Computer Graphics

- The Human Visual System -

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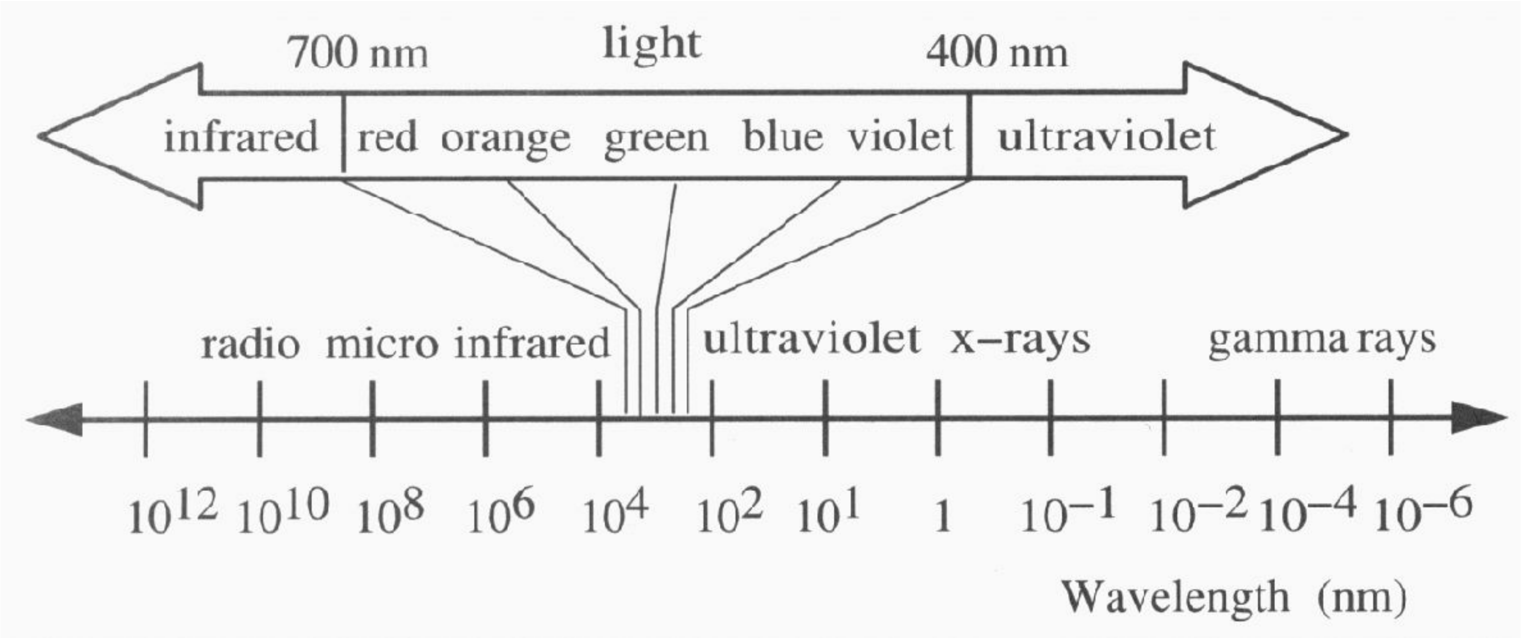
Overview

- **Last time**
  - Antialiasing
  - Super-Sampling
- **Today**
  - The Human Visual System
    - The eye
    - Early vision
    - High-level analysis
    - Color perception
- **Next lecture**
  - Color spaces

Light

- **Electromagnetic radiation**
- **Visible spectrum: ~ 400 to 700 nm**



Radiation Law

- **Physical model for light**
  - Wave/particle-dualism
    - Electromagnetic radiation wave model
    - Photons: $E_{ph}=h\nu$ particle model & ray optics
  - Plenoptic function
    - $L= L(x, \omega, t, \nu, \gamma)$, 5 dimensional,

Ignored parameters:
- No polarization
- No fluorescence
  - Decoupling of the spectrum
- Not time dependent
  - Instant propagation with speed of light
  - no phosphorescence

Used parameters:
- Direction
- Location

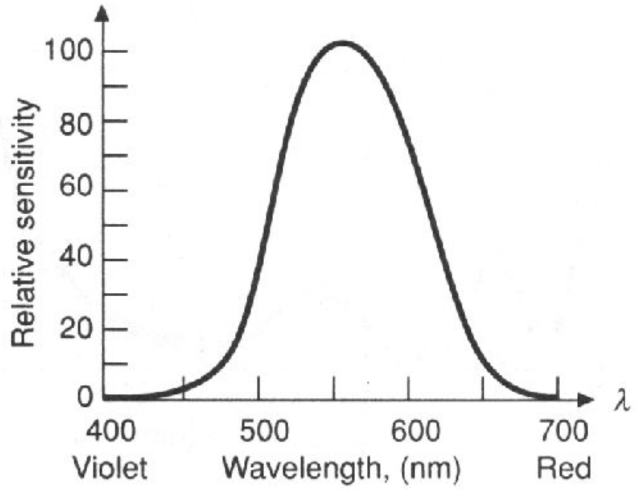
Photometry

- **Equivalent units to radiometry**
  - Weight with **luminous efficiency function** V(λ) (luminous efficiency function)
  - Spectral or "total" units

$$\Phi_{v} = K_m \int V(\lambda)\Phi_{e}(\lambda)d\lambda$$

$$K_m = 680\, lm / W$$

  - Distinction in English simple:
    - "rad": radiometric unit
    - "lum": photometric unit



Radiometric Units

Specification	Definition	Symbol	Unit	Notation
Energie energy		Q_e	[J= Ws] Joule	Strahlungsenergie radiant energy
Leistung, Fluß power, flux	dQ/dt	Φ_e	[W= J/s]	Strahlungsfluß radiant flux
Flußdichte flux density	dQ/dAdt	E_e	[W/m²]	Bestrahlungsstärke Irradiance
Flußdichte flux density	dQ/dAdt	$M_e = B_e$	[W/m²]	Radiom. Emissionsvermögen Radiosity
	$dQ/dA^{\Phi}d\omega dt$	L_e	[W/m²/sr]	Strahlungsdichte Radiance
Intensität intensity	$dQ/d\omega dt$	I_e	[W/sr]	Strahlungsstärke radiant intensity

Photometric Units

With luminous efficiency function weighted units

Specification	Definition	Symbol	Units	Notation
Energie energy		Q_v	[talbot]	Lichtmenge luminous energy
Leistung, Fluß power, flux	dQ/dt	Φ_v	[lm (Lumen) = talbot/s]	Lichtstrom luminous flux
Flußdichte flux density	dQ/dAdt	E_v	[lux= lm/m²]	Beleuchtungsstärke Illuminance
Flußdichte flux density	dQ/dAdt	$[M_v=]$ B_v	[lux]	Photom. Emissionsvermögen Luminosity
	$dQ/dA^{\Phi}d\omega dt$	L_v	[lm/m²/sr]	Leuchtdichte Luminance
Intensität intensity	$dQ/d\omega dt$	I_v	[cd (candela) = lm/sr]	Lichtstärke radiant intensity

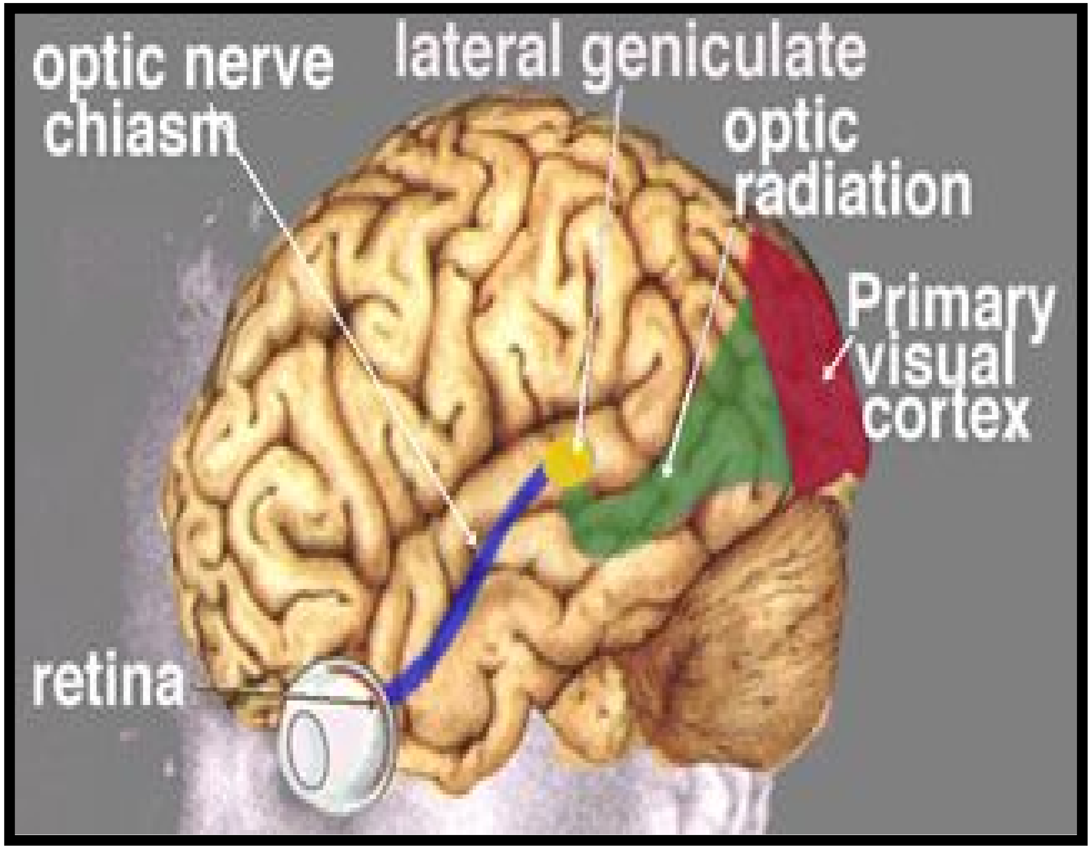
Illumination: samples

- **Typical illumination intensities**

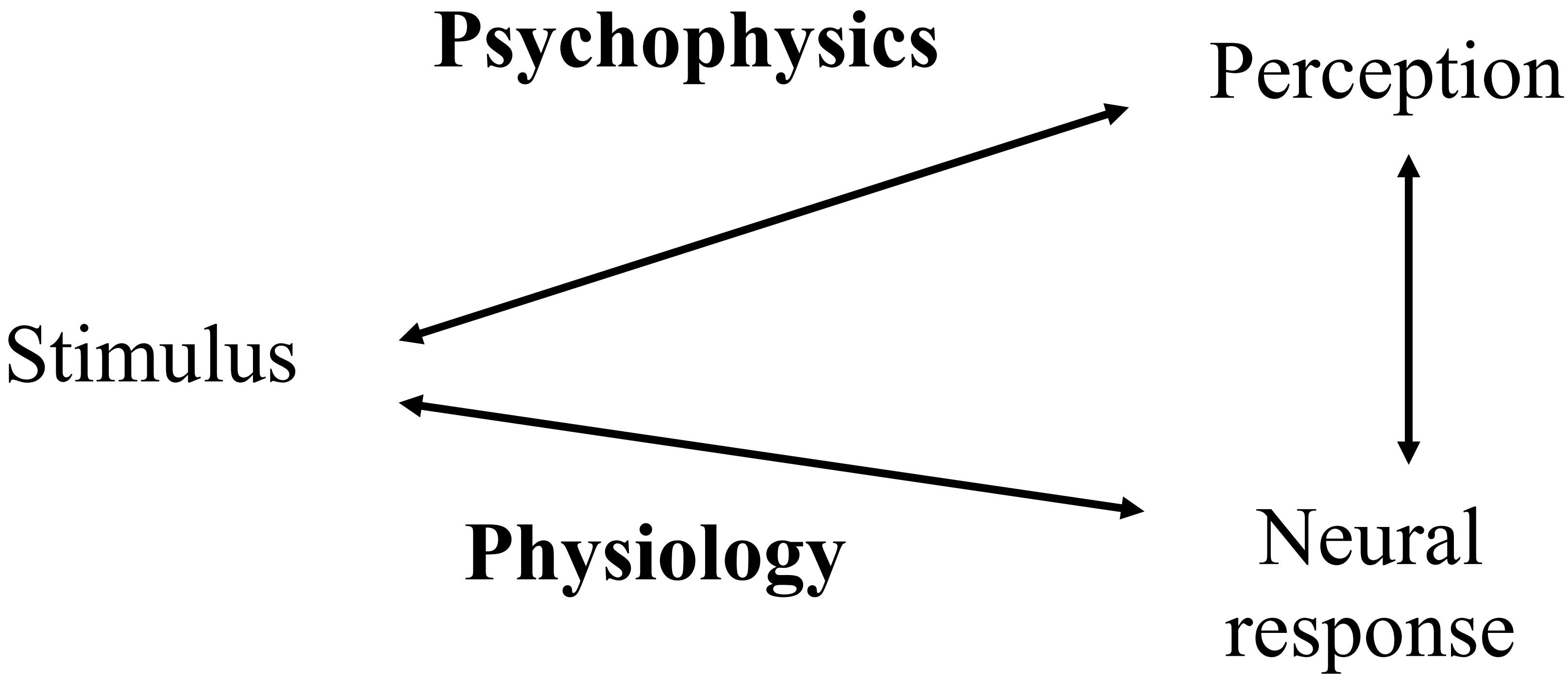
Light source	Illumination intensity [lux]
Direct solar radiation	25.000 – 110.000
Day light	2.000 – 27.000
Sunset	1 – 108
Moon light	0.01 – 0.1
Starry night	0.0001 – 0.001
TV studio	5.000 – 10.000
Shop lighting	1.000 – 5.500
Office lighting	200 – 550
Home lighting	50 – 220
Street lighting	0.1 – 20

