G89.2223 Perception
Maloney

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Color Perception 2

Acknowledgments (slides)
David Brainard
David Heeger

Review

Descriptive

Normative

Color matching as matrix multiplication

Color match settings — Color matching functions — SPD of test light

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} r(\lambda_1) & r(\lambda_2) & \ldots & r(\lambda_N) \\ g(\lambda_1) & g(\lambda_2) & \cdots & g(\lambda_N) \\ b(\lambda_1) & b(\lambda_2) & \cdots & b(\lambda_N) \end{pmatrix} \begin{pmatrix} t(\lambda_1) \\ t(\lambda_2) \\ . \\ . \\ . \\ t(\lambda_N) \end{pmatrix}$$

Intensities of the three primary lights

wavelengths: $\lambda_1 = 400$, $\lambda_2 = 401$, etc

Color matching: scaling

Scaling the input by α scales the output by α.

Color match settings — Color matching functions — SPD of test light

$$\begin{pmatrix} \alpha R \\ \alpha G \\ \alpha B \end{pmatrix} = \begin{pmatrix} r(\lambda_1) & r(\lambda_2) & \ldots & r(\lambda_N) \\ g(\lambda_1) & g(\lambda_2) & \cdots & g(\lambda_N) \\ b(\lambda_1) & b(\lambda_2) & \cdots & b(\lambda_N) \end{pmatrix} \begin{pmatrix} \alpha\, t(\lambda_1) \\ \alpha\, t(\lambda_2) \\ . \\ . \\ . \\ \alpha\, t(\lambda_N) \end{pmatrix}$$

Color matching: additivity

Adding two the inputs gives the sum of the two outputs.

$$\begin{pmatrix} R_1 \\ G_1 \\ B_1 \end{pmatrix} = \begin{pmatrix} r(\lambda) \\ g(\lambda) \\ b(\lambda) \end{pmatrix} \begin{pmatrix} t_1(\lambda) \end{pmatrix} \qquad \begin{pmatrix} R_2 \\ G_2 \\ B_2 \end{pmatrix} = \begin{pmatrix} r(\lambda) \\ g(\lambda) \\ b(\lambda) \end{pmatrix} \begin{pmatrix} t_2(\lambda) \end{pmatrix}$$

$$\begin{pmatrix} R_1 + R_2 \\ G_1 + G_2 \\ B_1 + B_2 \end{pmatrix} = \begin{pmatrix} r(\lambda) \\ g(\lambda) \\ b(\lambda) \end{pmatrix} \begin{pmatrix} t_1(\lambda) + t_2(\lambda) \end{pmatrix}$$

Measuring the color matching functions

Color match settings = Color matching functions × SPD of test light

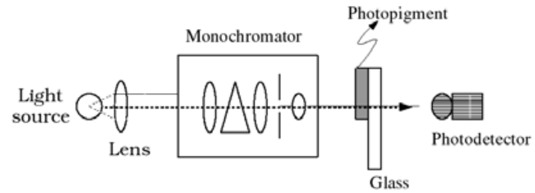
$$\begin{pmatrix} r(\lambda_1) \\ g(\lambda_1) \\ b(\lambda_1) \end{pmatrix} = \begin{pmatrix} r(\lambda_1) & r(\lambda_2) & \dots & r(\lambda_N) \\ g(\lambda_1) & g(\lambda_2) & \cdots & g(\lambda_N) \\ b(\lambda_1) & b(\lambda_2) & \cdots & b(\lambda_N) \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ . \\ . \\ . \\ 0 \end{pmatrix}$$

monochromatic test light

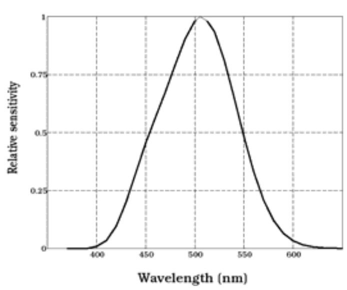
Repeat with monochromatic test lights of each wavelength, always using the same 3 primary lights.

Measuring rod spectral sensitivity

(wavelength-dependence of rhodopsin absorption)



Rod spectral sensitivity



Let's say you have a 500nm light with intensity 10. Can you match it's appearance with a 550nm light? If so, what will be the intensity of the matching light?

