How wavelength starts to become color

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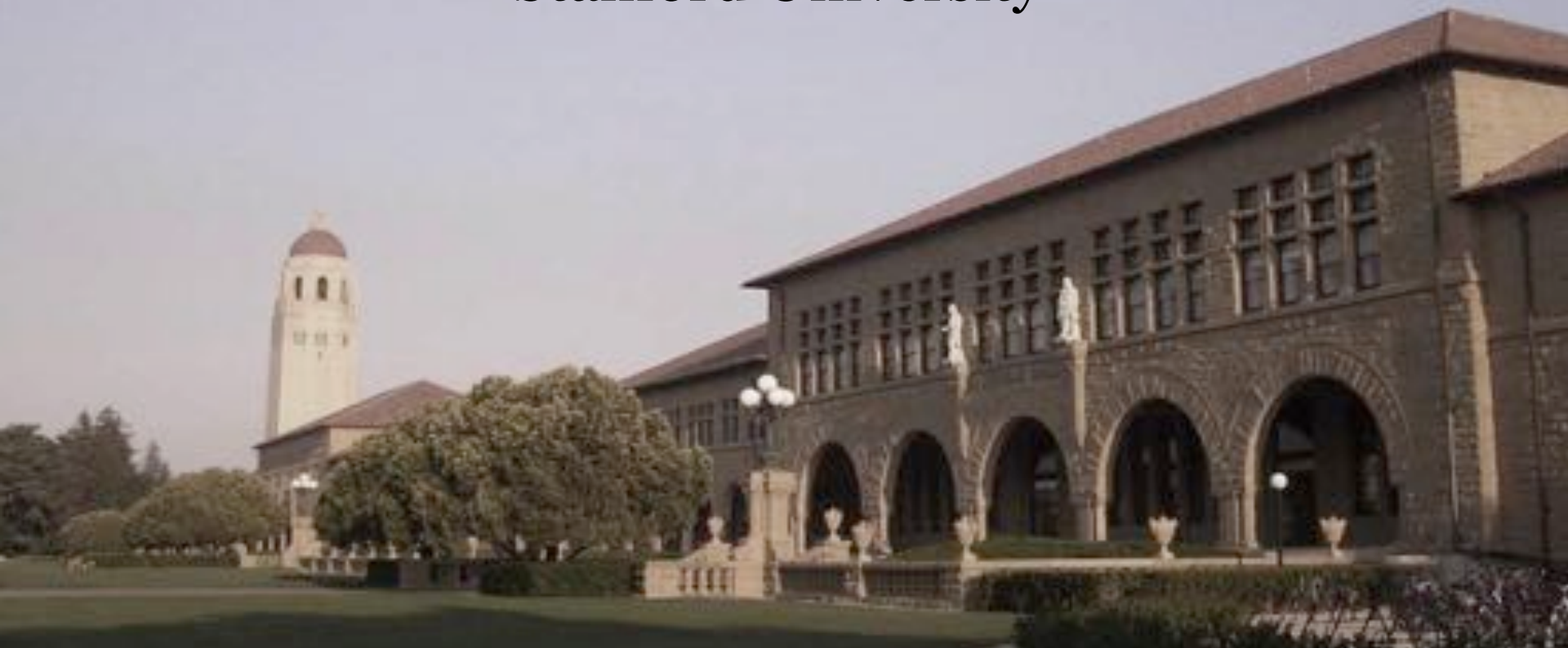
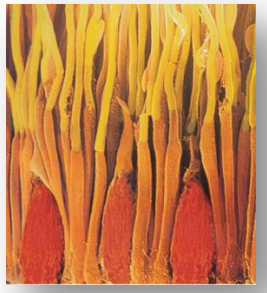


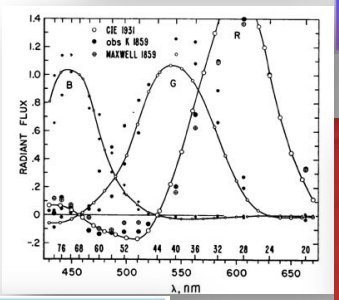
Fig. 7-1b, p. 143

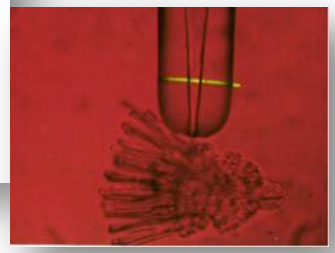
Fig. 7-1a, p. 143

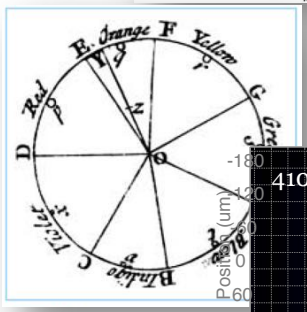
In 90 minutes today

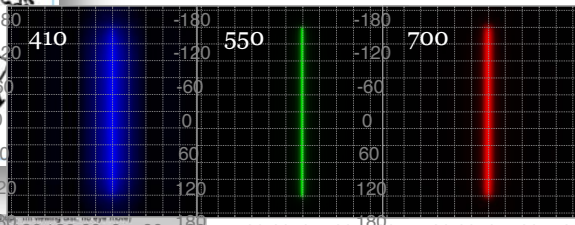
- Primate optics, retina, fovea
- Light
- Color matching experiment
- Color matching equations
- Cone physiology
- Historical notes
- ISETBIO – computation

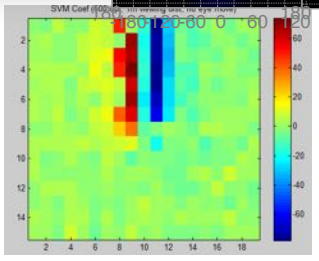








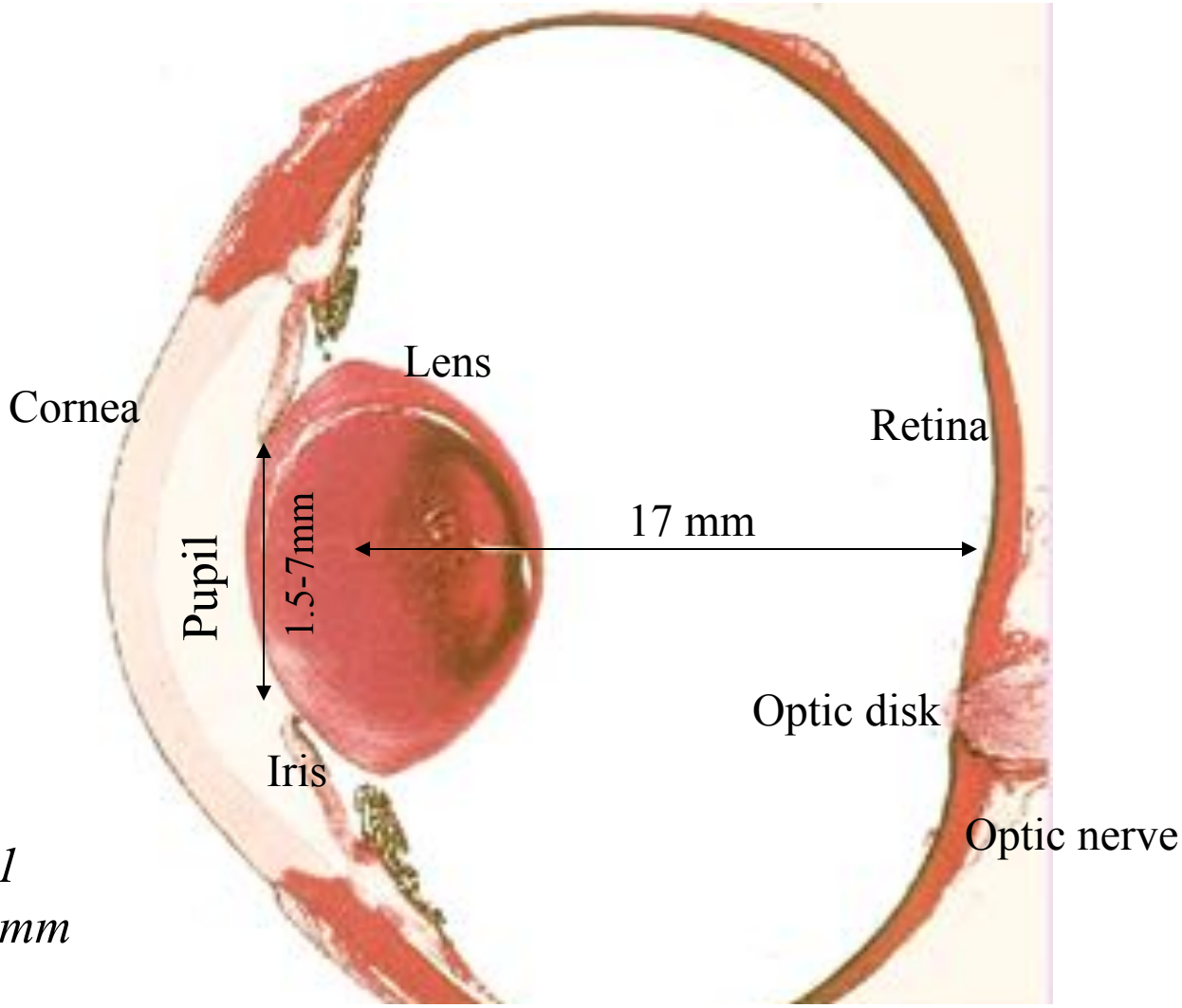




Color-matching is crucial to the display industry

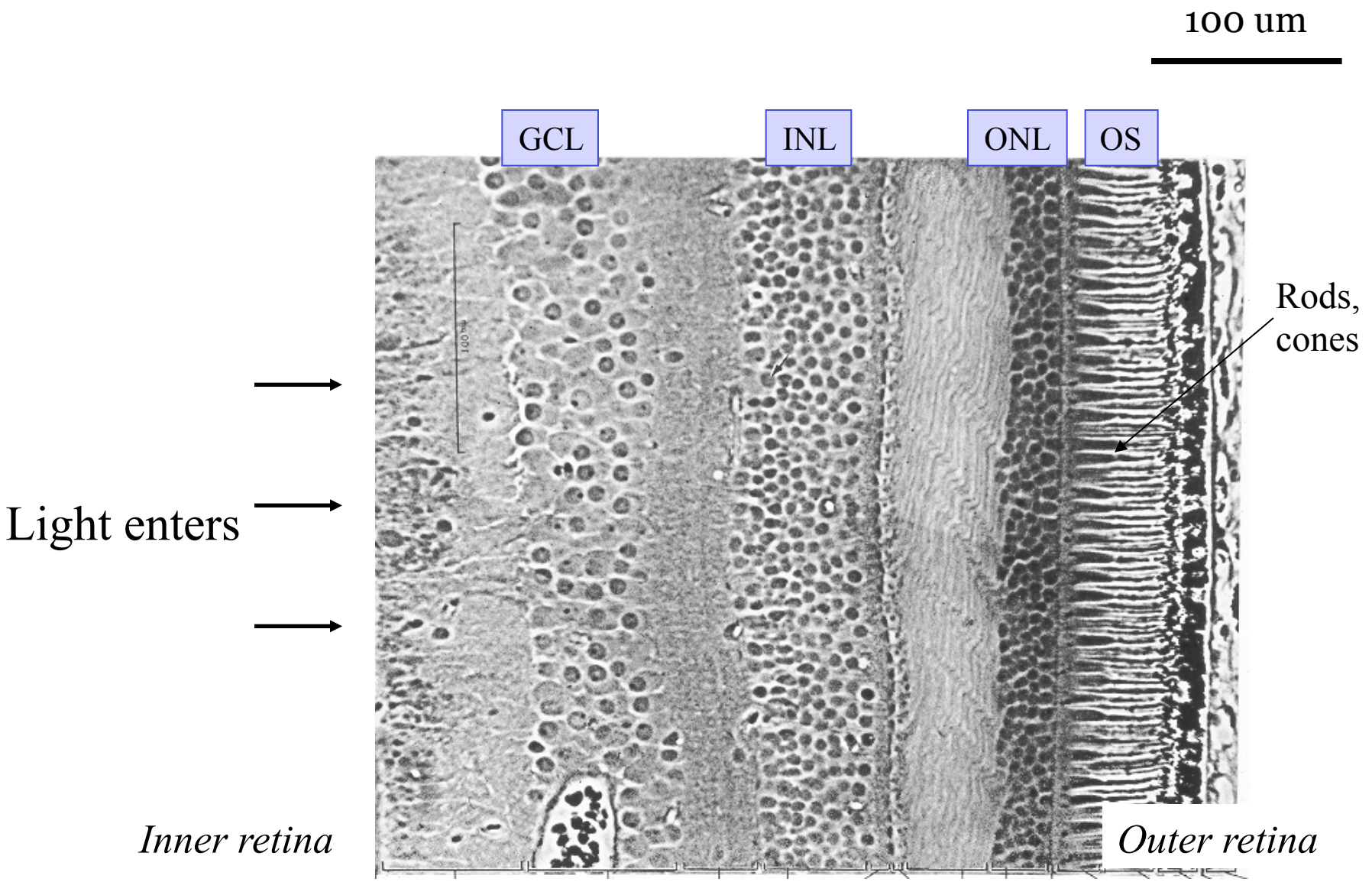
Primate optics, retina and fovea

Human eye in cross-Section

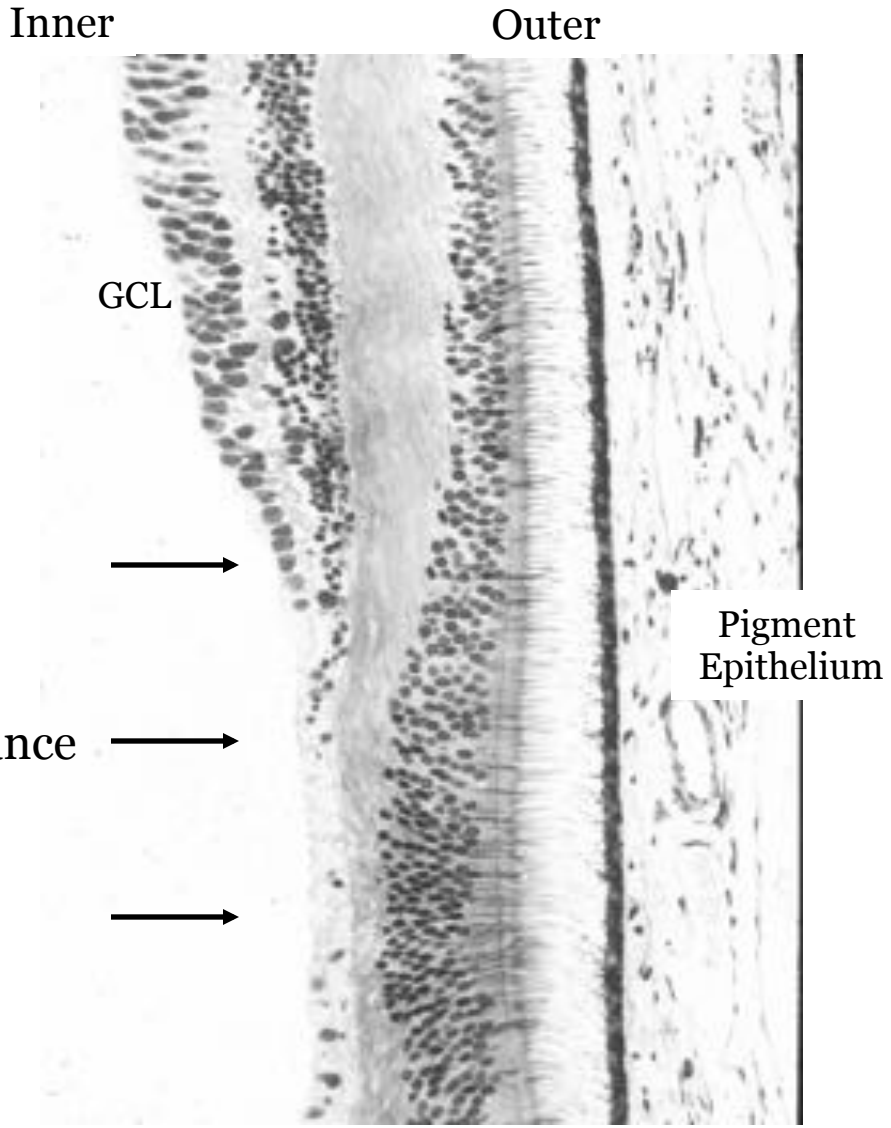


F-number (f/a) ~ 2.4-11
Retinal thickness ~ 0.5mm

Light passes through the retinal cells and a fraction is absorbed by the rod and cone photopigments



The primate central fovea (pit) contains only cones and combines with the eye movement system to specialize for acuity and color



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

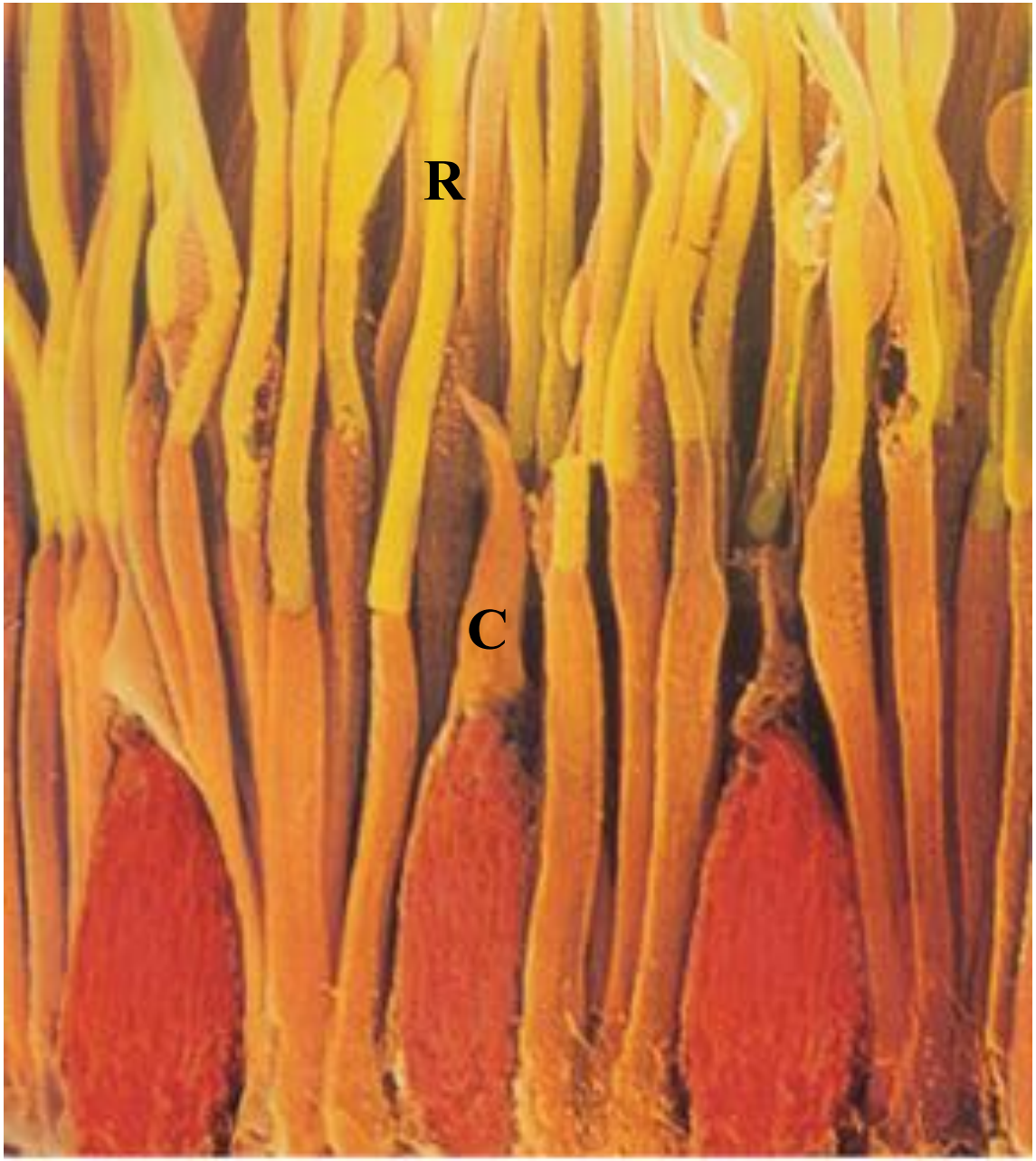
http://webvision.med.utah.edu/photo1.html

Rods and Cones

Outer segments

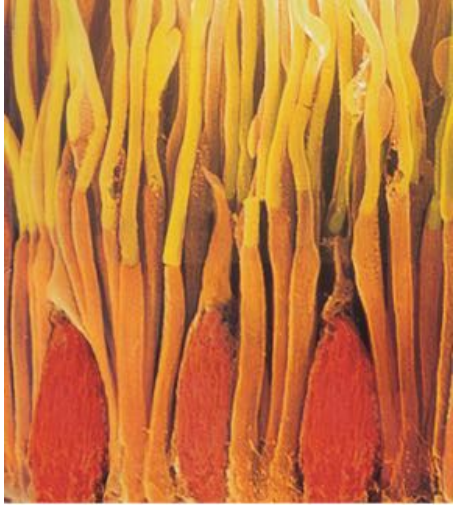
Rods and cones imaged by a scanning electron microscope. Each rod is about one micron cross-section.