Human Visual System

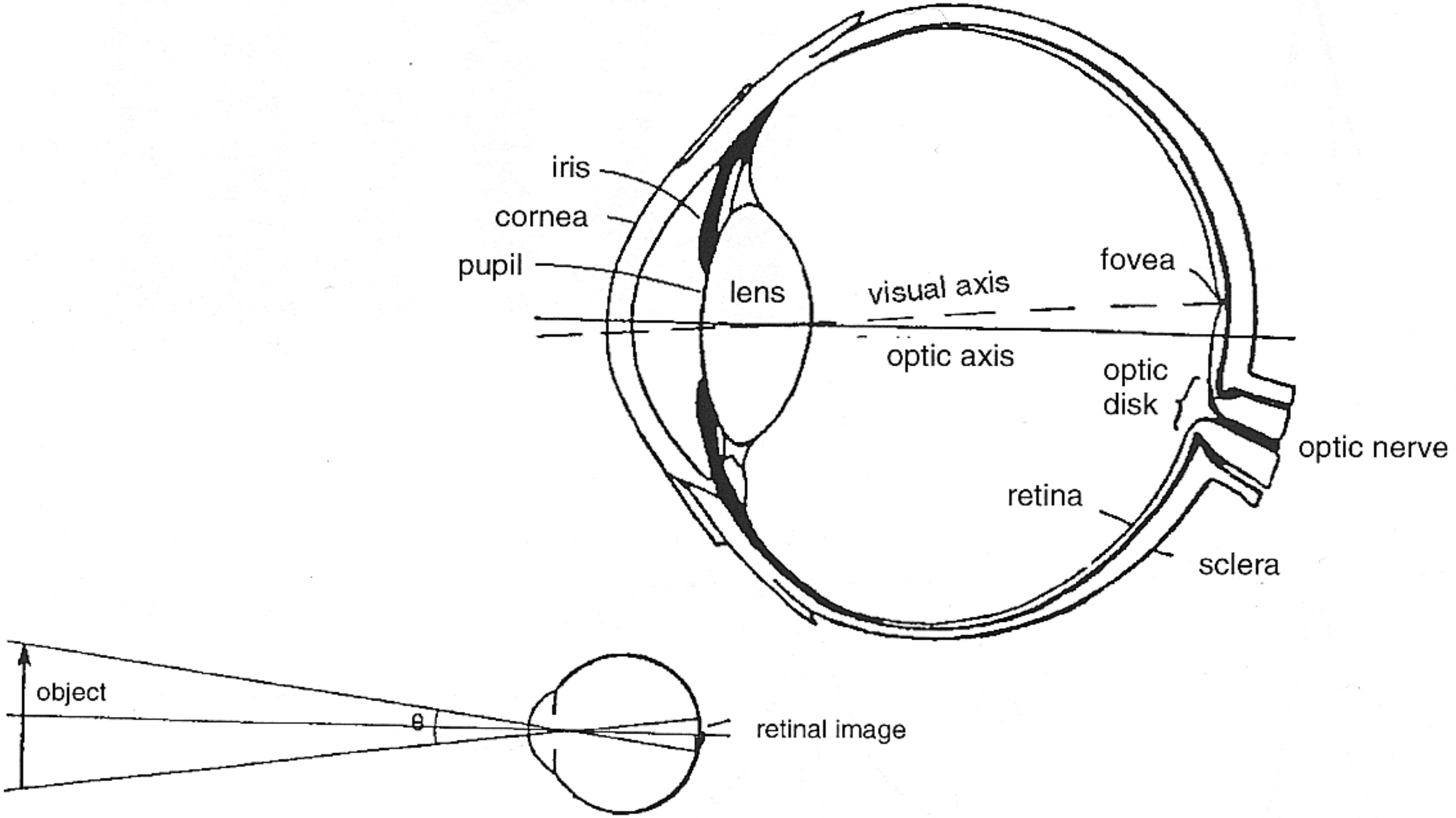
- **Physical structure well established**
- **Perceptual behaviour is a complex process**



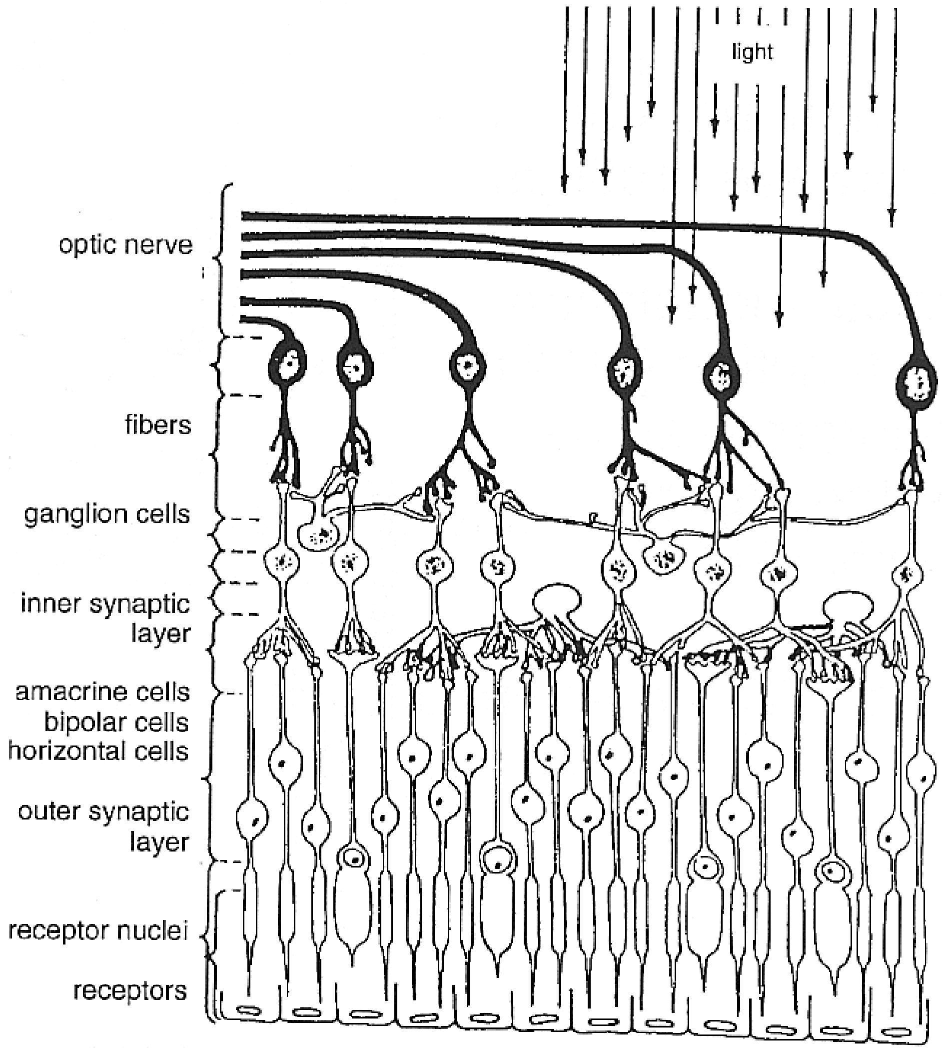
HVS - Relationships



Perception and Eye

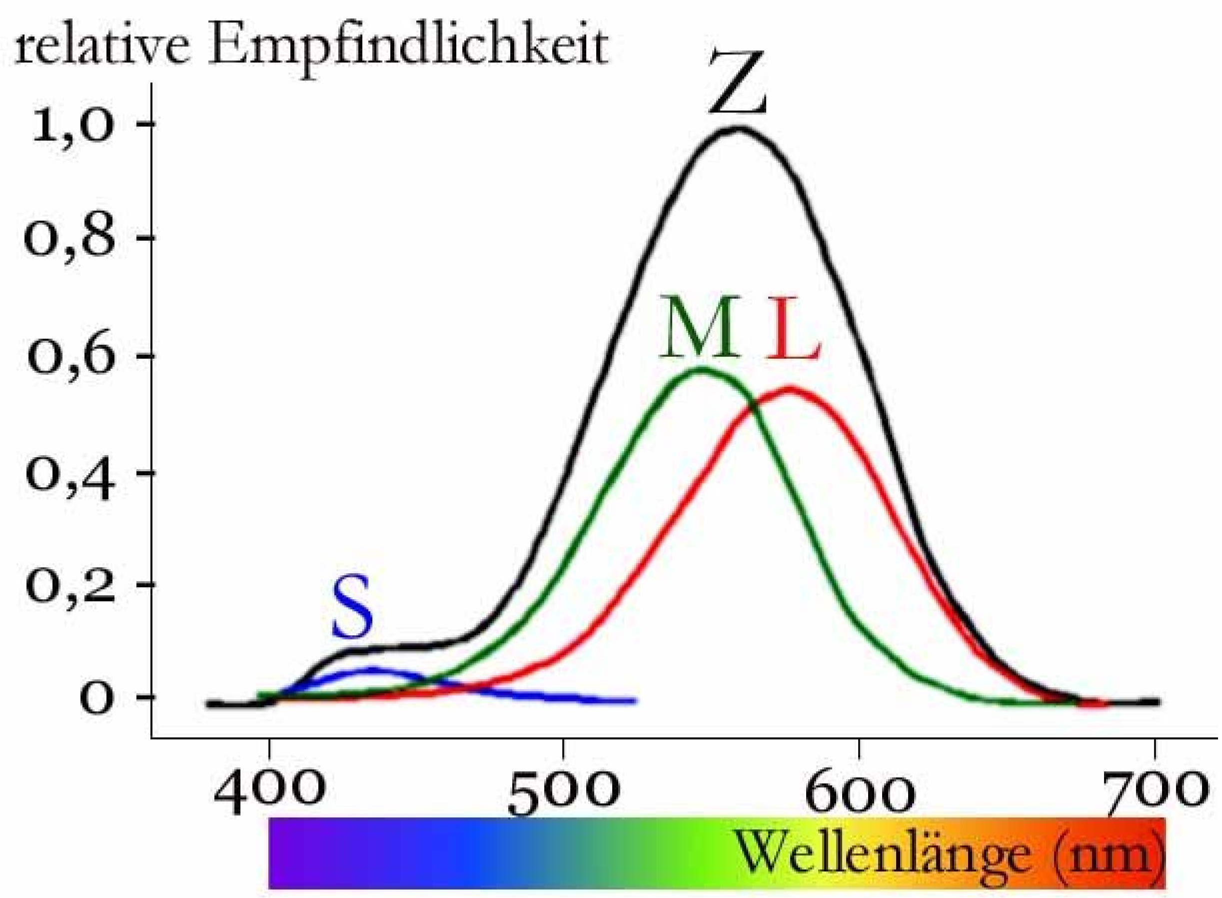


Retina


light
optic nerve
fibers
ganglion cells
inner synaptic layer
amacrine cells
bipolar cells
horizontal cells
outer synaptic layer
receptor nuclei
receptors

