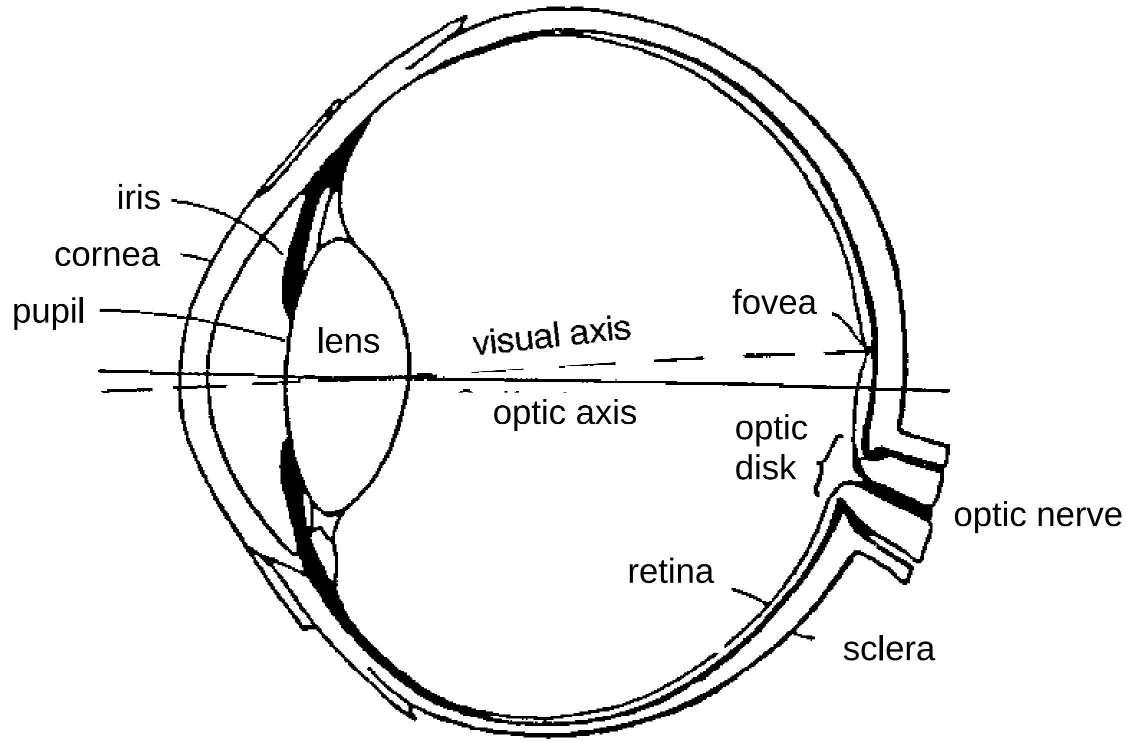
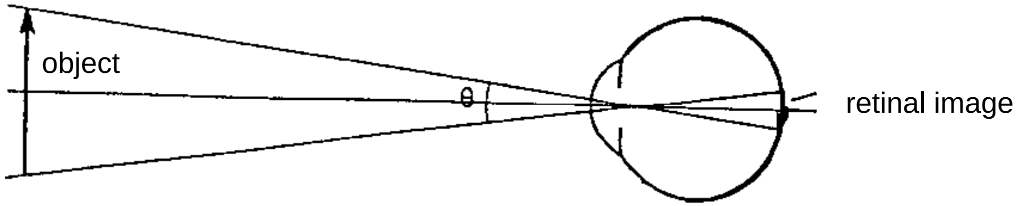
Human Visual Perception - Overview

- Anatomy of the Human Eye
- Trichromacy
- Color Systems
- Color Representation in the Chromacity Plane
- Weber-Fechner Law
- Lateral inhibition and excitation
- Transfer functions of the color channels
- Spatial and temporal masking

Anatomy of the Human Eye





The Human Retina I

Signal propagation in the retina:

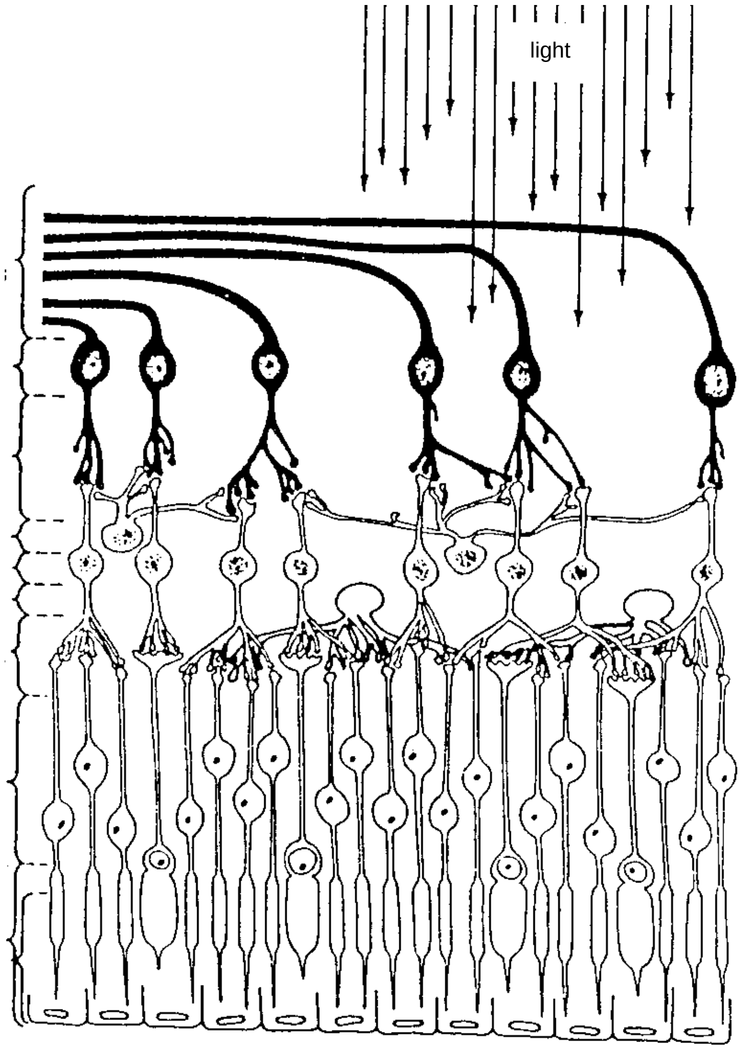
ganglion cells (= optic nerve)

↑

bipolar cells

↑

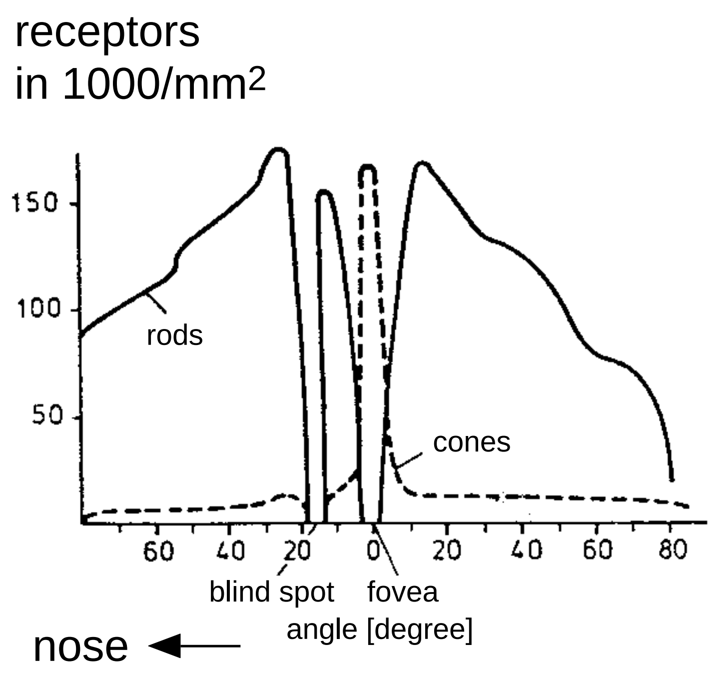
receptors



The Human Retina II

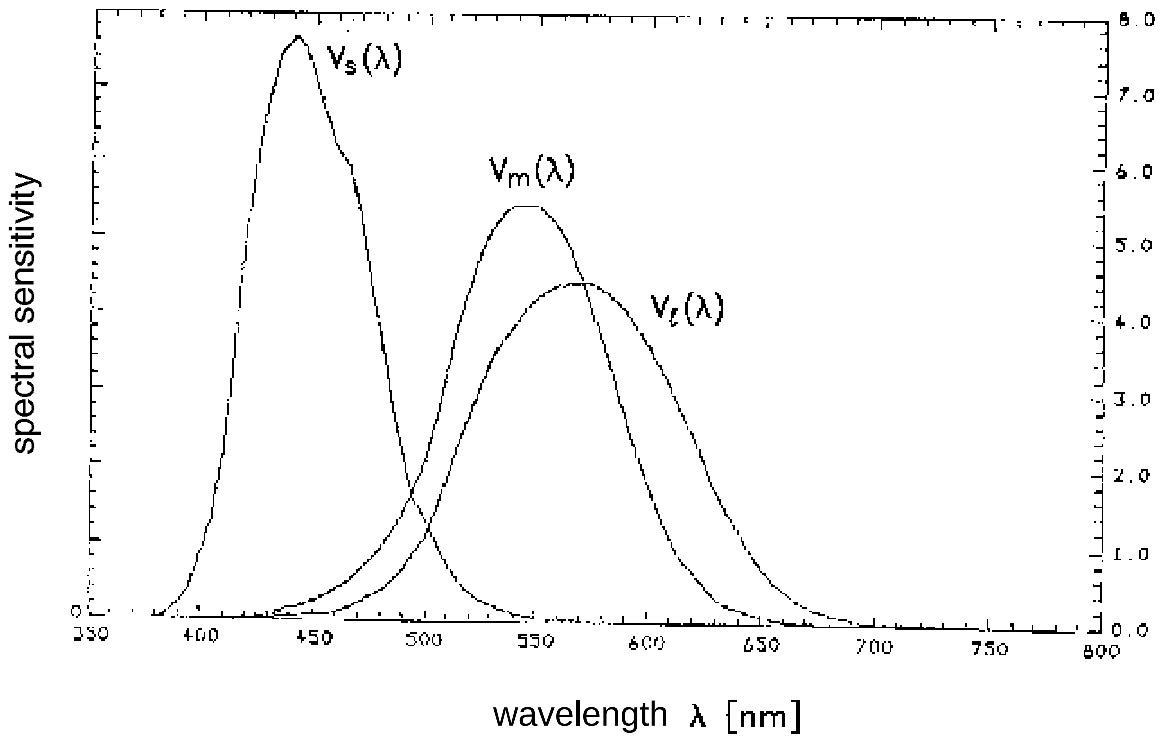
Rods	Cones
high sensitivity	low sensitivity
low light vision	day light vision > 1 cd/m^2
monochrome	color
"scotopic vision"	"photopic vision"

Video displays



Absorption Spectra of Cones in the Human Retina

Normalized absorption spectra



Trichromacy Theory

Spectral irradiance on the retina

$$i(\lambda) = \frac{dI(\lambda)}{d\lambda}$$

Cones "see" the physical quantities

“primary colors“

“color space“

$$I_s = \int_0^\infty V_s(\lambda)\, i(\lambda)\, d\lambda$$

$$I_m = \int_0^\infty V_m(\lambda)\, i(\lambda)\, d\lambda$$

$$I = \int_0^\infty V(\lambda)\, i(\lambda)\, d\lambda$$

⟹ Three numbers are sufficient to characterize each possible spectrum

Metamers: $i_1(\lambda) \neq i_2(\lambda)$ but

$$I_{s1} = I_{s2}$$

$$I_{m1} = I_{m2}$$

$$I_1 = I_2$$

Additive Color Mixing

Mapping $i(\lambda) \rightarrow I_s, I_m, I_l$ is linear

Superposition

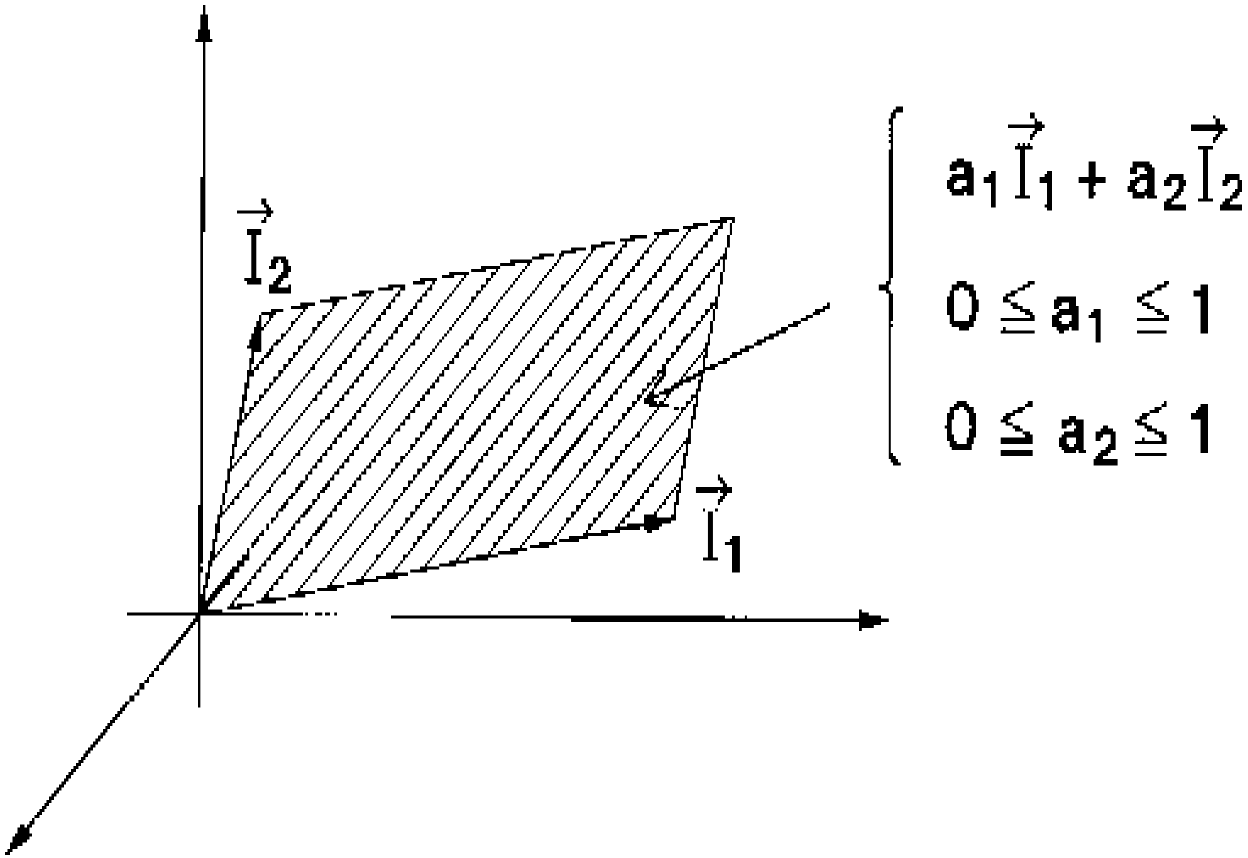
if $i(\lambda) = a_1 i_1(\lambda) + a_2 i_2(\lambda)$

