Computer Graphics

The Human Visual System (HVS)

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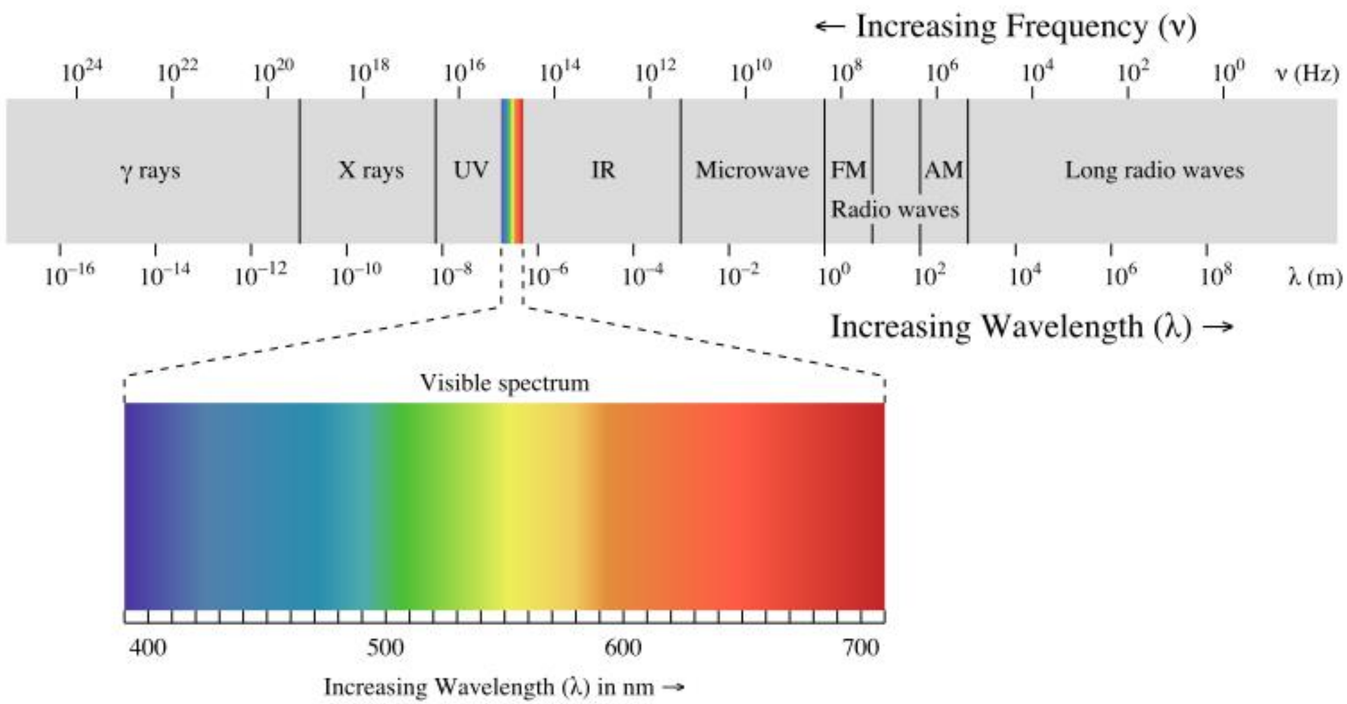
Light

- **Electromagnetic (EM) radiation**
  - From long radio waves to ultra short wavelength gamma rays
- **Visible spectrum: ~400 to 700 nm (all animals)**
  - Likely due to development of early eyes in water
    - Only very small window that lets EM radiation pass though



Radiation Law

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

Ignored parameters:
- No polarization
- No fluorescence
  - Decoupling of the spectrum
- No time dependence
  - Instant propagation with speed of light
  - No phosphorescence

Used parameters:
- Direction
- Location

Radiometric Units

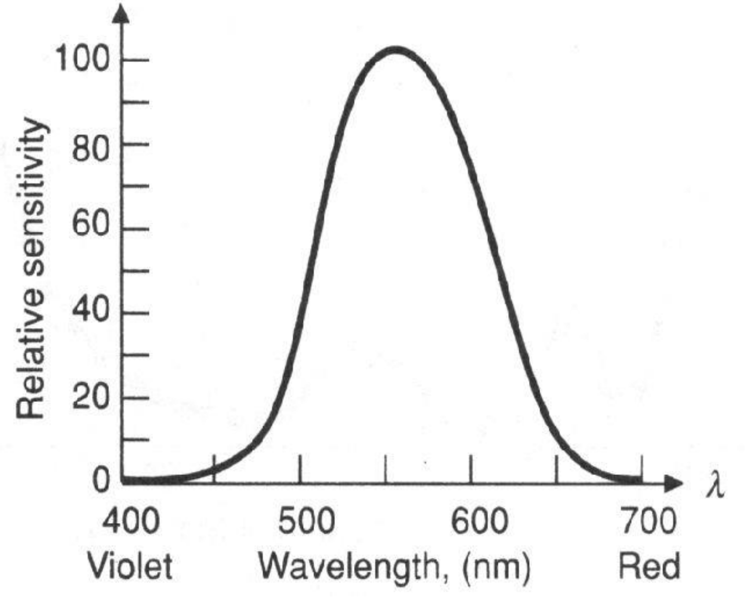
Specification	Definition	Symbol	Unit	Quantity
Energy		Q_e	[J = W·s] (joule)	Radiant energy
Power, flux	dQ/dt	Φ_e	[W = J/s] (watt)	Radiant flux
Flux density	dQ/dAdt	E_e	[W/m^2]	Irradiance
Flux density	dQ/dAdt	B_e	[W/m^2]	Radiosity
Intensity	dQ/dωdt	I_e	[W/sr]	Radiant intensity
	dQ/dAdωdt	L_e	[W/(m^2·sr)]	Radiance

Photometry

- **Equivalent units to radiometry**
  - Weighted with luminous efficiency function V(λ)
  - Considers the spectral sensitivity of the human eye
    - Measured across different humans
  - Spectral or (typically) “total” units
    - Integrate over the entire spectrum and deliver a single scalar value

$$\Phi_v = K_m \int V(\lambda)\Phi_e(\lambda)d\lambda$$

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



Luminous efficiency function

  - Simple distinction (in English!):
    - Names of radiometric quantities contain “radi”
    - Names of photometric quantities contain “lumi”

Photometric Units

Specification	Definition	Symbol	Unit	Quantity
Energy		Q_v	[T = lm·s] (talbot)	Luminous energy
Power, flux	dQ/dt	Φ_v	[lm = T/s] (lumen)	Luminous flux (e.g. emitted power of lamp)
Flux density	dQ/dAdt	E_v	[lx = lm/m^2] (lux)	Illuminance
Flux density	dQ/dAdt	B_v	[lx = lm/m^2] (lux)	Luminosity (e.g. illumination on a desk)
Intensity	dQ/dωdt	I_v	[cd = lm/sr] (candela)	Luminous intensity (e.g. intensity of a point light)
	dQ/dAdωdt	L_v	[lm/(m^2·sr)] (nits)	Luminance (e.g. brightness of a monitor)

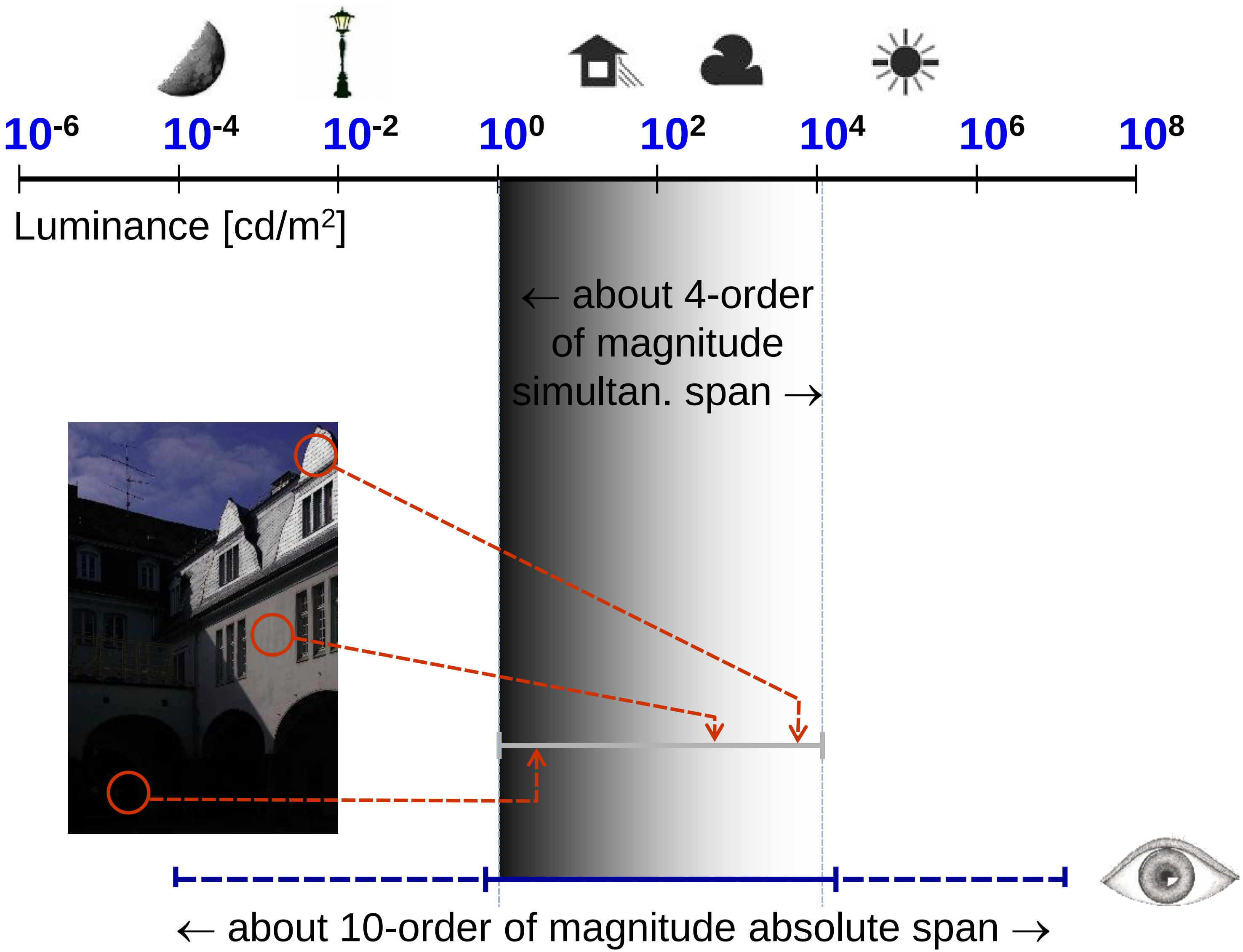
With luminous efficiency function weighted units

Illumination: Examples

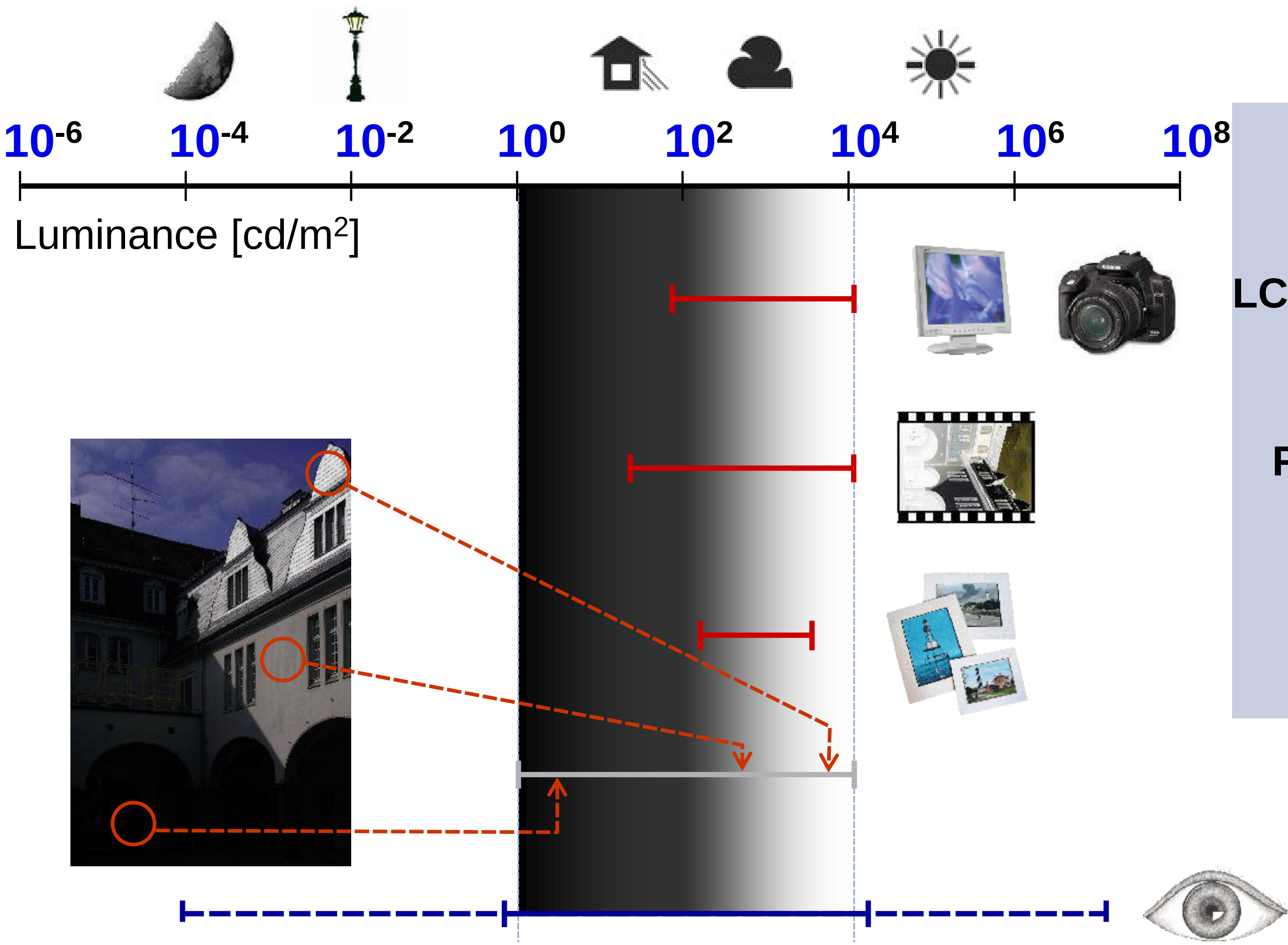
- **Typical illumination intensities**

Light source	**Illuminance [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

