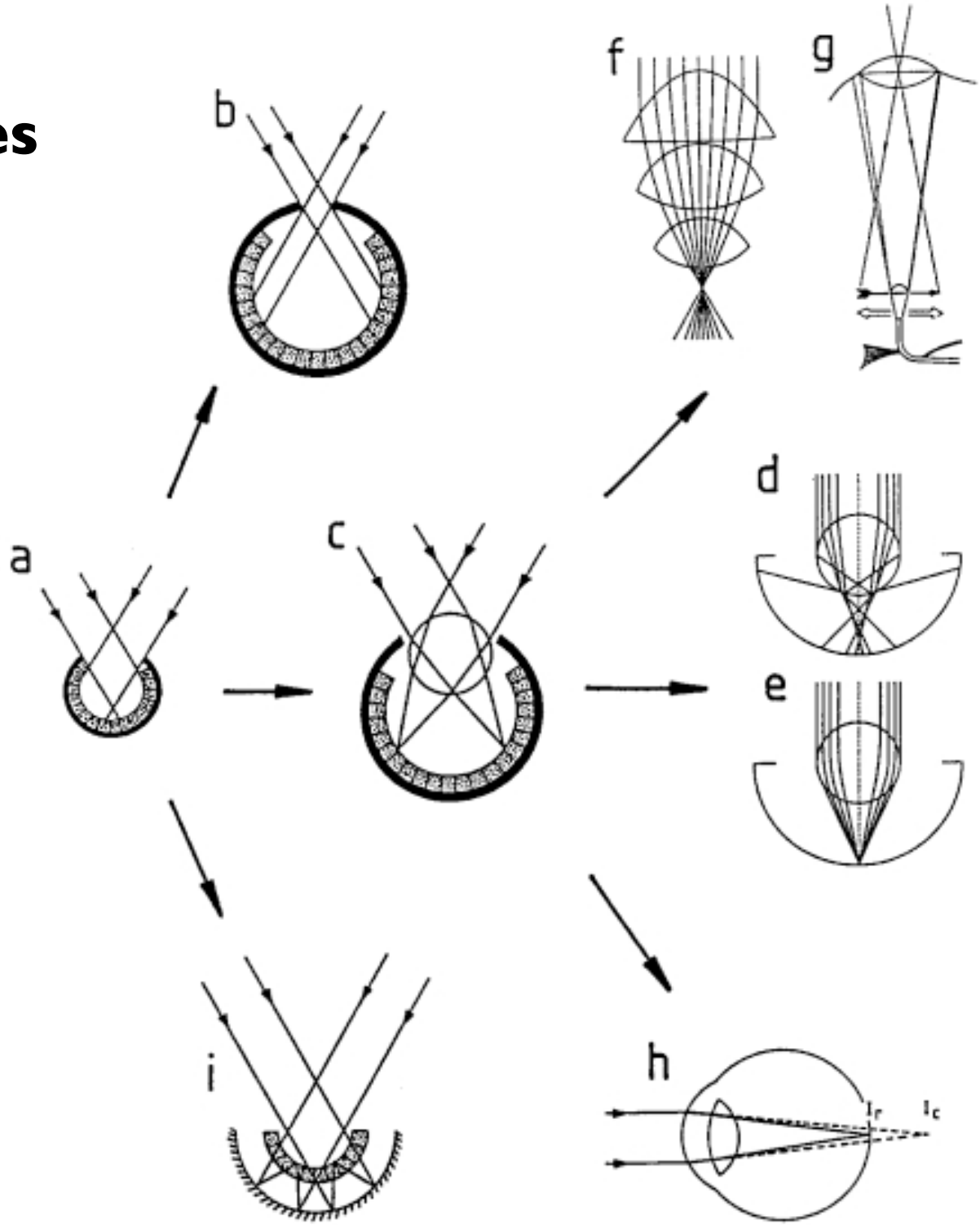
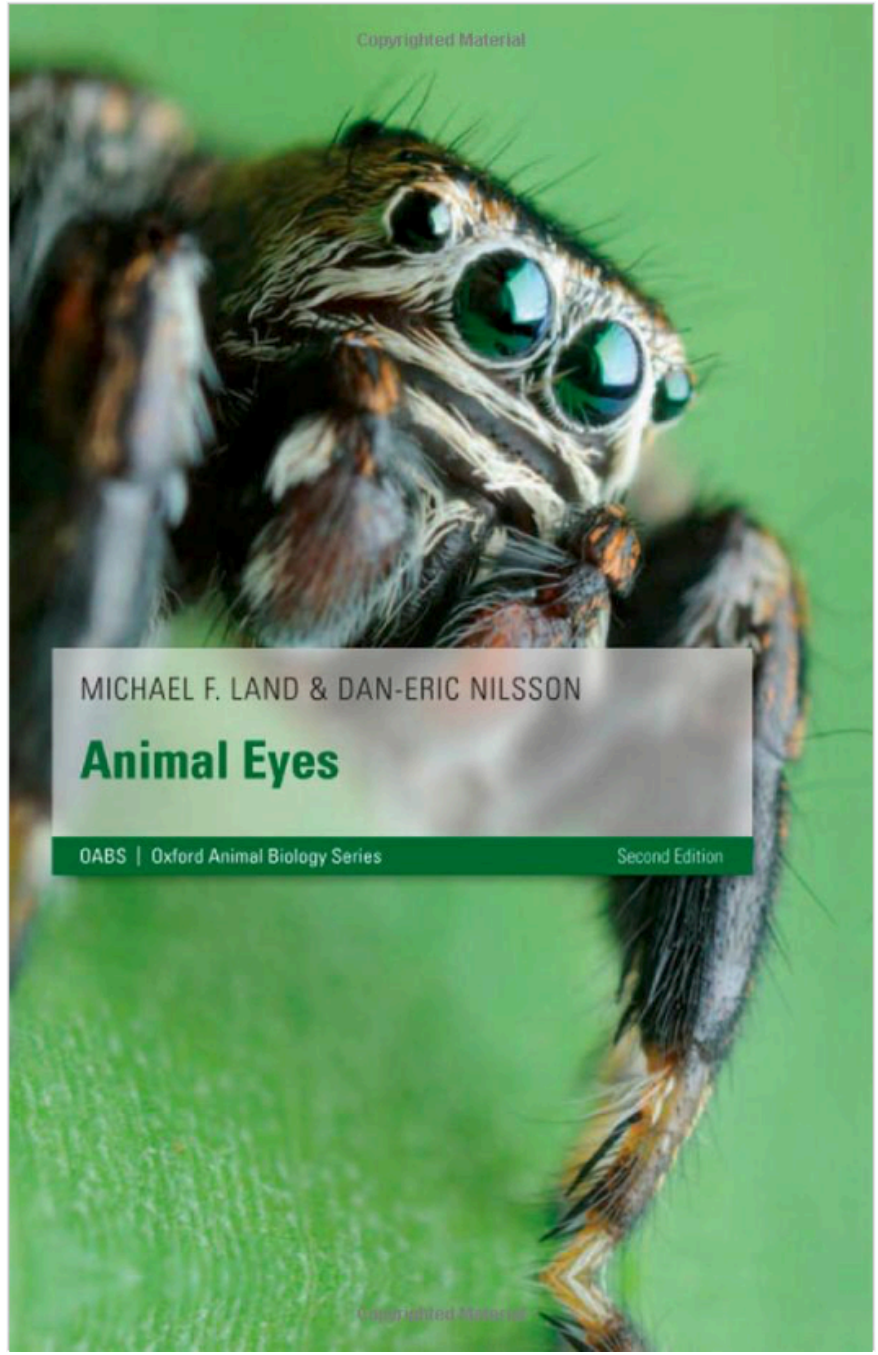
Redwood Center for Theoretical Neuroscience - April 2018

1. How did vision evolve? What is it for?
2. What constitutes an efficient code of color information?
3. How to form a stable color percept from unstable images?
4. How are color categories learned? How and where are they represented in brain?

The evolution of eyes

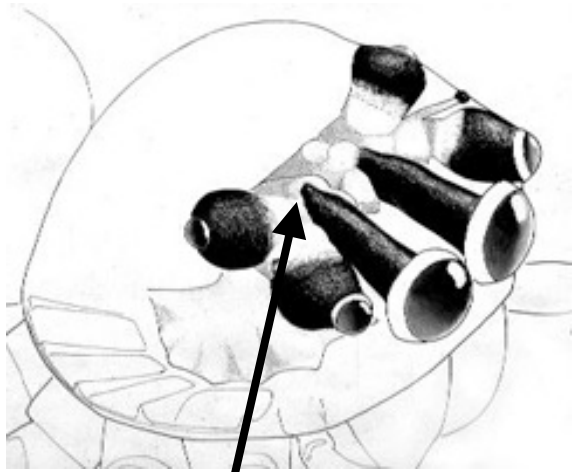
Land & Fernald (1992)



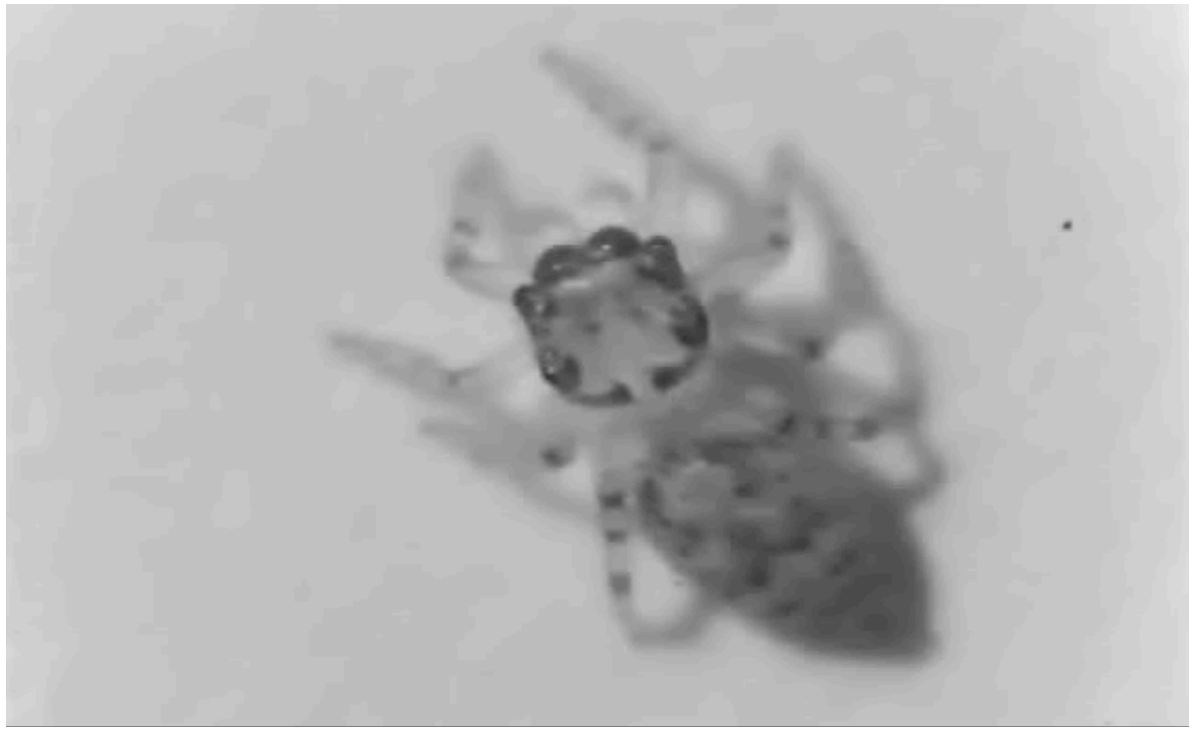


http://rctn.org/wiki/VS298:_Animal_Eyes

Vision in jumping spiders



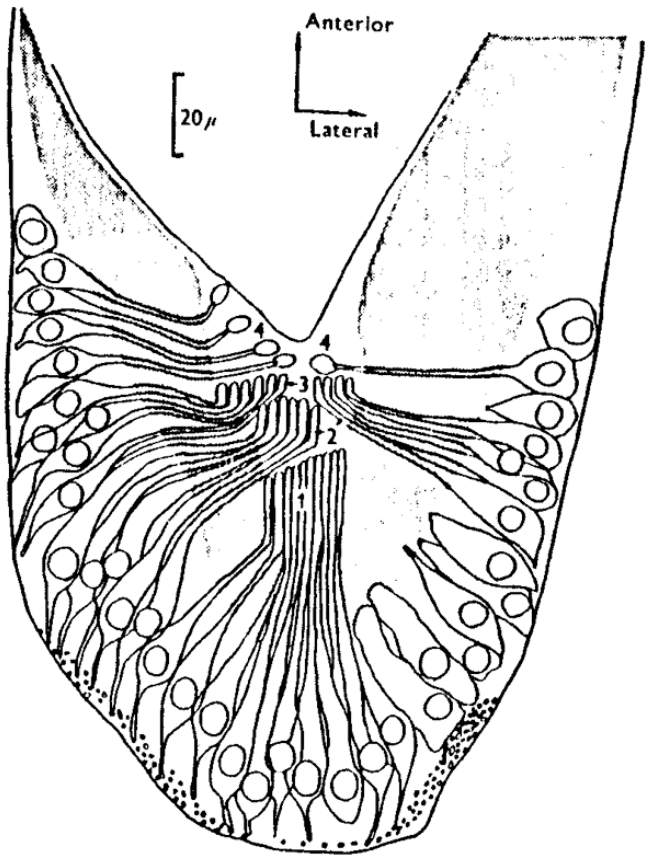
(Wayne Maddison)



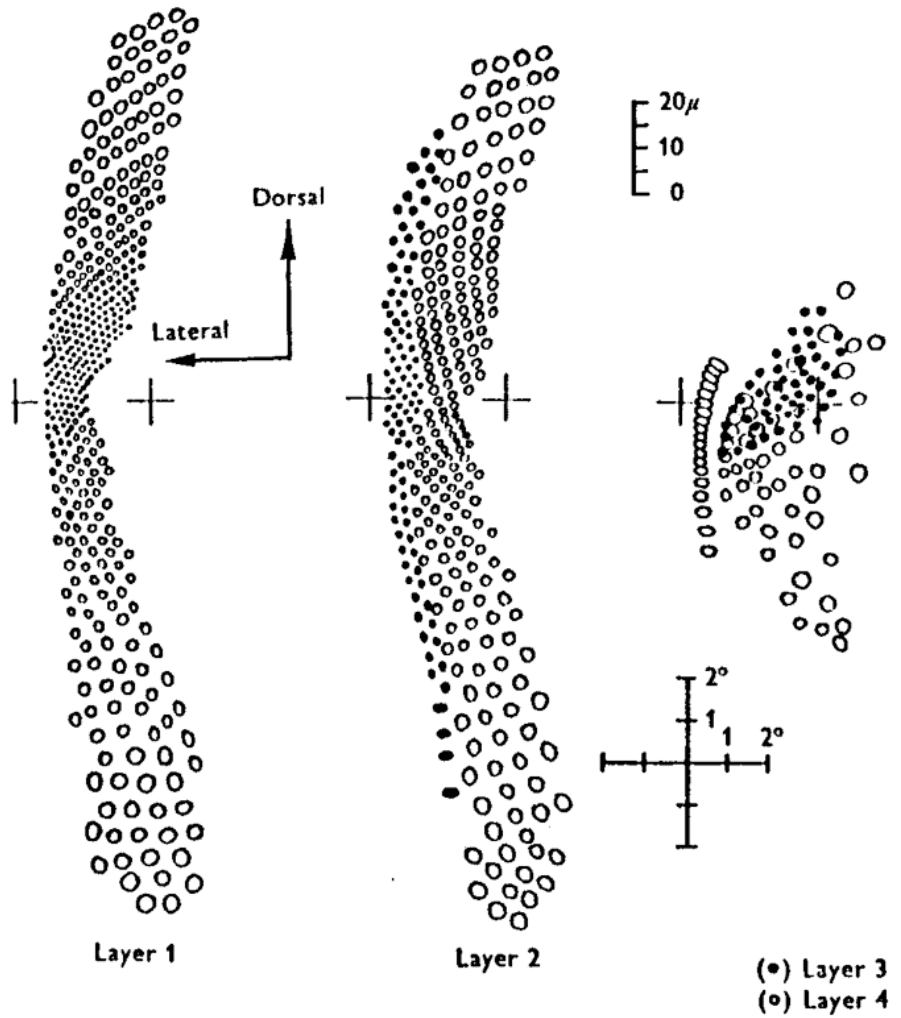
(Bair & Olshausen, 1991)

