

How wavelength becomes color

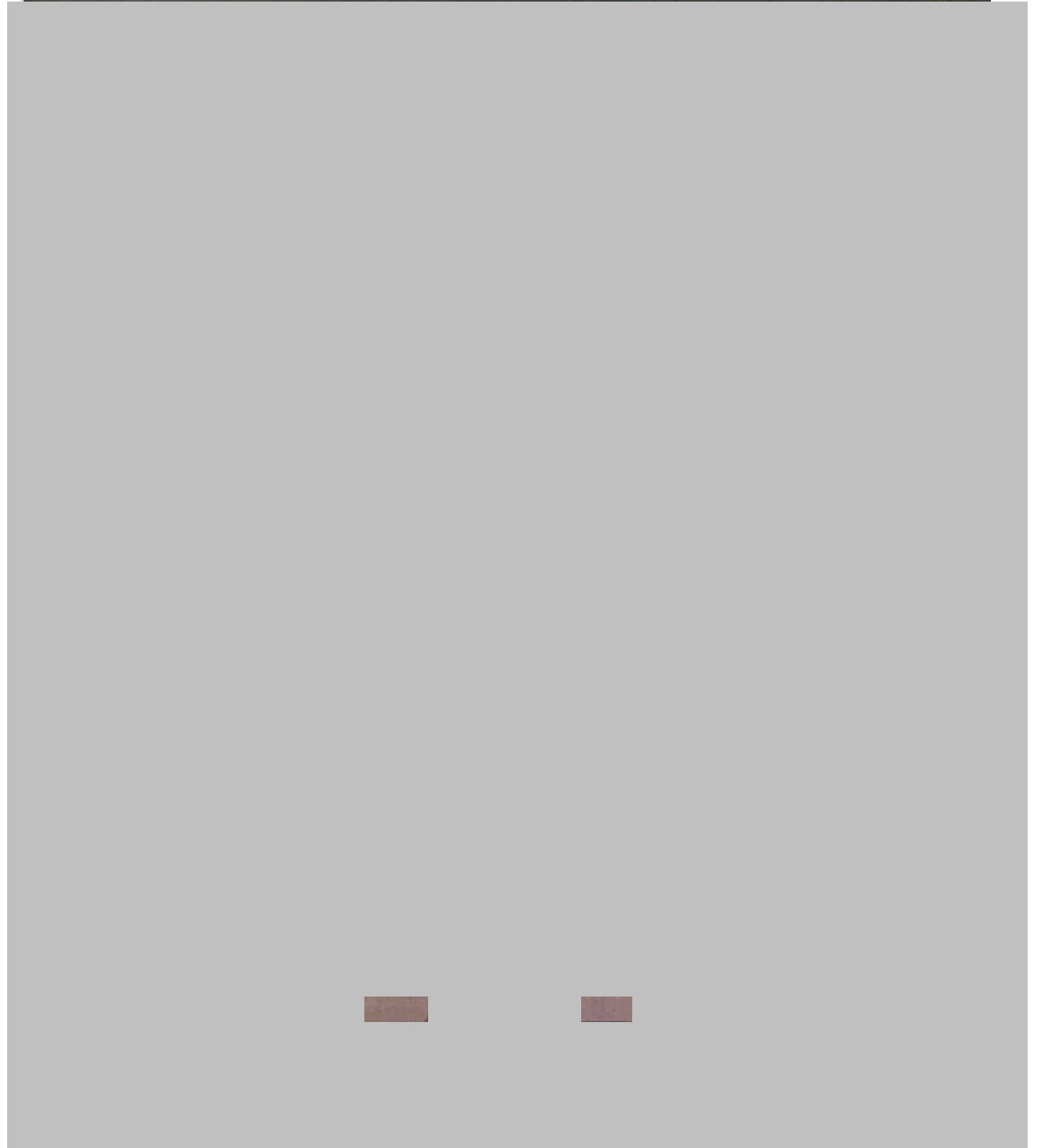
Brian A. Wandell
Psychology, Stanford

- Color – the warm up
- Primate retina and fovea
- Light
- Color matching experiment
- Metamerism calculations
- Cones and color
- Historical notes
- Appearance – Opponency and Pattern





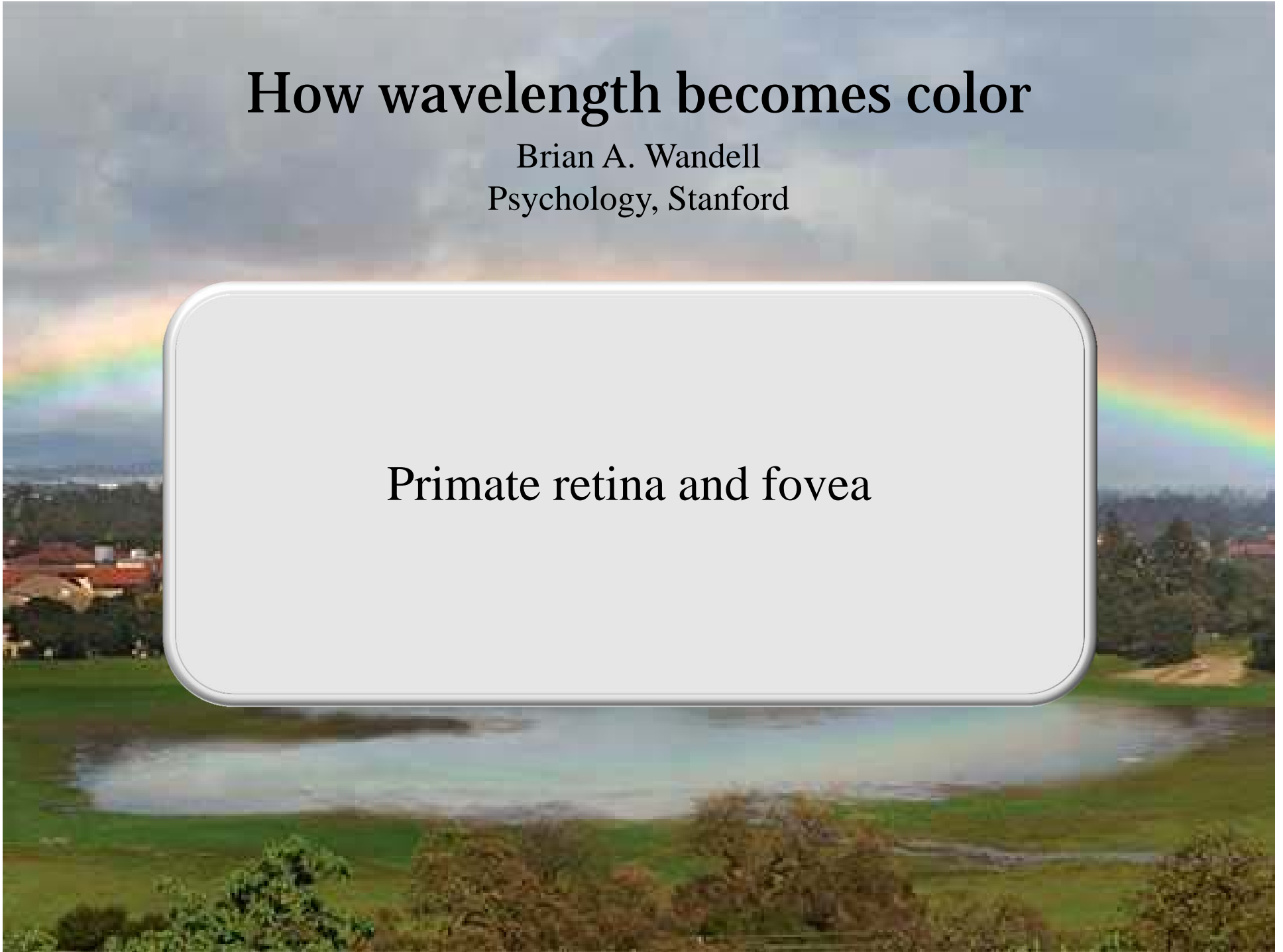
Lightness Perception (Lotto and Purves)



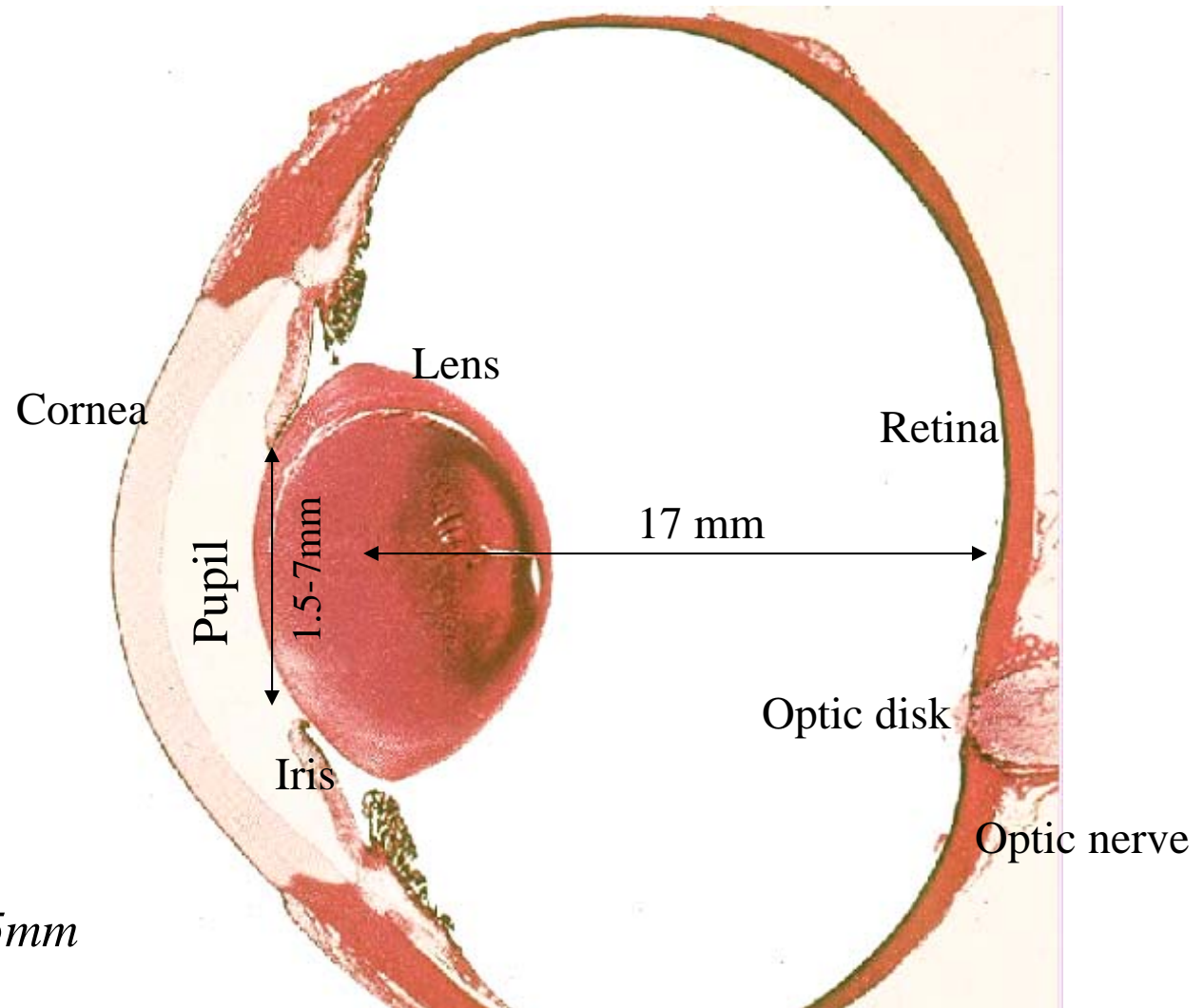
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Primate retina and fovea



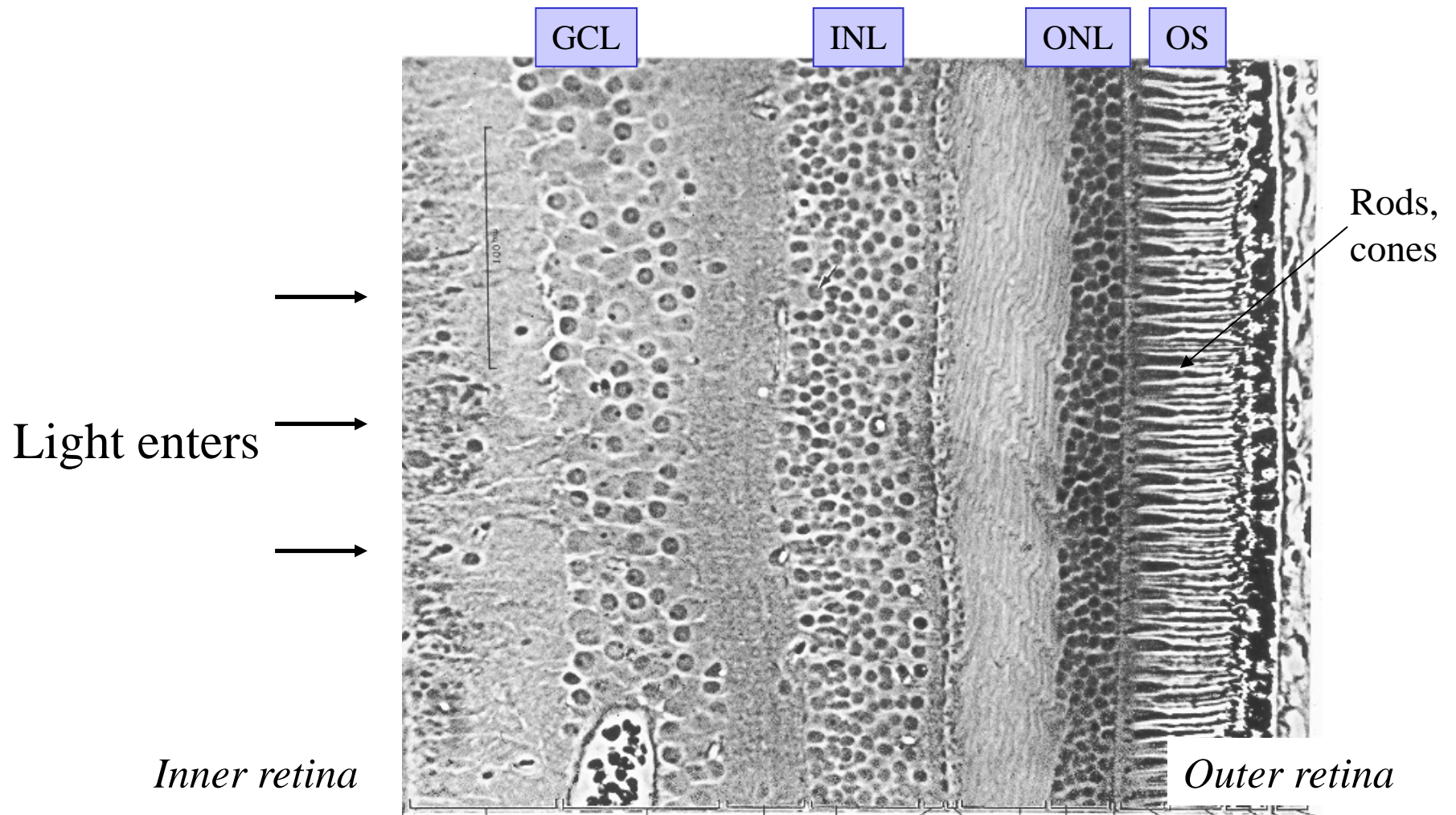
Human Eye in Cross-Section



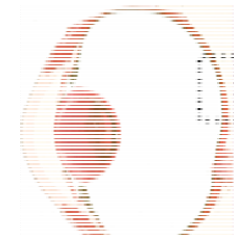
F-number ~ 2.4-11

Retinal thickness ~ 0.5mm

Light Passes Through The Retinal Cells And Is Absorbed by the Rods and Cones

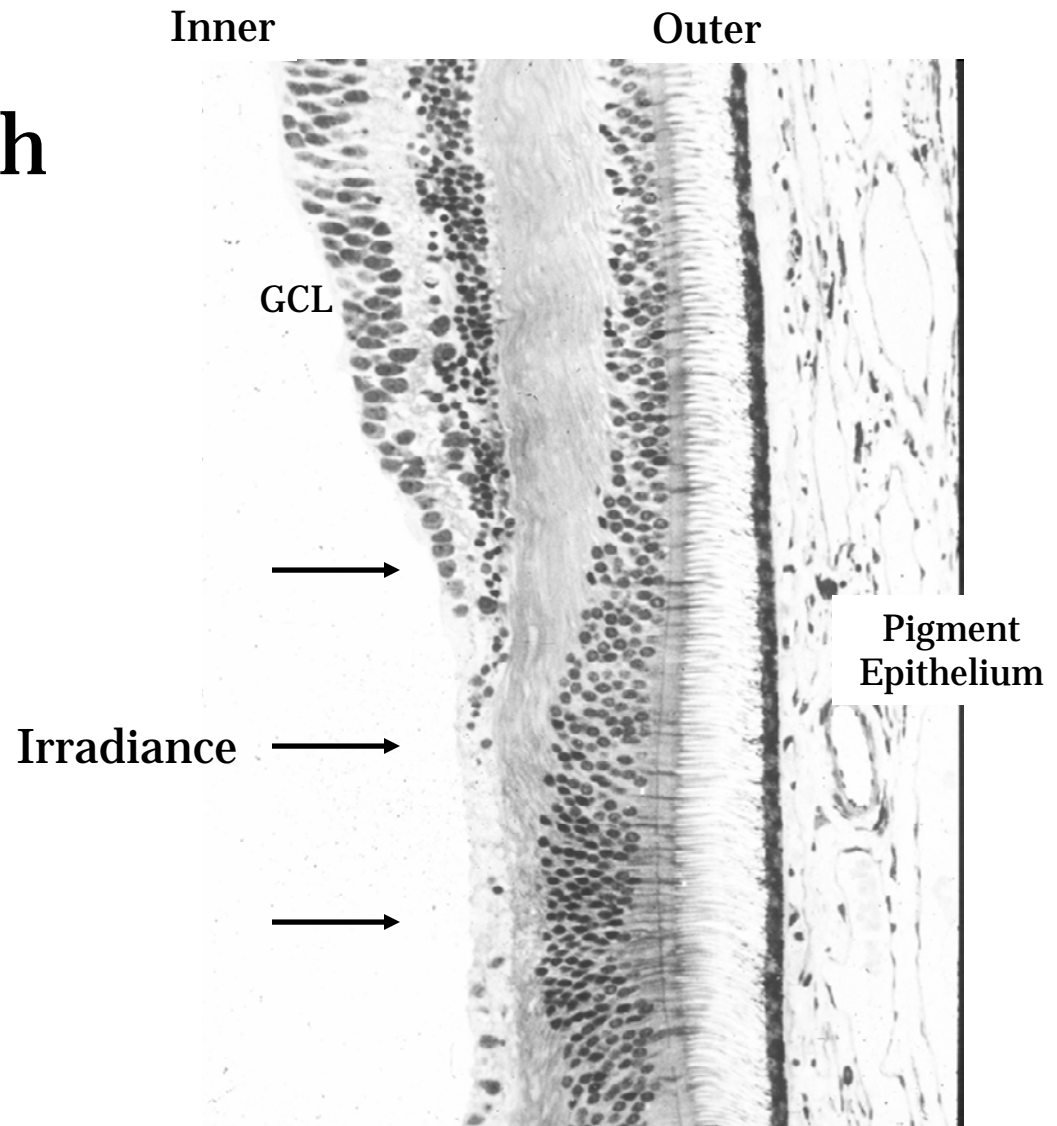


The Primate fovea (pit) contains mainly cones and is specialized for high acuity and color

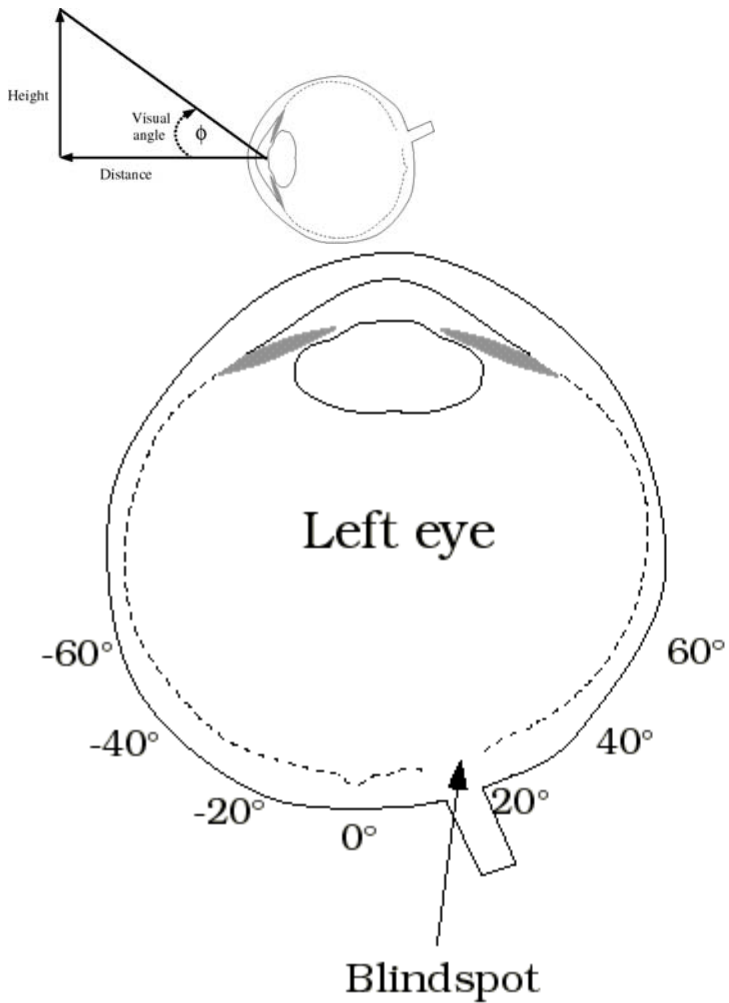


The Retina

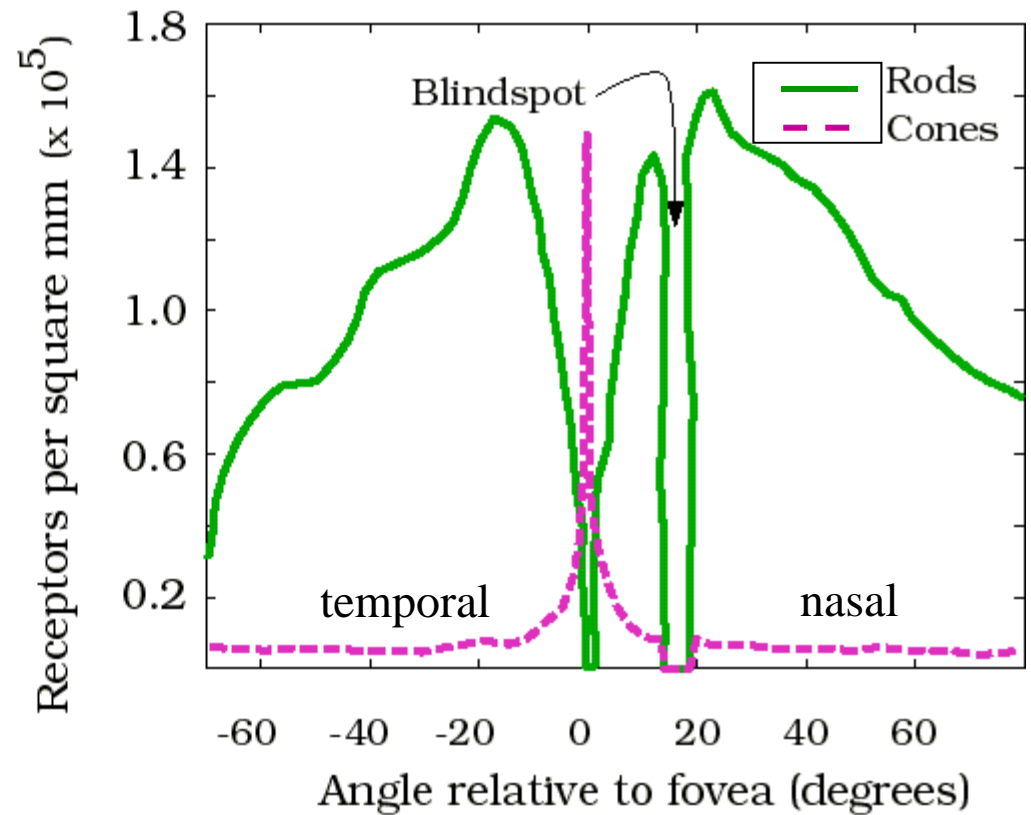
- 5 x 5 cm, 0.4 mm thick
- 5×10^6 cones
- 10^8 rods
- Foveal cone width: 1 μ m
- Contacts per cone: 250
- 10^6 optic nerve fibers



