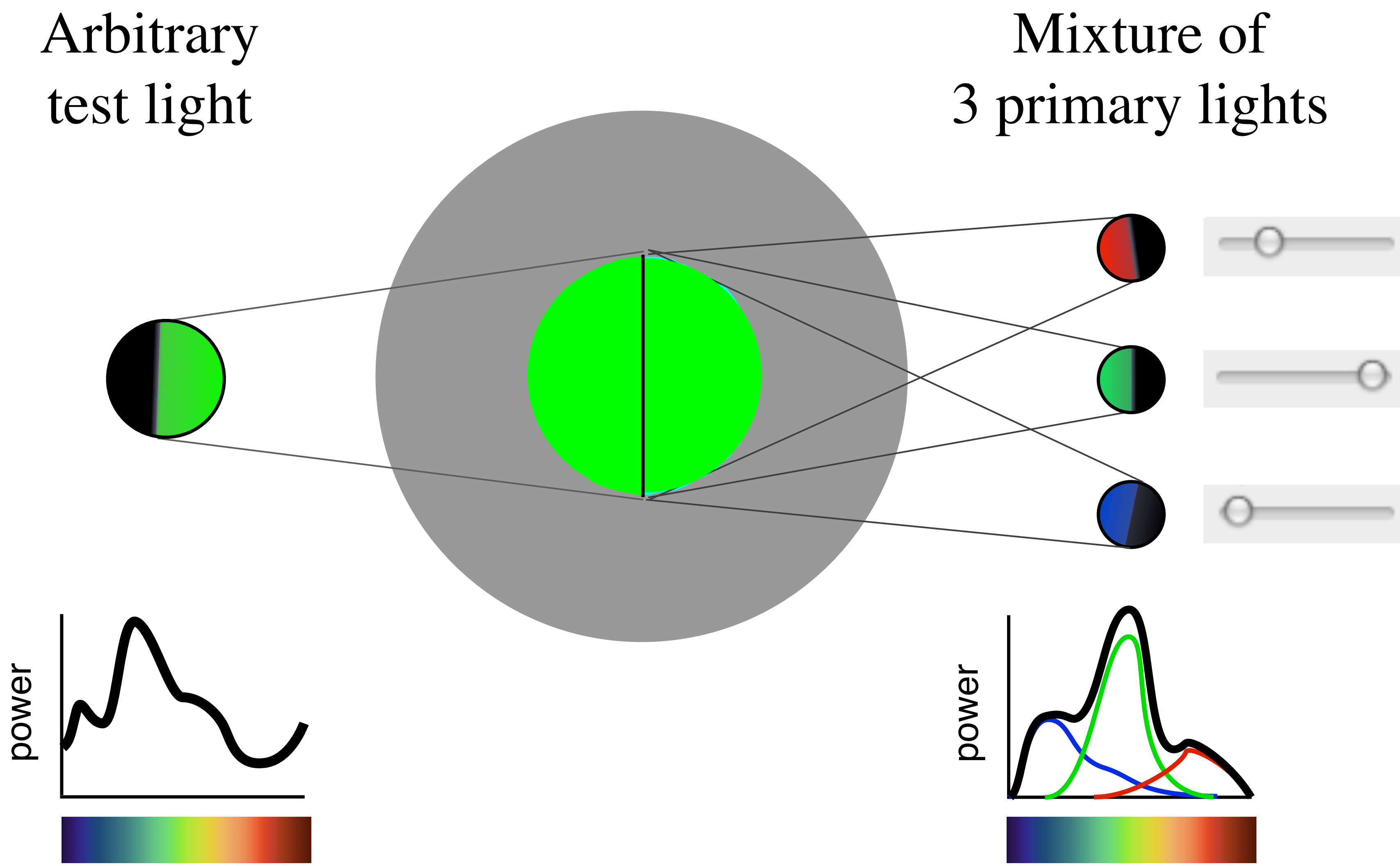
[Newton, 1665]

Perceptual color matching experiment



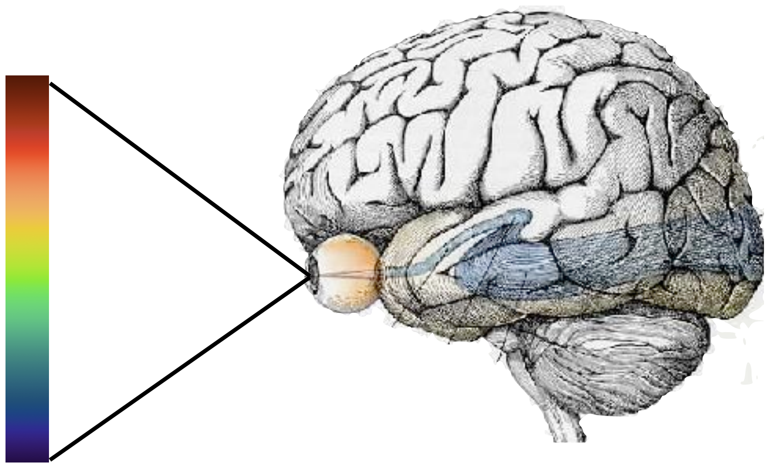
[Young, Helmholtz, Grassman, etc, 1800's; slide c/o D. Brainard]

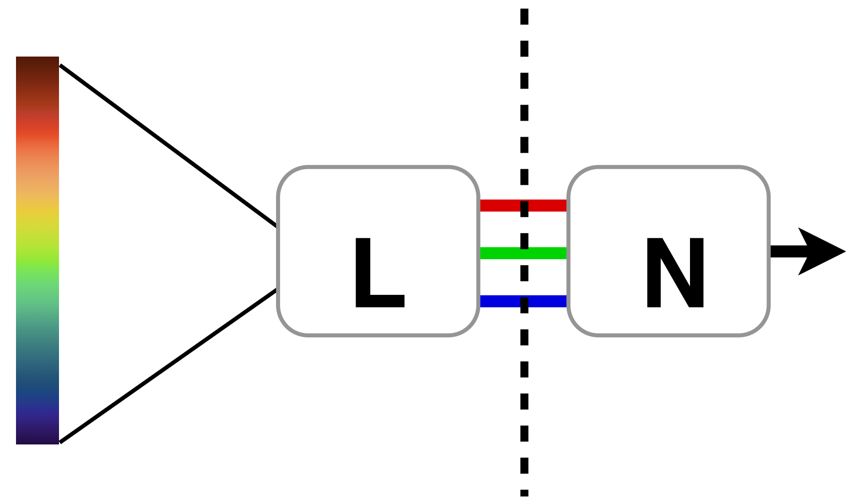
Perceptual color matching experiment



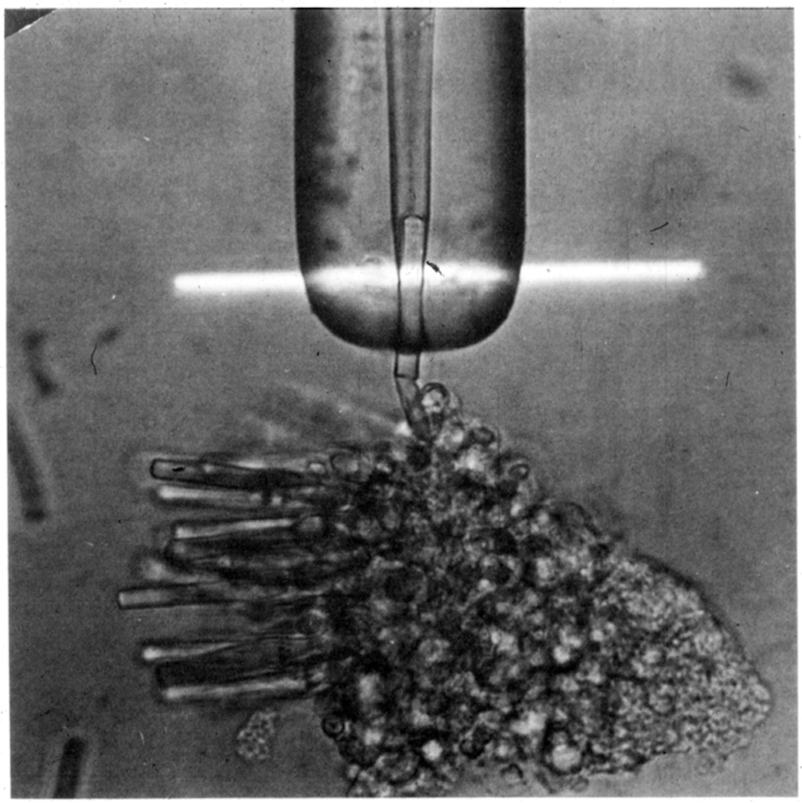
[Young, Helmholtz, Grassman, etc, 1800's; slide c/o D. Brainard]

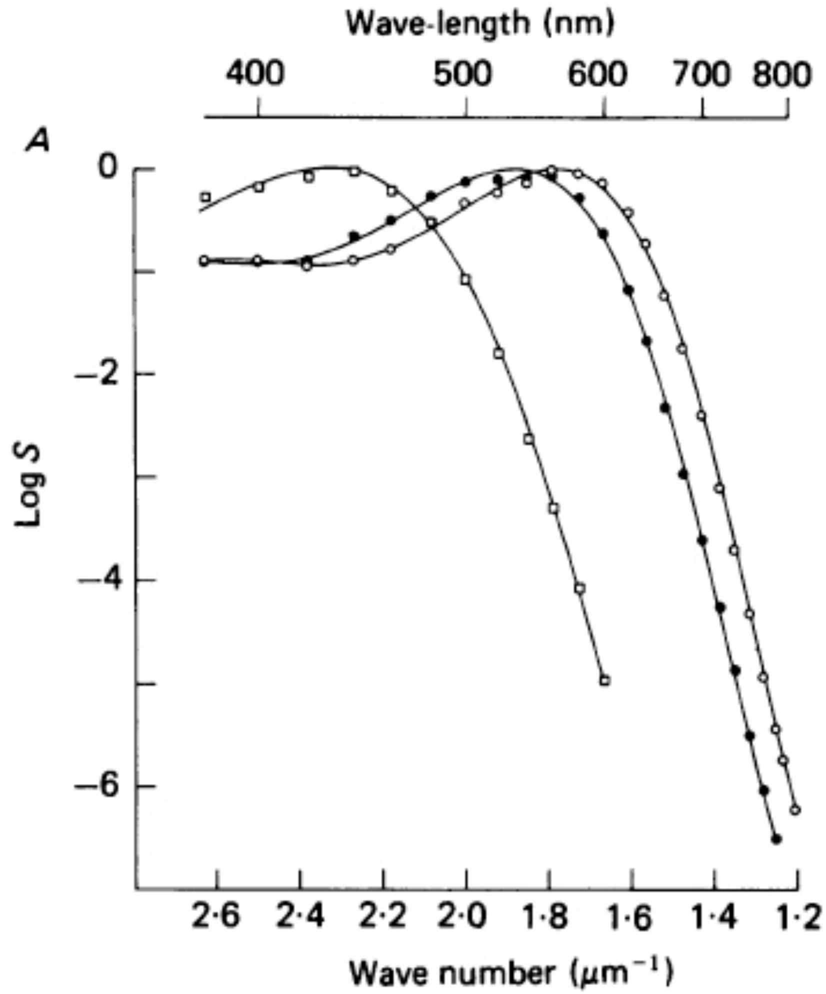
Theory (Grassman, 1853): the visual system performs a **linear projection** of the wavelength spectrum onto a three-dimensional response space





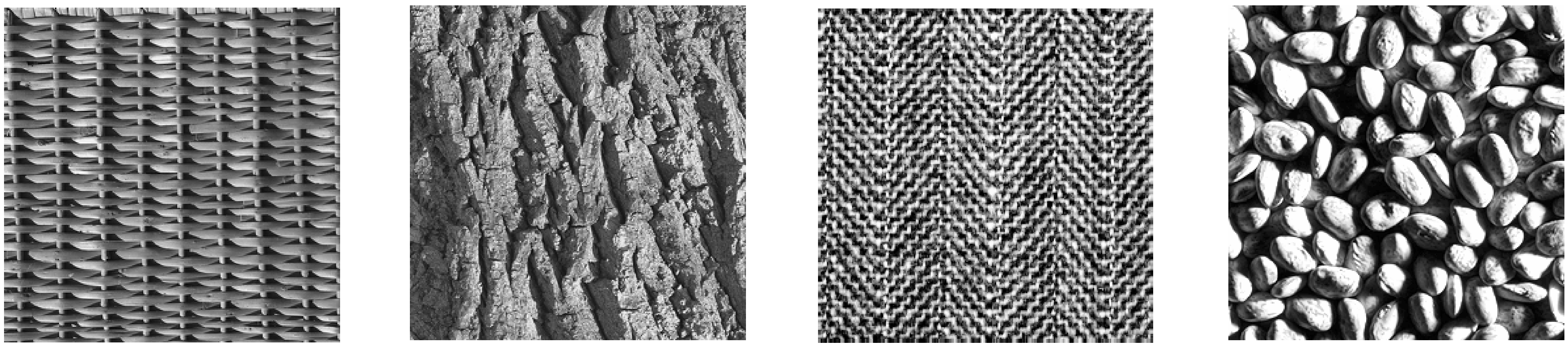
- Predicts/explains perceptual “metamers” - lights that appear identical, but have physically distinct wavelength spectra (1800’s)
- Codified in CIE standards for color representation (1931)
- Underlying mechanism (cone photoreceptors) verified (1987)





[Baylor, Nunn & Schnapf, 1987]

Visual texture



Homogeneous, with repeated structures

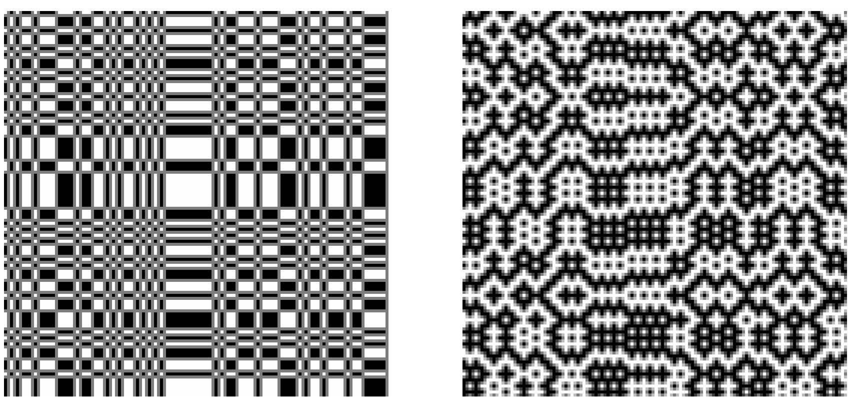
Let us say that to the extent that visible objects are different and far apart, they are forms. To the extent that they are similar and congregated they are a texture. A man has form; a crowd has man-texture. A leaf has form; an arbor has leaf texture, and so on.

[Lettvin, 1976]

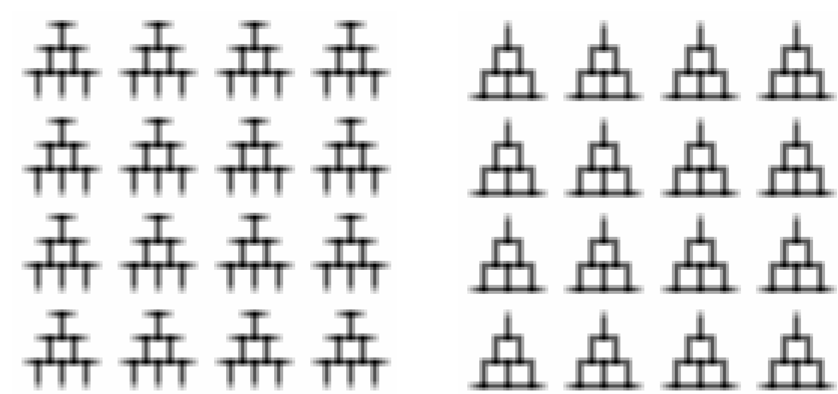
Julesz (1962)

- Hypothesis: Two textures with identical Nth-order pixel statistics will appear the same (for some N).

- Hand-constructed counter-examples (N=3):

