Lecture 21

Color

6.869/6.819 Advances in Computer Vision

Fall 2019

Bill Freeman, Antonio Torralba, Pl

Why does a visual system need color?

http://www.hobbylinc.com/gr/pll/pll5019.jpg

Why does a visual system need color? (an incomplete list…)

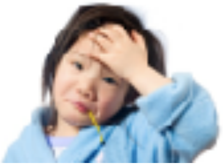
- To tell what food is edible.

- To distinguish material changes from shading changes.

- To group parts of one object together in a scene.

- To find people’s skin.

- Check whether a person’s appearance looks normal/healthy.



http://www.pouted.com/know-10-points-information-unicorn/sick-child/

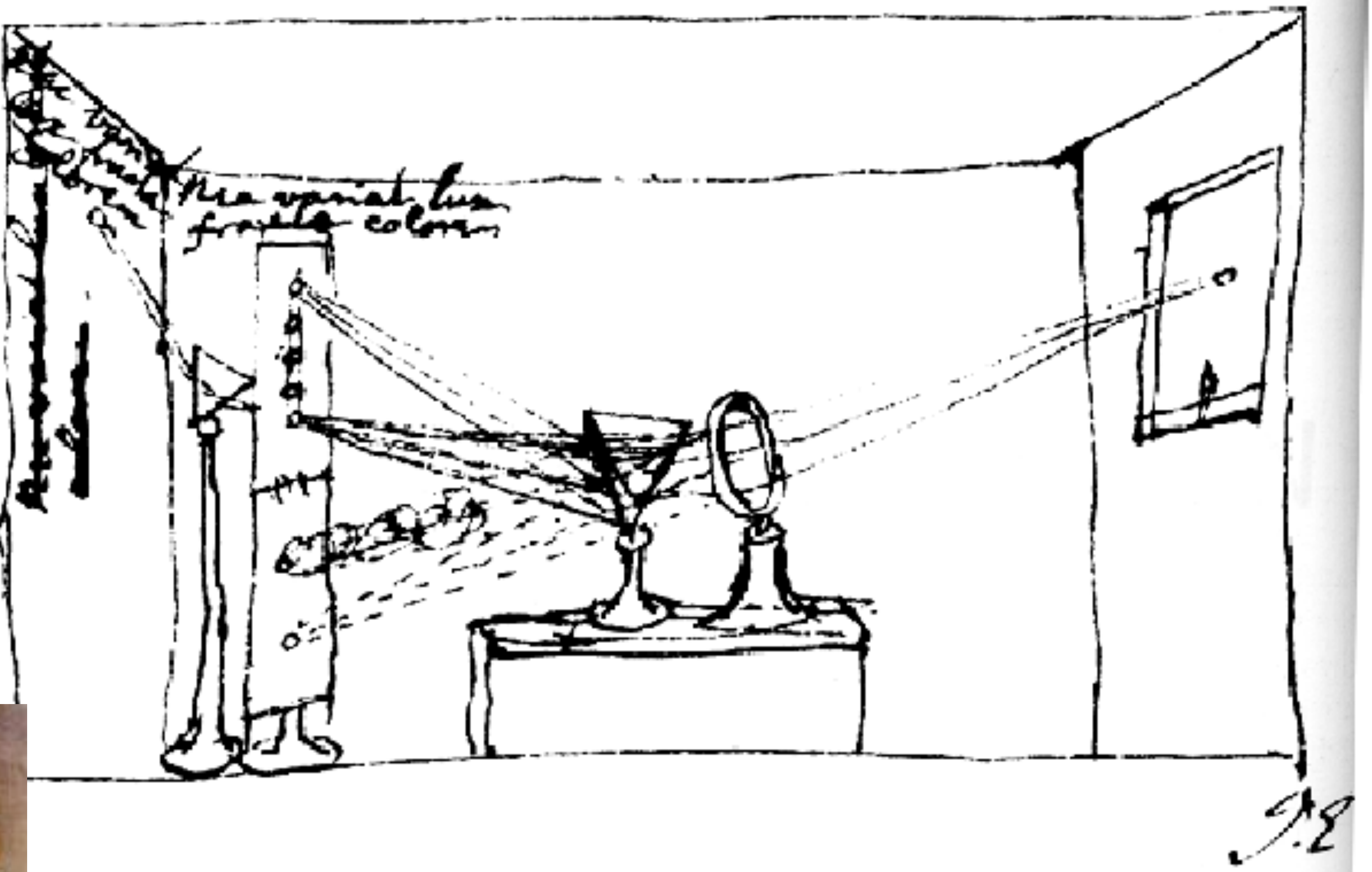
Lecture outline

- Color physics.
- Color perception.

Lecture outline

- Color physics.
- Color perception.

Color

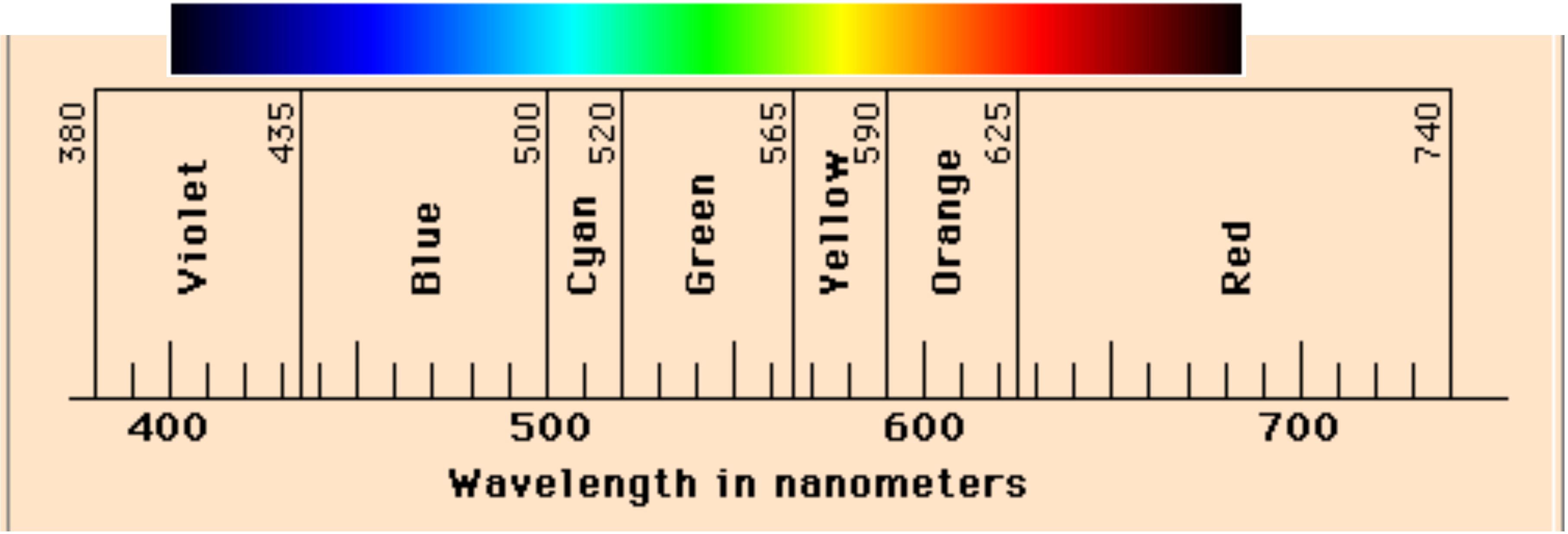


4.1 NEWTON'S SUMMARY DRAWING of his experiments with light. Using a point source of light and a prism, Newton separated sunlight into its fundamental components. By reconverging the rays, he also showed that the decomposition is reversible.

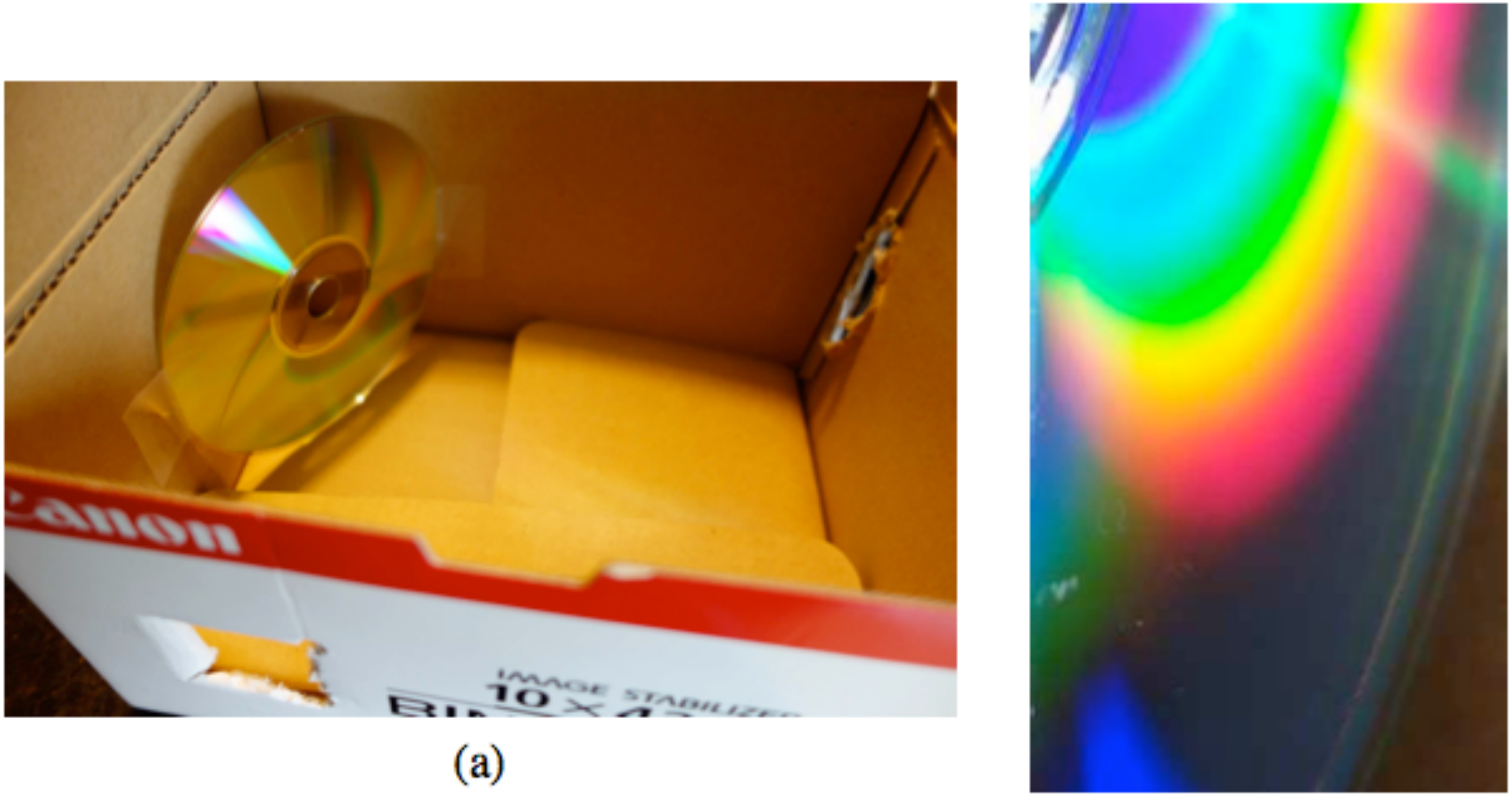
www.popularpersons.org

From Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Spectral colors



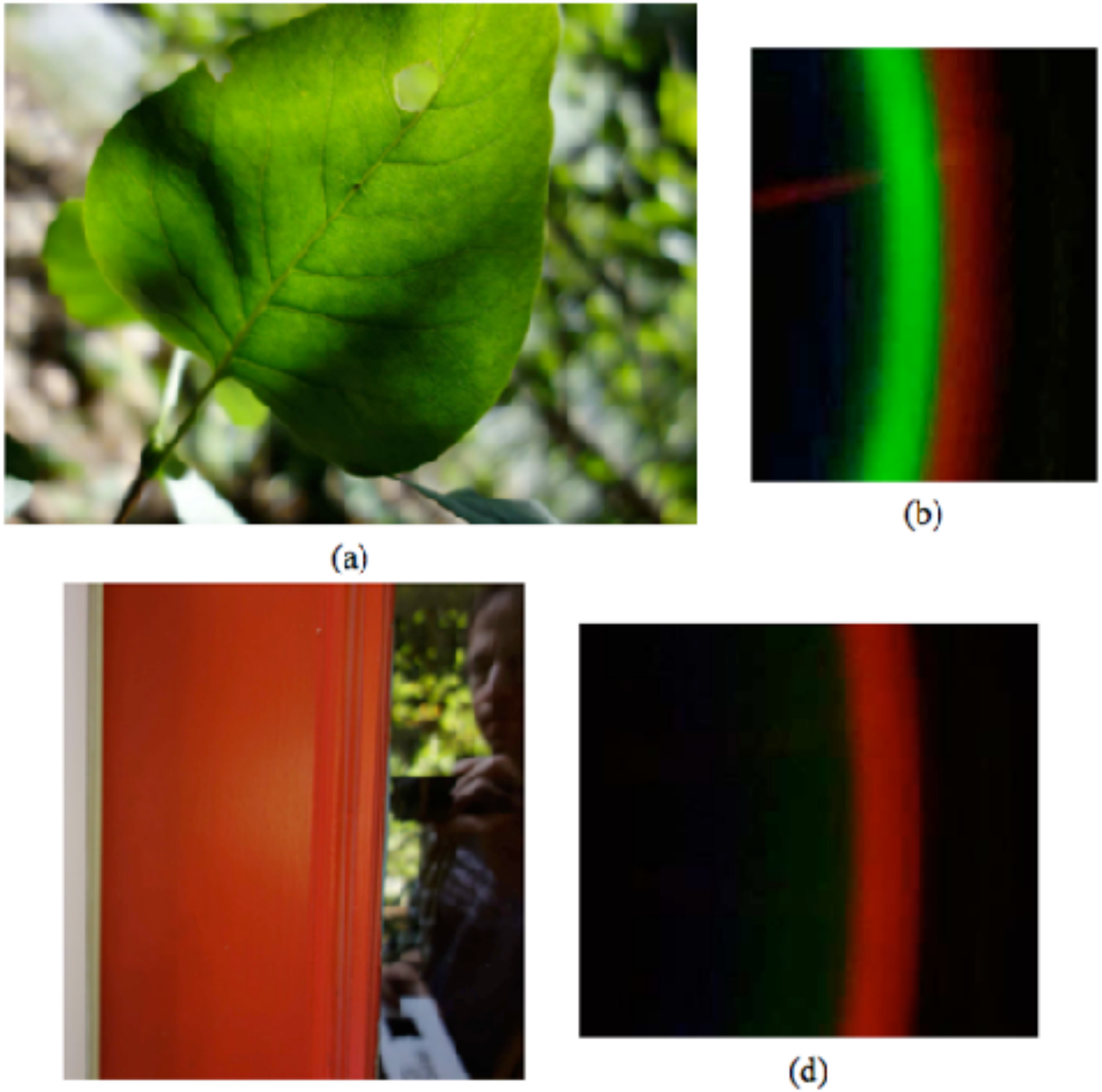
http://hyperphysics.phy-astr.gsu.edu/hbase/vision/specol.html#c2



(a)

