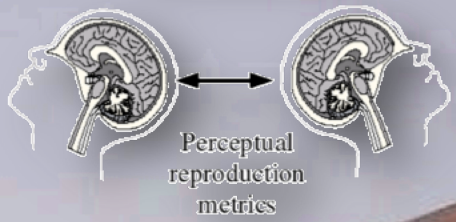
Human color encoding and image system engineering

- Types of photoreceptors
- Photoreceptors spatial arrangement
- Color-matching experiment



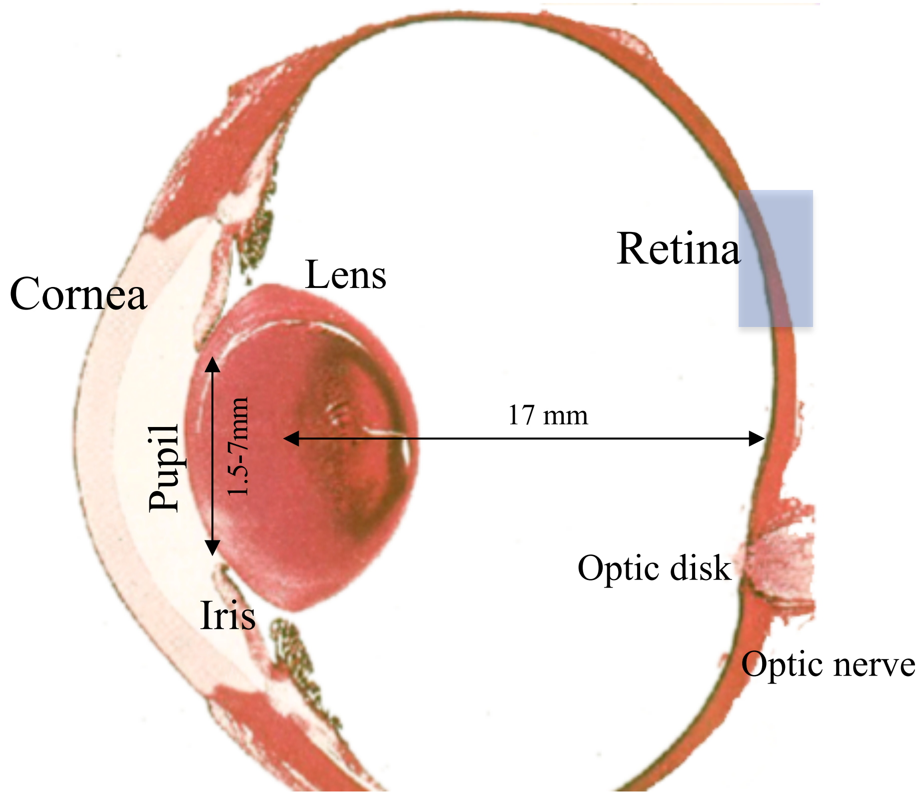
Color vision is interesting: Blue Man Group

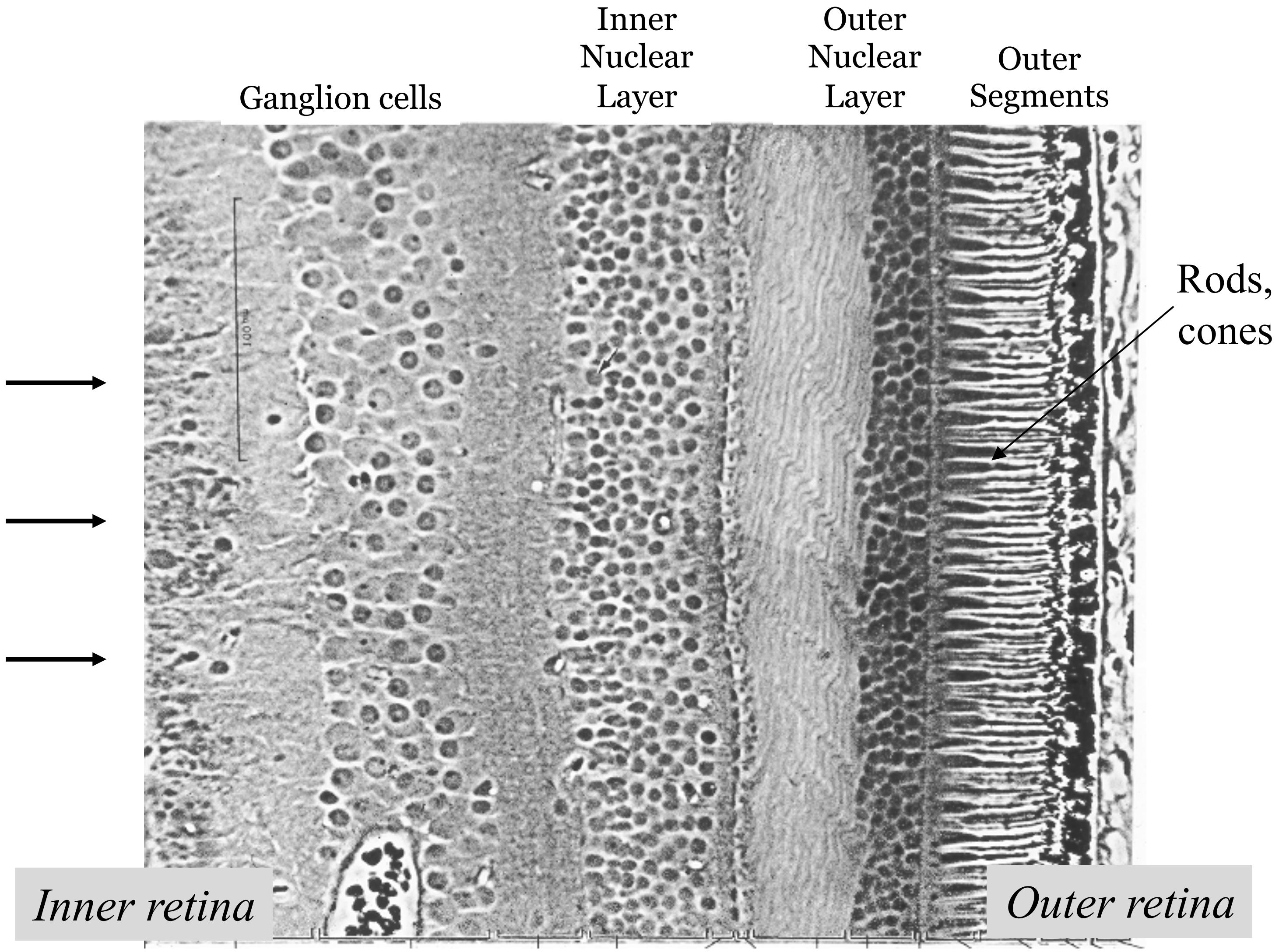
Oct. 2016: 2,614,430 views

sHc&feature=youtube_gdata_player

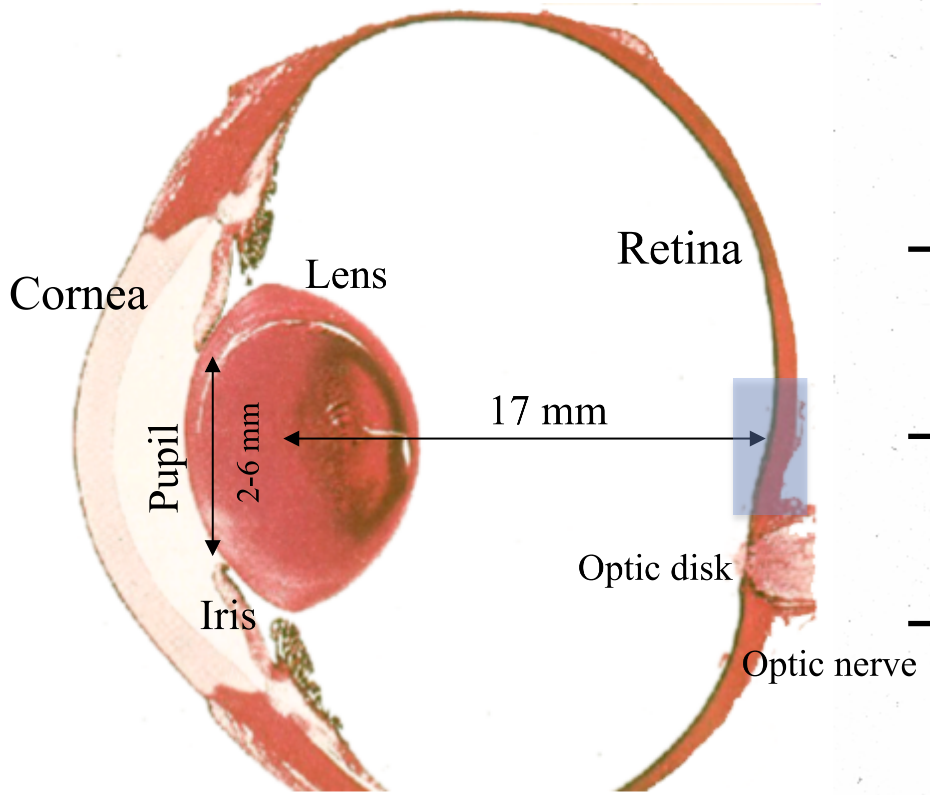
Human eye in cross-section

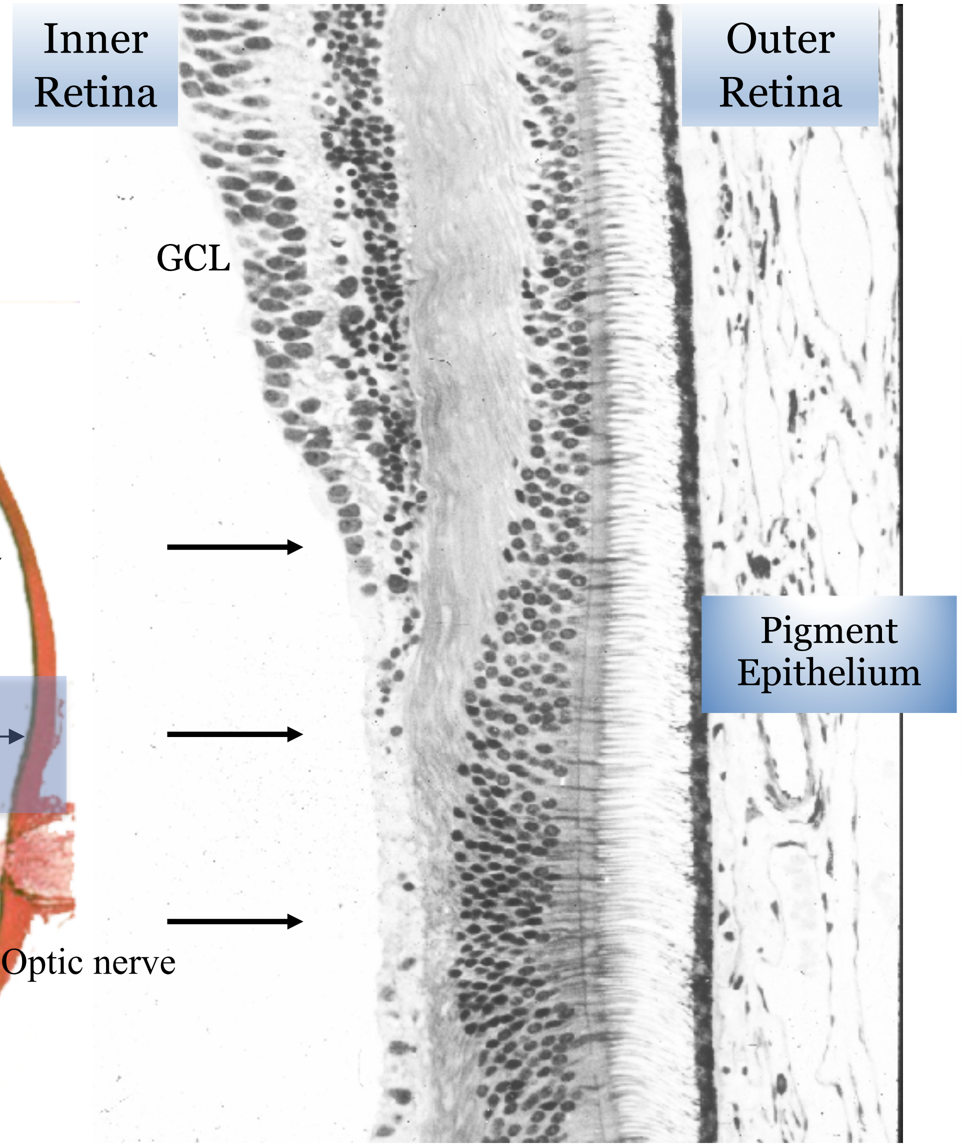
F-number ~ 2.4-11
Retinal thickness ~ 0.4mm





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





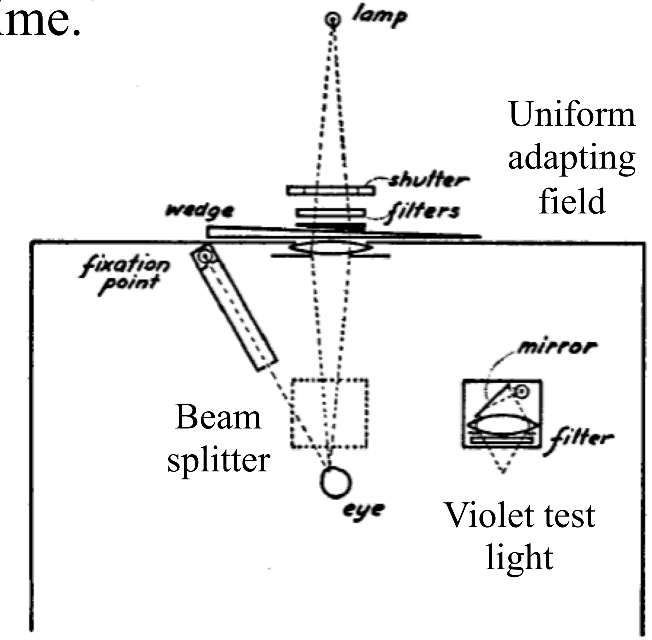
- 5 x 5 cm, 0.4 mm thick
- 5 x 10^6 cones
- 10^8 rods
- Foveal cone width: 1 um
- Contacts per cone: 250
- 10^6 optic nerve fibers

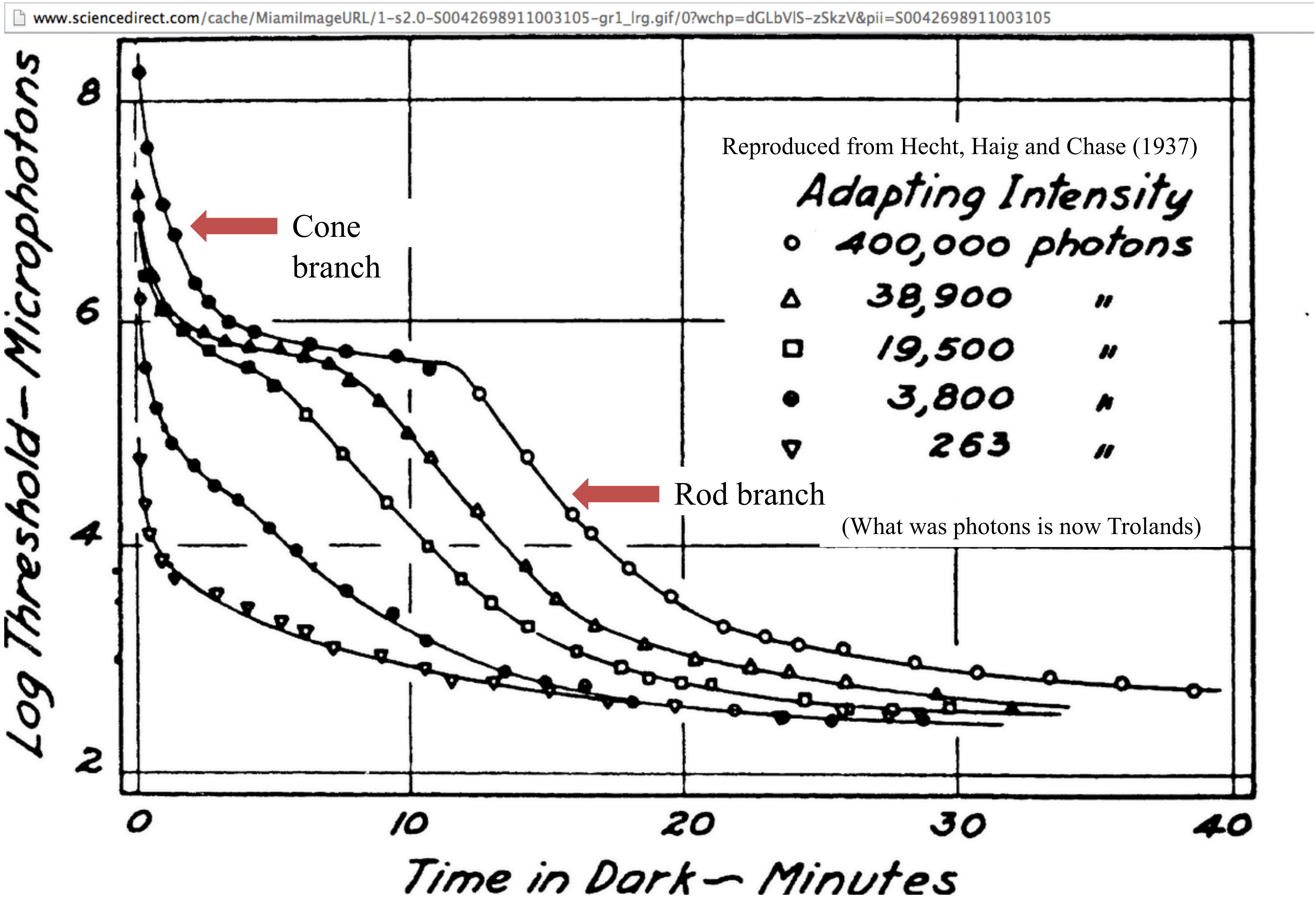
Dark adaptation distinguishes cones and rods

The subject is exposed to a large, (30 deg) uniform field, in the periphery.

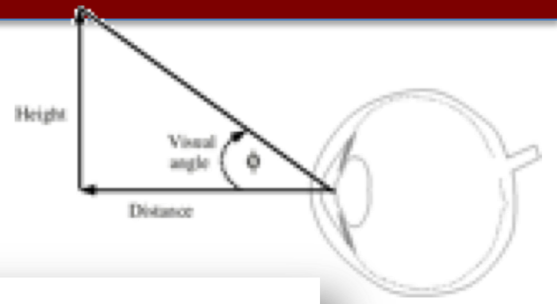
The field is extinguished, and a violet test light is presented.

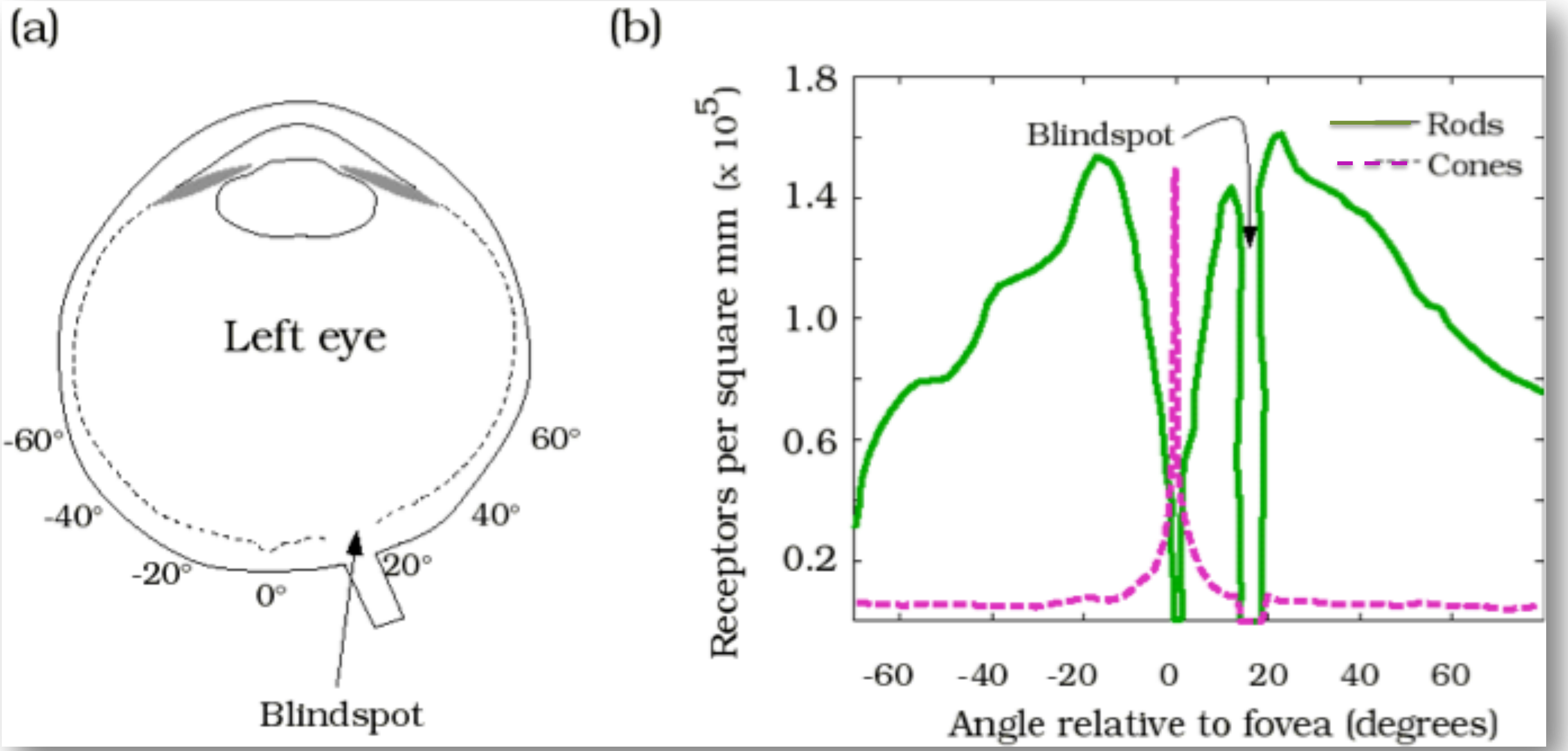
The subject adjusts the test intensity to threshold, over time.





Spatial distribution of human photoreceptors (rods and cones)

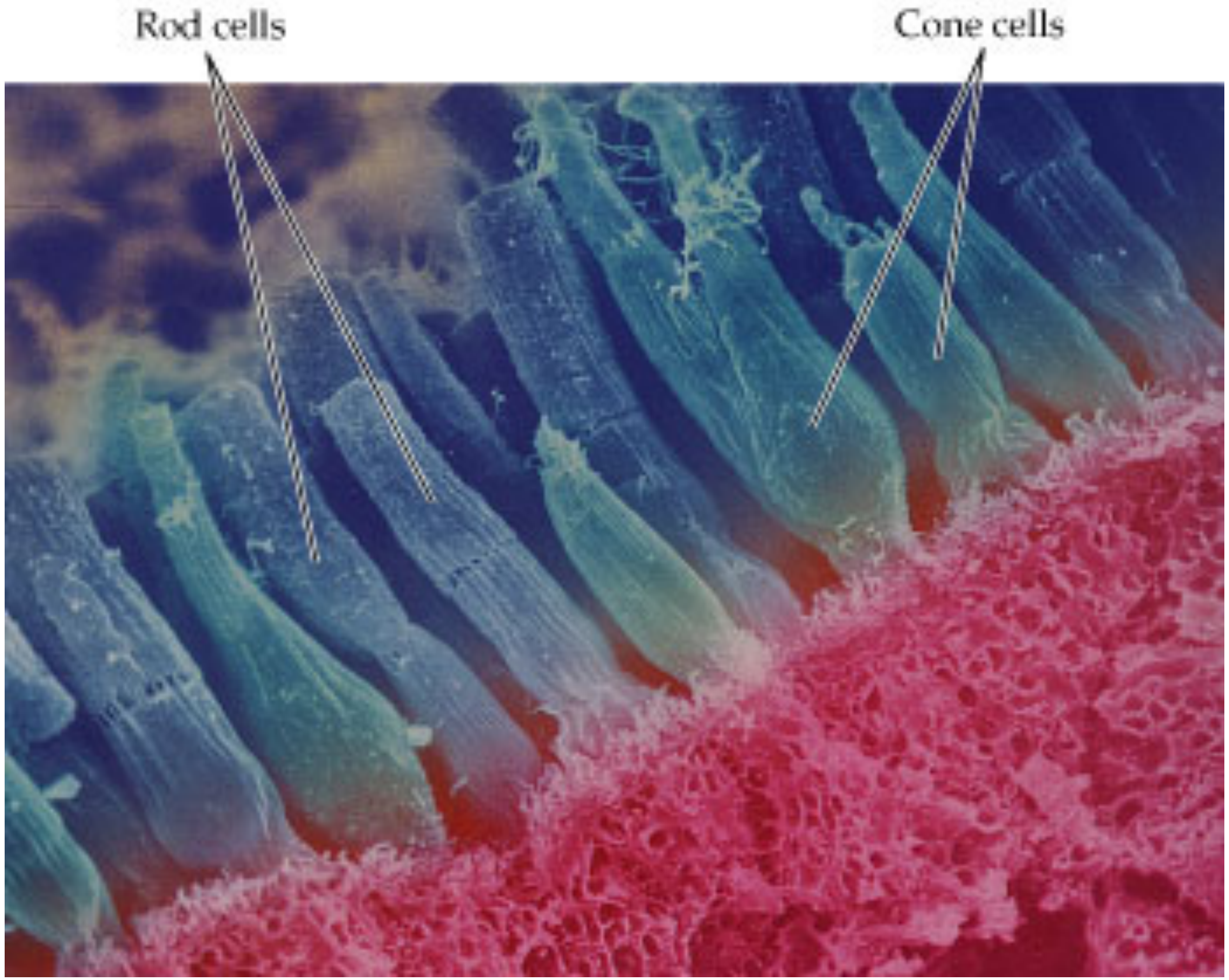




Rods and cones

http://ebooks.bfwpub.com/life.php Figure 45.18

- Rods and cones seen through a scanning electron microscope.
- Each rod is about one micron across.
- Rods and cones are intermingled in the visual periphery

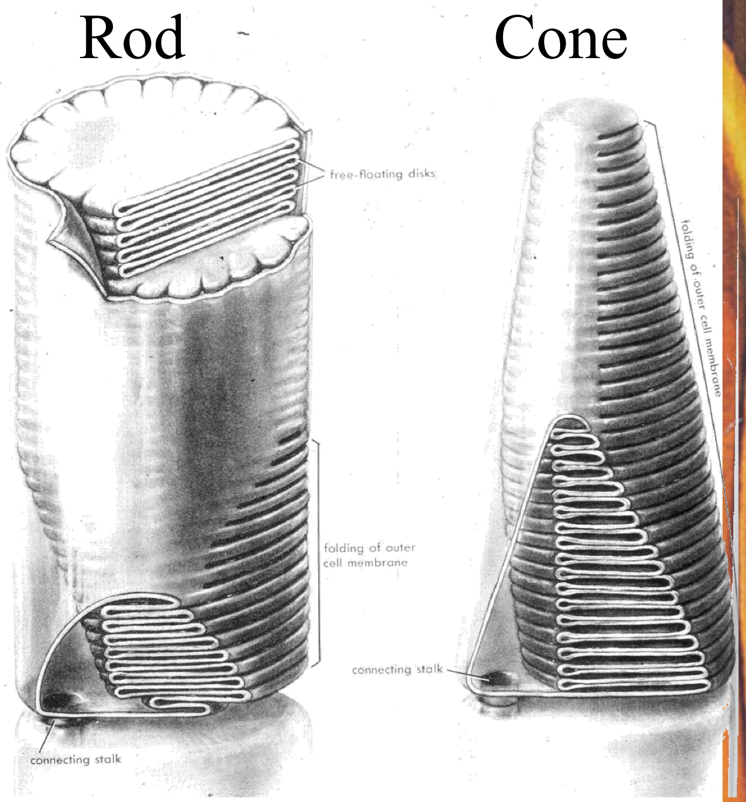


Rods and cones

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

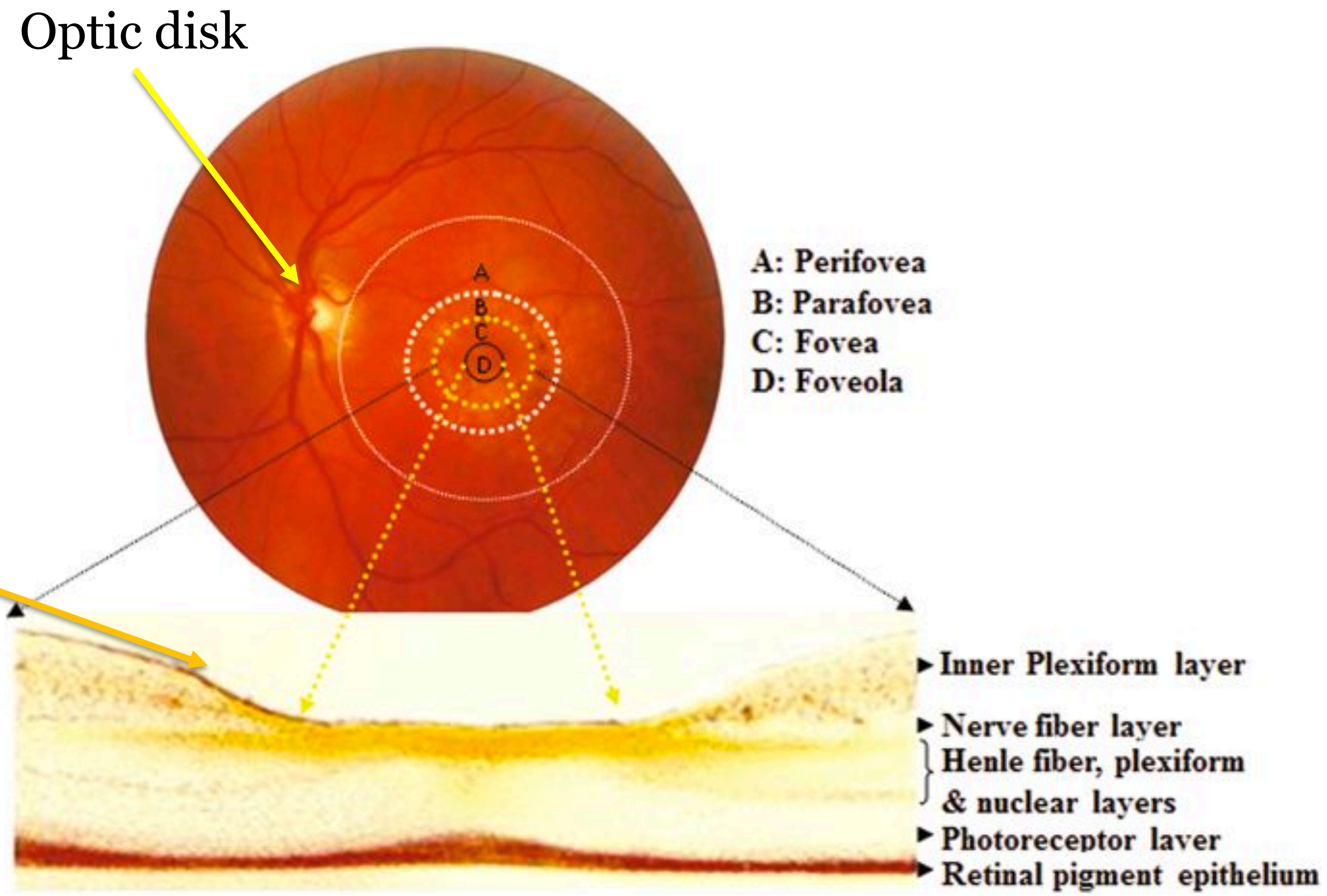
Rods and cones in schematic, and as estimated through a scanning electron microscope.

Each rod is about one micron across.