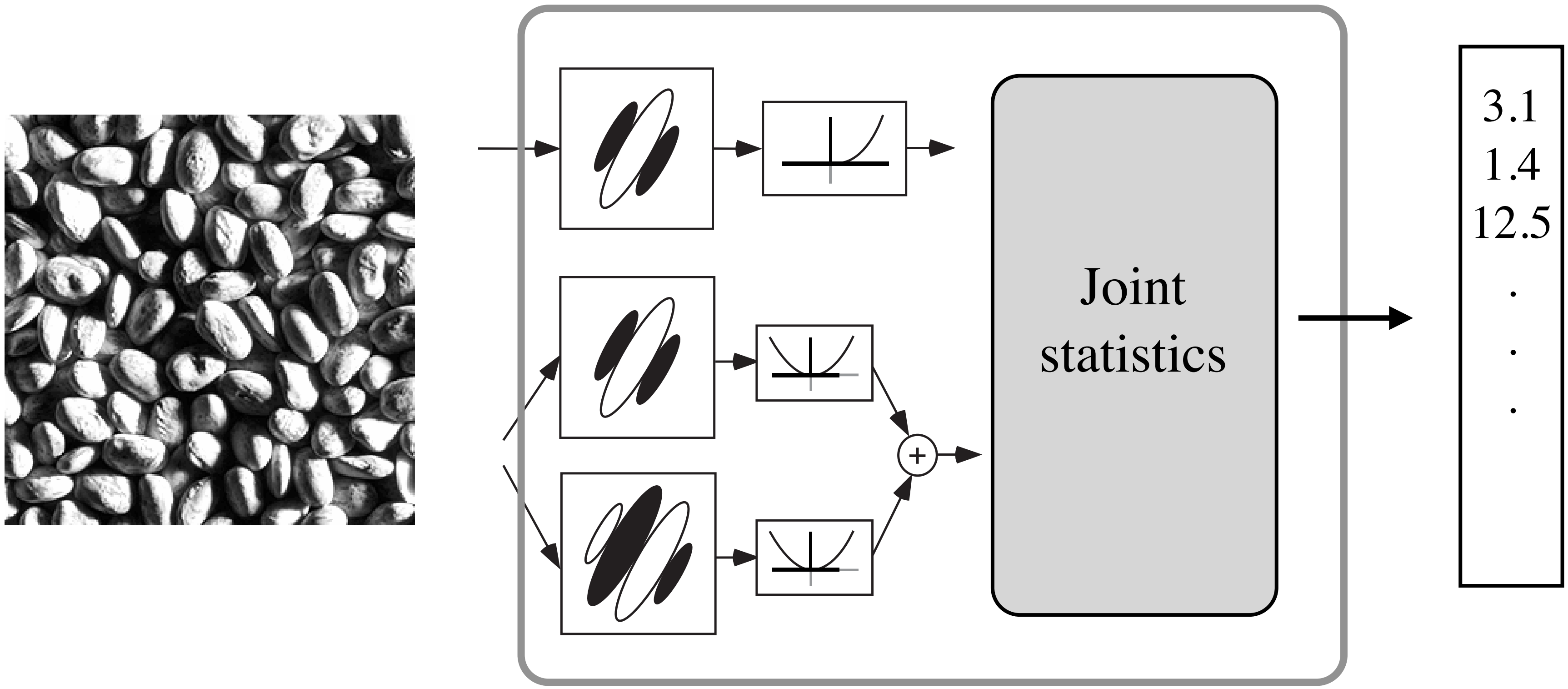


Julesz ‘78



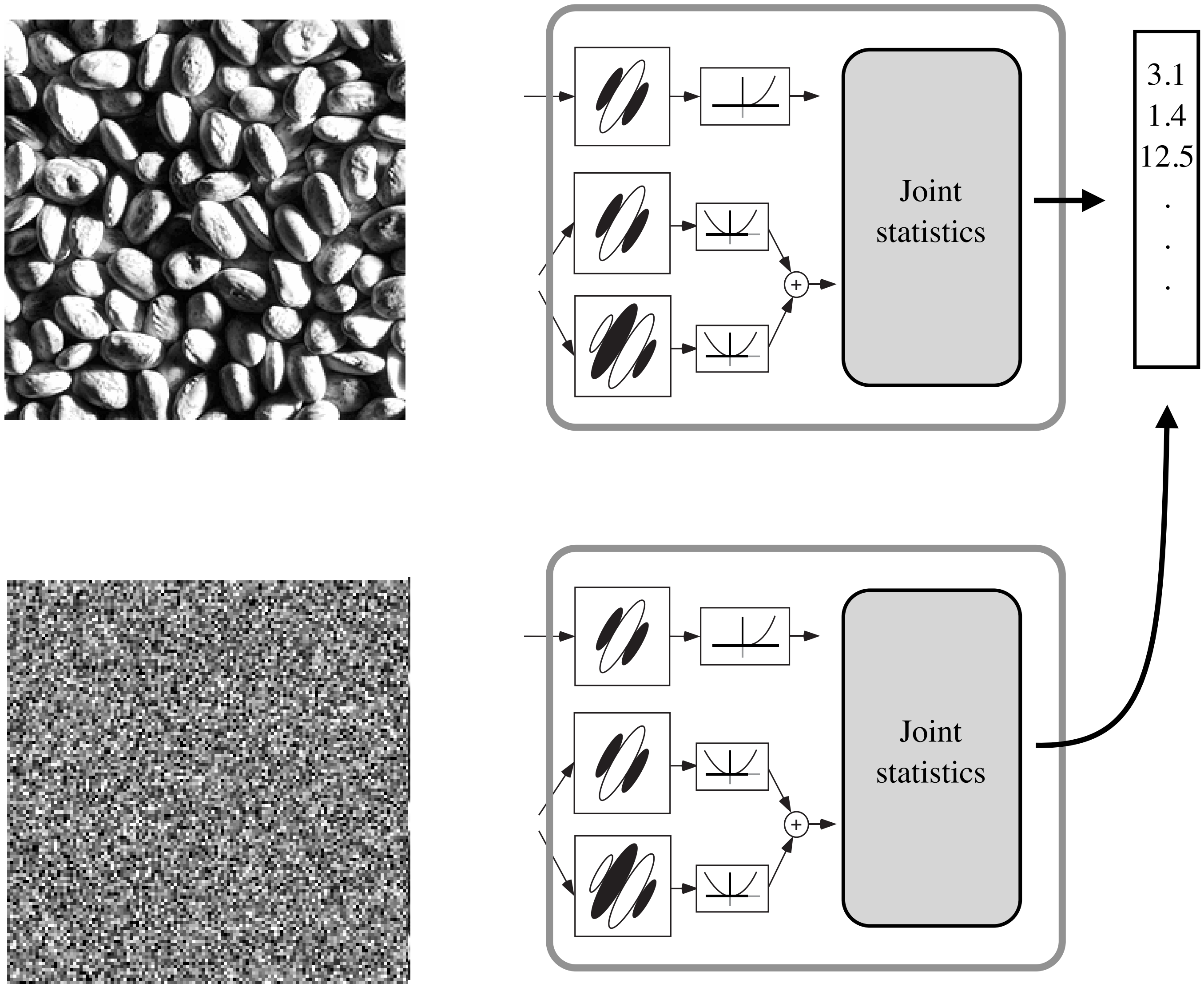
Yellott ‘93

Physiologically-inspired Julesz-style texture model

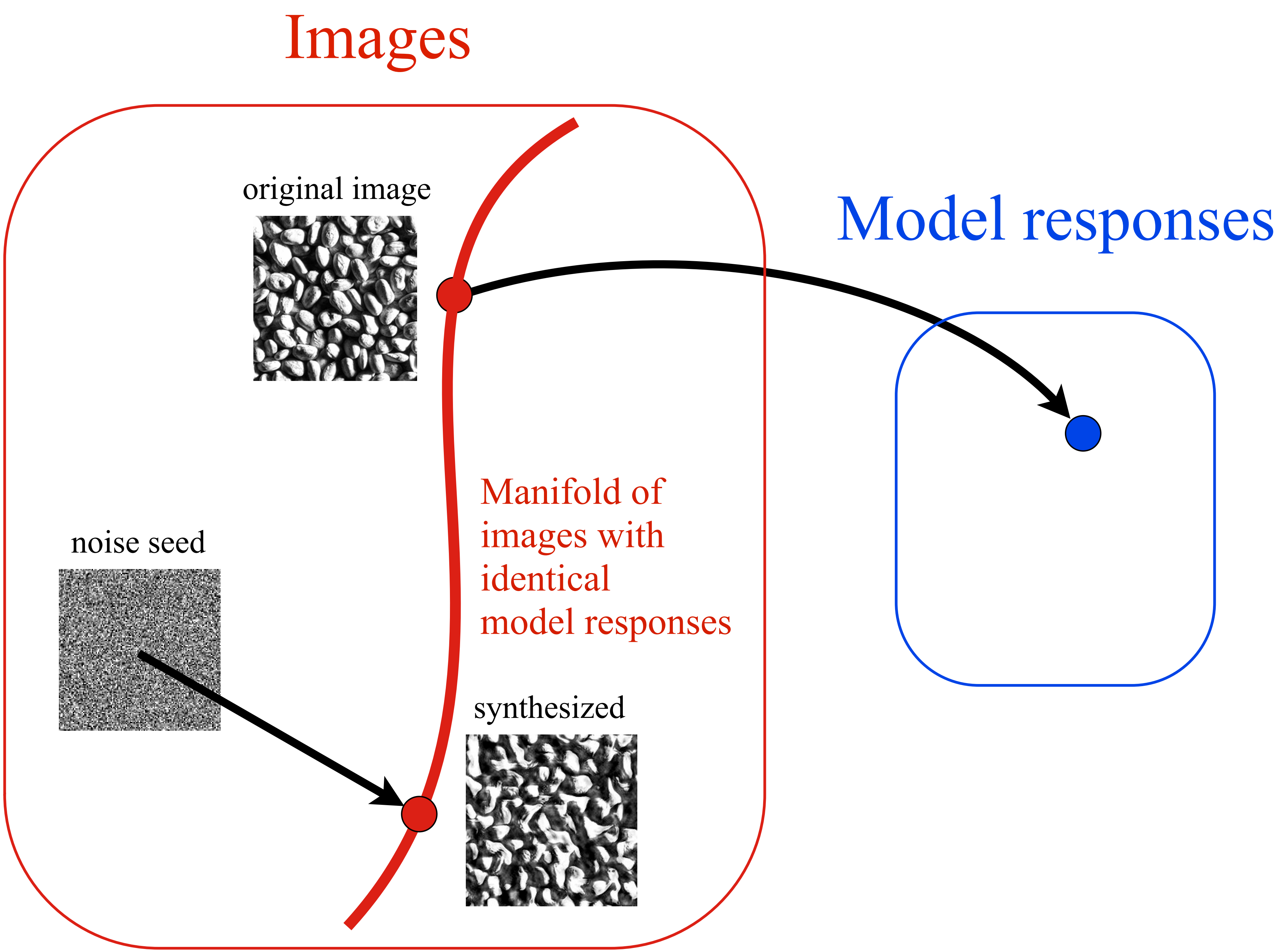


[Portilla & Simoncelli, 2000]

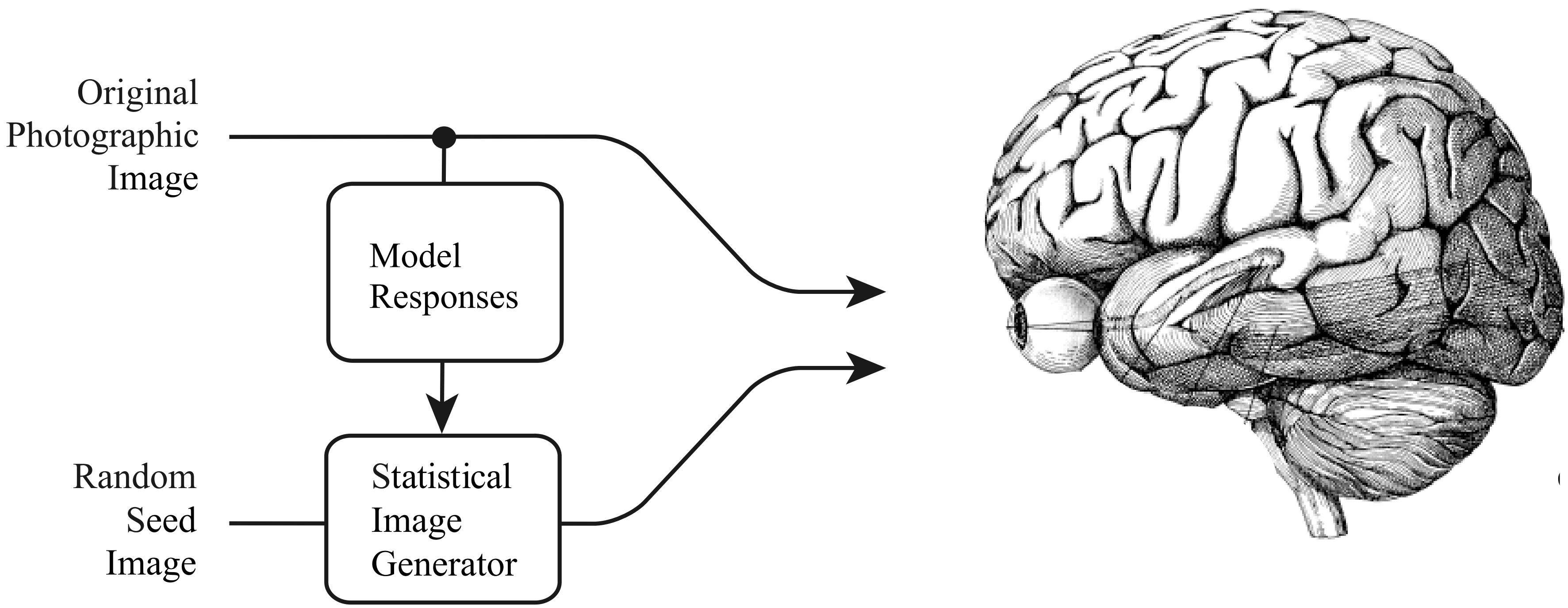
Texture synthesis



[Portilla & Simoncelli, 2000]

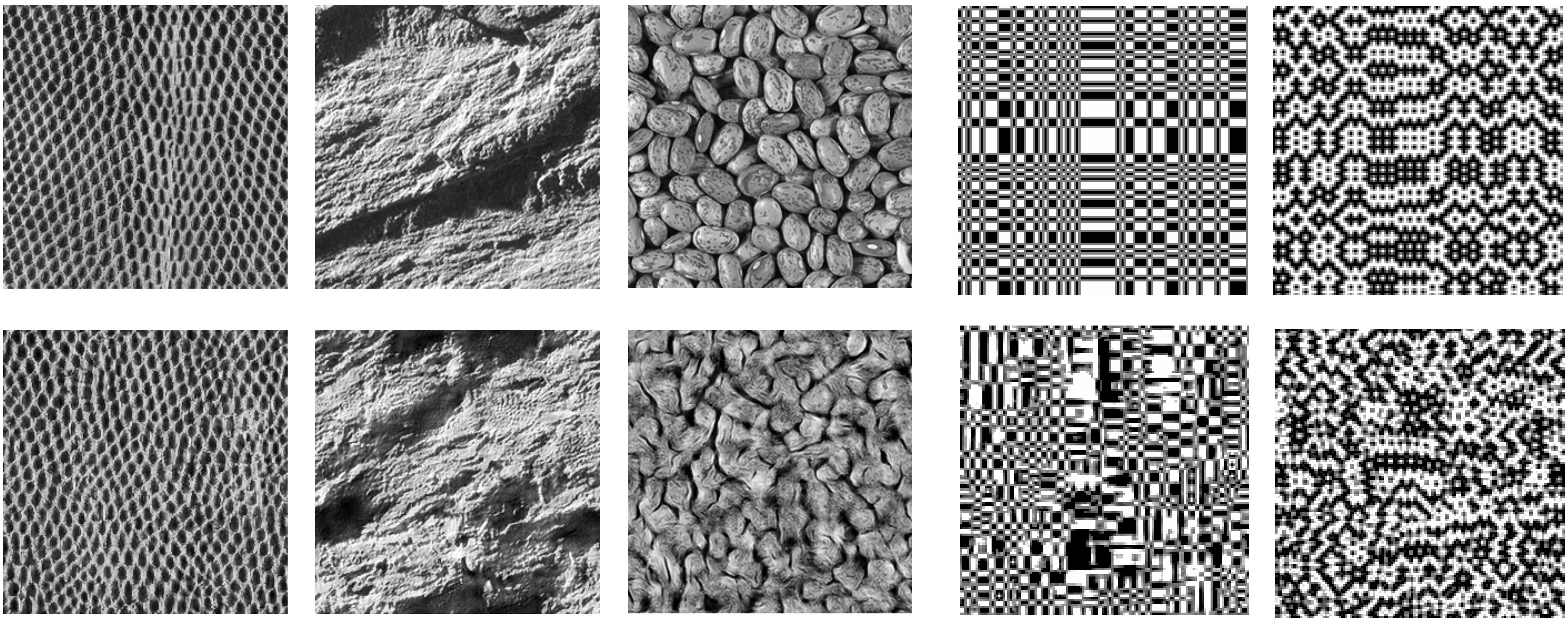

Images
original image
noise seed
Manifold of
images with
identical
model responses
synthesized
Model responses

Experimental logic



If model captures the same properties as the visual system, images with identical model responses should appear identical to a human.

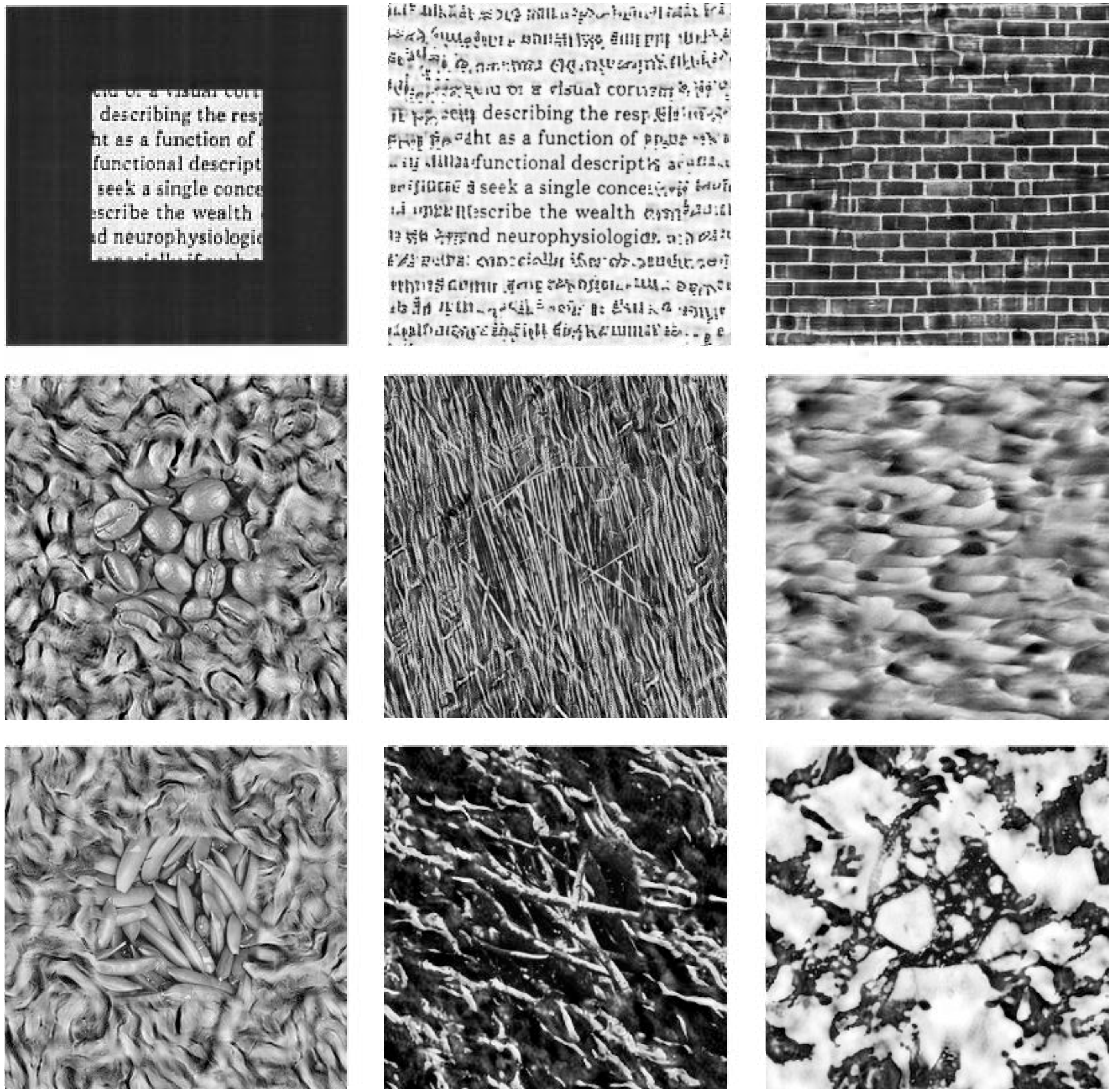
Pairs of images with identical model responses:



Top: original, Bottom: synthesized

[Portilla & Simoncelli 2000]

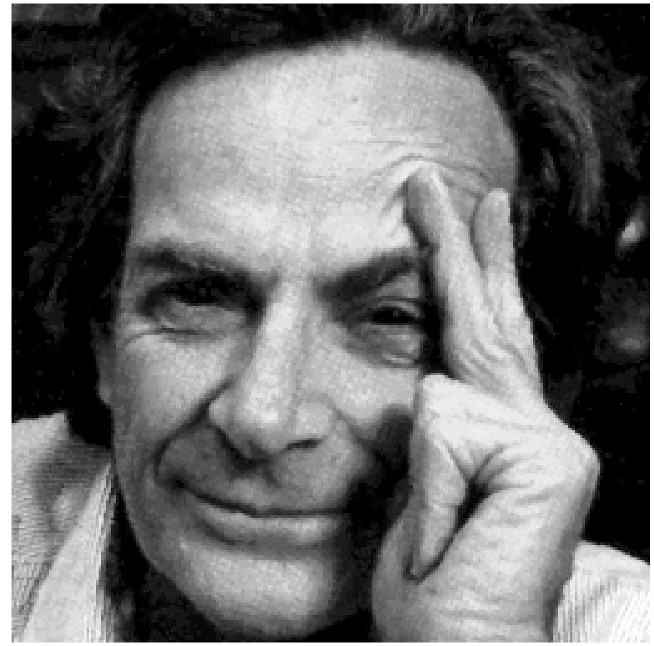
“outpainting”



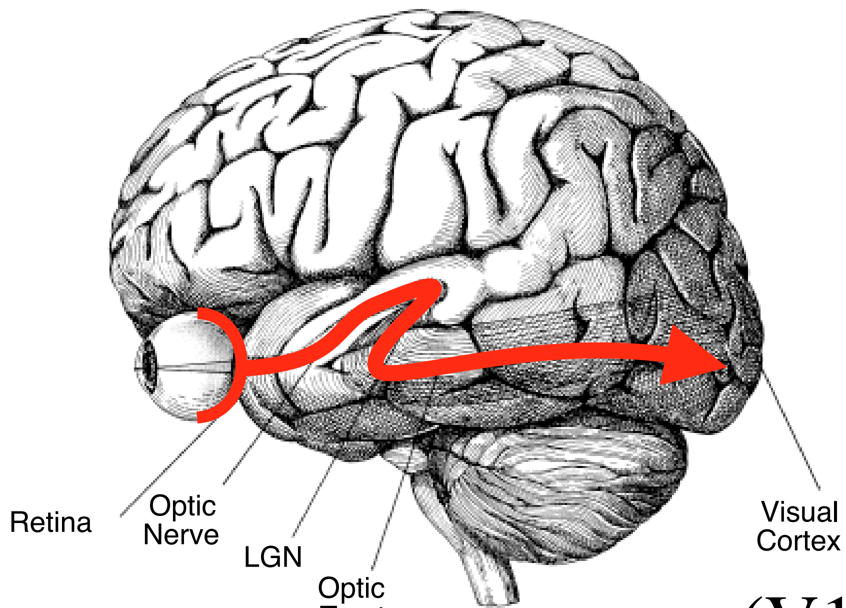
Central square of each image is original texture. Surround is synthesized.

Structural seeding [cf. “adversarial examples” - Szegedy et. al. 2014]

Can we generalize to inhomogeneous stimuli?



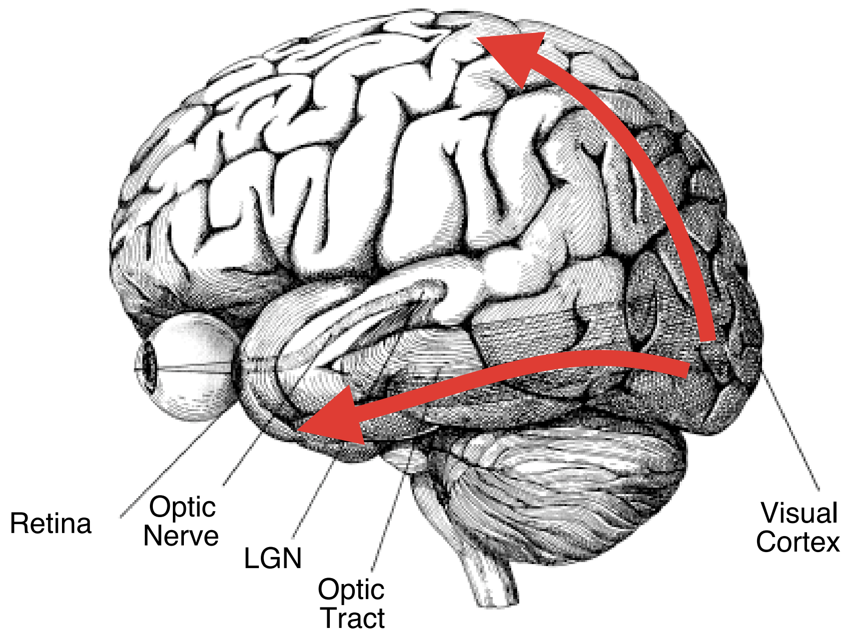
Can we make the model more physiological?