then
$$I_s = a_1 I_{s1} + a_2 I_{s2}$$
$$I_m = a_1 I_{m1} + a_2 I_{m2}$$
$$I_\ell = a_1 I_{\ell 1} + a_2 I_{\ell 2}$$

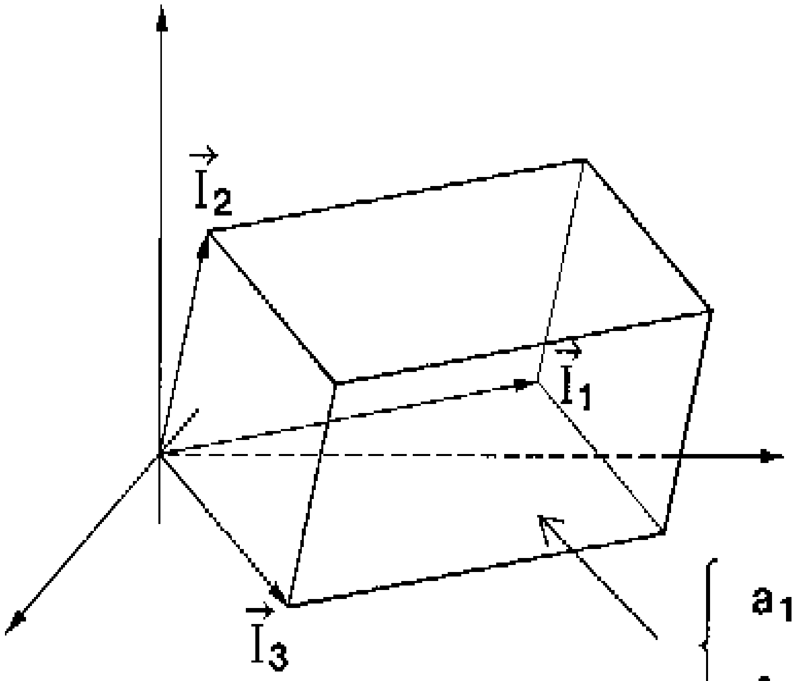
Written as a vector

$$I = \begin{pmatrix} I_s \\ I_m \\ I \end{pmatrix} = a_1 I_1 + a_2 I_2$$

Gamut Spanned by Two Primary Colors



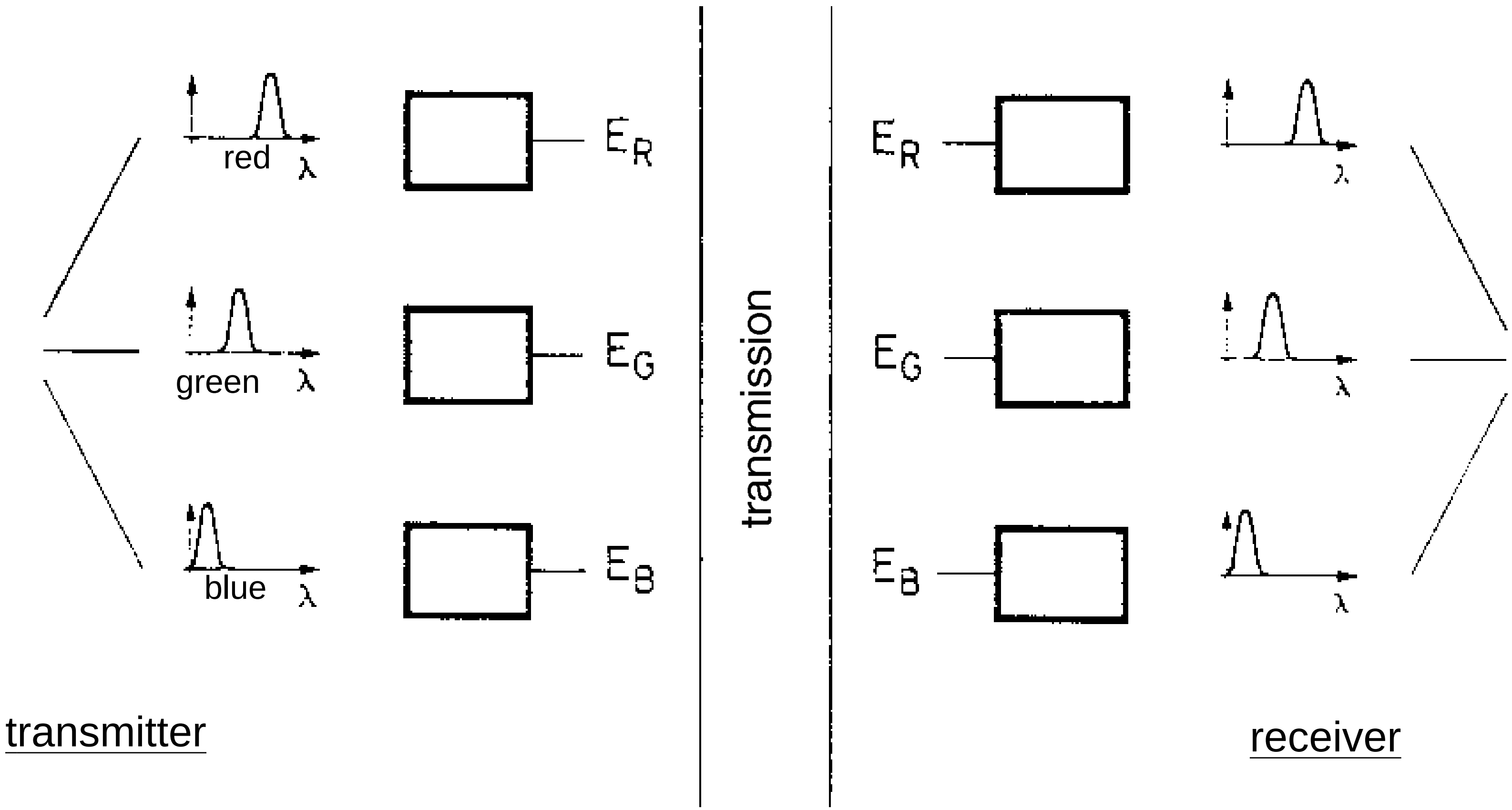
Gamut Spanned by Three Primary Colors



$$
\left\{
\begin{array}{l}
a_1\vec{I}_1 + a_2\vec{I}_2 + a_3\vec{I}_3 \\
0 \leq a_1, a_2, a_3 \leq 1
\end{array}
\right.
$$

Each color inside the parallelepiped can be generated uniquely by additive mixture of the three primary colors.

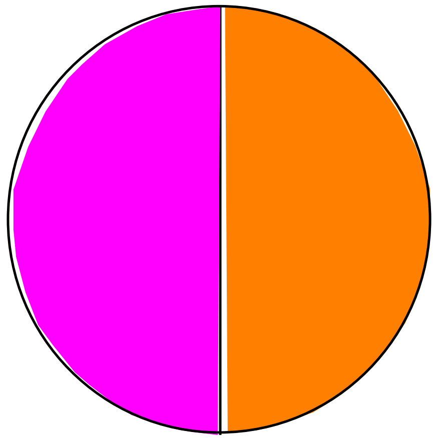
Color Transmission with Three Signals



Negative colors ??

- Agree on arbitrary primary colors as reference values
- Relax restriction $0 \leq a_1, a_2, a_3 \leq 1$

<u>Color matching experiment</u>



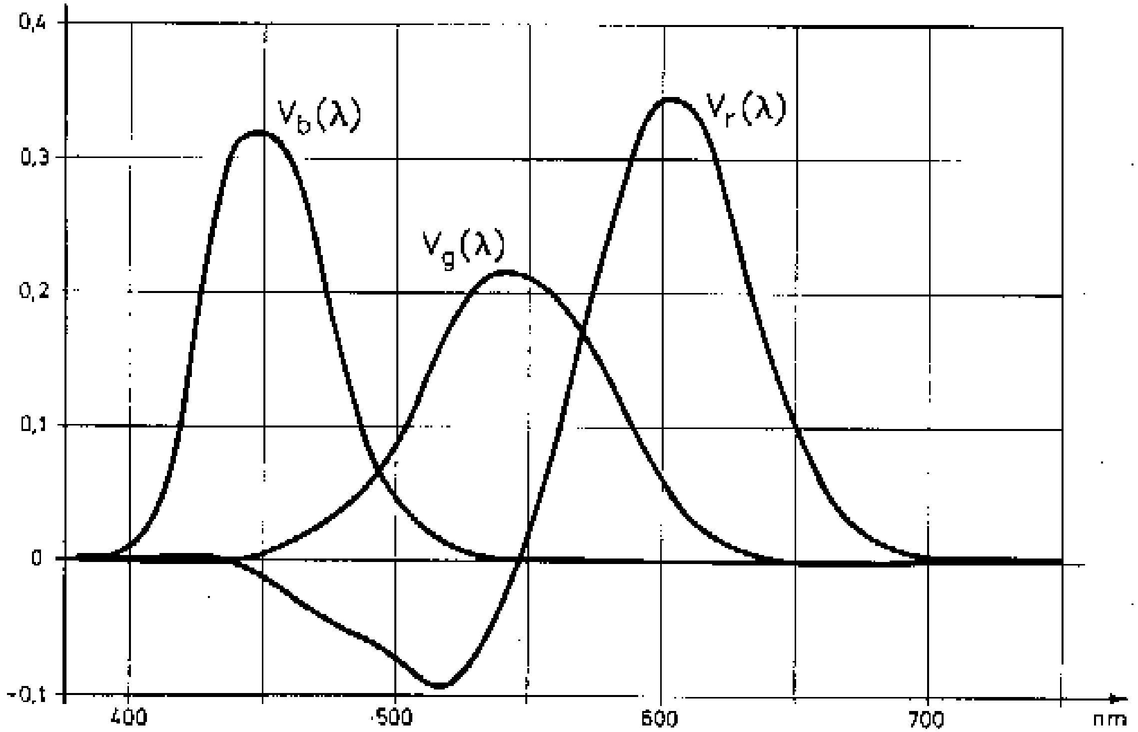
$0 \leq a_1, a_2, a_3$ $\qquad$ $I = a_1 I_1 + a_2 I_2 + a_3 I_3$

$a_1 < 0, \quad 0 \leq a_2, a_3$ $\qquad$ $I - a_1 I_1 = a_2 I_2 + a_3 I_3$

Spectral Color Matching Experiment

- Monochromatic primary colors λ_r = 700 nm λ_g = 546.1 λ_b = 435.8 nm

color matching functions C.I.E.: Commission Internationale de l'Eclairage, 1931



C.I.E. Color Coordinate Systems

C.I.E. RGB color coordinate system

$$R_0 = \int_{\lambda=0}^{\infty} V_r(\lambda)\, i(\lambda)\, d\lambda \qquad G_0 = \int_{\lambda=0}^{\infty} V_g(\lambda)\, i(\lambda)\, d\lambda \qquad B_0 = \int_{\lambda=0}^{\infty} V_b(\lambda)\, i(\lambda)\, d\lambda$$

