Foundations of Color Vision: Retina and Brain

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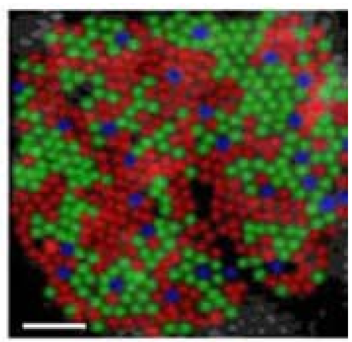
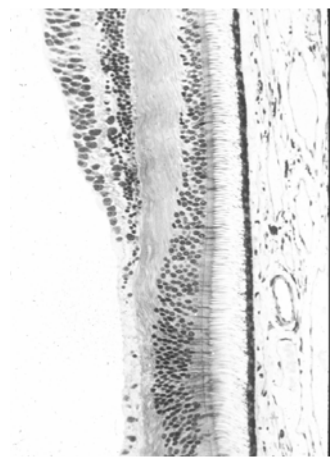
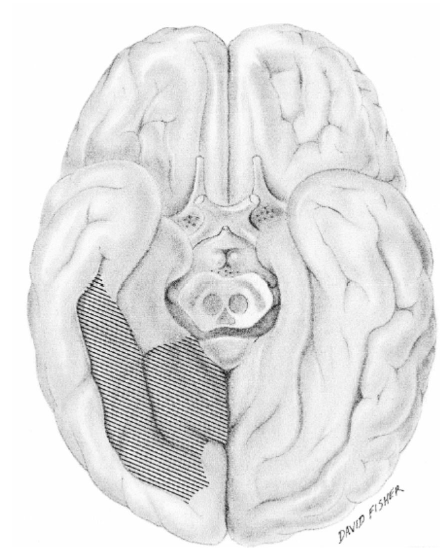
Imageval.com



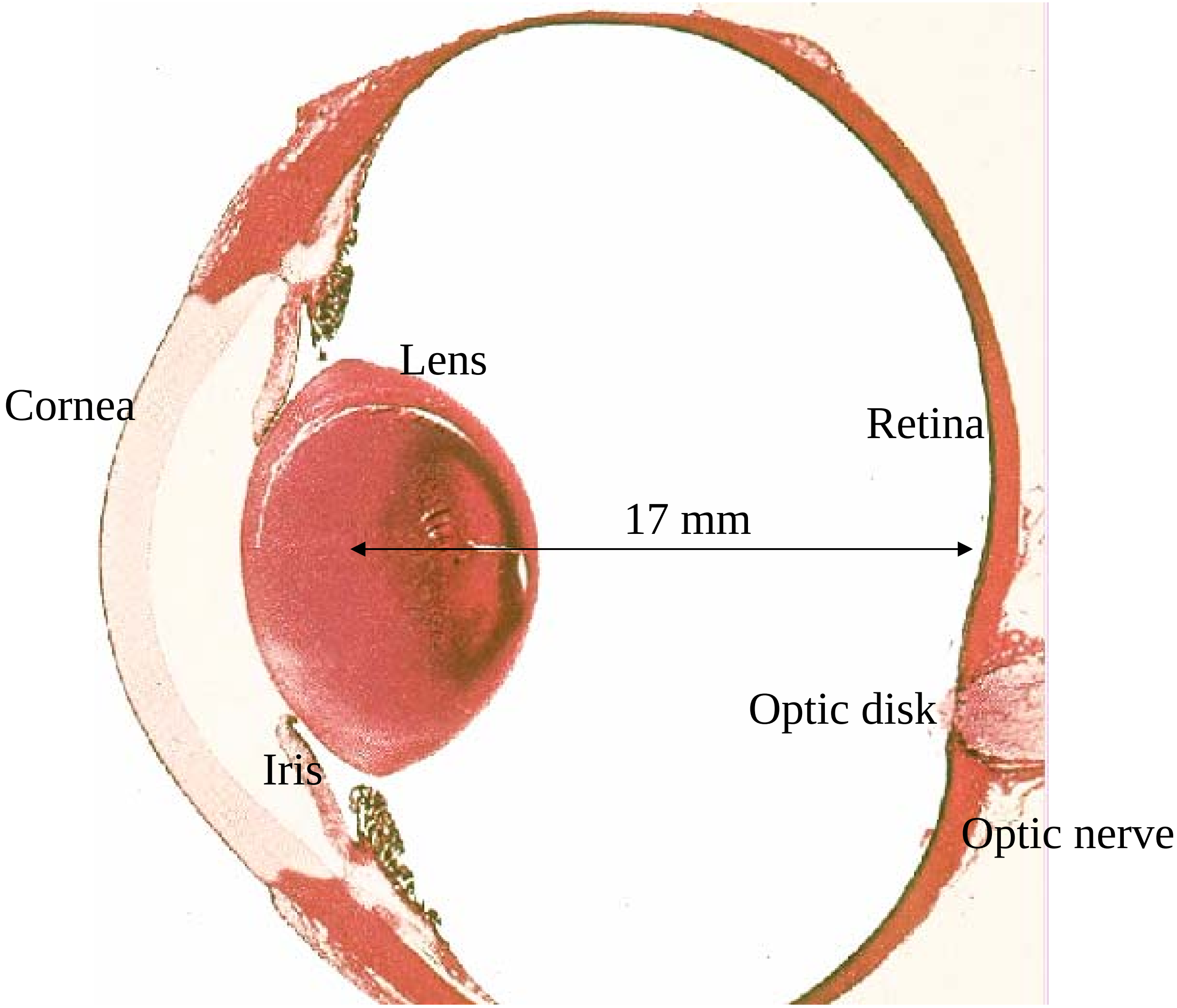




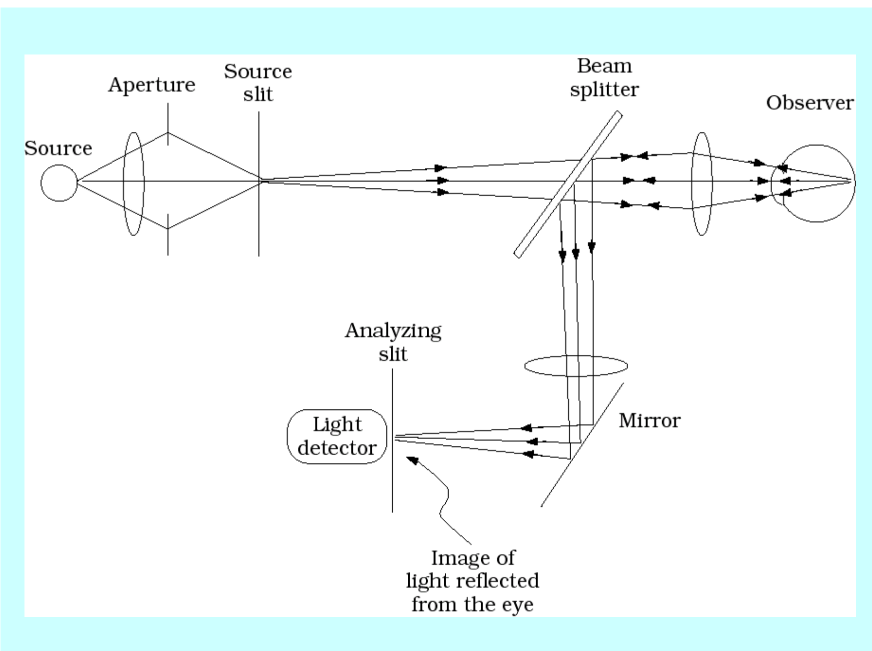
Overview

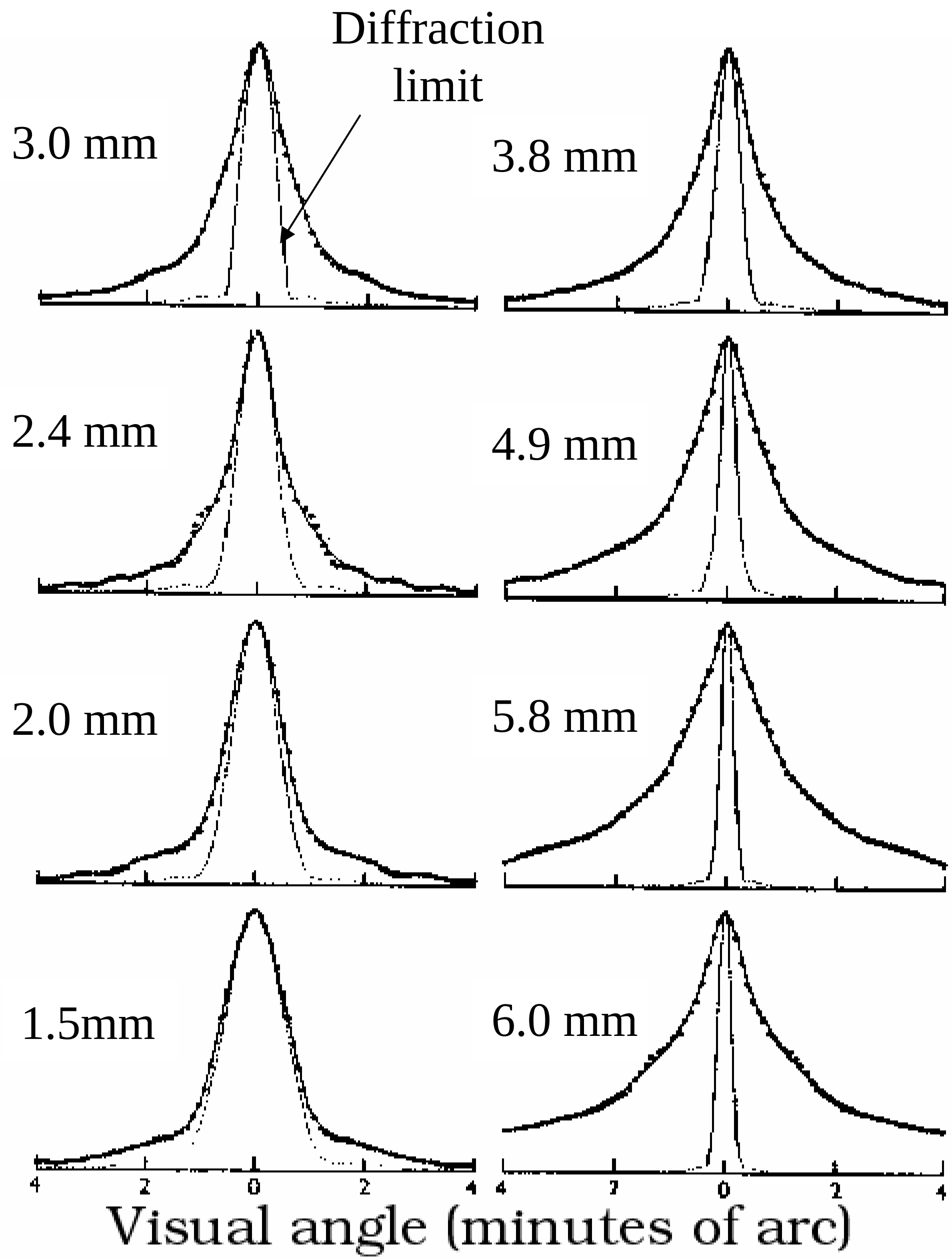
- Image formation – Chromatic aberration
- The light sensitive receptors in the retina
- Color matching – CIE XYZ
- Retinal outputs
- Visual cortex

Human Eye in Cross-Section

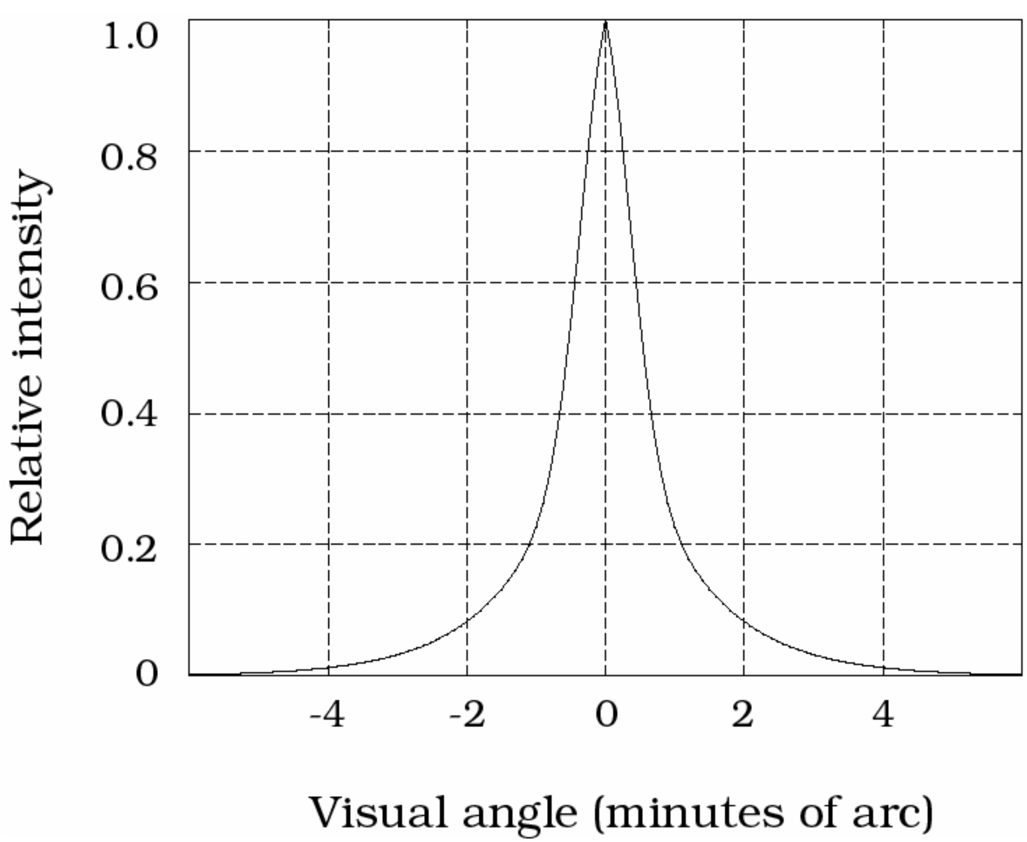


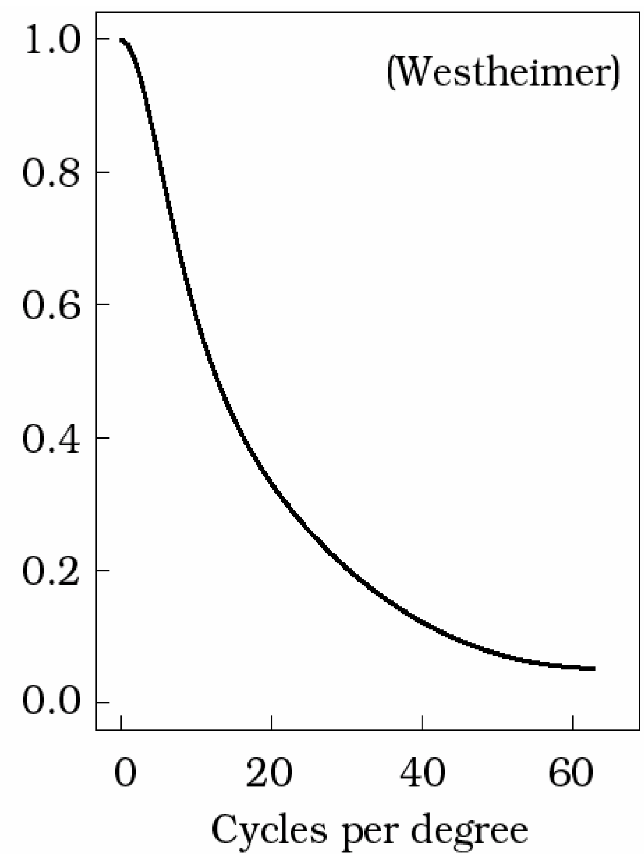
Line spread measurement
(Campbell and Gubisch)



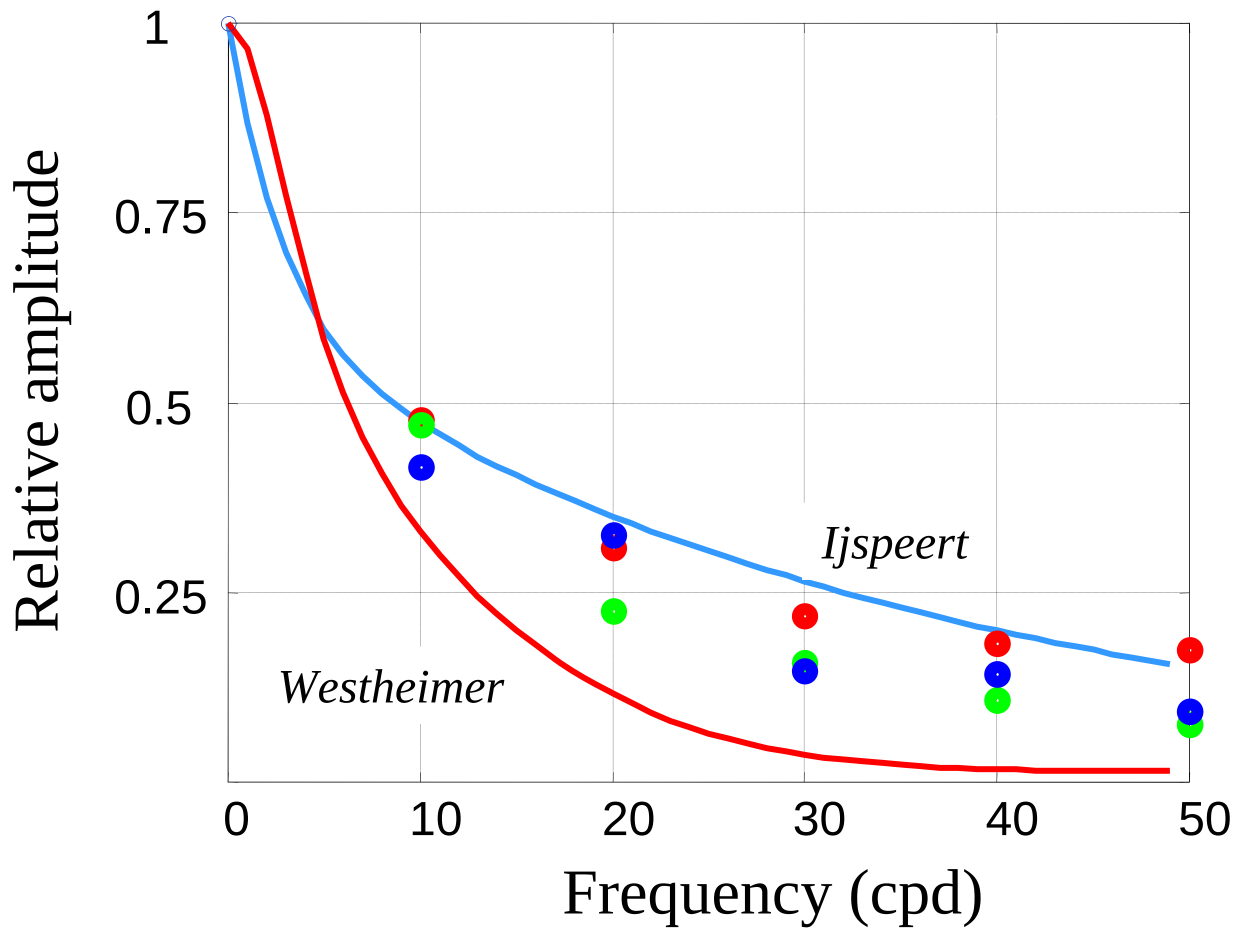


Inferred linespread and MTF
(Westheimer)