Spatial Distribution of Human Photoreceptors (rods and cones)



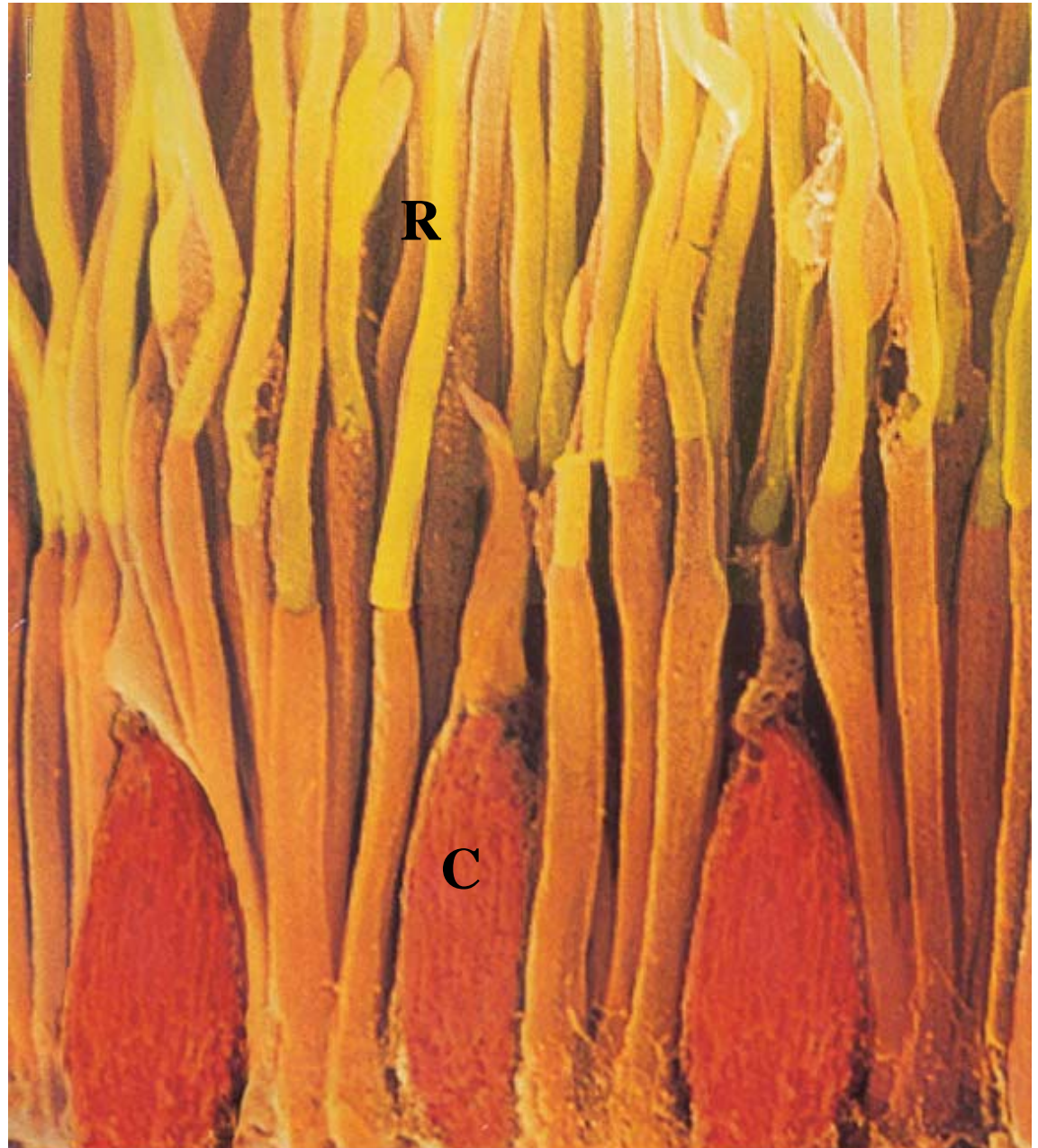
(b)



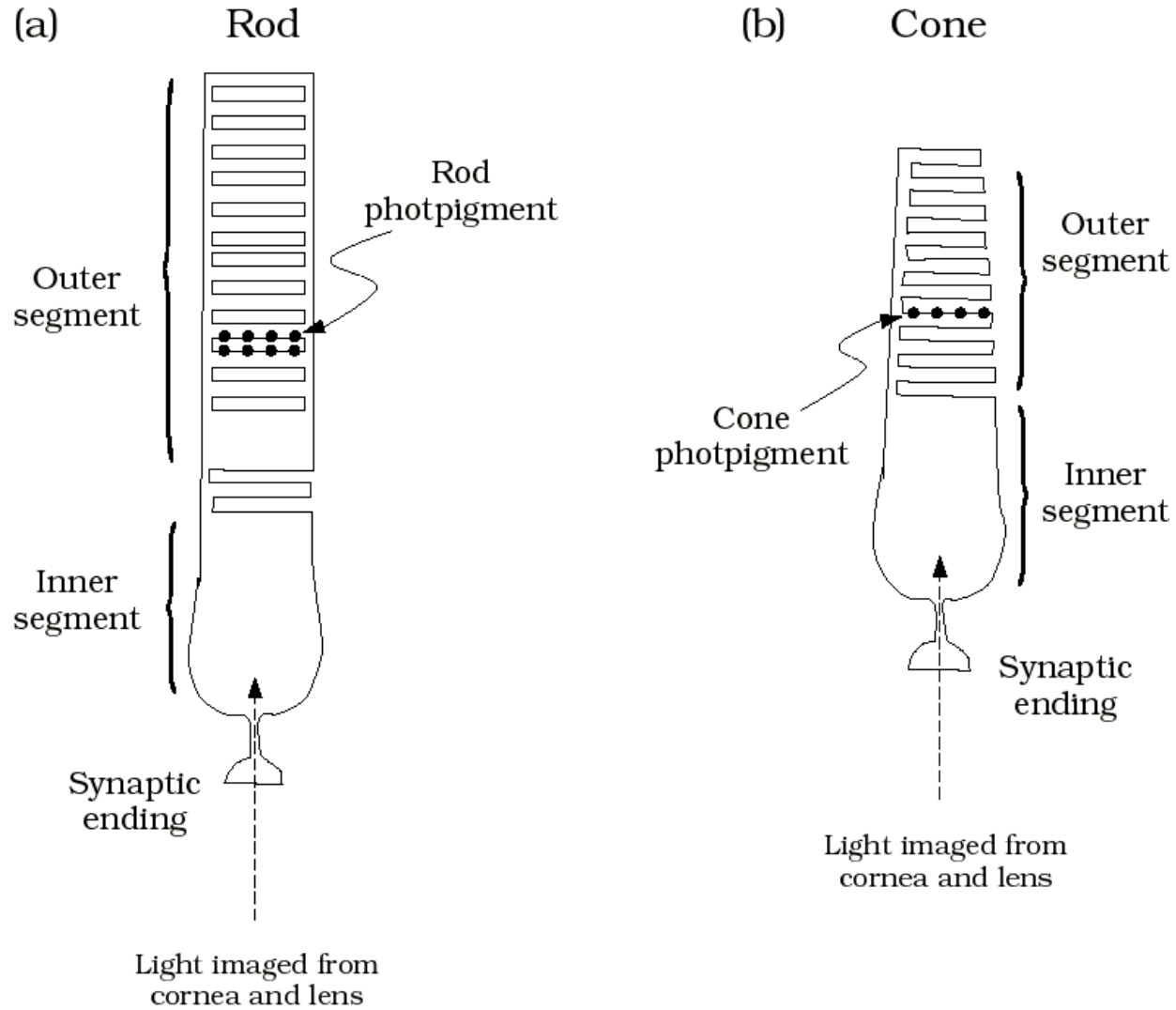
Rods and Cones

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

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



Receptor schematics



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



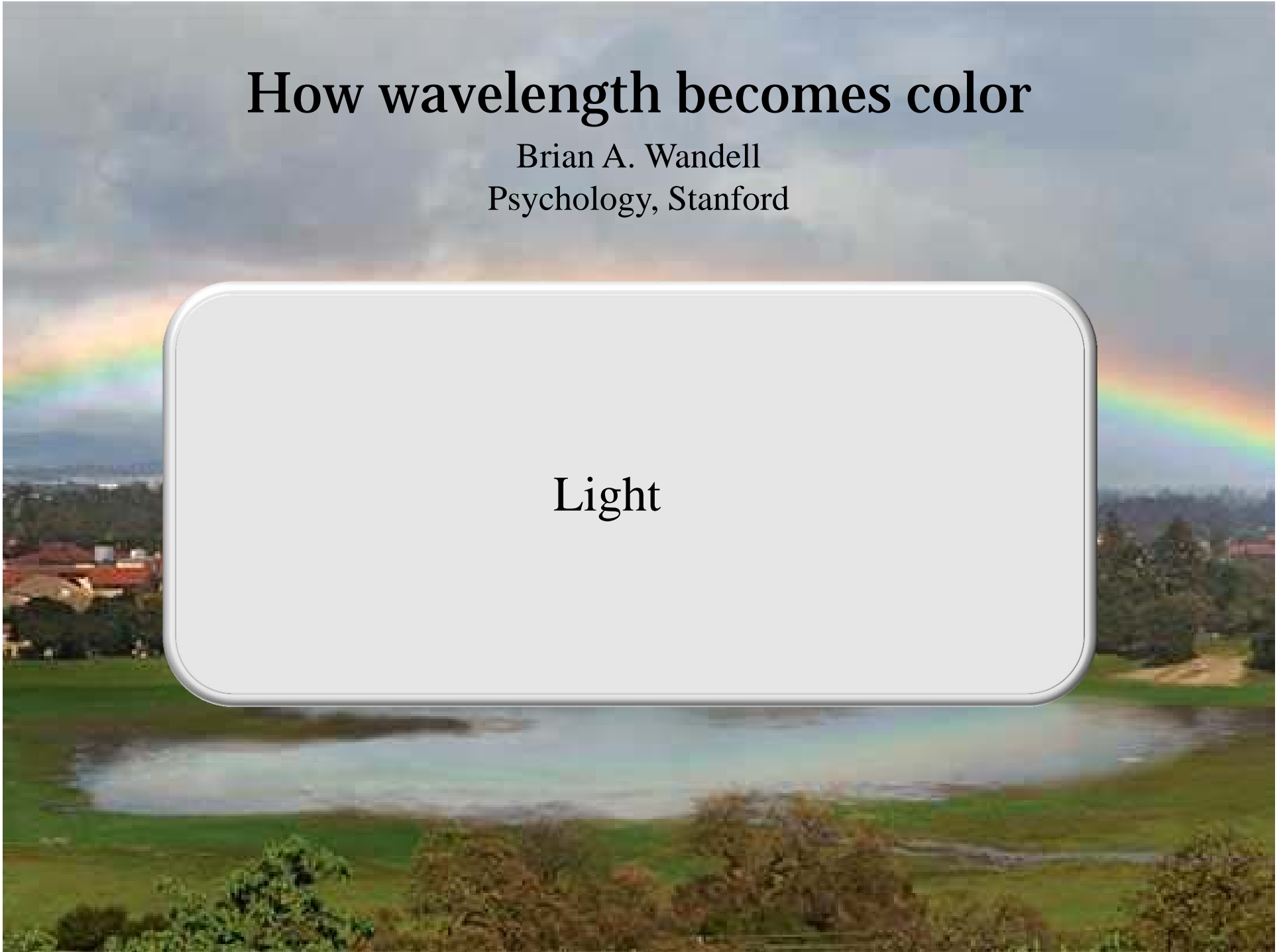
After exposure to light, the pigment becomes transparent



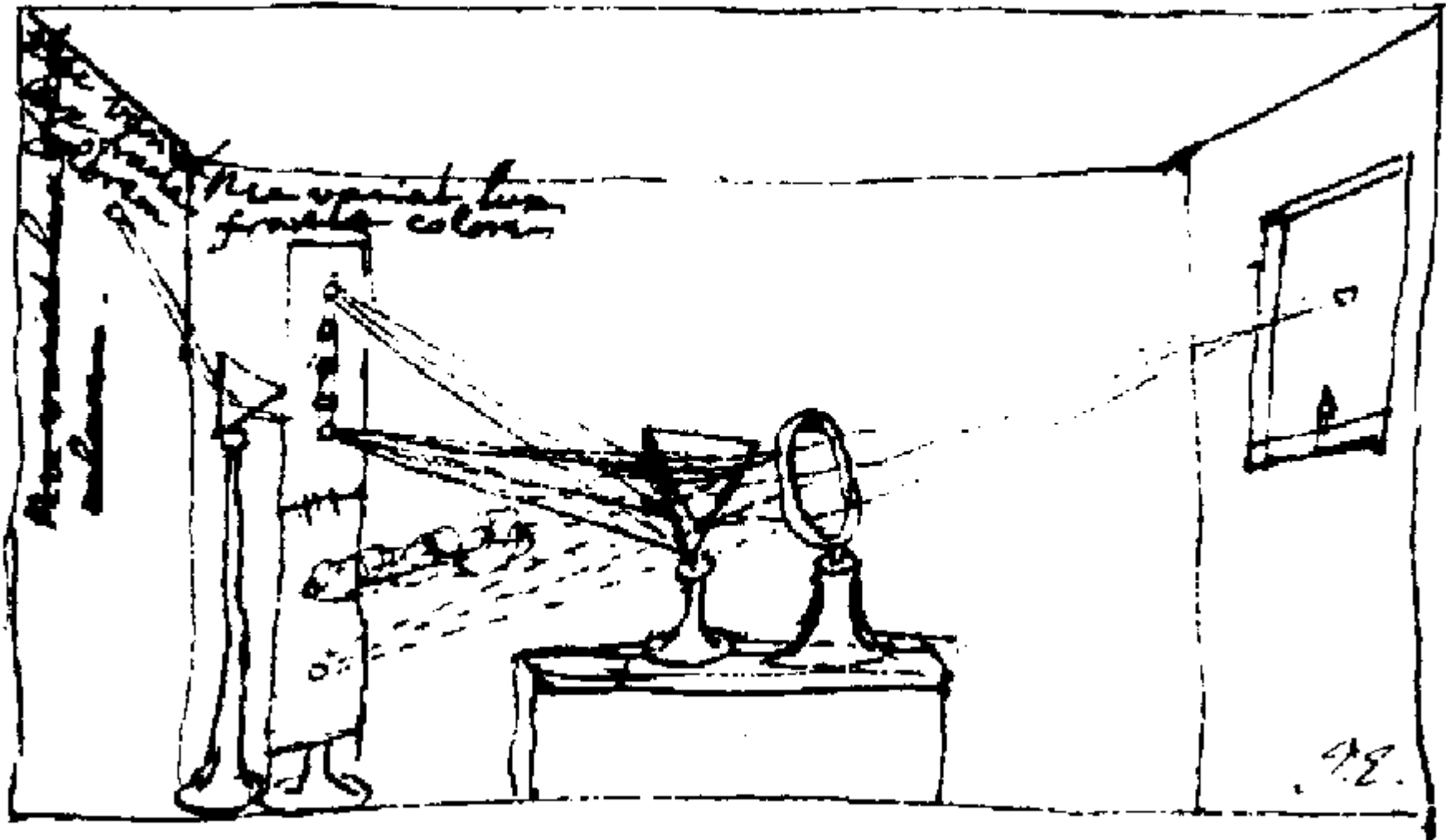
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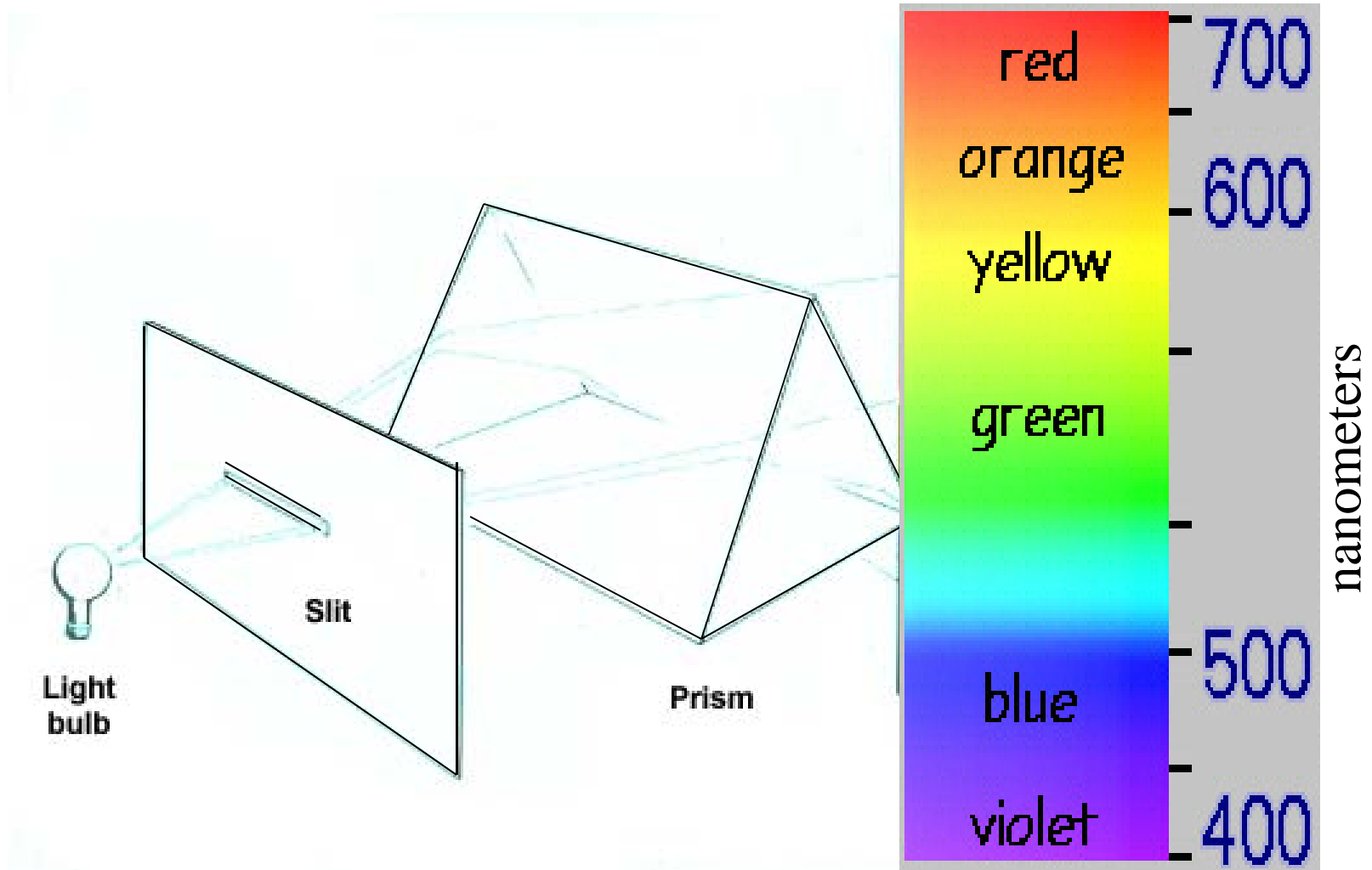
Light