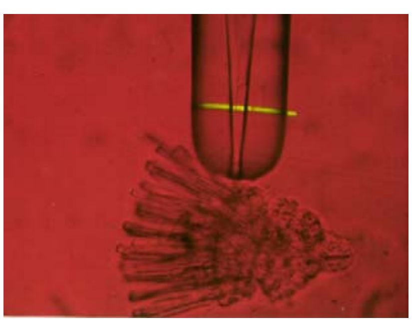
The principle of univariance

The response of a photoreceptor is a function of just one variable (namely, the number of photons absorbed).

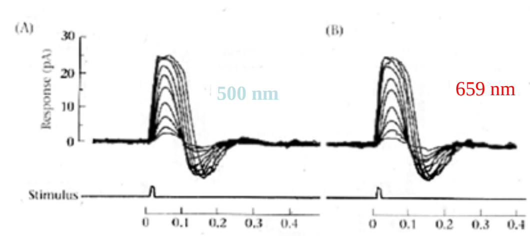
Thus, the response can be identical for:

- a *weak* light at the wavelength of *peak sensitivity*
  - few incident photons, a large fraction of them absorbed
- a *strong* light at a wavelength of *lower sensitivity*
  - many incident photons, a small fraction of them absorbed

Measuring cone photocurrents

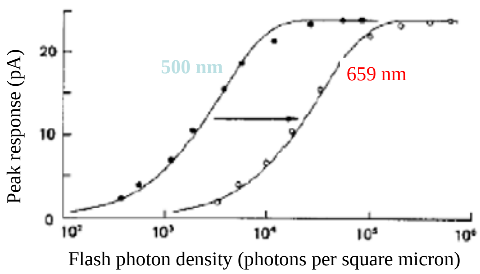


Cone photocurrent

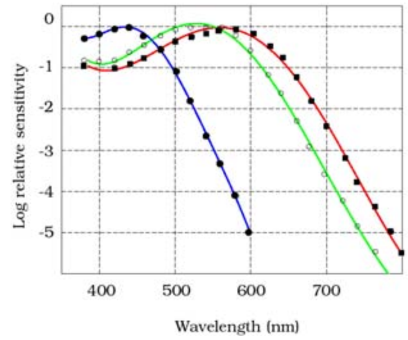


Baylor et al.

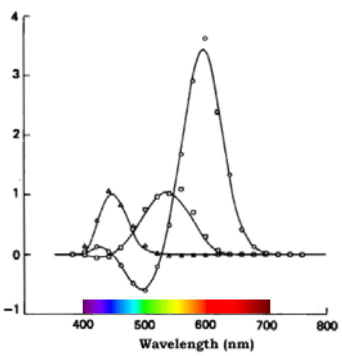
Cone responses are nonlinear
(but can be equated by scaling intensity)



Cone spectral sensitivities



Cone responsivities
(and optical filters)
predict color matching functions



Baylor et al.

Wavelength encoding equation

Response — Cone responsivity — Input SPD

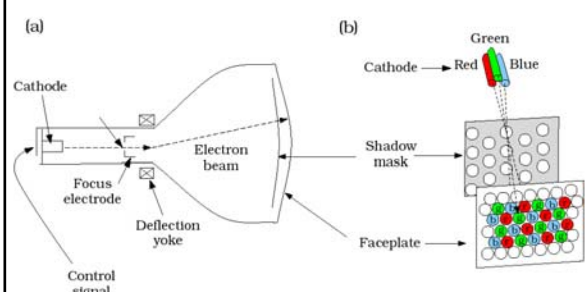
$$\begin{pmatrix} L \\ M \\ S \end{pmatrix} = \begin{pmatrix} \cdots & l(\lambda) & \cdots \\ \cdots & m(\lambda) & \cdots \\ \cdots & s(\lambda) & \cdots \end{pmatrix} \begin{pmatrix} t_1 \\ \vdots \\ t_n \end{pmatrix}$$

Metamers revisited

$$\begin{pmatrix} L \\ M \\ S \end{pmatrix} = \begin{pmatrix} \cdots & l(\lambda) & \cdots \\ \cdots & m(\lambda) & \cdots \\ \cdots & s(\lambda) & \cdots \end{pmatrix} \begin{pmatrix} t_1 \\ \vdots \\ t_n \end{pmatrix} = \begin{pmatrix} \cdots & l(\lambda) & \cdots \\ \cdots & m(\lambda) & \cdots \\ \cdots & s(\lambda) & \cdots \end{pmatrix} \begin{pmatrix} s_1 \\ \vdots \\ s_n \end{pmatrix}$$