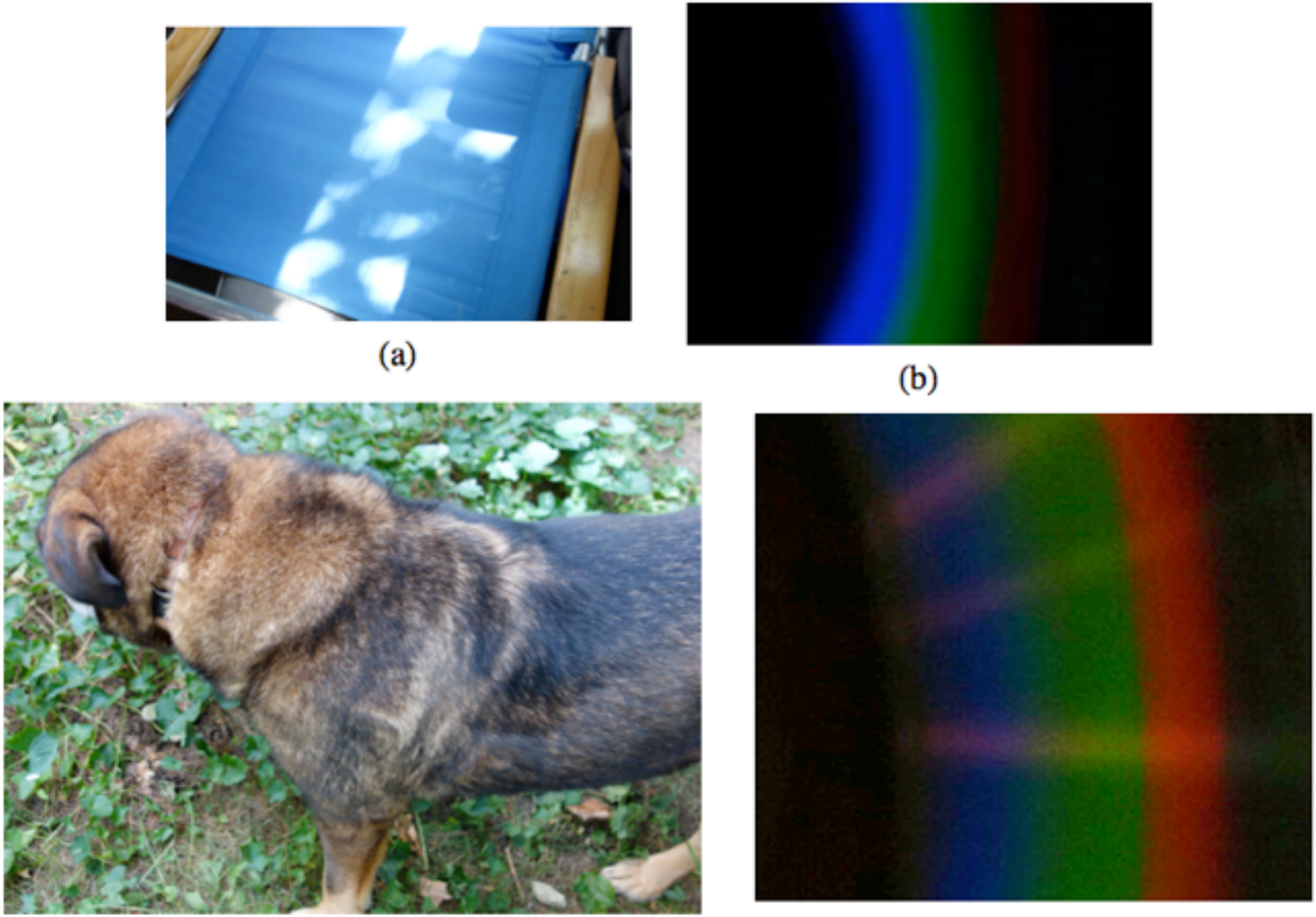
(b)

e 6.3: (a) A spectrograph constructed using a compact disk (CD). Light enters through a slit at diffracting from the narrowly spaced lines of the CD. (b) Photograph of diffraction pattern f ght, seen thorugh hole at bottom left.



(a) (b) (c) (d)

Figure 6.5: Some real-world objects and the reflected light spectra (photographed using Fig. (6.3) (a)) from outdoor viewing. (a) Leaf and (b) its reflected spectrum. (c) A red door and (d) its reflected



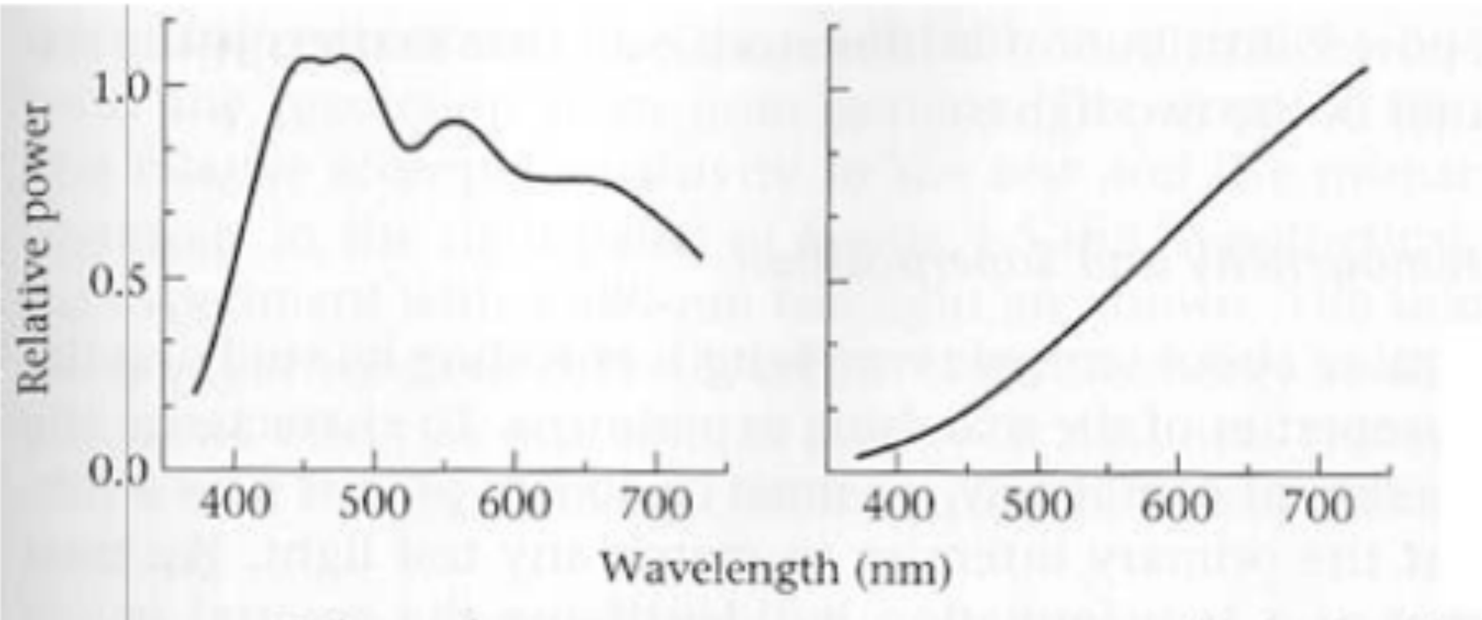
(a)

(b)

(c)

(d)

Figure 6.6: More real-world objects and the reflected light spectra. (a) Blue-green chair and (b) its reflected light. (c) Toby the dog and (d) his reflected spectrum.

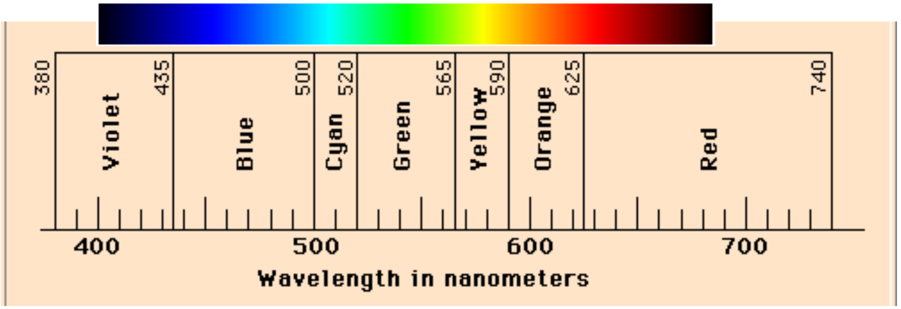


Blue sky

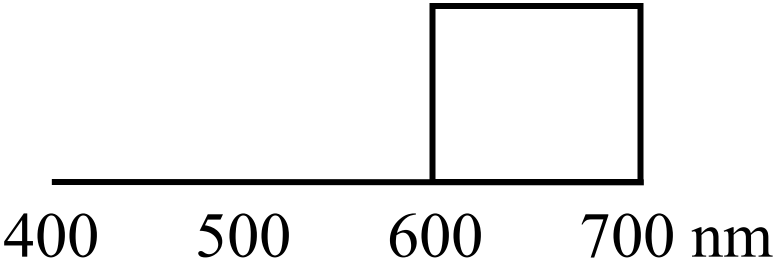
Tungsten light bulb

Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

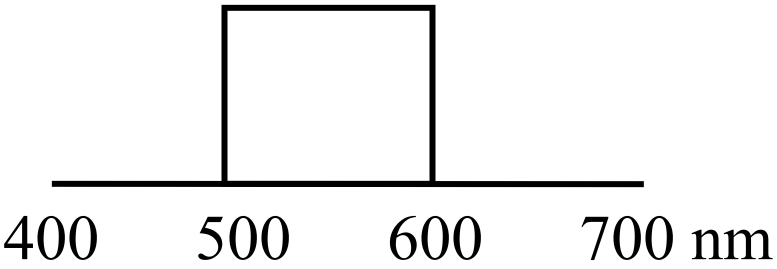
Color names for cartoon spectra



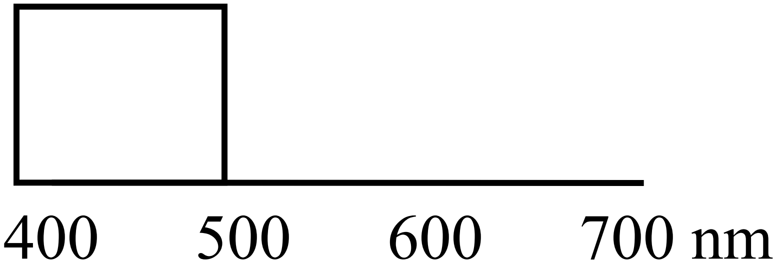
red



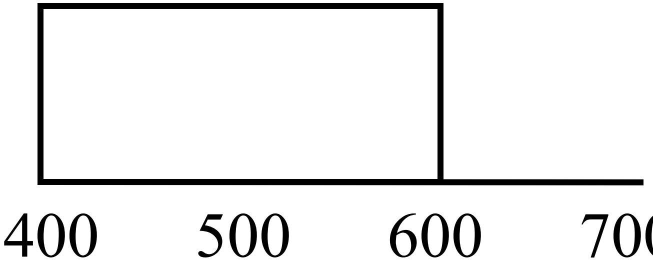
green



blue

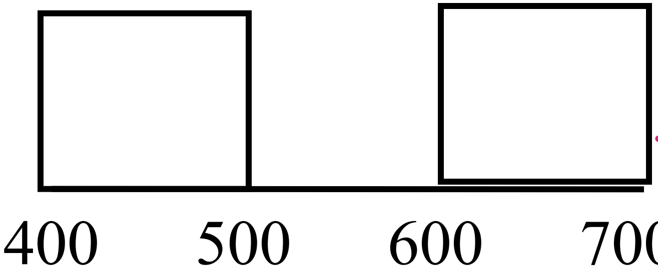


cyan



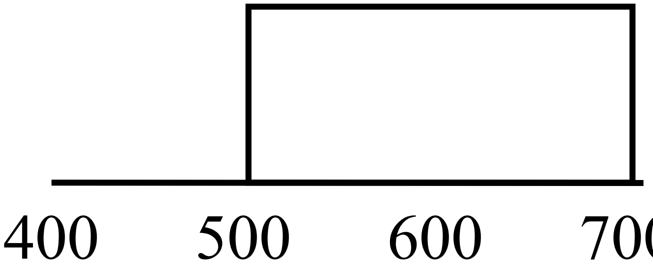
minus red

magenta



minus green

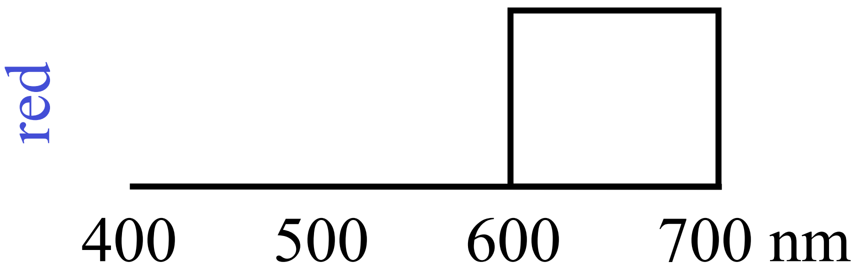
yellow

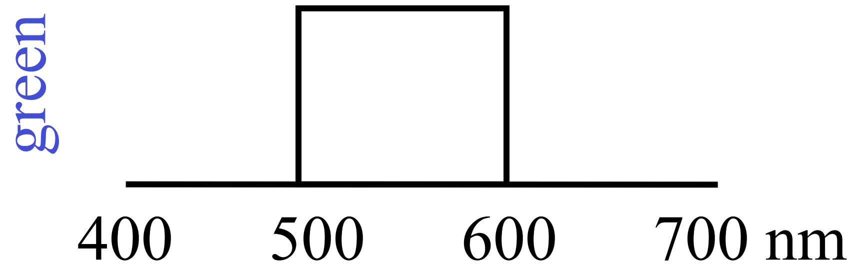


minus blue

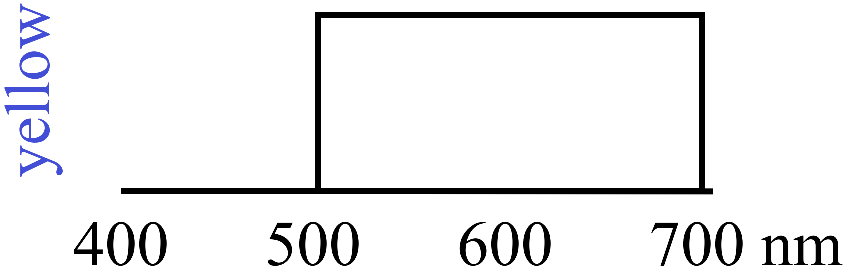
Additive color mixing

When colors combine by *adding* the color spectra. Example color displays that follow this mixing rule: tiny display dots on a monitor screen, multiple projectors aimed at a screen.