C.I.E. XYZ color coordinate system

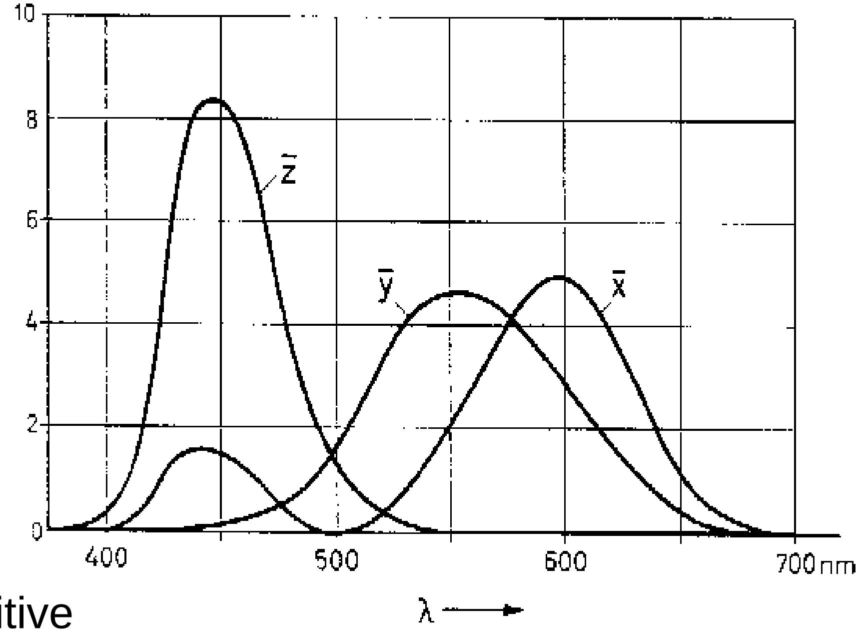
$$\begin{aligned} X &= 2.365\, R_0 - 0.515\, G_0 + 0.005\, B_0 \\ Y &= -0.897\, R_0 + 1.426\, G_0 - 0.014\, B_0 \\ Z &= -0.468\, R_0 + 0.089\, G_0 + 1.009\, B_0 \end{aligned}$$

Inverse transform

$$\begin{aligned} R_0 &= 0.490\, X + 0.177\, Y \\ G_0 &= 0.310\, X + 0.813\, Y + 0.010\, Z \\ B_0 &= 0.200\, X + 0.010\, Y + 0.990\, Z \end{aligned}$$

Properties of XYZ Color Coordinate System

Color matching functions of standard observer (DIN 5033)



- XYZ color matching function always positive
- X, Y, Z are virtual primary colors
- Y curve corresponds to luminous efficiency curve
- Equal energy white $i(\lambda)$ = const.

$$X = Y = Z$$

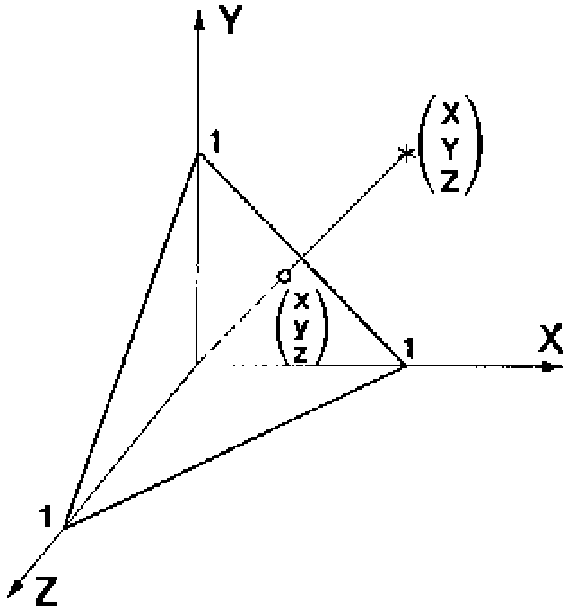
C.I.E. Chromaticity Coordinates (x,y)

Chromaticity

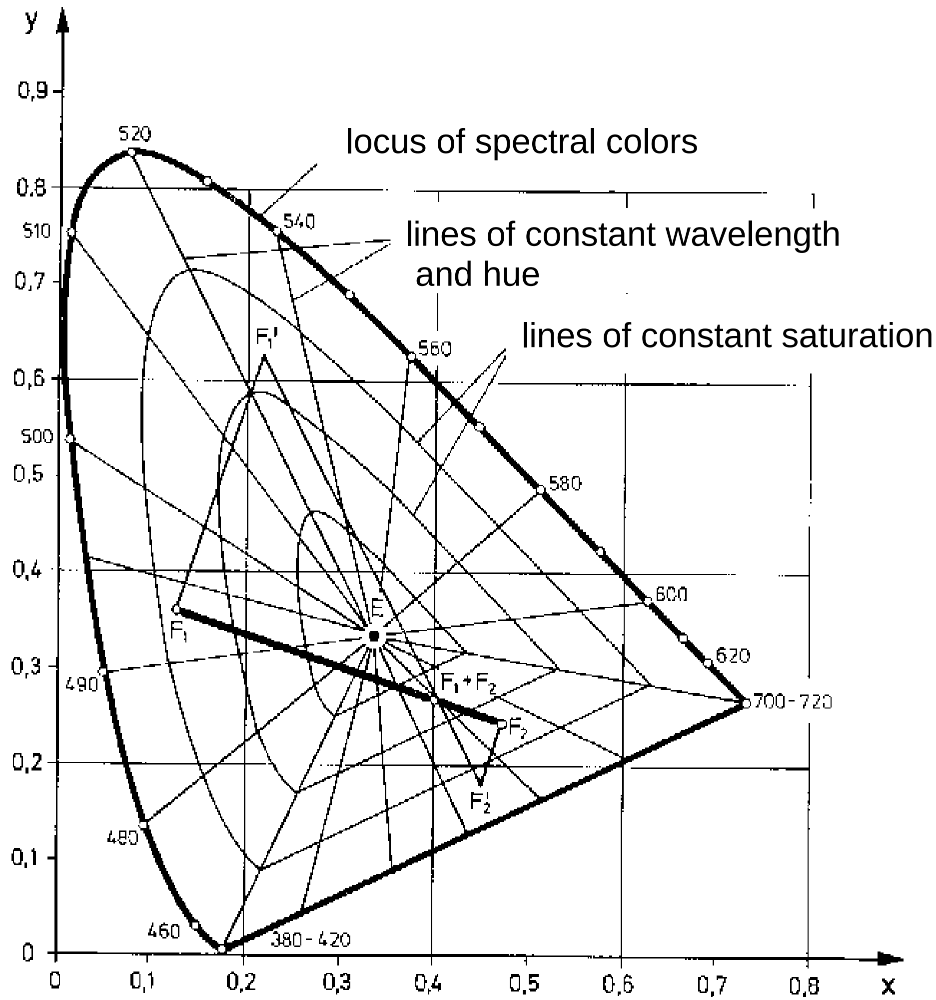
$$x = \frac{X}{X+Y+Z} \quad ; y = \frac{Y}{X+Y+Z} \quad ; z = \frac{Z}{X+Y+Z}$$

redundant, because $x + y + z = 1$

Geometric interpretation



C.I.E. Chromaticity Diagram



Additive Color Mixture in the Chromaticity Diagram

color 1: (Y_1, x_1, y_1)

color 2: (Y_2, x_2, y_2)

$$Y = Y_1 + Y_2$$
$$x = a_1 x_1 + a_2 x_2$$
$$y = a_1 y_1 + a_2 y_2$$

color mixture

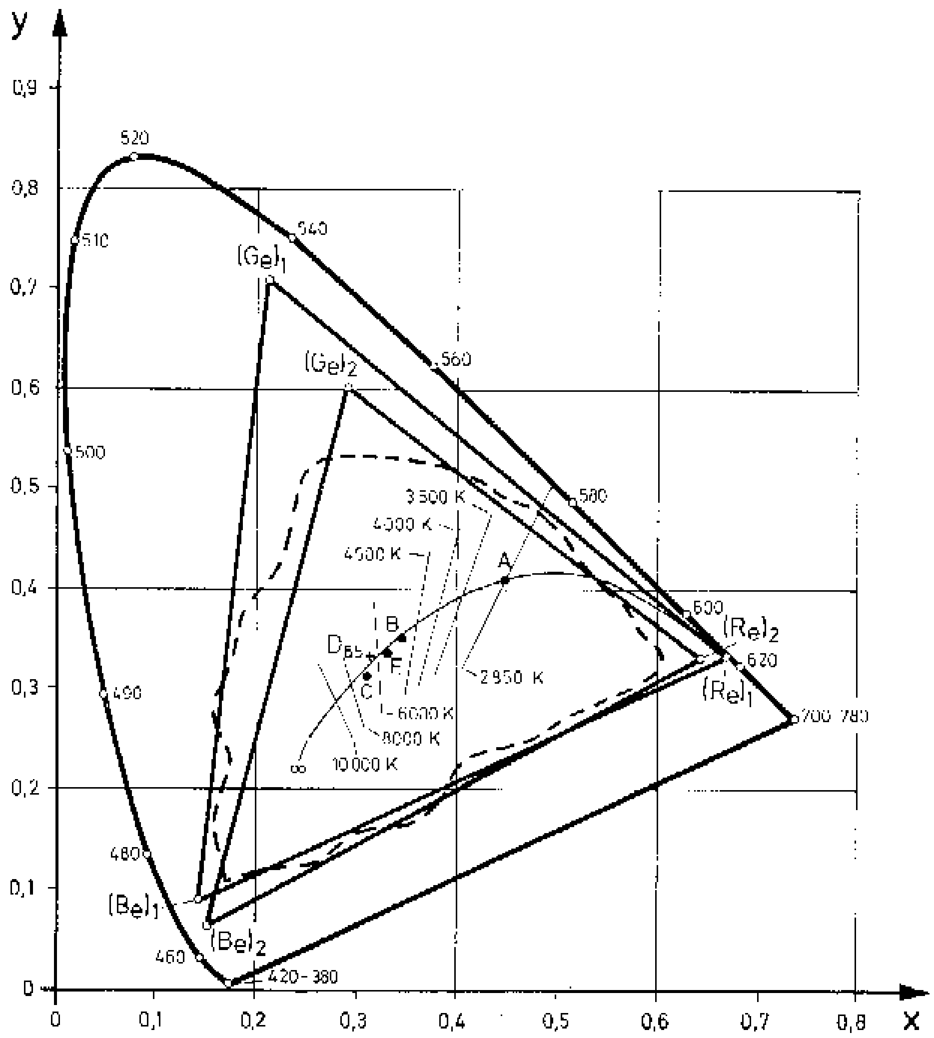
with

$$a_1 = \frac{\frac{Y_1}{y_1}}{\frac{Y_1}{y_1} + \frac{Y_2}{y_2}}$$

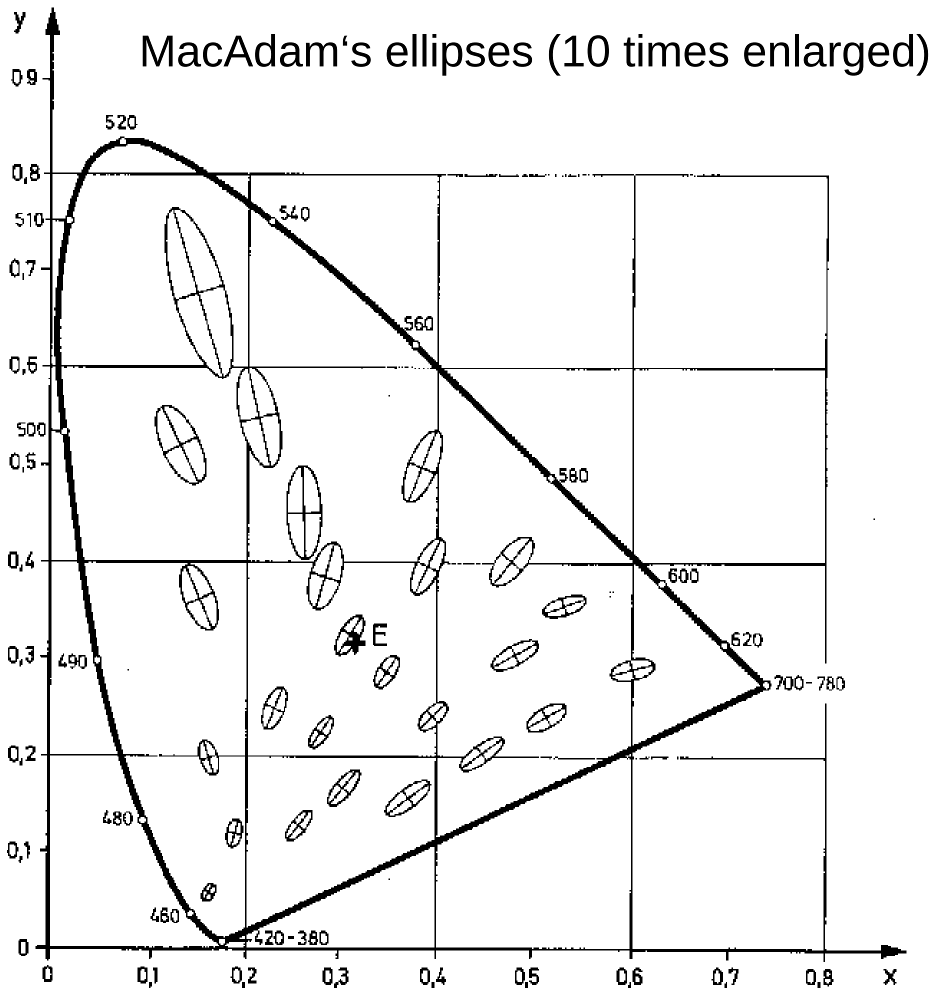
$$a_2 = \frac{\frac{Y_2}{y_2}}{\frac{Y_1}{y_1} + \frac{Y_2}{y_2}}$$

⇨ geometric construction

Color Coordinates of Phosphors Used in Television Receivers



Just Noticeable Color Differences



CIE UCS System (1960)