Retinal terminology

- Fundus image of the retina
- Fovea and blindspot
- Macular pigment

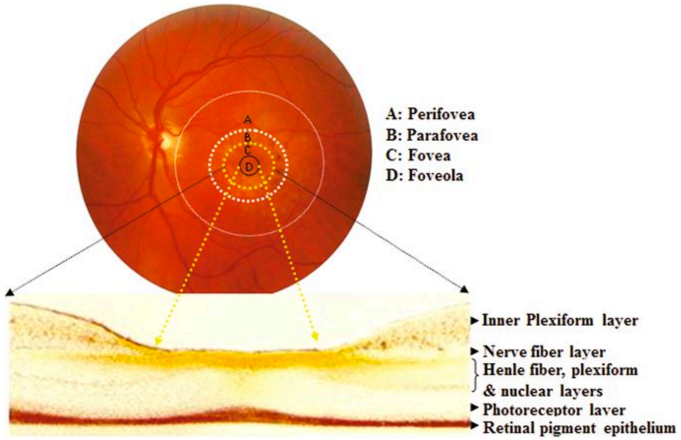


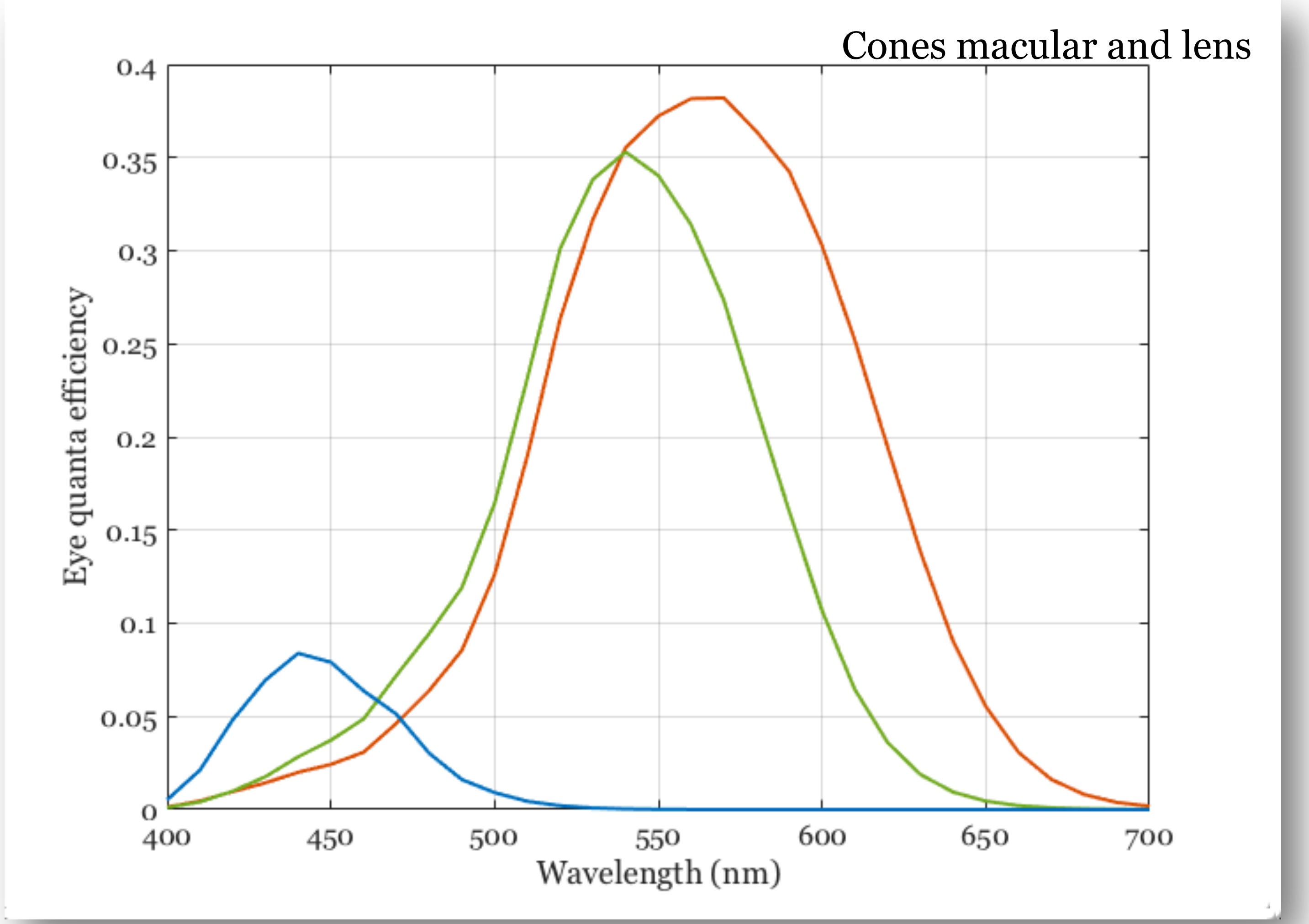
Henle fiber -
the layer of inner cone fibers in the central area of the retina.

Human wavelength absorptions depend on a series of factors

- Cone photopigments (L,M,S) absorption efficiency for standard pigment density

- Including the effect of the lens and macular pigment



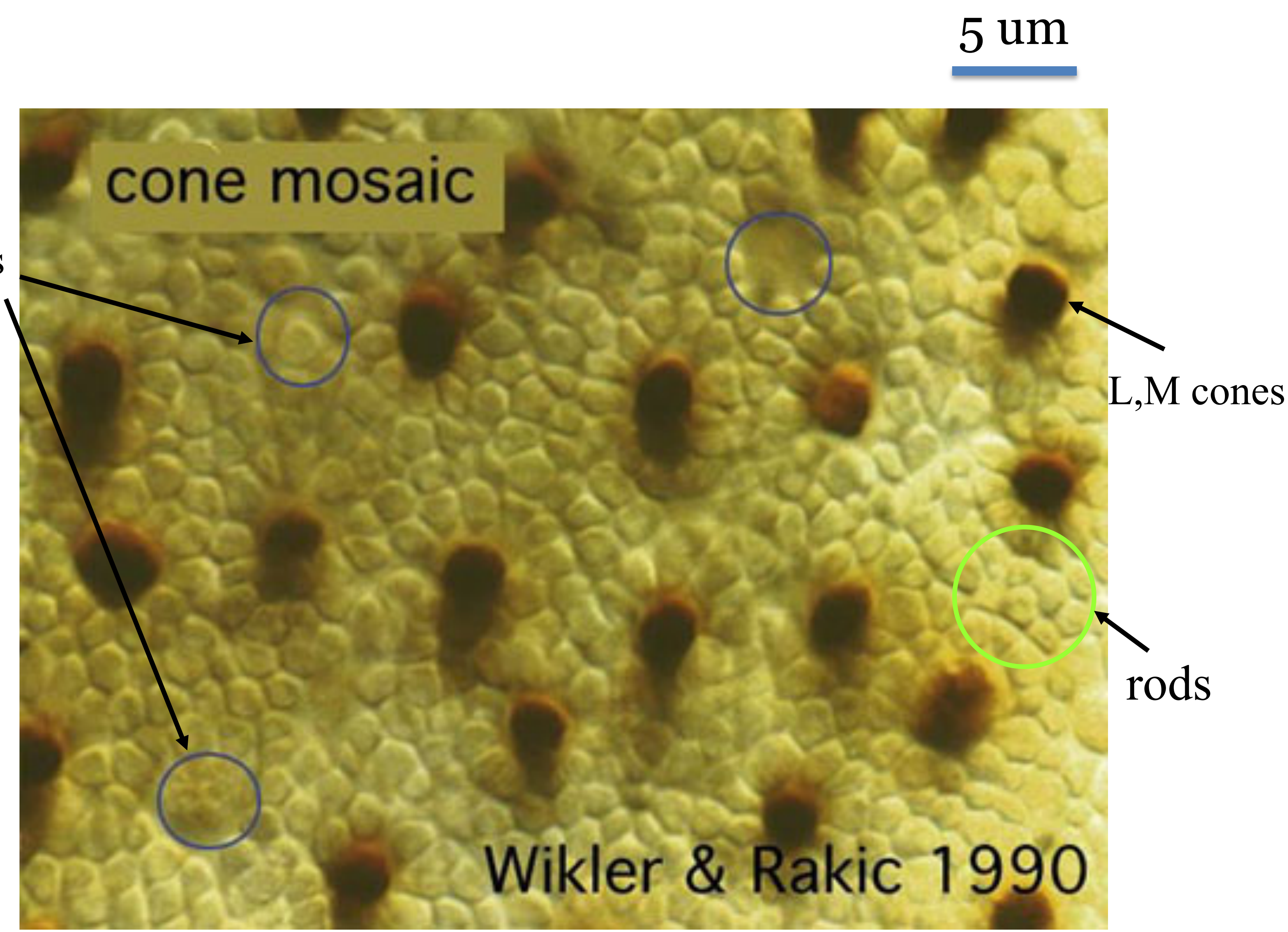


Impact of the lens and macular pigment

The lens and macular pigment have a dramatic impact on the light that gets to the cone photoreceptors

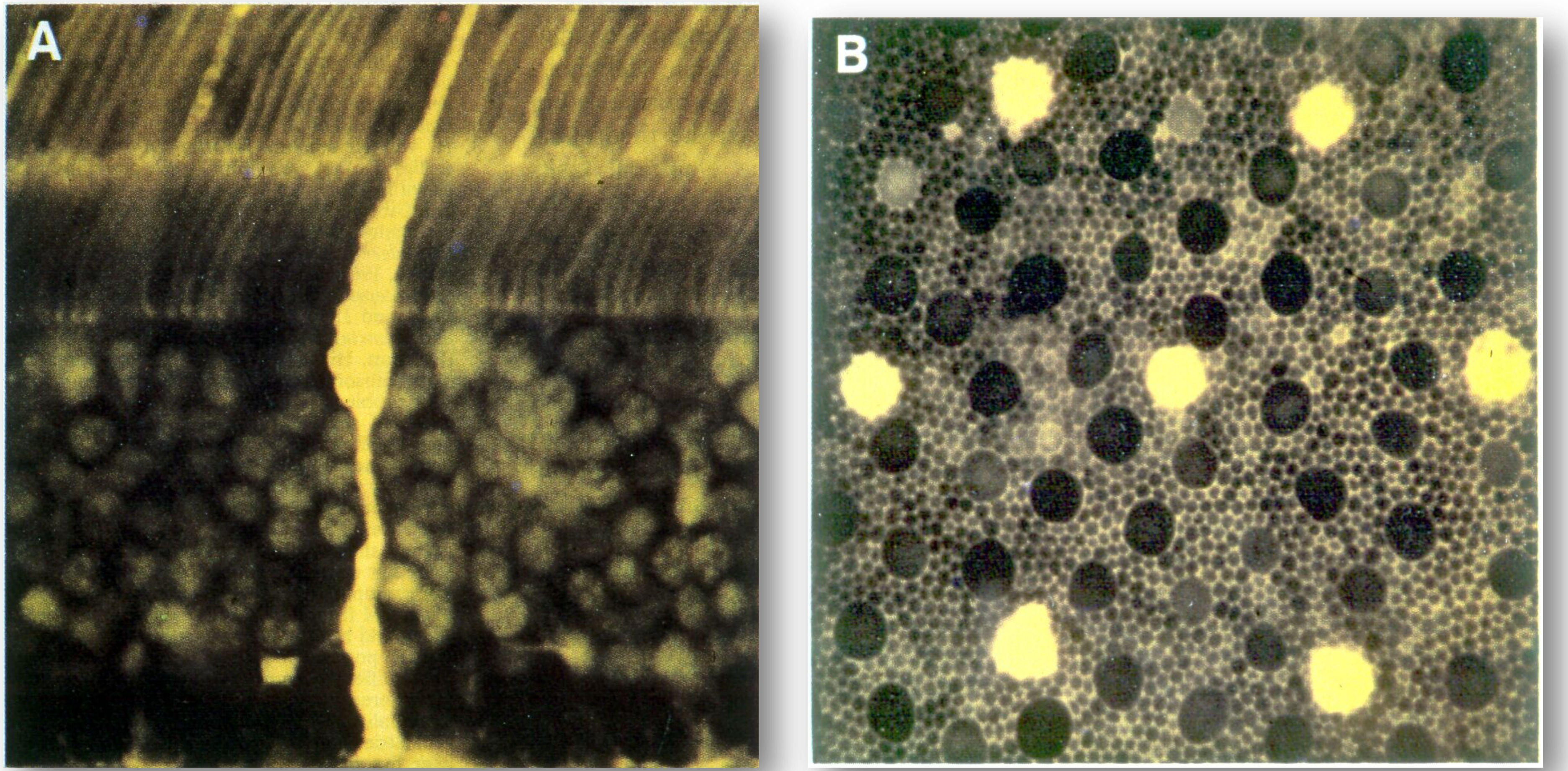
Cone mosaic

- L,M cones stained
- S-cones not stained
- Small cross-sections are rods
- Near periphery in the retina

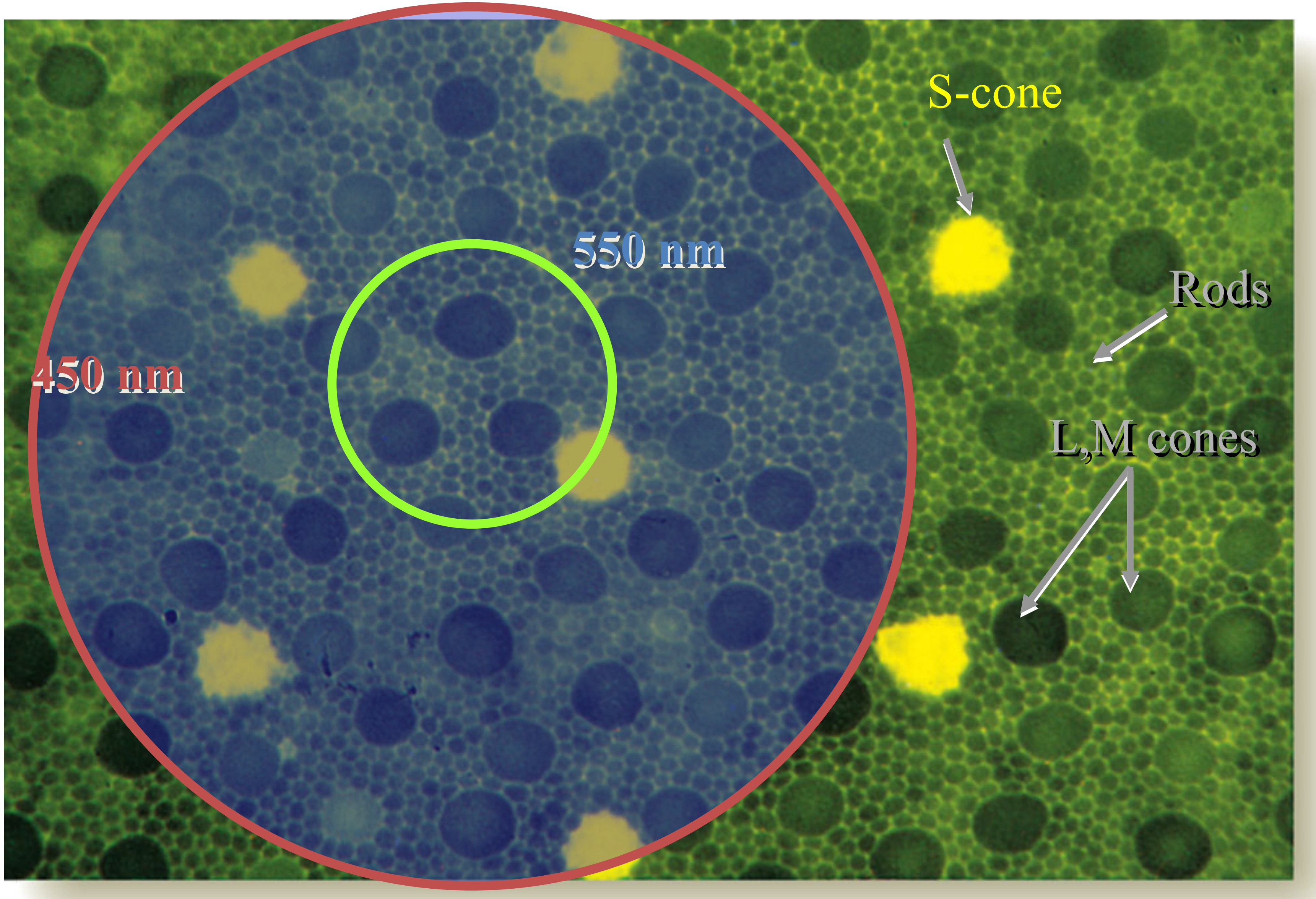


S-cones labeled

5 um



Photoreceptor mosaic

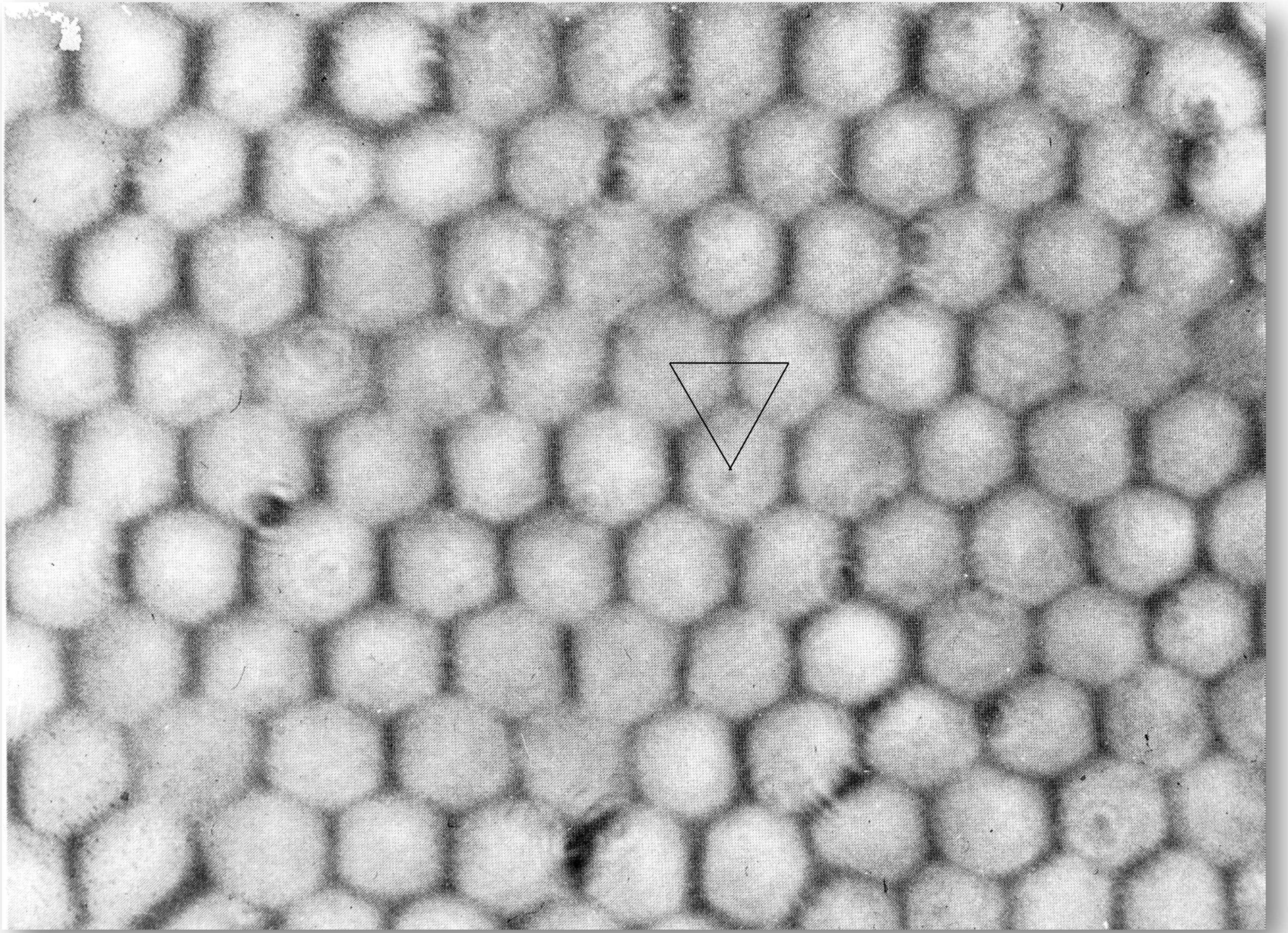


5 um

Foveal cone mosaic in central foveola

- Triangular (hexagonal) packing
- All cones
- Inner segment
- Miller et al.

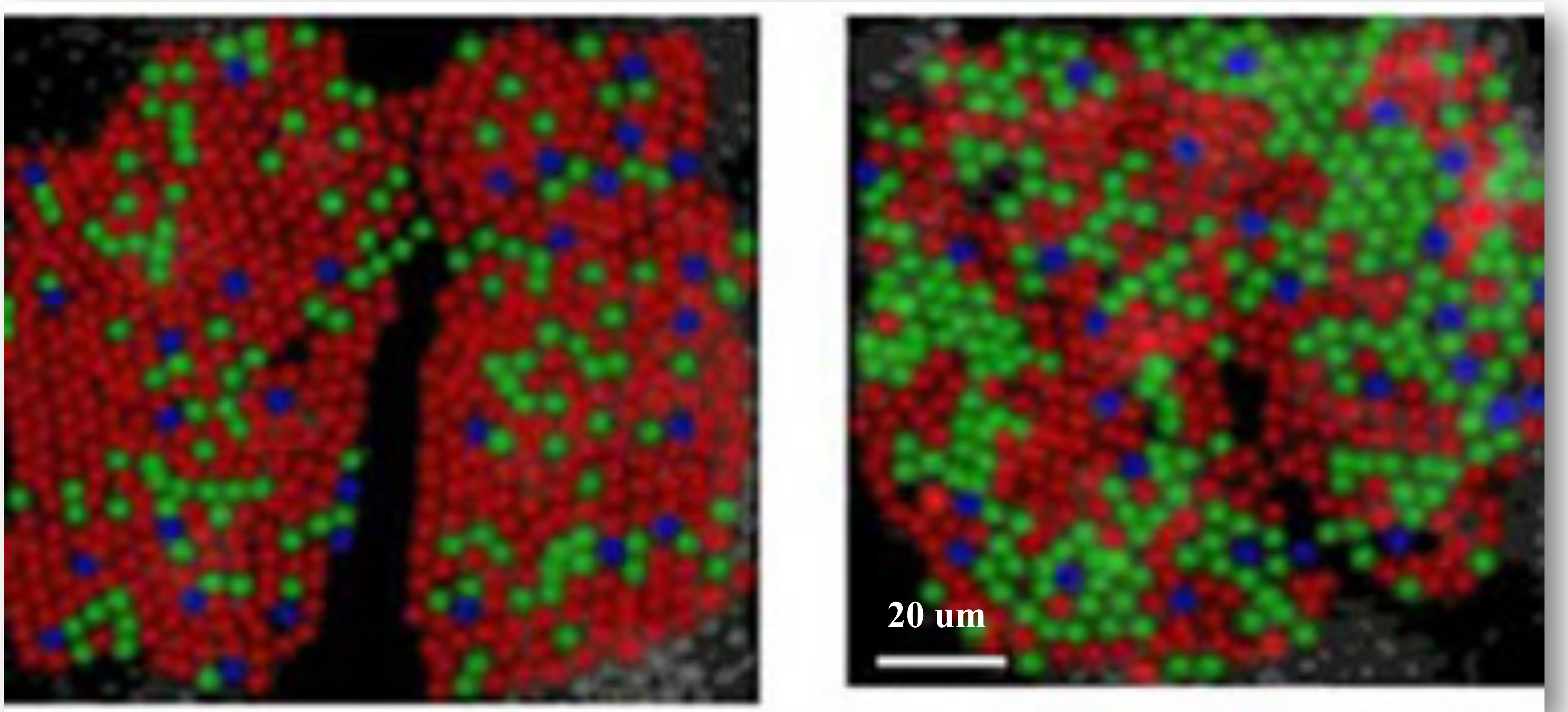
5 um



Cone receptor mosaic (Roorda and Williams, 1999)

L:M cone ratios: 3.8:1 and 1.15:1 – yet both are normal

Enormous variation in the number of L and M cones in different people



Ratio of L/M cones differs greatly between normals

- 1 deg is about 300 microns (um)
- Cone inner segments
  - 1-2 um diameter (central fovea)
  - 3-4 um (0.6 deg eccentricity)
- If average diameter is 3 um, then ~100 cones/deg in foveola (central 1 deg)
- Nyquist is about 50 cpd

10 um

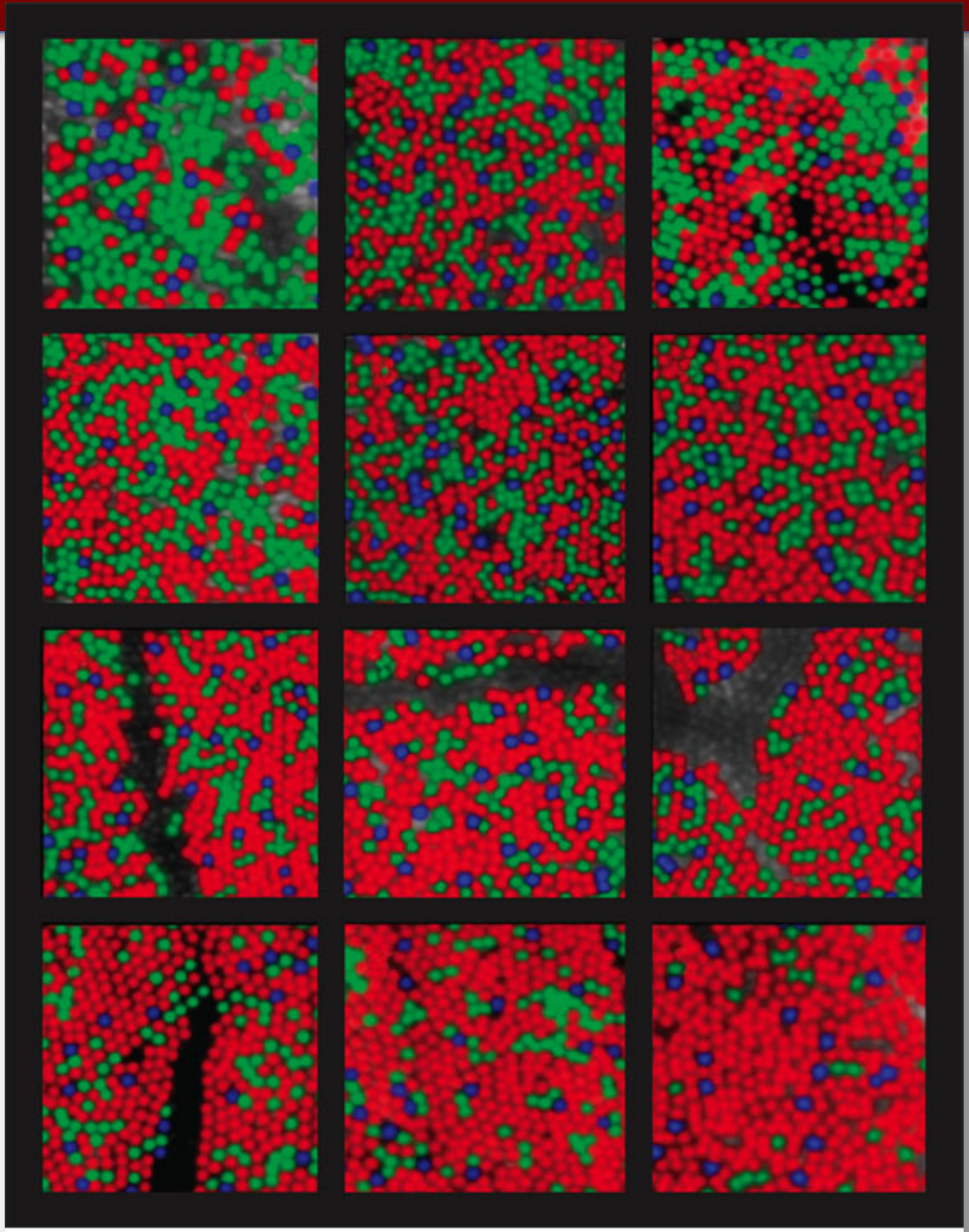
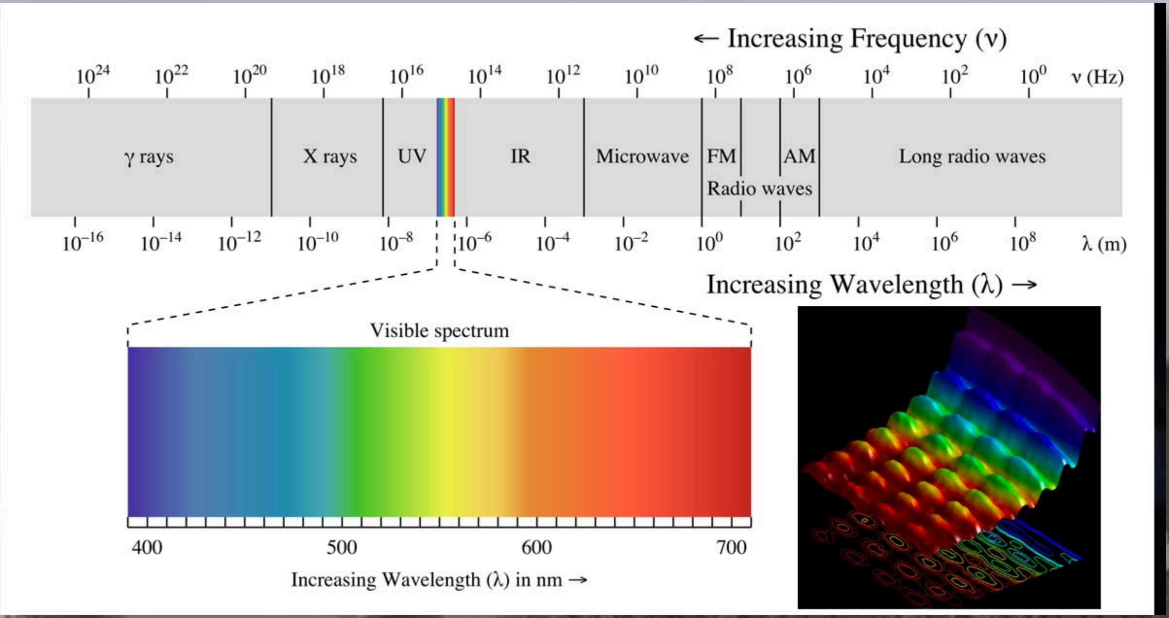