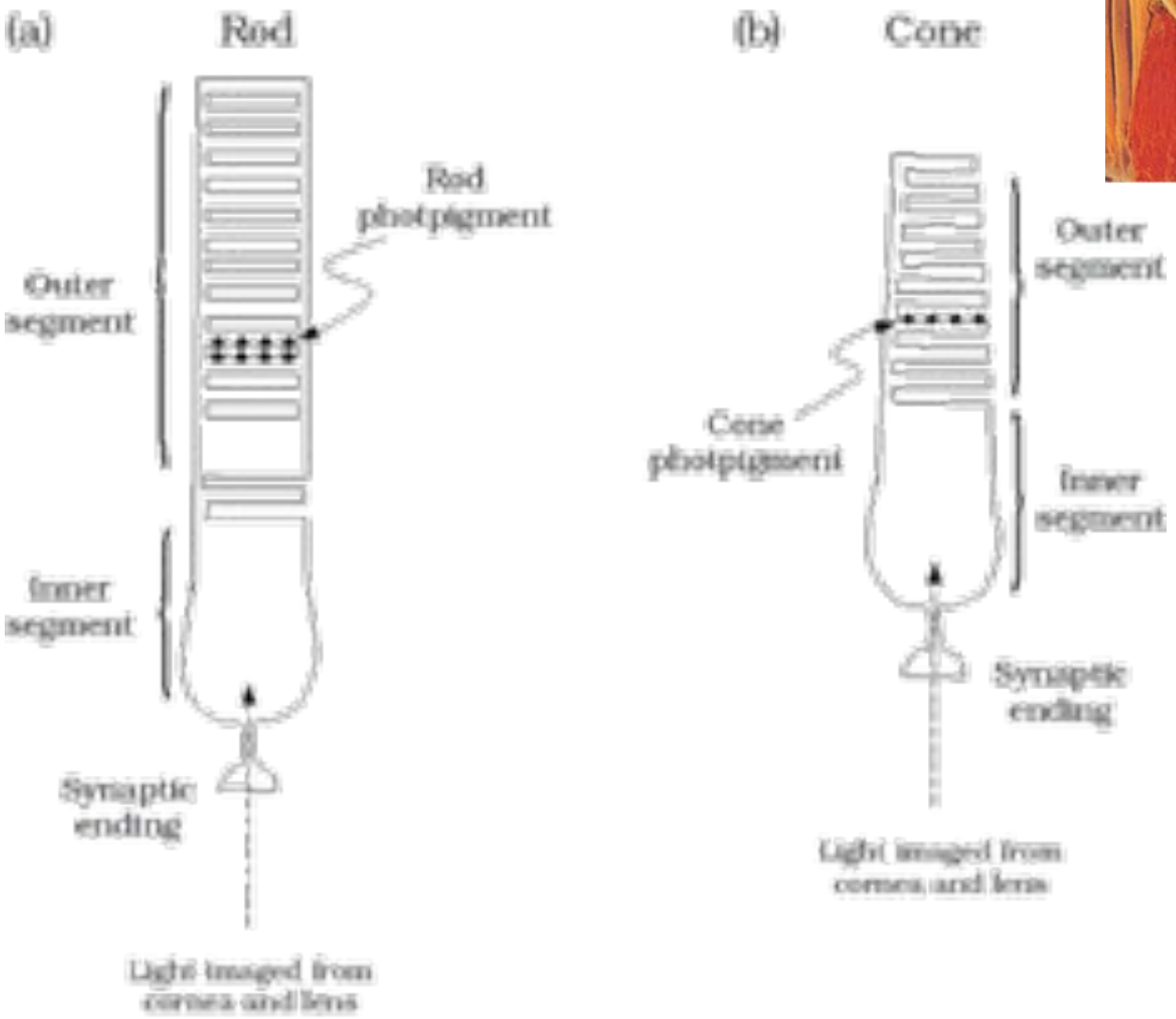
Inner segments



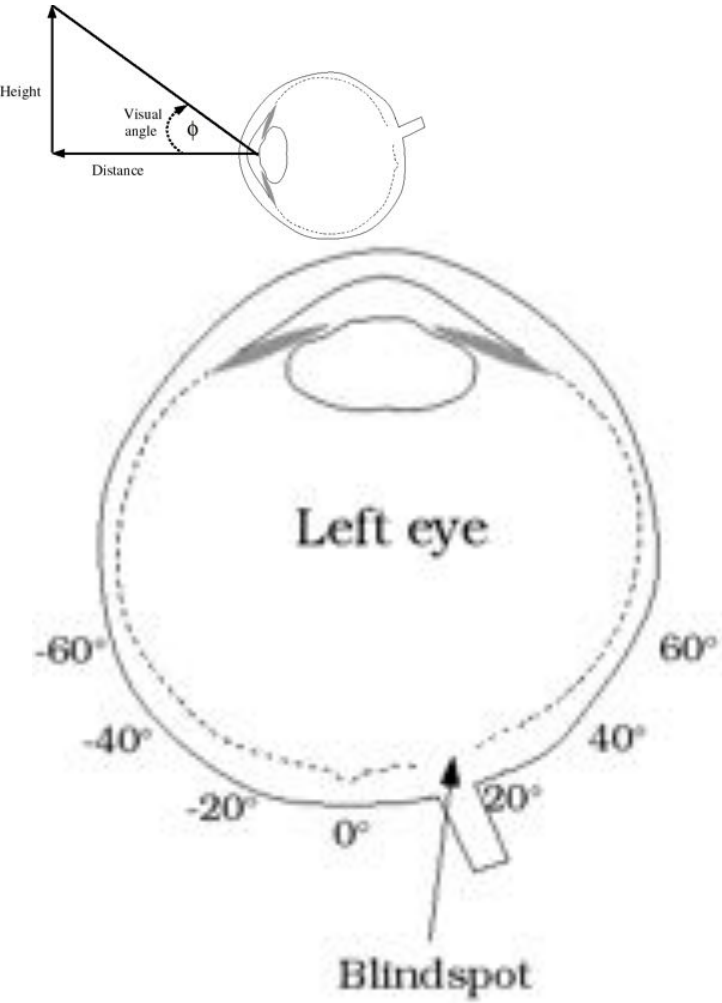
Receptor schematics

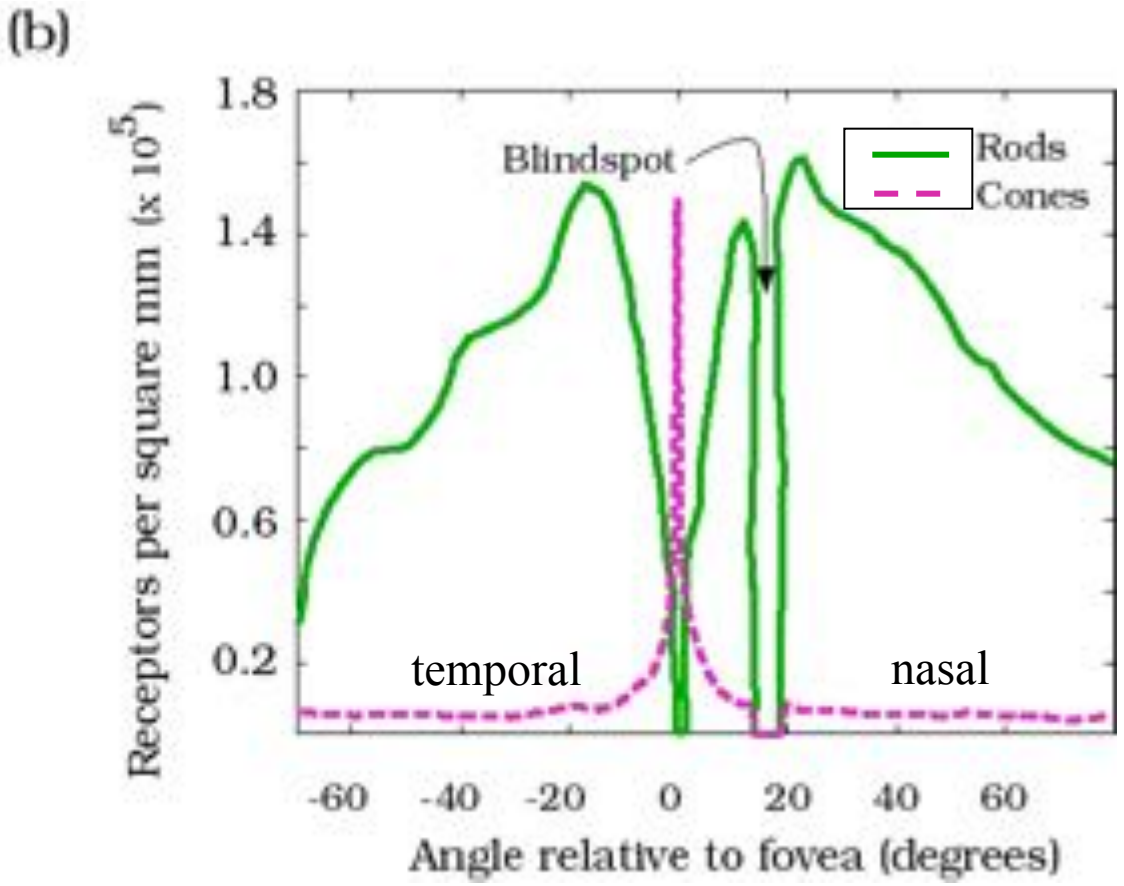
(Baylor, Proctor lecture, 1987)





Spatial distribution of human photoreceptors (rods and cones)

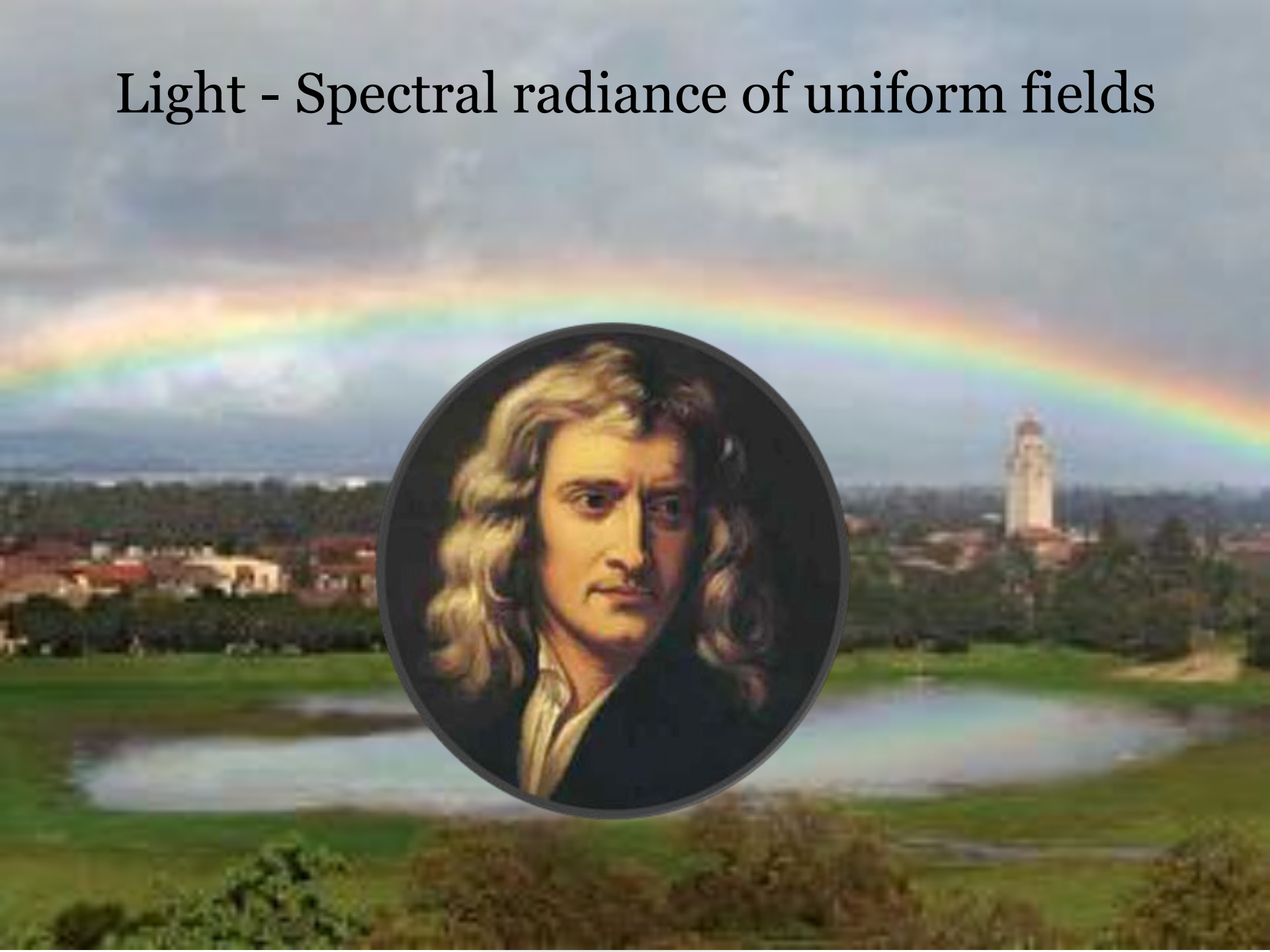




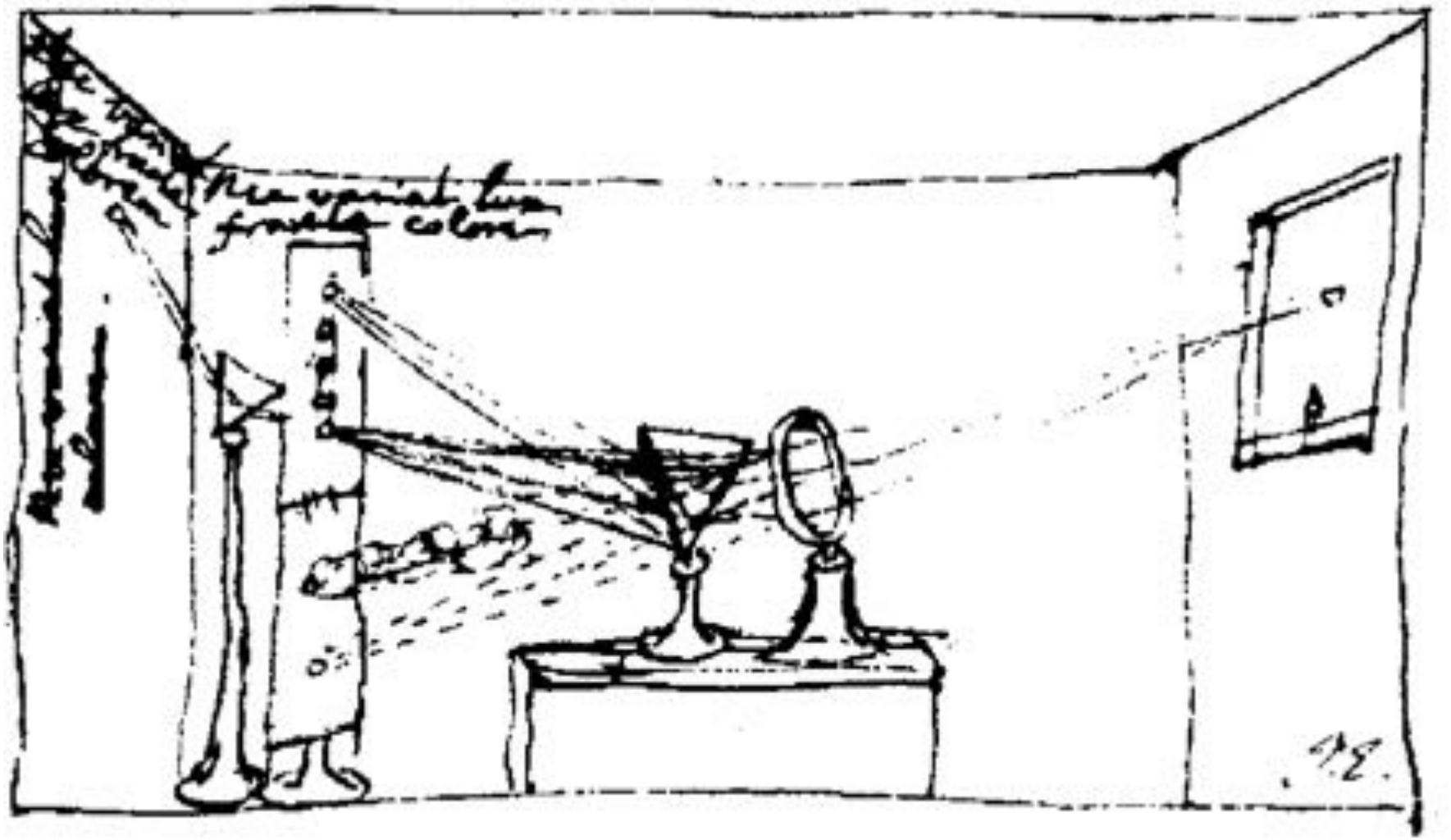
The unbleached rod photopigment, rhodopsin, can be seen in the living eye

After exposure to light, the pigment becomes transparent

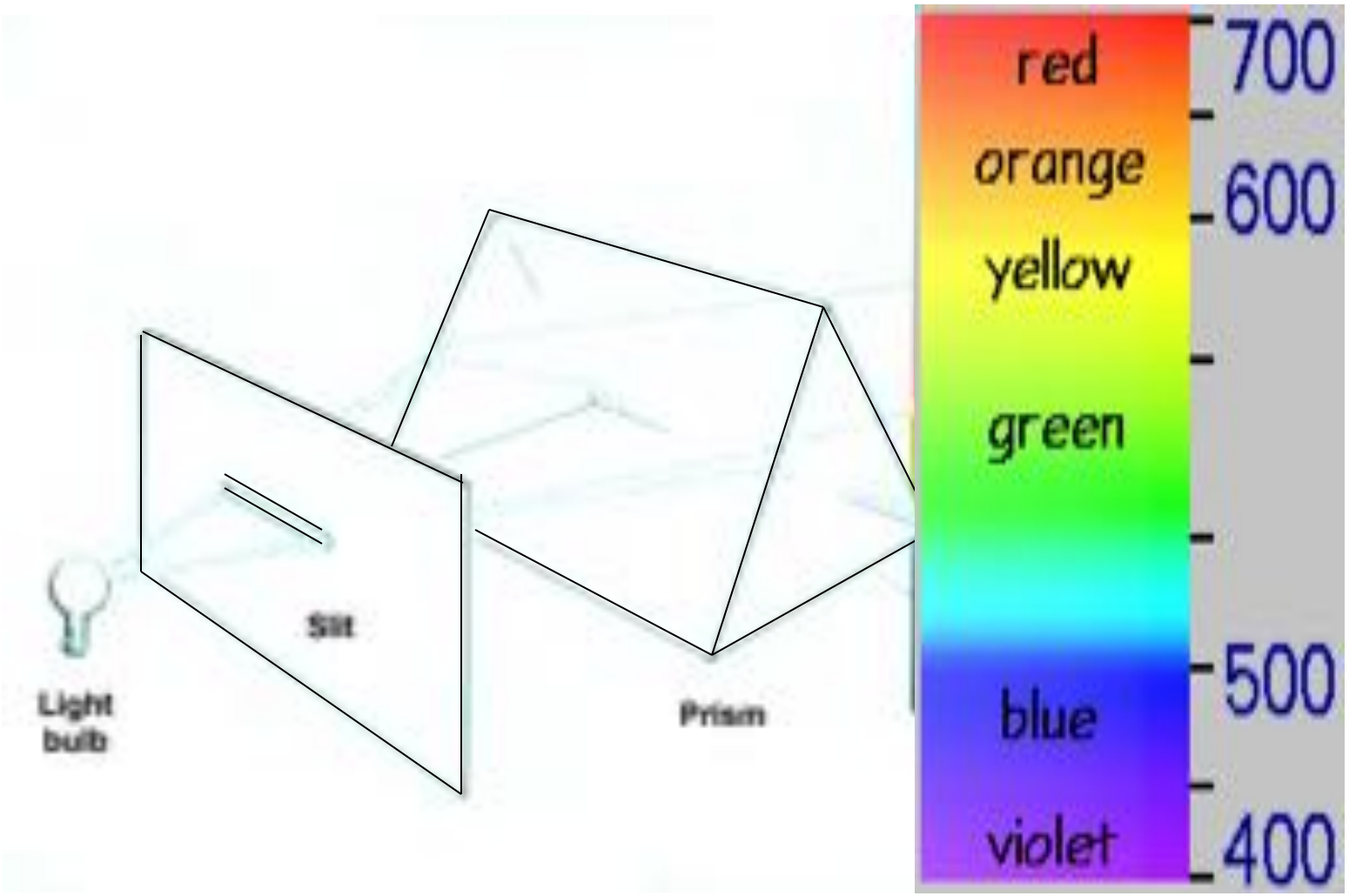
Light - Spectral radiance of uniform fields



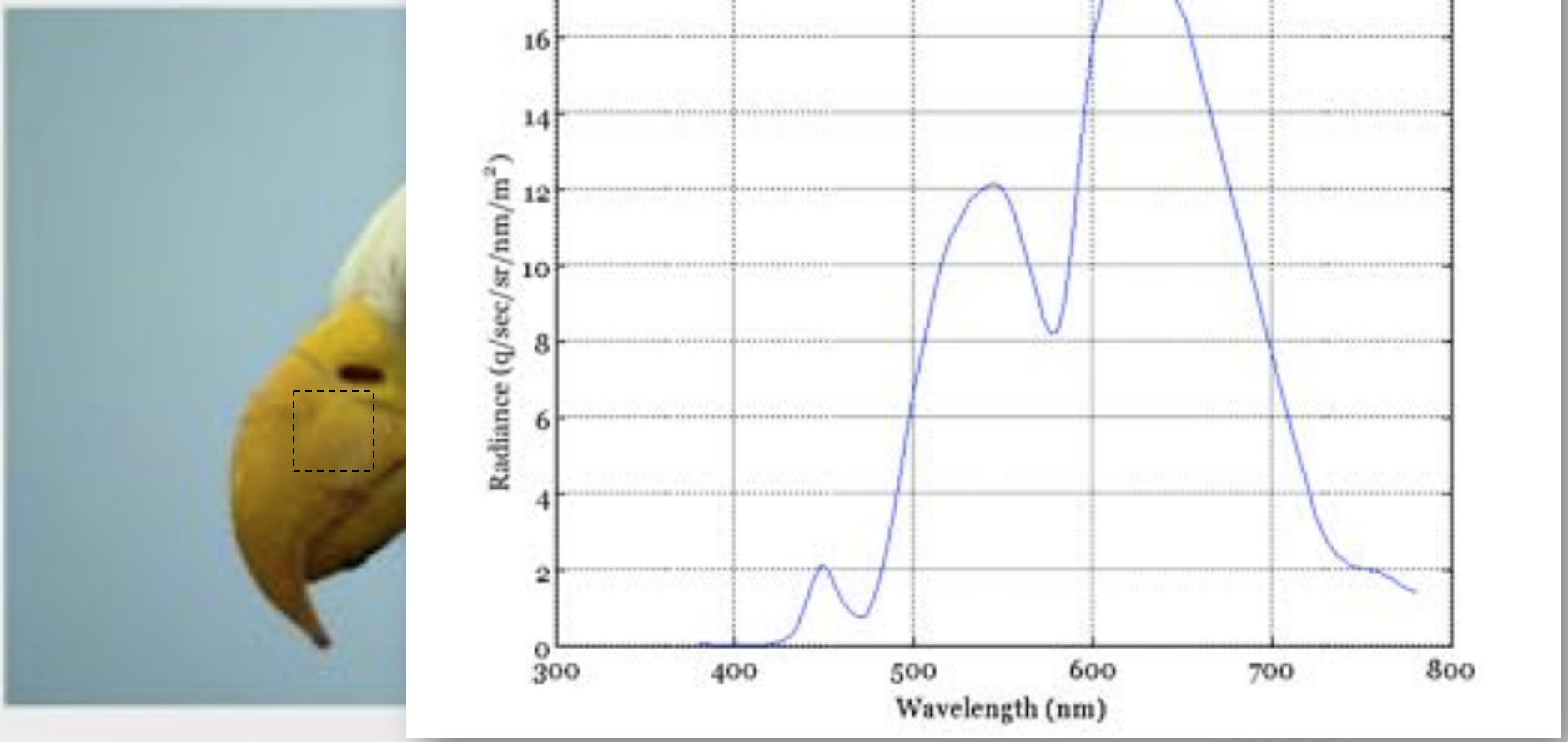
The fundamental components of light



Monochromators measure the energy at different wavelengths



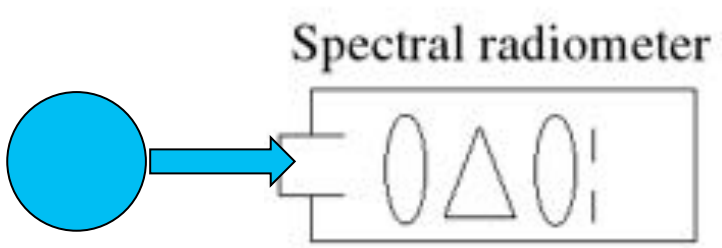
ISETBIO: scene window

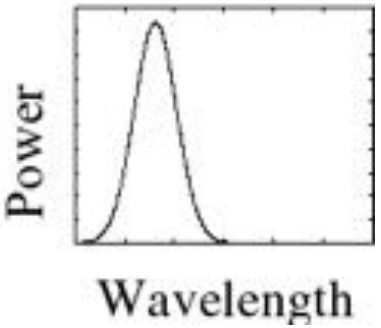


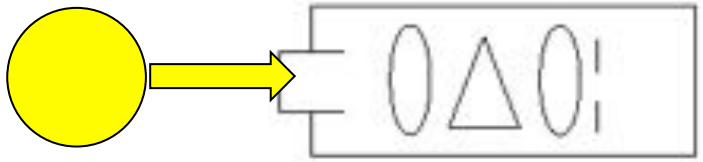
Color-matching

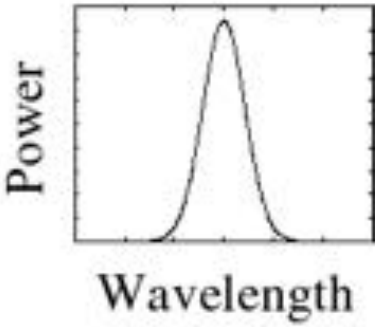
Superposition of light

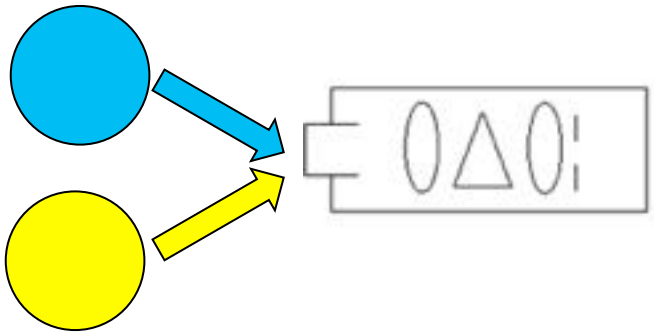
- Mixture (summation) experiments are fundamental throughout science
- Mixtures of incoherent lights sum

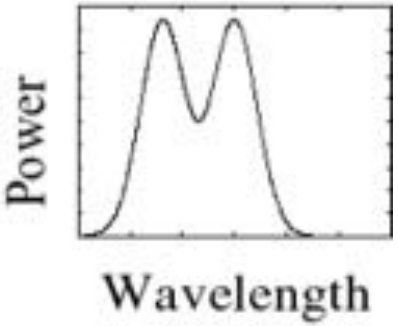




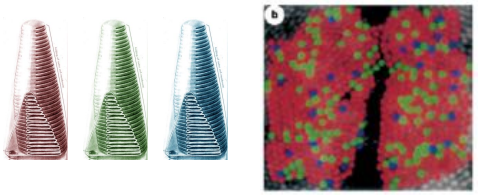




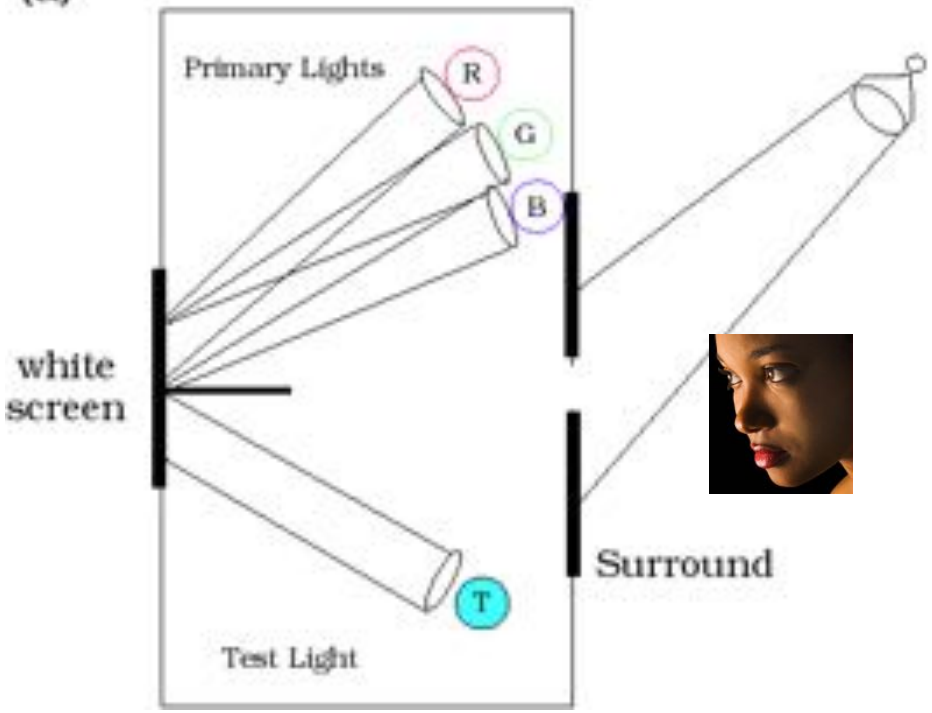




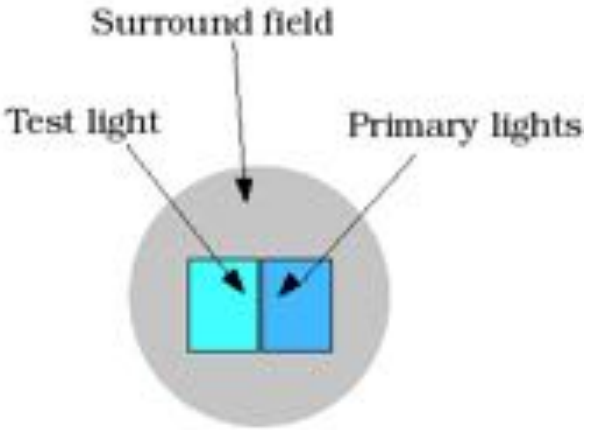
Cone color matching experiment



(a)