Jumping spider retina

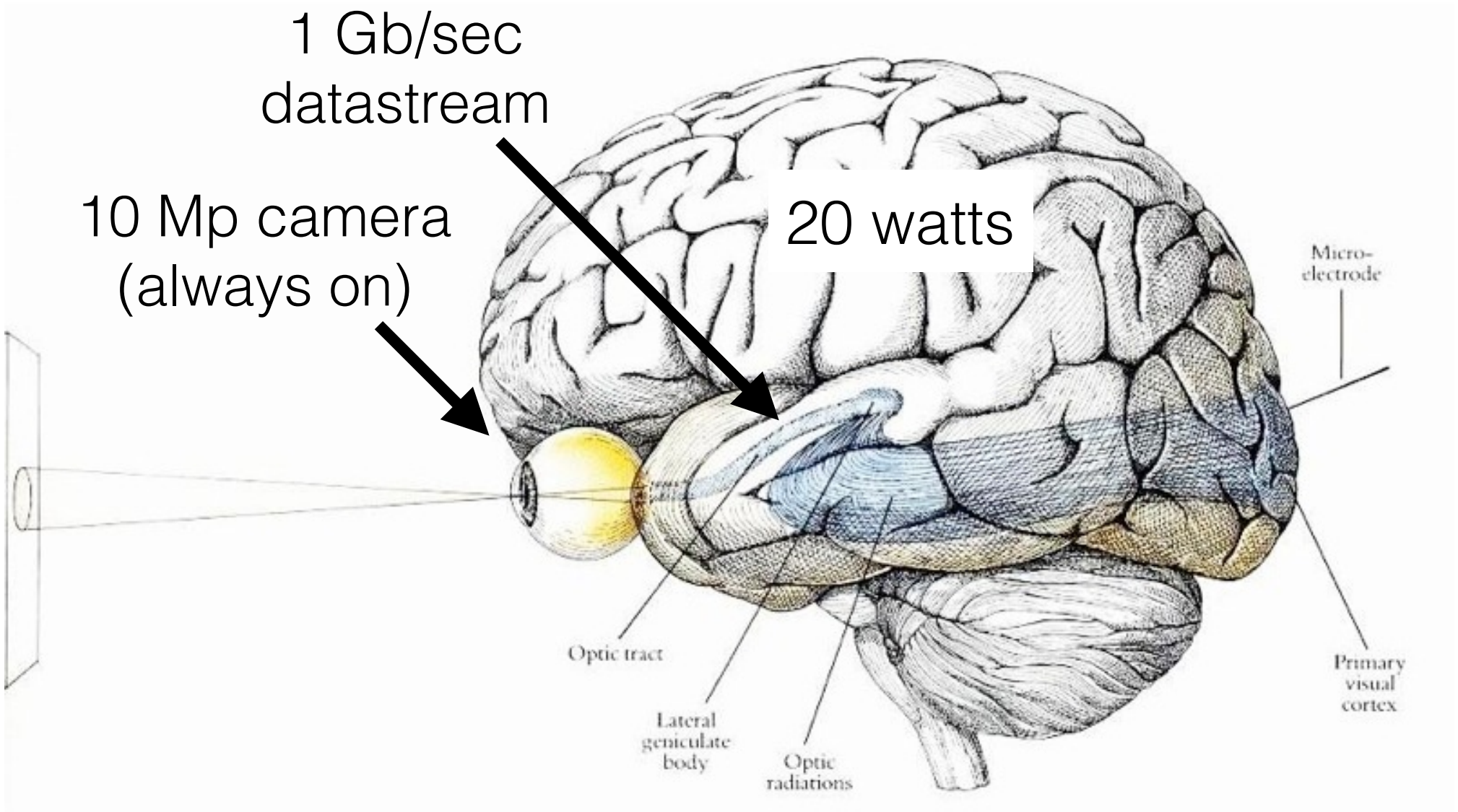
horizontal section

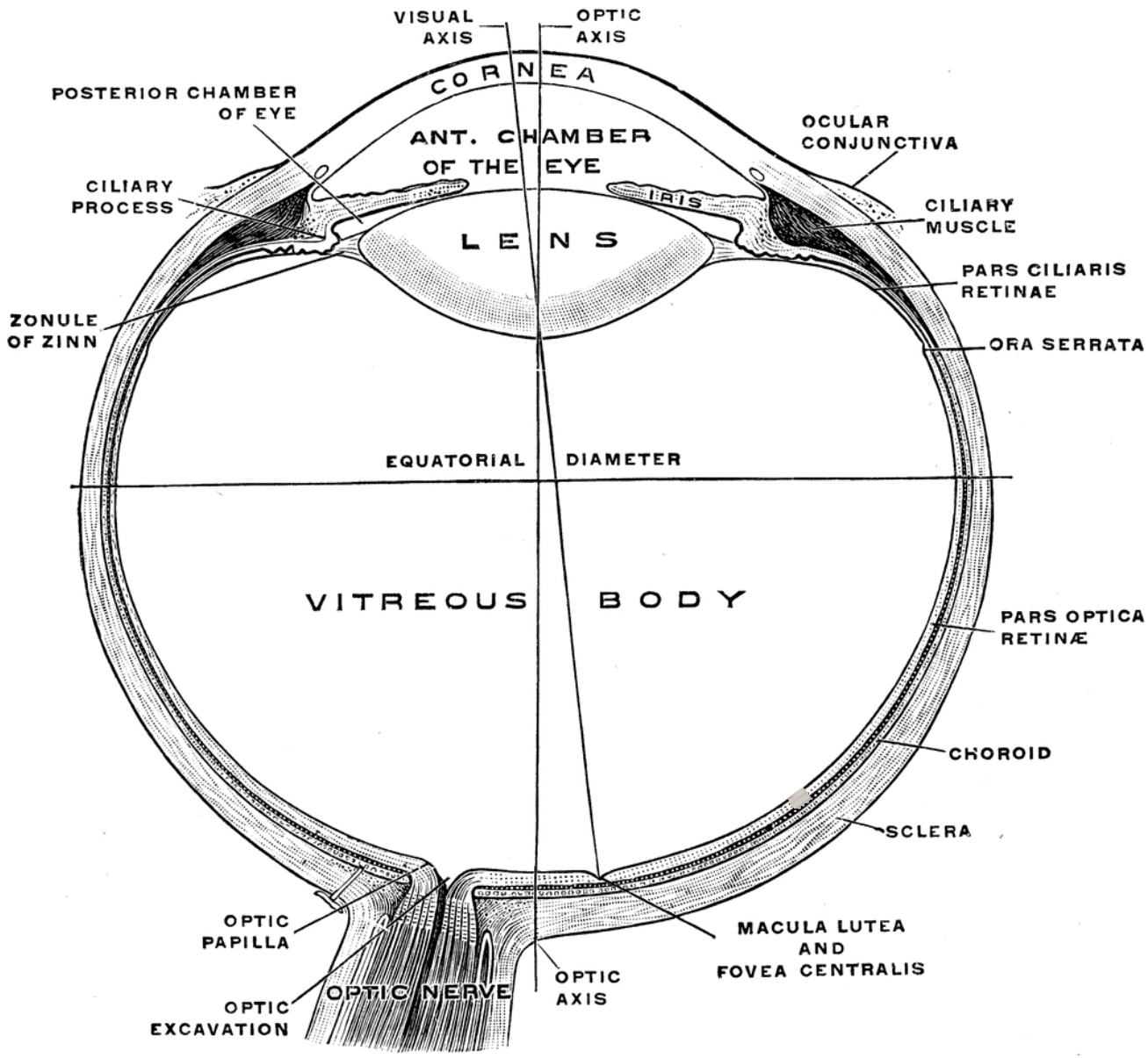


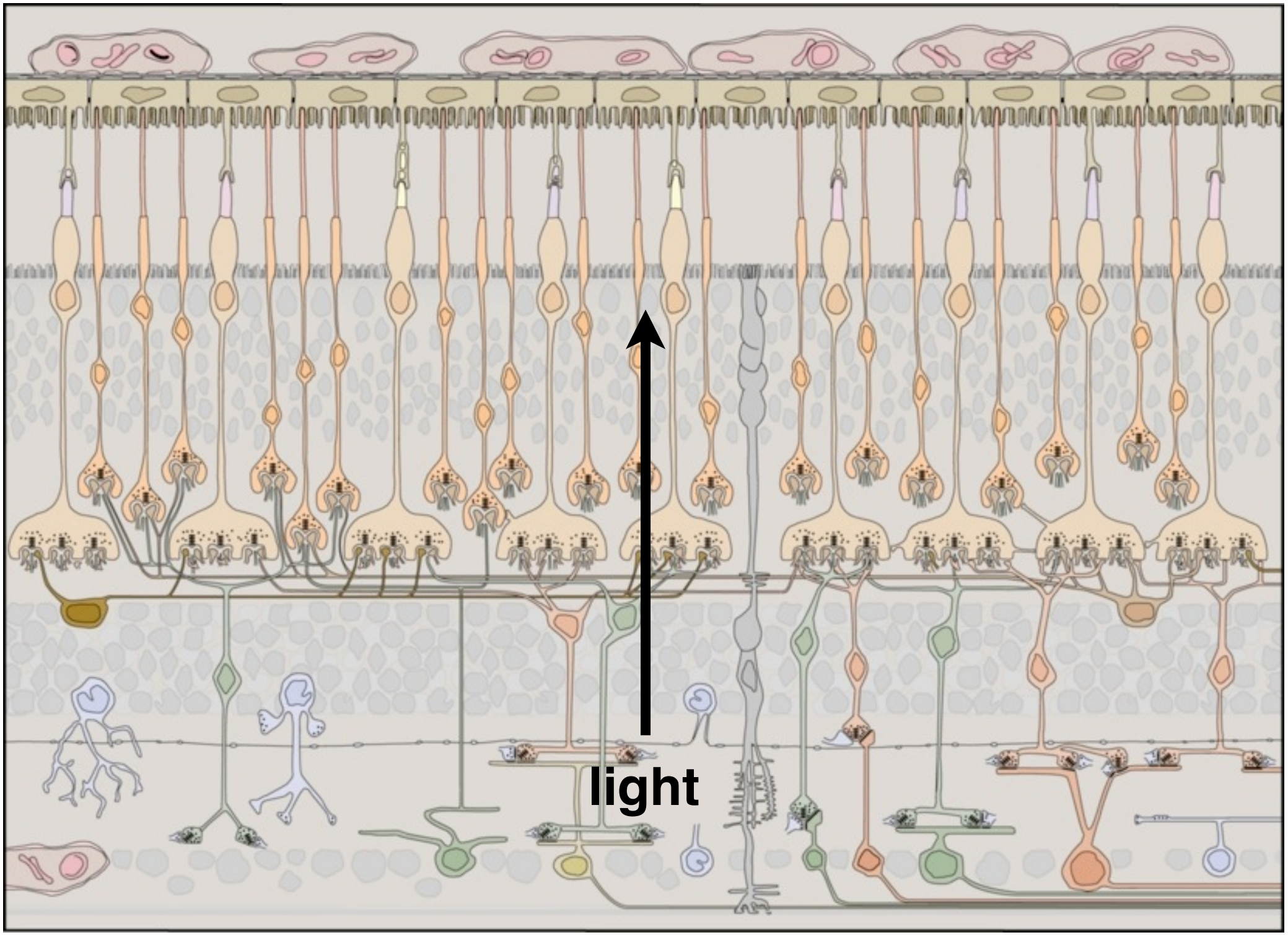
photoreceptor array



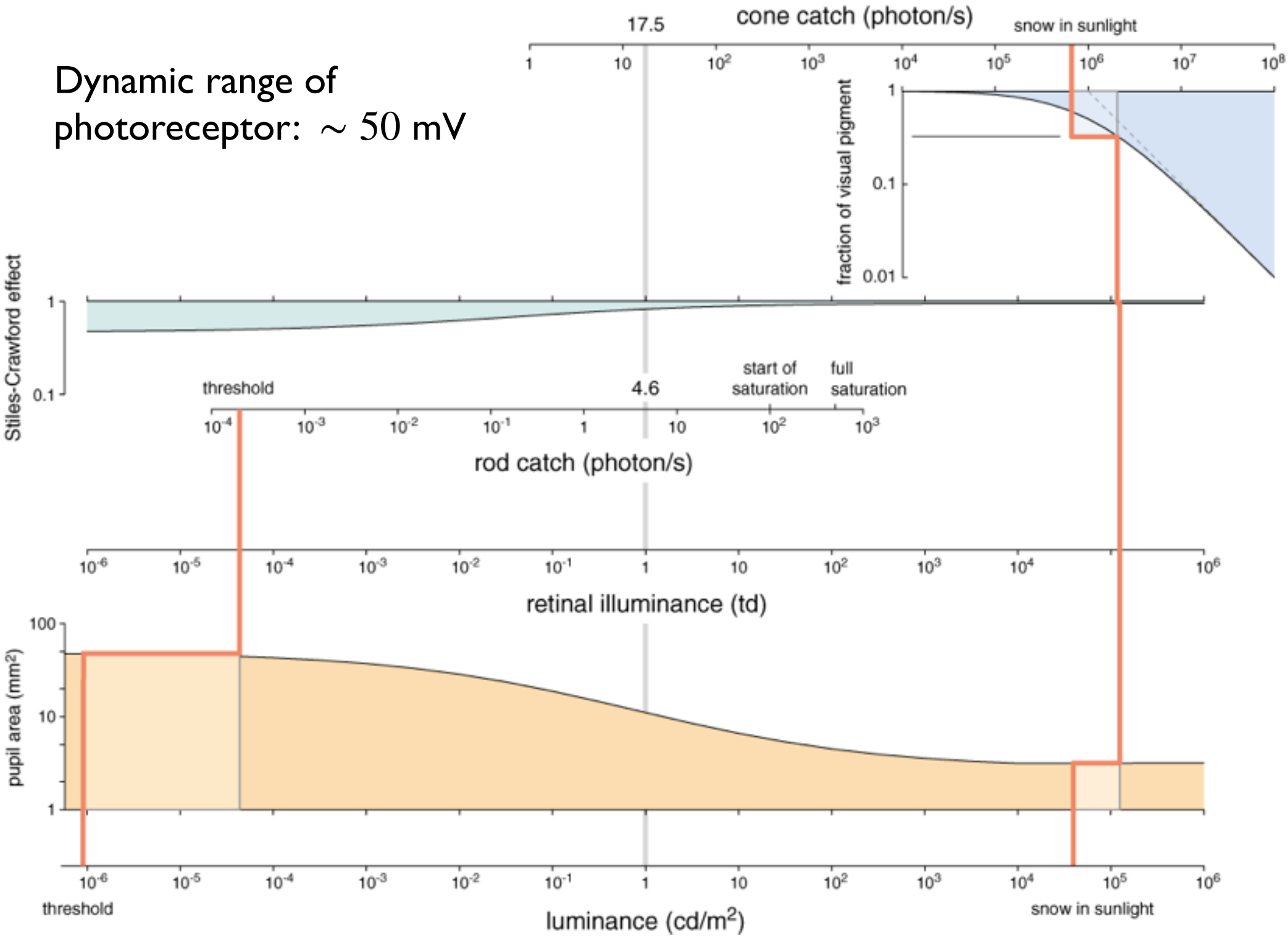
2. What constitutes an efficient code of color information?


1 Gb/sec
datastream
10 Mp camera
(always on)
20 watts
Micro-
electrode
Optic tract
Lateral
geniculate
body
Optic
radiations
Primary
visual
cortex

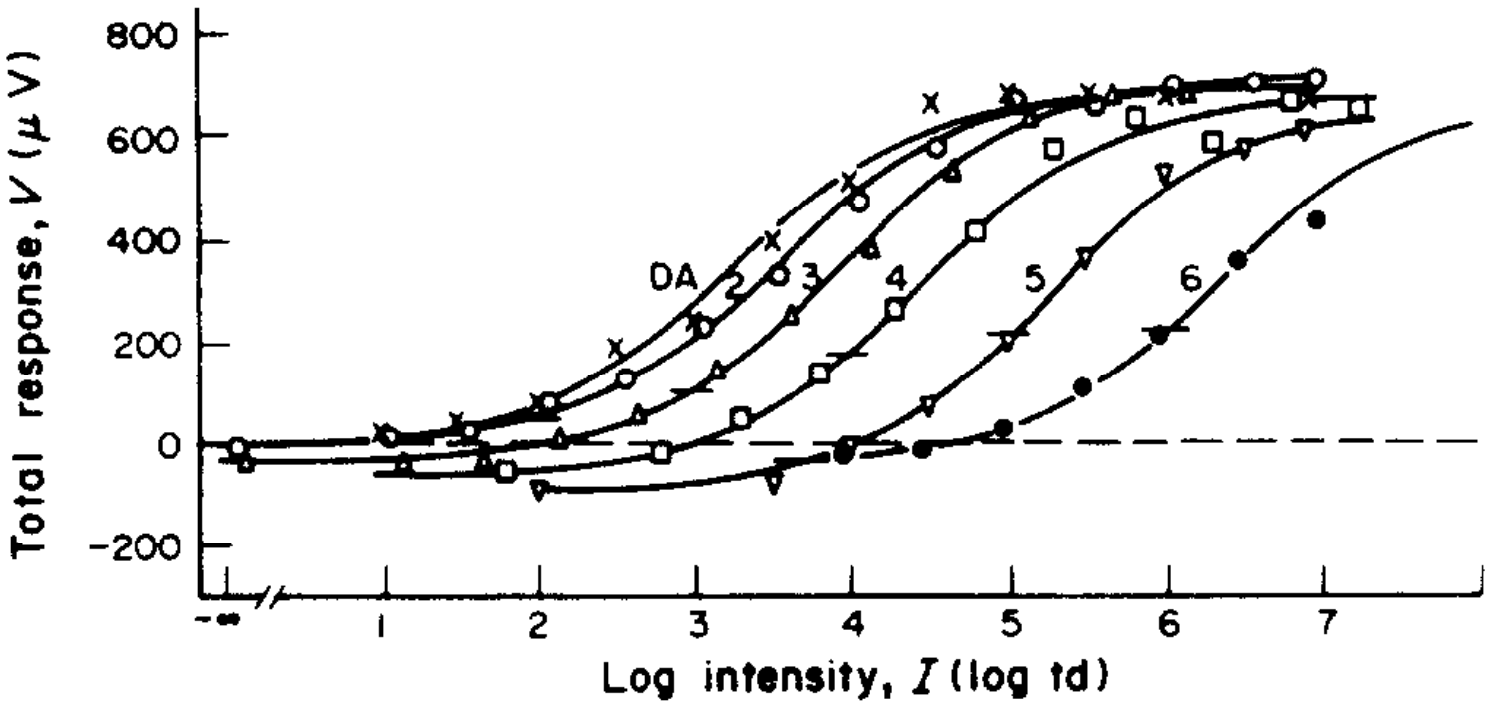

VISUAL AXIS
OPTIC AXIS
CORNEA
POSTERIOR CHAMBER OF EYE
ANT. CHAMBER OF THE EYE
OCULAR CONJUNCTIVA
CILIARY PROCESS
IRIS
CILIARY MUSCLE
LENS
PARS CILIARIS RETINAE
ZONULE OF ZINN
ORA SERRATA
EQUATORIAL DIAMETER
VITREOUS BODY
PARS OPTICA RETINÆ
CHOROID
SCLERA
OPTIC PAPILLA
MACULA LUTEA AND FOVEA CENTRALIS
OPTIC AXIS
OPTIC NERVE
OPTIC EXCAVATION


light

Dynamic range of photoreceptor: ~ 50 mV

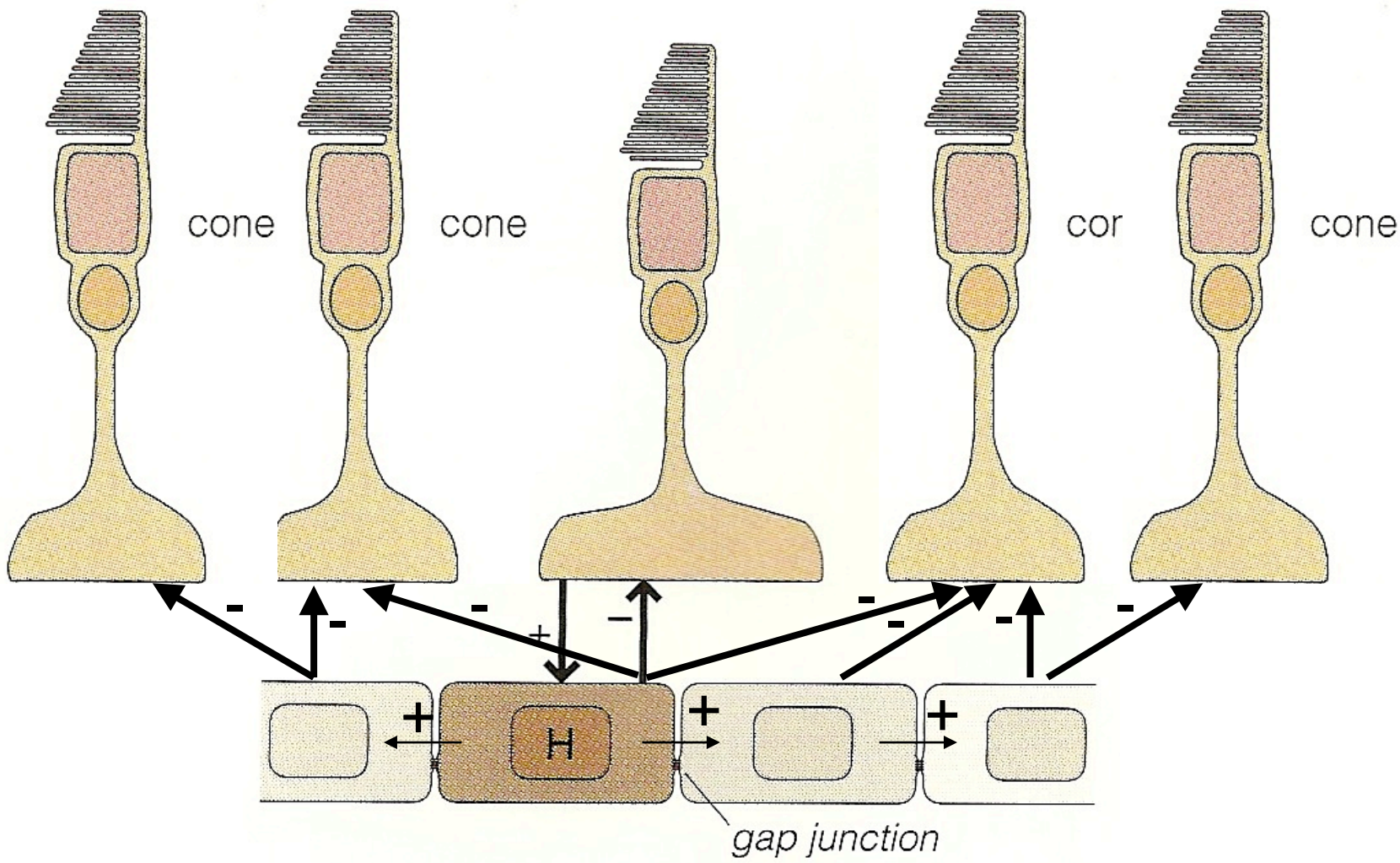


Light adaptation
(primate cones)



