

Color appearance: Light, brain, and perception

Brian A. Wandell

Deputy Directory, Wu Tsai Neurosciences Institute

Director, Center for Cognitive and Neurobiological Imaging

Psychology Department, Stanford

QUANTITATIVE MEASUREMENTS

∞

COMPUTATIONAL MODELS

∞

CHECK AND SHARE

Human vision works reasonably well without some of its subsystems.

For example, we can see the leaves and berries in this image even though we are deprived of wavelength information.



Goldstein textbook
Sensation and Perception

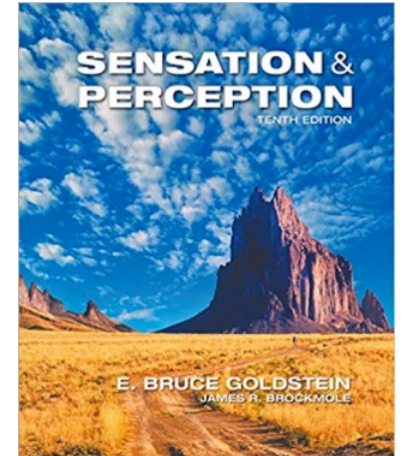


Fig. 7-1b, p.

Human vision works reasonably well without some of its subsystems.

For example, we can see the leaves and berries in this image even though we are deprived of wavelength information.

Providing the information helps vision distinguish objects.

The “good but not absolutely necessary” characterization is true of other systems, such as stereo perception.



© 2007 Thomson Higher Education

Goldstein textbook
Sensation and Perception

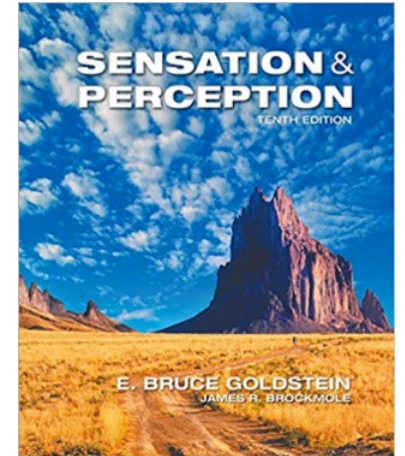


Fig. 7-1a, p.

The visual system interprets the wavelength information.

Some interpretation (processing) is done in the peripheral pathways (retina)

Some interpretation is done in central brain (cortex, thalamus).

Lightness
Perception
(Lotto and Purves)

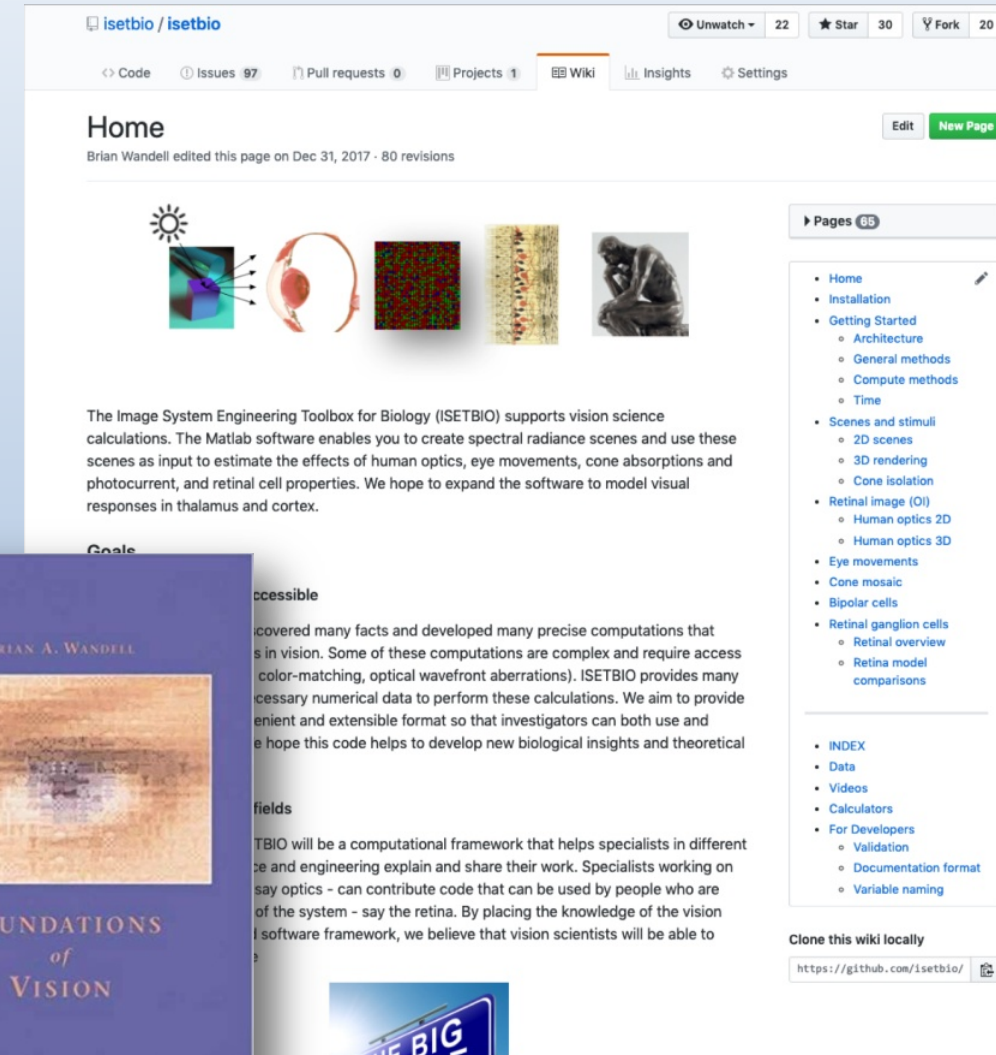
Goals for this 40 minute presentation

Describe how two centuries of physics, psychology and neuroscience enable us to model the early parts of the visual pathways quantitatively

Explain how these quantitative measurements and models establish a relationship between certain neural responses and aspects of color

Speculate about what is next

Github – ISETBio project



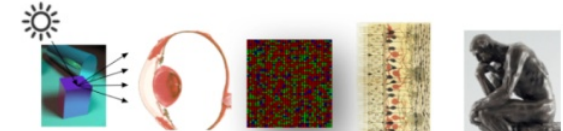
isetbio / isetbio

Unwatch 22 Star 30 Fork 20

Code Issues 97 Pull requests 0 Projects 1 Wiki Insights Settings

Home

Brian Wandell edited this page on Dec 31, 2017 · 80 revisions



Pages 35

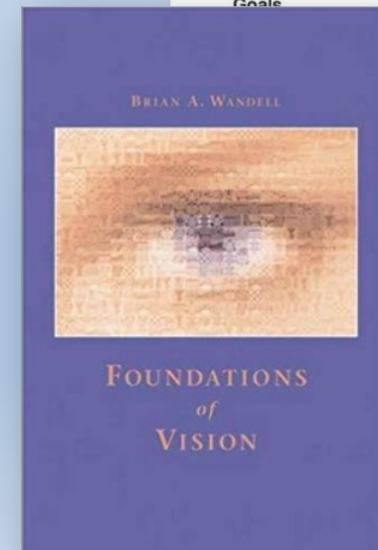
- Home
- Installation
- Getting Started
 - Architecture
 - General methods
 - Compute methods
 - Time
- Scenes and stimuli
 - 2D scenes
 - 3D rendering
 - Cone isolation
- Retinal image (OI)
 - Human optics 2D
 - Human optics 3D
- Eye movements
- Cone mosaic
- Bipolar cells
- Retinal ganglion cells
 - Retinal overview
 - Retina model comparisons

INDEX

- Data
- Videos
- Calculators
- For Developers
 - Validation
 - Documentation format
 - Variable naming

Clone this wiki locally

<https://github.com/isetbio/>

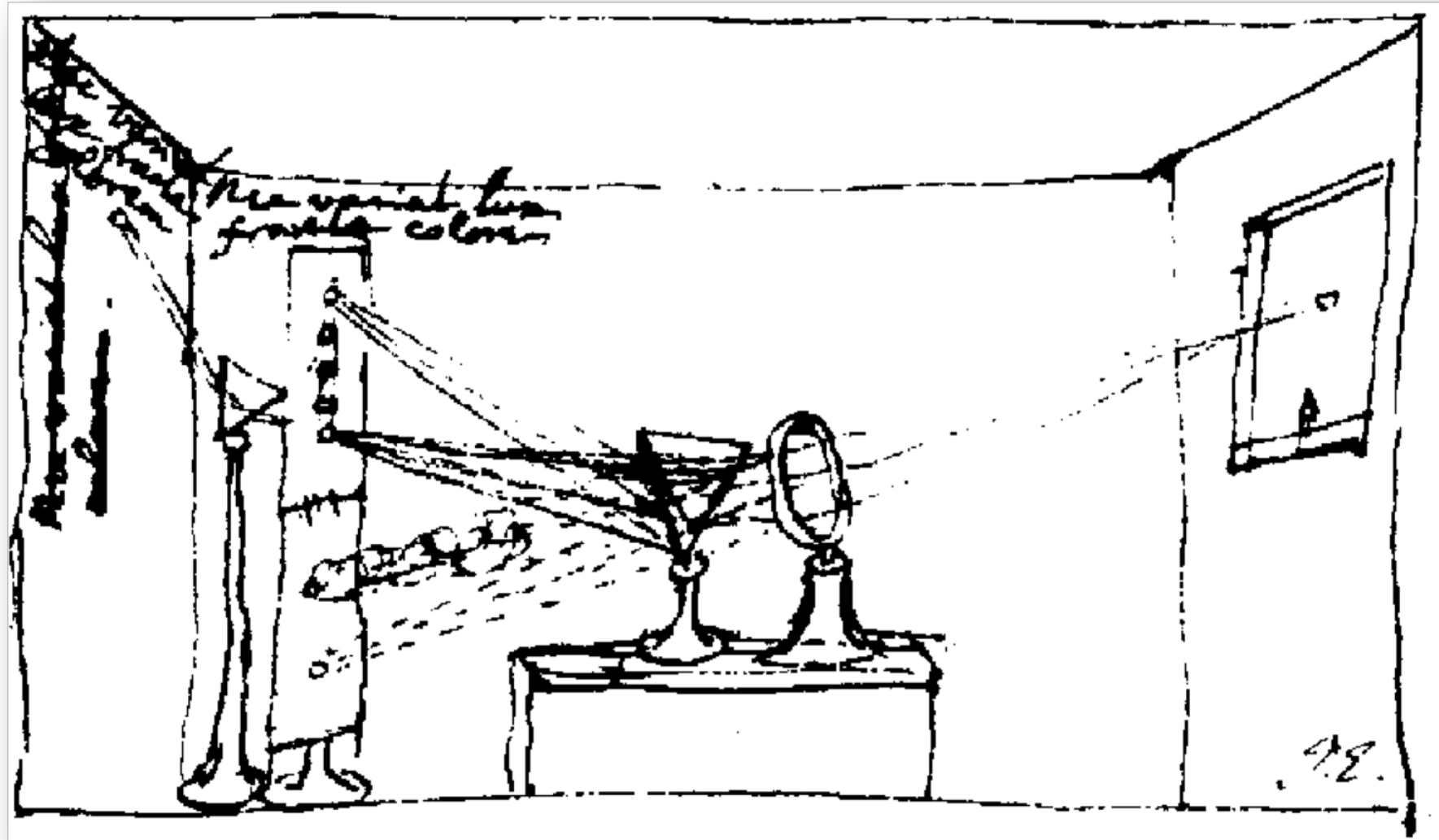


History: The color and the uniform spatial patch



The fundamental components of light

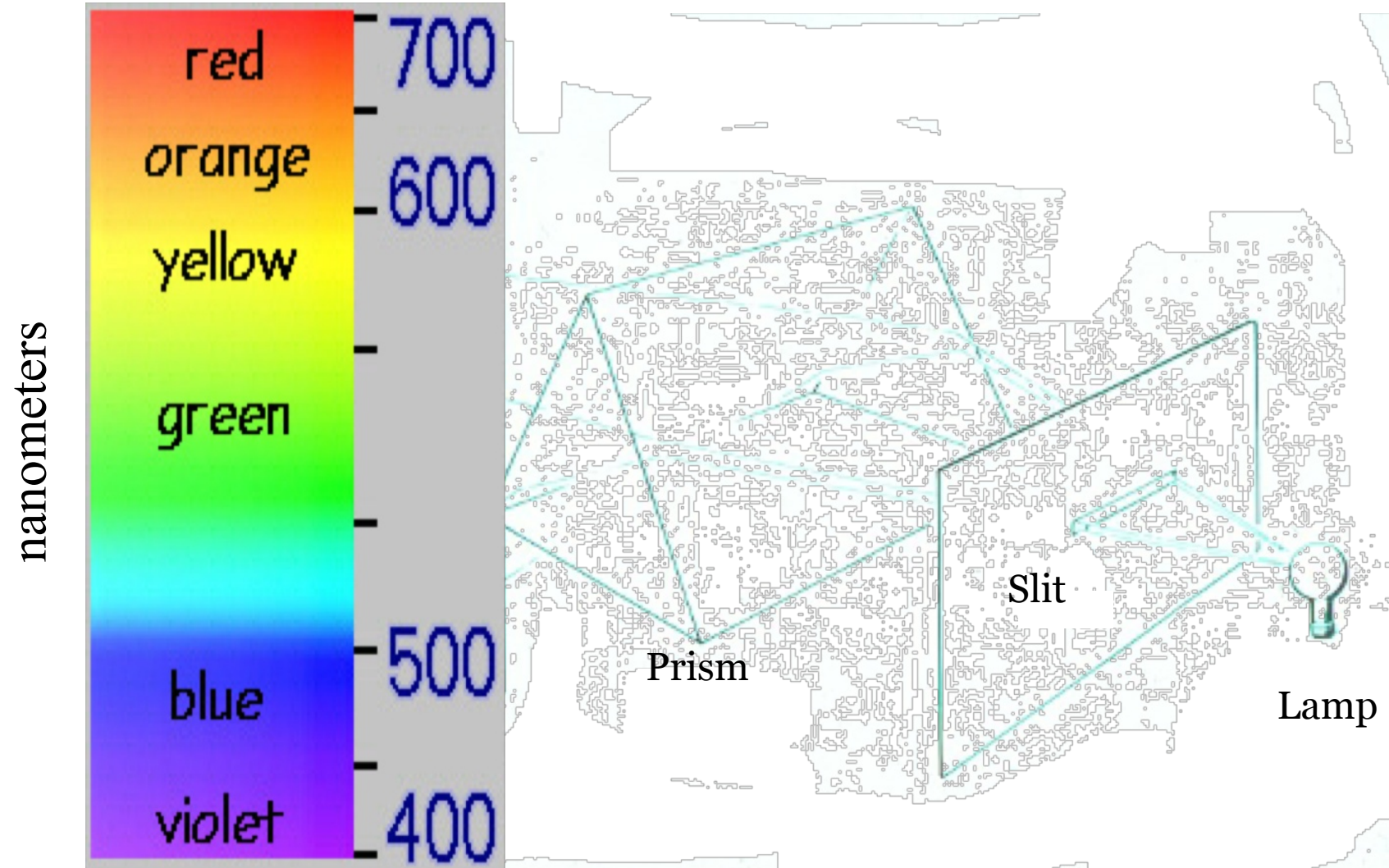
Demonstration that sunlight is comprised of waves of differing 'refrangibility'



Spectroradiometers (double-prism design)

Demonstration that sunlight is comprised of waves of differing 'refrangibility'

Until 30 years ago, most spectroradiometers used a version of Newton's design

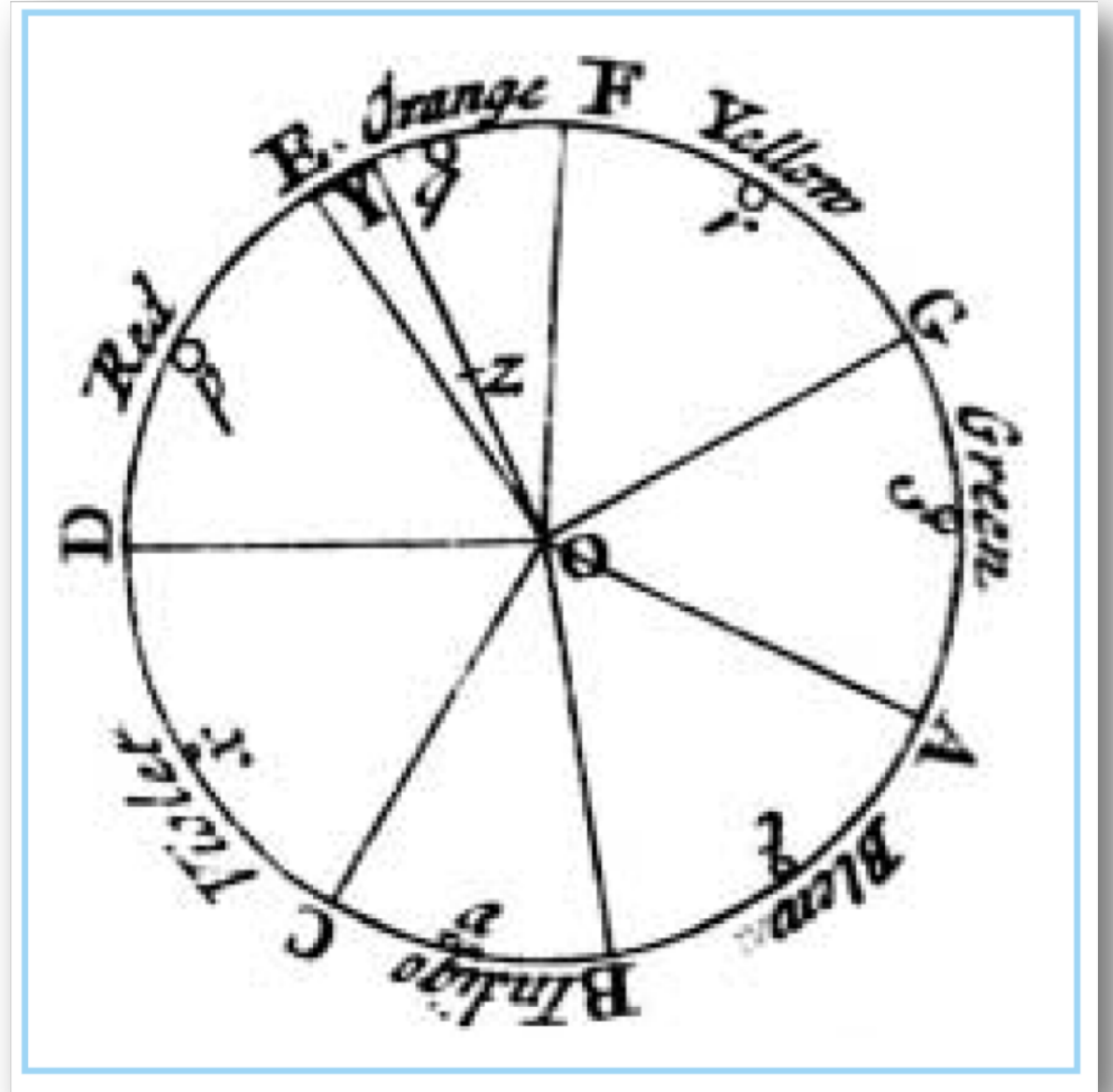


Newton as a psychologist (Opticks, 1704)

“For the rays to speak properly are not coloured. In them there is nothing else than a certain power and disposition to stir up a sensation of this or that Colour (Newton)”