(V1)

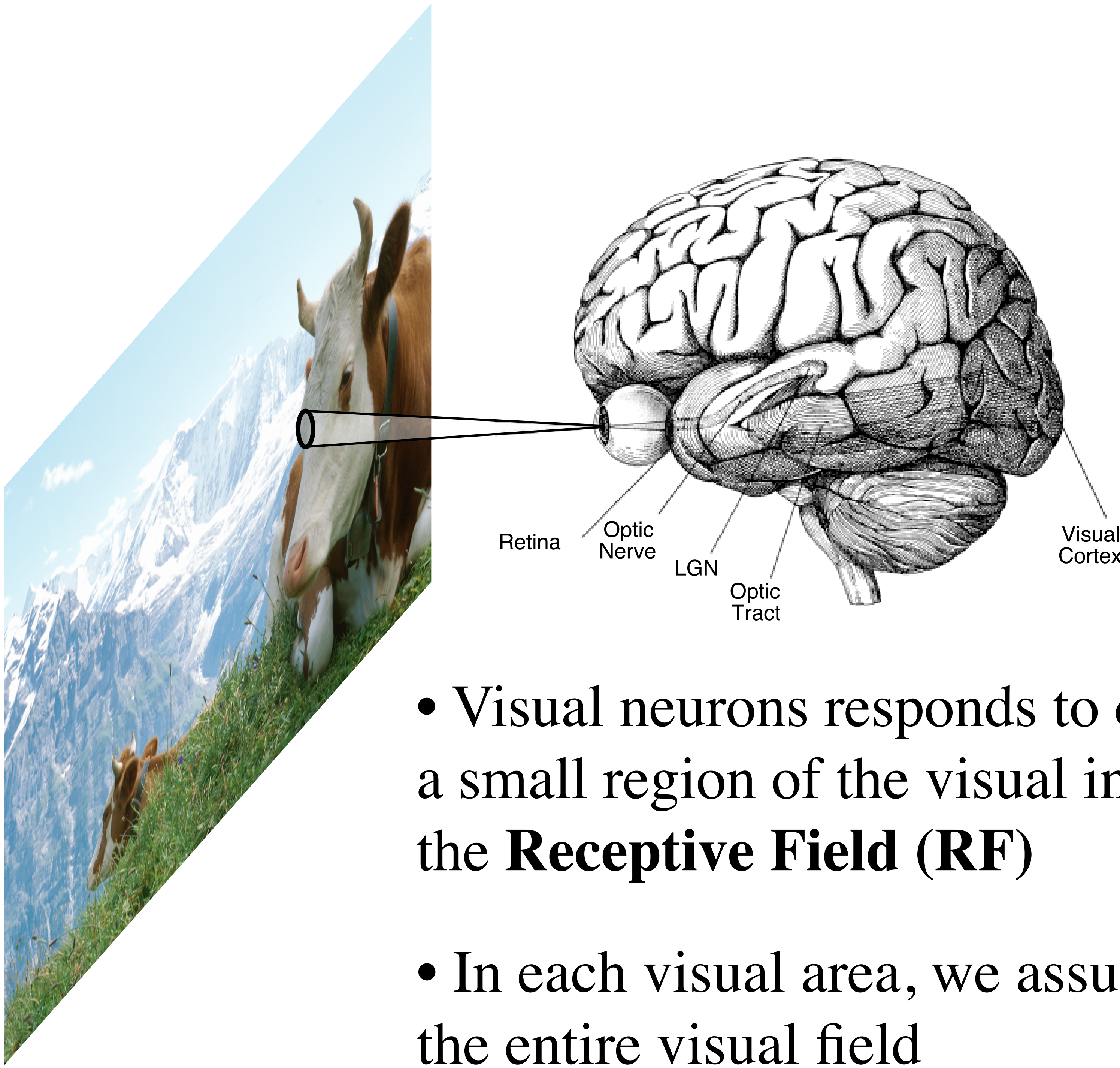
[figure: Hubel '95]

Dorsal pathway: V1->V3->V5
position, motion, action



Ventral pathway: V1->V2->V4-> IT
spatial form, recognition, memory

[Ungerleider & Mishkin, 1982]

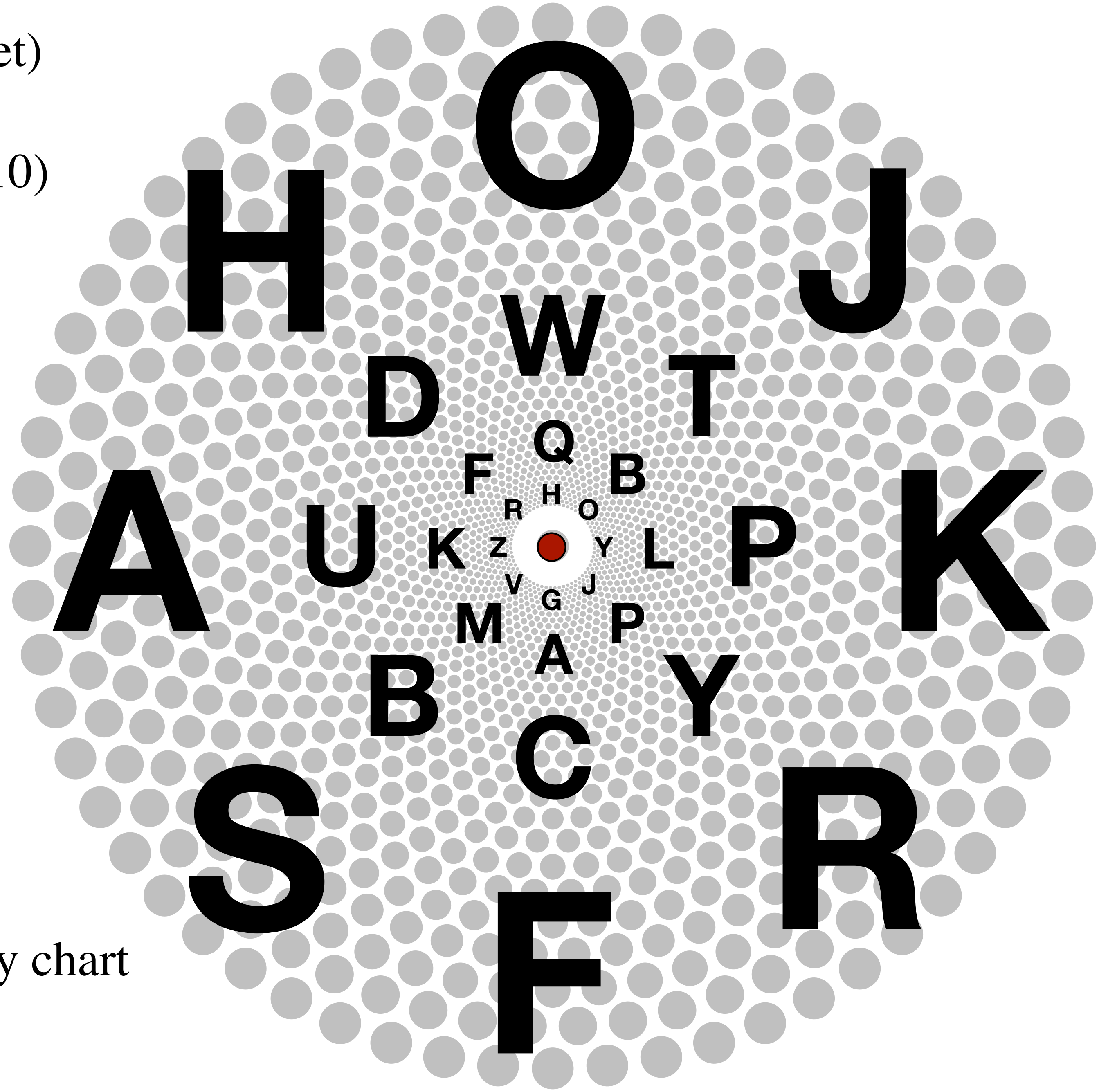


- Visual neurons responds to content within a small region of the visual input known as the **Receptive Field (RF)**

- In each visual area, we assume RFs cover the entire visual field

Inhomogeneity - RF sizes grow with eccentricity

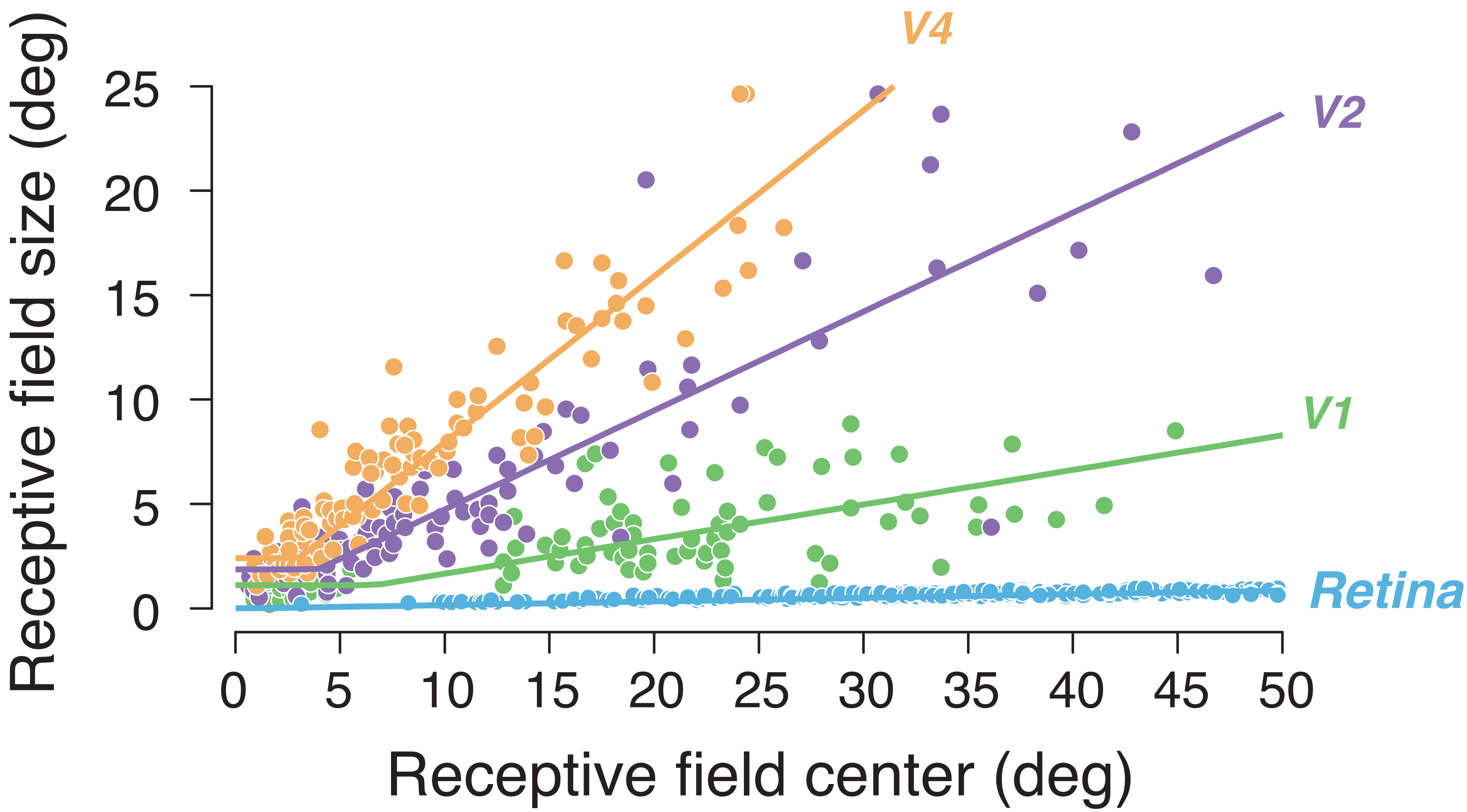
Retinal ganglion (midget)
cell receptive fields
(macaque, magnified x10)
[Perry et.al., 1984;
Watanabe & Rodiek, 1989]



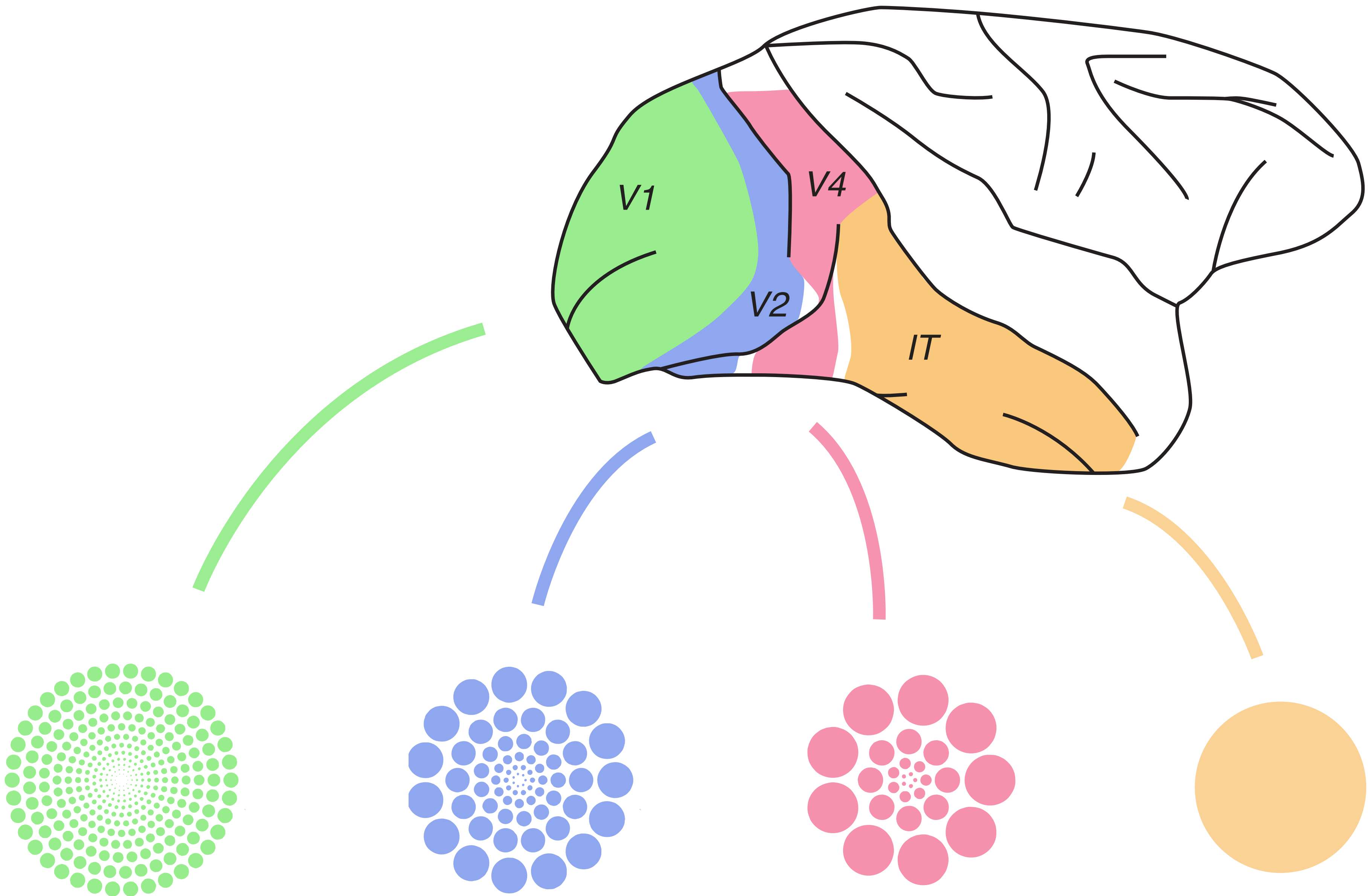
Modified Snellen acuity chart
(threshold, x10)
[after Anstis, 1973]

[after Geisler et al., 1999]

RF sizes grow with eccentricity



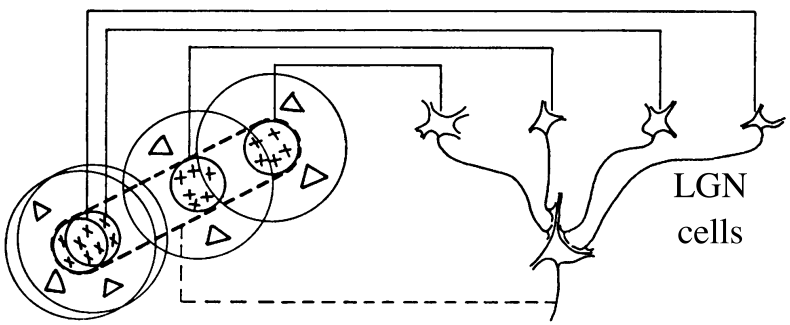
[Freeman & Simoncelli 2011,
data from Gattass et. al., 1981; Gattass et. al., 1988; Perry et. al., 1984]



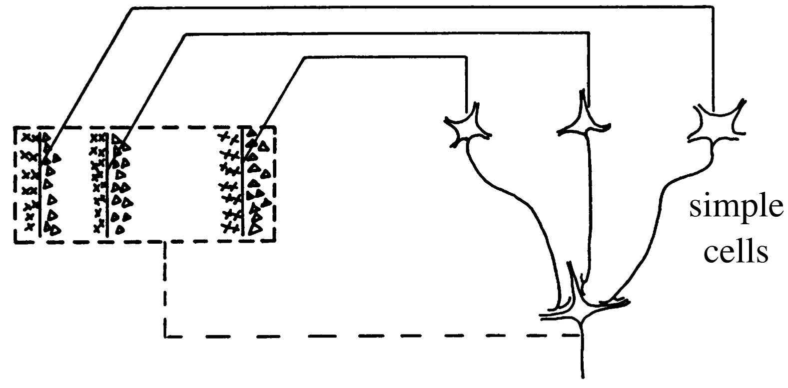
[Freeman & Simoncelli, 2011]

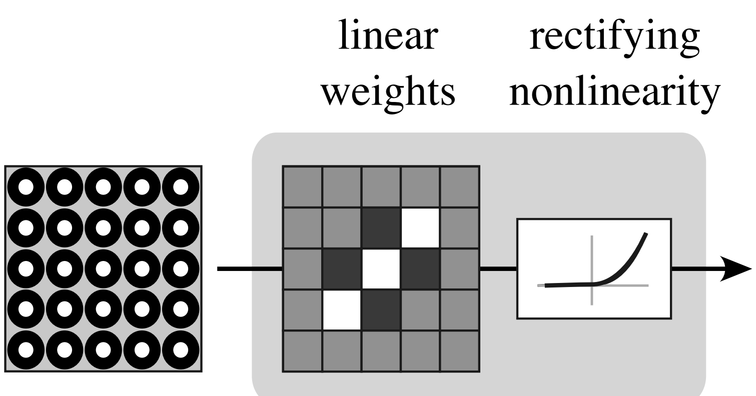
V1 simple cell

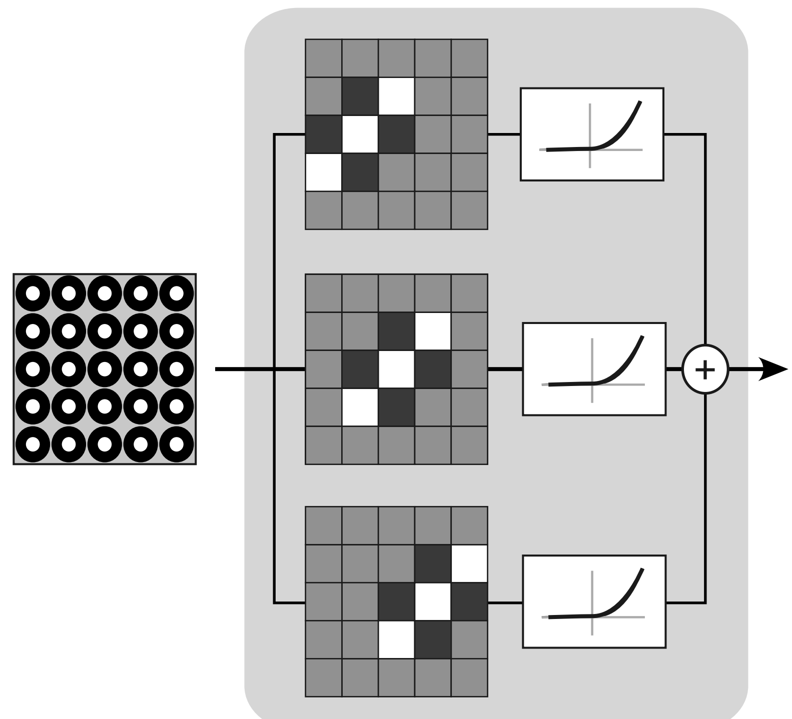
V1 complex cell



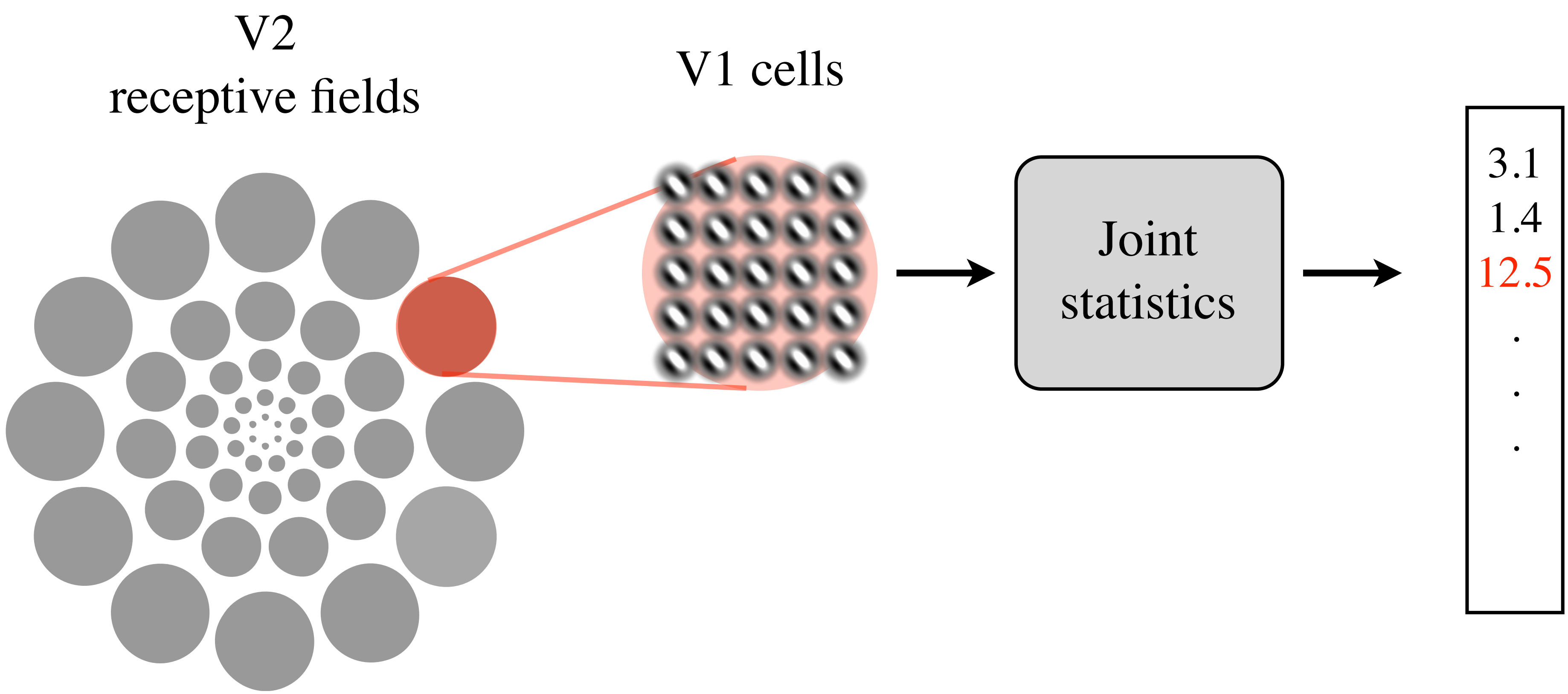
[Hubel & Wiesel, 1962]