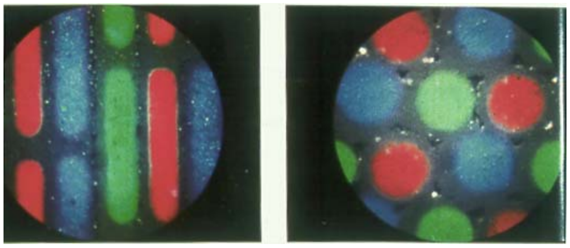
SPDs of two lights

Displays and color matching

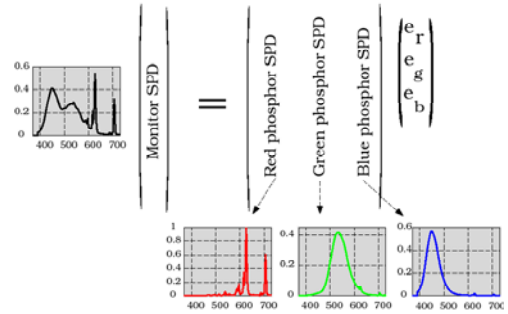


Application: Color TV

Trinitron | Conventional tri-dot

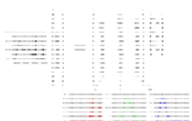


Color display equation



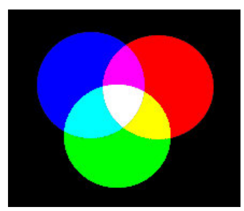
Color matching and trichromacy caveats

1. The 3 primary lights must be linearly independent:

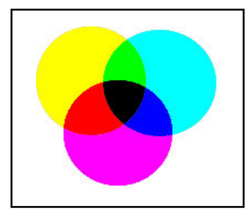


2. For any set of primaries, there are test lights that are out of range such that the primary intensities must be higher than achievable or "negative" (which is physically impossible).
3. Trichromacy determines when two lights look the same, not what they look like.
4. Additive vs "subtractive" color mixtures.

RGB
red, green, blue--used in TVs
Additive mixing of light sources



CMYK
cyan, magenta, yellow, black–used in printing
Subtractive mixing of absorbing pigments



http://www.bbso.njit.edu/Documentations/gimpdoc-html/color.html

Color blindness

Color blindness

normal | red/green color blind | blue-yellow color blind

- Dichromats: missing one of the three photopigment/cone types.
- Can match with 2 primaries in the color matching experiment
- Will accept trichromat's match but trichromat will not always accept dichromats match.

Color blindness

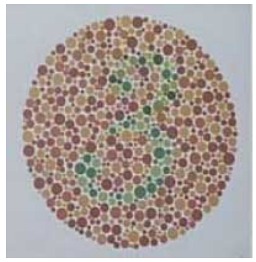

normal

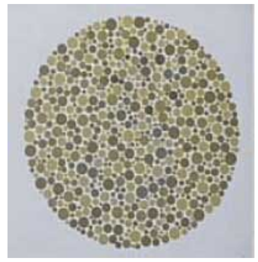

red/green color blind


blue/yellow color blind

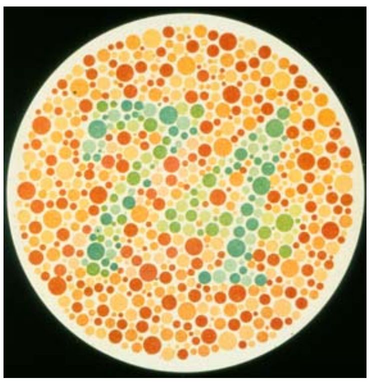
People with color deficiencies may have difficulty distinguishing certain colors (e.g., a red/green color deficiency means that reds and greens are more difficult to distinguish). But as this photo demonstrates, many other colors are just as distinguishable to a person with a color deficiency as to someone with normal color vision.