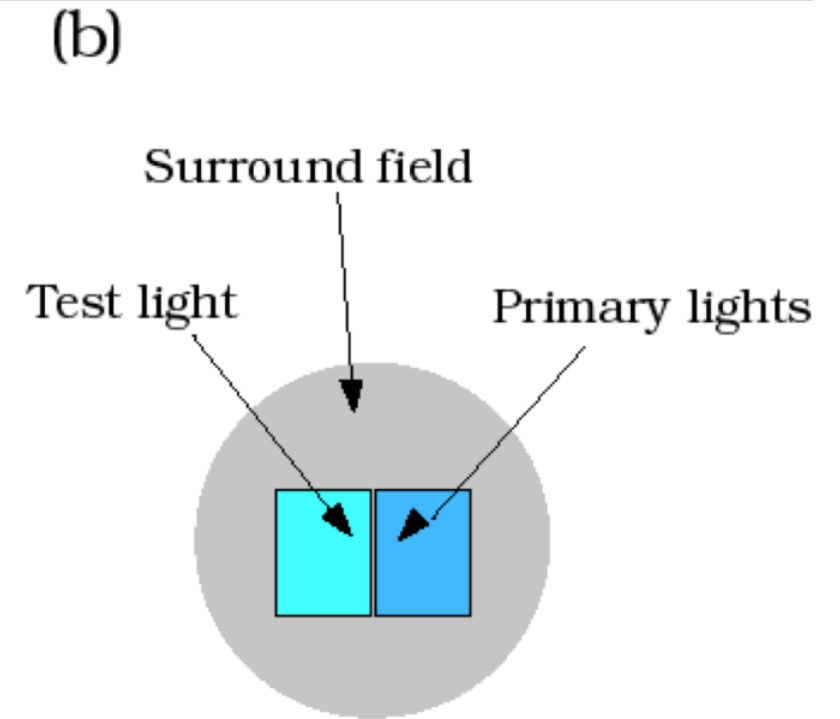
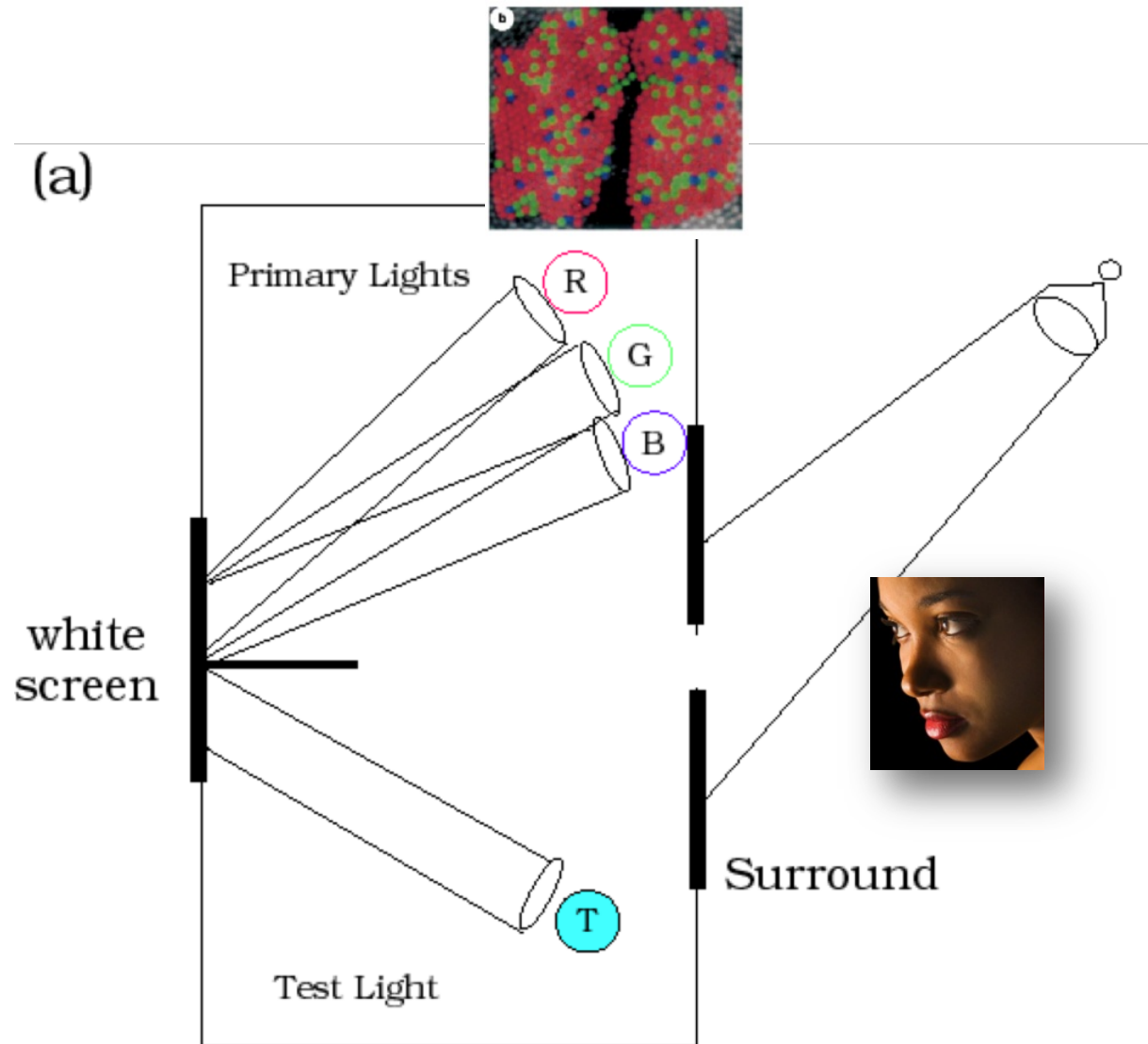
The color circle – a good idea that contained an error addressed by Helmholtz.

Newton combined psychology and physics.
Placing the colors on a circle was an error,
subsequently fixed by Helmholtz.



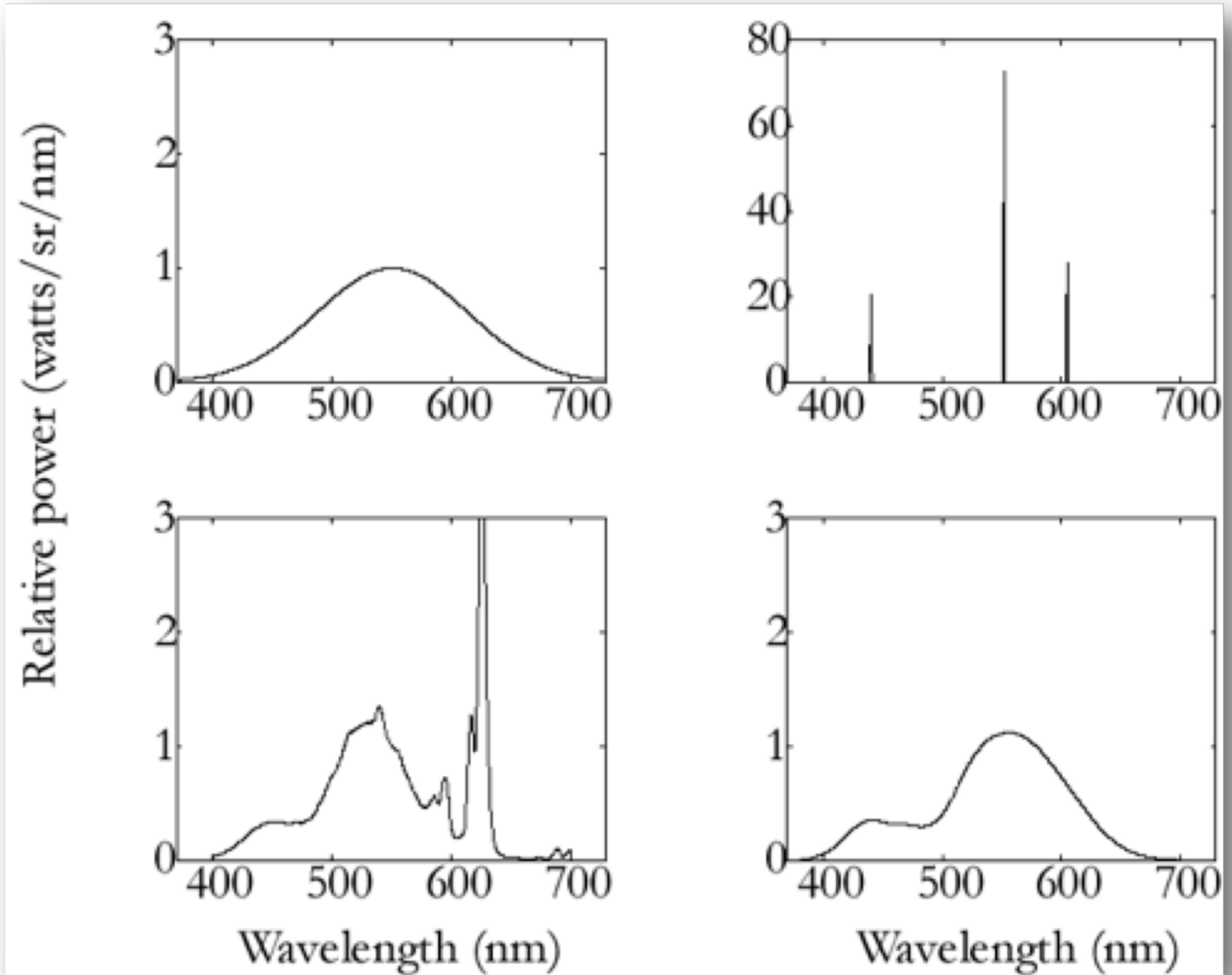
(From Mollon Chapter in Science of Color)

Cone color matching experiment (cone vision)



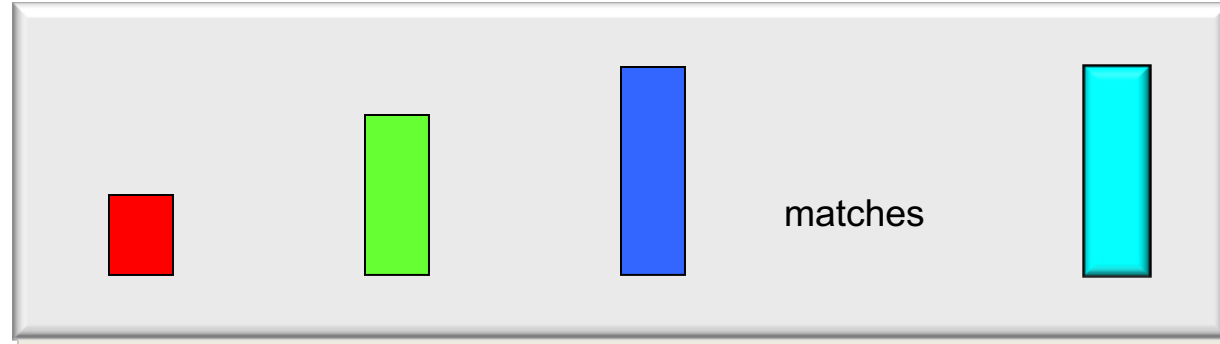
Metamerism is a big effect

These spectral power distributions appear the same color to the eye



The color matching experiment is linear

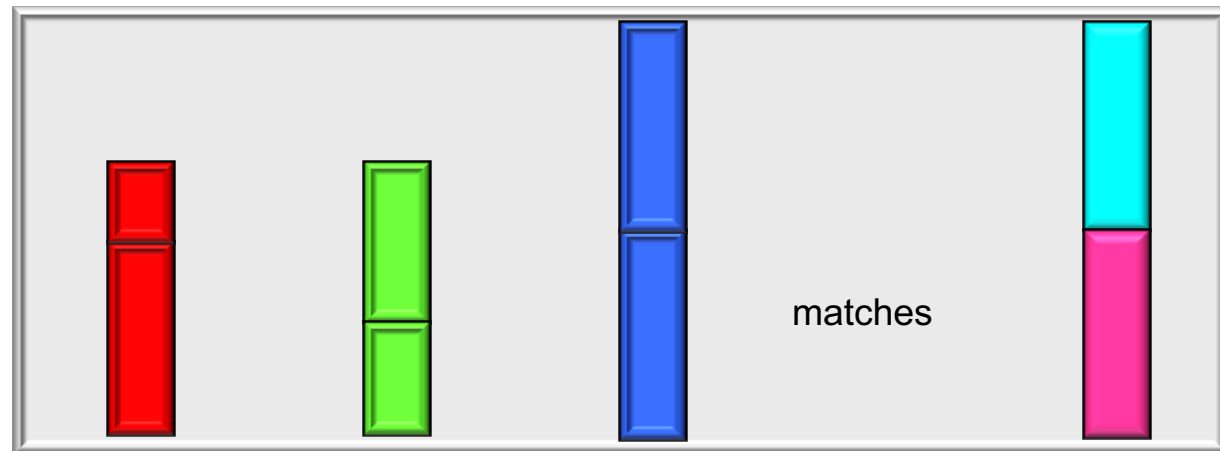
If



and



then

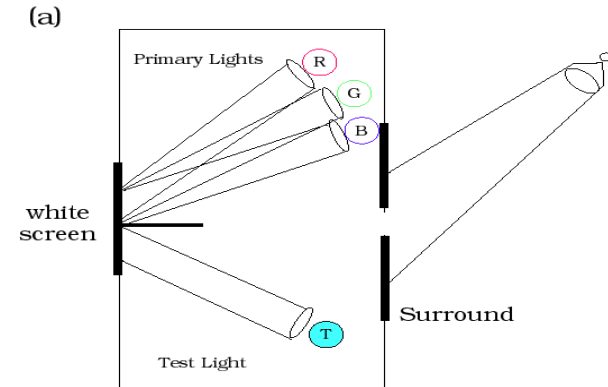


Color matching experiment equation



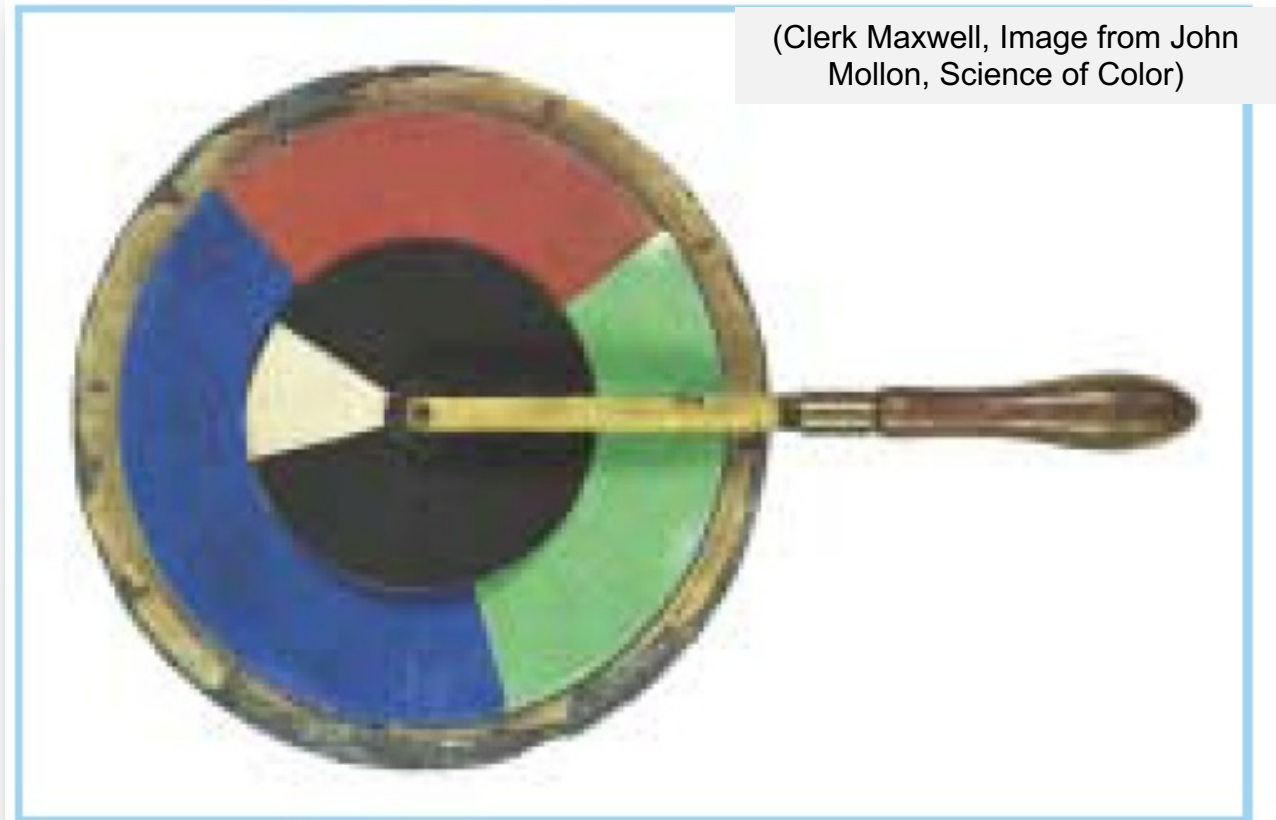
Historical note: Grassmann's laws of color-matching were the motivation for his mathematical development of high dimensional linear algebra methods. He developed them to defend Newton against Helmholtz.

$$\begin{array}{c} \text{Response} \\ \left(\begin{array}{c} R \\ G \\ B \end{array} \right) \end{array} = \begin{array}{c} \text{CIE RGB functions} \\ \left(\begin{array}{c} \text{---} r(\lambda) \text{---} \\ \text{---} g(\lambda) \text{---} \\ \text{---} b(\lambda) \text{---} \end{array} \right) \end{array} \left(\begin{array}{c} E(\lambda) \\ \text{Test light SPD} \end{array} \right)$$



Original color-matching technology

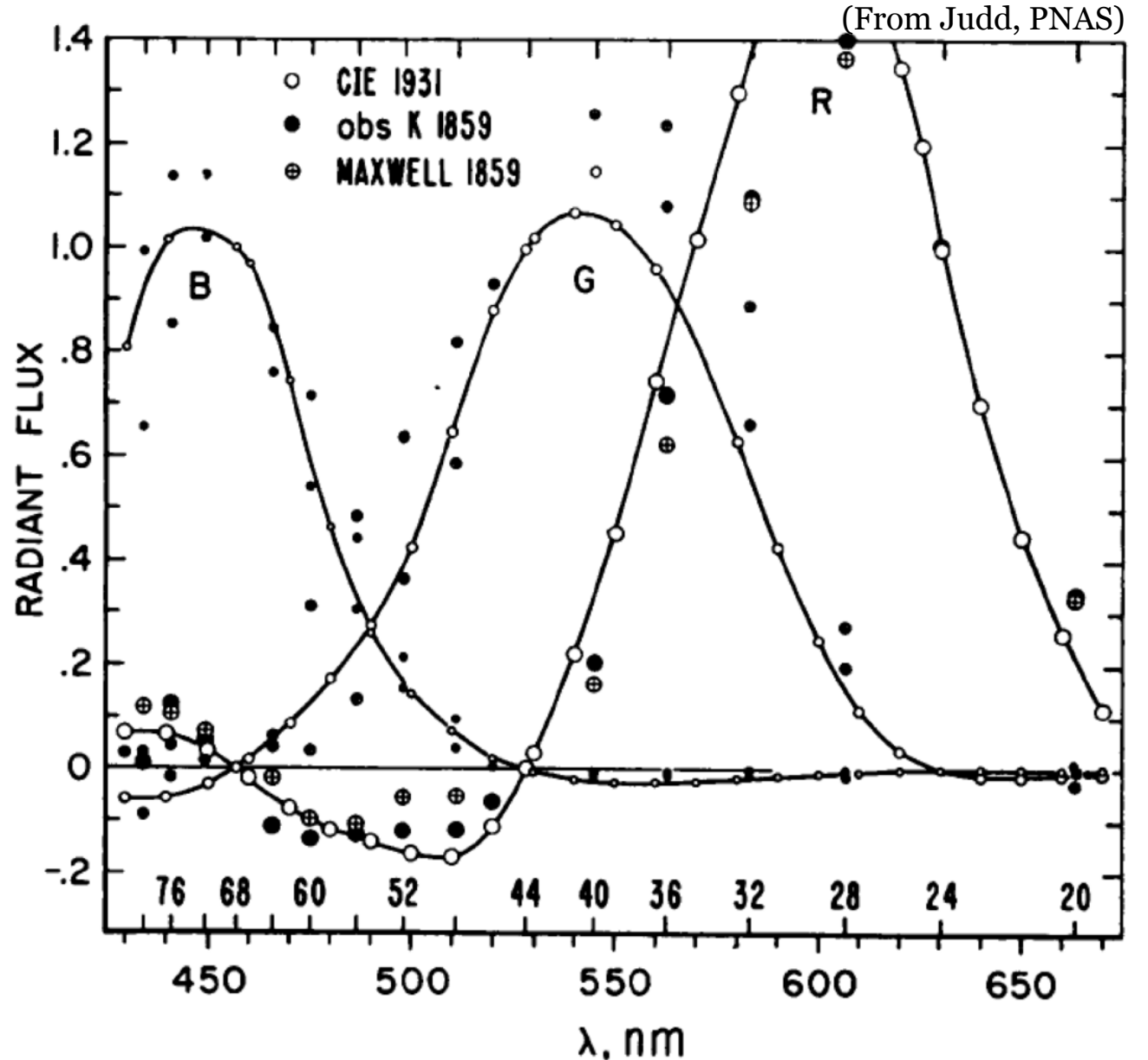
In the course of his 1855 paper on the perception of colour, Maxwell proposed that if three black-and-white photographs of a scene were taken through red, green and blue filters, and transparent prints of the images were projected onto a screen using three projectors equipped with similar filters, when superimposed on the screen the result would be perceived by the human eye as a complete reproduction of all the colours in the scene (Wikipedia),



(Clerk Maxwell, Image from John Mollon, Science of Color)

Figure 1.19 The color-mixing top of James Clerk Maxwell. The instrument survived in the collection of the Cavendish Laboratory, Cambridge. This photograph was taken in 1982. (Copyright: Department of Experimental Psychology, Cambridge University, reproduced with permission.)