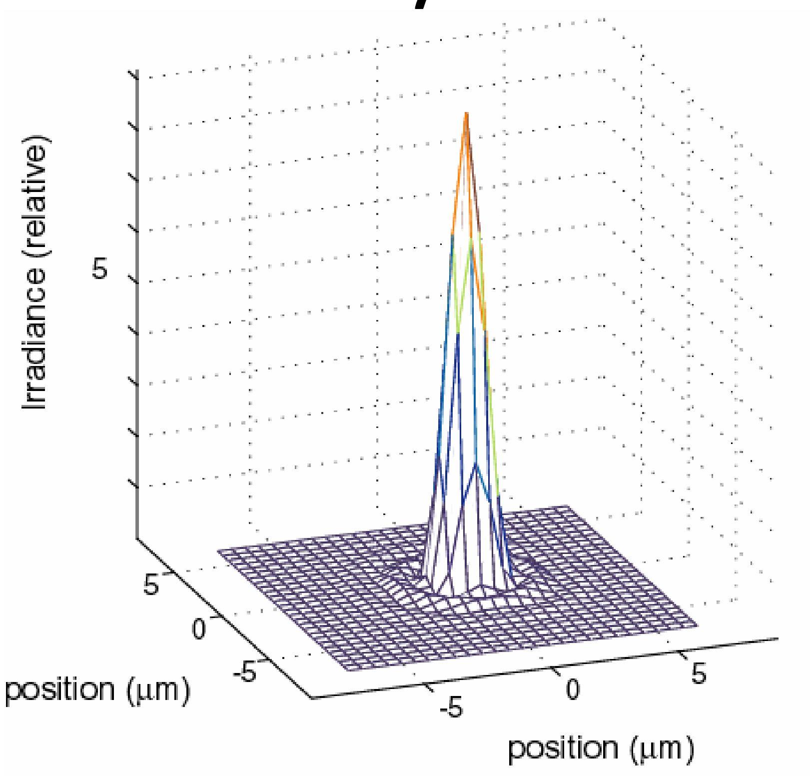


Theoretical modulation transfer functions are similar to data, but not exact (10% Field)



The diffraction pattern formula for a disk can be calculated from first principles

Airy disk



$$I(\upsilon) = I_0 \left(\frac{2 J_1(\upsilon)}{\upsilon} \right)^2$$

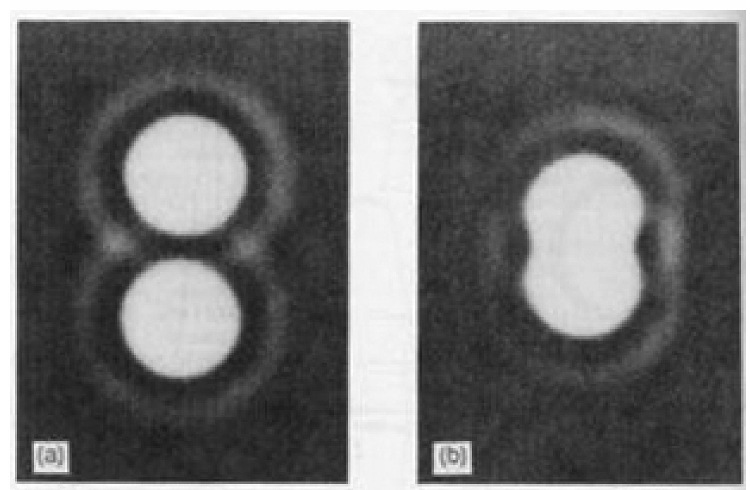
$$\upsilon = 2\pi \left(\frac{NA}{M\lambda} \right) r_i$$

First order Bessel

Numerical aperture

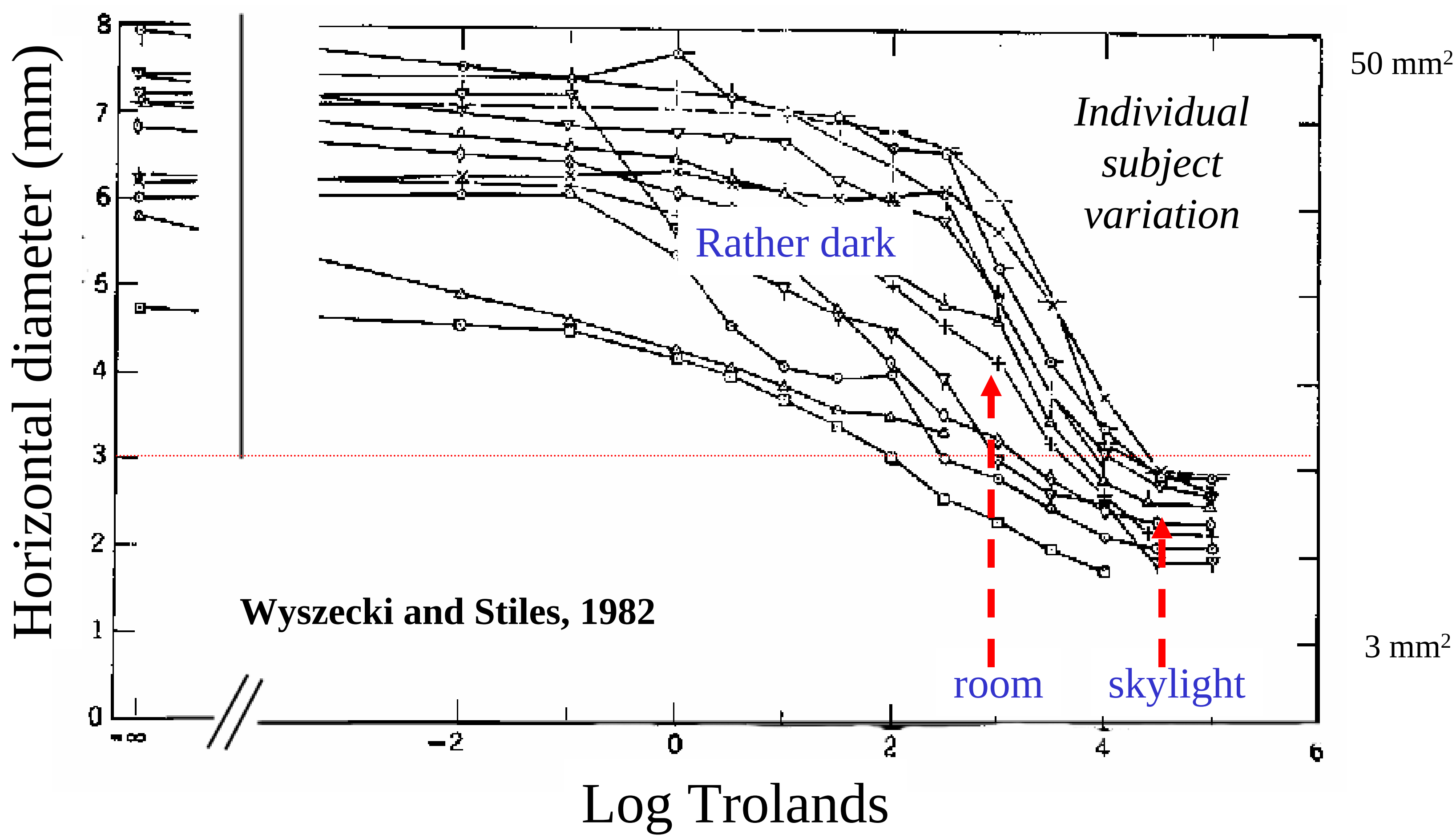
Magnification

Radial distance

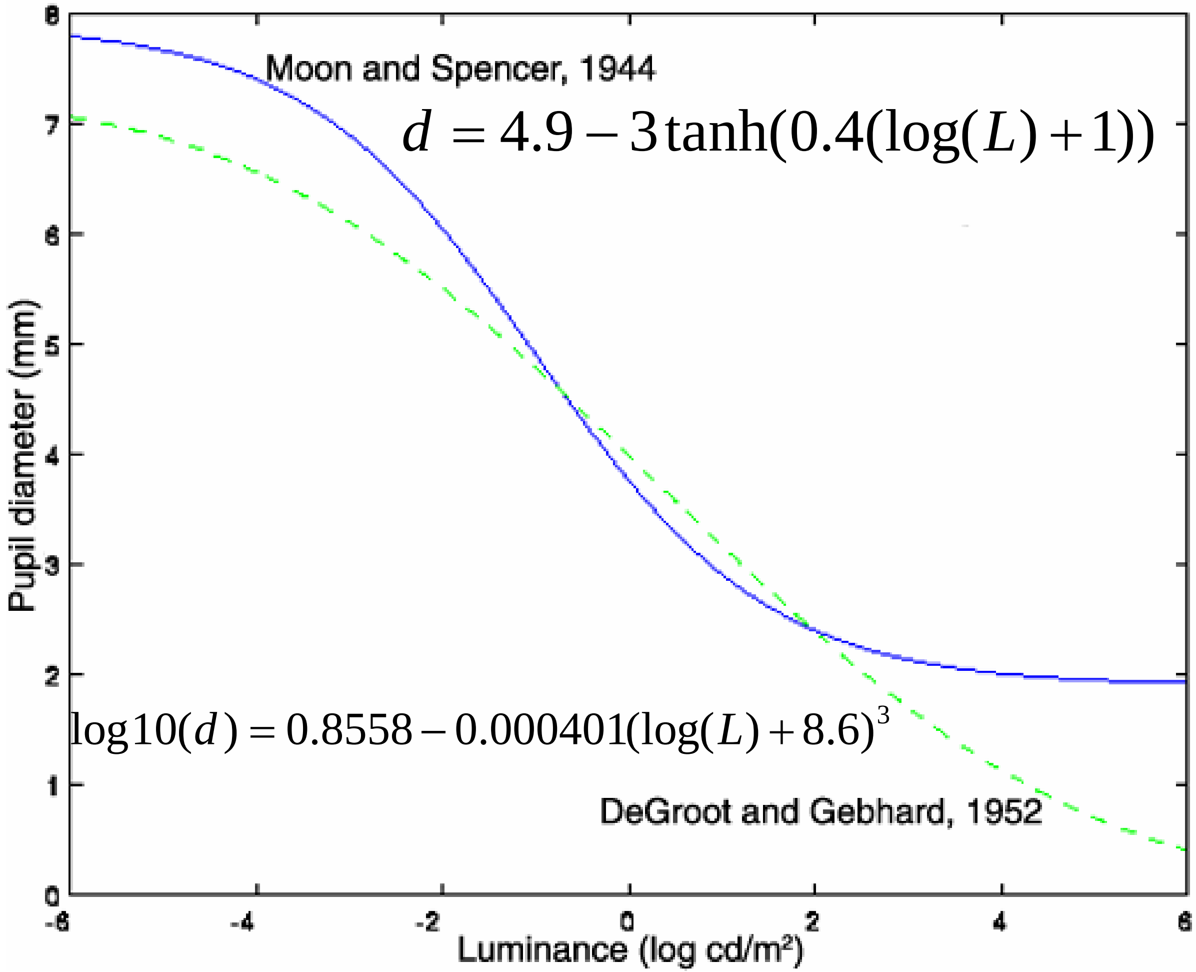


Rayleigh criterion: central peak of one is at the first minimum of the other

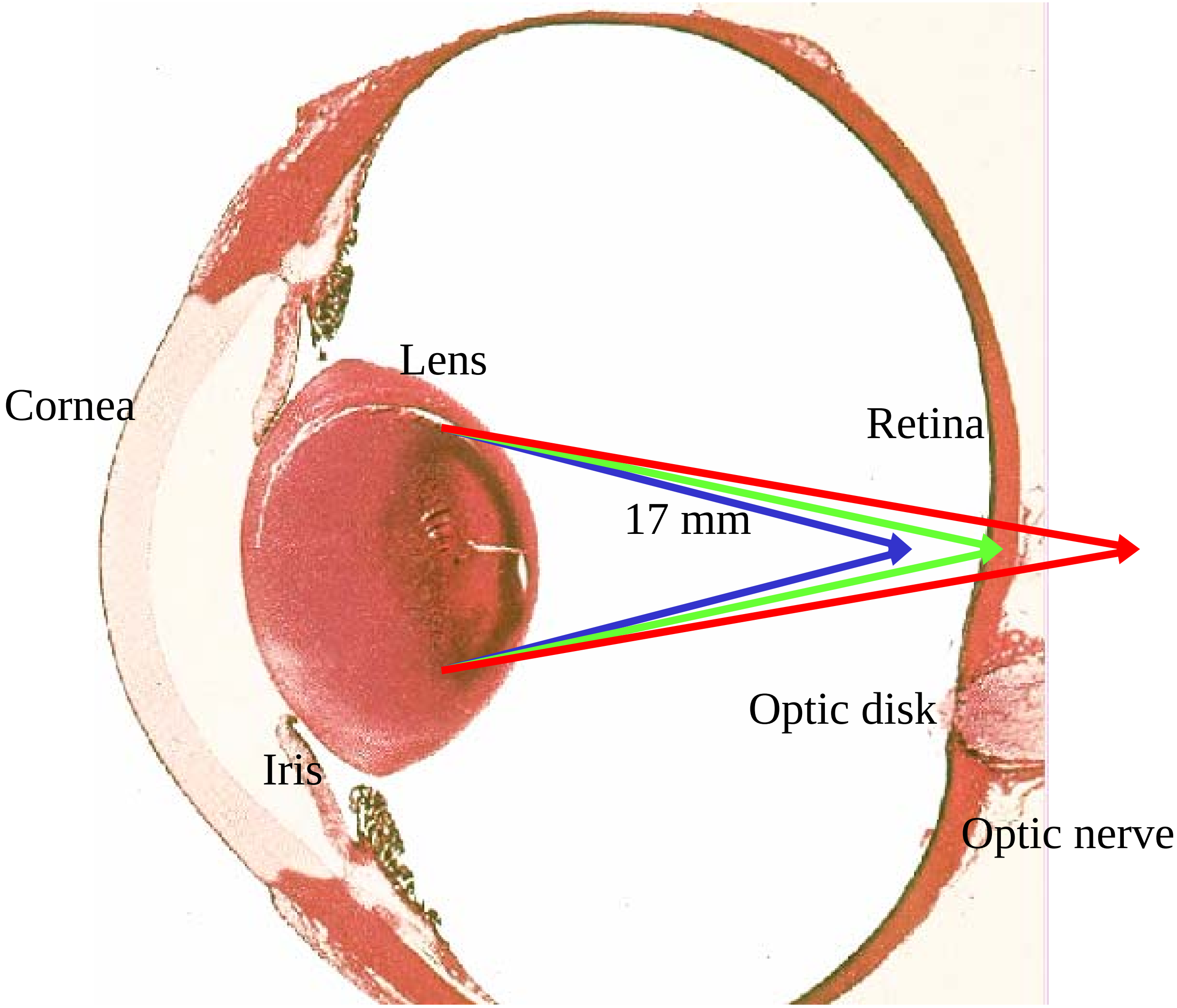
Pupil diameters at different light levels



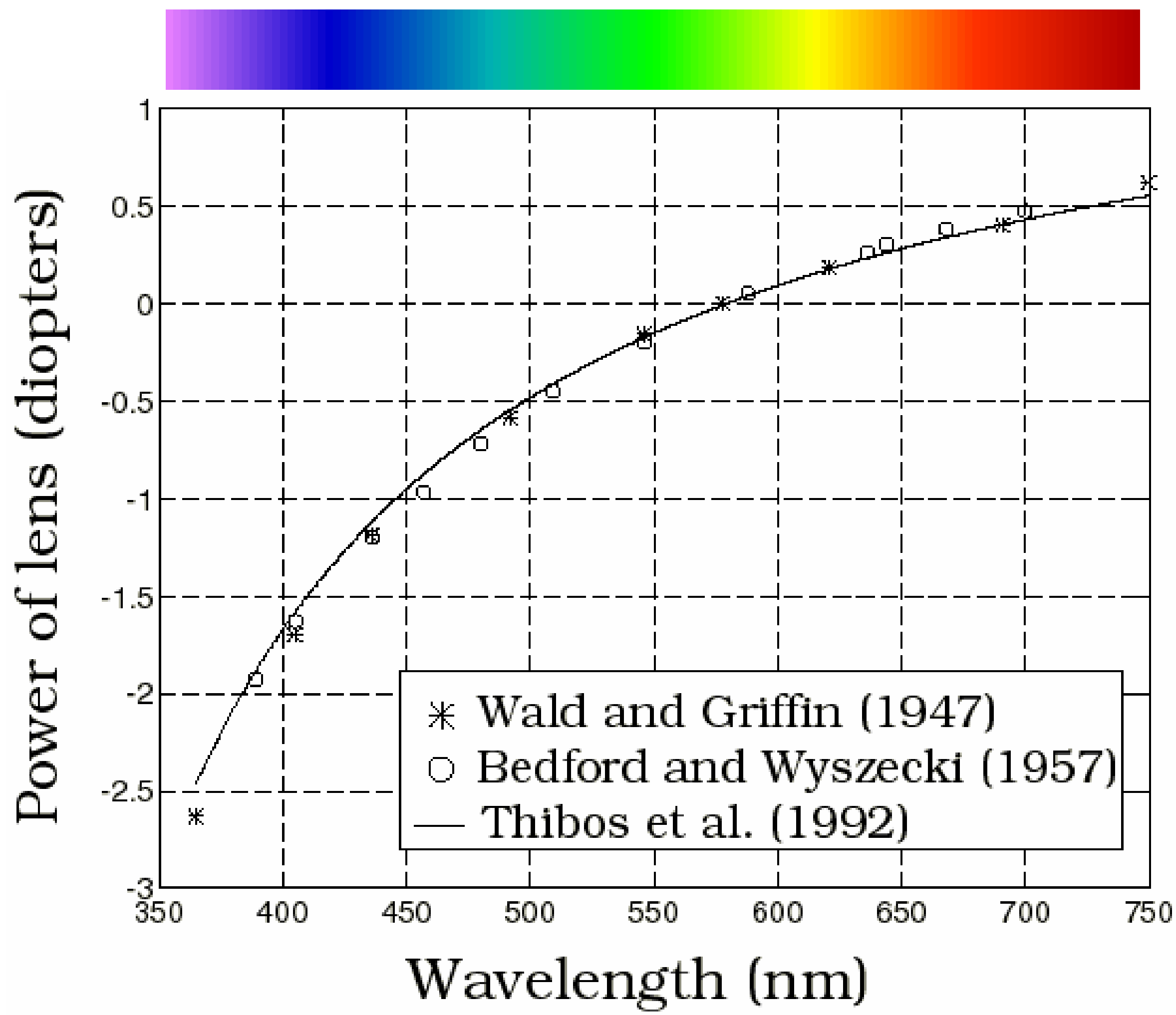
Pupil Size Changes With Mean Luminance, Influencing Acuity



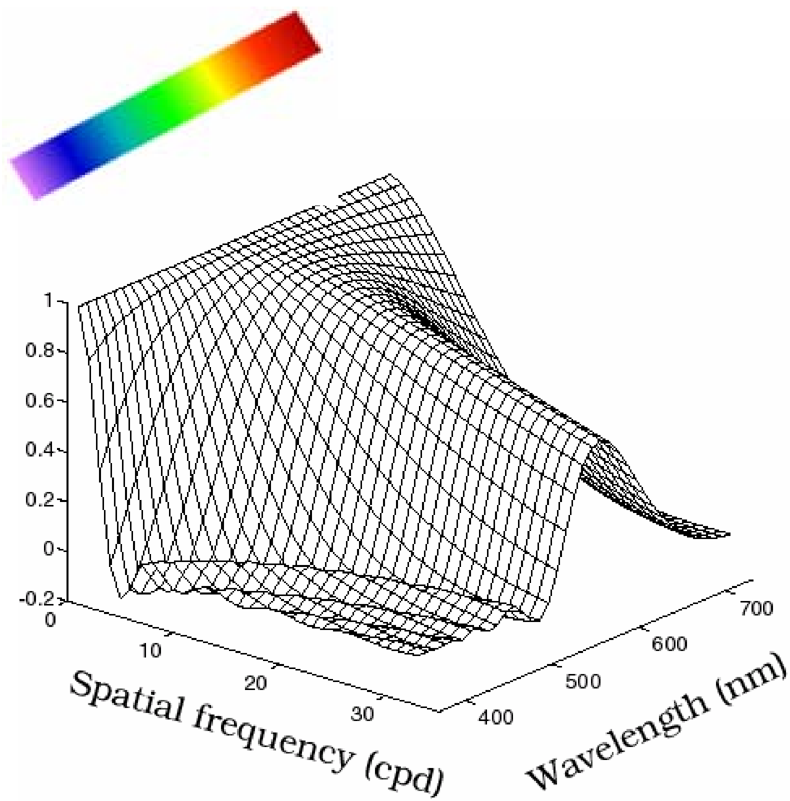
Chromatic aberration is the largest human optical aberration