Color blindness

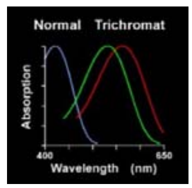

Ishihara plate

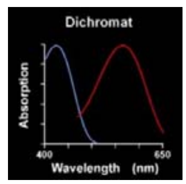

What a red/green color-blind person might see

Test for Color Blindness



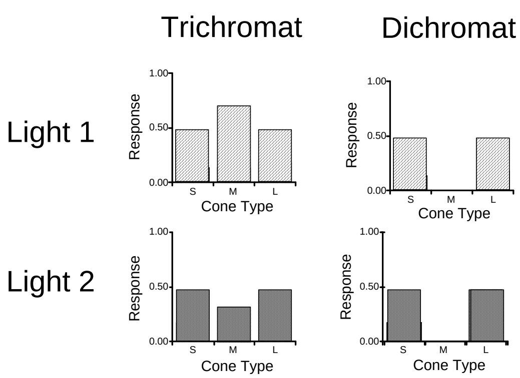
Cones in a Dichromat





http://www.mcw.edu/cellbio/colorvision/introduction.html

Color Matching for a Dichromat



Types of Color Deficiency

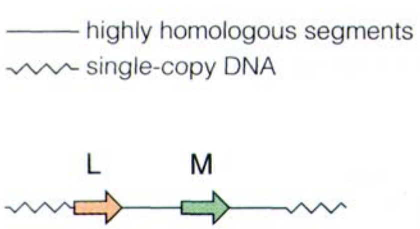
Common (X-chromosome linked)

Protanope - missing L cones
Deuteranope - missing M cones
Protanomalous - has two variants of M cones, no L cones
Deuteranomalous - has two variants of L cones, no M cones

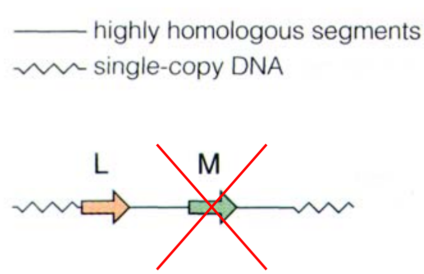
Less common

Tritanope - missing S cones
Tritanomalous - missing S, has three types of L/M cones
S-cone monochromat - missing L & M cones
Rod monochromat - missing all cones

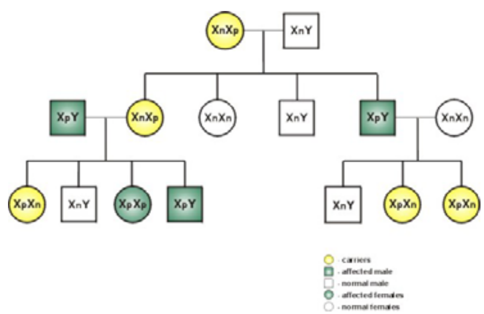
L and M Genes on X chromosome



Dichromacy Occurs When One Gene is Missing

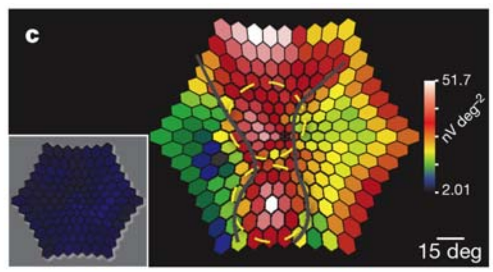


X-Linked Genetics of Dichromacy



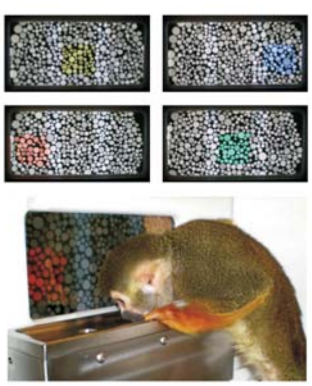
http://www.mcw.edu/cellbio/colorvision/introduction.htm

Gene Therapy for Color Blindness !?



Mancuso et al., 2009

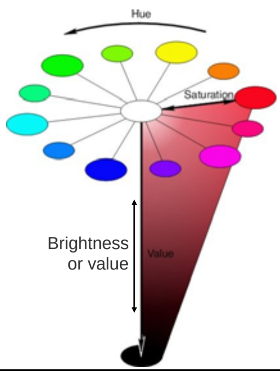
Gene Therapy for Color Blindness !?