The first color-matching functions



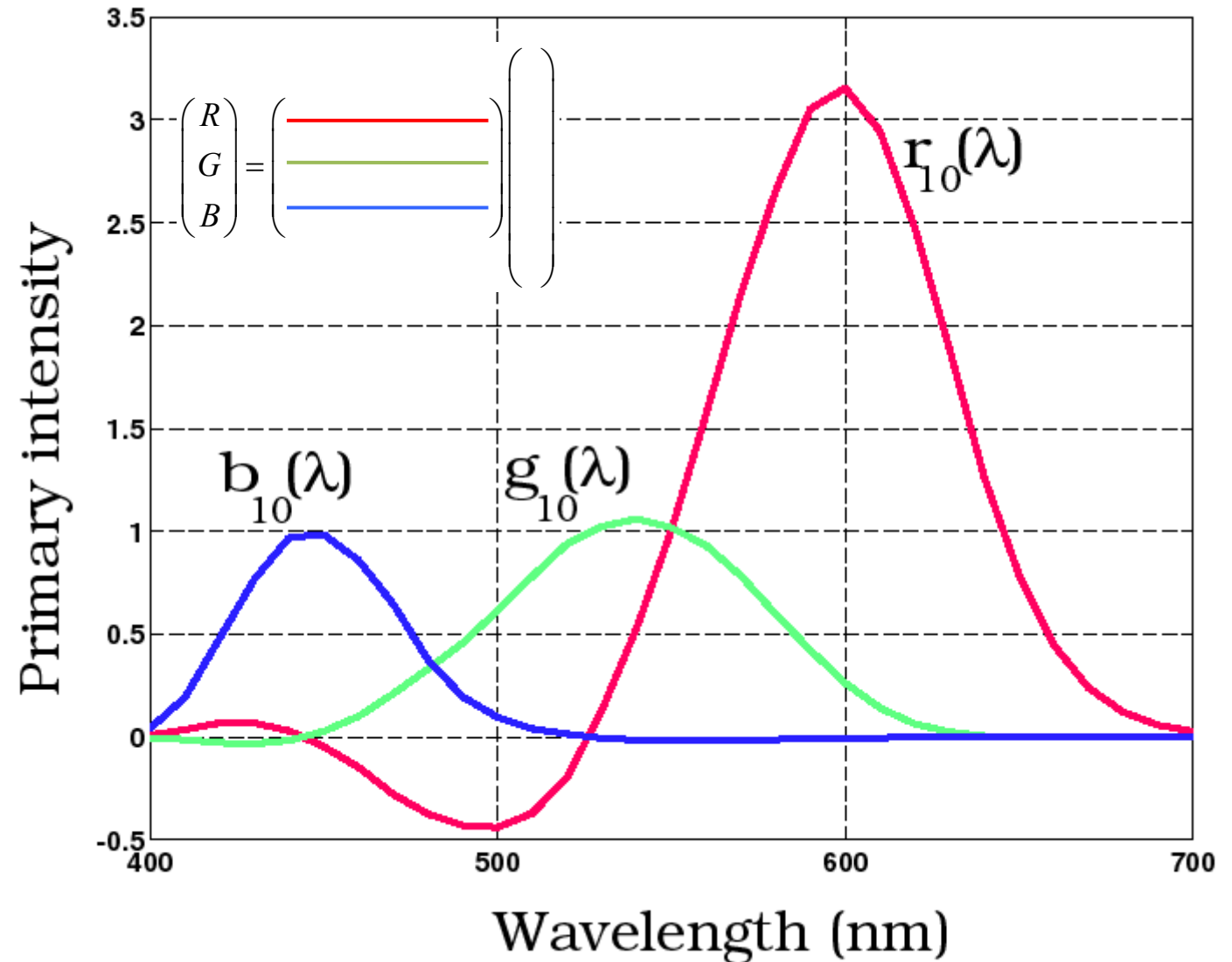
Maxwell
Observer K – JCM's spouse
Comparison with 1931 Standard observer

Behavioral color matching functions (CMFs; 10 deg)

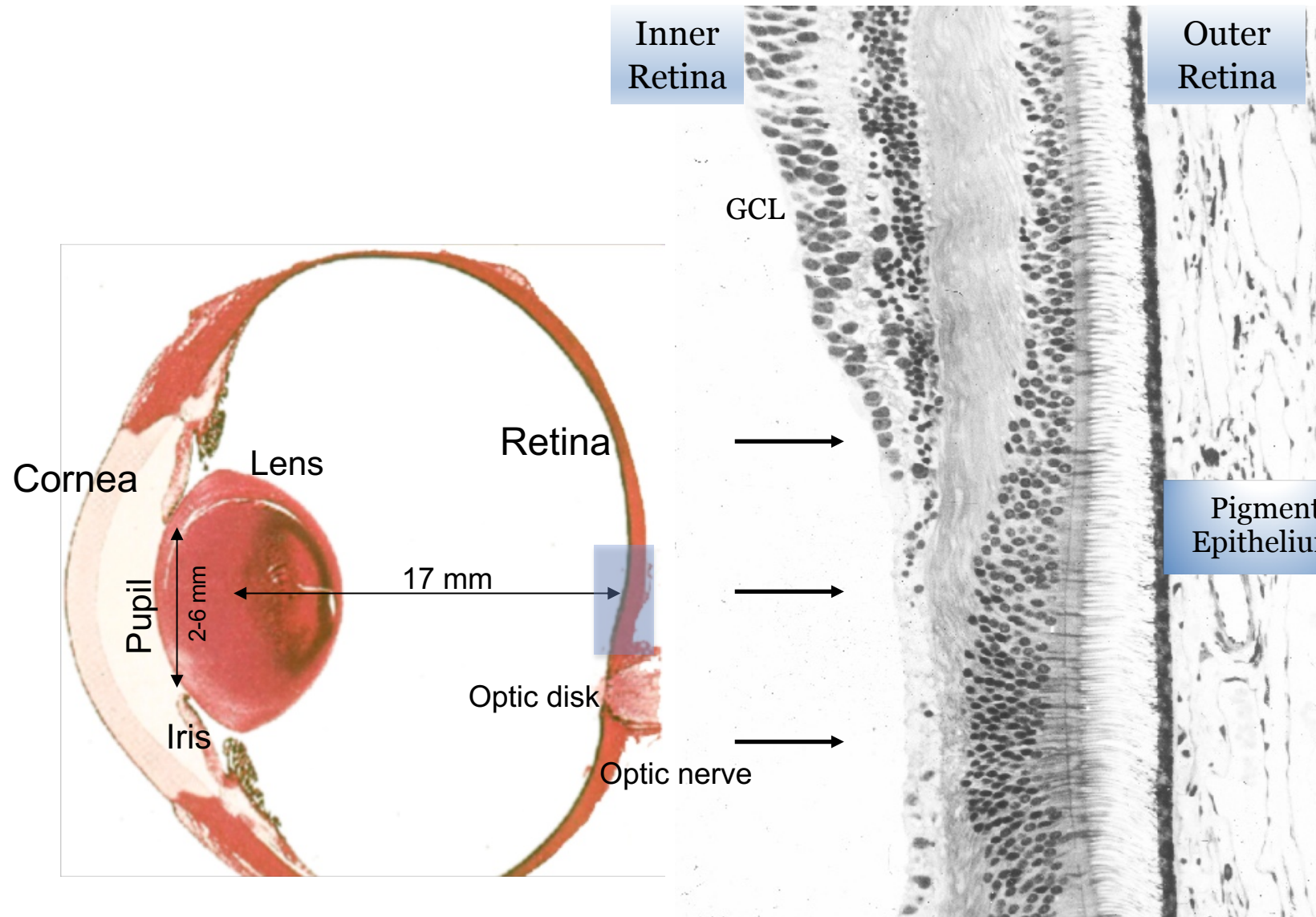
Modern color-matching functions, rather like those measured by Maxwell, were standardized in 1931 by international committees

These functions are at the heart of all color standards in use today

Engineers use these ideas to build any color television, computer display, print a document, or watch a movie



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

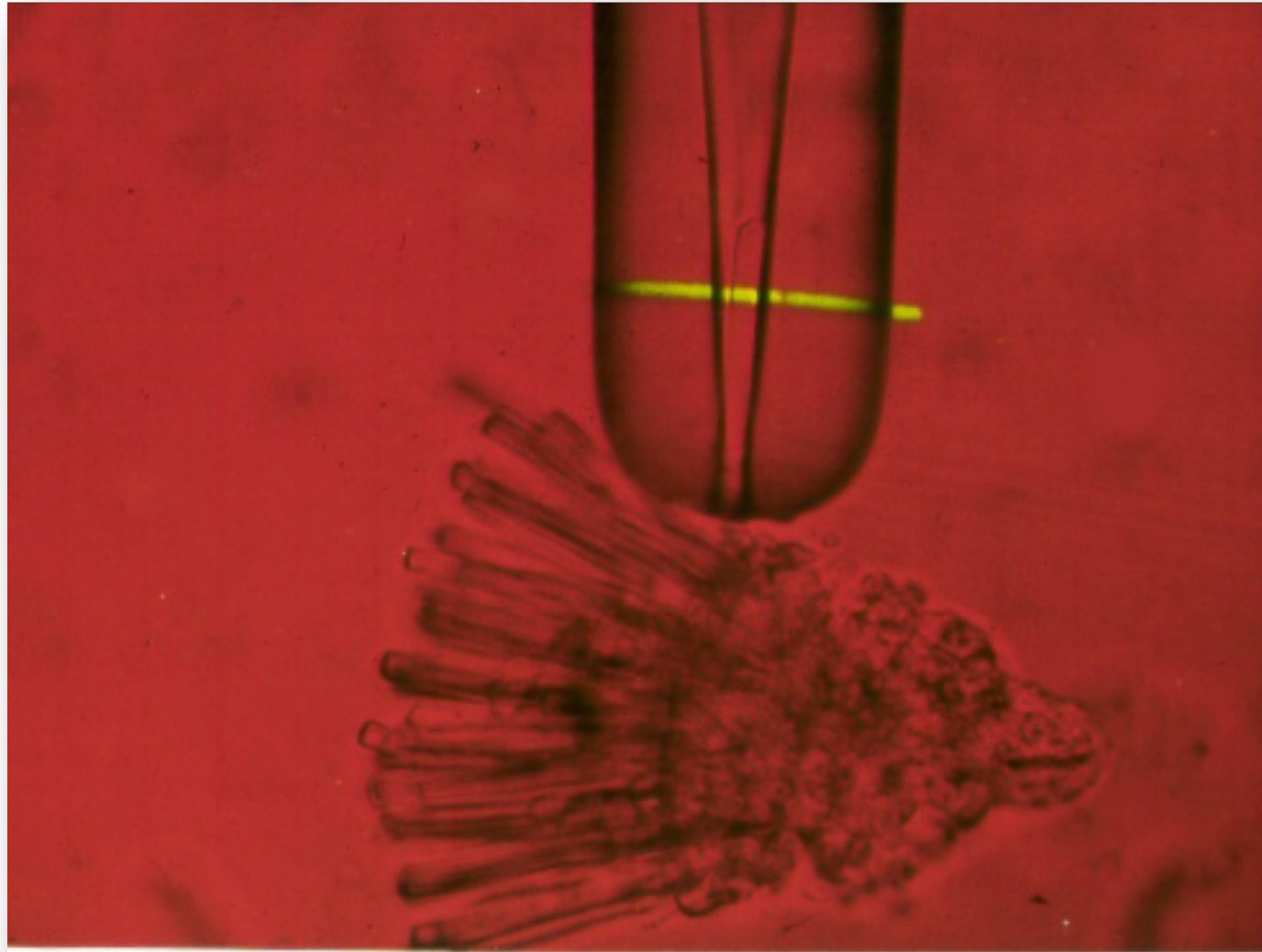


- 5 x 5 cm, 0.4 mm thick
- 5×10^6 cones
- 10^8 rods
- Foveal cone width: 1 μ m
- Contacts per cone: 250
- 10^6 optic nerve fibers

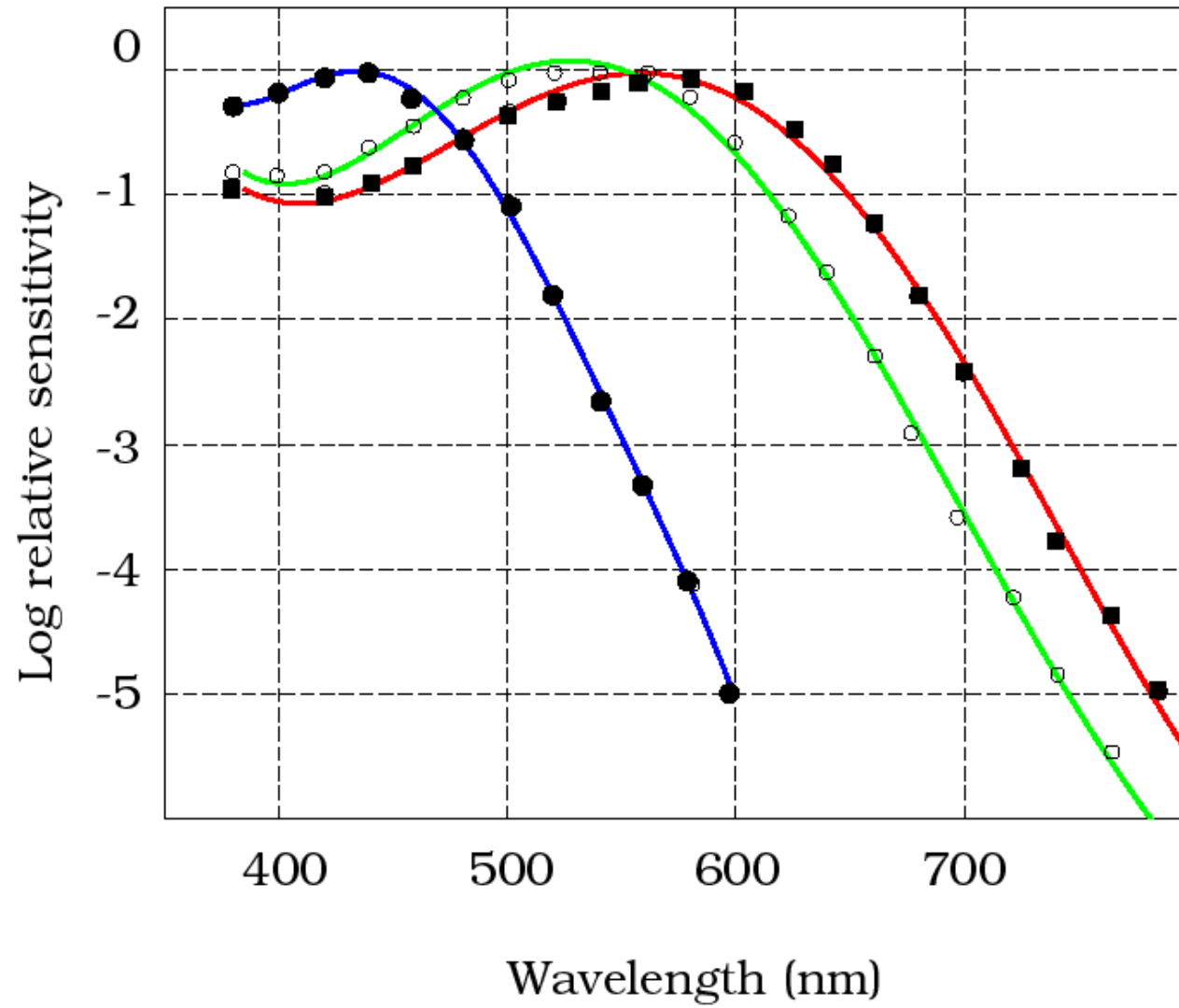
Single cone photocurrent measurements



(Schnapf, Baylor et al., 1986)