Luminance Range



Contrast (Dynamic Range)



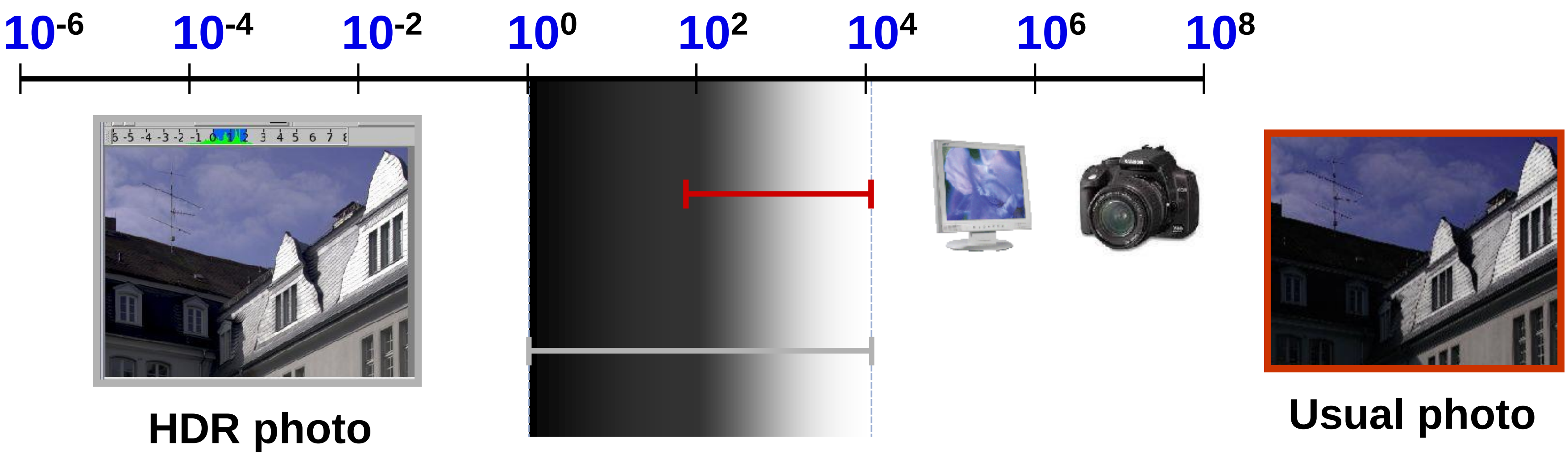
Dynamic range

LCD/CCD: 1:500

Film: 1:1500

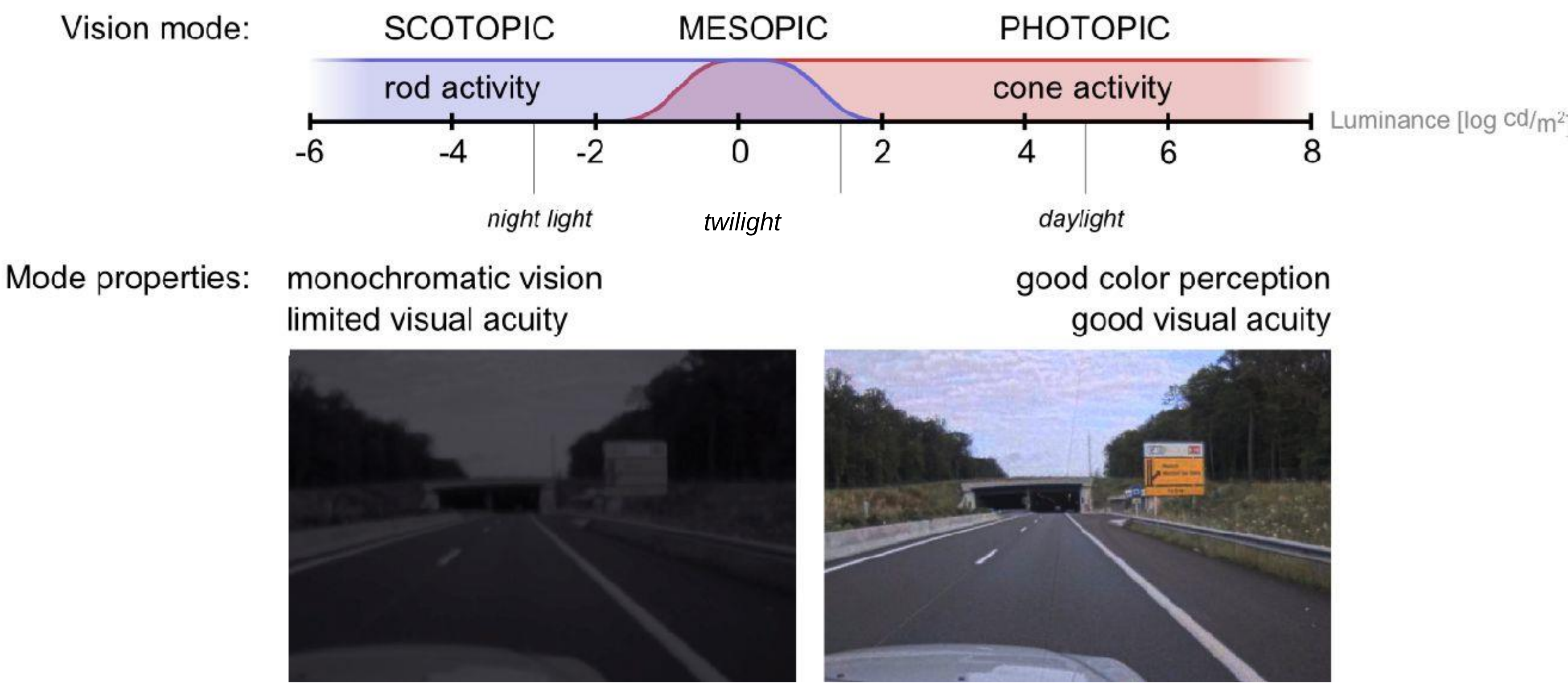
Print: 1:30

High Dynamic Range (HDR)



- **How to display computed/measured HDR values on an LDR device ?**
  - Tone mapping

Percept. Effects: Vision Modes

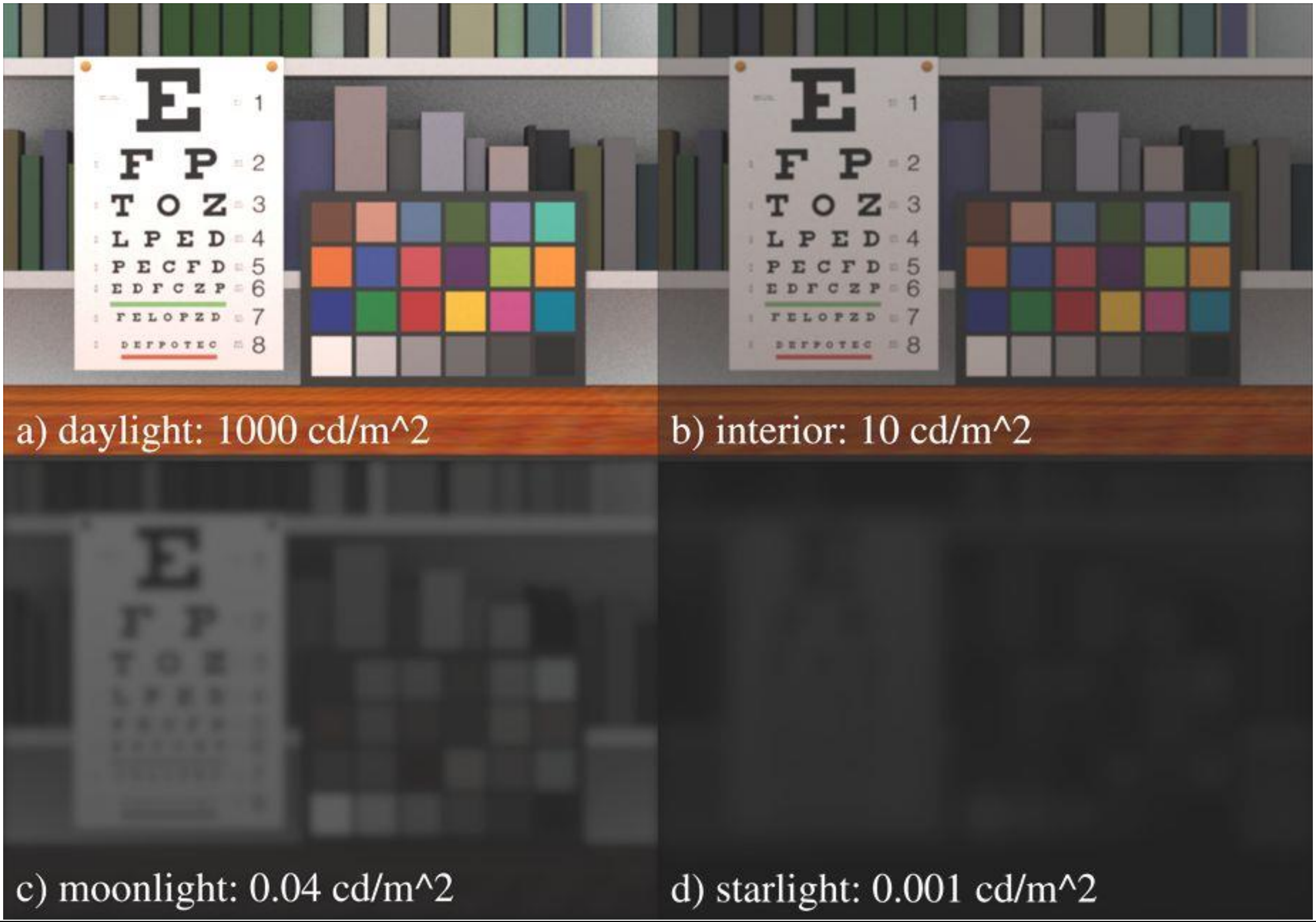


- **Simulation requires:**
  - Control over color reproduction
  - Local reduction of detail visibility (computationally expensive)