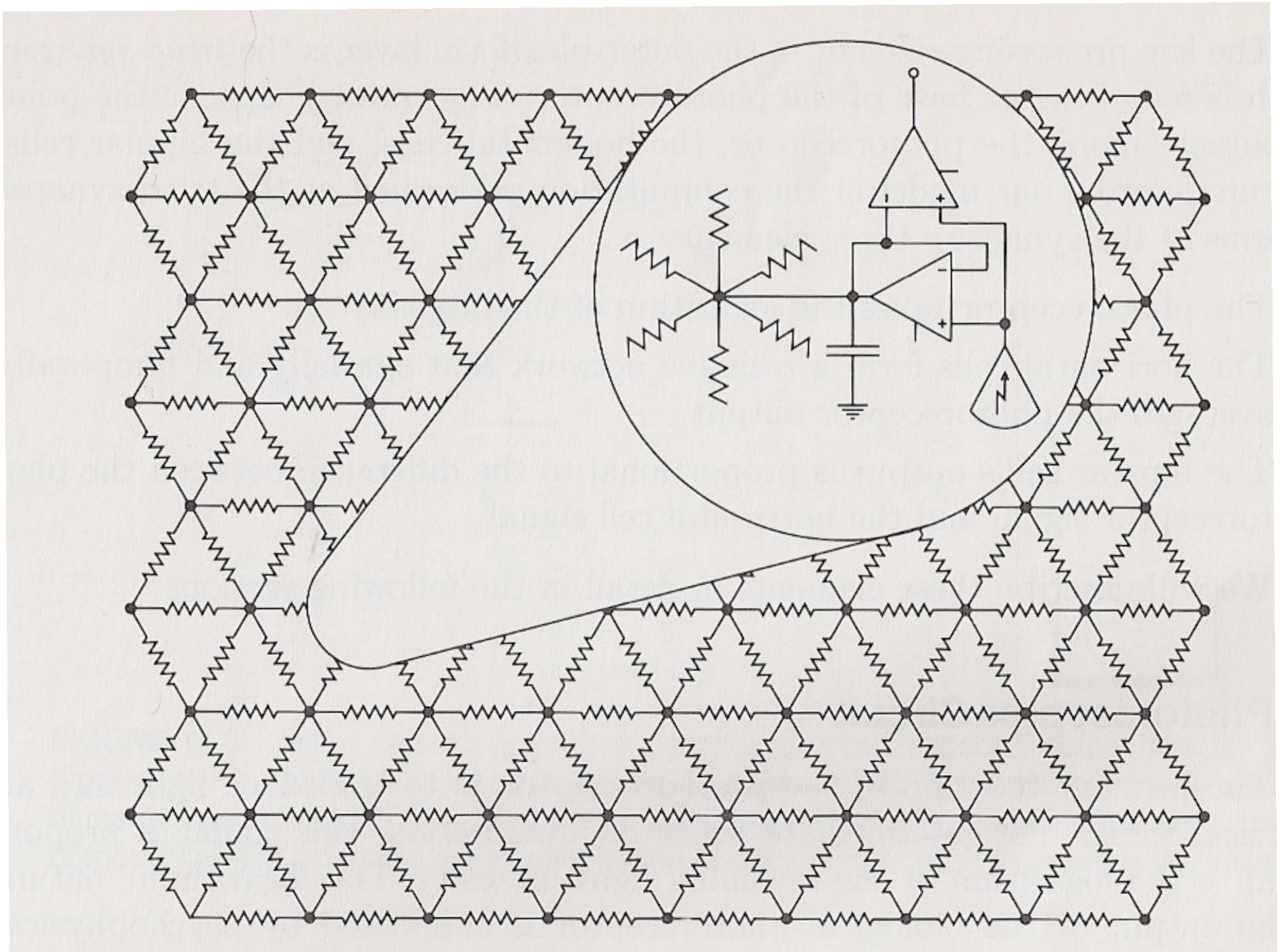
Valeton & van Norren (1983)

Hyperpolarization of horizontal cell spreads to other horizontal cells via gap junctions

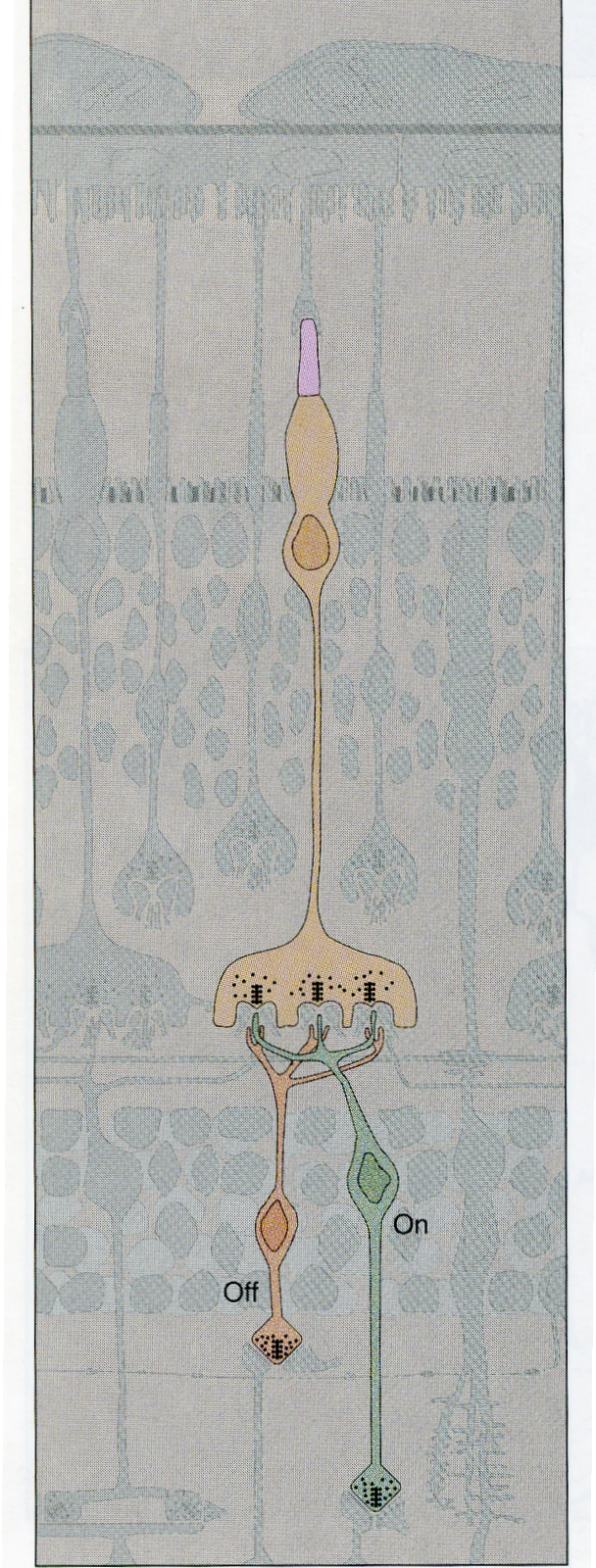


Analog VLSI retina

(Mead & Mahowald, 1989)

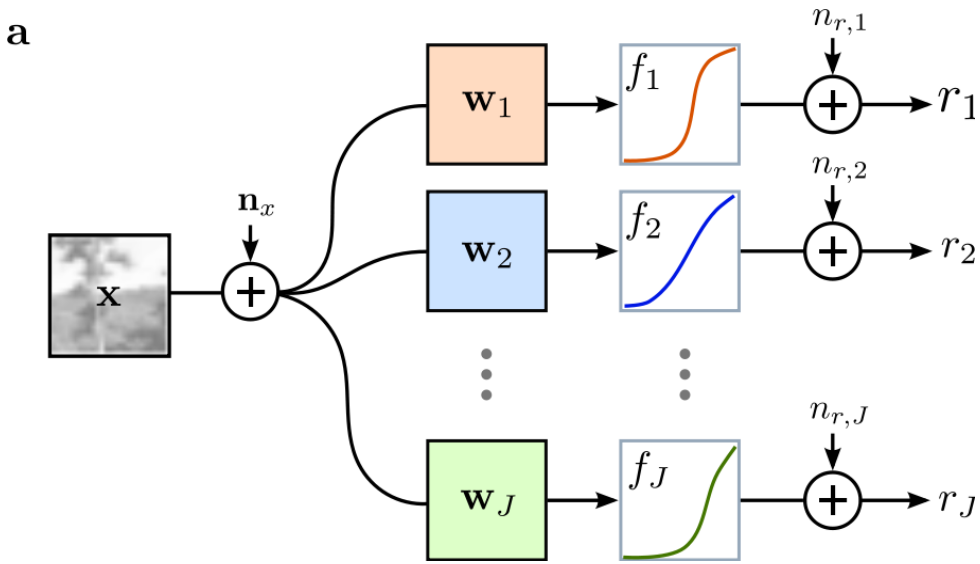


On vs. *off* cone bipolar cells



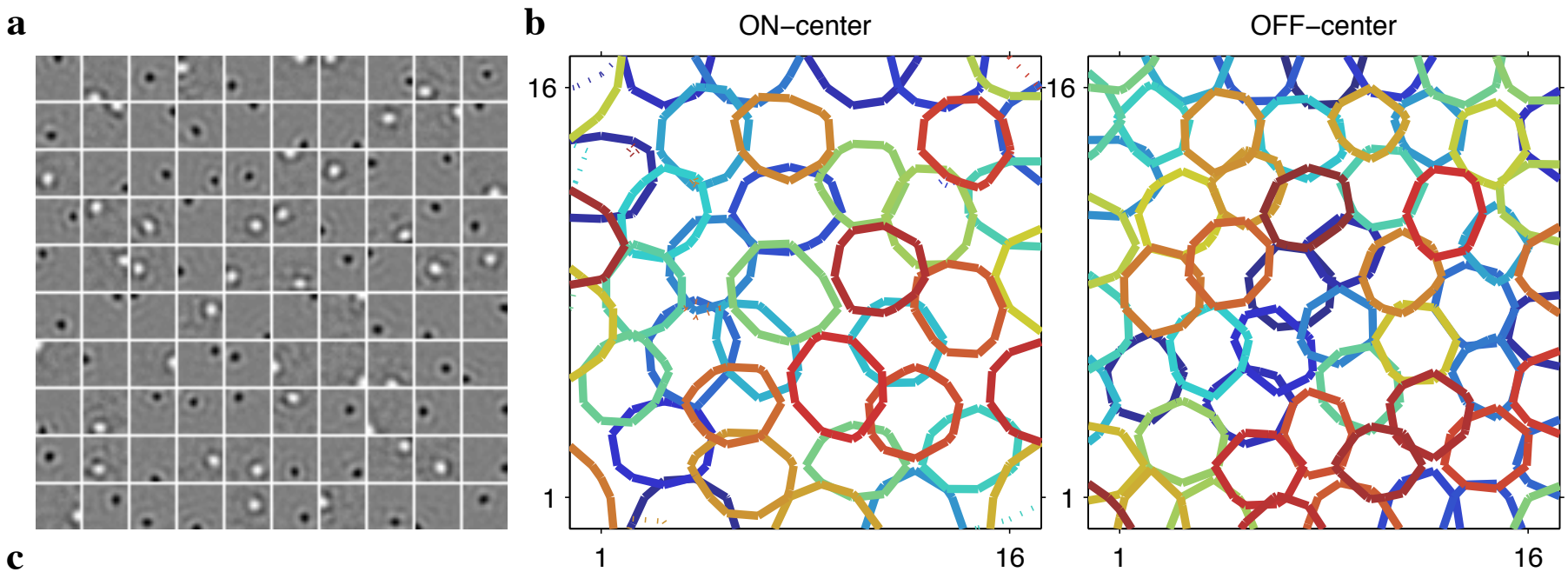
Efficient coding model of retina

(Karklin & Simoncelli 2012)



Objective function:

$$I(X;R) - \sum_j \lambda_j \langle r_j \rangle$$



Efficient coding model of retina

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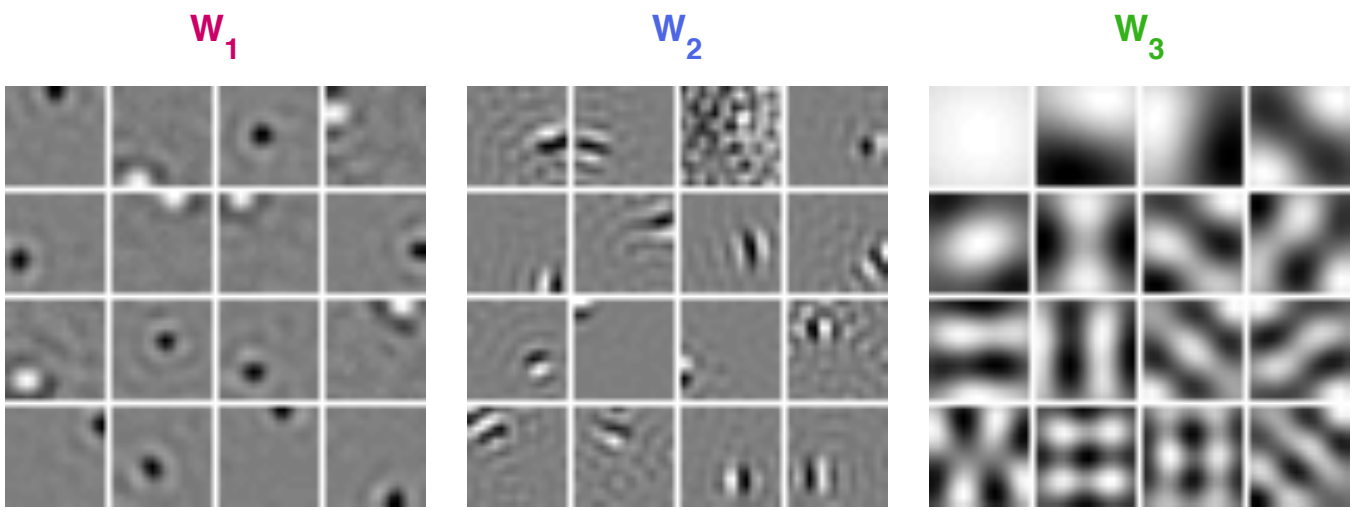
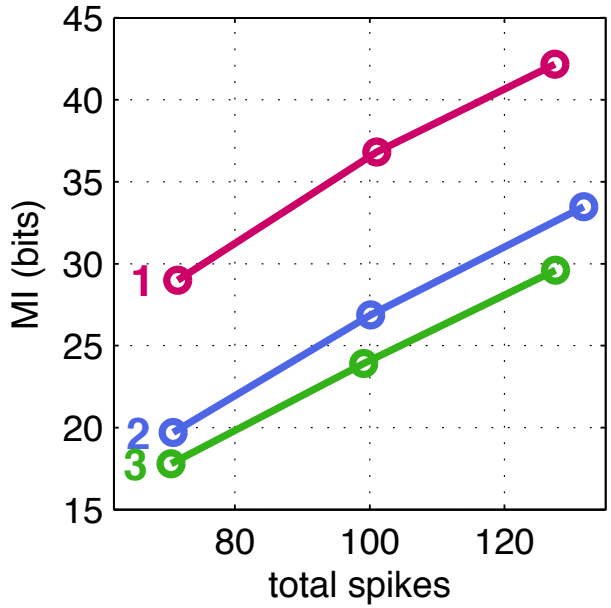
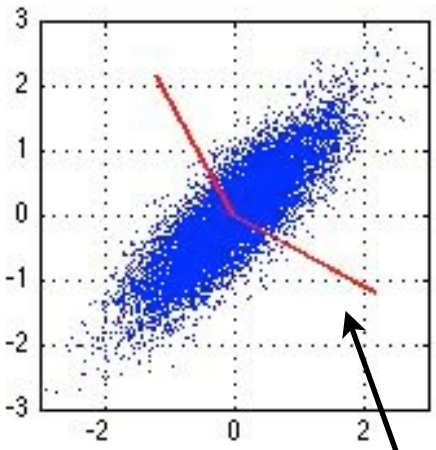
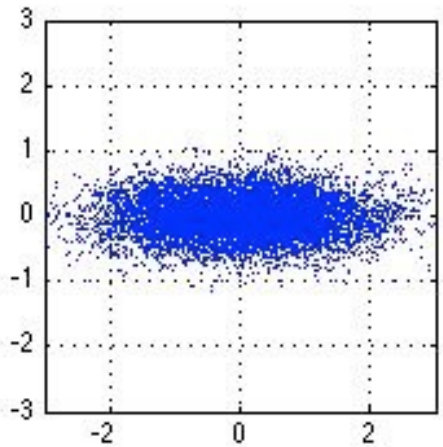