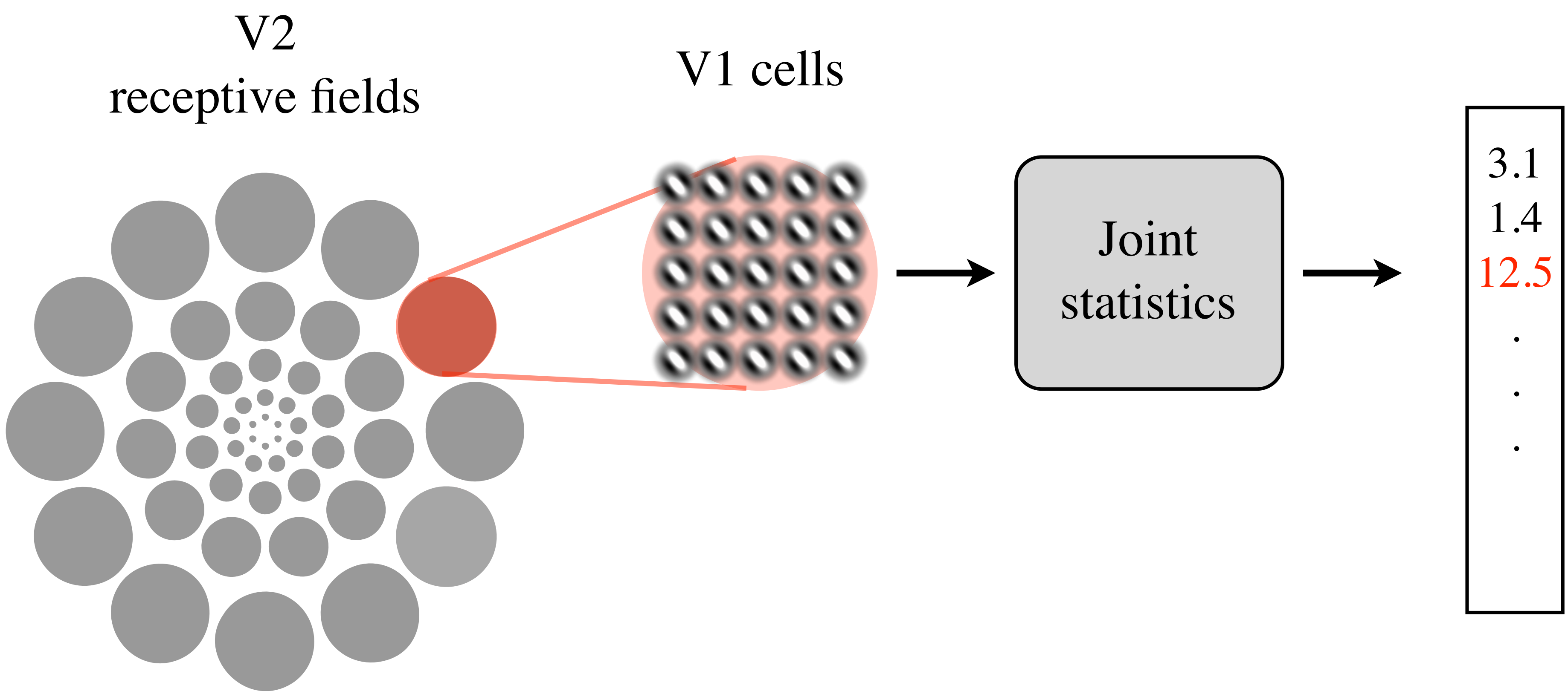




Local texture representation in the ventral stream

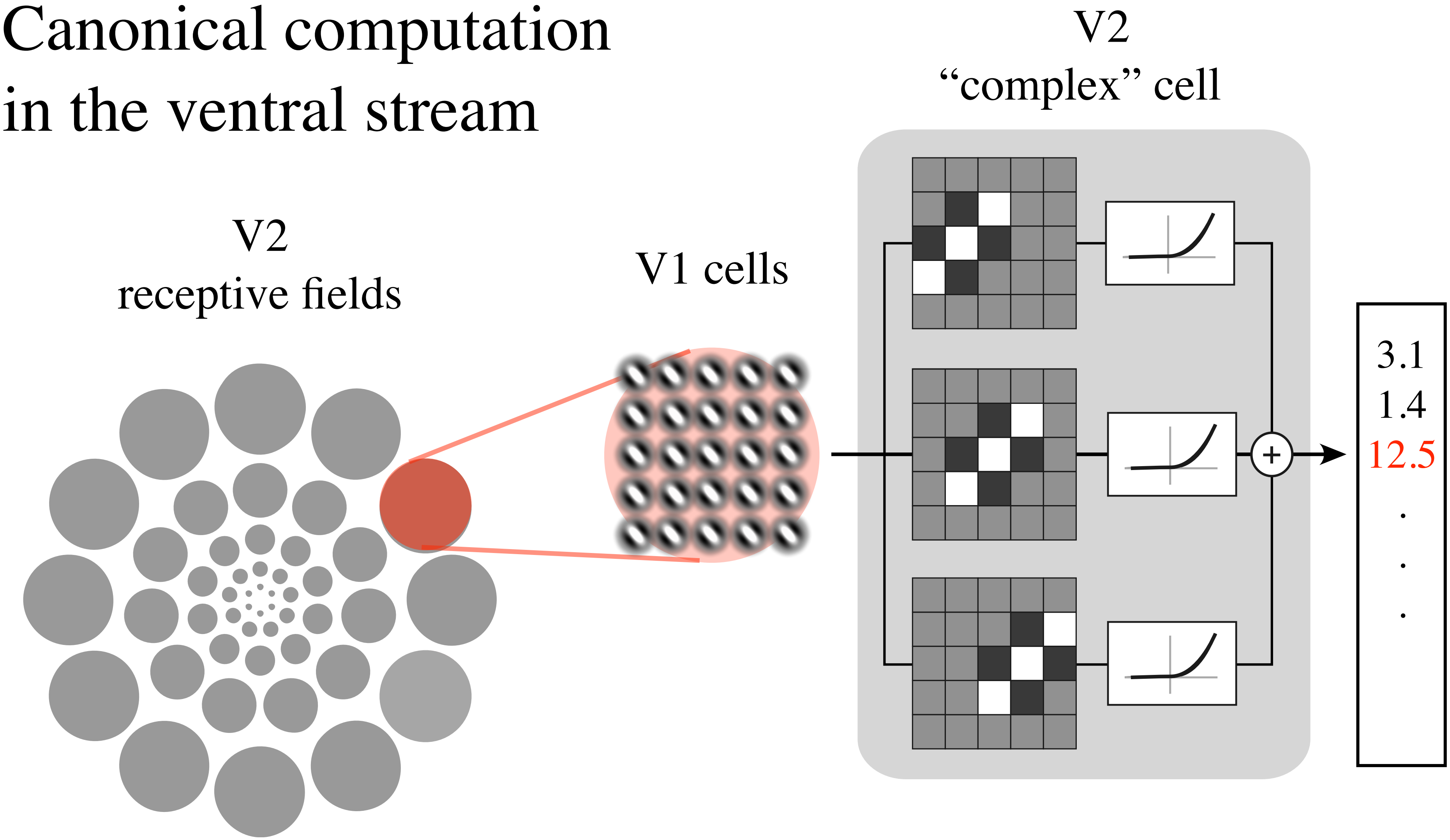


Local texture representation in the ventral stream



Local correlational statistics can be re-expressed as a "subunit" model...

Canonical computation in the ventral stream



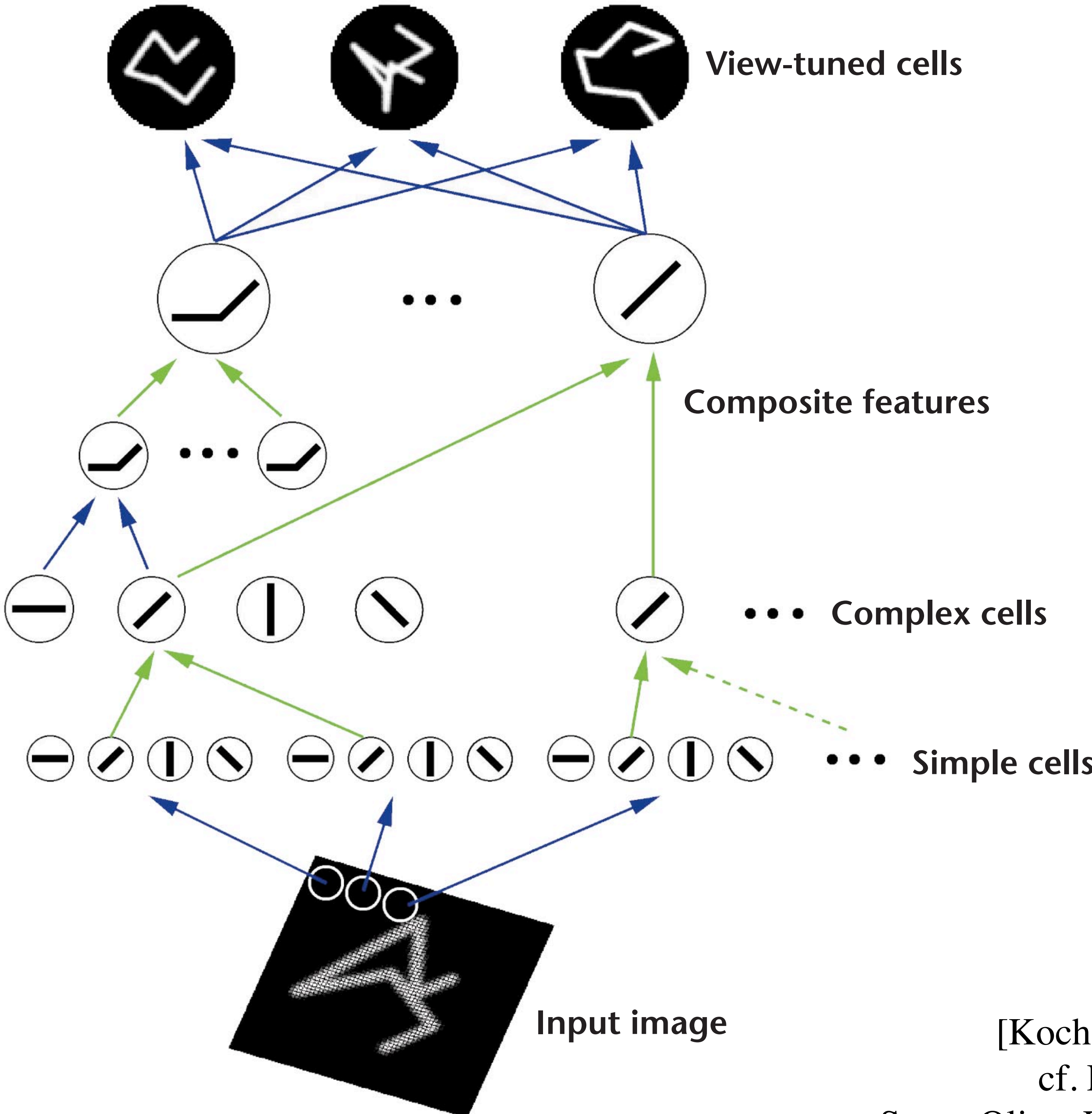
Substantial information loss => model predicts **metamers**

Canonical sensory computation

- Linear filter (determines pattern selectivity)
- Rectifying nonlinearity
- Local pooling (e.g., average, max)
- Local gain control
- Noise

Cascaded ...

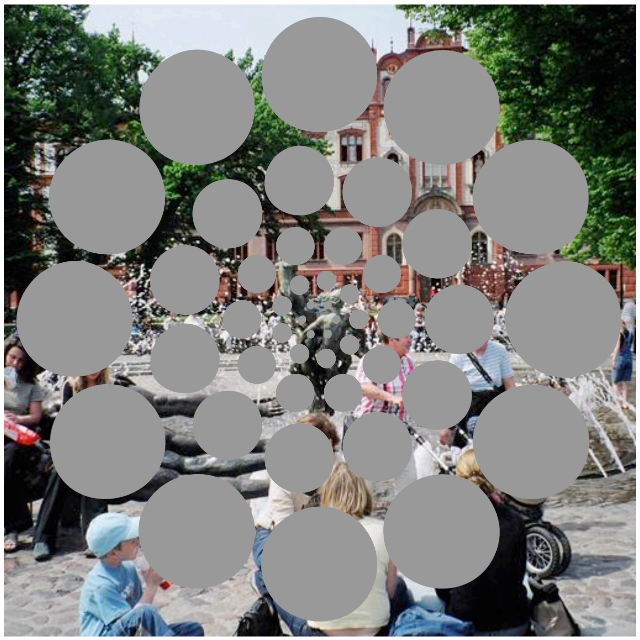
[eg. Douglas, 1989;
Heeger, Simoncelli & Movshon 1996;
Heeger & Carandini 2014]



[Koch & Poggio, 1999;
cf. Fukishima, 1980;
Serre, Oliva, Poggio 2007; etc]

Synthesizing Ventral Stream Metamers

Original image

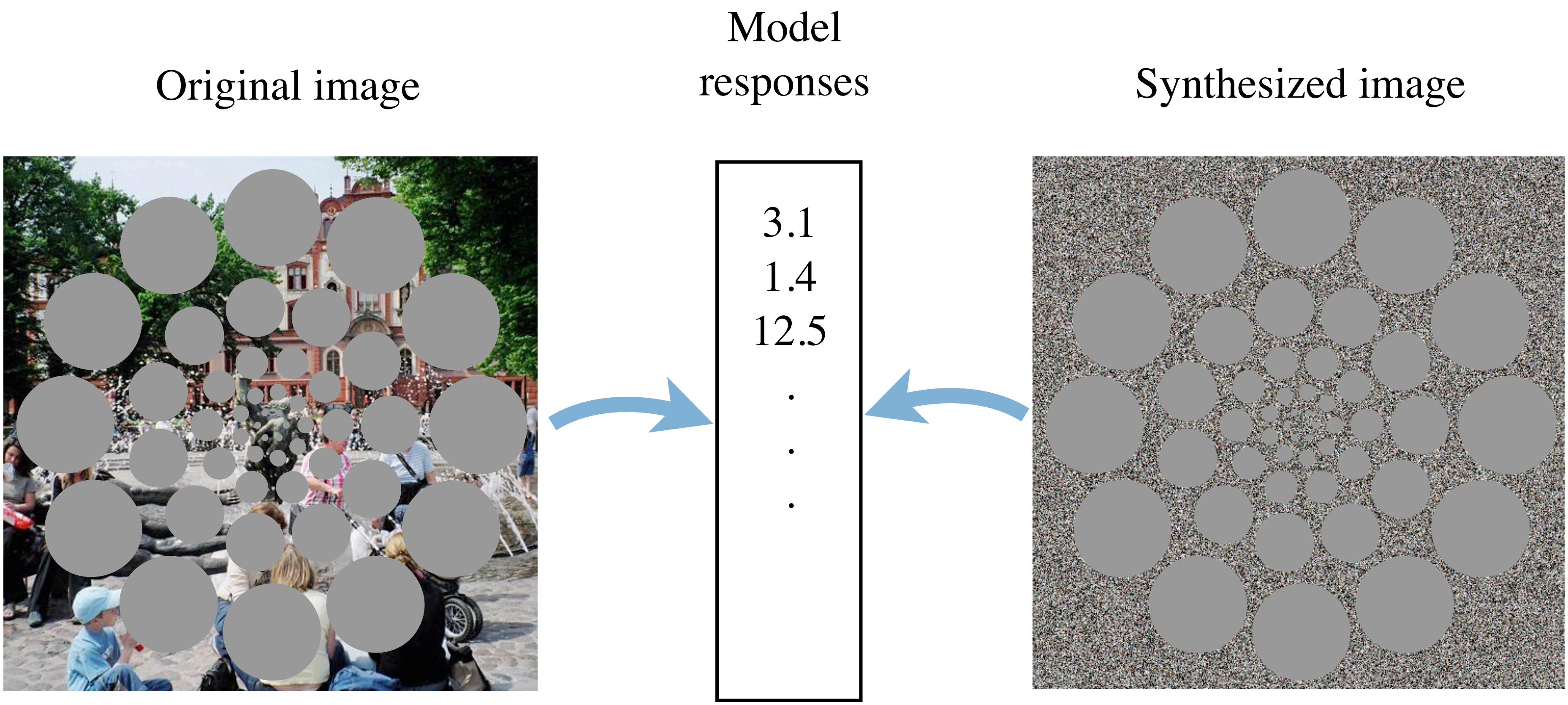


Model responses

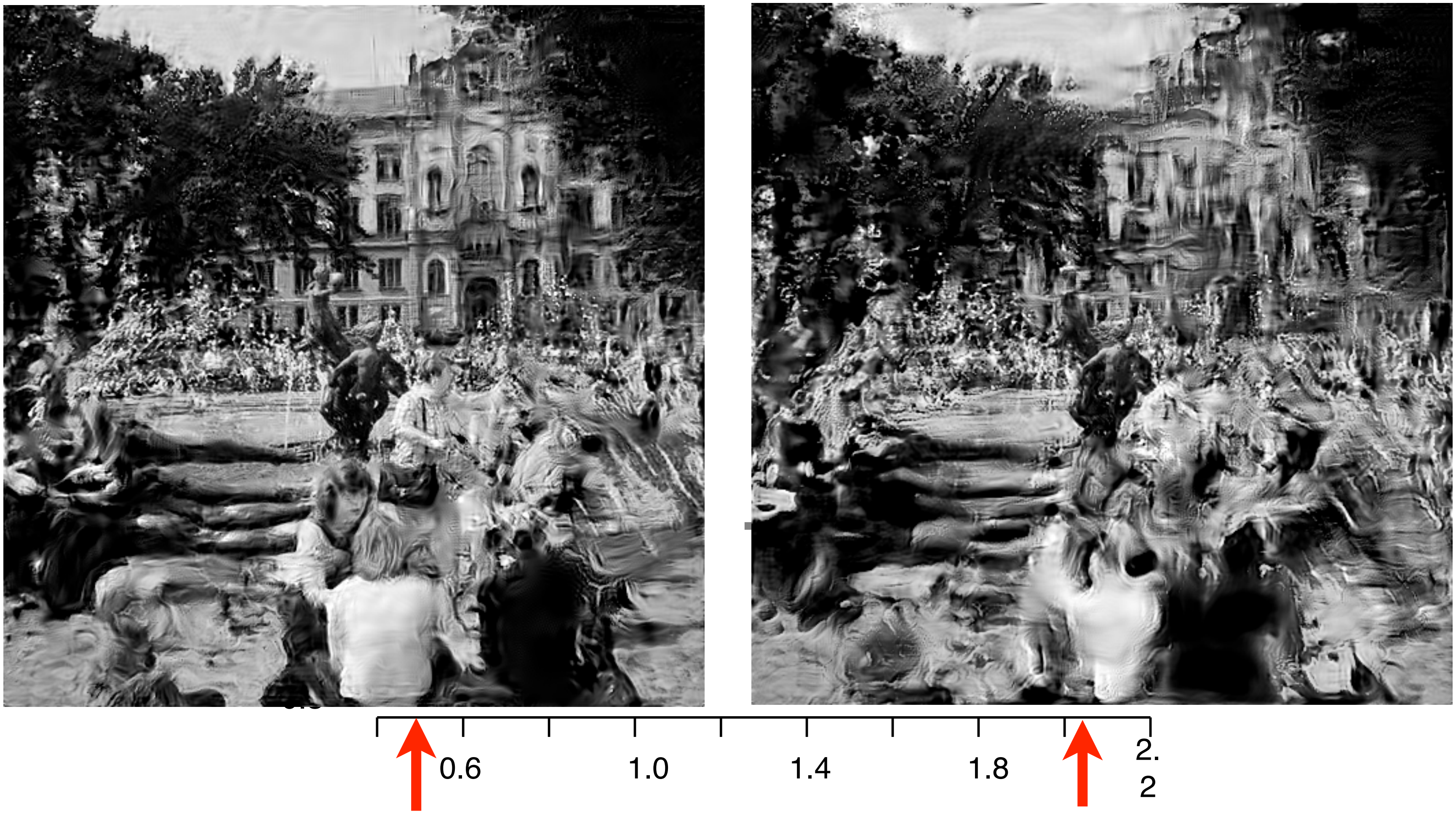
3.1
1.4
12.5
.
.
.