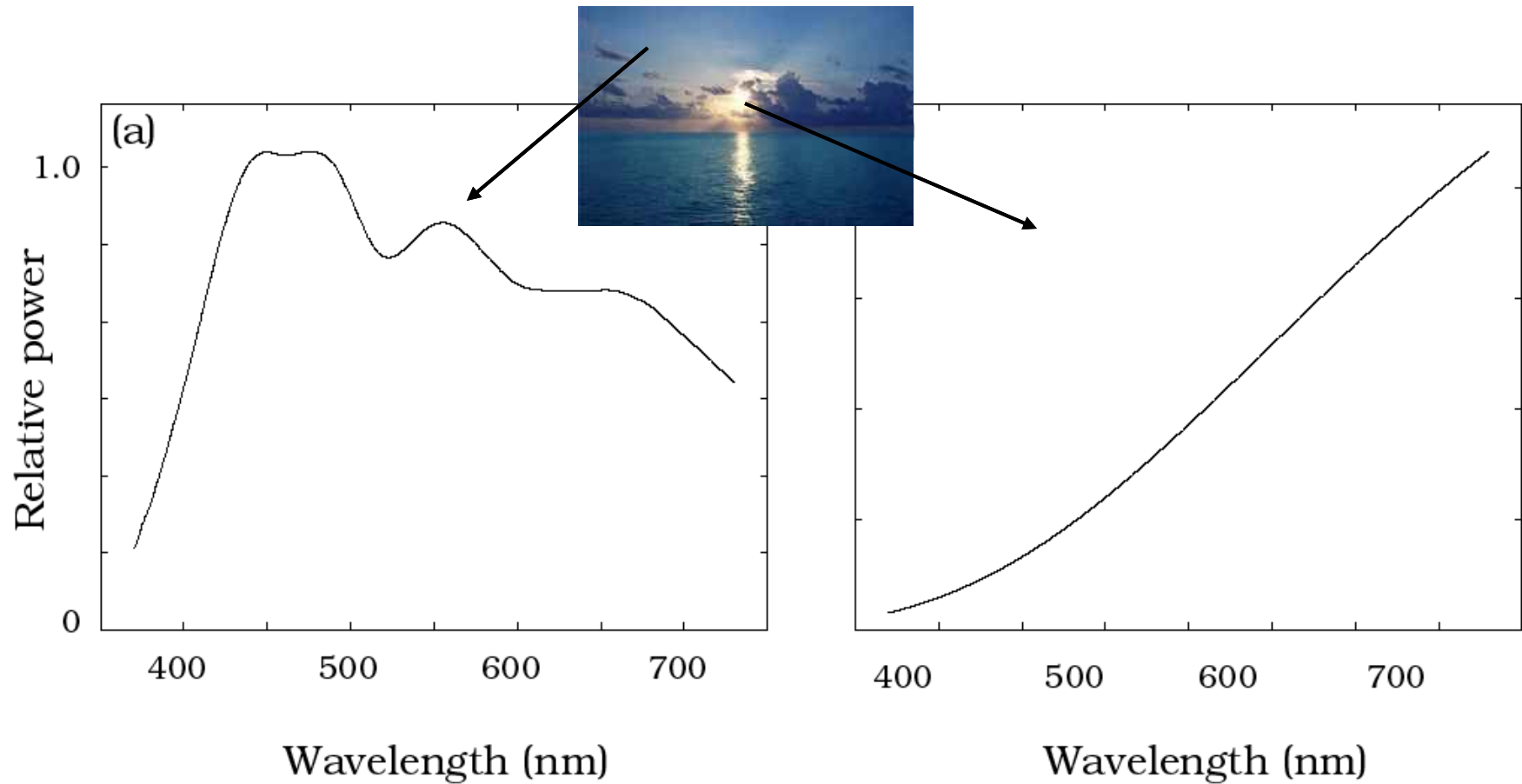
The fundamental components of light



Monochromators measure the energy at different wavelengths



Typical daylight SPDs vary

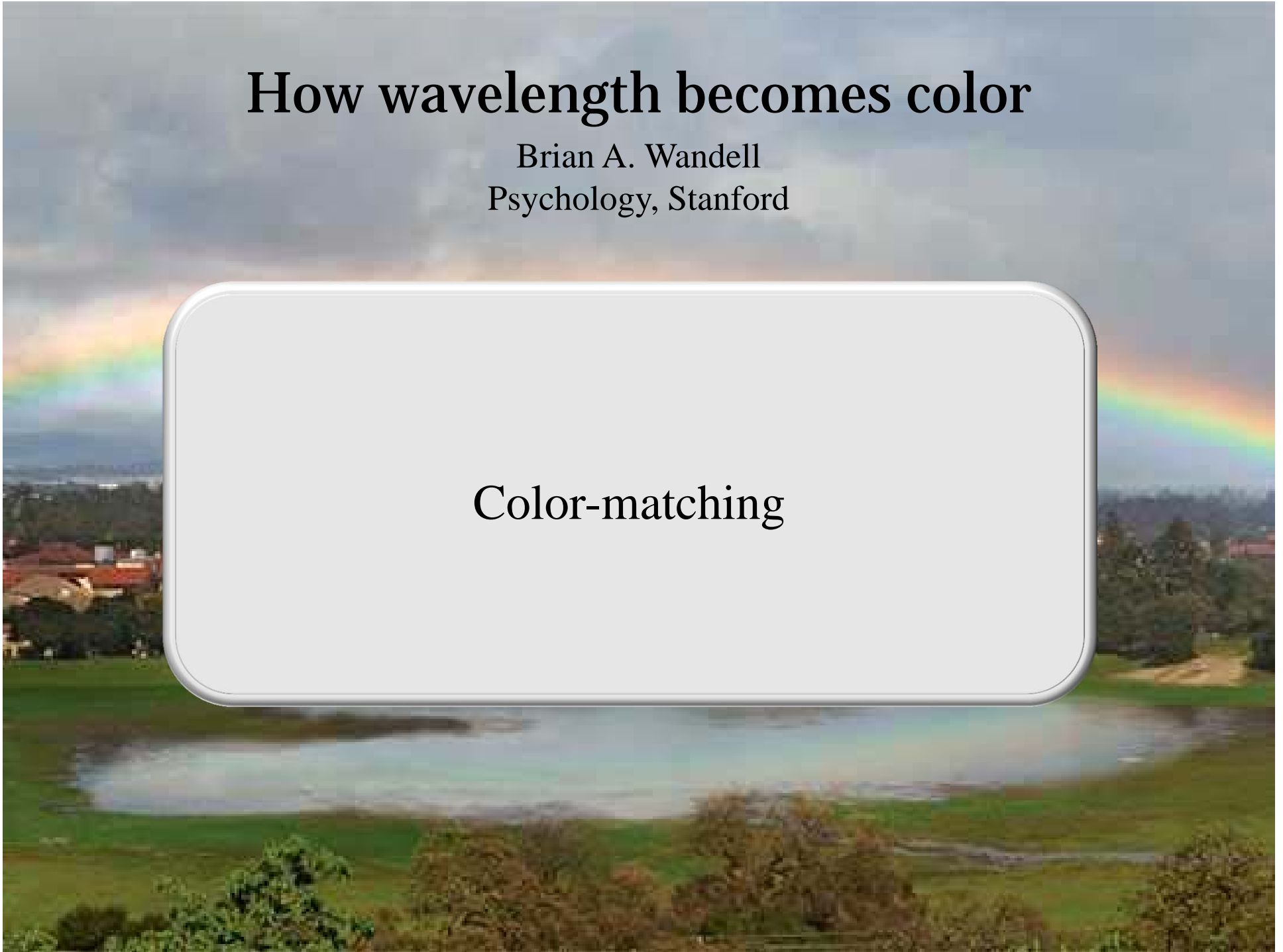


SPD: spectral power distribution

How wavelength becomes color

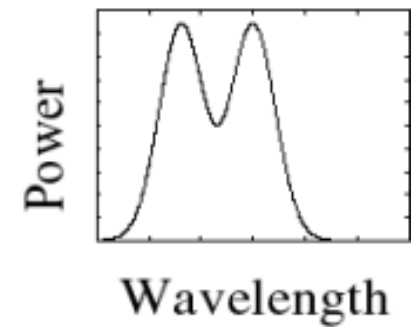
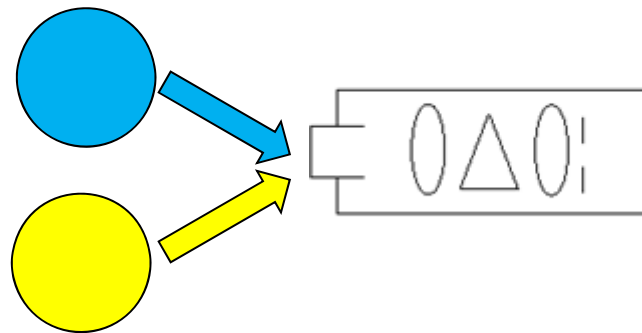
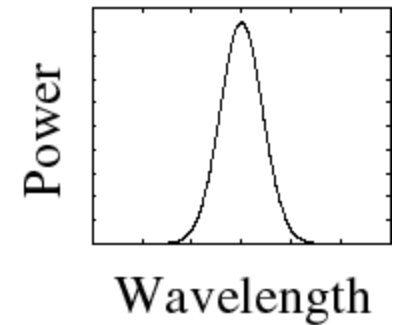
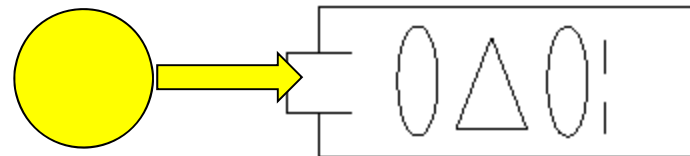
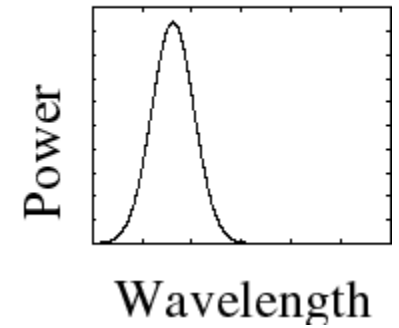
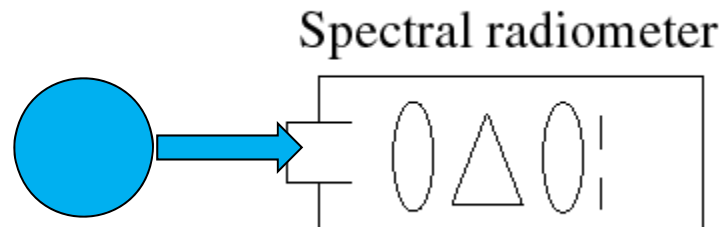
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Color-matching

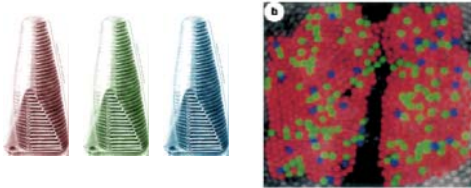


Superposition of light

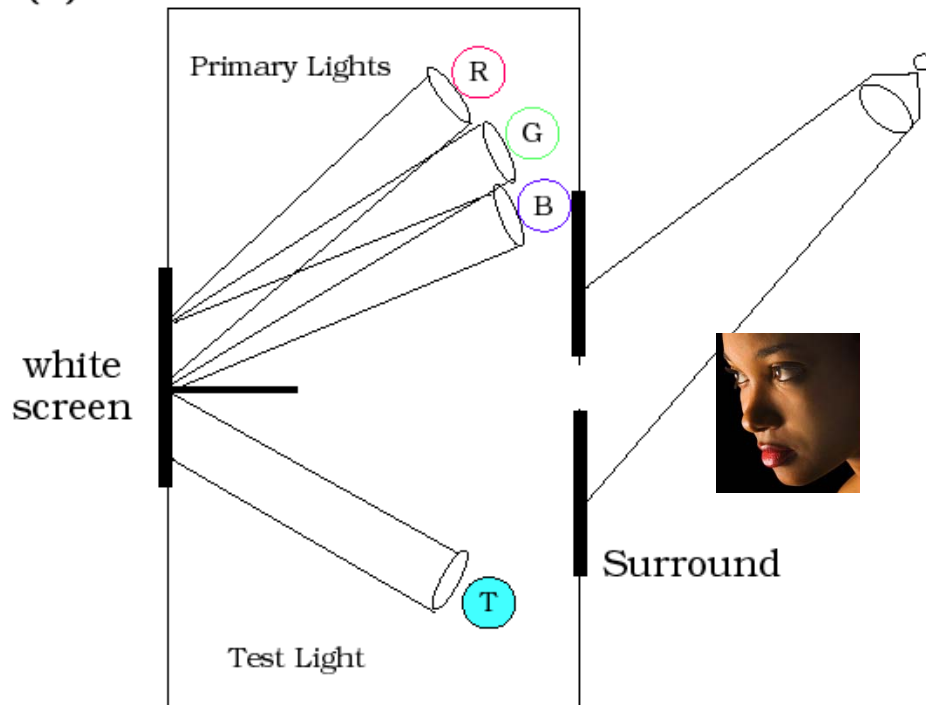
- Experiments with mixtures are fundamental throughout science
- Mixtures of light sum



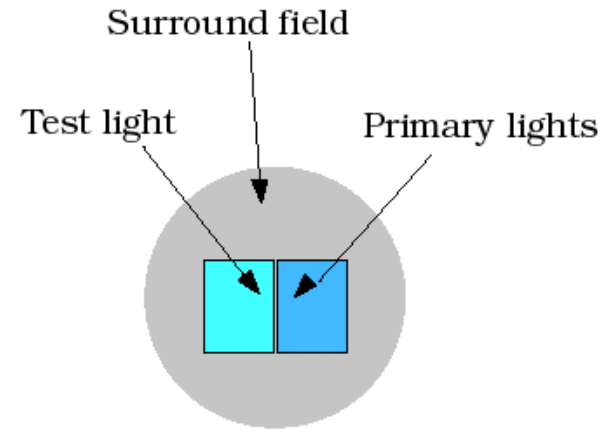
Cone Color Matching Experiment



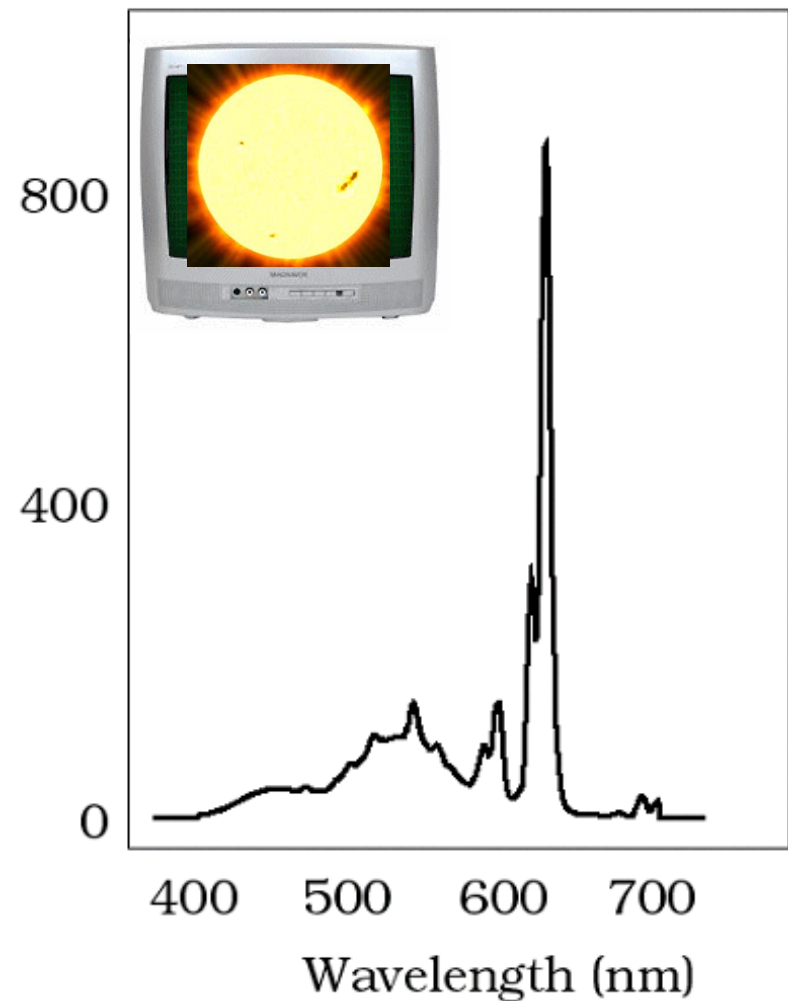
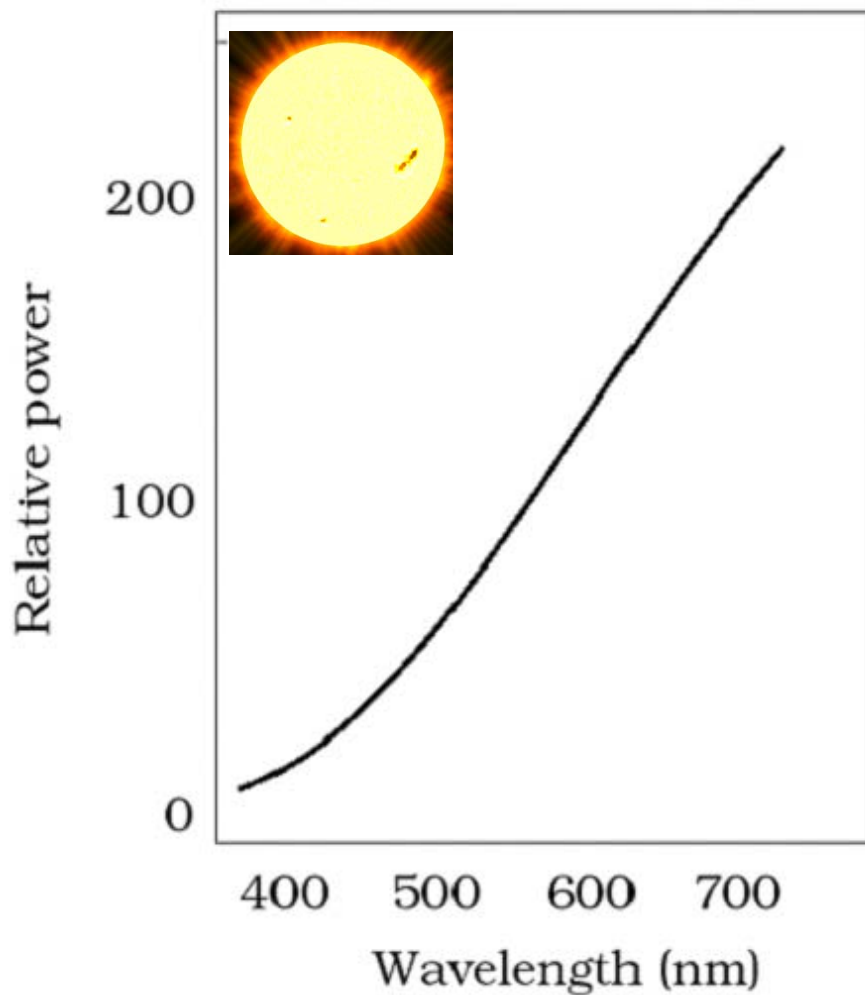
(a)



(b)

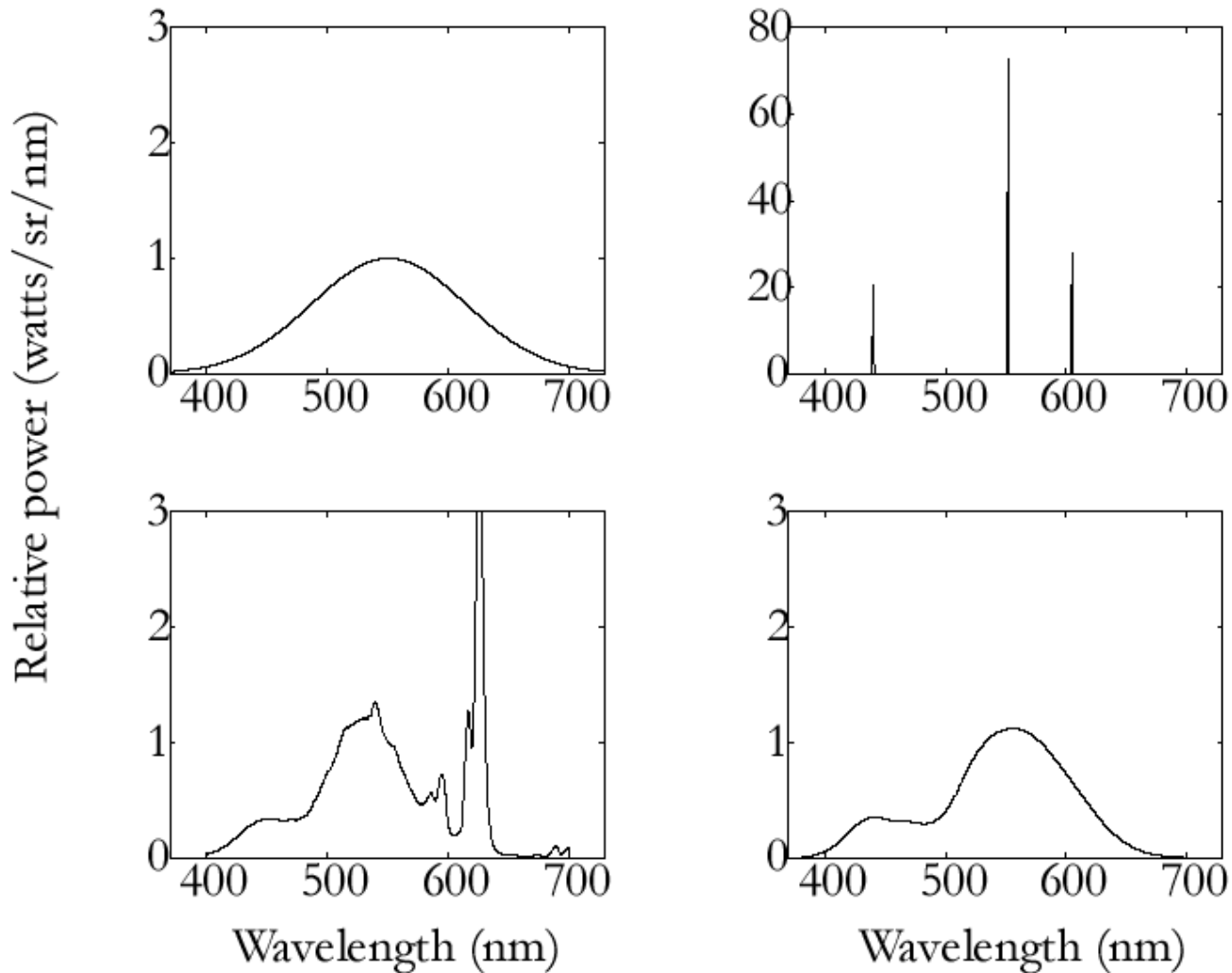


Color matching (**metamerism**) is an important illusion that can be predicted quantitatively