Eye as a Sensor

- **Relative Sensitivity of Cones**
  - S scaled by 3x



Eye

- **Fovea:**
  - Ø 1-2 visual degrees
  - 6-7 Mio. ***cones***, about 0.4 arc seconds wide
  - No rods, but three different cone types:
    - L(ong, 64%), M(edium, 32%), S(hort wavelength, 4%)
    - Results in varying resolution depending on color
    - Resolution: 10 arc minutes (S, blue), 0.5 arc minutes (L, M)
  - Linked directly with optical nerves
  - Adaptation of light intensity only through cones
- **Periphery:**
  - 75-150 Mio. ***rods***, night vision, S/W
  - Response to stimulation of approx. 5 photons/sec. (@ 500 nm)
  - Many thousands of cells are combined before linked with nerves
    - Bad resolution
    - Good flickering sensitivity

This is a text in red

This is a text in green

This is a text in blue

This is a text in red

This is a text in green

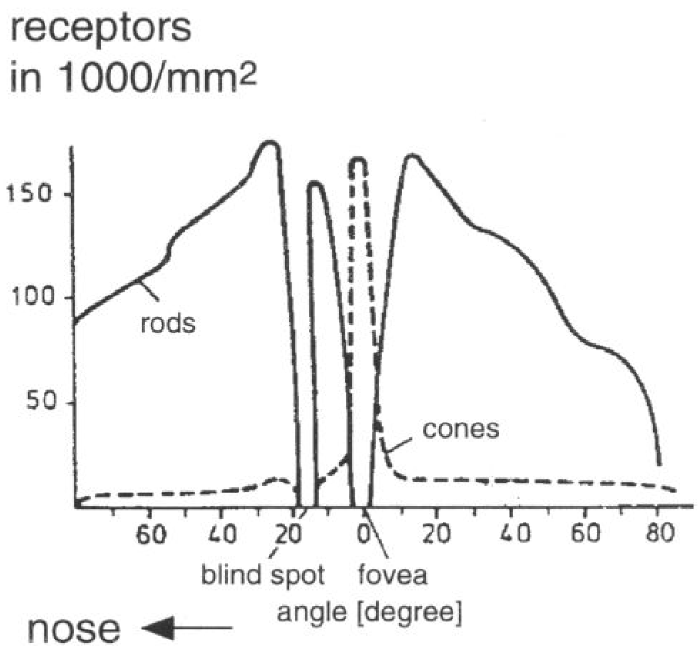
This is a text in blue

This is a text in red

This is a text in green

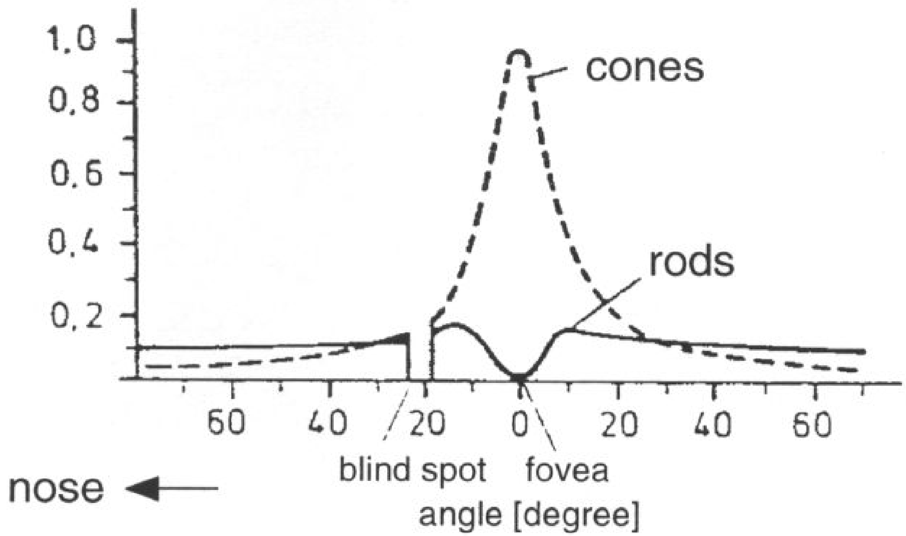
This is a test in blue

Visual Acuity



Receptor density

Resolution in line-pairs/arc minute

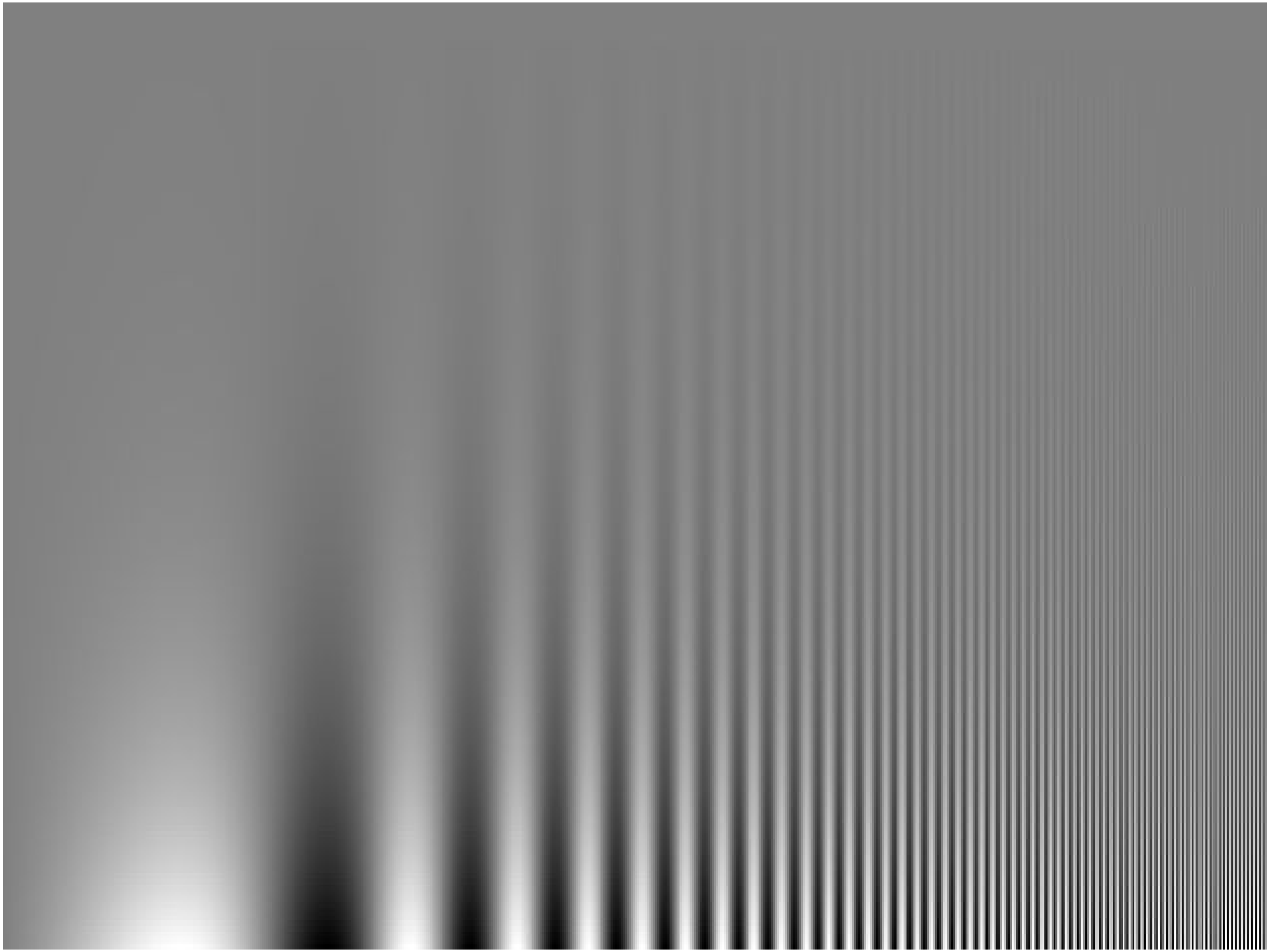


Resolution of the Eye

- **Resolution-experiments**
  - Line pairs: 50-60/degree ➔ resolution .5 arc minutes
  - Line offset: 5 arc seconds (hyperacuity)

  - Eye micro-tremor: 60-100 Hz, 5 μm (2-3 photoreceptor spacings)
    - Allows to reconstruct from super-resolution
  - Together corresponds to
    - 19“ display at 60 cm: 18.000^2 Pixel (3000^2 w/out hyperacuity)
- **Automatic fixation of eye onto region of interest**
  - Automatic gaze tracking
  - Apparent overall high resolution of fovea
- **Visual acuity increased by**
  - Brighter objects
  - High contrast

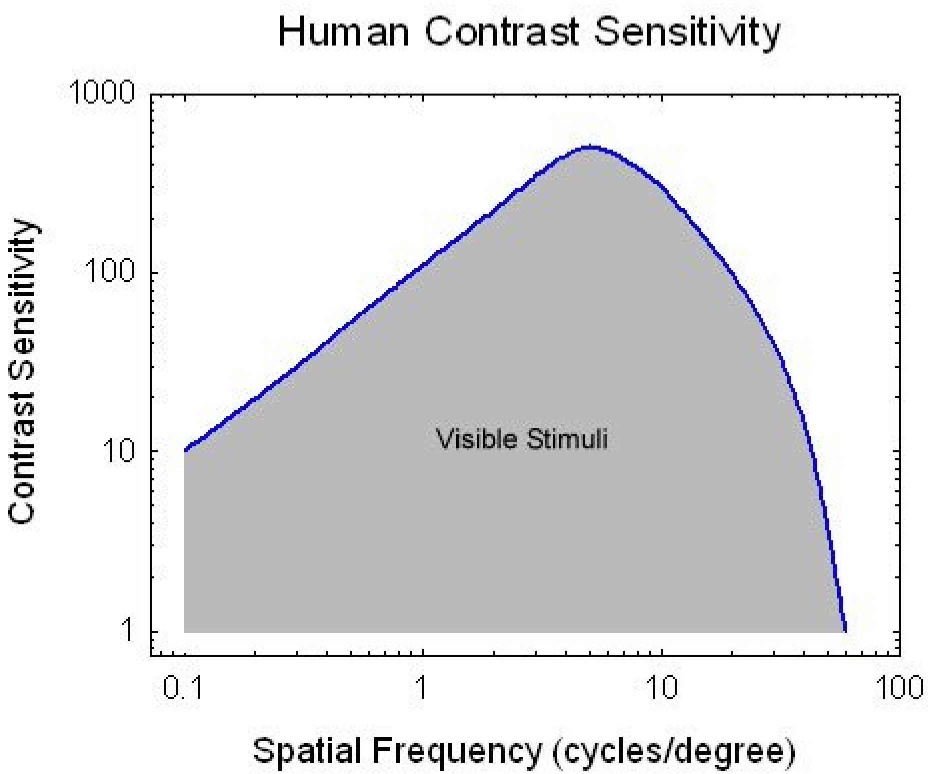
Luminance Contrast Sensitivity



Campbell-Robson contrast sensitivity chart

Contrast Sensitivity

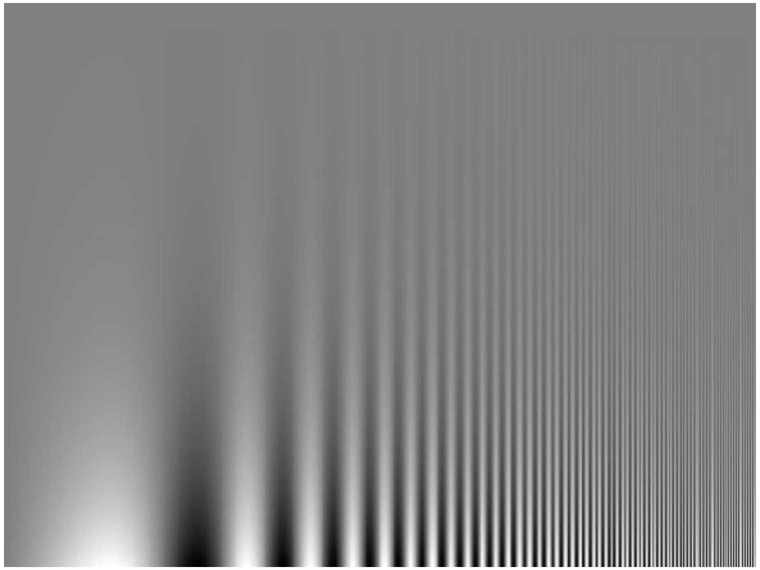
- **Sensitivity: 1 / threshold contrast**
- **Maximum acuity at 5 cycles/degree (0.2 %)**
  - Decrease toward low frequencies: lateral inhibition
  - Decrease toward high frequencies: sampling rate (Poisson disk)
  - Upper limit: 60 cycles/degree