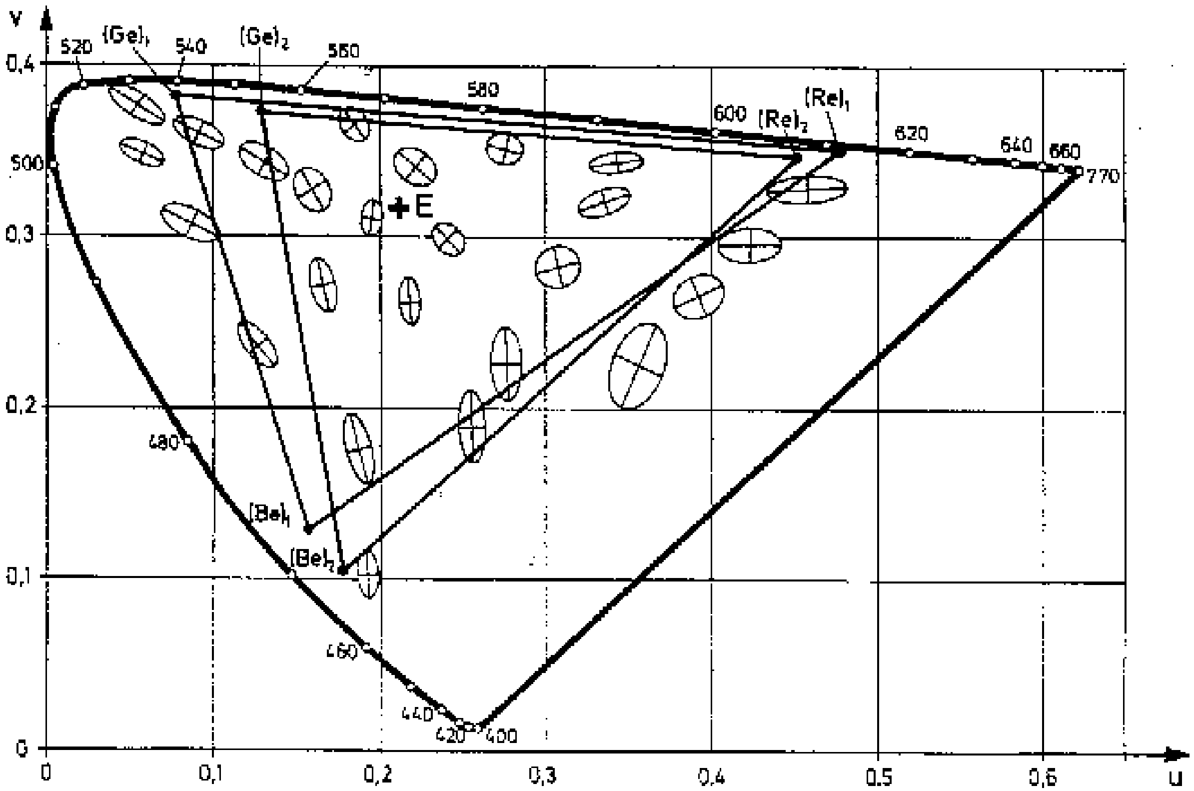
New chromaticity coordinates

$$u = \frac{4x}{-2x + 12y + 3} \qquad v = \frac{6y}{-2x + 12y + 3}$$

Equal energy white E

$$u_E = \frac{4}{19}$$

$$v_E = \frac{6}{19}$$



CIE L*u*v* Color Difference Measure (1976)

Color space

$$L^* = \begin{cases} 116\left(\frac{Y}{Y_0}\right)^{\frac{1}{3}} - 16 & \text{for } \frac{Y}{Y_0} > 0,01 \\ 903\left(\frac{Y}{Y_0}\right) & \text{otherwise} \end{cases}$$

$$u^* = 13\, L^*(u' - u'_0)$$

$$v^* = 13\, L^*(v' - v'_0)$$

with

$$u' = \frac{4X}{X + 15Y + 3Z}$$

$$v' = \frac{9Y}{X + 15Y + 3Z}$$

Y_0, u'_0, v'_0 - reference white

Euclidean distance

$$\Delta s = \sqrt{\left(\Delta L^*\right)^2 + \left(\Delta u^*\right)^2 + \left(\Delta v^*\right)^2}$$

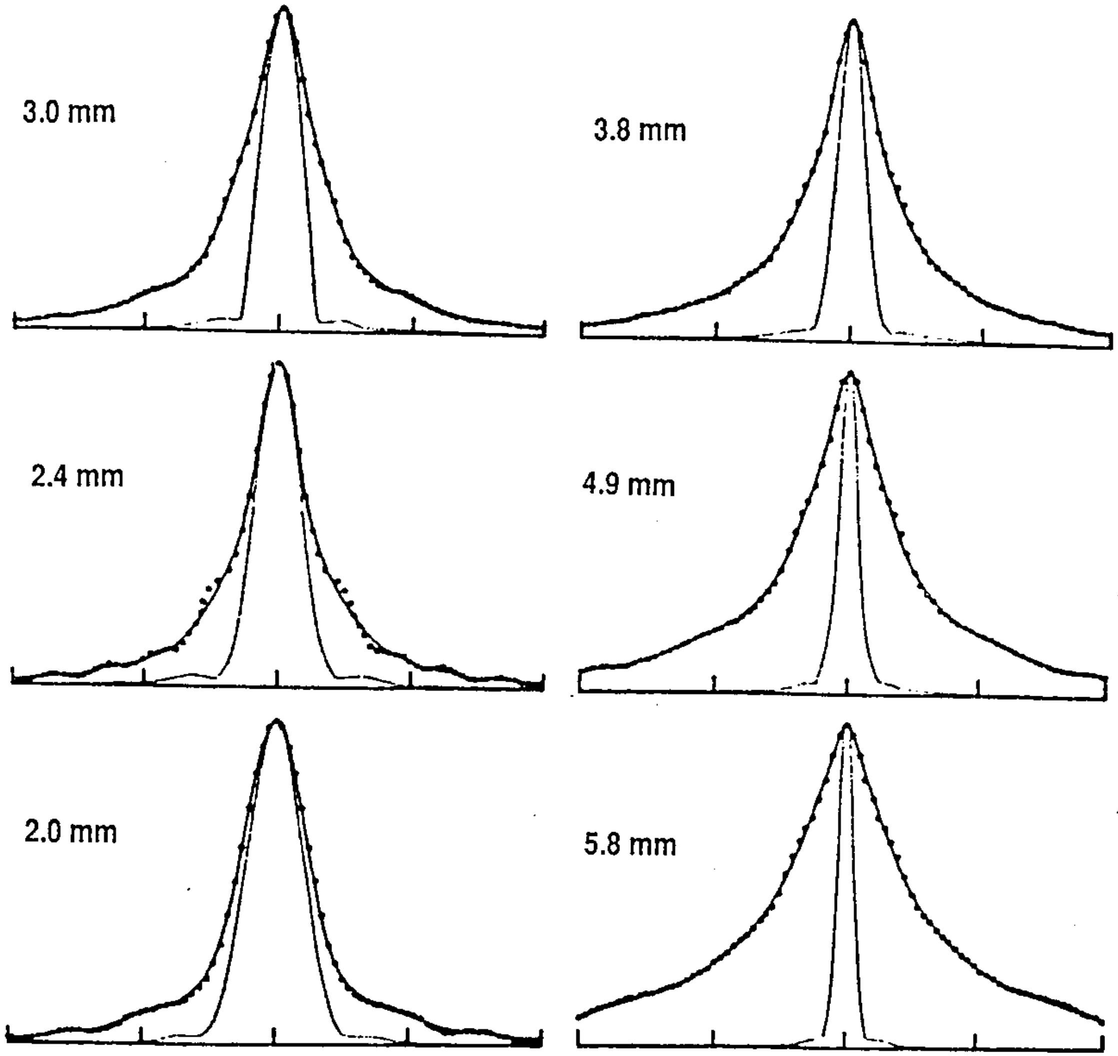
Optical Properties of the Human Eye

- Deviations from ideal perspective projection due to
  - Aperture of the eye
  - Focus errors (spherical aberration)
  - Chromatic aberration
  - Dispersion

- Effects can be summarized by a 2D convolution with the optical point-spread function (PSF).

- Instead of a PSF, an optical line-spread function (LSF) is often given, which can be measured more easily.

Optical LSF of the Human Eye

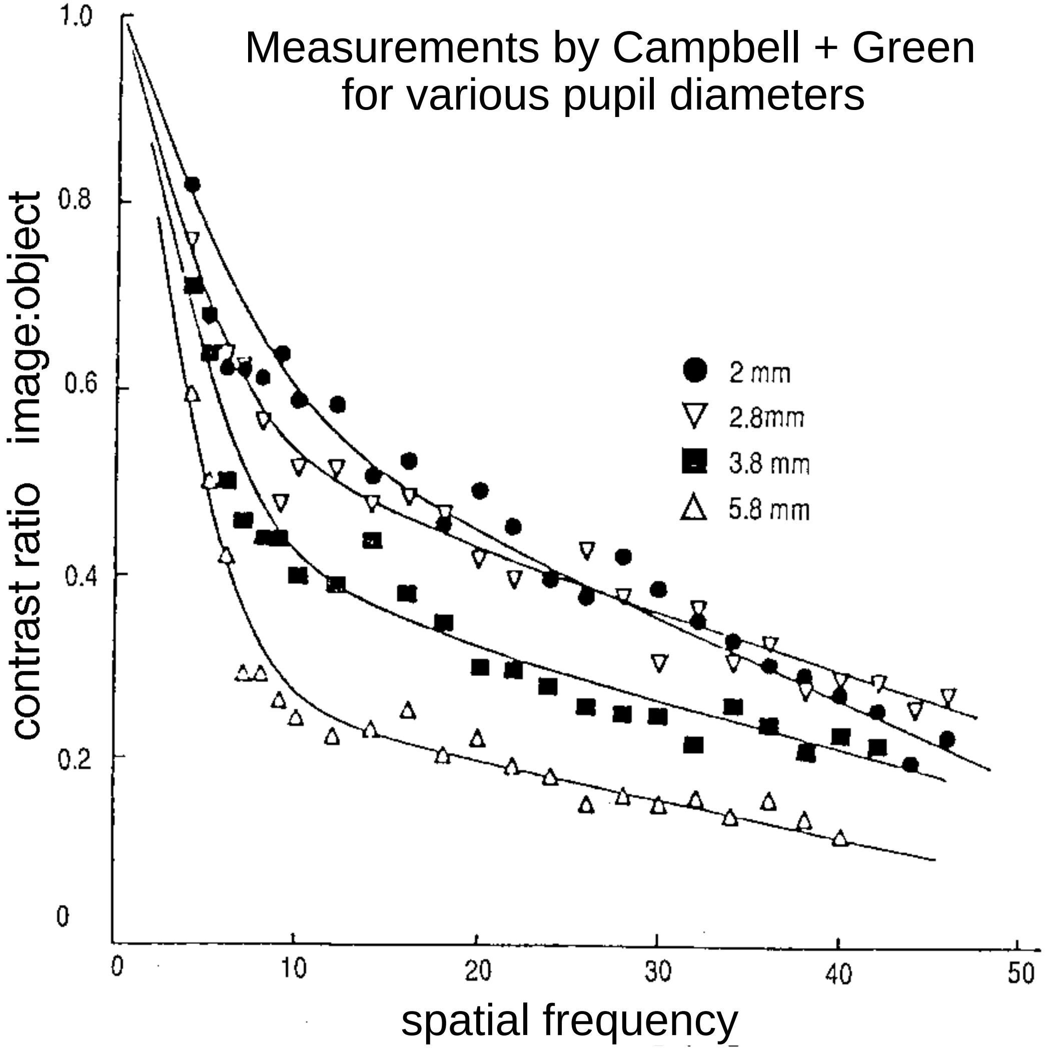


LSF measured for different pupil diameters (Campbell + Gubisch)

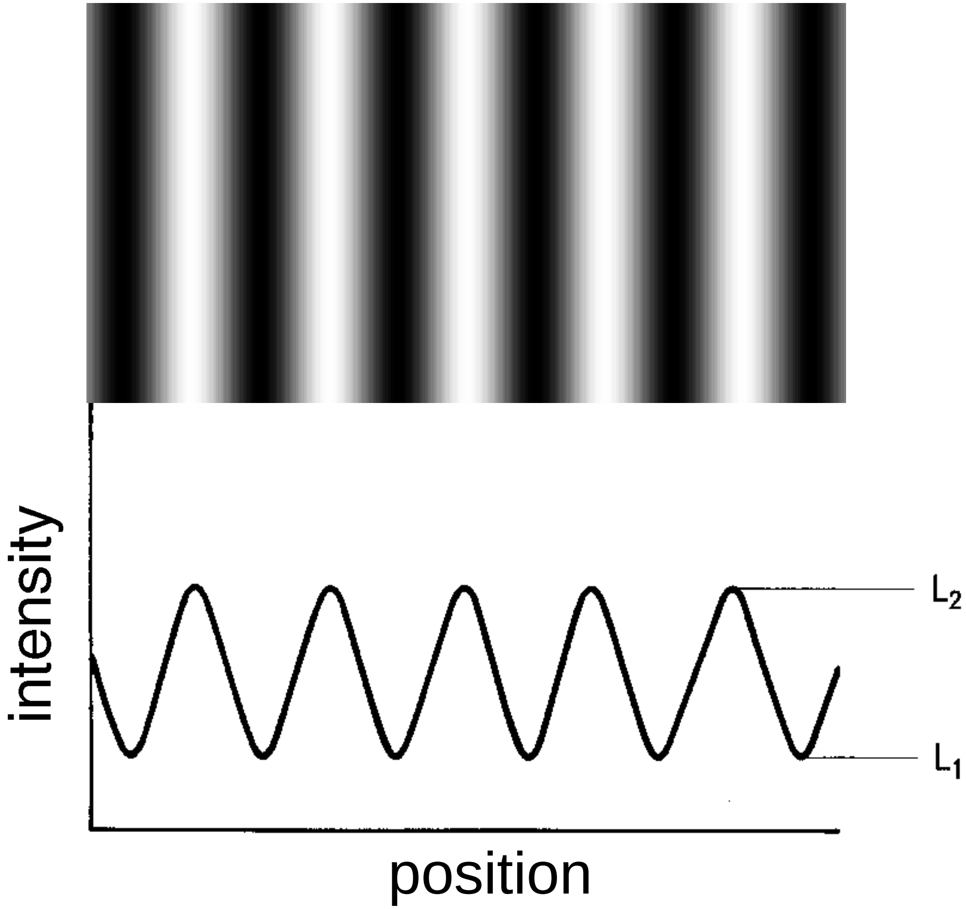
LSF calculated from eye aperture (due to diffraction)

Optical Modulation Transfer Function (MTF) of the Human Eye

- MTF is measured directly with sinewave gratings.
- The optical modulation transfer function (MTF) can be interpreted as Fourier transform of the optical LSF.