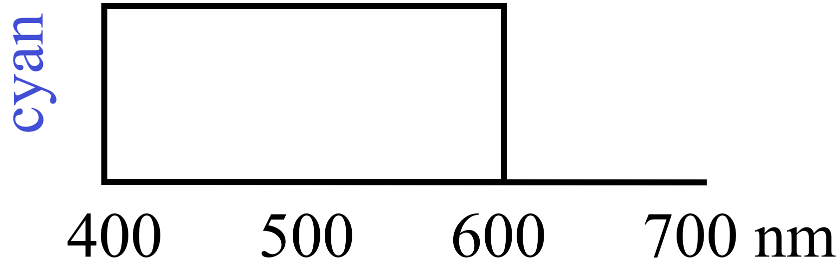


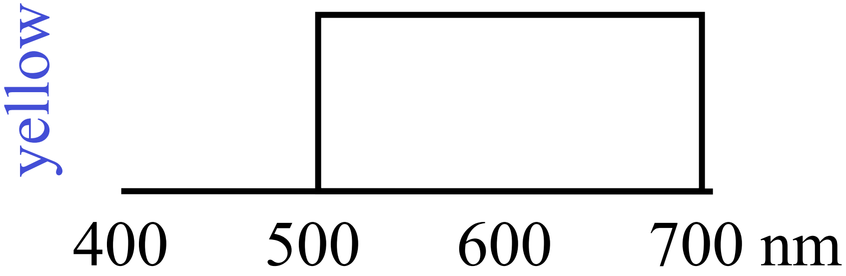
Red and green make…

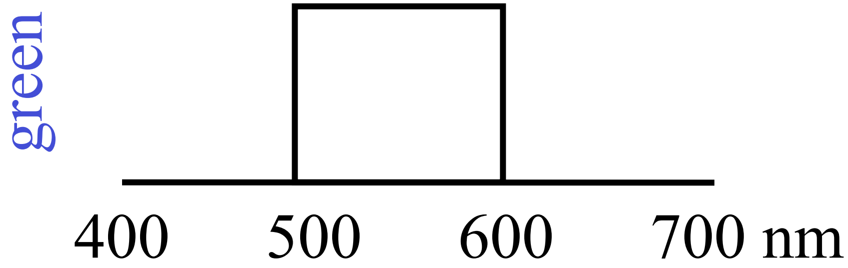


Yellow!

Subtractive color mixing





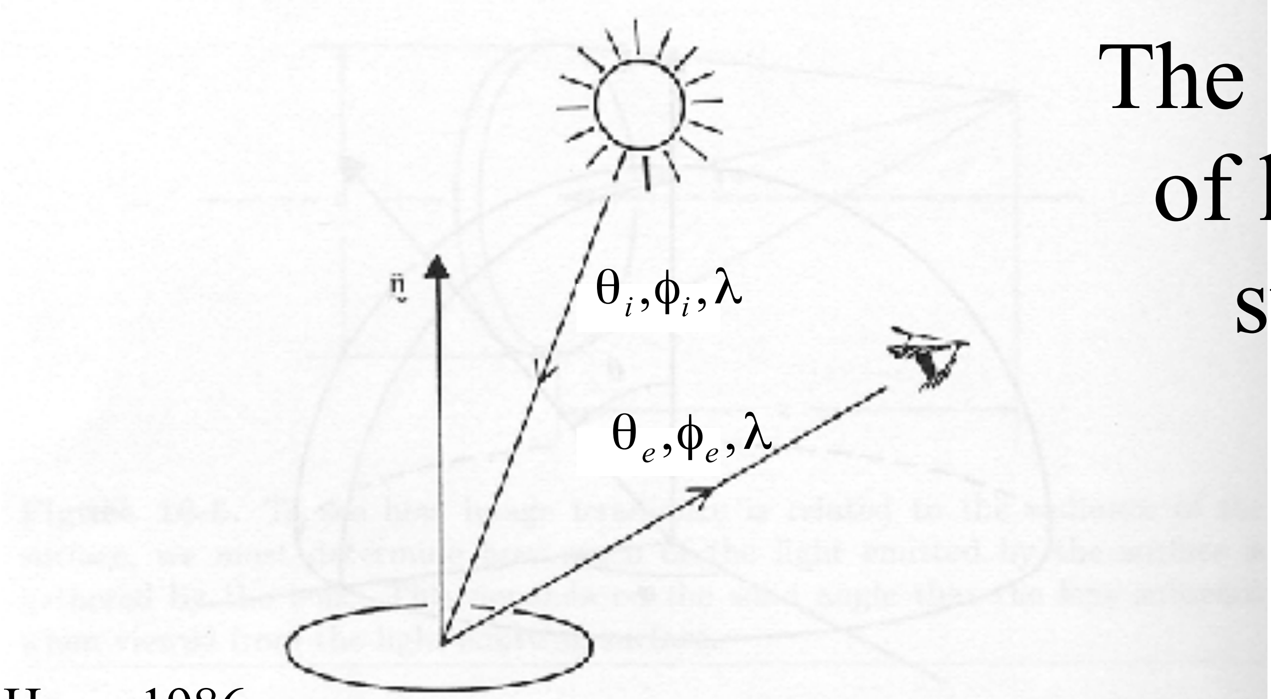


When colors combine by *multiplying* the color spectra. Examples that follow this mixing rule: most photographic films, paint, cascaded optical filters, crayons, light reflecting off a diffuse surface.

Cyan and yellow (in crayons, called “blue” and yellow) make…

Green!

The interaction of light with surfaces



Horn, 1986

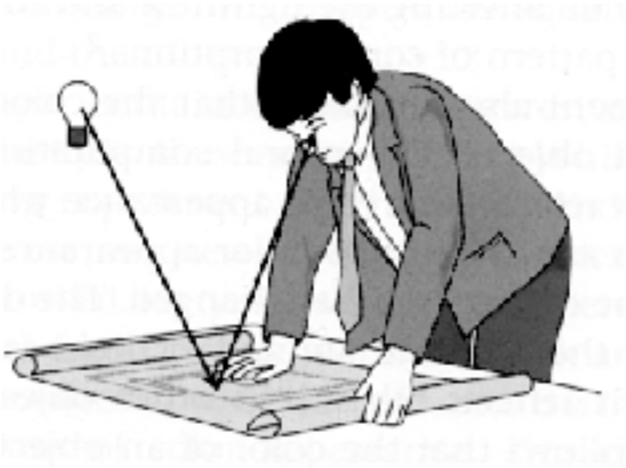
Figure 10-7. The bidirectional reflectance distribution function is the ratio of the radiance of the surface patch as viewed from the direction (θ_e, ϕ_e) to the irradiance resulting from illumination from the direction (θ_i, ϕ_i).

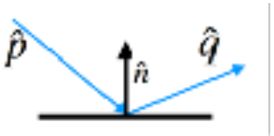
Spectral radiance: power in a specified direction, per unit area, per unit solid angle, per unit wavelength

$$BRDF = f(\theta_i, \phi_i, \theta_e, \phi_e, \lambda) = \frac{L(\theta_e, \phi_e, \lambda)}{E(\theta_i, \phi_i, \lambda)}$$

Spectral irradiance: incident power per unit area, per unit wavelength

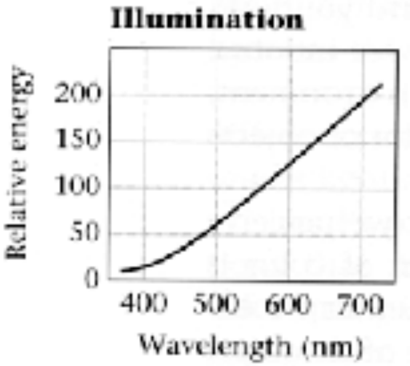
Simplified rendering models: BRDF → reflectance as function of wavelength





$$I_{\text{out}} = I_{\text{in}}(\lambda)\, A(\lambda)\, \hat{n} \cdot \hat{p}$$

For diffuse reflections, we replace the BRDF calculation with a wavelength-by-wavelength scalar multiplication



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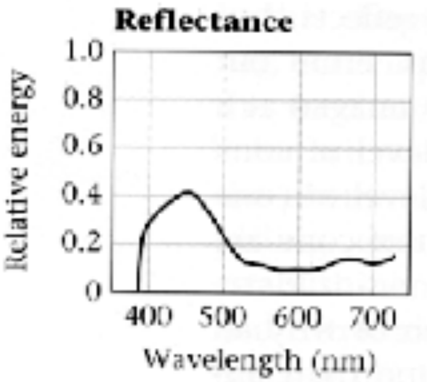

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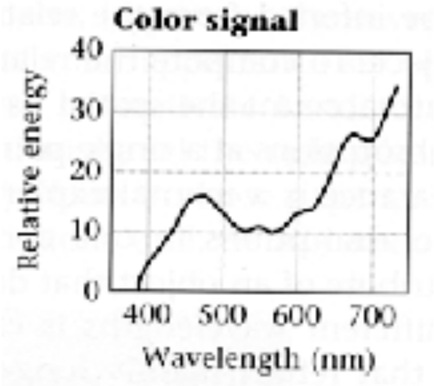
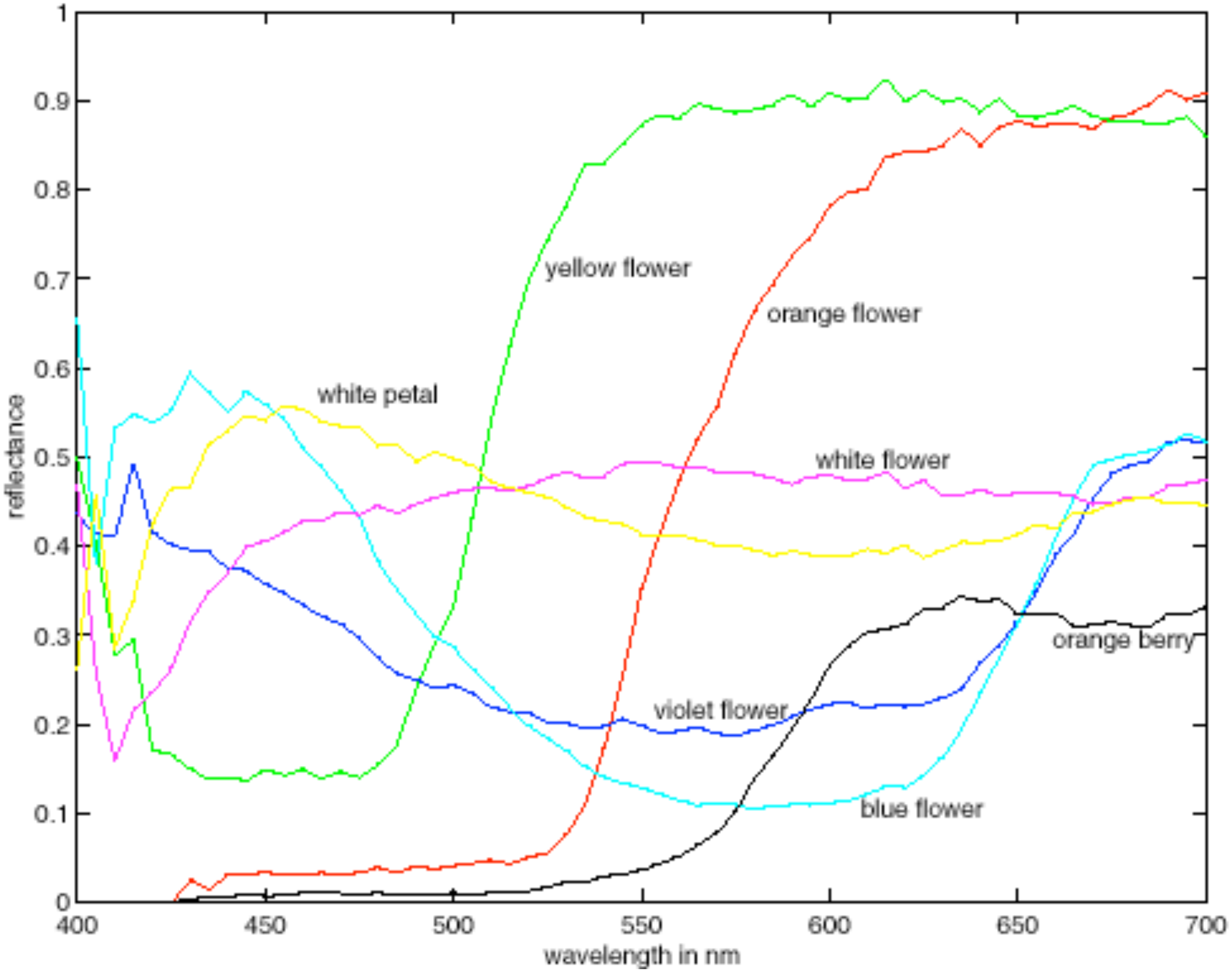


Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

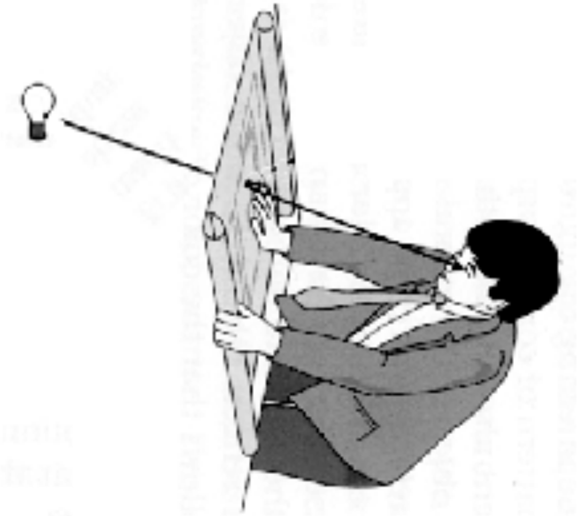
Some reflectance spectra

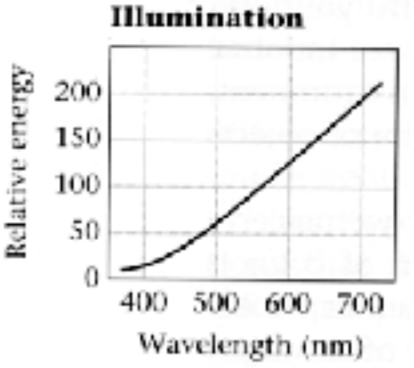


Spectral albedoes for several different leaves, with color names attached. Notice that different colours typically have different spectral albedo, but that different spectral albedoes may result in the same perceived color (compare the two whites). Spectral albedoes are typically quite smooth functions. Measurements by E.Koivisto.

Forsyth, 2002

Simplified rendering models: transmittance





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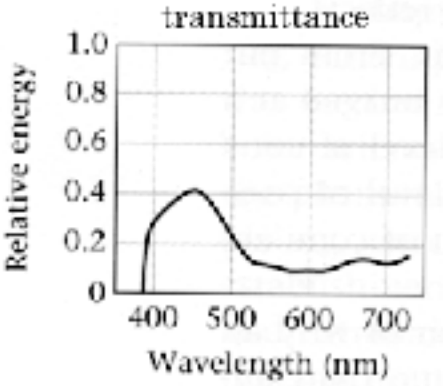

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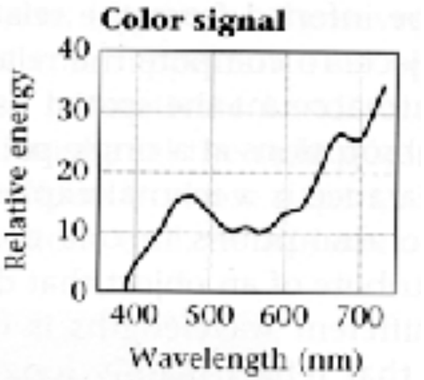


Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Overhead projector demo

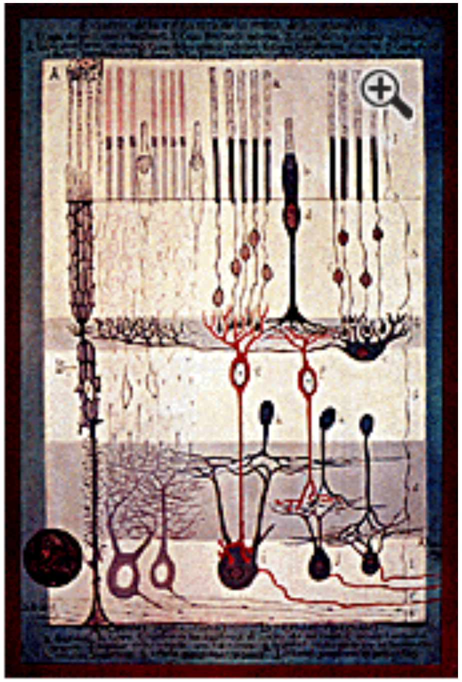
Subtractive color mixing

Lecture outline

- Color physics.
- Color perception.