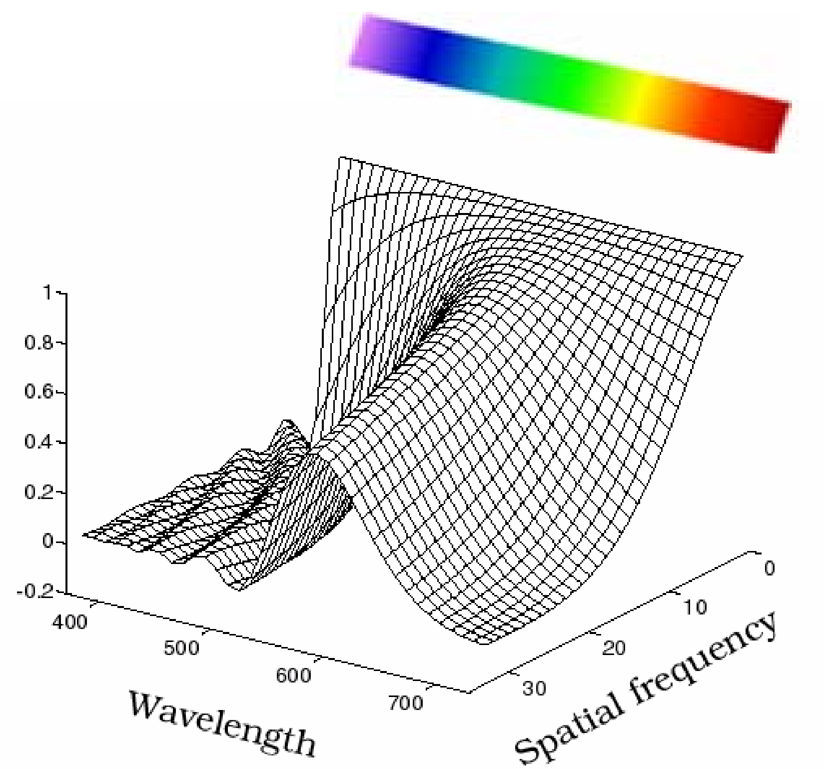


Chromatic aberration is summarized by variation in optical power across wavelength; very similar across people



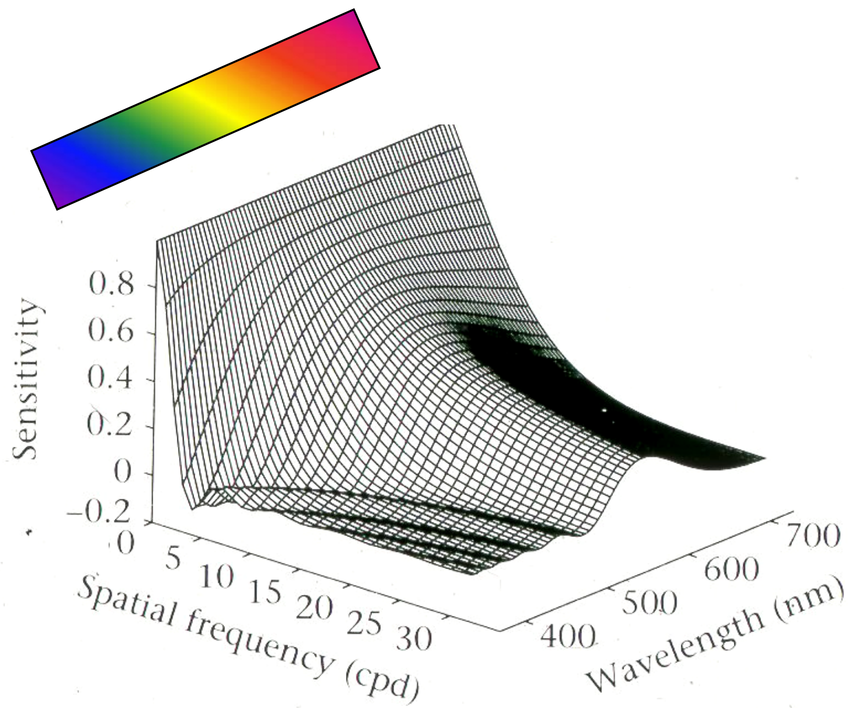
Chromatic aberration summarized by the MTF

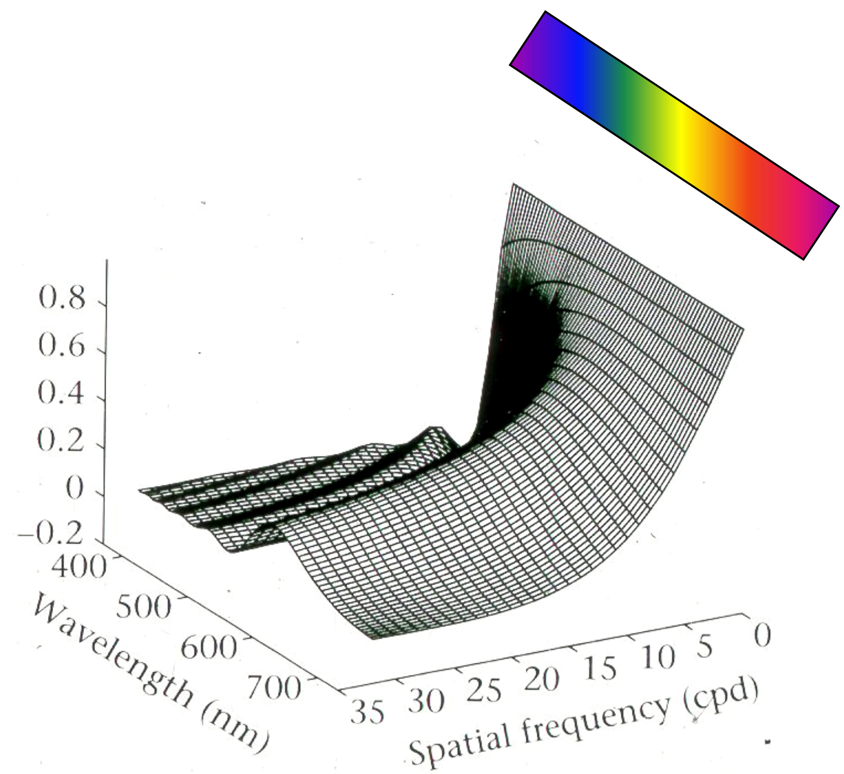




Combined chromatic and spherical aberration of the human optics

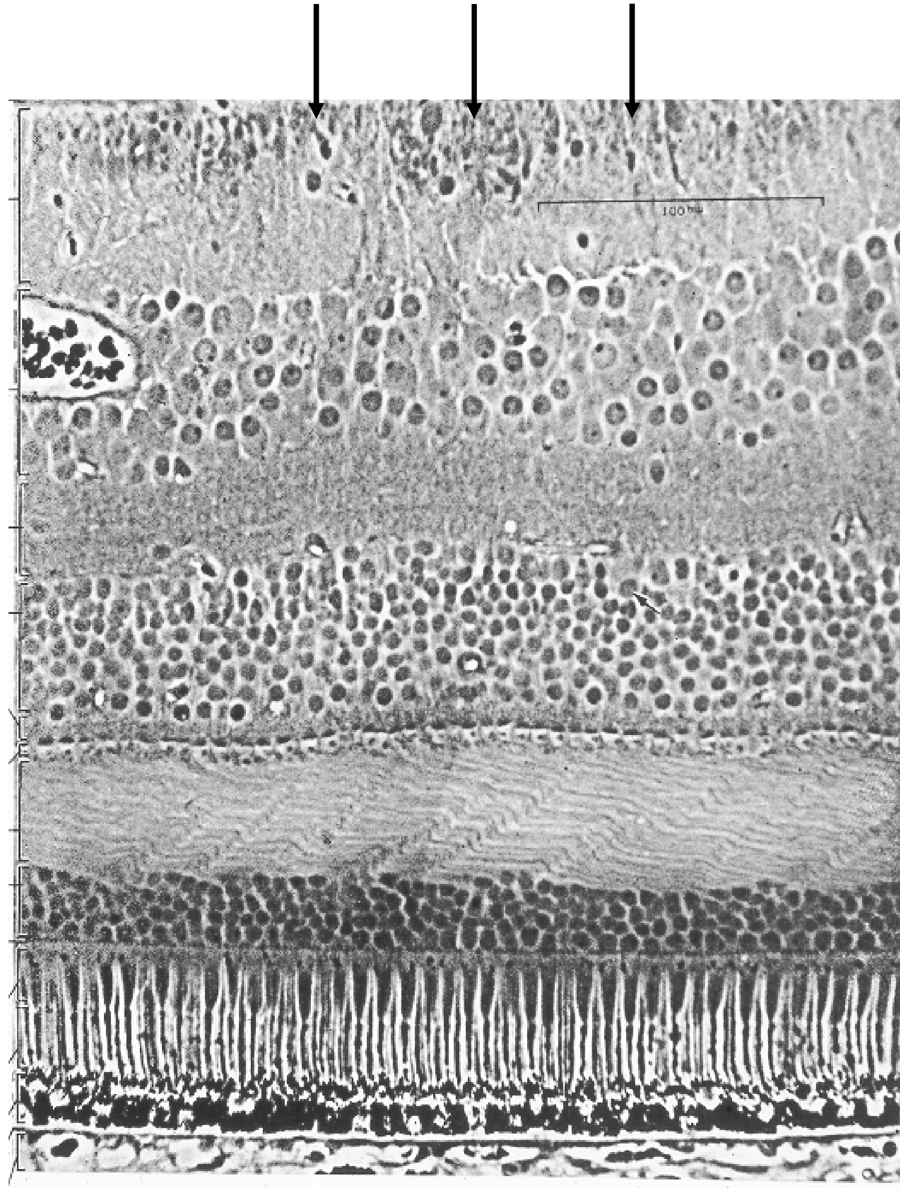
(ISET and Marimont and Wandell J. Opt. Soc Am. A.)

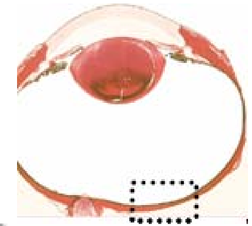




Light passes through the retinal cells and is absorbed by pigments in the rod and cone outer segments

Rodieck





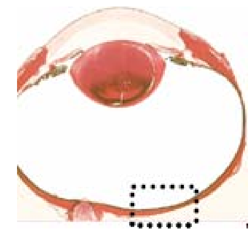
The unbleached rod photopigment, rhodopsin, can be seen in the living eye

After exposure to light, the pigment becomes transparent

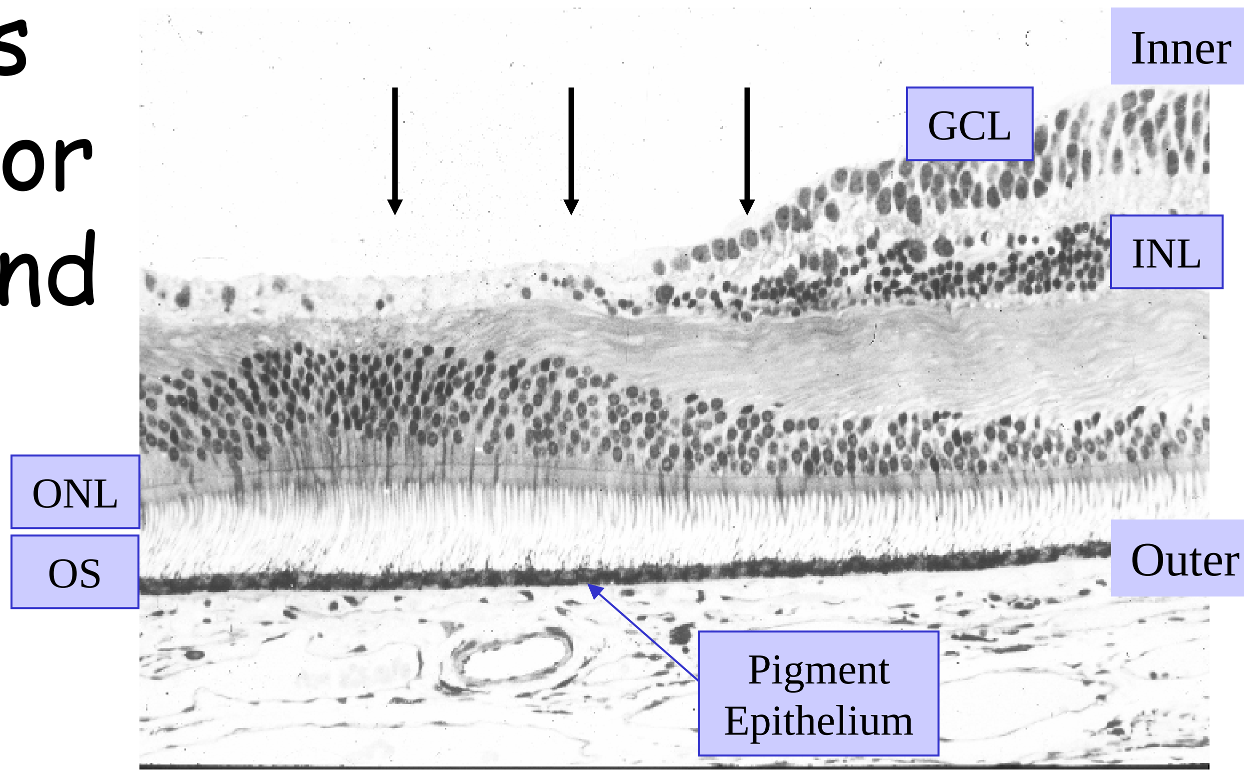
The Primate fovea (pit) contains mainly cones and is specialized for high acuity and color

Curcio
Rodieck

The Retina

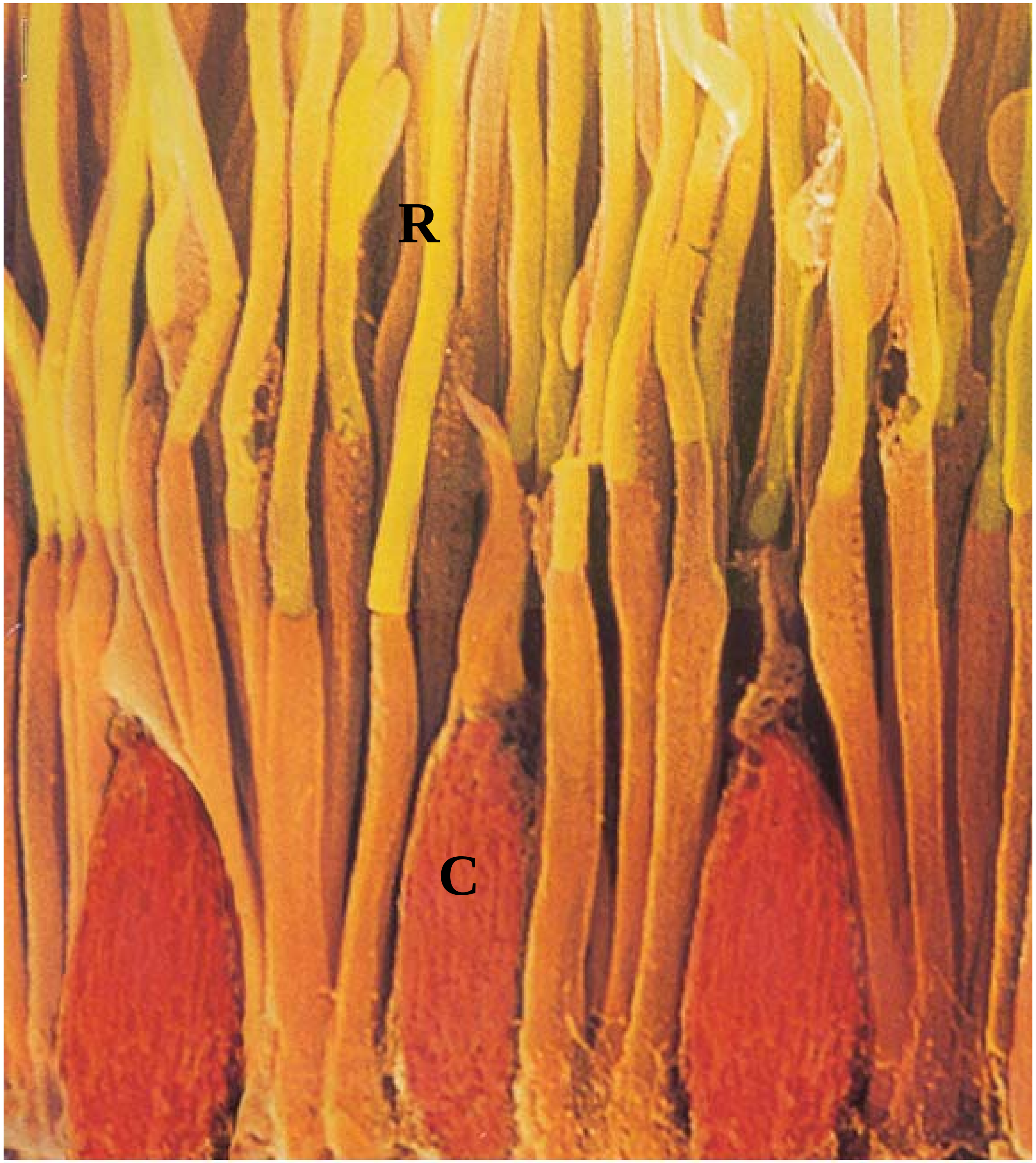


- 5 x 5 cm, 0.4 mm thick
- 5 x 10^6 cones
- 10^8 rods
- Foveal cone width: 1 mu
- Contacts per cone: 250
- 10^6 optic nerve fibers



Rods and Cones

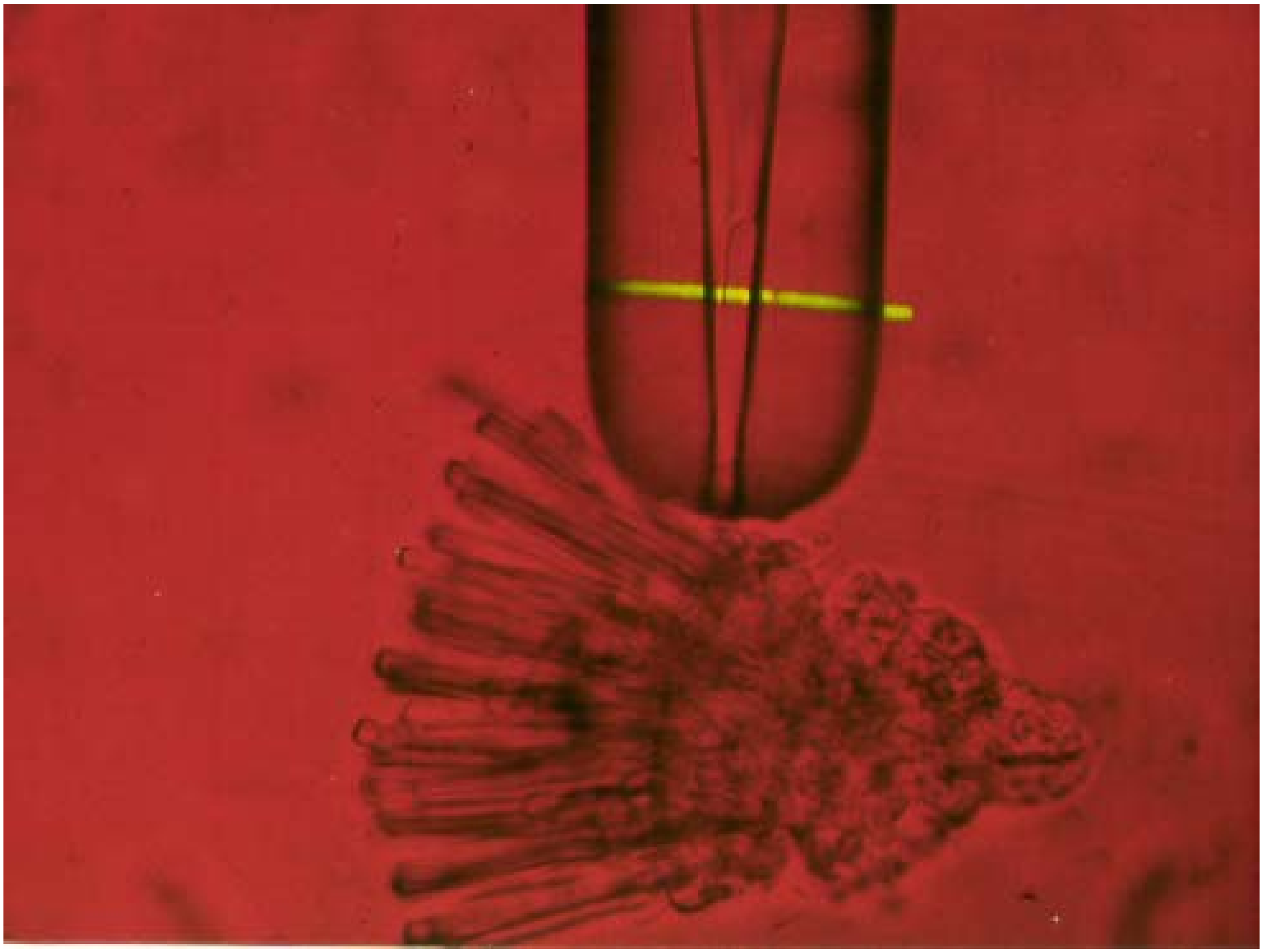
http://webvision.med.utah.edu/photo1.html