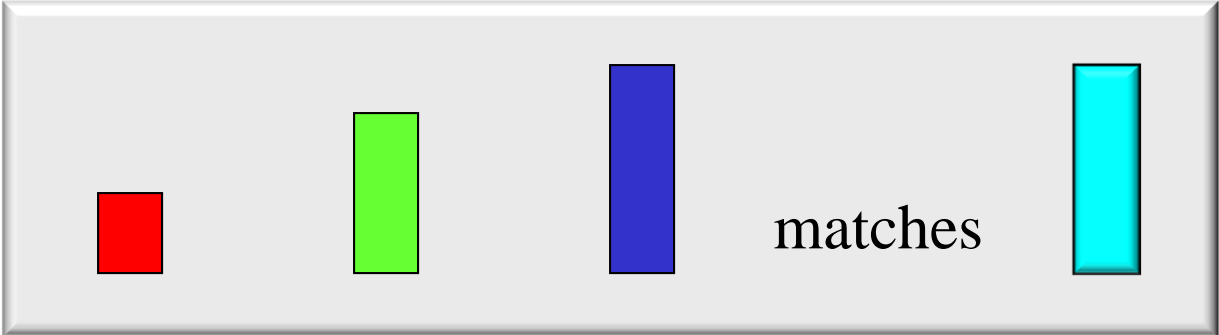
Metamerism examples

These lights appear the same color

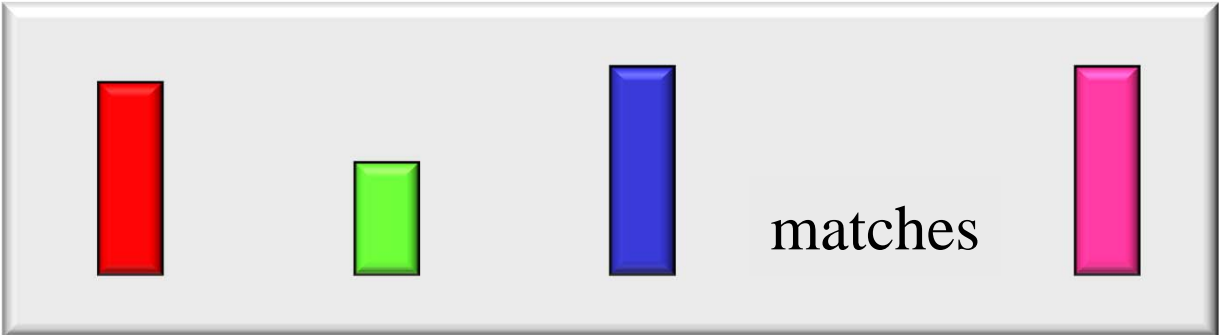


The color matching experiment is linear

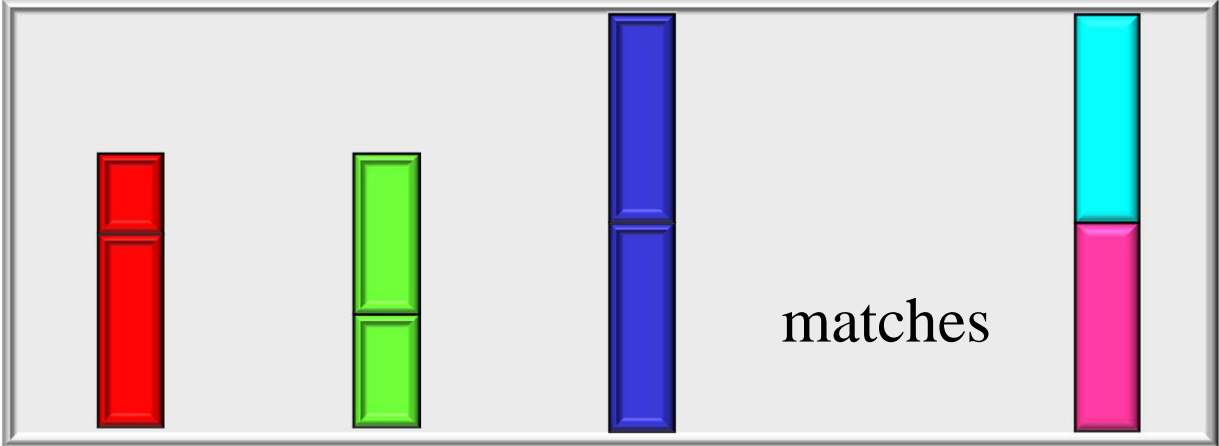
If



and



then



Color Matching Experiment Equation

Response

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

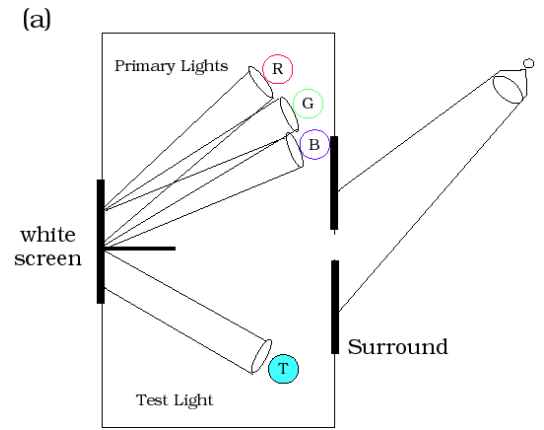
=

CIE RGB functions

$$\begin{pmatrix} \text{---} \\ \text{---} \\ \text{---} \end{pmatrix}$$

$$\begin{pmatrix} \text{---} \\ \text{---} \\ \text{---} \end{pmatrix}$$

Test light
SPD



Color Matching Experiment Equation

Response

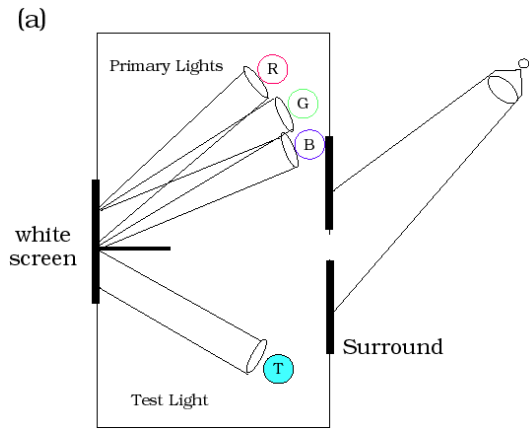
$$\begin{pmatrix} r \\ g \\ b \end{pmatrix}$$

=

CIE RGB functions
0 0 0 0 0 0 1 0 0 0 0 0 0

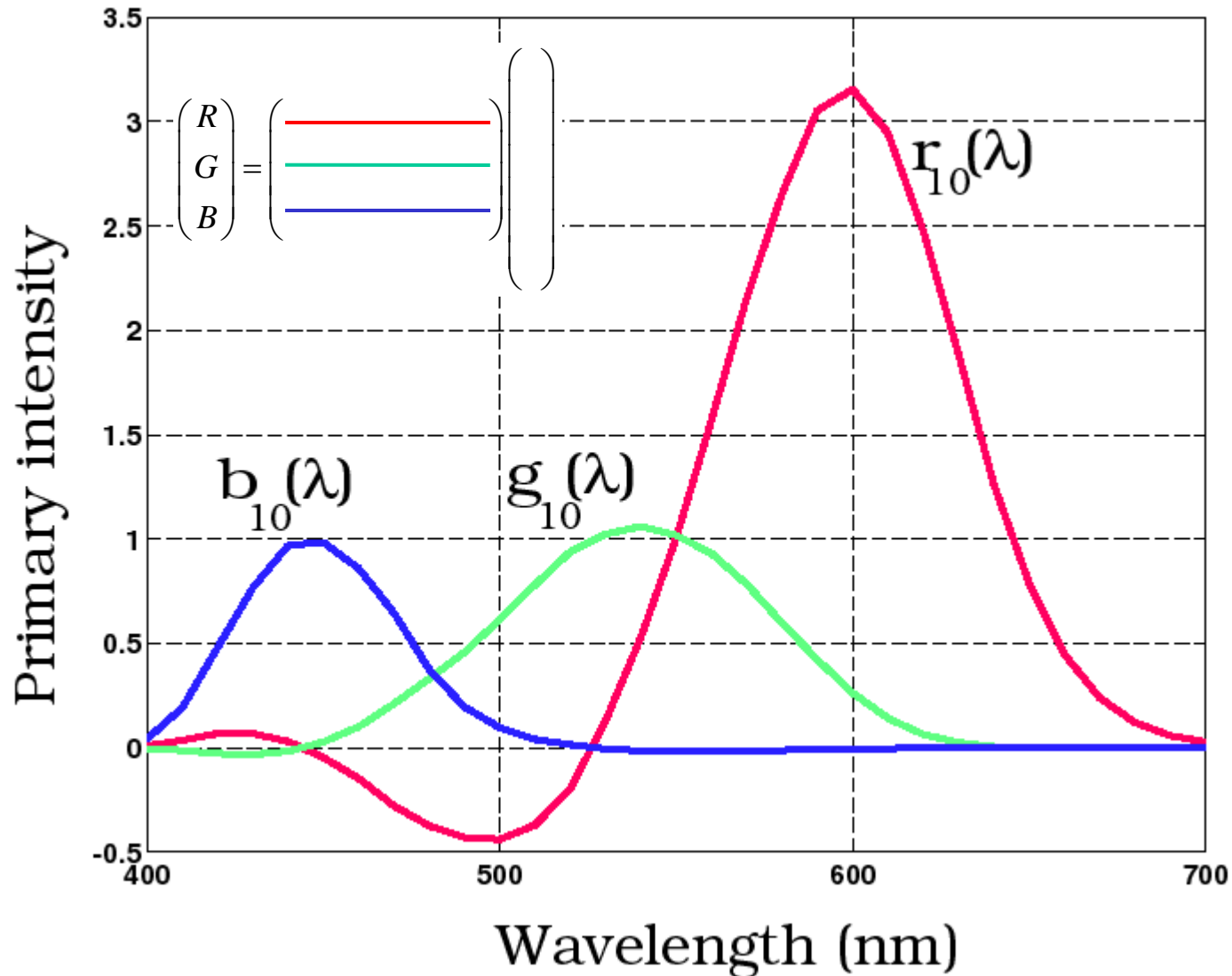
$$\begin{pmatrix} \text{red bar} & r & \text{red bar} \\ \text{green bar} & g & \text{green bar} \\ \text{blue bar} & b & \text{blue bar} \end{pmatrix}$$

$$\begin{pmatrix} 0 \\ 0 \\ 0 \\ \dots \\ 1 \\ \dots \\ 0 \\ 0 \\ 0 \end{pmatrix}$$



Test light
SPD

Behavioral color matching functions (CMFs; 10 deg)



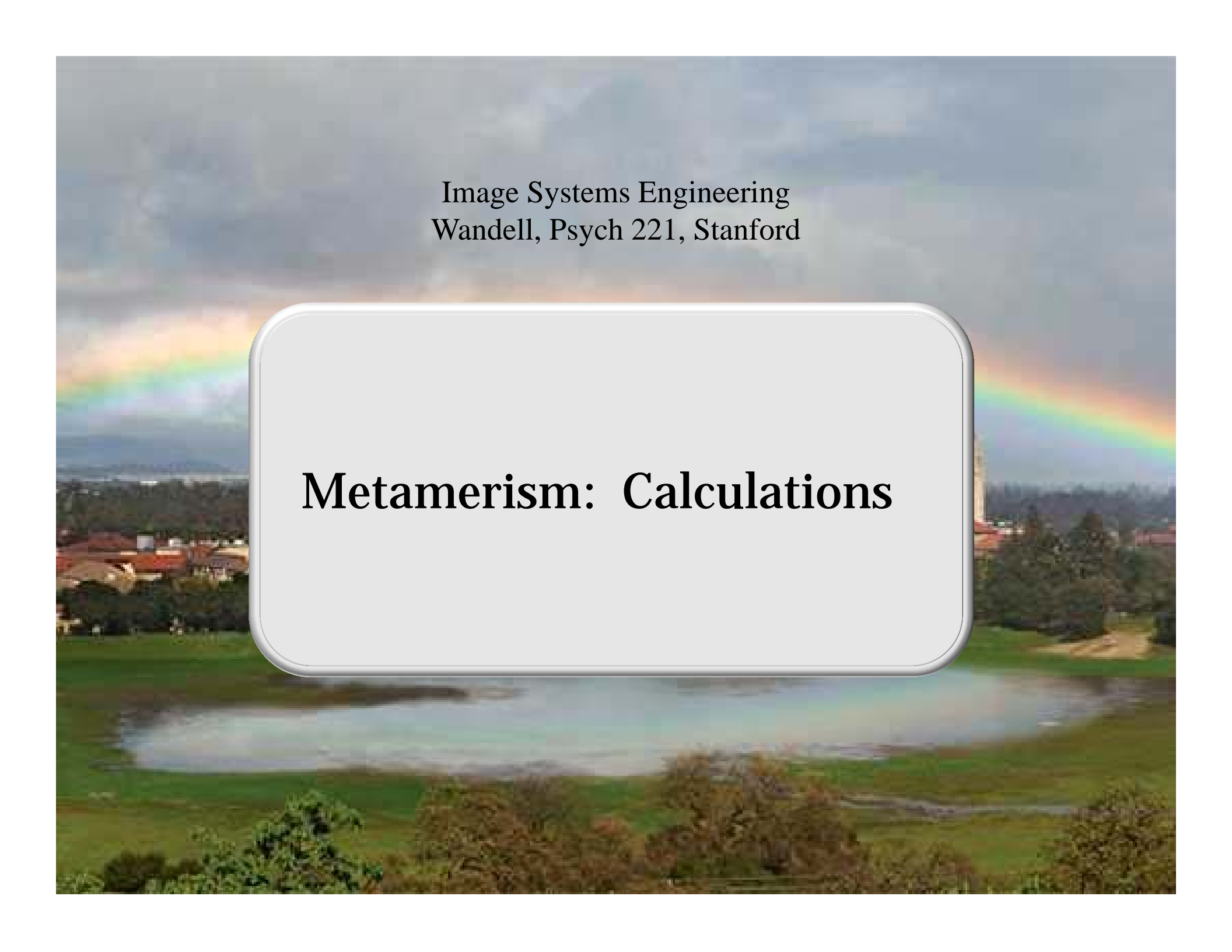
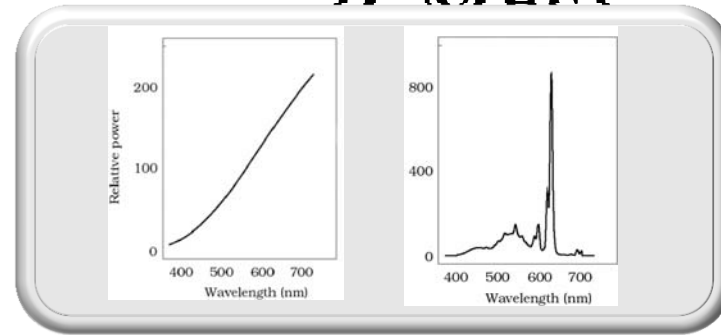
A scenic landscape photograph featuring a rainbow arching over a body of water in the foreground. In the background, a town with red-roofed buildings is visible under a cloudy sky. The image is used as a background for a presentation slide.

Image Systems Engineering
Wandell, Psych 221, Stanford

Metamerism: Calculations

Using the color matching functions

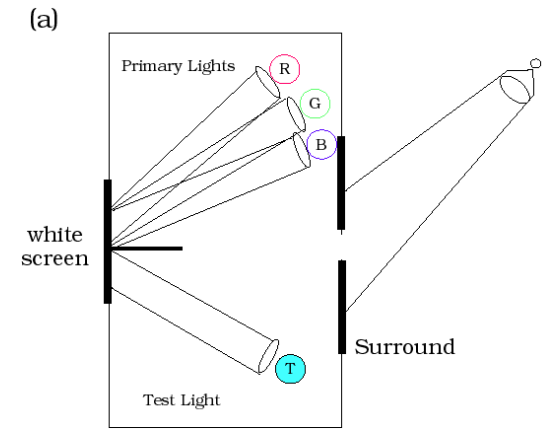
(CIE)



Response

CIE RGB functions

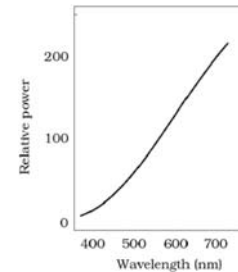
$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} \text{Red bar} \\ \text{Green bar} \\ \text{Blue bar} \end{pmatrix} \begin{pmatrix} \text{Test light SPD} \end{pmatrix}$$



Test light
SPD

When two different lights look the same

Metamers: Lights that appear identical to the normal eye, but which are physically different

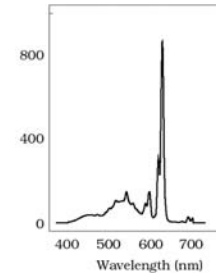


$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} \text{CIE RGB functions} \end{pmatrix} \begin{pmatrix} S \end{pmatrix}$$

*S and T match perceptually; they are **metamers***

When two different lights look the same

Metamers: Lights that appear identical to the normal eye, but which are physically different



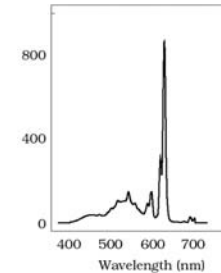
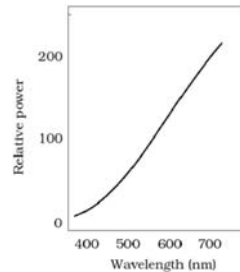
$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} \text{CIE RGB functions} \end{pmatrix} \begin{pmatrix} T \end{pmatrix}$$

*S and T match perceptually; they are **metamers***

Predicting when different lights look the same

Metamerism

Metamers: Lights that appear identical to the normal eye, but which are physically different

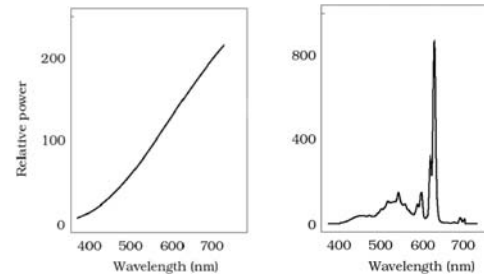


$$\left(\begin{array}{c} \text{CIE RGB functions} \end{array} \right) \left(\begin{array}{c} S \end{array} \right) = \left(\begin{array}{c} \text{CIE RGB functions} \end{array} \right) \left(\begin{array}{c} T \end{array} \right)$$

*S and T match perceptually; they are **metamers***

The SPD difference of the lights is in the **null space** of the CIE functions

Metamers: Lights that appear identical to the normal eye, but which are physically different

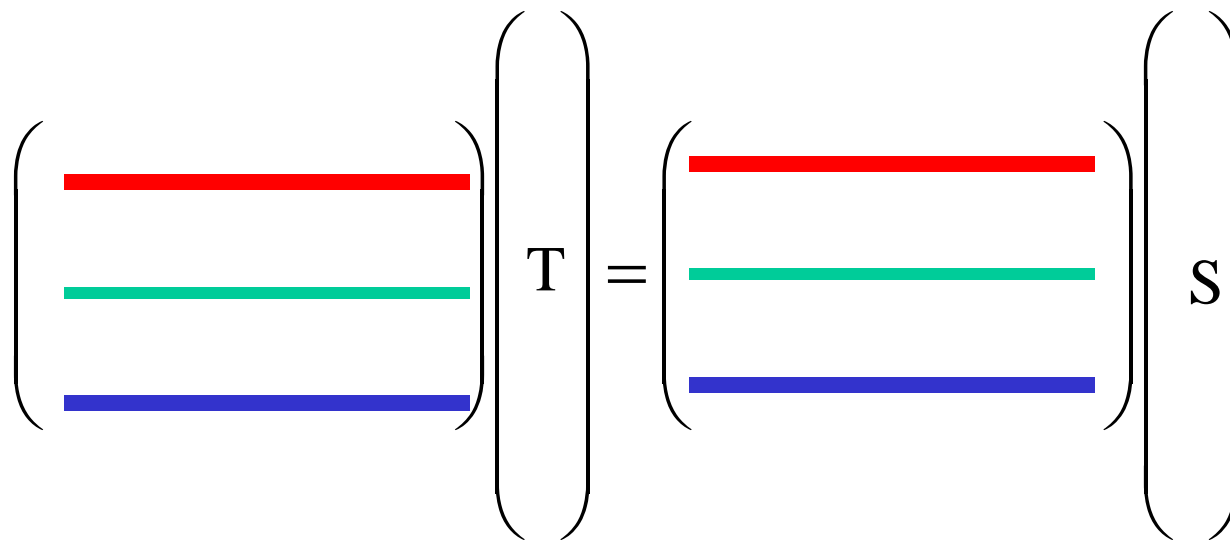


$$0 = \left(\text{CIE RGB functions} \right) \left\{ \begin{array}{c} S \\ - \\ T \end{array} \right\}$$

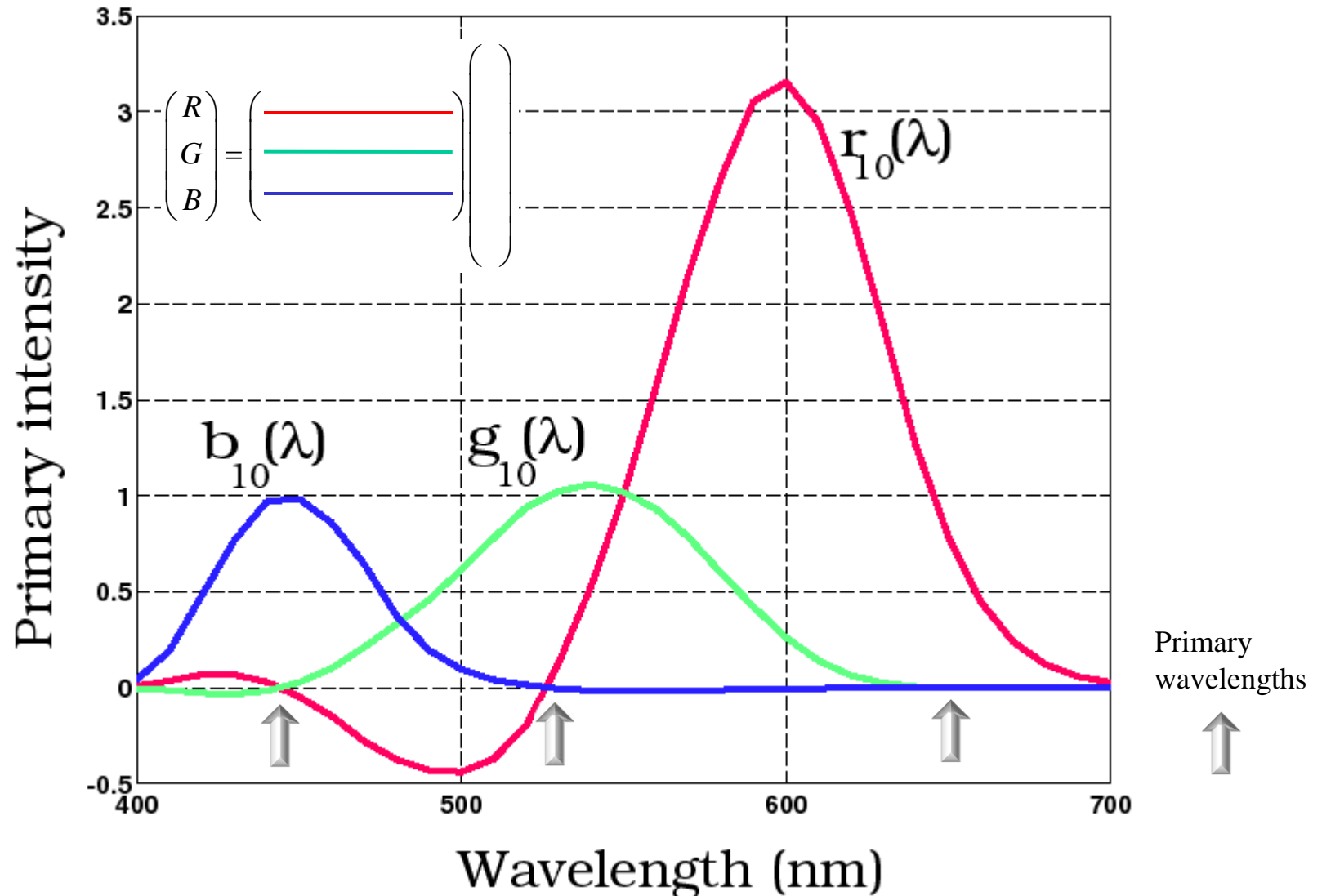
*S and T match perceptually; they are **metamers***

CMFs: A Uniqueness Theorem

Suppose two lights are predicted to be metamers



A perfectly good set of color-matching functions (CMFs; 10 deg)



CMFs: A Uniqueness Theorem

What if we used another set of primaries?

