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

Girod: Image Communication
The Human Retina II

<table>
<thead>
<tr>
<th>Rods</th>
<th>Cones</th>
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<td>high sensitivity</td>
<td>low sensitivity</td>
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<tr>
<td>low light vision</td>
<td>day light vision &gt; 1 cd/m²</td>
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<tr>
<td>monochrome</td>
<td>color</td>
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<tr>
<td>&quot;scotopic vision&quot;</td>
<td>&quot;photopic vision&quot;</td>
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</table>

Video displays

Rods
- High sensitivity
- Low light vision
- Monochrome
- "Scotopic vision"

Cones
- Low sensitivity
- Day light vision > 1 cd/m²
- Color
- "Photopic vision"

The graph shows the distribution of receptors in 1000/mm².
Absorption Spectra of Cones in the Human Retina

Normalized absorption spectra

Graph showing normalized absorption spectra vs. wavelength (nm).
Trichromacy Theory

Spectral irradiance on the retina
\[ i(\lambda) = \frac{dI(\lambda)}{d\lambda} \]

Cones "see" the physical quantities

"primary colors"
\[ I_s = \int_0^{\infty} V_s(\lambda) i(\lambda) \, d\lambda \]

"color space"
\[ I_m = \int_0^{\infty} V_m(\lambda) i(\lambda) \, d\lambda \]
\[ I = \int_0^{\infty} V(\lambda) i(\lambda) \, d\lambda \]

\[ \text{Metamers: } i_1(\lambda) \neq i_2(\lambda) \quad \text{but} \quad I_{s1} = I_{s2} \]
\[ I_{m1} = I_{m2} \]
\[ I_1 = I_2 \]
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 \[ I_s = a_1 I_s1 + a_2 I_s2 \]
\[ I_m = a_1 I_m1 + a_2 I_m2 \]
\[ I_l = a_1 I_l1 + a_2 I_l2 \]

Written as a vector

\[
I = \begin{pmatrix} I_s \\ I_m \\ I_l \end{pmatrix} = a_1 I_1 + a_2 I_2
\]
Gamut Spanned by Two Primary Colors

\[
\begin{align*}
\begin{cases}
a_1 \vec{I}_1 + a_2 \vec{I}_2 \\
0 \leq a_1 \leq 1 \\
0 \leq a_2 \leq 1
\end{cases}
\end{align*}
\]
Gamut Spanned by Three Primary Colors

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

\[ a_1 \vec{I}_1 + a_2 \vec{I}_2 + a_3 \vec{I}_3 \]

\[ 0 \leq a_1, a_2, a_3 \leq 1 \]
Color Transmission with Three Signals

transmitter

red $\lambda$

green $\lambda$

blue $\lambda$

$E_R$

$E_G$

$E_B$

receiver

$E_R$

$E_G$

$E_B$
Negative colors ??

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

Color matching experiment

\[
0 \leq a_1, a_2, a_3 \quad \text{I} = a_1 I_1 + a_2 I_2 + a_3 I_3
\]

\[
a_1 < 0, \quad 0 \leq a_2, a_3 \quad \text{I} - a_1 I_1 = a_2 I_2 + a_3 I_3
\]
Spectral Color Matching Experiment

- Monochromatic primary colors $\lambda_r = 700$ nm $\lambda_g = 546.1$ $\lambda_b = 435.8$ 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

\[
R_0 = \int_0^\infty V_r(\lambda) i(\lambda) \, d\lambda \quad G_0 = \int_0^\infty V_g(\lambda) i(\lambda) \, d\lambda \quad B_0 = \int_0^\infty V_b(\lambda) i(\lambda) \, d\lambda
\]

C.I.E. XYZ color coordinate system

\[
X = 2.365 \, R_0 - 0.515 \, G_0 + 0.005 \, B_0 \\
Y = -0.897 \, R_0 + 1.426 \, G_0 - 0.014 \, B_0 \\
Z = -0.468 \, R_0 + 0.089 \, G_0 + 1.009 \, B_0
\]