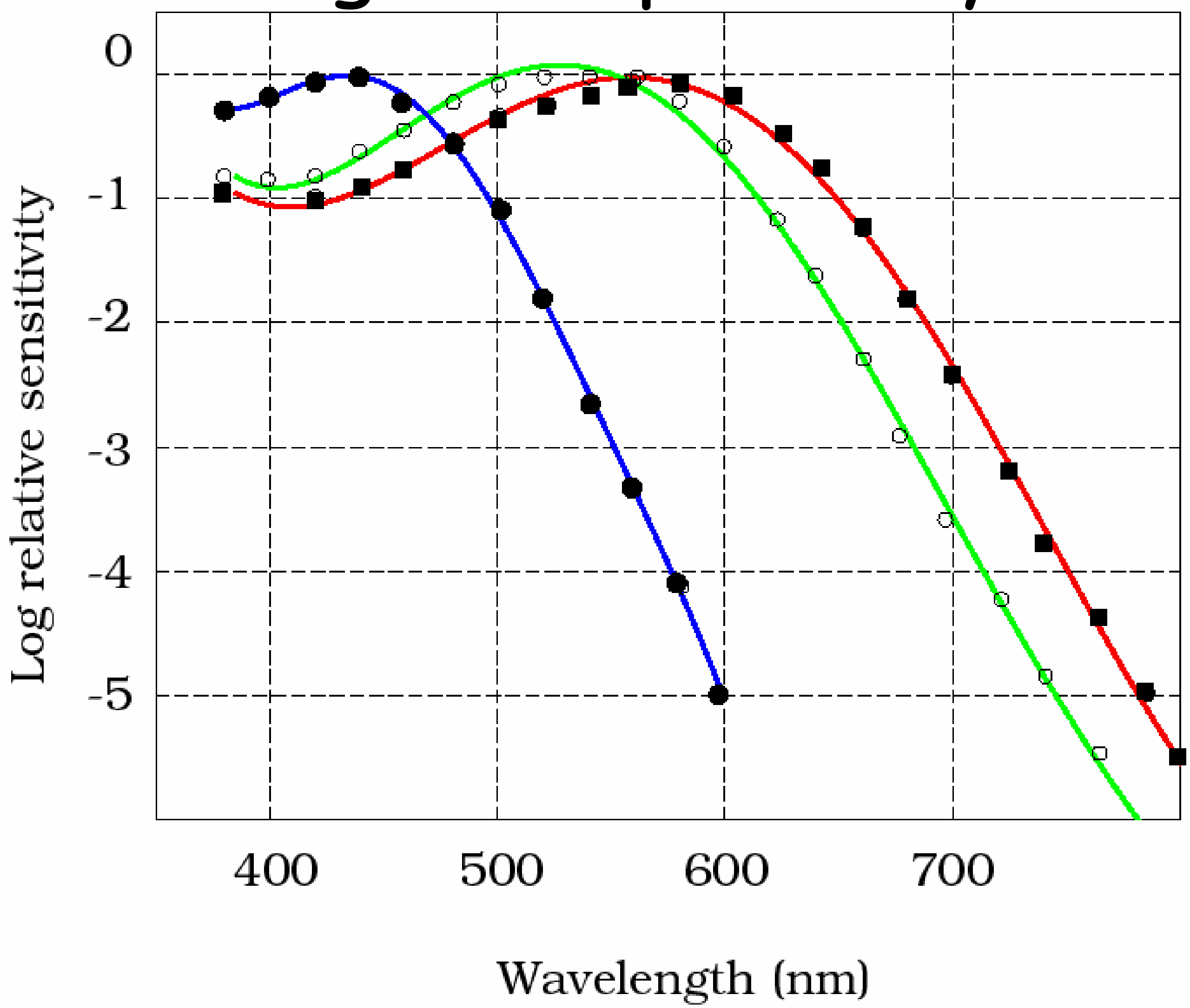
Rods and cones seen through a scanning electron microscope. Each rod is about one micron across.

Single cone photocurrent measurements

(Schnapf, Baylor et al).

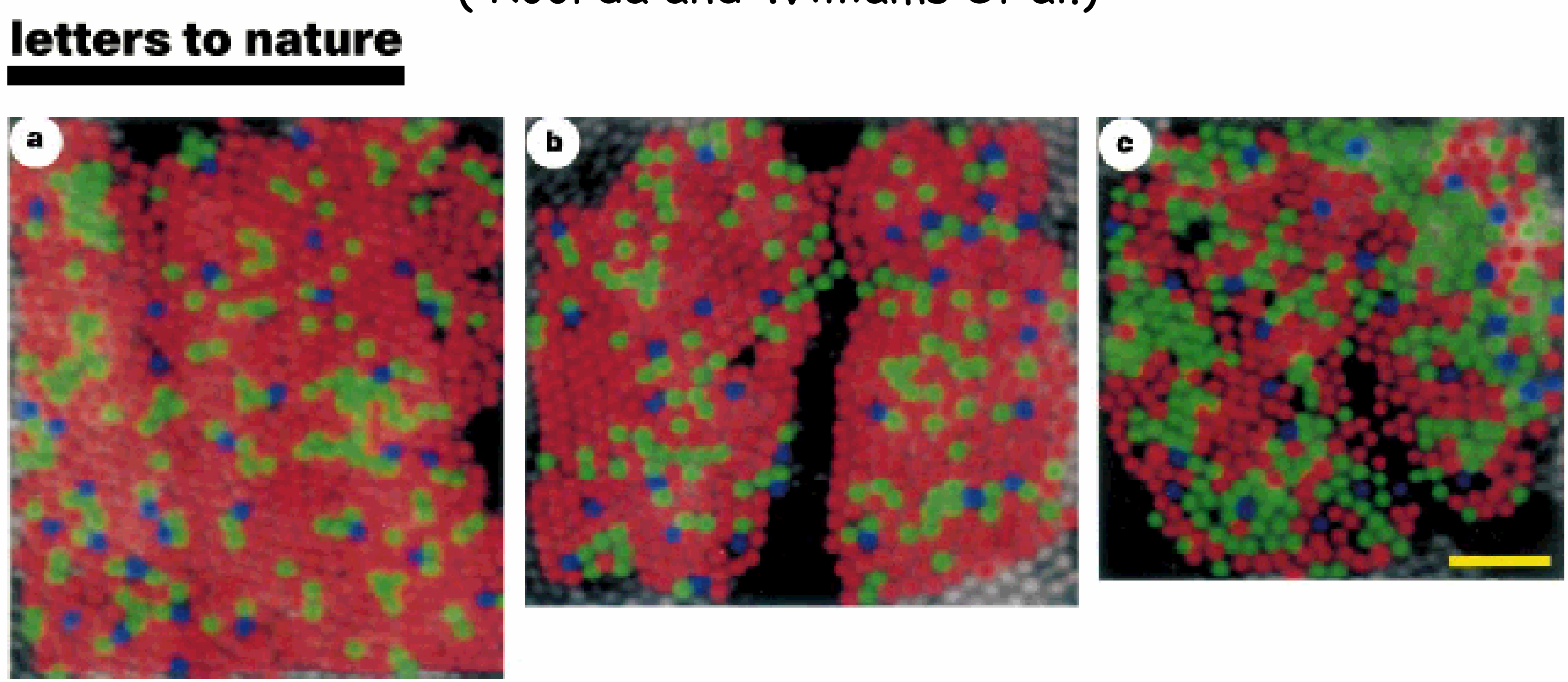


There are three types of cone wavelength responsivity curves



Recent advances in adaptive optics make it possible to visualize the cone mosaic of the human eye

(Roorda and Williams et al.)

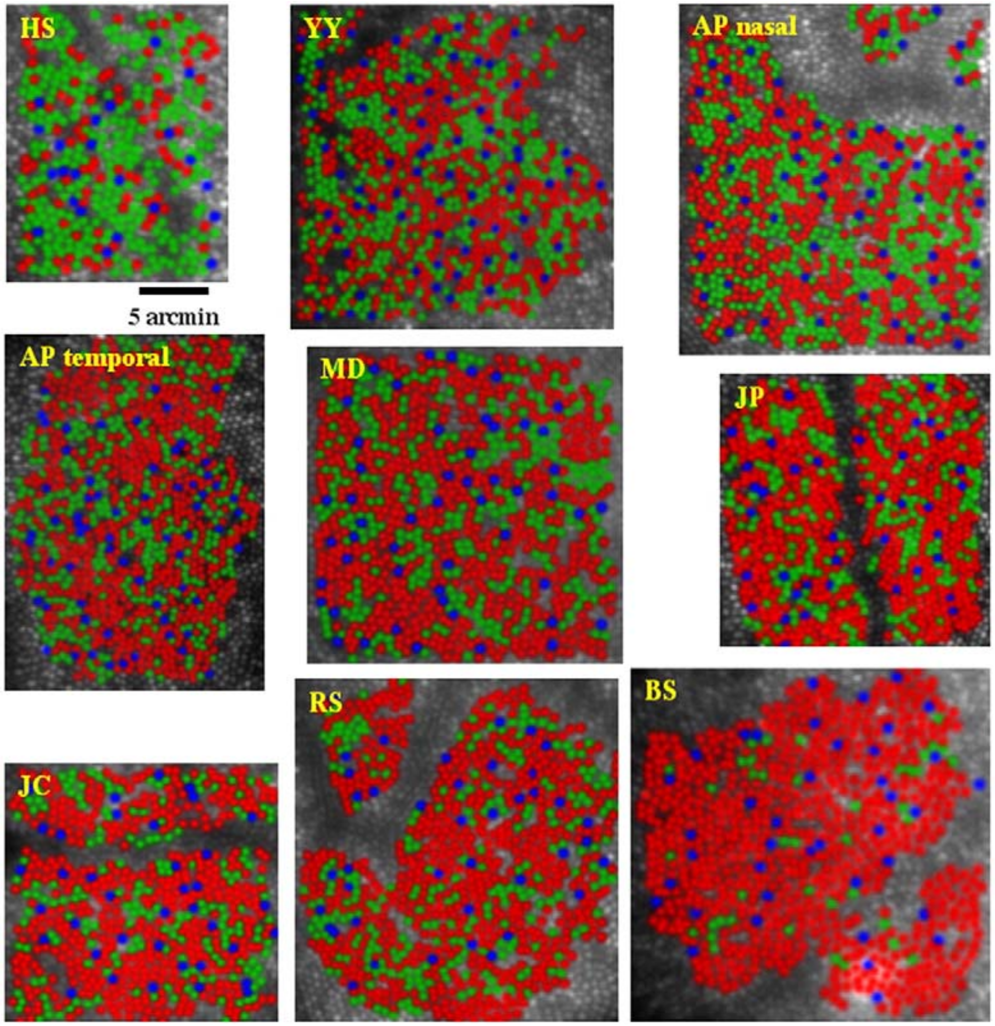


Cone receptor mosaics differ greatly between individuals

Hofer, H. et al. J. Neurosci. 2005;25:9669-9679

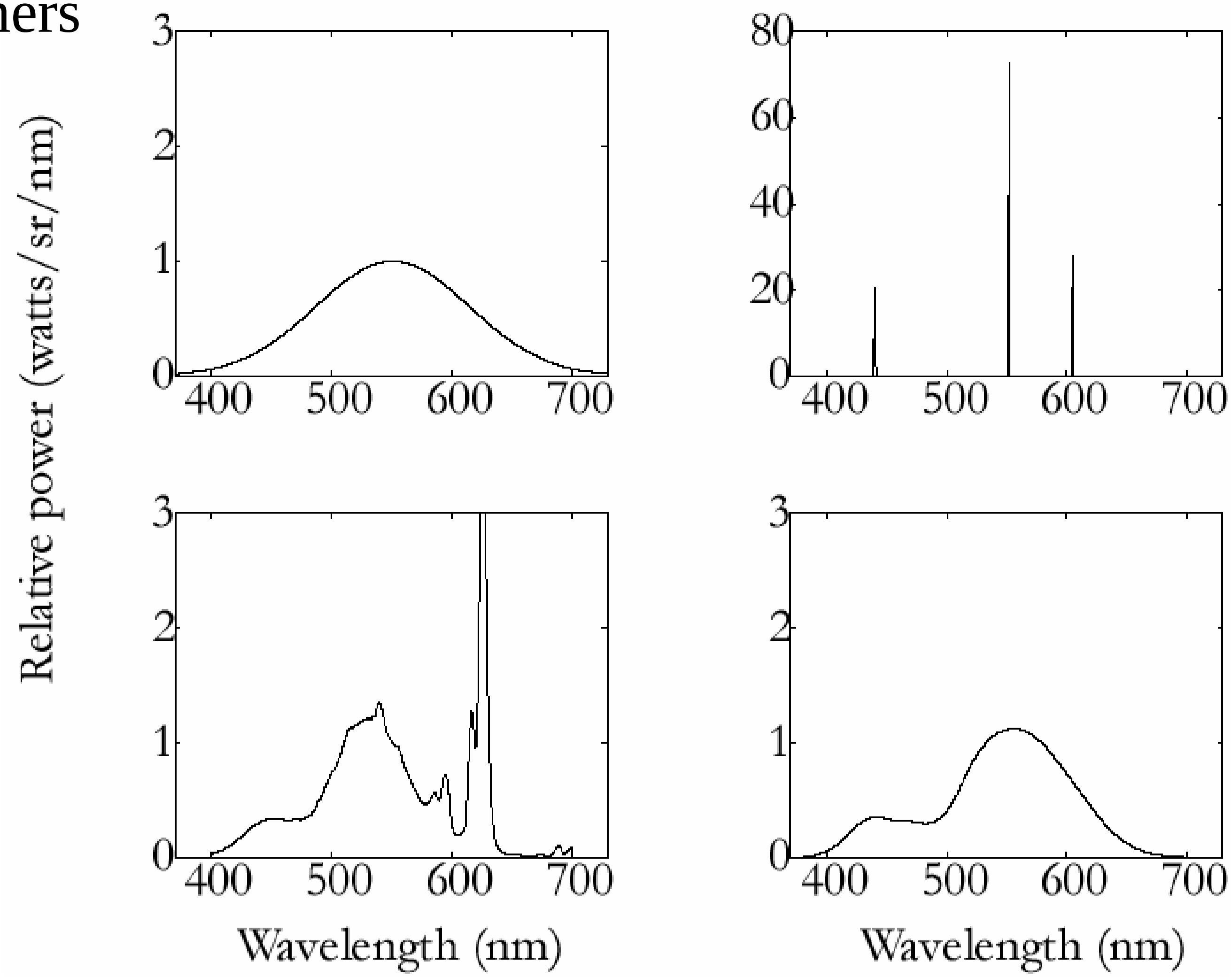
Cone inner segments 1-2 micron diameter in foveola; much larger in the periphery.
Two individuals shown have cone ratios: 3.8:1 and 1.15:1 – yet both are normal

Foveolar edge – cone diameter is 3-4 microns (330 microns ~ 1 deg)

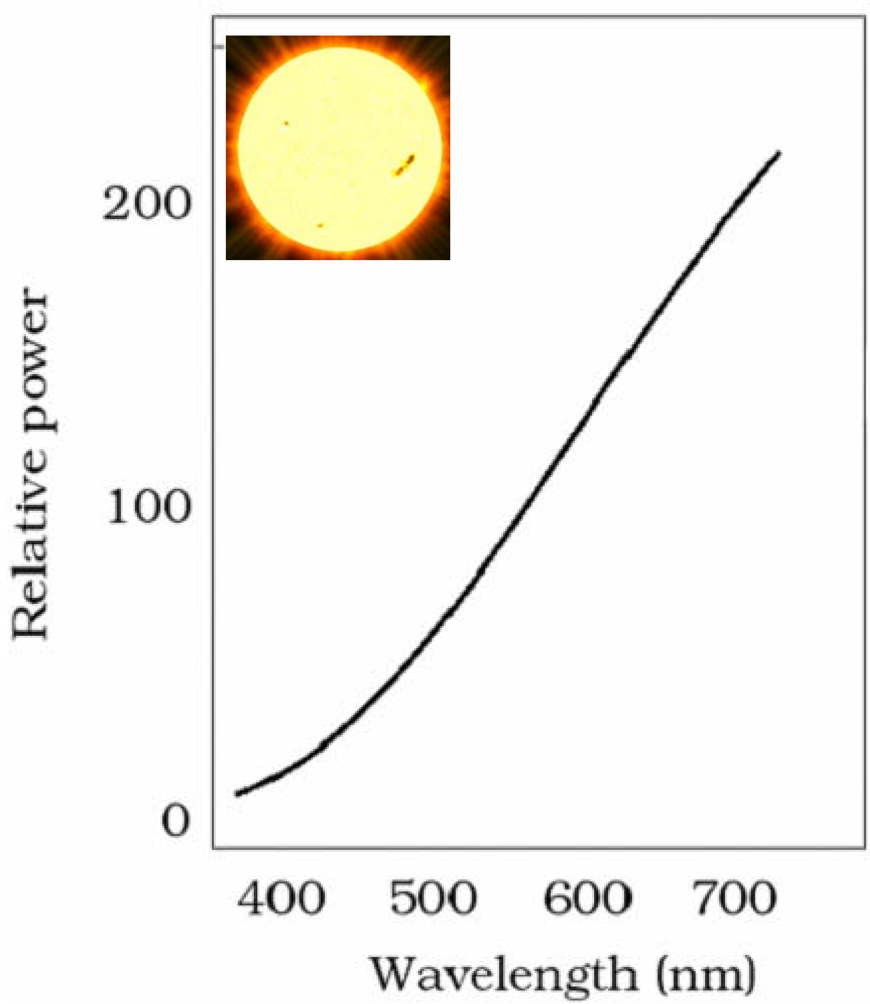


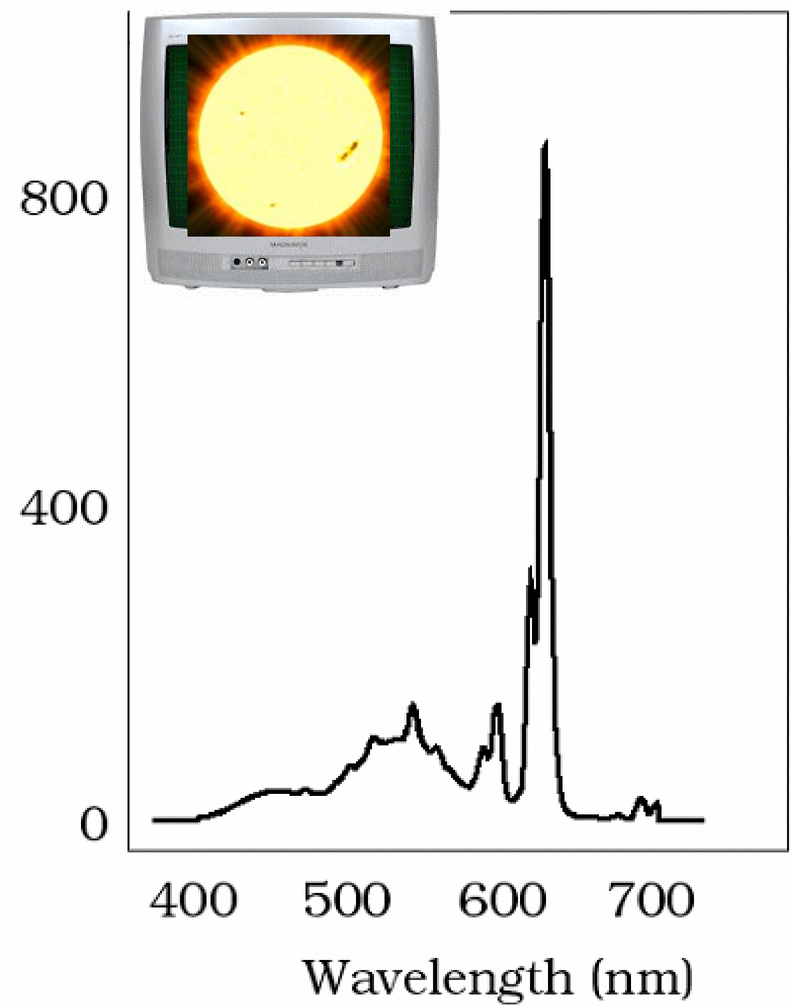
The eye is very poor at discriminating different spectral power distributions