- Any invertible linear transformation, L , of the CMFs predicts the same metamers
- Different choices of primaries produce different CMFs
- Related by a linear transformation (see Foundations of Vision for proof)

Invertible 3x3

$$\begin{pmatrix} L \end{pmatrix} \begin{pmatrix} \text{red} \\ \text{green} \\ \text{blue} \end{pmatrix} \begin{pmatrix} T \end{pmatrix} = \begin{pmatrix} L \end{pmatrix} \begin{pmatrix} \text{red} \\ \text{green} \\ \text{blue} \end{pmatrix} \begin{pmatrix} S \end{pmatrix}$$

The CIE (1931) XYZ standard CMFs

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

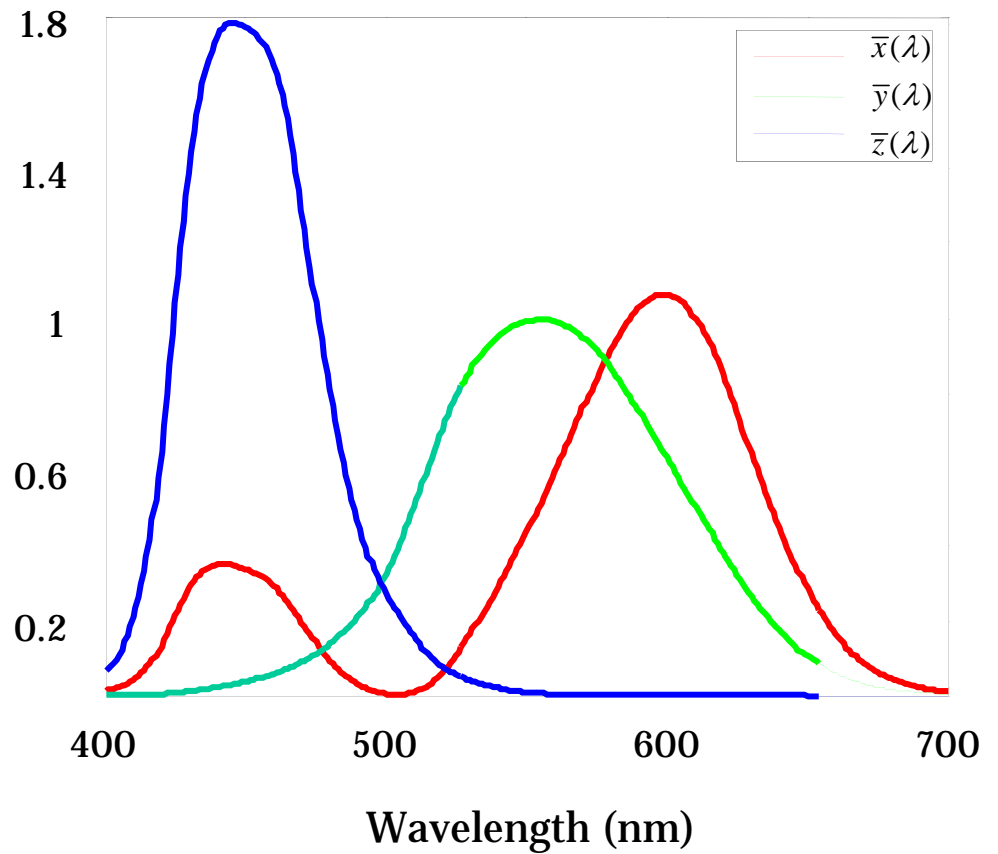
Radiance

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

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

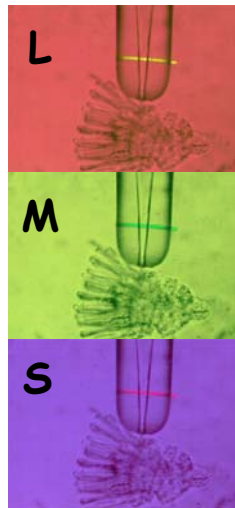
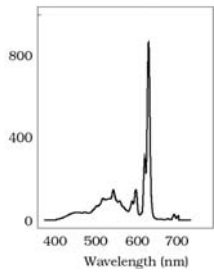
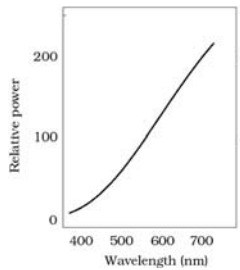
$$Z = \sum_{\lambda} \bar{z}(\lambda) t(\lambda) d\lambda$$

CIE (1931) 10 deg XYZ functions



The cones and the XYZ standard

The cones spectral sensitivities predict color matches.



Response

$$\begin{pmatrix} L \\ M \\ S \end{pmatrix}$$

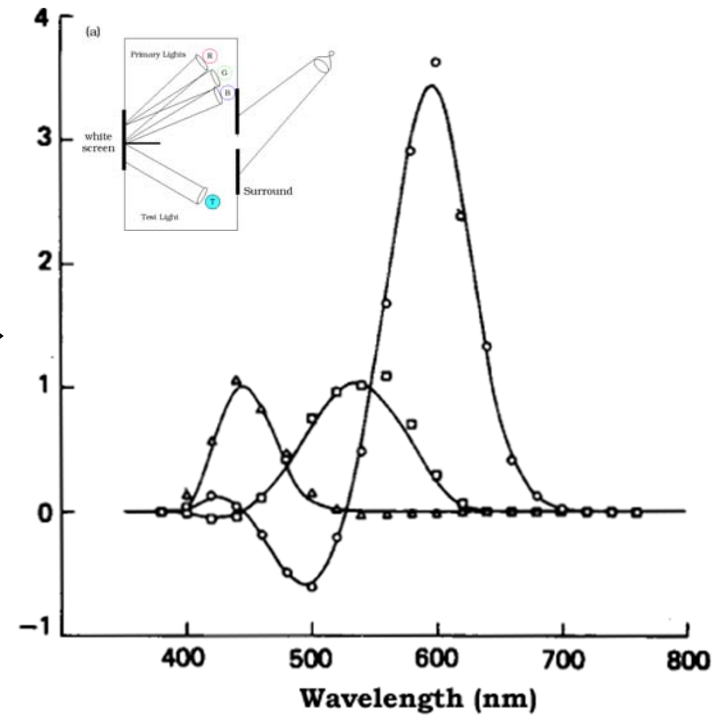
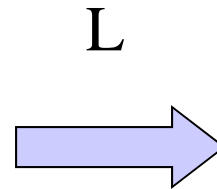
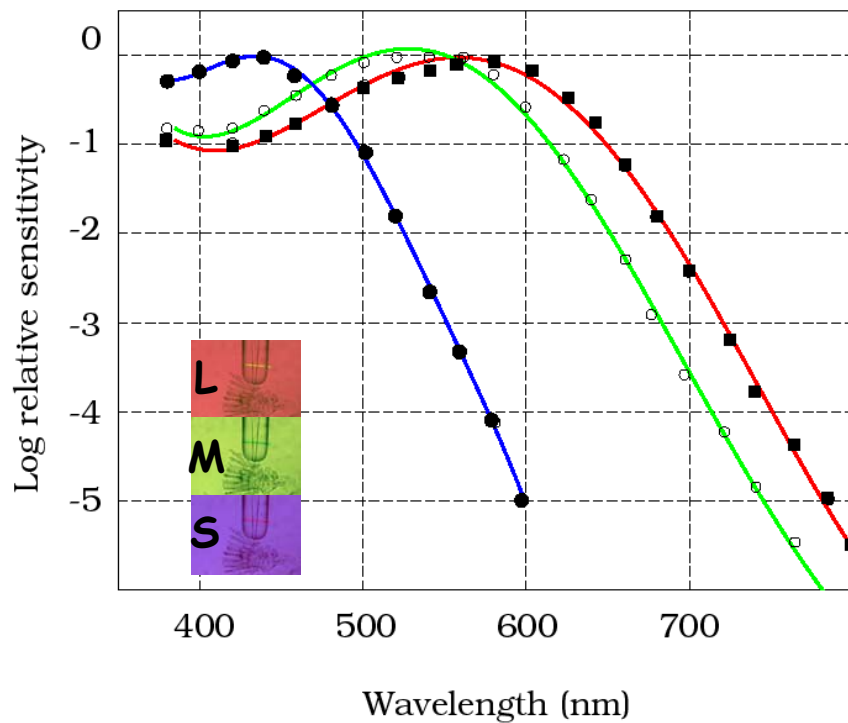
Cone responsivity

$$= \begin{pmatrix} \text{Red bar} \\ \text{Green bar} \\ \text{Blue bar} \end{pmatrix}$$

Input

The cones and the XYZ standard

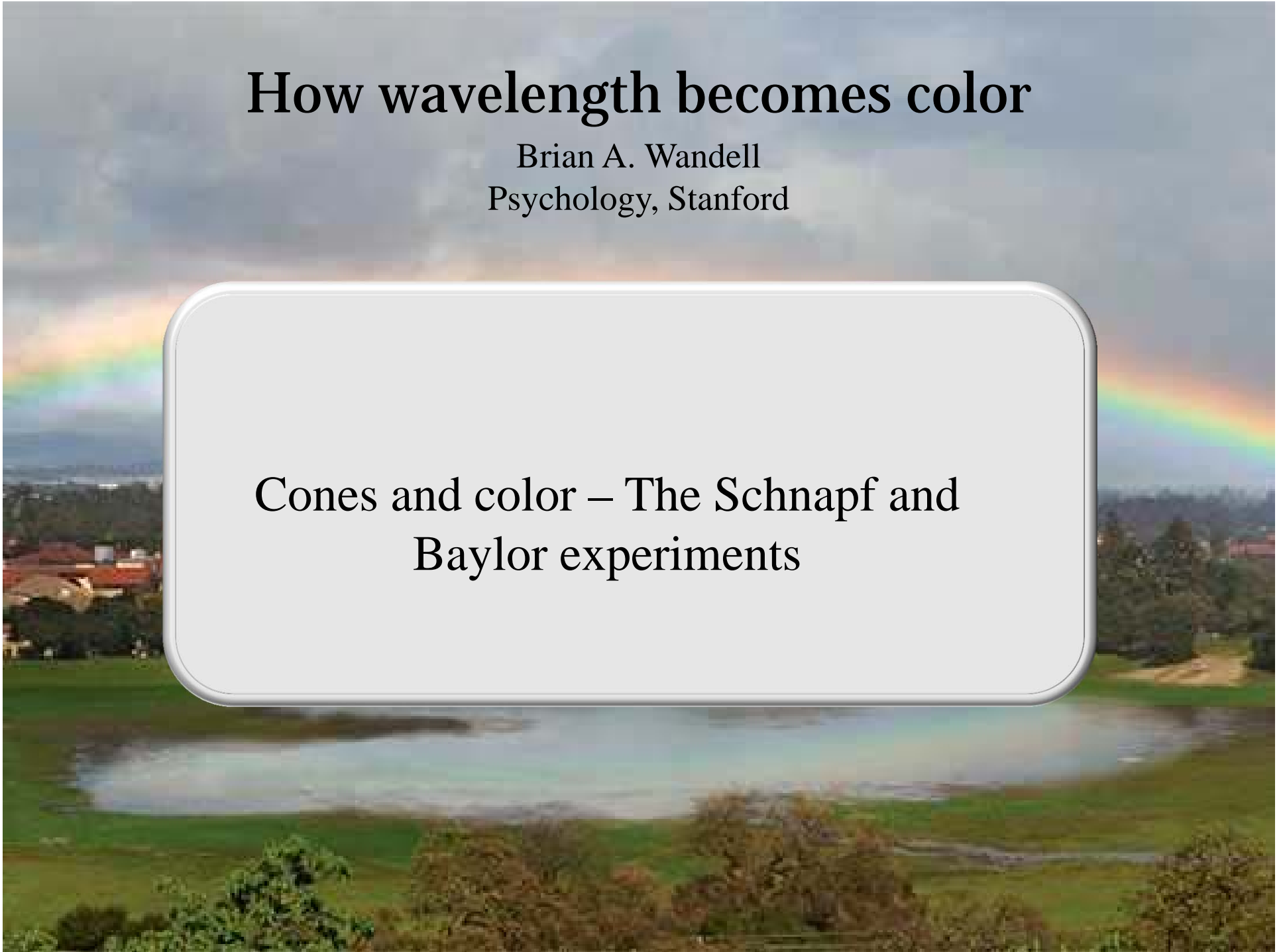
The cone spectral sensitivities must be within a linear transformation of the XYZ functions



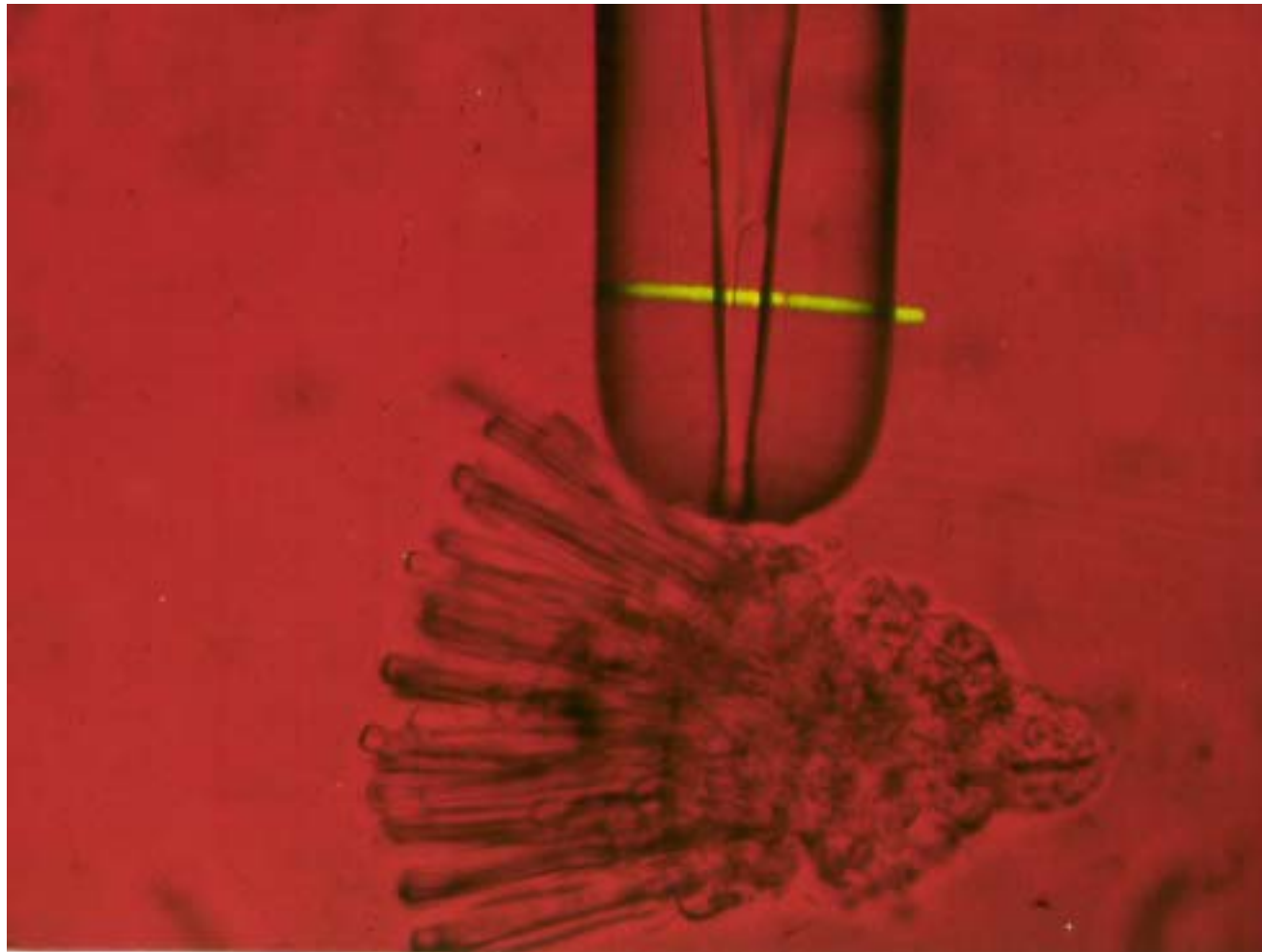
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Cones and color – The Schnapf and
Baylor experiments

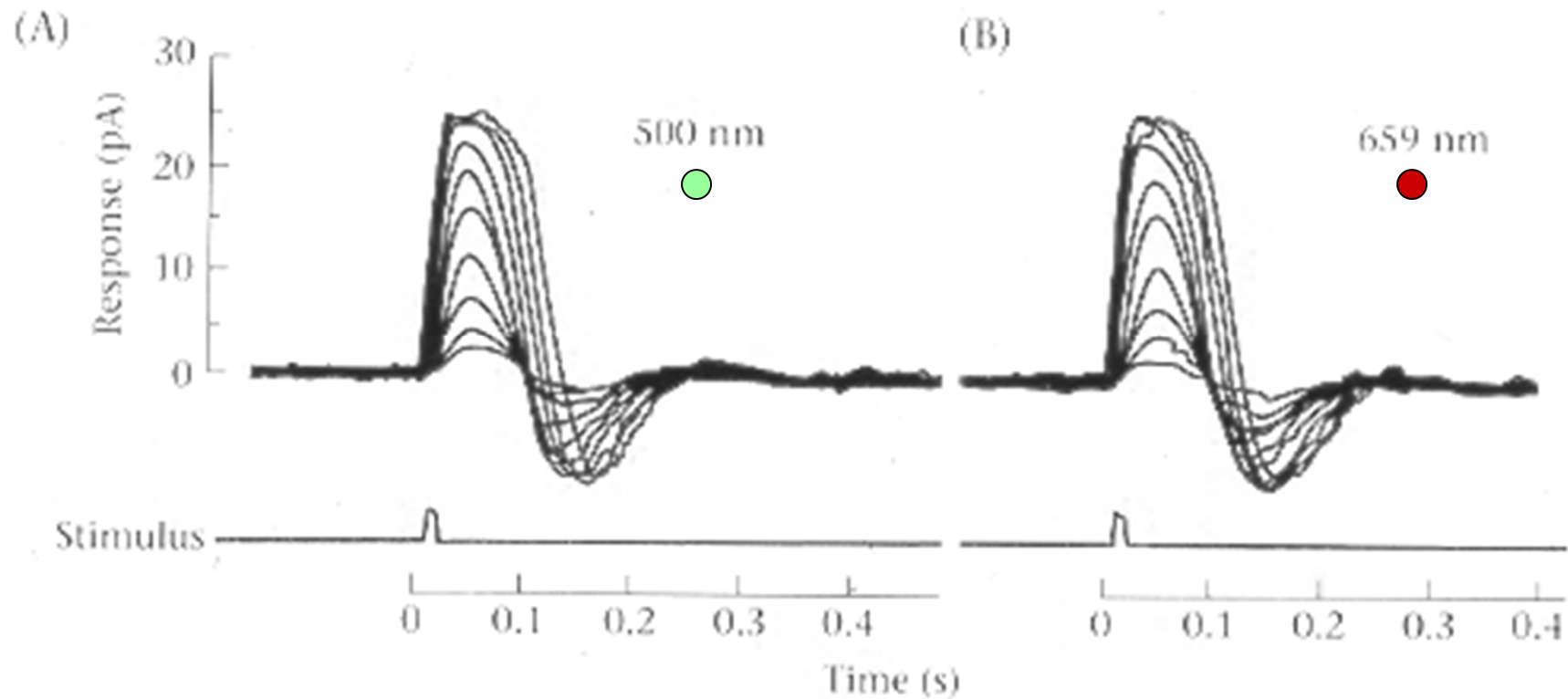


Single cone photocurrent measurements (Schnapf, Baylor et al., 1986)