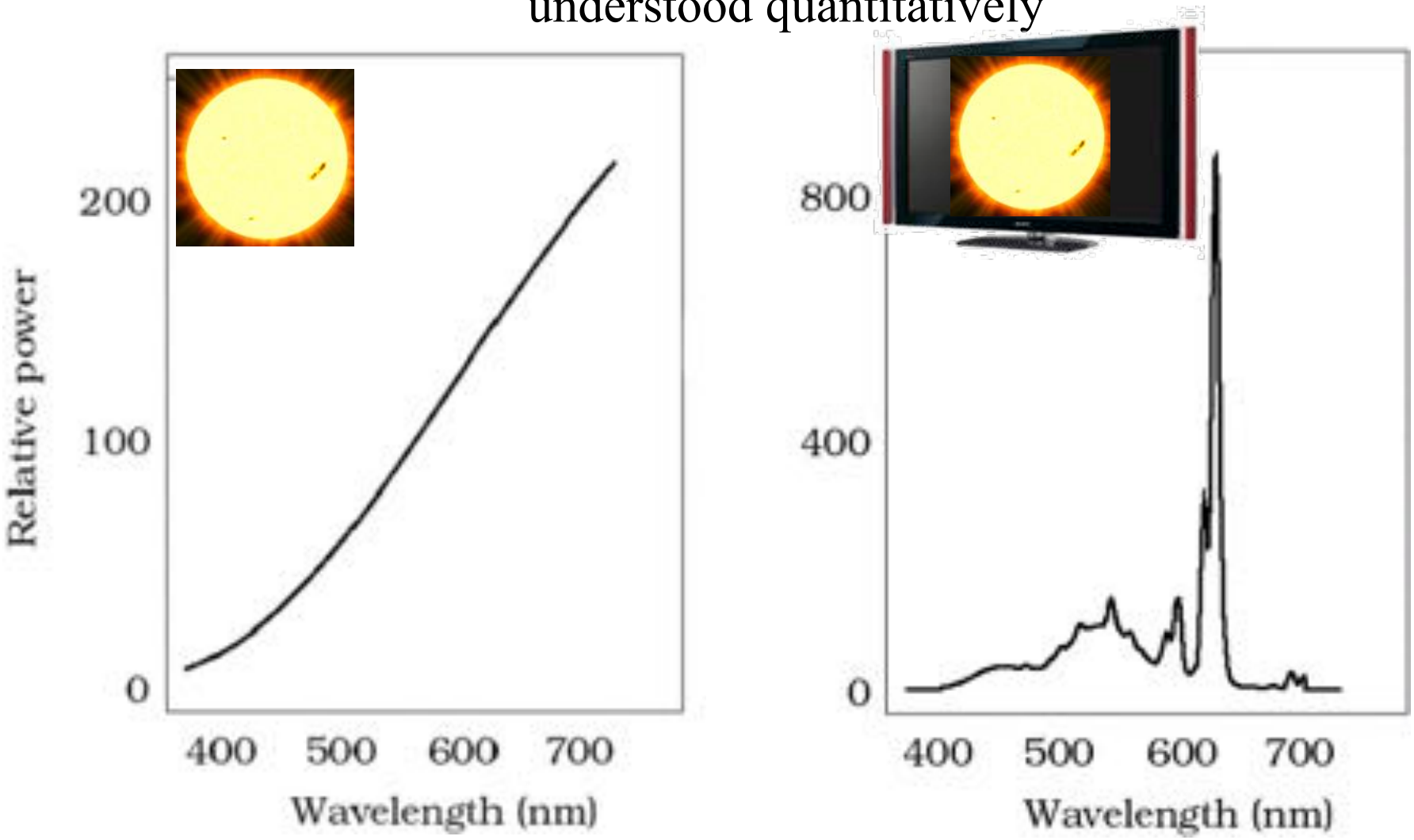


(b)

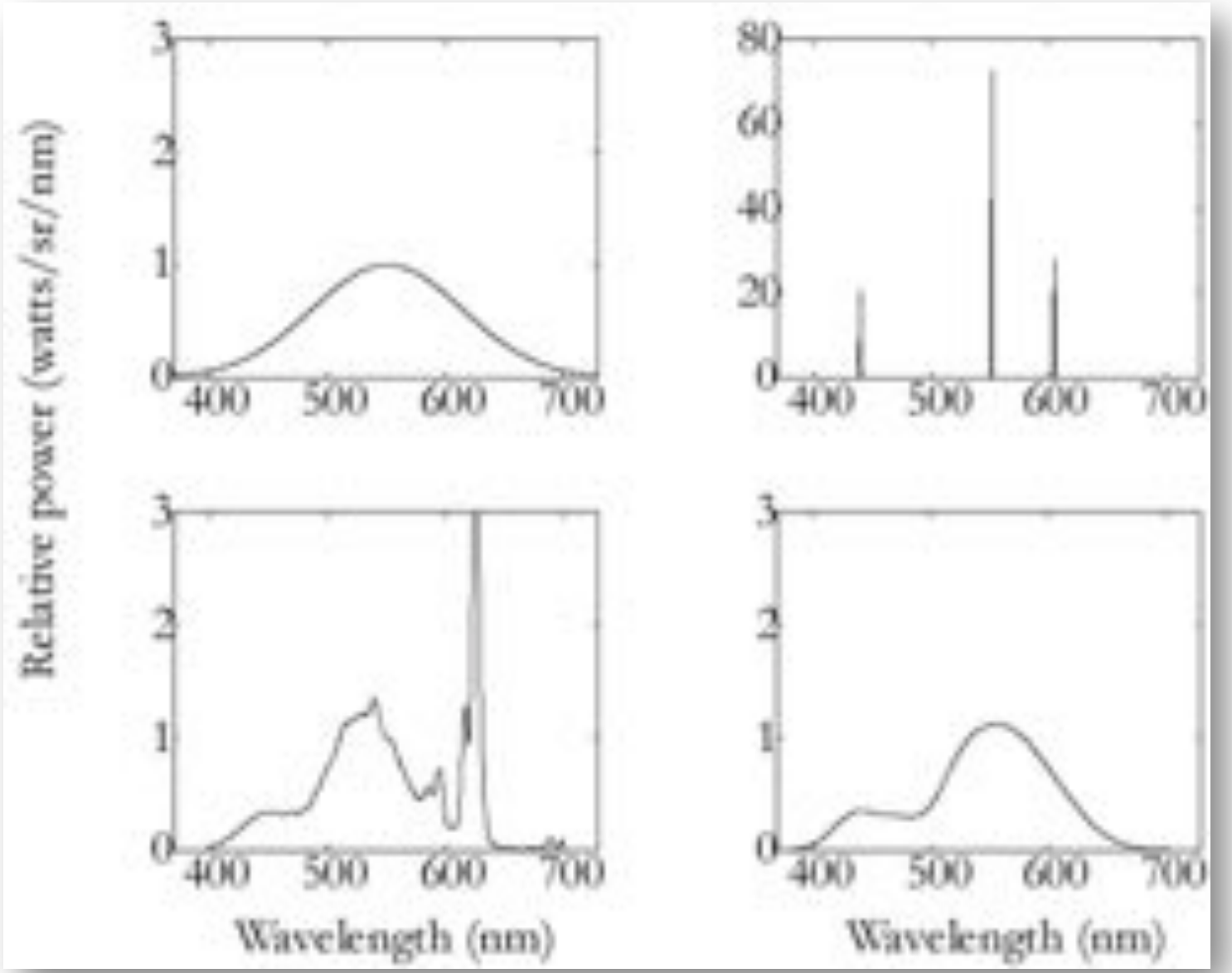


Metamerism

Color matching is an important illusion that is understood quantitatively

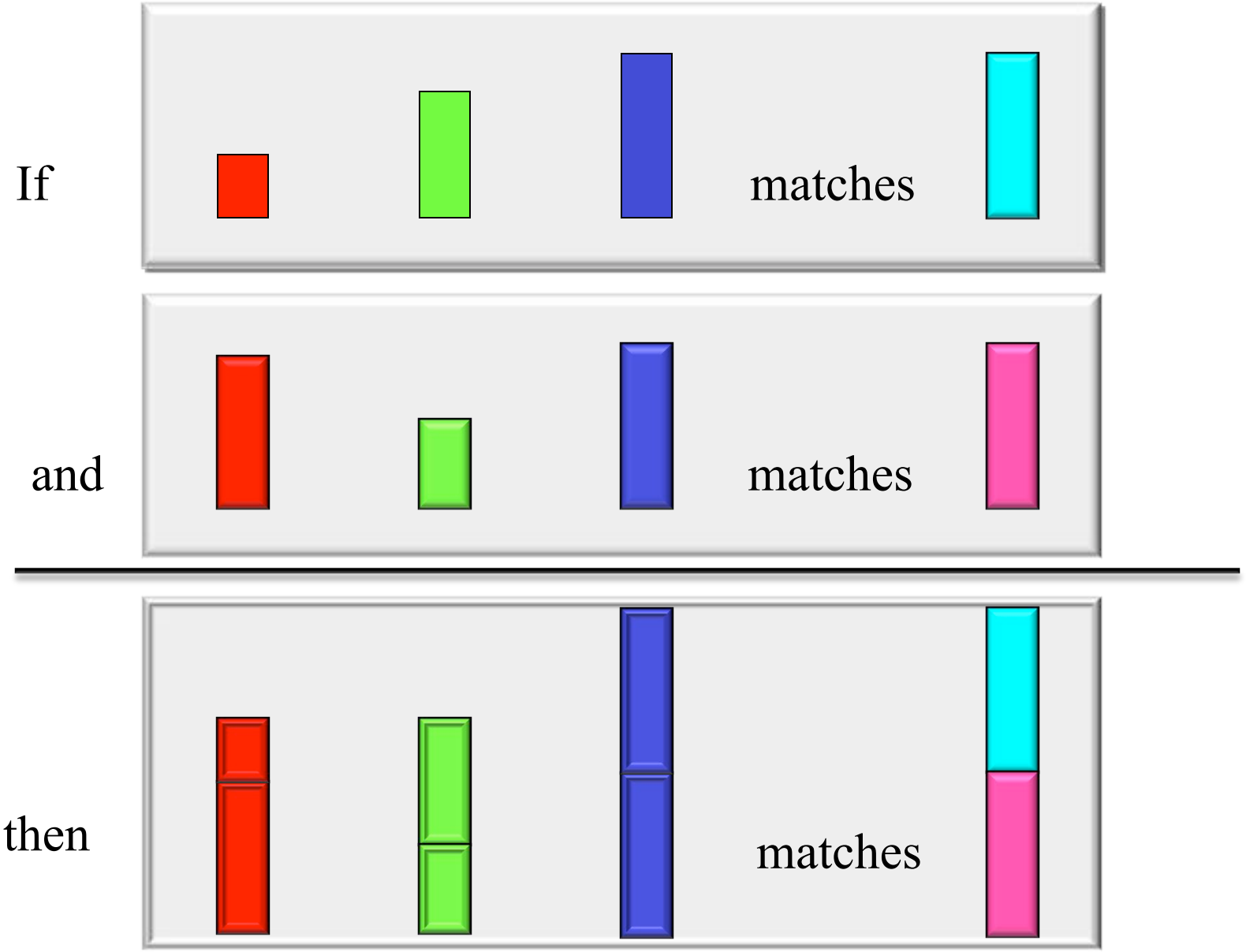


Metamerism is a big effect



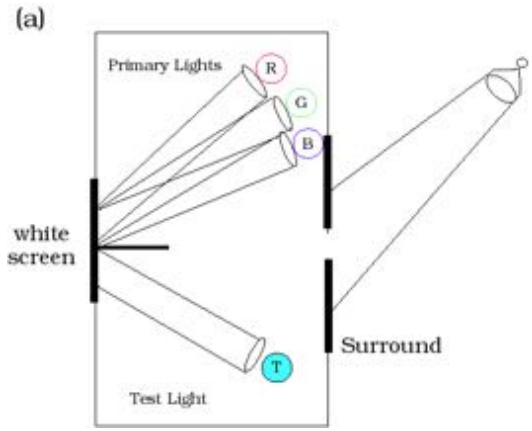
The color matching experiment is linear

(Grassmann's Law)



The invention of linear vector spaces

Color matching experiment equation



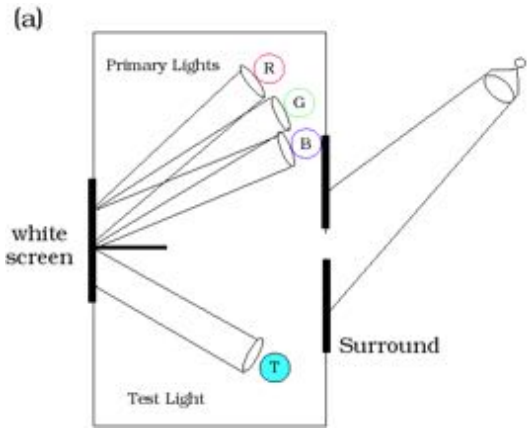
Response

CIE RGB functions

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} \text{—} \\ \text{—} \\ \text{—} \end{pmatrix} \begin{pmatrix} \\ \\ \end{pmatrix}$$

Test light SPD

Color matching equations



Response

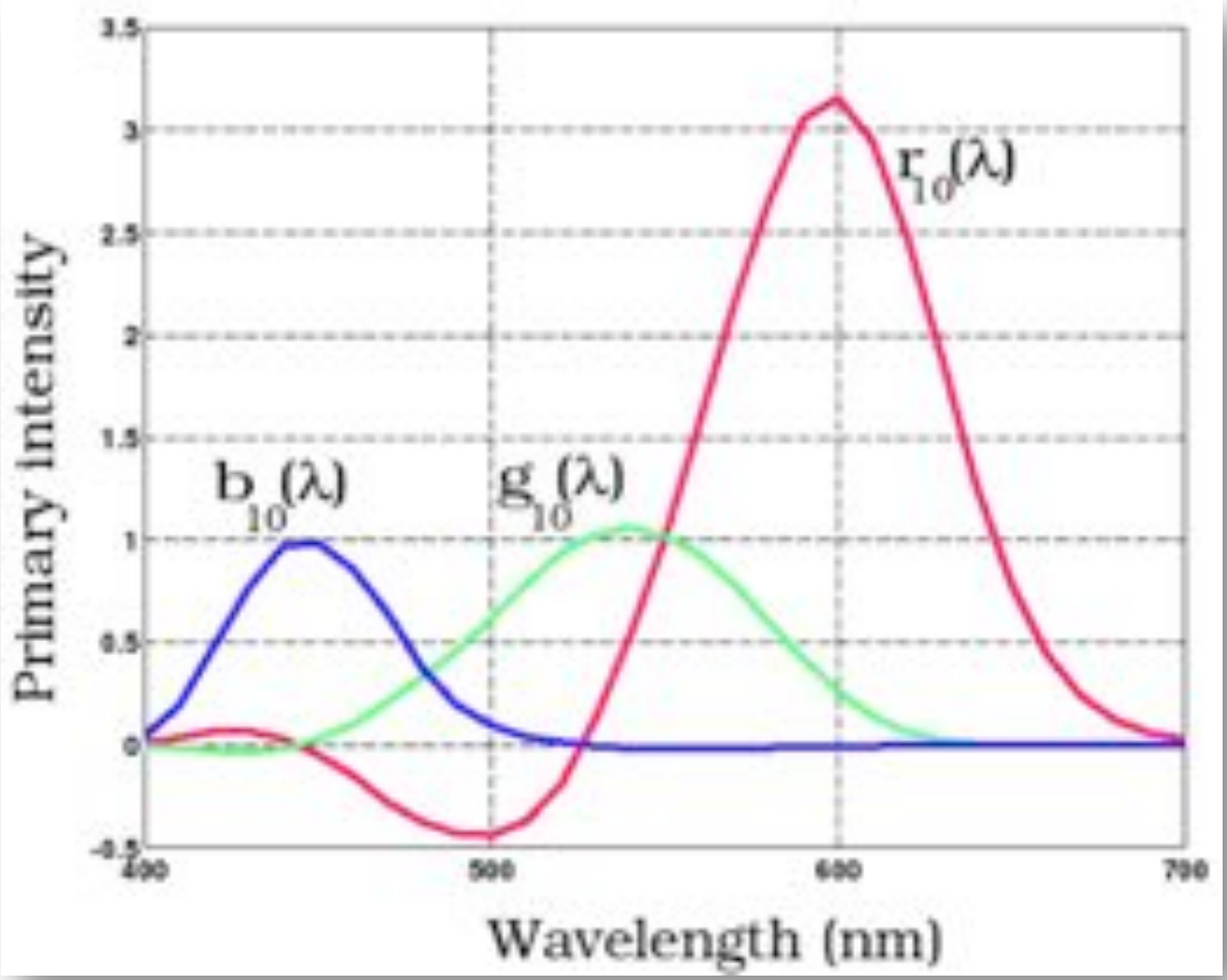
CIE RGB functions

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

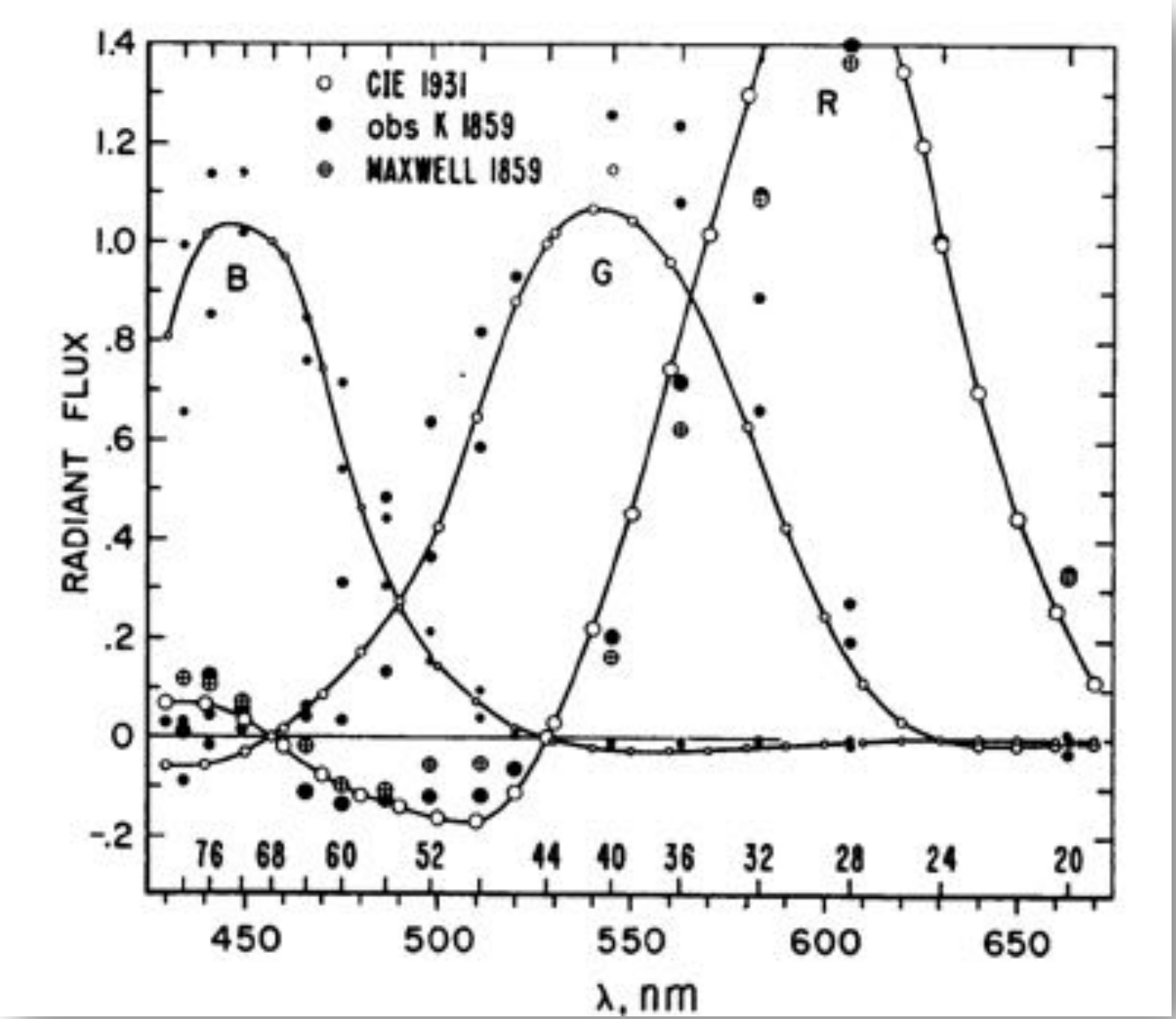
$$\begin{pmatrix} r \\ g \\ b \end{pmatrix} = \begin{pmatrix} r & & \\ & g & \\ & & b \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 0 \\ \cdots \\ 1 \\ \cdots \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

Test light SPD

CIE color matching functions
(CMFs; 10 deg, Wright and Guild)

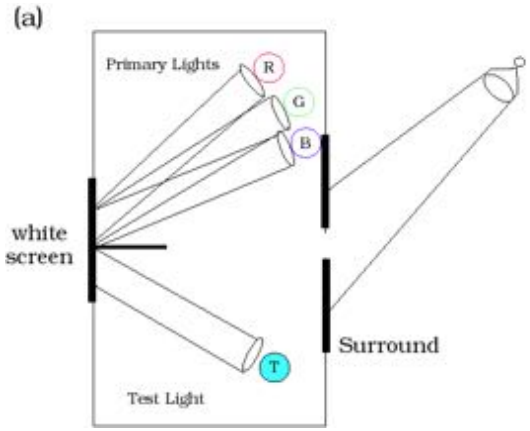


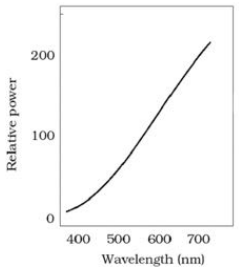
Maxwell measured the color-matching functions
(From Judd, PNAS)

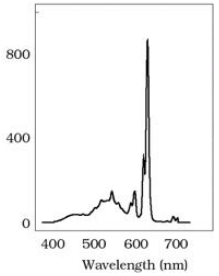


CMFs predict appearance matches

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





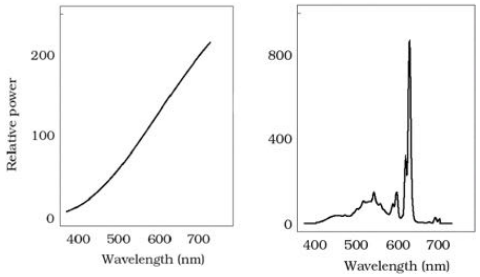


$$\begin{pmatrix} \\ \\ \end{pmatrix} = \begin{pmatrix} \\ \\ \\ \end{pmatrix} \begin{pmatrix} \\ T \\ \\ \end{pmatrix} = \begin{pmatrix} \\ \\ \\ \end{pmatrix} \begin{pmatrix} \\ S \\ \\ \end{pmatrix}$$

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 energy somewhere in the spectrum

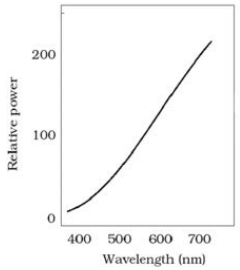


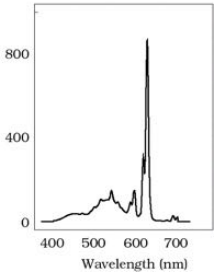
$$0 = \left(\begin{array}{c} \\ \\ \\ \end{array} \right) \left\{ \left(T \right) - \left(S \right) \right\}$$

(all positive)