Metamers

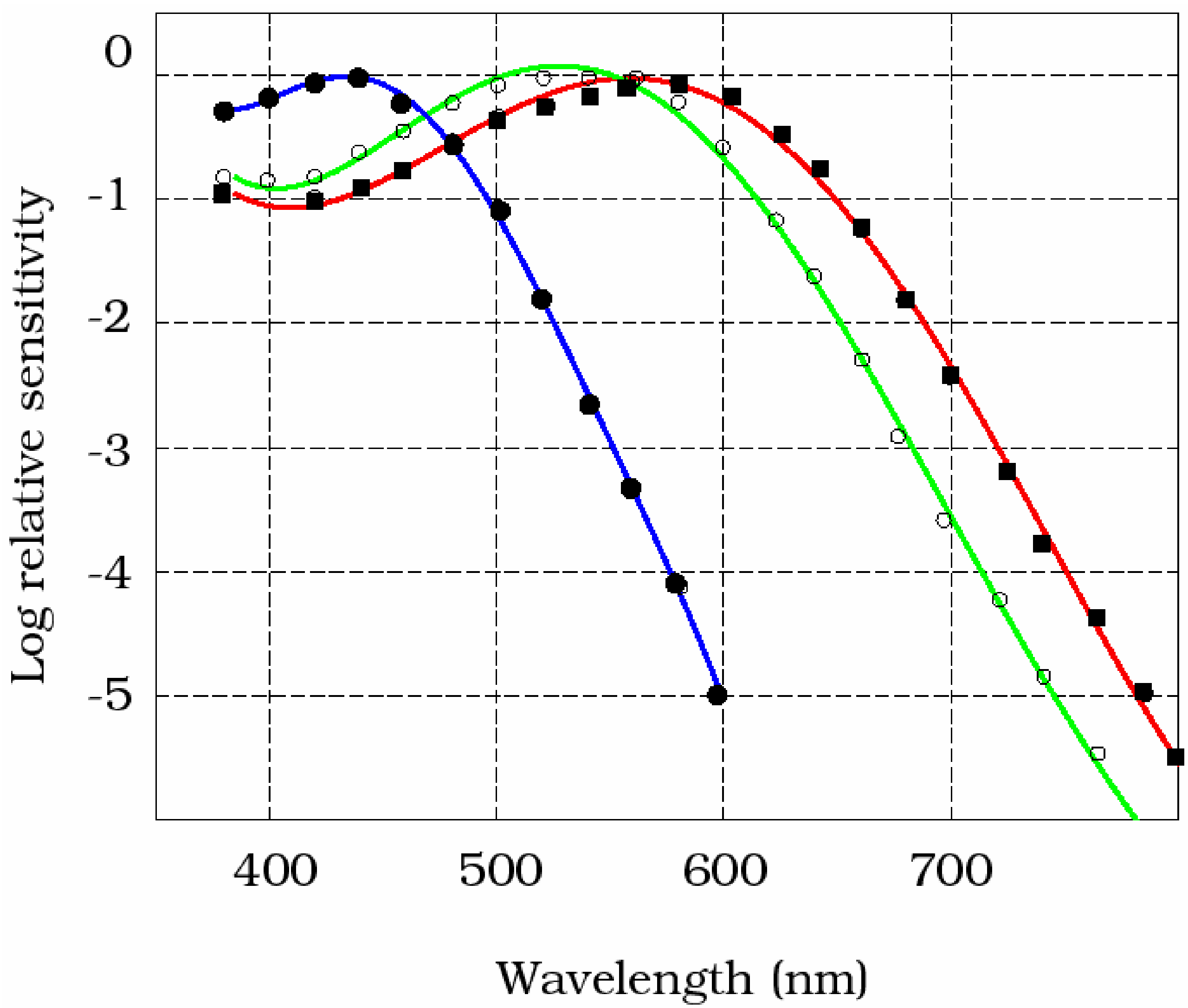


Color Matching Is An Important Illusion That Is Understood Quantitatively

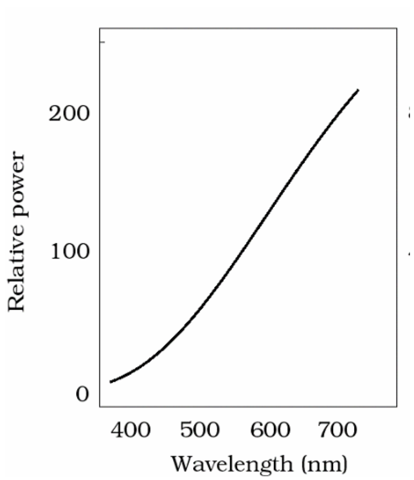


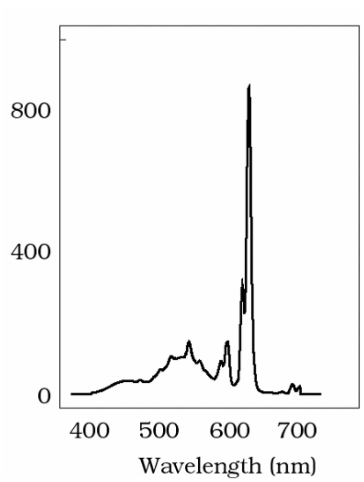


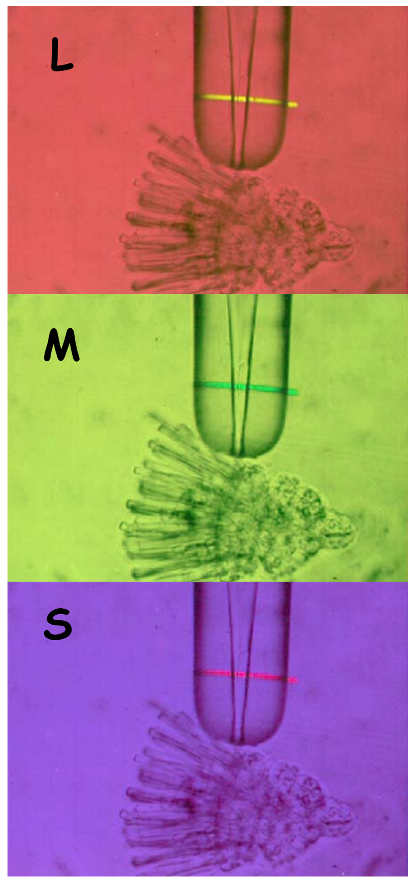
The cone spectral absorption functions predict important color properties

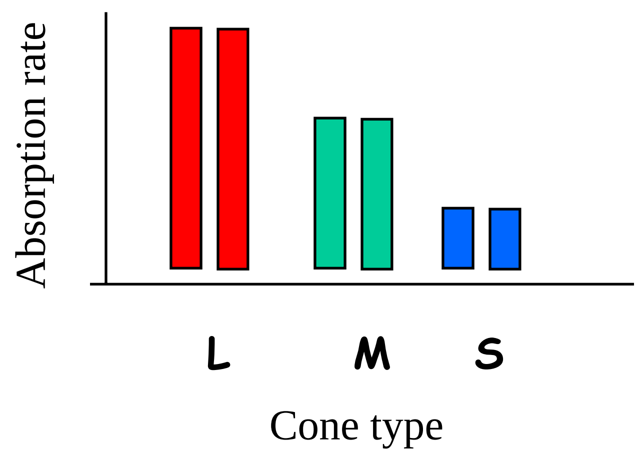


Stimuli causing equal cone absorptions match perceptually

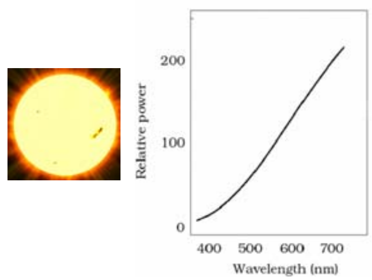


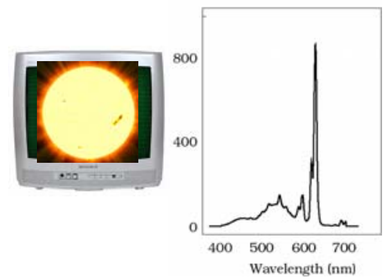


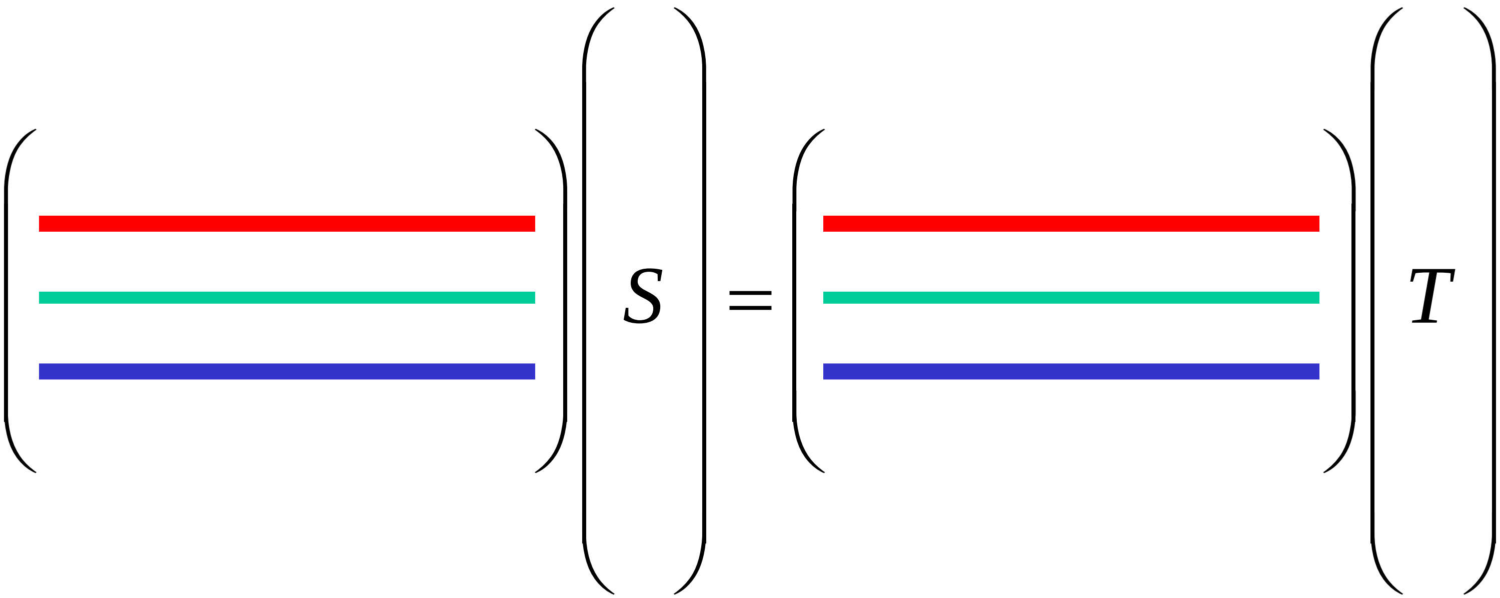




The color matching experiment predicts metameric matches

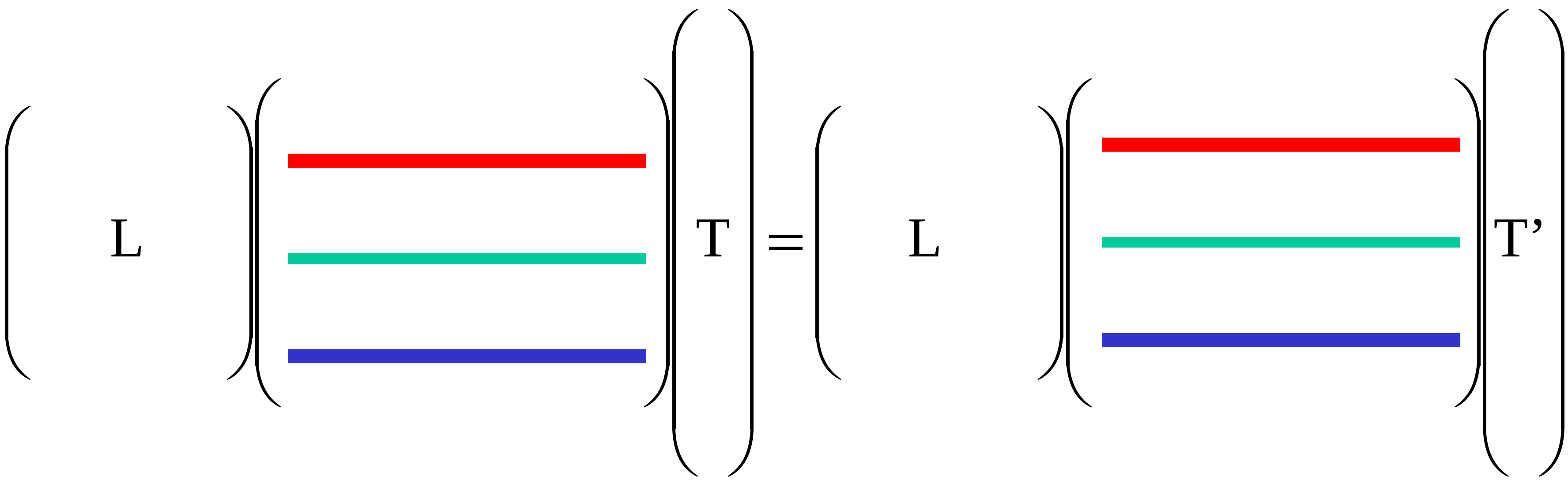




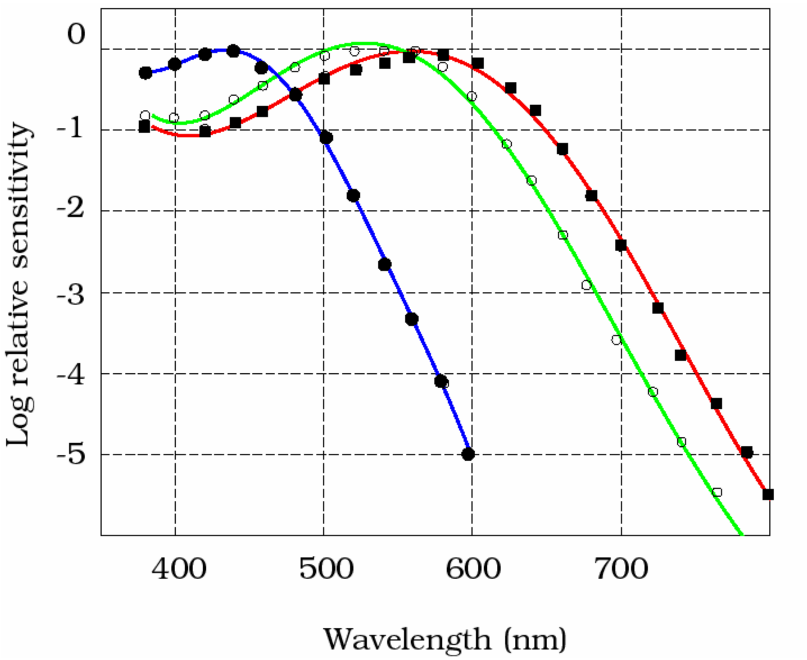


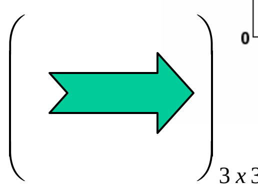
S and T match perceptually; they are metamers

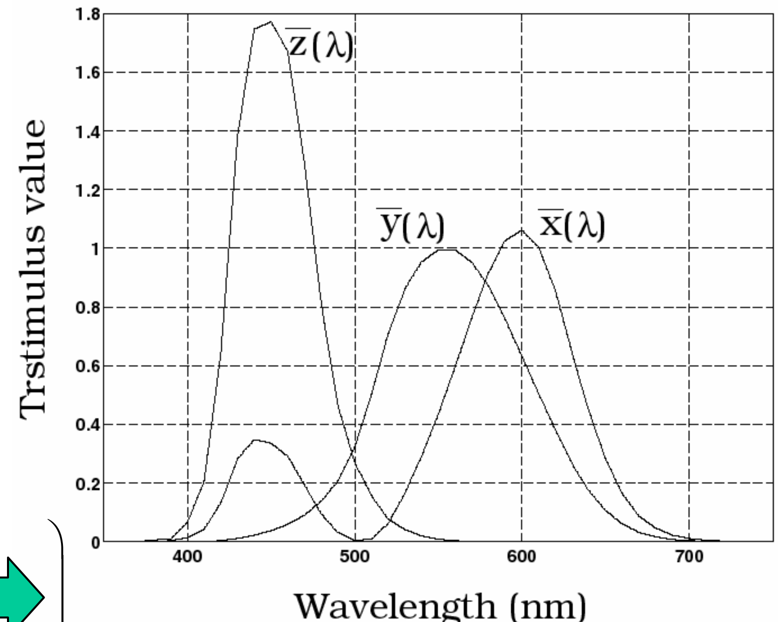
Linear transformation of the CMFs predict metamers, as well



CIE-XYZ functions are a linear transformation away from the cones







The CIE XYZ functions predict metamers

CIE XYZ functions

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} \cdots & \bar{x}(\lambda) & \cdots \\ \cdots & \bar{y}(\lambda) & \cdots \\ \cdots & \bar{z}(\lambda) & \cdots \end{pmatrix} \begin{pmatrix} \vdots \\ t(\lambda) \\ \vdots \end{pmatrix}$$