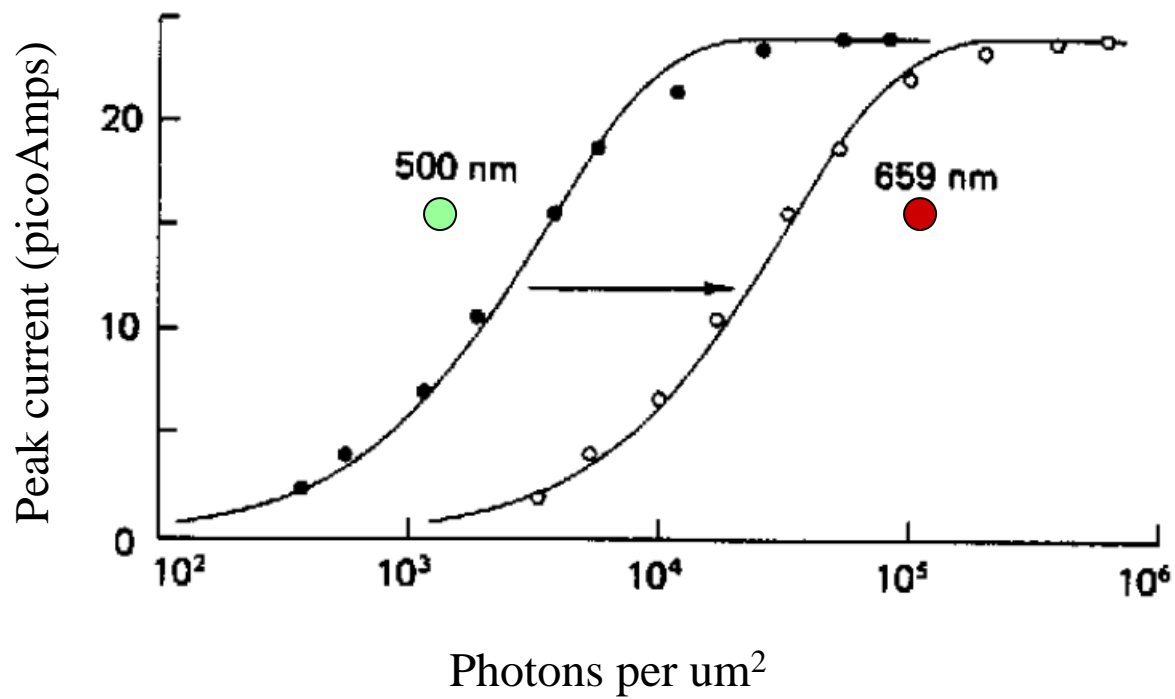


Cone Current Recordings at two wavelengths

univariance

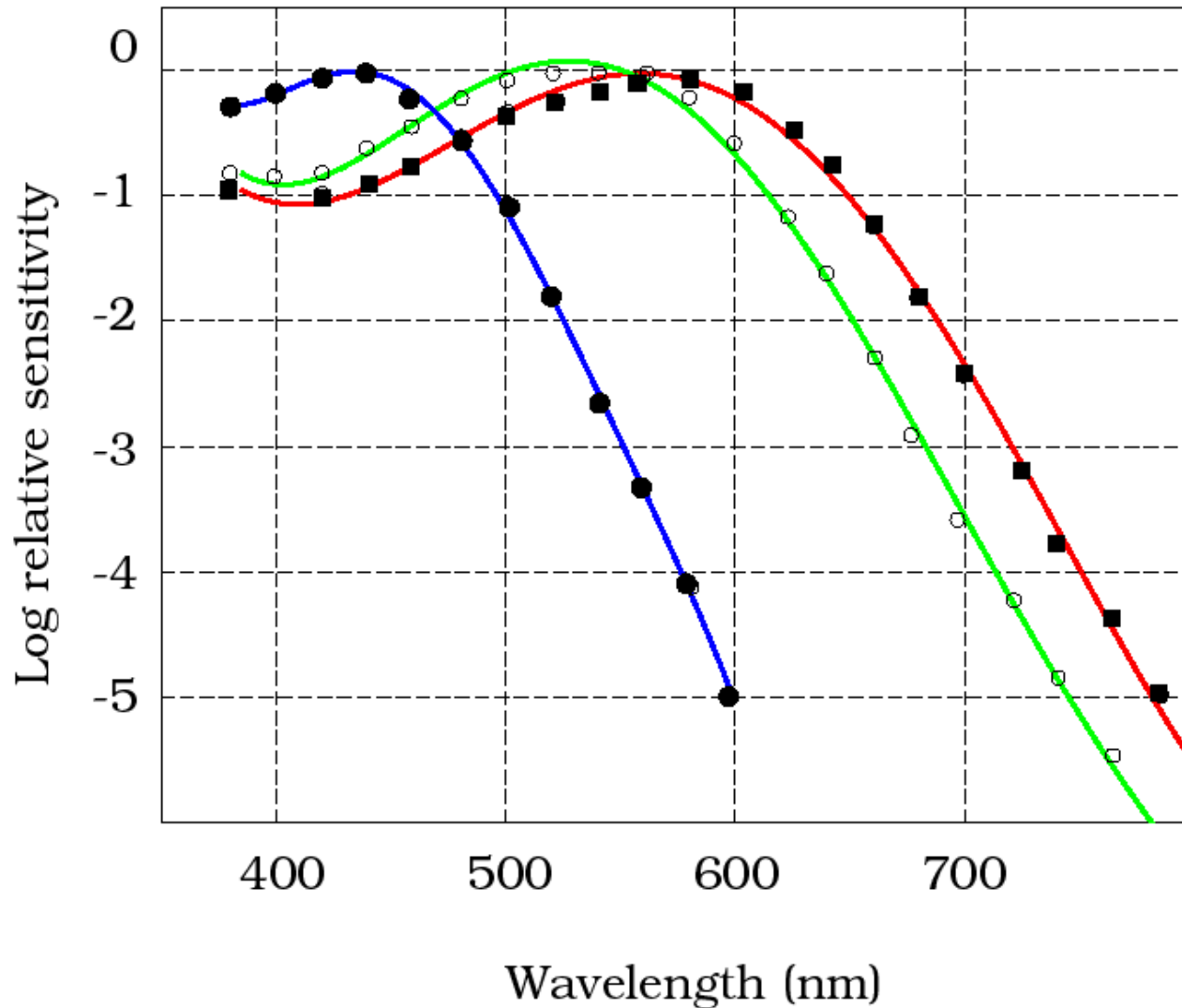


Spectral response of nonlinear systems

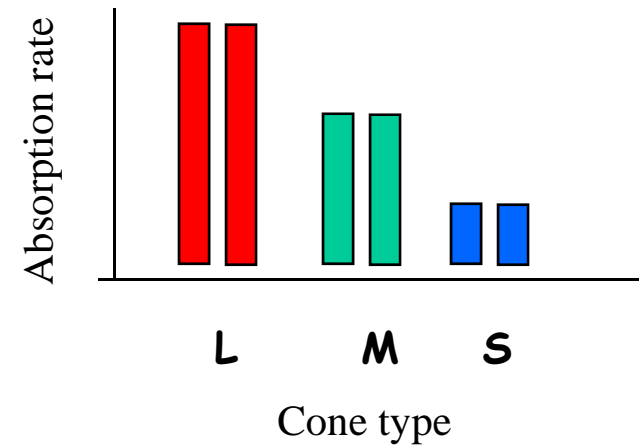
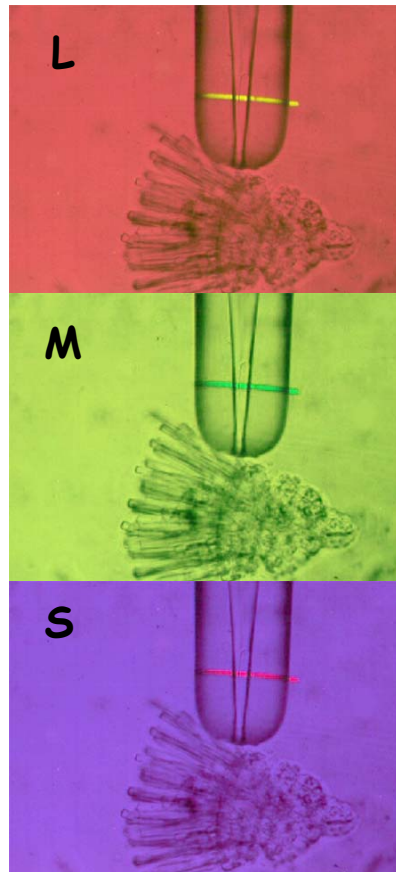
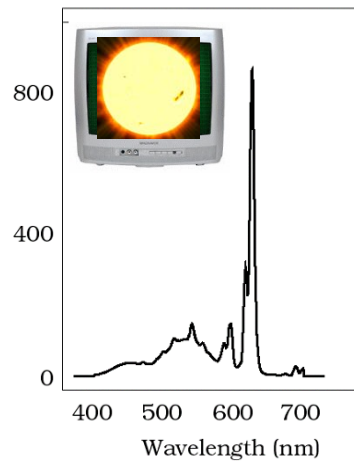
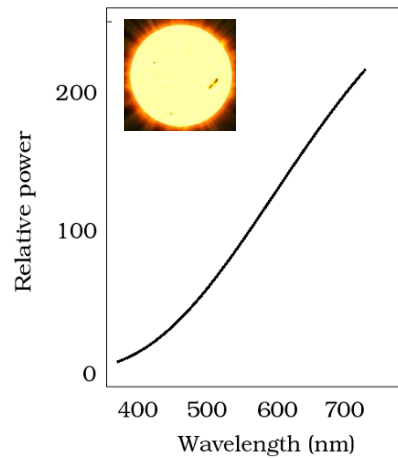


Three types of cones

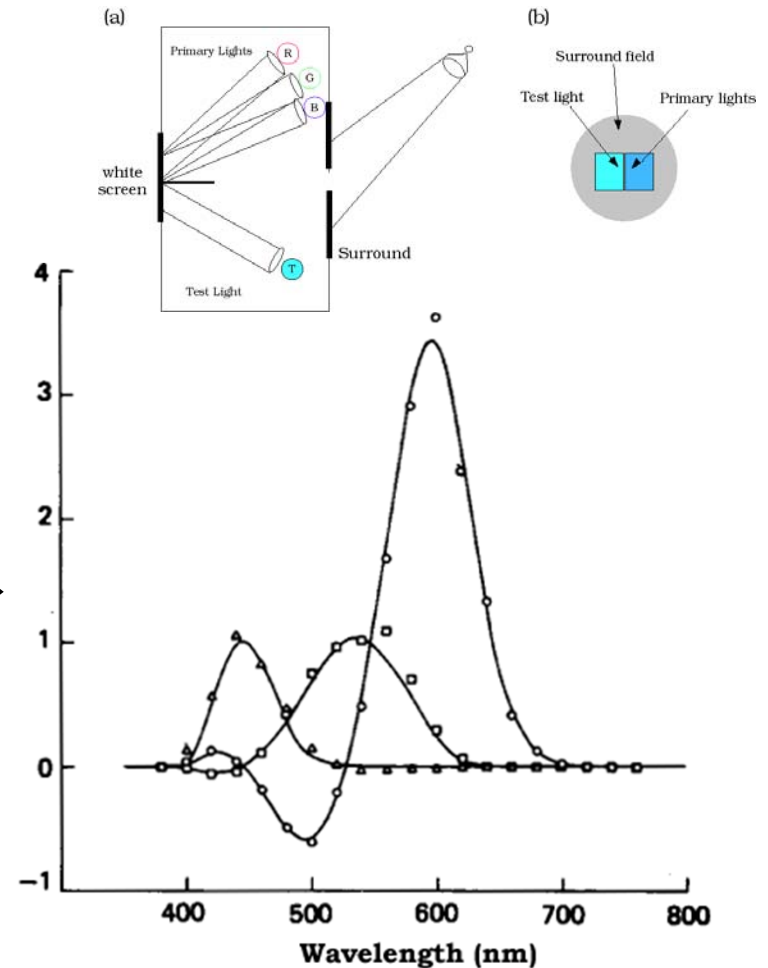
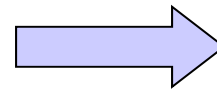
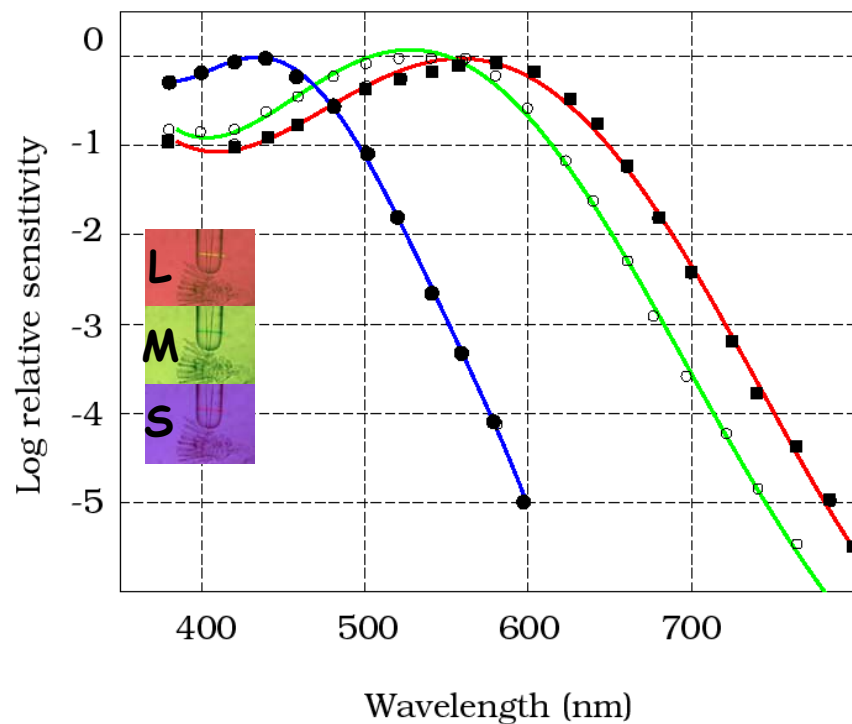
Schnapf, Nunn and Baylor



Stimuli causing equal cone absorptions match perceptually



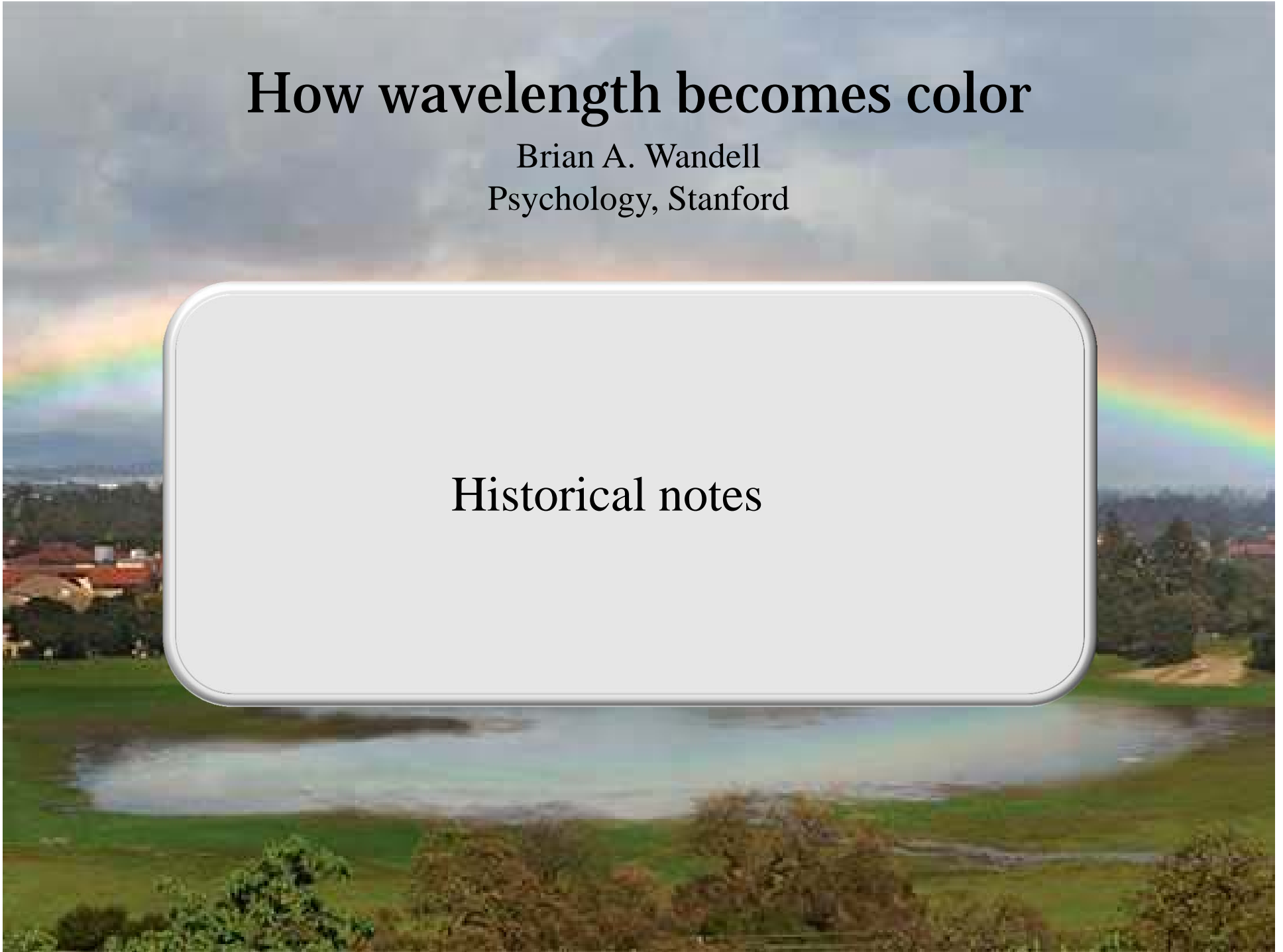
The measured cone responses predict the color-matching experiment quantitatively



How wavelength becomes color

Brian A. Wandell
Psychology, Stanford

Historical notes





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.

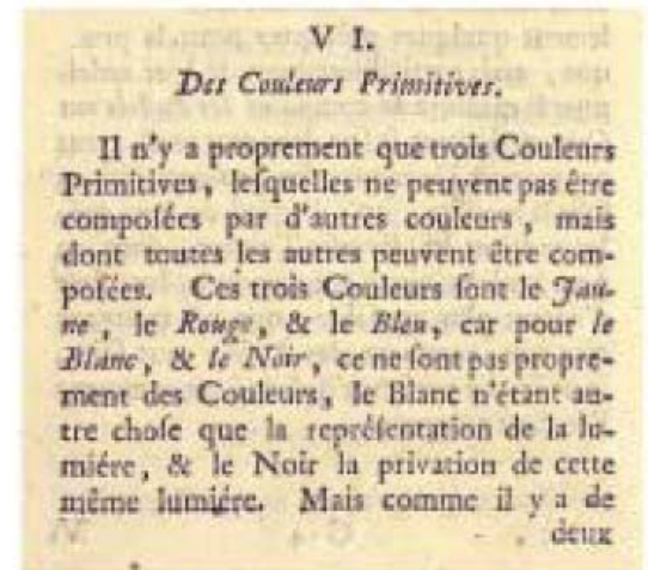
Trichromacy

put into
practice

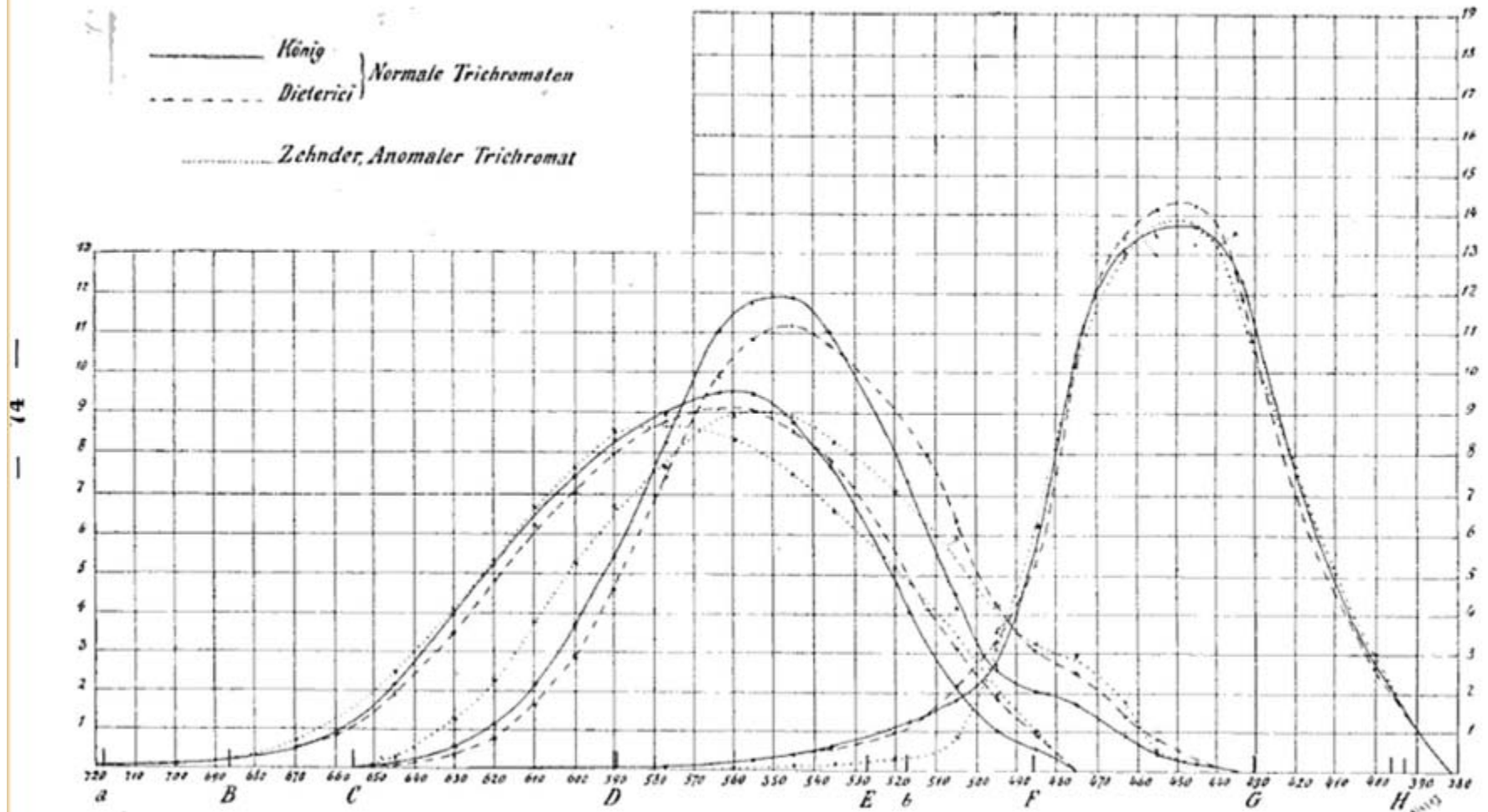
The Hague, 1708,
Anonymous



There are but three basic colors, which can not be composed by other colors. These three are yellow, red and blue, because white and black are not properly colors....



Koenig and Dieterici (1892)

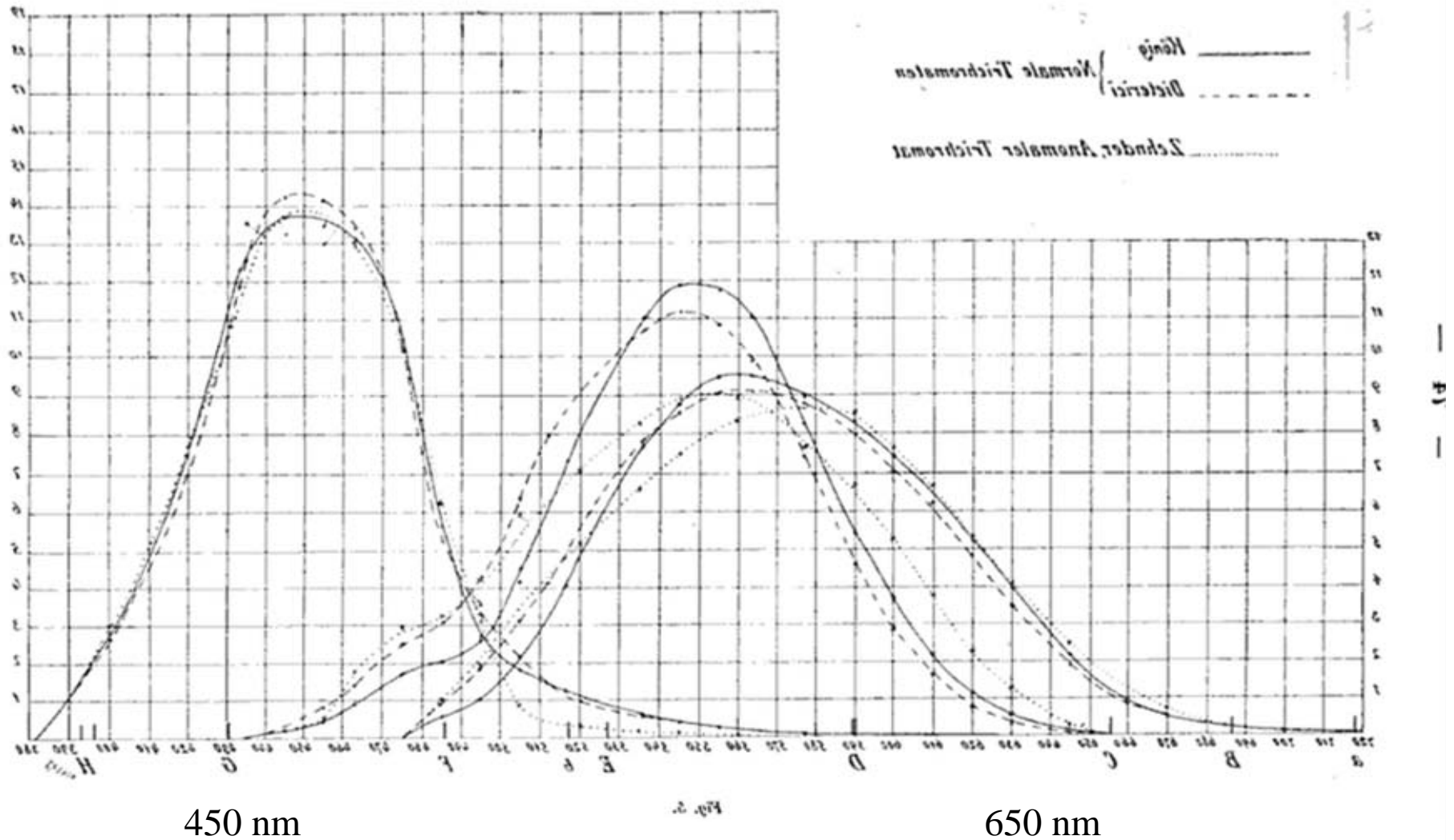


650 nm

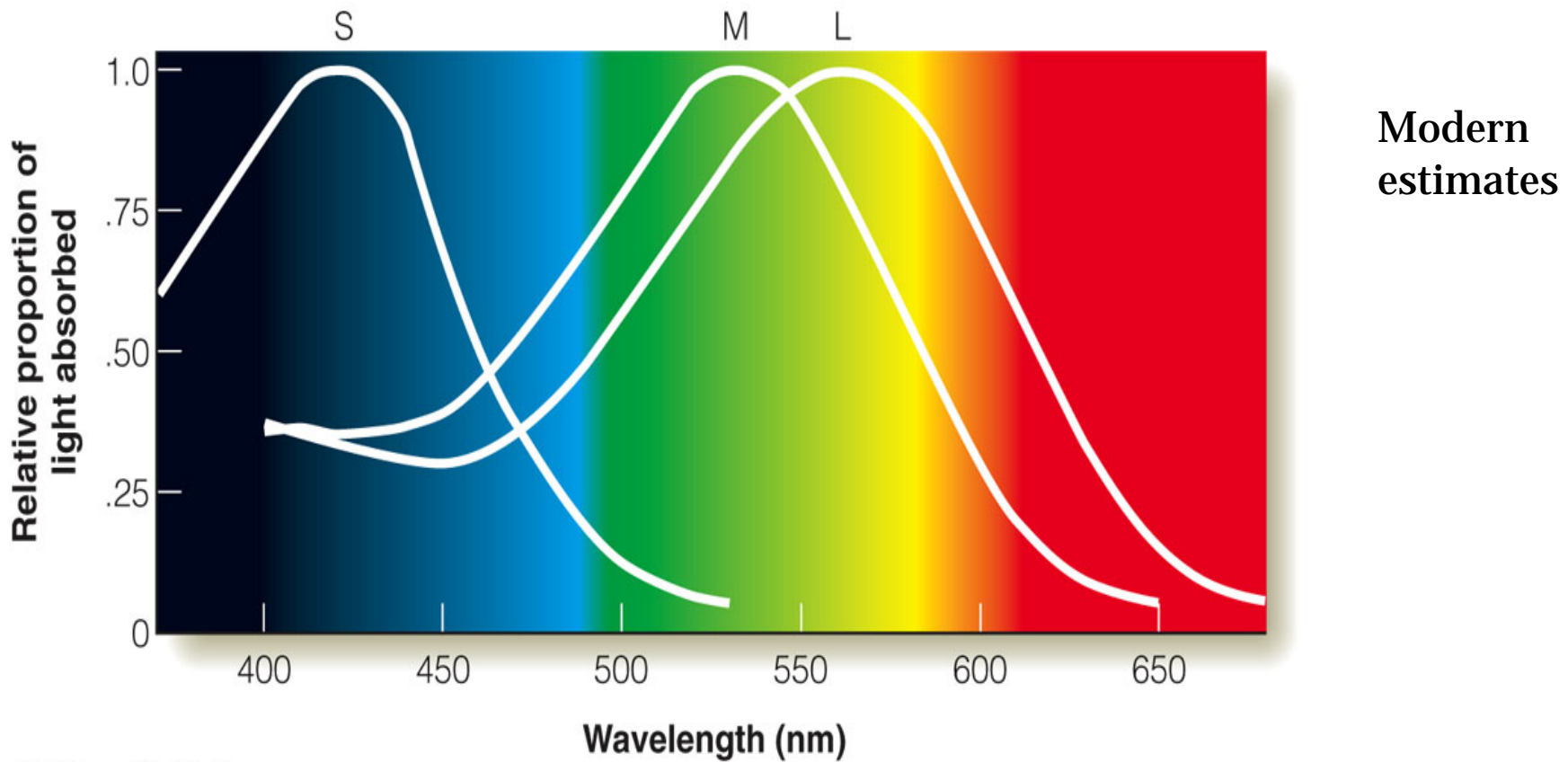
Wavenumber

450 nm

Koenig and Dieterici (1892)