[Freeman & Simoncelli, 2011]

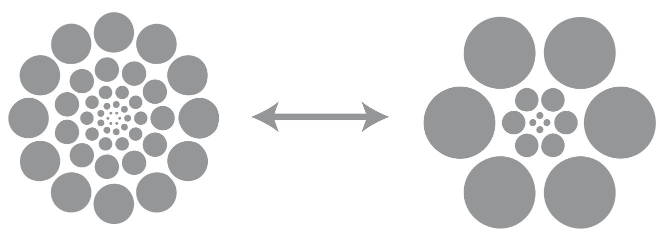
Synthesizing Ventral Stream Metamers



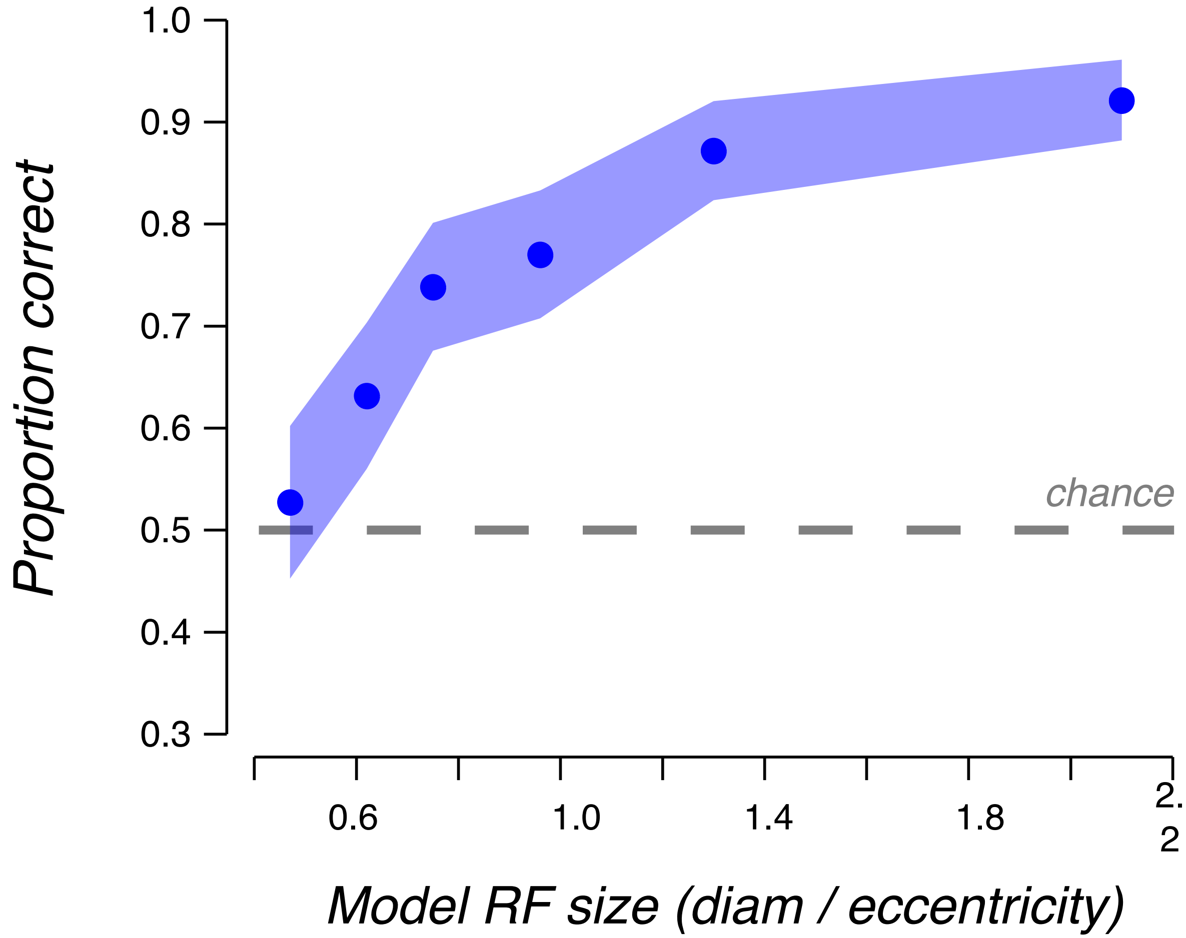
[Freeman & Simoncelli, 2011]

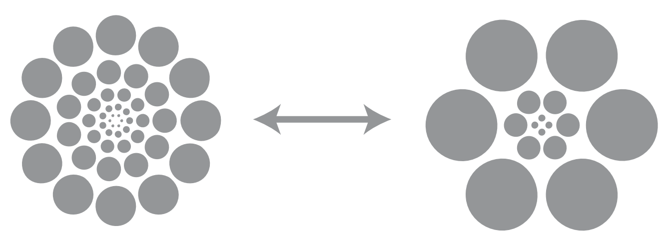


Model RF size (diam / eccentricity)

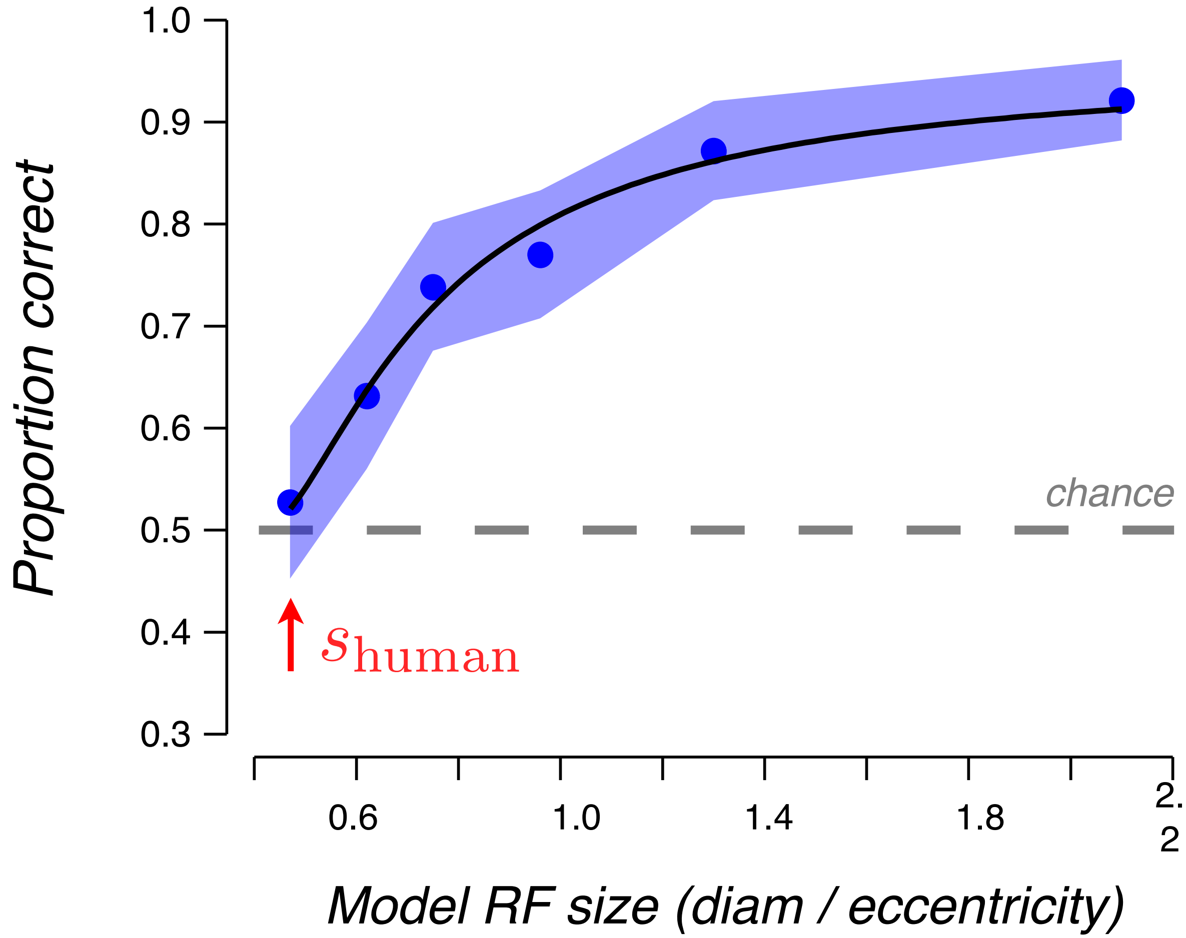


[Freeman & Simoncelli, 2011]



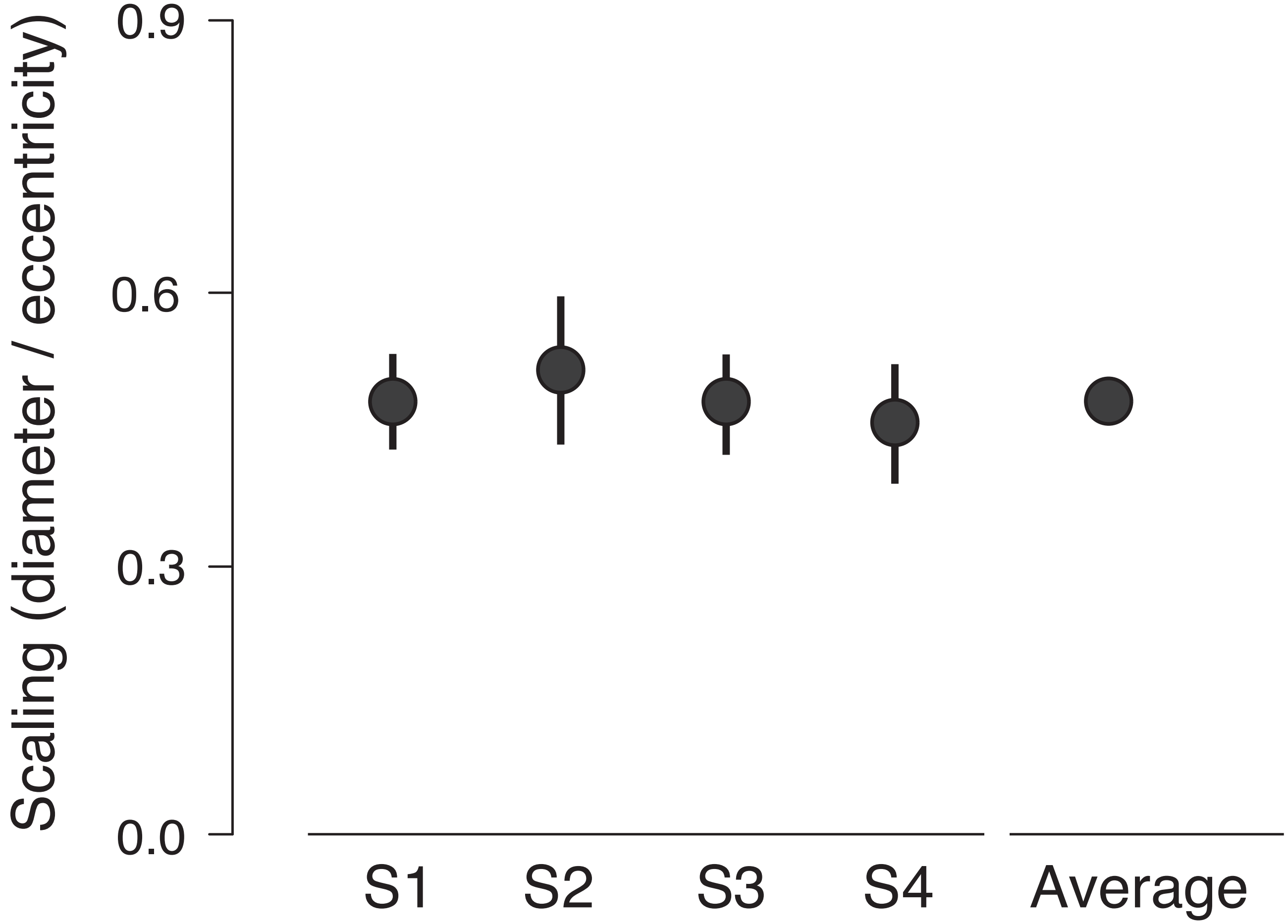


[Freeman & Simoncelli, 2011]



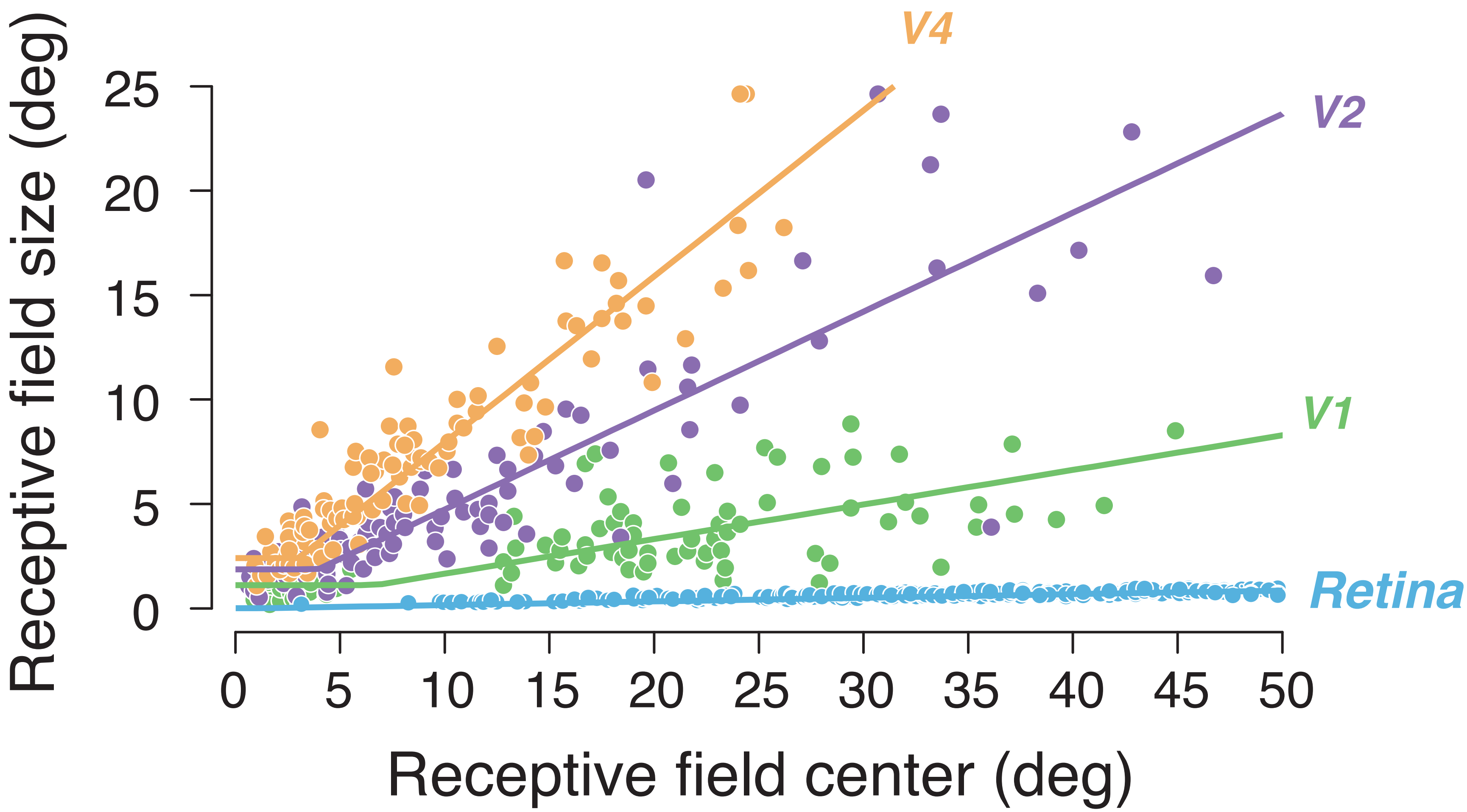
$$D = \Phi\left(\left\lfloor 1 - \frac{s_{\text{human}}^2}{s_{\text{model}}^2} \right\rfloor\right)$$

[Freeman & Simoncelli, 2011]

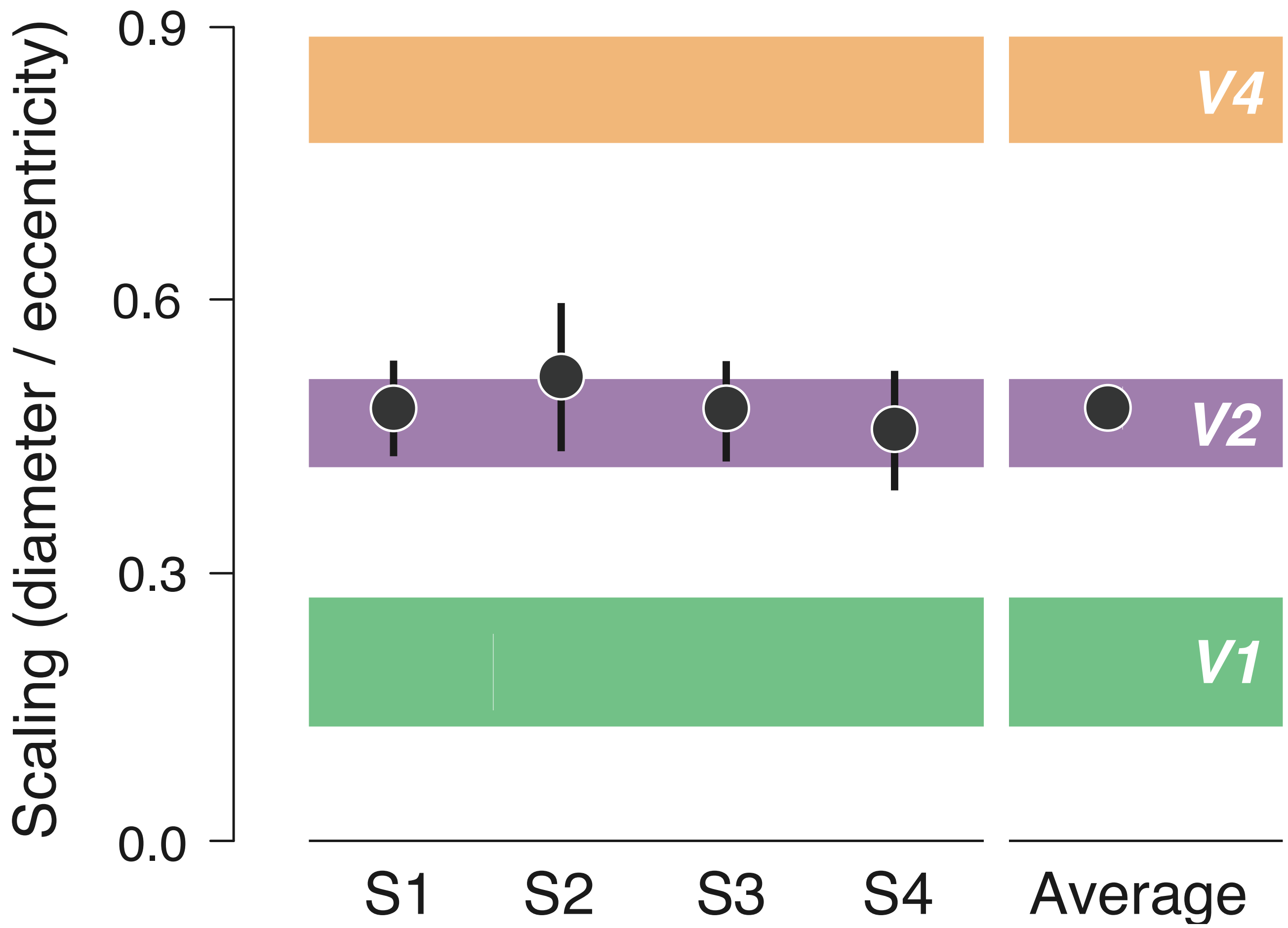


[Freeman & Simoncelli, 2011]

RF sizes grow with eccentricity



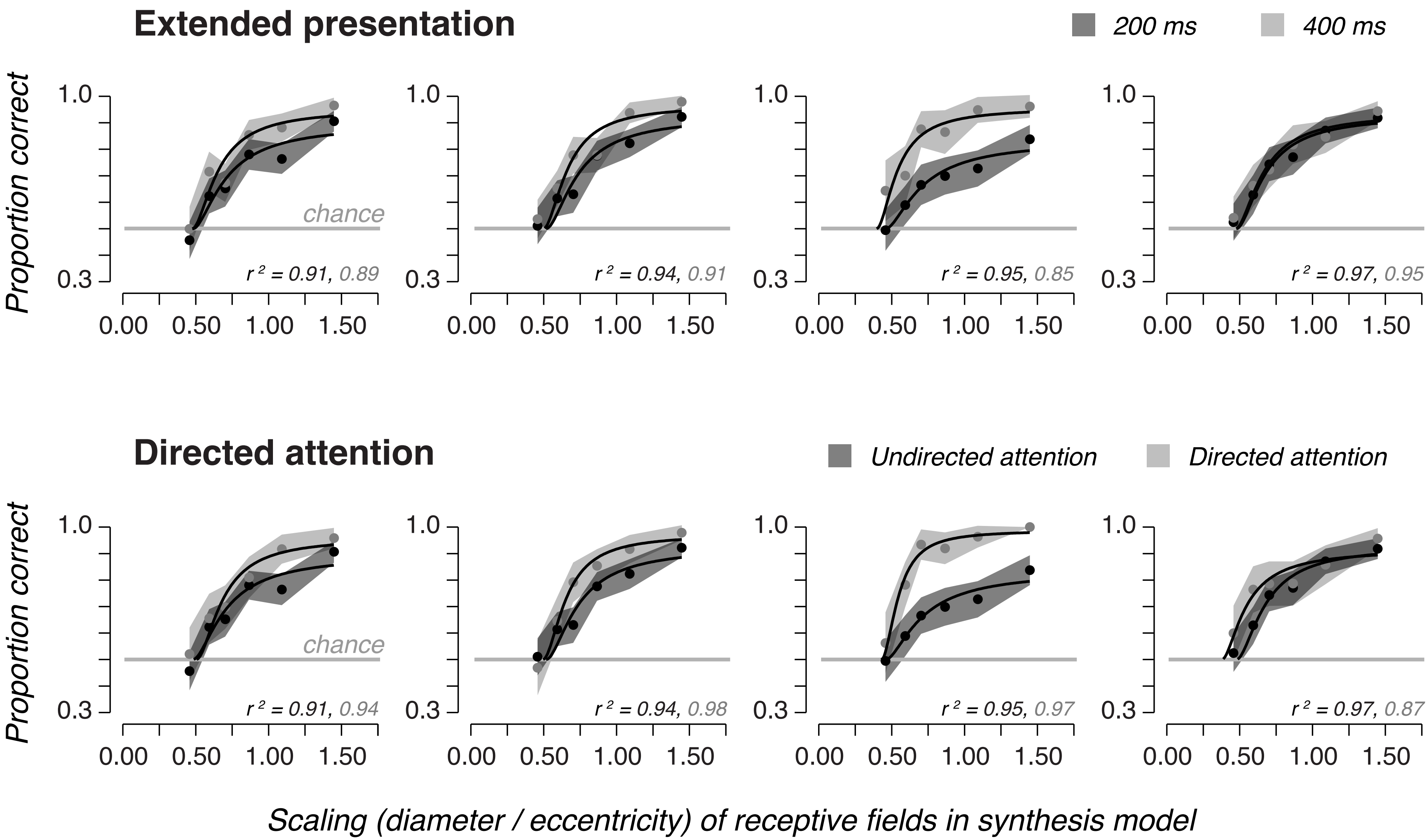
[Freeman & Simoncelli 2011,
from Gattass et. al., 1981; Gattass et. al., 1988; Perry et. al., 1984]