There are three cone wavelength responsivity functions



Stimuli causing equal cone absorptions match perceptually

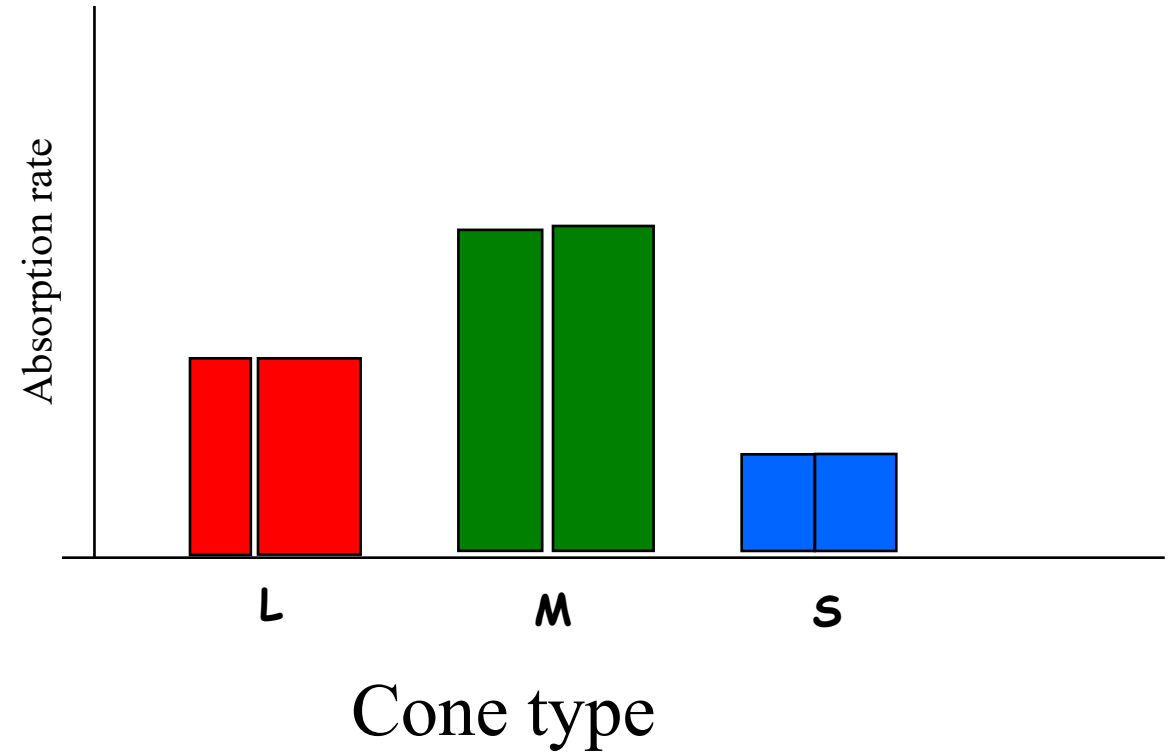
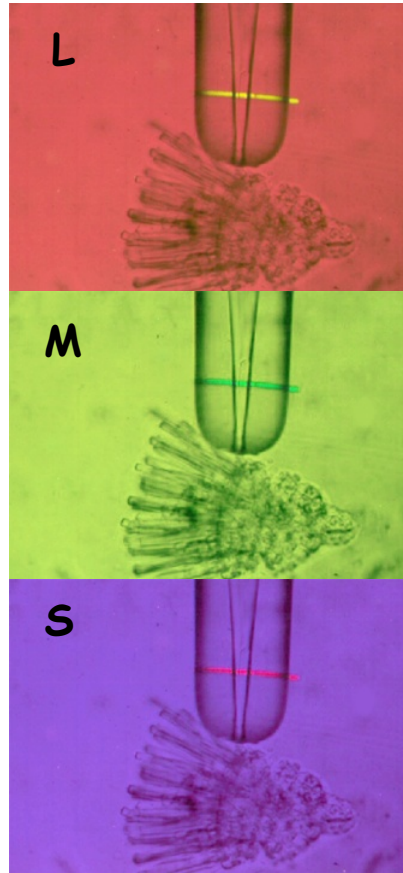
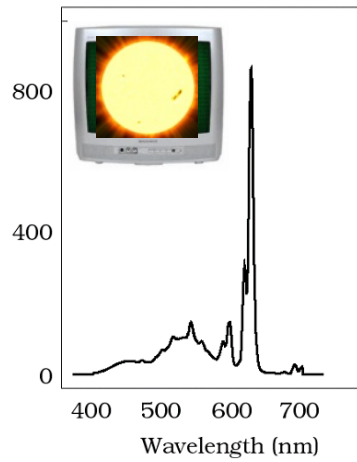
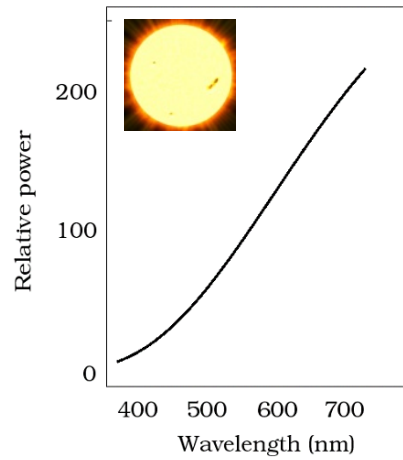


Image formation: color in spatial patterns



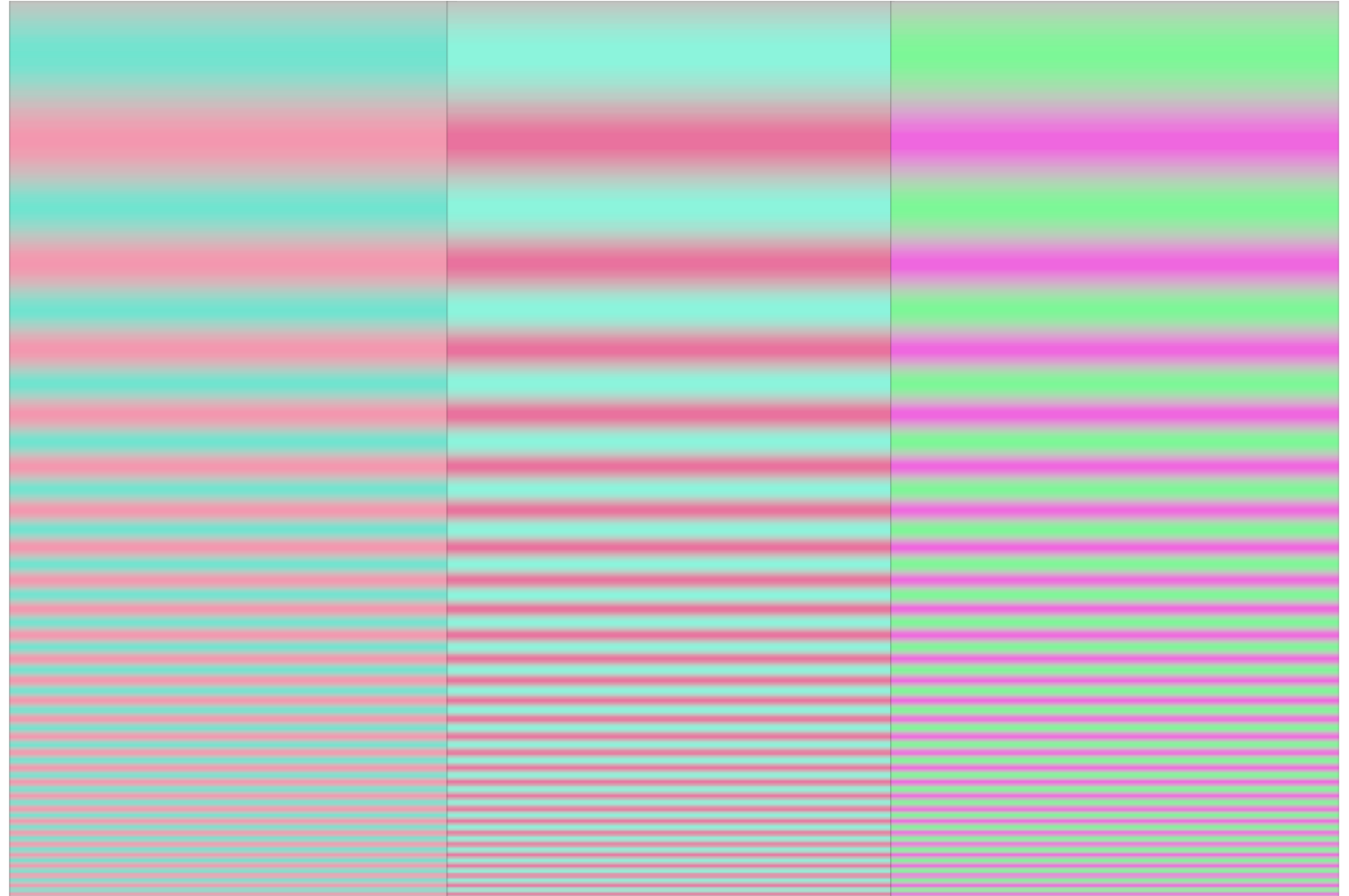
Spatial pattern and color interactions

Since the development of the earliest color standards for television, it has been recognized that there is a strong interaction between the perception of color and pattern

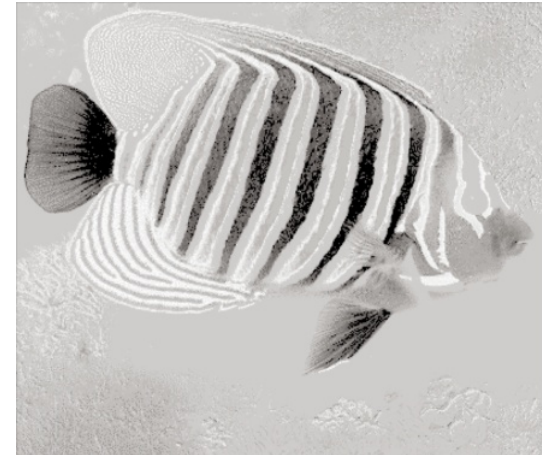
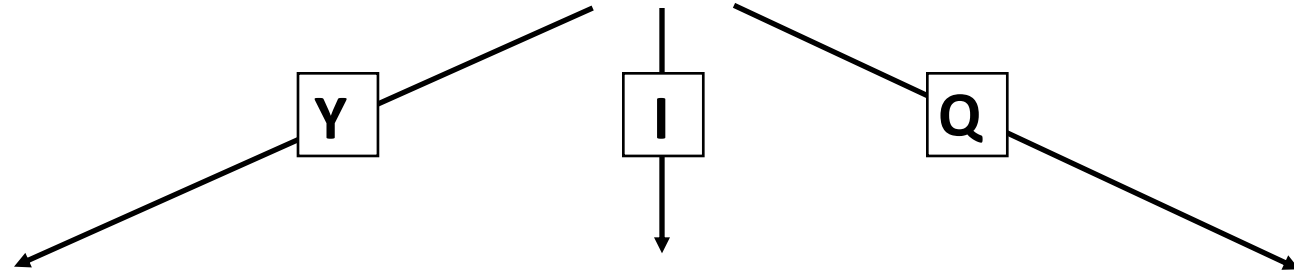
**Reduced
luminance
contrast**

Original

**Reduced
blue-yellow
contrast**



Pattern and Color in technology



Blurred Y



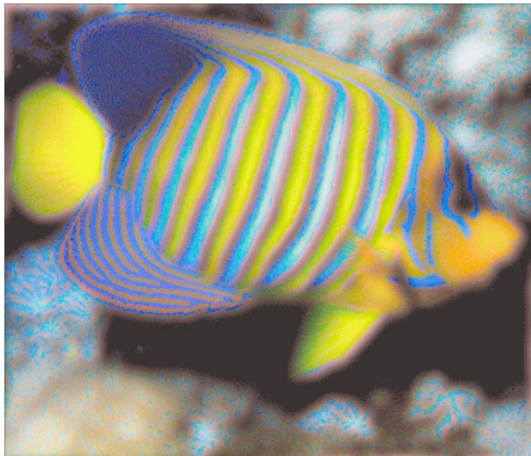
Blurred I



Blurred Q



**Blurred Y
I,Q**



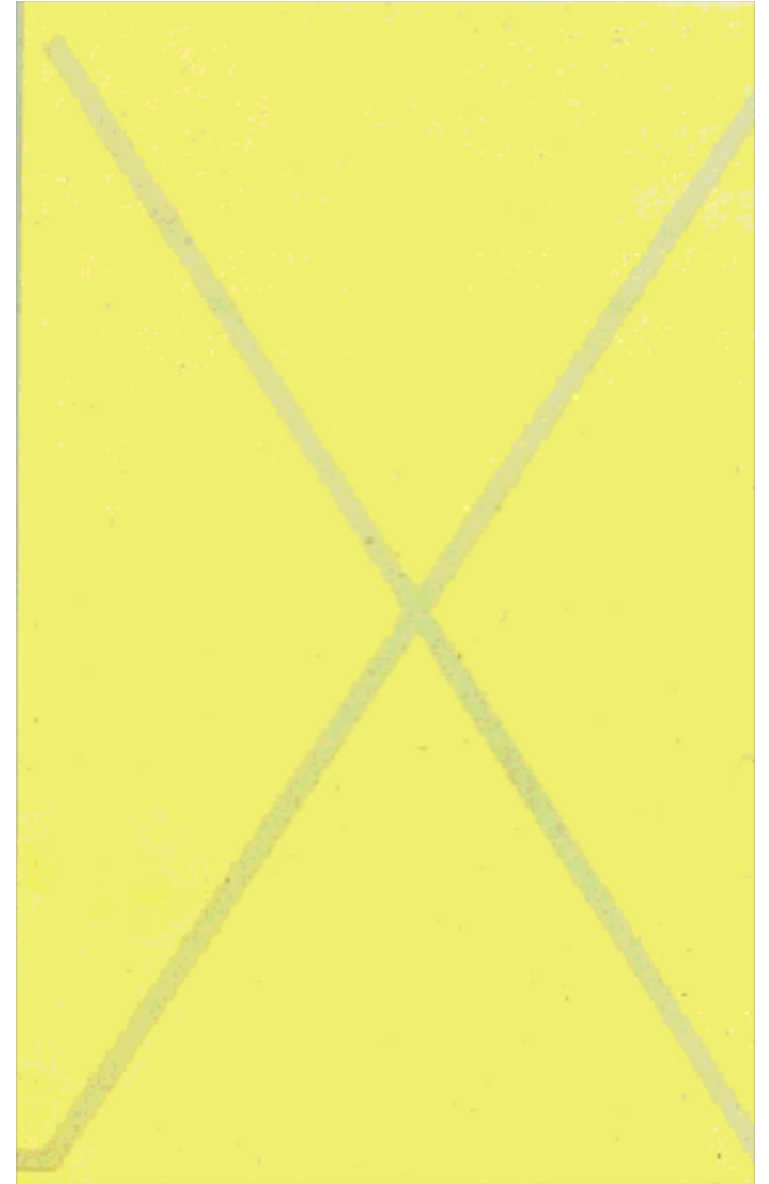
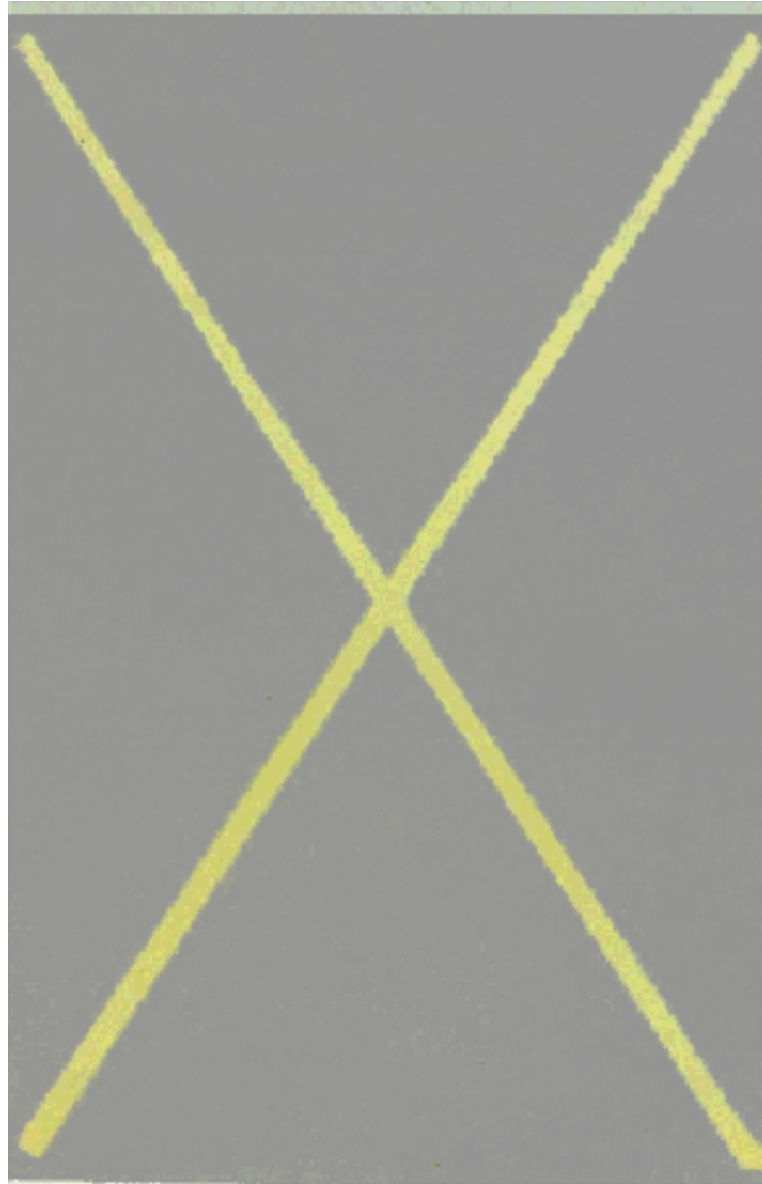
**Blurred I
Y,Q**



**Blurred Q
Y,I**



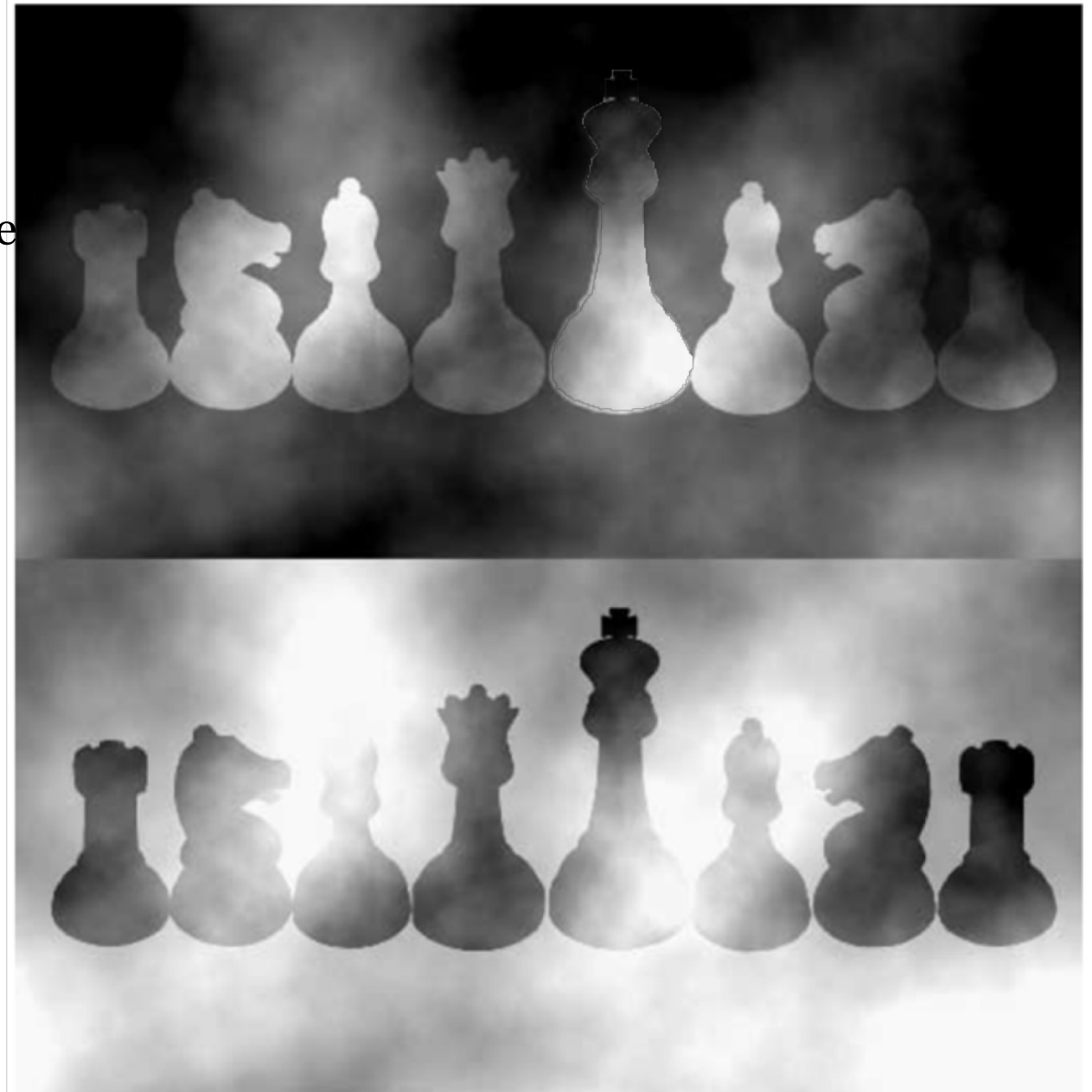
Color appearance and context



Vision and computation

- Even simple judgments – such as lightness - depend on substantial interpretation of the image data carried out by brain circuits
- The vision science has been influential in developing principles for other neuroscience fields and artificial intelligence
- Vision science fundamentals are important for the entire imaging industry