The cone response functions predict color matching



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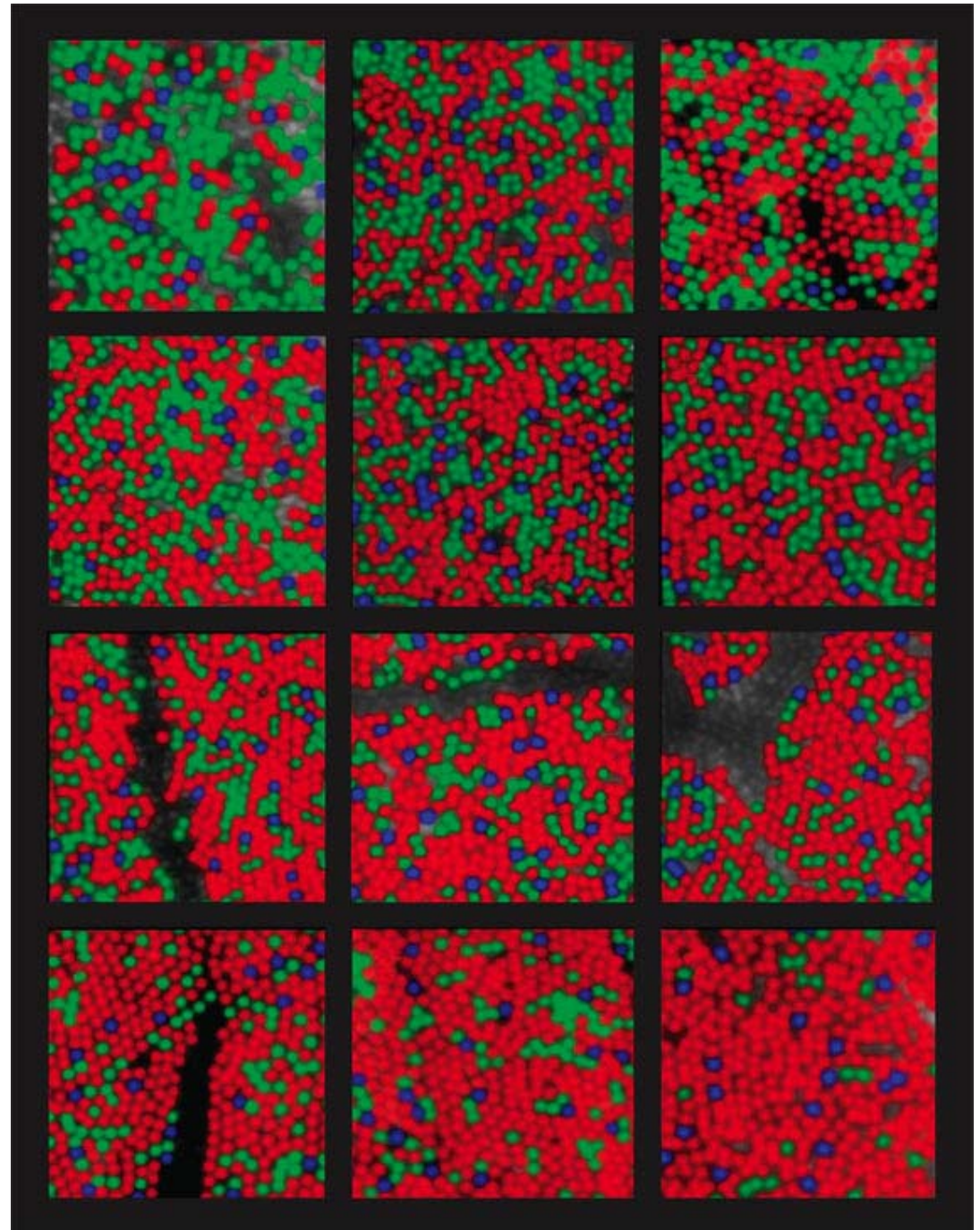
Fig. 7-8, p. 147

Ratio of L/M cones differs greatly between normals

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

*Cone inner segments 1-2
micron diameter in foveola;
much larger in the
periphery.*

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

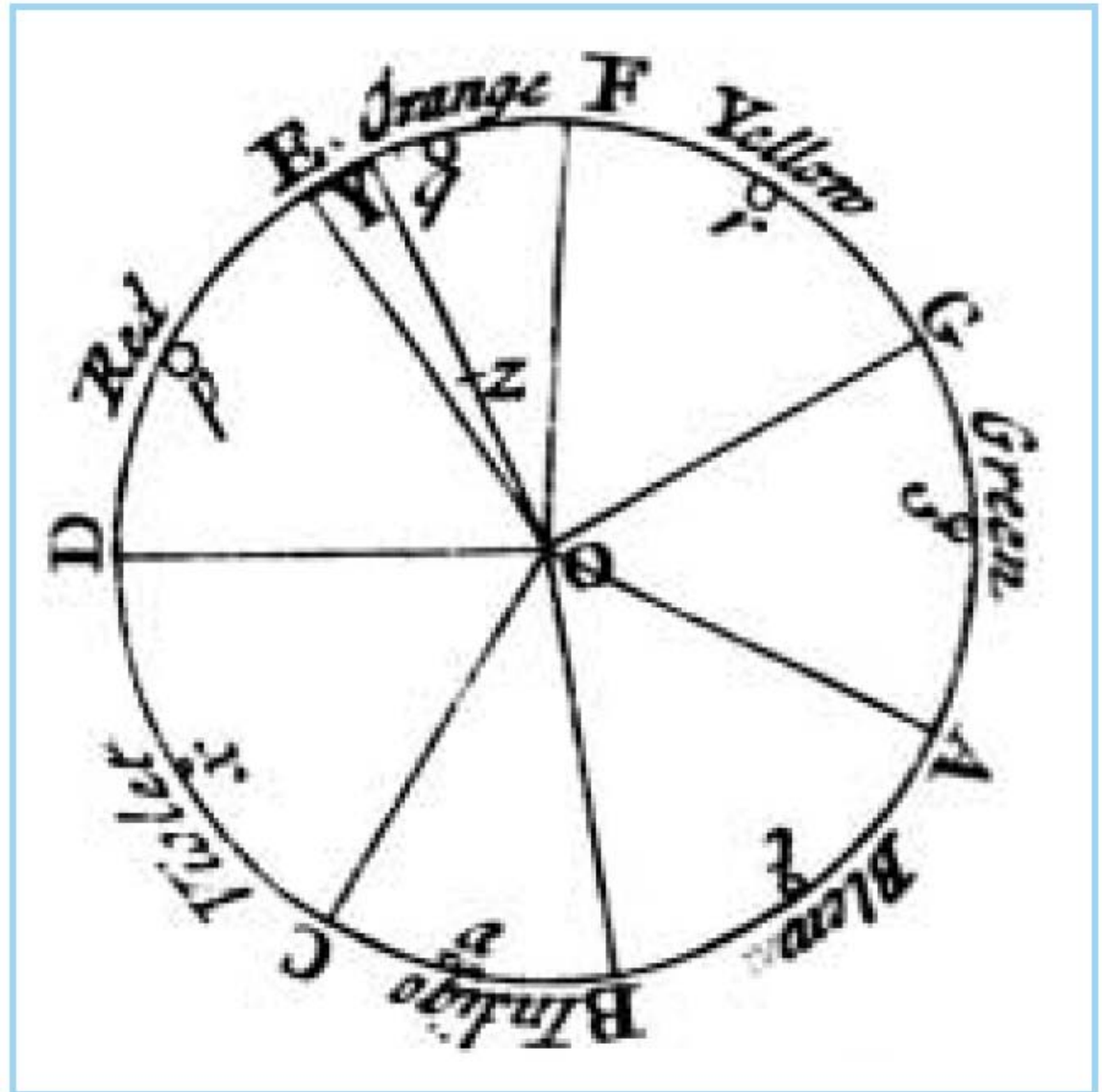


Newton's color circle

Introduced in his book
Opticks (1704)
(Mollon)

Newton combined
psychology and physics.

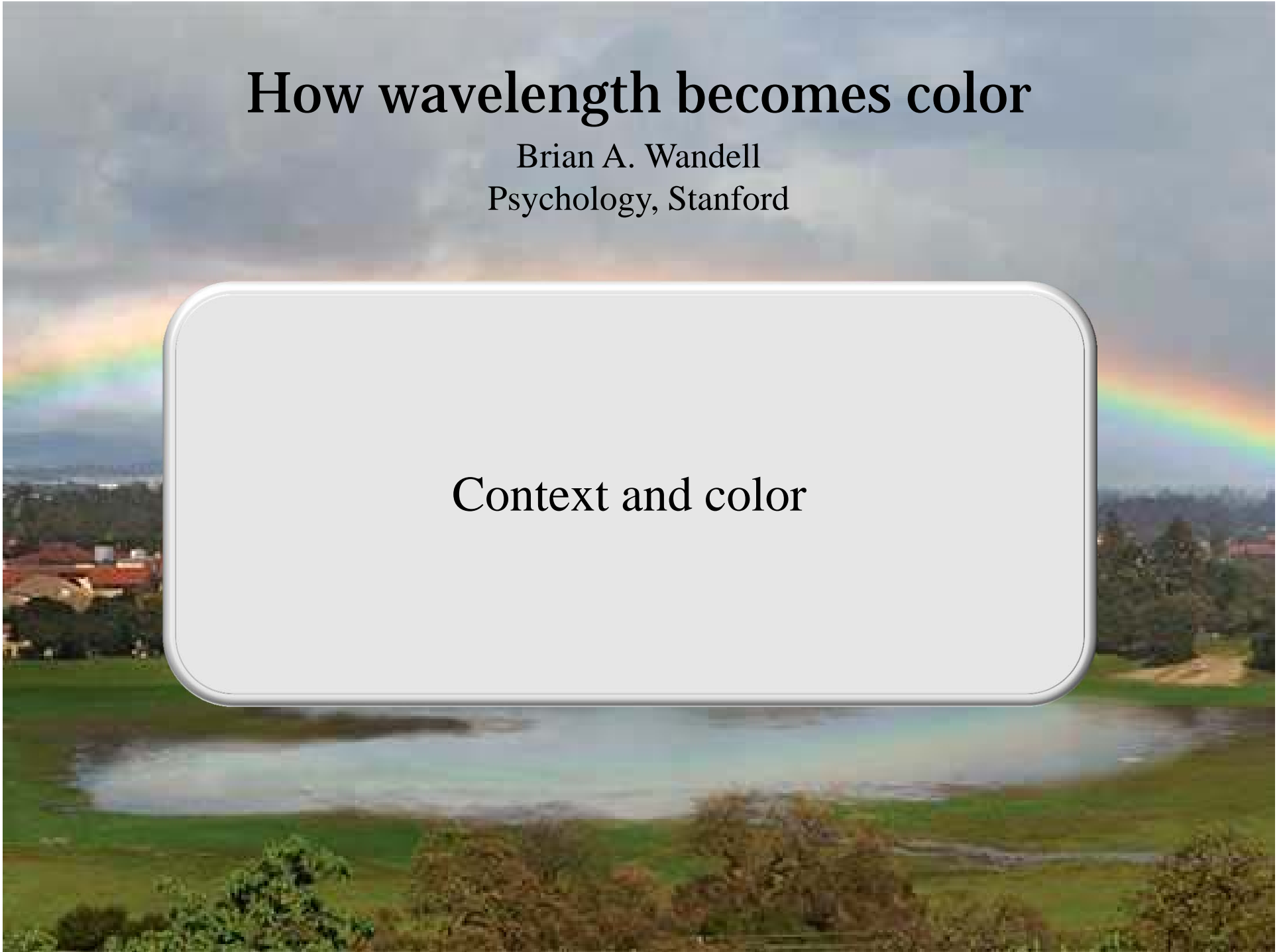
Placing the colors on a
circle was an error,
subsequently fixed by
Helmholtz.



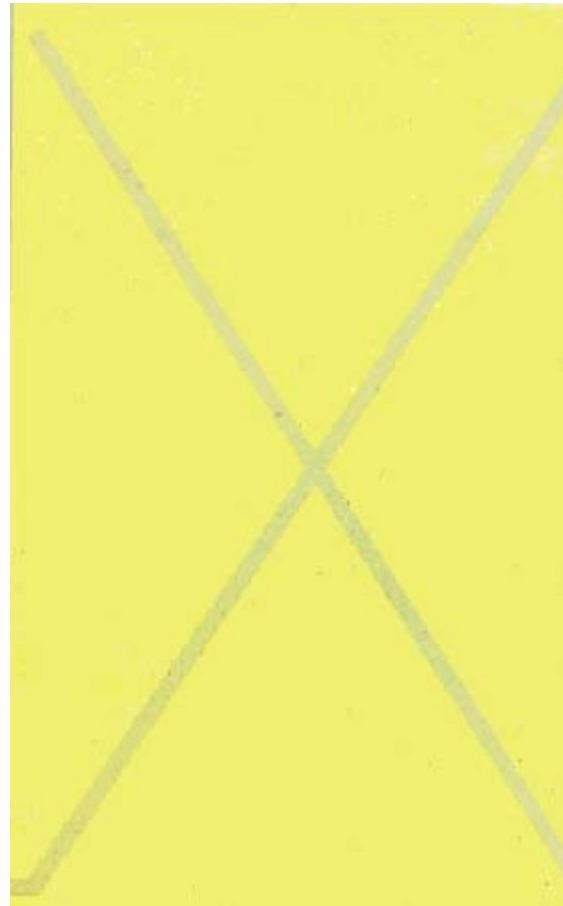
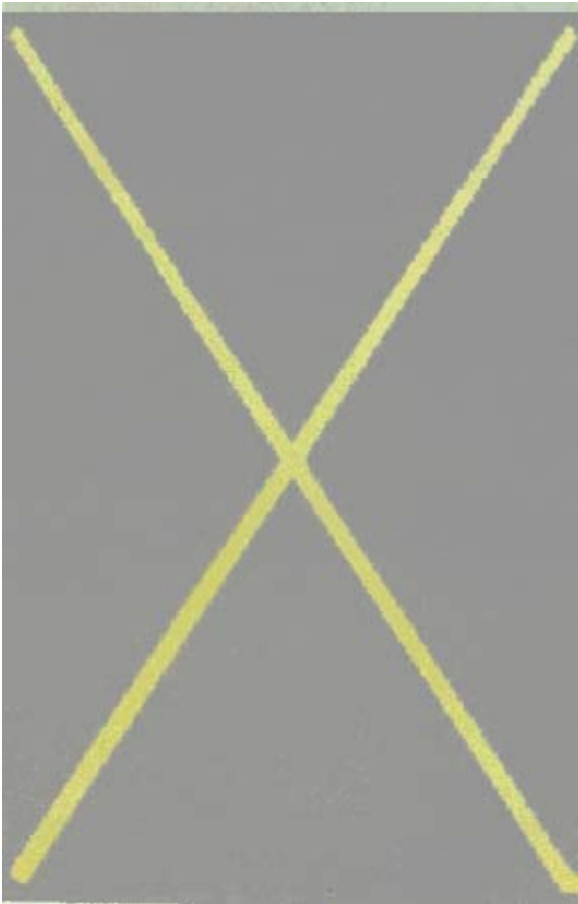
How wavelength becomes color

Brian A. Wandell
Psychology, Stanford

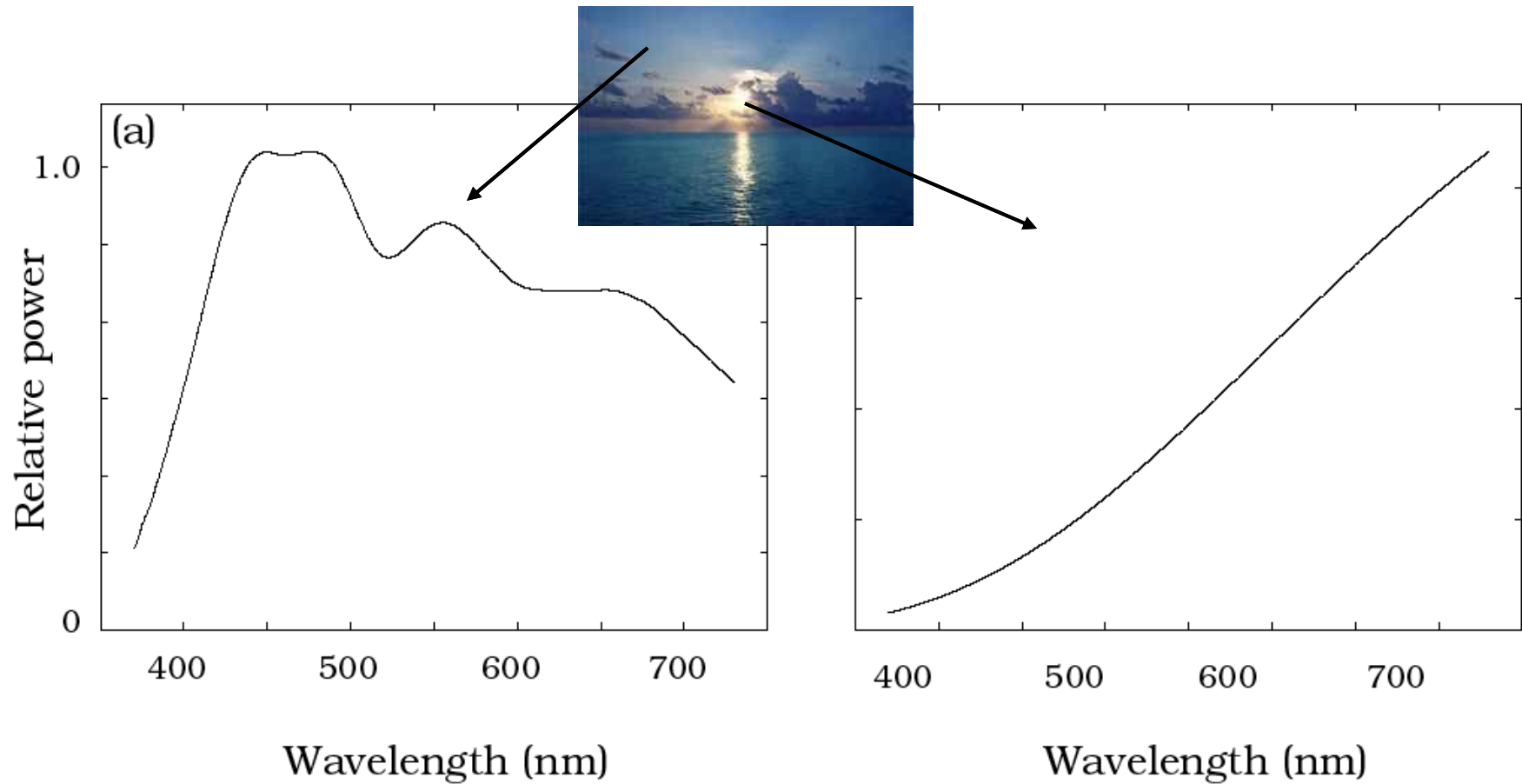
Context and color



Color appearance and context

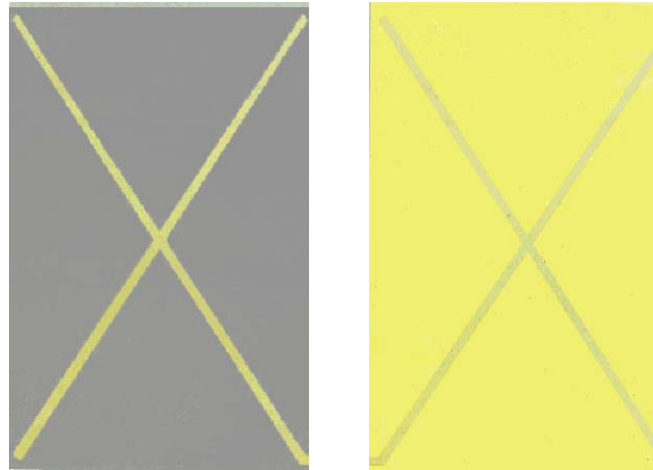


An important context: Ambient lighting



SPD: spectral power distribution

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)

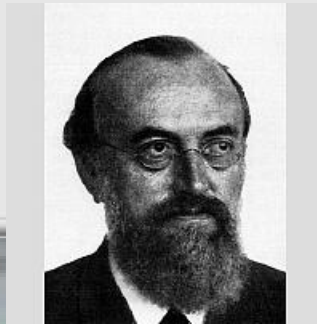
**Judgments of
lightness depend
on brain
processing**
(Anderson and Winawer,
Nature, 2005)