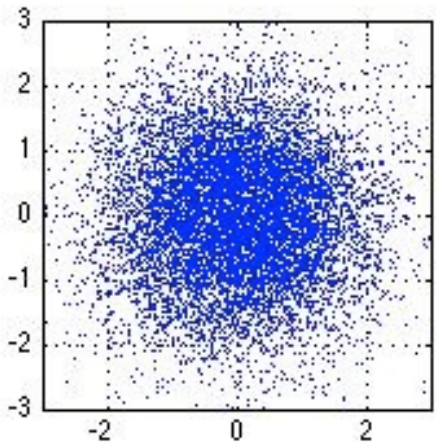
Whitening



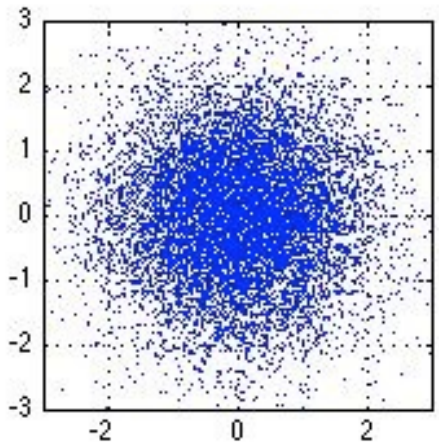
$\mathbf{X}$



$\mathbf{E}^T \mathbf{X}$



$\mathbf{\Lambda}^{-\frac{1}{2}} \mathbf{E}^T \mathbf{X}$



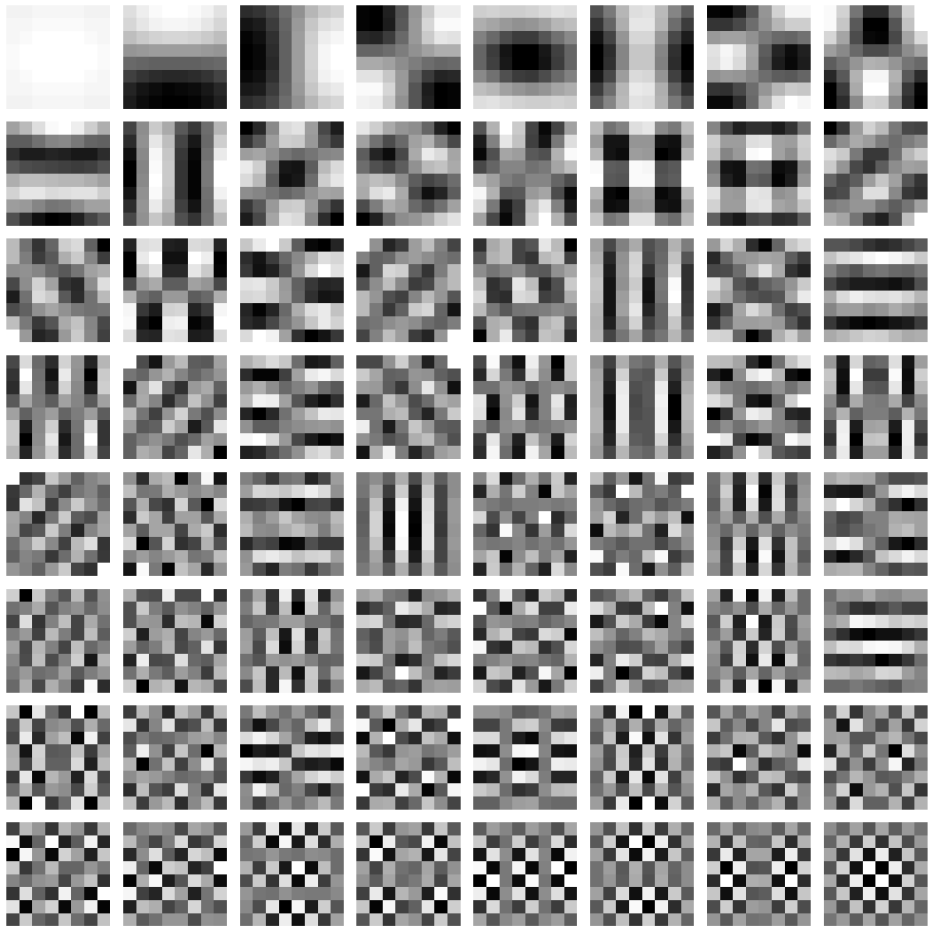
$\mathbf{E} \mathbf{\Lambda}^{-\frac{1}{2}} \mathbf{E}^T \mathbf{X}$

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

$$\mathbf{W} = \mathbf{E} \mathbf{\Lambda}^{-\frac{1}{2}} \mathbf{E}^T$$

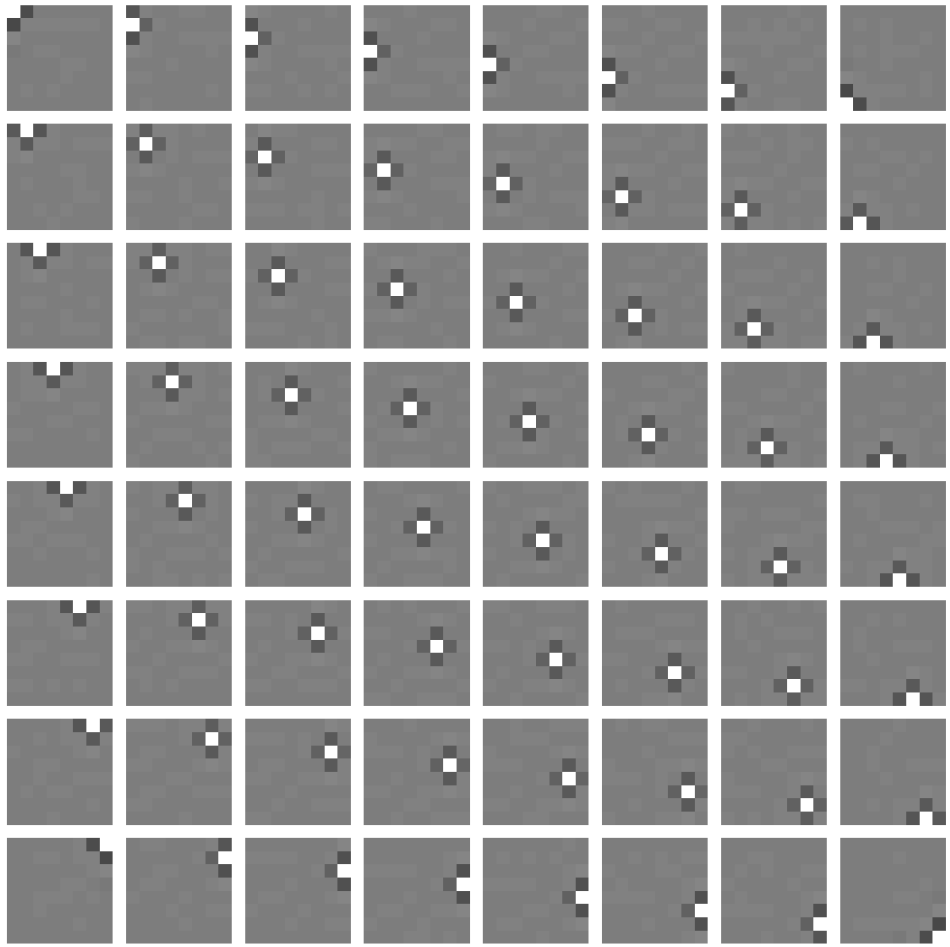
PCA

$$\mathbf{W} = \mathbf{E}^T$$



Whitening

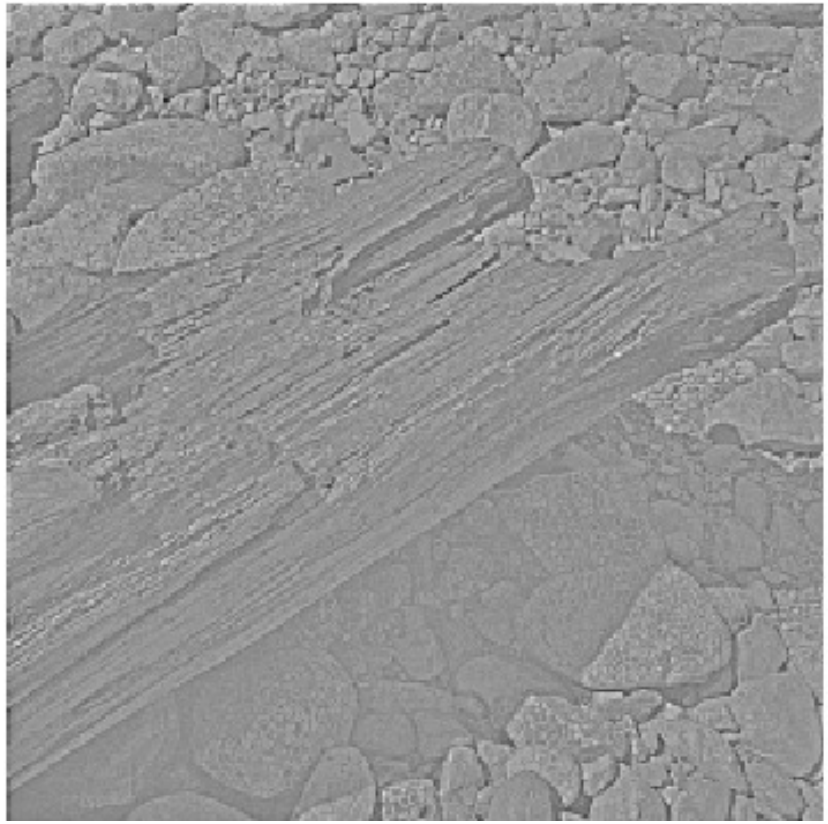
$$\mathbf{W} = \mathbf{E}\mathbf{\Lambda}^{-\frac{1}{2}}\mathbf{E}^T$$



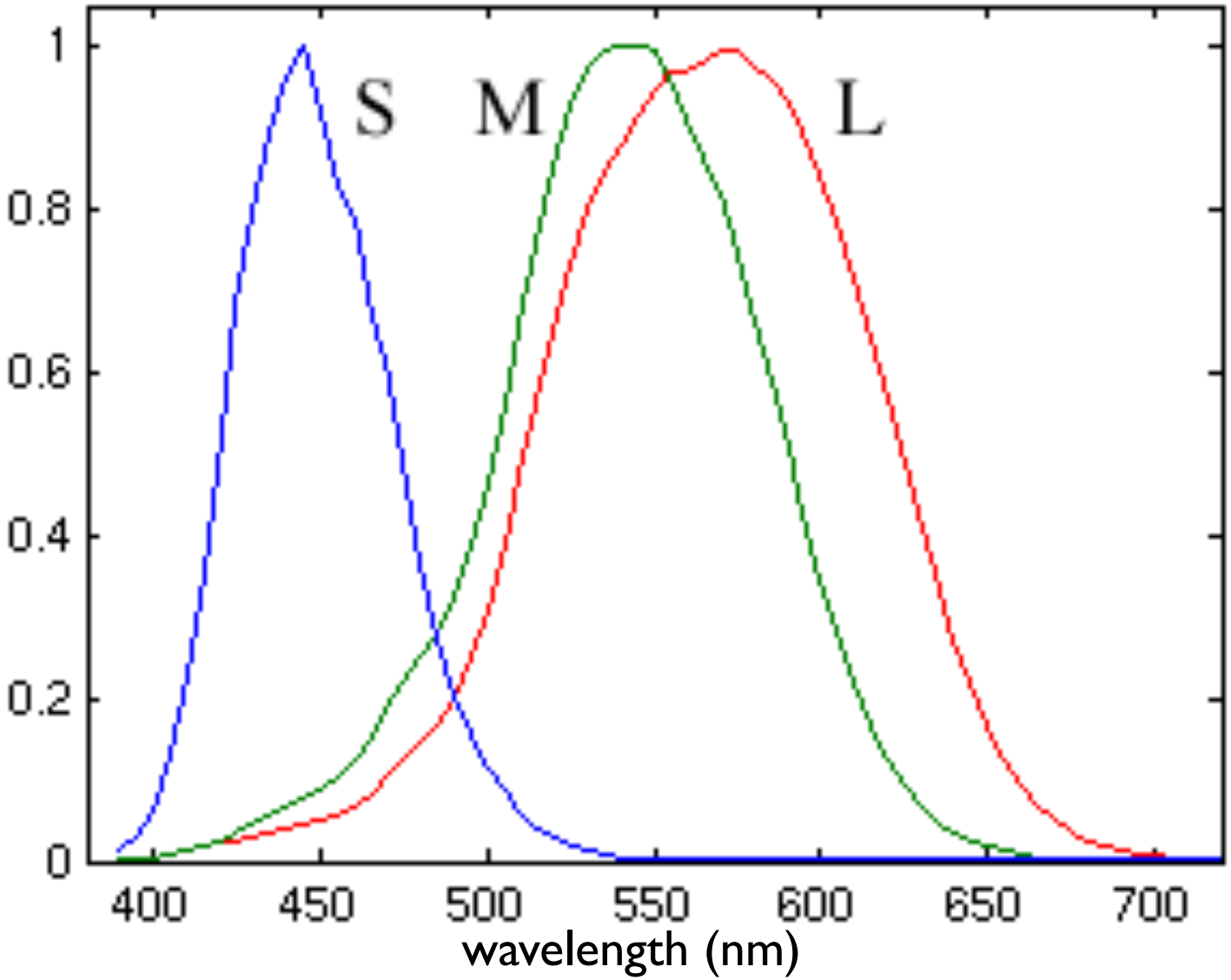
Whitening

before

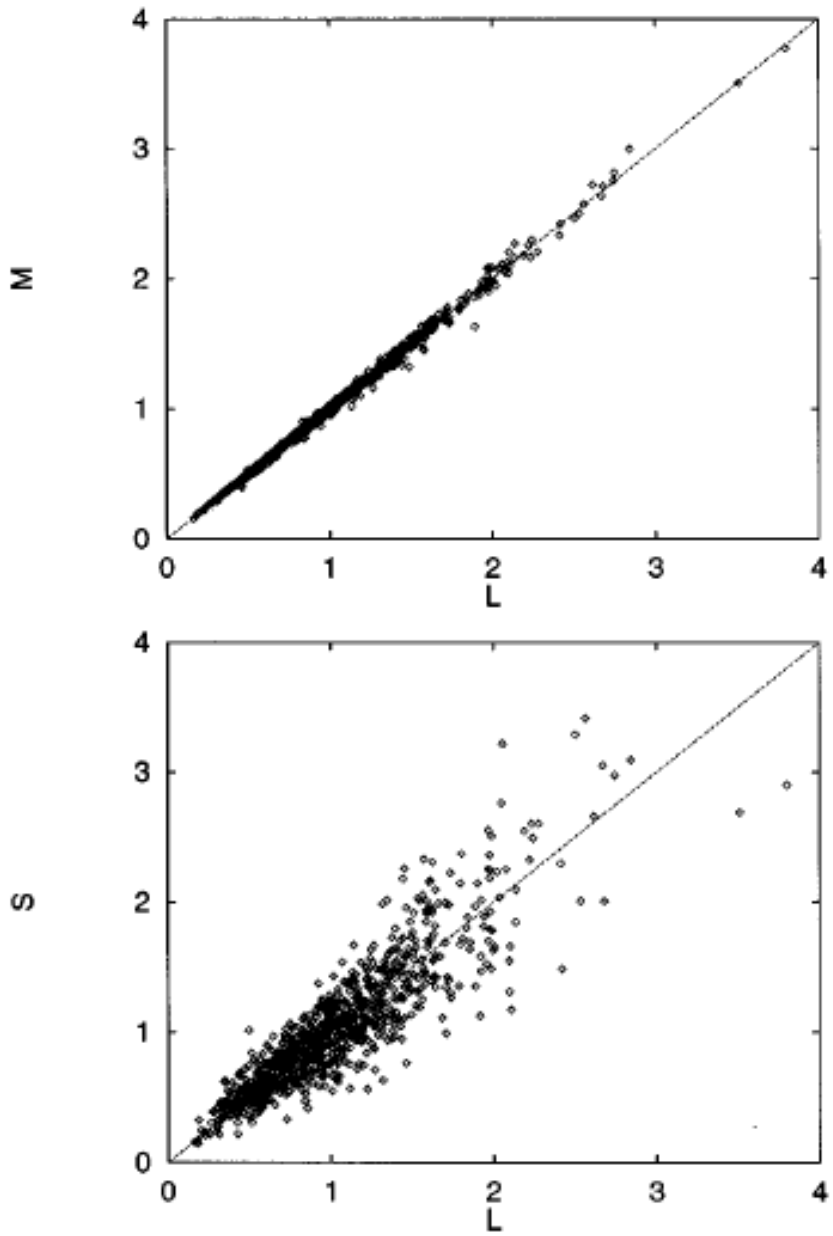
after



Human - cone spectral sensitivities



Joint statistics of cone responses
(Ruderman et al. 1998)



PCA of cone responses
(Ruderman et al. 1998)

$$\hat{l} = \frac{1}{\sqrt{3}}(\hat{\mathcal{L}} + \hat{\mathcal{M}} + \hat{\mathcal{S}}),$$

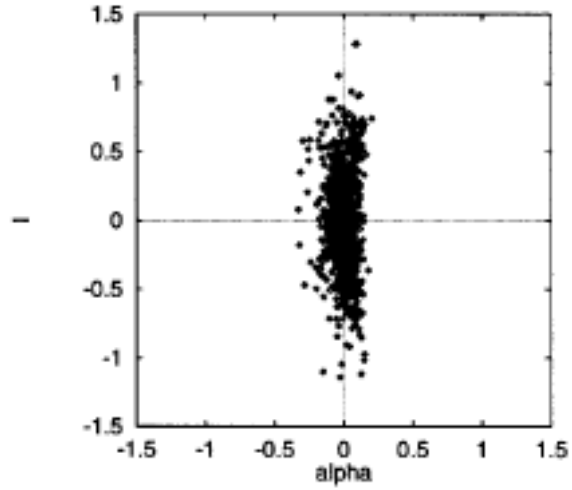
$$\hat{\alpha} = \frac{1}{\sqrt{6}}(\hat{\mathcal{L}} + \hat{\mathcal{M}} - 2\hat{\mathcal{S}}),$$

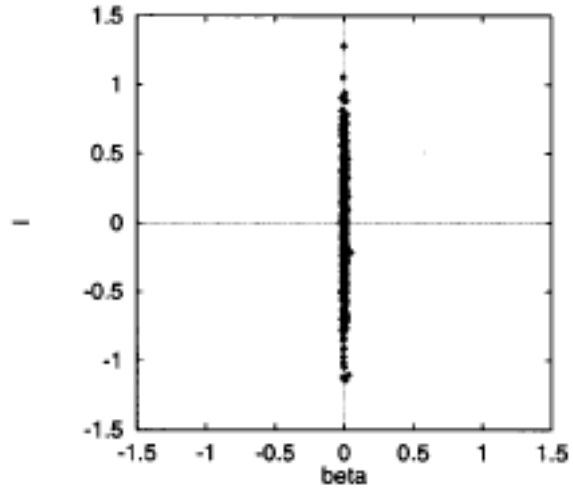
$$\hat{\beta} = \frac{1}{\sqrt{2}}(\hat{\mathcal{L}} - \hat{\mathcal{M}}),$$