What’s the machinery in the eye?

Eye Photoreceptor responses

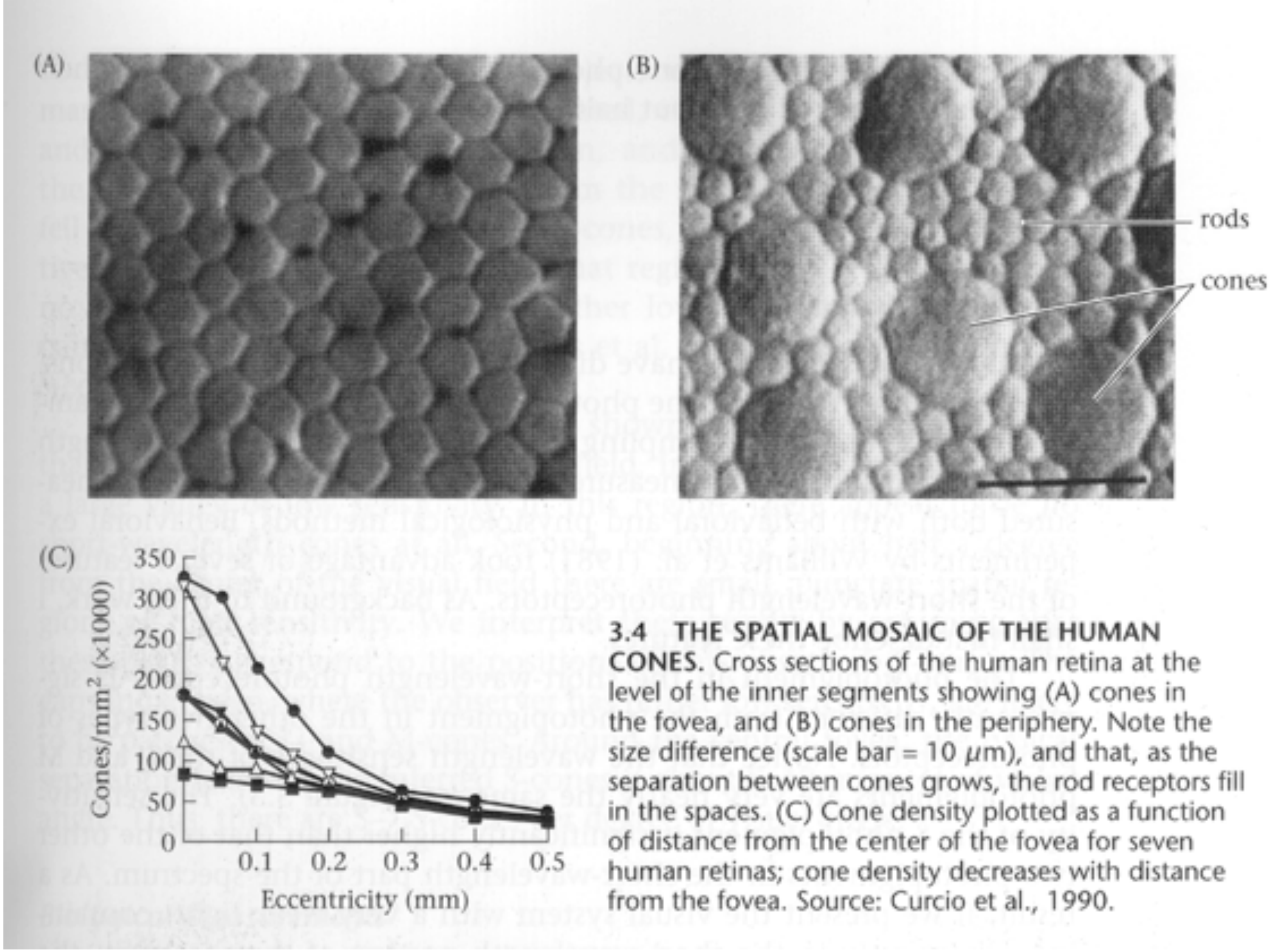


The intricate layers and connections of nerve cells in the retina were drawn by the famed Spanish anatomist Santiago Ramón y Cajal around 1900. Rod and cone cells are at the top. Optic nerve fibers leading to the brain may be seen at bottom right.

Instituto Cajal. CSIC. Madrid.

(Where do you think the light comes in?)

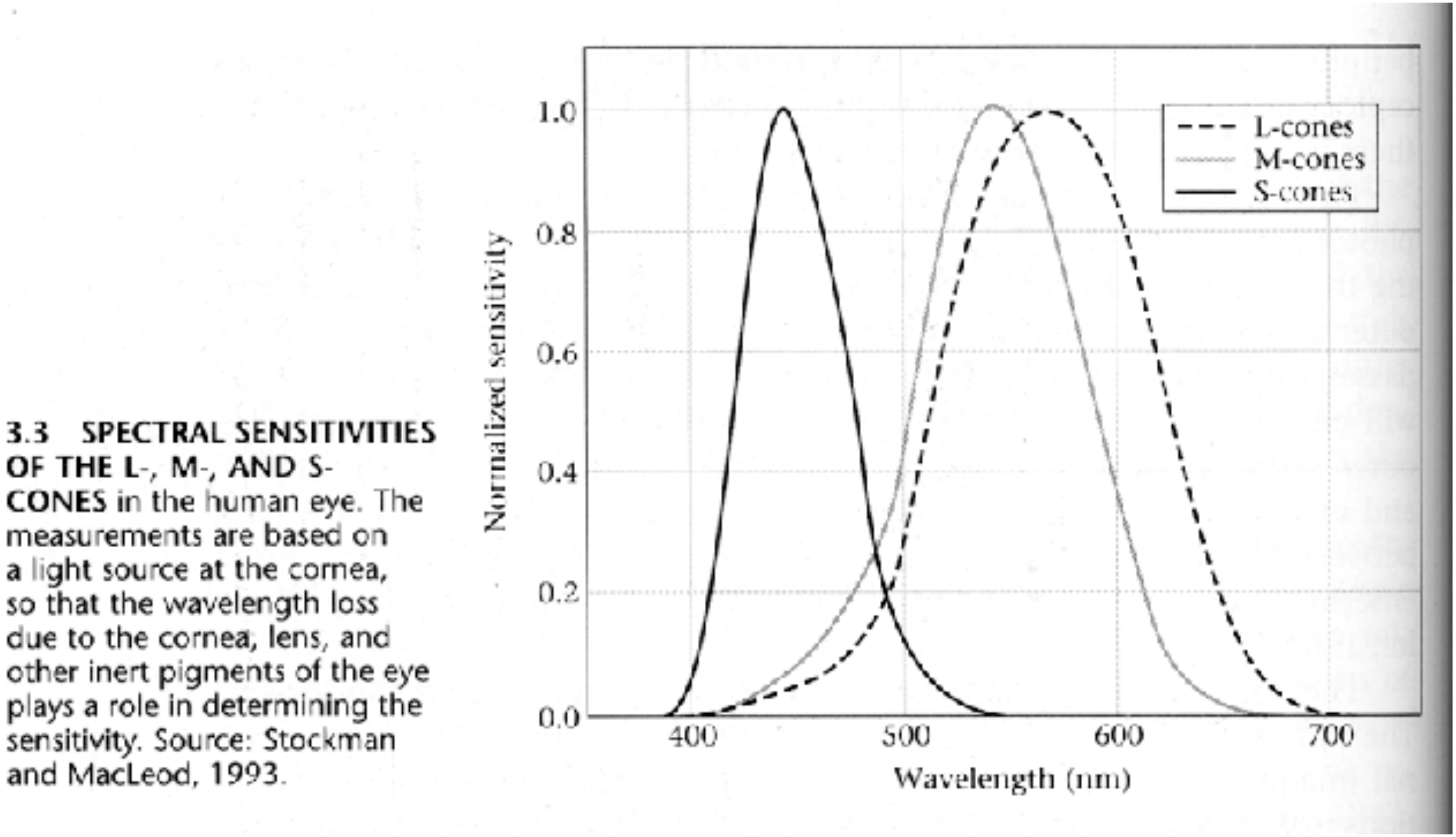
Human Photoreceptors



3.4 THE SPATIAL MOSAIC OF THE HUMAN CONES. Cross sections of the human retina at the level of the inner segments showing (A) cones in the fovea, and (B) cones in the periphery. Note the size difference (scale bar = 10 μm), and that, as the separation between cones grows, the rod receptors fill in the spaces. (C) Cone density plotted as a function of distance from the center of the fovea for seven human retinas; cone density decreases with distance from the fovea. Source: Curcio et al., 1990.

Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

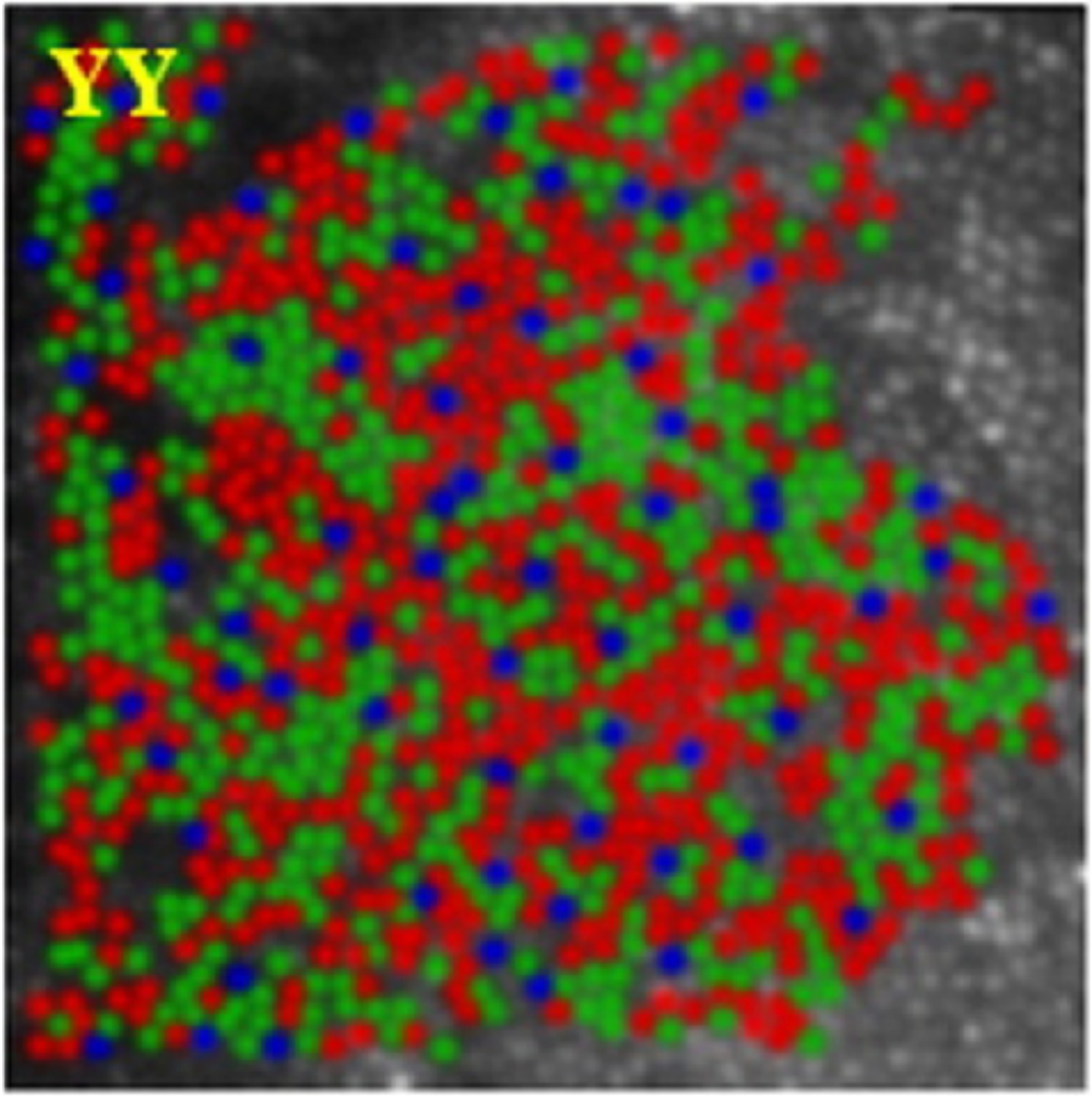
Human eye photoreceptor spectral sensitivities



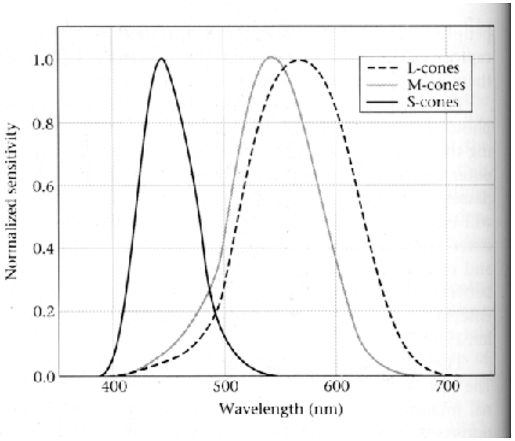
3.3 SPECTRAL SENSITIVITIES OF THE L-, M-, AND S-CONES in the human eye. The measurements are based on a light source at the cornea, so that the wavelength loss due to the cornea, lens, and other inert pigments of the eye plays a role in determining the sensitivity. Source: Stockman and MacLeod, 1993.

Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

L, M, and S cone receptor types colored as R, G, B



What are some color artifacts we might expect our visual system to experience, based on this way of measuring the light spectra falling on our eye?