Fig. 7-CO, p. 140

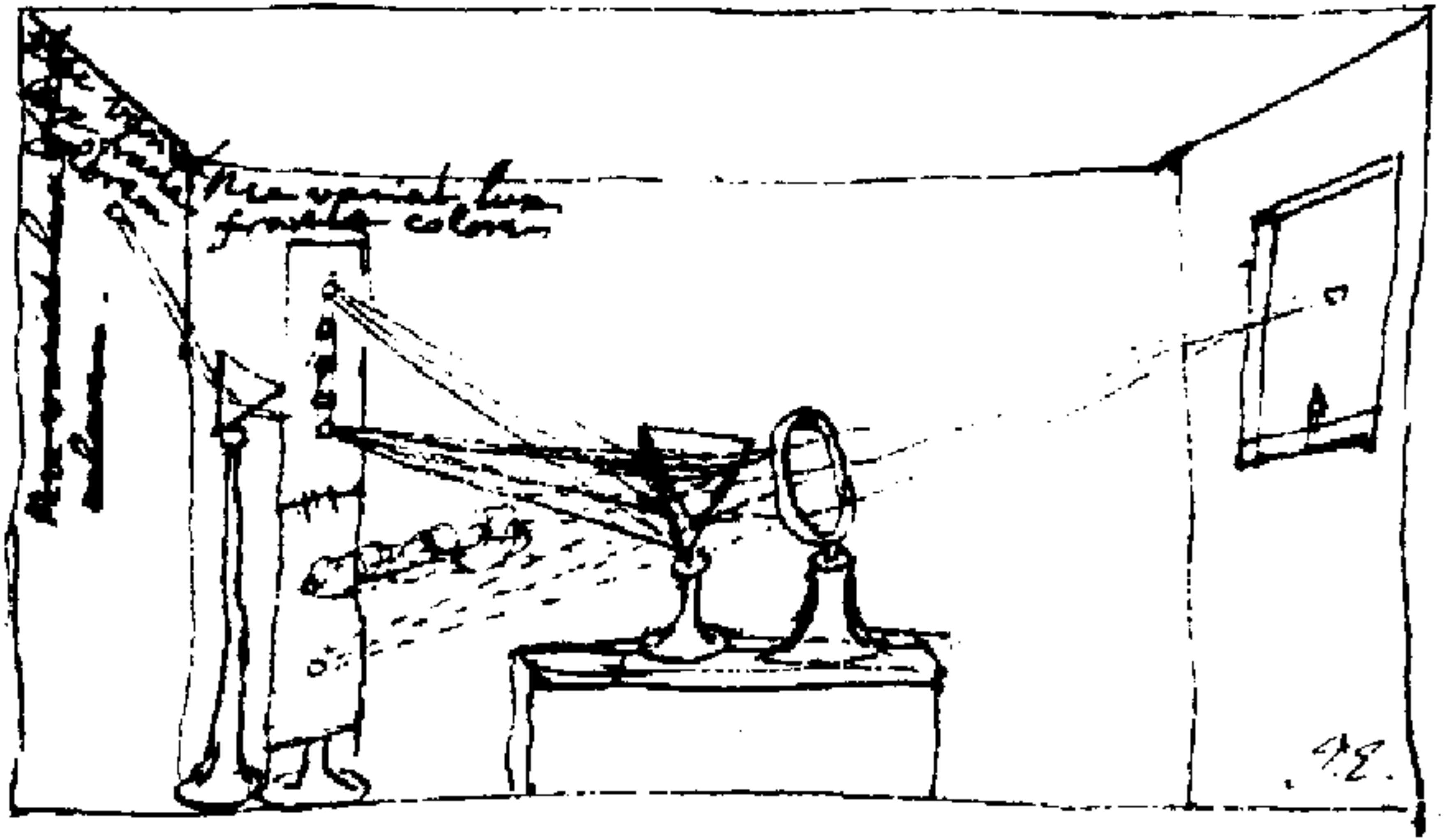
Hofer et al.
J. Neurosci. 2005

Light and superposition

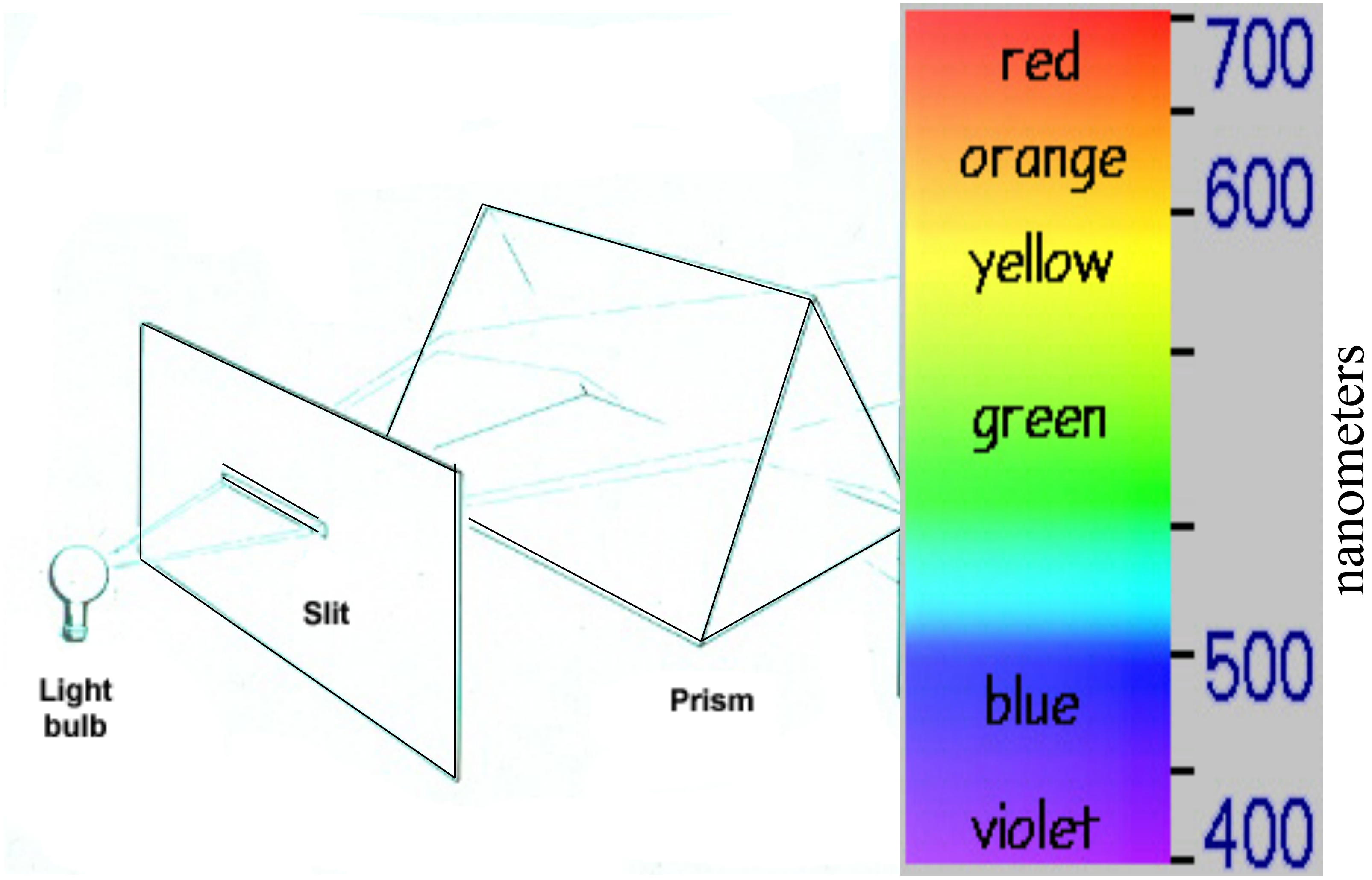
- Spectrum
- Superposition



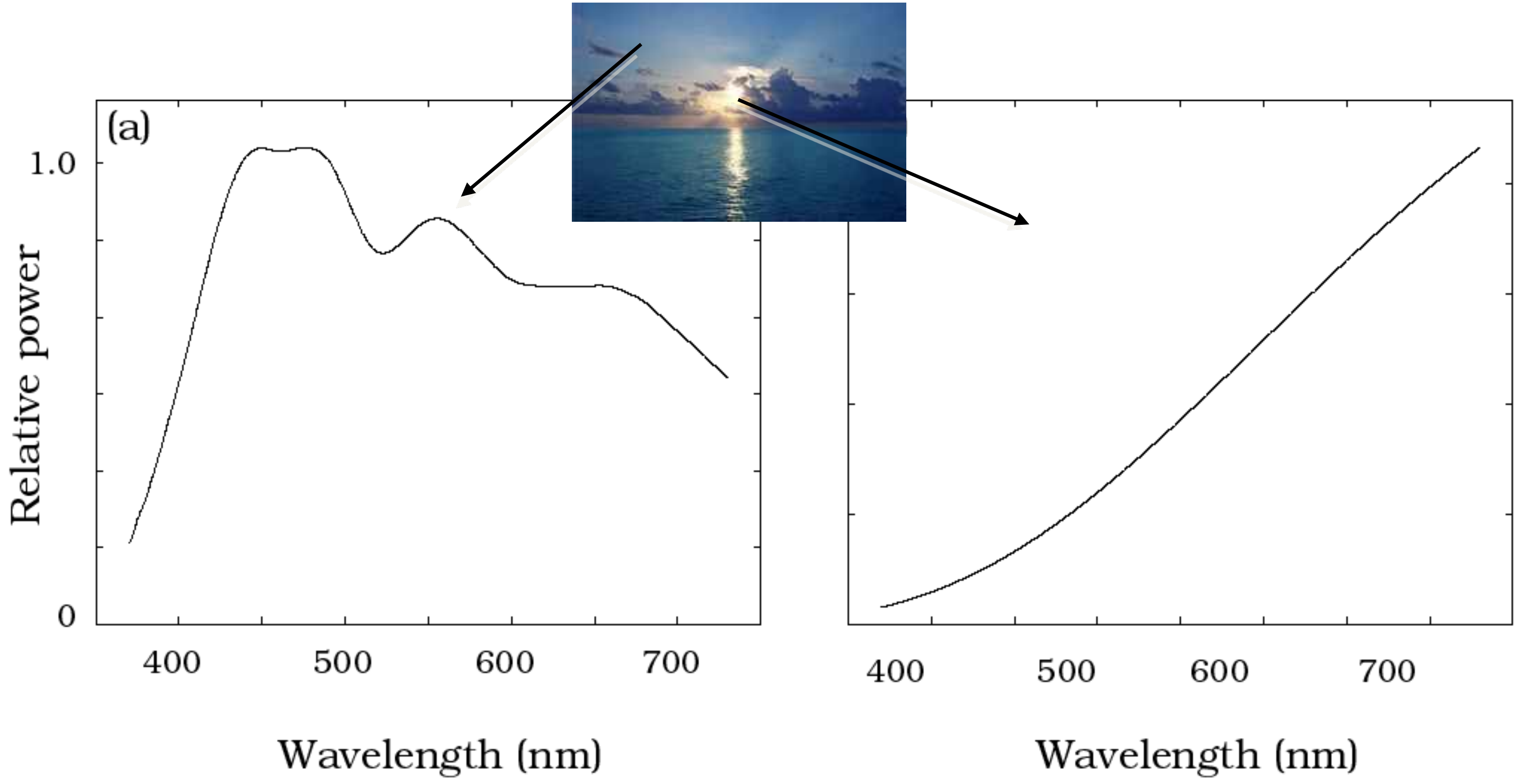
The fundamental components of light



Monochromators measure the energy at different wavelengths



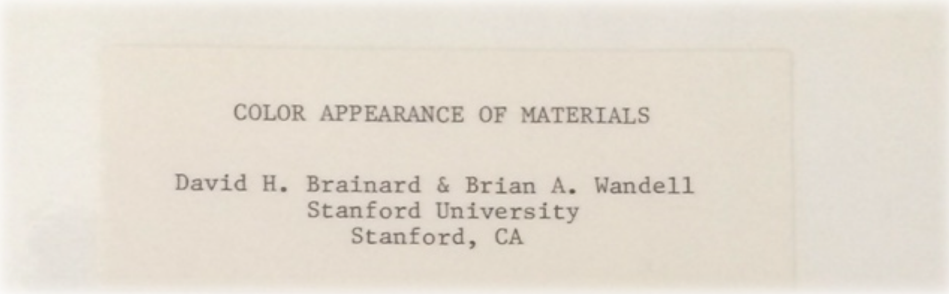
Typical daylight SPDs vary



SPD: spectral power distribution

Same objects but illuminated by two different sources

Objects and lights interact on a wavelength basis, not in RGB space



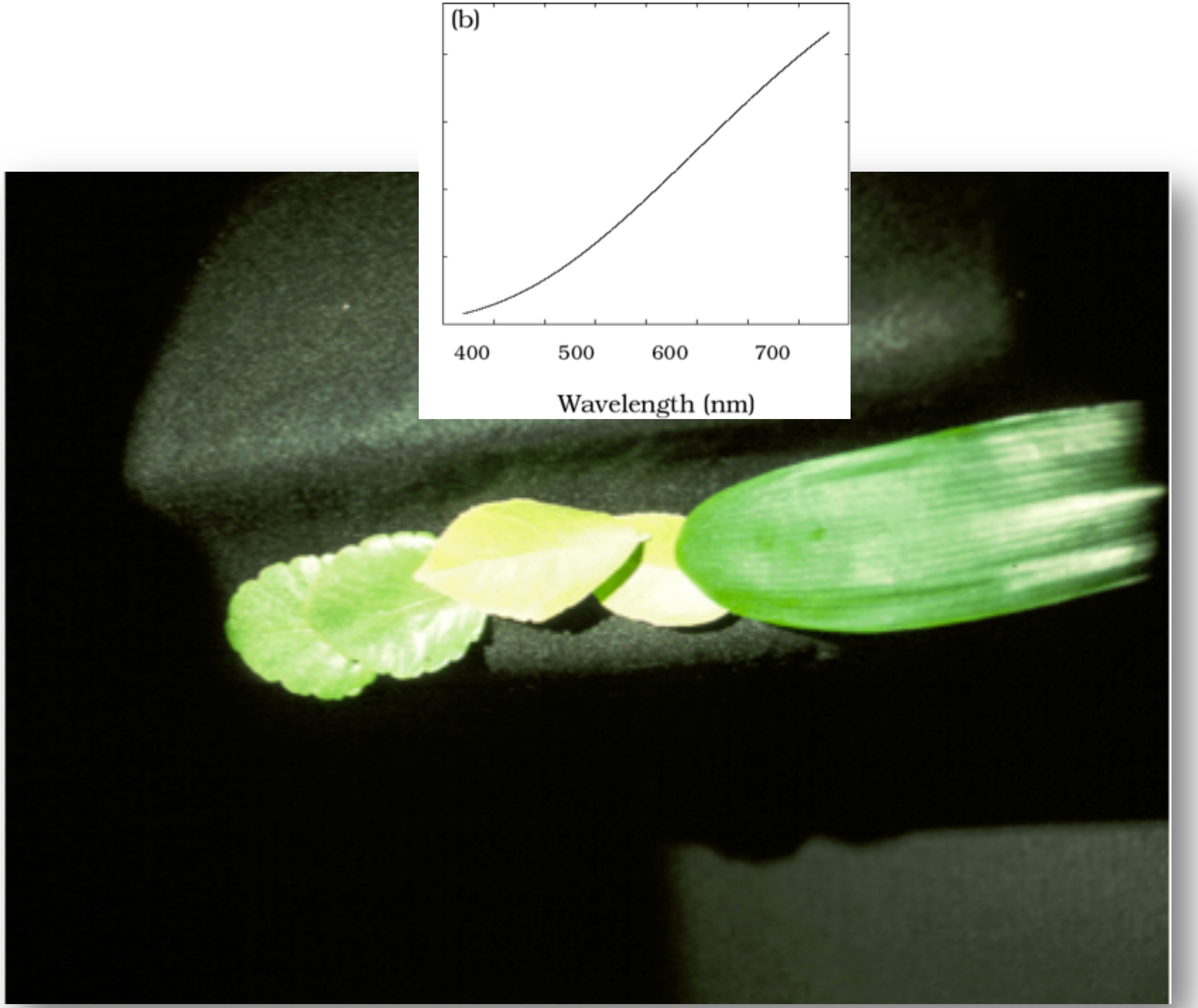
COLOR APPEARANCE OF MATERIALS

David H. Brainard & Brian A. Wandell
Stanford University
Stanford, CA

From R.M. Evans work at Kodak in the 1940s

Scene radiance depends on reflectance and illumination

- People want to recognize the object – hence estimate reflectance
- The visual system interprets color in a way that accounts for the spectral properties of the illuminant



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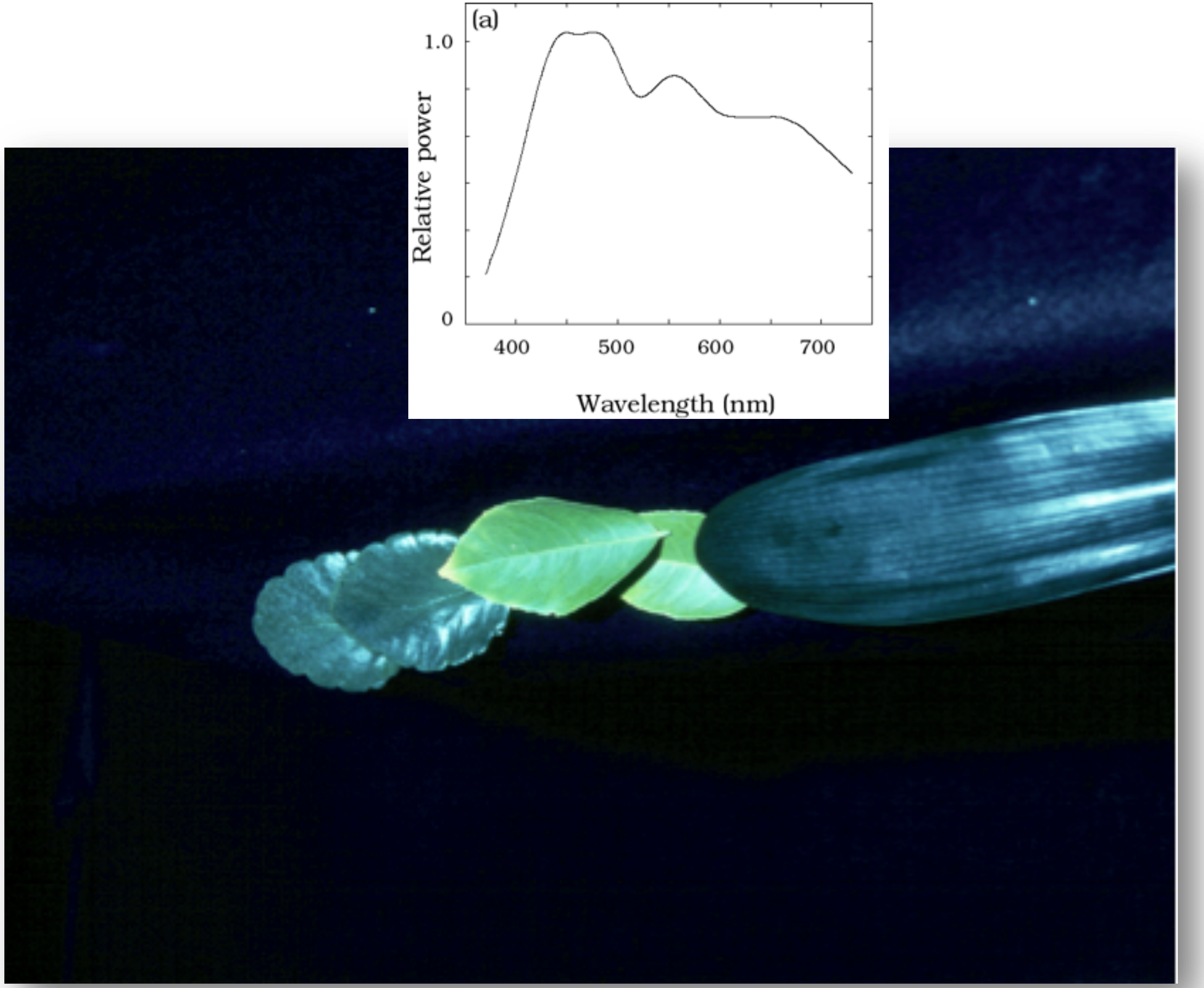
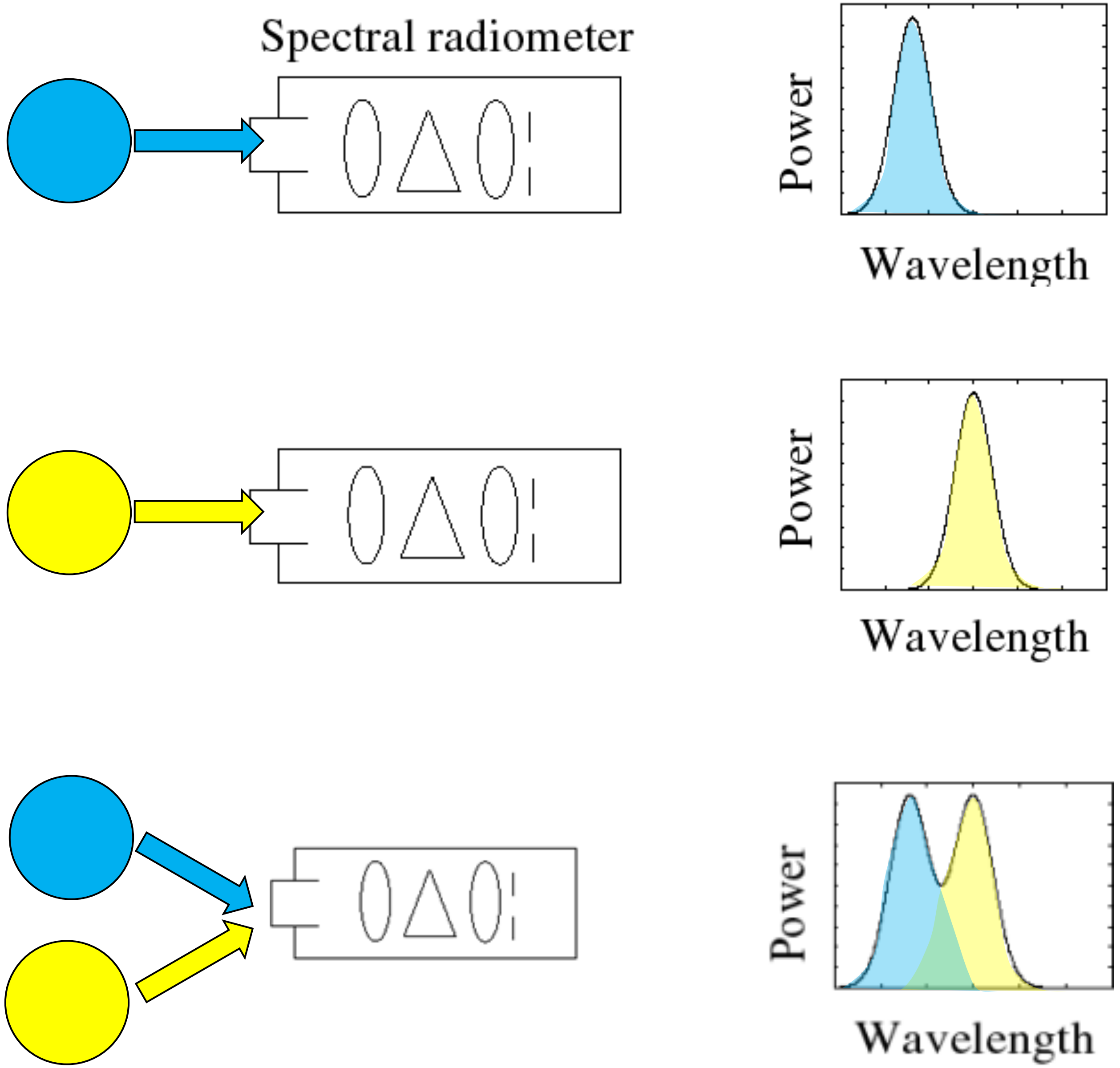
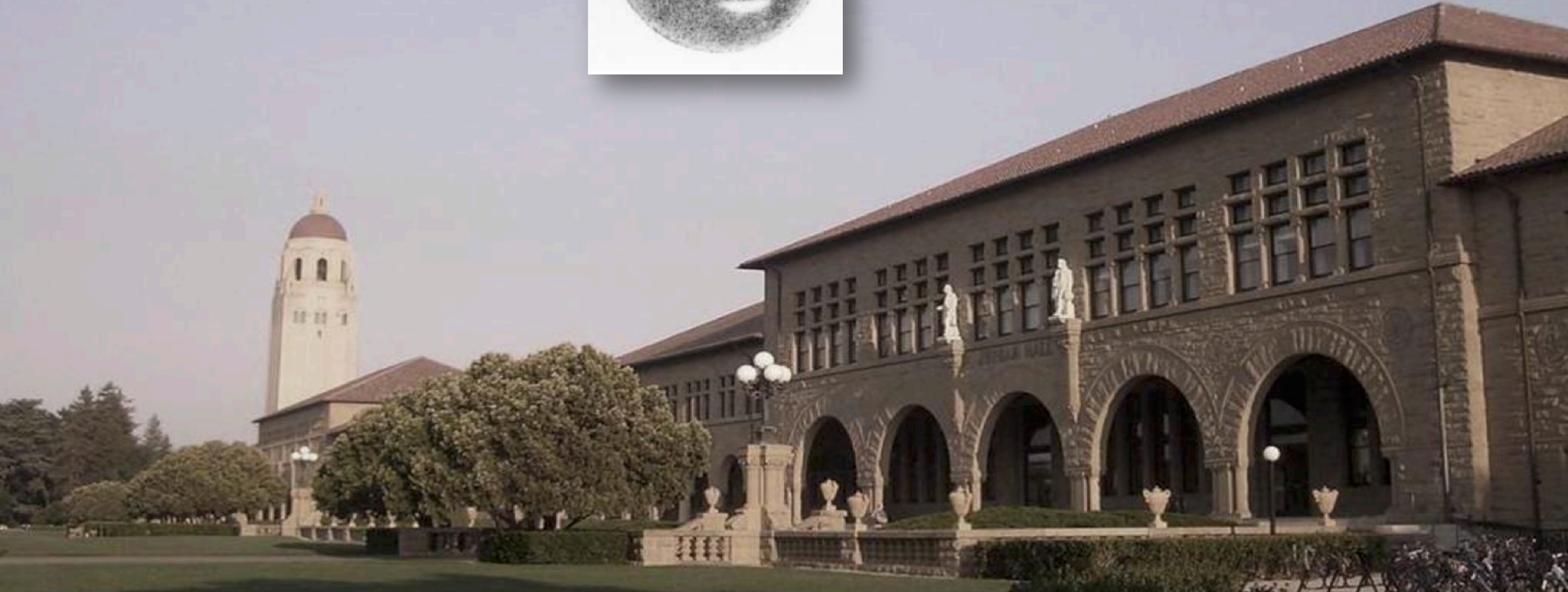


Superposition of light spectral power distributions



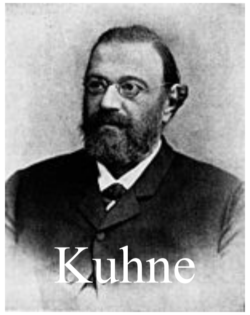
Rod (scotopic) color matching

Rhodopsin
Rod color-matching



Visual purple and the optogram

Boll



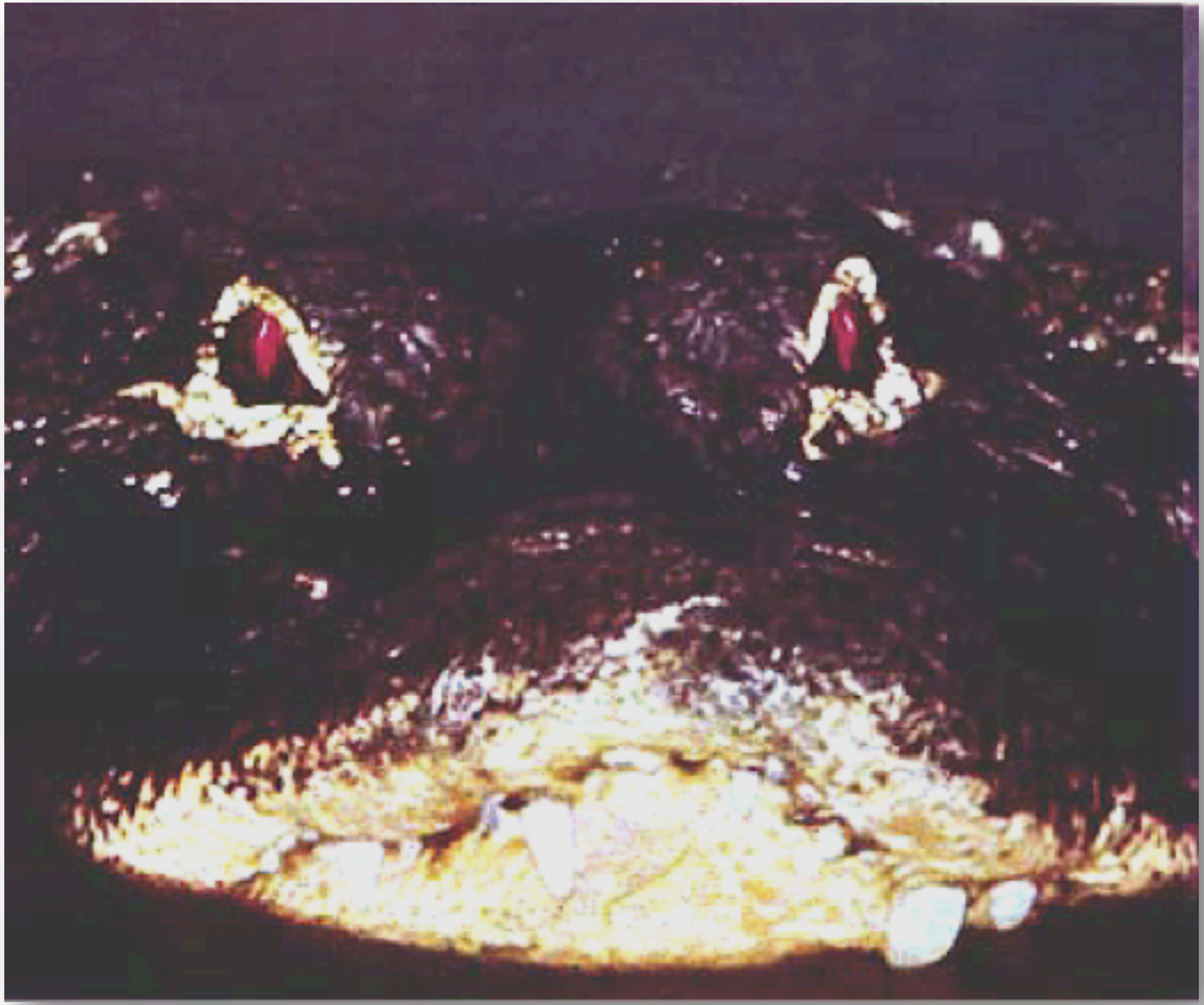
- Boll noticed that the light-sensitive pigment in the rods of the retina had a tendency to fade in the presence of illumination

- Kuhne made optograms, such using intact rabbit retina whose retina was fixed after dark adaptation, and then fastening its head to a barred window before slicing the retina