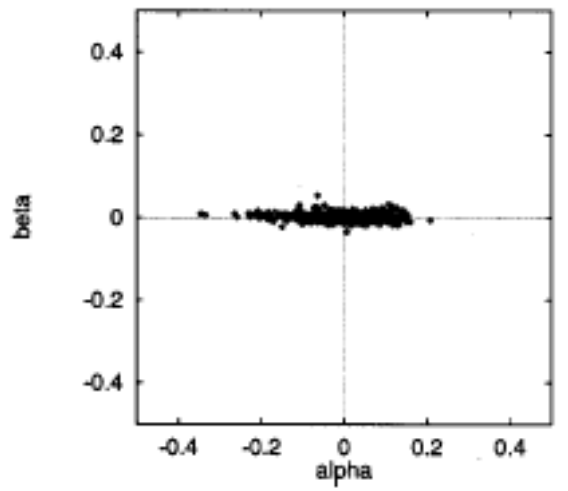
where $\mathcal{L} = \log L - \langle \log L \rangle,$

$\mathcal{M} = \log M - \langle \log M \rangle,$

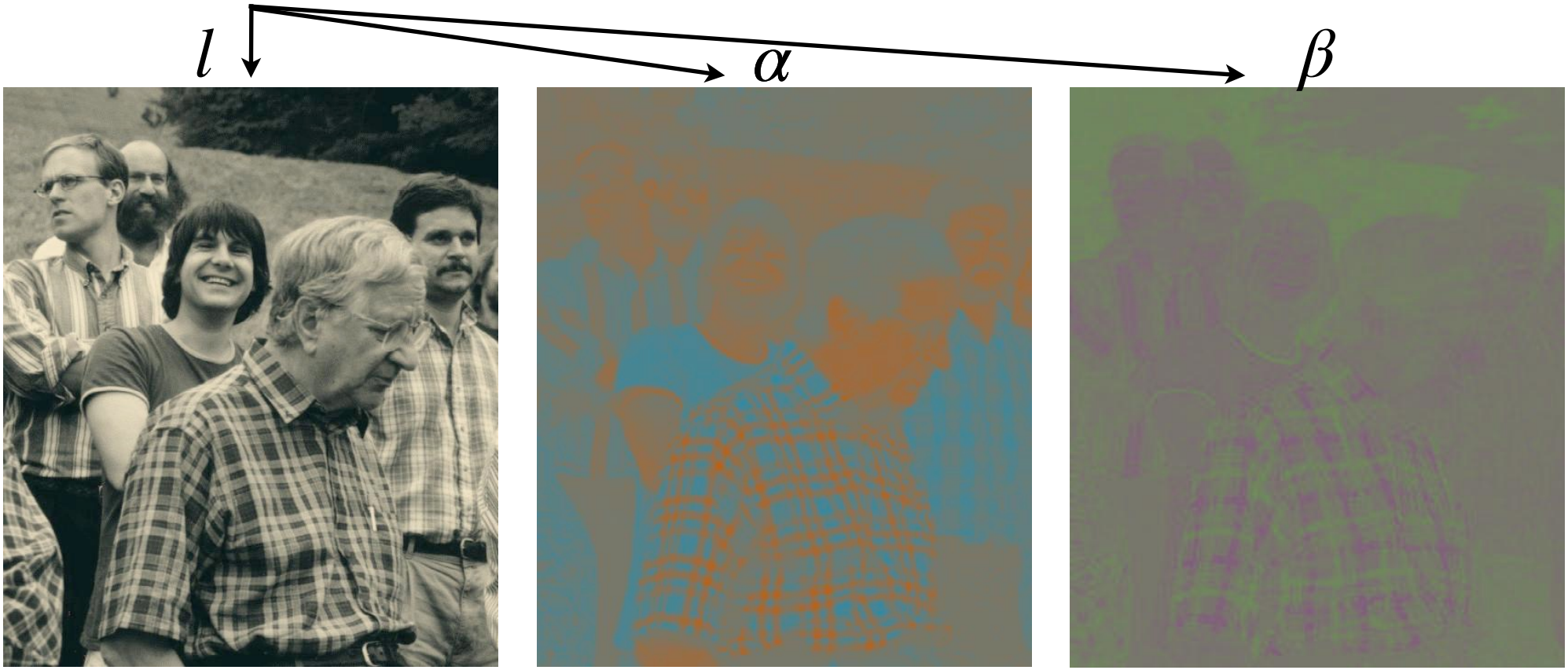
$\mathcal{S} = \log S - \langle \log S \rangle.$



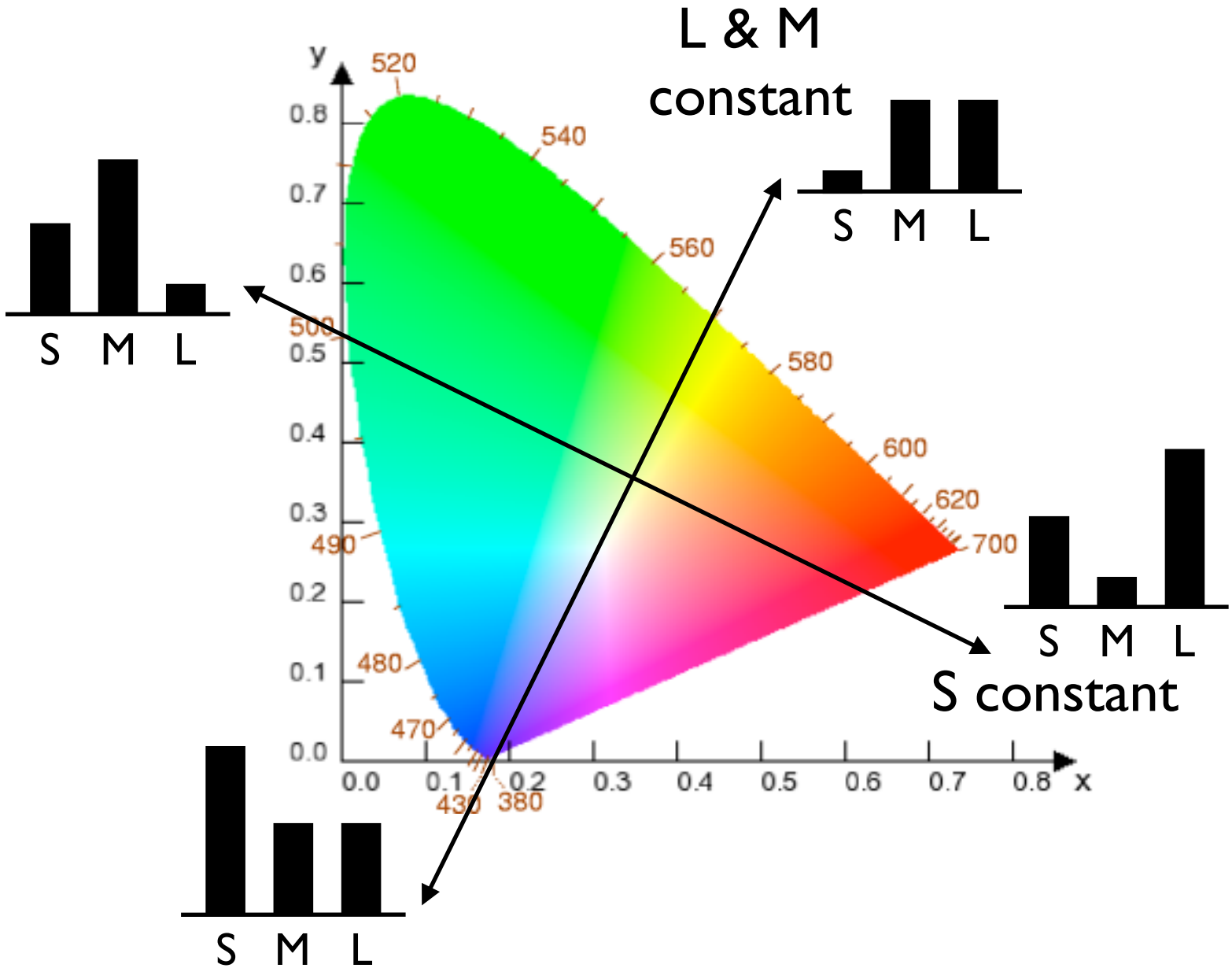




Decomposition into luminance and color-opponent channels

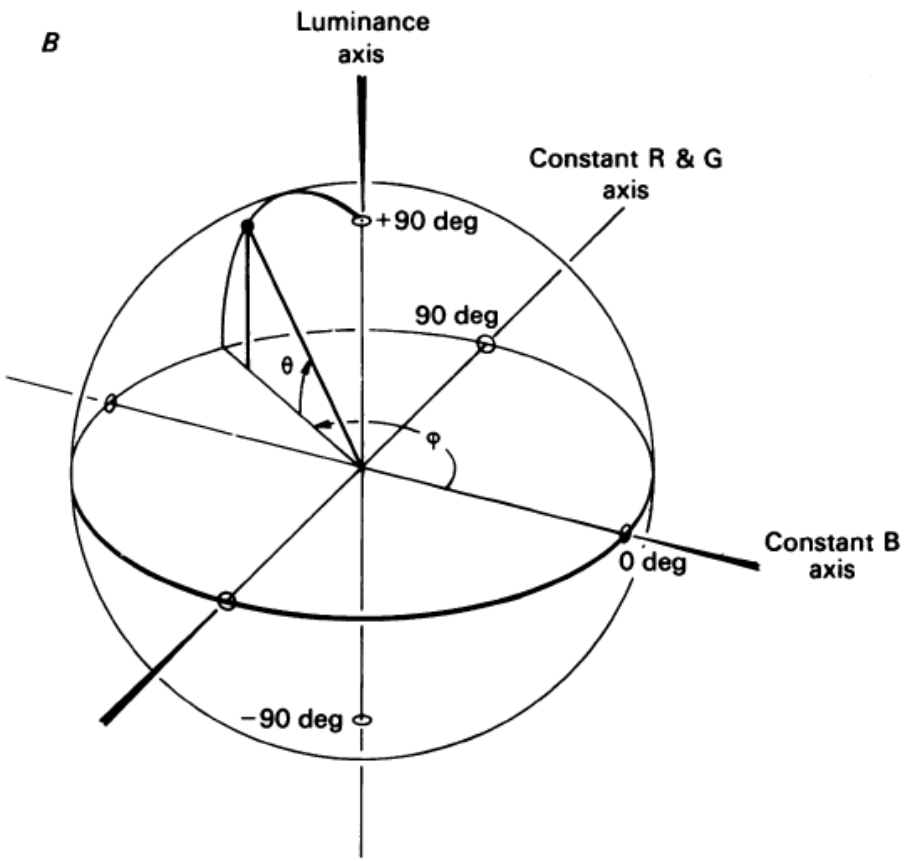


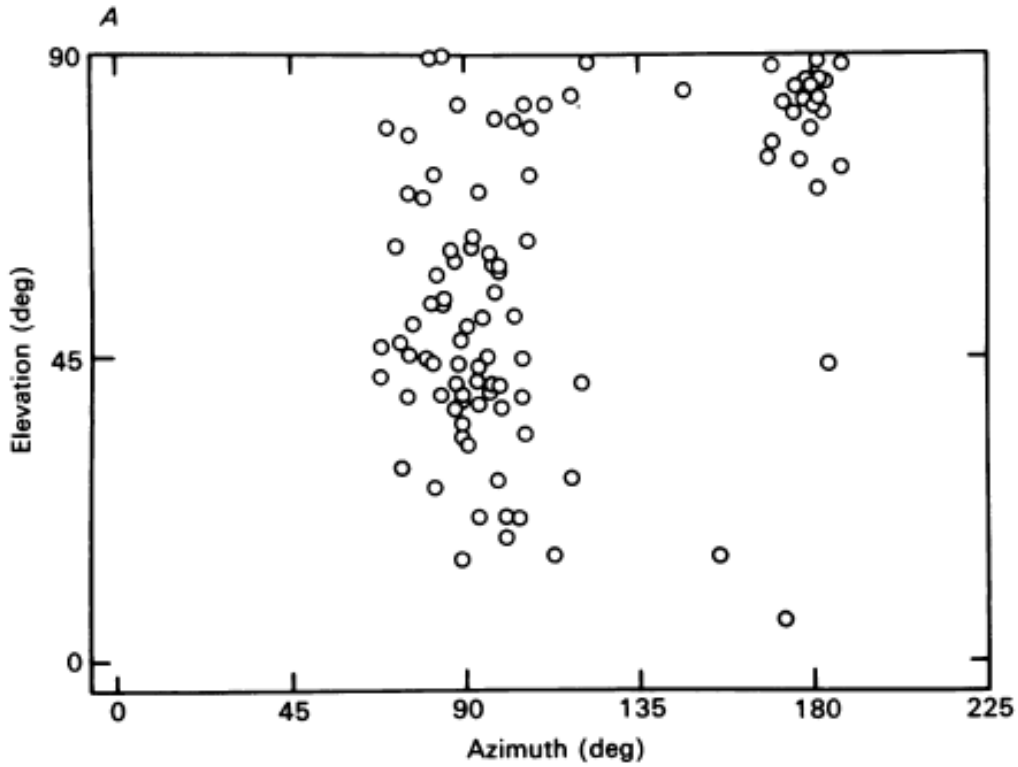
Color oppenency

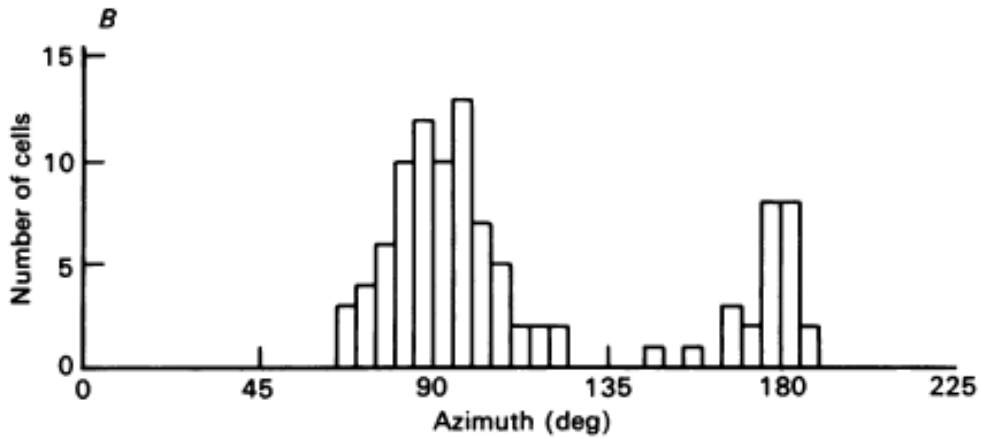


Color opponency in LGN

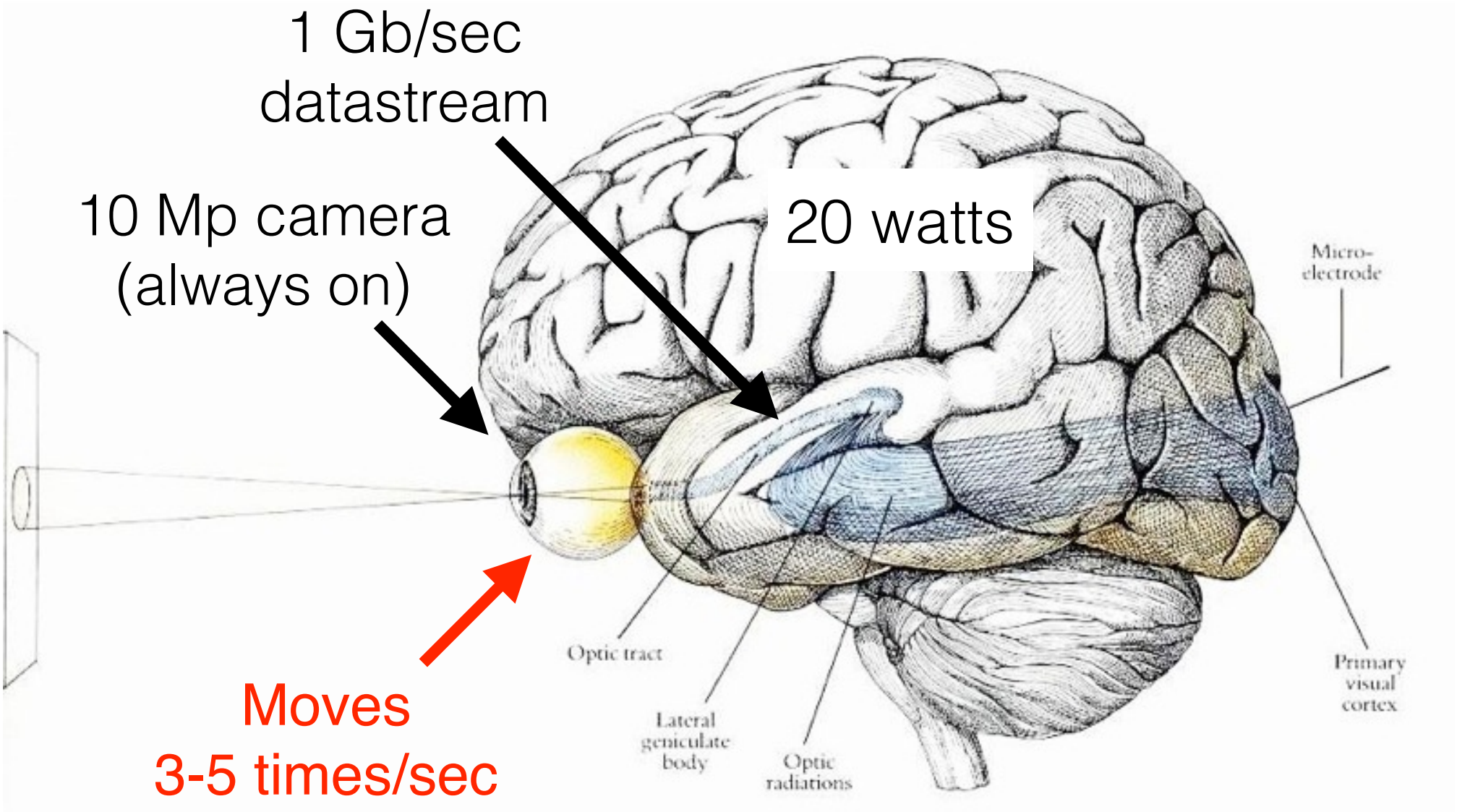
(Derrington, Krauskopf & Lennie, 1984)