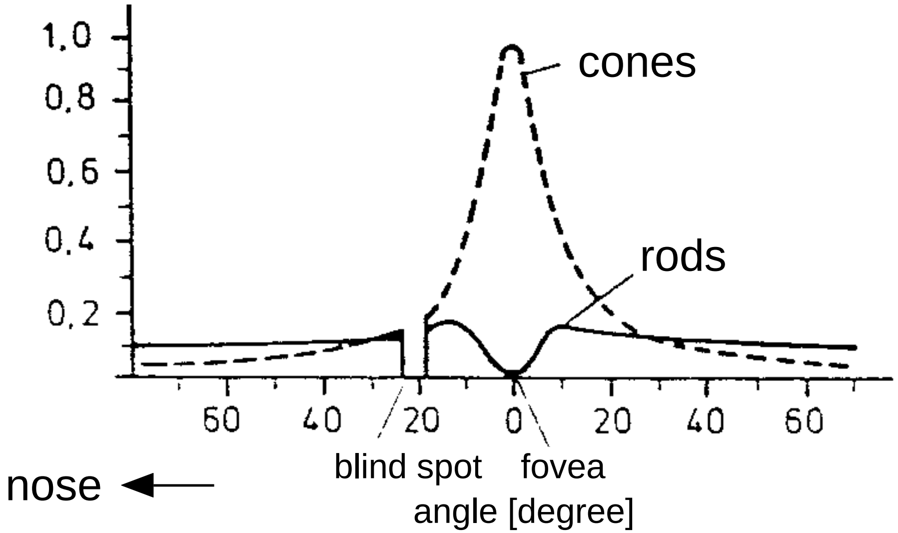
Sine Wave Grating



$$\text{contrast ratio} = \frac{L_2 - L_1}{L_2 + L_1}$$

Visual Acuity

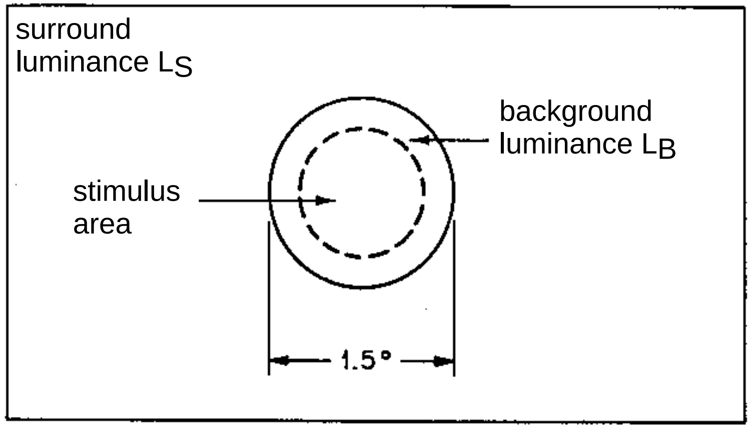
- Spatial resolution in lines/arcmin:



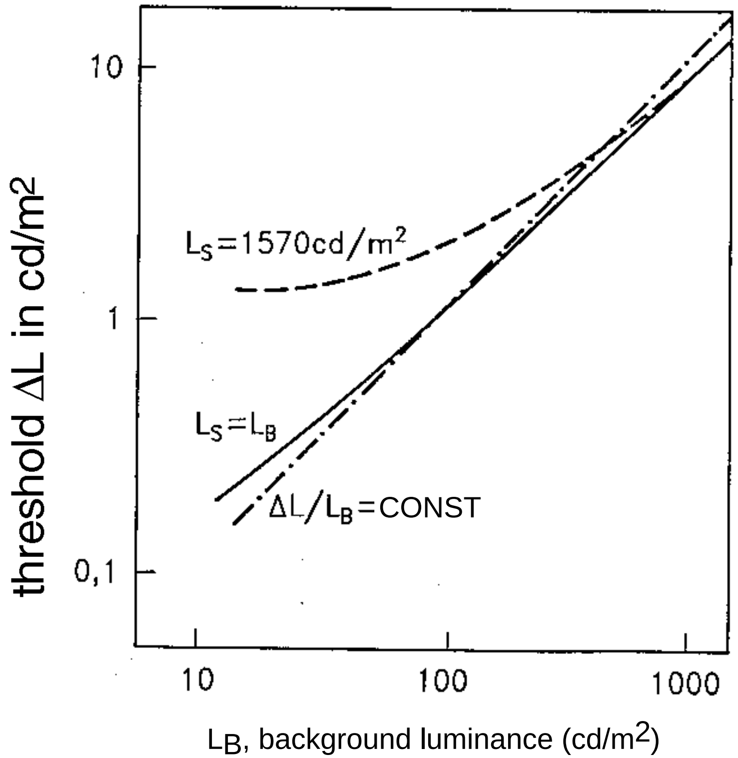
- Minimum distance of adjacent cones in the central fovea limits spatial resolution. (2 - 2.3 µm ⟷ 25 . . . 29 sec of arc)

Weber-Fechner Law, I

- Experiment:



- Result:



Weber-Fechner Law, II

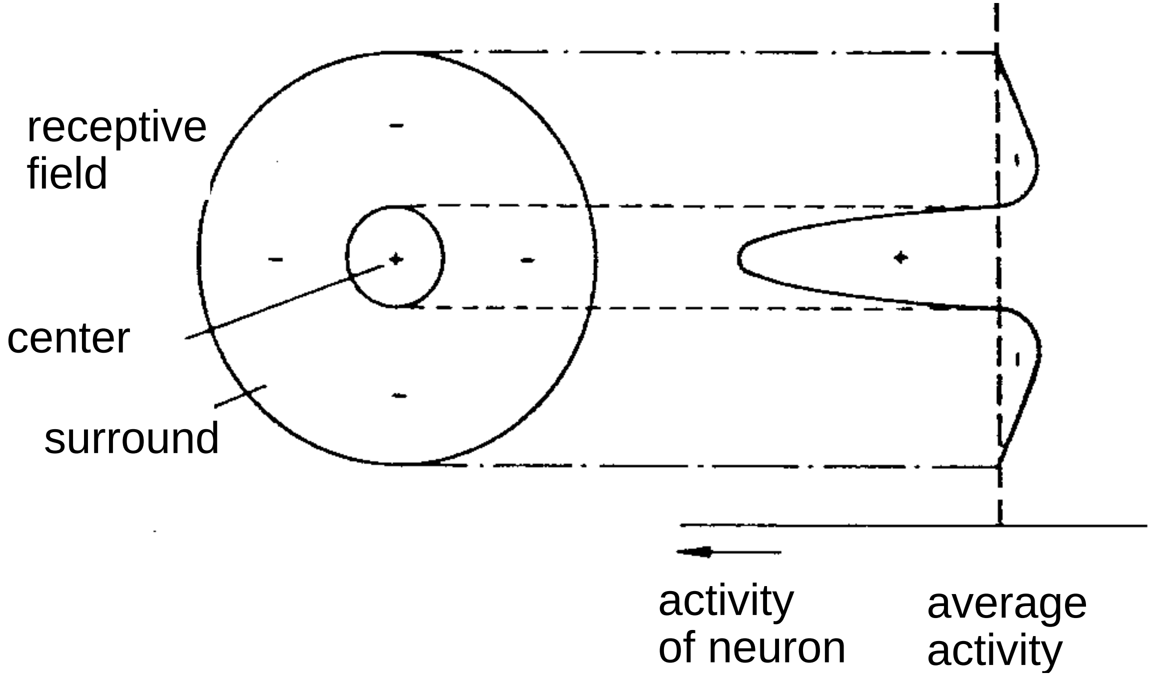
- "Weber-Fechner Law"

$$\Delta L = c \bullet L_B \qquad c = 0.01 \,...\, 0.02$$

- Implies logarithmic relationship between physical luminance and subjectively perceived brightness.
- Other proposed nonlinearities: square-root, cube-root, polynomials
- γ-characteristic of CRT displays is approximate inverse of nonlinearity of human brightness perception.

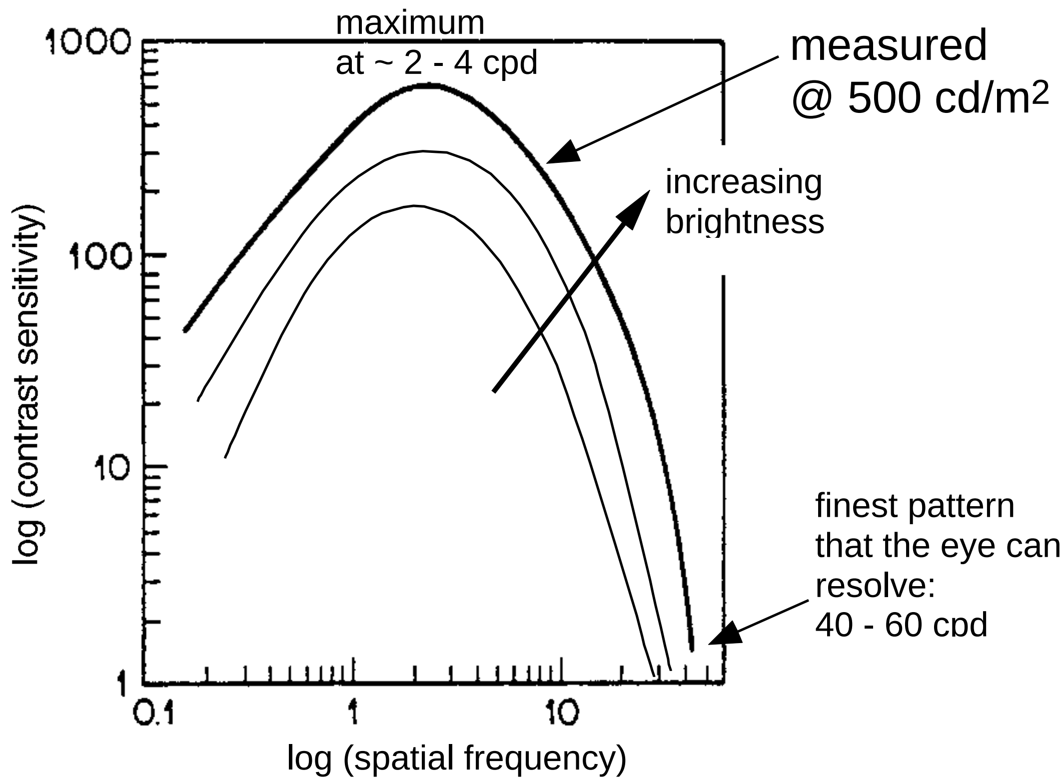
Inhibition and Excitation in the Retina

- Receptive field of a ganglion cell (=fiber of the optic nerve) shows „center-surround response“ with both
  - Lateral inhibition
  - Lateral excitation



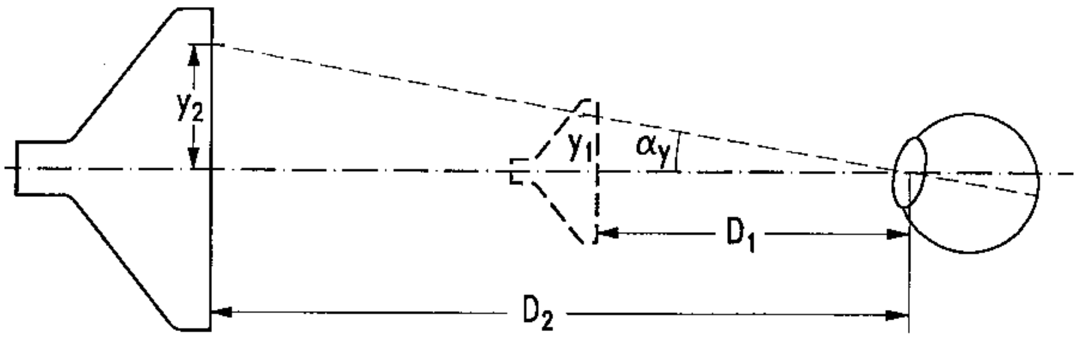
Contrast Sensitivity of Human Vision

Lateral inhibition and excitation together lead to a bandpass characteristic of the contrast sensitivity function of the human visual system



$$\text{contrast sensitivity} = \frac{\text{background luminance}}{\text{just noticeable amplitude of a sinusoid}}$$