Visual Acuity and Color Perception

Photopic vision

Mesopic/photopic transition

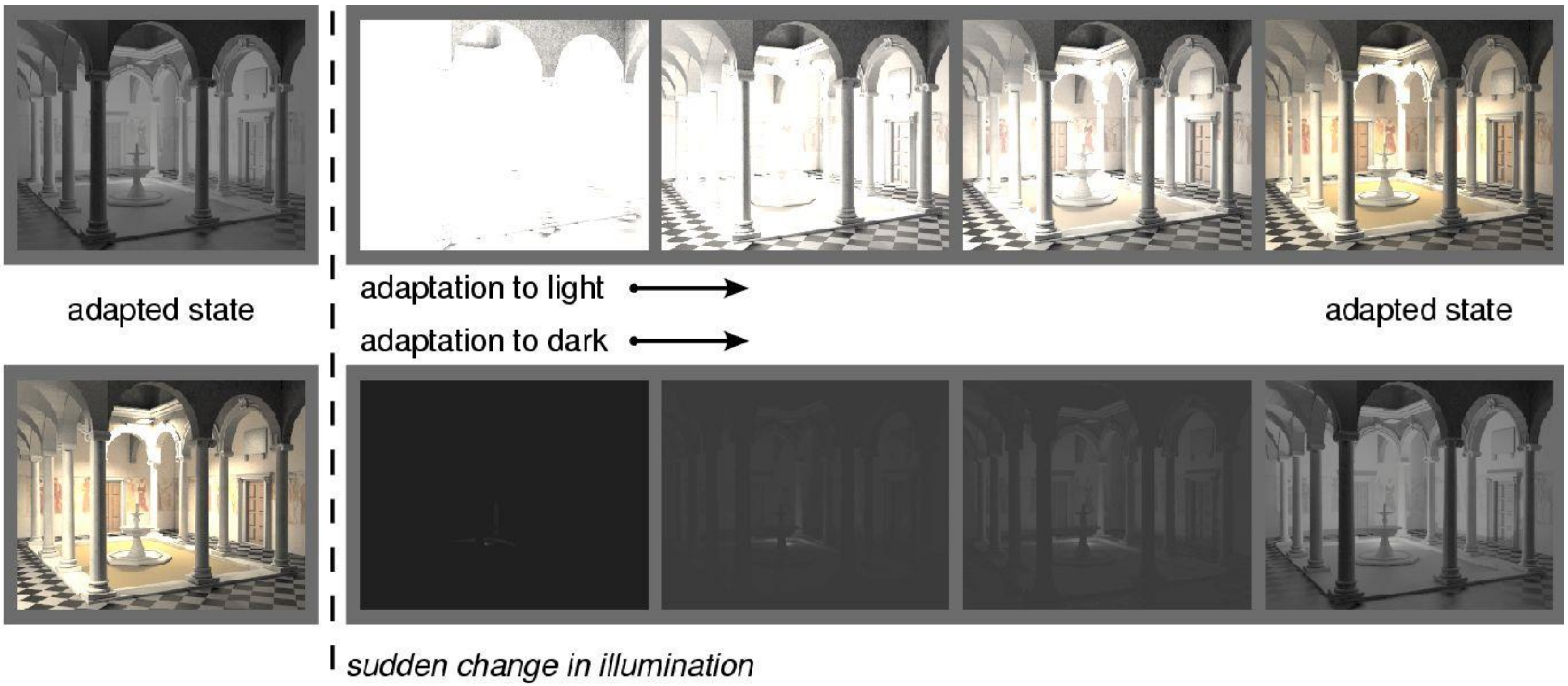


Scotopic/mesopic transition

Scotopic vision

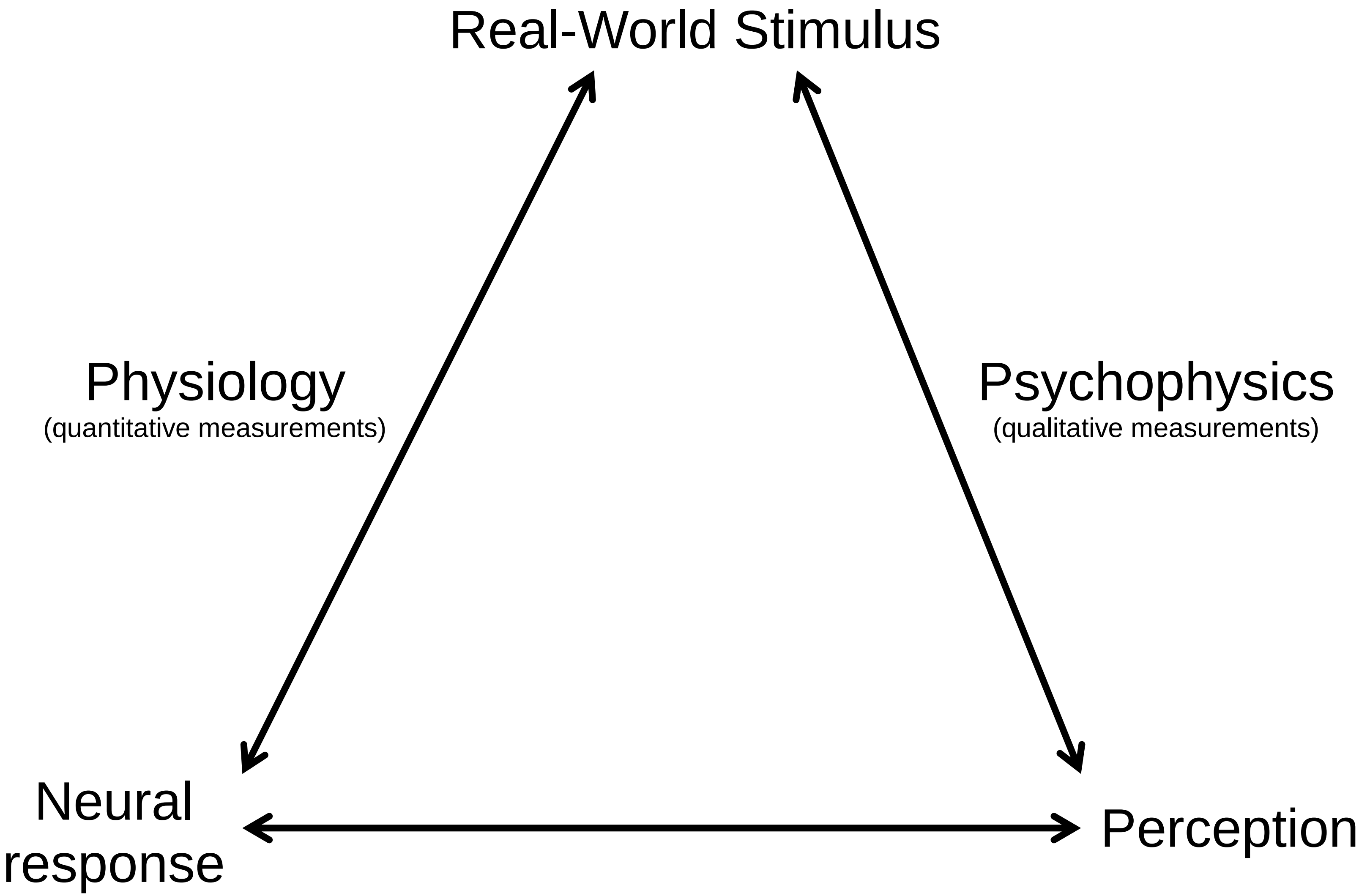
Percept. Effects: Temp. Adaptati.

- **Adaptation to dark much slower**



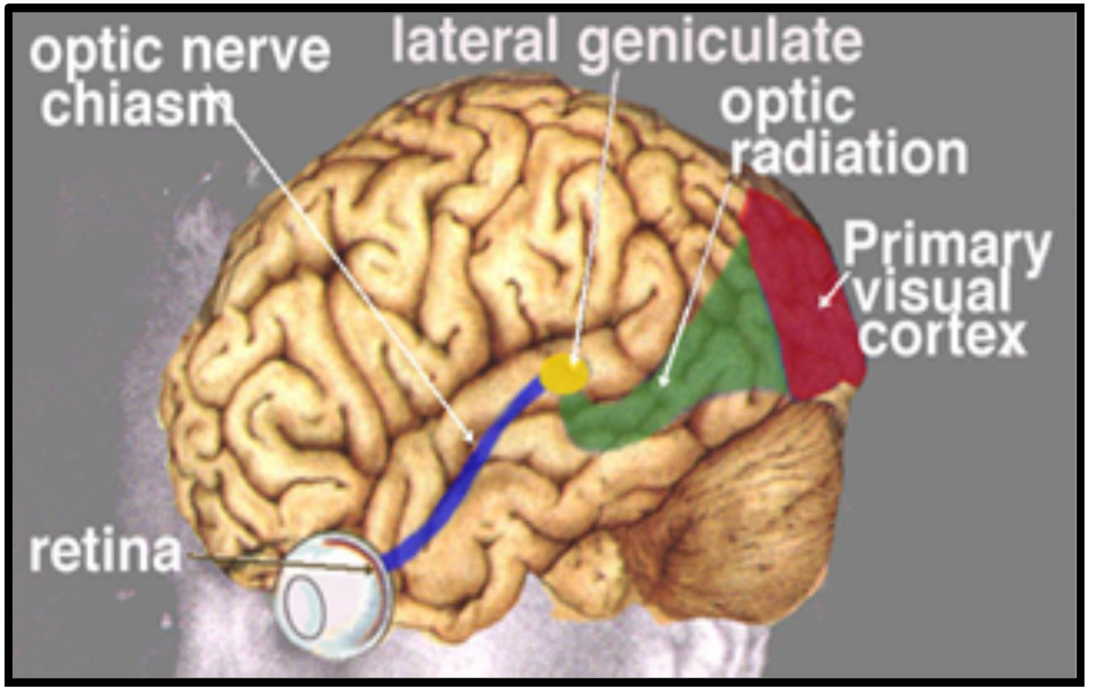
- **Simulation requires:**
  - Time-dependent filtering of light adaptation

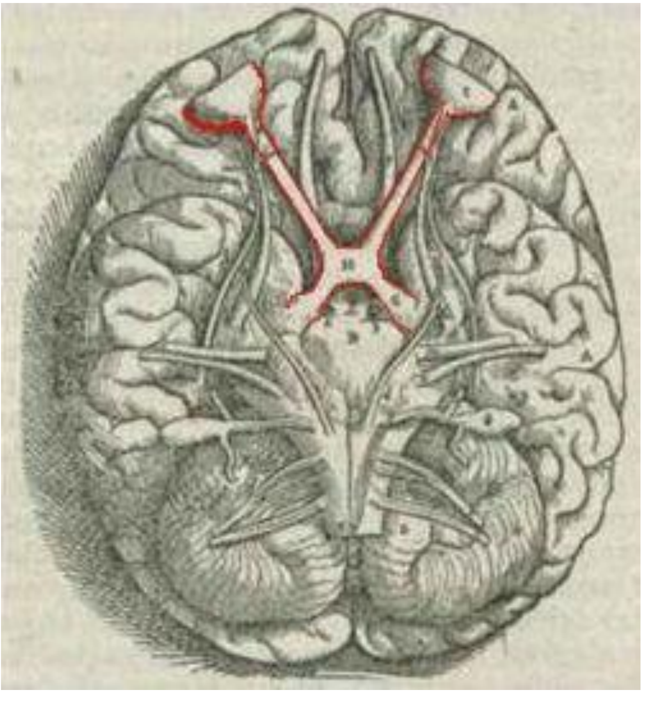
HVS - Relationships



Human Visual System

- **Physical structure well established**
- **Percept. behavior complex & less understood process**