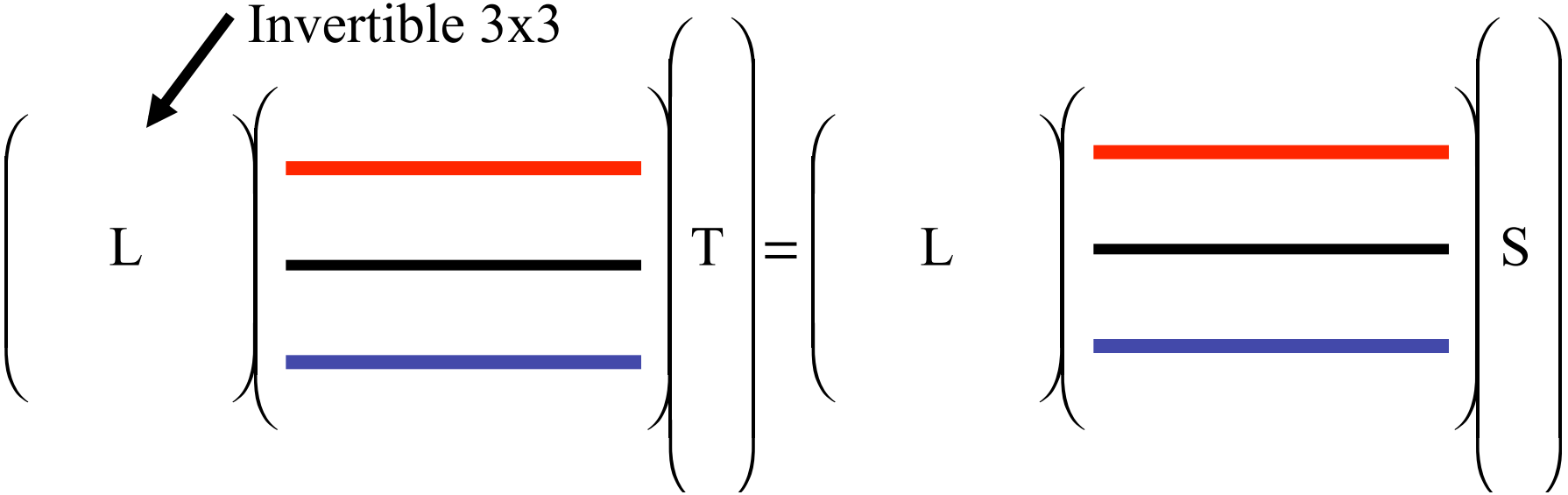
CMFs: A uniqueness theorem

Any invertible linear transformation, L, of the CMFs predicts the same metamers



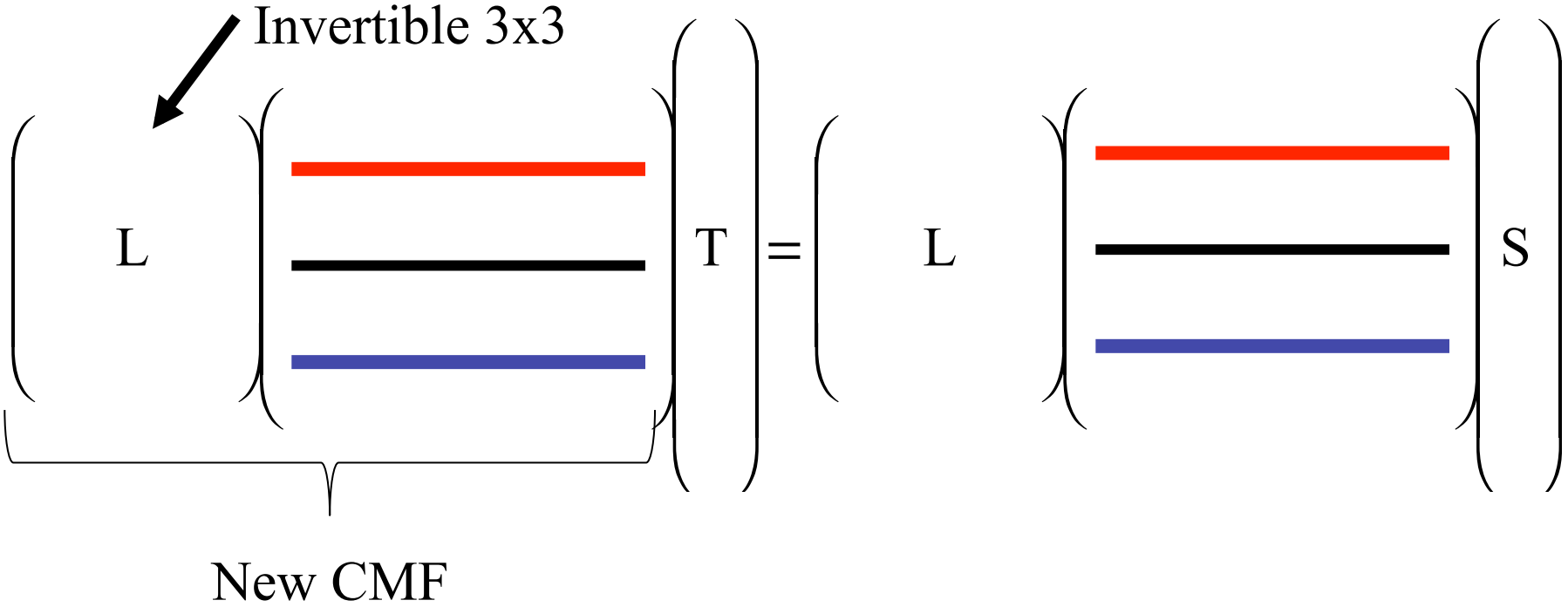


Invertible 3x3



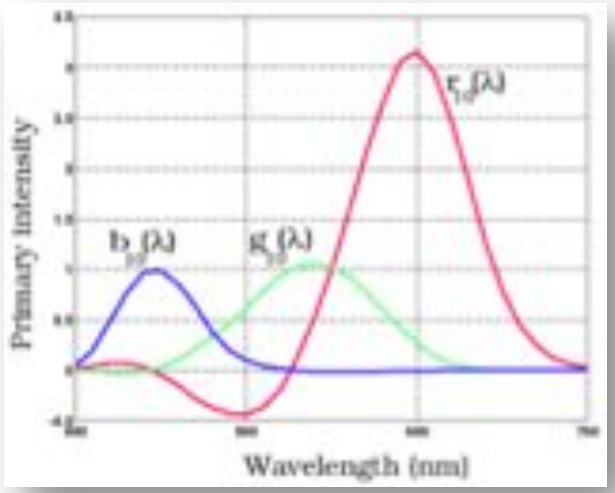
CMFs: A uniqueness theorem

Different choices of primaries produce different CMFs
Related by a linear transformation
(see *Foundations of Vision* for proof)



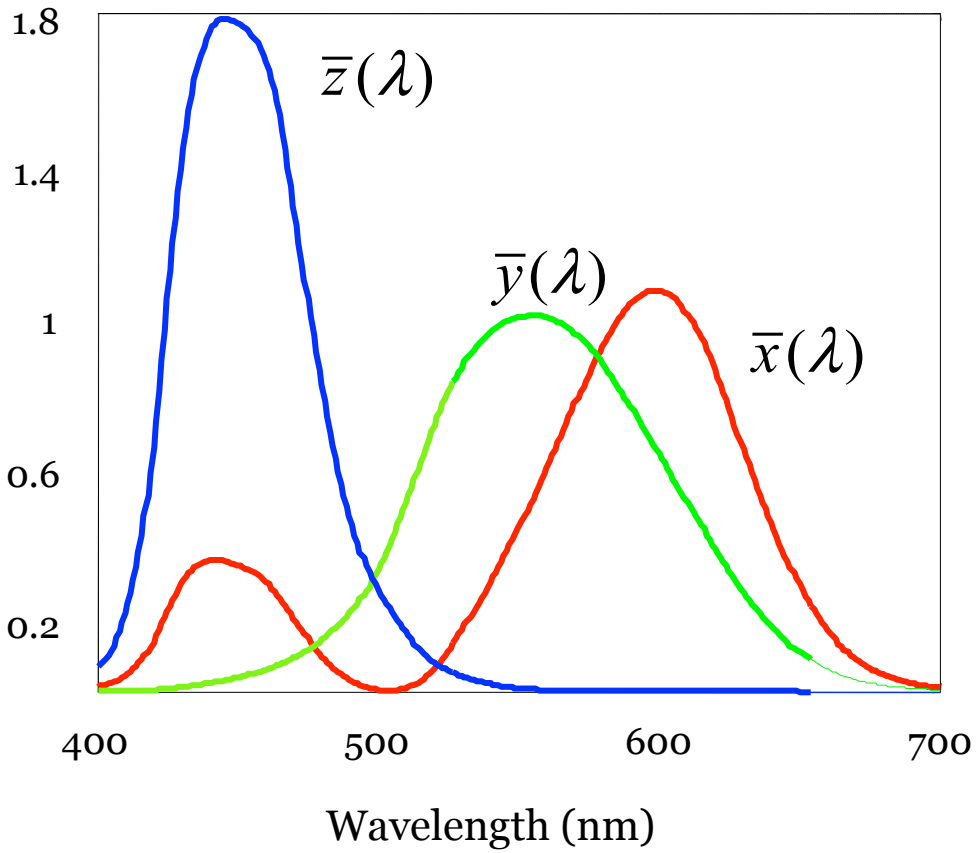
The CIE (1931) standard CMFs used today

Color-matching functions
(empirical)



L

CIE (1931) 10 deg XYZ functions



The CIE (1931) XYZ standard CMFs

Standards are specified with radiance in **energy**, not photons

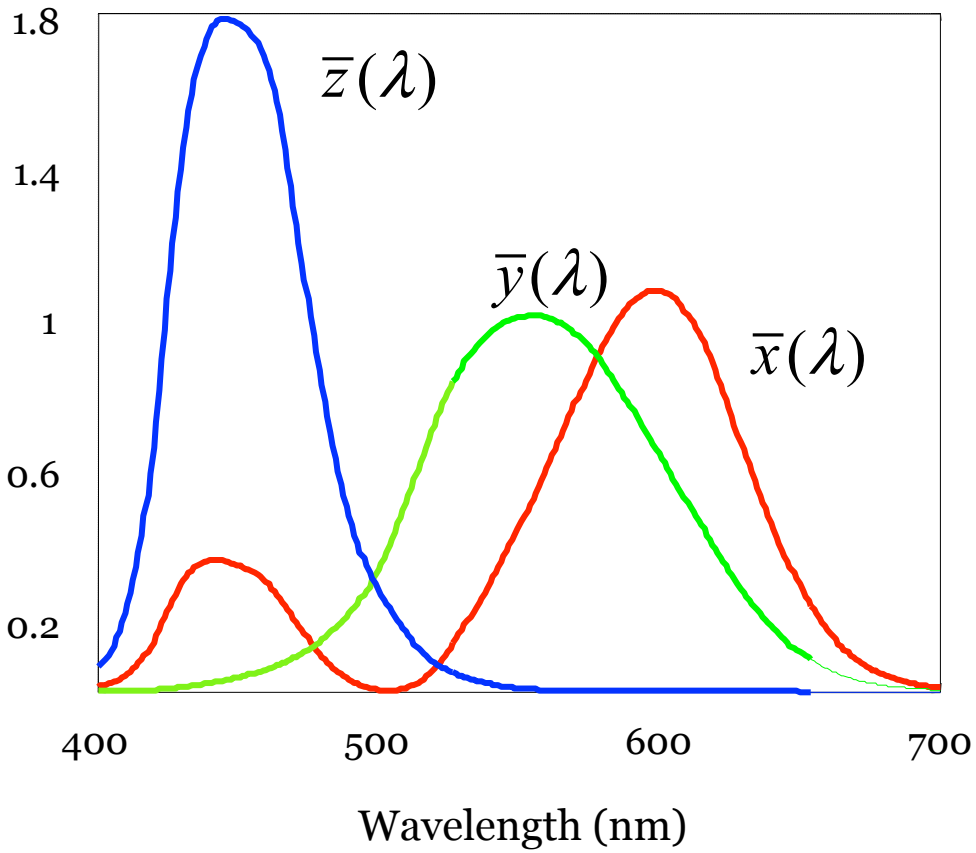
Radiance

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

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

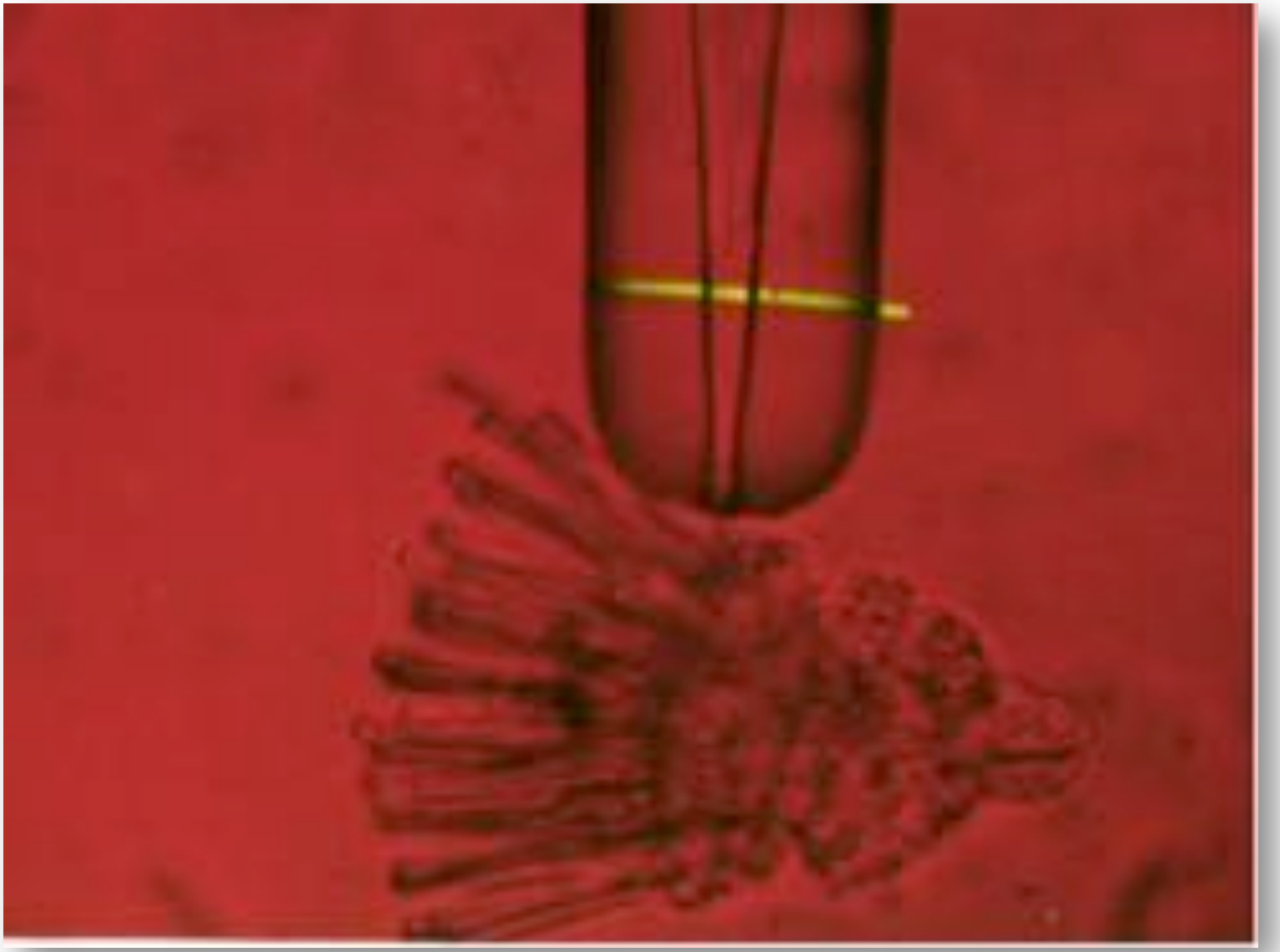
$$Z = \sum_{\lambda} \bar{z}(\lambda) t(\lambda) d\lambda$$

CIE (1931) 10 deg XYZ functions



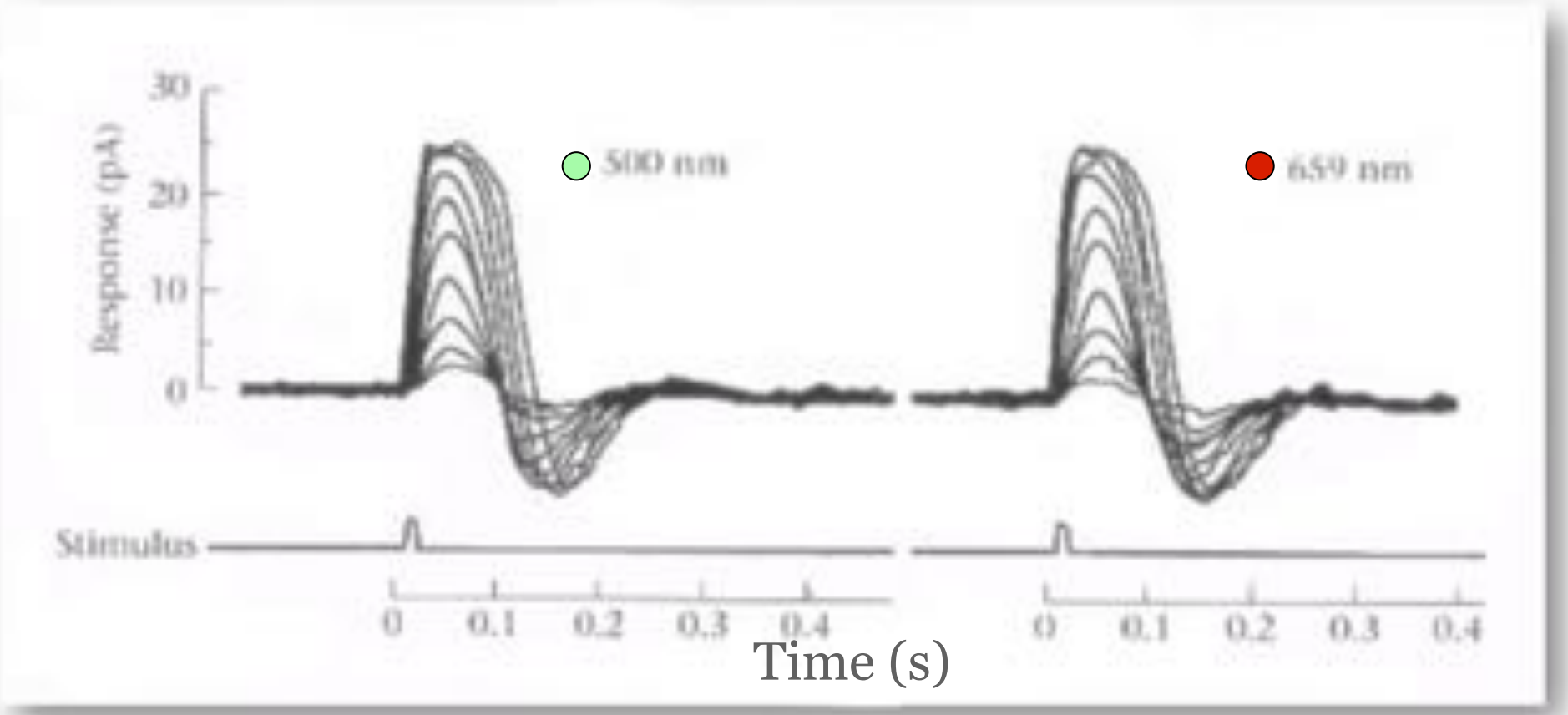
Photoreceptor physiology catches up
(Baylor and Schnapf)

Single cone photocurrent measurements

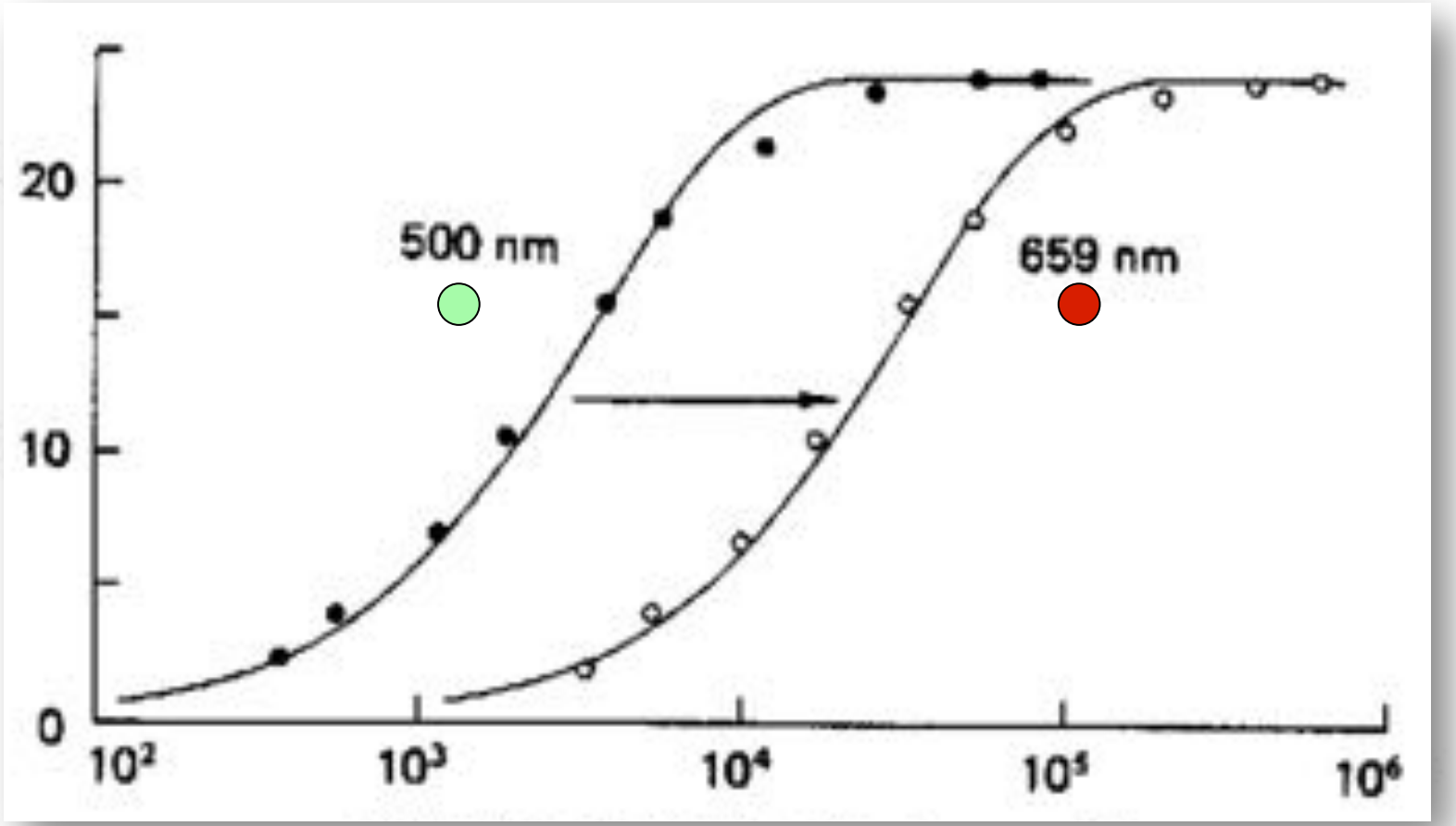


Principle of univariance
(Rushton)

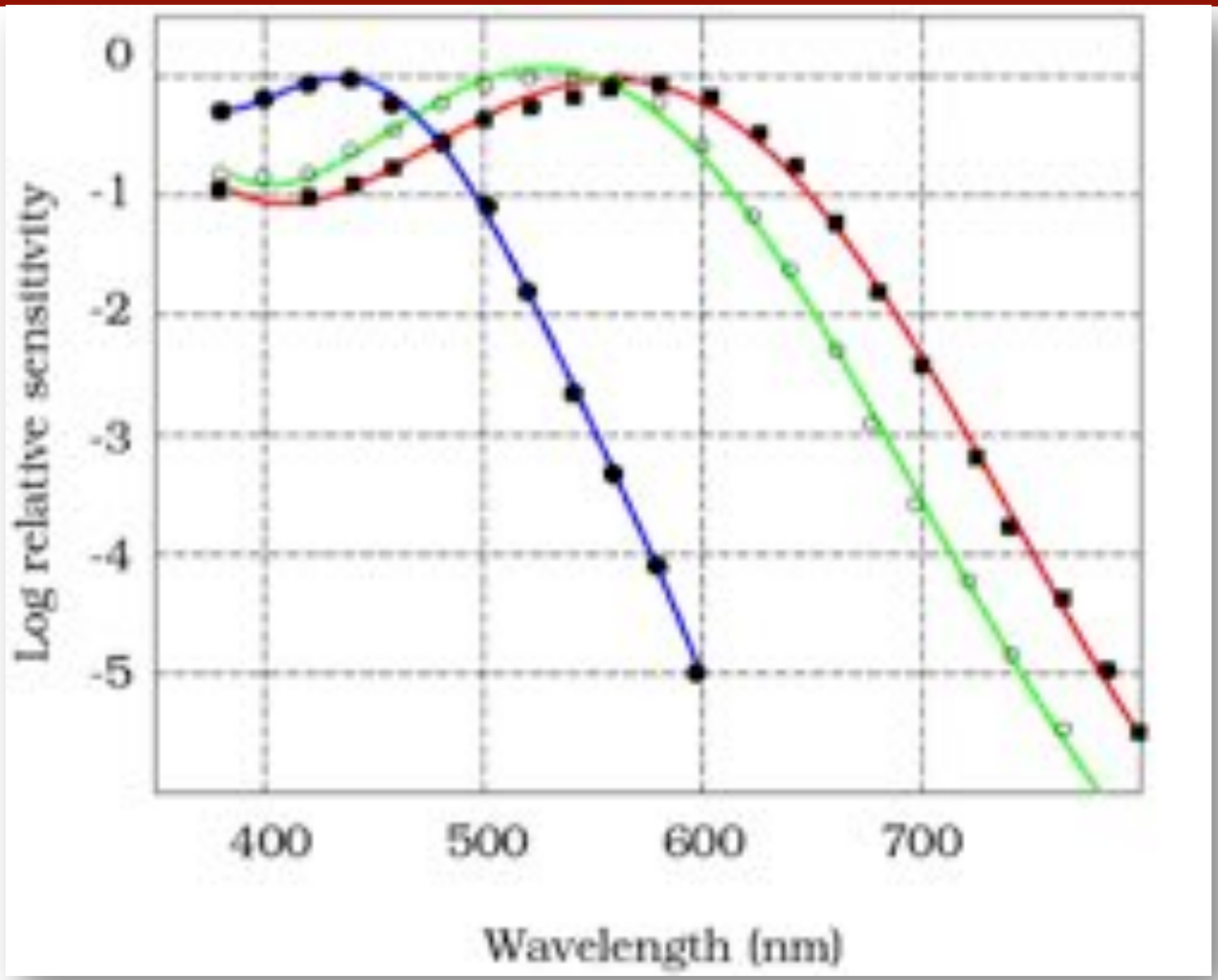
Cone photocurrent using stimuli with different wavelengths