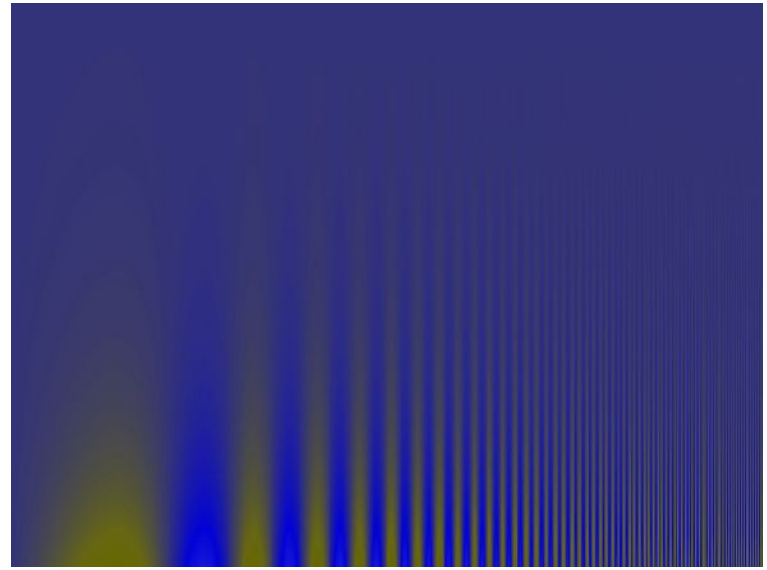


- **Medical diagnosis**
  - Glaucoma (affects peripheral vision: low frequencies)
  - Multiple sclerosis (affects optical nerve: notches in contrast sensitivity)

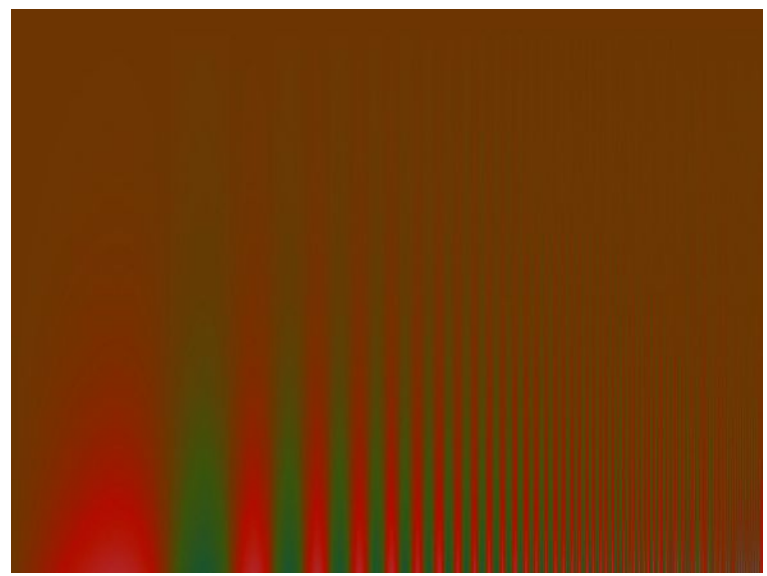
www.psychology.psych.ndsu.nodak.edu

Color Contrast Sensitivity





- **Color vs. luminance vision system**
  - Higher sensitivity at lower frequencies
  - High frequencies less visible
- **Image compression**

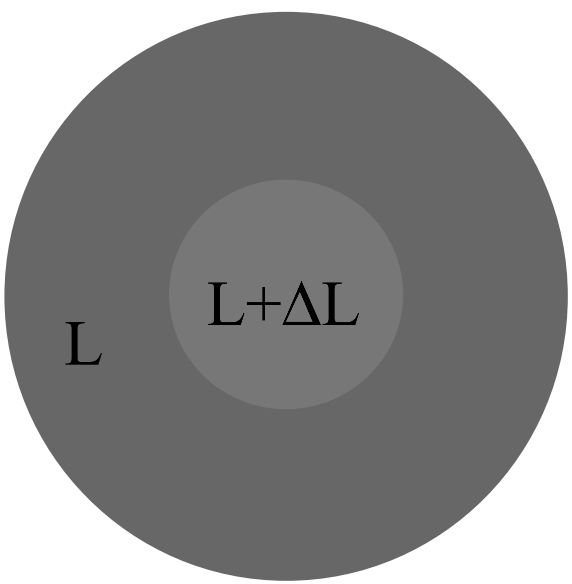


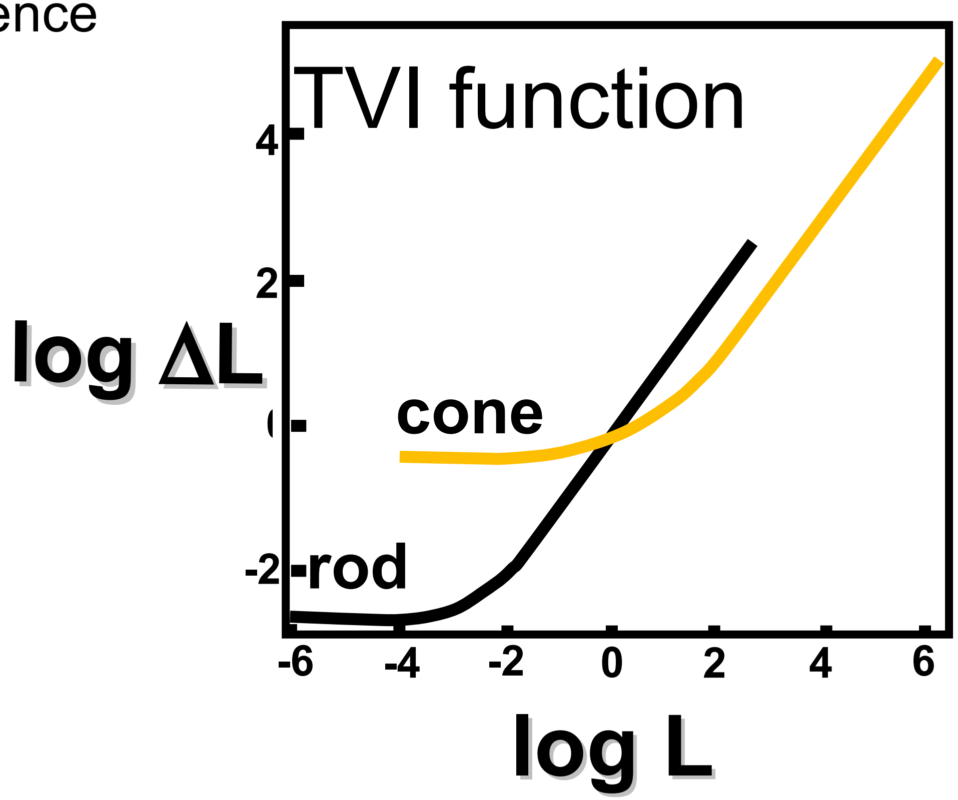
Threshold Sensitivity Function

- Weber-Fechner Law (Treshhold Versus Intensity, TVI)
  - Perceived brightness = log (radiant intensity)

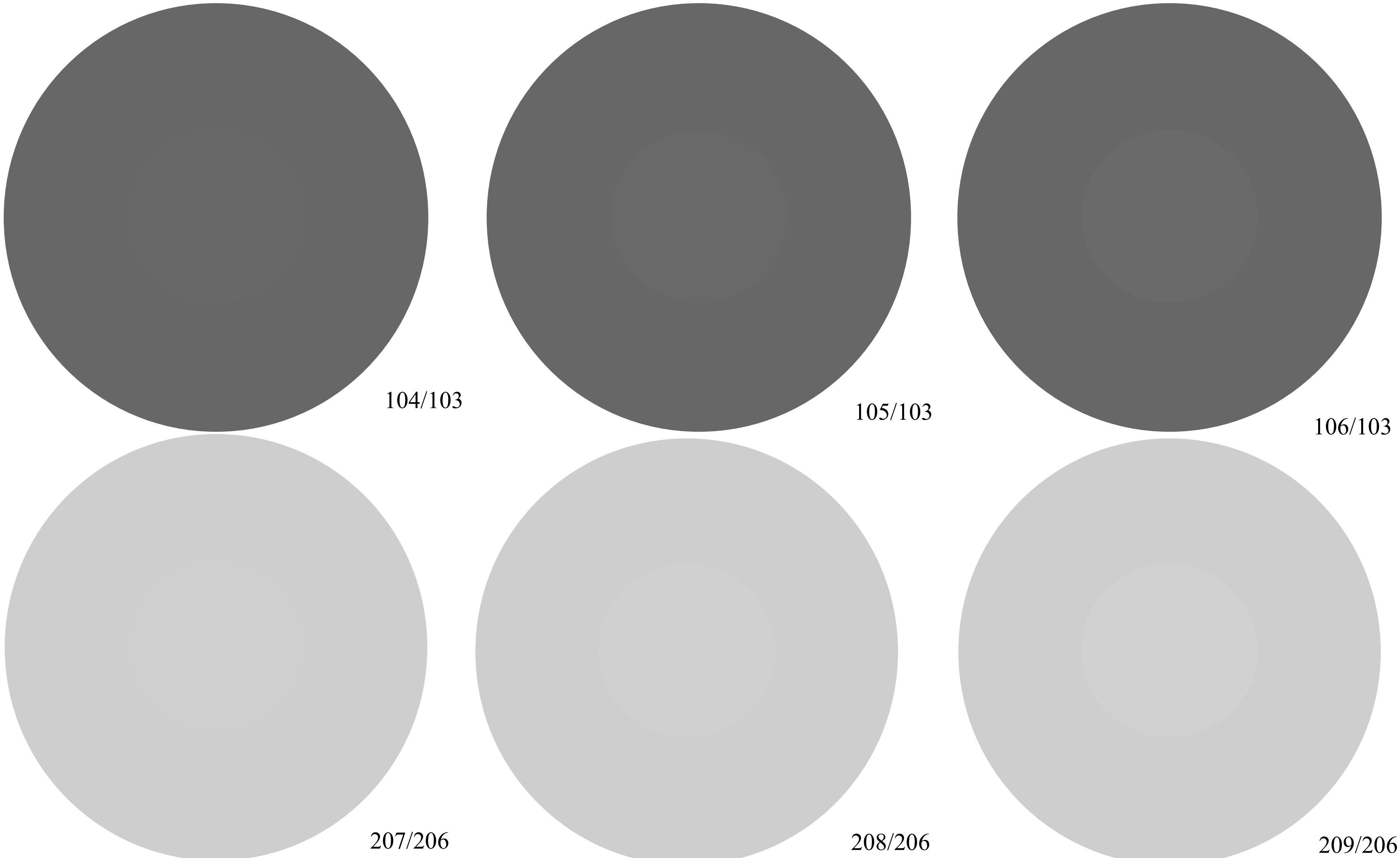
    $$E=K+c \log I_v$$

  - Perceivable intensity difference
    - 10 cd vs. 12 cd: **ΔL=2cd**
    - 20 cd vs. 24 cd: **ΔL=4cd**
    - 30 cd vs. 36 cd: **ΔL=6cd**