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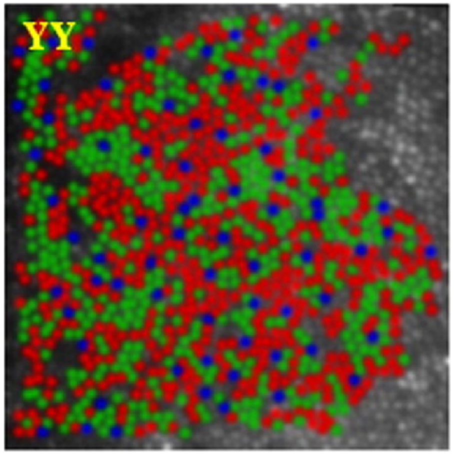
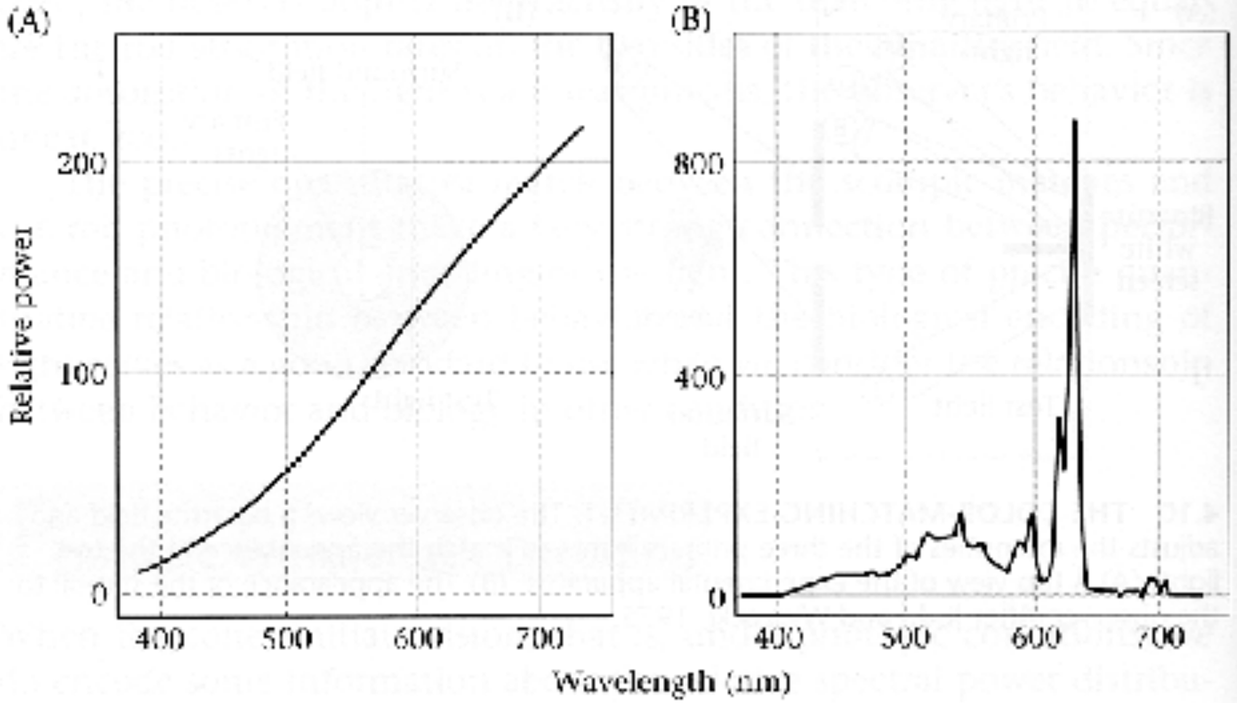
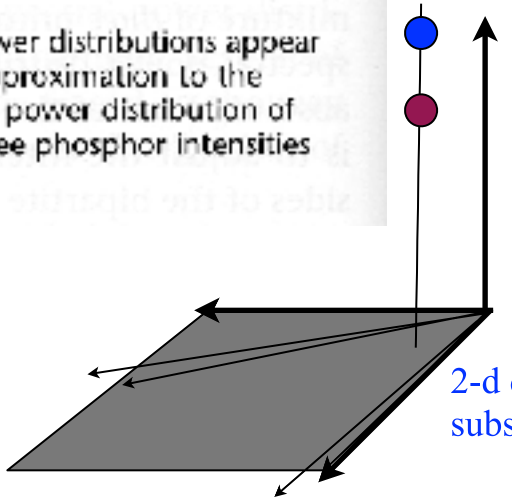


A property of our visual system: these two spectra look the same

Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995



4.11 METAMERIC LIGHTS. Two lights with these spectral power distributions appear identical to most observers and are called metamers. (A) An approximation to the spectral power distribution of a tungsten bulb. (B) The spectral power distribution of light emitted from a conventional television monitor whose three phosphor intensities were set to match the light in panel A in appearance.



3-d depiction of the high-dimensional space of all possible power spectra

2-d depiction of the 3-d subspace of sensor responses

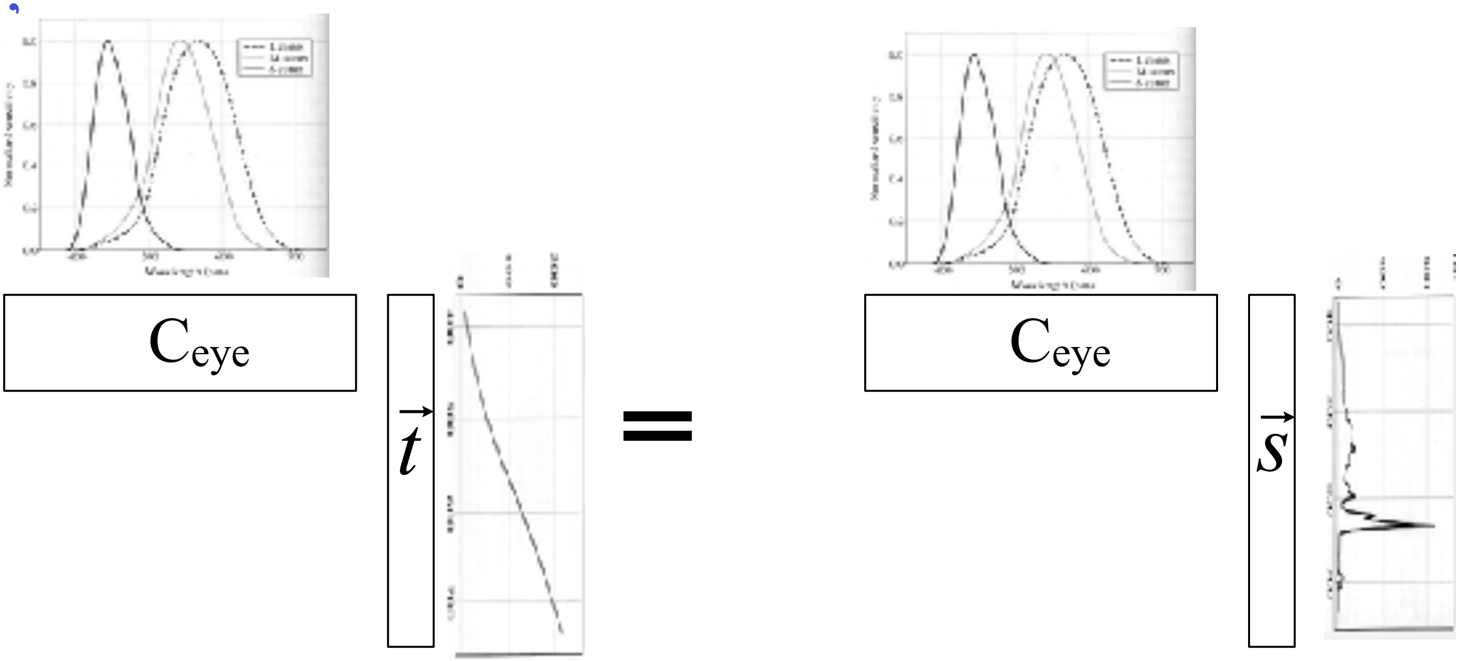
Color metamerism: different spectra looking the same color

Two spectra, t and s, perceptually match when

$$C_{eye}\vec{t} = C_{eye}\vec{s}$$

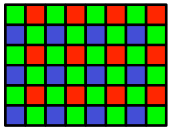
where C_{eye} are the cone response curves.

Graphically,



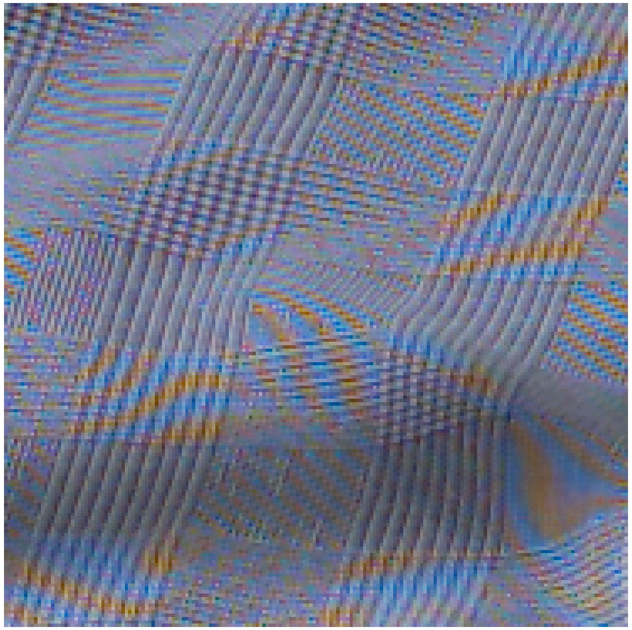
C_{eye} $\vec{t}$ = C_{eye} $\vec{s}$

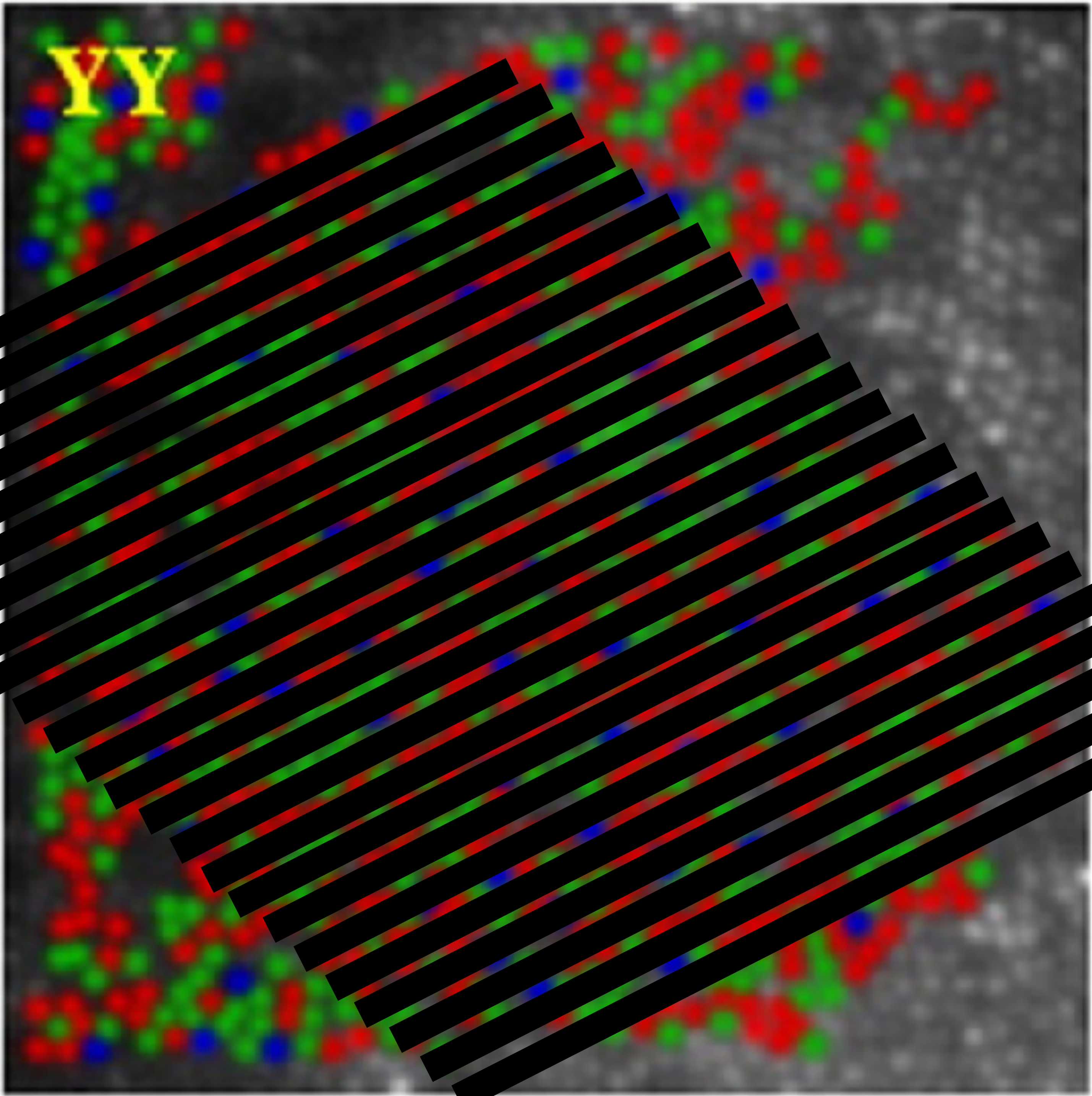
Evidence of spatially offset color sampling in an old digital camera



sensor color sampling pattern

- Color fringes or jaggies





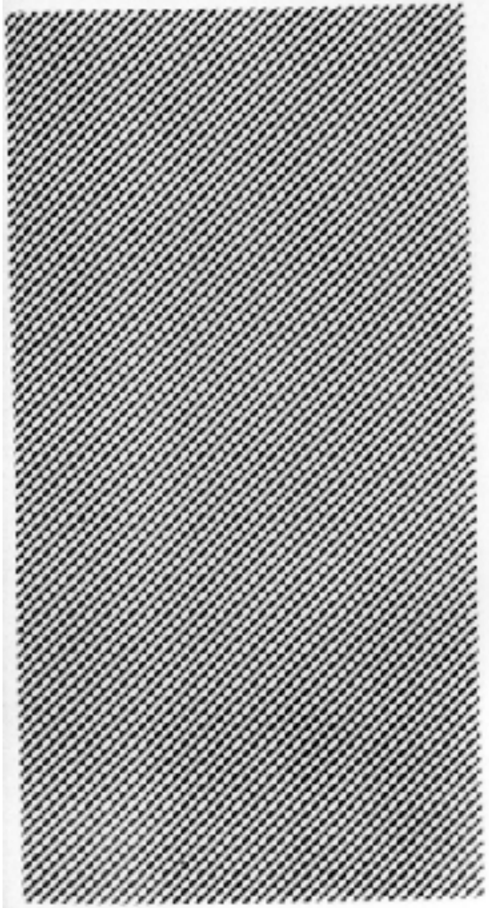
[redacted]

Where you can see color fringe reconstruction artifacts from your own eye

http://static.flickr.com/21/31393422_23013da003.jpg

Brewster's colors—evidence of interpolation from spatially offset color samples

Scale relative to human photoreceptor size: each line covers about 7 photoreceptors.



8 STATIONARY BLACK-AND-WHITE PATTERN in which pastel-like hues are seen as the eyes move slowly over the pattern.

from: Color Vision, by Leo M. Hurvich
Sinauer Assoc.

Lecture outline

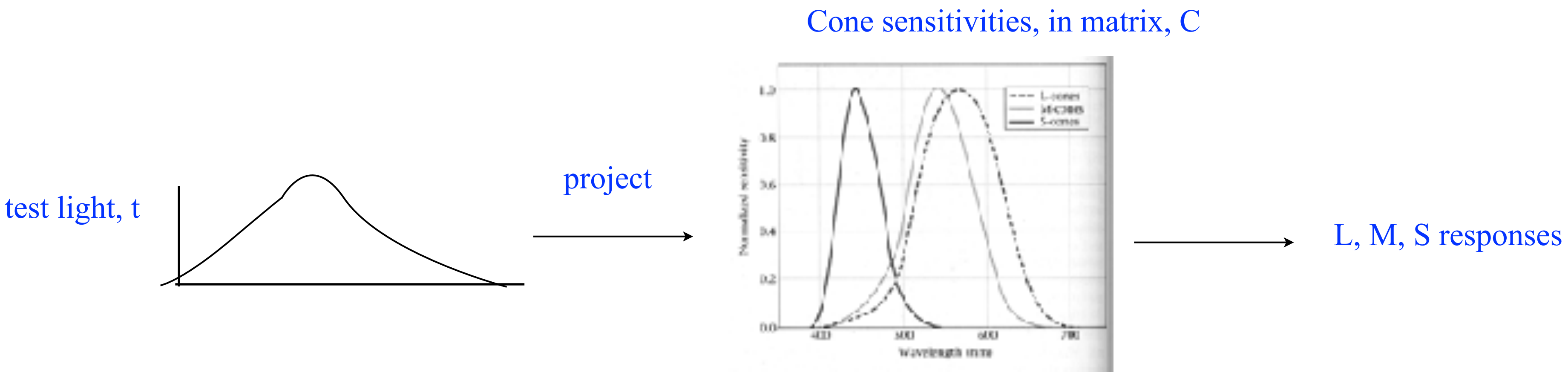
- Color physics.
- Color perception
  - part 1: assume perceived color only depends on light spectrum.
  - part 2: the more general case.