Rhodopsin: Regenerated

Rushton

The rhodopsin pigment can be seen directly in the eye of some animals

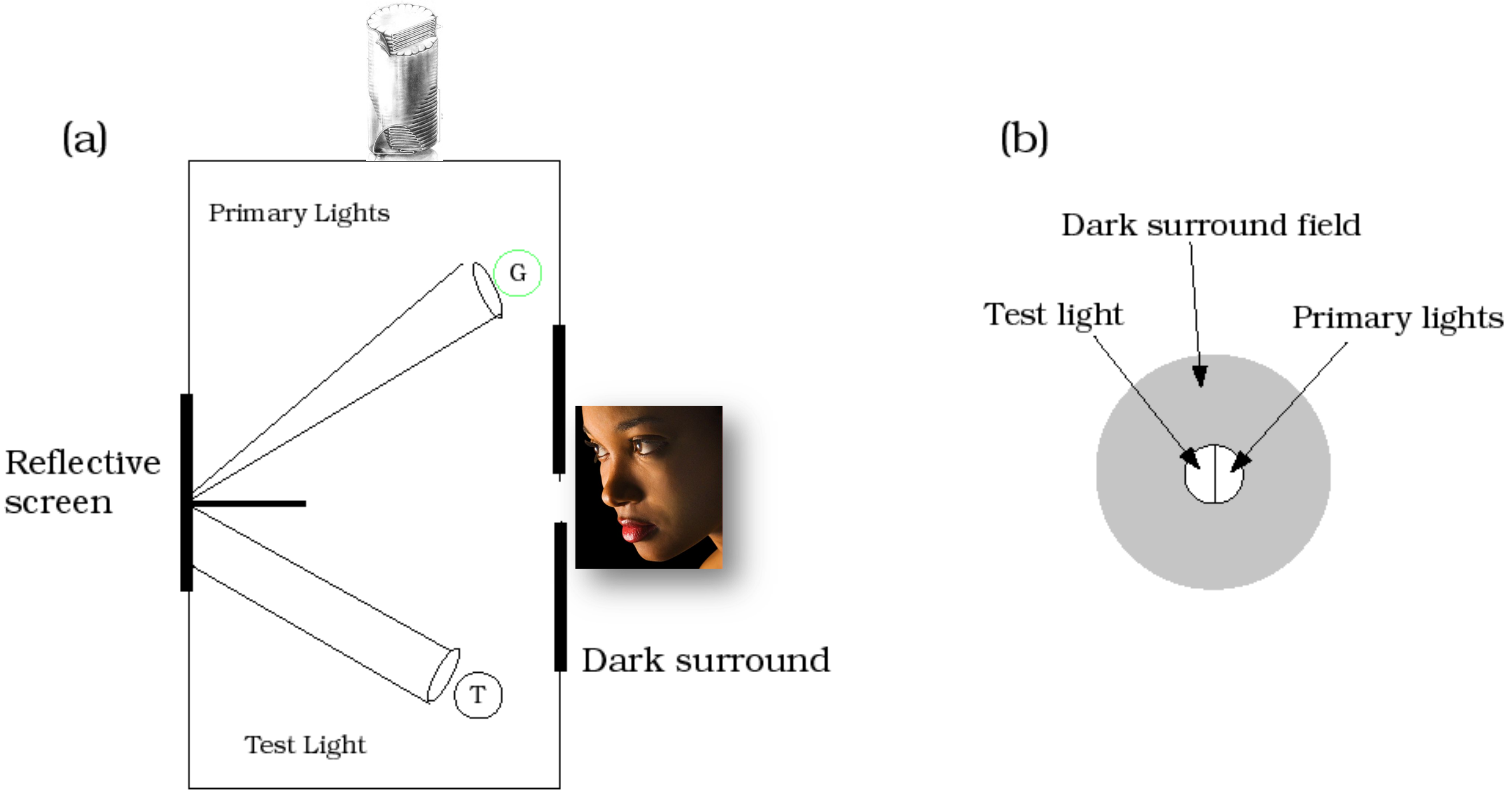


Visual purple is a synonym for rhodopsin

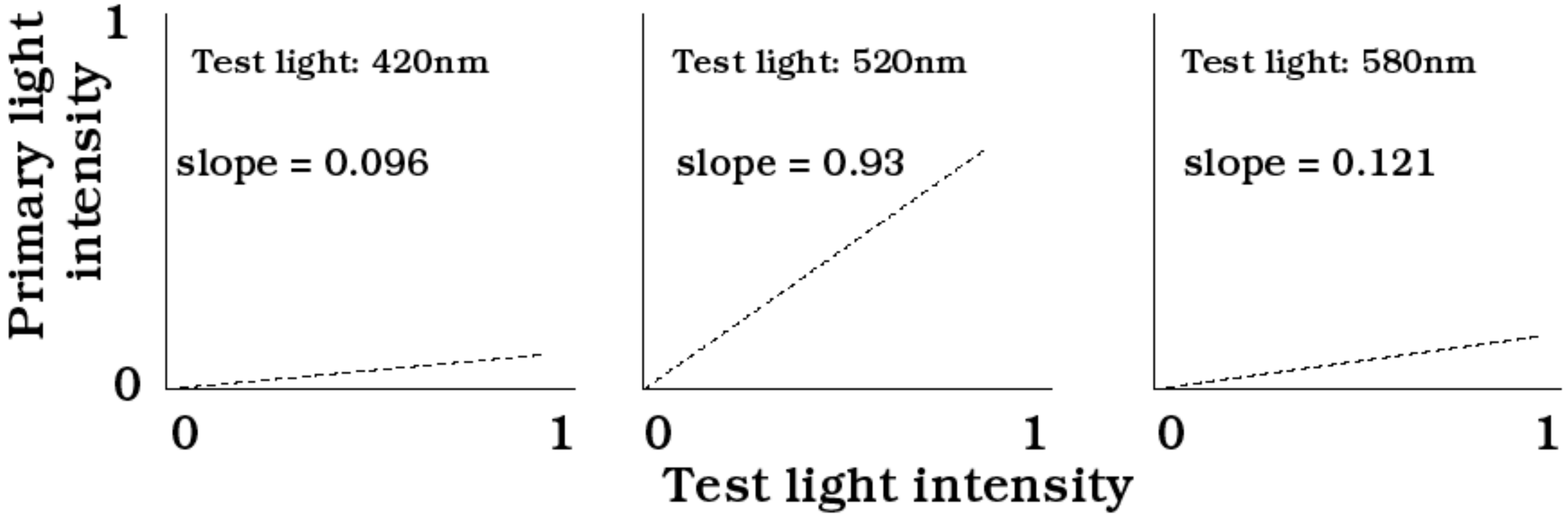
Rhodopsin: Bleached

After the eye is exposed to light, the rhodopsin is bleached and invisible

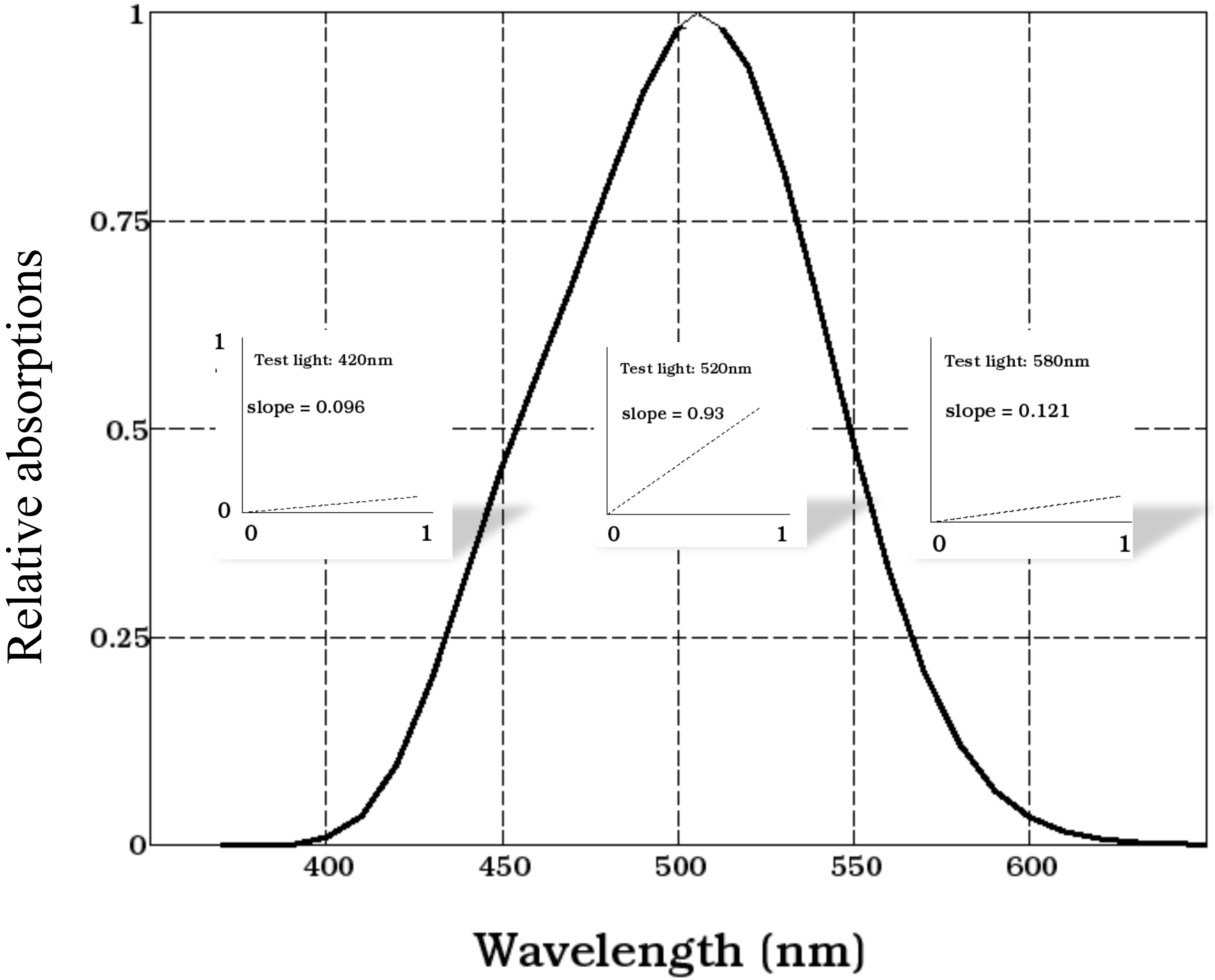
Rod color matching



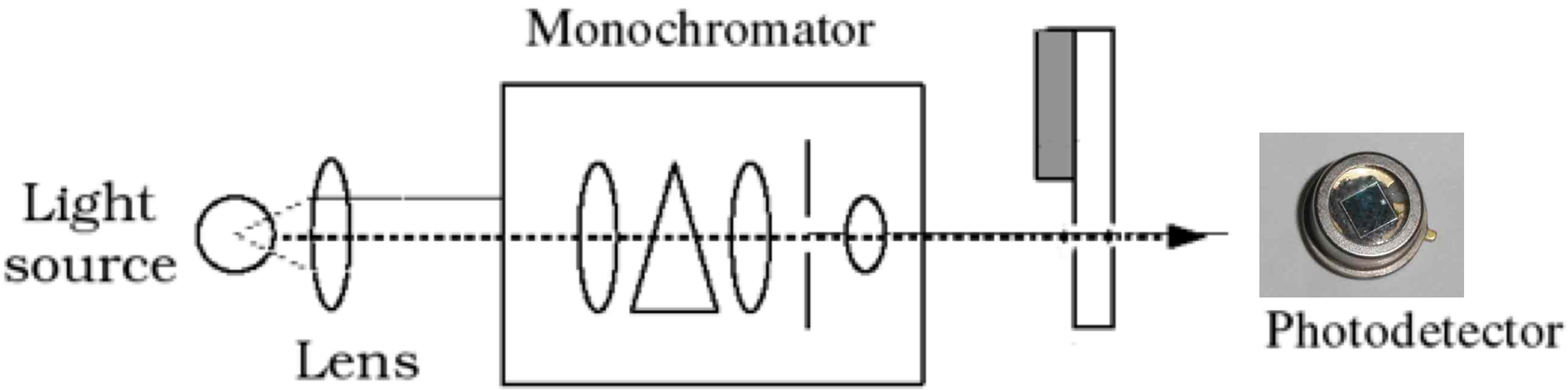
Example: Rod matches



Rhodopsin absorption curve

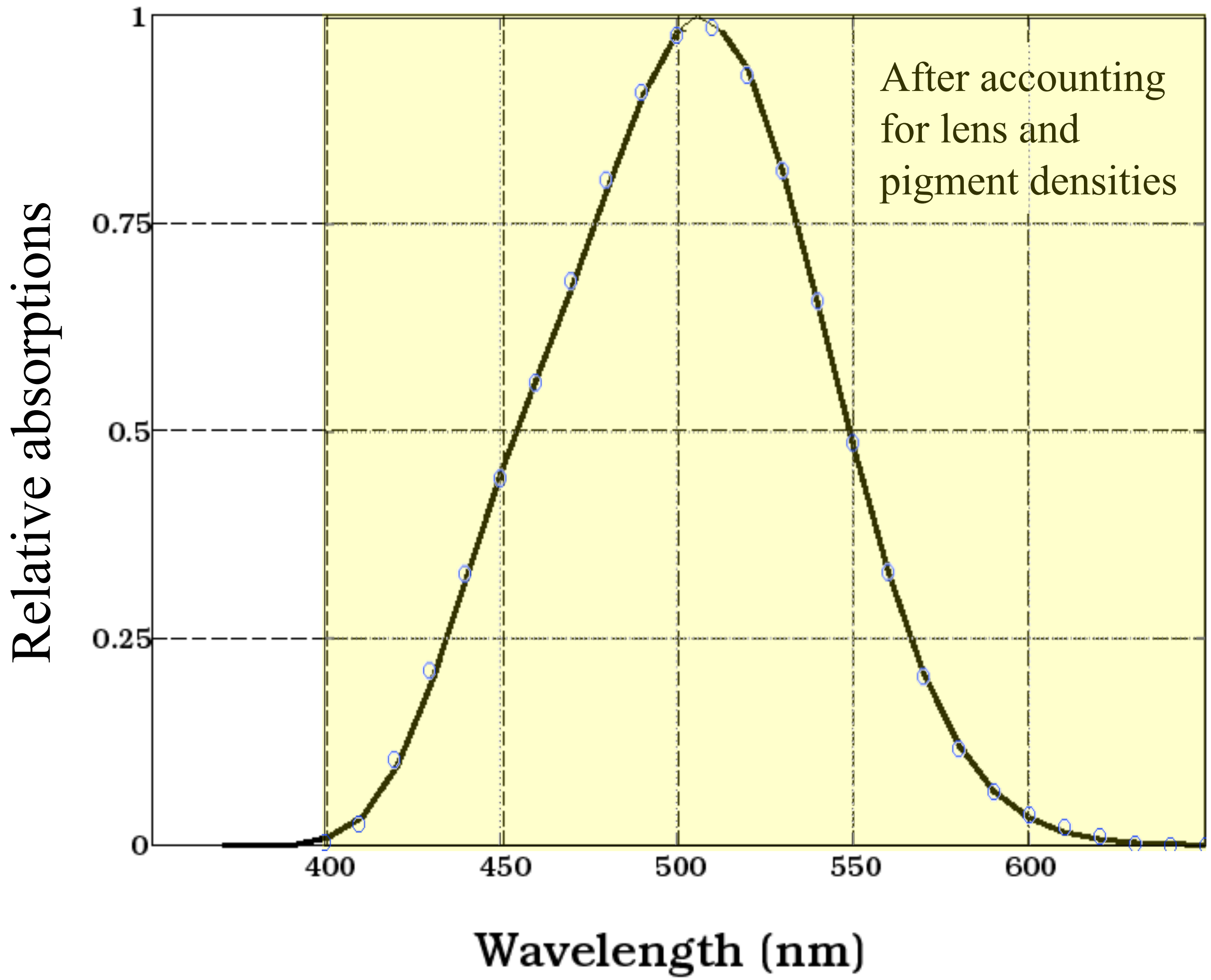


Measuring photopigment absorptions



Absorption = ratio of signals

Human light sensitivity through the rods matches the rhodopsin absorption curve



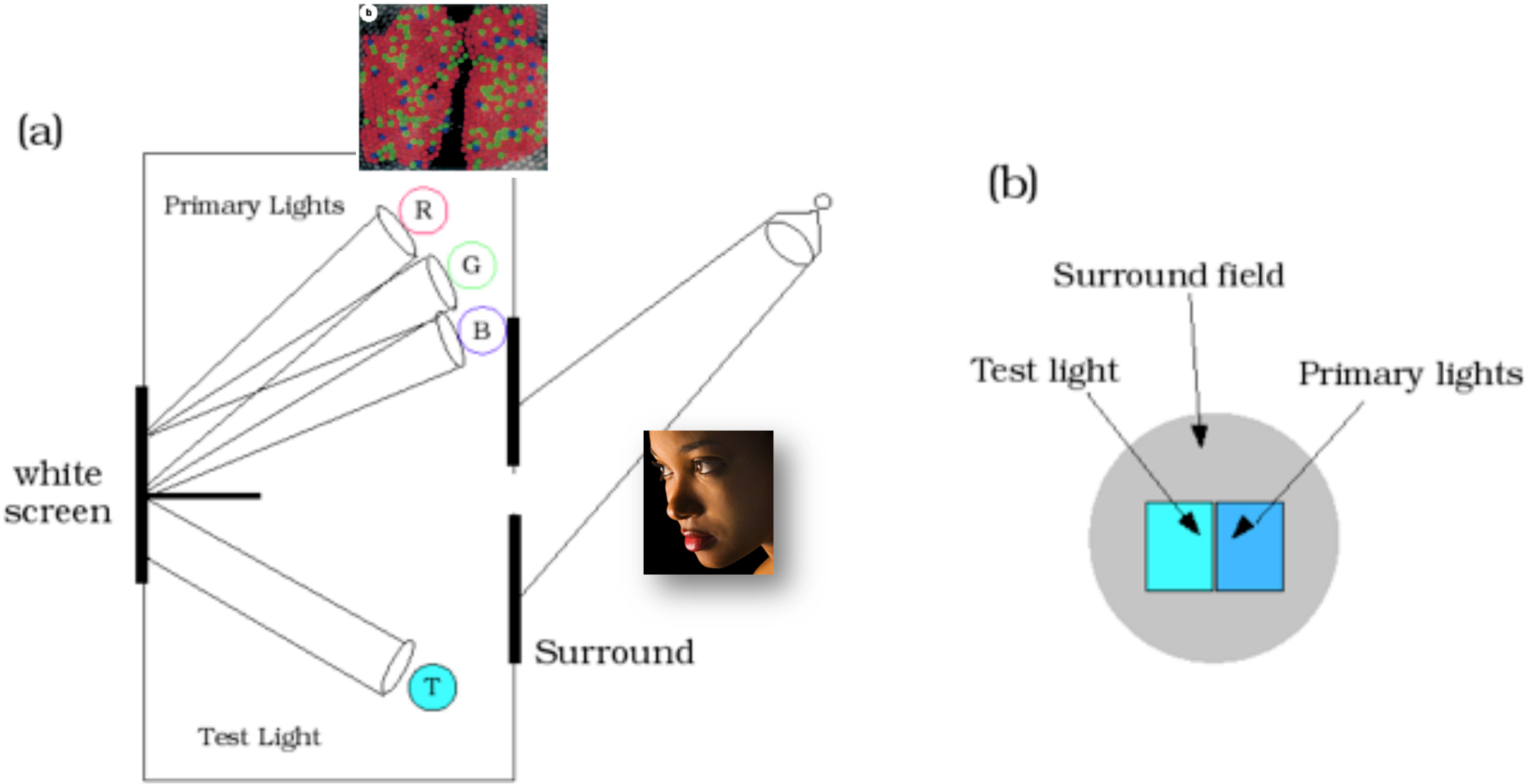
Cone (photopic) color matching

Photopic color-matching
Metamerism
CMF and additivity

Fig. 7-1b, p. 143

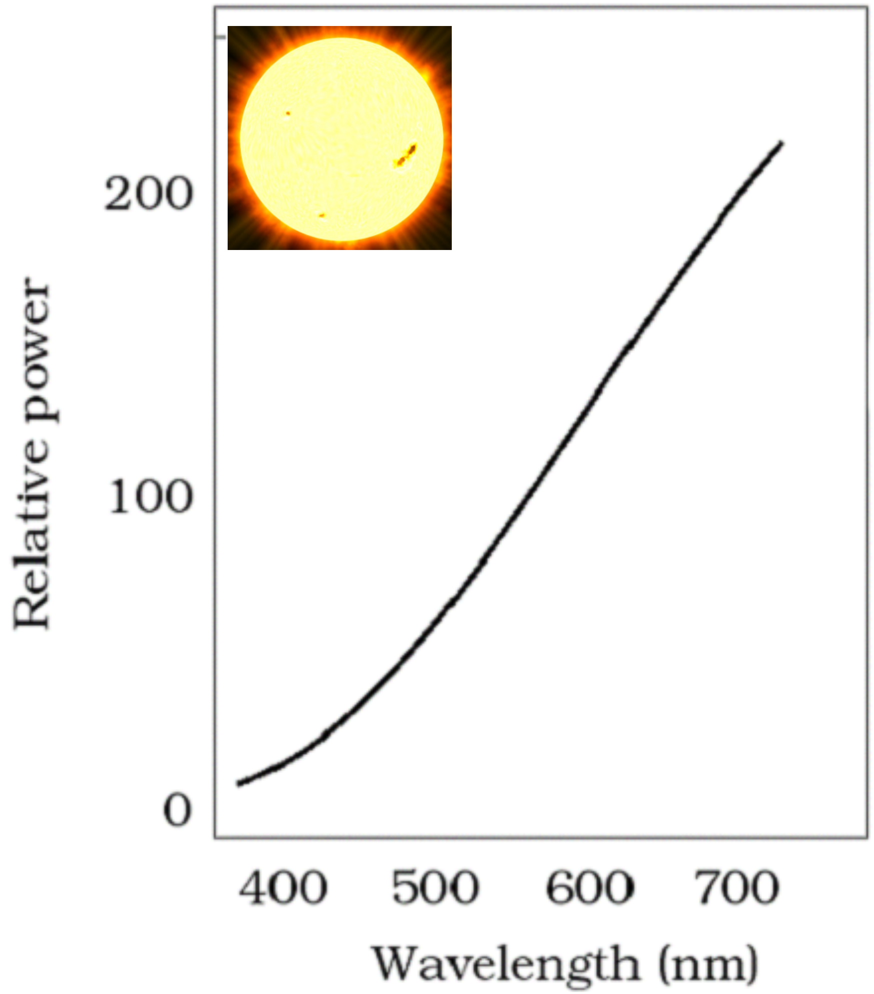
Fig. 7-1a, p. 143

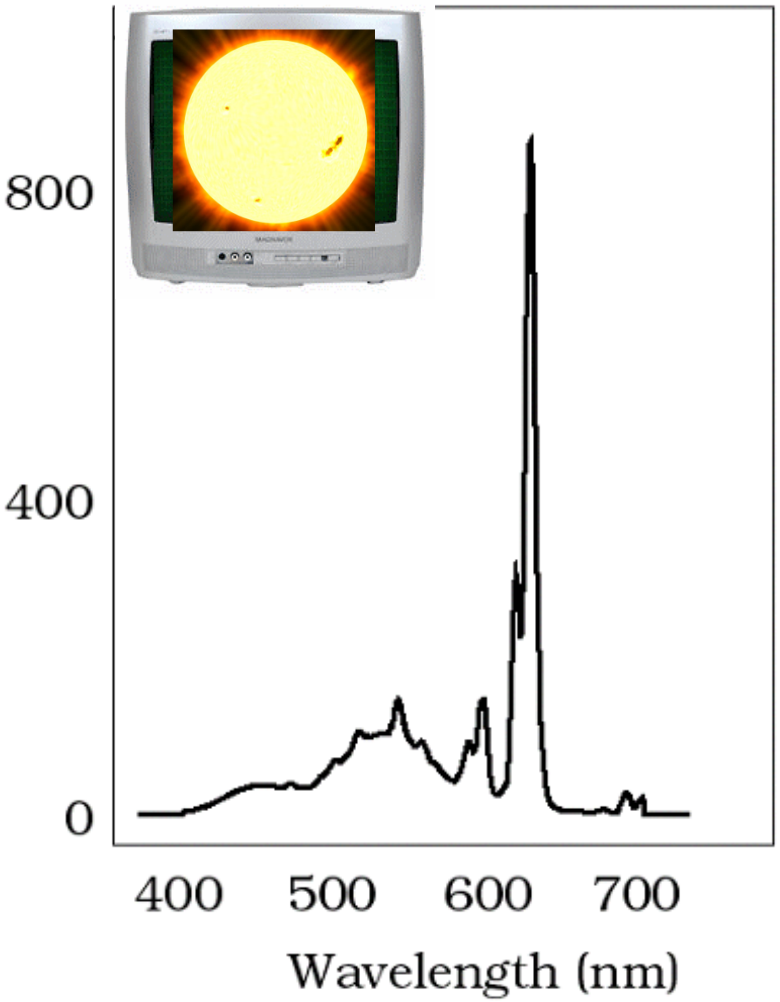
Cone color matching experiment (cone vision)



Metamerism

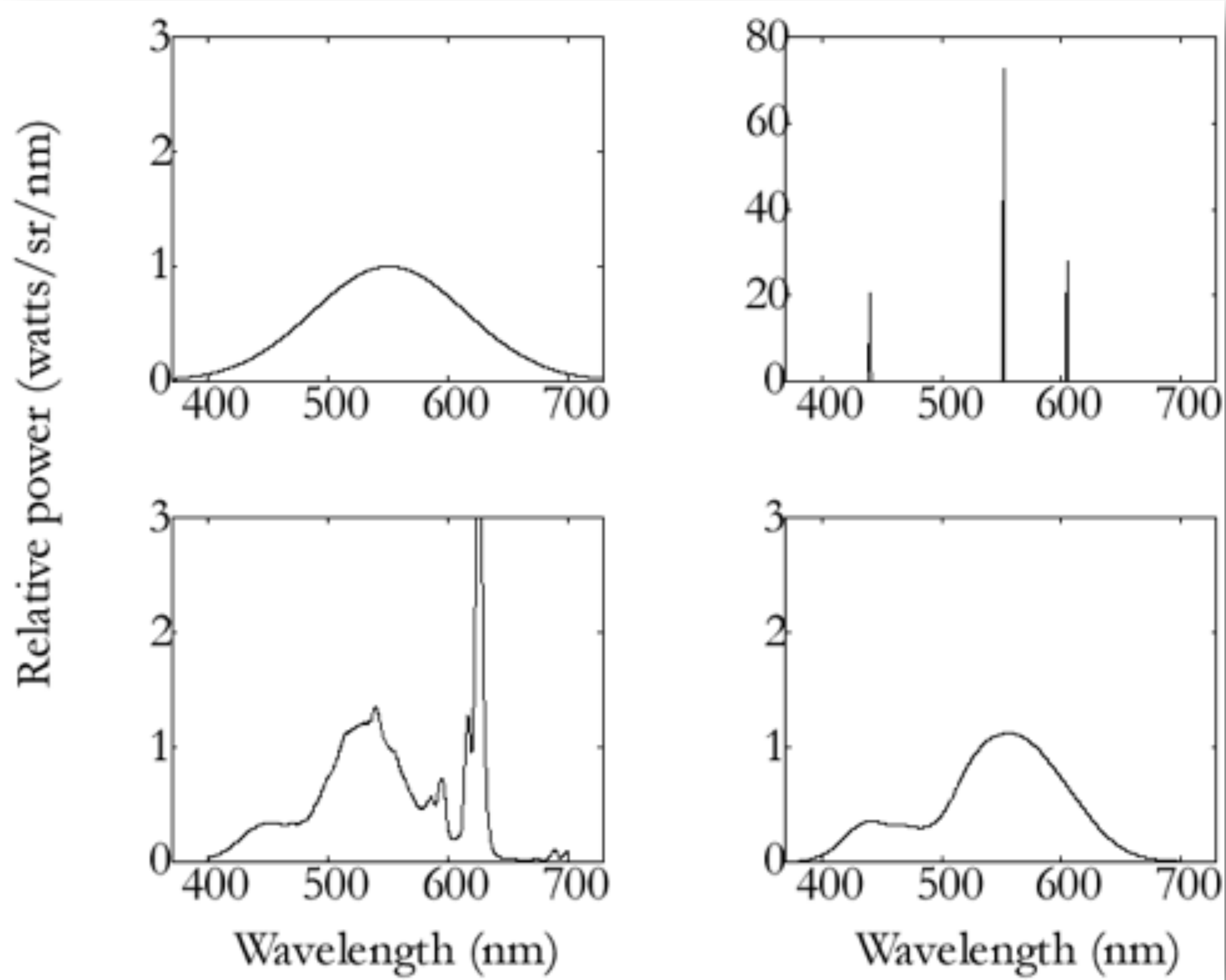
Color matching is an important illusion that is understood quantitatively



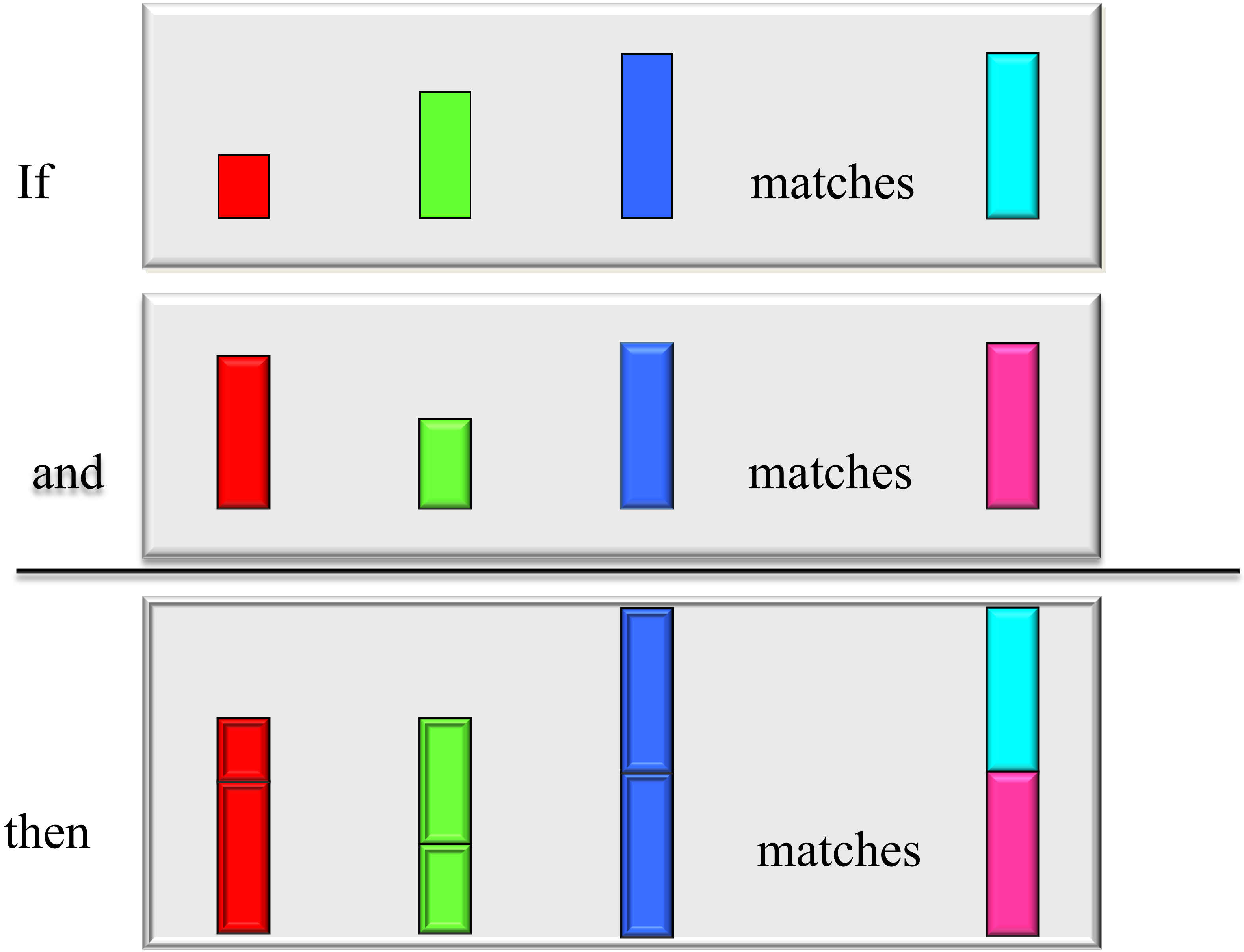


Metamerism is a big effect

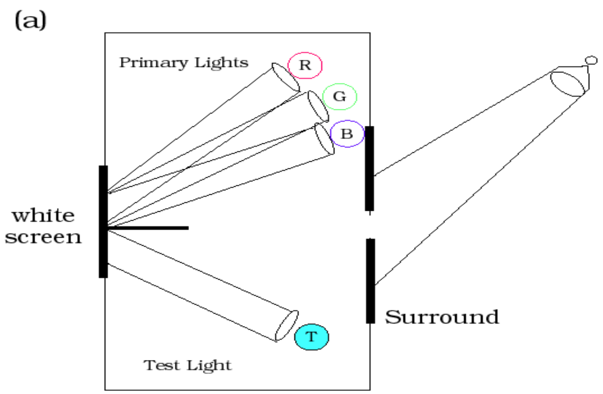
These spectral power distributions appear the same color to the eye



The color matching experiment is linear



Color matching experiment equation



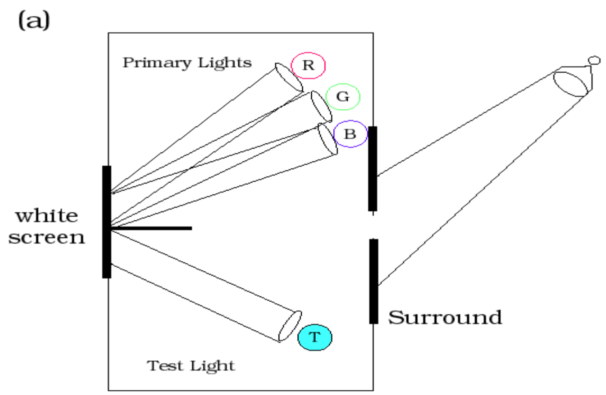

Grassmann

Response — CIE RGB functions

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} \quad \\ \quad \\ \quad \end{pmatrix} \begin{pmatrix} \quad \\ \quad \\ \quad \end{pmatrix}$$

Test light SPD

Color matching experiment equation



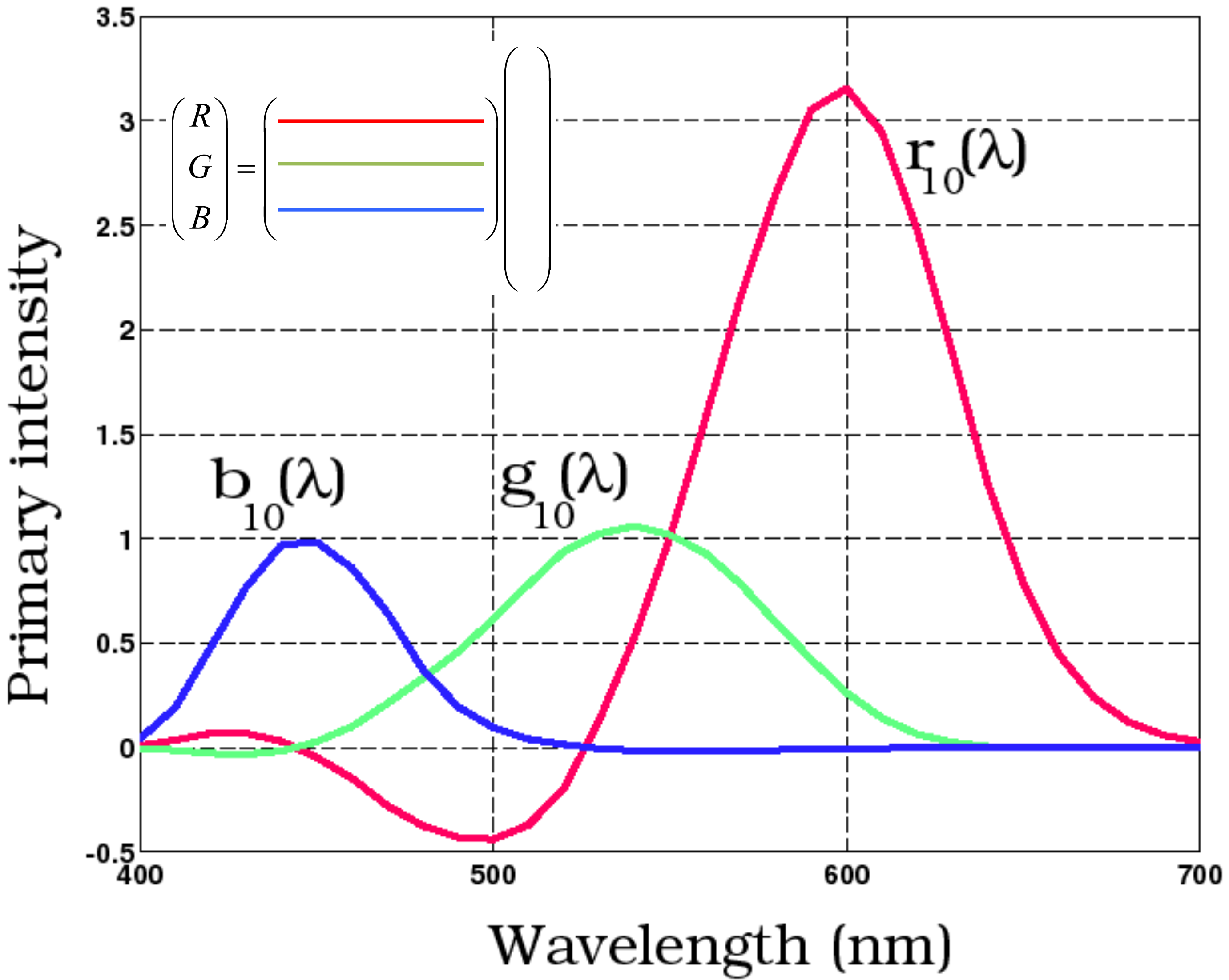
Response CIE RGB functions

0 0 0 0 0 0 1 0 0 0 0 0 0

$$\begin{pmatrix} r \\ g \\ b \end{pmatrix} = \begin{pmatrix} \cdots & r & \cdots \\ \cdots & g & \cdots \\ \cdots & b & \cdots \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 0 \\ \cdots \\ 1 \\ \cdots \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

Test light SPD

Behavioral color matching functions (CMFs; 10 deg)

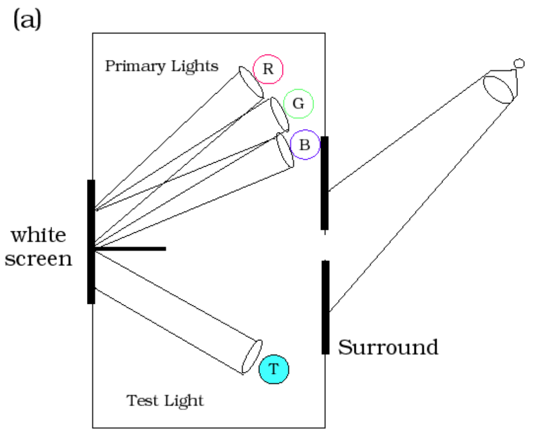


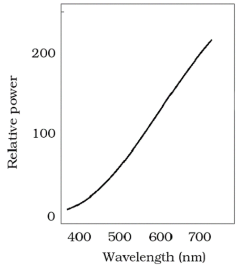
Color matching functions

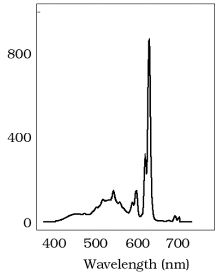
Metamer definition
Uniqueness
CIE (1931) XYZ standard

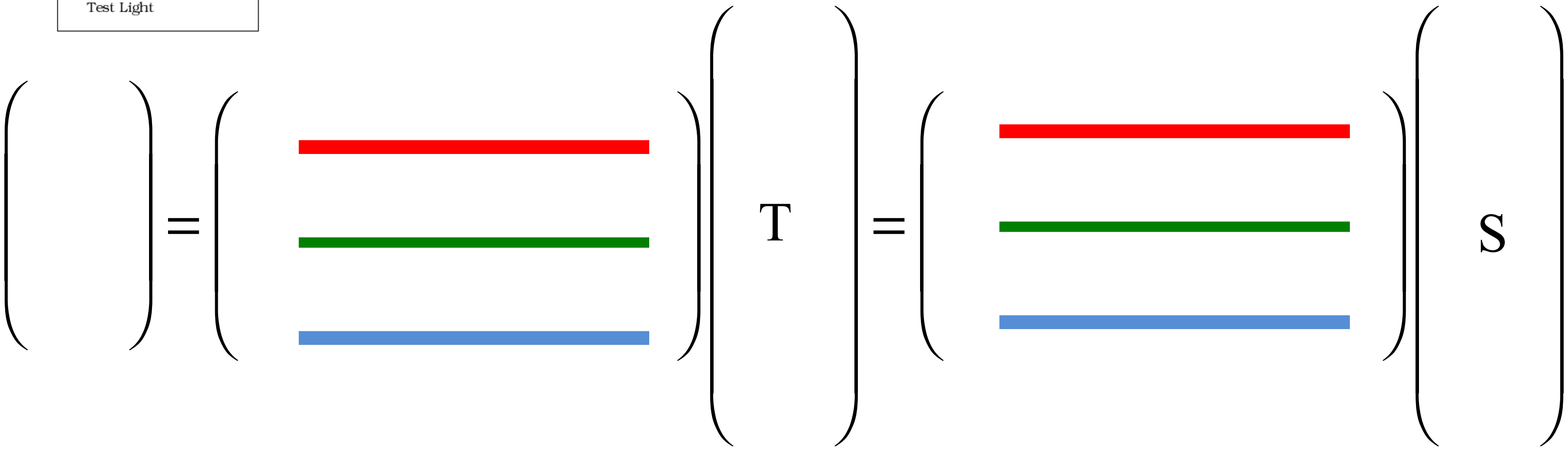
CMFs predict appearance matches

Two SPDs are **metamers** when they differ physically but are matched in the color-matching experiment