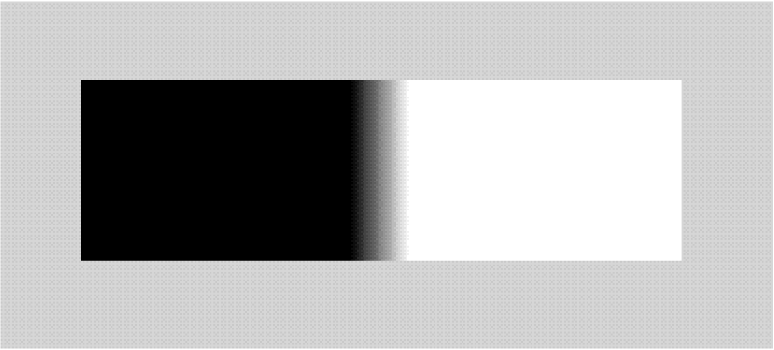


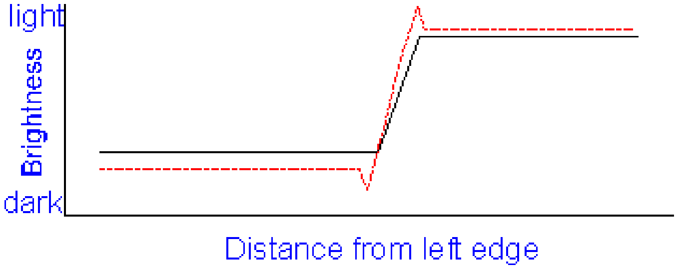
Weber-Fechner Examples

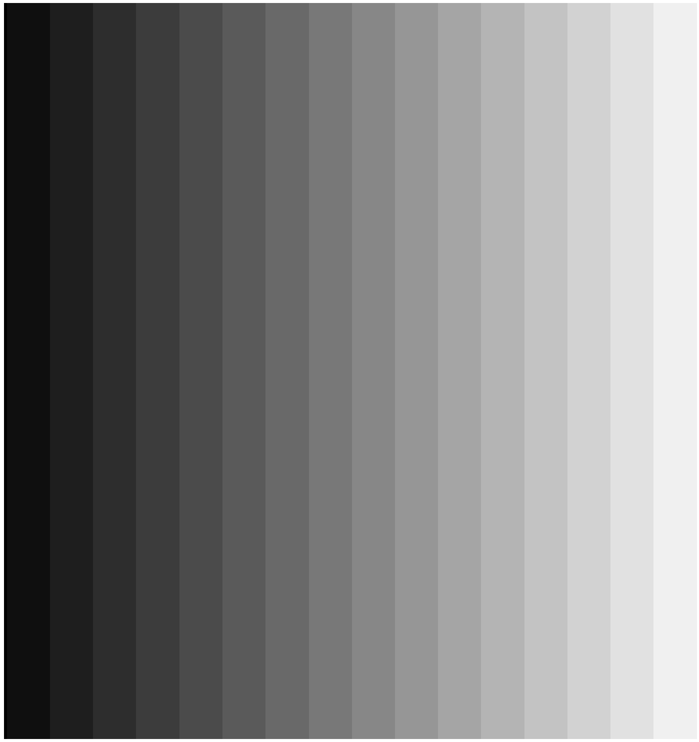


Mach Bands

- "Overshooting" along edges
  - Extra-bright rims on bright sides
  - Extra-dark rims on dark sides
- Due to "Lateral Inhibition"

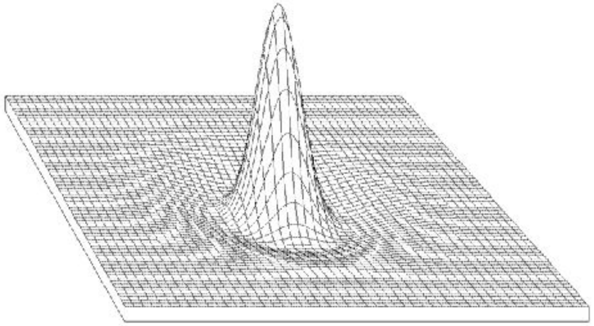


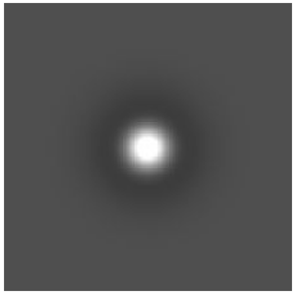


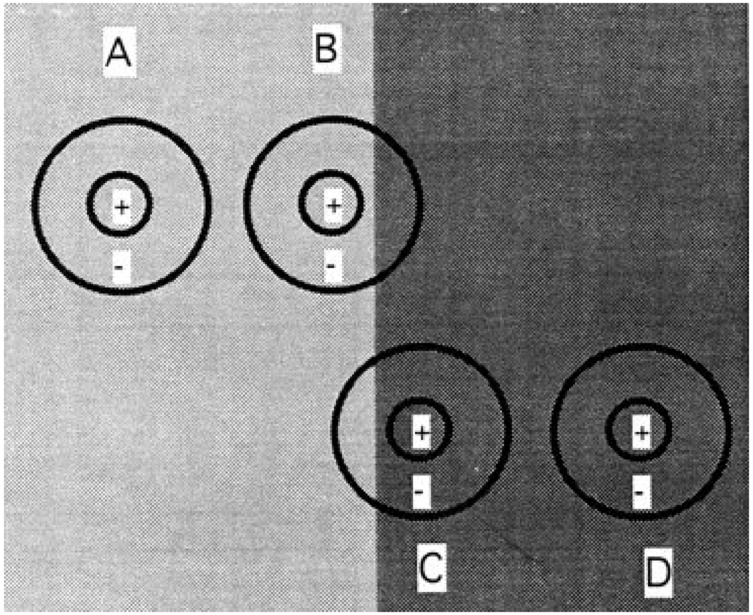


Lateral Inhibition

- **Pre-processing step within retina**
  - Surrounding brightness level weighted negatively
    - A: high stimulus, maximal bright inhibition
    - B: high stimulus, reduced inhibition ➔ stronger response
    - D: low stimulus, maximal inhibition
    - C: low stimulus, increased inhibition ➔ weaker response
- **High-pass filter**
  - Enhances contrast along edges
  - Difference-of-Gaussians (DOG) function