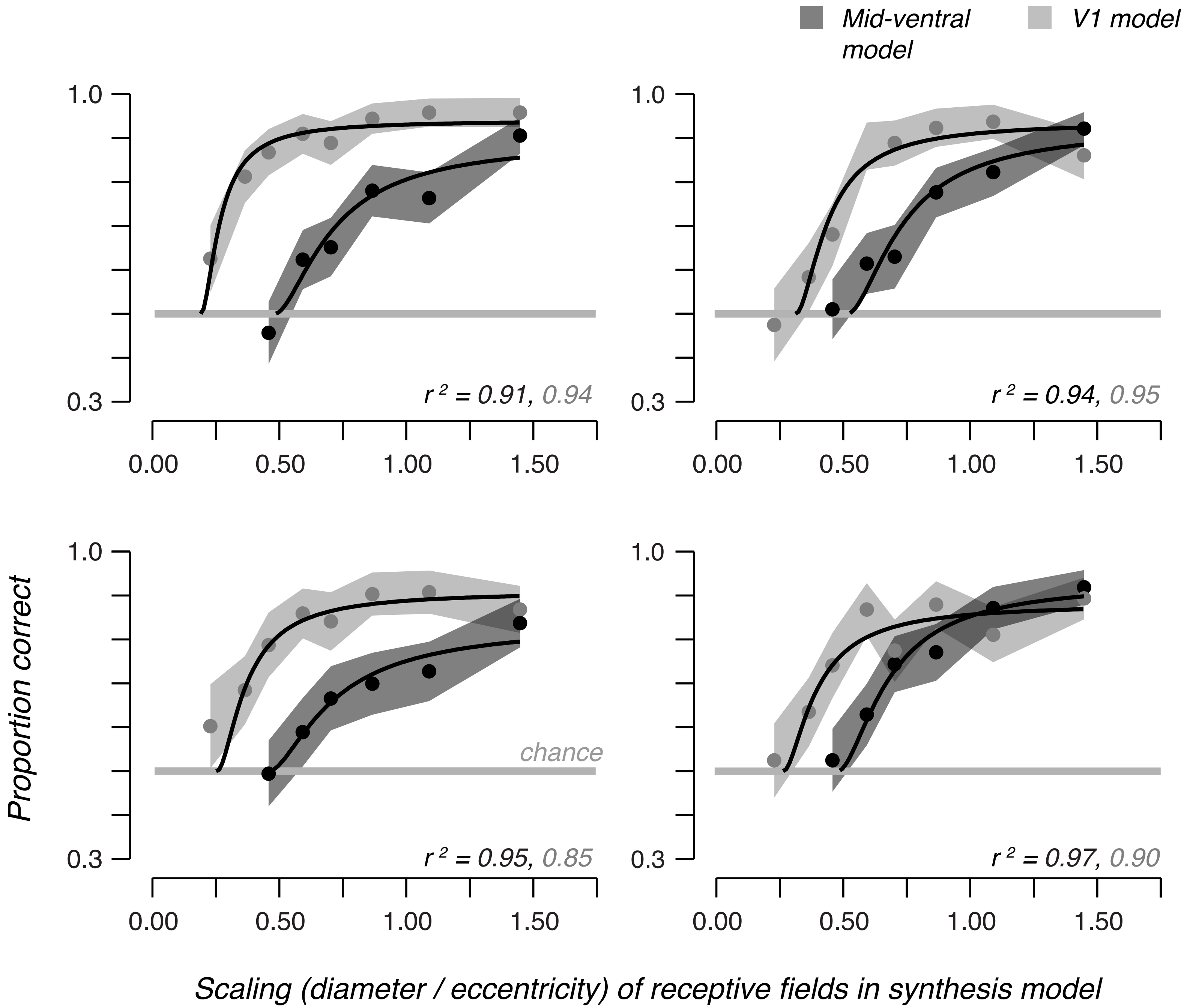
Macaque Physiology

[Allman & Kaas, 1971; Allman & Kaas, 1974; Gattass et.al., 1981; van Essen et.al., 1984; Maguire & Baizer, 1984; Burkhalter & van Essen, 1986; Gattass et.al., 1987; Desimone & Schein, 1987; Gattass et.al., 1988; Cavanaugh et. al., 2002]

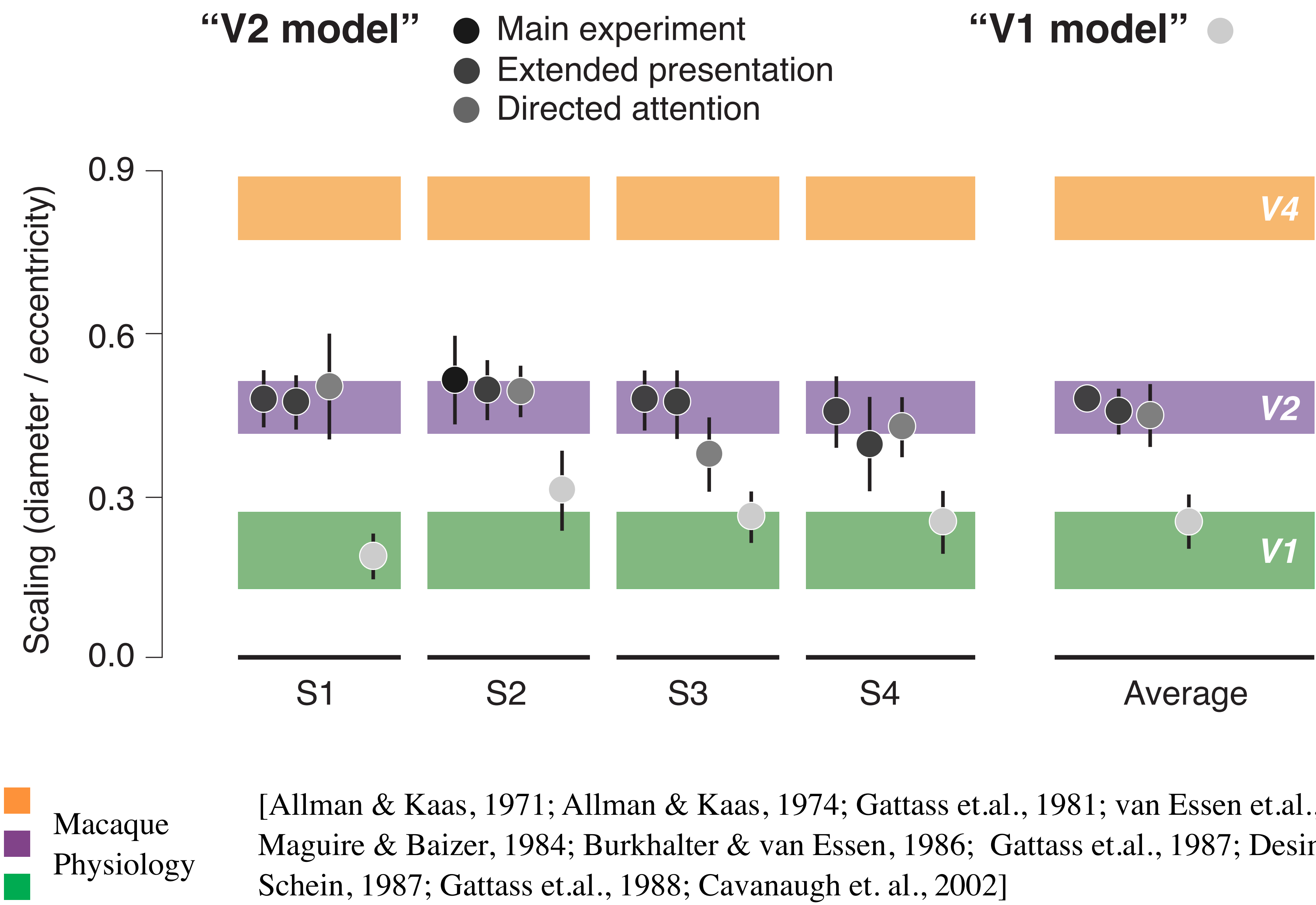
[Freeman & Simoncelli, 2011]



[Freeman & Simoncelli, 2011]



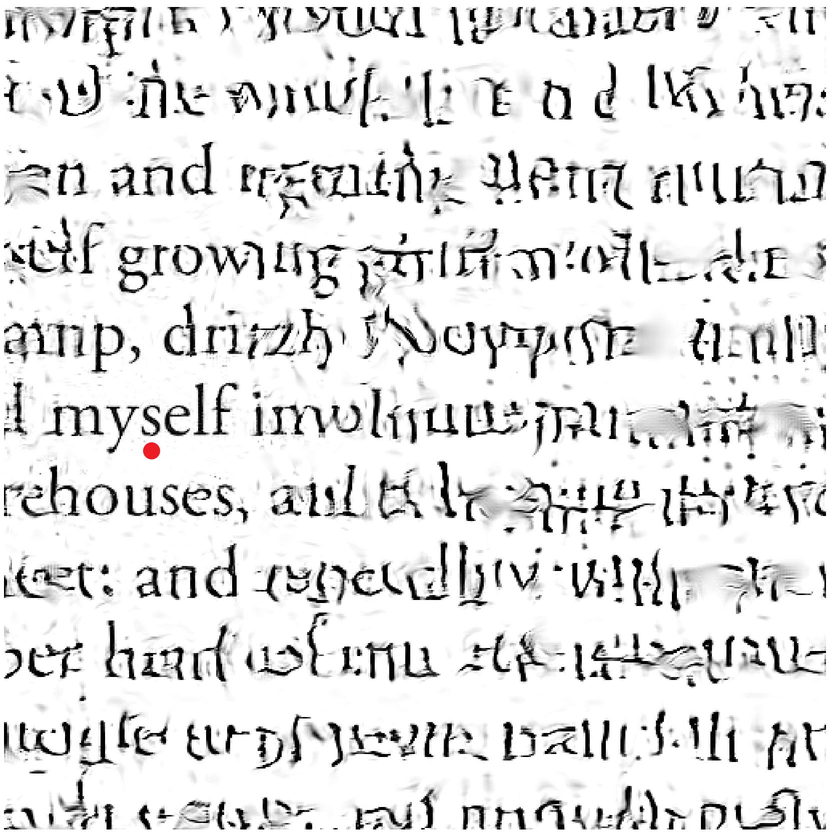
[Freeman & Simoncelli, 2011]

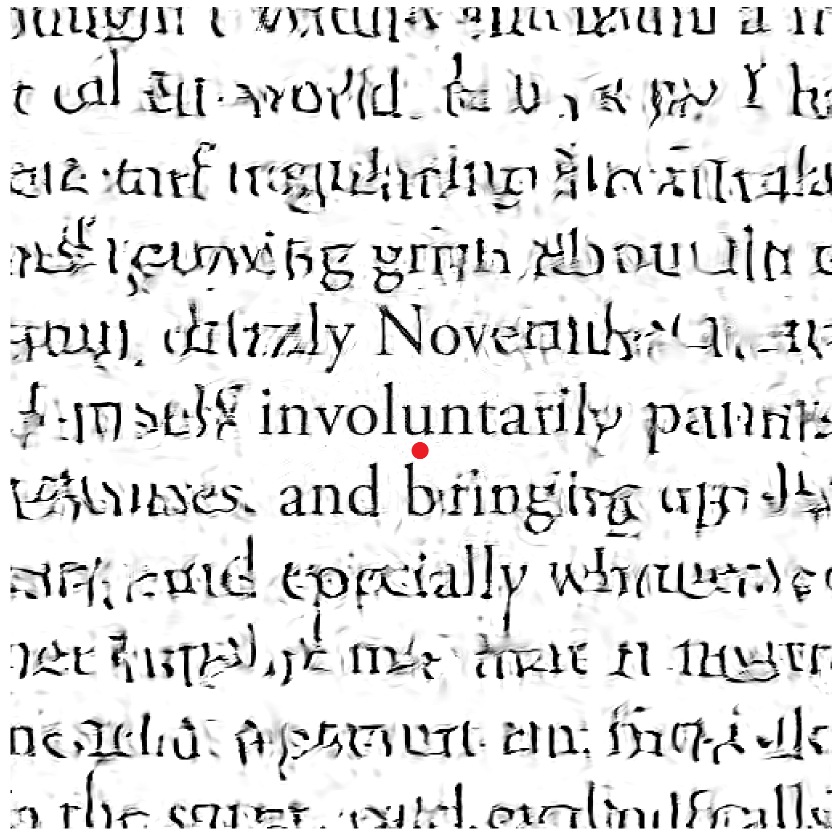


[Allman & Kaas, 1971; Allman & Kaas, 1974; Gattass et.al., 1981; van Essen et.al., 1984; Maguire & Baizer, 1984; Burkhalter & van Essen, 1986; Gattass et.al., 1987; Desimone & Schein, 1987; Gattass et.al., 1988; Cavanaugh et. al., 2002]

[Freeman & Simoncelli, 2011]

Reading



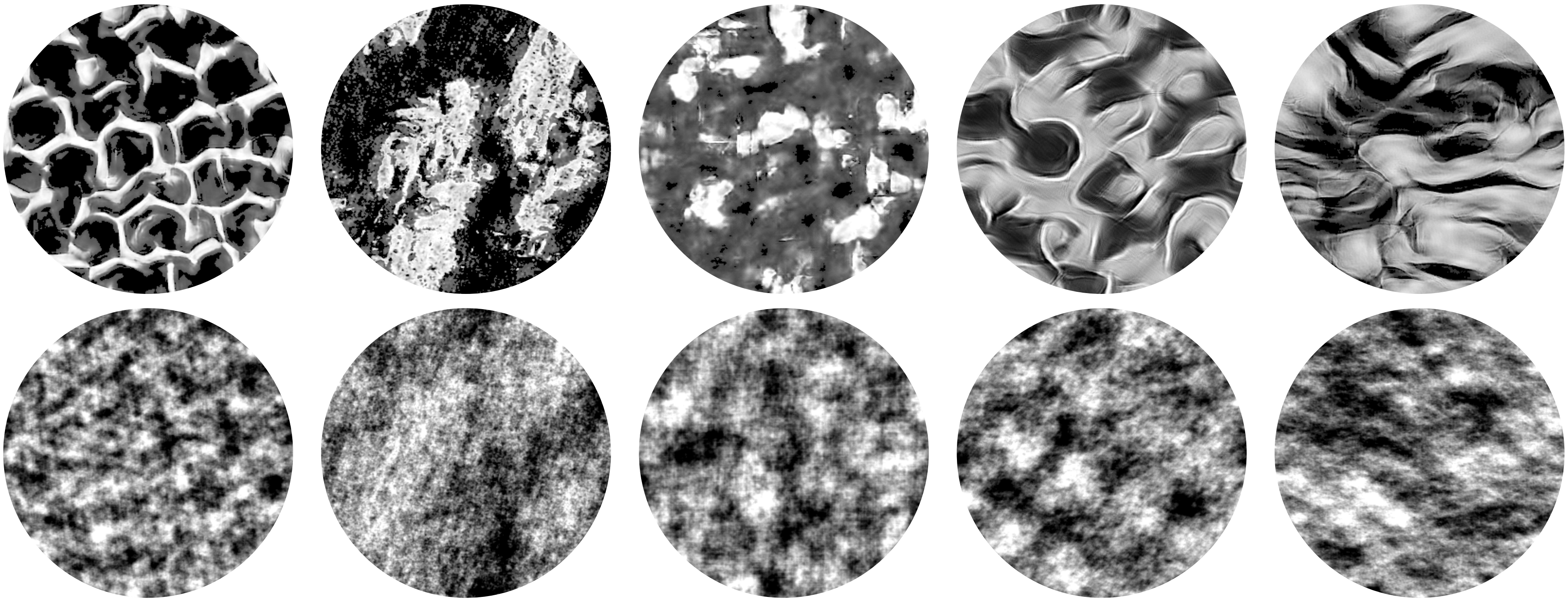


[Freeman & Simoncelli, 2011]

Camouflage

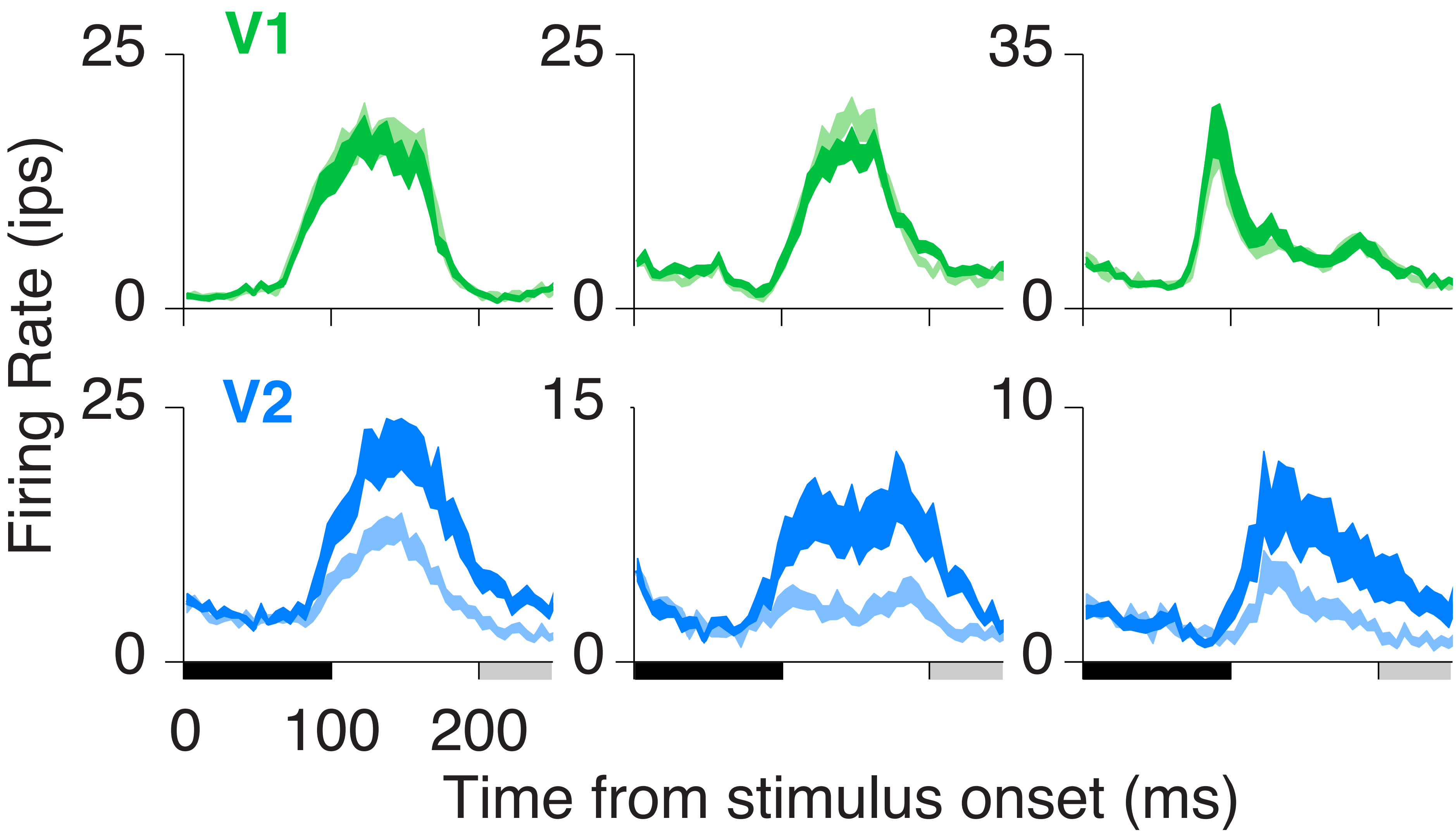
[Freeman & Simoncelli, 2011]

Can we drive individual V2 neurons using local texture stimuli?