(Anderson and Winawer,
Nature, 2005)



Scene spectral radiance in the world

Gershun (1936)



Ray intensities: $L(x,y,z,\alpha,\beta,\lambda,\theta)$

Position (x,y,z)

Azimuth and elevation (α, β)

Wavelength (λ)

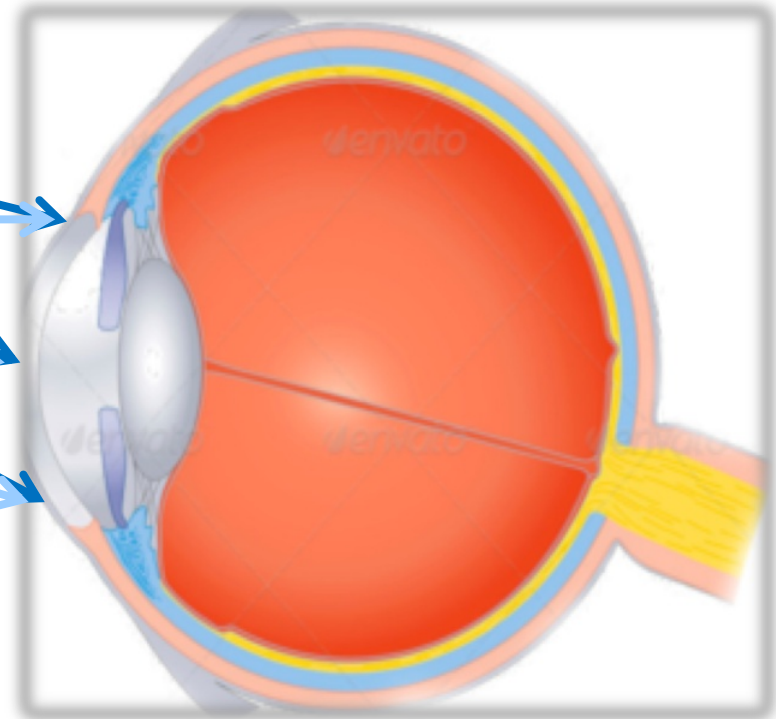
Polarization (θ)

Light field at the eye (plenoptic function)

(Adelson and Bergen, 1991)



Ray intensities: $L(u,v,\alpha,\beta,\lambda)$
Position (u,v)
Azimuth and elevation (α, β)
Wavelength (λ)



**Set Pivot Point to
Move object freely**



Quantitative computer graphics simulations of complex automotive scene spectral radiance, including the rays at the lens (plenoptic function)





Simulated

VISTALAB2018

Pixel Labels

Irradiance



Depth



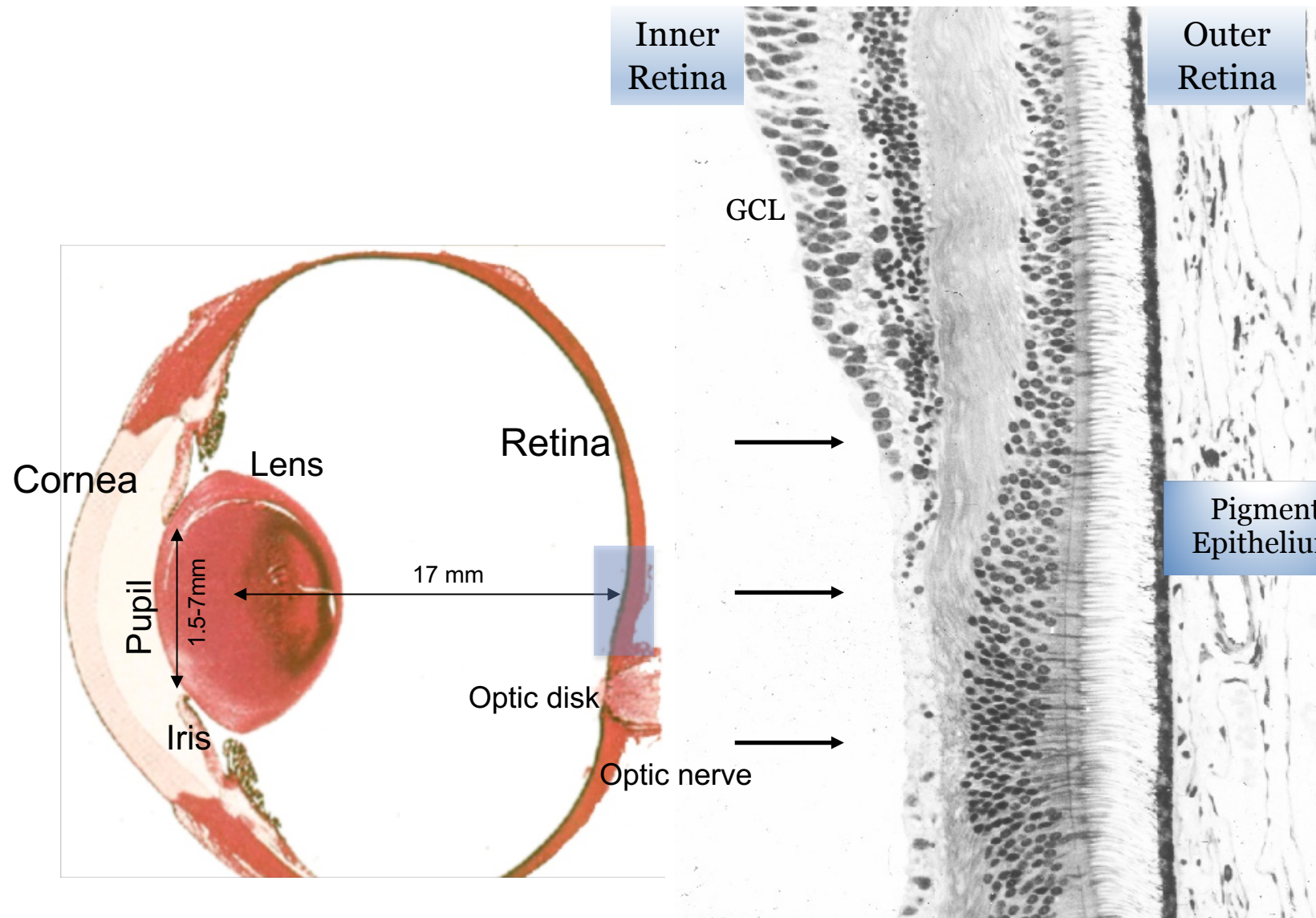
Class Segmentation



Instance Segmentation



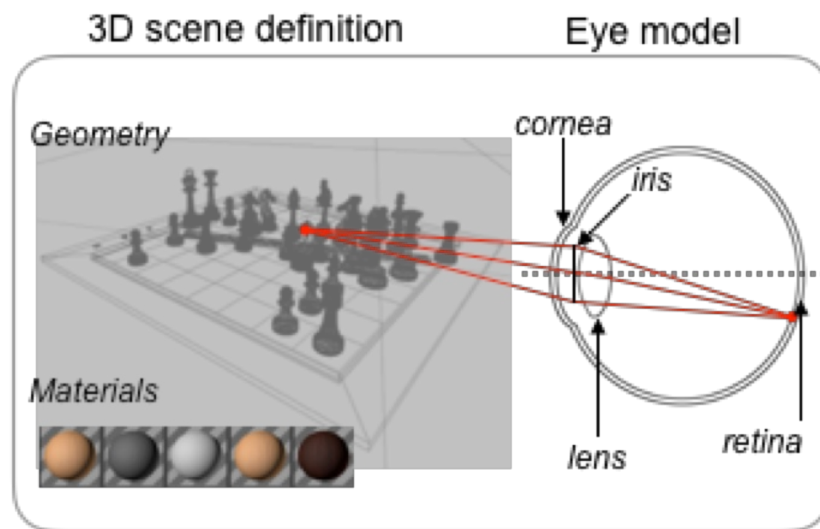
The primate fovea (pit) contains mainly cones and is specialized for high acuity and color



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

Quantitative computer graphics (PBRT) simulates image formation

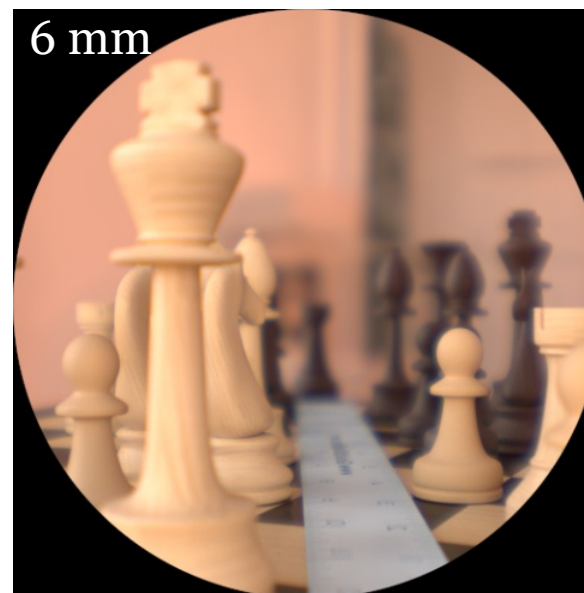
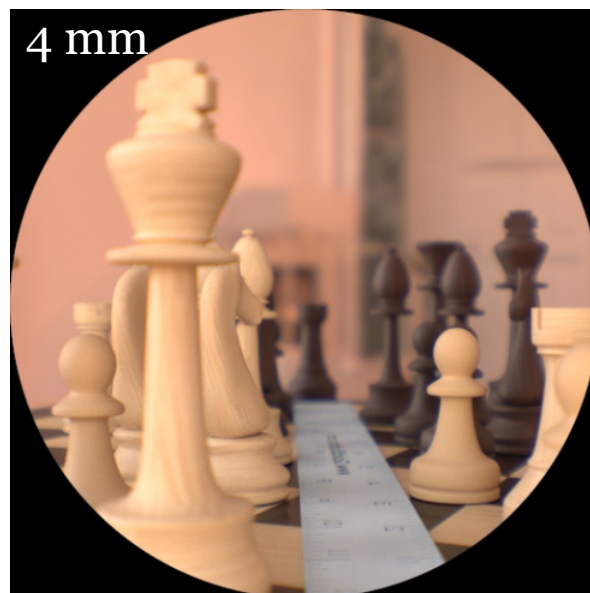
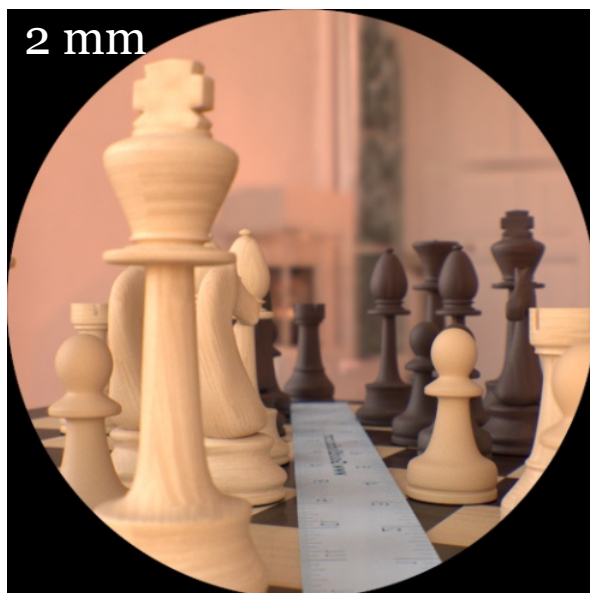
3D scene computer graphics scene is ray-traced through an eye model to form the retinal spectral irradiance



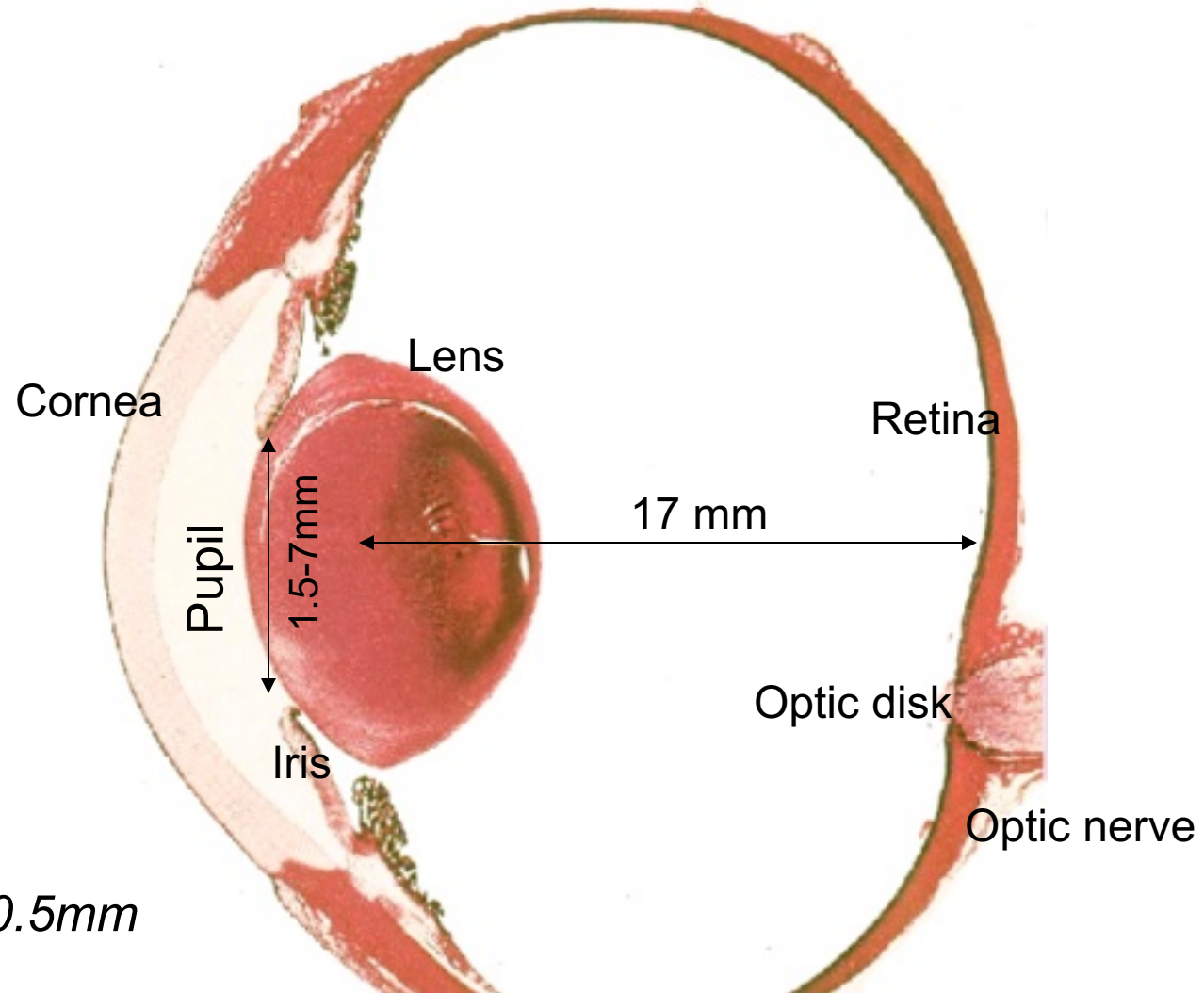
Ray tracing 3D spectral scenes through human optics models

Trisha Lian¹, Kevin J. Mackenzie², David H. Brainard³, Nicolas P. Cottaris³, Zhenyi Liu¹, Brian A. Wandell¹