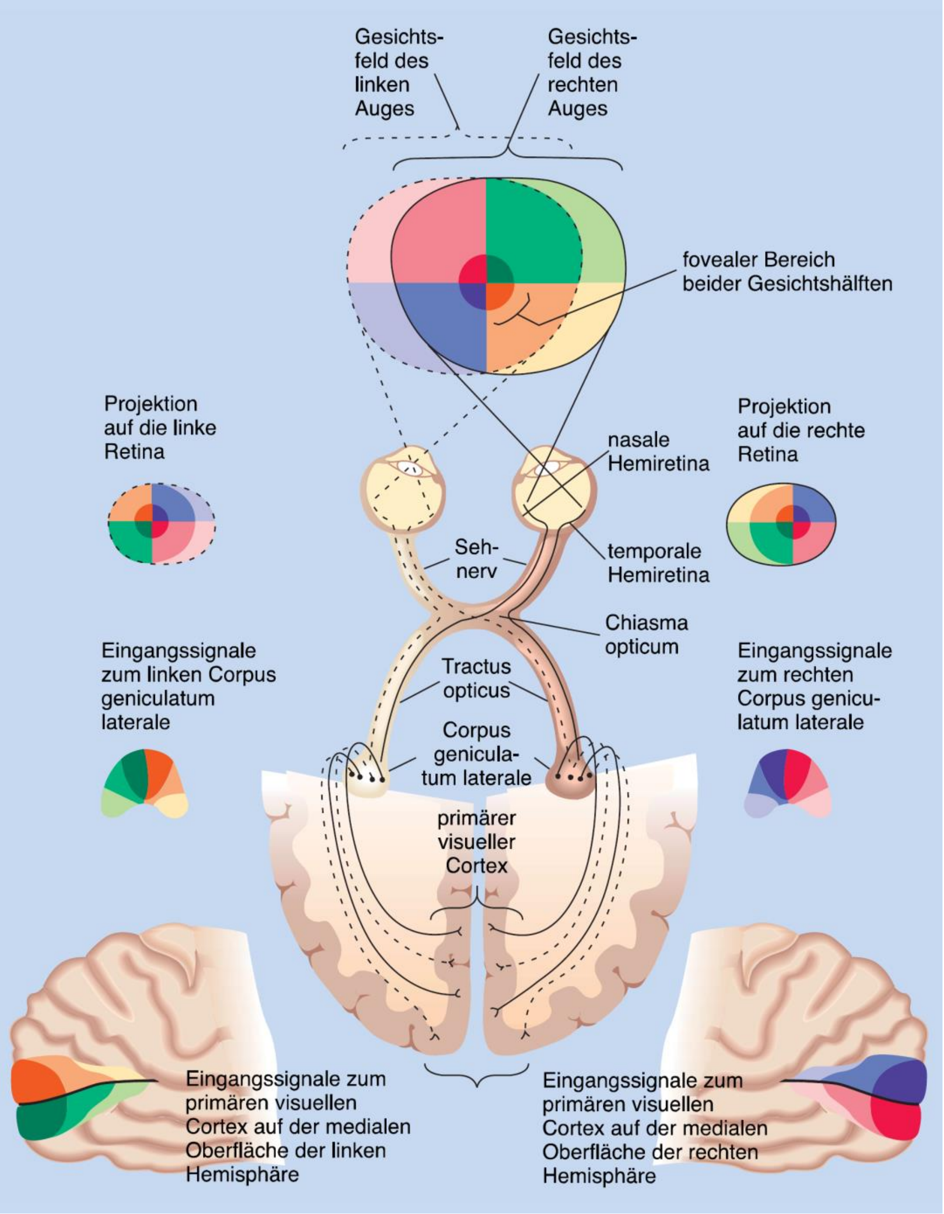




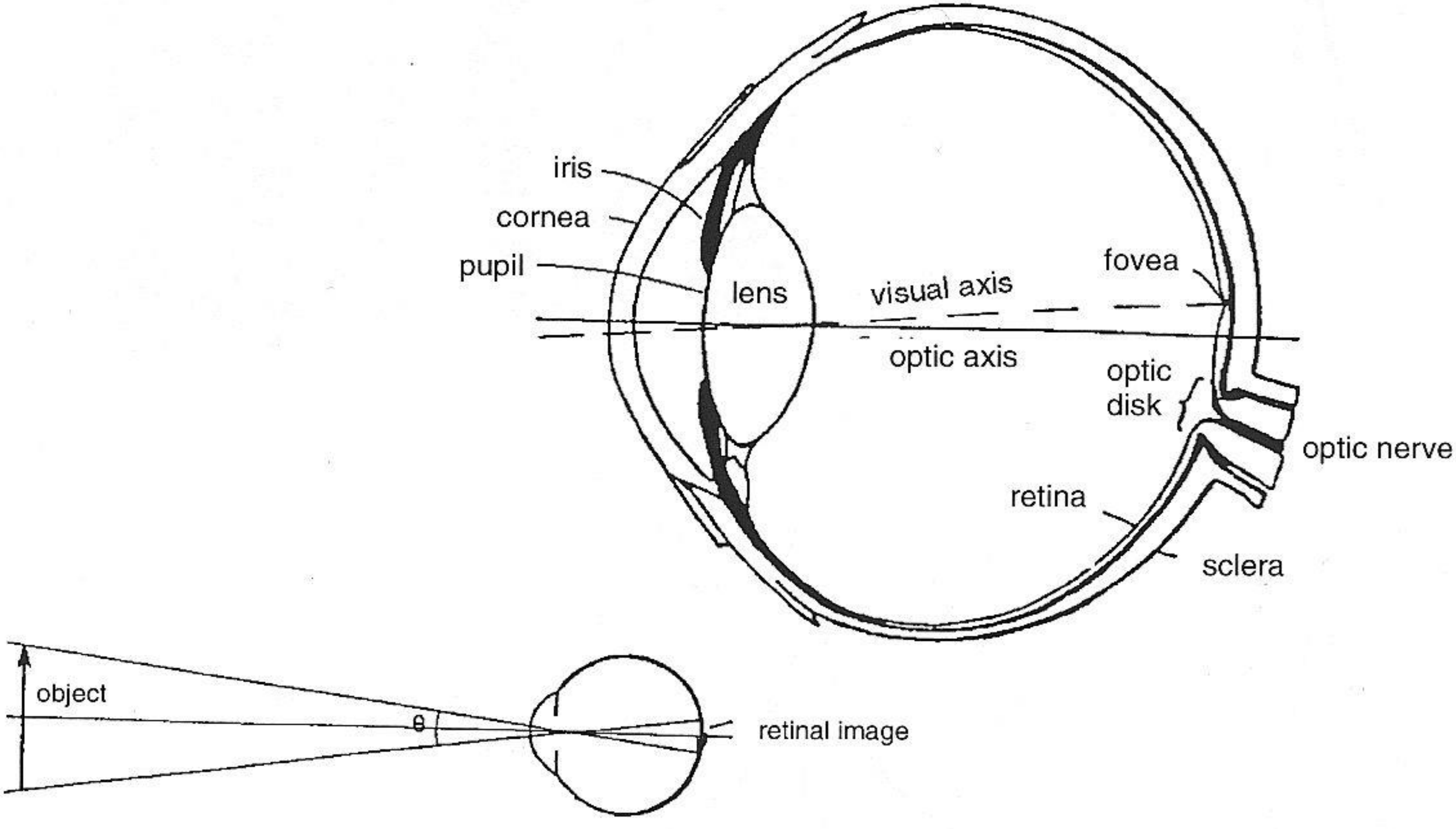
Optic chiasm

Optical Chiasm

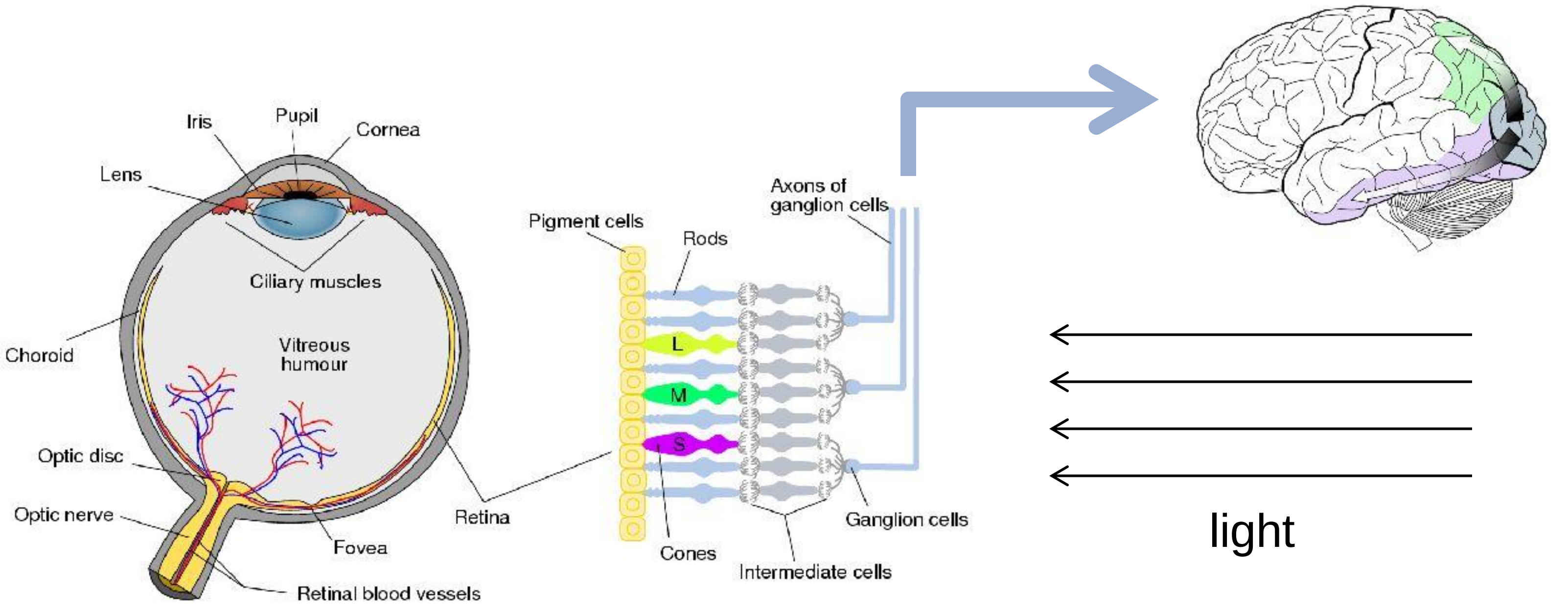
- **Right half of the brain operates on left half of the field of view**
  - From both eyes!!
- **And vice versa**
  - Damage to one half of the brain can results in loss of one half of the field of view



Perception and Eye



Human Visual Perception



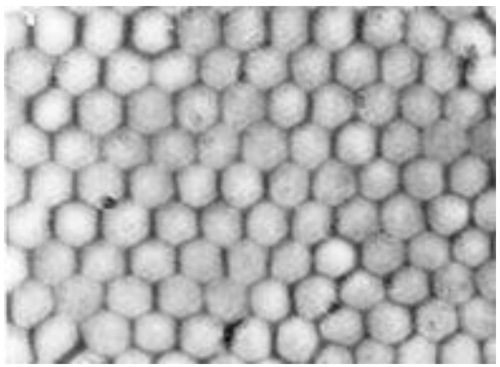
early vision (eyes)

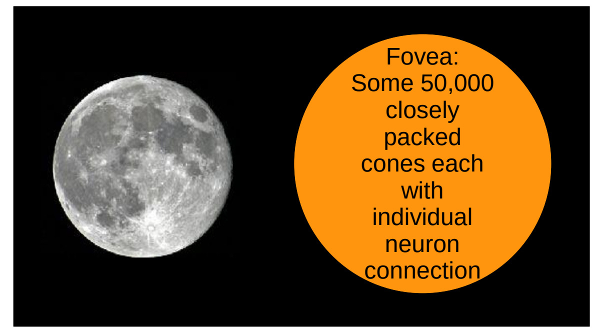
- **Determines how real-world scenes appear to us**
- **Understanding of visual perception is necessary to reproduce appearance, e.g. in tone mapping**

Distribution of Rods and Cones

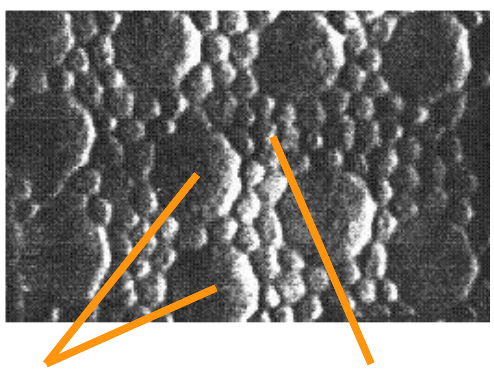
- **High-res. foveal region with highest cone density**
- **Poisson-disc-like distribution**

Cone mosaic in fovea which subtends small solid angle



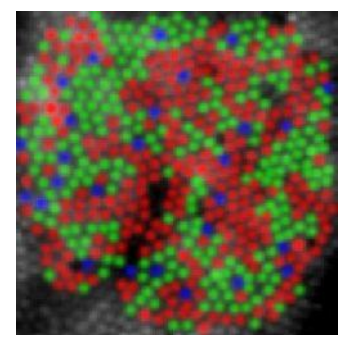


Cone mosaic in periphery with almost 180° field of view



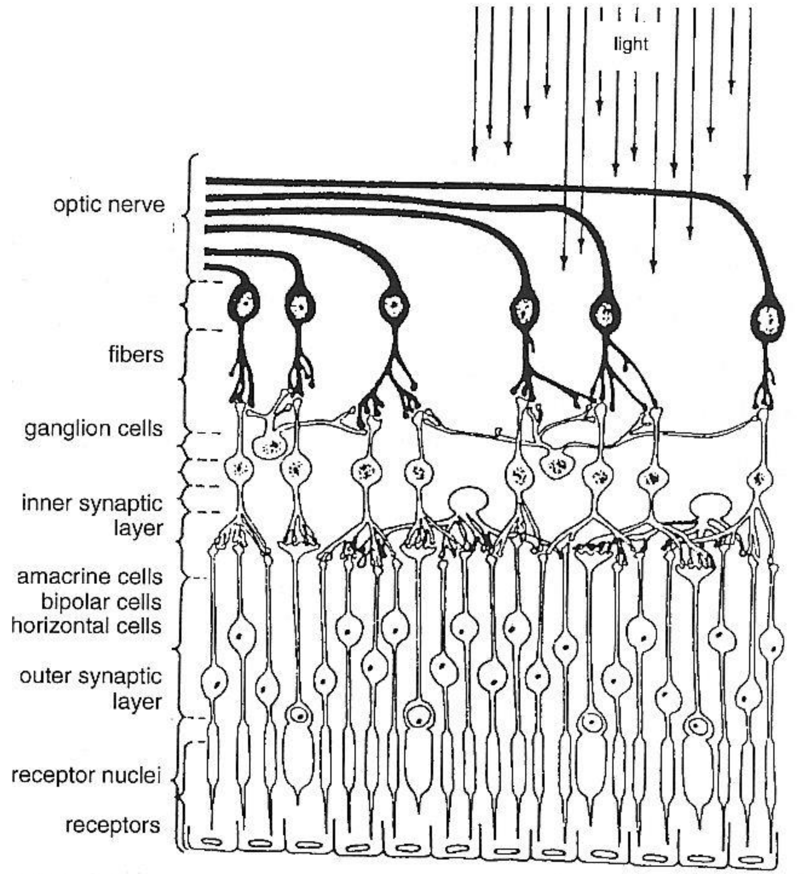
Cones Rods

L-cones
~
M-cones
>>
S-cones



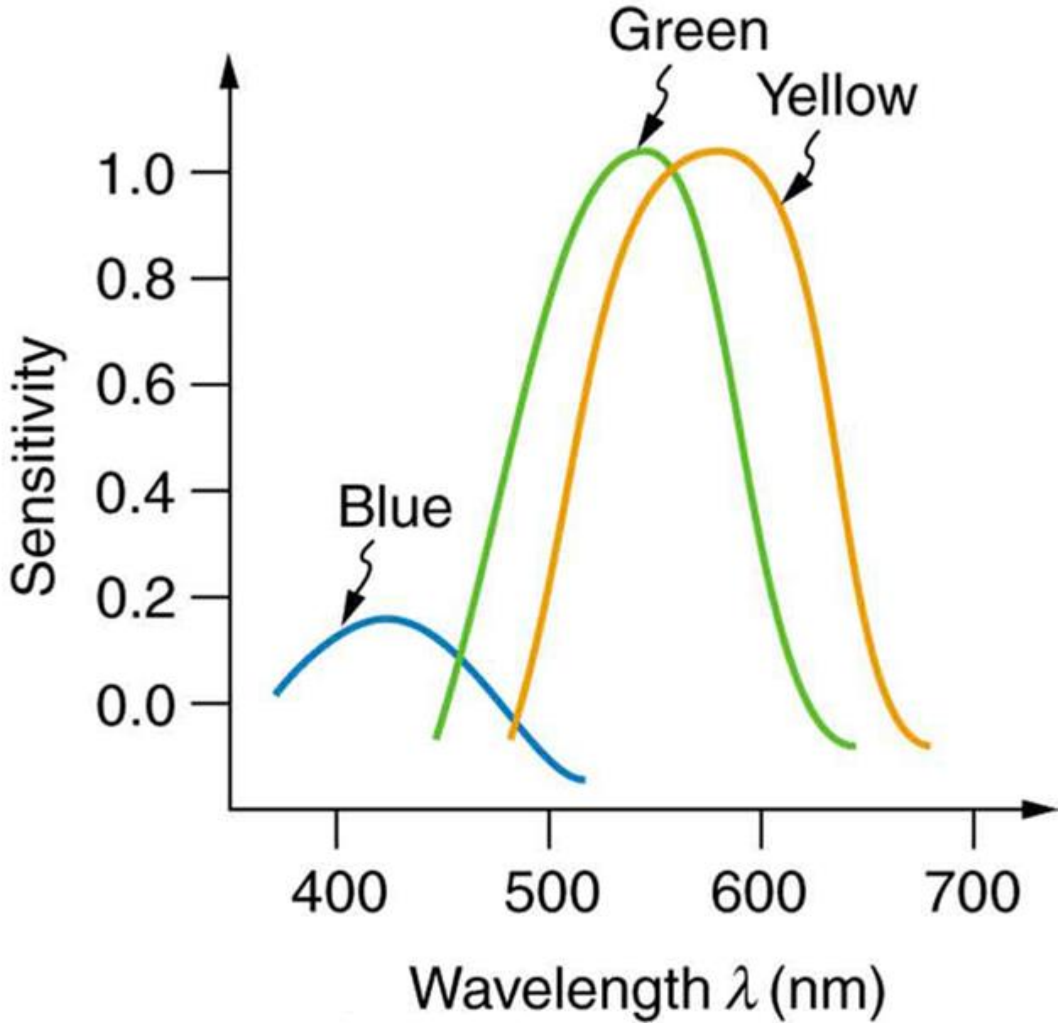
Retina

- **Receptors on opposite side of incoming light**
- **Early cellular processing between receptors & nerves**
  - Mainly for rods