Viewing Geometry



tube

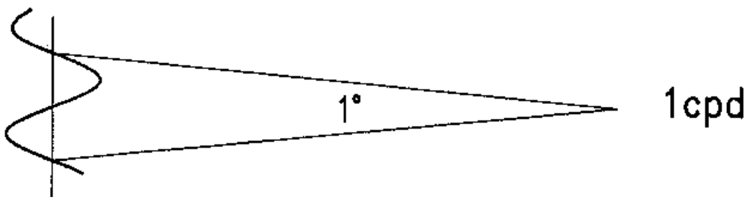
eye

for small angles:

$$\alpha_y \approx \frac{y_1}{D_1} = \frac{y_2}{D_2}$$

$$\alpha_y = \arctan \frac{y_1}{D_1} = \arctan \frac{y_2}{D_2}$$

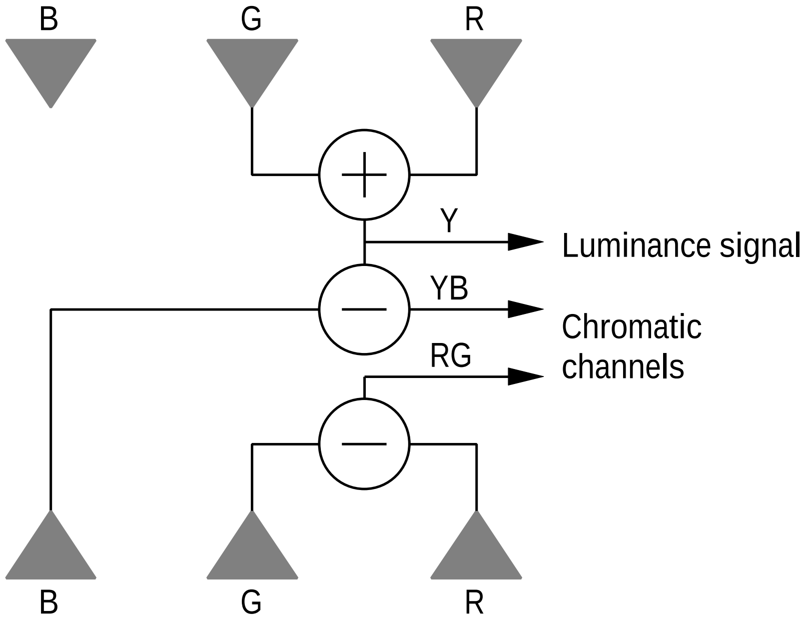
Spatial frequency in cycles/degree [cpd]:



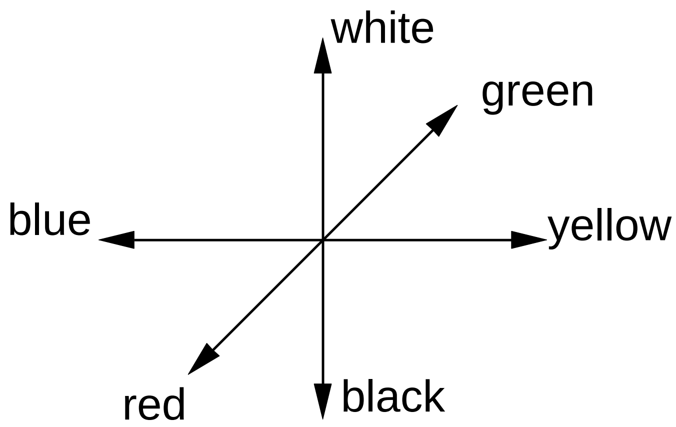
Color Vision: Opponent Color Theory

- Retina carries out “matrix operation“ to represent colors in the opponent color system (Y, Y-B, R-G)

- Opponent color model:

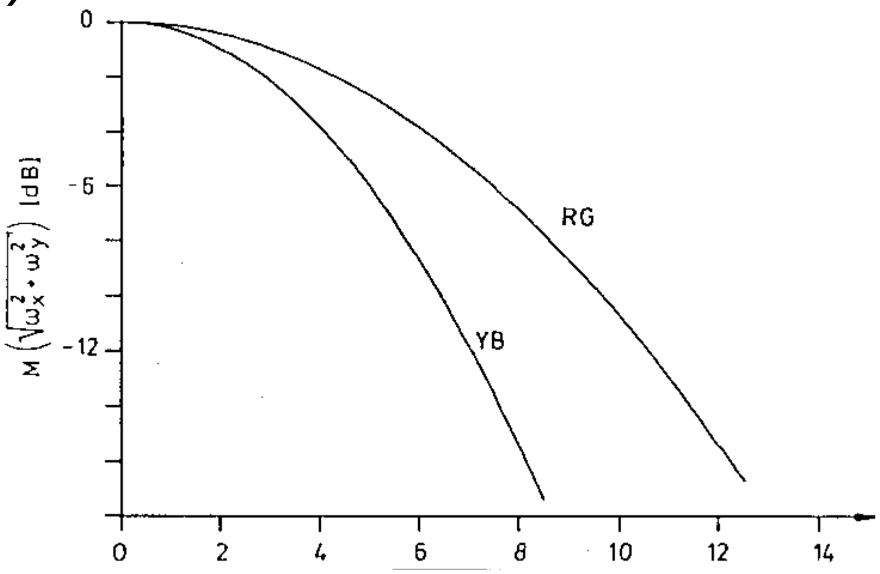


- Opponent color space:



Color Vision: Contrast Sensitivity in Opponent Color Space

- Spatial frequency response of Y-B and R-G channel (Girod, 1988):



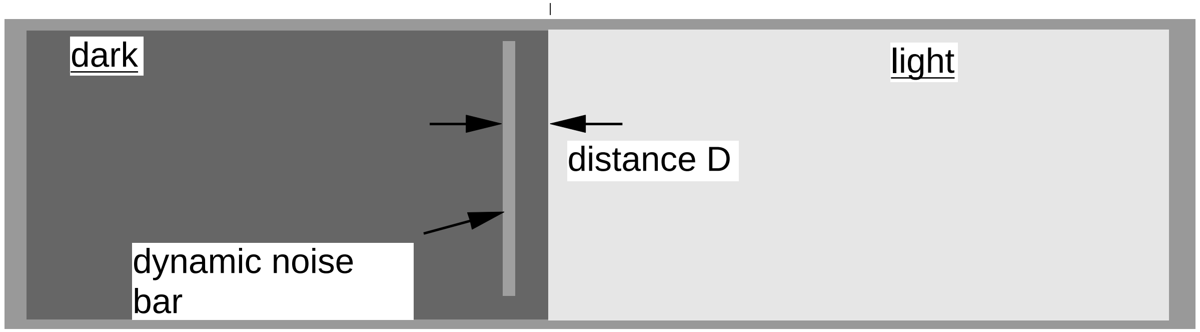
spatial frequency (cpd)

- Bandwidth Y:RG:YB approximately 8:5:3.

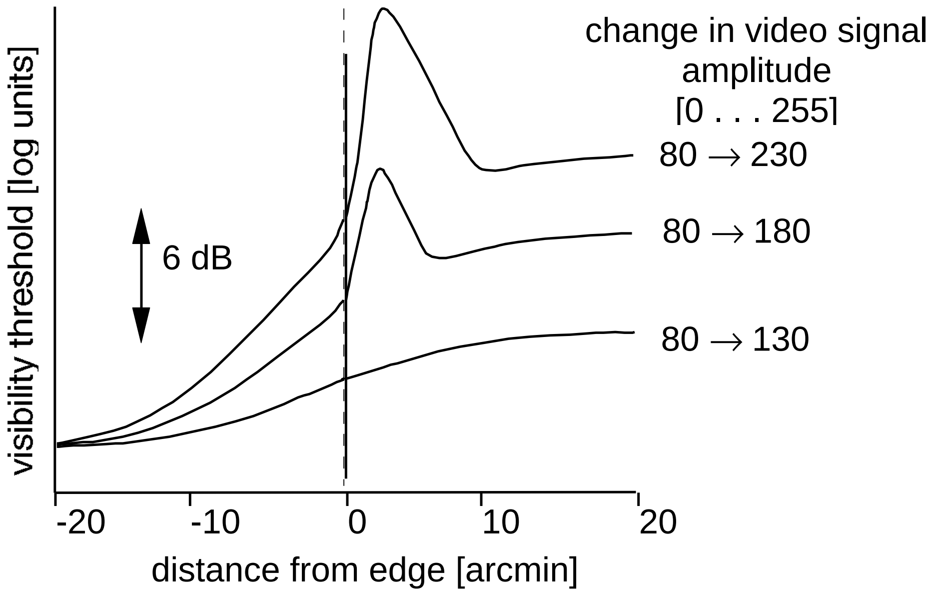
- Some researchers have observed bandpass characteristic also for chromaticity channels.

Spatial Masking, I

Experiment:

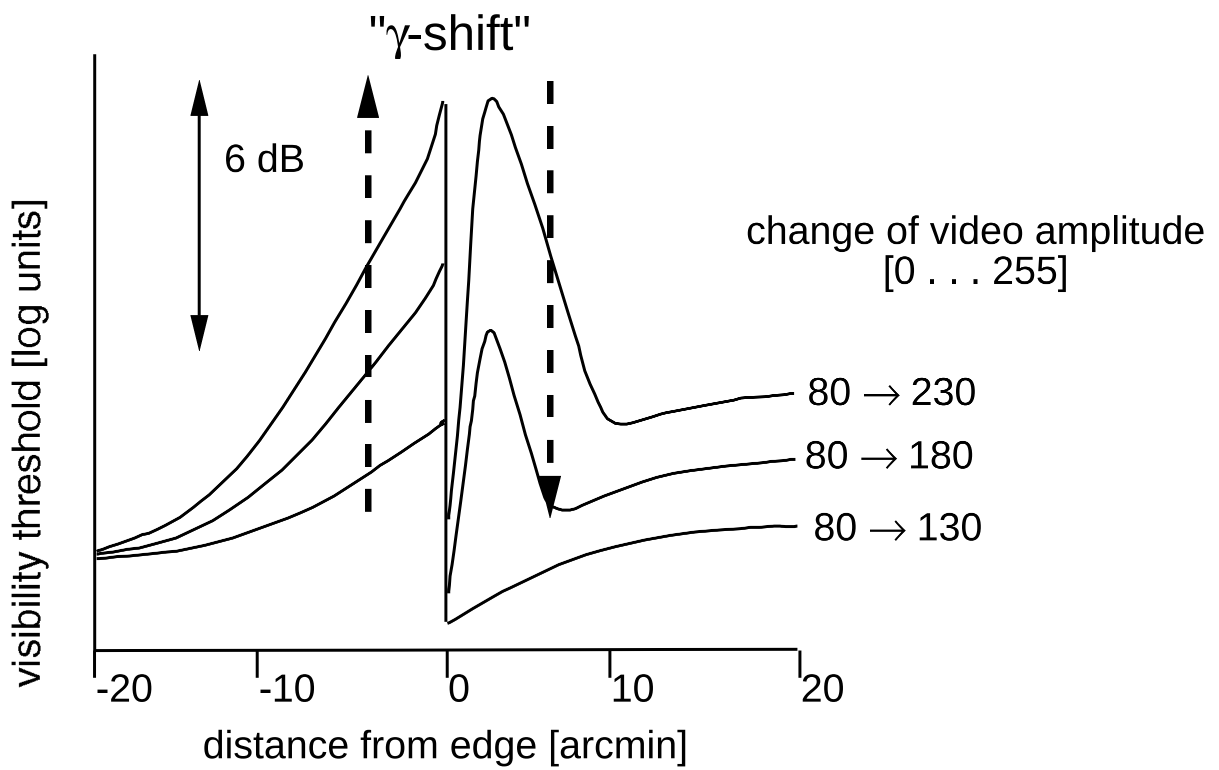


visibility threshold
(w-Modell, Girod, 1987)