Stanford University, Facebook Reality Labs, University of Pennsylvania



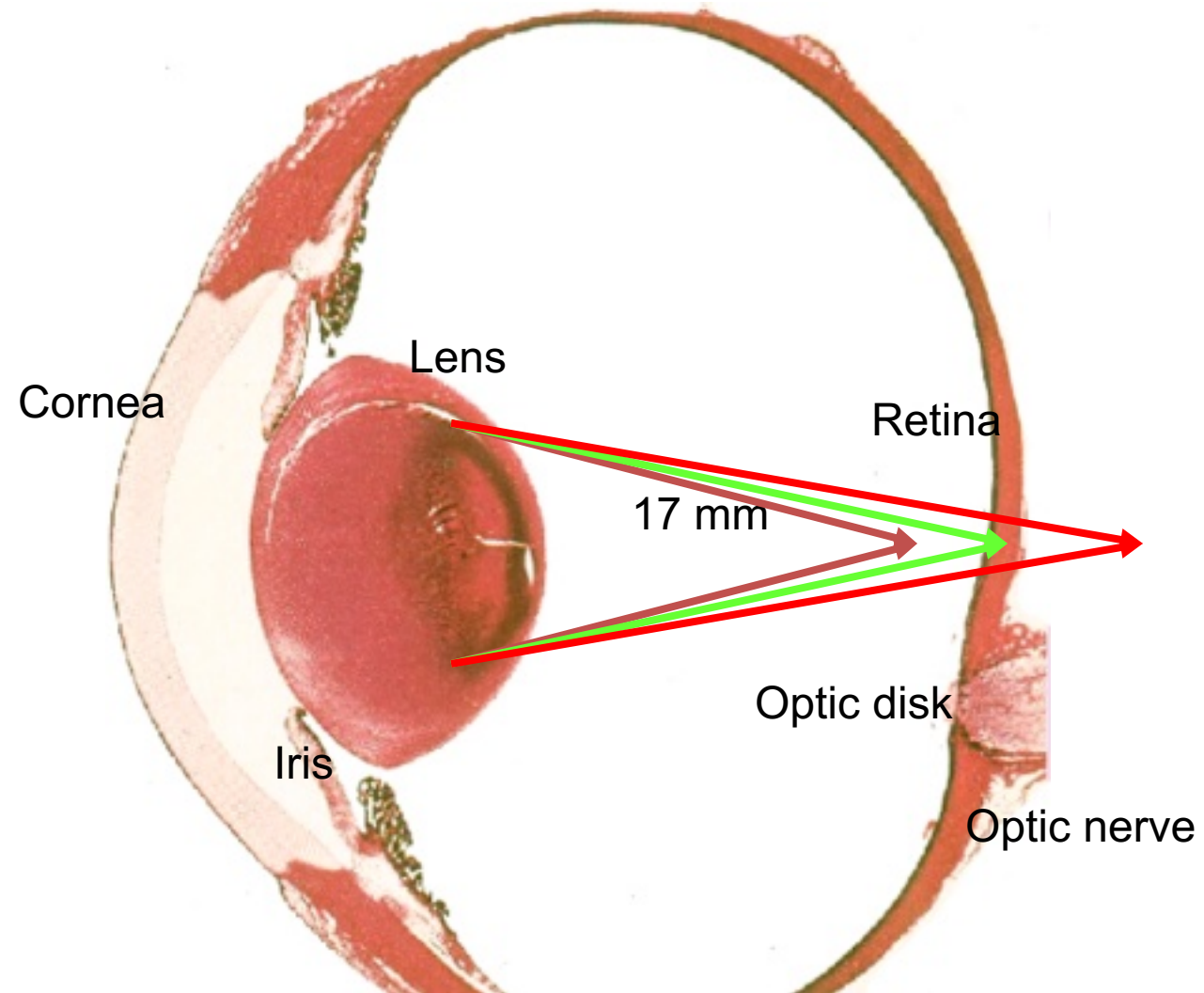
Human eye in cross-section



F-number ~ 2.4-11

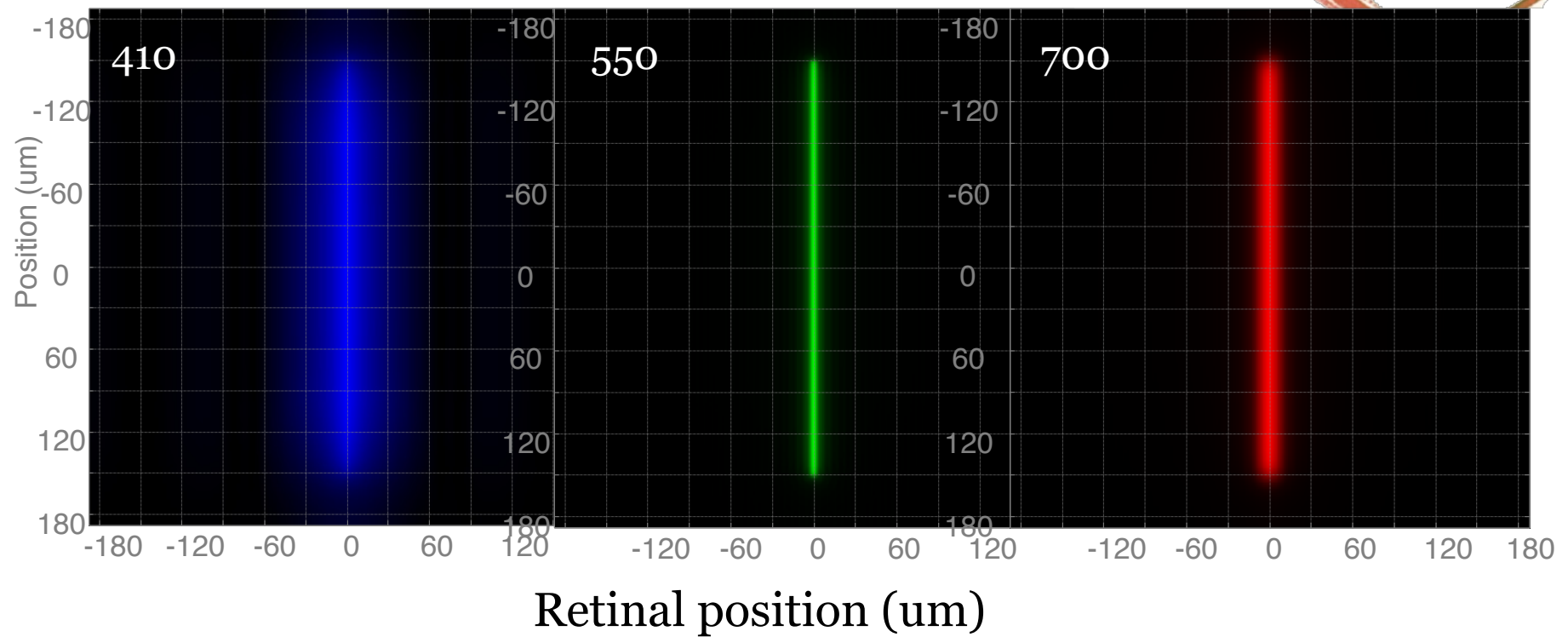
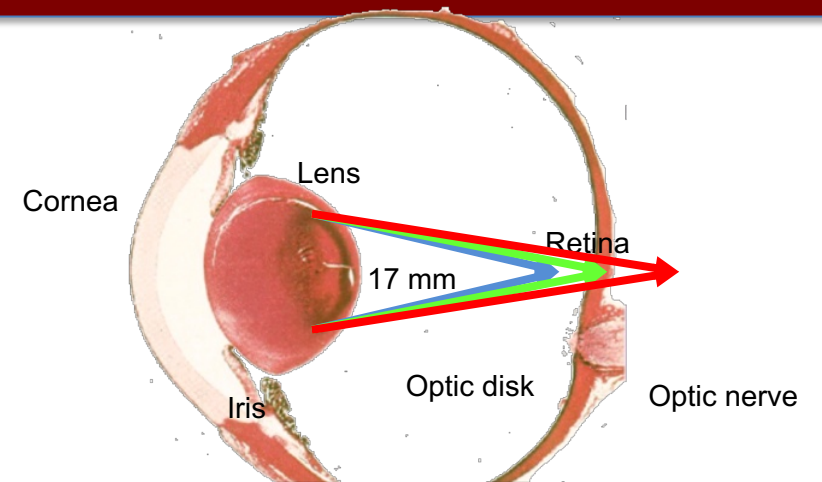
Retinal thickness ~ 0.5mm

Chromatic aberration is a difference in optical focus across wavelength



At the retina, the line spread differs by wavelength

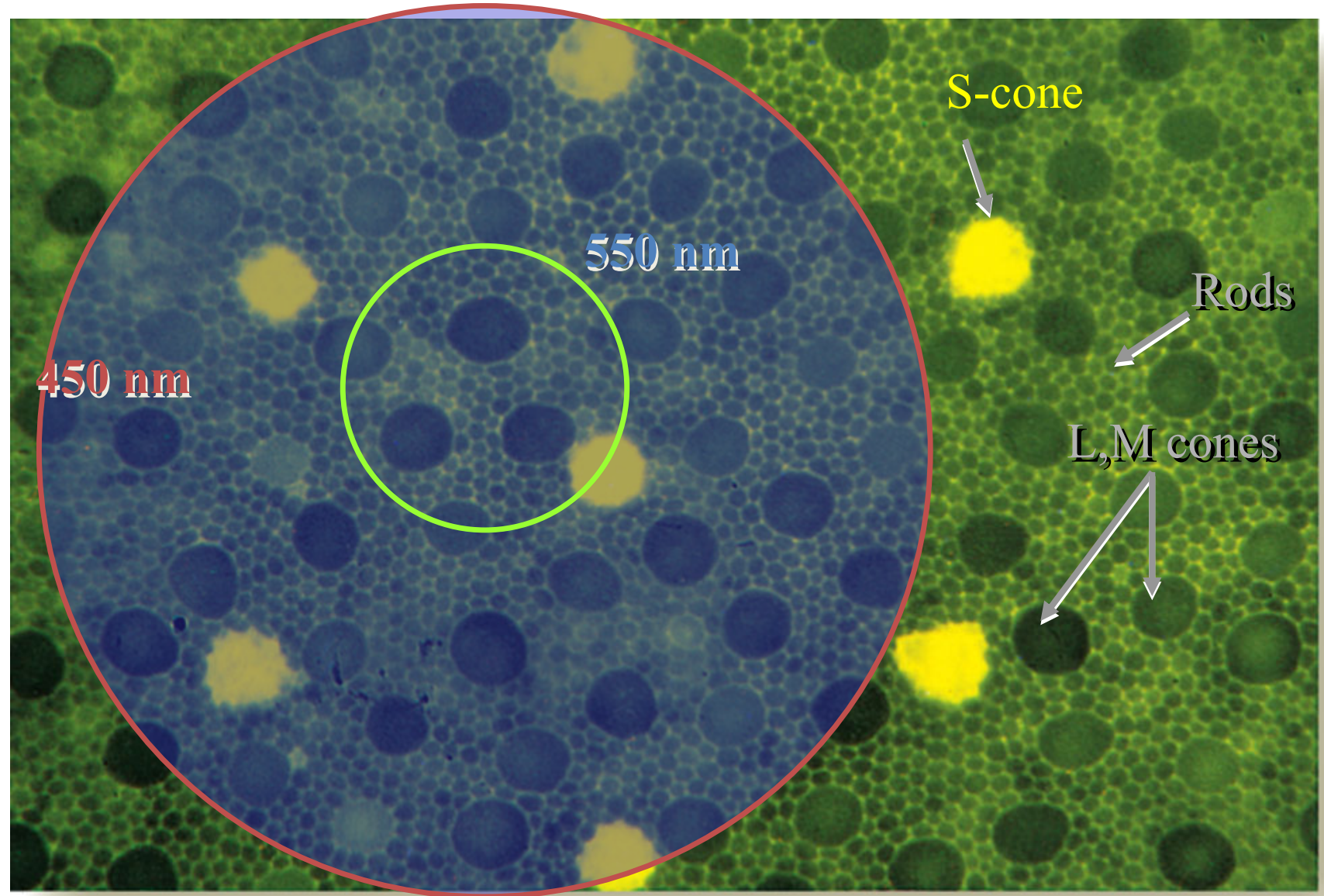
ISETBio: s_HumanLSF



Photoreceptor mosaic

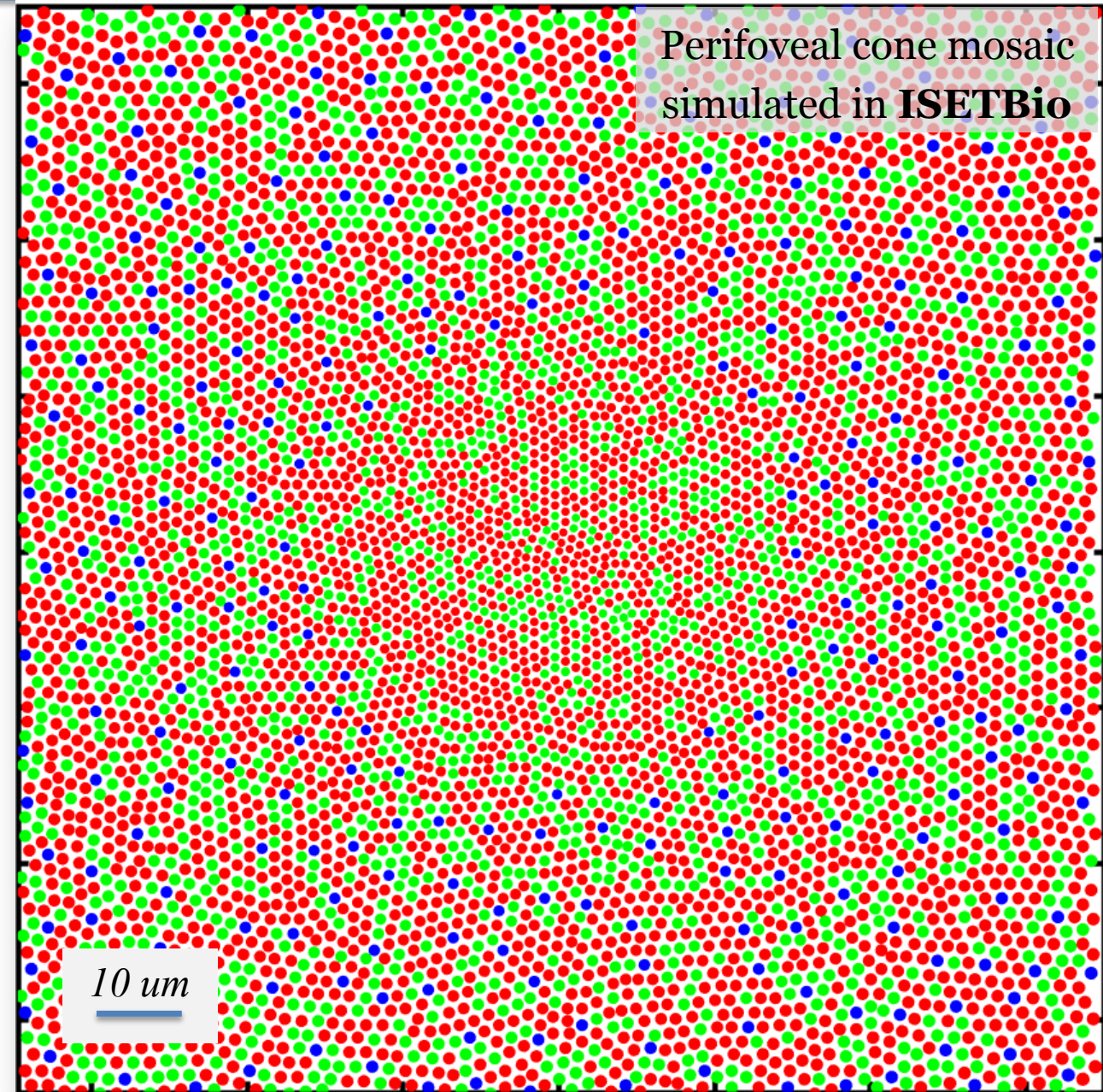
The wavelength-dependent point spread function covers about 3-5 cones, even in the central retina

In natural vision, we never experience excitation of a single cone



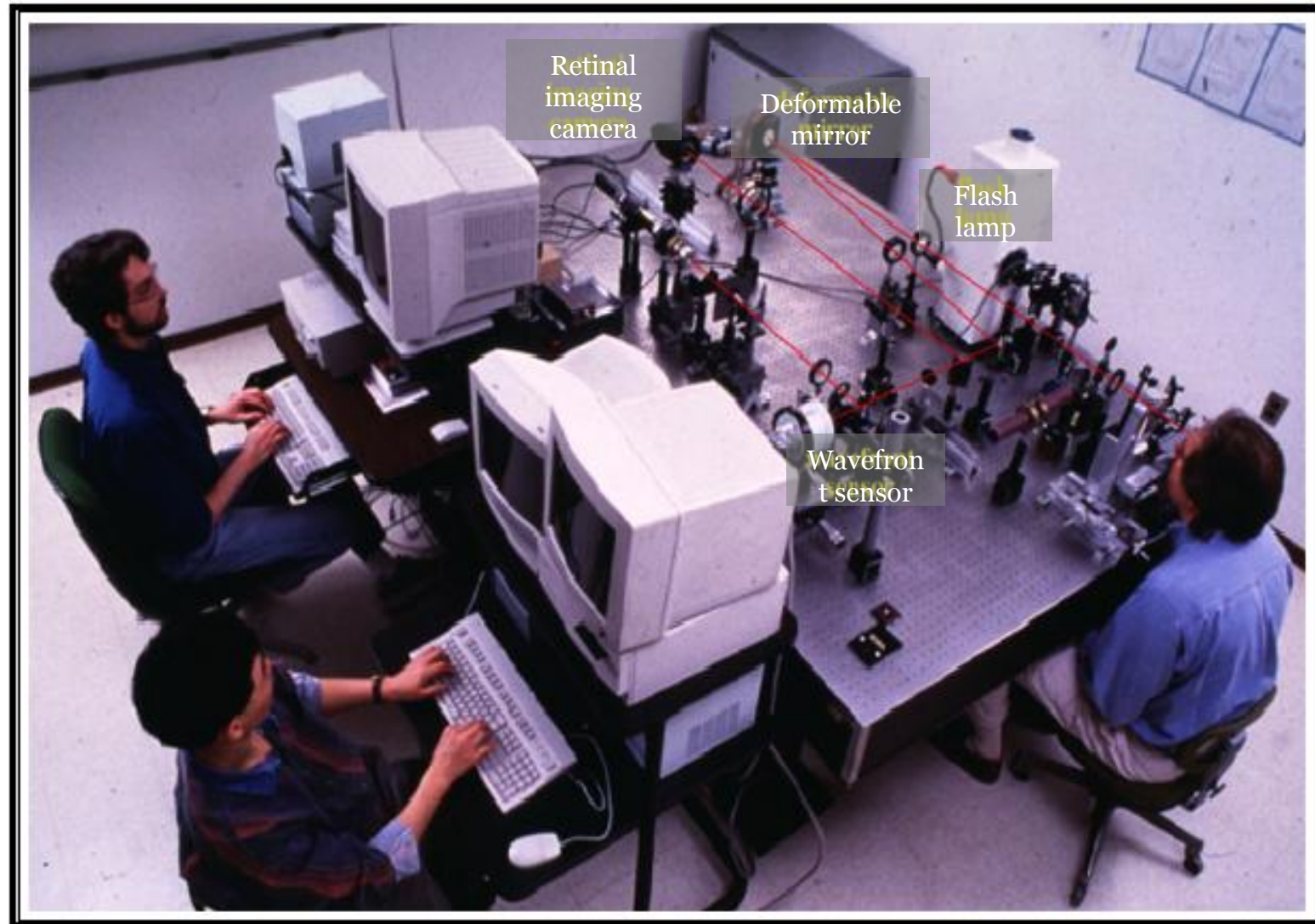
What if we had the neuroscience data first?

- We have also implemented computational models that implement many specific measurements of retinal properties
- Had we started our analysis from the neuroscience data, we would still be struggling to understand the color matching principles
- The retina is inhomogeneous in many ways – aperture size, nonuniform inert pigments, nonuniform spatial sampling of the receptor types



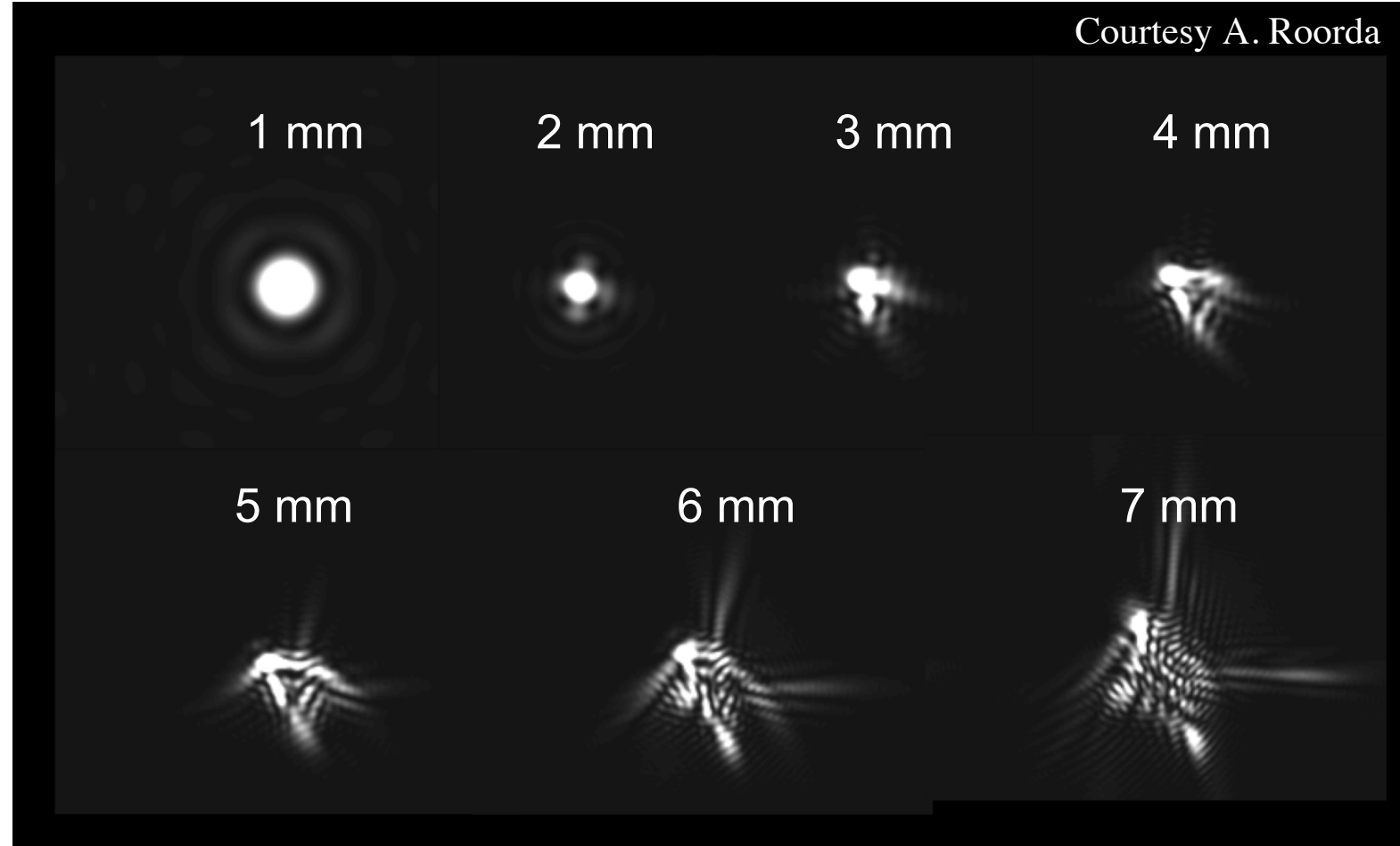
Rochester Adaptive Optics Ophthalmoscope ~ 2000