The assumption for color perception, part 1

- We know color appearance really depends on:
  - The illumination
  - Your eye's adaptation level
  - The colors and scene interpretation surrounding the observed color.

- But for now we will assume that <u>the spectrum of the light arriving at your eye completely determines the perceived color</u>.

How we sense light spectra



test light, t

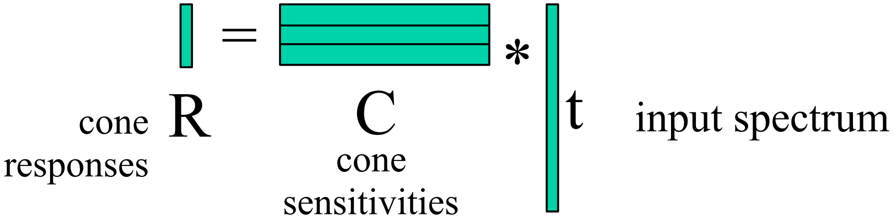
project

Cone sensitivities, in matrix, C

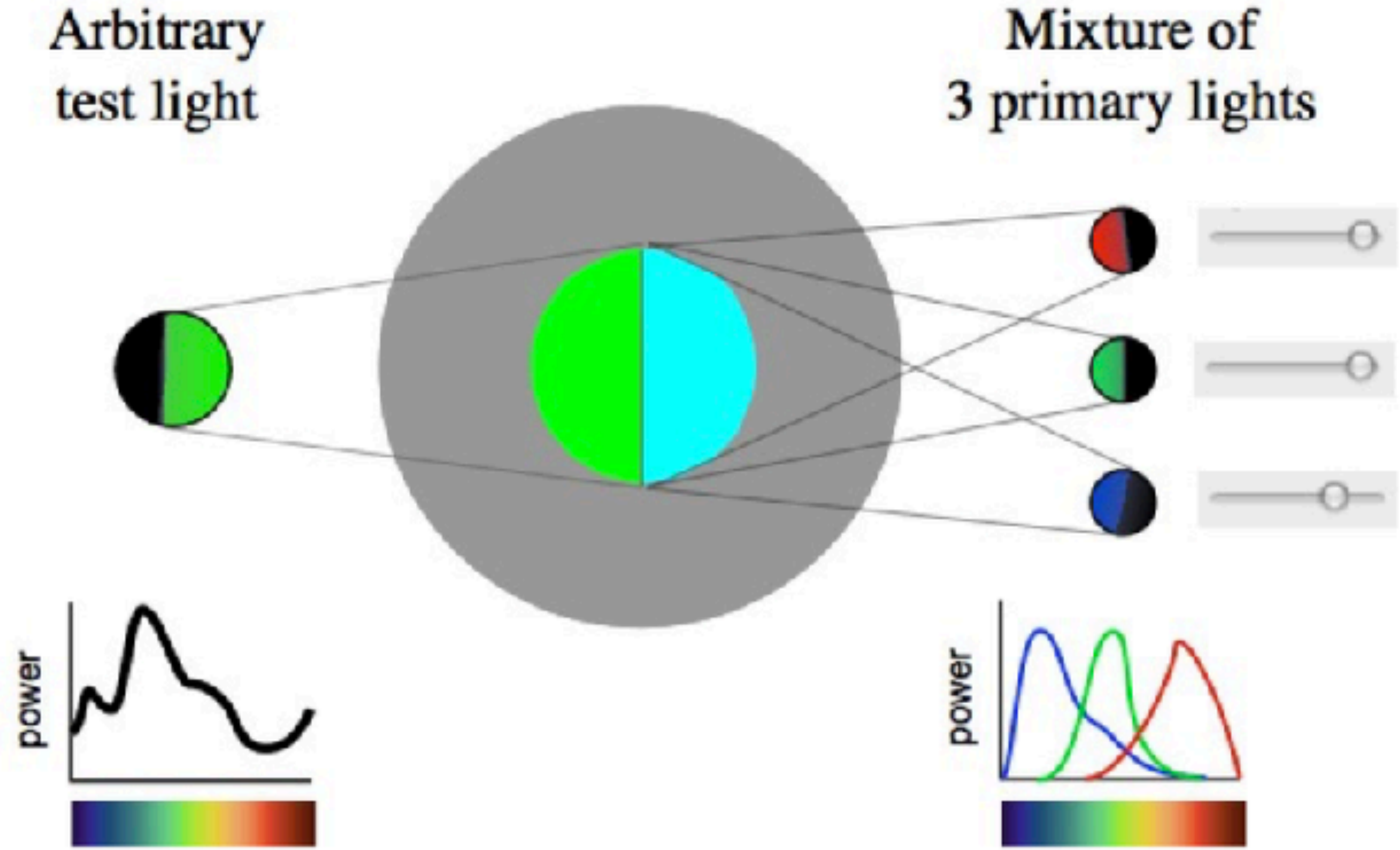
L, M, S responses

<u>biophysics:</u> integrate the response over all wavelengths, weighted by the photosensor's sensitivity at each wavelength.

<u>mathematically:</u> take dot product of input spectrum with the cone sensitivity basis vectors. Project the high-dimensional test light into a 3-d space. $R = C\, t$



Perceptual color matching experiment



Arbitrary test light

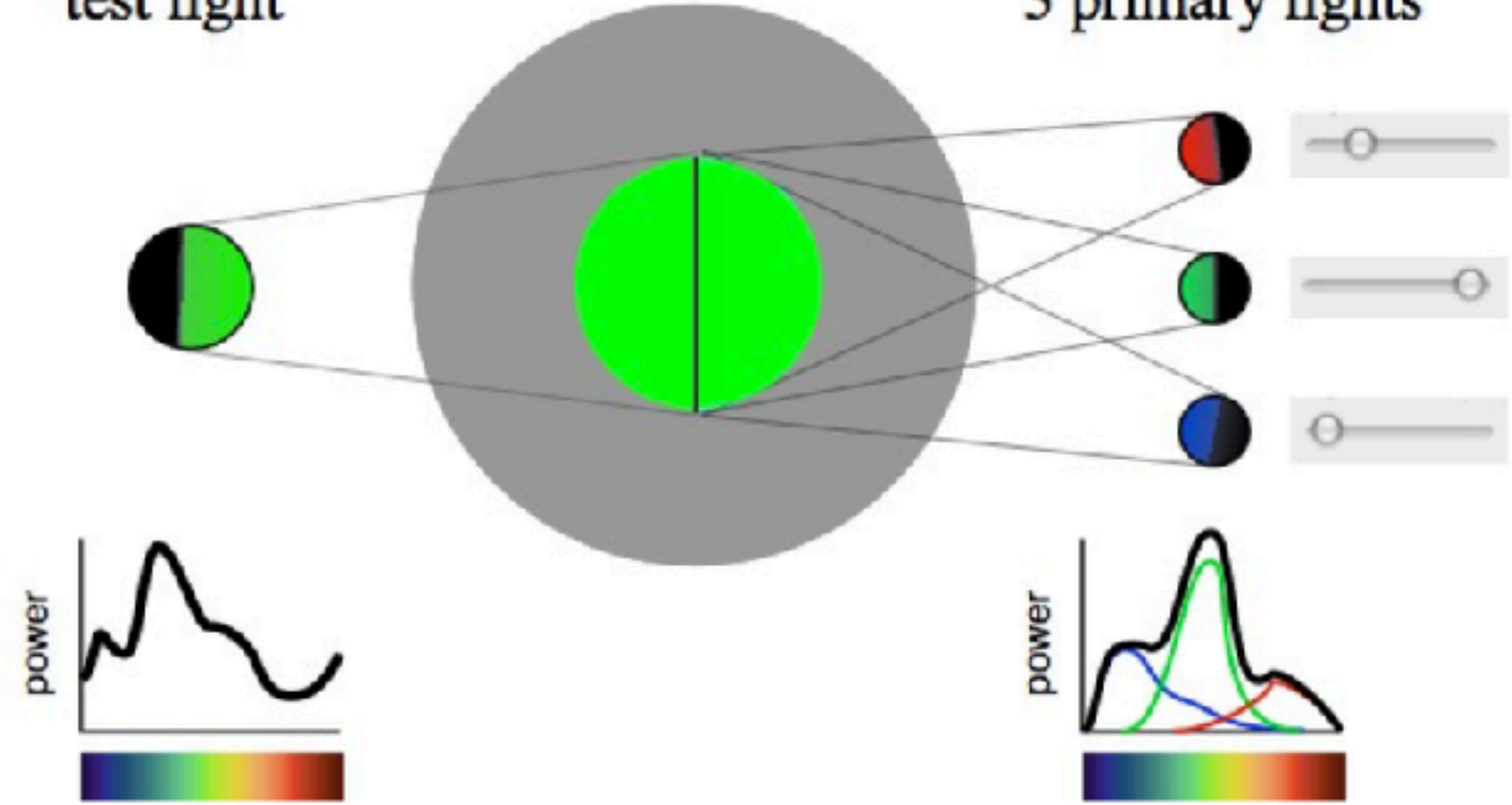
Mixture of 3 primary lights

[Young, Helmholtz, Grassman, etc, 1800's; slide c/o D. Brainard]

Perceptual color matching experiment

Arbitrary
test light

Mixture of
3 primary lights

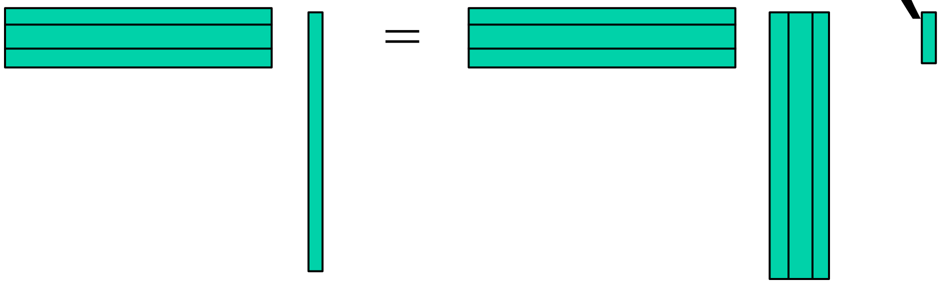


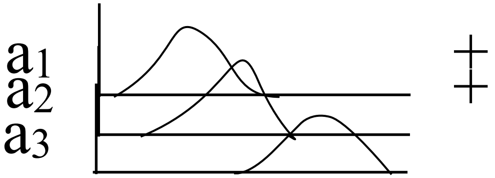
[Young, Helmholtz, Grassman, etc, 1800's; slide c/o D. Brainard]

To measure a color

1. Choose a set of 3 primary colors (three power spectra).
2. Determine how much of each primary needs to be added to a probe signal to match the test light.

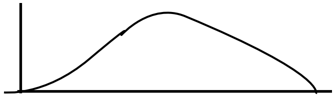
$$C_{eye} \quad t \quad = \quad C_{eye} \quad P \begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix}$$



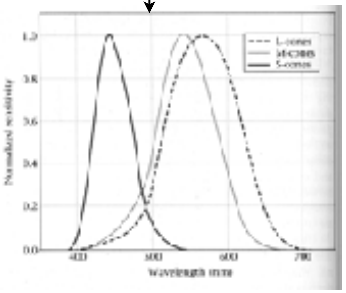


Primaries, P

weighted sum of primaries

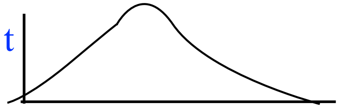


project

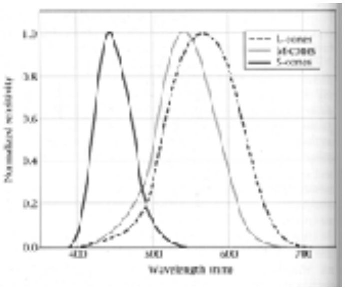


Cone sensitivities

test light, t



project

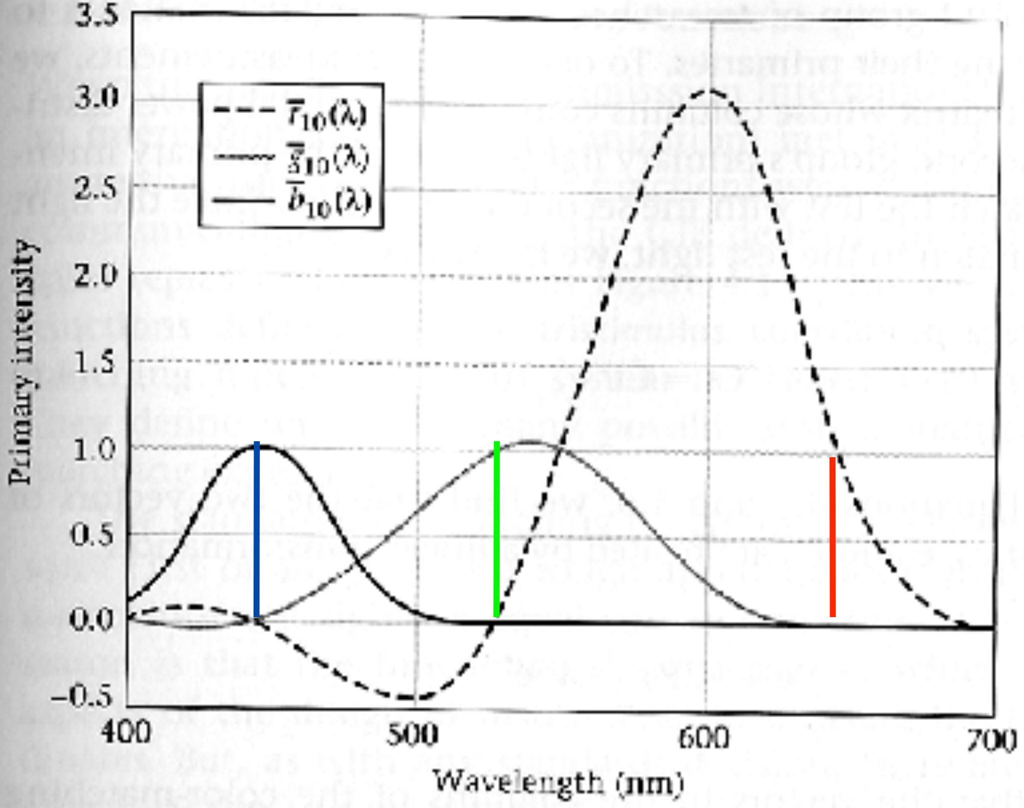


Cone sensitivities, C_{eye}

L, M, S responses

“Color matching functions” tell us how to control primary lights in order to perceptually match a given spectrum

🟥 $p_1 = 645.2$ nm
🟩 $p_2 = 525.3$ nm
🟦 $p_3 = 444.4$ nm



4.13 THE COLOR-MATCHING FUNCTIONS ARE THE ROWS OF THE COLOR-MATCHING SYSTEM MATRIX. The functions measured by Stiles and Burch (1959) using a 10-degree bipartite field and primary lights at the wavelengths 645.2 nm, 525.3 nm, and 444.4 nm with unit radiant power are shown. The three functions in this figure are called $\bar{r}_{10}(\lambda)$, $\bar{g}_{10}(\lambda)$, and $\bar{b}_{10}(\lambda)$.

Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Requirements on C, P to form a color matching system:

(1) the rows of C must be some (non-degenerate) linear combination of the eye photosensor response curves: $C = A C_{eye}$, where A is some 3x3 matrix.

That ensures that if two spectra match when projected into the subspace spanned by C, they will match when projected into the subspace of the eye response curves.

(2) for projecting onto C to tell you how much of each primary P is needed to make a perceptual match, C, P must satisfy:

$$C P = I_{3x3}$$

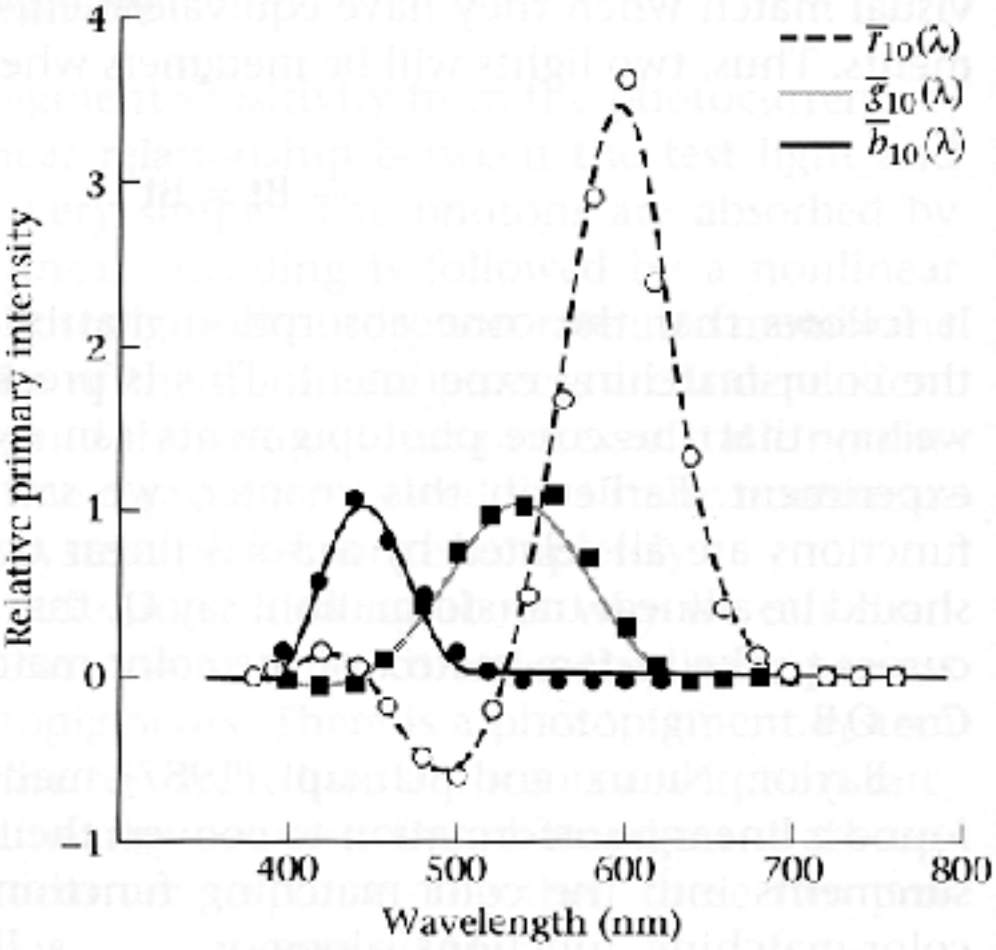
why must this hold? Because the amounts of the 3 primaries needed to match the spectrum of each primary (the columns of P) must be [1;0;0], [0;1;0], [0;0;1].

If those conditions hold, then the spectrum PCt will be a perceptual match to t, because

$Ct = CPCt$

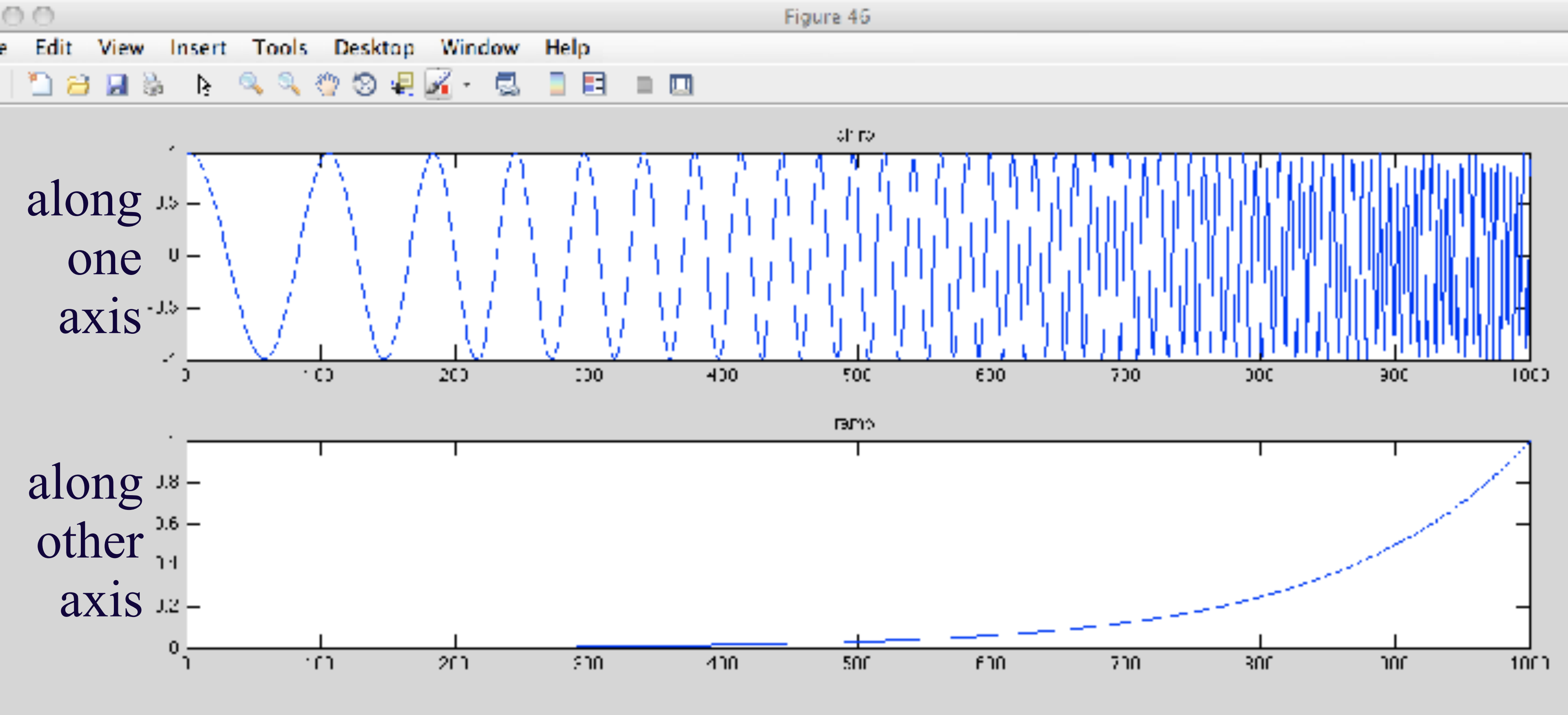
Comparison of color matching functions with best linear combination of cone response curves

4.20 COMPARISON OF CONE PHOTOCURRENT RESPONSES AND THE COLOR-MATCHING FUNCTIONS. The cone photocurrent spectral responsivities are within a linear transformation of the color-matching functions, after a correction has been made for the optics and inert pigments in the eye. The smooth curves show the Stiles and Burch (1959) color-matching functions. The symbols show the matches predicted from the photocurrents of the three types of macaque cones. The predictions included a correction for absorption by the lens and other inert pigments in the eye. Source: Baylor, 1987.



Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Displaying Contrast Sensitivity Function (CSF)



along one axis

along other axis

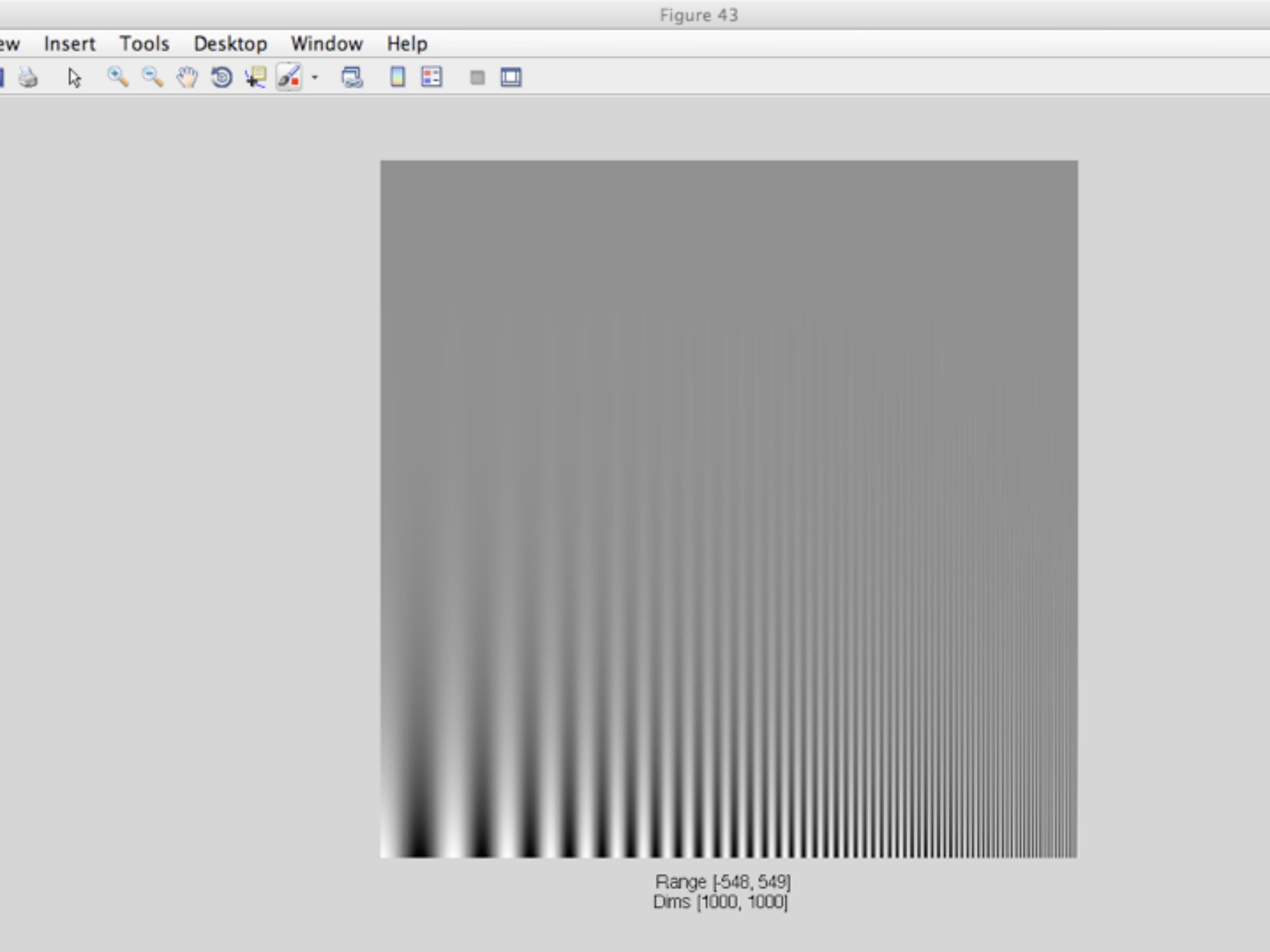


Figure 43
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Insert
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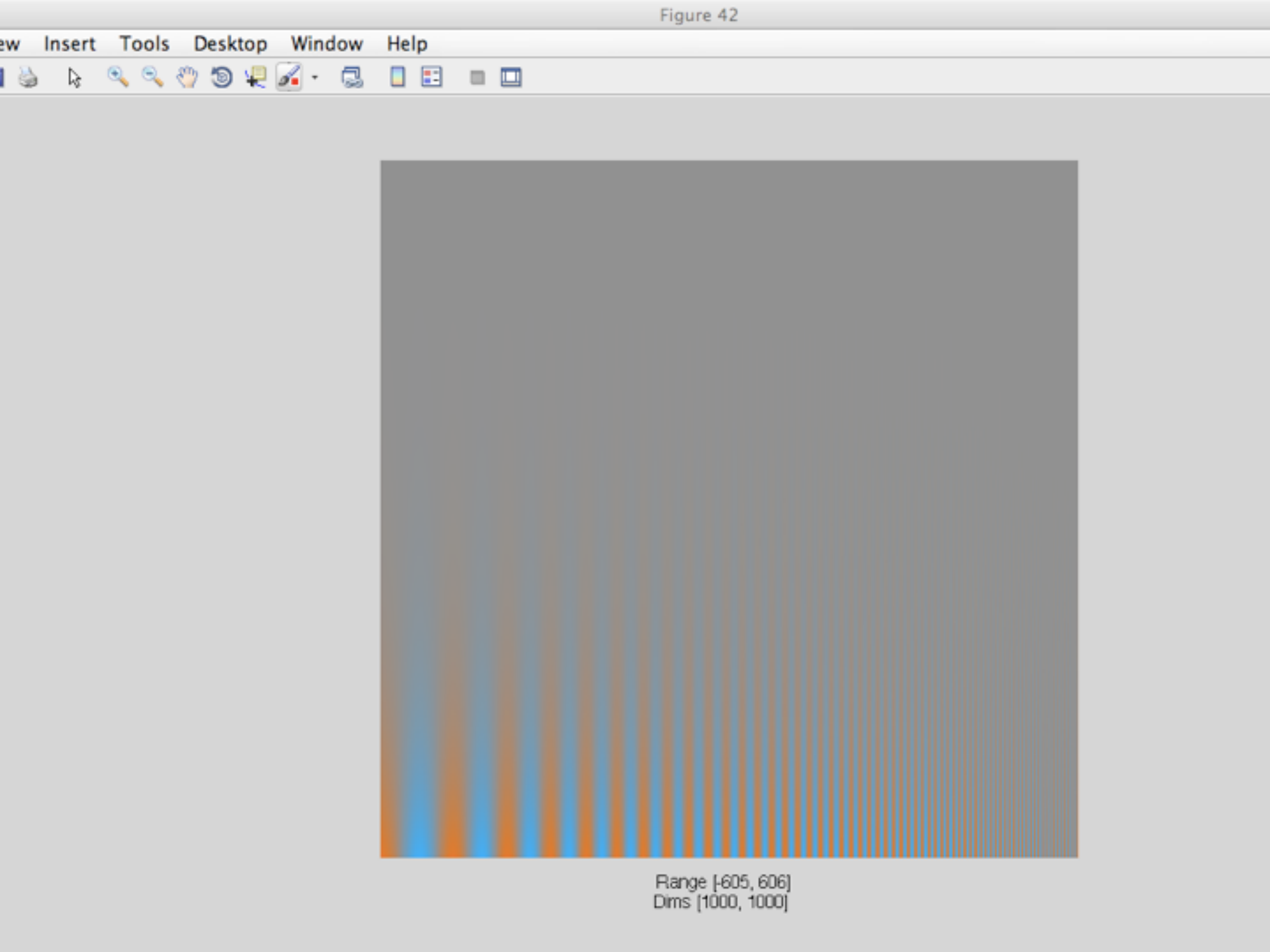