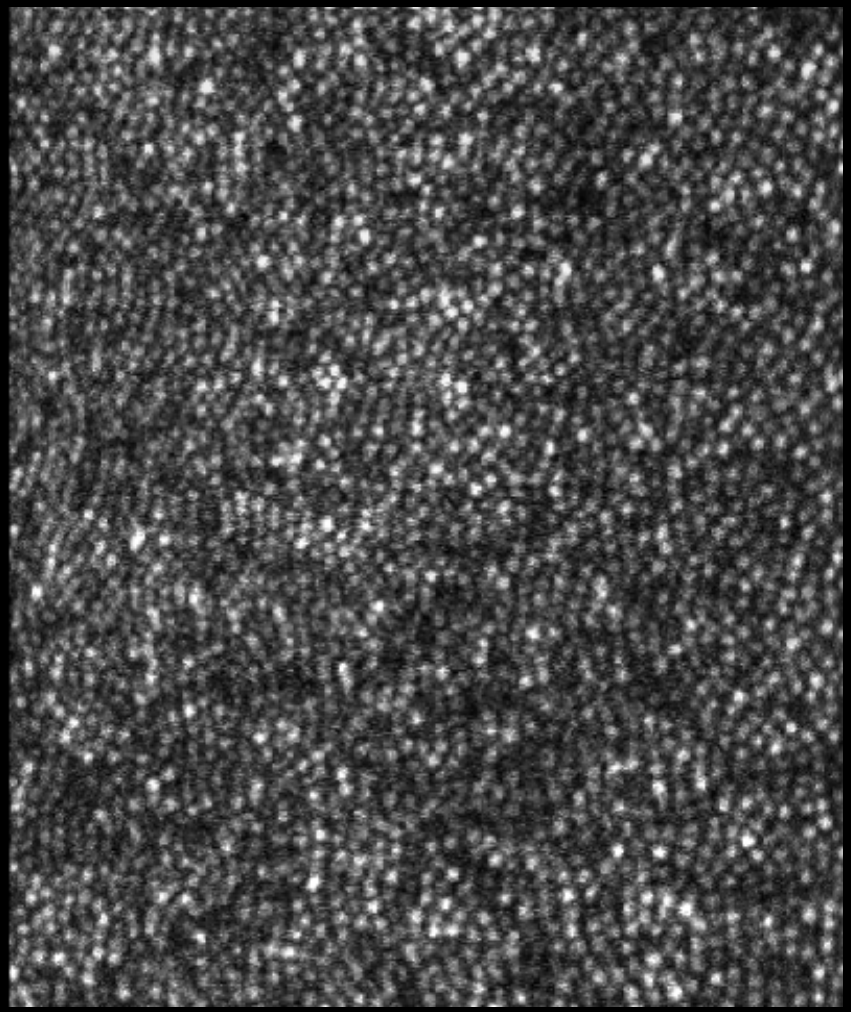




3. How to form a stable color percept from unstable images?

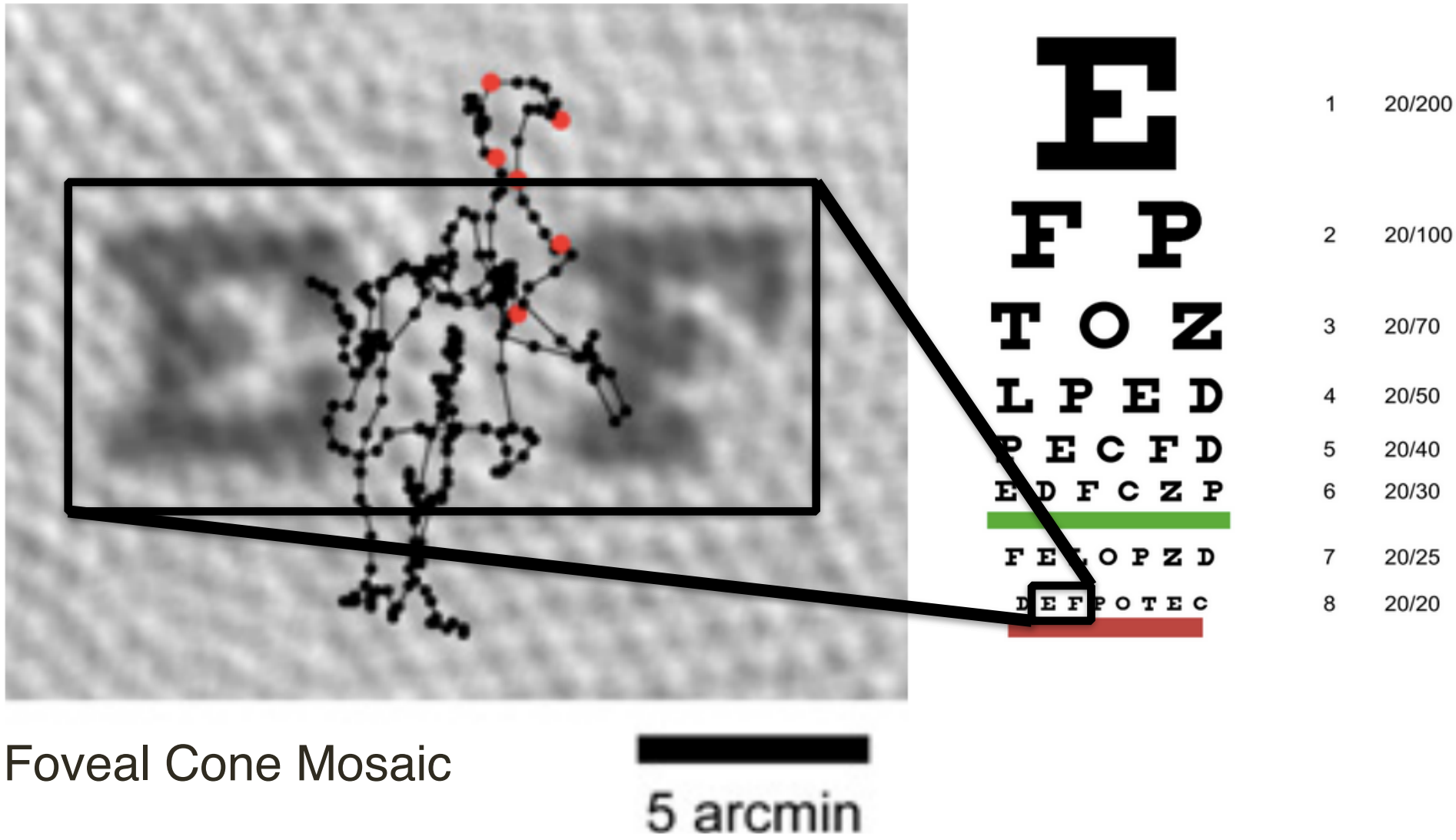

1 Gb/sec
datastream
10 Mp camera
(always on)
20 watts
Micro-
electrode
Optic tract
Lateral
geniculate
body
Optic
radiations
Primary
visual
cortex
Moves
3-5 times/sec

Fixational eye movements (drift)



(from Austin Roorda, UC Berkeley)

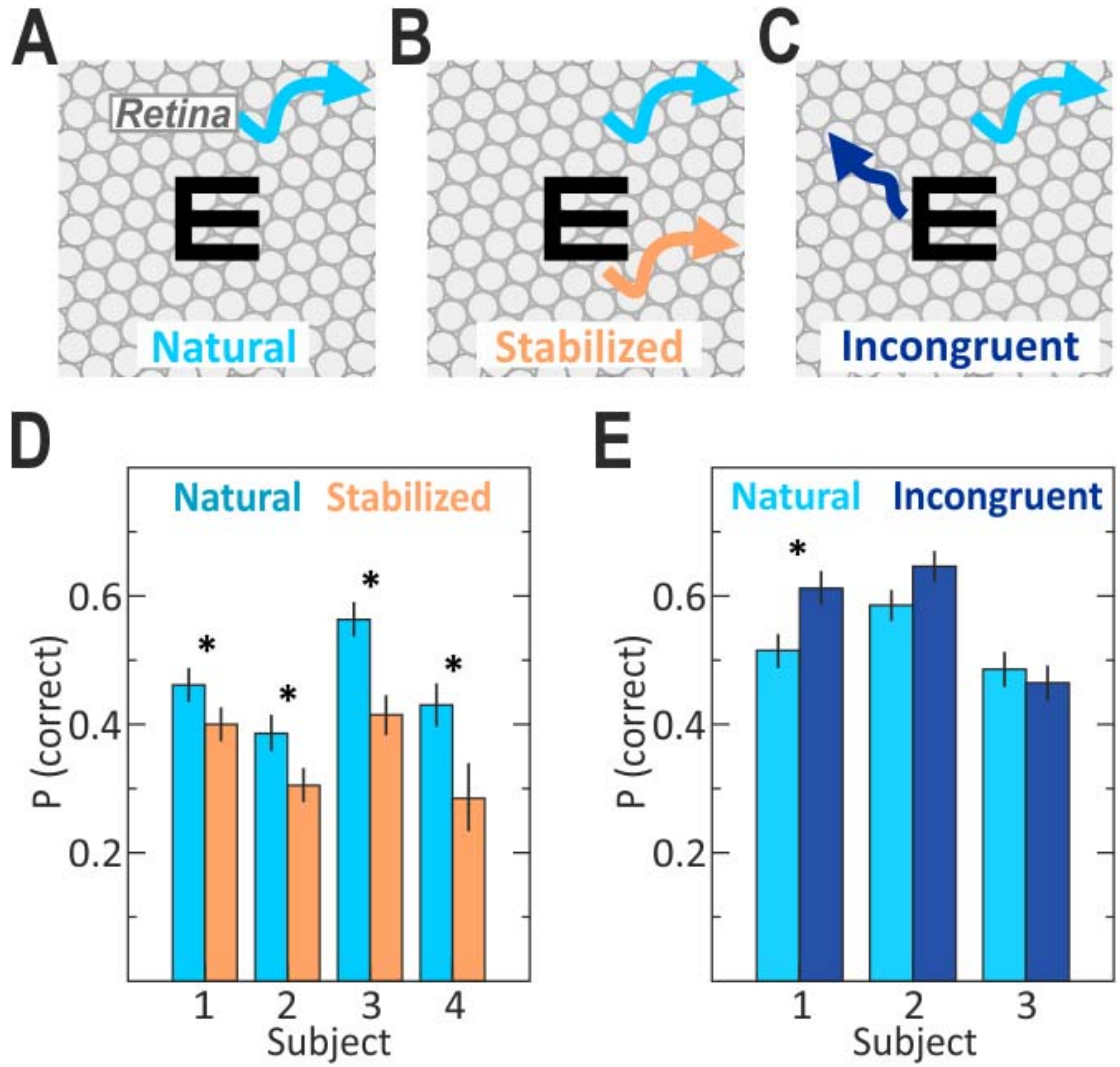
Retinal image drift is large relative to cone spacing



Foveal Cone Mosaic

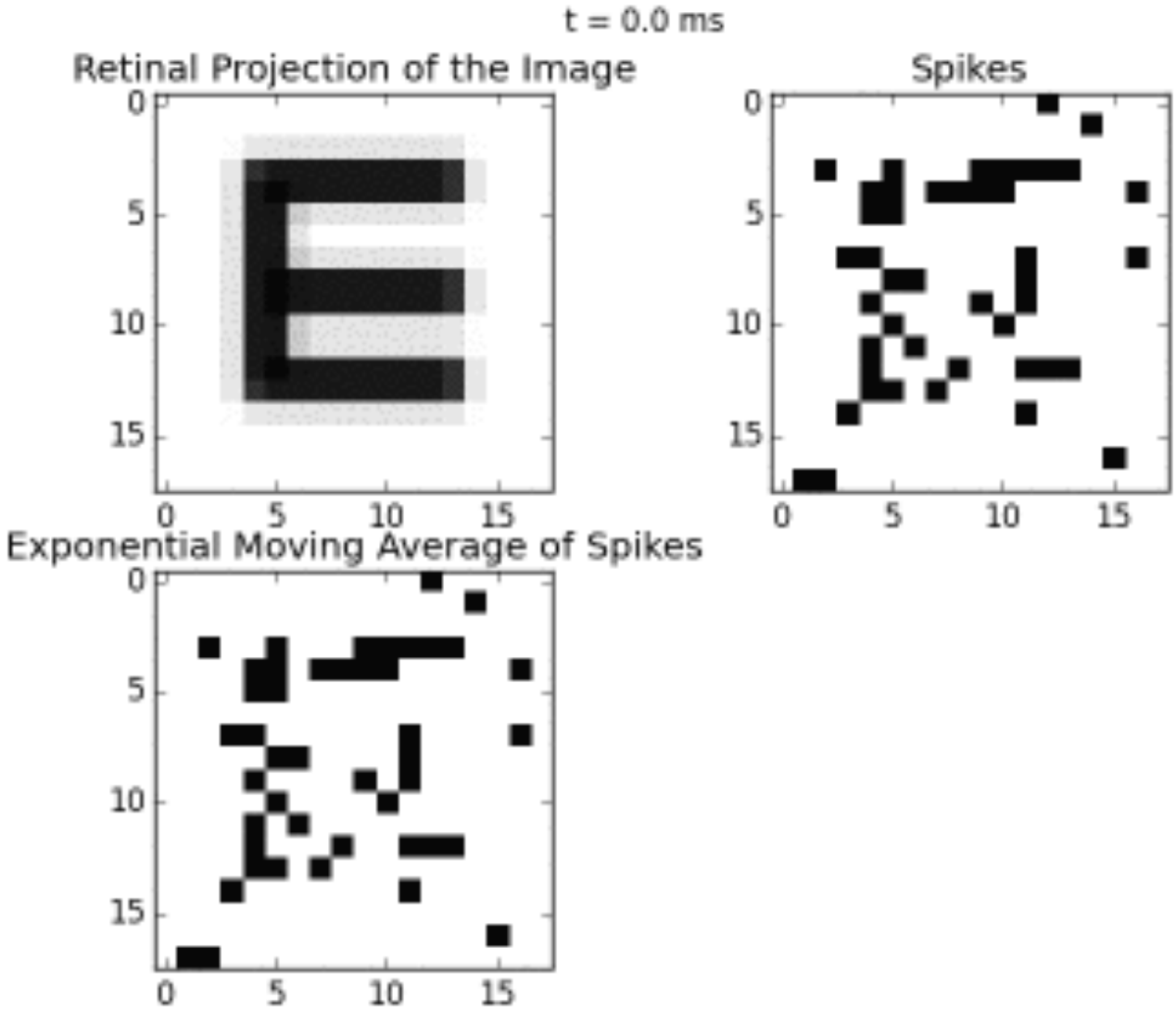
(from Burak et al., 2010)

Retinal image motion helps pattern discrimination



Ratnam, K., Domdei, N., Harmening, W. M., & Roorda, A. (2017). Benefits of retinal image motion at the limits of spatial vision. *Journal of Vision, 17*, 1–11.

Simple averaging is not sufficient



The problem

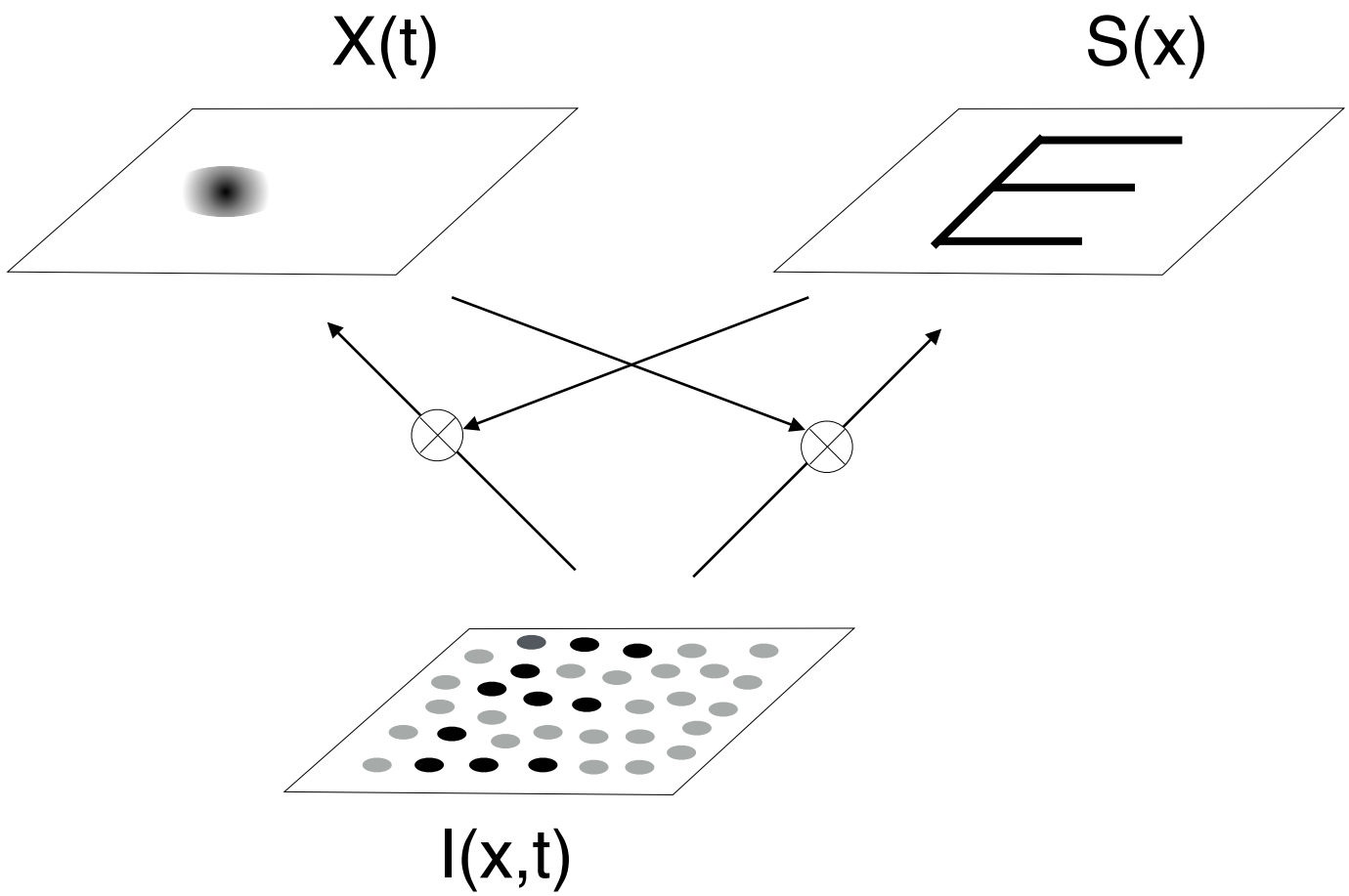
$$I(\vec{x}, t) = S(\vec{x} - \Delta\vec{x}(t)) + \epsilon(\vec{x}, t)$$

$$\hat{\Delta\vec{x}}(t) = \arg\min_{\Delta\vec{x}(t)} |I(\vec{x}, t) - S(\vec{x} - \Delta\vec{x}(t))|^2$$