- Following work in astronomy, Dave Williams and his students and postdocs realized that Shack-Hartman wavefront sensors could be used to correct for most aberrations of the in vivo human eye
- They built rigs that allowed them to characterize the optics and then to correct for these aberrations



Human point spread functions for different pupil diameters

- Following work in astronomy, Dave Williams and his students and postdocs realized that Shack-Hartman wavefront sensors could be used to correct for most aberrations of the in vivo human eye
- They built rigs that allowed them to characterize the optics and then to correct for these aberrations



Application: Seeing The Arrangement of Cone Classes in the Human Eye

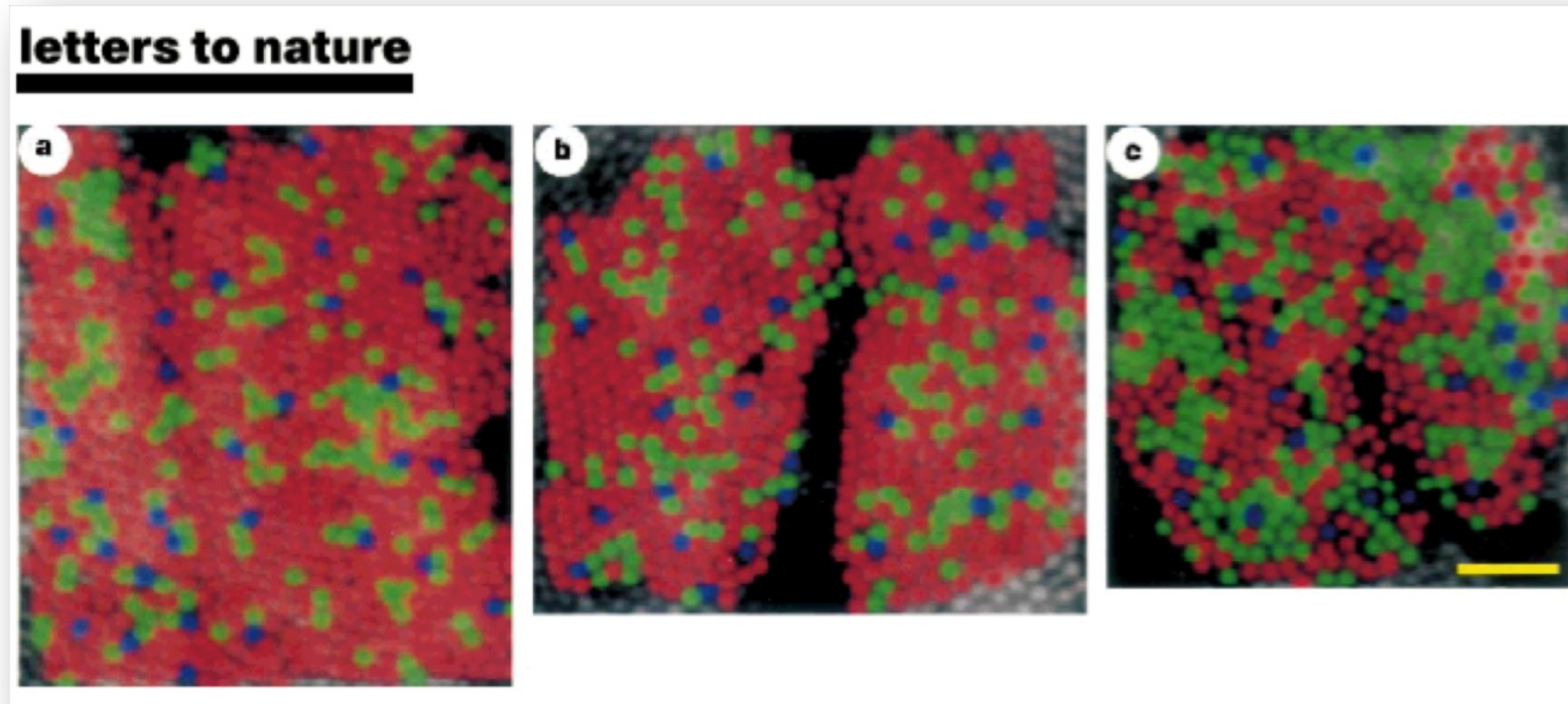
(Roorda and Williams et al., 1999)

Austin Roorda

Heidi Hofer



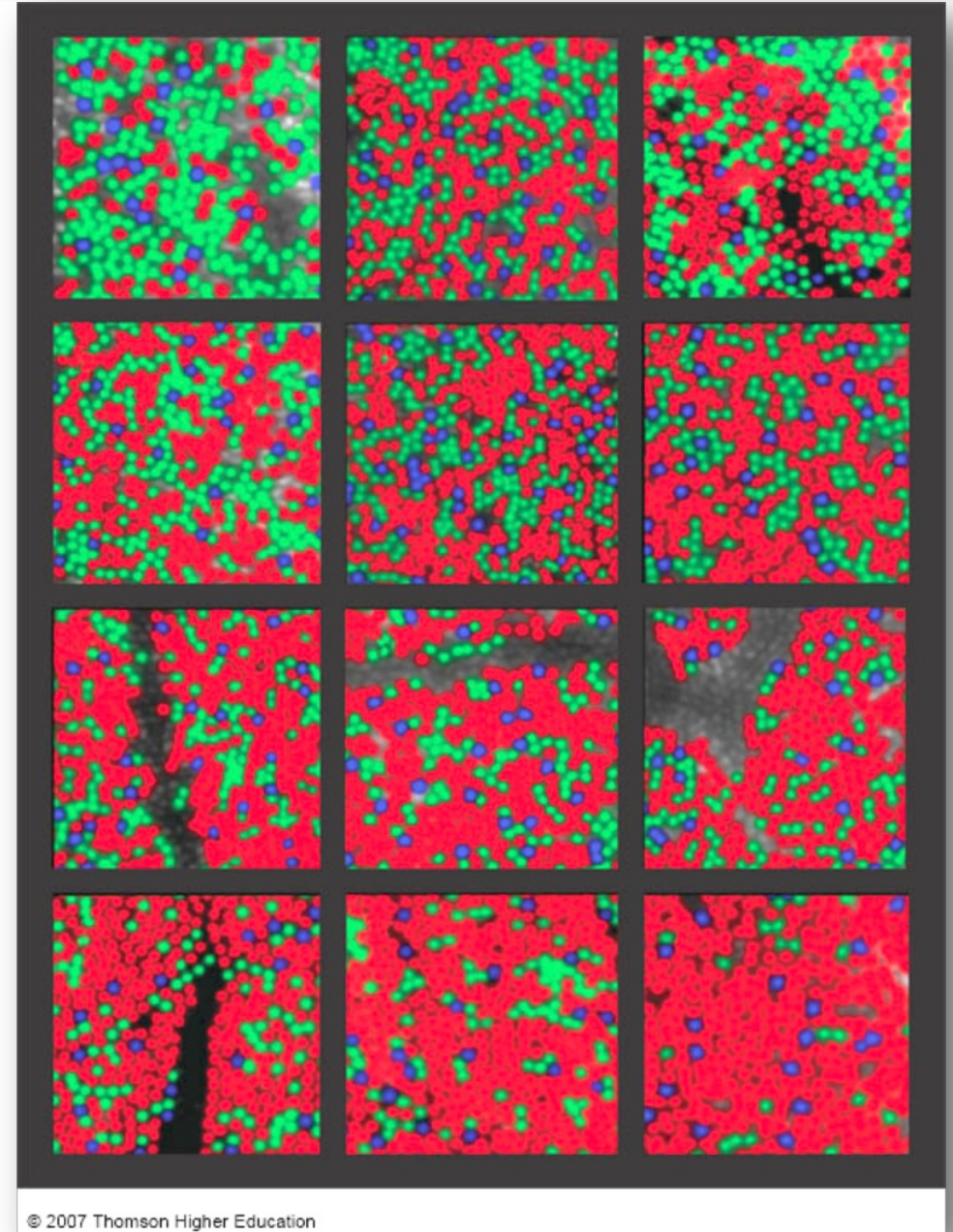
- Following work in astronomy, Dave Williams and his students and postdocs realized that Shack-Hartman wavefront sensors could be used to correct for most aberrations of the in vivo human eye
- They built rigs that allowed them to characterize the optics and then to correct for these aberrations
- They developed techniques to estimate which of the three types of cones was present at each location



What if we had the neuroscience data first?

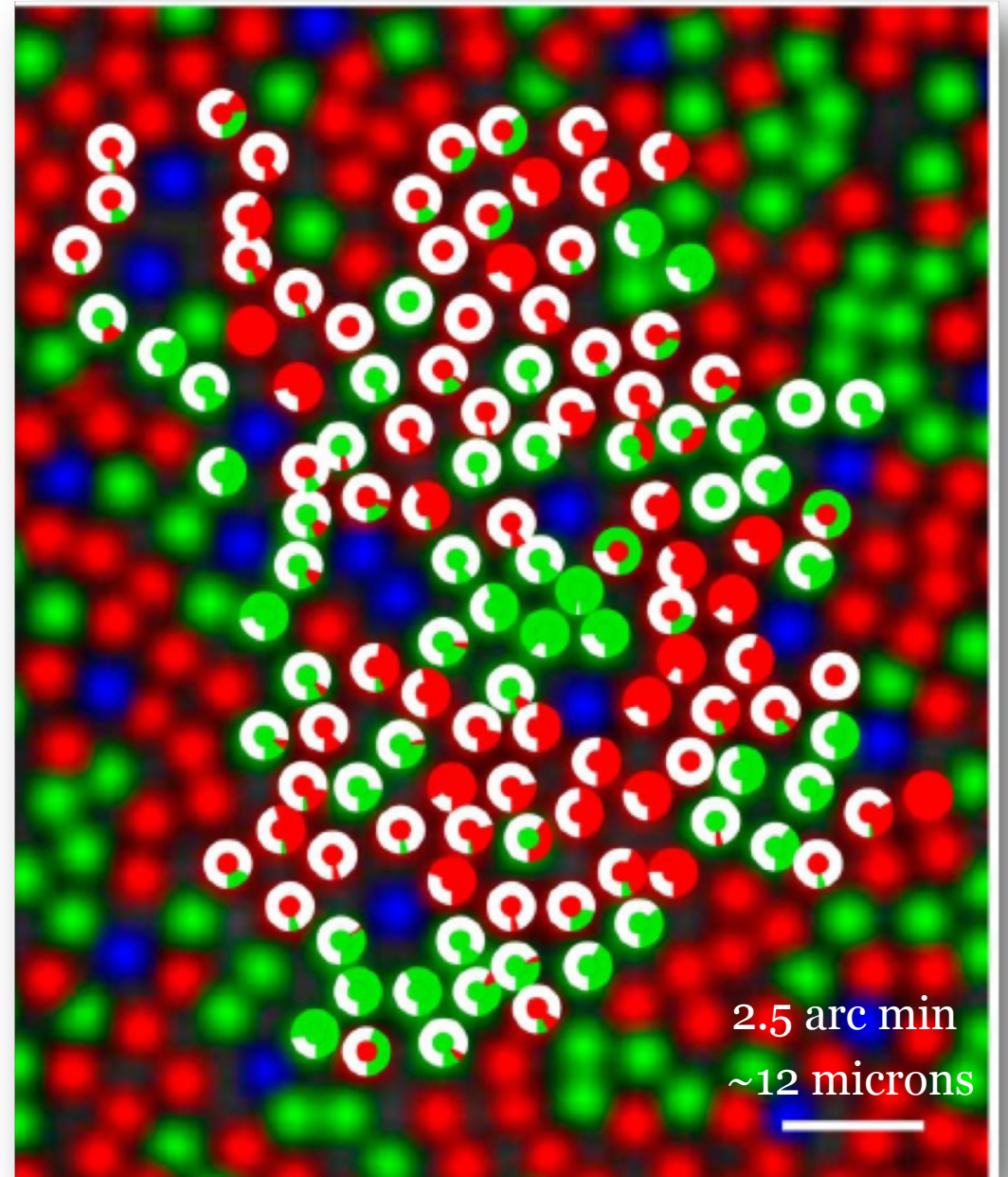
Hofer, H. et al. J. Neurosci.
2005;25:9669-9679

Individual cone mosaics differ greatly in density and ratios of the three cone types



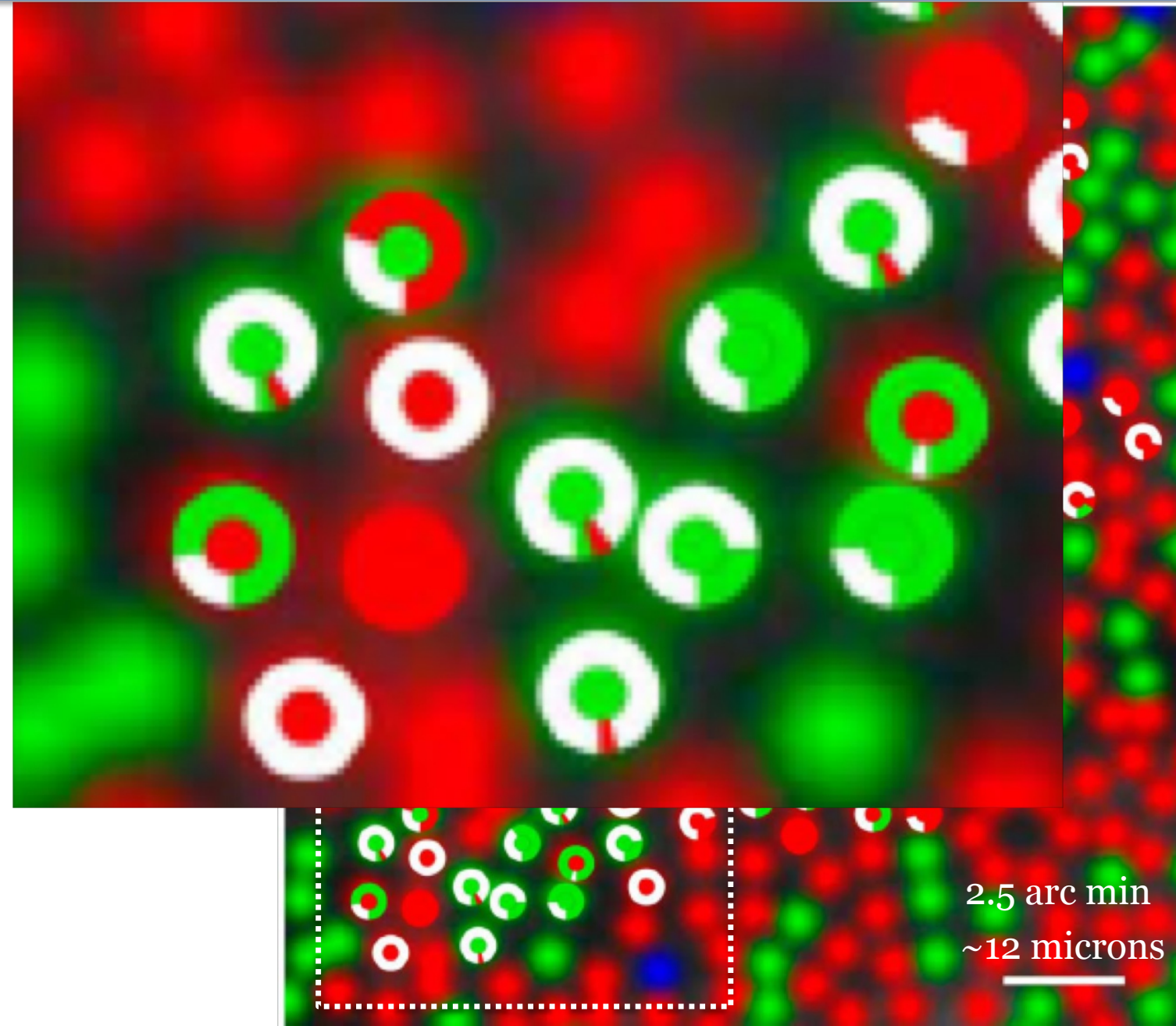
Color names when single cones are stimulated on a gray background

- Tracking eye position as well (video version of the system) it is possible to target individual cones for stimulation.
- Subjects name the color appearance of these stimulations, which differ on different stimulations
- A very common response is 'white'; there are M cones that evoke 'red' response and other L cones that reliably evoke a 'green' response.
- Some cones evoke red or green responses (the stimulating light is always the same, 543 nm).



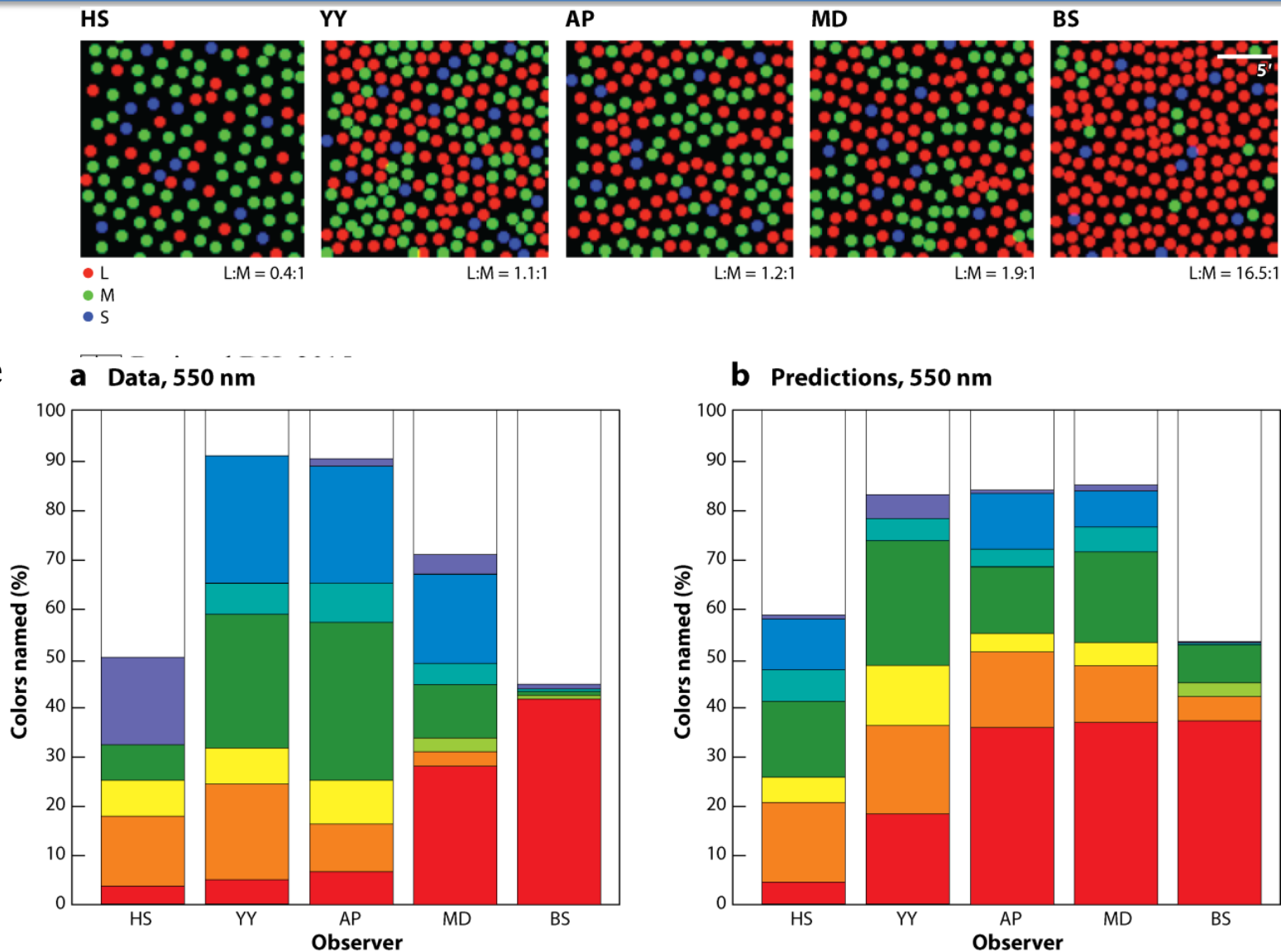
A second subject

- Tracking eye position as well (video version of the system) it is possible to target individual cones for stimulation.
- Subjects name the color appearance of these stimulations, which differ on different stimulations
- A very common response is 'white'; there are M cones that evoke 'red' response and other L cones that reliably evoke a 'green' response.
- Some cones evoke red or green responses (the stimulating light is always the same, 543 nm).