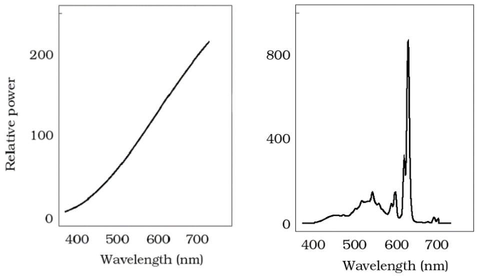




Metamer differences: CMF null space

Two SPDs are **metamers** when they differ physically but are matched in the color-matching experiment

Metamer differences always have negative values somewhere in the spectrum; otherwise the difference would produce a signal in the L,M,S cones



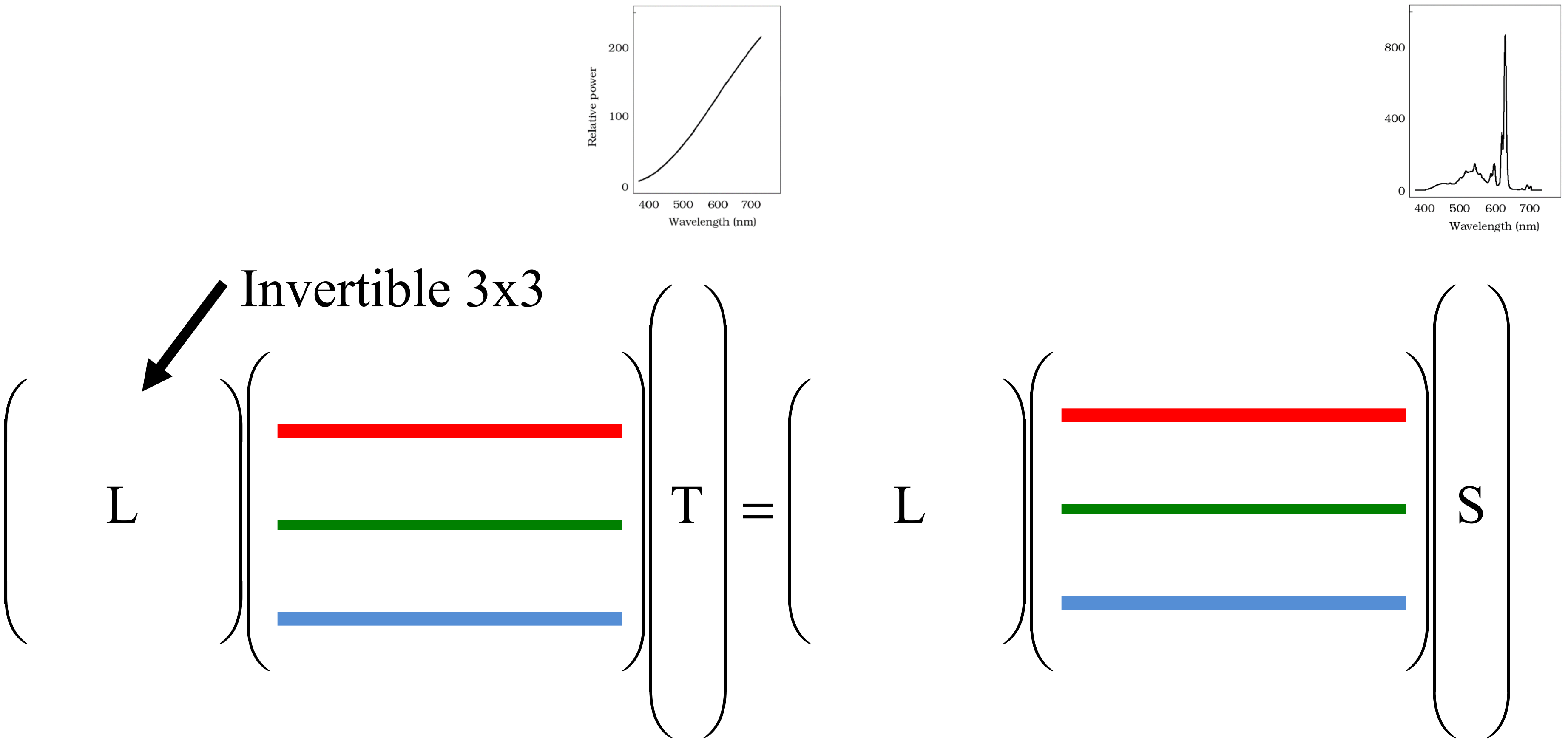
$$0 = \left(\quad \right) \left\{ \left(T \right) - \left(S \right) \right\}$$

(all positive)

CMFs: A uniqueness theorem

Any invertible linear transformation, L, of the CMFs

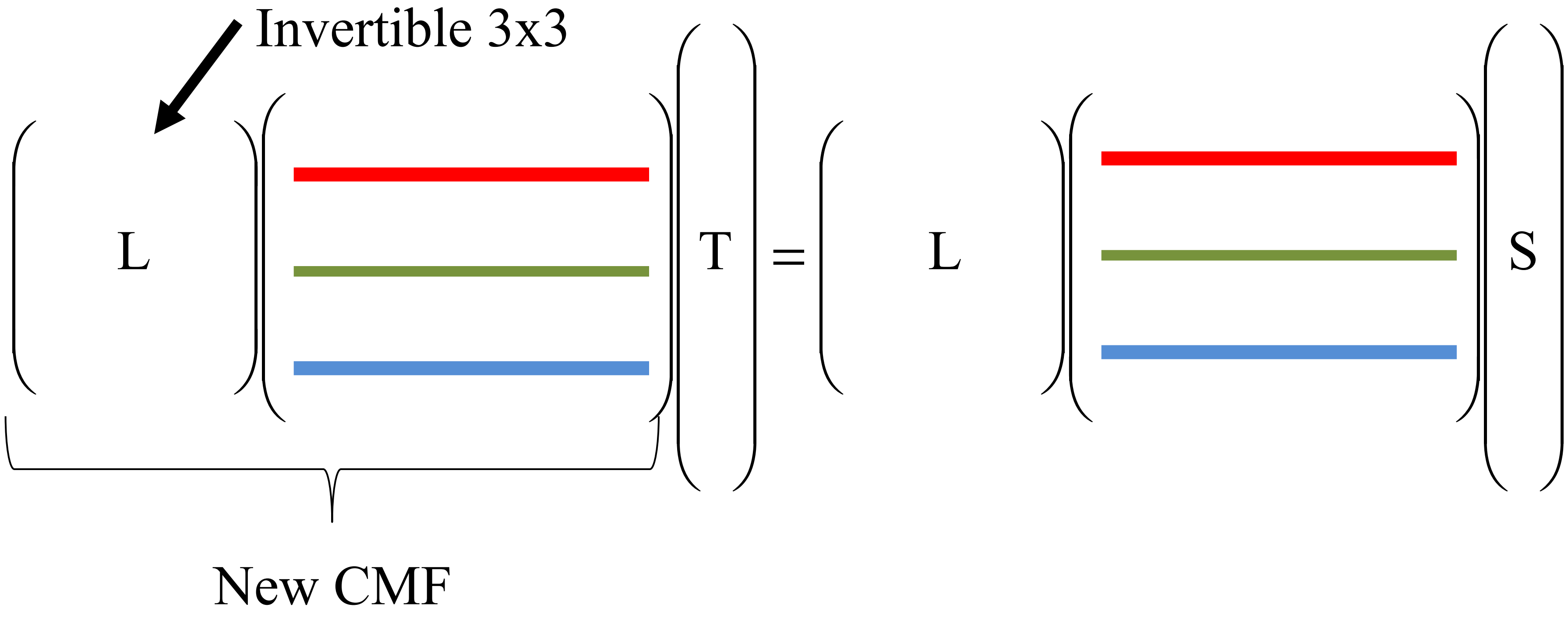
predicts the same metamers



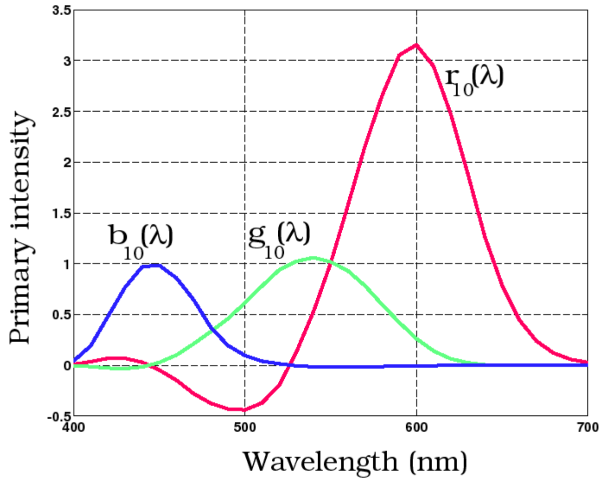
CMFs: A uniqueness theorem

Different choices of primaries produce different CMFs

Related by a linear transformation (see **Foundations of Vision** for proof)

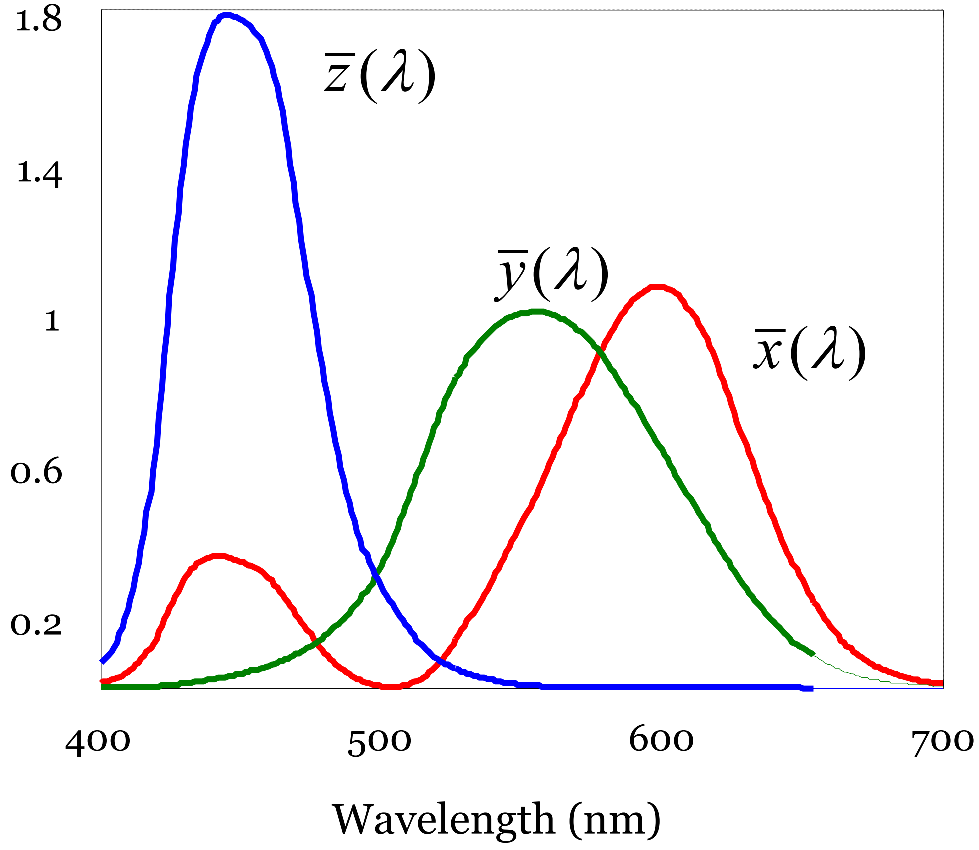


The CIE (1931) XYZ standard CMFs



L

CIE (1931) 10 deg XYZ functions



The CIE (1931) XYZ standard CMFs

You must specify radiance
using **energy**, not photons

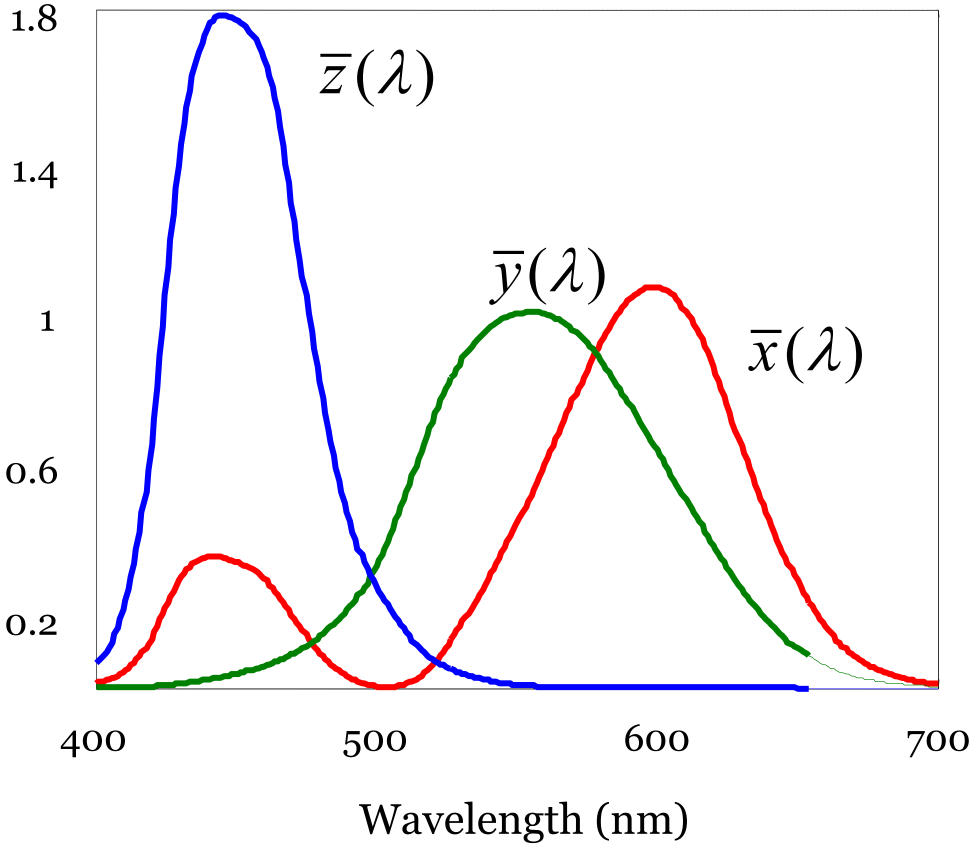
Radiance

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

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

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

CIE (1931) 10 deg XYZ functions

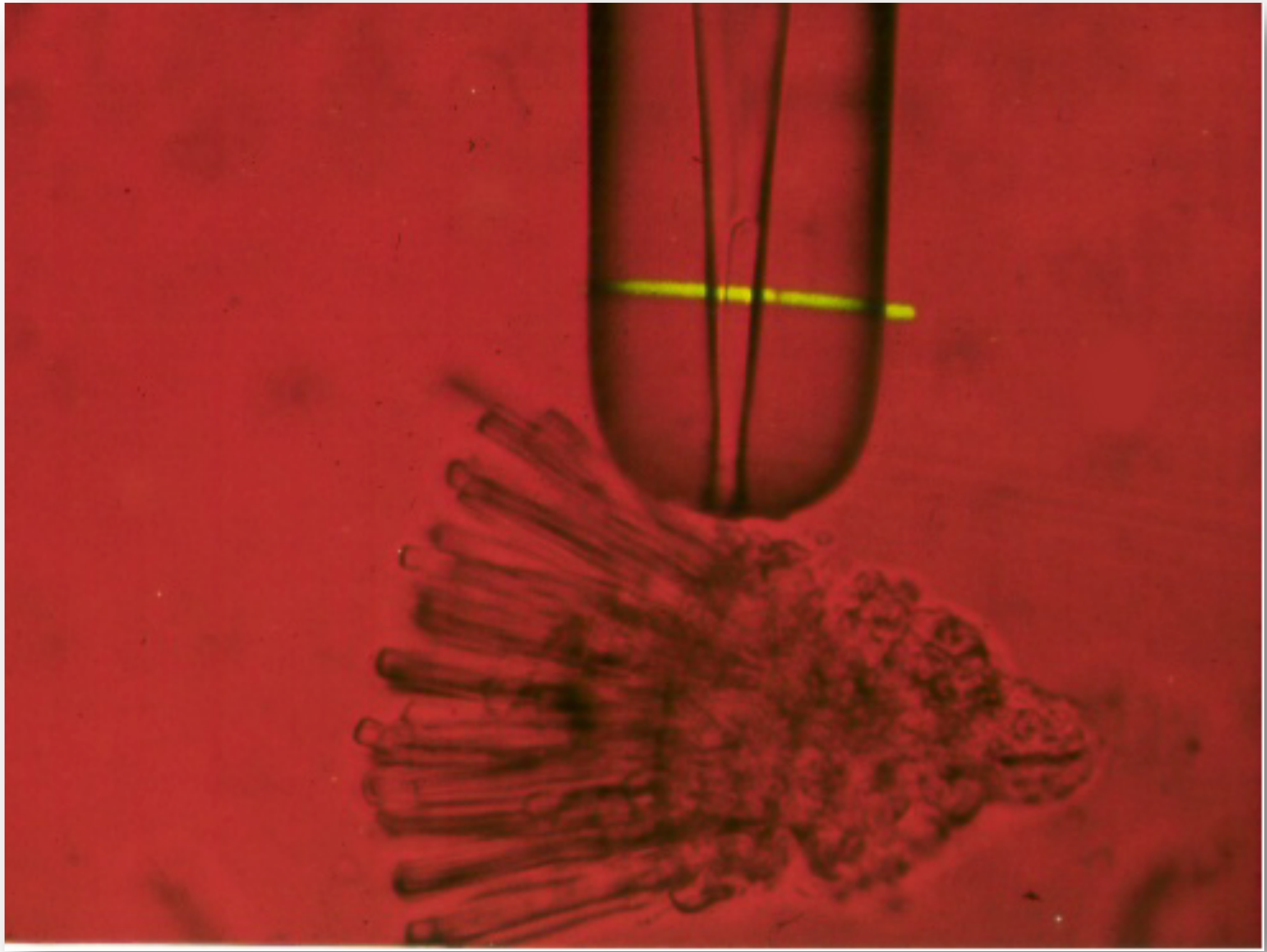


Physiology and color-matching

- Relating cone responses to color matches
- Static nonlinearities

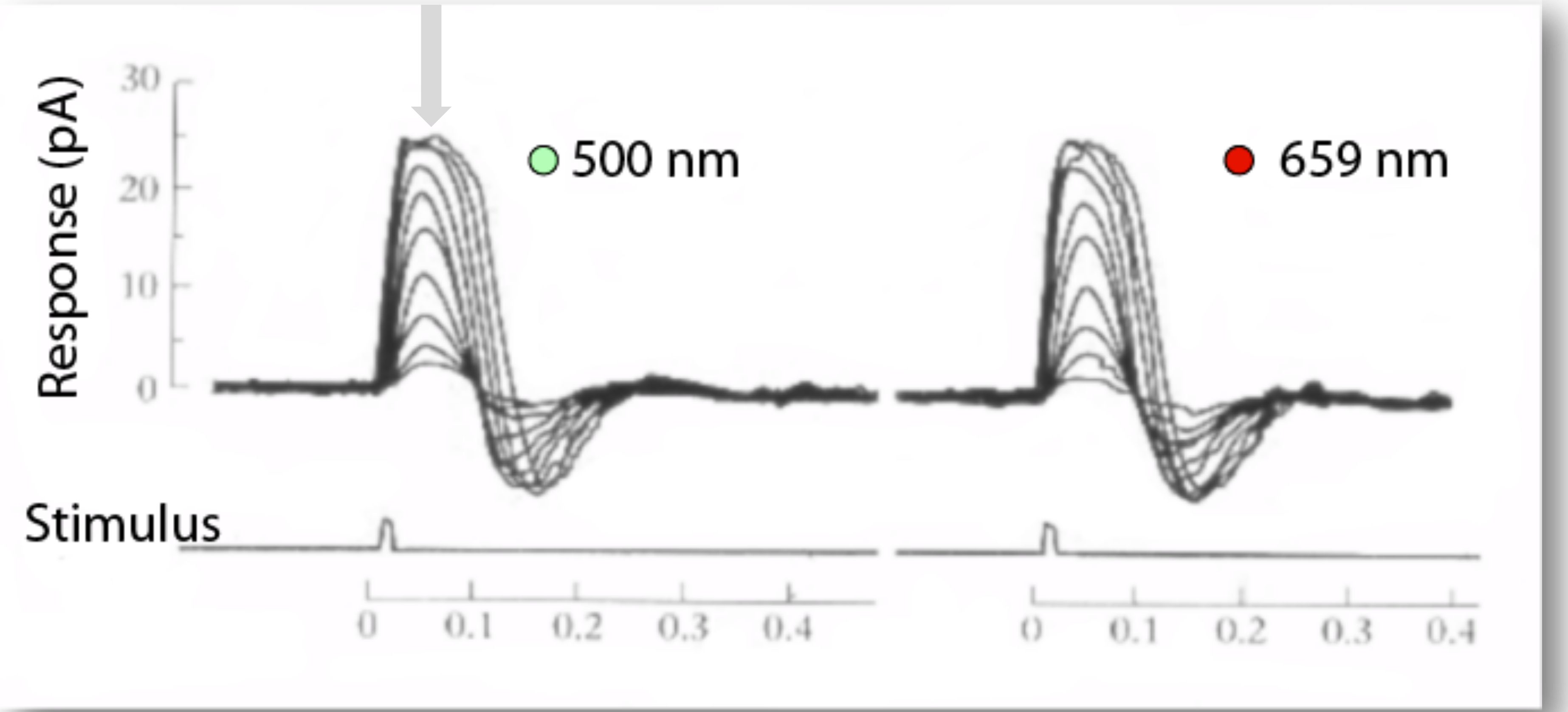
Single cone photocurrent measurements

(Schnapf, Baylor et al., 1986)



Principle of univariance (Rushton)

Cone photocurrent using stimuli with different wavelengths

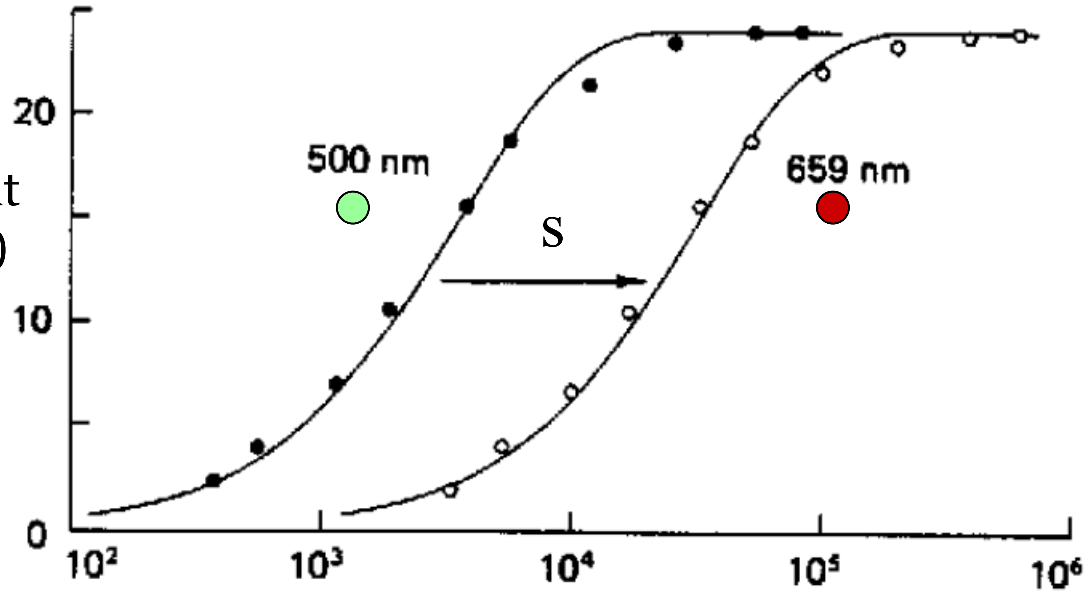


Time (sec)

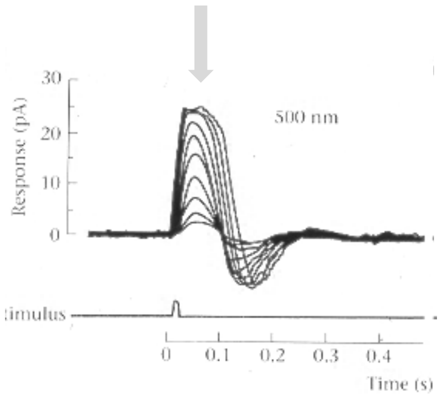
Spectral sensitivity of nonlinear systems

$$N(I_{500}) = N(sI_{659})$$

Peak current (picoAmps)



Photons per um²



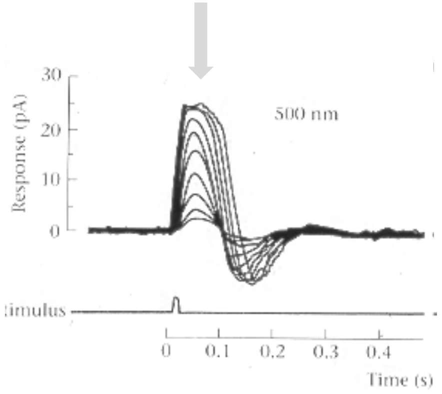
Spectral sensitivity of nonlinear systems

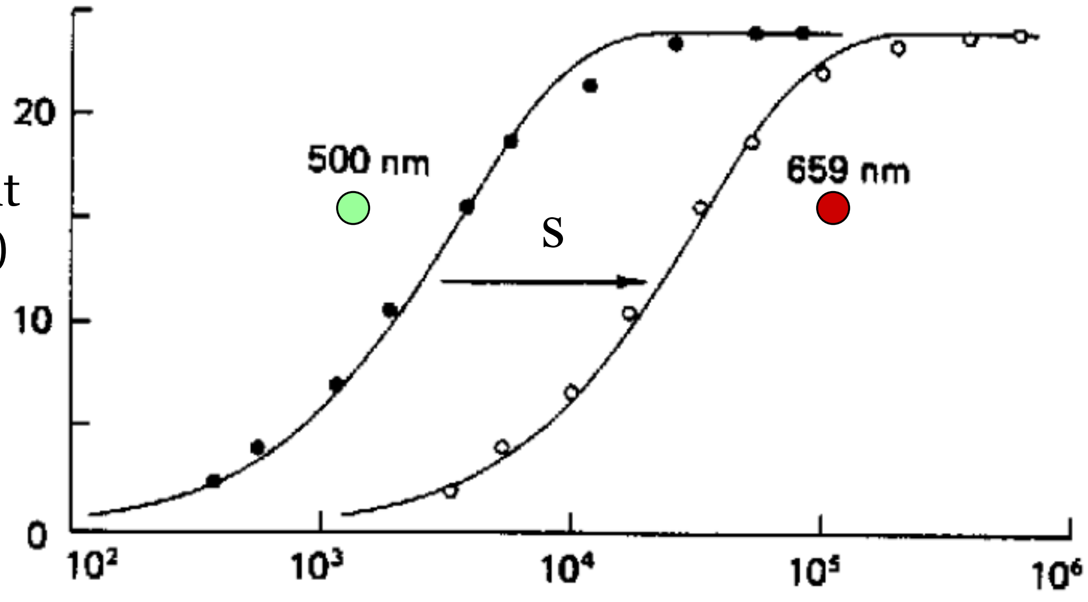
Static nonlinearity:

$$N(I_{500}) = N(sI_{659})$$

$$N(I_{500} + sI_{659}) = N(2I_{500})$$

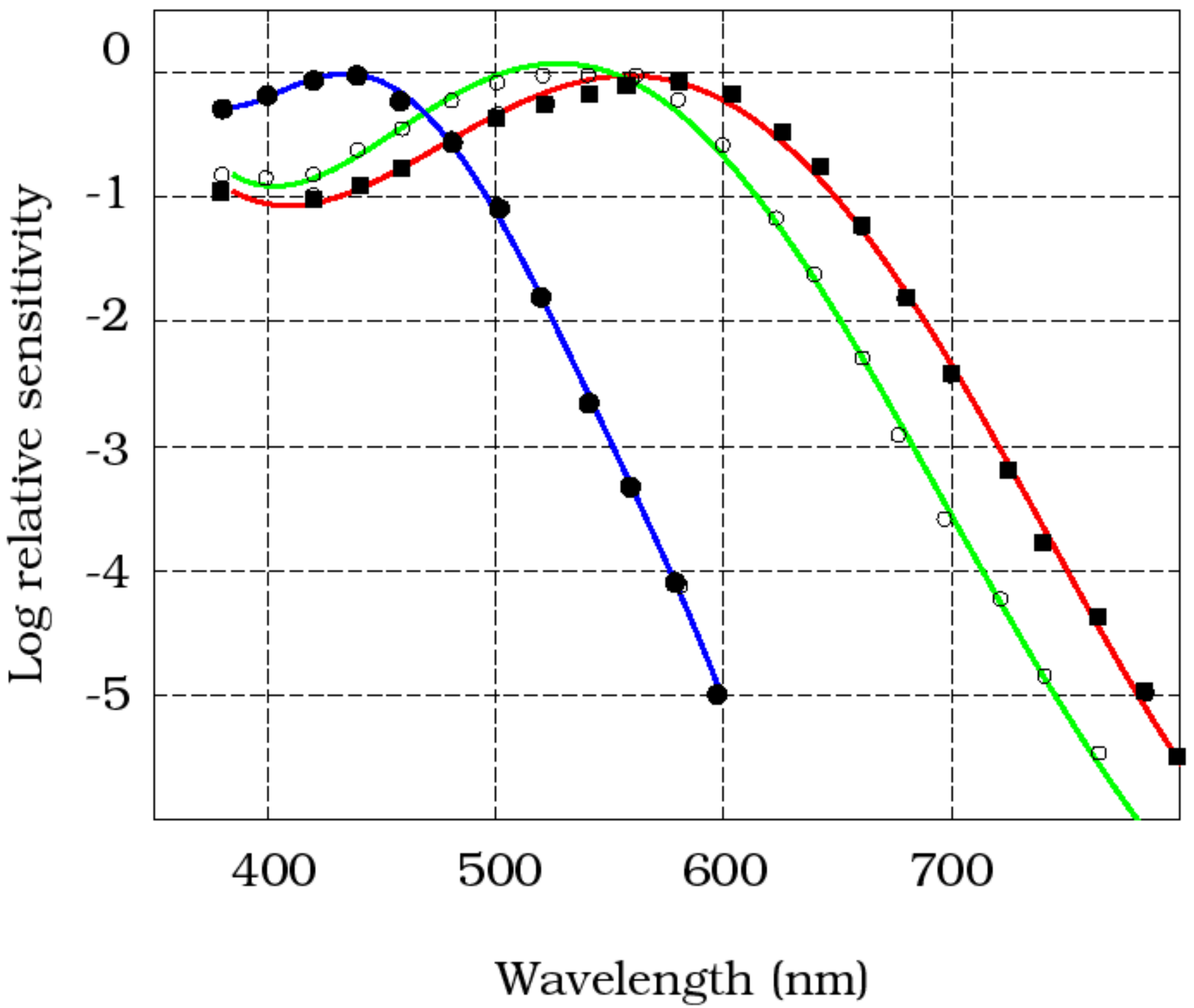
Peak current (picoAmps)





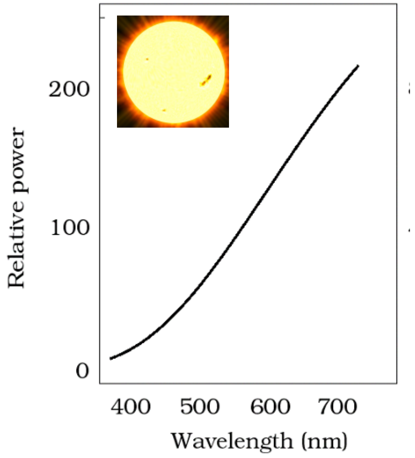
Photons per um²

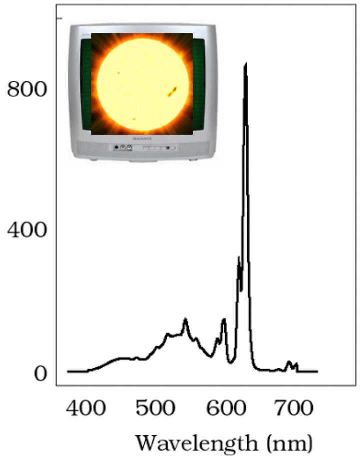
There are three cone wavelength responsivity functions

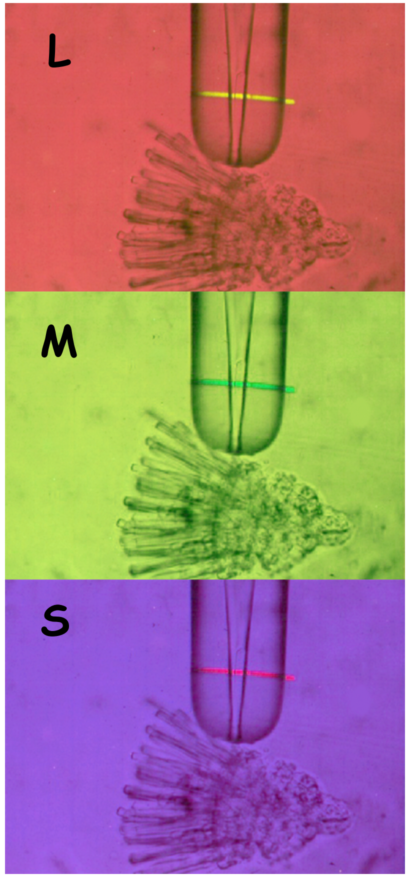


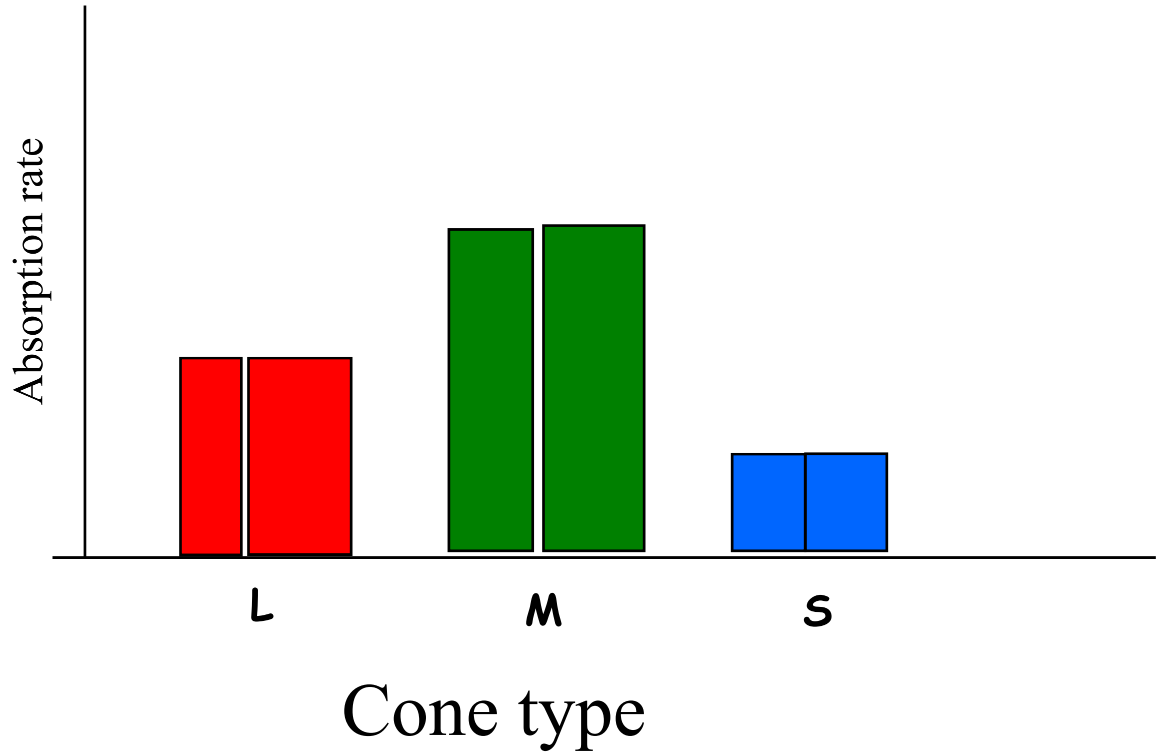
Stimuli causing equal cone absorptions match perceptually

What about the rods?