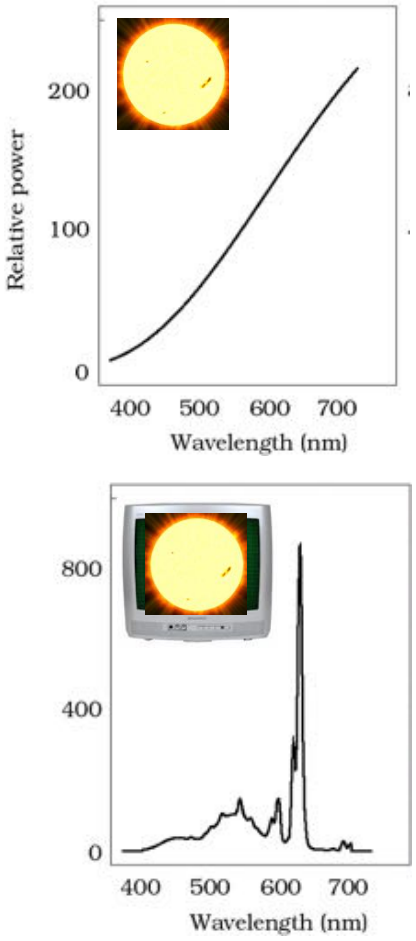
Spectral response of nonlinear systems

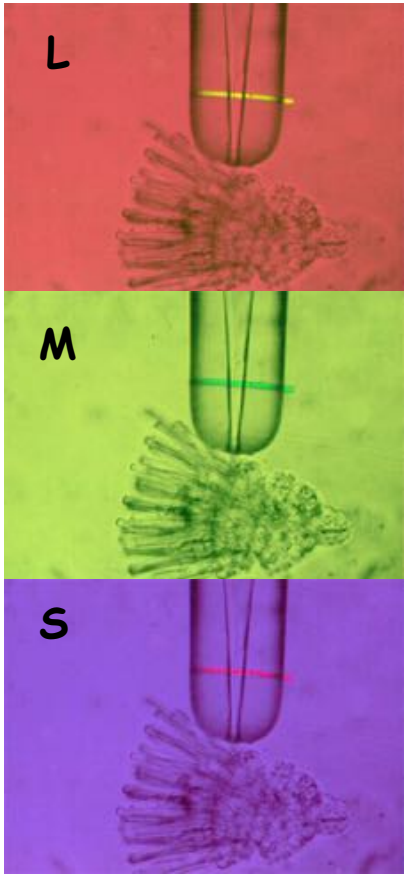


Three types of cones
(Baylor, Schnapf, Nunn)

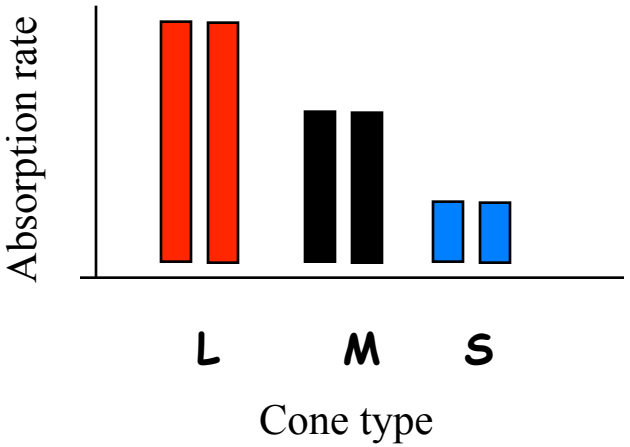


Stimuli causing equal cone absorptions and seen in the same context look the same



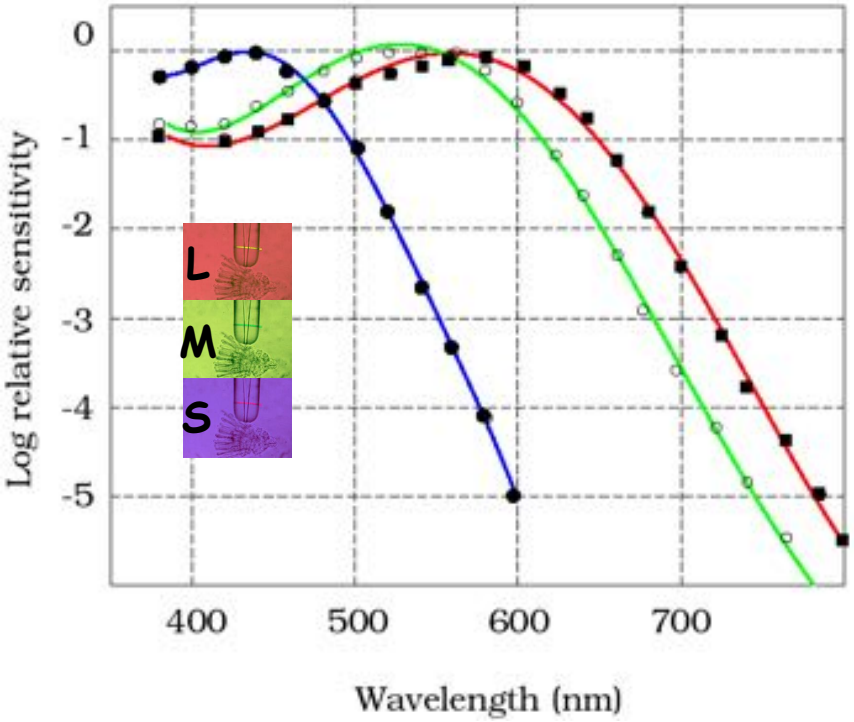


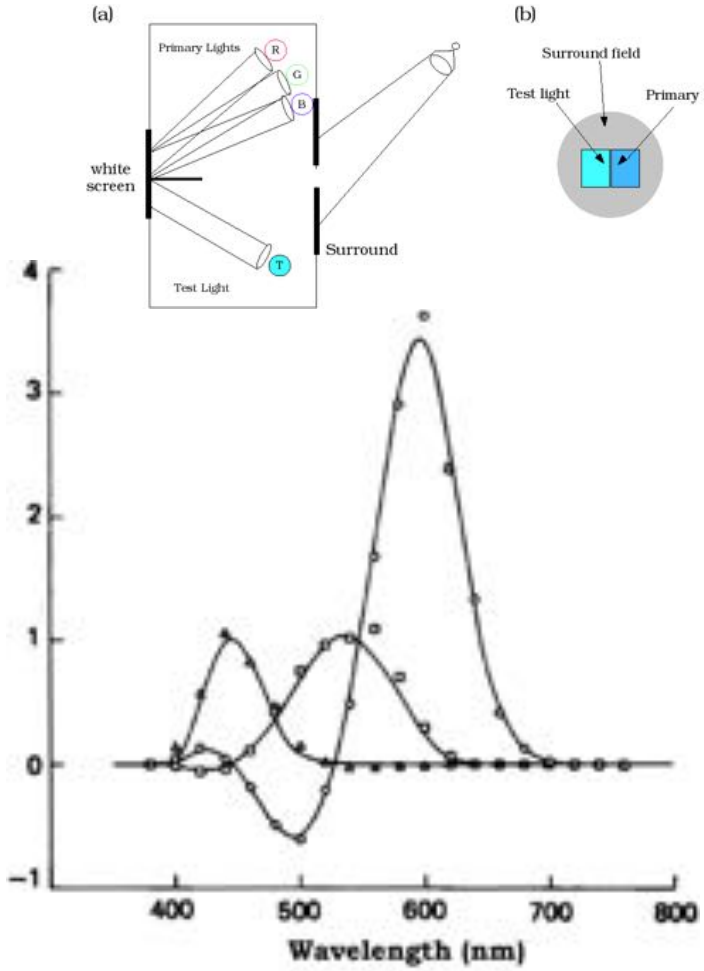
The cones spectral sensitivities predict color matches.



The measured cone responses predict the color-matching experiment quantitatively

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





Selective comments on the history of color science

Trichromacy put into practice

The Hague, 1708, Anonymous

TRAITÉ
DE LA
PEINTURE
EN
MIGNATURE.
Pour apprendre sûrement à Peindre sans Maître.

Ouvrage corrigé & augmenté sur le plan du Traité de diverses Instructions Preliminaires sur la Peinture en général, & de Préceptes sur le Dessein pour en faciliter l'Etude & la Pratique.

AUQUEL ON A AJOUTÉ

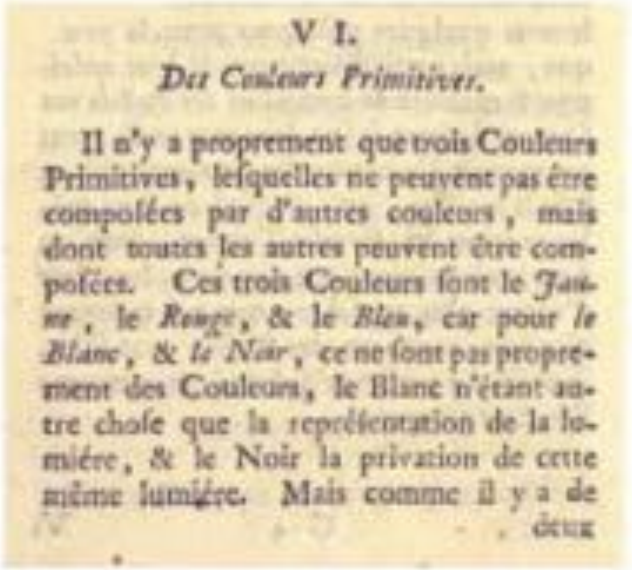
Un petit Traité de la Peinture au Pastel, avec la Méthode de composer les Pastels.

Le Secret de faire les plus belles Couleurs, l'Or Beuit, l'Or en Coquille, & le Vernis de la Chine.

A LA HAYE,

Chez Louis & Henry van Dole, Marchands Libraires, dans le Passage.

M. DCC. VIII.



VI.

Des Couleurs Primitives.

Il n'y a proprement que trois Couleurs Primitives, lesquelles ne peuvent pas être compolées par d'autres couleurs, mais dont toutes les autres peuvent être compolées. Ces trois Couleurs sont le *Jaune*, le *Rouge*, & le *Bleu*, car pour *le Blanc*, & *le Noir*, ce ne sont pas proprement des Couleurs, le Blanc n'étant autre chose que la repréfentation de la lumiére, & le Noir la privation de cette même lumiére. Mais comme il y a de deux

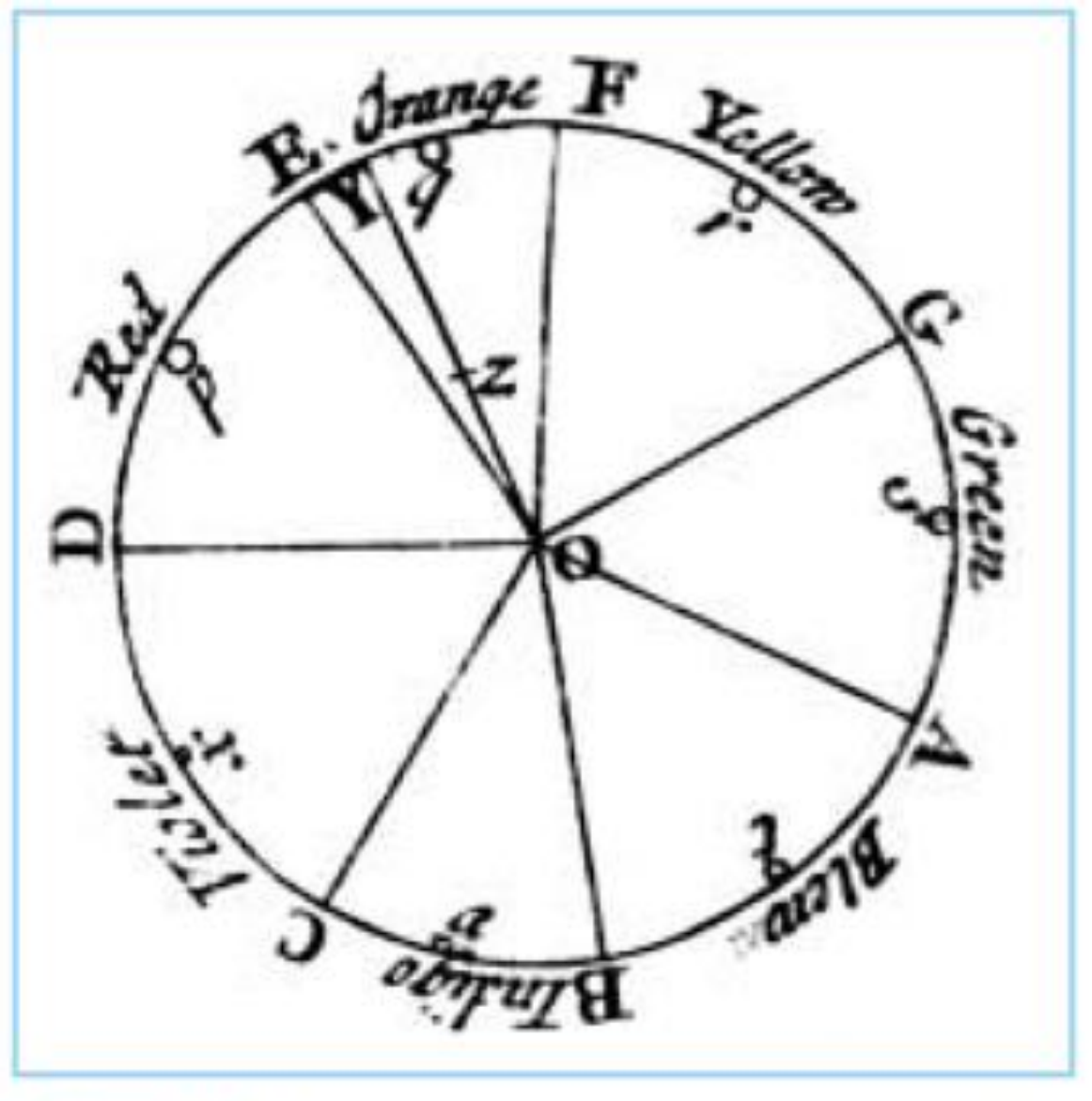
Newton's color circle from Opticks (1704)

(Image from John Mollon's chapter)

Newton combined psychology and physics, showing which colors are complementary by placing them on a circle

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

He is still Isaac Newton



Thomas Young explains trichromacy as biology

"**Now, as it is almost impossible to conceive each sensitive point of the retina to contain an infinite number of particles, each capable of vibrating in perfect unison with every possible undulation, it becomes necessary to suppose the number limited, for instance to the three** principal colours, red, yellow and blue, of which the undulations are related in magnitude nearly as the numbers 8, 7, and 6; and that each of the particles is capable of being put in motion less or more forcibly, by undulations differing less or more from perfect unison; for instance, the undulations of green light being nearly in the ratio of 6 1/2, will affect equally the particles in unison with yellow and blue, and produce the same effect as a light composed of those two species"

On the theory of lights and colours. Philosophical Transactions of the Royal Society 92, 12-48.

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...."

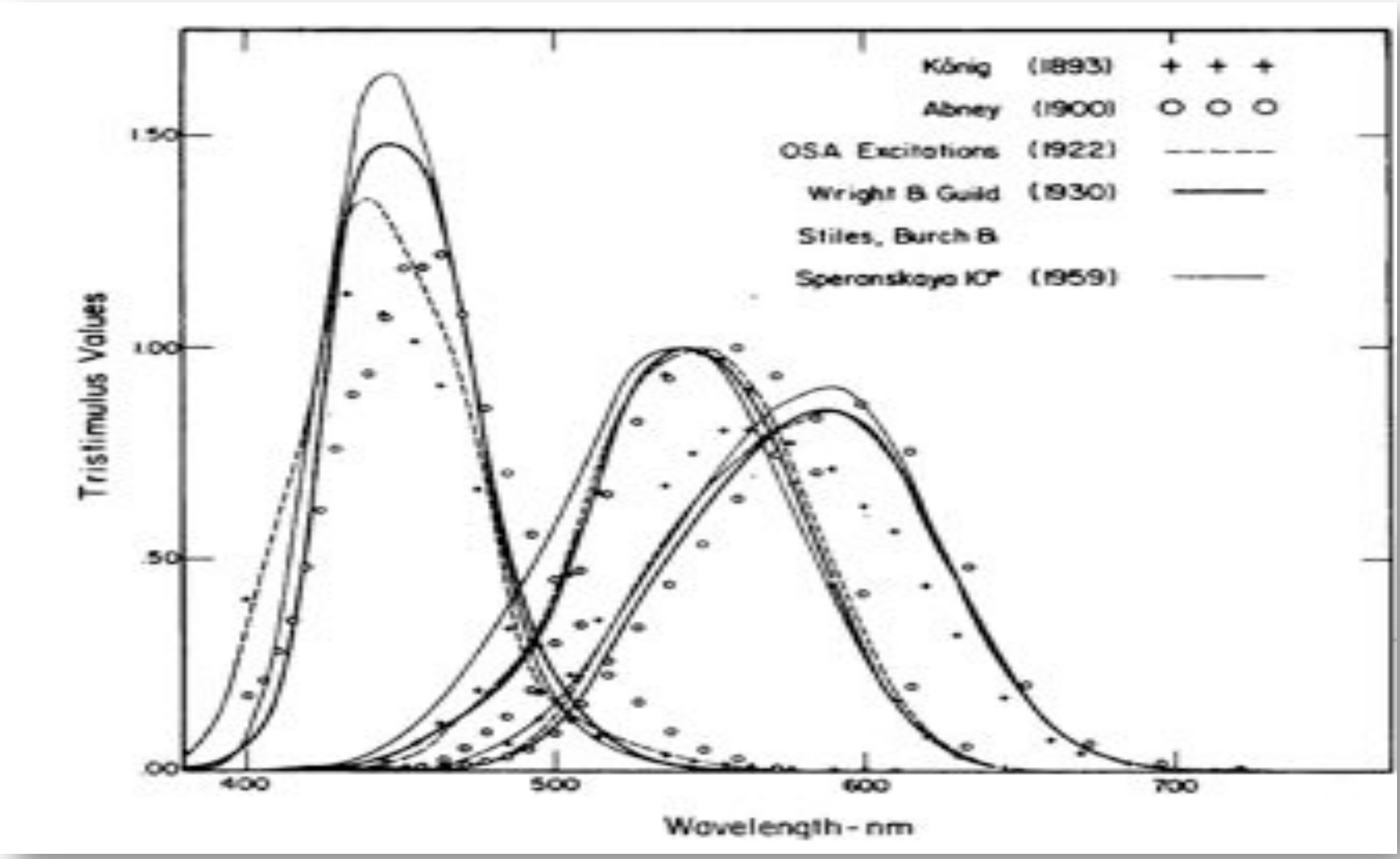
Henry Brougham in Edinburgh Review, an ardent admirer of Newton, criticizing Thomas Young's Bakerian Lectures.

Early estimates of the cone curves

- After Maxwell, Young, Helmholtz and Grassmann scientists wondered what might be the spectral sensitivity of the biological sensors that encode the light.

- They knew of the free linear transform. They made some guesses by finding a transform that produced all positive (photochemical) sensors.

Early estimates of the cone curves



Early estimates of the cone curves

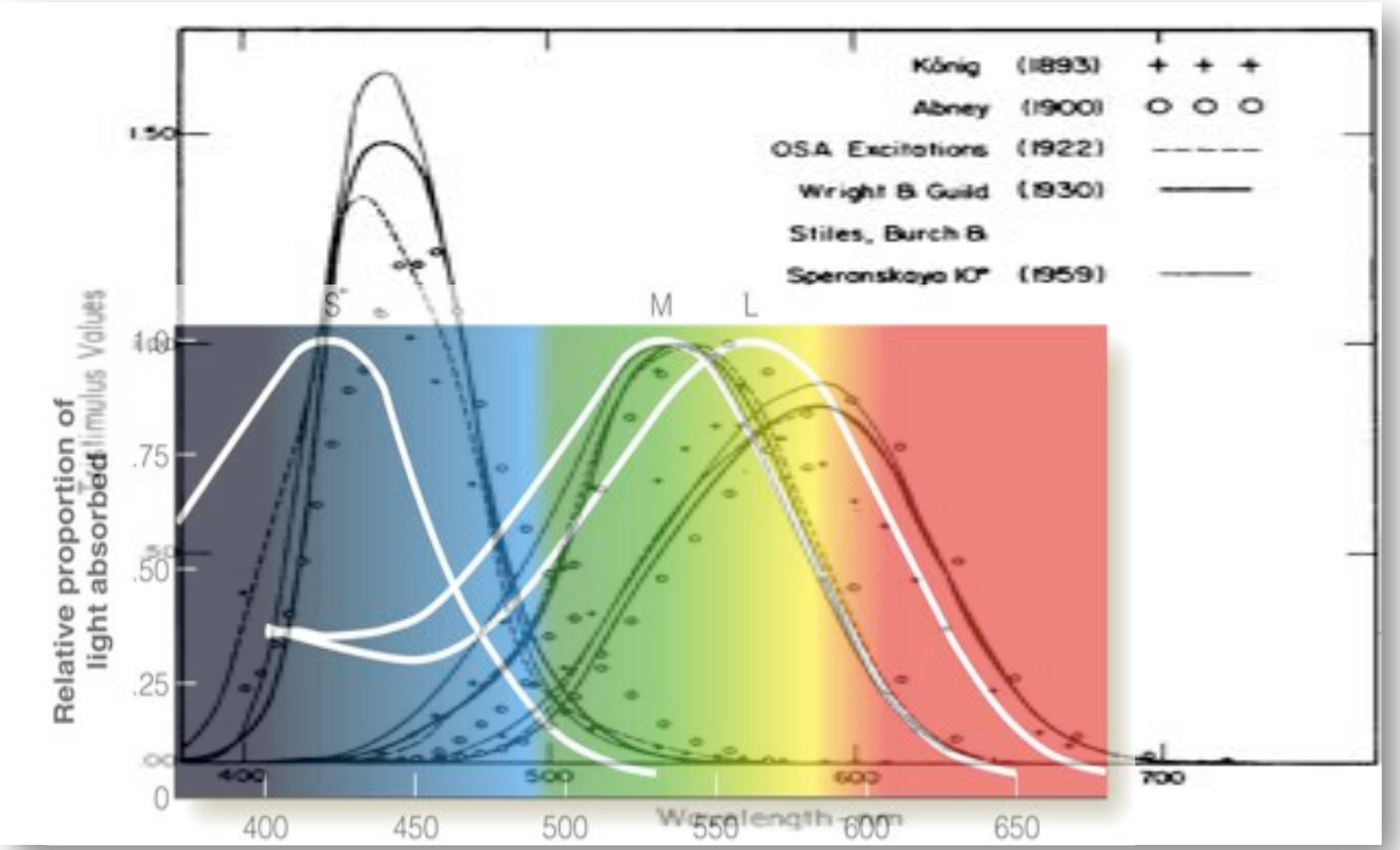
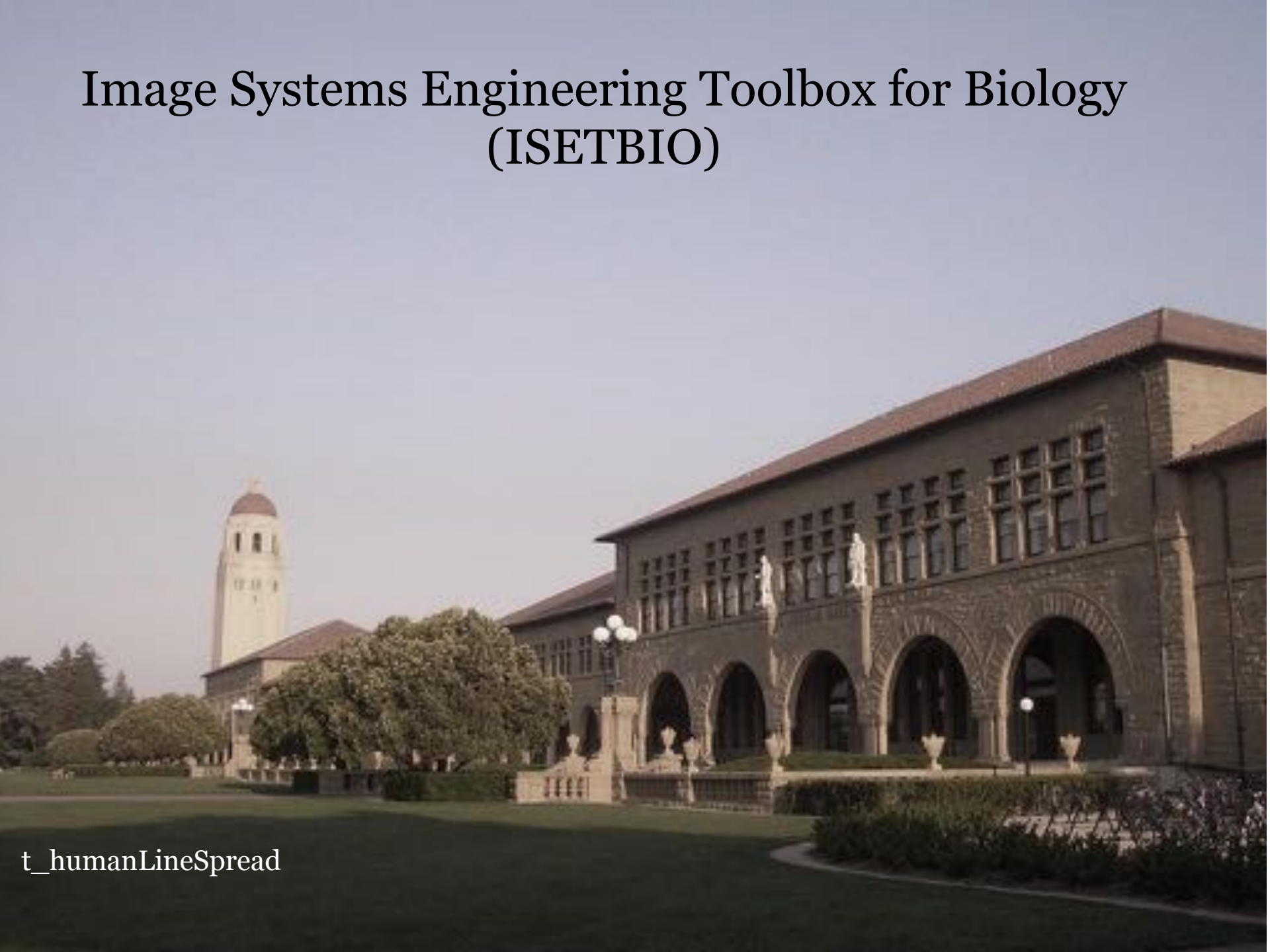