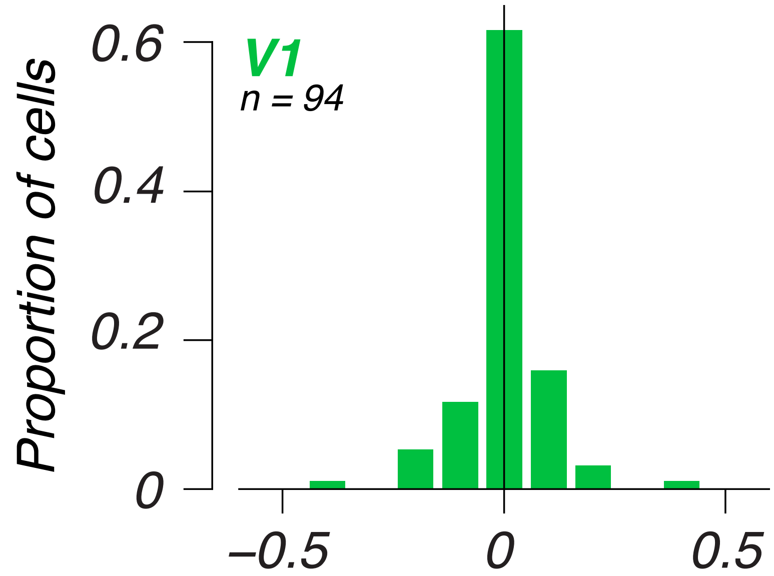
Top: synthetic textures, full model
Bottom: "spectral noise" (matched only for "V1" statistics)

[Freeman, et. al. 2013]

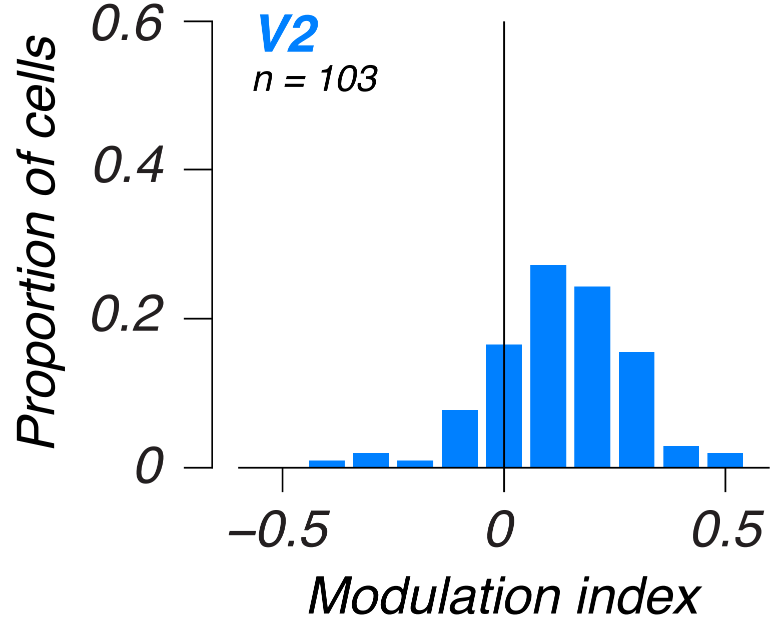


[Freeman, et. al. 2013]

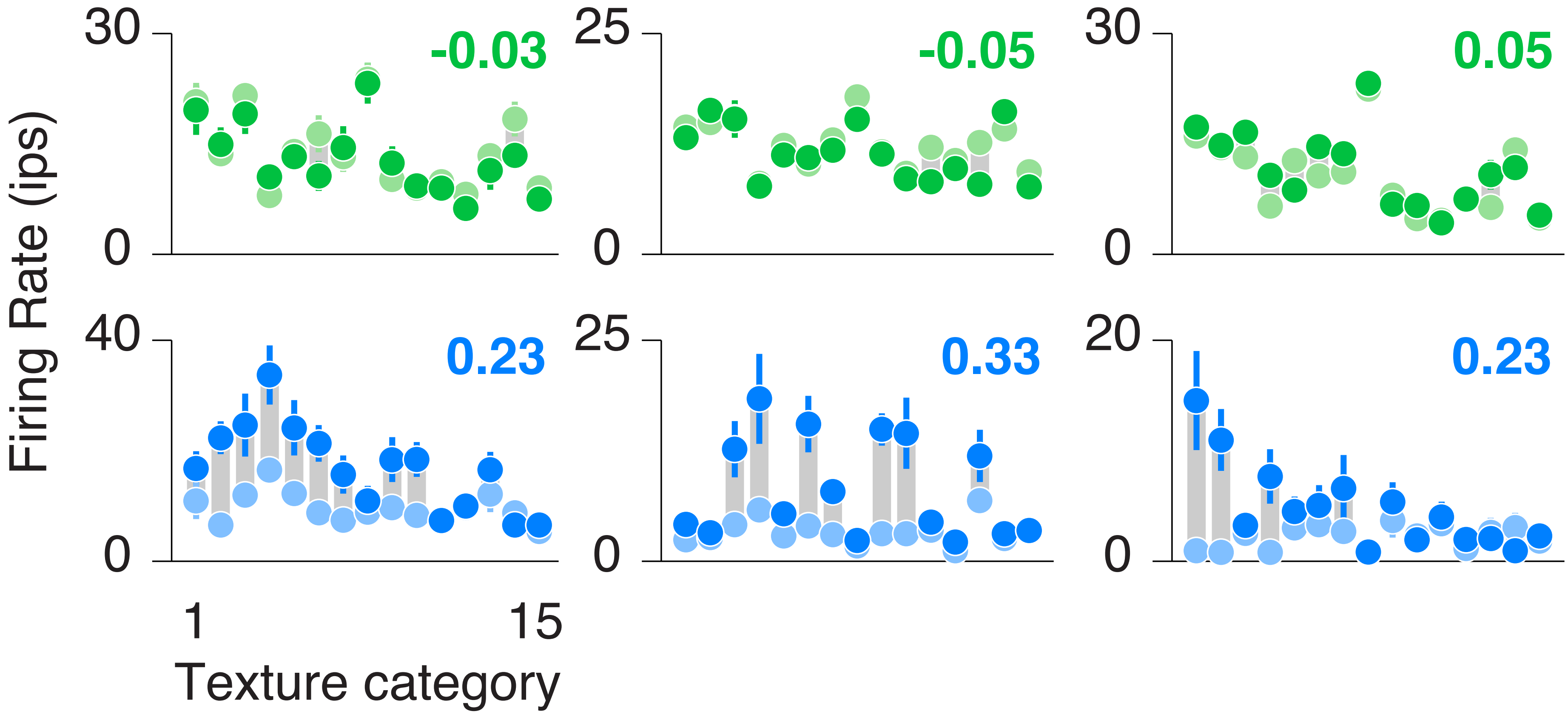
15% of V1 neurons significantly positively modulated



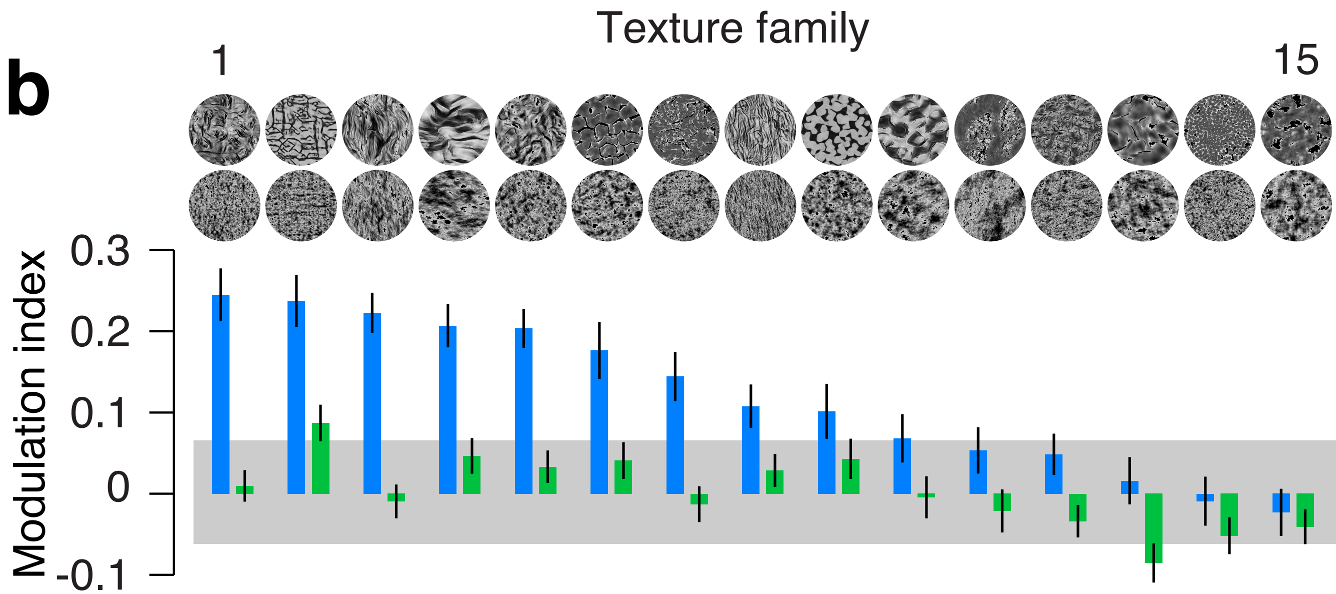
63% of V2 neurons significantly positively modulated

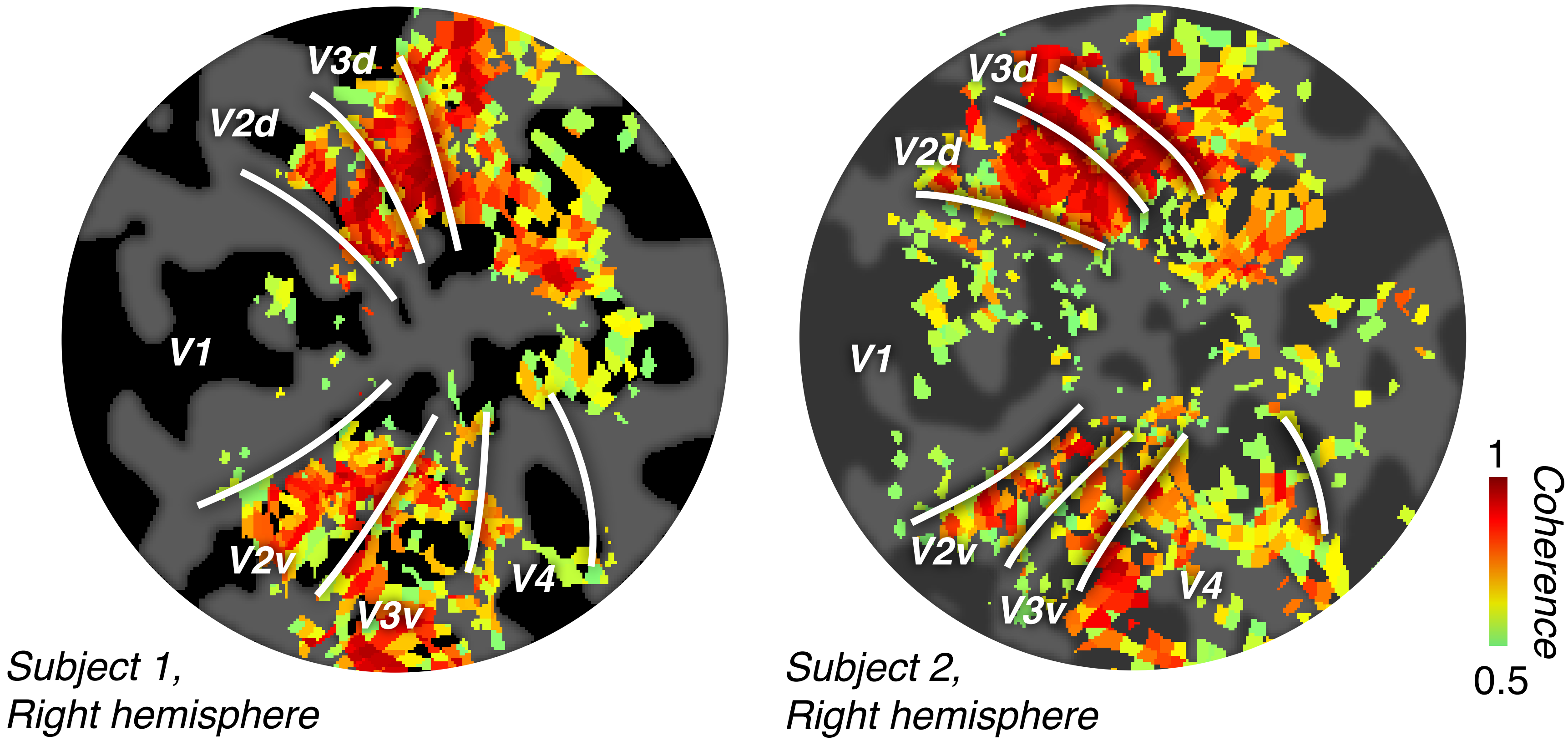


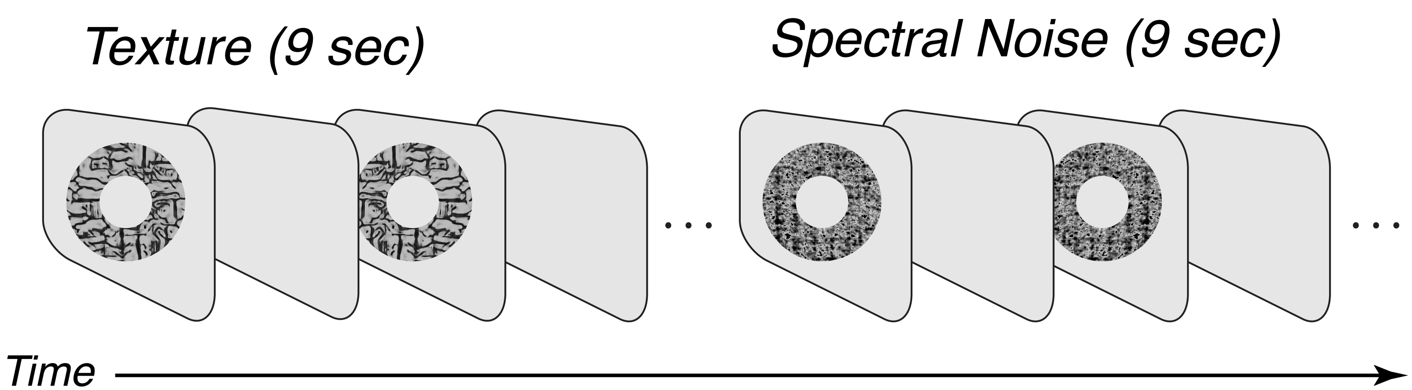
[Freeman, et. al. 2013]



[Freeman, et. al. 2013]


b
Texture family
1
15
Modulation index
0.3
0.2
0.1
0
-0.1

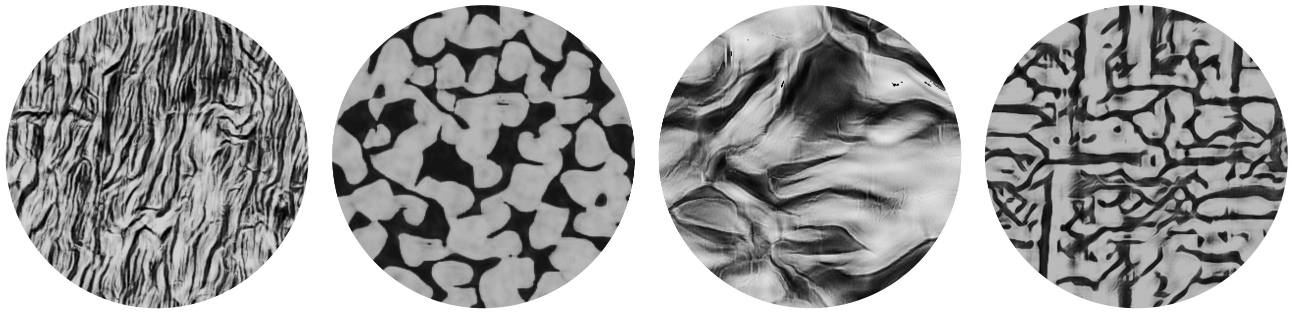




[Freeman, et. al. 2013]

Predicting discriminability

Different families



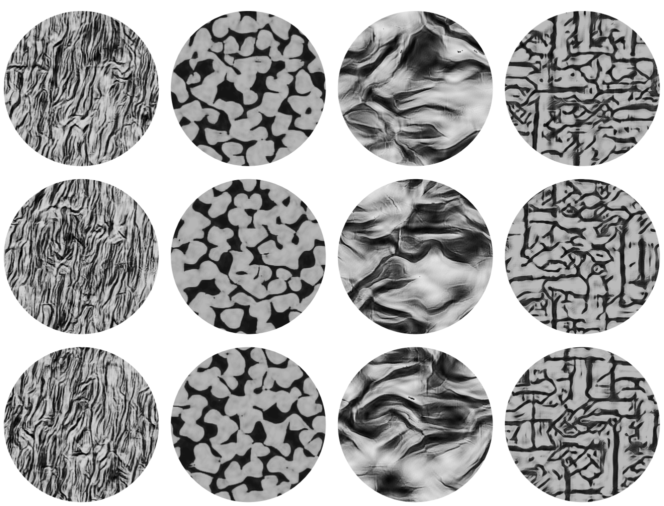
[Ziemba, Freeman, Movshon, Simoncelli - unpublishd]

Anesthetized macaque

- V1: 102 neurons
- V2: 103 neurons

Stimuli presented for 100ms within a 4° aperture

20 repetitions each



[Ziemba, Freeman, Movshon, Simoncelli - unpublishd]

Example V1 neuron

Anesthetized macaque

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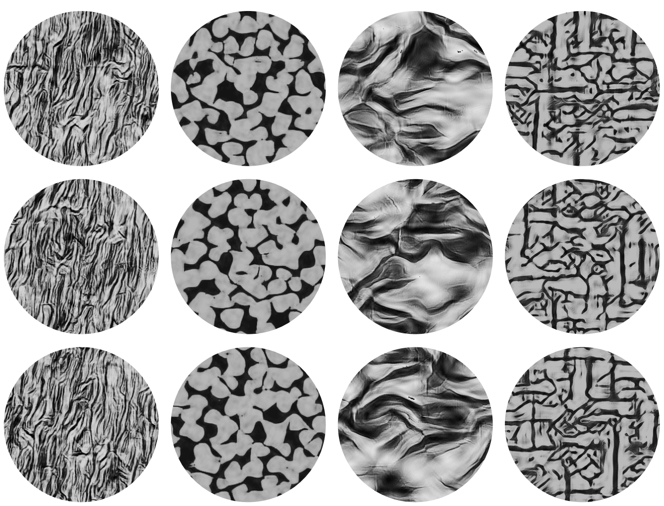
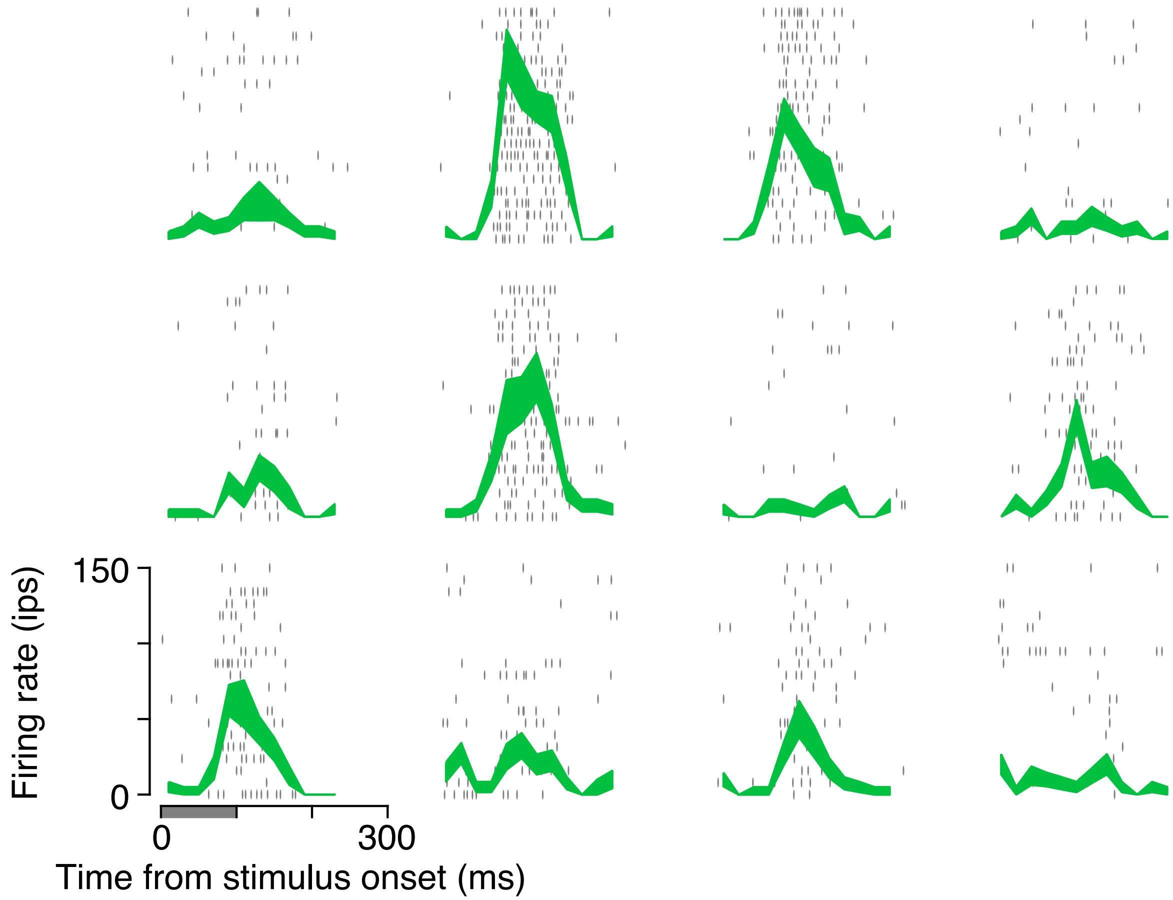
20 repetitions each





[Ziemba, Freeman, Movshon, Simoncelli - unpublishd]