Input SPD

The CIE XYZ functions are commonly used for this prediction

CIE XYZ functions

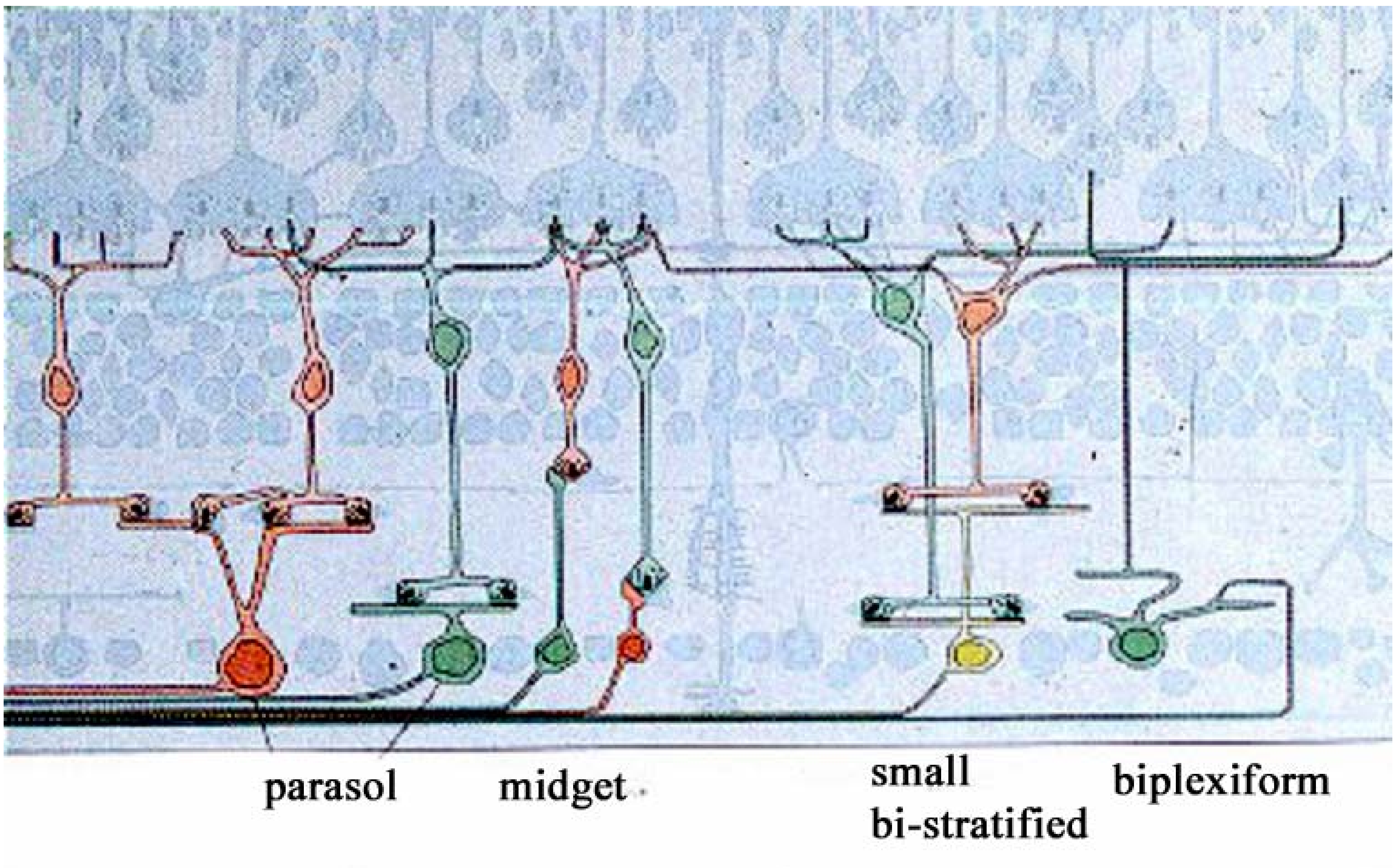
$$X = \sum_{\lambda} \overline{x}(\lambda) t(\lambda) d\lambda$$

$$Y = \sum_{\lambda} \overline{y}(\lambda) t(\lambda) d\lambda$$

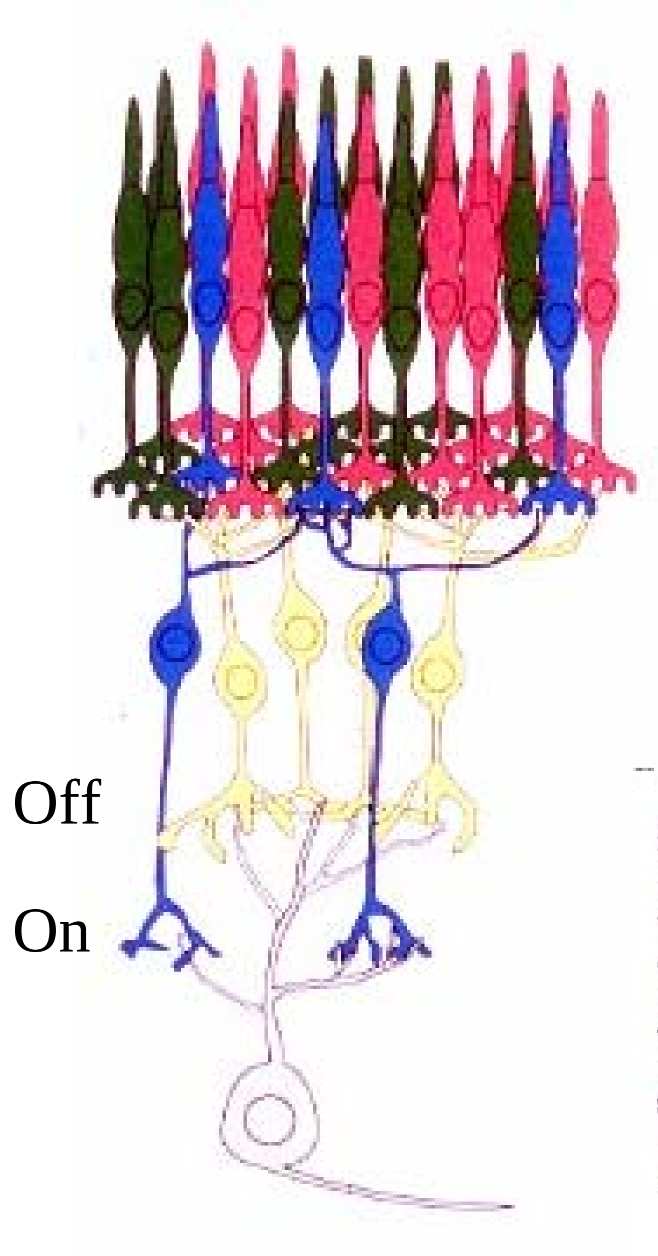
$$Z = \sum_{\lambda} \overline{z}(\lambda) t(\lambda) d\lambda$$

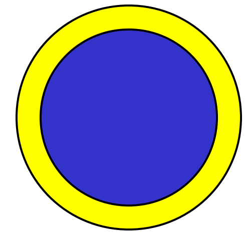
Multiple retinal output pathways, each with a specific spatial mixture of cone signals

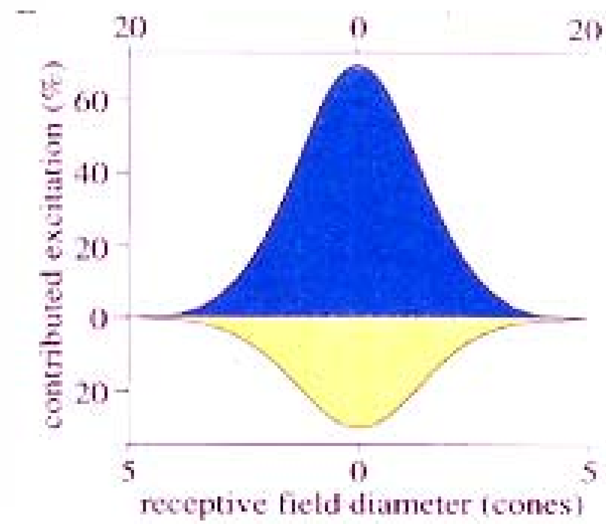
(Rodieck, 1998)



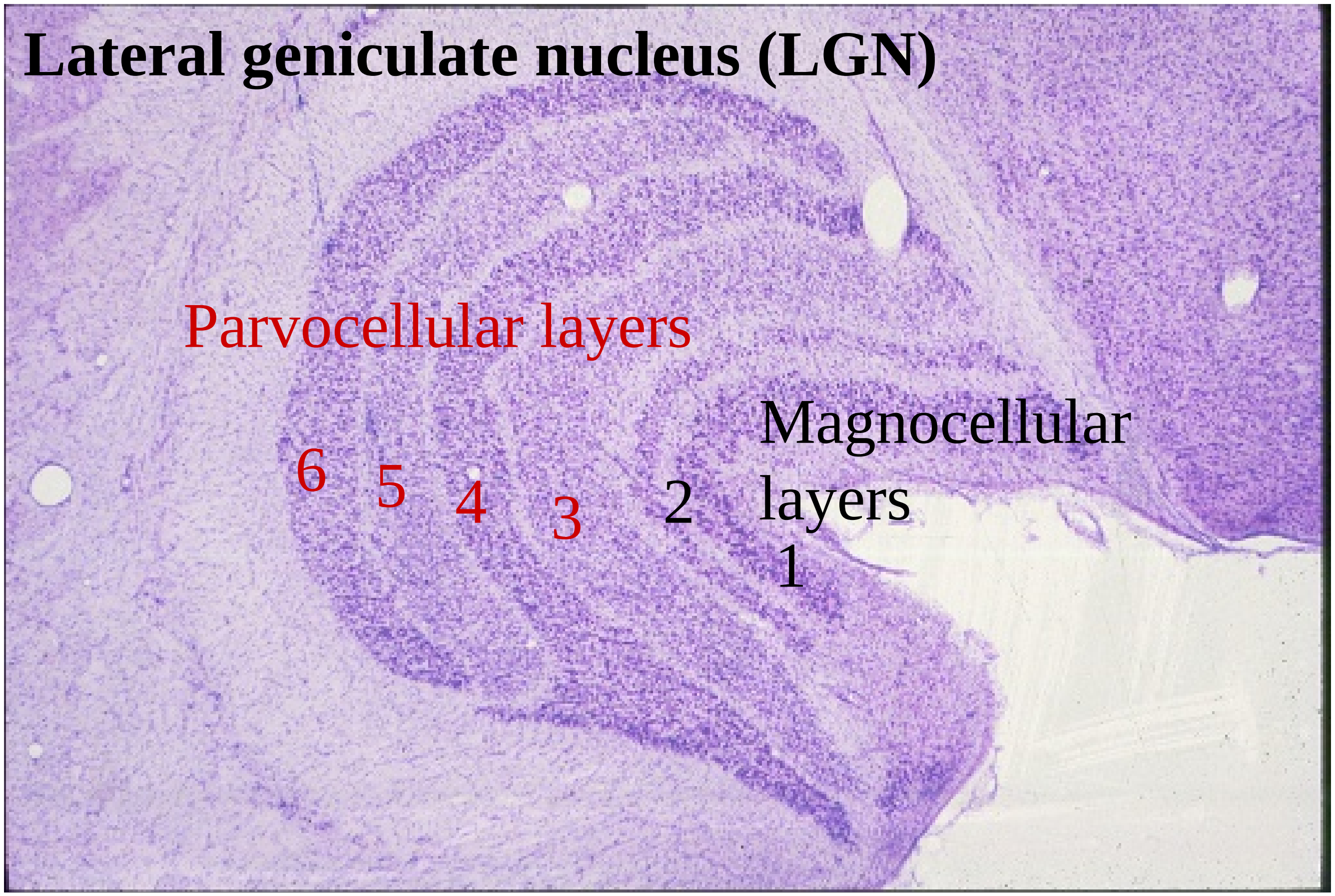
Small bistratified retinal ganglion cells code blue-on and yellow-off







Retinal pathways send their outputs to distinct brain destinations



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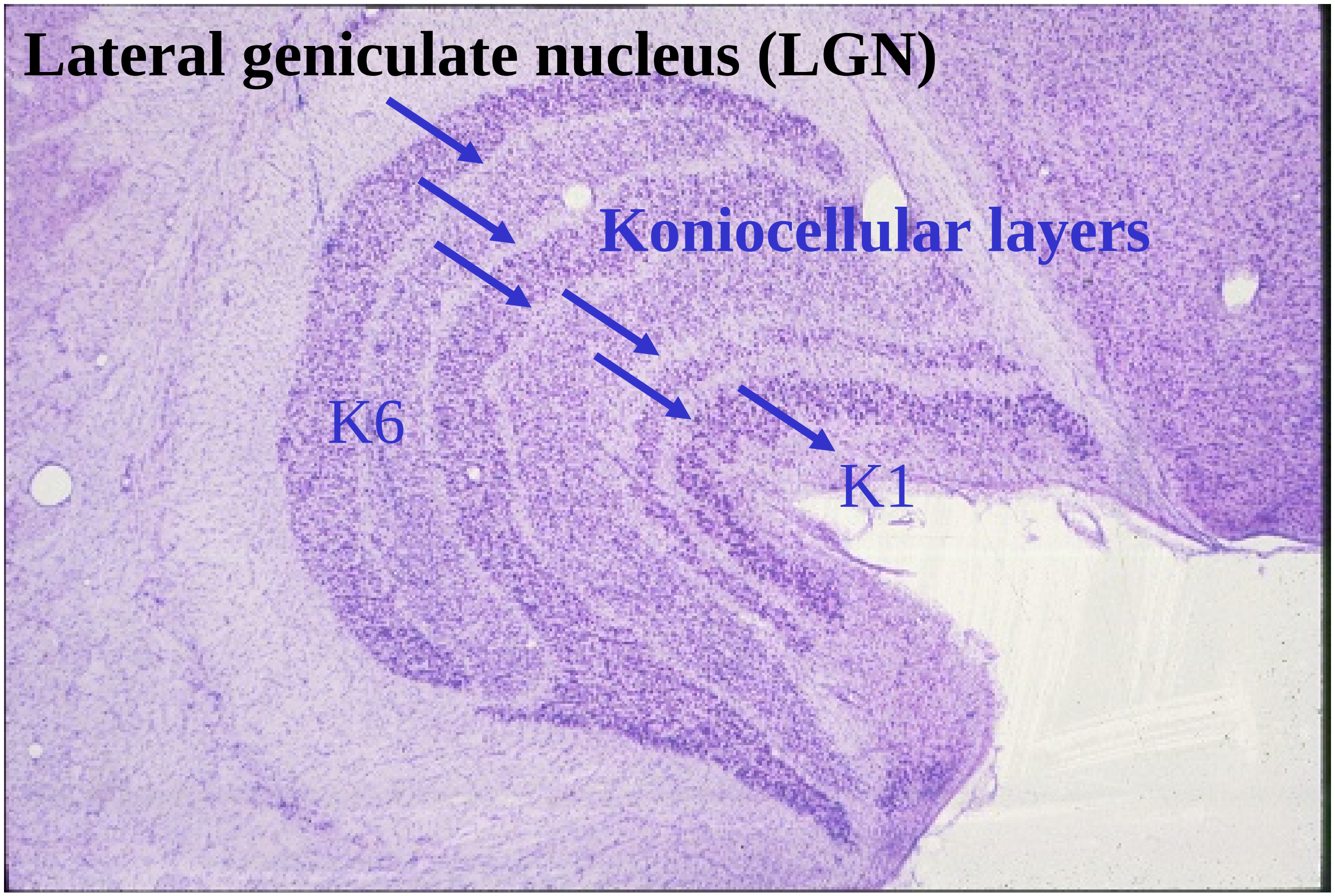
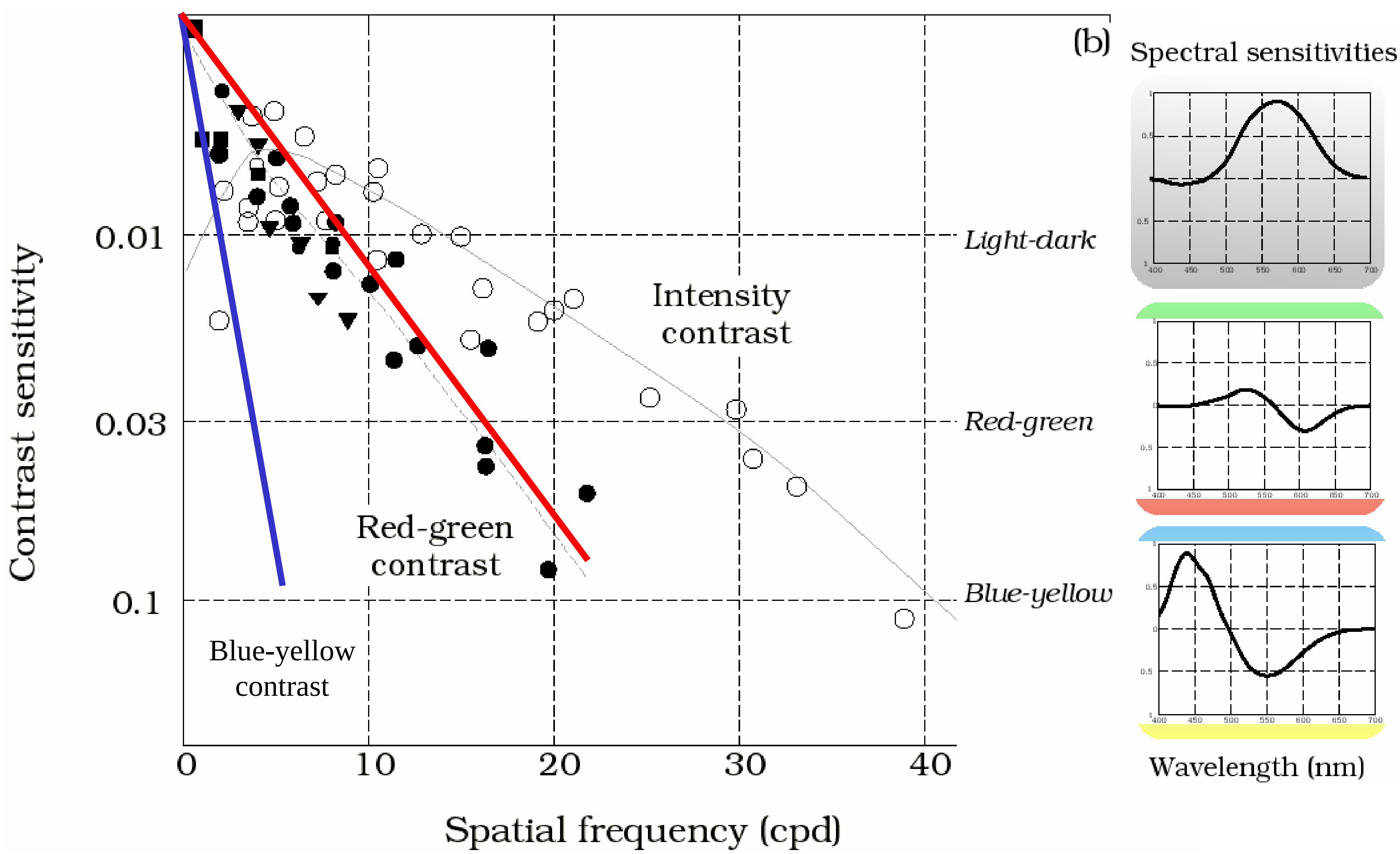
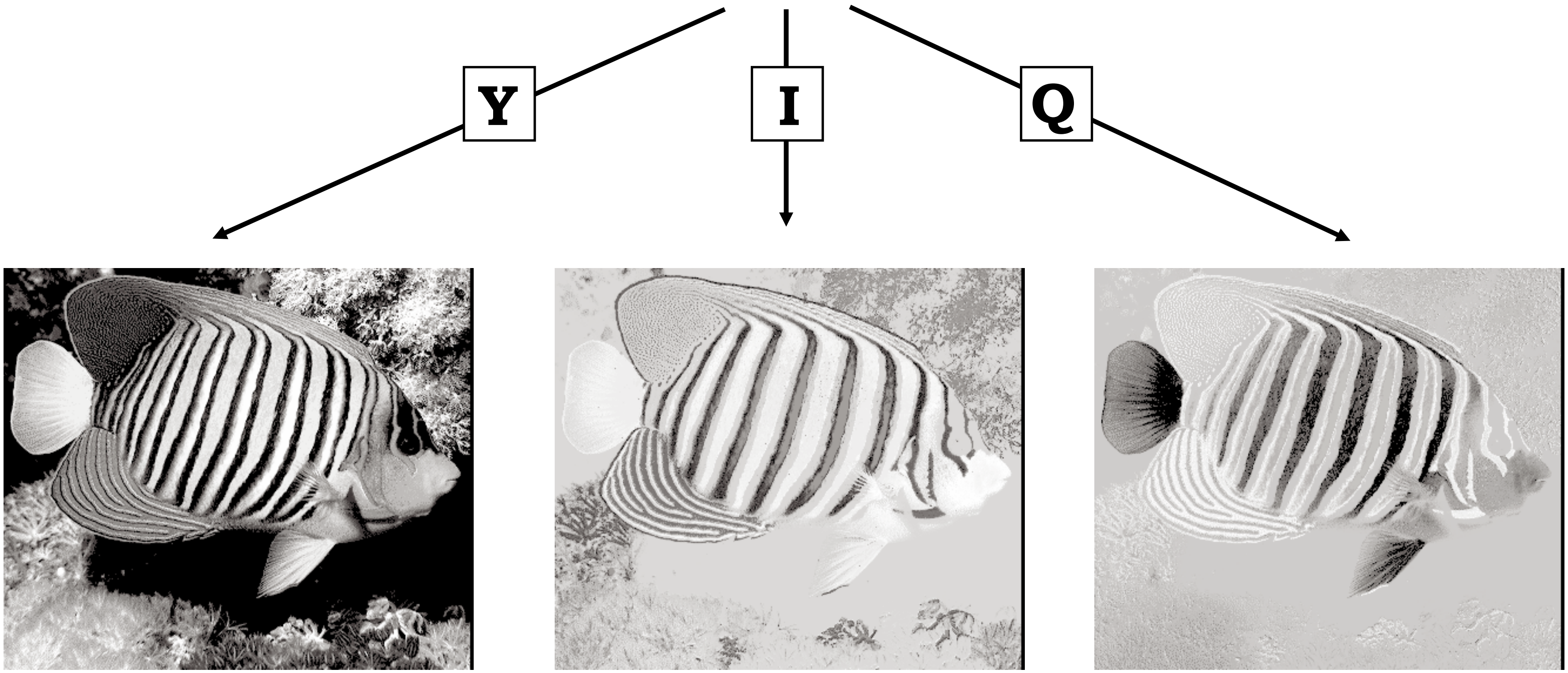
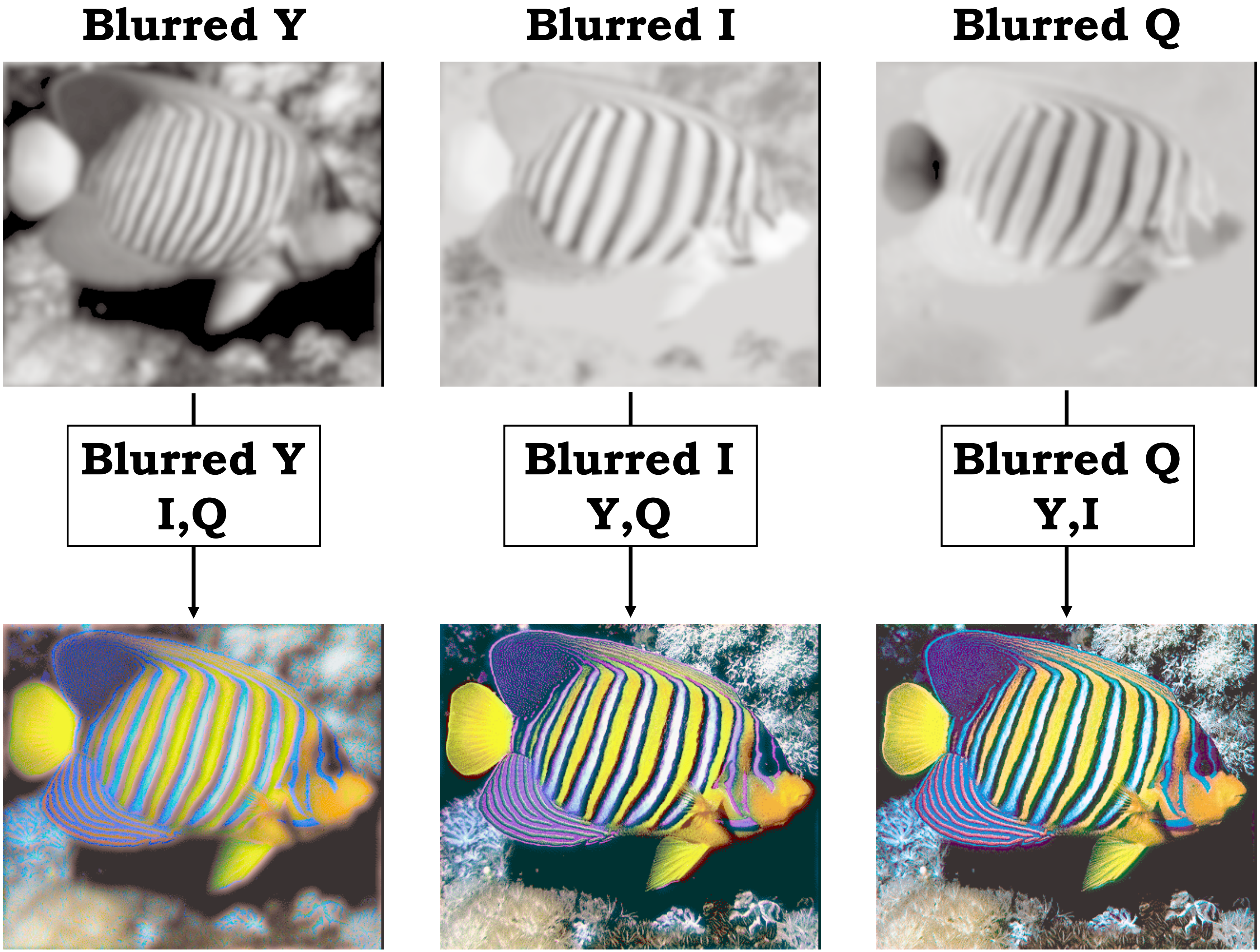