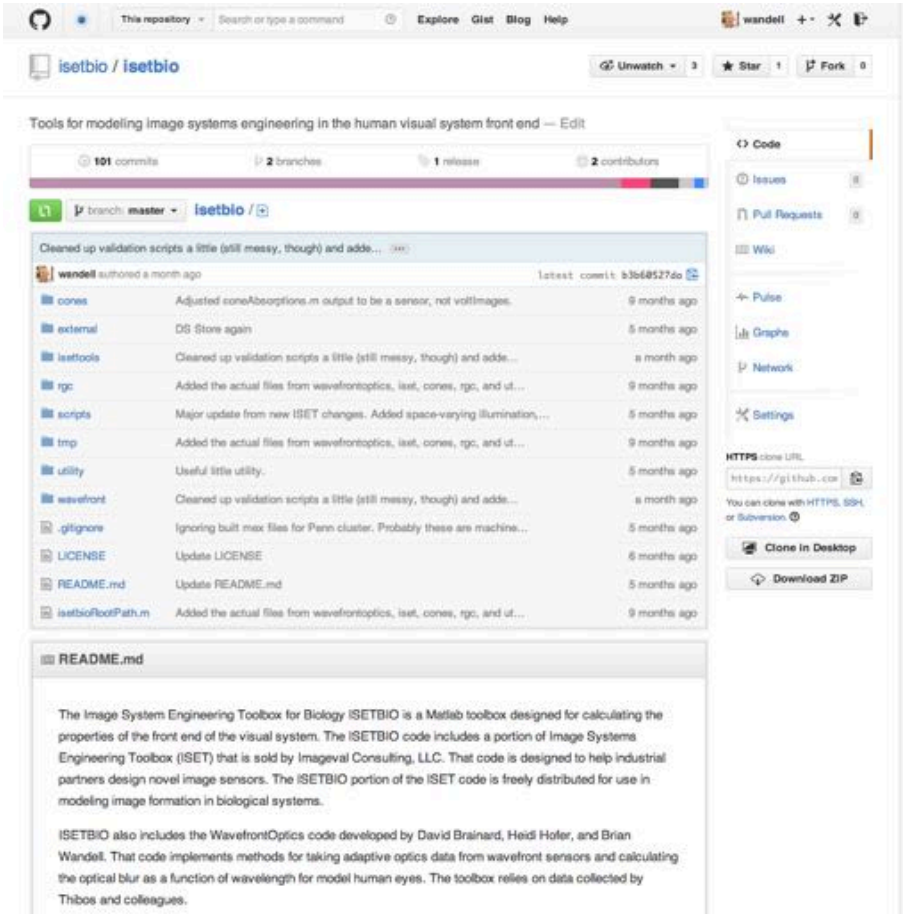
Image Systems Engineering Toolbox for Biology (ISETBIO)



t_humanLineSpread

Image Systems Engineering Toolbox for Biology (ISETBIO)

https://github.com/isetbio/isetbio



Goal: Develop an open-source computational model that calculates the upper bounds of human visibility for realistic targets

Why now: Important advances in modeling and understanding of human image formation (optics) and retinal encoding; enormous advances in computational power

Methodology: Combine quantification of scene radiance, retinal irradiance, and cone absorbance with high quality machine learning computational algorithms for classification

Where we stand

Scene radiance modeling –
Quantified multispectral representations of the scene radiance, 2D screens, 3D light fields, high dynamic range

Image formation modeling –
Image formation from different optics models, chromatic aberration, shift-invariant, AO-derived wavefronts, wavelength-dependent and space-varying

Light transduction –
Inert pigments and cone absorption modeling. Includes Poisson characteristics, cone array properties, noise, dynamics

Light adaptation models –
Static and dynamic models

Eye movements –
First implementation

Computational observer theory –
Uses principles from biology, computing power and quantification of the front end encoding to understand and predict the limits of human performance in complex conditions (uncertainty, eye movements)

MUCH TODO

- Further into the nervous system (Retina, LGN, V1 …)
- Different measurement methods (action potentials, LFPs, fMRI, ECoG, and EEG)
- Psychophysics (Detection, discrimination, acuity, temporal)

Color and spatial pattern

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)

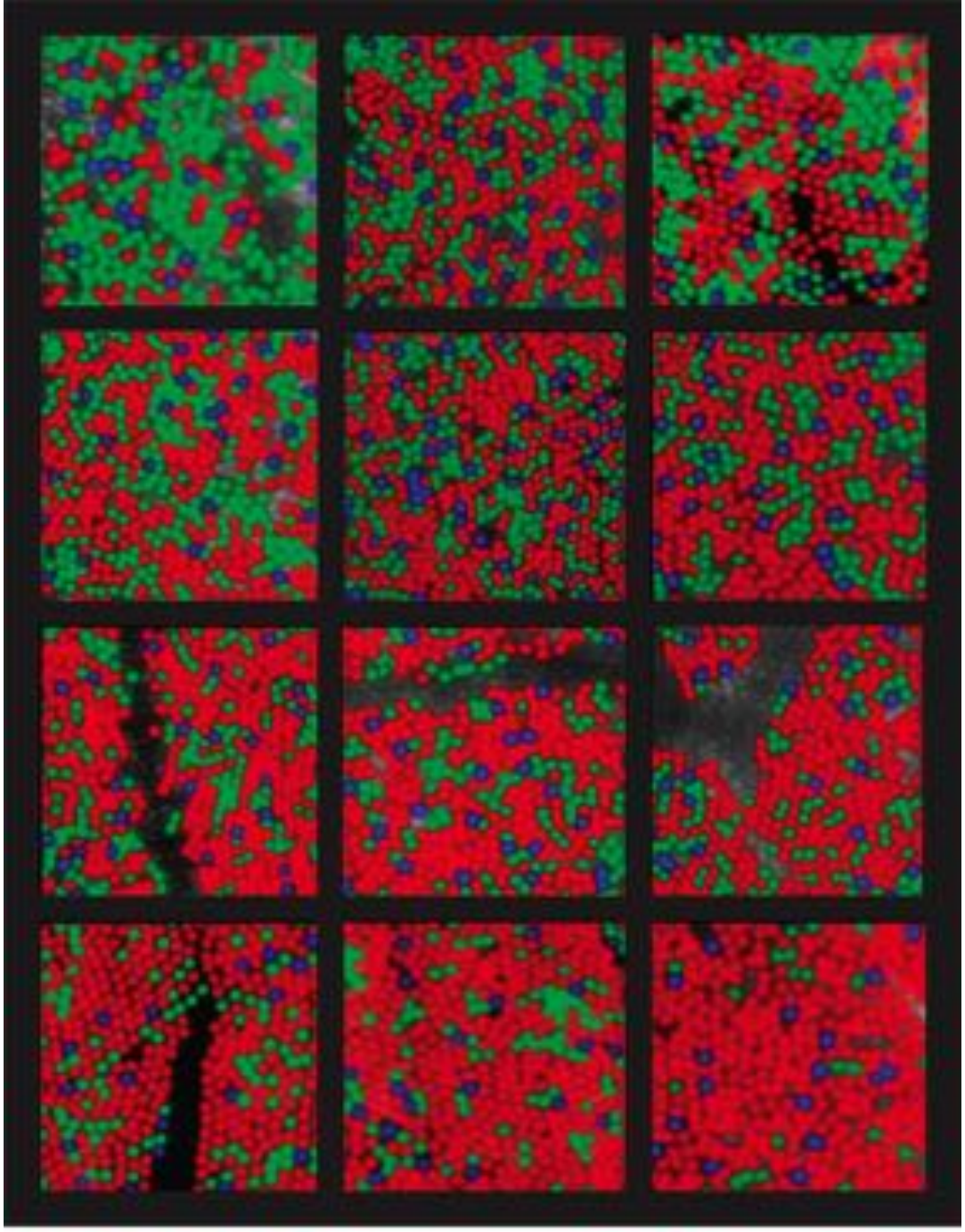
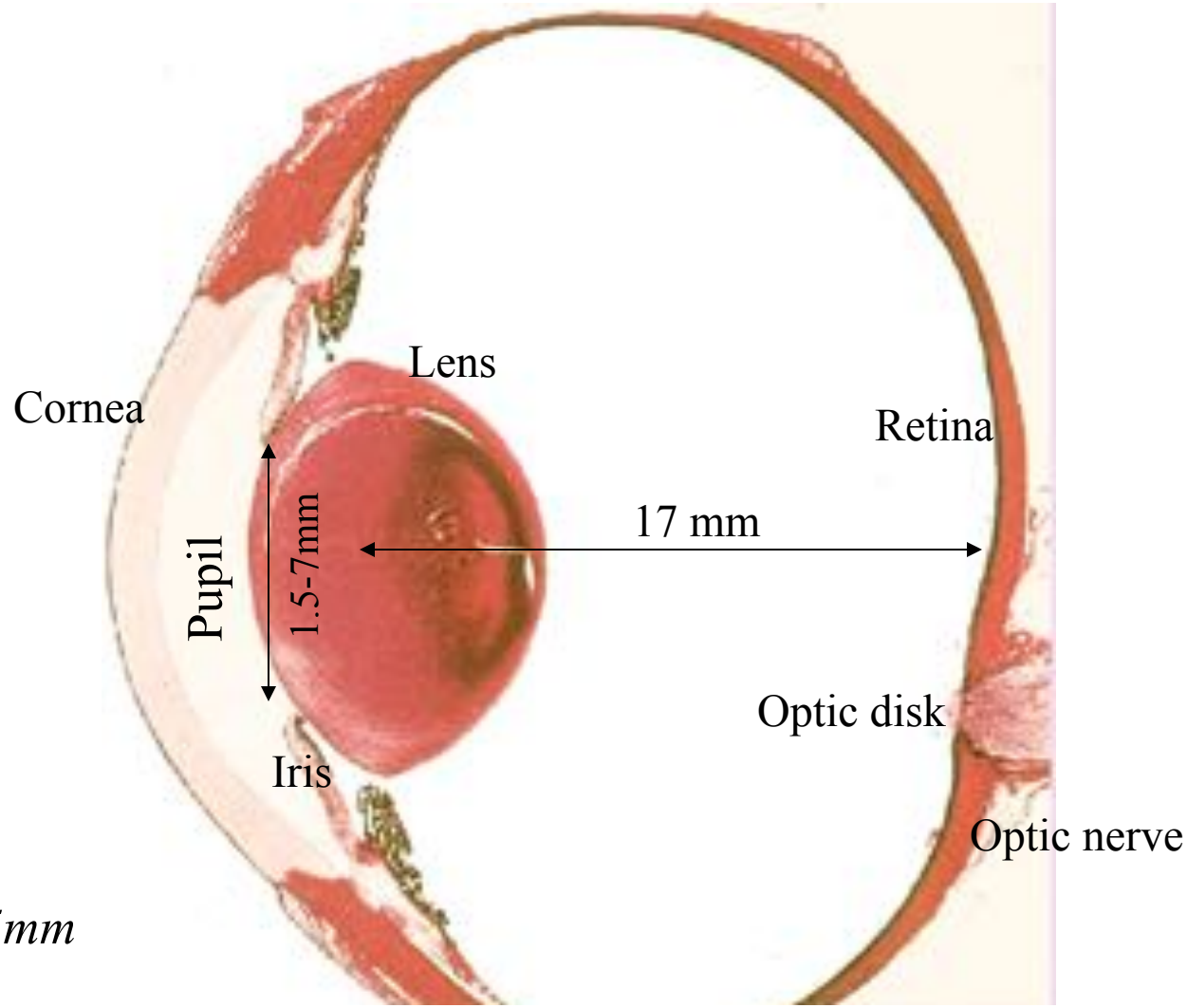


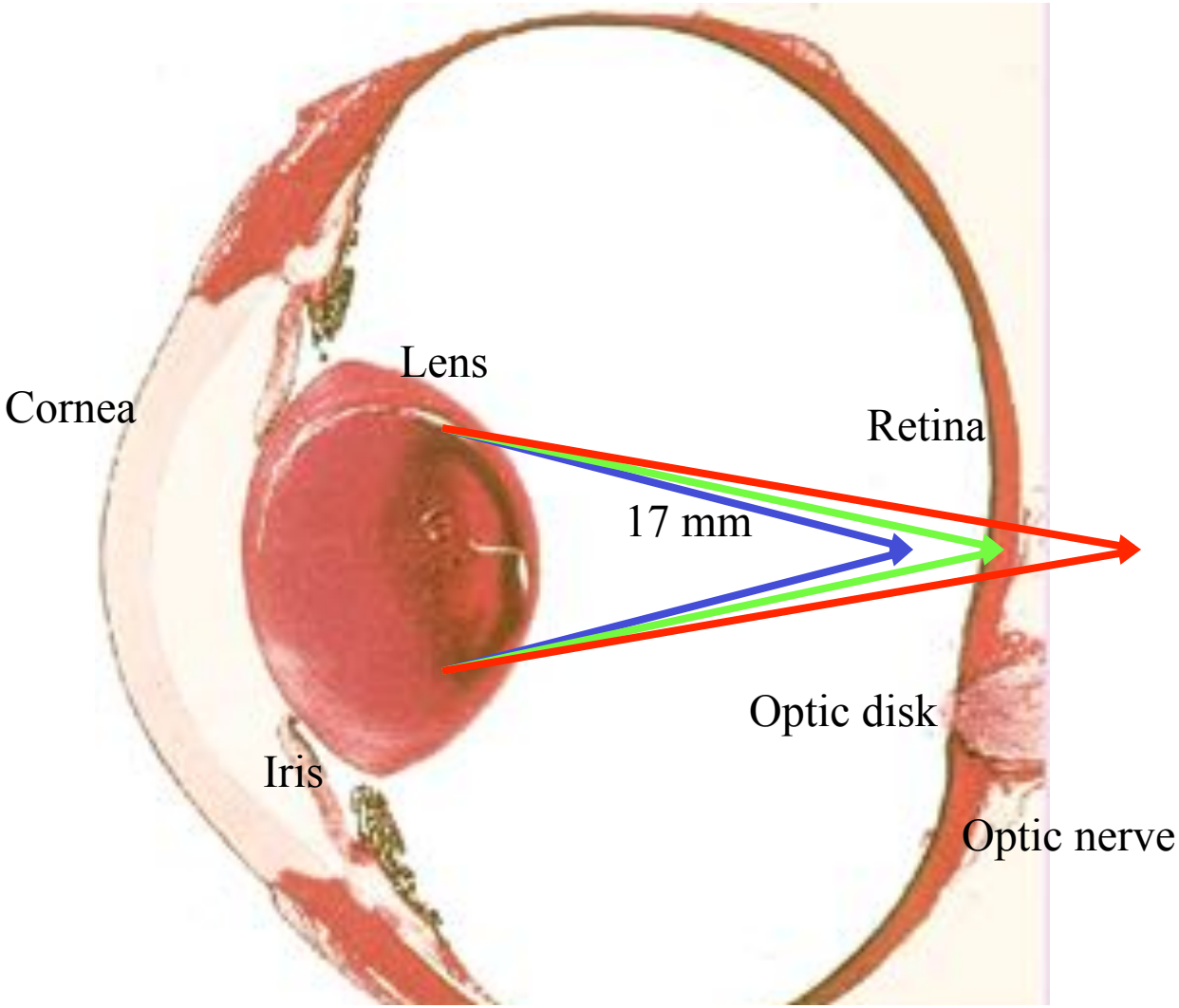
Fig. 7-CO, p. 140

Human eye in cross-section



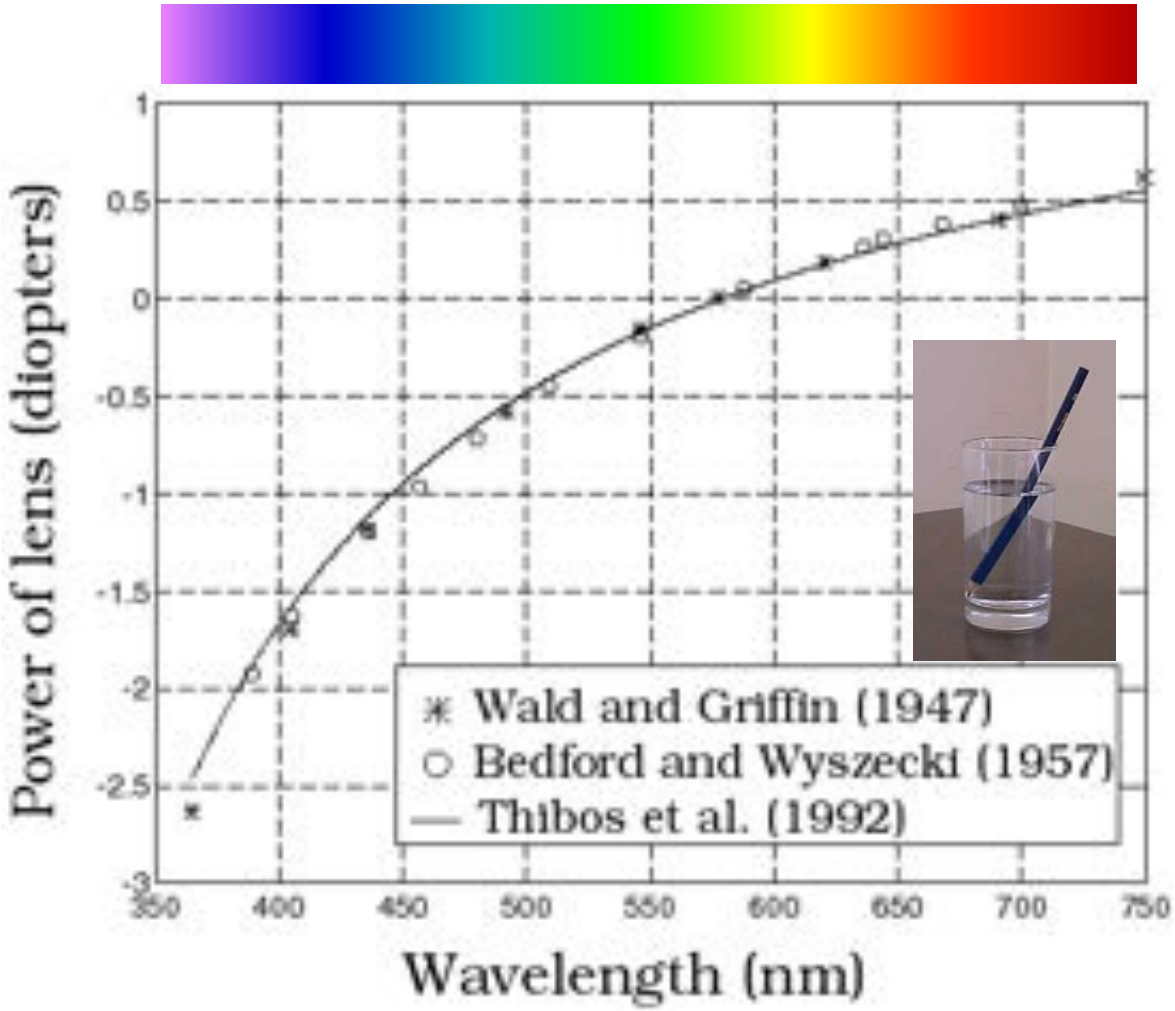
F-number ~ 2.4-11
Retinal thickness ~ 0.5mm

Chromatic aberration is wavelength-dependent difference in focal length



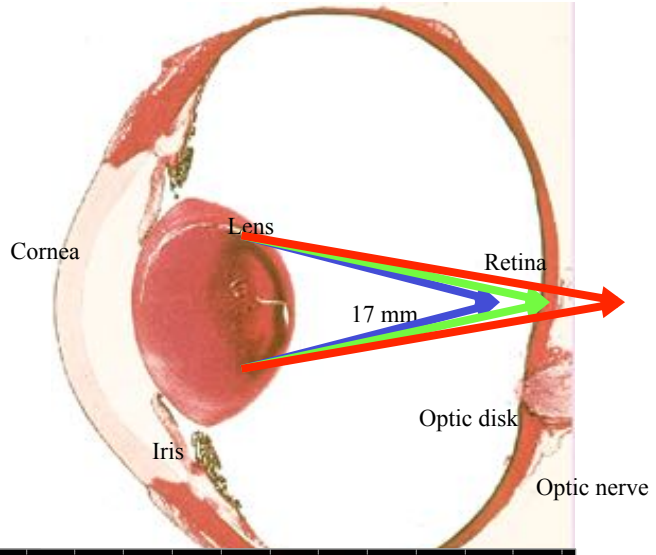
Chromatic aberration size is quantified by optical power (1/meters)

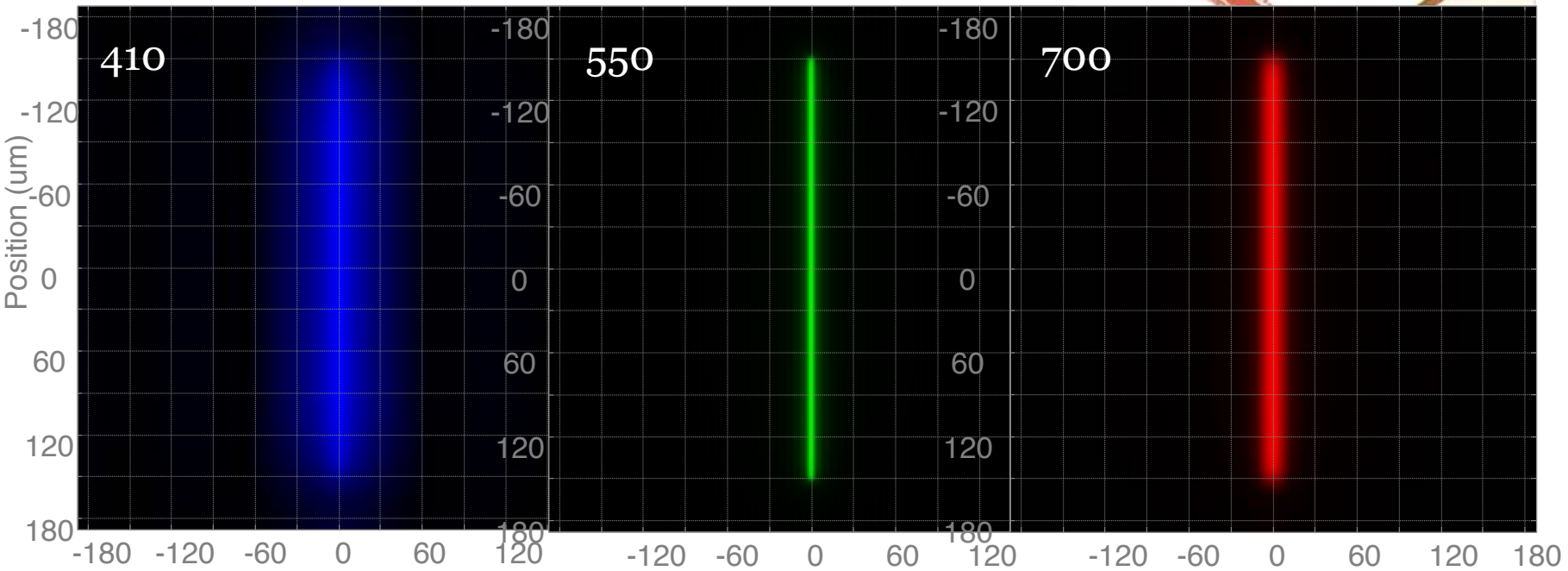
- Largest optical aberration
- Size is very similar across people



ISETBIO: t_humanLineSpread

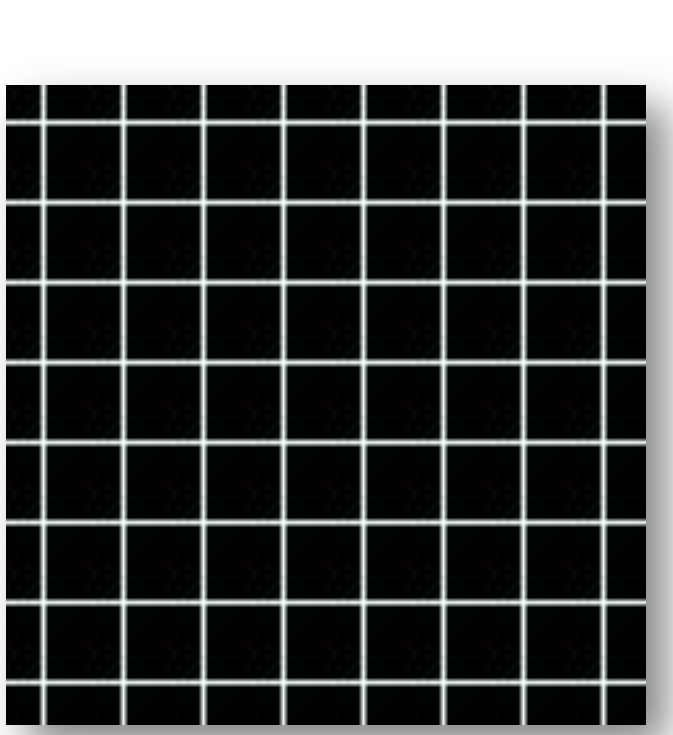
Line spread function by wavelength



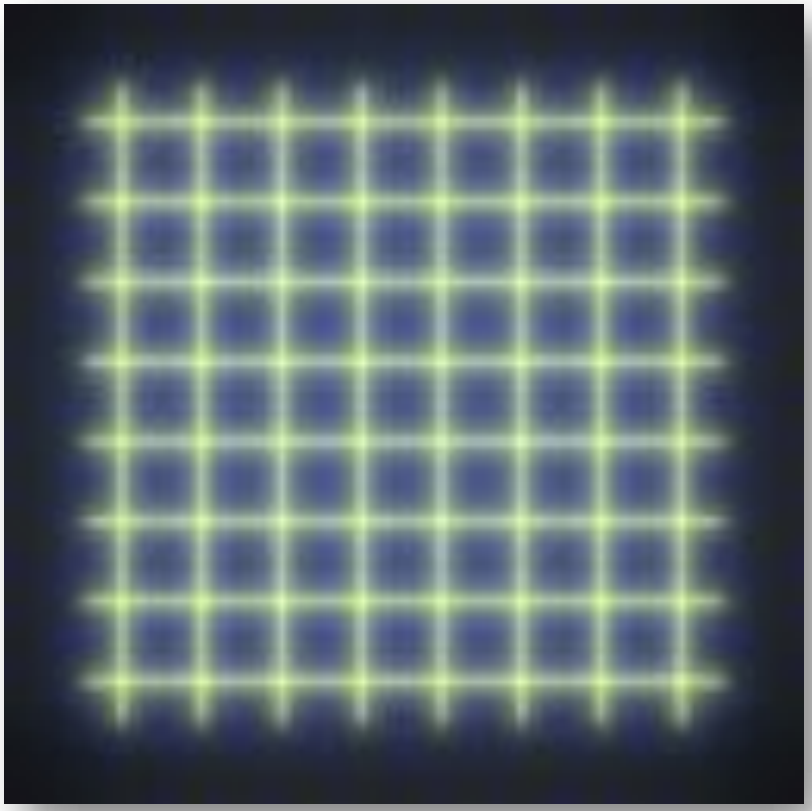


Example: Wavelength-dependent spread of a broadband light (D65)