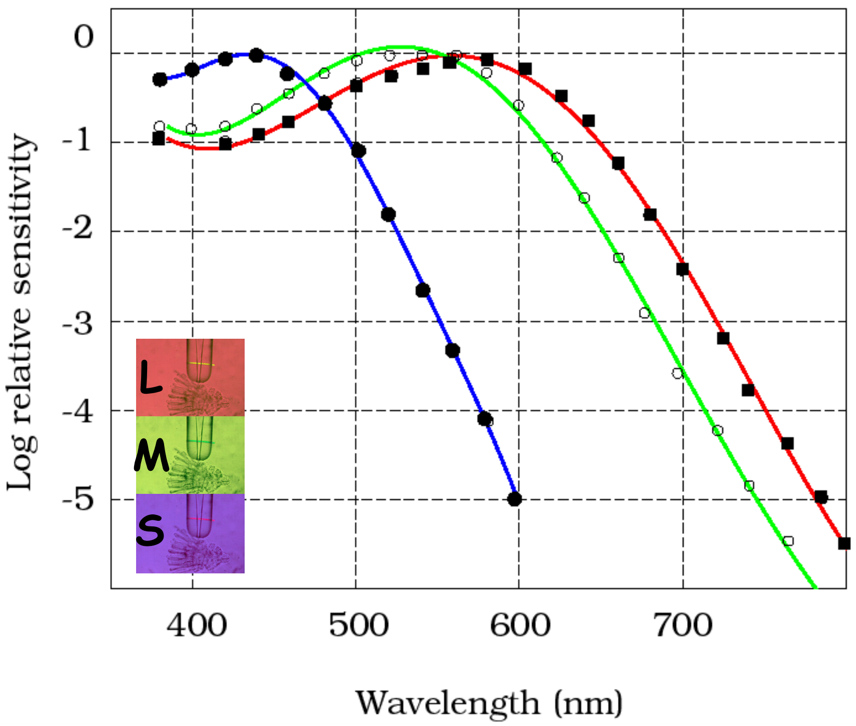




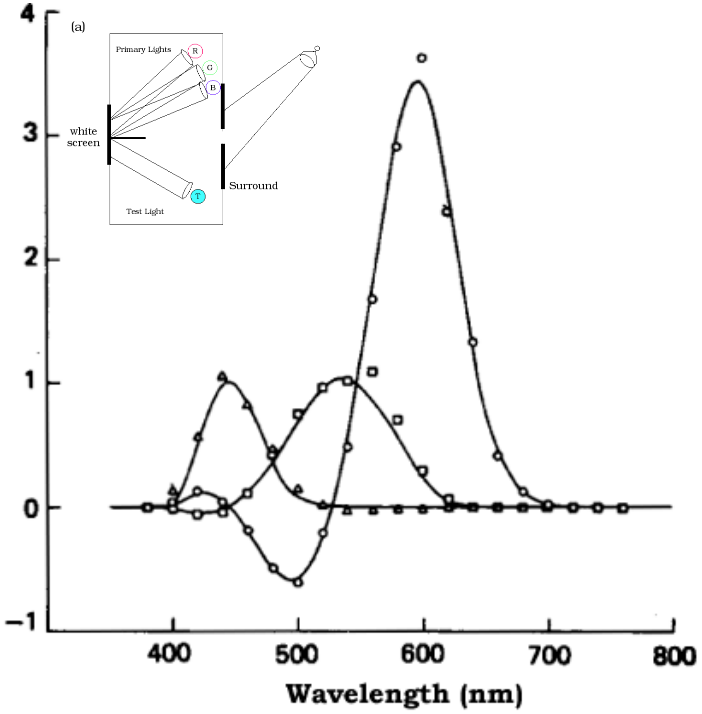
The cone responsivities predict the CMFs

Recall the point about all CMFs being unique up to a linear transformation

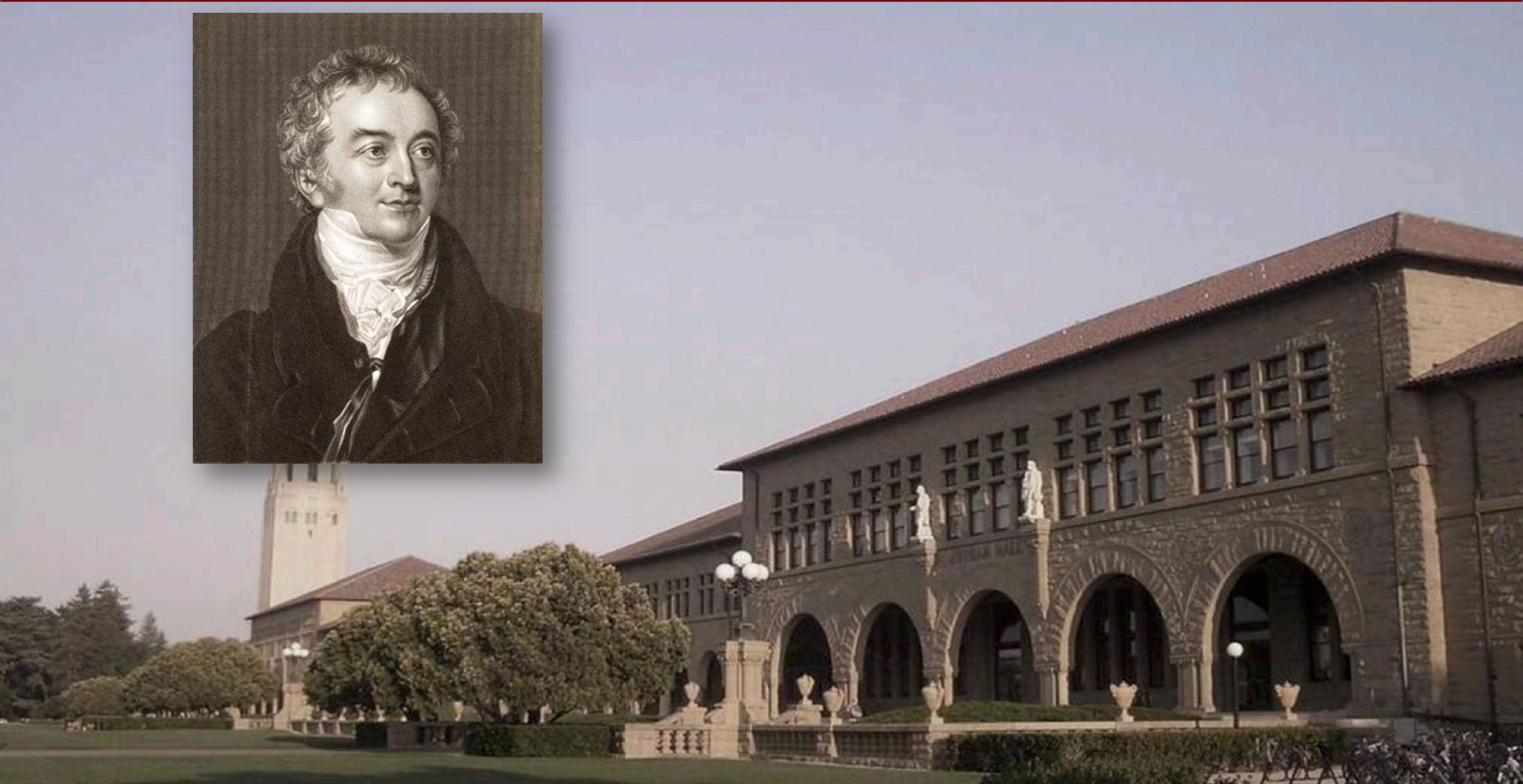
The relationship between the cones and the XYZ functions is a linear transform

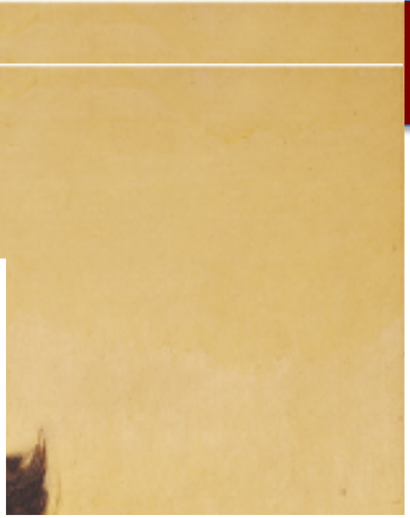


L



Historical notes



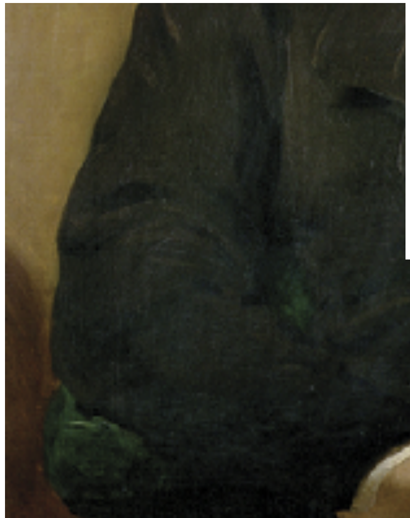


Who deciphered the Rosetta Stone and the Egyptian hieroglyphs? The usual answer is Jean-François Champollion, beginning in 1822. But ever since that time, Egyptologists have debated the role of his rival, the

Thomas Young and the Rosetta Stone

Andrew Robinson

13 Lonsdale Square, London N1 1EN, United Kingdom



script as a whole, the evidence suggests that Young's early detailed study of the Rosetta Stone created the conceptual framework that made possible Champollion's later breakthrough.

Thomas Young (1802) On the theory of lights and colours. Philosophical Transactions of the Royal Society 92, 12-48.

"....this paper contains nothing which deserves the name, either of experiment or of discovery, and as it is, in fact, destitute of every species of merit...."

"We now dismiss, for the present, the feeble lucubrations of this author, in which we have searched without success for some traces of learning, acuteness, and ingenuity, that might compensate his evident deficiency in the powers of solid thinking, calm and patient investigation...."

Henry Brougham in Edinburgh Review, an ardent admirer of Newton, criticizing Thomas Young's Bakerian Lectures.

Original color-matching technology

(Clerk Maxwell, Image from John Mollon, Cambridge)

Color-mixing was done by spinning a top rapidly, rather than by mixing lights.

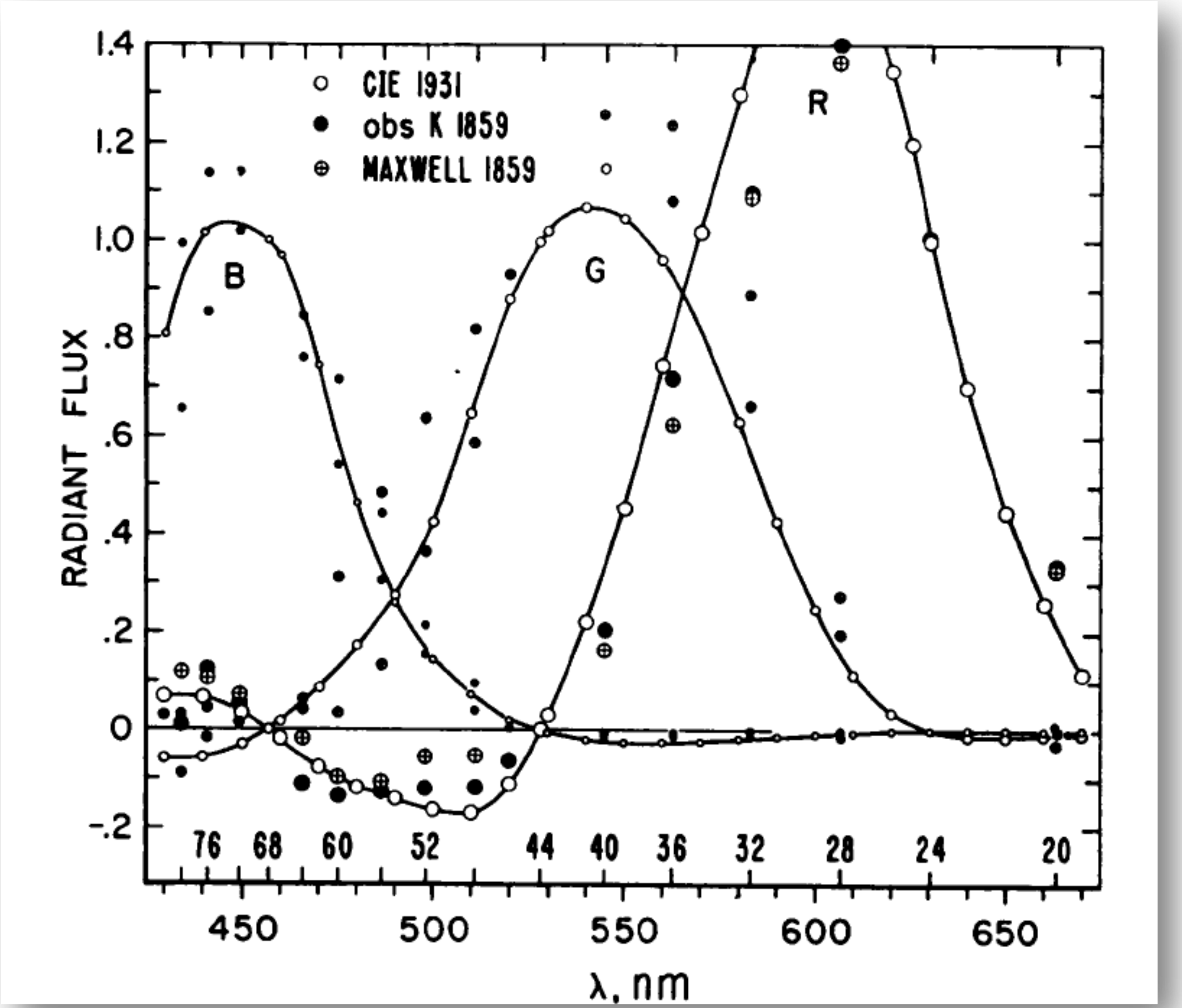
In the course of his 1855 paper on the perception of colour, Maxwell proposed that if three black-and-white photographs of a scene were taken through red, green and blue filters, and transparent prints of the images were projected onto a screen using three projectors equipped with similar filters, when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

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.)

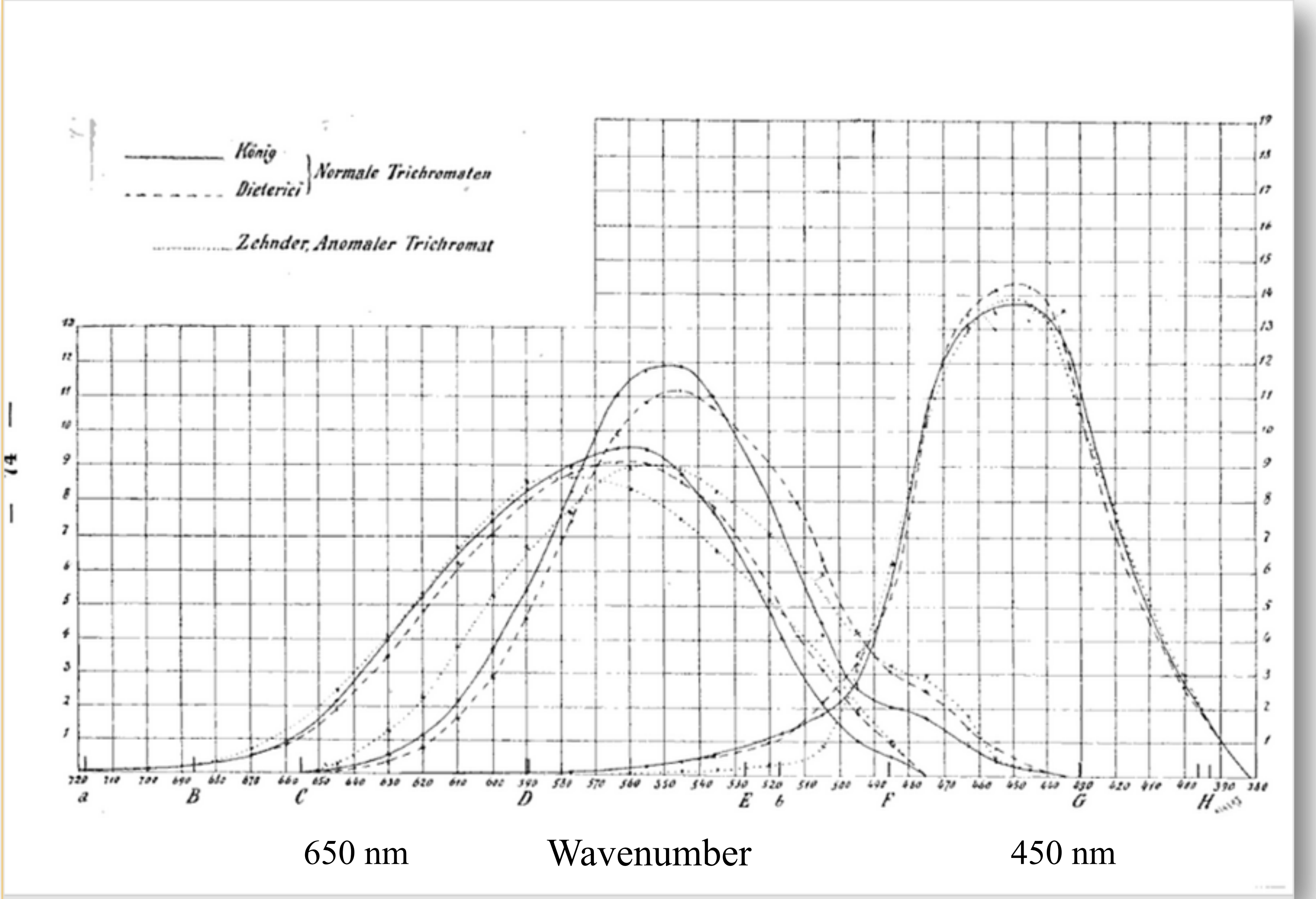
JC Maxwell was the first to measure the color-matching functions

Observer K – JCM's spouse
Maxwell
Comparison with 1931

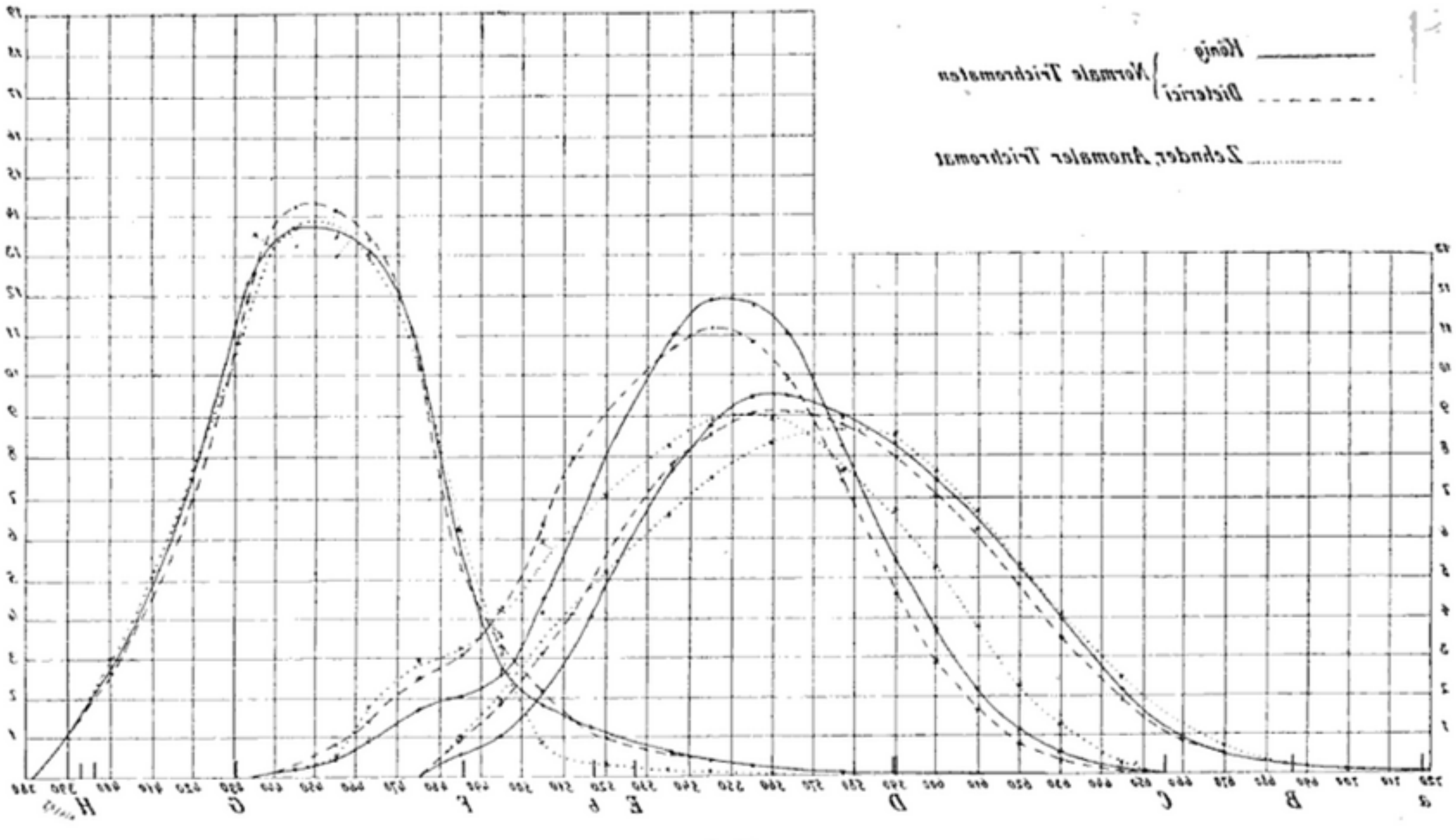
(From Judd, PNAS)



Koenig and Dieterici (1892) – Estimated cone absorptions



Koenig and Dieterici (1892) – Estimated cone absorptions



450 nm

650 nm

The cone response functions predict color matching

Modern estimates

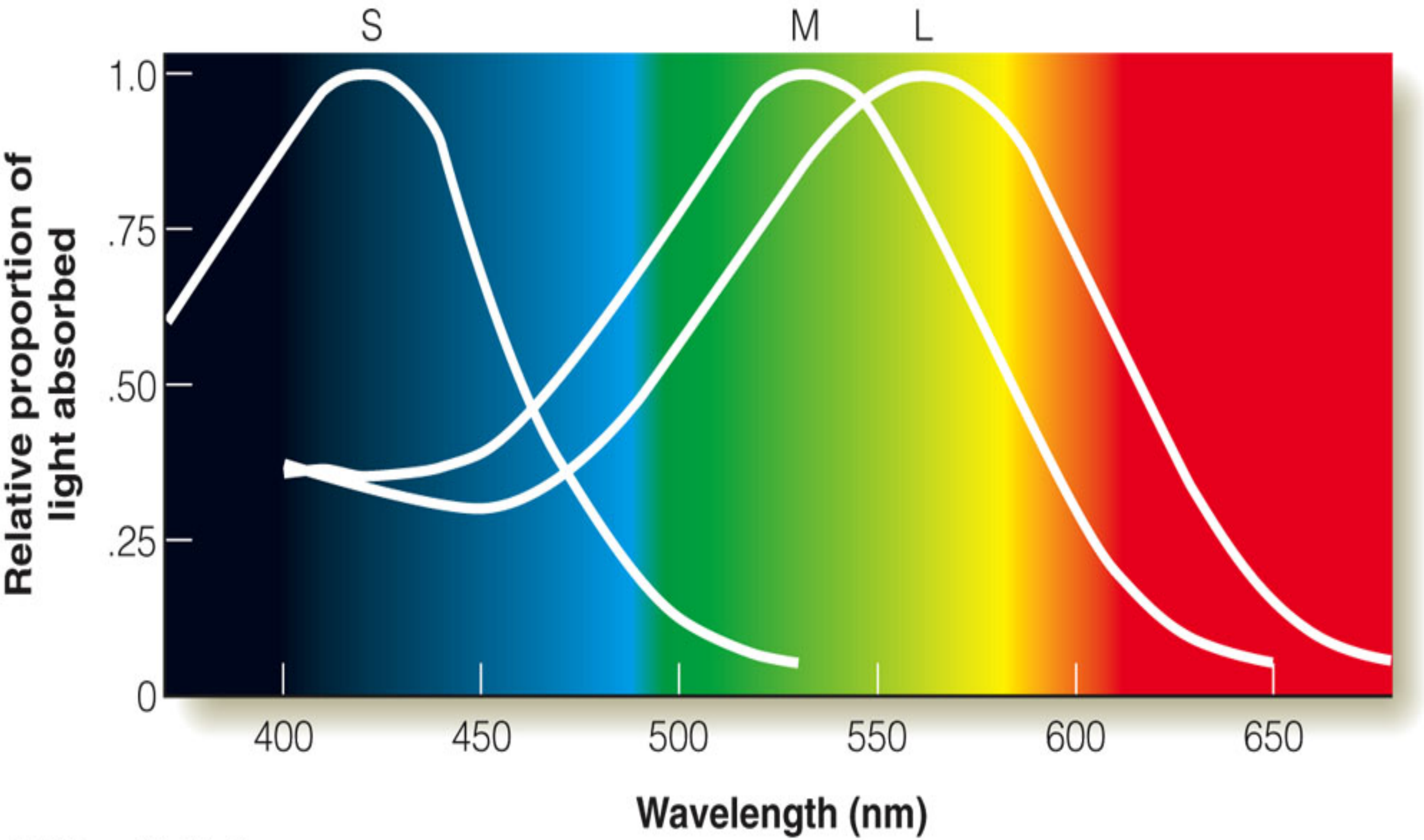
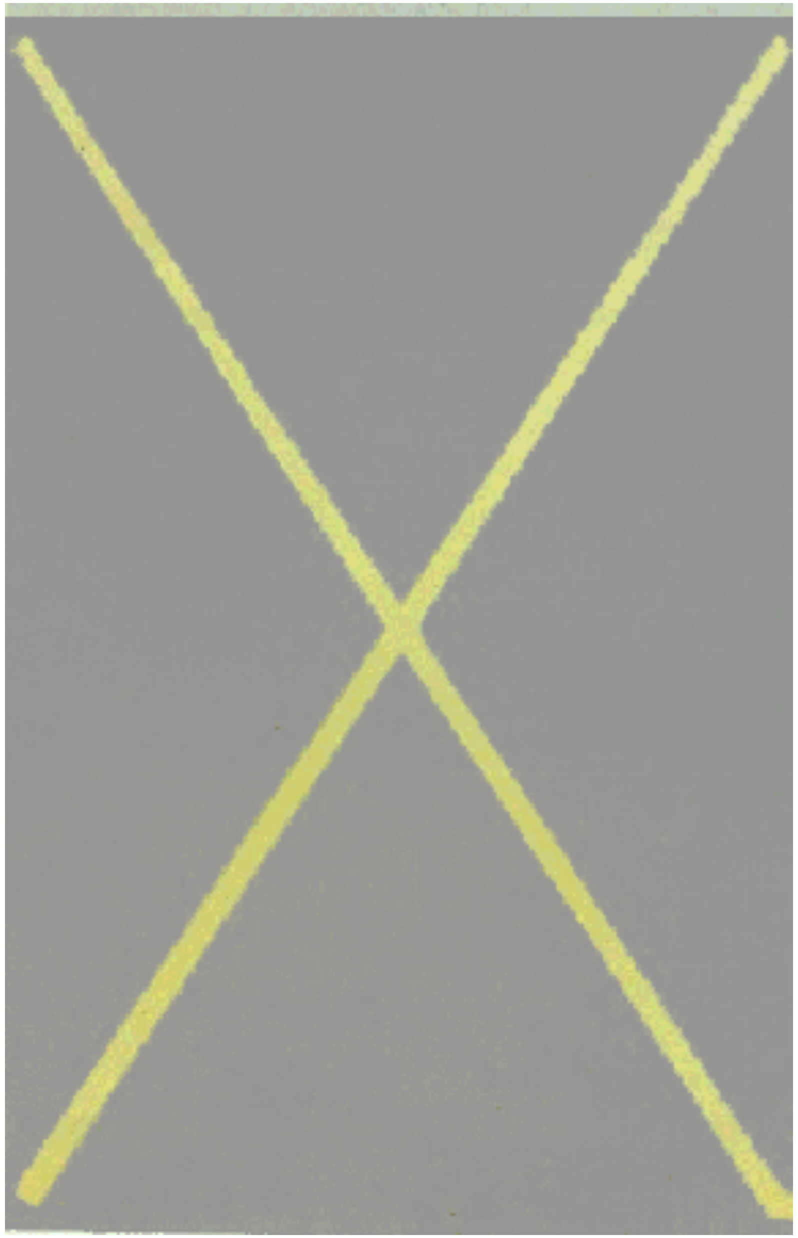