Color names to single cone excitations for 5 observers with very different mosaics

- People differ enormously
- Related experiments by Hofer et al. suggest that people would use more color names in response to single cone excitation



Colorblind appearance simulations are widespread

<http://www.vischeck.com/>

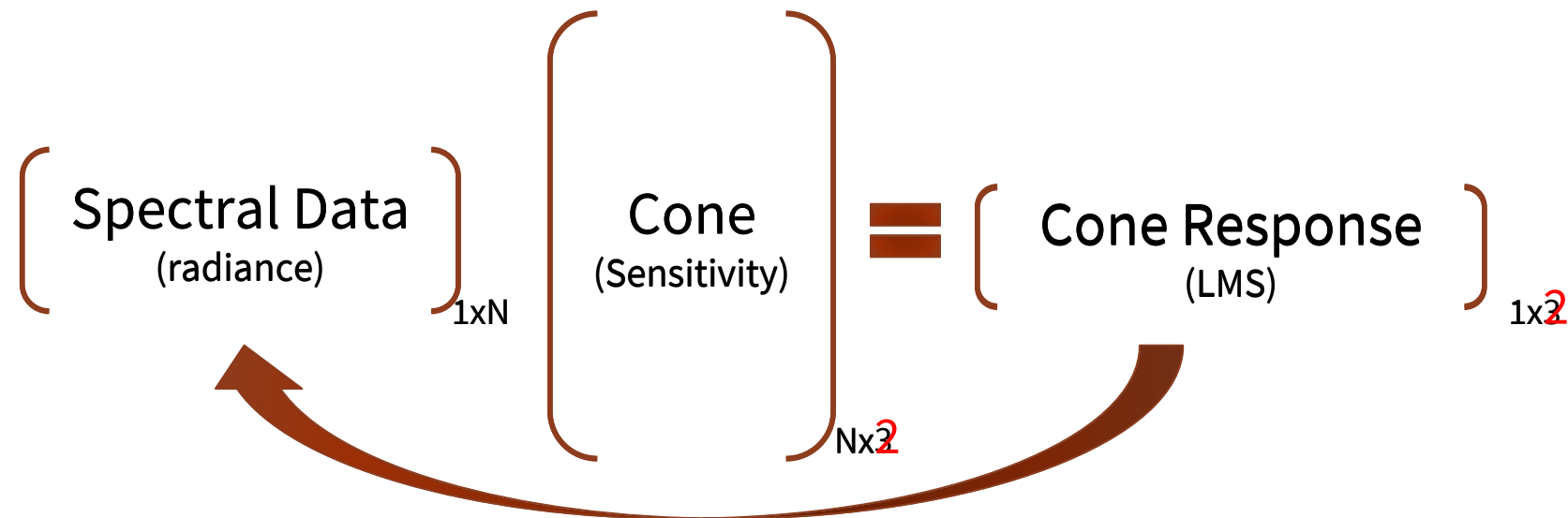
<http://colorvisionawareness.com/livingwithcolorblindness.html>



Theory: Color Appearance as Spectral Estimation

Hypothesis

- Dichromats and Trichromats use the cone absorptions to estimate the spectral irradiance *in the same way*
- Spectral irradiance is a smooth function of wavelength



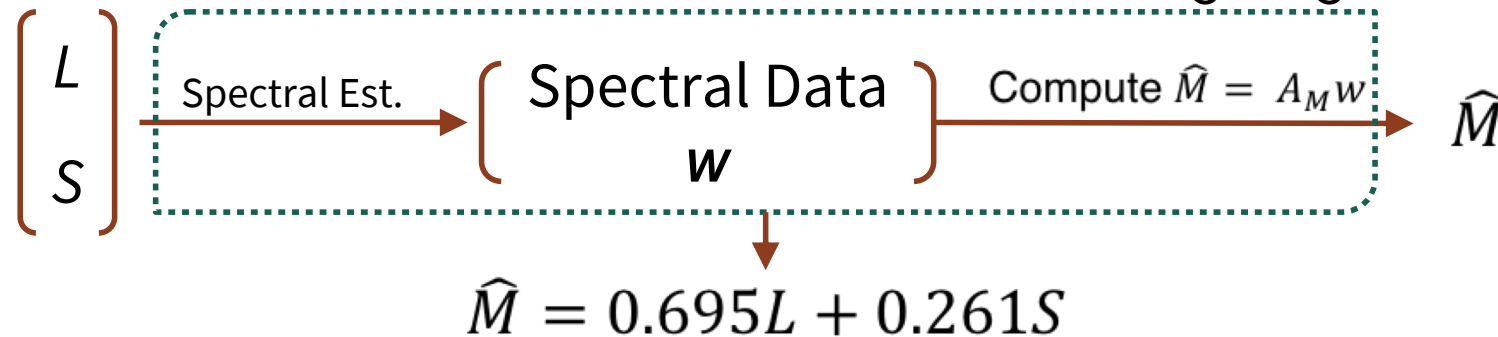
Color Appearance as Spectral Estimation (SE)

Formalize the problem

Find *Smoothest Spectral Radiance* that matches the cone absorptions

$$\text{minimize } \|\nabla \mathbf{w}\|^2 \quad \text{s. t. } \mathbf{A}\mathbf{w} = \mathbf{c}$$

Convex and closed form solution can be found with *Lagrangian multiplier*

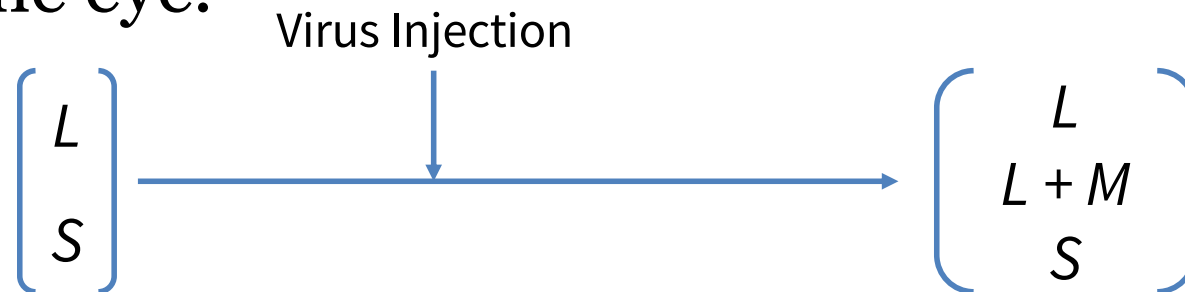


Linear transforms also exist for the other two types of dichromats



Avalanche (now [Adverum](#)) announced their next generation gene therapy treatment for dichromatic observers.

The therapy uses non-surgical intravitreal injection method to deliver the gene for missing cone type directly to cone cells at the back of the eye.



- **Related Research**

Squirrel monkeys make discriminations after gene therapy. But no conclusions are possible about color appearance

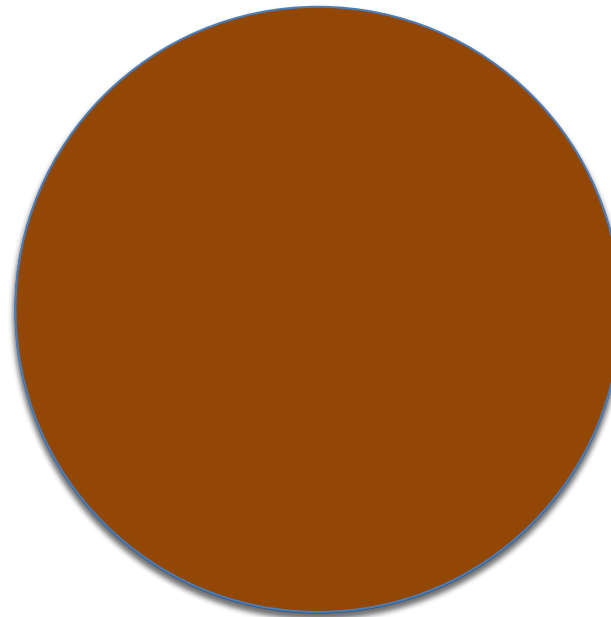
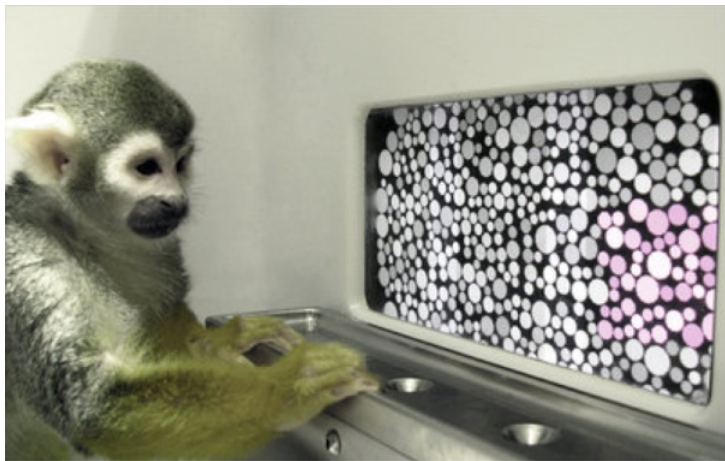


Jacobs et al., 2007, Science
Mancuso, et al. 2009, Nature
Neitz, et al. 2014, CSHL

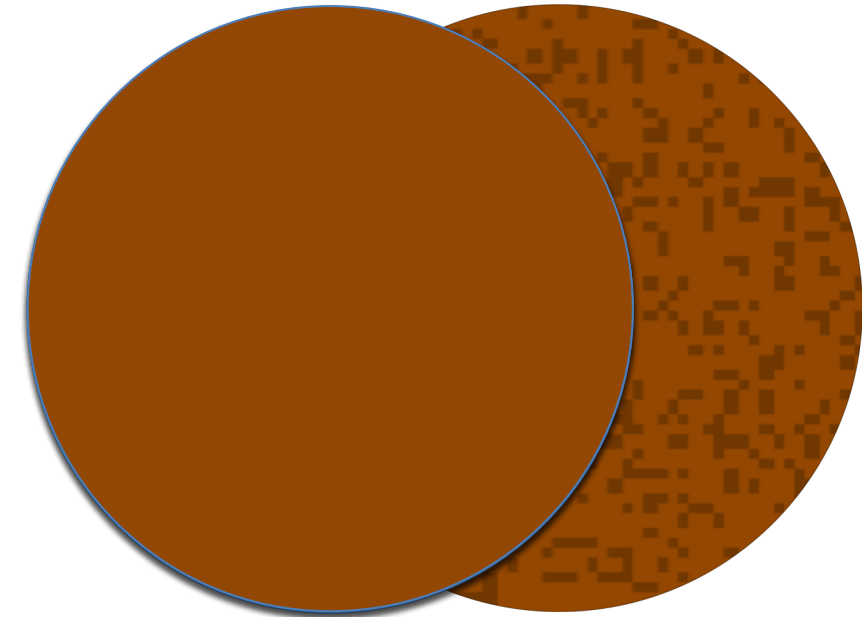
And see
Makous, 2007 Science

Applications – Predictions for Gene Therapy Treatment

If there is no learning, still be able to have trichromatic discrimination (Makous, 2007)



(L, M_1, S)
 $L = M_1$



(L, M_2, S)
 $L > M_2$

Applications – Predictions for Gene Therapy Treatment

- Even though trichromatic discrimination, still dichromatic vision
- Noisy and blotchy

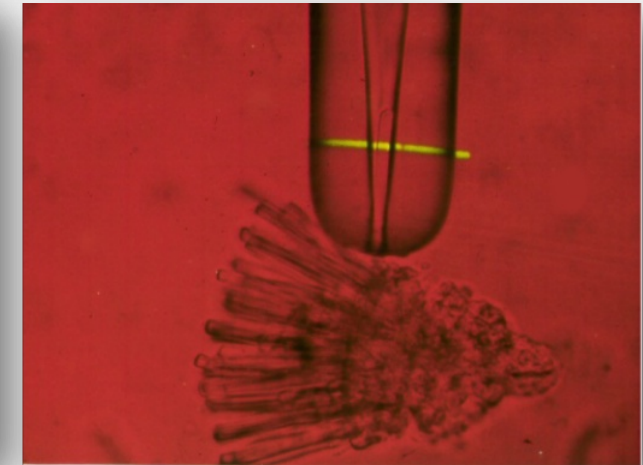
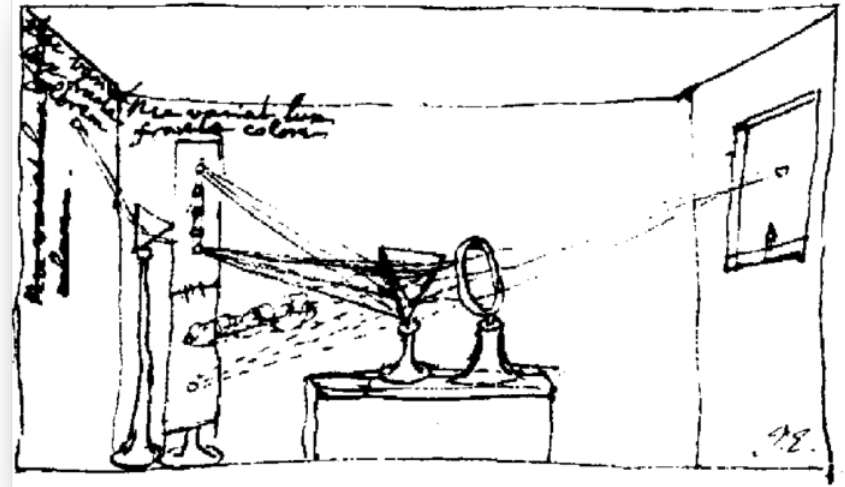


- **Ideal Case: position and spectral sensitivity learned for mutated cones**
 - Color anomalous, E.g. Deuteranope (L, S) \rightarrow (L, L+M, S)
 - Trichromatic, close to normal trichromats



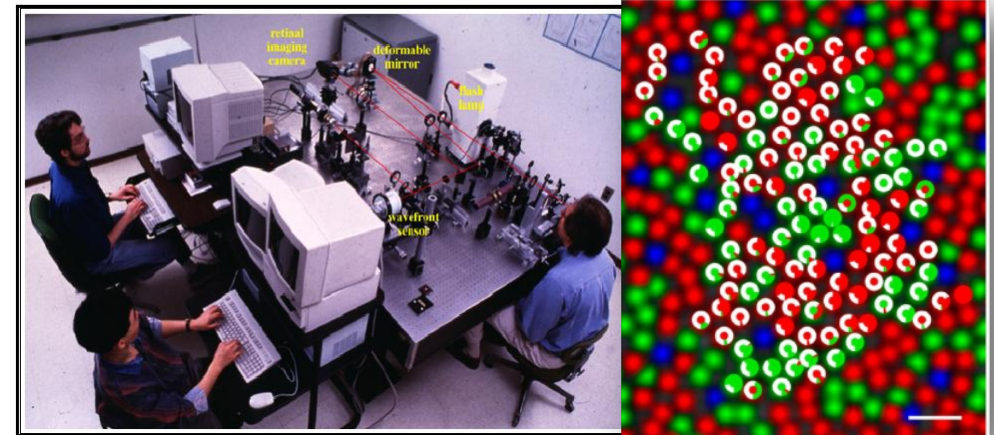
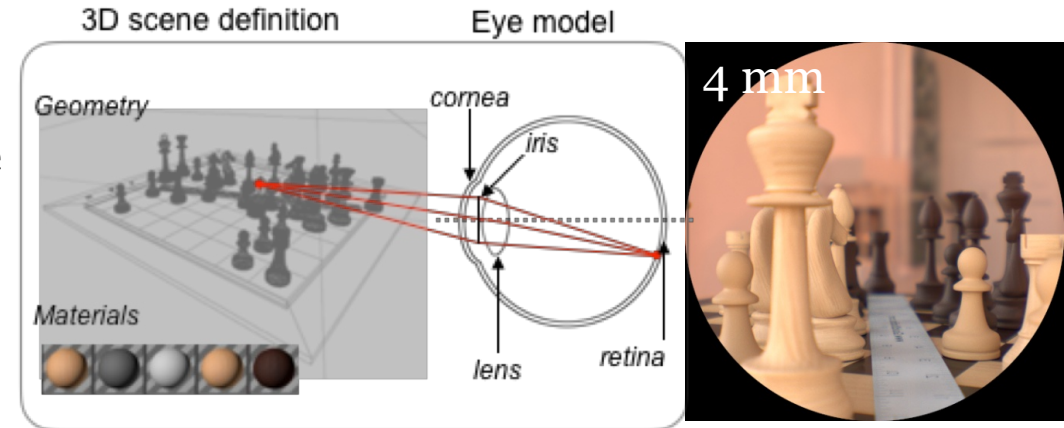
Summary

- Color is a relatively simple component of the visual system
- Early advances in color came from careful study of the signal and the psychology (Newton, Helmholtz, Maxwell); these characterized **equivalence classes of stimuli**
- The psychophysics made it possible to interpret neuroscience findings
- These findings have found application in a massive amount of current technology

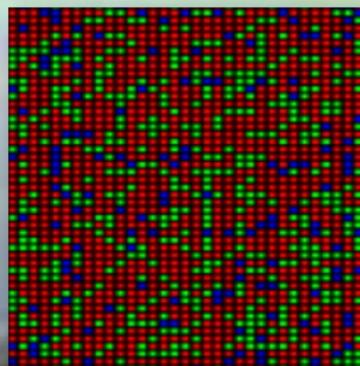
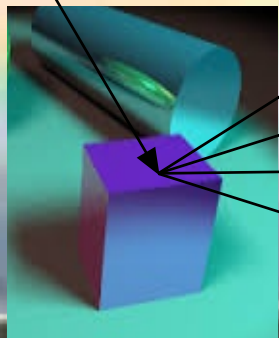
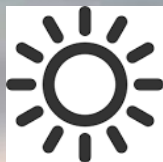


Summary

- The next generation of questions in color address color pattern, context, and time
- The ability to control the spatio-chromatic color stimulus is one advance; computer graphics methods to model such stimuli are a second advance; new optics devices to control precisely the delivery spatial chromatic stimuli a third advance
- It is my opinion that the modern neuroscience findings about color and cortex will clarify following further advances in behavioral modeling and measurements
- These findings, too, will find application in technologies; it is my hope perhaps most likely as that such analyses will serve as a model for how to think about high dimensional neural data in other parts of sensory and cognitive neuroscience



Color appearance: Light, brain, and perception



Scene spectral radiance

Physiological optics

Photo transduction

Retinal processing

Inference



Thanks to Simons Foundation
Oculus Research, Samsung,
Qualcomm, NIH, NSF