Inverse transform

\[
R_0 = 0.490 \, X + 0.177 \, Y \\
G_0 = 0.310 \, X + 0.813 \, Y + 0.010 \, Z \\
B_0 = 0.200 \, X + 0.010 \, Y + 0.990 \, Z
\]
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 \( i(\lambda) = \text{const.} \)
  \[ X = Y = Z \]
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

locus of spectral colors

lines of constant wavelength and hue

lines of constant saturation
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_1x_1 + a_2x_2
y = a_1y_1 + a_2y_2

with

\[ a_1 = \frac{Y_1}{Y_1/y_1 + Y_2/y_2} \]
\[ a_2 = \frac{Y_2}{Y_1/y_1 + Y_2/y_2} \]
Color Coordinates of Phosphors Used in Television Receivers
Just Noticeable Color Differences

MacAdam’s ellipses (10 times enlarged)
CIE UCS System (1960)

New chromaticity coordinates

\[ u = \frac{4x}{-2x + 12y + 3} \quad \quad \quad v = \frac{6y}{-2x + 12y + 3} \]

Equal energy white E

\[ u_E = \frac{4}{19} \quad \quad \quad \quad v_E = \frac{6}{19} \]
CIE L*u*v* Color Difference Measure (1976)

Color space

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

\[ u^* = 13 L^* (u' - u'_0) \]

\[ v^* = 13 L^* (v' - v'_0) \]

with

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

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

\[ Y_0, u'_0, v'_0 \ - \text{ reference white} \]

Euclidean distance

\[ \Delta s = \sqrt{(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2} \]
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.

Measurements by Campbell + Green for various pupil diameters
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 $\leftrightarrow$ 25 . . . 29 sec of arc)
Weber-Fechner Law, I

Experiment:

- Surround luminance $L_S$
- Stimulus area
- Background luminance $L_B$

Result:

- Plot showing threshold $\Delta L$ in cd/m$^2$ vs. $L_B$, background luminance (cd/m$^2$)
  - $L_S = 1570$ cd/m$^2$
  - $L_S = L_B$
  - $\Delta L/L_B = \text{CONST}$

- Graph with axes:
  - Y-axis: Arrows indicating $\Delta L$ values
  - X-axis: $L_B$, background luminance (cd/m$^2$)
"Weber-Fechner Law"

\[ \Delta L = c \cdot L_B \quad c = 0.01 \ldots 0.02 \]

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

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

- Measured at 500 cd/m²
- Maximum at ~ 2 - 4 cpd
- Finest pattern that the eye can resolve: 40 - 60 cpd

Increasing brightness
Viewing Geometry

for small angles:

\[ \alpha_y \approx \frac{y_1}{D_1} = \frac{y_2}{D_2} \]

Spatial frequency in cycles/degree [cpd]:

1° 1cpd
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):

- 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 $\gamma$-predistorted video signal (w-Modell, Girod, 1987):

![Graph showing visibility threshold vs. distance from edge with "$\gamma$-shift" indicated and change of video amplitude from 80 to 230, 80 to 180, and 80 to 130.]
Temporal Contrast Sensitivity of Human Vision

Maximum at 5 - 10 Hz

increasing brightness

flicker fusion at 25 - 80 Hz
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 $\gamma$-predistorted video signal after luminance discontinuity (w-model, Girod, 1987):

![Graph showing visibility thresholds over time after discontinuity]
Eye Movements

SPEM: smooth pursuit eye movement
Temporal Masking and SPEMs

Temporal masking

Eye fixates screen

Eye tracks moving edge
Human Visual Perception - Summary

- Anatomy of the Human Eye
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- Color Systems and Representation
- 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").
Assume SPEM of constant velocity:

\[
\begin{align*}
x' &= x - v_x t \\
y' &= y - v_y t \\
t' &= t
\end{align*}
\]

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

\[
\begin{align*}
\omega_{x}' &= \omega_x \\
\omega_{y}' &= \omega_y \\
\omega_{t}' &= \omega_t + \omega_x v_x + \omega_y v_y
\end{align*}
\]
relative velocity between eye and coordinate system

\[ v_x = 0 \]

\[ v_x = 2^0 / s \]
relative velocity between eye and coordinate system

$v_x = 2^\circ/s$

$v_x = 8^\circ/s$
Perception of a Temporally Sampled Image Signal, Without Movement

spatial frequency

"window of perception"

temporal frequency
Perception of a Temporally Sampled Image Signal, Without Movement

- Phosphors with fast decay reproduce more than 20 temporal baseband replicas
- No spectral overlap -> perfect reconstruction of original signal possible

"window of perception", with SPEM

3 pel/frame

Girod: Image Communication
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- Eye movements