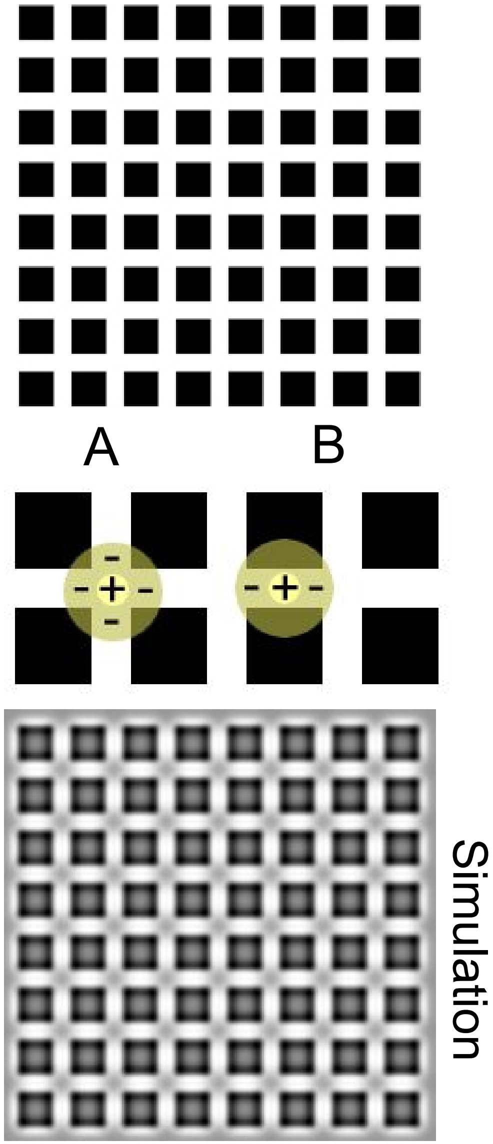


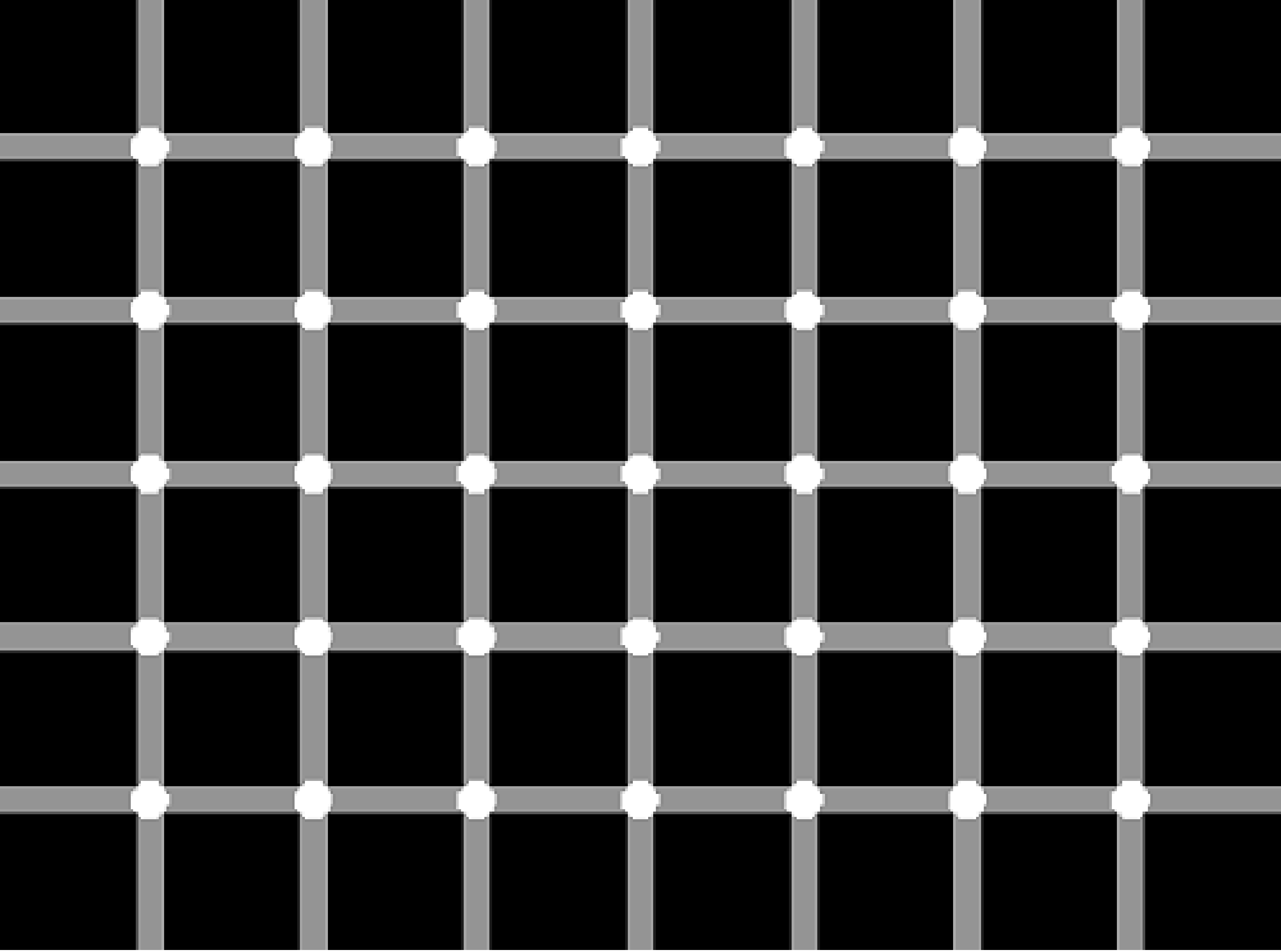




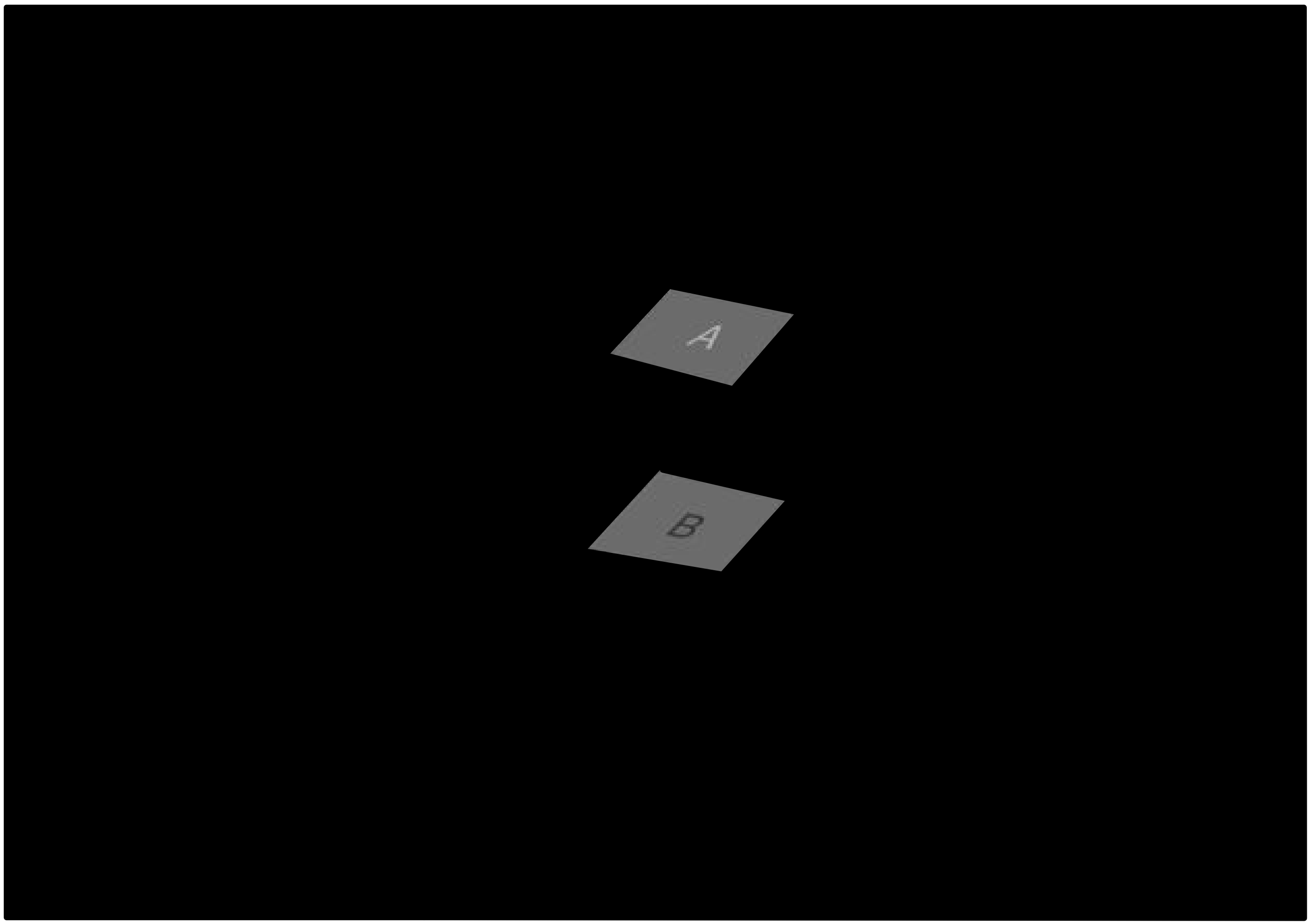
Lateral Inhibition: Hermann Grid

- Dark dots at crossings
- Explanation
  - Crossings (A)
    - More surround stimulation (more bright area)
    - ⇒ More inhibition
    - ⇒ Weaker response
  - Streets (B)
    - Less surround stimulation
    - ⇒ Less inhibition
    - ⇒ Greater response
- Filtered with DOG function
  - Darker at crossings, brighter in streets
  - Appears more steady
  - What if reversed ?