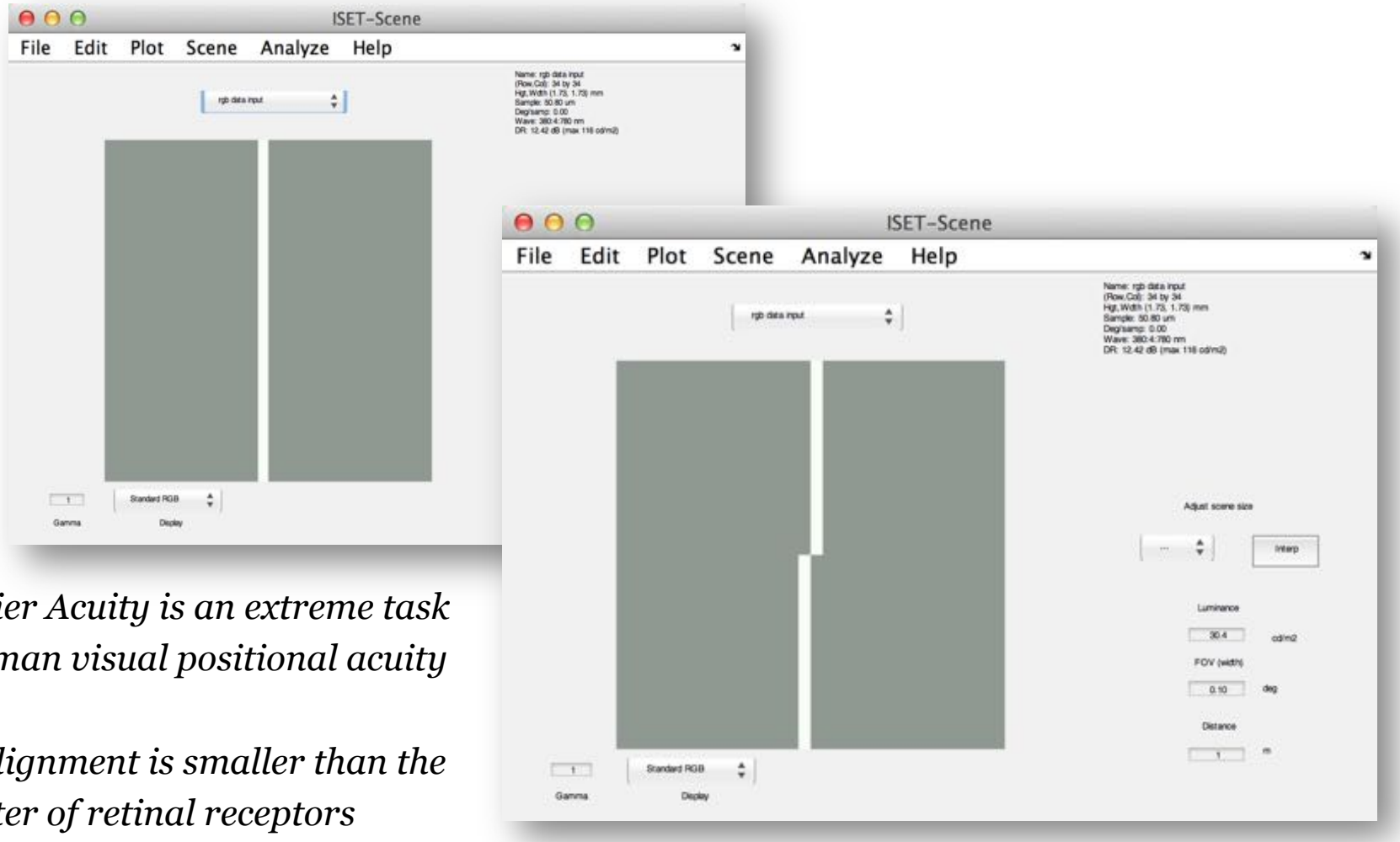
Broadband radiance produces chromatic irradiance



Human optics



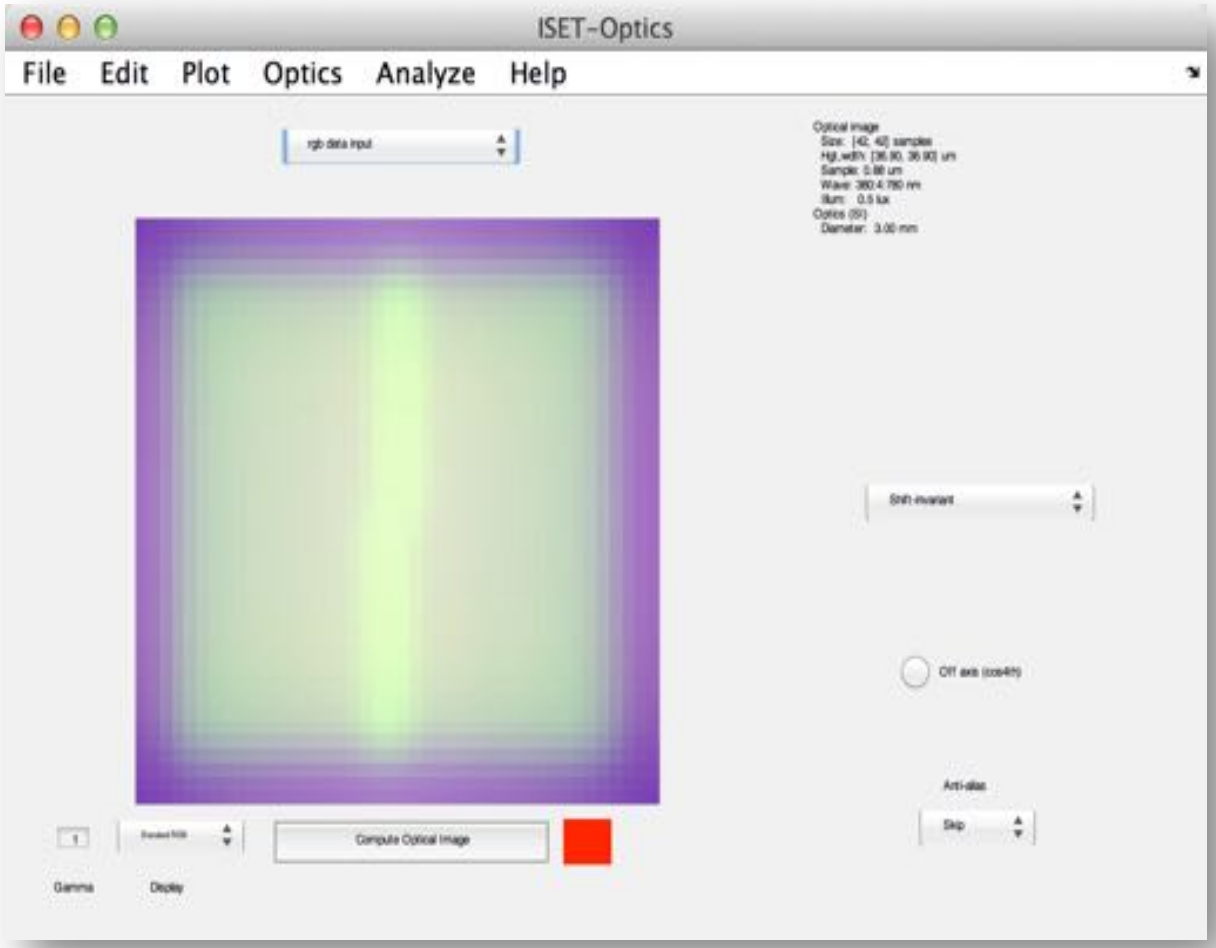
ISETBIO: Scene radiance



- *Vernier Acuity is an extreme task for human visual positional acuity*

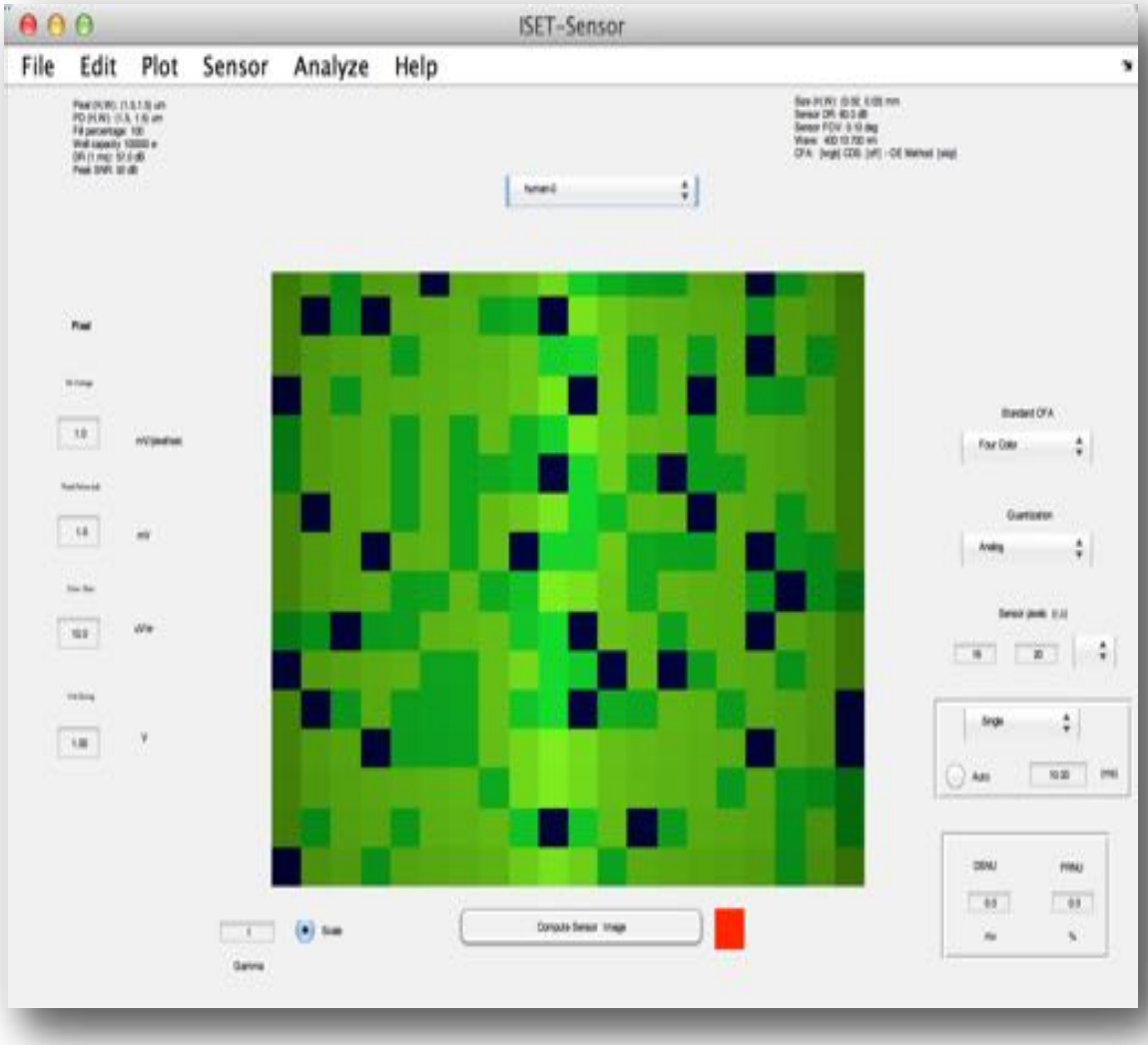
- *Misalignment is smaller than the diameter of retinal receptors*

Optical image (irradiance)



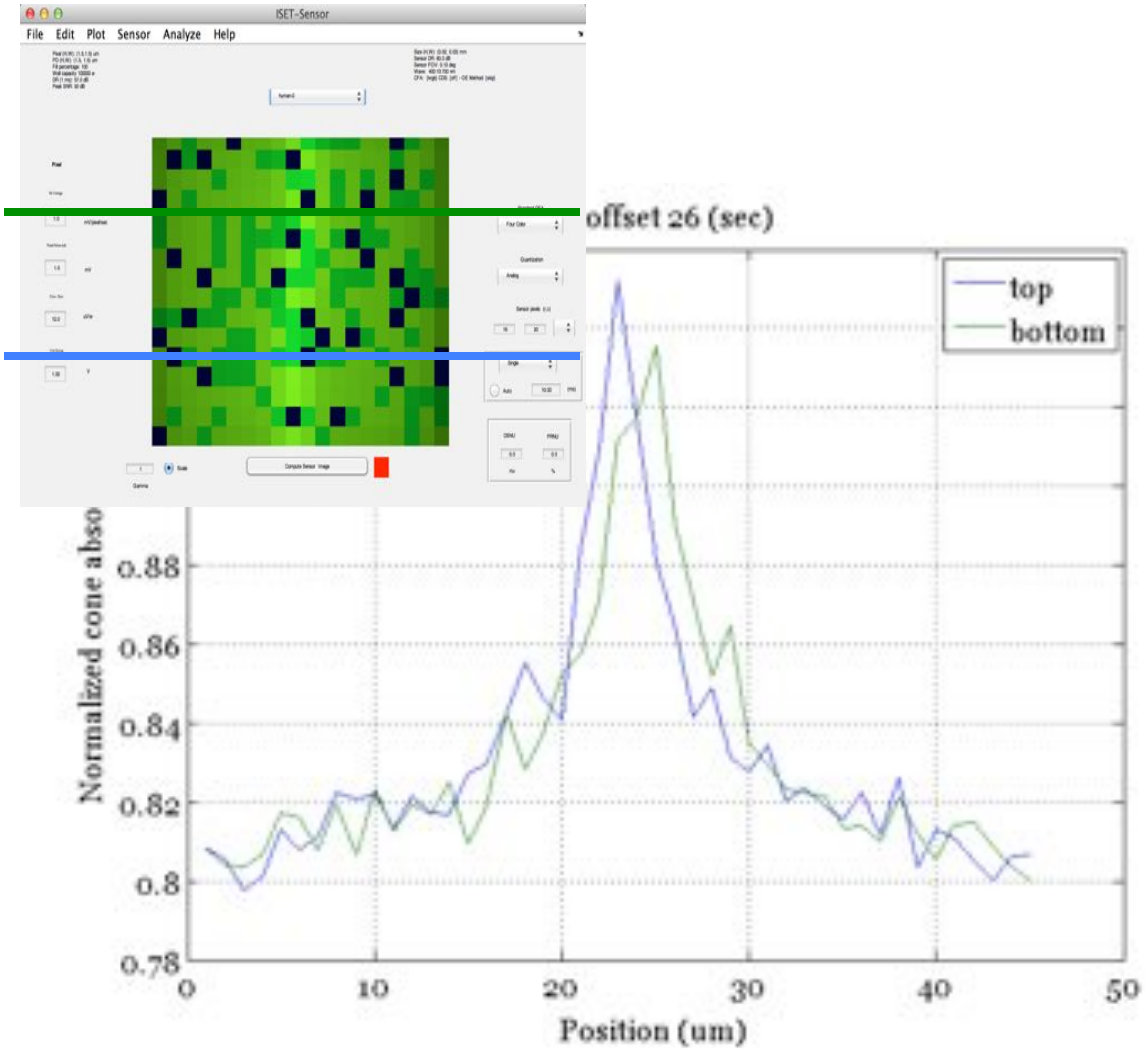
- Irradiance image blurred by human eye, lose some spatial frequency information
- Chromatic aberration
- Differs in eyes of different groups of people (astigmatism, presbyopia, etc.)

Sensor (cone absorptions)



- Compute expected number of photons to be absorbed by each retinal photo receptor
- Photon noise is added to generate a bunch of samples
- Non-additive noise (e.g. eye movement) is considered