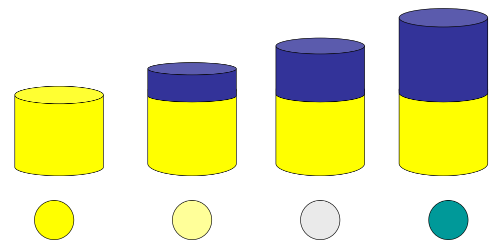
Mancuso et al., 2009

Color opponency

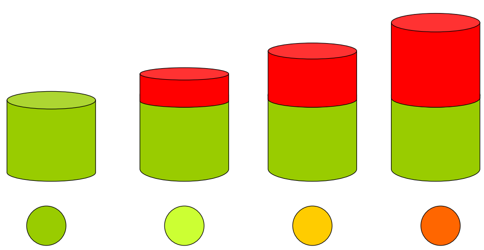
Color appearance



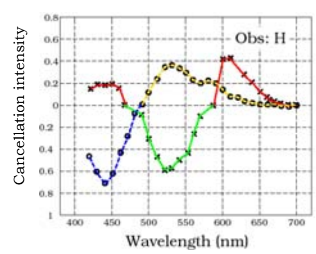
Hue cancellation experiment



Hue cancellation experiment



Hue cancellation

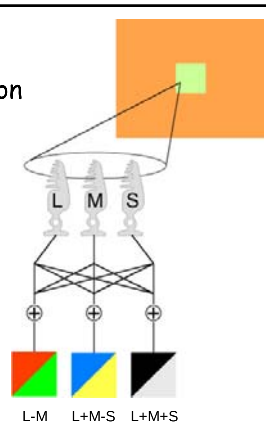


Blue curve, wavelengths that appear blue were cancelled by adding yellow light. Likewise for red and green.

Why is the curve red below 475nm as well as above 580nm?

Hurvich & Jameson (1957)

Color opponency neural computation

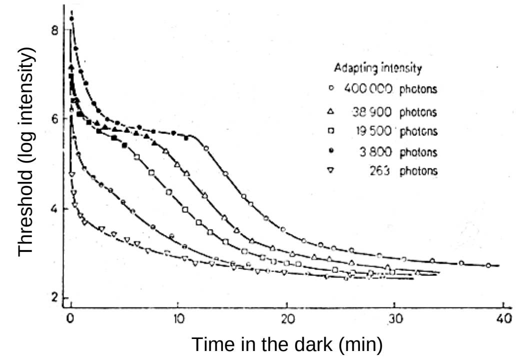


Light and dark adaptation

Surface luminance levels

- Sunlight: 10^5 candelas/meter^2 (cd/m^2)
  - Approx. 10^{22} photons/m^2/sec
  - 3%-90% of photons are reflected as luminance
  - 3% for black surfaces, 90% for white surfaces
  - Only some of the reflected photons enter the pupil of eye
- Indoor lighting, CRTs: 10^2 cd/m^2
- Moonlight: 10^{-1} cd/m^2
- Starlight: 10^{-3} cd/m^2
- The eye can adjust to changes in light level by a factor of 100,000,000!
- Yet firing rates typically range from only 0-400Hz.

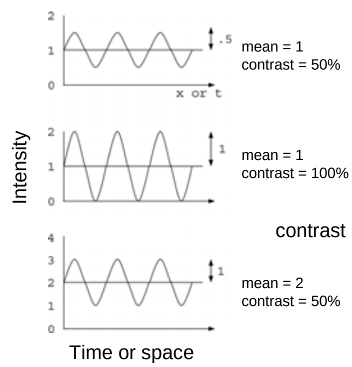
Dark adaptation



Mechanisms of light/dark adaptation

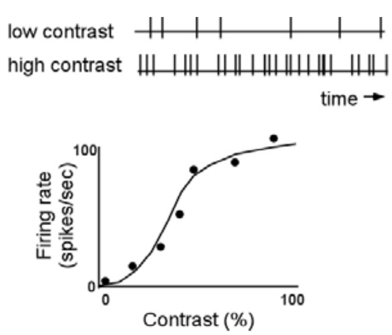
1. Pupil size
2. Switchover between rods and cones
3. Bleaching/regeneration of photopigment
4. Feedback from horizontal cells to control the responsiveness of photoreceptors