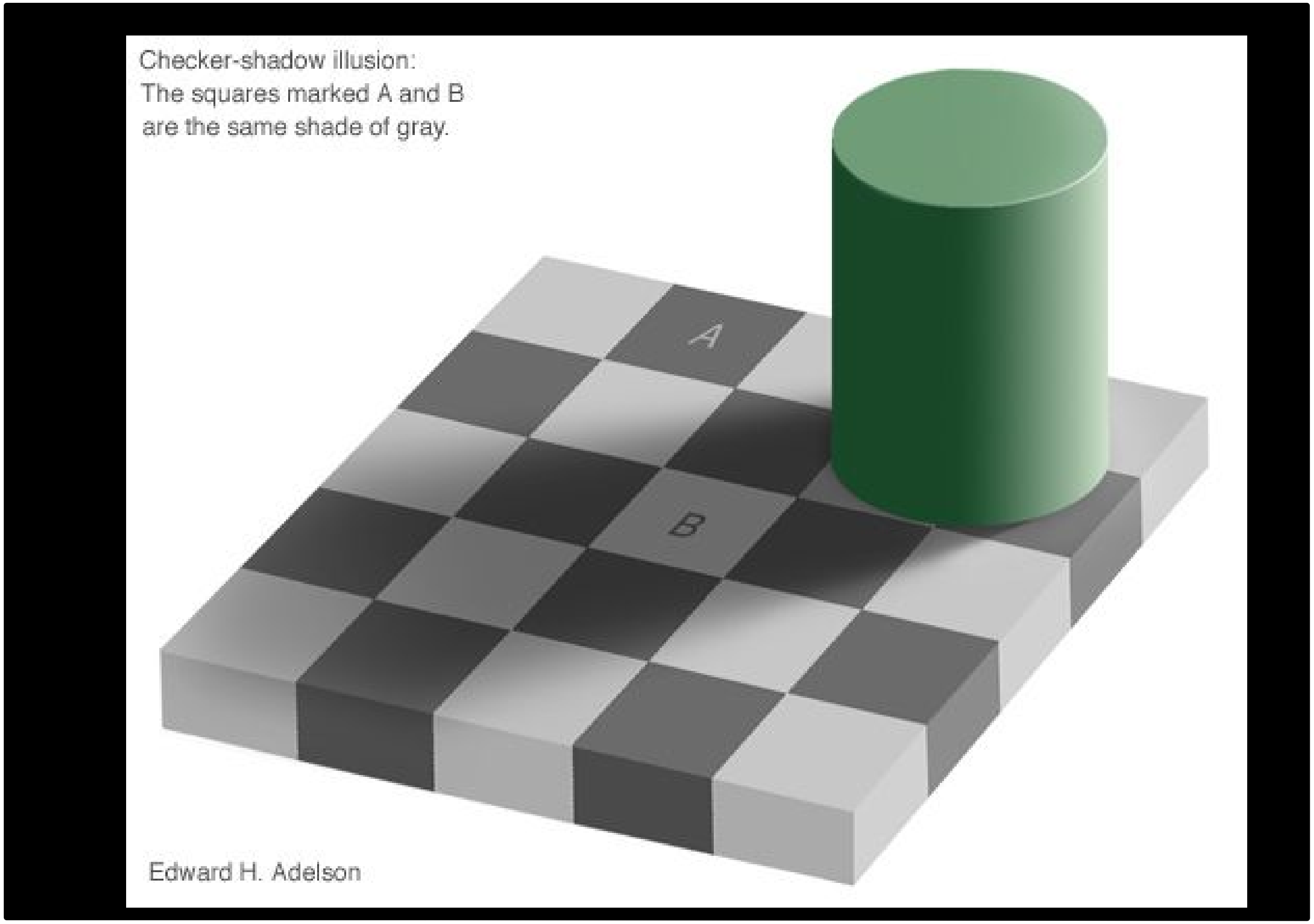




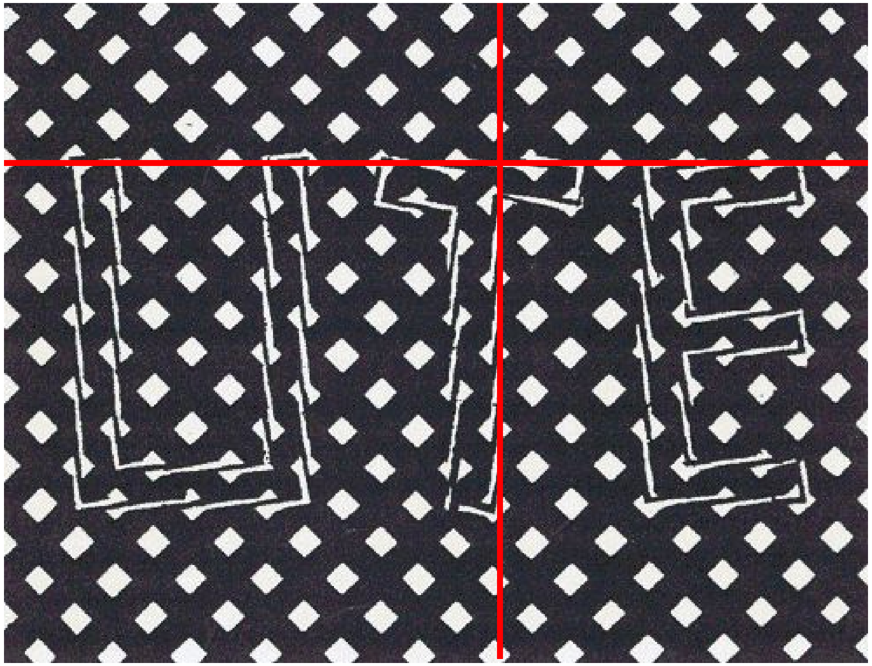
High-Level Contrast Processing

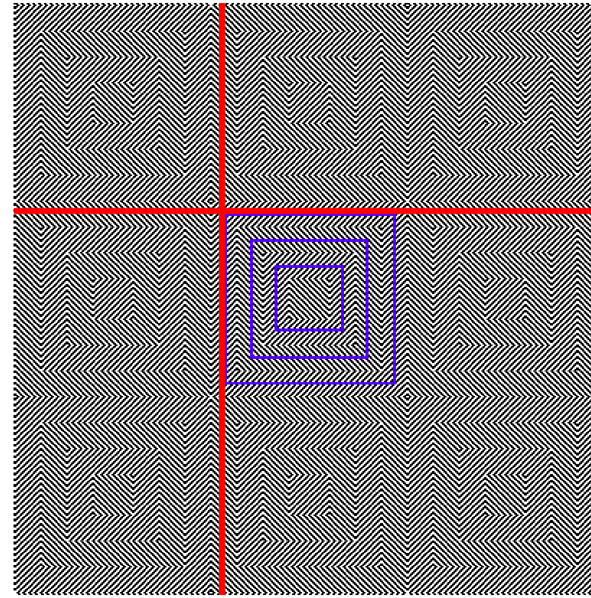


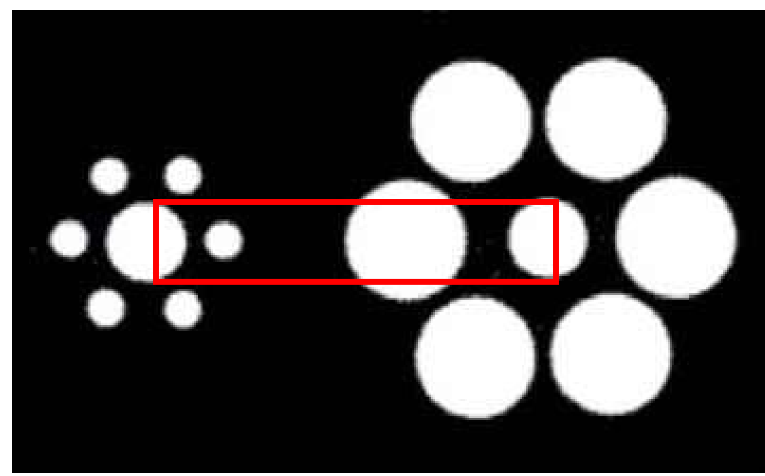
High-Level Contrast Processing



Shape Perception



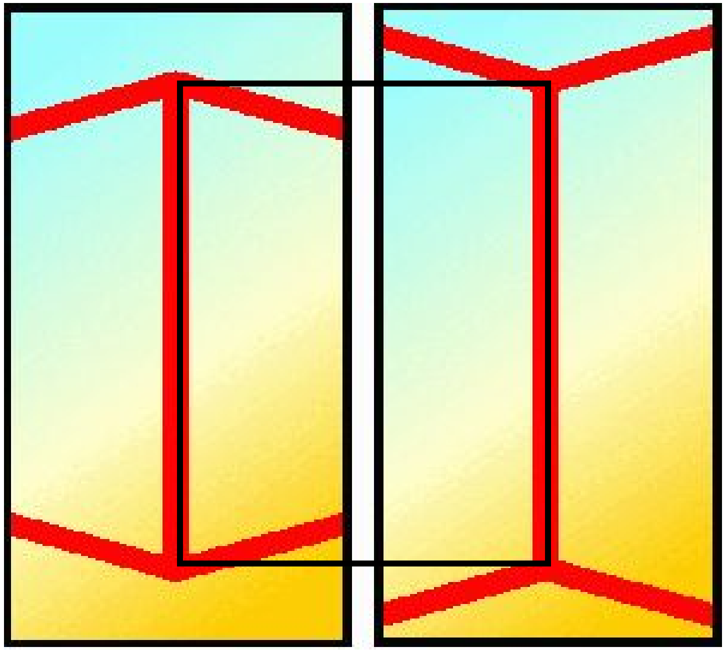


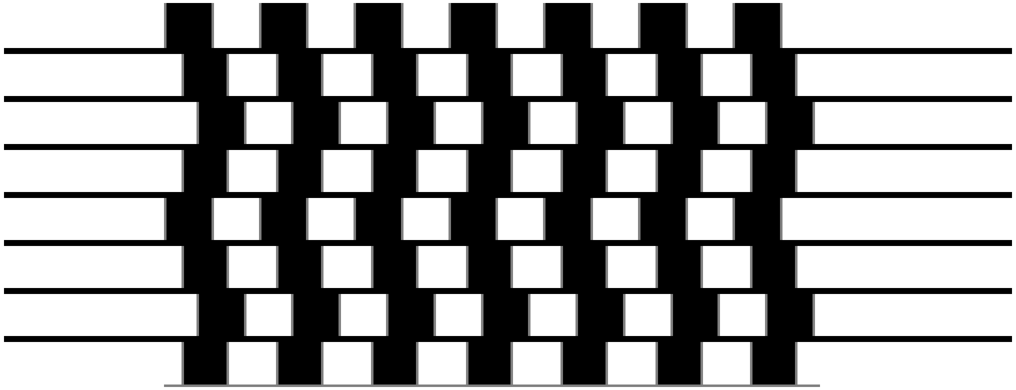


- Depends on surrounding primitives
  - Directional emphasis
  - Size emphasis

http://www.panoptikum.net/optischetaeuschungen/index.html

Shape Processing: Geometrical Clues





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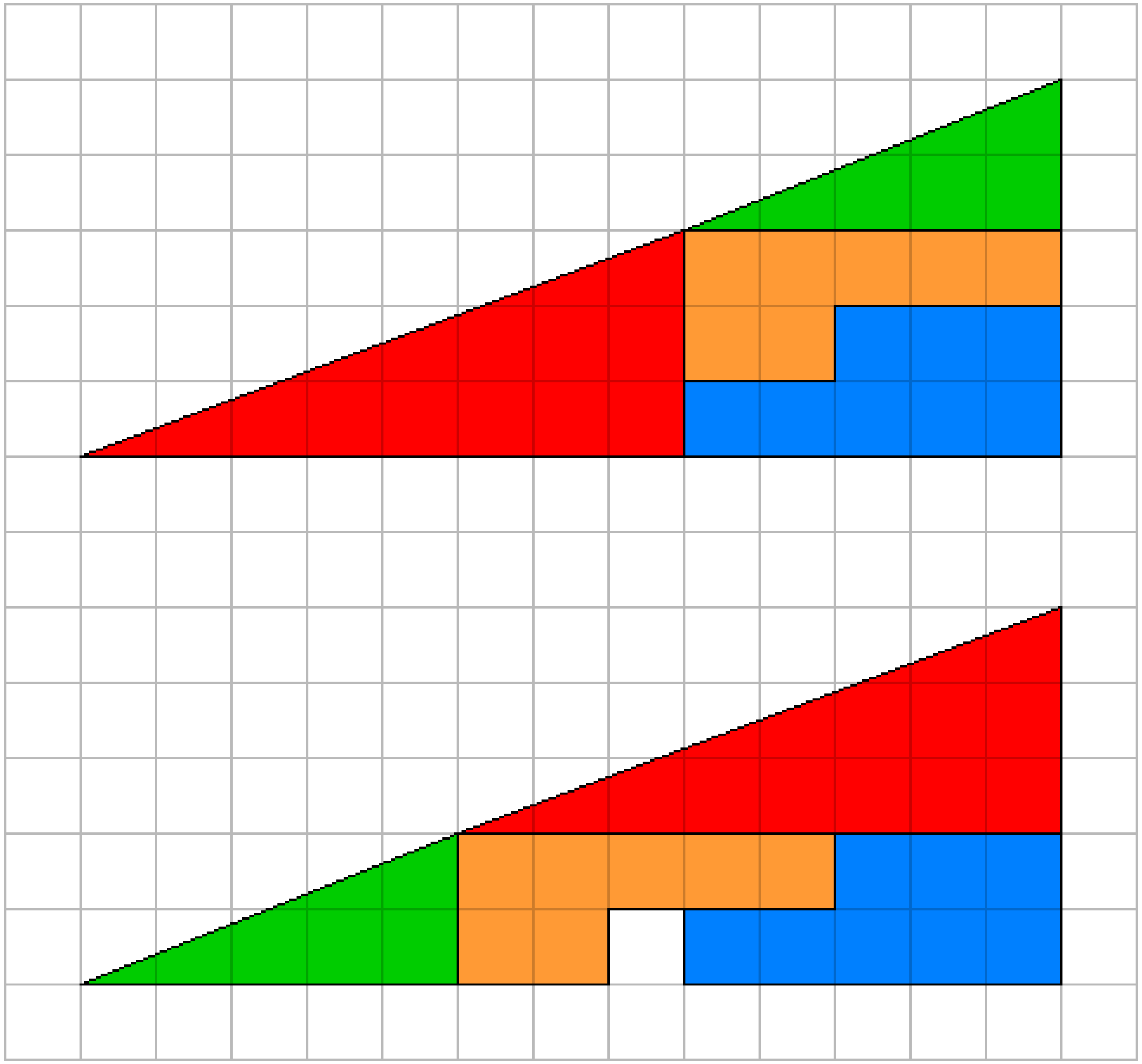
- Automatic geometrical interpretation
  - 3D perspective
  - Implicit scene depth

Visual “Proofs”



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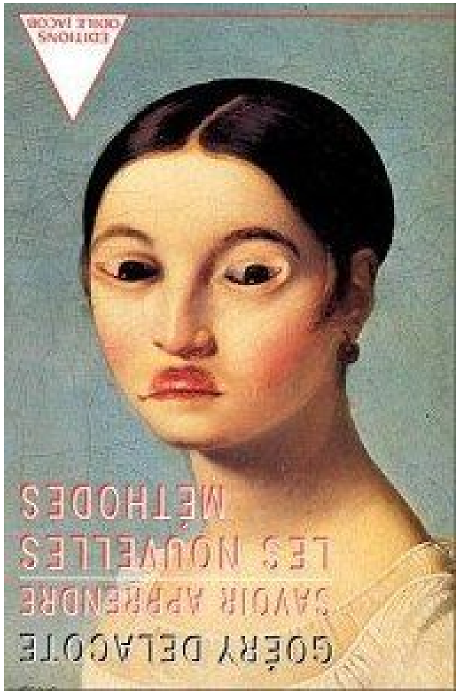
HVS: High-Level Scene Analysis

- Experience
- Expectation
- Local clue consistency



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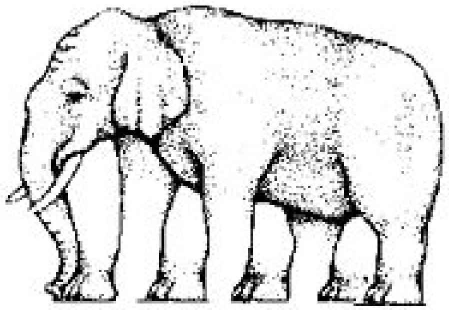
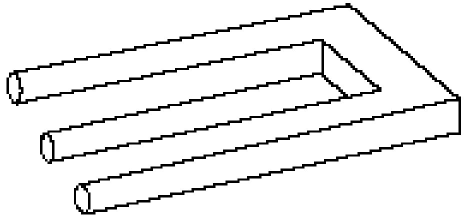
Impossible Scenes

- Escher et.al.
  - Confuse HVS by presenting contradicting visual clues





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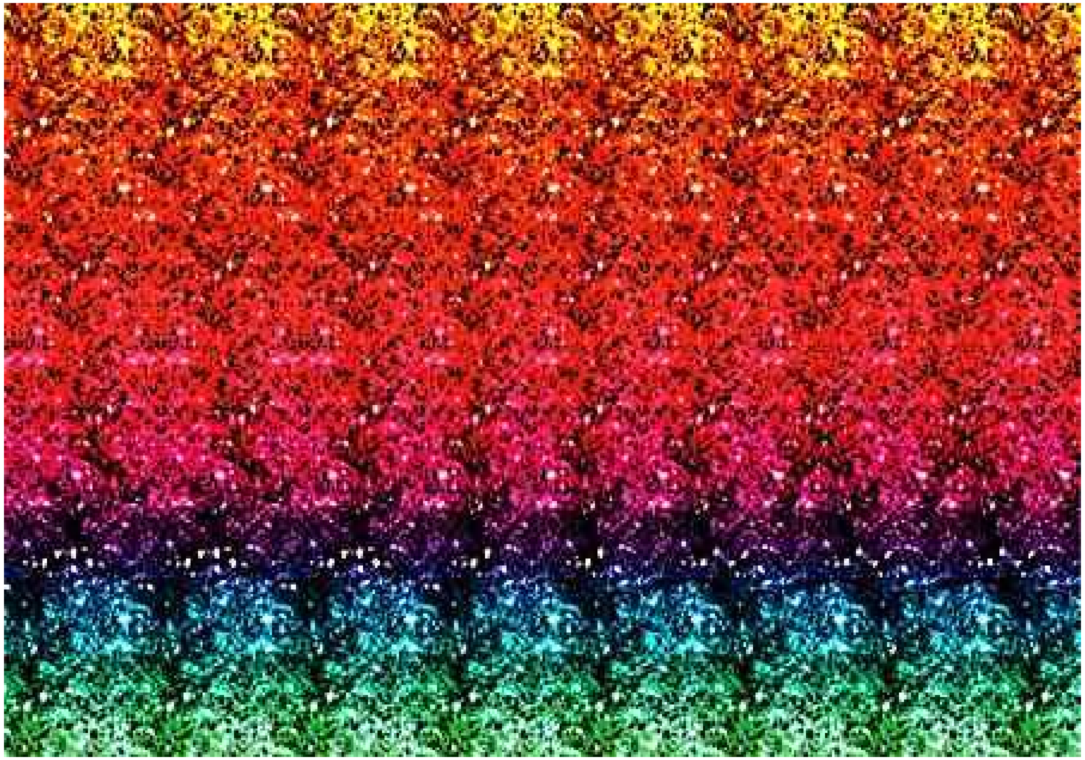
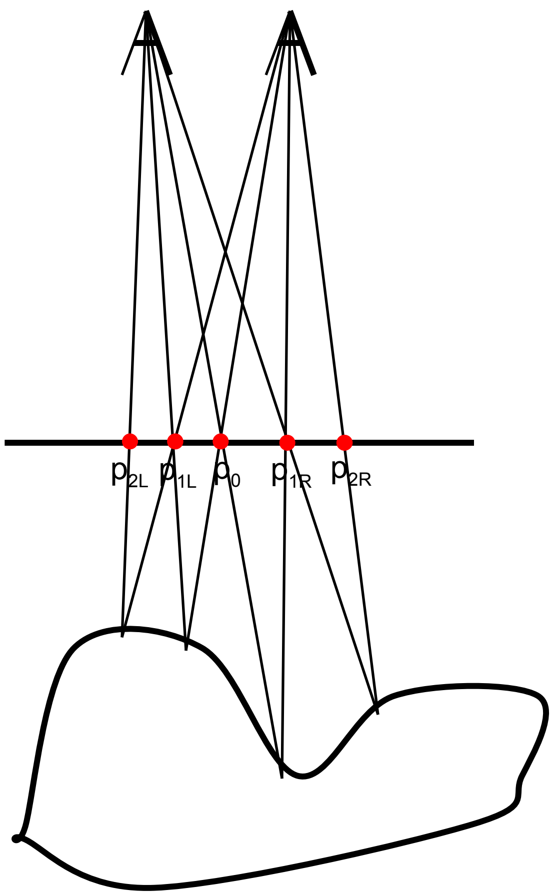
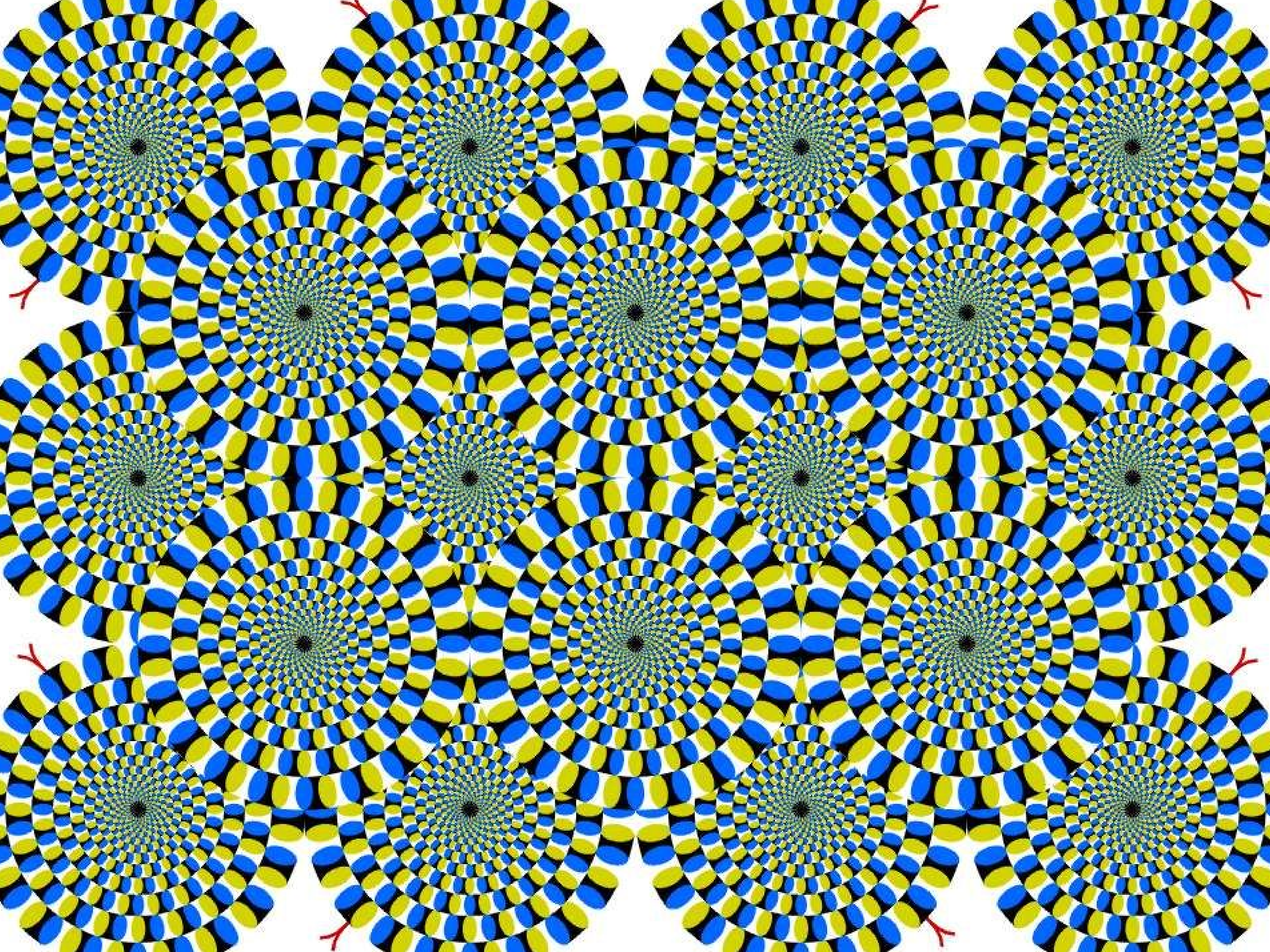
Single Image Random Dot Stereograms