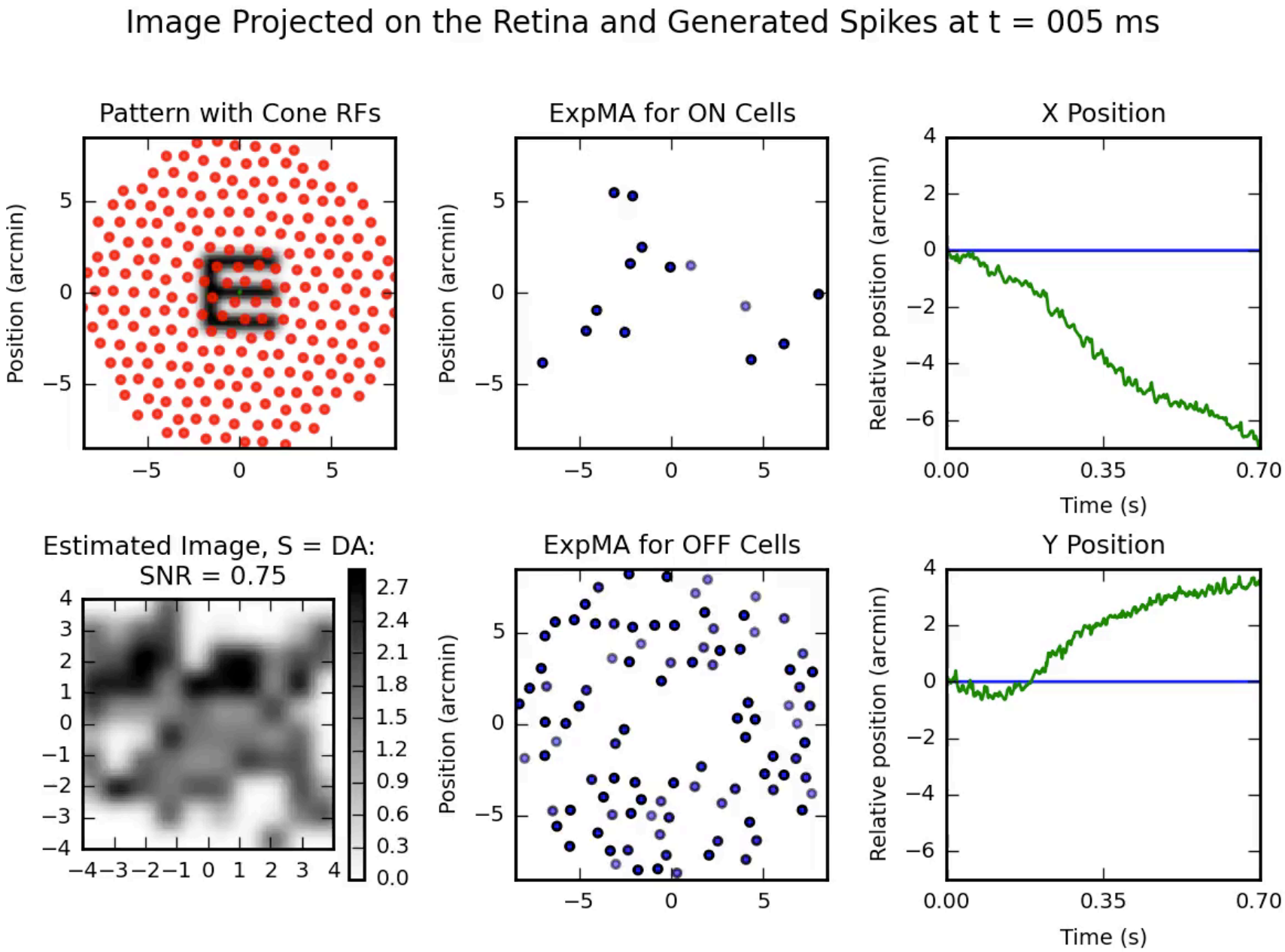
$$\hat{S}(\vec{x}) = \int I(\vec{x} + \Delta\vec{x}(t))\, dt$$

Joint estimation of pattern (S) and position (X) from retinal spike trains (R)

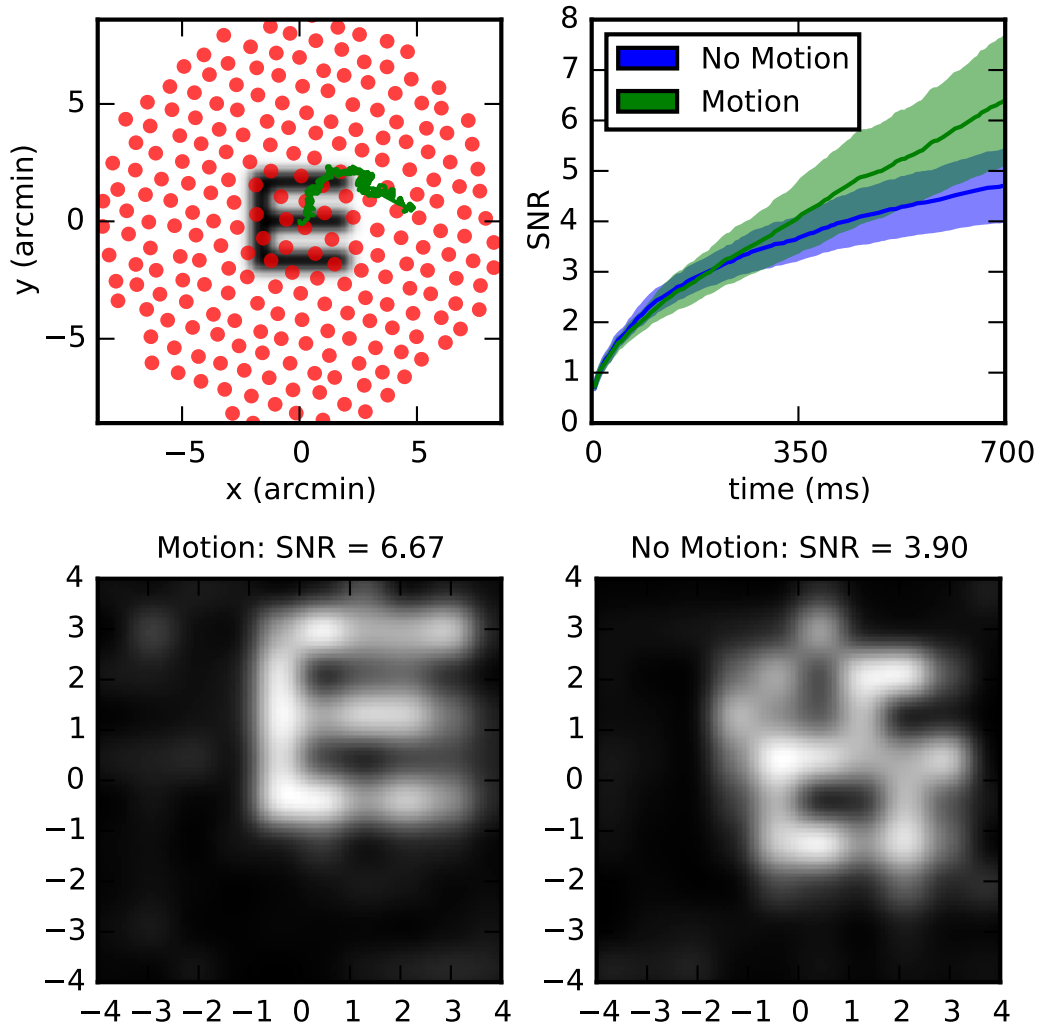
(Anderson, Ratnam, Roorda & Olshausen, 2020)



Joint estimation of pattern (S) and position (X)

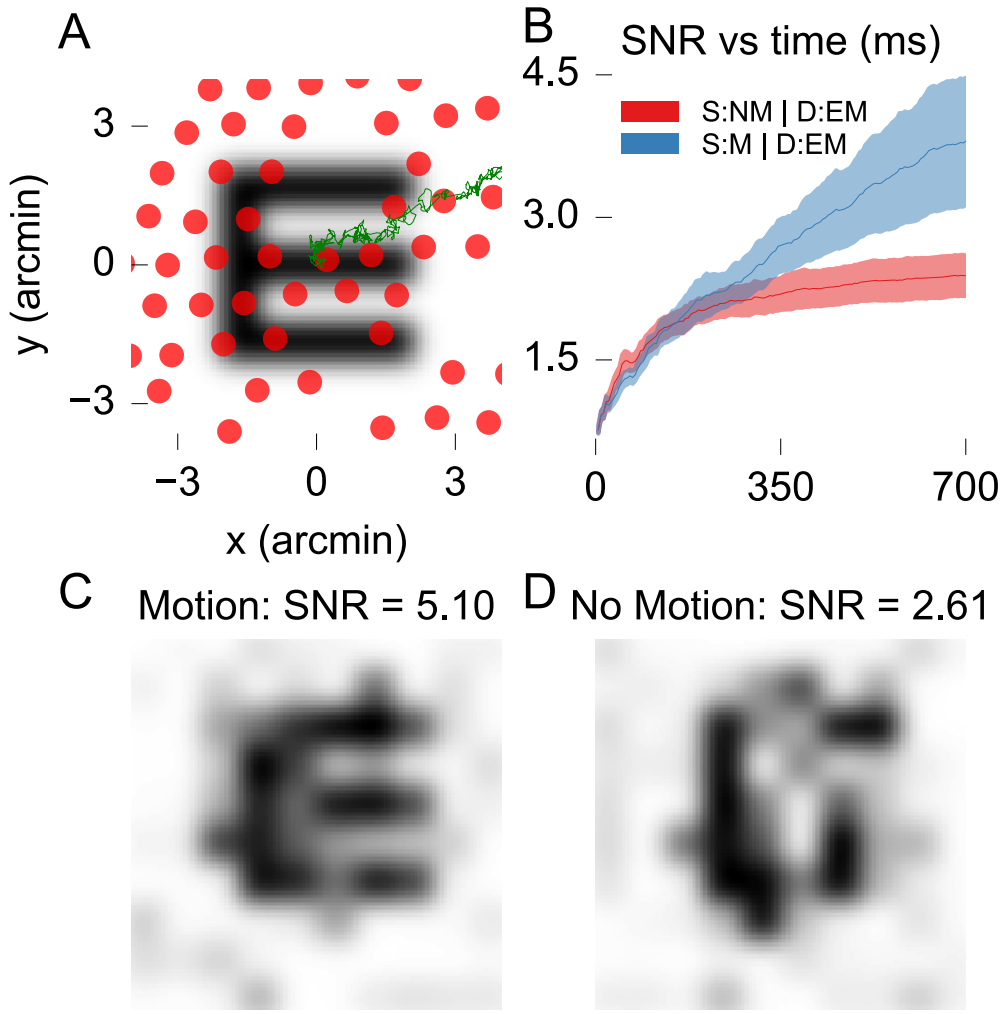


Motion helps estimation of pattern *S*

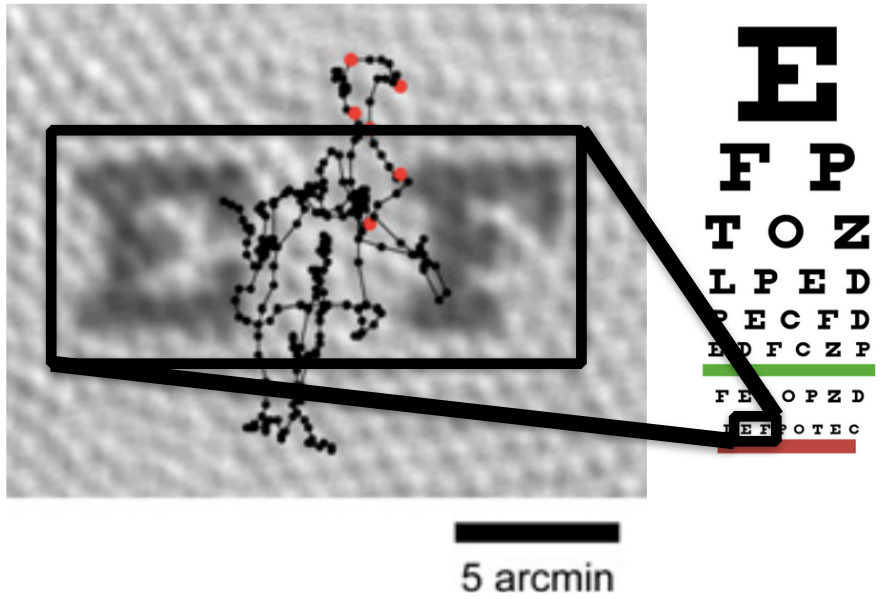


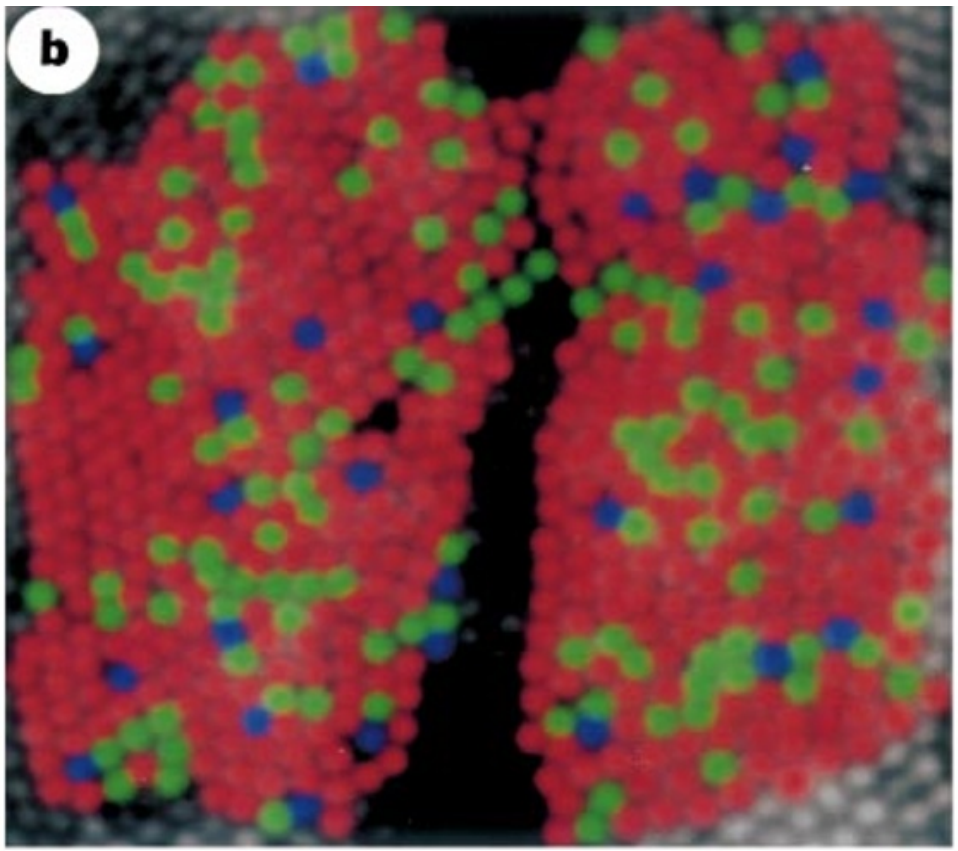
...especially under conditions of cone loss.

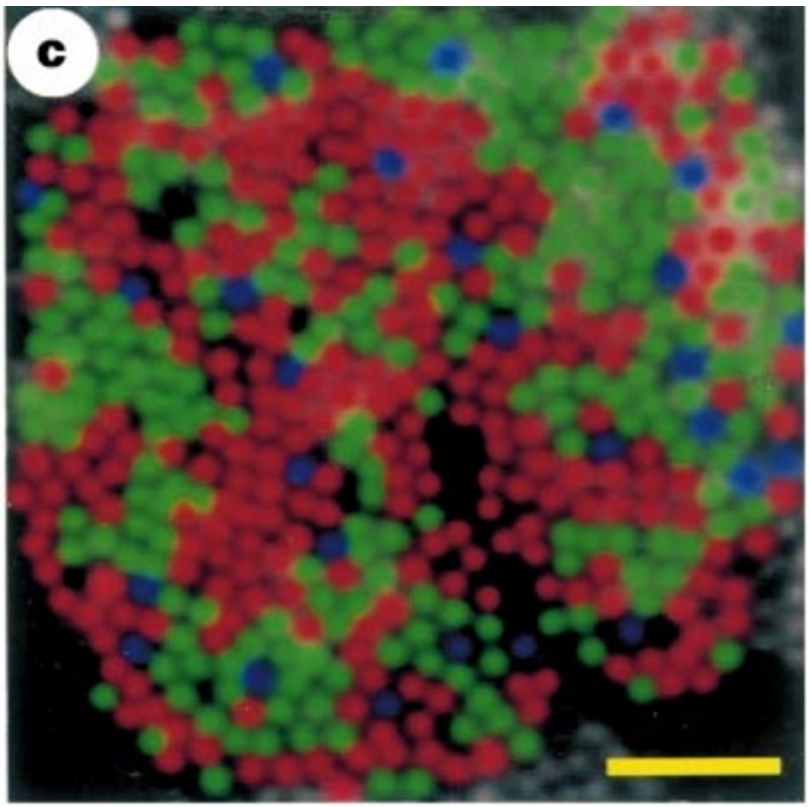
simulated
30% dropout



How to extend this to color?