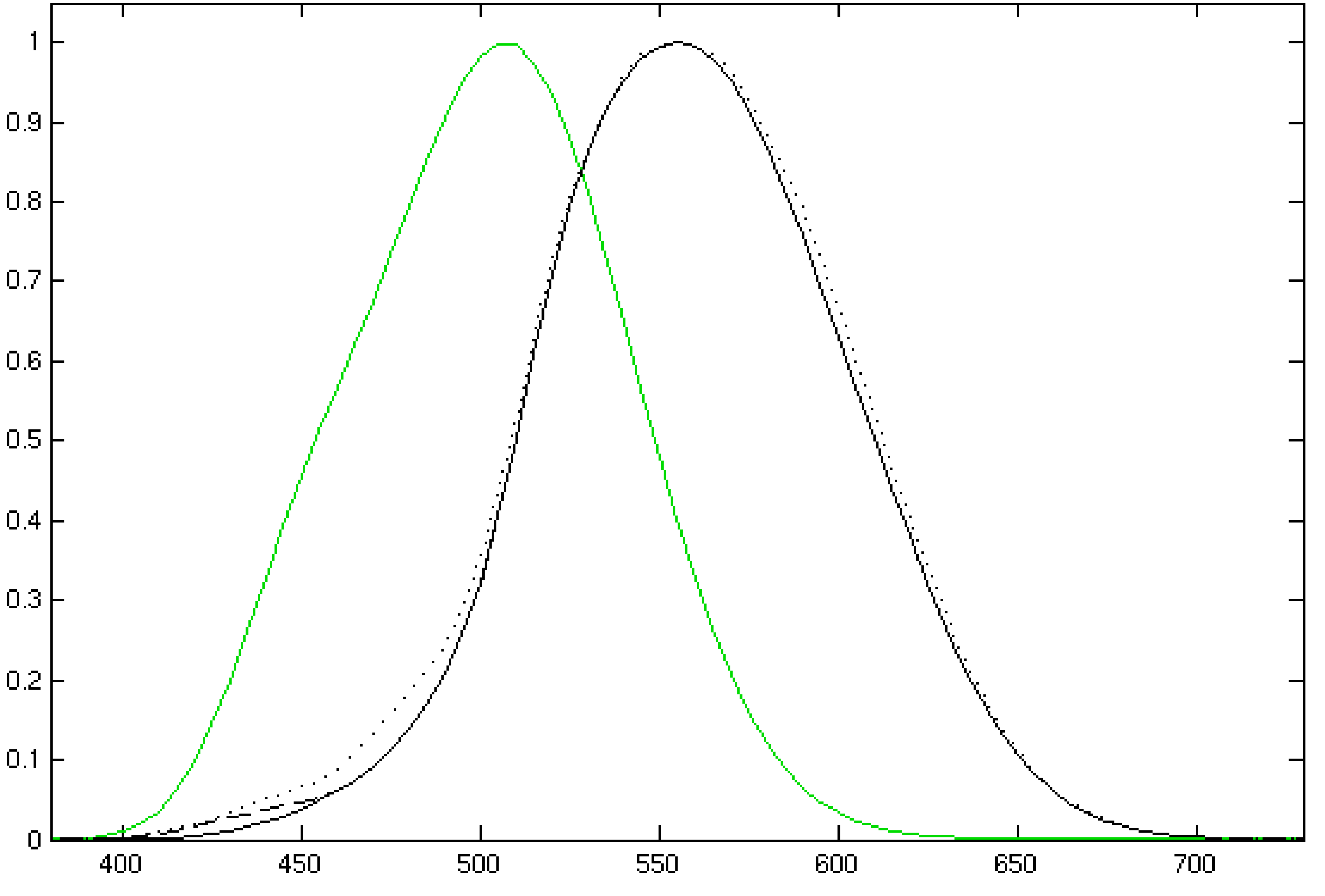
Eye as a Sensor

- **Relative sensitivity of cones**



Luminuous Sensitivity Function

- **Different for cones (black, diff. studies) & rods (green)**



Eye

- **Fovea (centralis):**
  - Ø 1-2 visual degrees
  - 50,000 cones each of ~ 0.5 arcminutes angle and ~2.5 μm wide
  - No rods in central fovea, but three different cone types:
    - L(ong, 64%), M(edium, 32%), S(hort wavelength, 4%)

    ⇒ Varying resolution: 10 arcminutes for S vs. 0.5 arcminutes for L & M
  - Linked directly 1:1 with optical nerves,
    - 1% of retina area but covers 50% visual cortex in brain
  - Adaptation of light intensity only through cones
- **Periphery:**
  - 75-150 M. rods: night vision (B/W)
  - 5-7 M. cones (color)
  - Response to stimulation by single 1 photons (@ 500 nm)
    - 100x better than cones, integrating over 100 ms
  - Signals from many rods are combined before linking 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

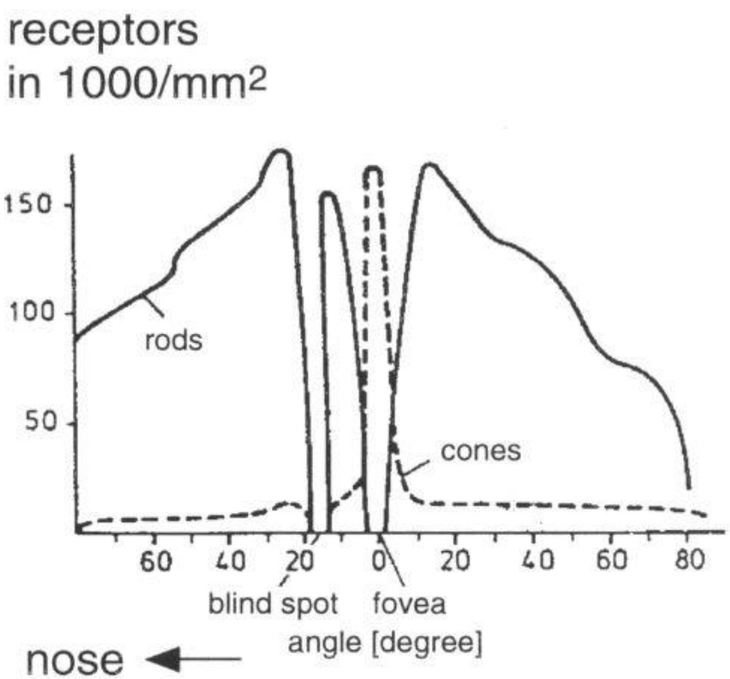
This is a text in blue

This is a text in red

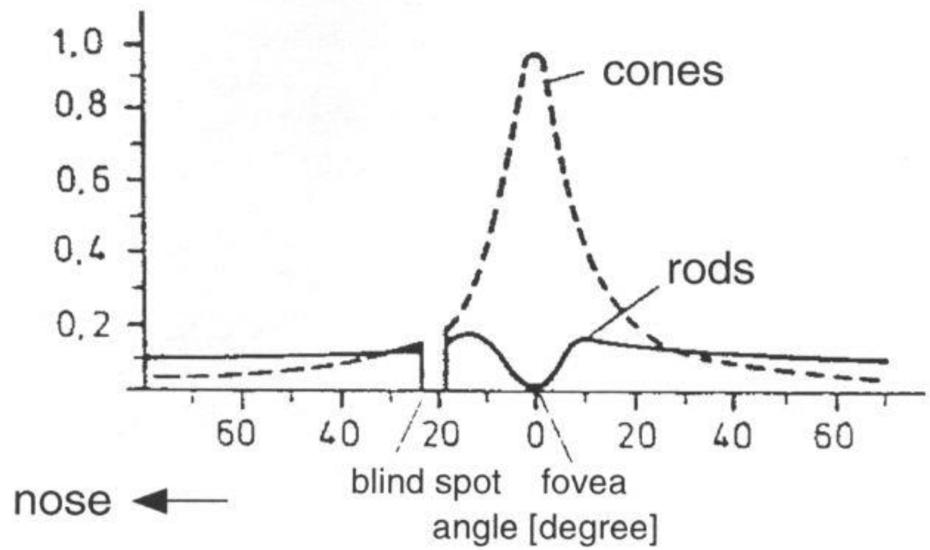
This is a text in green

This is a test in blue

Visual Acuity



Receptor density



Resolution in line-pairs/arcminute

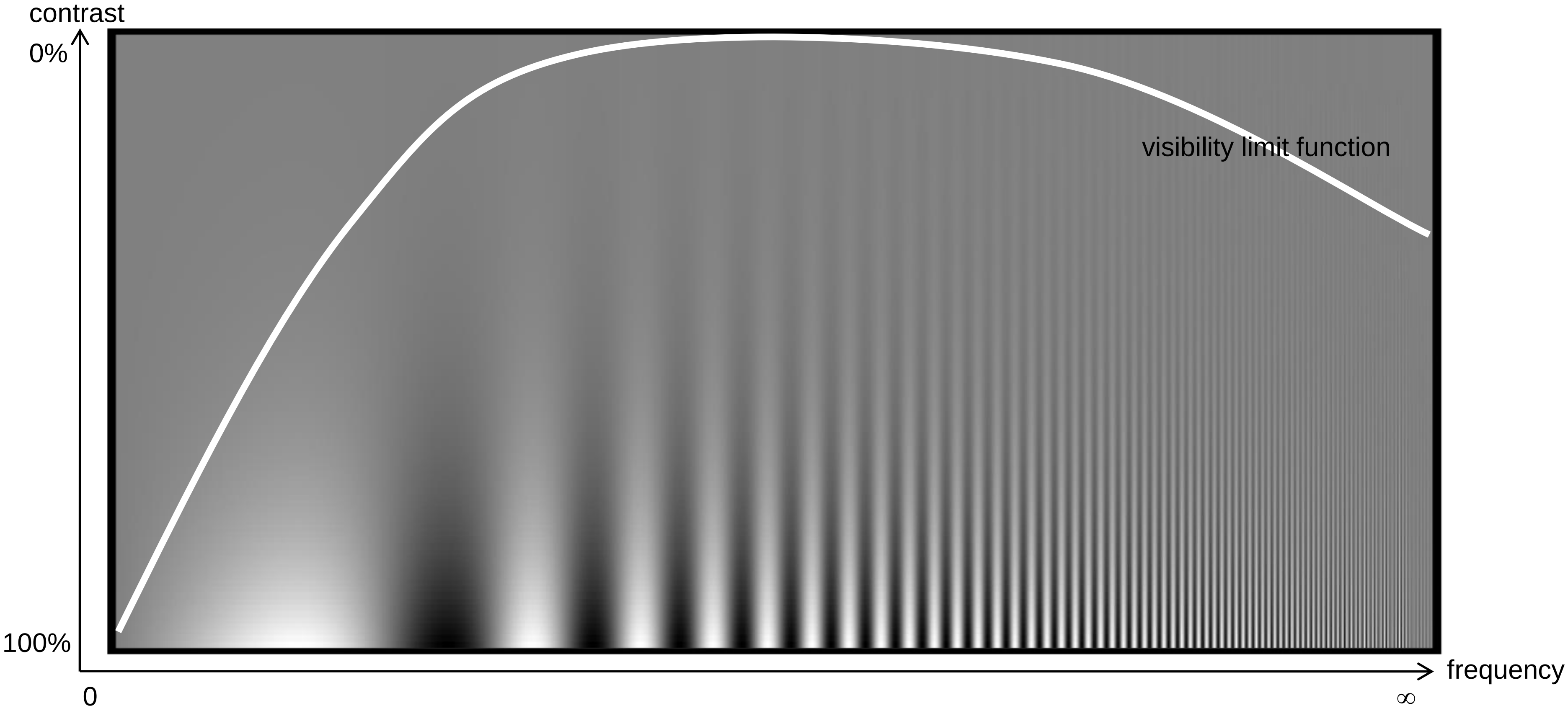
Resolution of the Eye

- **Resolution-experiments**
  - Line pairs: eye ~ 50-60 p./degree → resolution of 0.5 arcminutes
  - Line offset: 5 arcseconds (hyperacuity)

  - Eye micro-tremor: 60-100 Hz, 5 µm (2-3 photoreceptor spacing)
    - Allows to reconstruct from super-resolution (w/ Poisson pattern)
  - Together corresponds to 19” display at 60 cm away from viewer: $18{,}000^2$ pixels with hyperacuity - $3{,}000^2$ without hyperacuity
- **Fixation of eye onto (moving) region of interest**
  - Automatic gaze tracking, autom. compensation of head movement
  - Apparent overall high resolution of fovea
- **Visual acuity increased by**
  - Brighter objects
  - High contrast

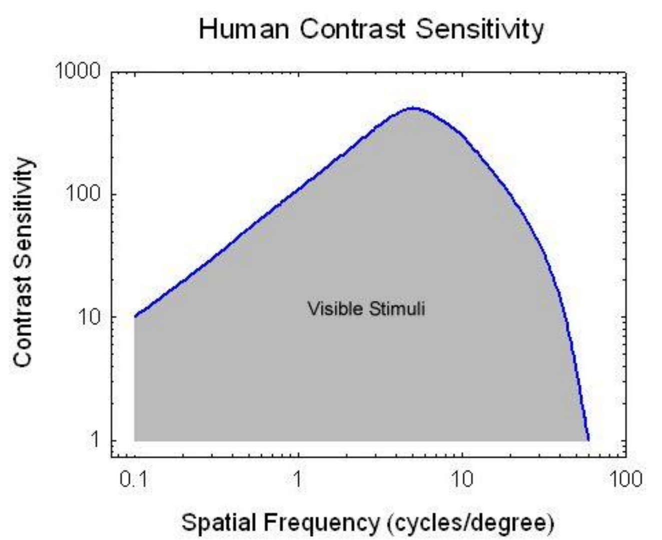
Poisson-Disk Experiment

- **Human visual system**
  - Perception very sensitive to regular structures
  - Insensitive against (high-frequency) noise
  - Campbell-Robson sinusoidal contrast sensitivity chart