Pattern color sensitivity is best explained with respect to this representation (e.g., S-CIELAB references)



JPEG, NTSC and other transmission standards all use this representation

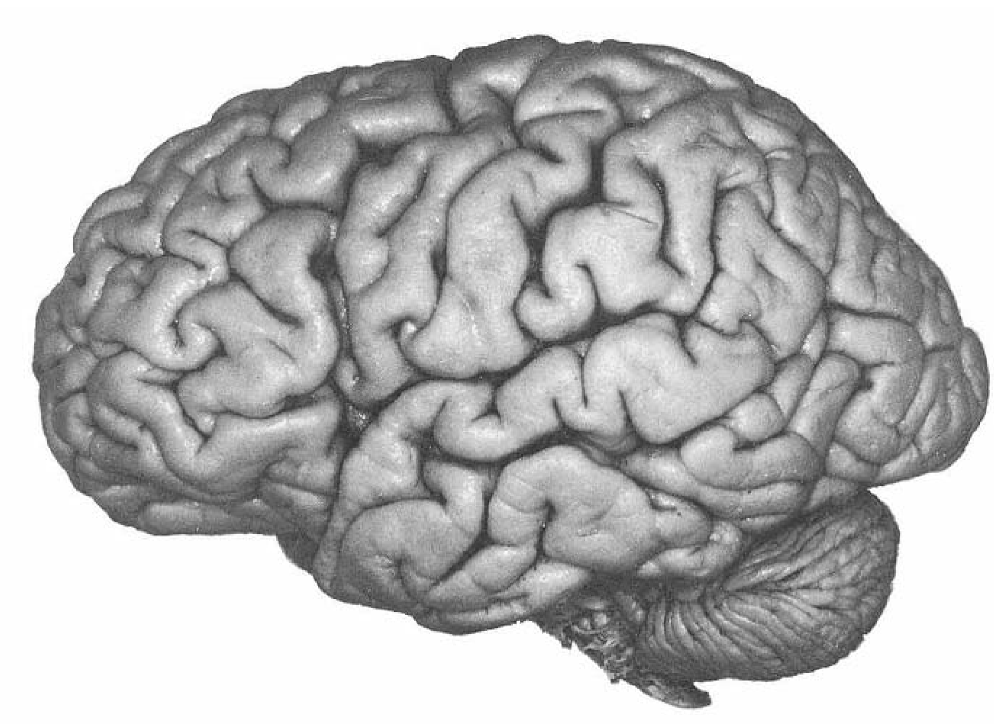



Blurred Y
Blurred I
Blurred Q
Blurred Y
I,Q
Blurred I
Y,Q
Blurred Q
Y,I

Human brain by the numbers

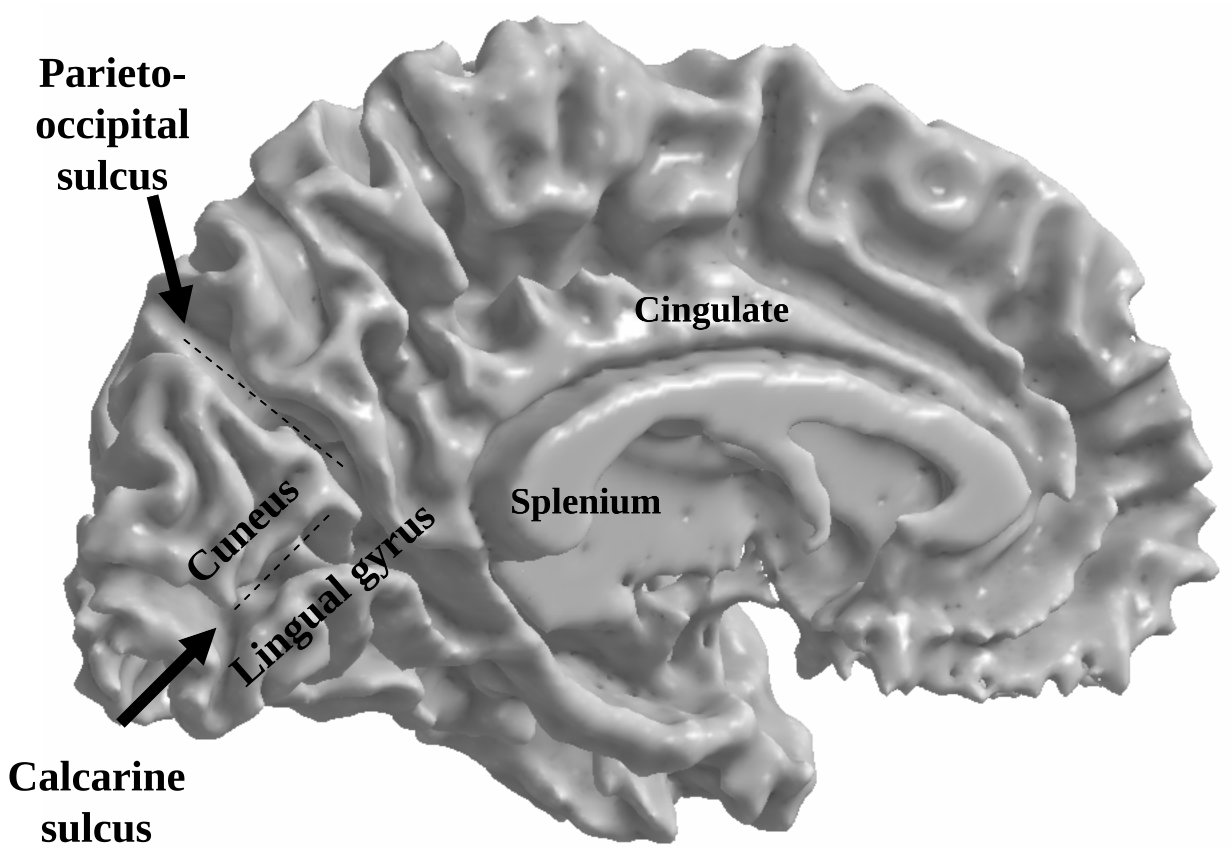
(Braitenberg and Schutz, 1991)

Neurons are the computational elements
White matter connects the neurons via axons
The connection is called the synapse



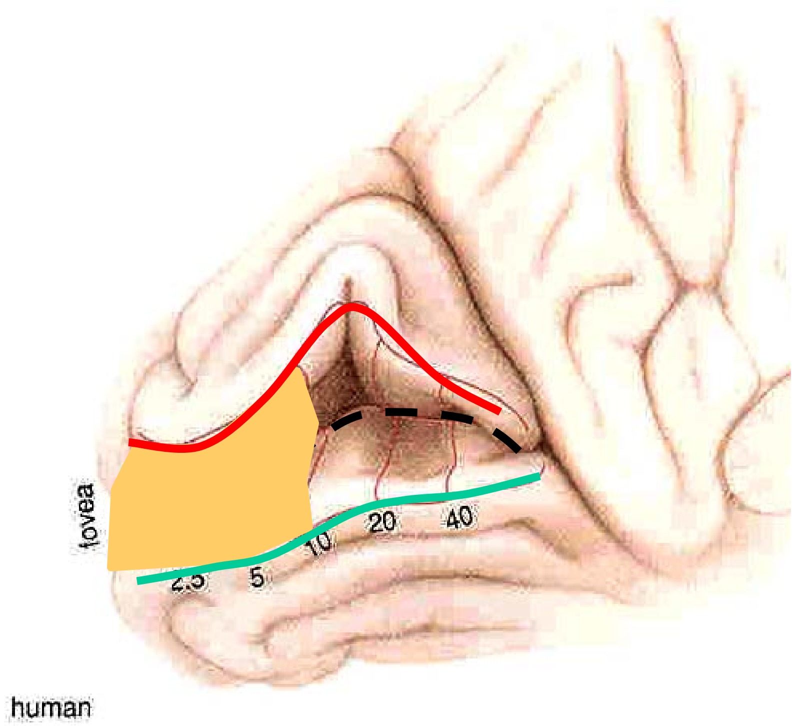
- Neurons: 10^{11} (total)
- Synapses: 10^{14} (total)
- Synapses/neuron 10^{3}
- Surface area of each hemisphere: 25 x 30 cm^2
- Most connections are local (10-100 um); some span many cm
- Neurons/mm^3: 10^4-10^6
- Axon length/mm^3: 3 km

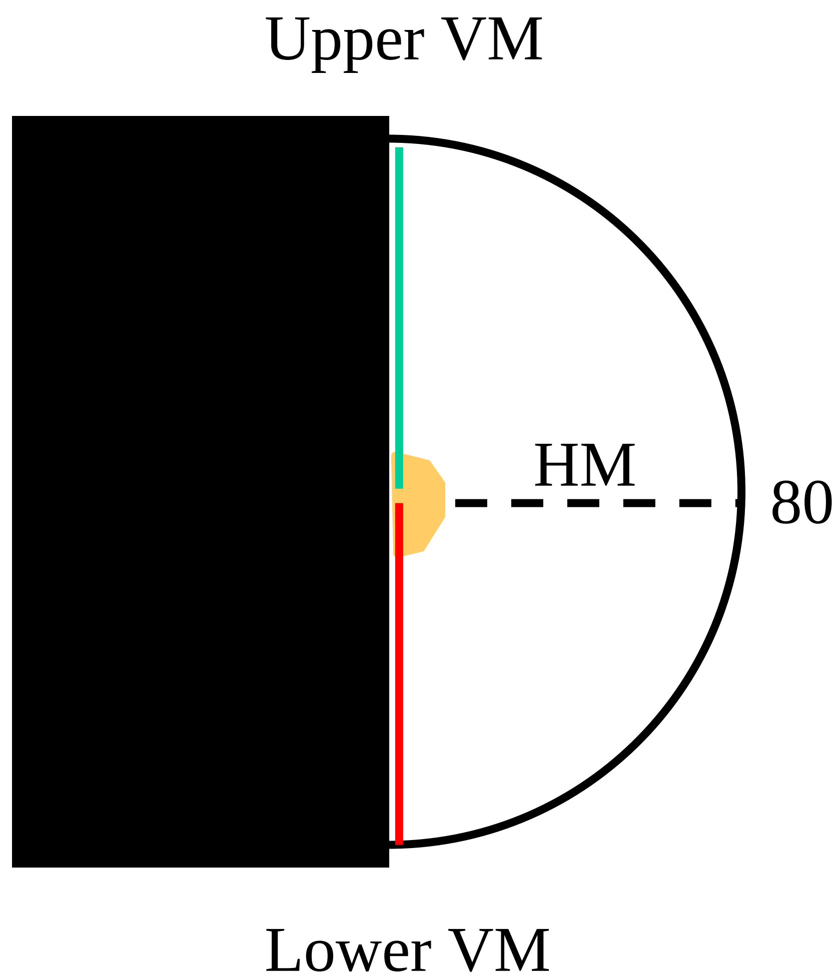
Sagittal view of the white matter surface of a human brain (mine)



Primary visual cortex is located mainly in calcarine cortex, wrapping around onto the lateral surface of the brain

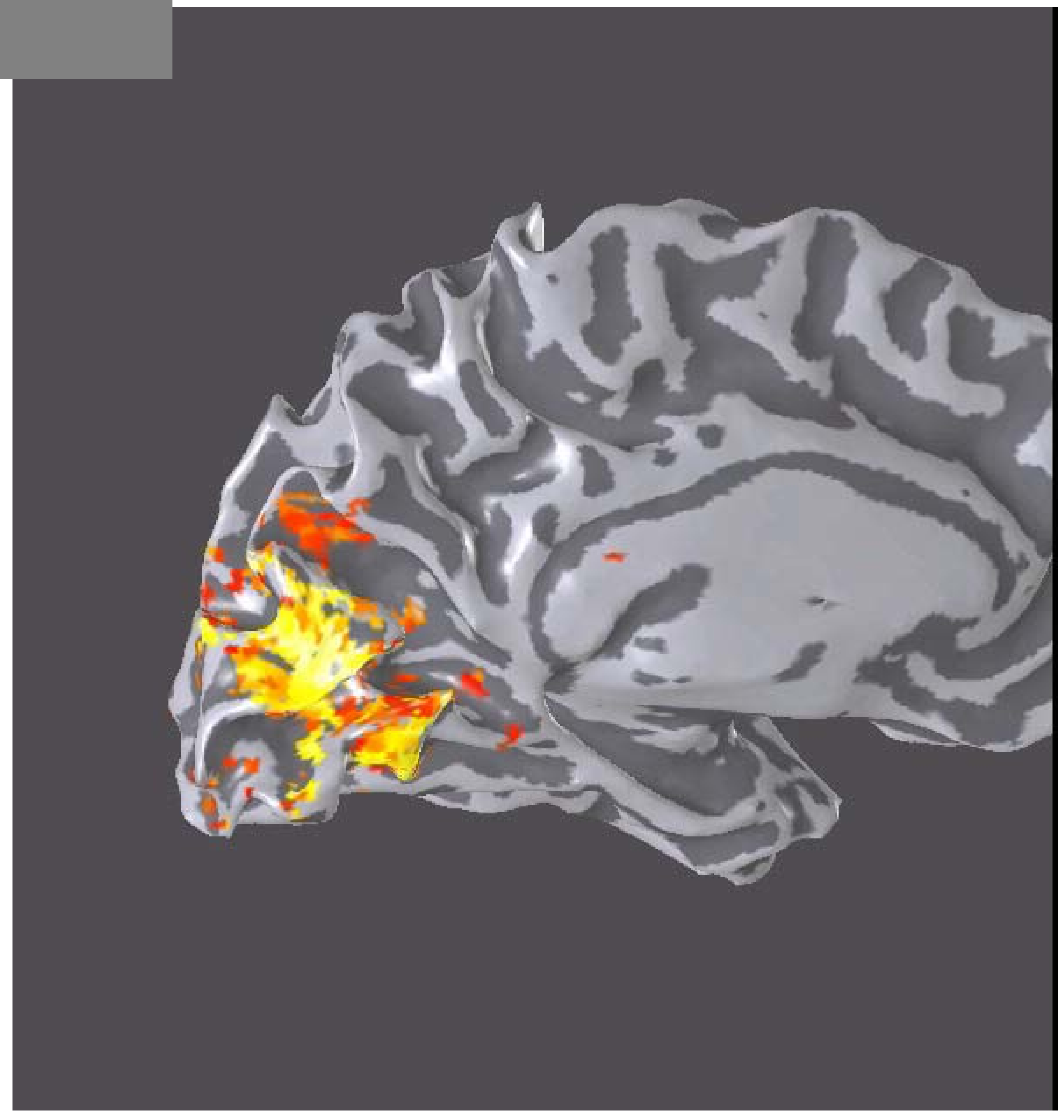
Primary visual cortex (V1) contains a visual field map