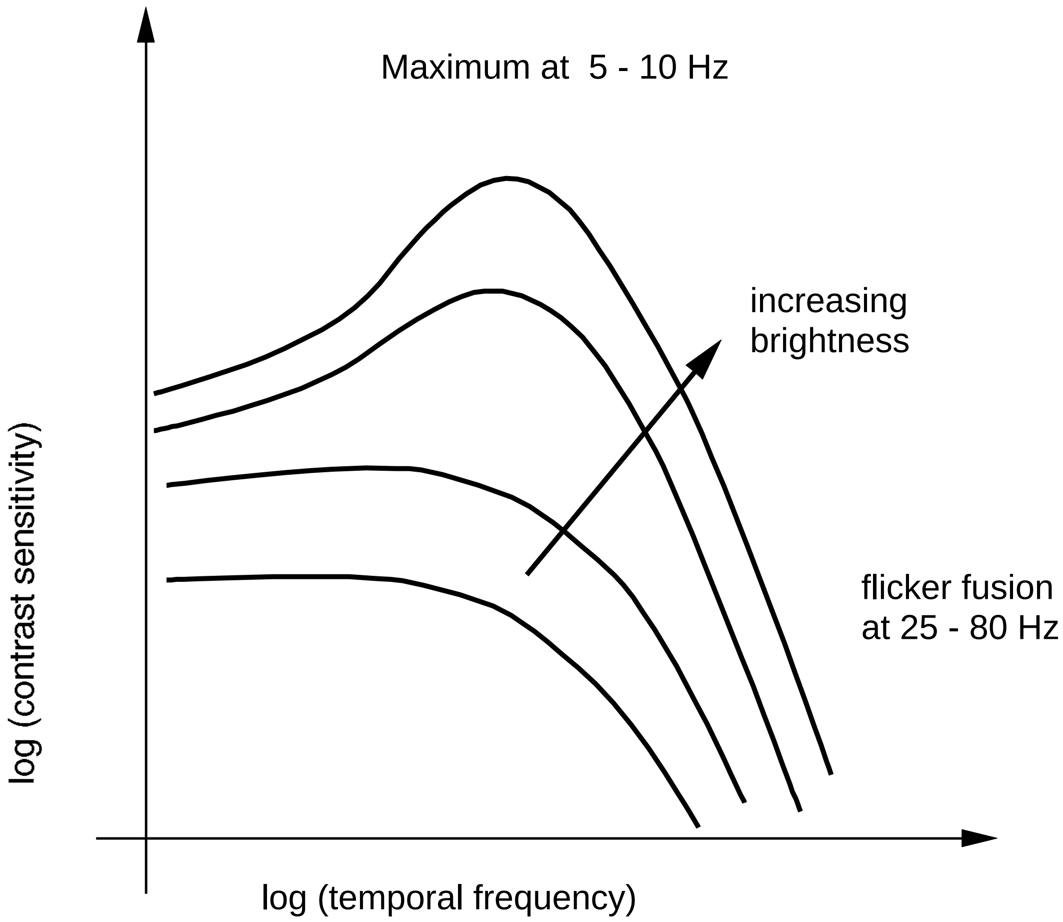


Spatial Masking, II

Visibility threshold for the γ-predistorted video signal
(w-Modell, Girod, 1987):

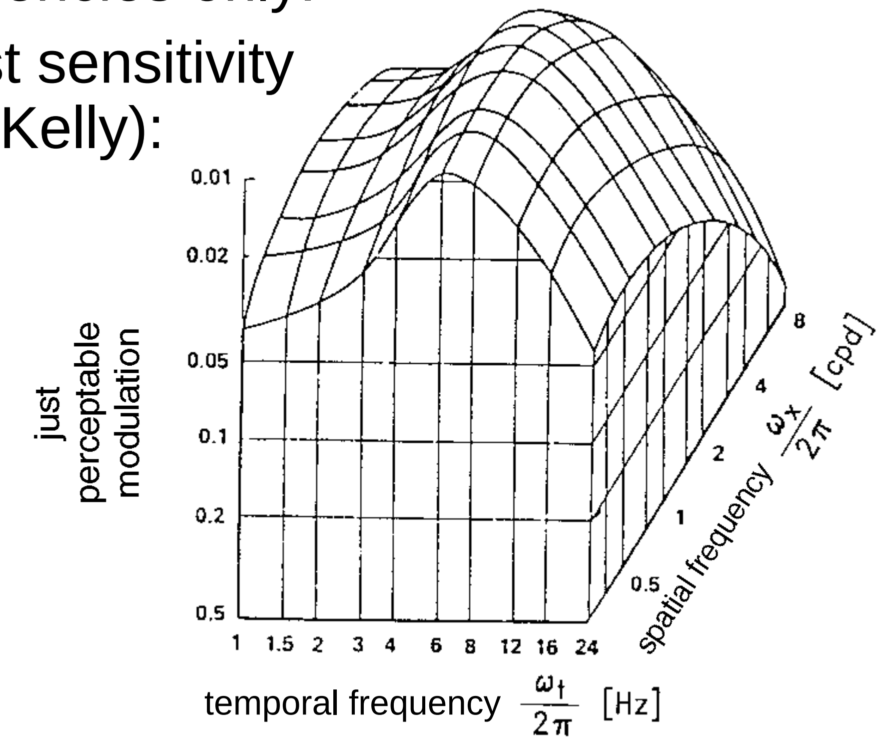


Temporal Contrast Sensitivity of Human Vision



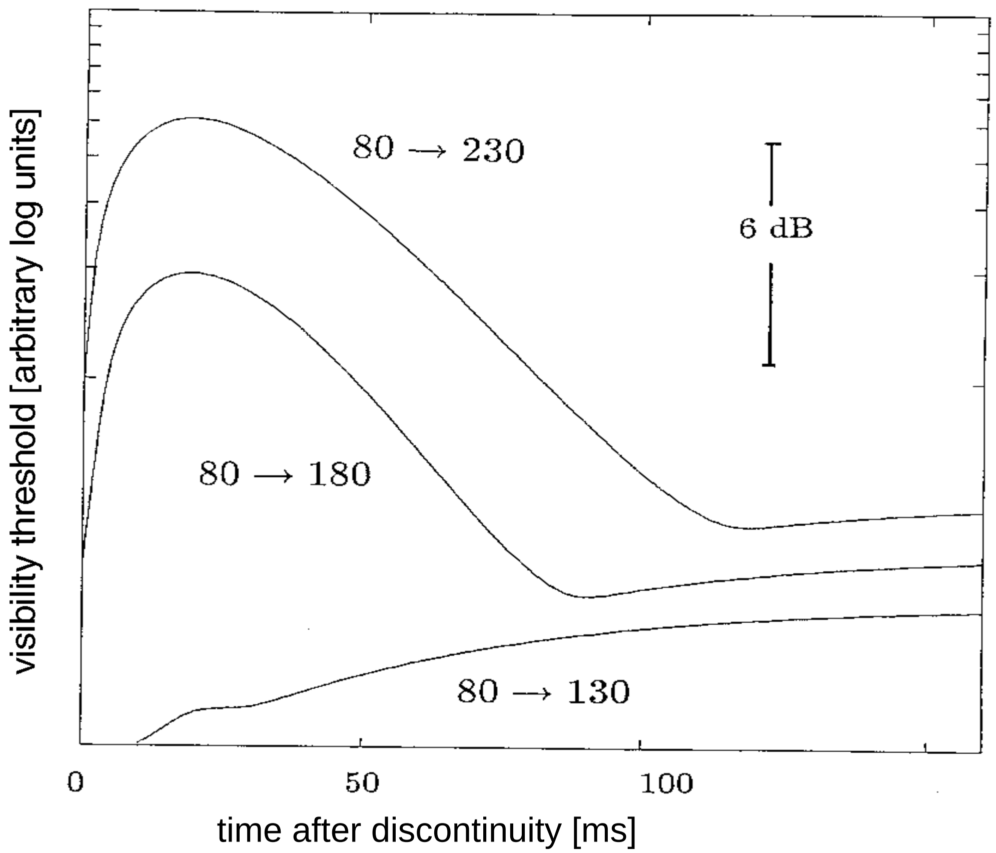
Spatiotemporal Contrast Sensitivity of Luminance Perception

- Spatiotemporal contrast sensitivity of the luminance channel has bandpass characteristic.
- Contrast sensitivity function separable for high spatial and temporal frequencies only.
- Plot of contrast sensitivity function (from Kelly):

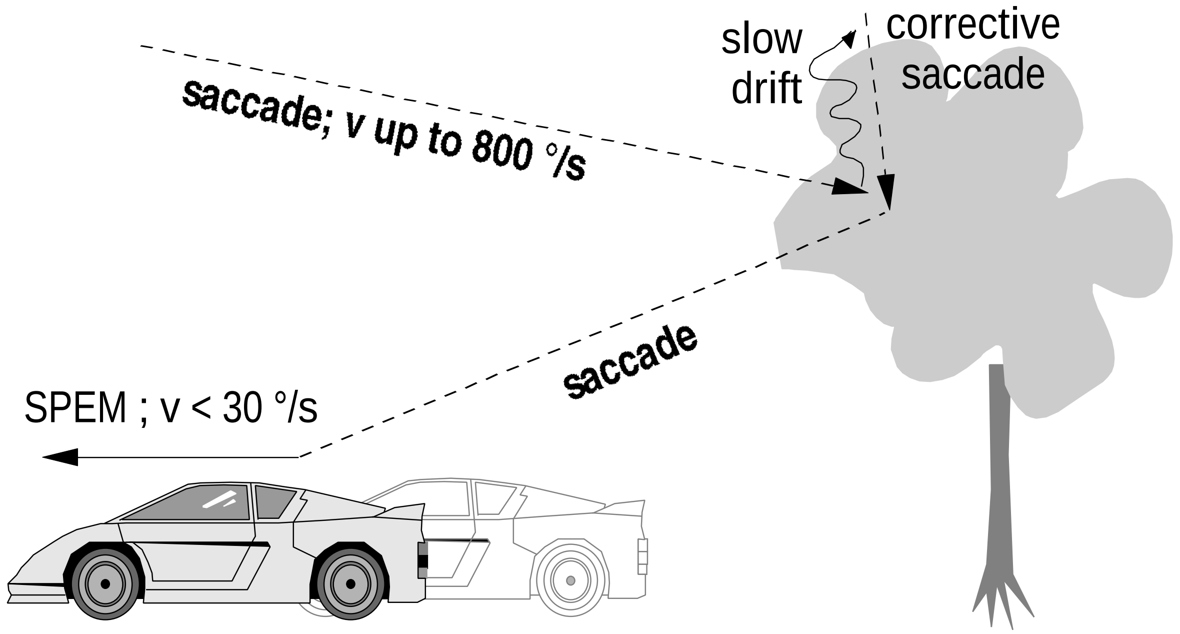


Temporal Masking

- Visibility thresholds for γ-predistorted video signal after luminance discontinuity (w-model, Girod, 1987):

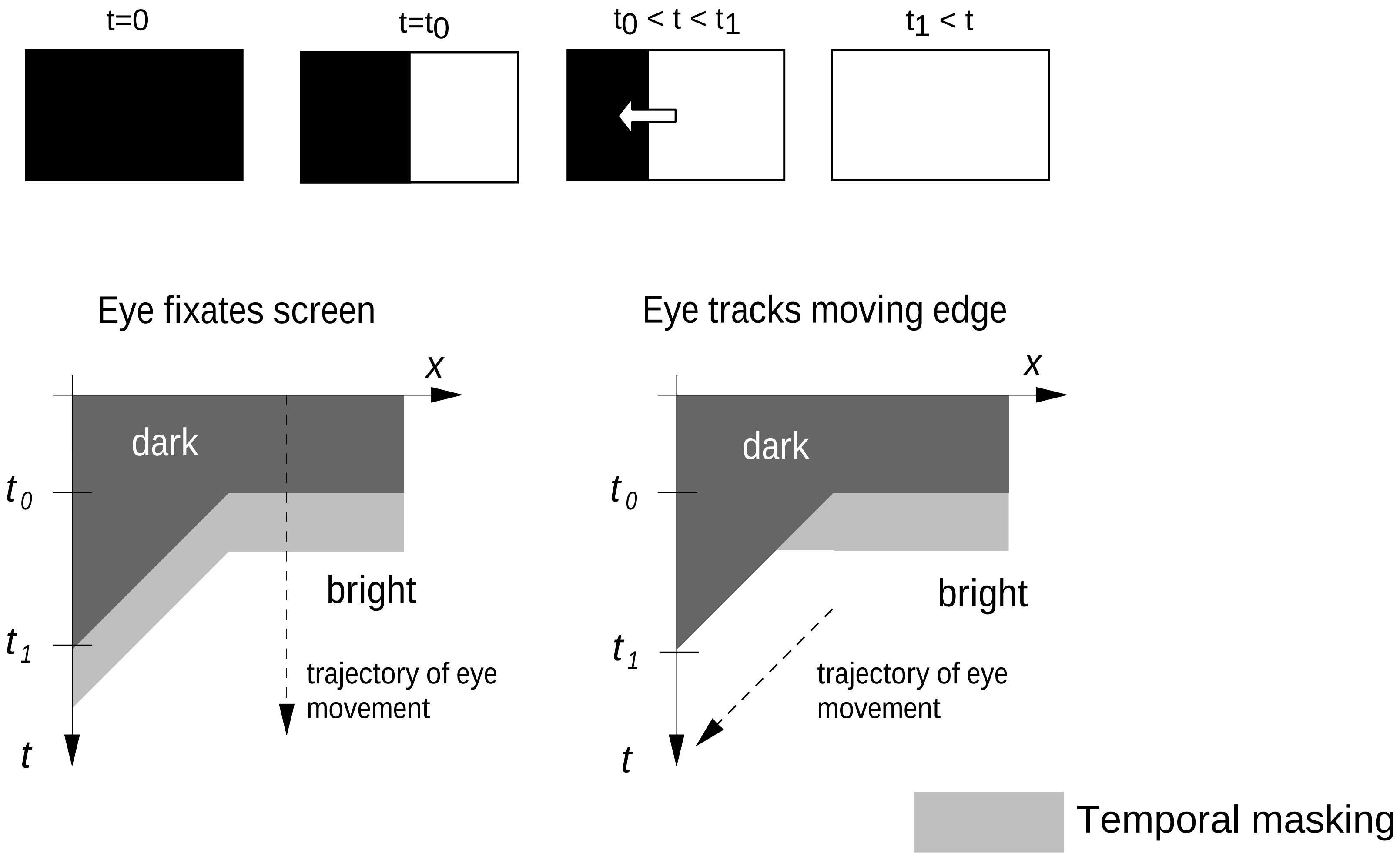


Eye Movements



SPEM: smooth pursuit eye movement

Temporal Masking and SPEMs



Human Visual Perception - Summary

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- Spatial frequency components visible up to 60 cpd
- Logarithmic relationship between luminance and subjective impression
- Lateral inhibition -> spatial bandpass characteristic
- Chromaticity channels have lower bandwidth
- Visibility threshold often increased in the vicinity of edges, but sometimes decreased („masking“).