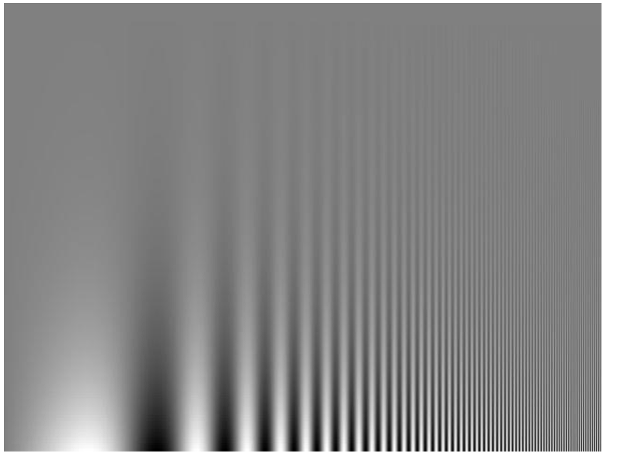
Luminance Contrast Sensitivity

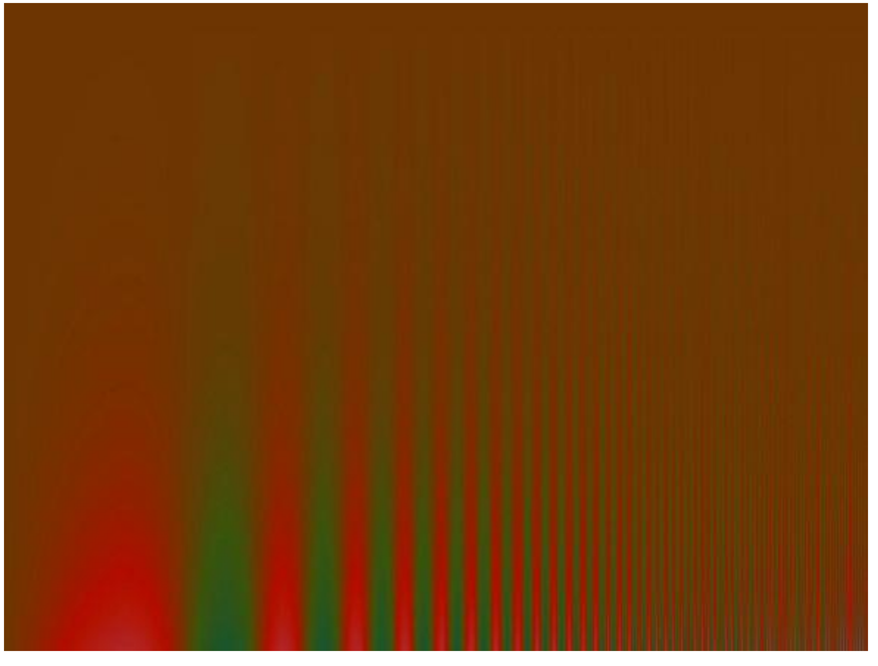
- **Sensitivity: inverse of perceptible contrast threshold**
- **Maximum acuity at 5 cycles/degree (0.2 %)**
  - Decrease toward low frequencies: lateral inhibition
  - Decrease toward high frequencies: sampling rate (Poisson disk)
  - Upper limit: 60 cycles/degree
- **Medical diagnosis**
  - Glaucoma (affects peripheral vision: low frequencies)
  - Multiple sclerosis (affects optical nerve: notches in contrast sensitivity)

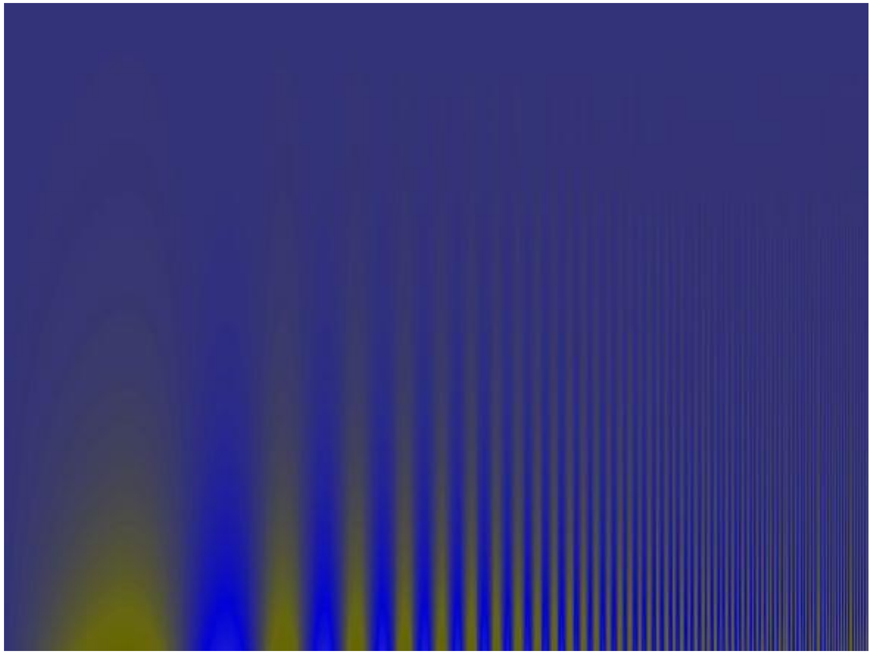


Color Contrast Sensitivity

- **Color vs. luminance vision system**
  - Similar but slightly different curves
  - Higher sensitivity at lower frequencies
  - High frequencies less visible
- **Image compression**
  - Exploit color sensitivity in lossy compr.

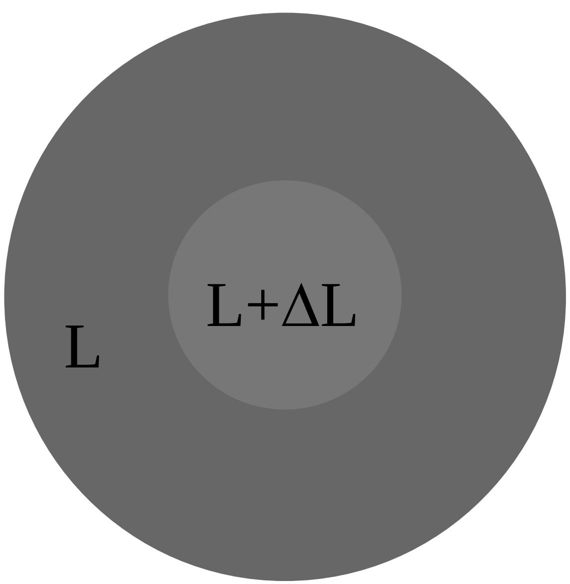




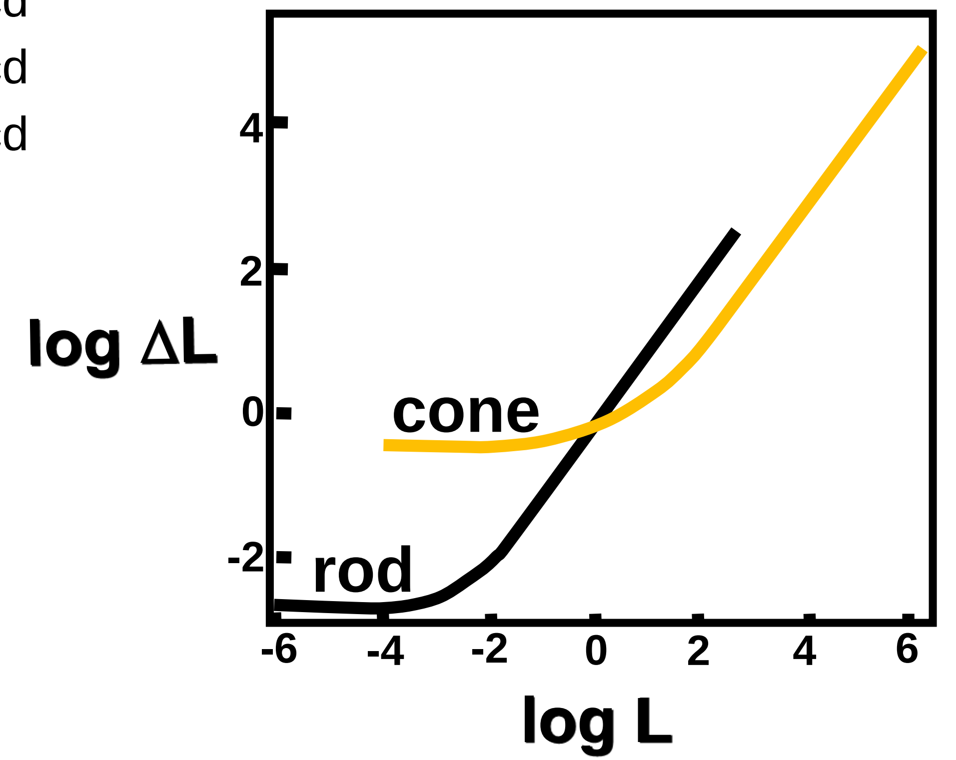


Threshold Sensitivity Function

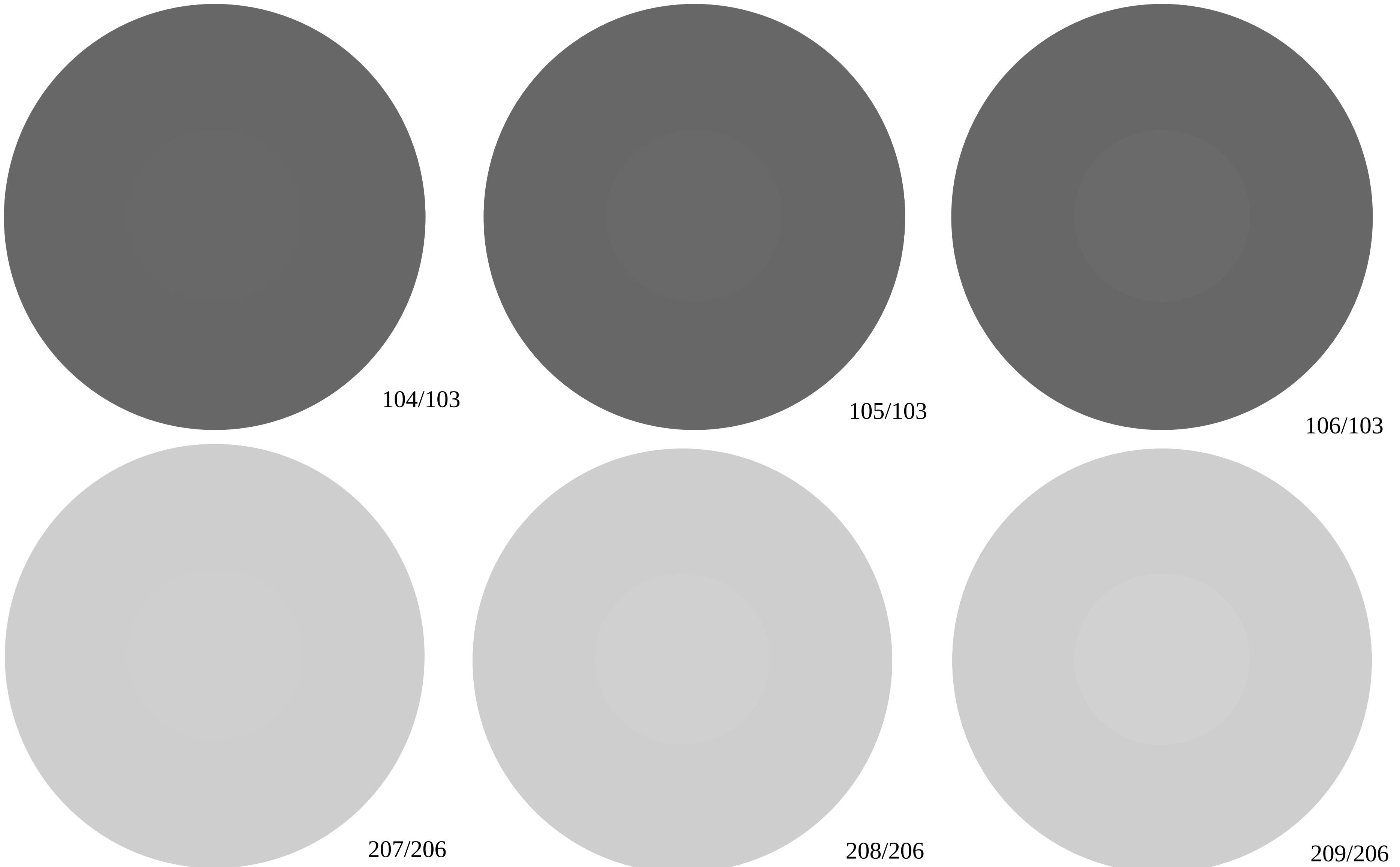
- **Weber-Fechner law (Threshold Versus Intensity, TVI)**
  - Perceived brightness varies linearly with log(radiant intensity)
    - $E = K + c \log I$
  - Perceivable intensity difference
    - 10 cd vs. 12 cd: ΔL = 2 cd
    - 20 cd vs. 24 cd: ΔL = 4 cd
    - 30 cd vs. 36 cd: ΔL = 6 cd