Contrast

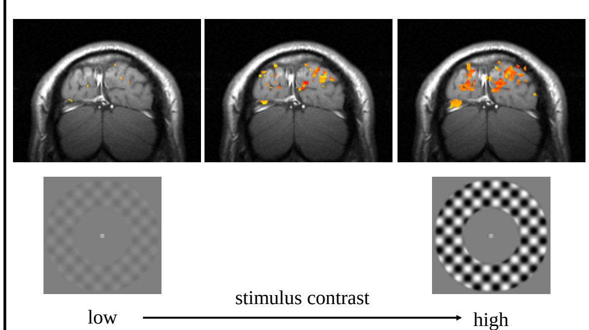


$$\text{contrast} = \frac{\text{amp of modulation}}{\text{mean}}$$

Responses increase with contrast

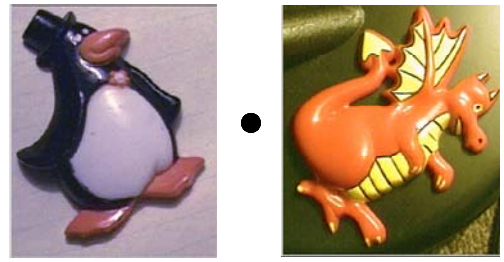


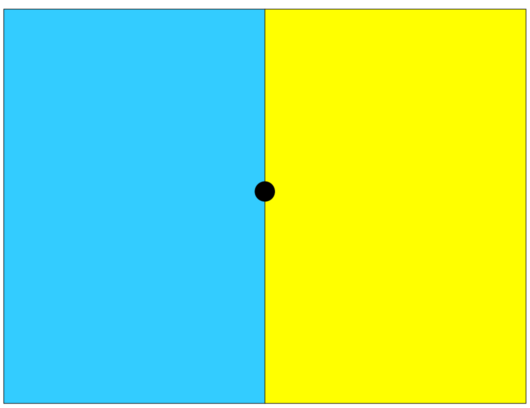
Responses increase with contrast

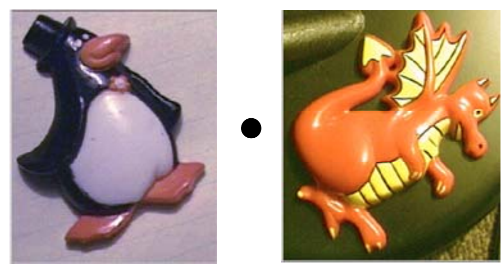


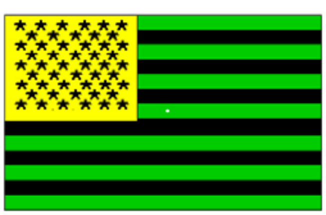
Chromatic adaptation

Chromatic adaptation



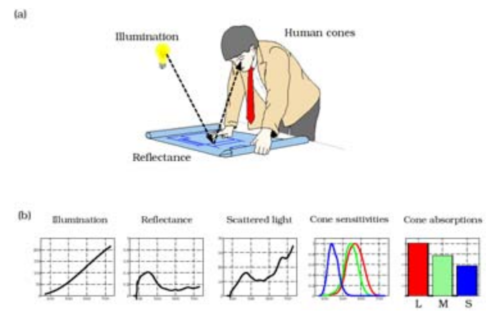




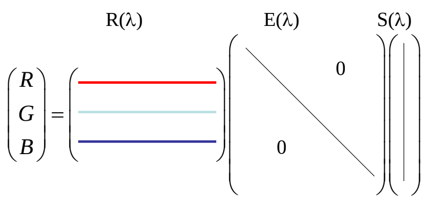


Color constancy

Color signaling



Surface-illuminant equations



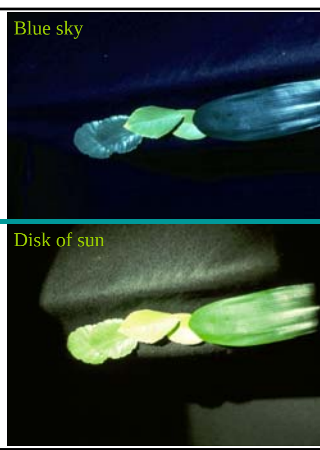
$$G = \int E(\lambda)S(\lambda)R_g(\lambda)d\lambda$$