Human Eccentricity Mapping

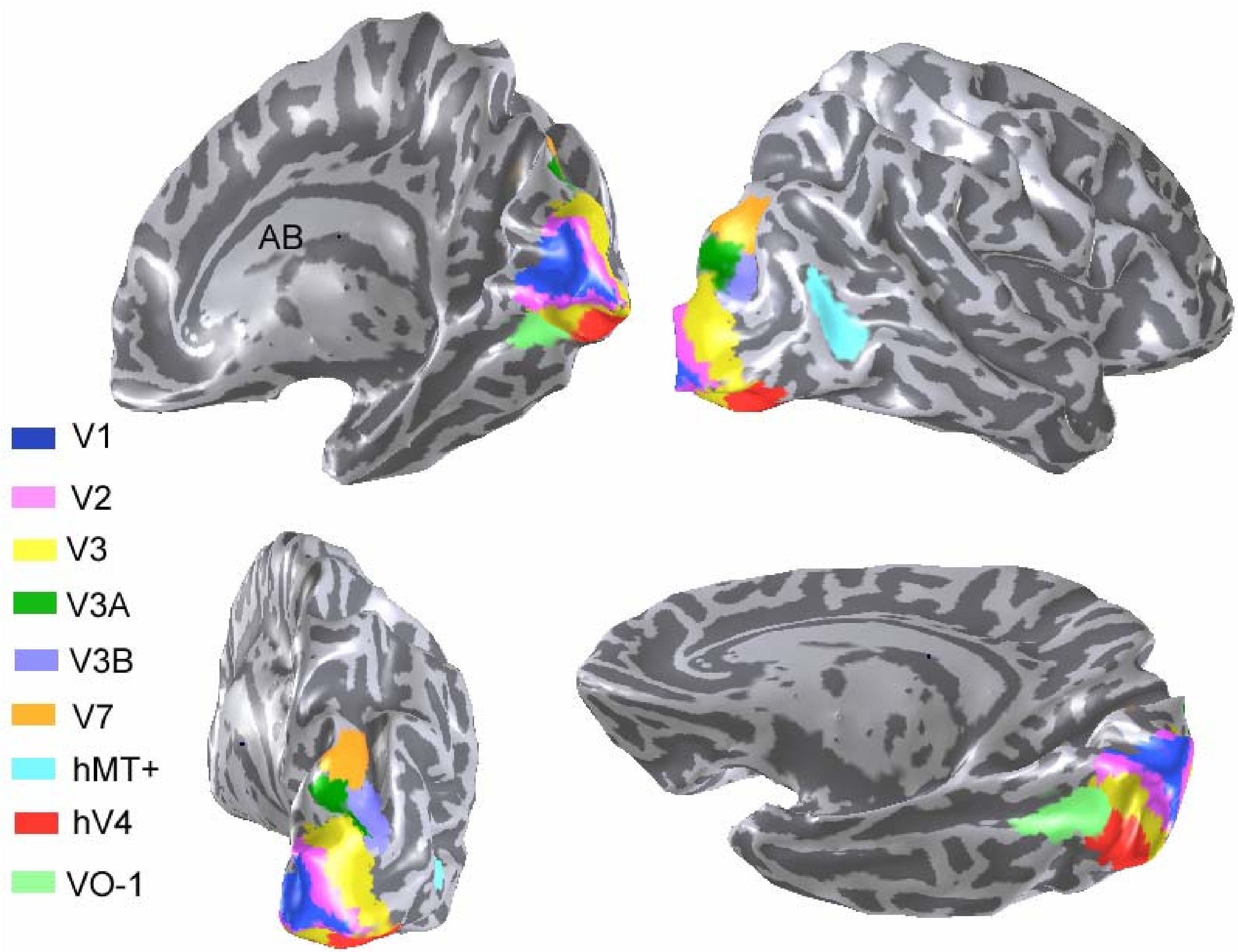
(Engel et al., 1994,1997; Sereno; DeYoe; Others)



Nine known visual field maps

More maps to come

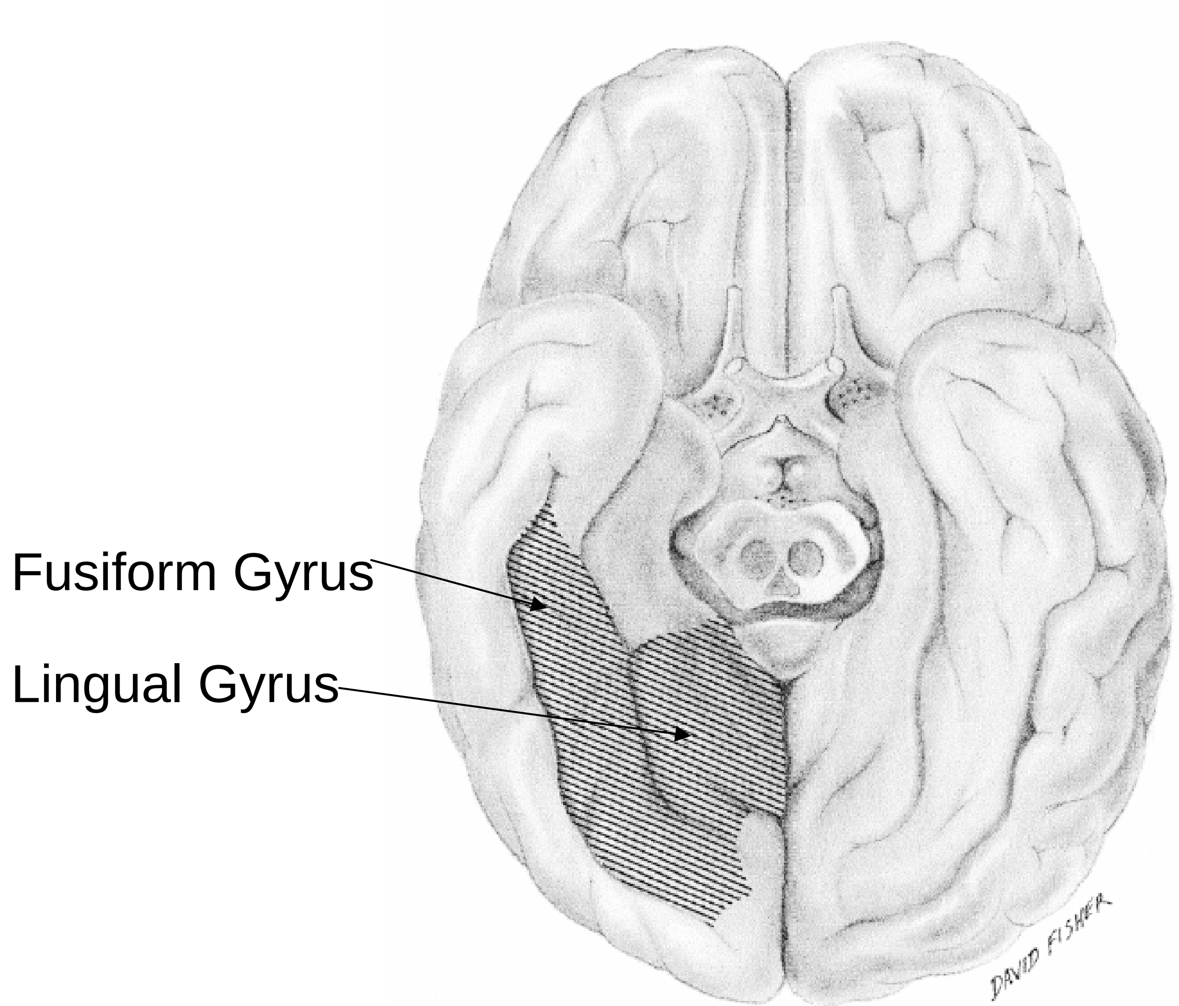
Reviewed in January 2005 Phil Trans Royal Society



Human ventral occipital cortex responds powerfully to color signals; Damage can cause a hemifield loss of color perception

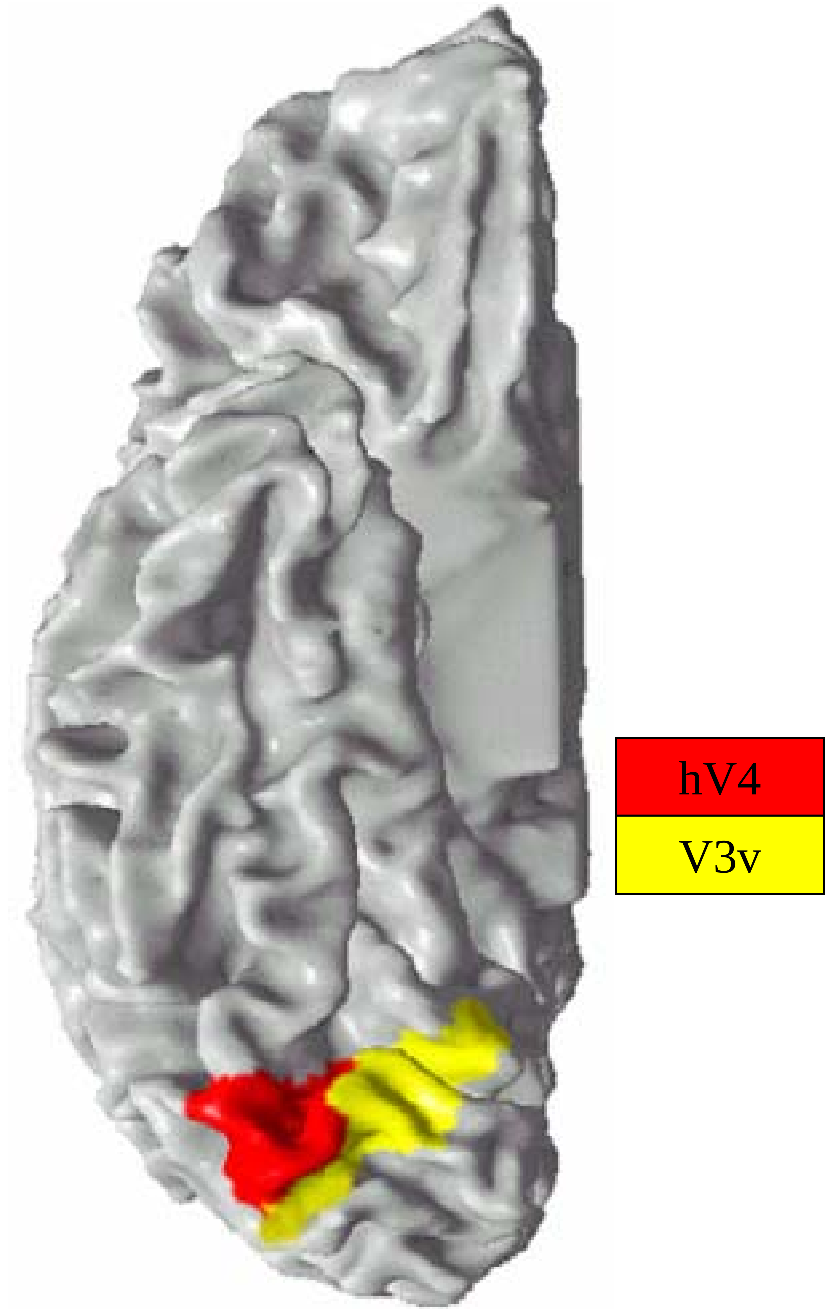
(Meadows)

Three-D view demos



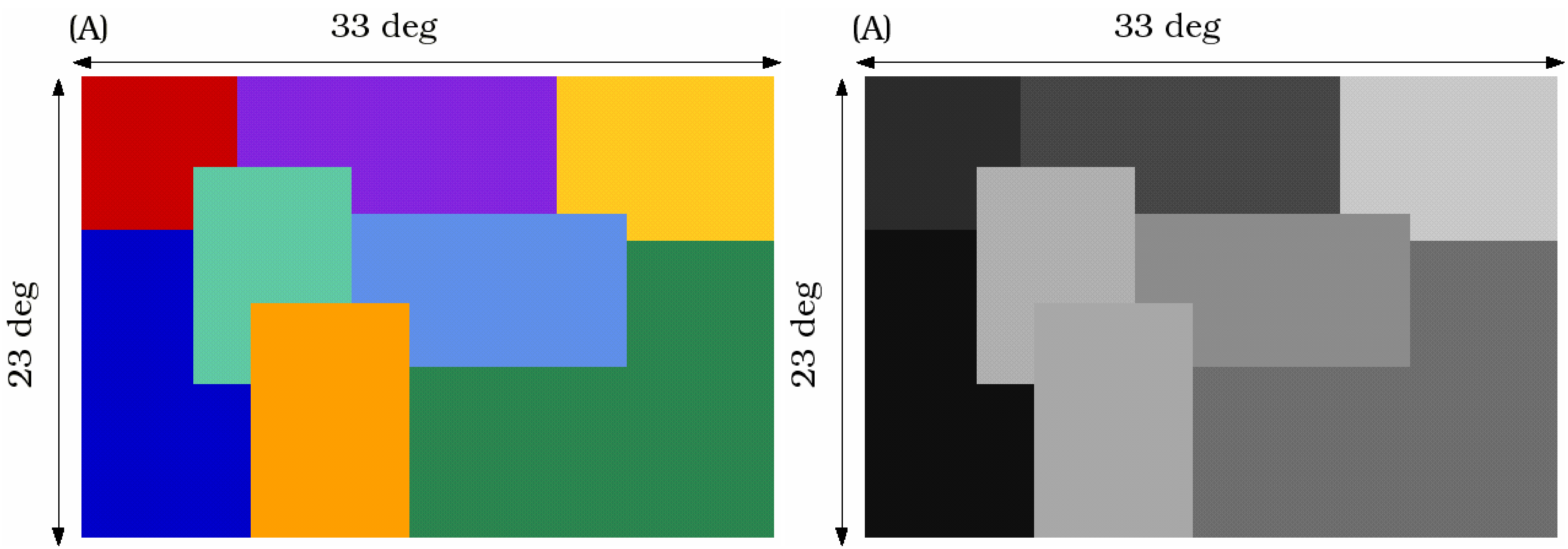
The human ventral surface contains a hemifield visual field map adjacent to V3

(Wade et al. 2002)

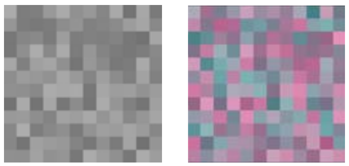


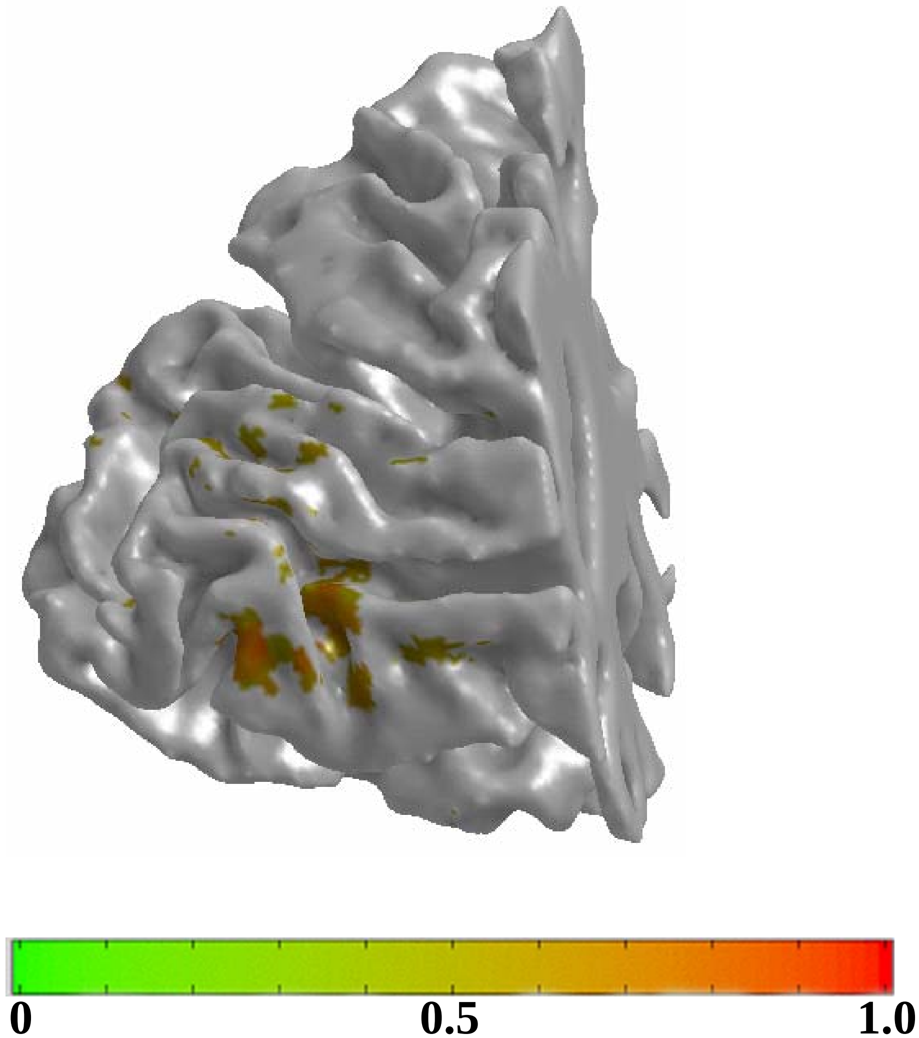
Exchange measurements are a way to begin the exploration of color signals in human cortex

(Zeki, many papers)

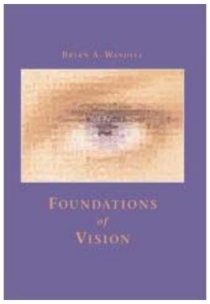


The color exchange experiments replicate well; largest response is ventral

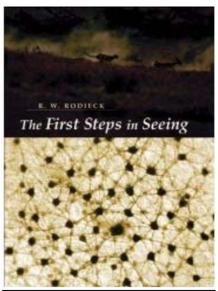




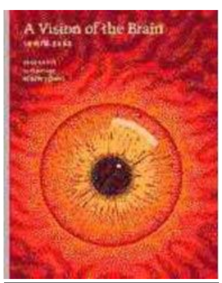
Annotated Bibliography



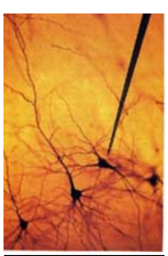
Foundations of Vision, 1995 (Sinauer Press)
B. A. Wandell
An introduction to the human visual pathways. Needs to be updated, but the author is an honest and decent fellow – I think. The book covers basic concepts concerning image formation, retinal encoding, color, visual cortex, and computational modeling of sensitivity and visual perception.



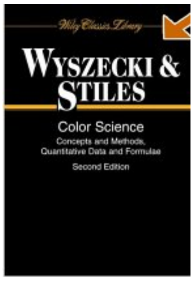
First Steps in Seeing (Sinauer Press)
R. W. Rodieck
Written to summarize his understanding at the end of his illustrious career. This is a fascinating and personal view of the retina written from a unique perspective. The book is beautifully illustrated and provides a detailed examination of the retinal circuitry and photochemistry.



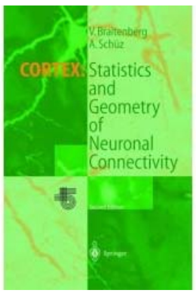
A Vision of the Brain (Blackwell)
Semir Zeki
Semir pioneered the anatomical and functional understanding of cortex beyond V1. He tells a great story over dinner, and his personality comes through nicely in this book. This is a personal account, not a basic textbook. It is a wonderful personal account, particularly if you like Semir.



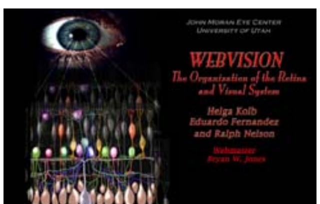
Eye, Brain and Vision (Scientific American library)
D. Hubel
A summary of this Nobel Laureate's investigation into the brain, mainly done collaboration with Wiesel. An online form of the book can be found at
http://neuro.med.harvard.edu/site/dh/bcontex.htm

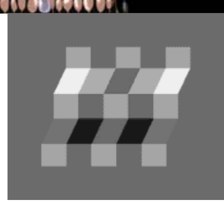


Color Science : Concepts and Methods, Quantitative Data and Formulae (Wiley)
G. Wyszecki and W. S. Stiles
This is the classic book for formulae concerning color science. While it is now out of date for technology, it is the definitive volume for radiometry and colorimetry.
An excellent online source of data is: http://www.cvrl.org/



Cortex: Statistics and Geometry of Neuronal Connectivity (Springer)
Braitenberg and Schuz
A fascinating slim volume concerning the form and connectivity of the cortical circuitry. The volume is filled with suggestions about the implications of these numbers for computation.





Online resources
Many scientists publish PDF format of their papers online; these can be found using Google Scholar. My papers, for example, are at http://white.stanford.edu/~brian/refs

Webvision
http://webvision.med.utah.edu
This excellent web-site is filled with good explanations and nice images of the visual pathways. It is an excellent resource for downloadable teaching material that emphasizes the neural basis of vision.

Viperlib
A excellent site for general materials is:
http://viperlib.york.ac.uk/links_websites.asp

Vischeck
A fun site for color vision and color deficiency tests:
http://www.vischeck.com/
There are many sites that collect interesting visual illusions. Here are some that I use from time to time.

http://www.michaelbach.de/ot/
http://www.patmedia.net/marklevinson/cool/cool_illusion.html
http://www.ritsumei.ac.jp/~akitaoka/saishin-e.html