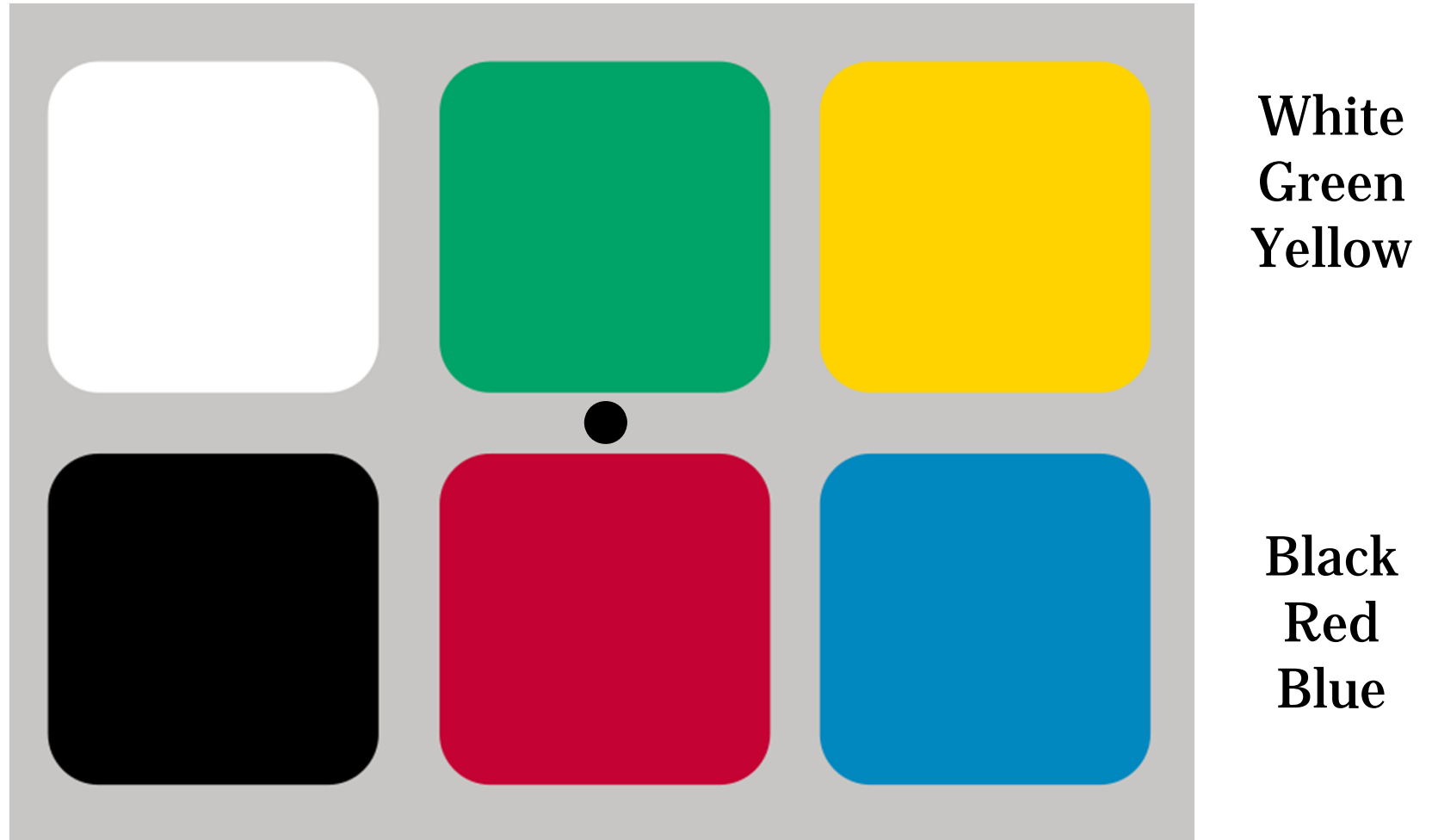
How wavelength becomes color

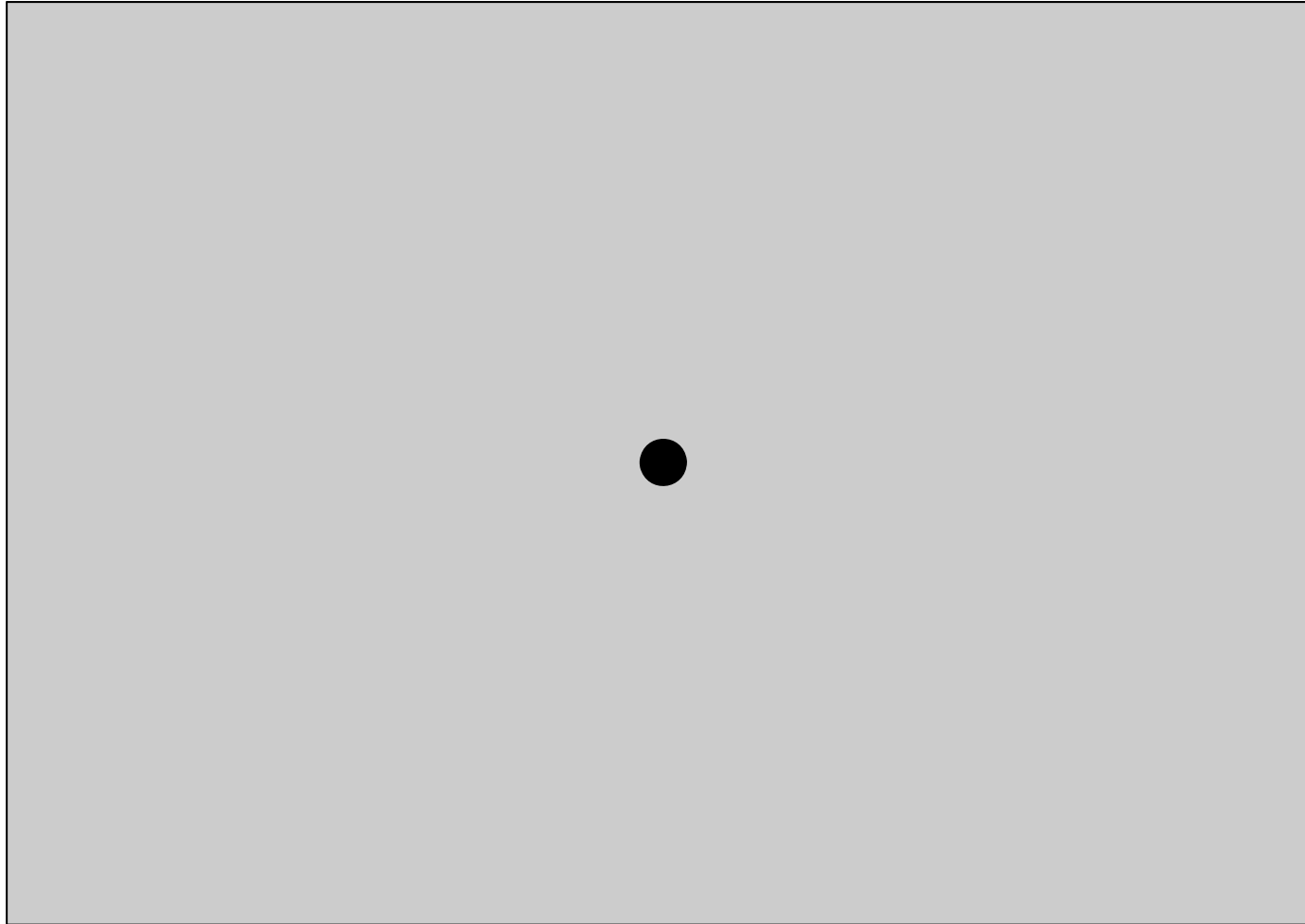
Brian A. Wandell
Psychology, Stanford

Opponent colors



Opponent-Colors – Afterimage demo





White
Green
Yellow

Black
Red
Blue



johnsadowski.com



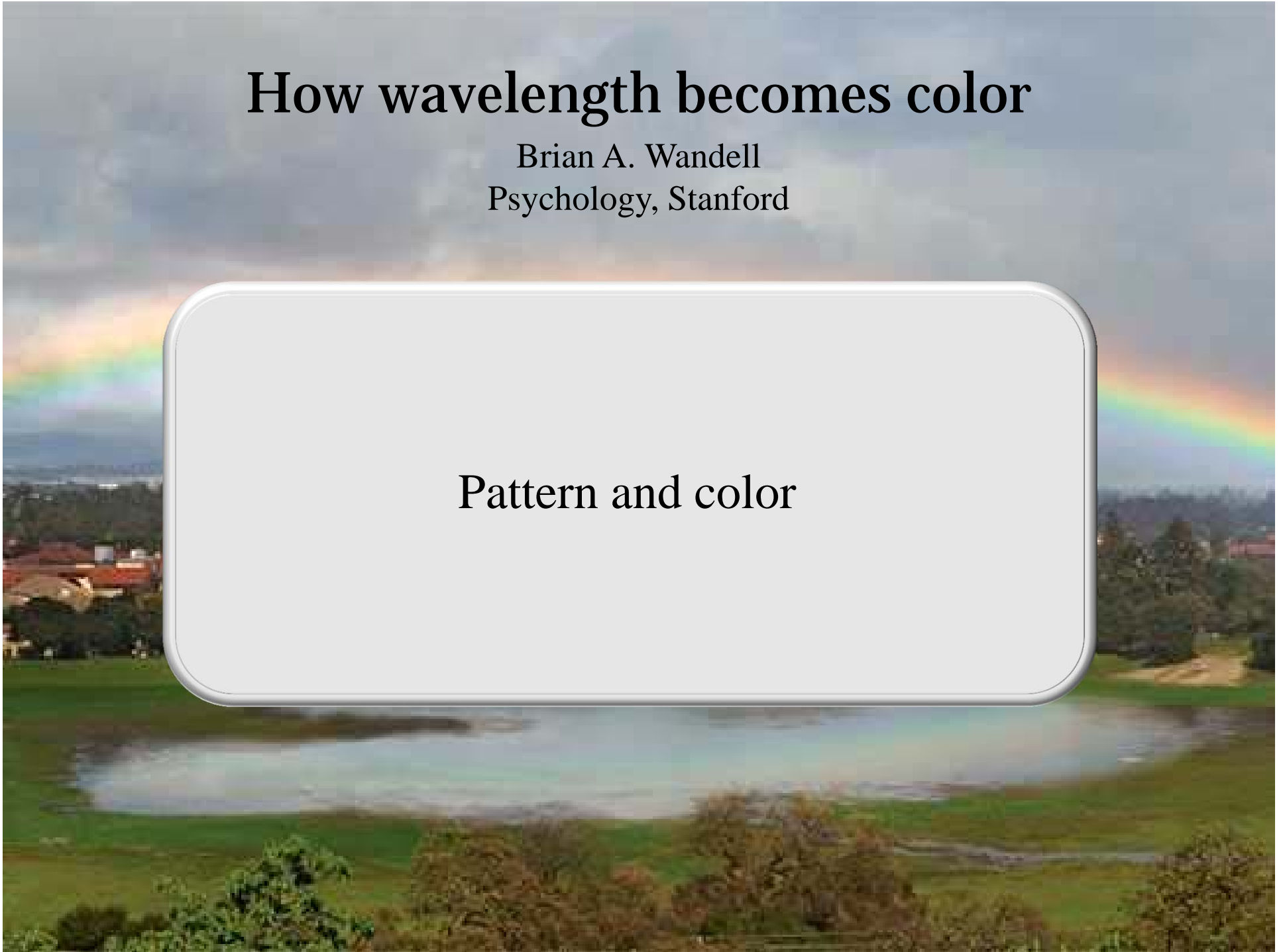


johnsadowski.com

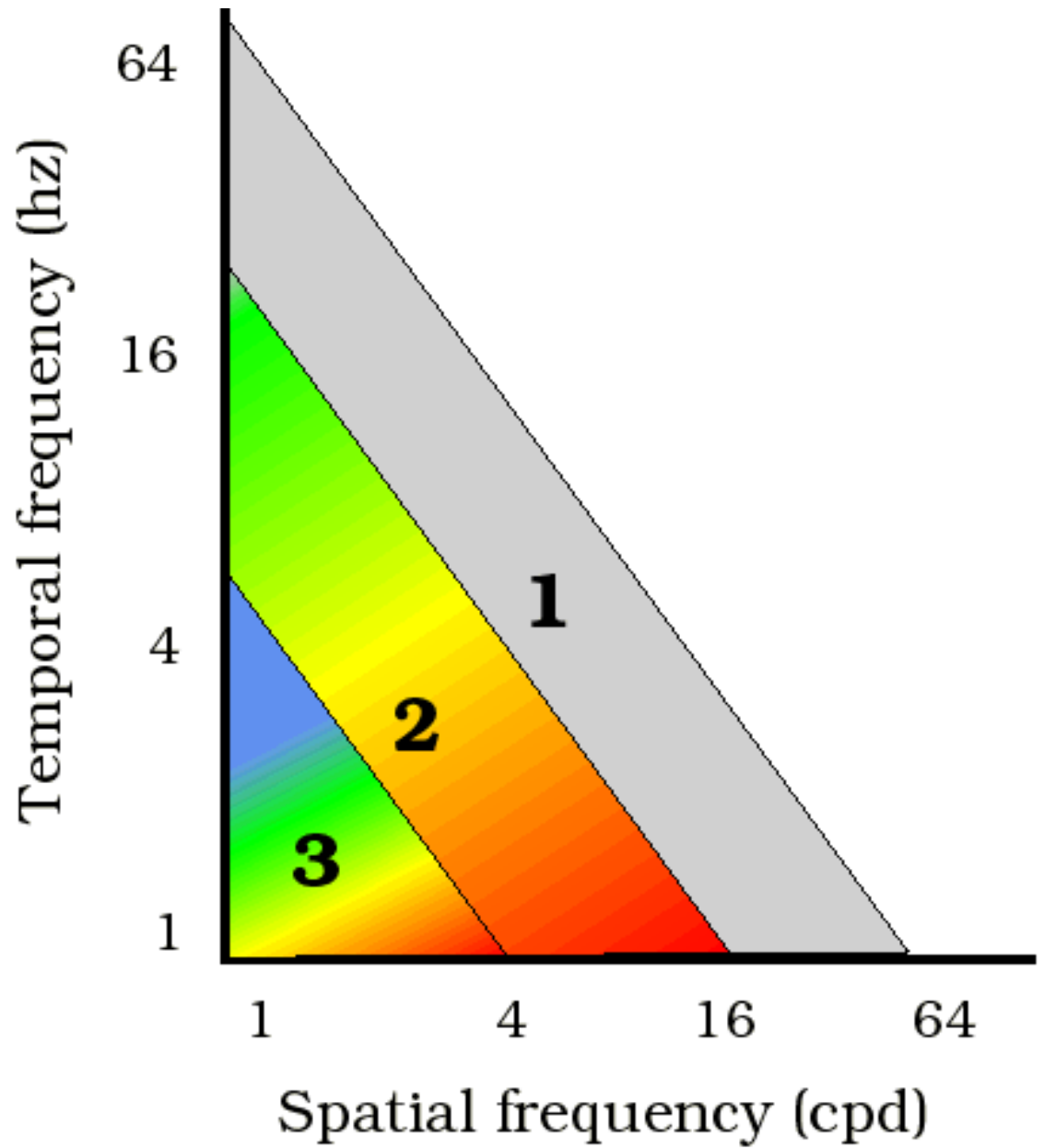
How wavelength becomes color

Brian A. Wandell
Psychology, Stanford

Pattern and color



Color Is Visible
Over A Limited
Range of Spatial-
Temporal
Frequencies



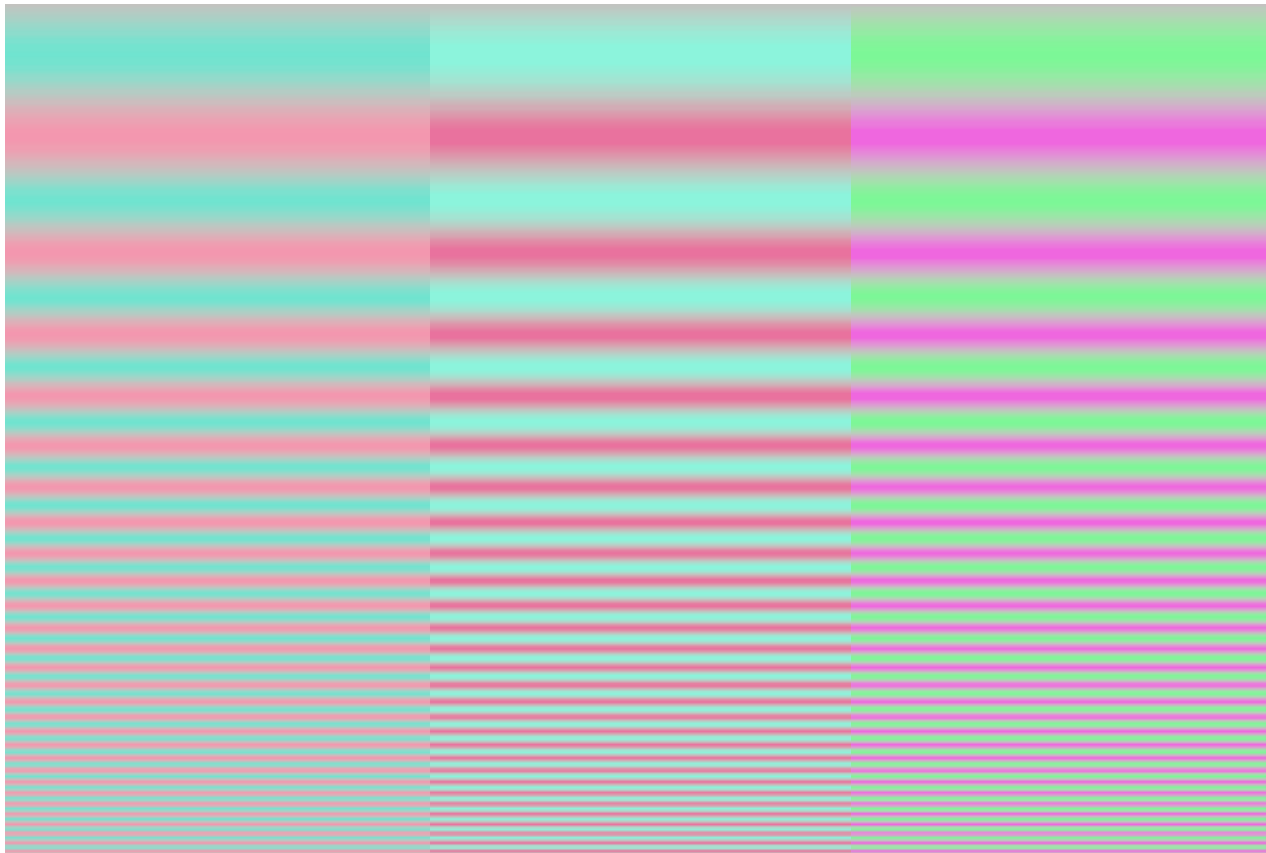
From Foundations of Vision

Pattern Color Interactions

**Reduced
luminance
contrast**

Original

**Reduced
blue-yellow
contrast**



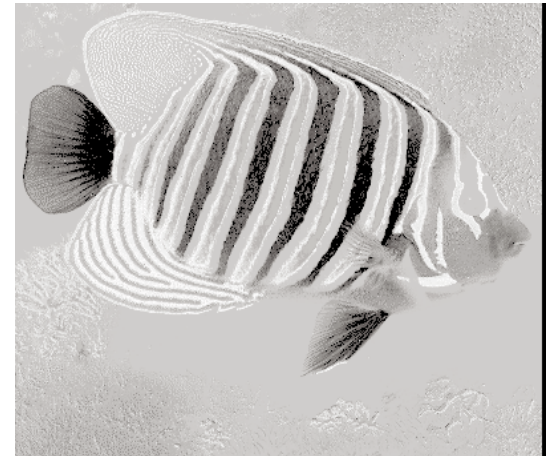
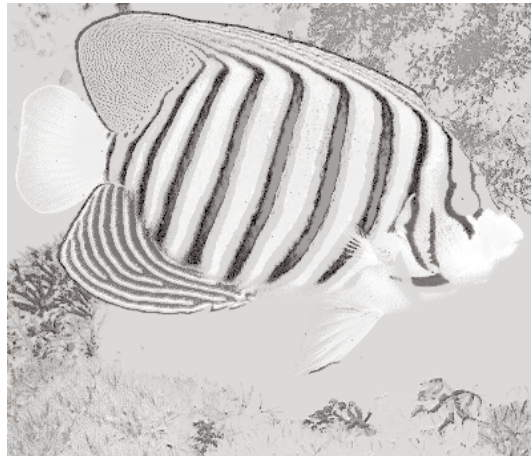
Pattern and Color in technology



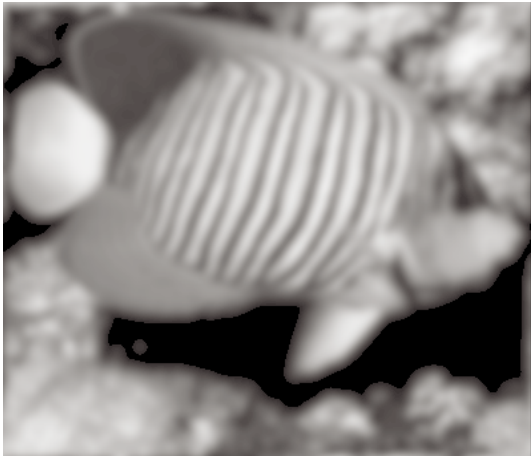
Y

I

Q



Blurred Y



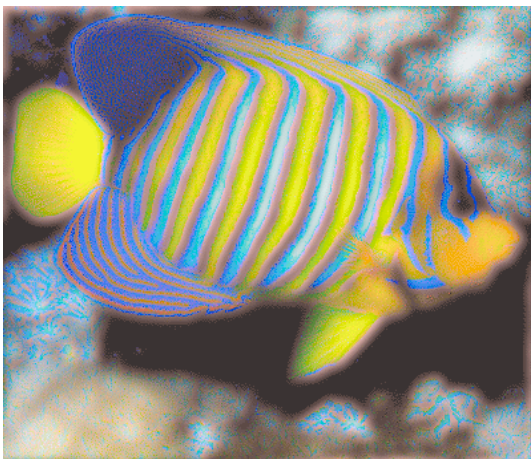
Blurred I



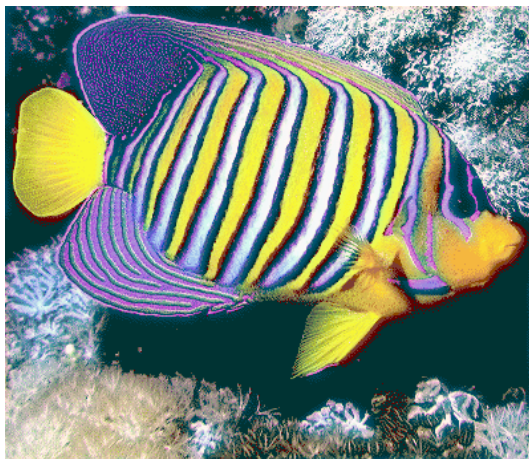
Blurred Q



**Blurred Y
I,Q**



**Blurred I
Y,Q**



**Blurred Q
Y,I**



How wavelength becomes color

Brian A. Wandell
Psychology, Stanford

Thanks to the people who did the work