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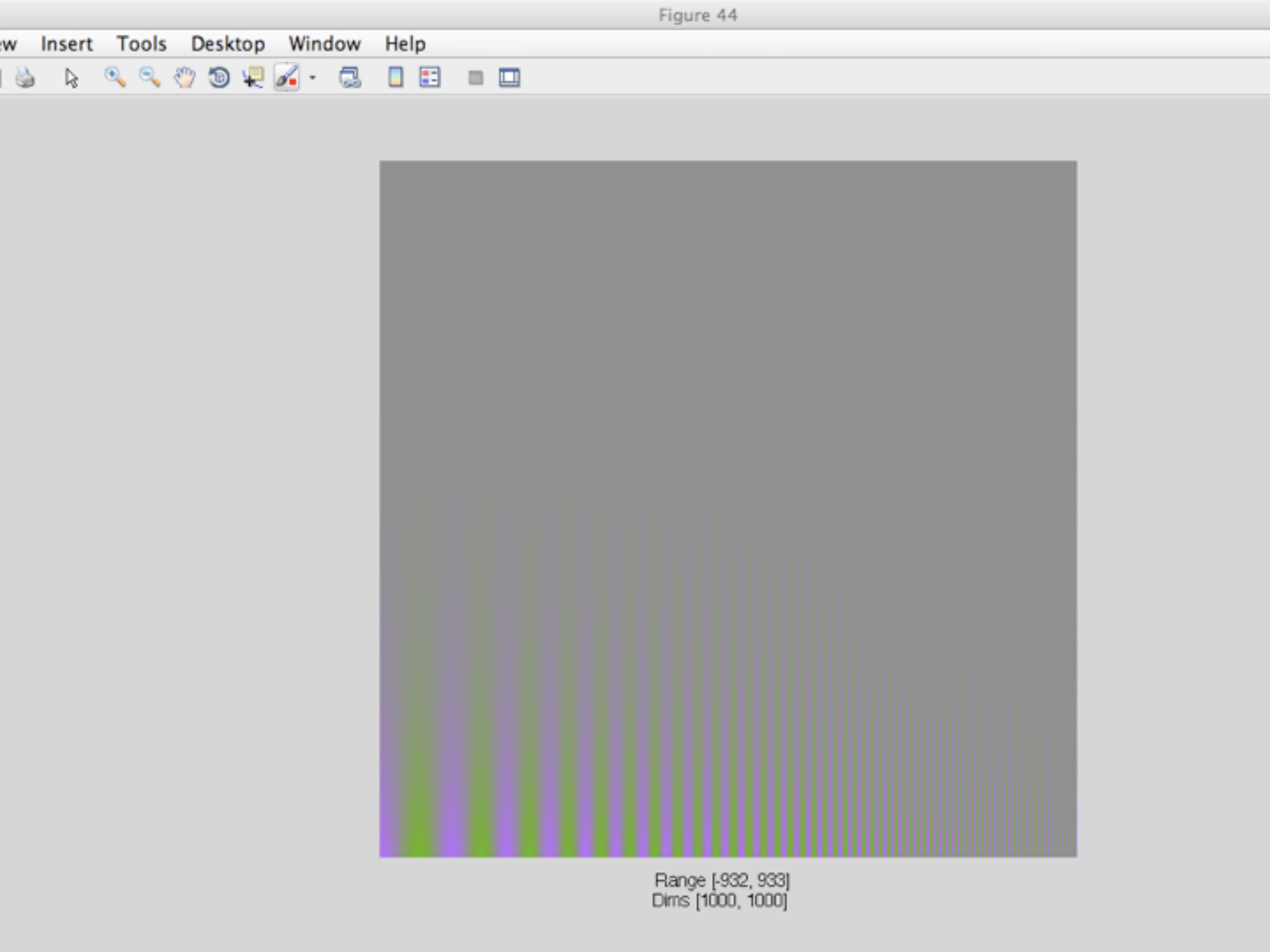

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Dims [1000, 1000]

Another psychophysical fact: luminance and chrominance channels in the brain

From W. E. Glenn, in Digital Images and Human Vision, MIT Press, edited by Watson, 1993

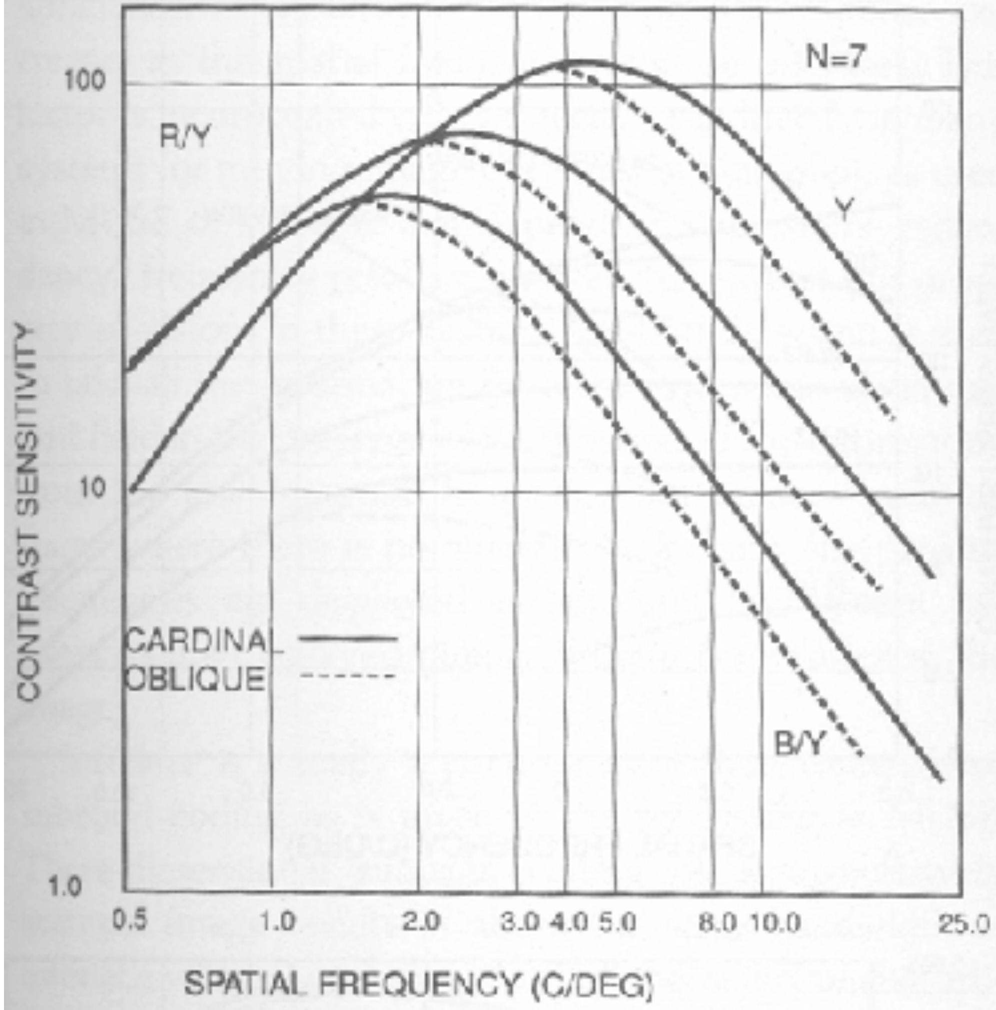


Figure 6.1
Contrast sensitivity threshold functions for static luminance gratings (Y) and isoluminance chromaticity gratings (R/Y.B/Y) averaged over seven observers.

luminance, chrominance color components: Y, I, Q

$$\begin{pmatrix} Y \\ I \\ Q \end{pmatrix} = \begin{pmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.274 & -0.322 \\ 0.211 & -0.523 & 0.312 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

YIQ - RGB


rgb color component 1

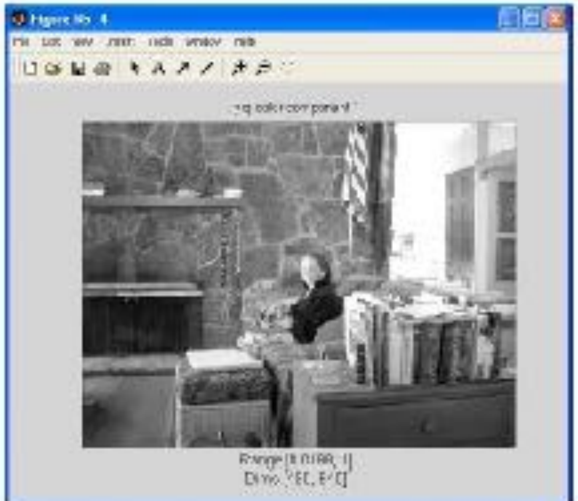
R

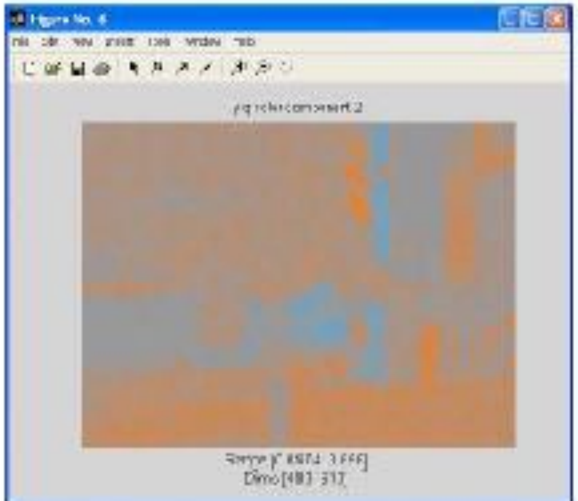

rgb color component 2

G


rgb color component 3

B


yiq color component 1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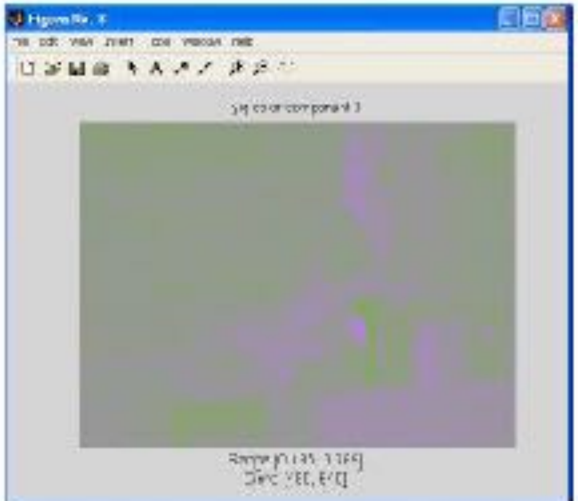

yiq color component 3

Spatial resolution and color

original

R

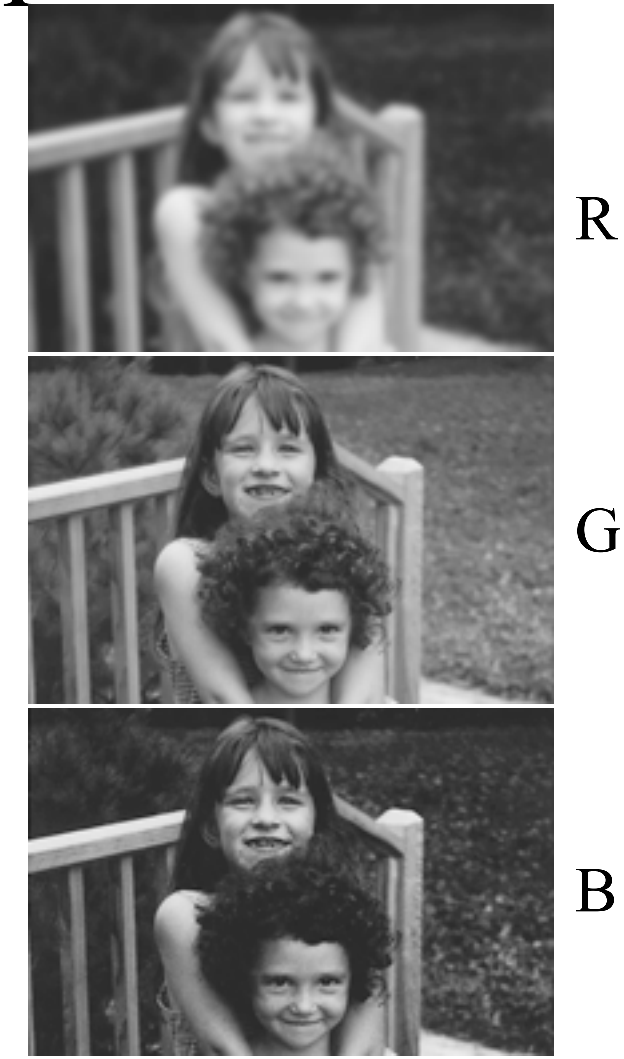
G

B

Blurring the R component

original

processed



Blurring the G component

original

processed

R

G

B

Blurring the B component

original

processed

R

G

B

Lab color components

L

a

b

A rotation of the color coordinates into directions that are more perceptually meaningful:
L: luminance,
a: red-green,
b: blue-yellow

Blurring the L Lab component

original

processed

L

a

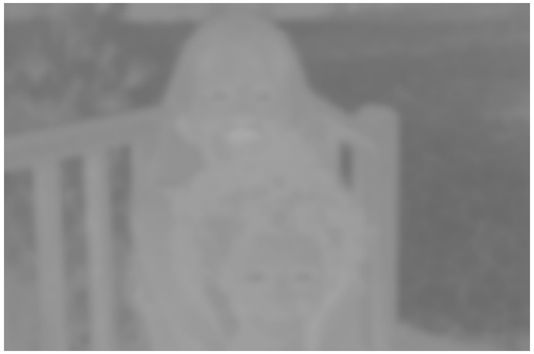
b

Blurring the a Lab component

original

processed

L



a

b

Blurring the b Lab component

original

processed

L

a

b

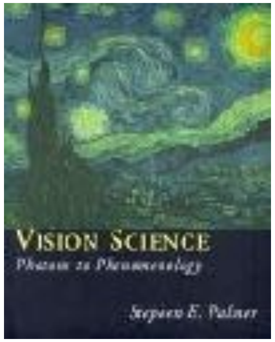
Lecture outline

- Color physics.
- Color perception
  - part 1: assume perceived color only depends on light spectrum.
  - part 2: the more general case.

Color constancy demo

- We assumed that the spectrum impinging on your eye determines the object color. That’s often true, but not always. Here’s a counter-example…

Selected Bibliography



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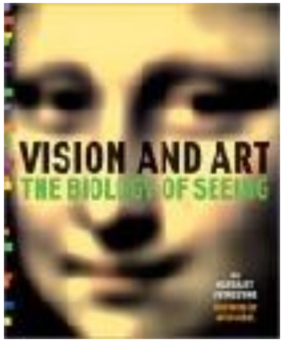

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Harry N Abrams; ISBN: 0810904063
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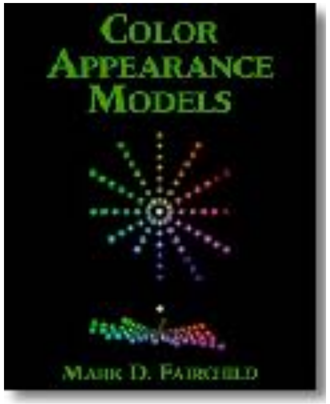

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Other color references

- Reading:
  - – Chapter 6, Forsyth & Ponce
  - – Chapter 4 of Wandell, Foundations of Vision, Sinauer, 1995 has a good treatment of this.