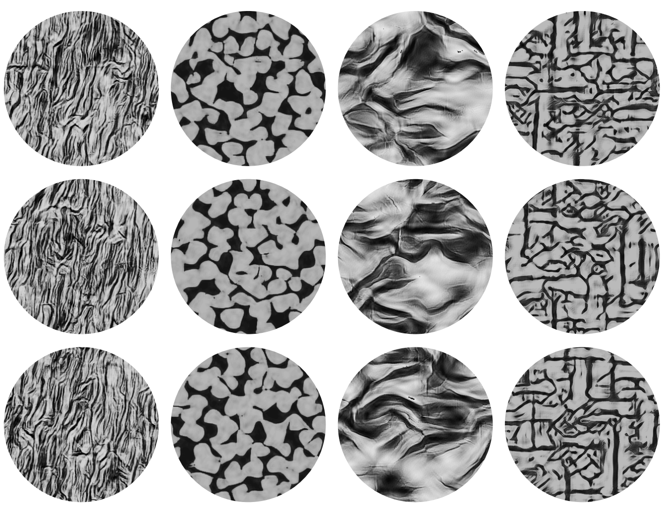
Example V2 neuron

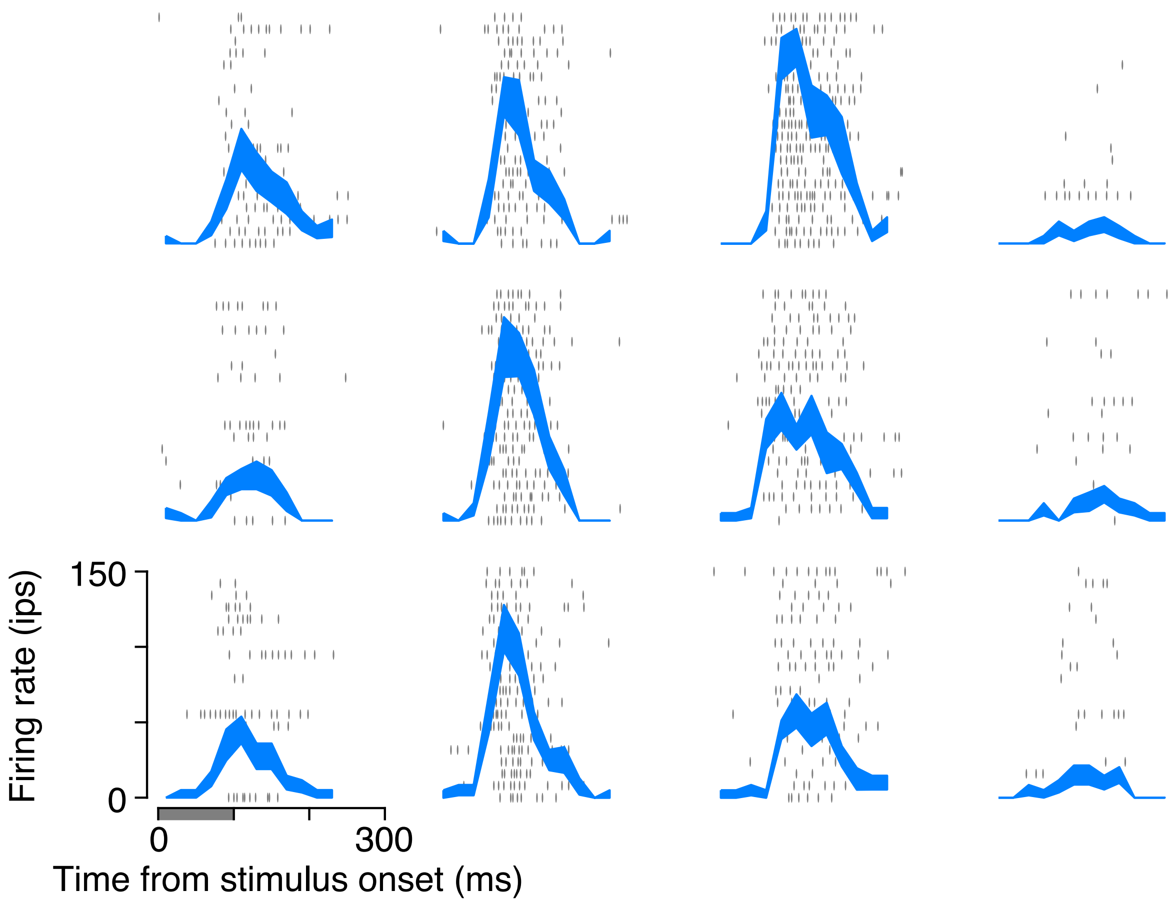
Anesthetized macaque

- V1: 102 neurons
- V2: 103 neurons

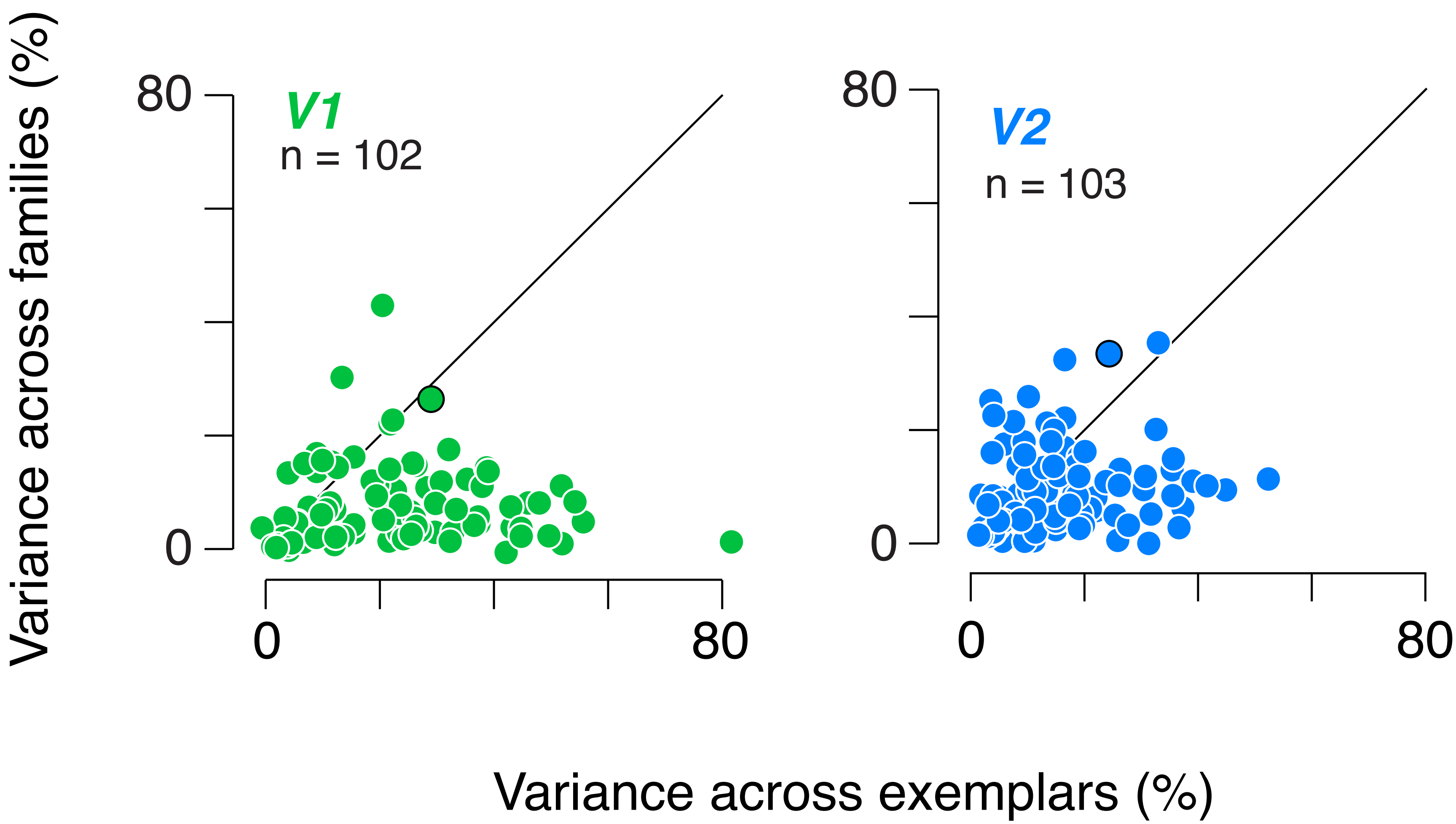
Stimuli presented for 100ms within a 4° aperture

20 repetitions each



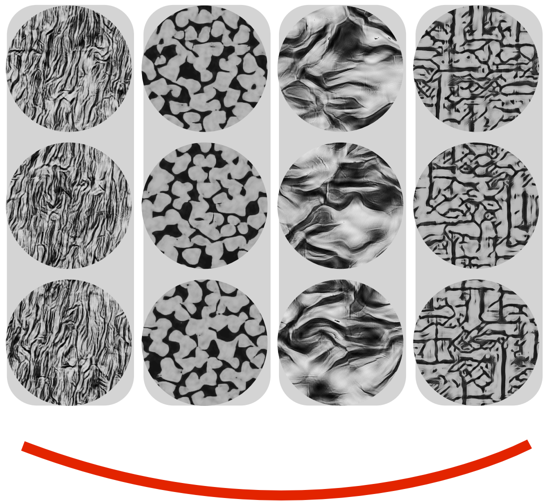


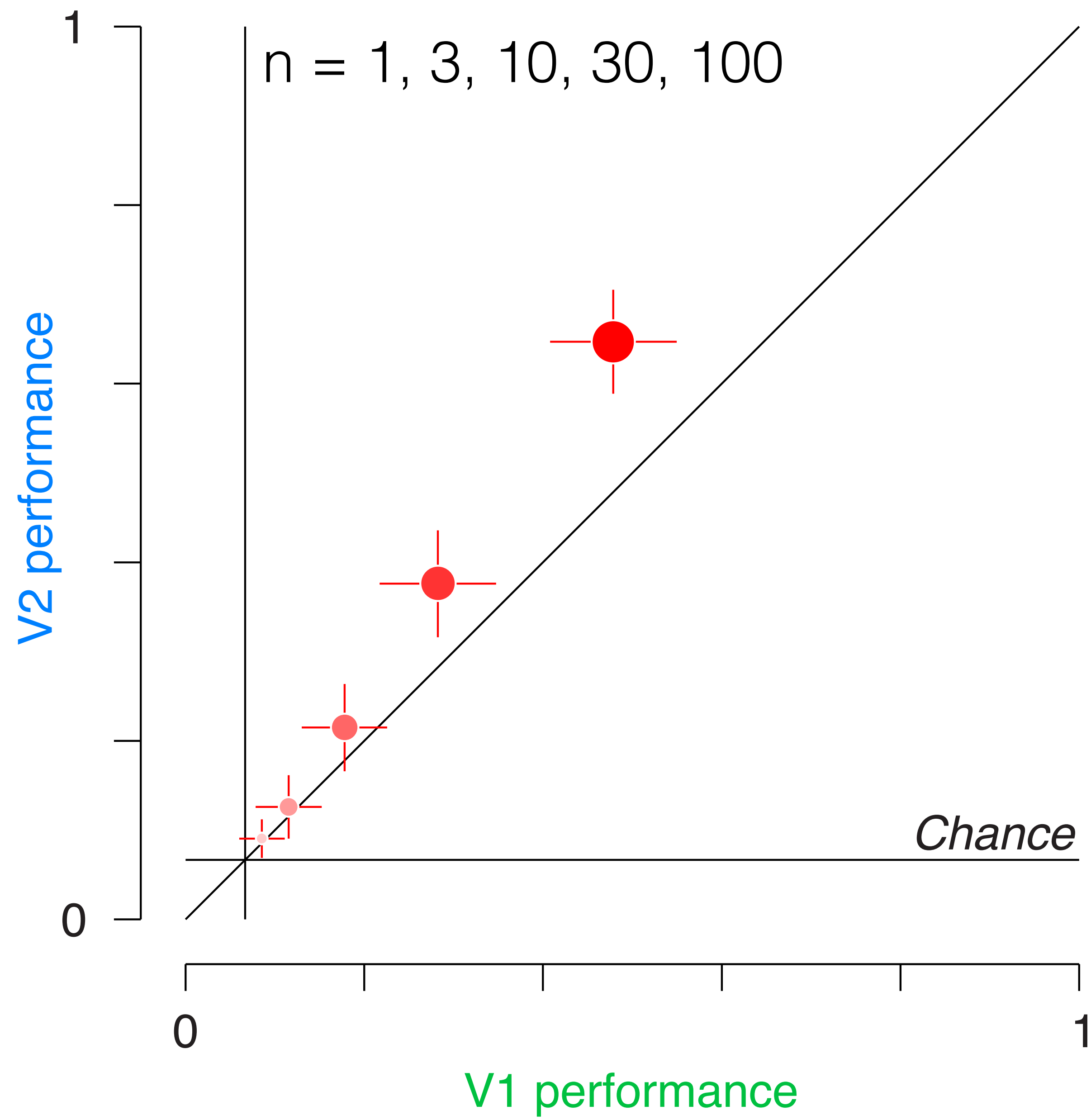
[Ziemba, Freeman, Movshon, Simoncelli - unpublishd]


Variance across families (%)
80
0
V1
n = 102
0
80
80
0
V2
n = 103
0
80
Variance across exemplars (%)

Decoding

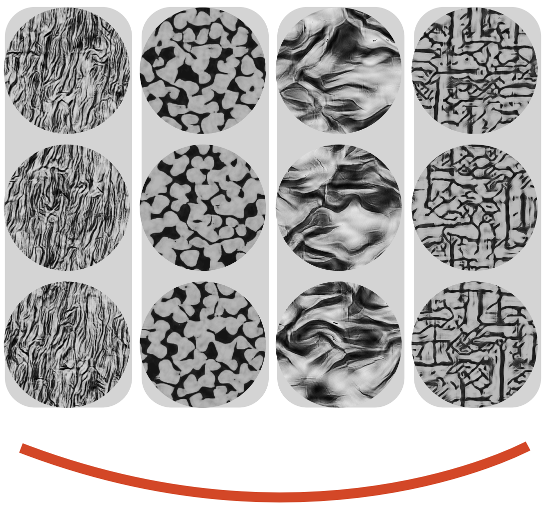
Family classification



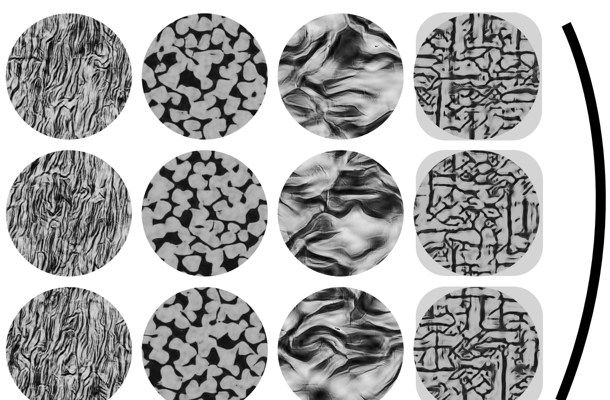


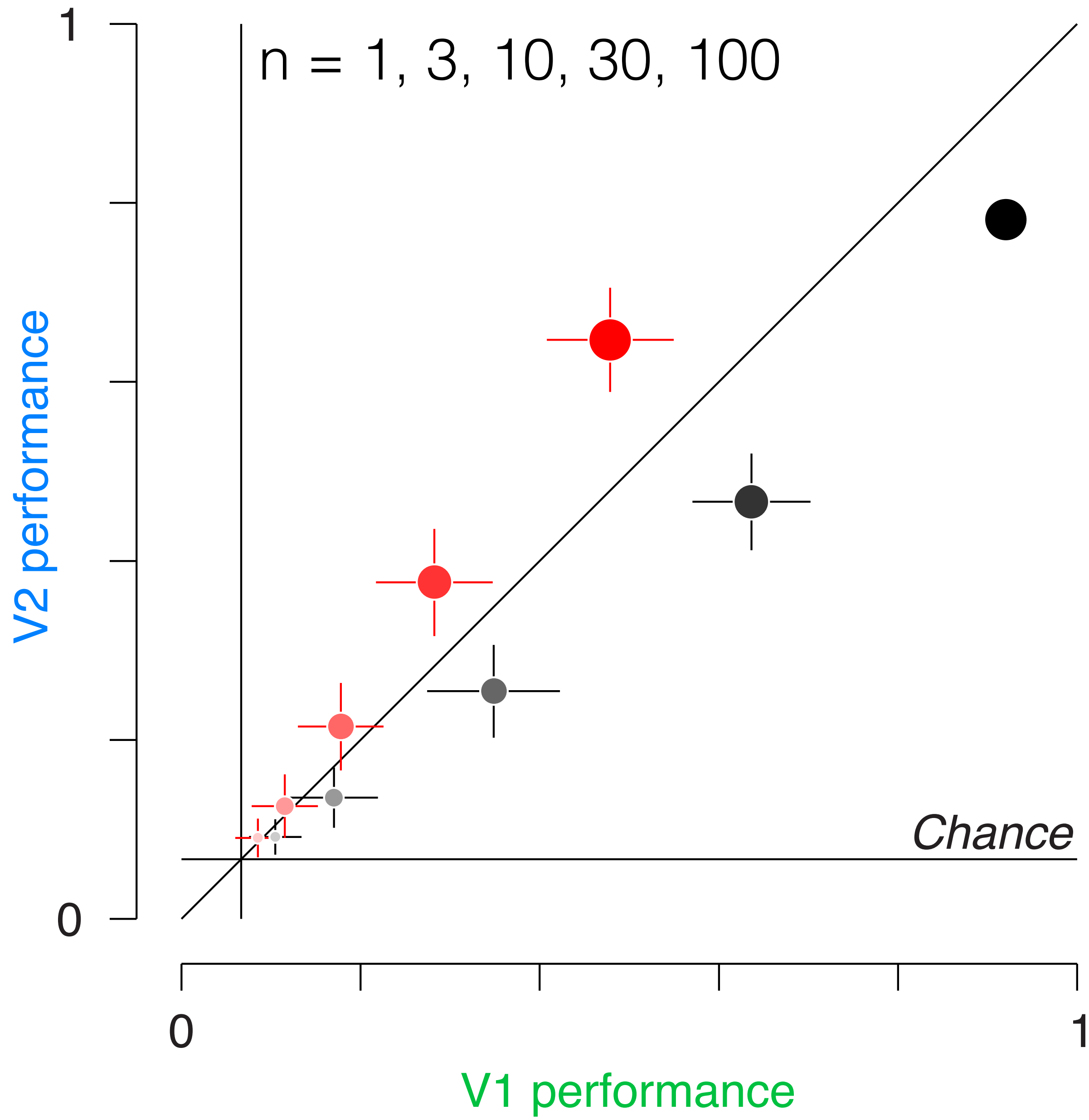
Decoding

Family classification



Exemplar identification





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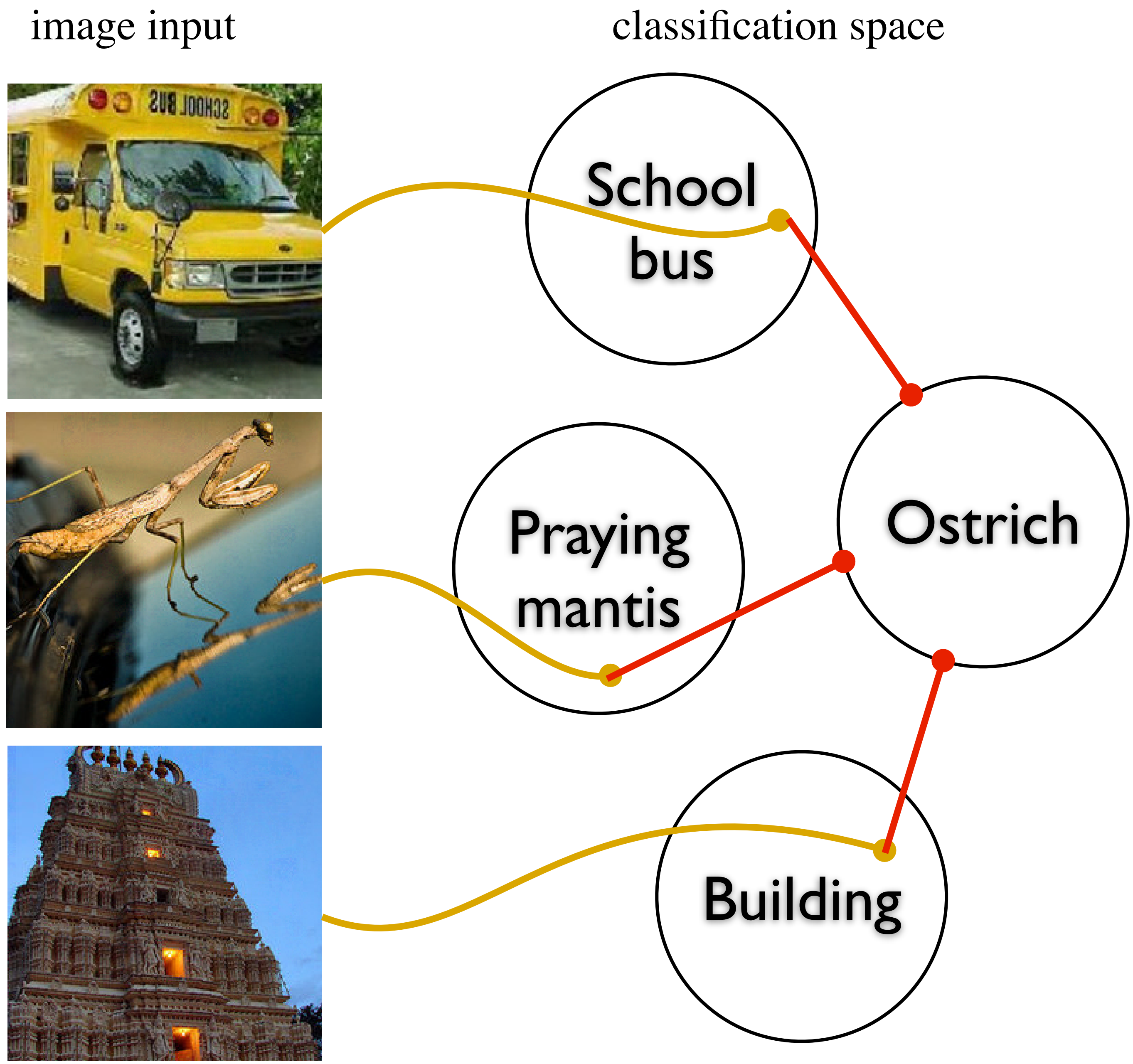
The power of synthesis tests...



Intriguing properties of neural networks, ArXiv 2014
Szegedy, Zaremba, Sutskever, Bruna, Erhan, Goodfellow, Fergus

The power of synthesis tests...

Shows that, at the very least, these networks are NOT good models for human vision!

Intriguing properties of neural networks, ArXiv 2014
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