SIRDS Construction

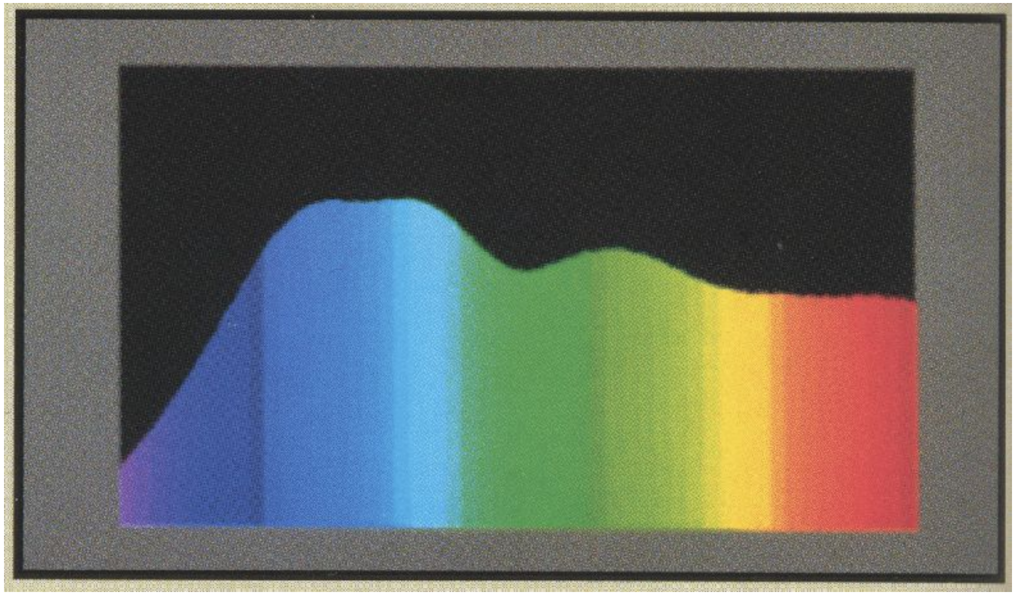
- Assign arbitrary color to p_0 in image plane
- Trace from eye points through p_0 to object surface
- Trace back from object to corresponding other eye
- Assign color at p_0 to intersection points p_{1L},p_{1R} with image plane
- Trace from eye points through p_{1L},p_{1R} to object surface
- Trace back to eyes
- Assign p_0 color to p_{2L},p_{2R}
- Repeat until image plane is covered

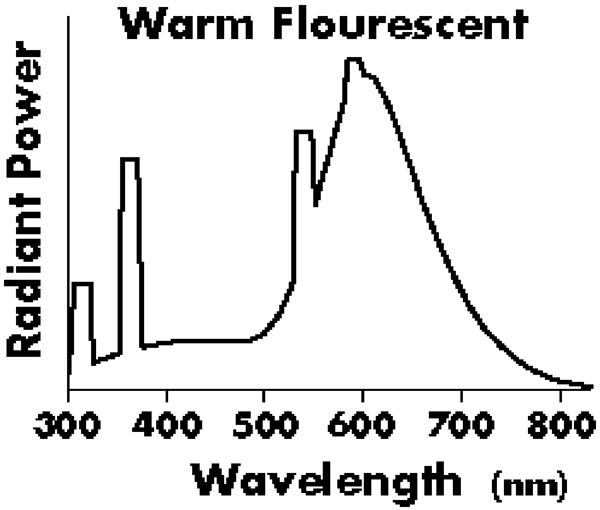




Color

- **Physics**
  - Continuous spectral energy distribution
- **Human color perception**
  - Cones in retina
  - 3 different cone types
  - Spectral mapping to 3 channels

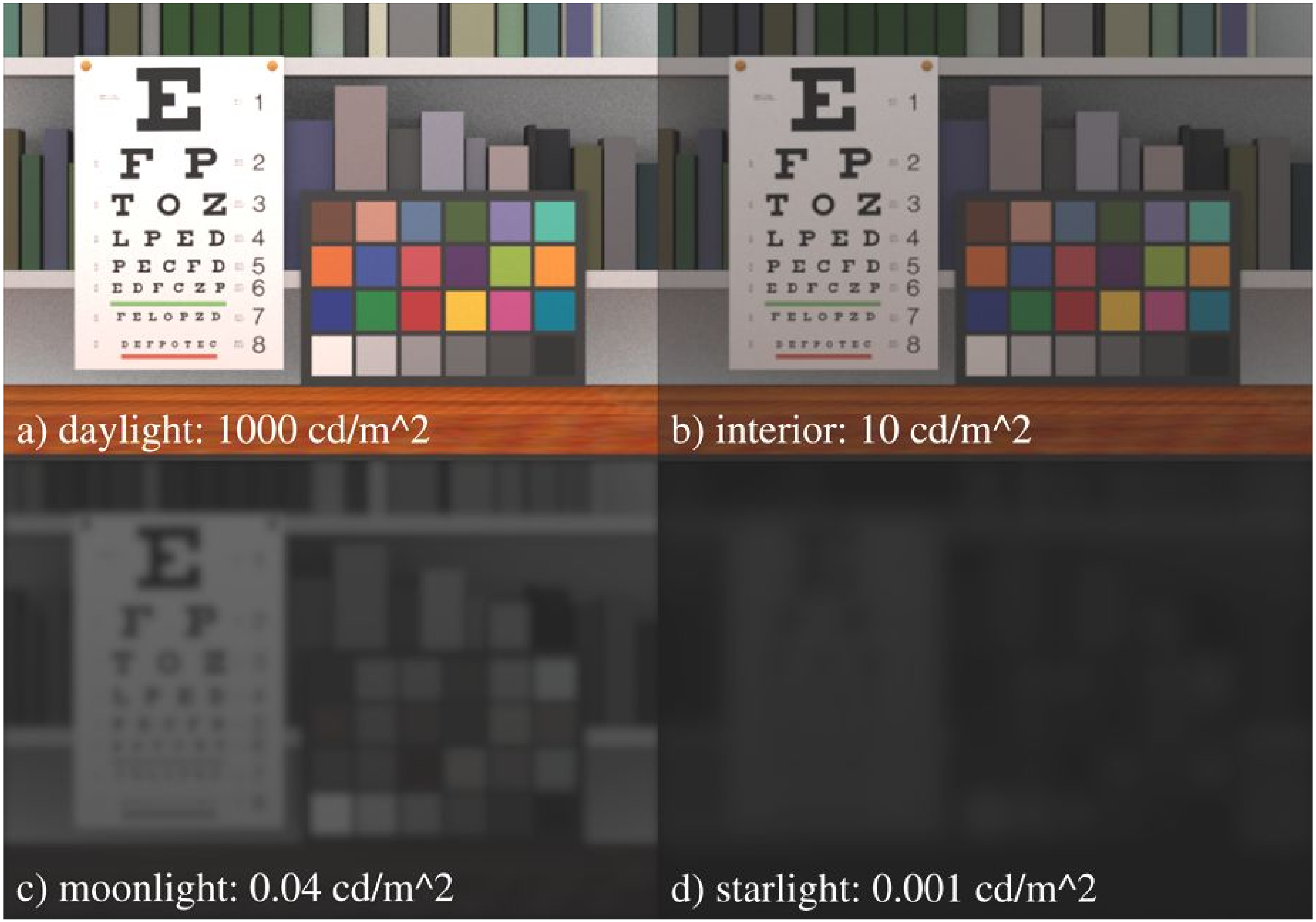




Visual Acuity and Color Perception

Photopic vision

Mesopic/photopic transition



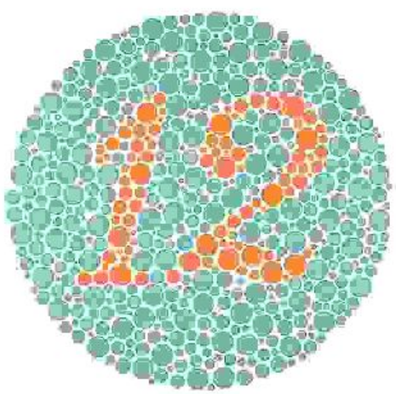
Scotopic/mesopic transition

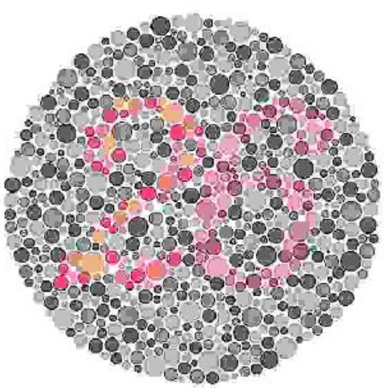
Scotopic vision

Color Perception

- **Di-chromaticity (dogs, cats)**
  - Yellow & blue-violet
  - Green, orange, red indistinguishable
- **Tri-chromaticity (humans, monkeys)**
  - Red, green, blue
  - Color-blindness
    - Most often men, green color-blindness

www.lam.mus.ca.us/cats/color/





www.colorcube.com/illusions/clrblnd.html