Eye Movements and Spatiotemporal Frequency Response of the Human Visual System, I

- Assume SPEM of constant velocity:

$$x' = x - v_x t$$
$$y' = y - v_y t$$
$$t' = t$$

retina coordinate system | display coordinate system

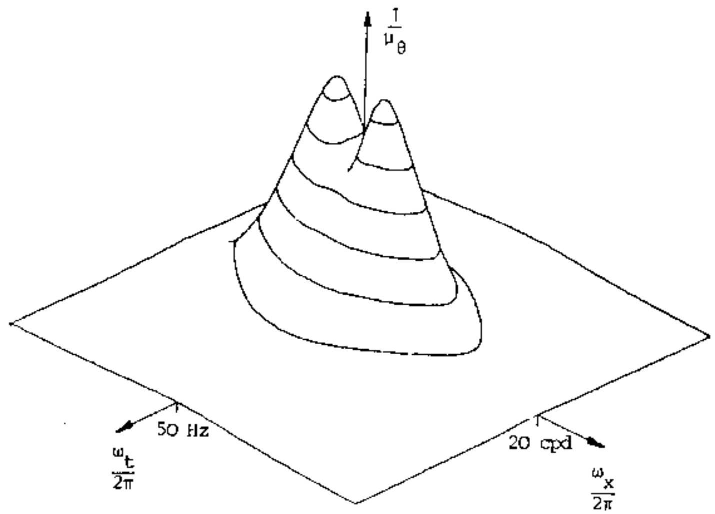
- Coordinate transformation in spatiotemporal frequency space ("Doppler effect")

$$\omega_x' = \omega_x$$
$$\omega_y' = \omega_y$$
$$\omega_t' = \omega_t + \omega_x v_x + \omega_y v_y$$

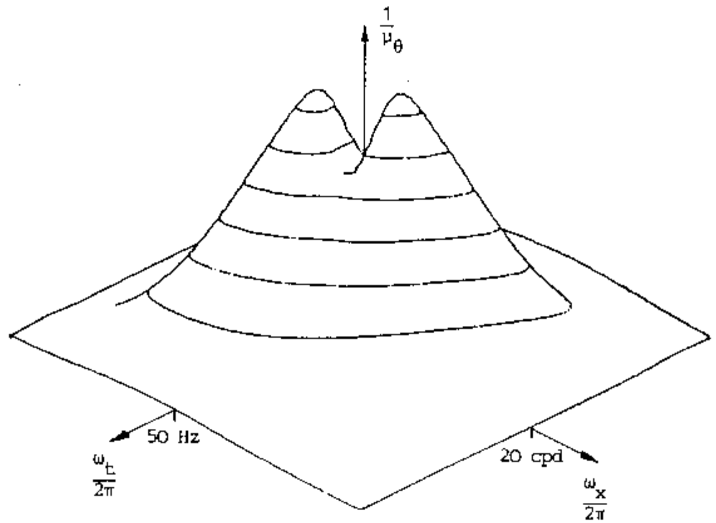
Eye Movements and Spatiotemporal Frequency Response of the Human Visual System, II

relative velocity between
eye and coordinate system

$v_x = 0$



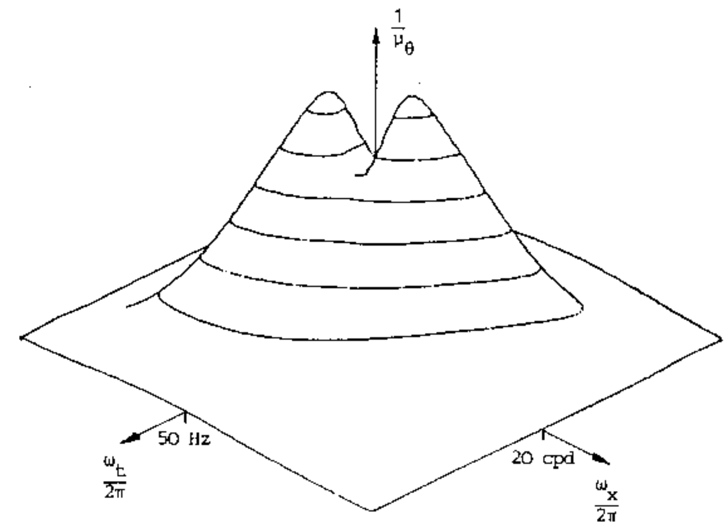
$v_x = 2\,^{\circ}/s$



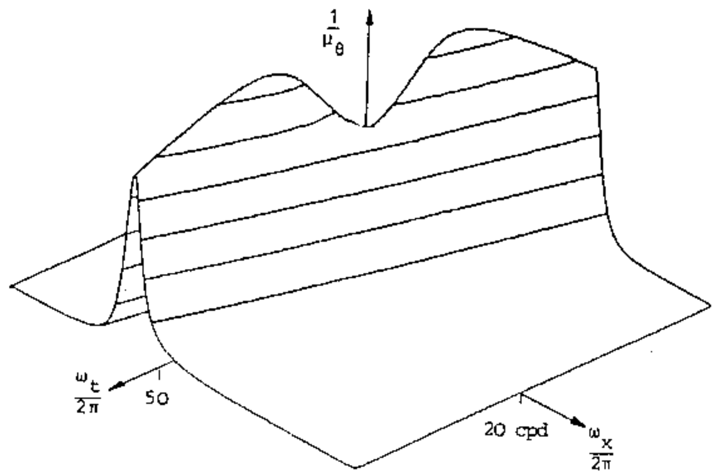
Eye Movements and Spatiotemporal Frequency Response of the Human Visual System, III

relative velocity between
eye and coordinate system

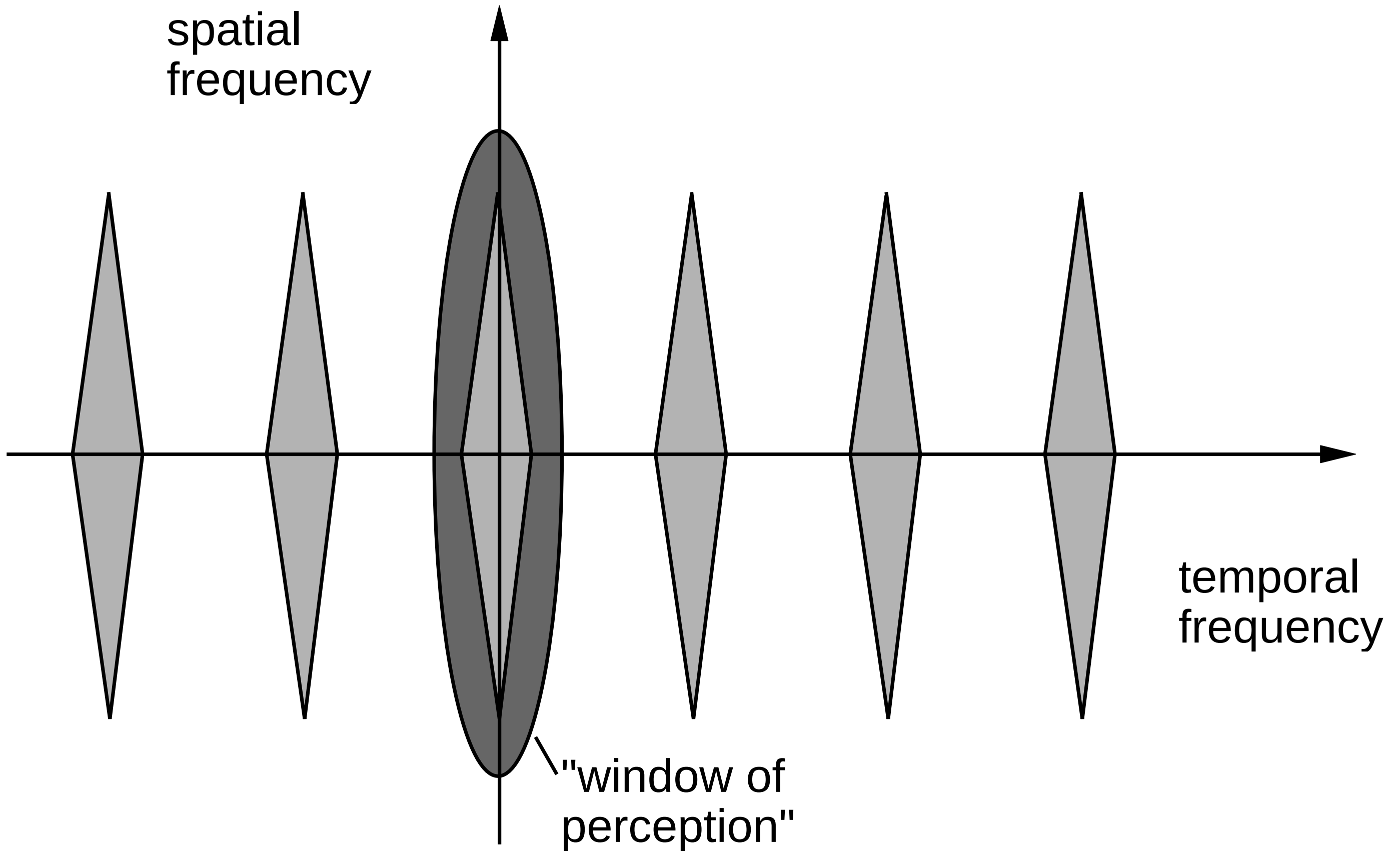
$v_x = 2\,°/s$



$v_x = 8\,°/s$



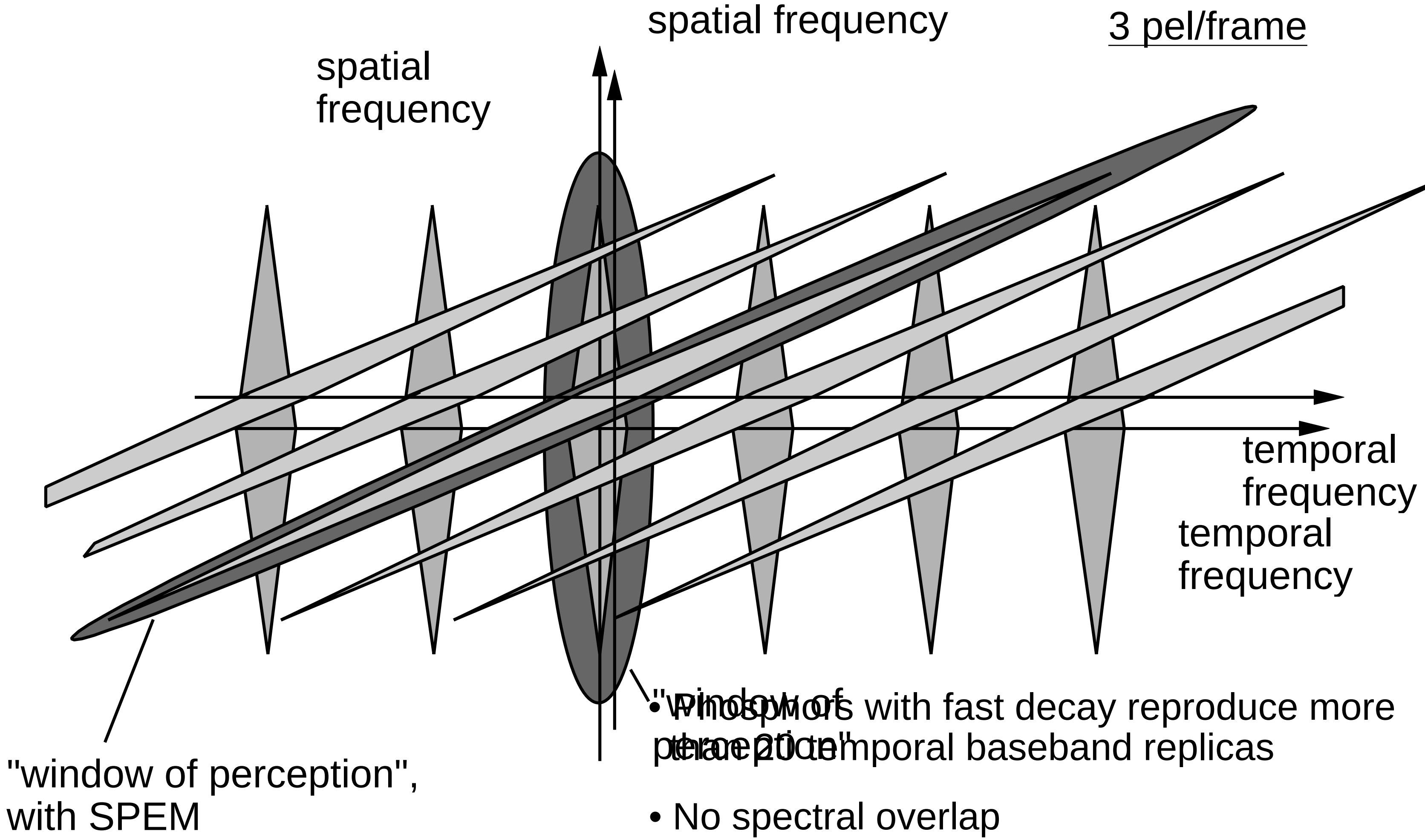
Perception of a Temporally Sampled Image Signal, Without Movement



Perception of a Temporally Sampled Image Signal, Translatory Movement

Perception of a Temporally Sampled Image Signal Without Movement

3 pel/frame



• Phosphors with fast decay reproduce more than 20 temporal baseband replicas

• No spectral overlap
-> perfect reconstruction of original signal possible

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