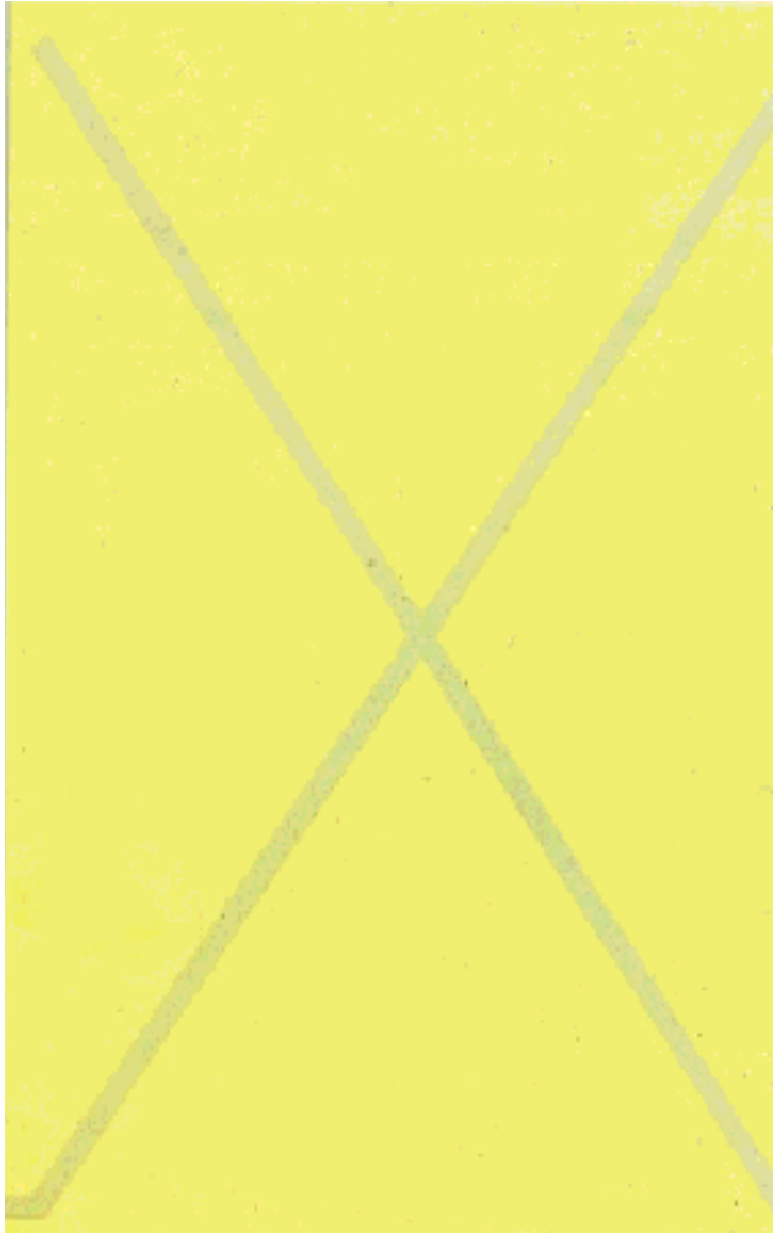
Fig. 7-8, p. 147

Color appearance: More than matching

Context
History

Matching does not predict appearance

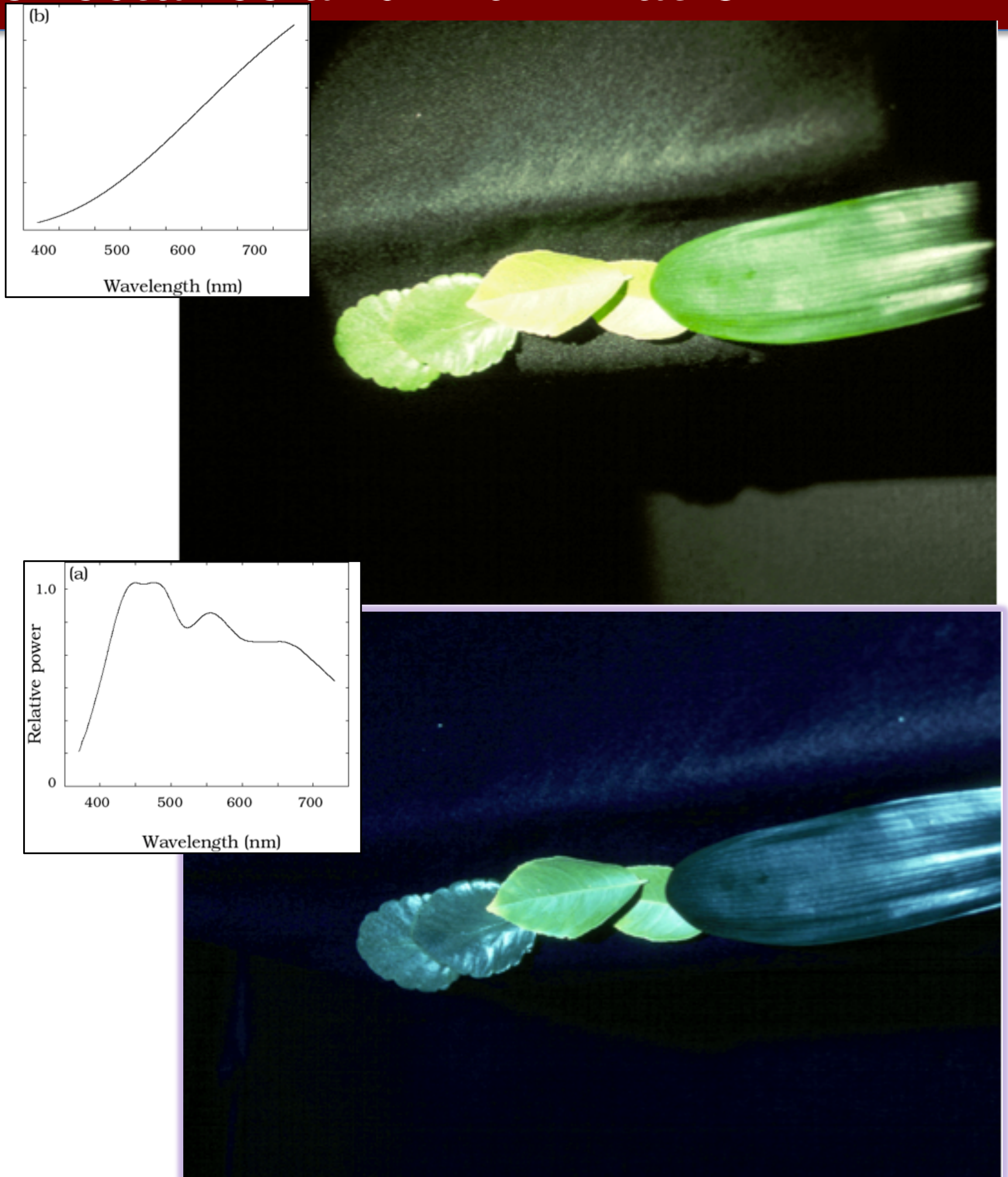




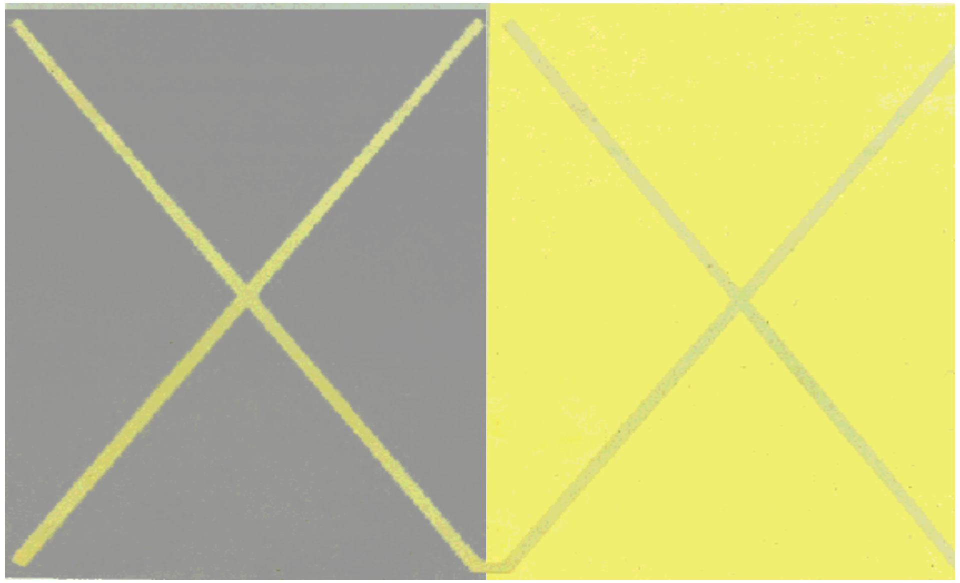
Scene radiance depends on reflectance and illumination

- People want to recognize the object – hence estimate reflectance

- The visual system interprets color in a way that accounts for the spectral properties of the illuminant



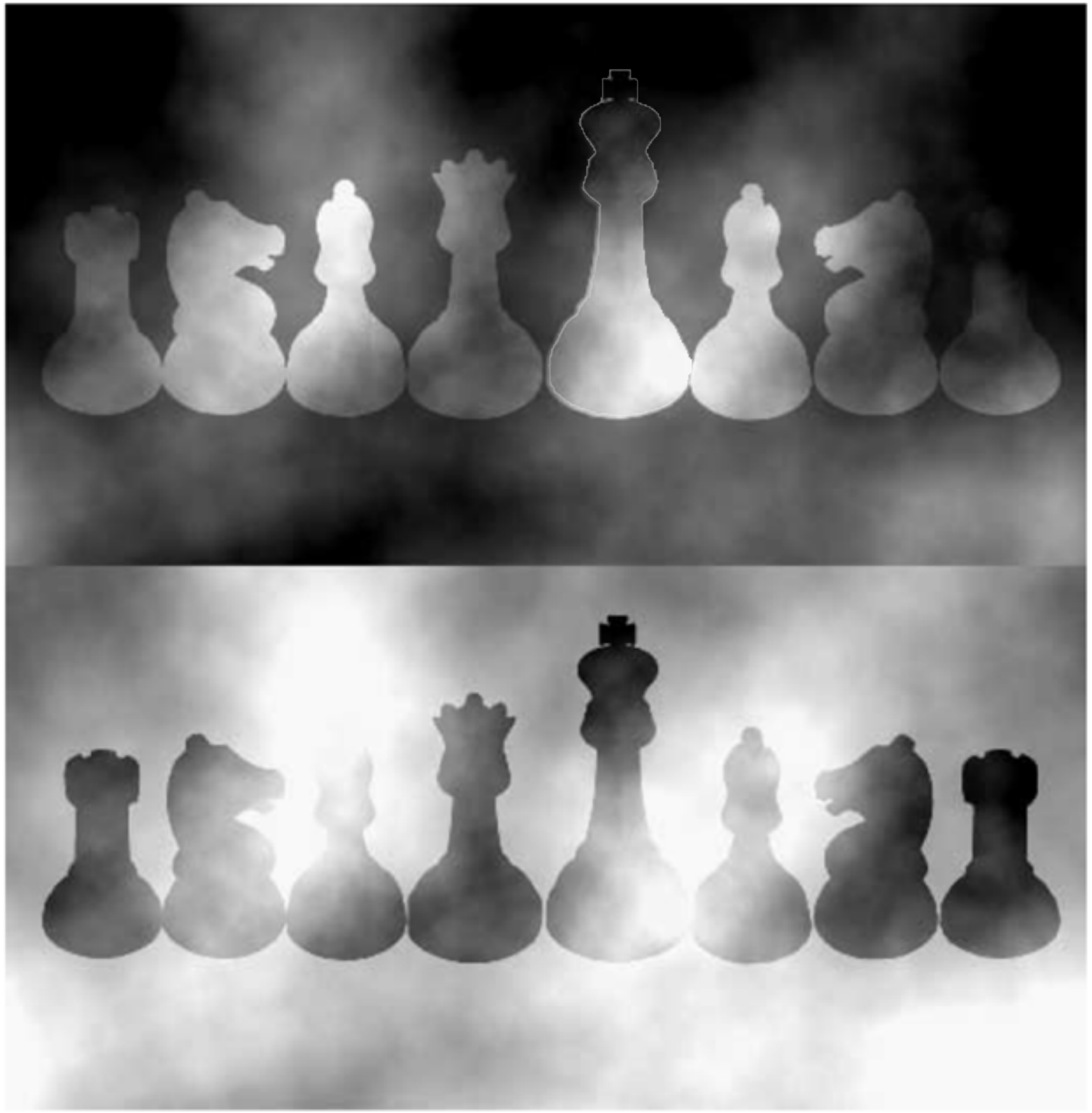
Color appearance and context



. . . passing then into another place illuminated by sunlight, if one looks through the door of the room, the objects that are lit by candlelight will appear tinted reddish-yellow in comparison with those lit by the sun and seen concurrently. One cannot appreciate this when he is in the candle-lit chamber.

(De La Hire, 1694/1730)

Even simple judgments – such as lightness - depend on interpreting the nature of the lighting
(Anderson and Winawer, Nature, 2005)




johnsadowski.com


keep staring at the black dot.


johnsadowski.com

END

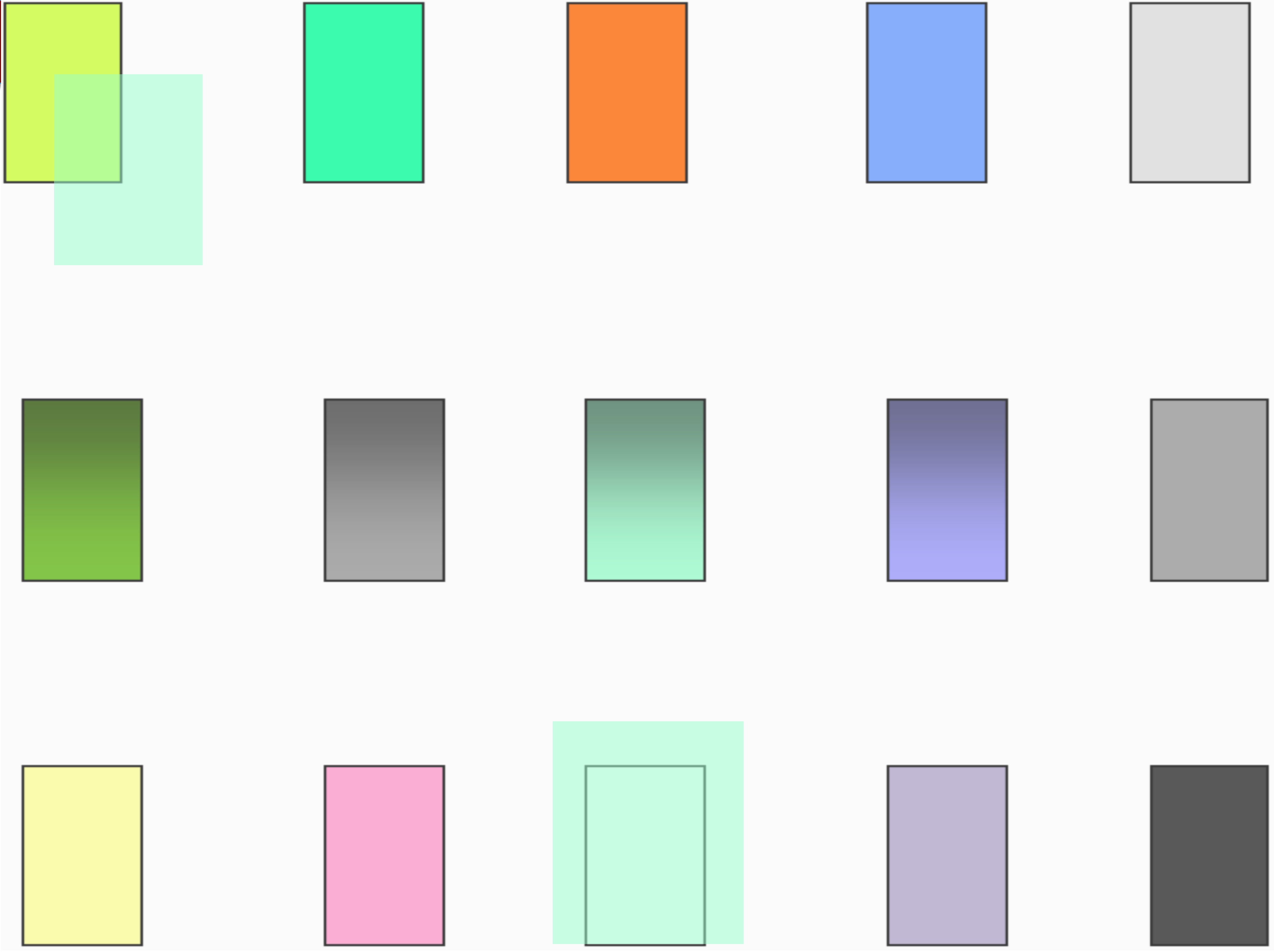
Artistic rendering – which one do you like better?

Notice that the hole and 2nd prism is missing!

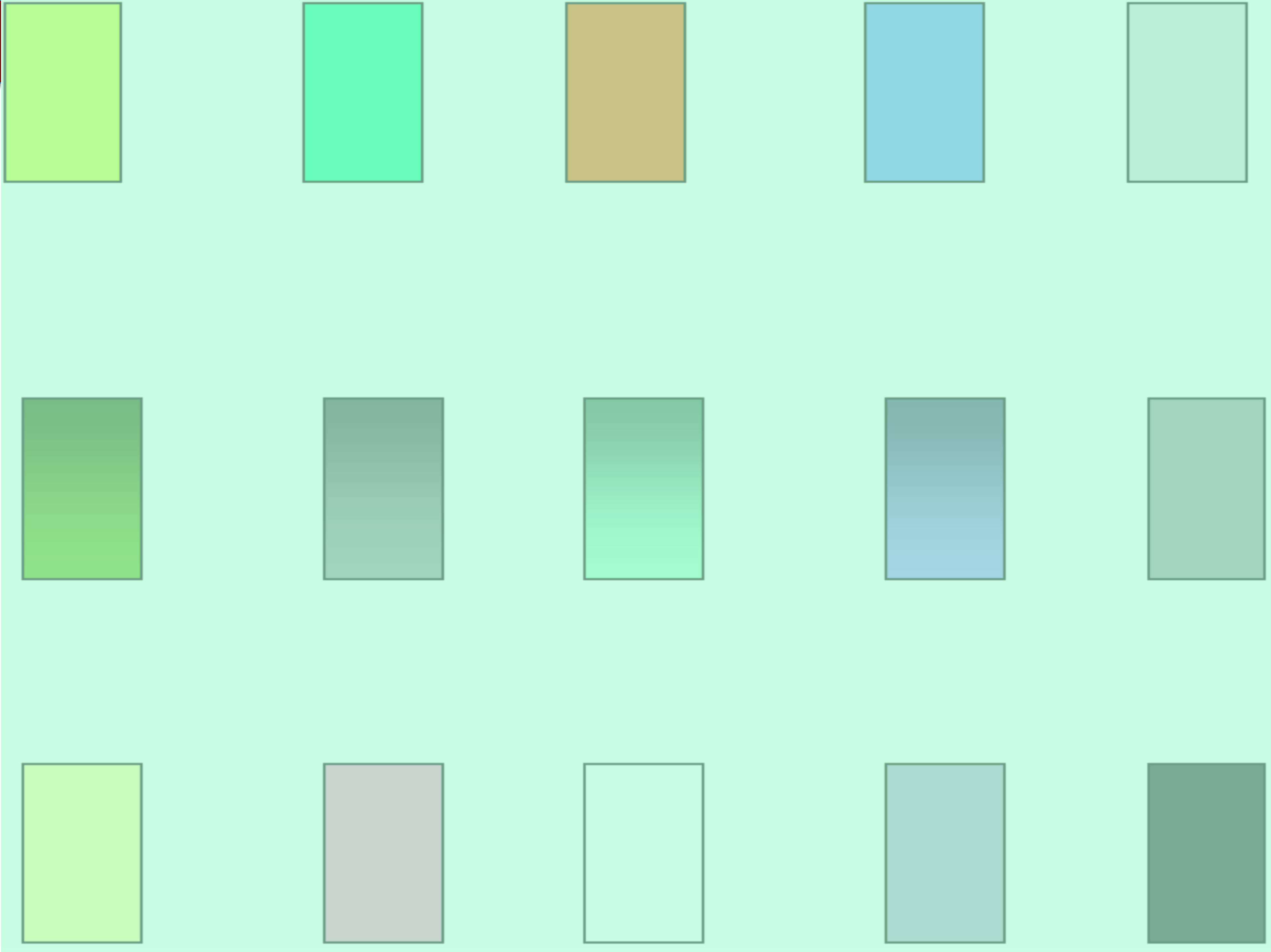
And what is that dude doing there in the background?

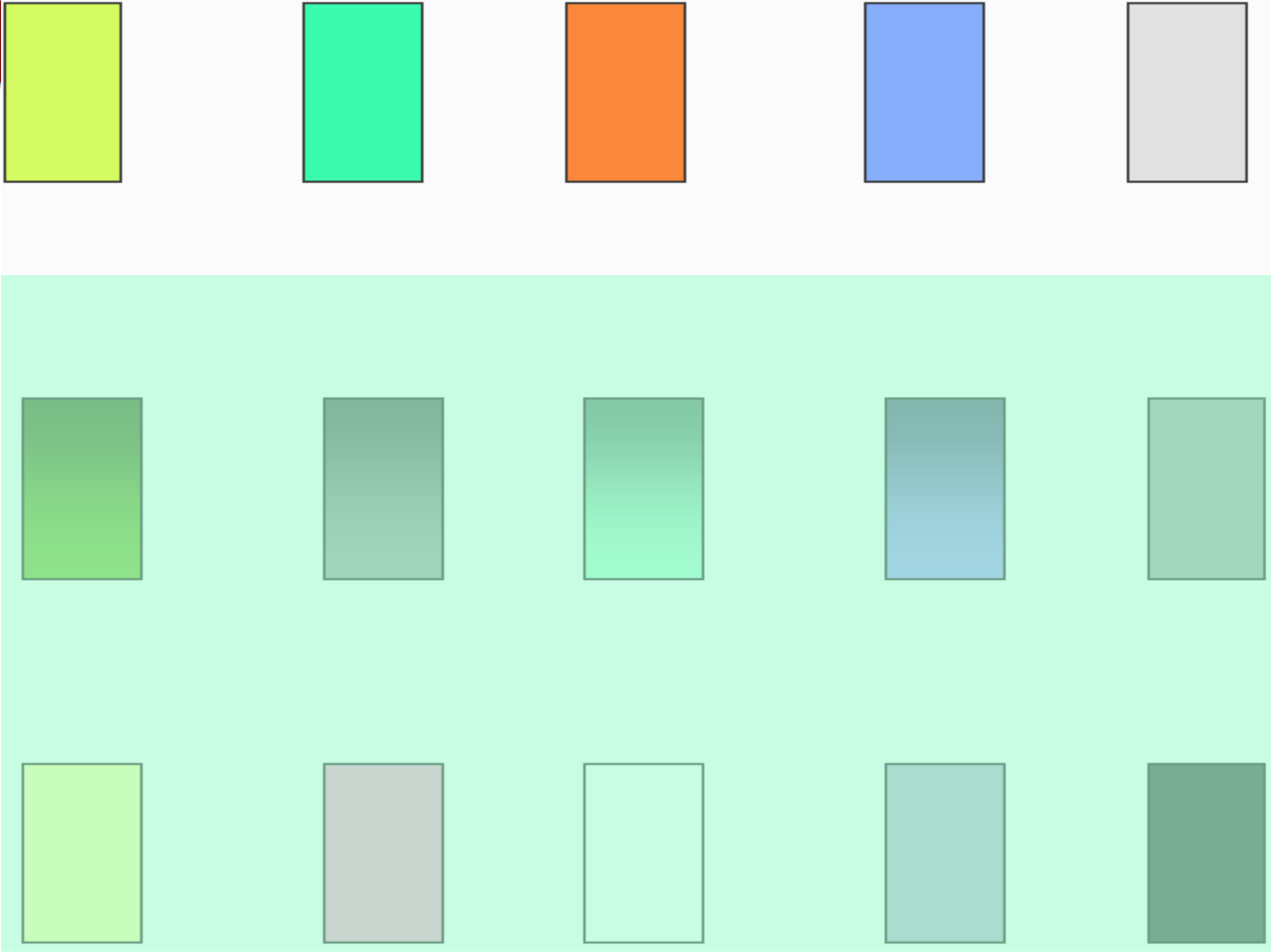
And where is the lens?

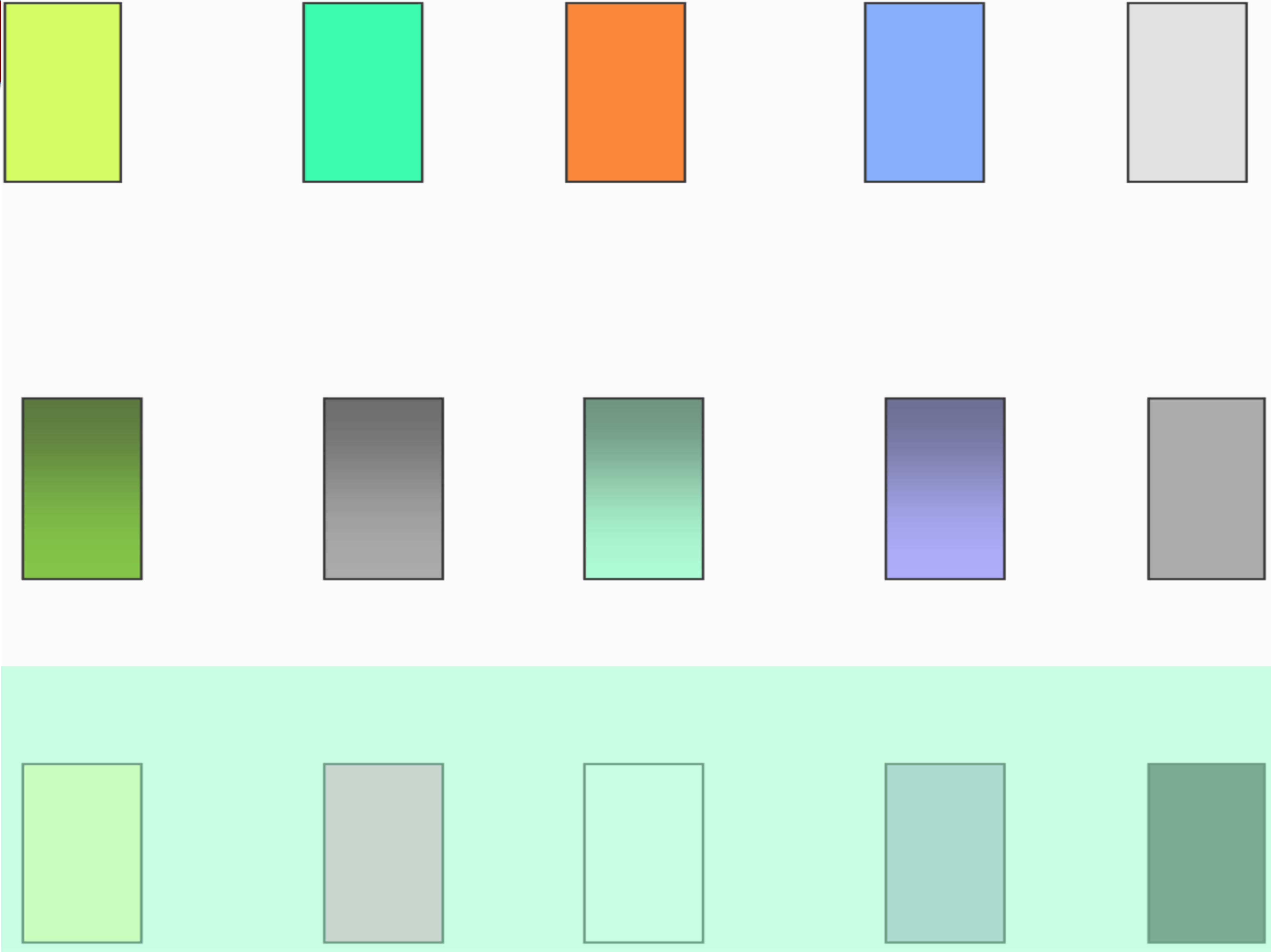
The fundamental components of light

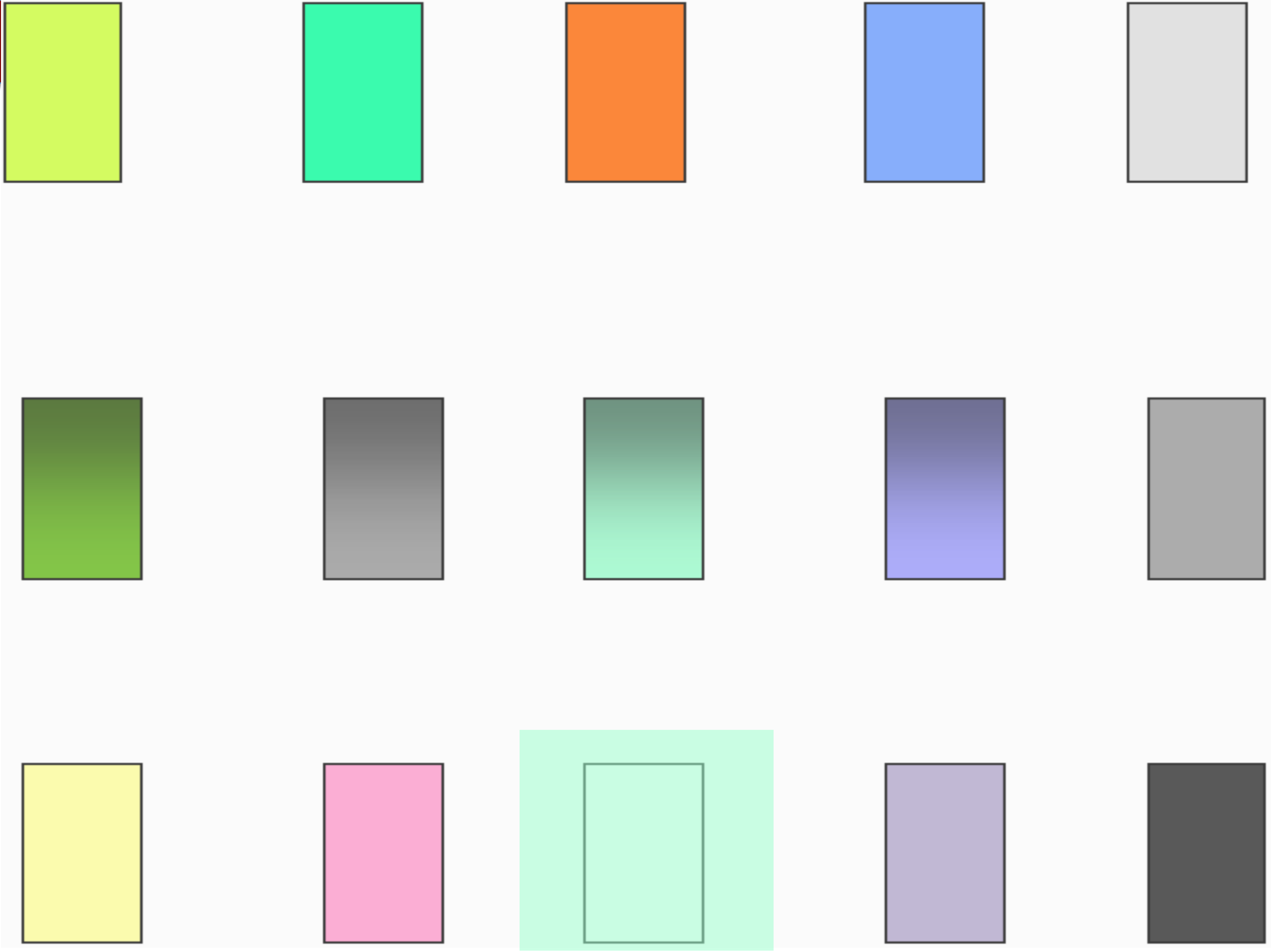


Color Appearance is Calculated Across Space

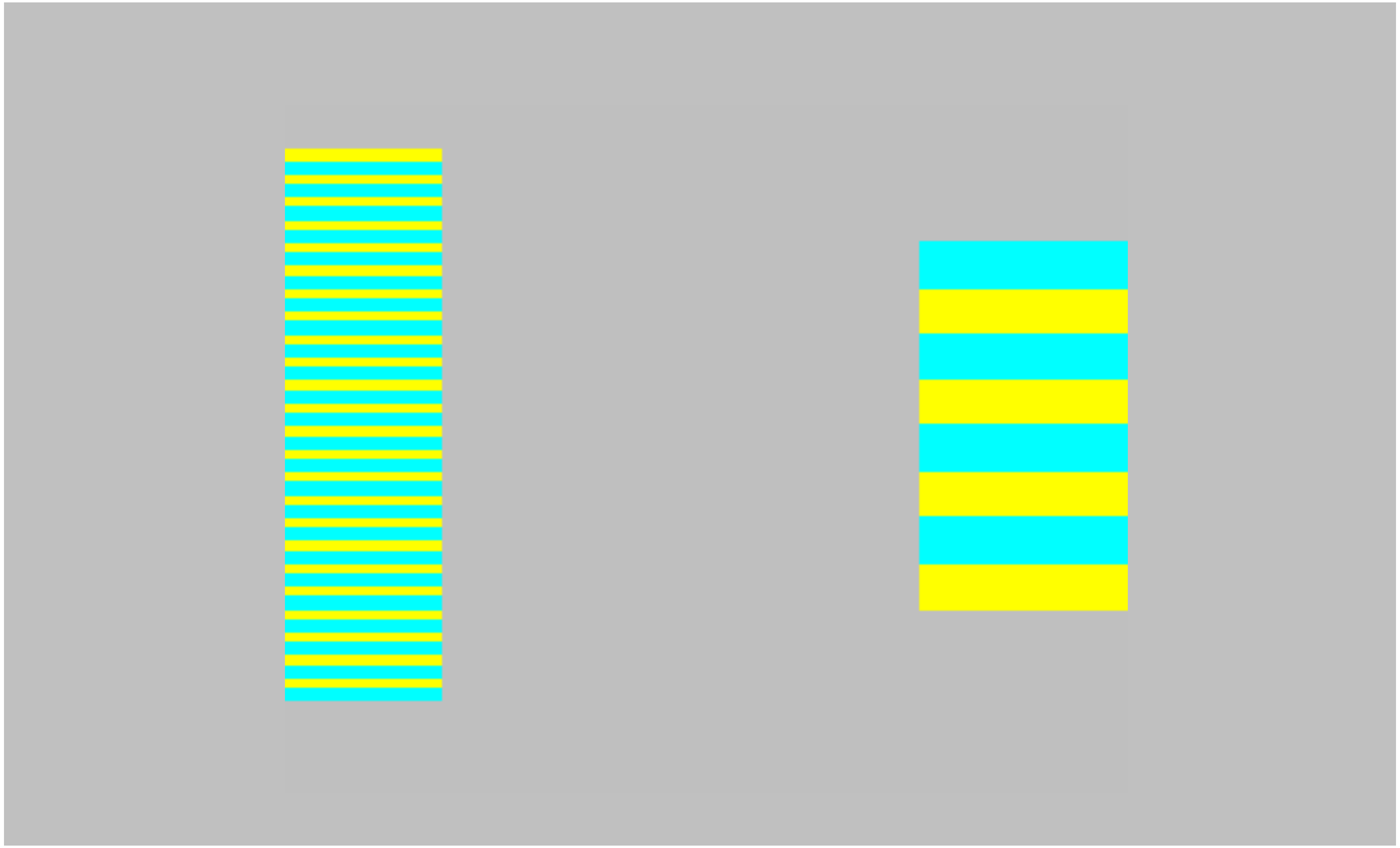








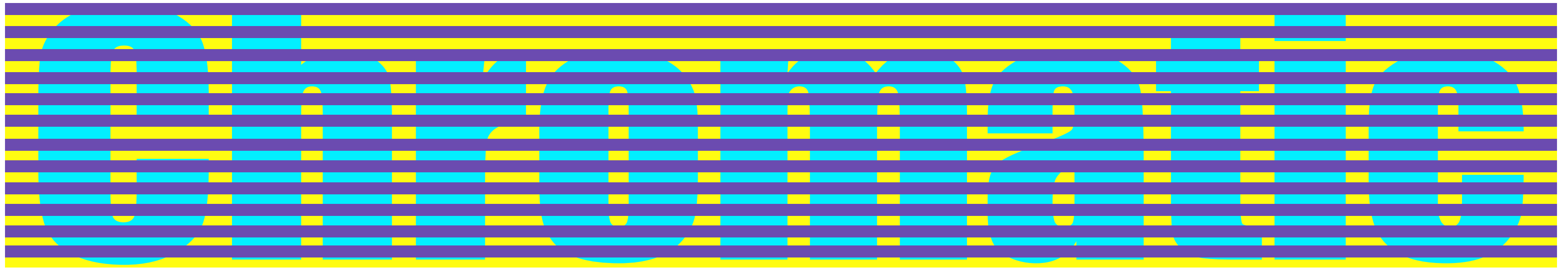
Chromatic Aberration Influences Appearance