TVI function

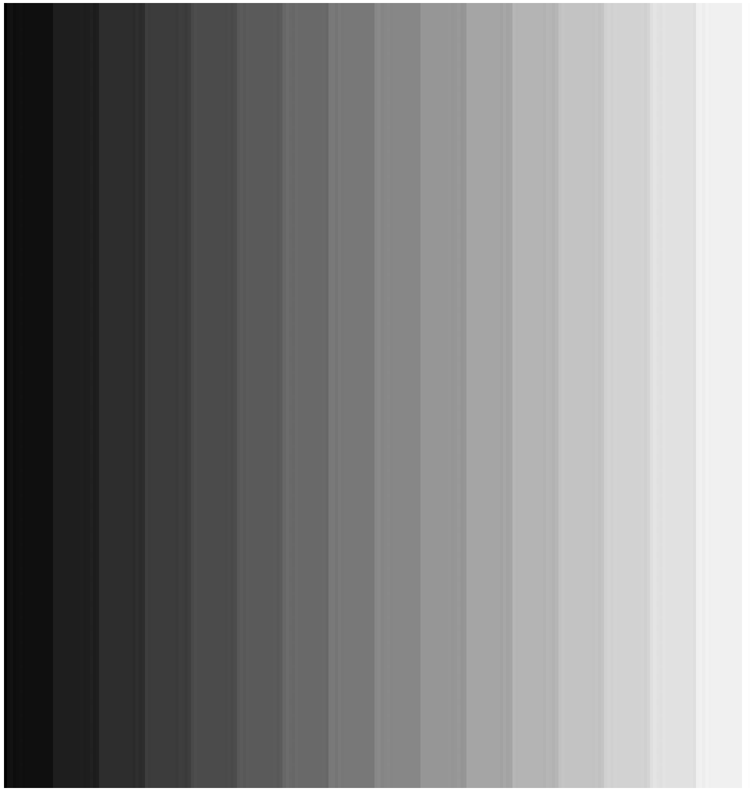


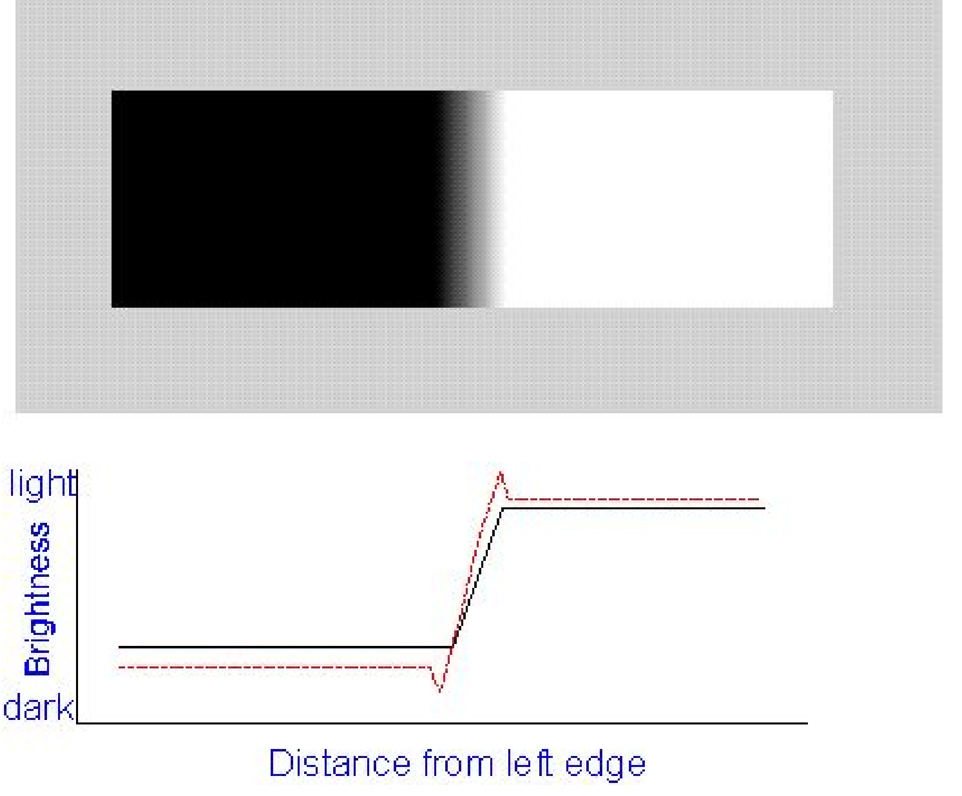
Weber-Fechner Examples



Mach Bands

- **"Overshooting" along edges**
  - Extra-bright rims on bright sides
  - Extra-dark rims on dark sides
- **Due to "lateral inhibition"**





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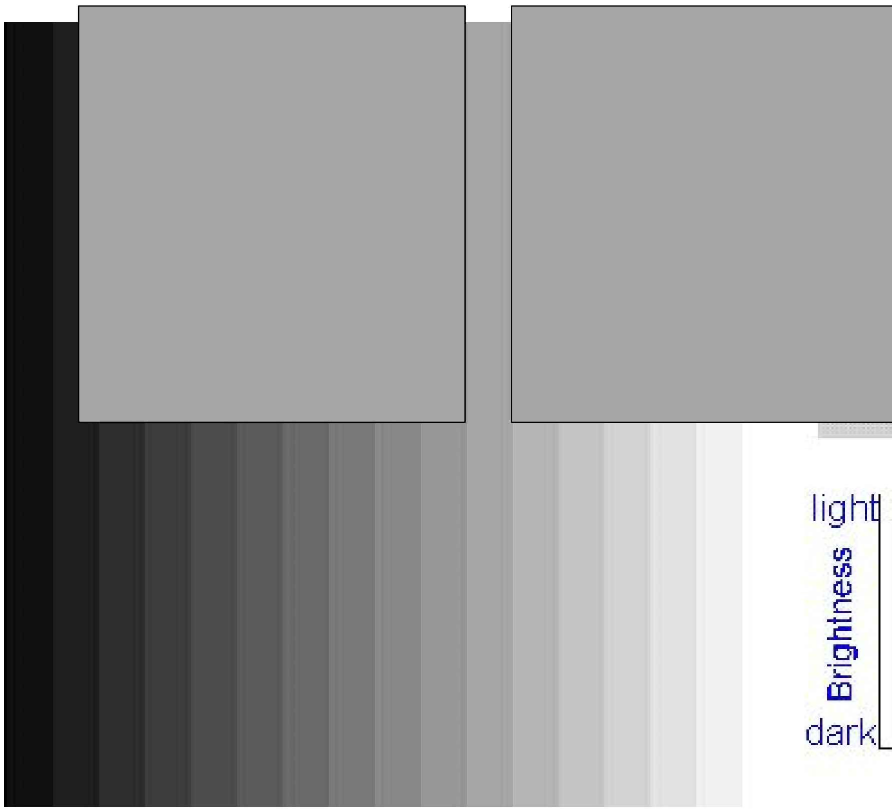
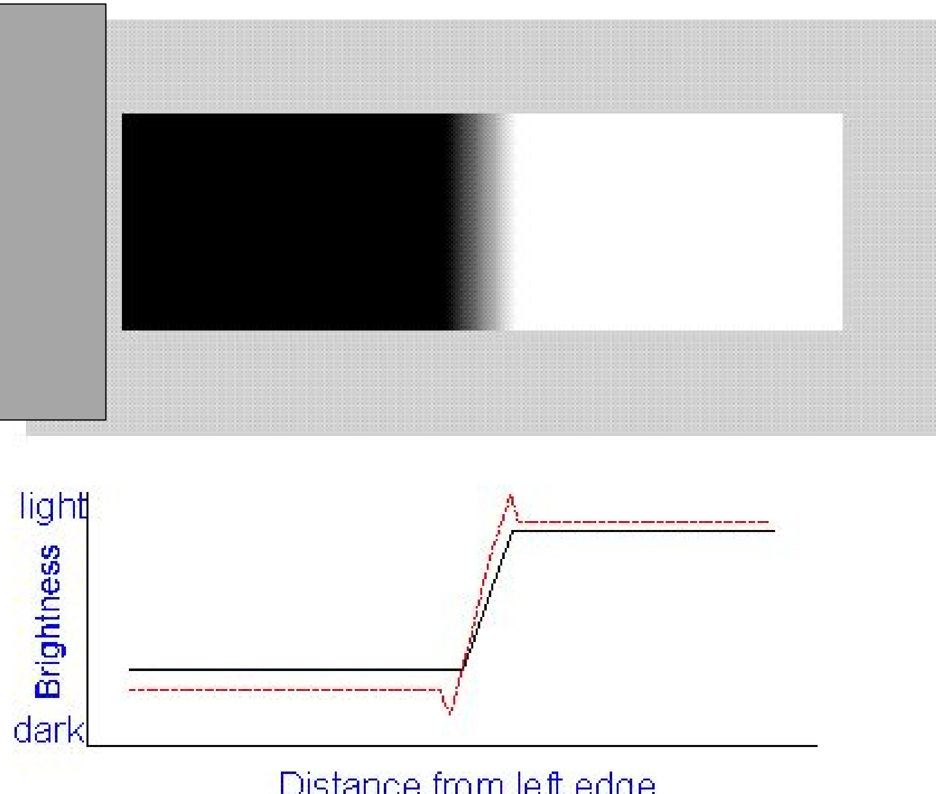
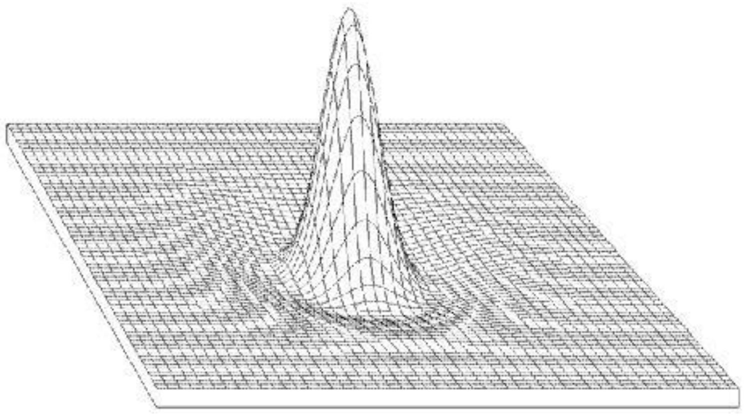
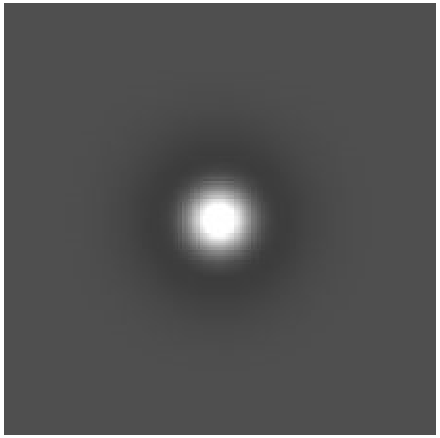


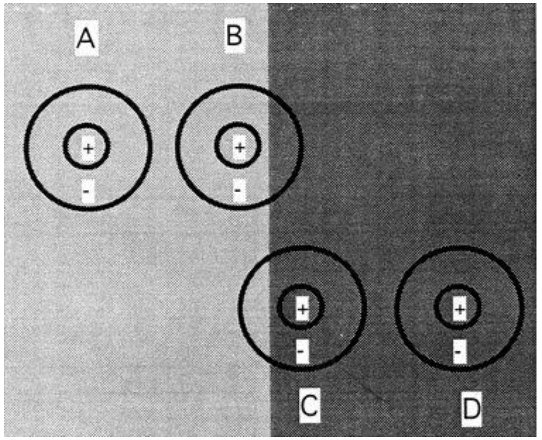


Lateral Inhibition

- **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 dark inhibition
    - C: low stimulus, increased inhibition → weaker response
- **High-pass filter**
  - Enhances contrast along edges
  - Differential operator (Laplacian/difference of Gaussian)

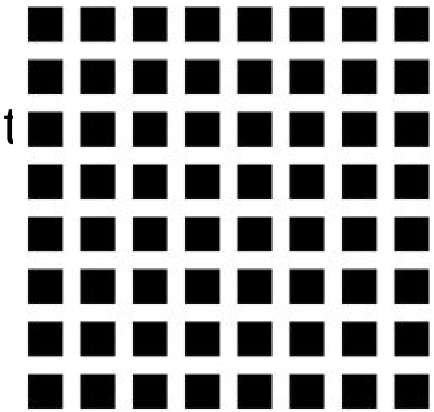


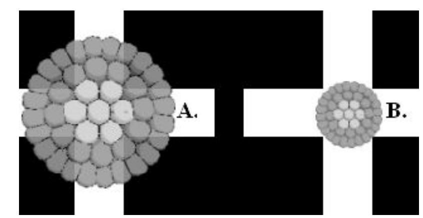




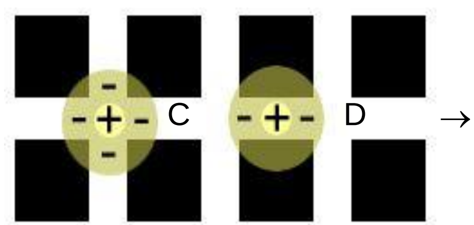
Lateral Inhibition: Hermann Grid

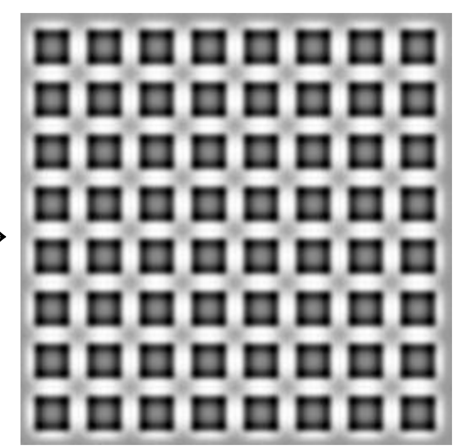
- **Apparent dark spots at perip. crossings**
  - Weakly if within foveal Ω (B): smaller filter extent
  - Strongly within periphery (A): larger filter extent
- **Explanation**
  - Crossings (C): more surround stimulation
    - More inhibition ⇒ weaker response
  - Streets (D): less surround stimulation
    - Less inhibition ⇒ greater response
- **Simulation**
  - Convolution with differential kernel
  - Darker at crossings, brighter in streets
  - Appears more steady
  - What if inversed colors ?