Cameras do not have color constancy

daylight

flourescent light

Daylight illumination examples

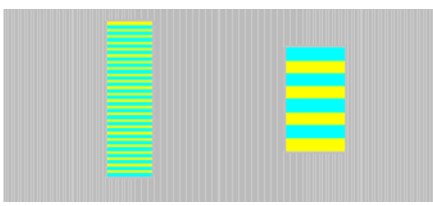


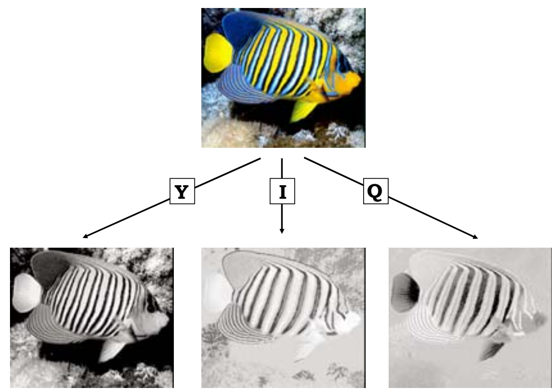
Principles

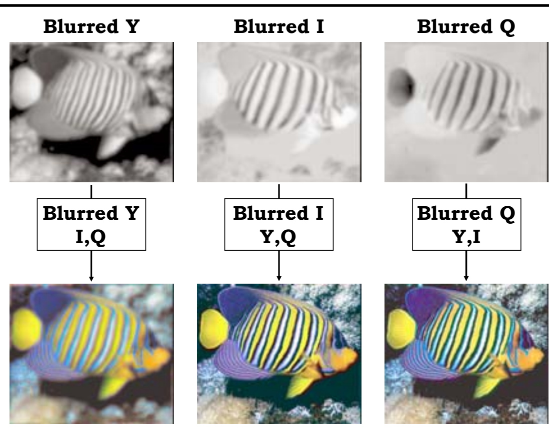
Psychophysics is part psycho and part physics.
Theory: linear systems.
Methodology: matching.
Computation: linear summation, static nonlinearity, adaptation.
Principle of univariance.
Parallel pathways.
Perceptual constancy (lightness, color, size, etc.), adaptation, and visual illusions (e.g., aftereffects).

Color and pattern

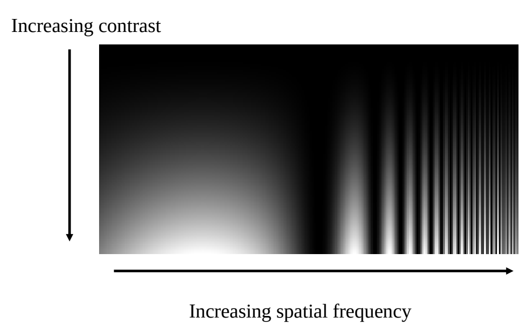
S-cones have low resolution





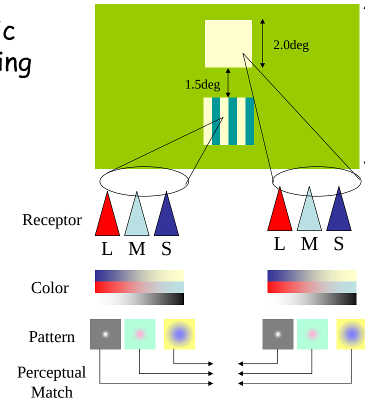


Monochrome MTF



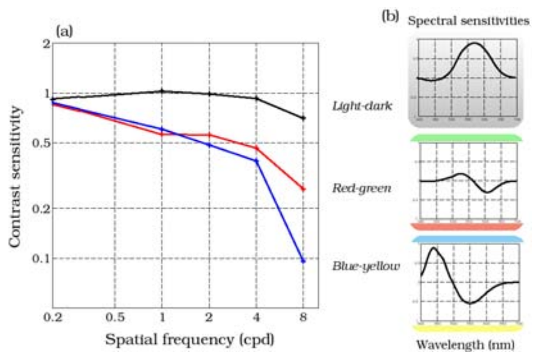
Chromatic MTF

Asymmetric color matching

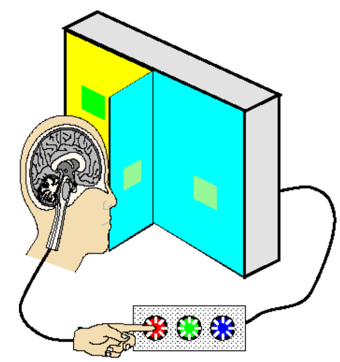


Poirson and Wandell,
J. Opt. Soc. Am A, 1993,
***10**, no. 12, pp. 2458-2470*

Asymmetric color matching results



Dichoptic color-matching: adaptation



Courtesy E.J. Chichilnisky