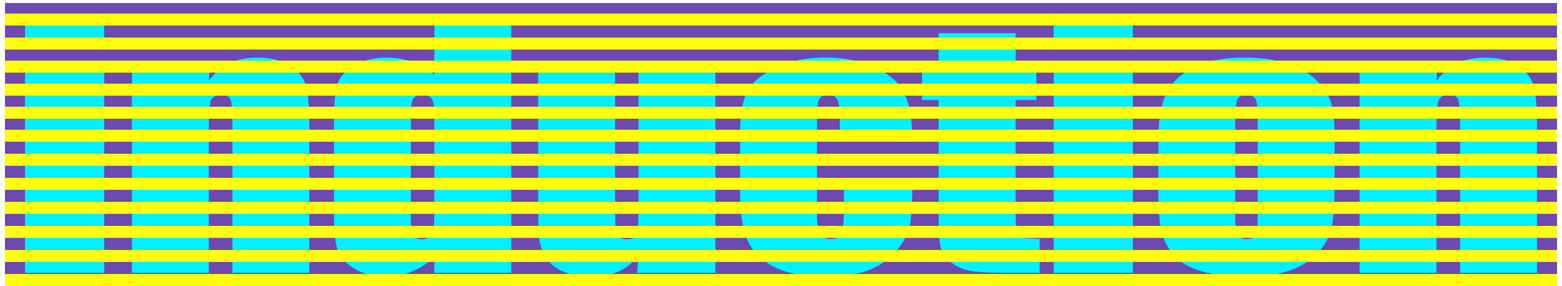
From Foundations of Vision

Text is the same in 3 slides

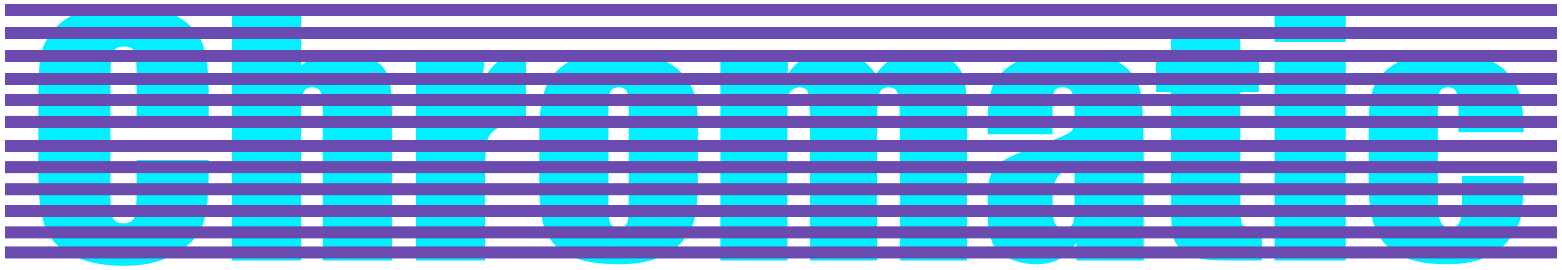
Chromatic induction



Purple in front, Yellow in back



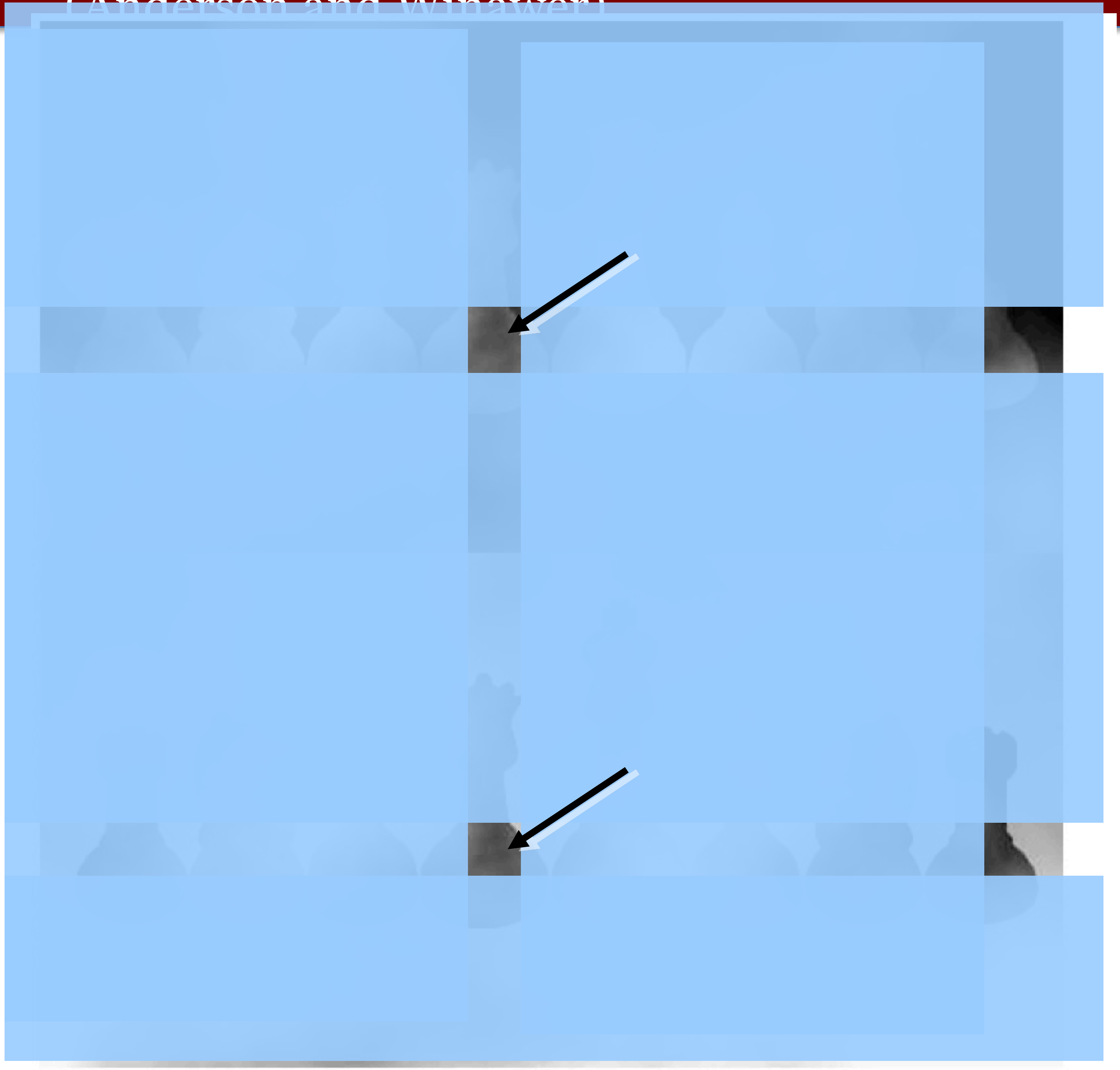
Yellow in front, Purple in back



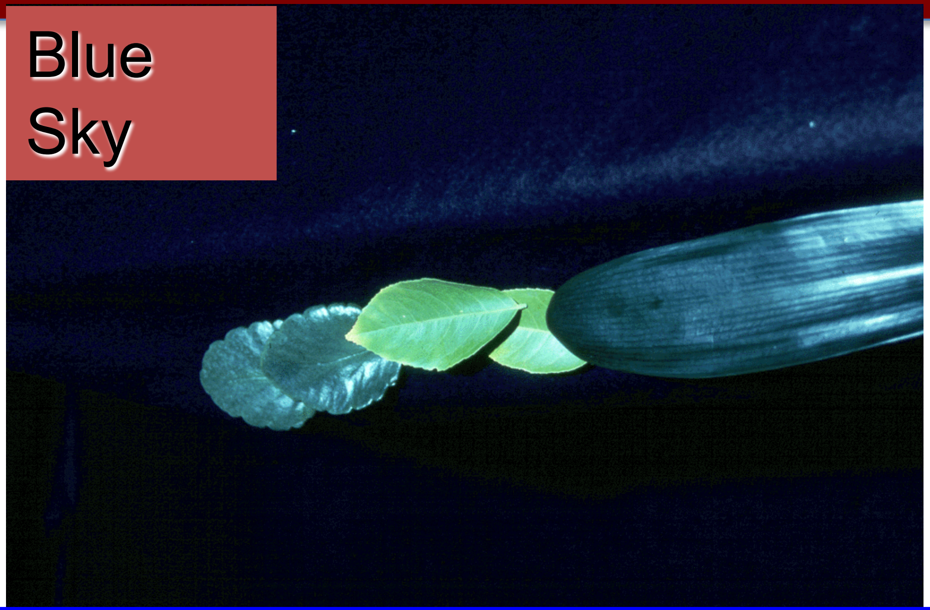
Purple in front, White in back

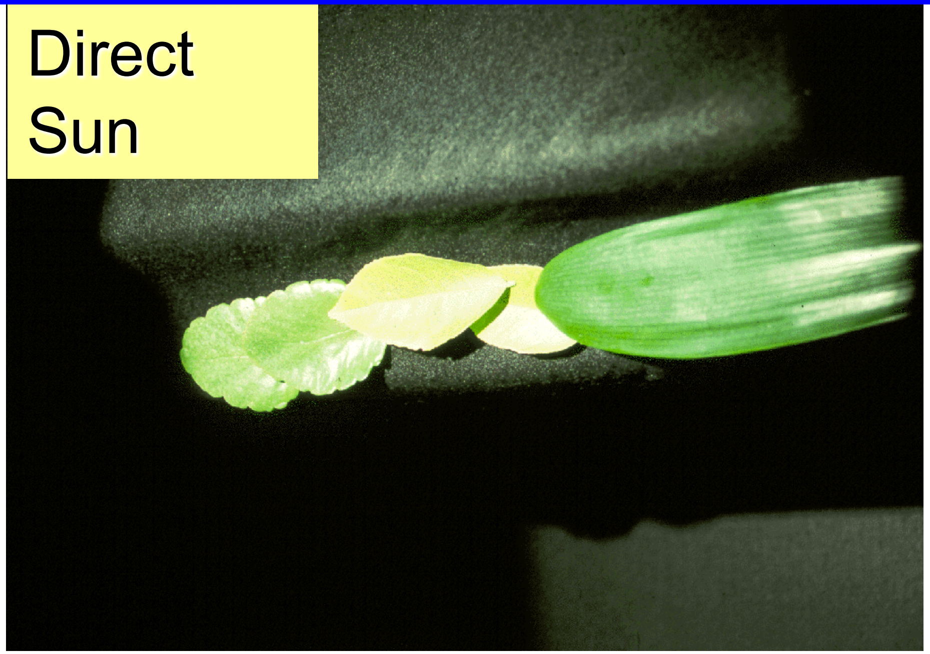
Yellow in front, White in back

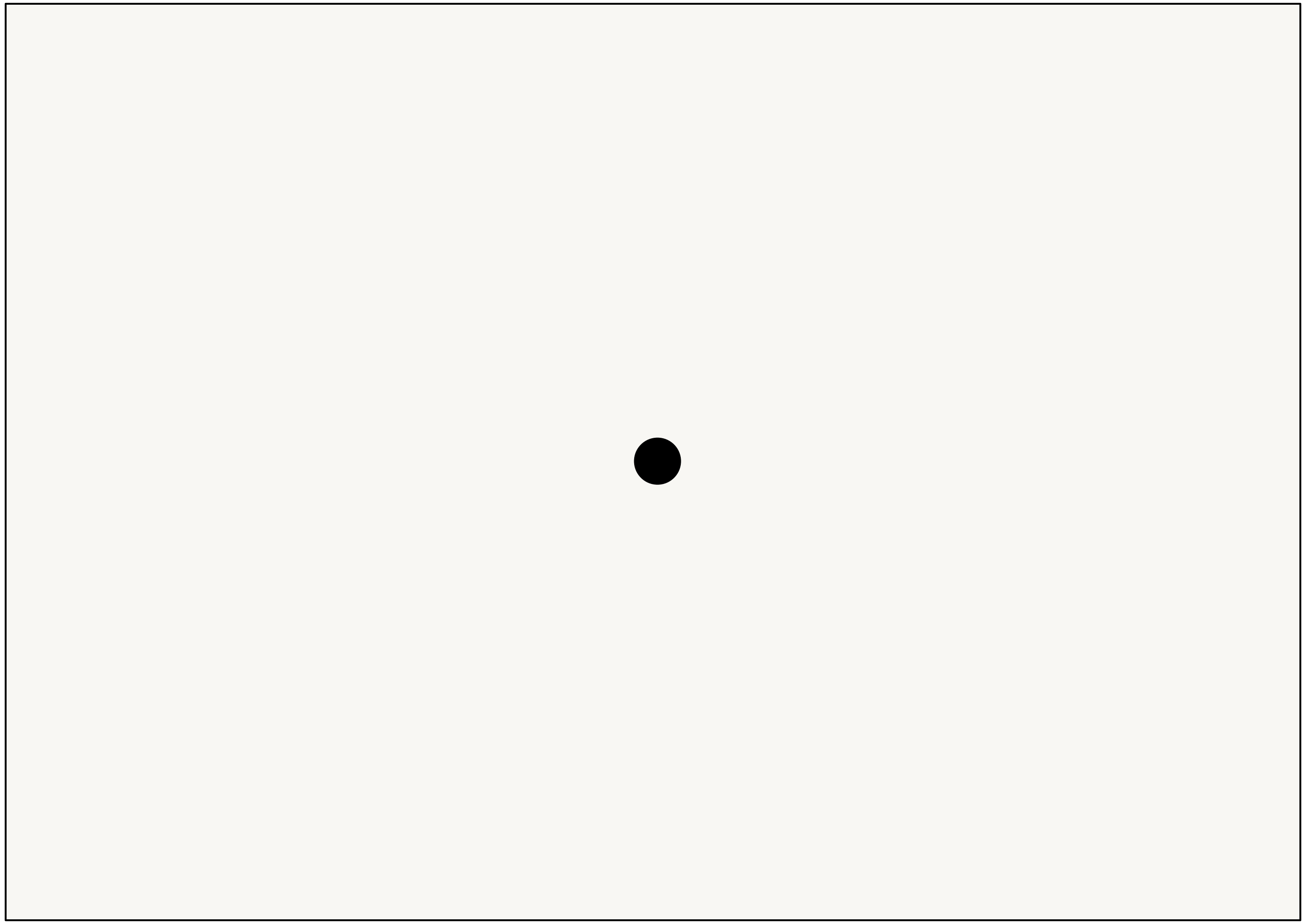
Lightness Perception (Anderson and Winawer)



The chess pieces are the same shade; really.


Blue
Sky

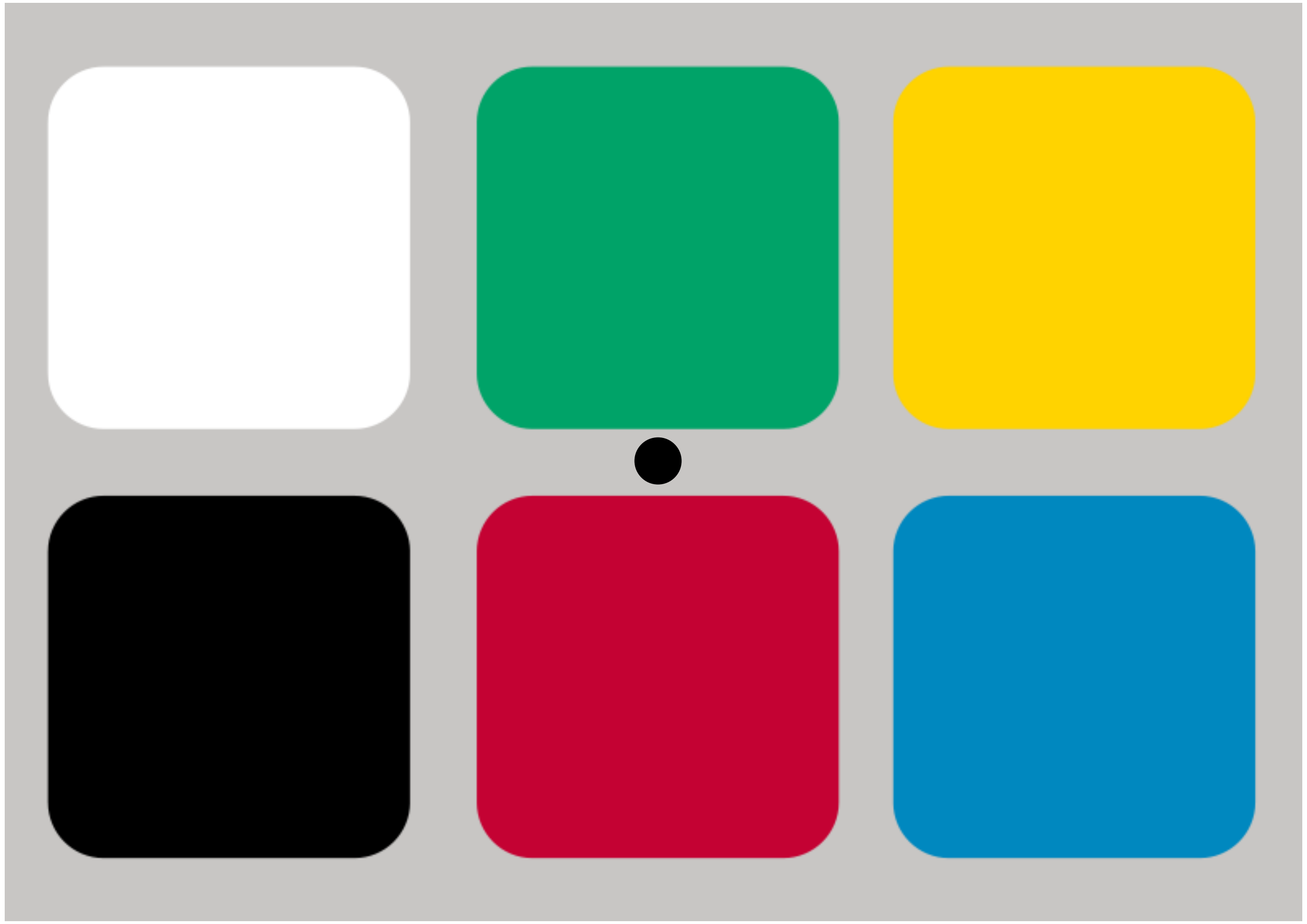

Direct
Sun



White
Green
Yellow

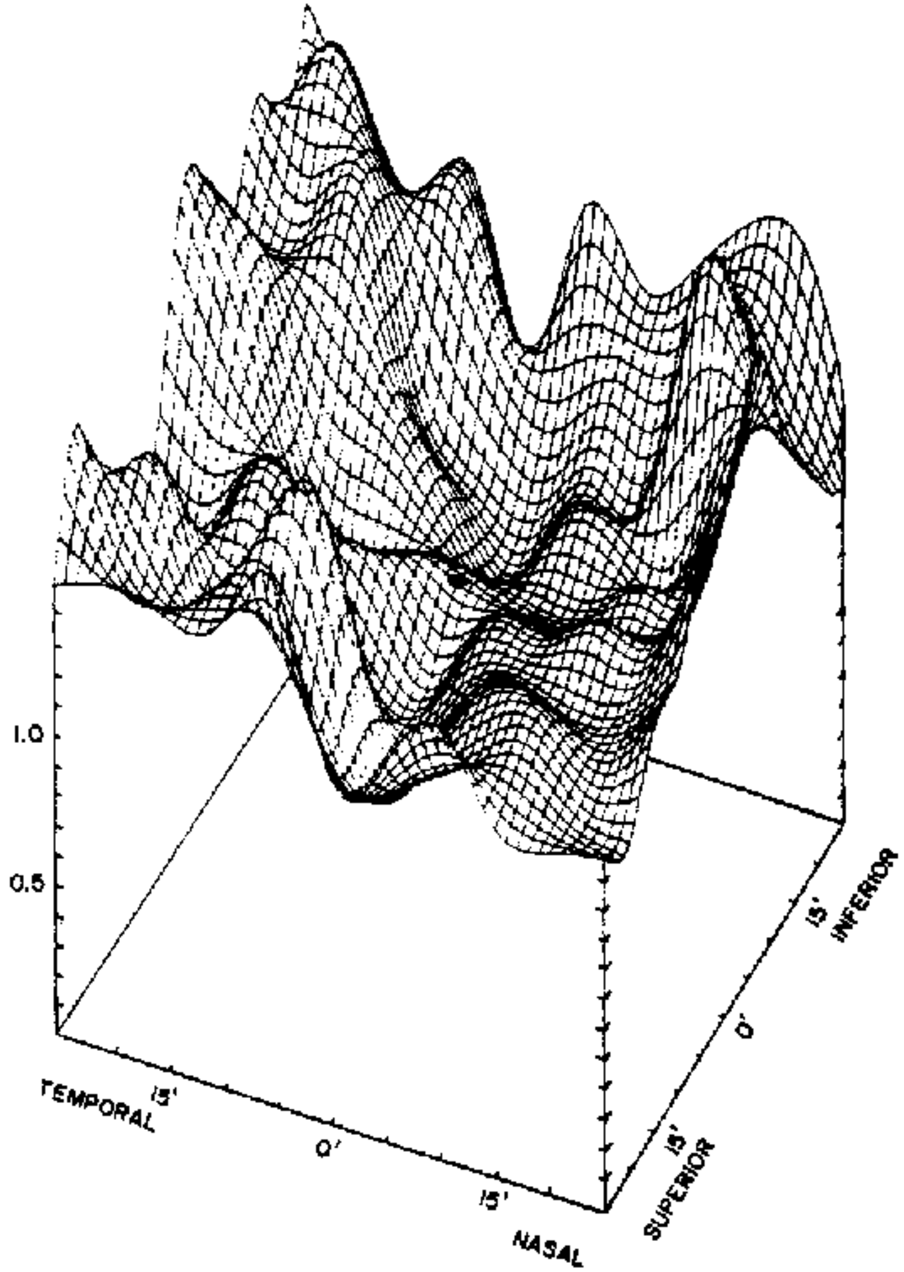
Black
Red
Blue

Opponent-Colors – Afterimage demo



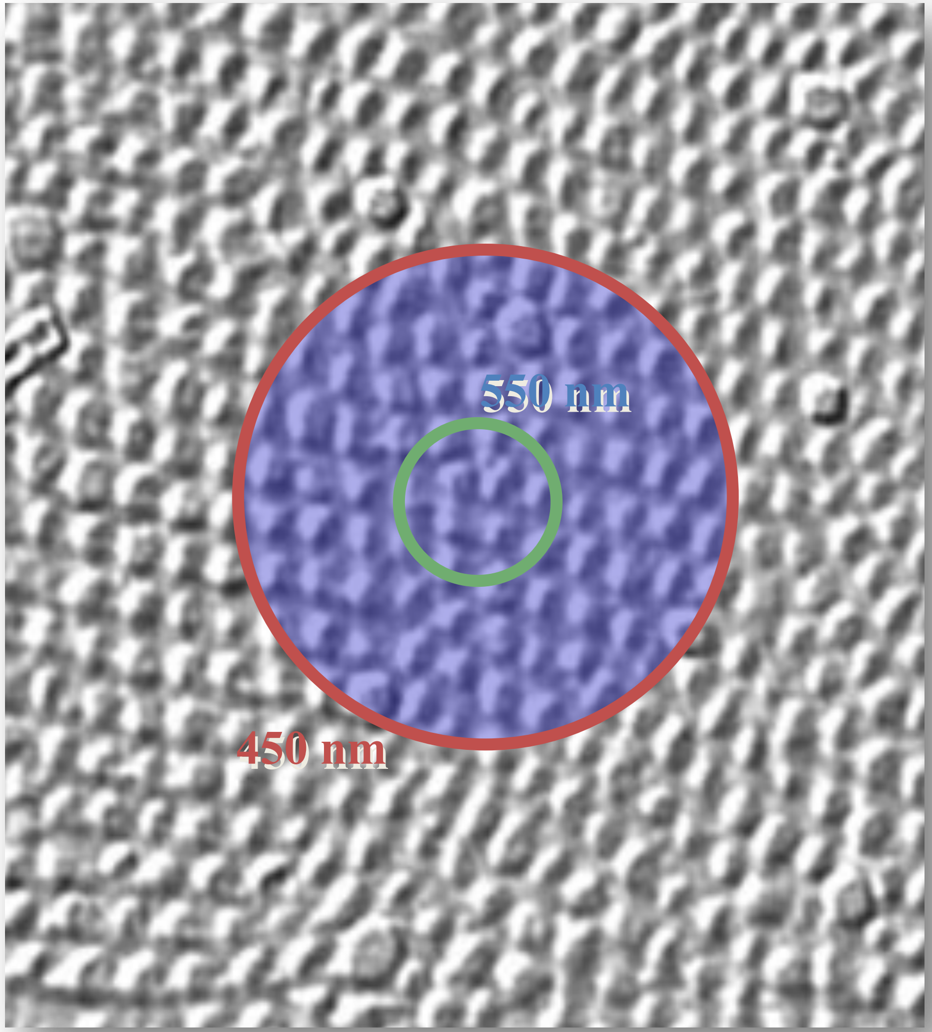
White
Green
Yellow

Black
Red
Blue


1.0
0.5
TEMPORAL
15'
0'
15'
NASAL
SUPERIOR
15'
0'
15'
INFERIOR

Optical point spread in the human fovea

for a 3mm pupil at 550nm and 450nm
(cone mosaic is shown in the background)

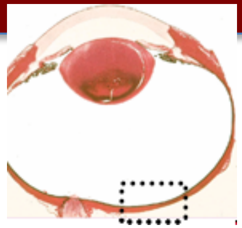


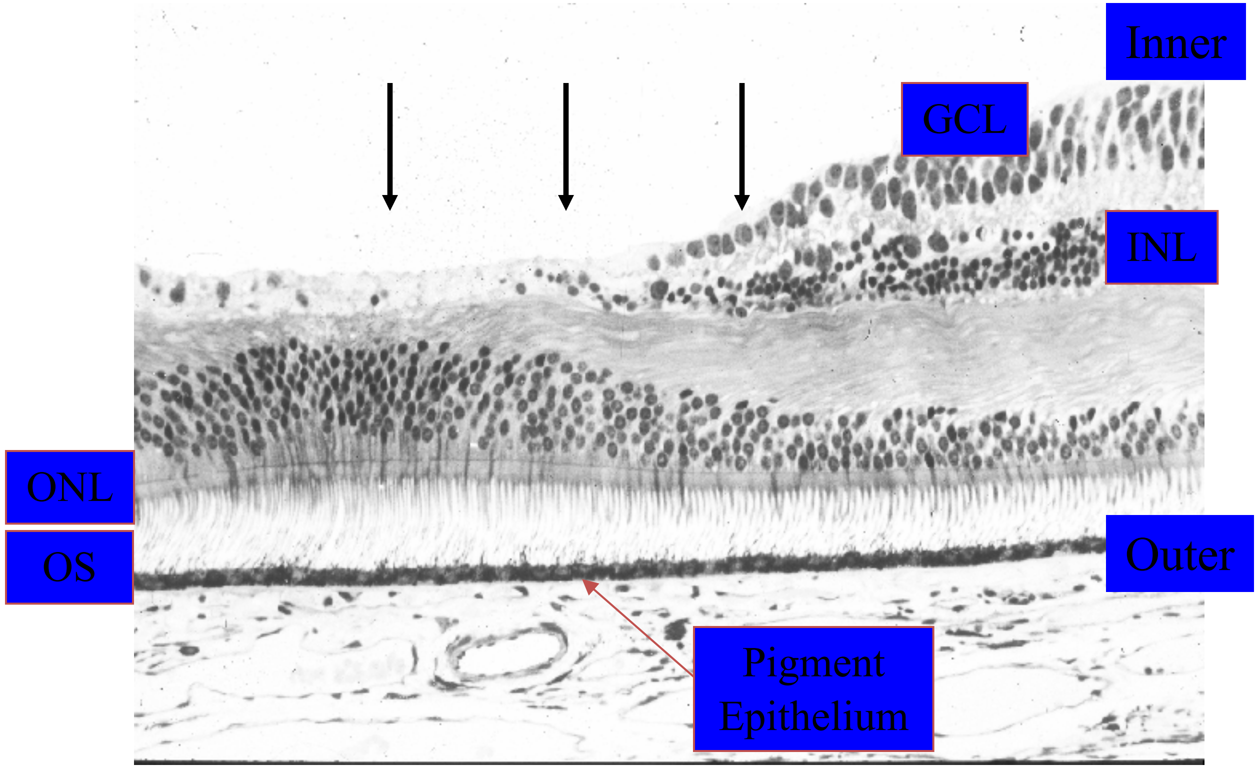
5 um

Short-wavelength
(450nm) light creates
a very blurry image

The Retina

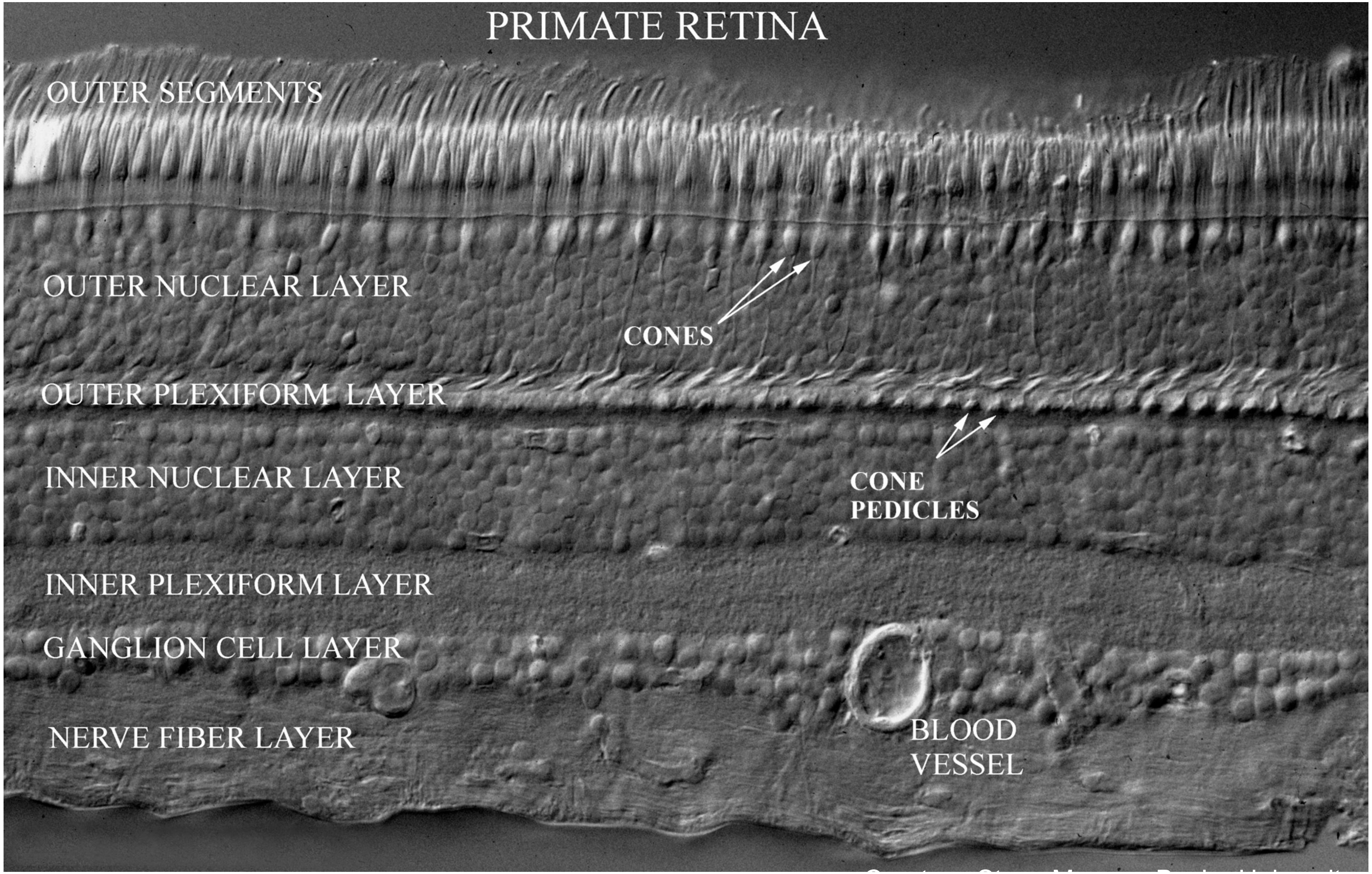
- 5 x 5 cm, 0.4 mm thick
- 5 x 10^6 cones
- 10^8 rods
- Foveal cone width: 1 mu
- Contacts per cone: 250
- 10^6 optic nerve fibers





Curcio
Rodieck

Peripheral retina



Color vision is interesting

[Blue Man Group](http://www.youtube.com/watch?v=W-yLfm5HsHc&feature=youtube_gdata_player)

Oct. 2016: 2,614,430 views

http://www.youtube.com/watch?v=W-yLfm5HsHc&feature=youtube_gdata_player