Cone vernier resolution

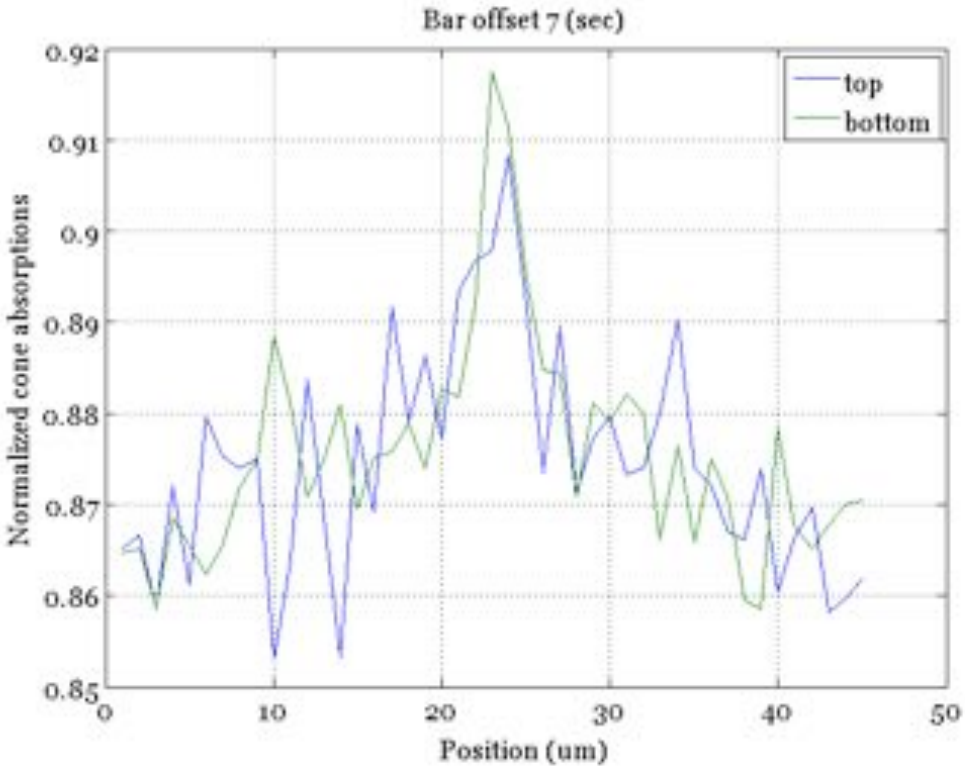


Display 200 dpi

M-cone spacing – 1.5 um

Compare no noise and photon noise only

Cone vernier resolution

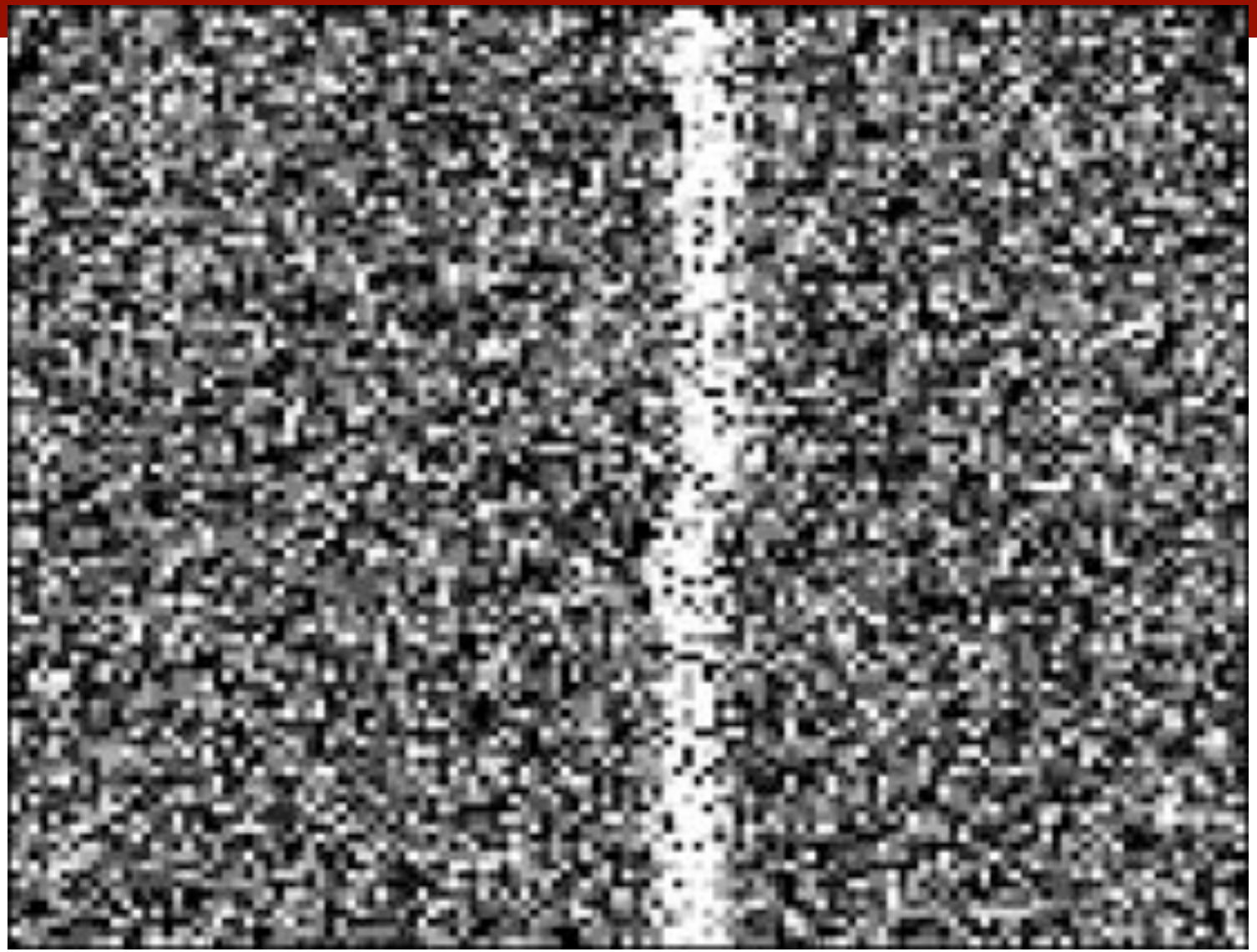


Display 800 dpi

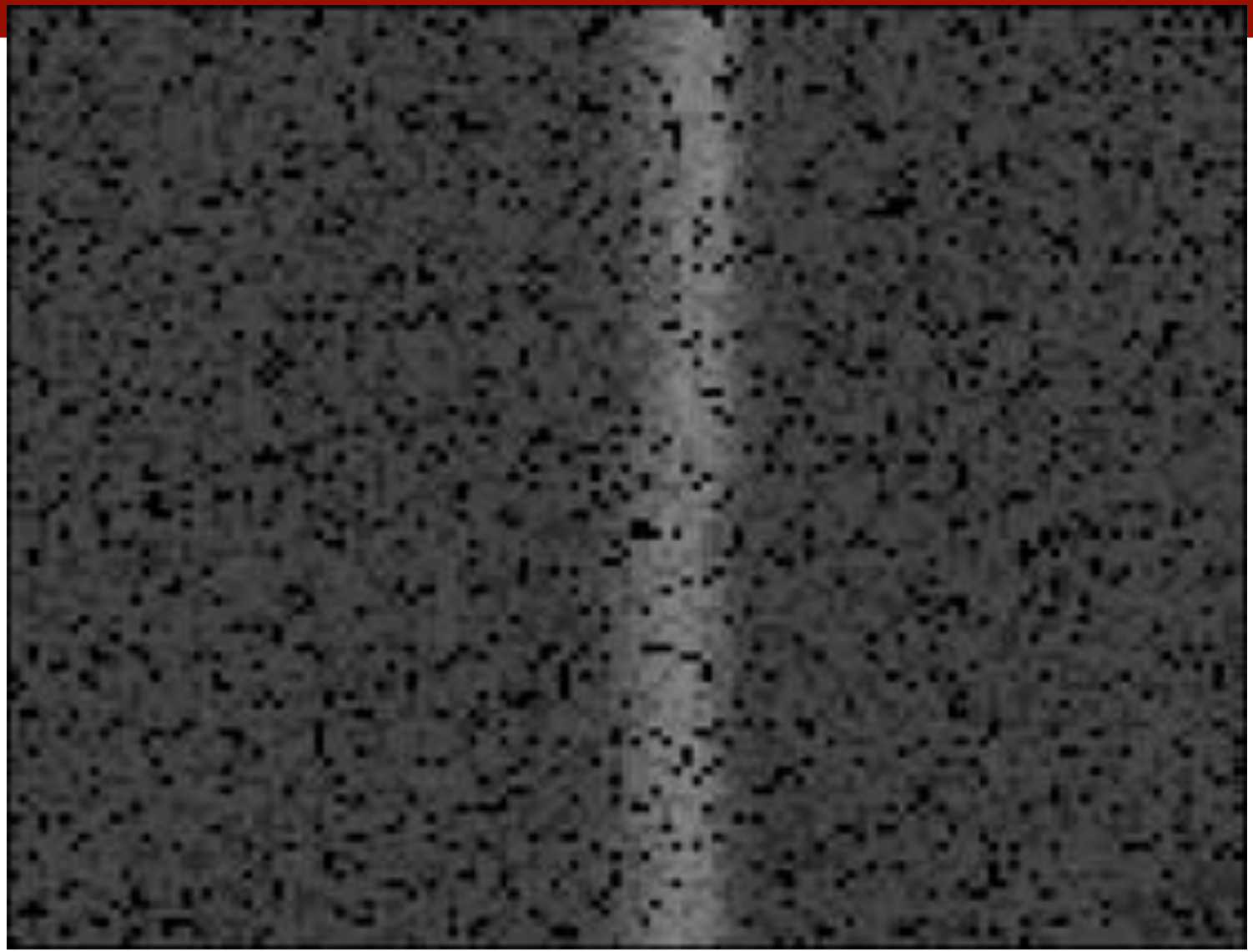
M-cone spacing – 1.5 um

Compare no noise and photon noise only

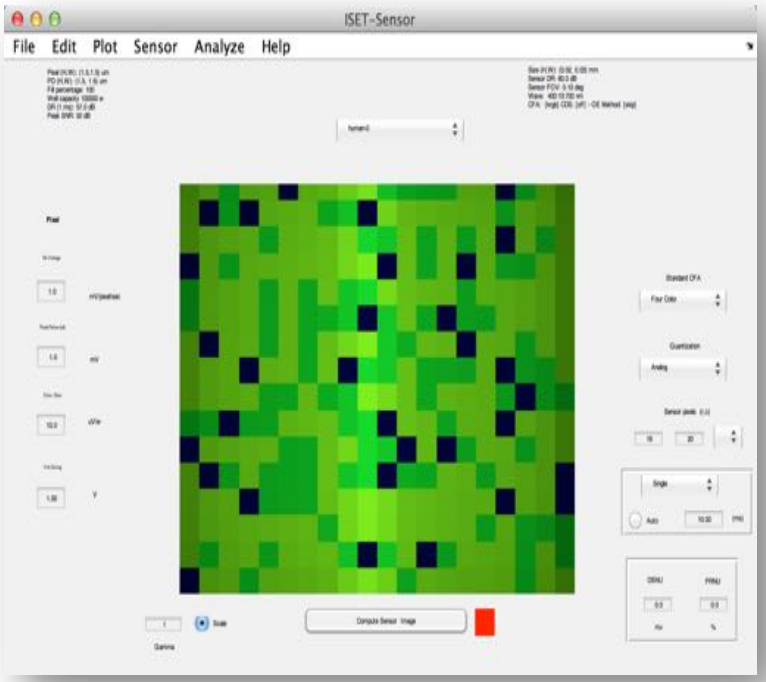
Photon absorptions



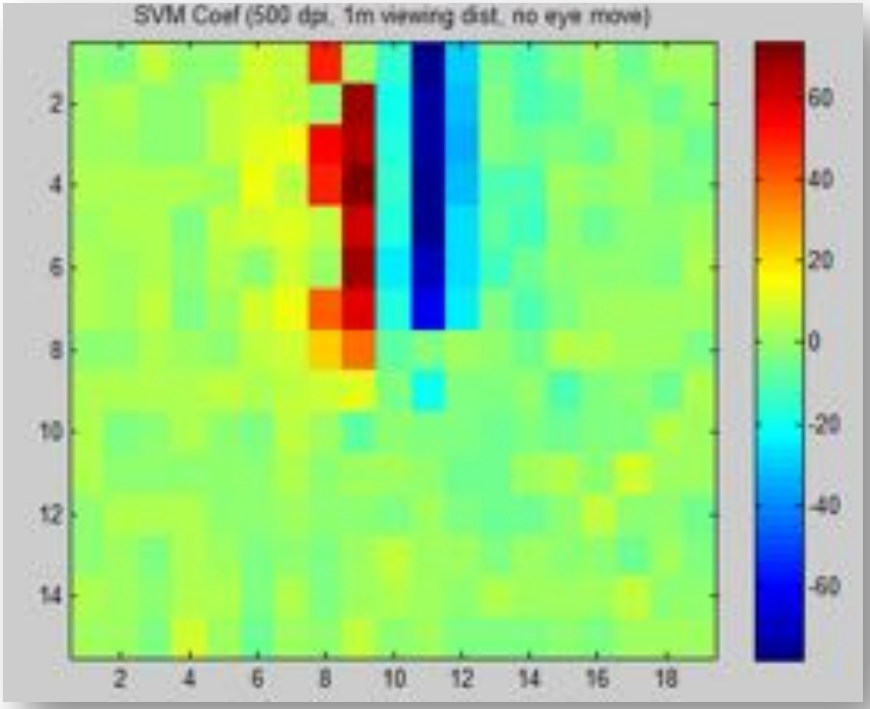
Cone adaptation model (Rieke)



Classifier
(Support vector machine)

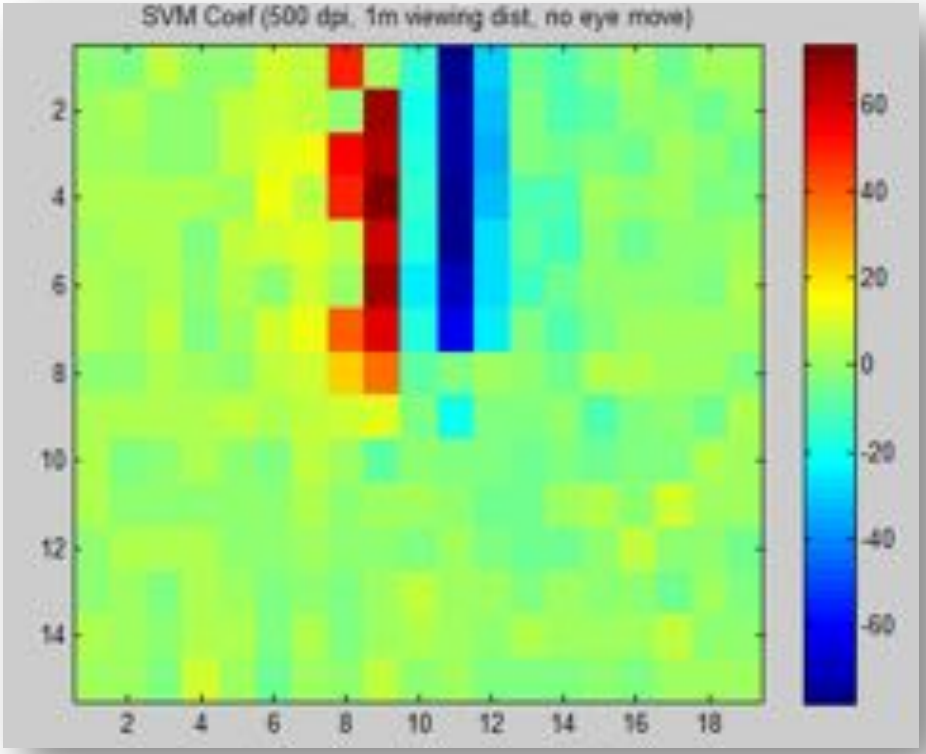


- Machine learning methods find spatial structure that can be used to decide offset vs. aligned

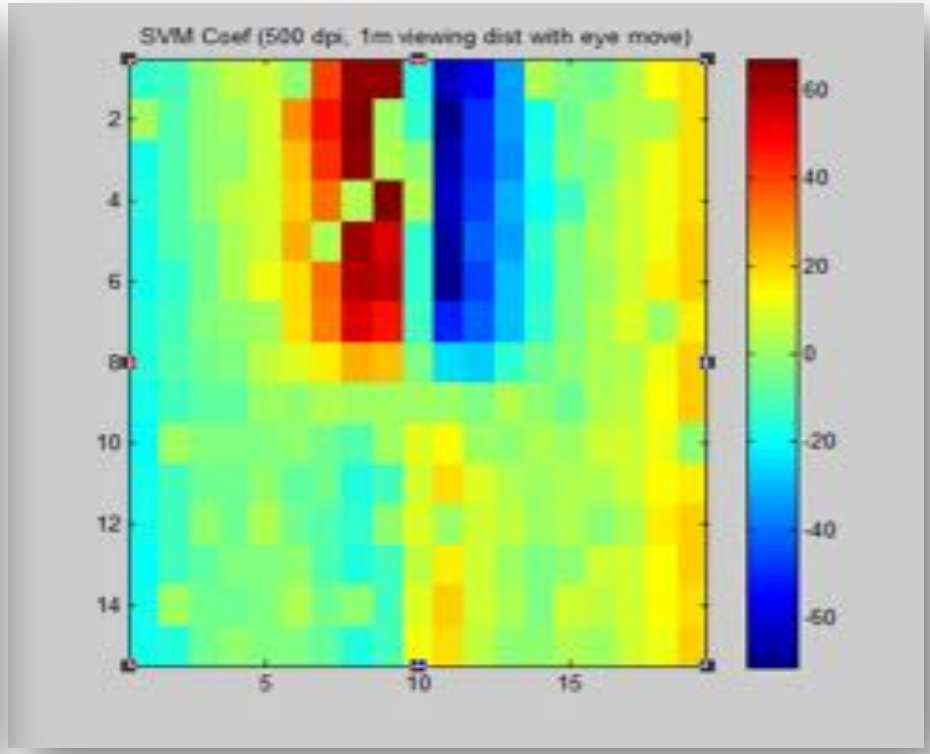


Classifier (SVM)

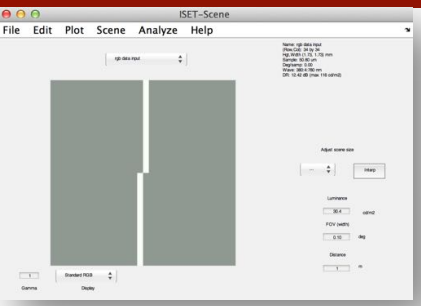
No eye movements



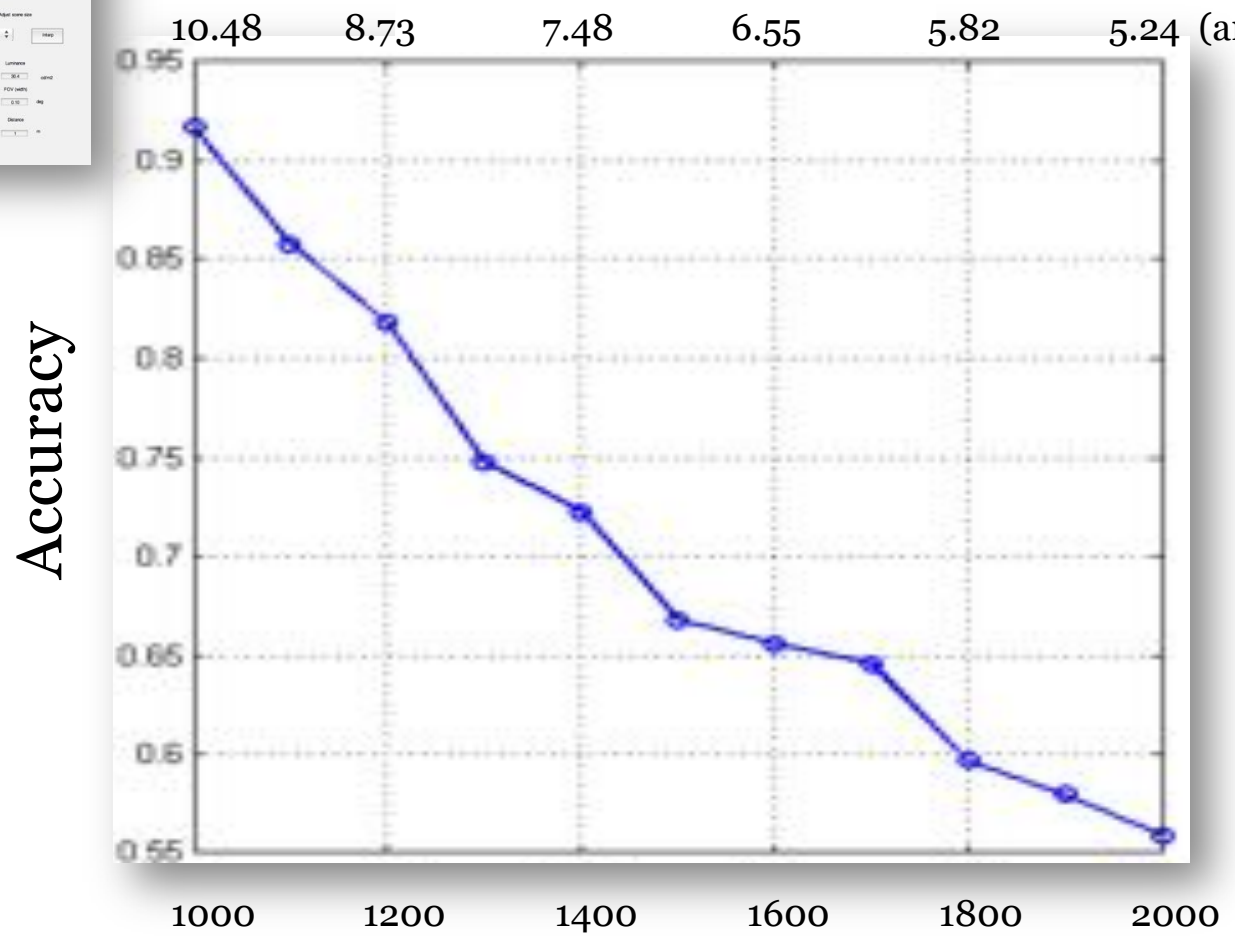
With eye movements



Used for engineering applications



SVM on vernier acuity



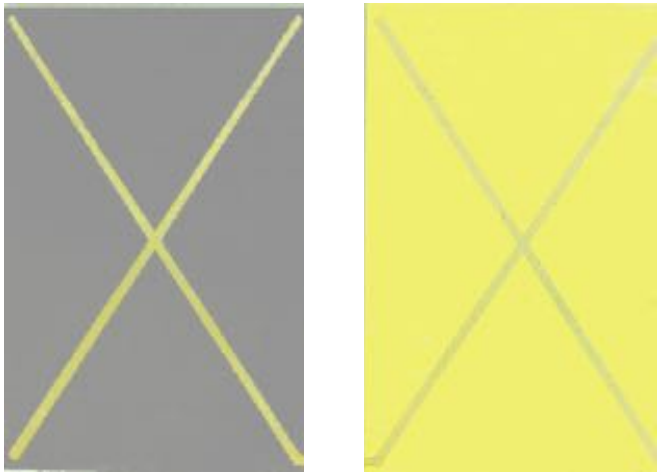
Context, pattern, and color for Engineering

An important context: Ambient lighting

SPD: spectral power distribution

Color appearance and context

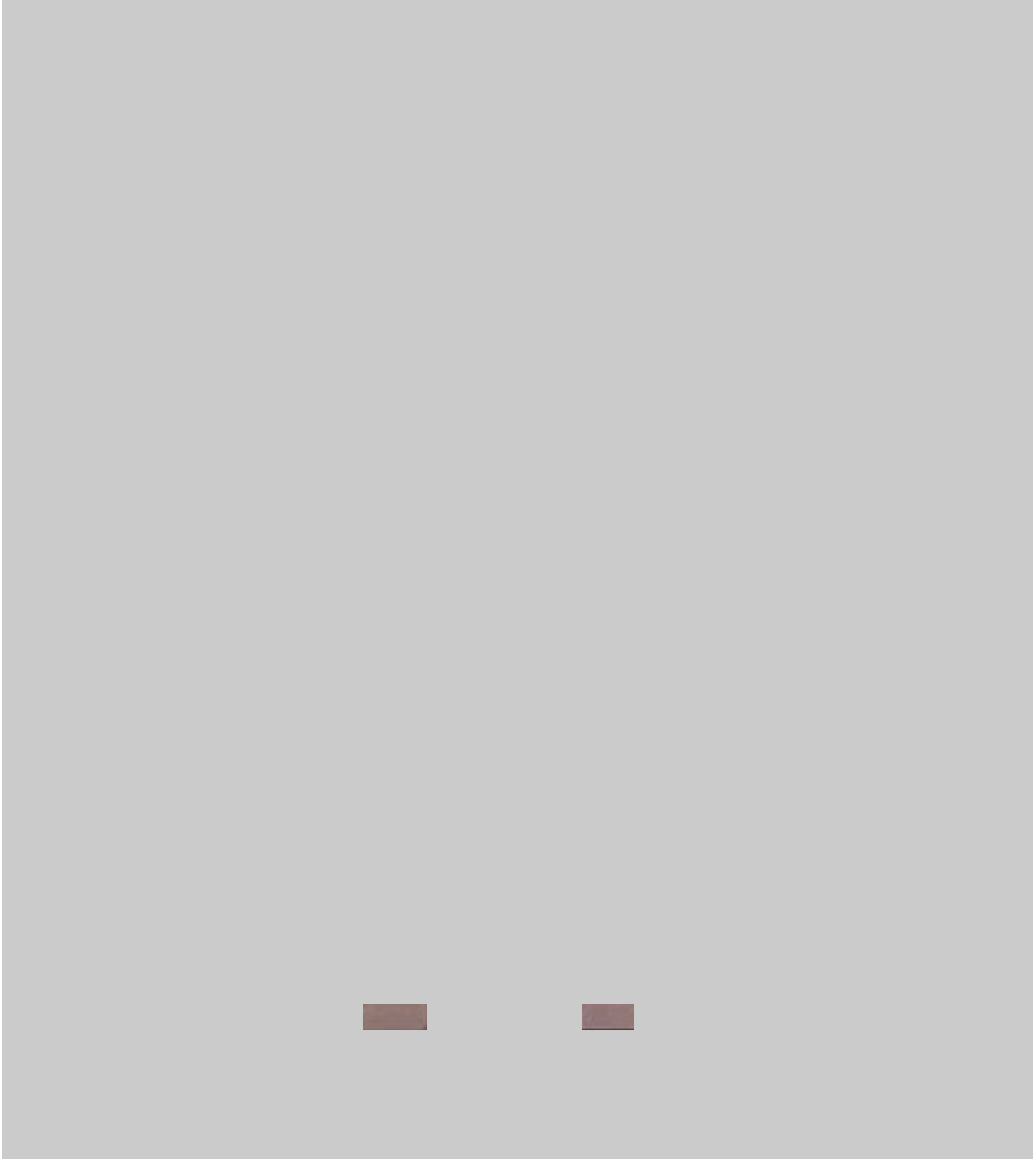
Color appearance and context



. . . 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)

Lightness Perception
(Lotto and Purves)

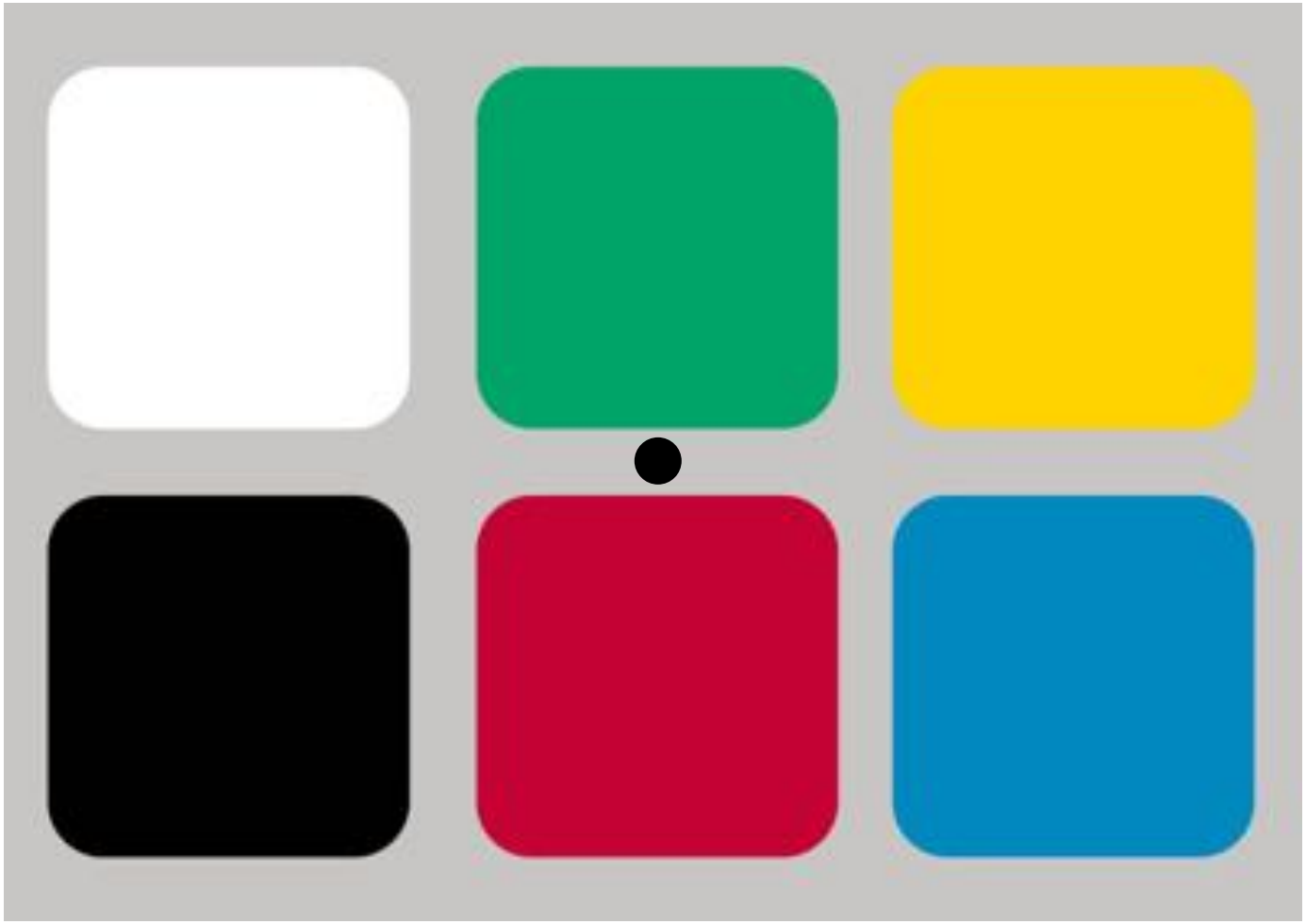


Judgments of lightness

(Anderson and Winawer, Nature, 2005)

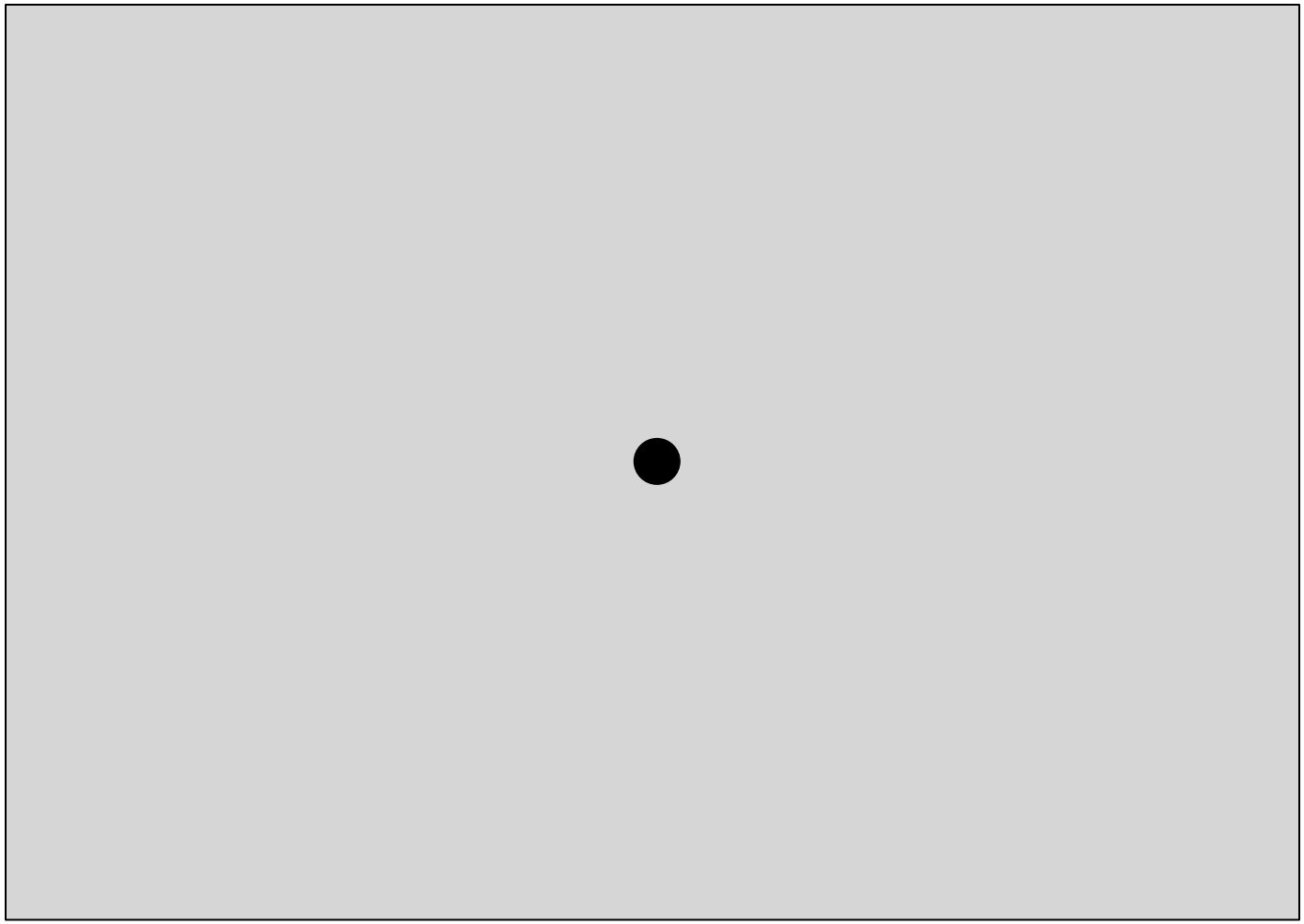
Opponent-colors

Opponent-colors – Afterimage demo



White
Green
Yellow

Black
Red
Blue



White
Green
Yellow

Black
Red
Blue


johnsadowski.com


keep staring at the black dot.


johnsadowski.com

Thanks to the people who did the work