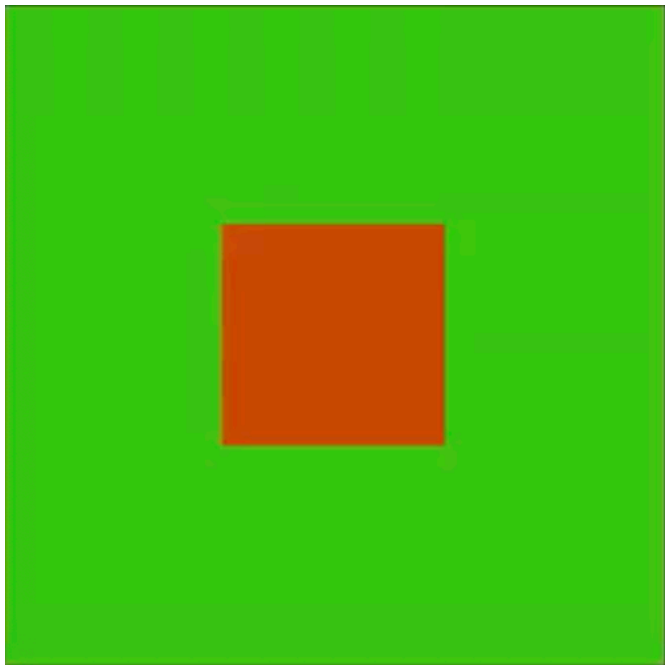




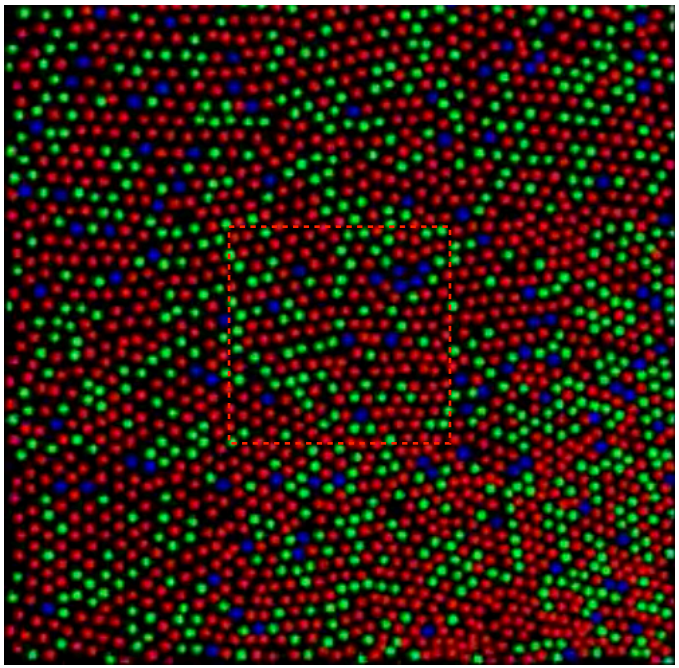


How do we perceive regular shape and uniform color from *irregular* and *non-uniform* sensory stimulation?

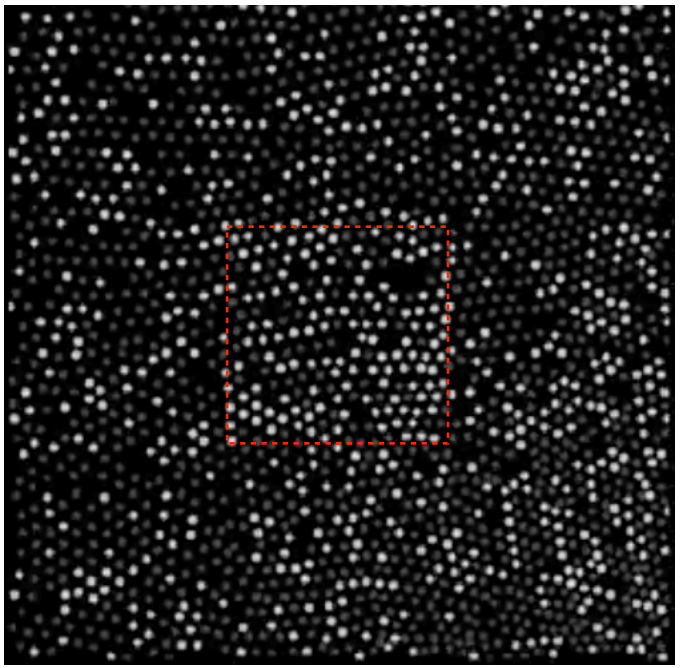
Stimulus

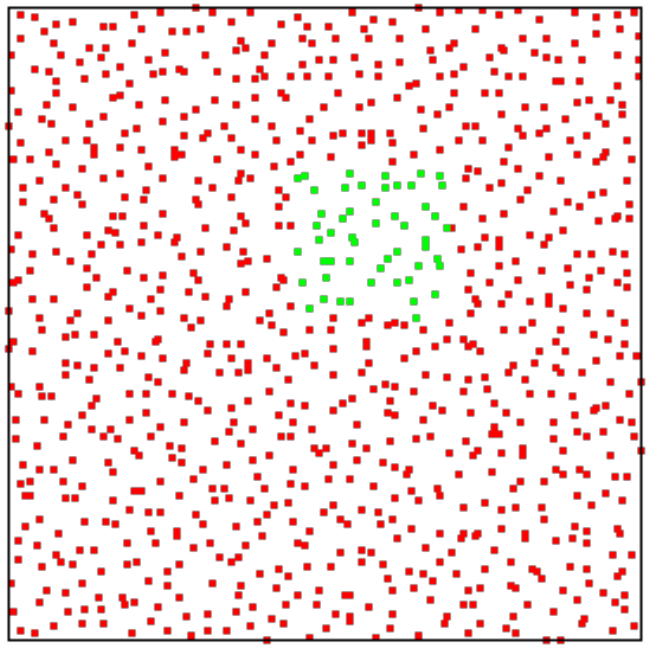


Retinal Mosaic



Cone Excitations

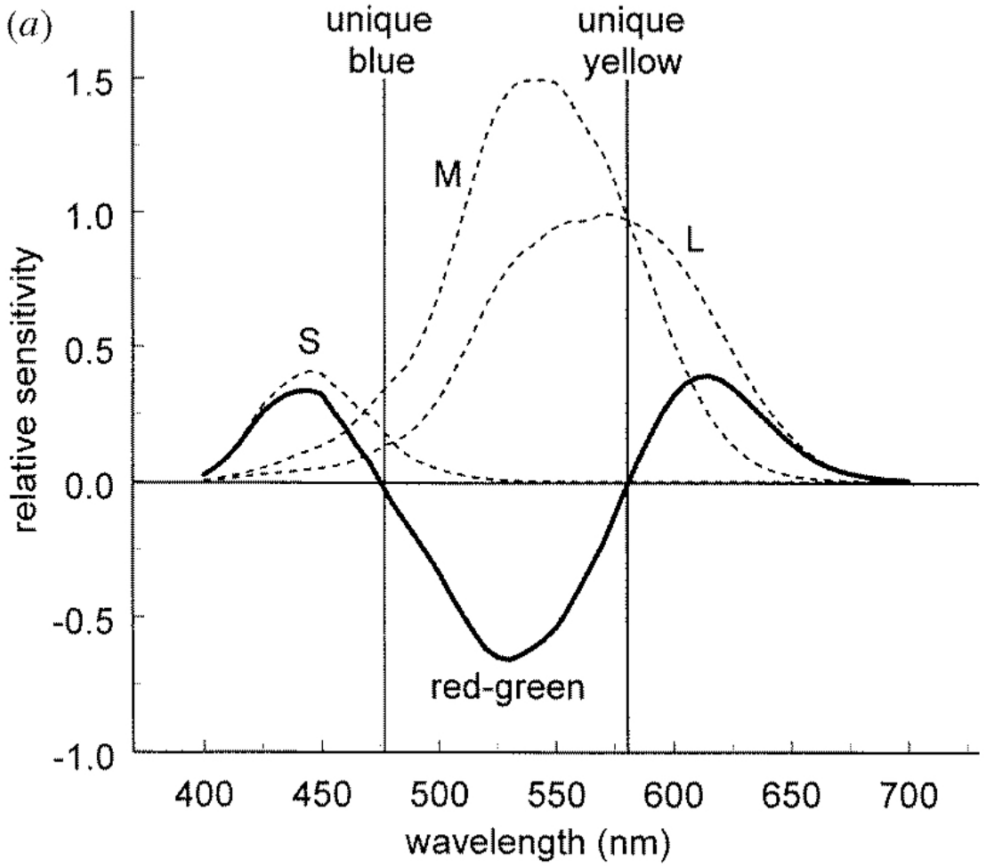


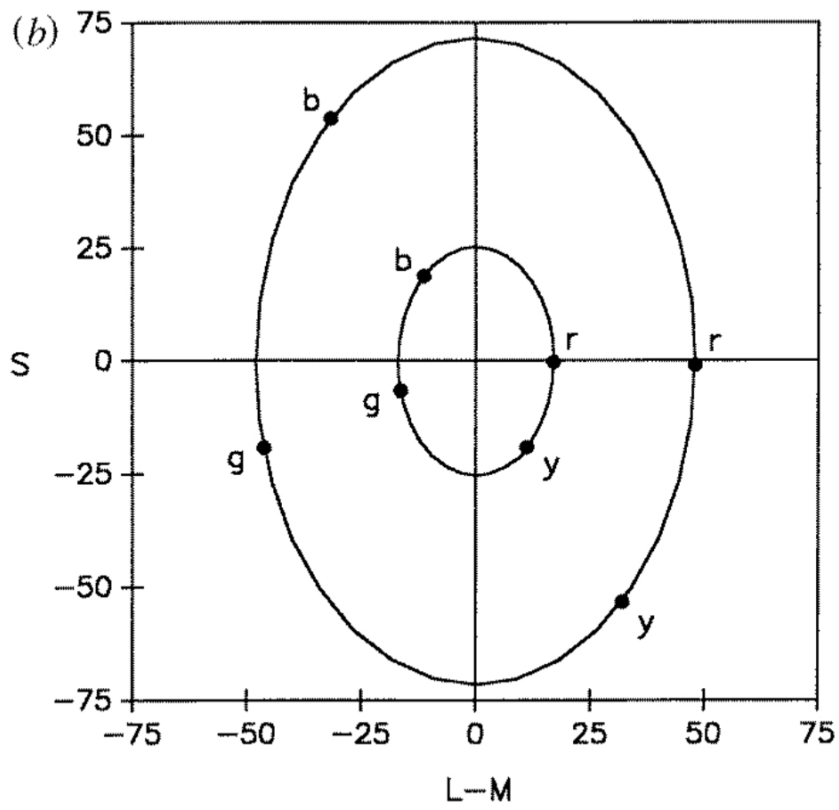


(From Hoffman, *Visual Intelligence*, 1998)

4. How are color categories learned? How and where are they represented in brain?

Unique hues do not align with color-opponent axes





(from Webster 1996)

Visual Neuroscience (2006), **23**, 331–339. Printed in the USA.

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Color naming, unique hues, and hue cancellation predicted from singularities in reflection properties

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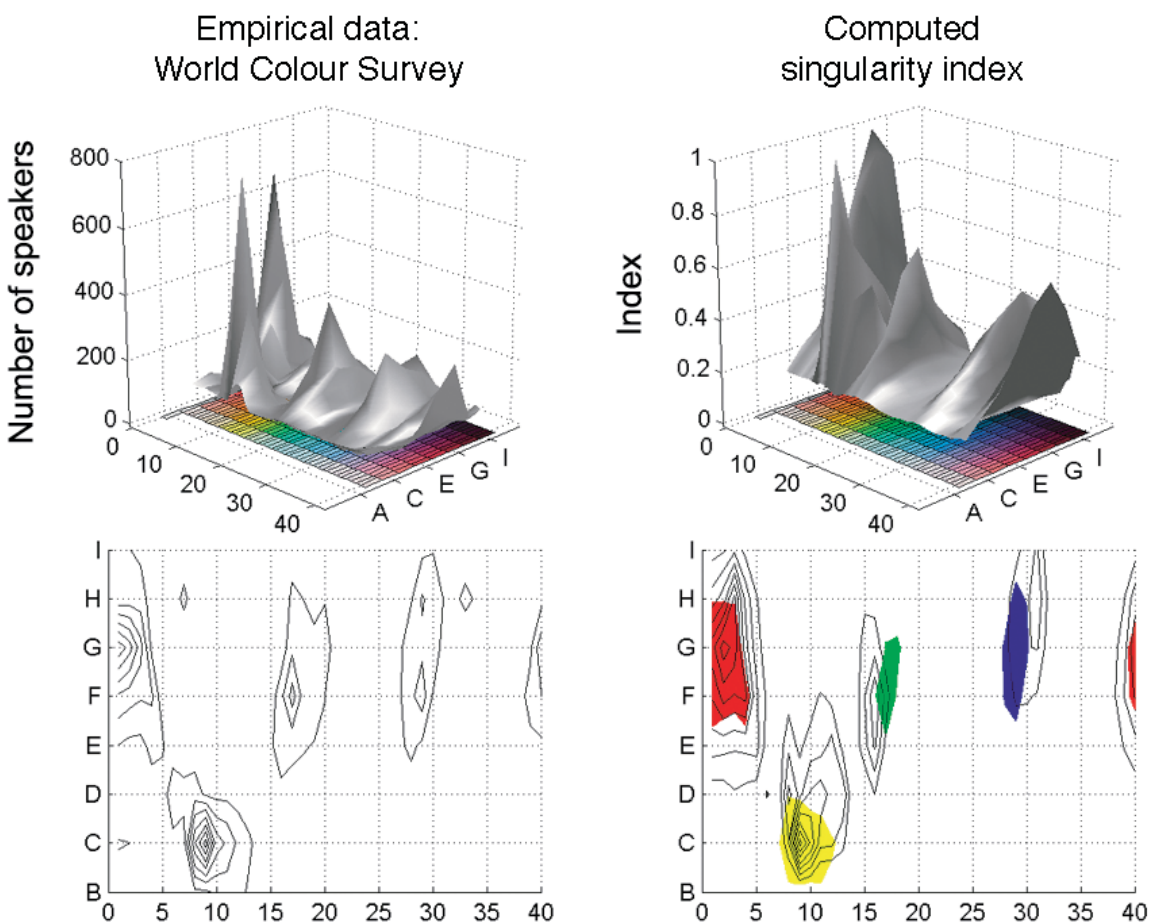
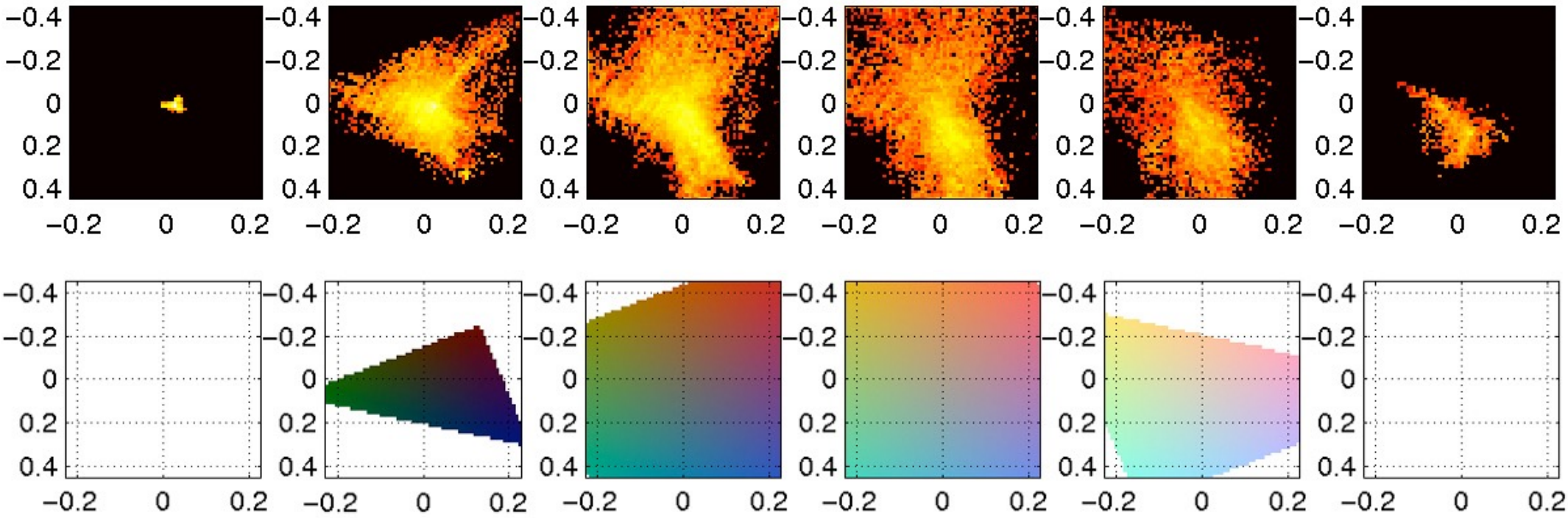
(RECEIVED August 1, 2005; ACCEPTED December 29, 2005)



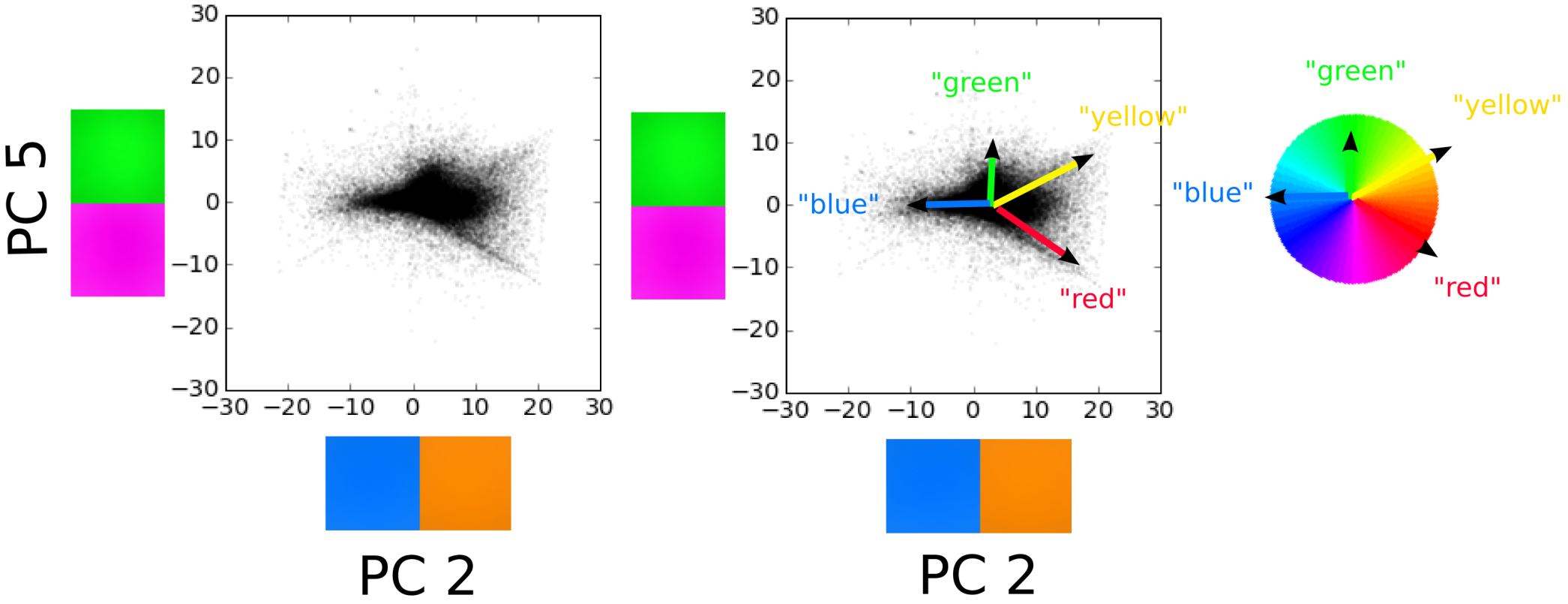
Joint statistics of color are non-Gaussian

probability distribution



colorspace

Sparse coding recovers unique hues
(Paxon Frady 2016)



Wild hummingbirds discriminate nonspectral colors

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