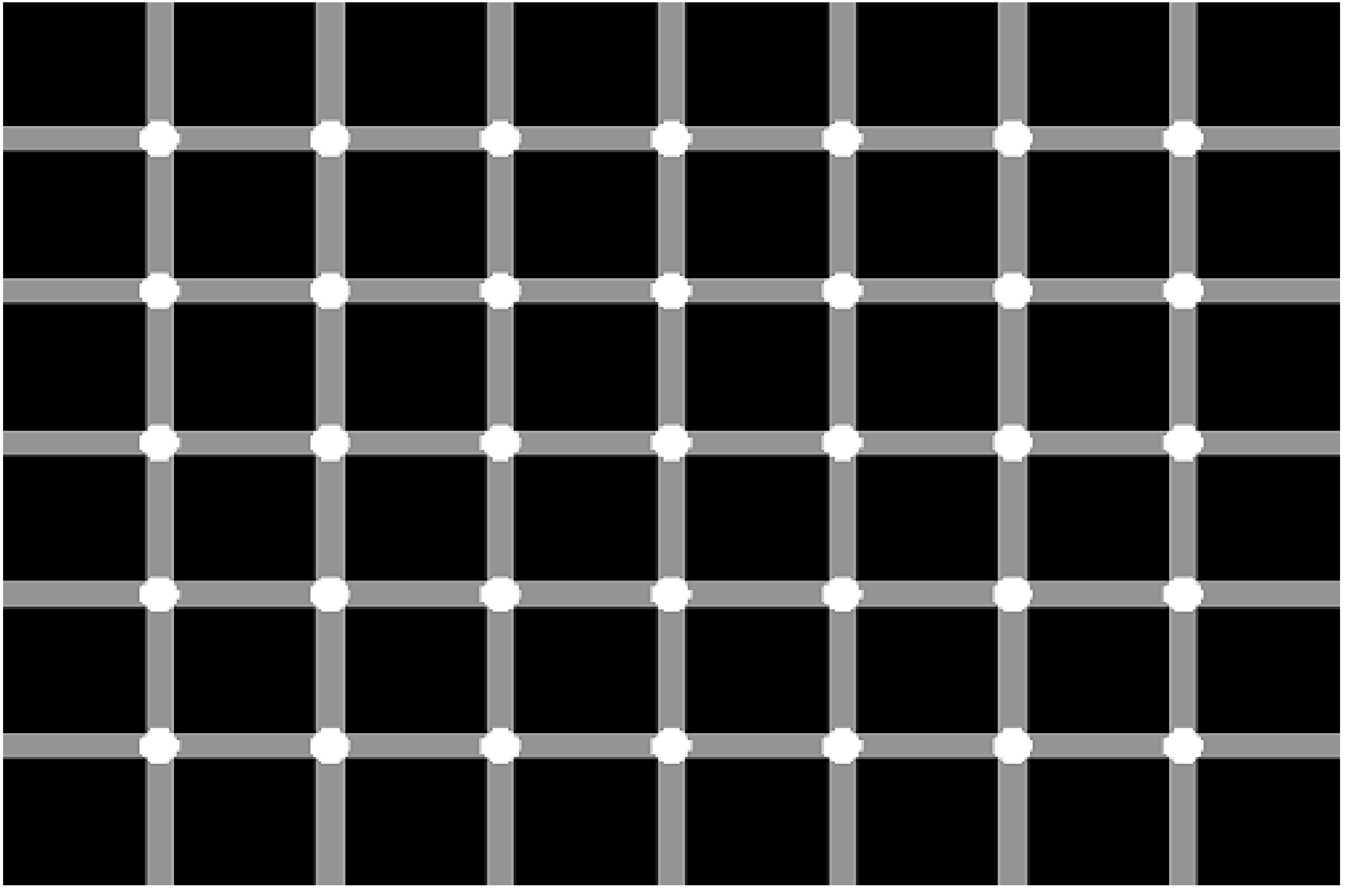


Periphery Fovea

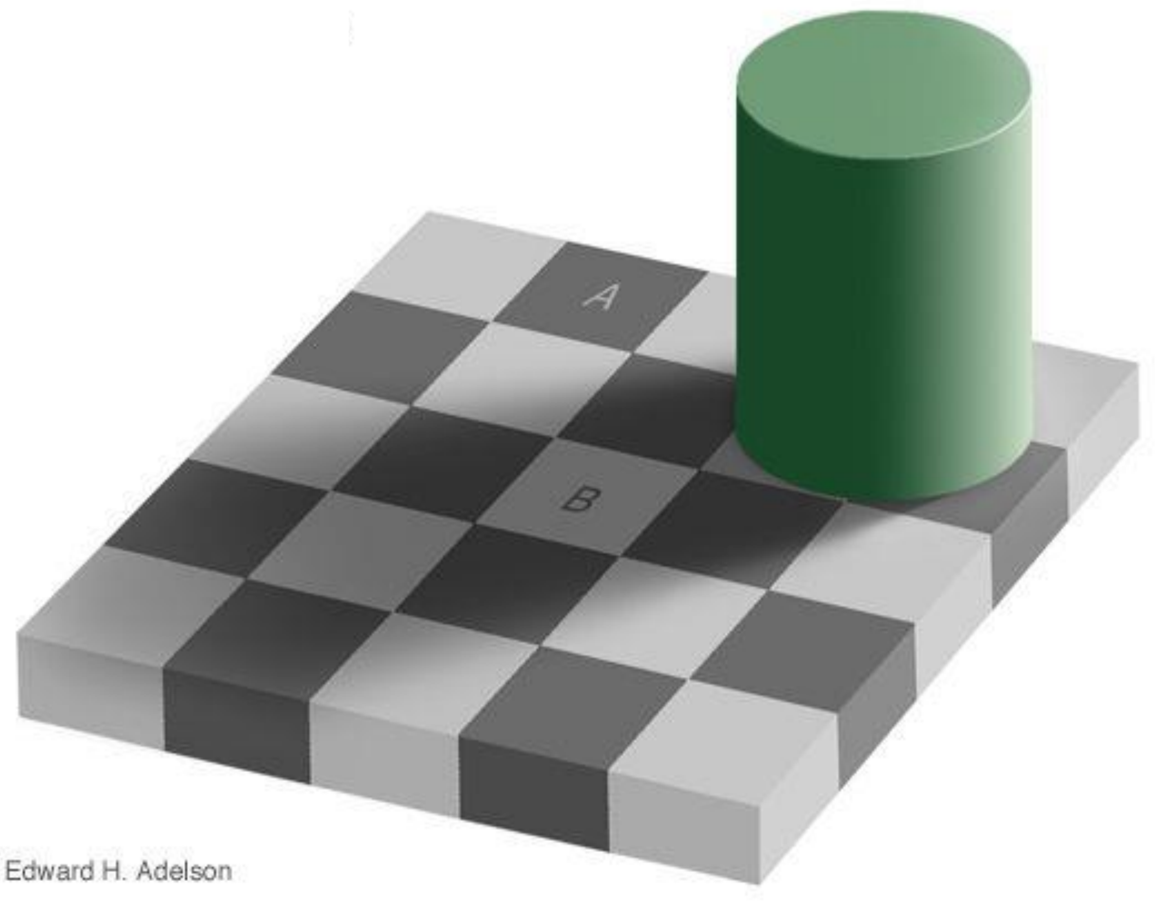




Some Further Weirdness



High-Level Contrast Processing



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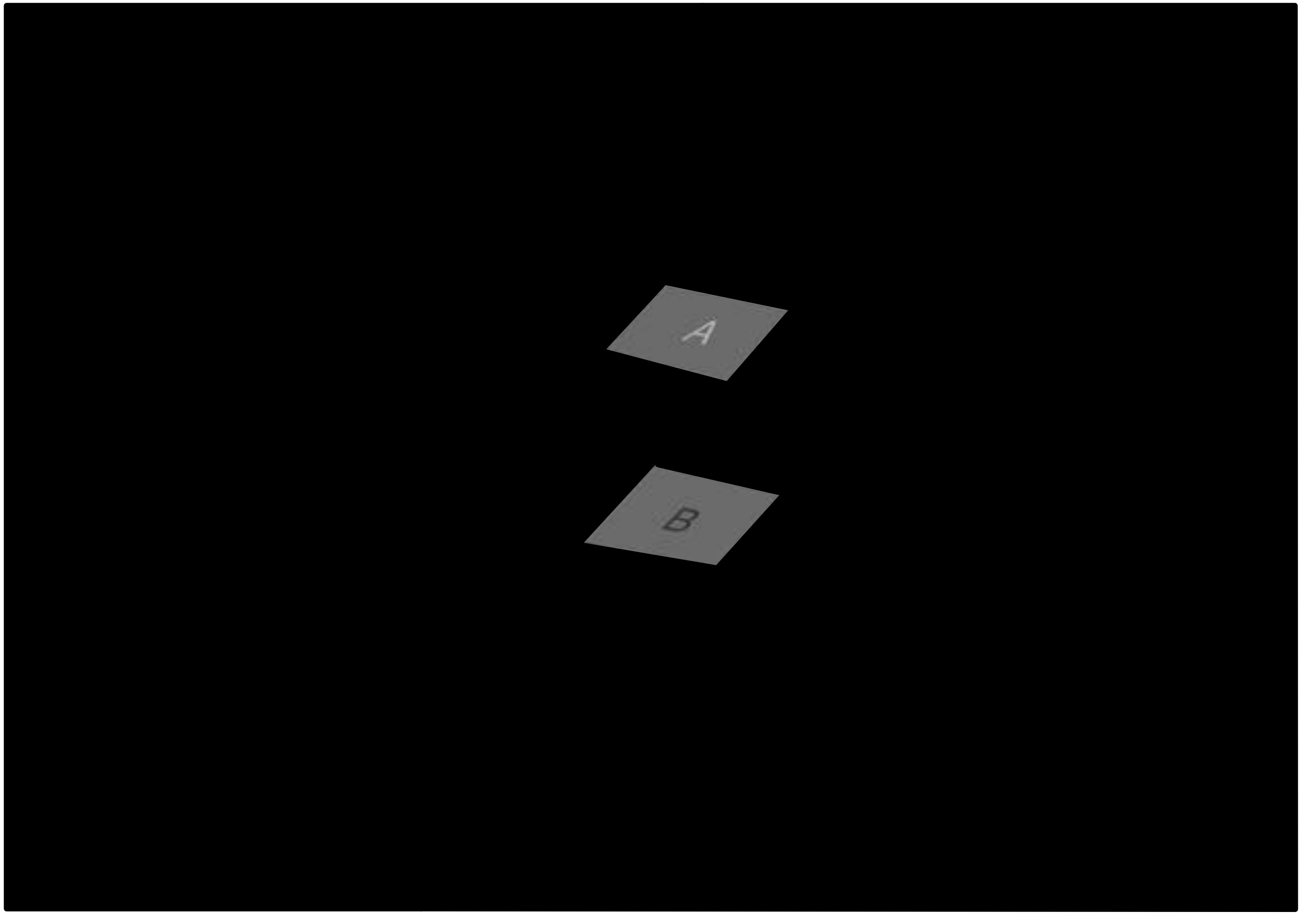
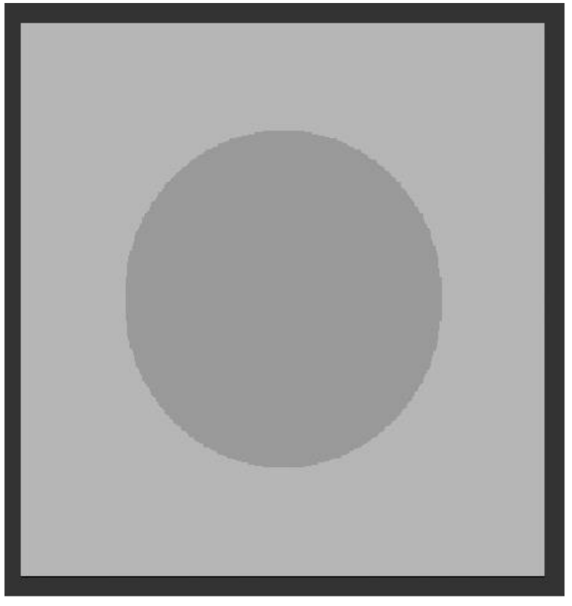
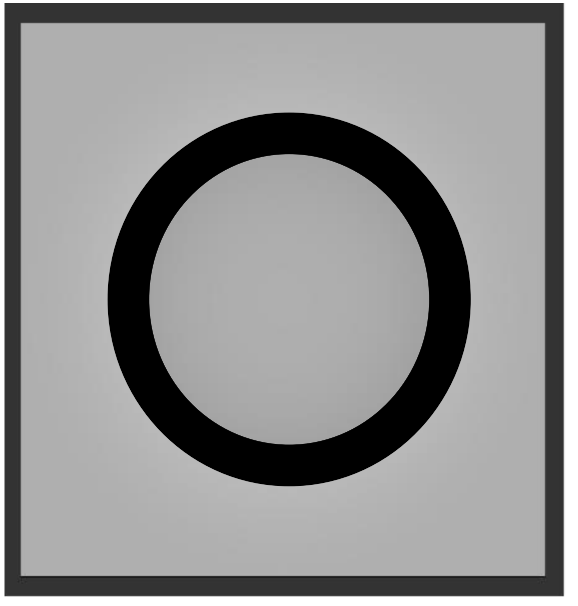


Cornsweet Illusion

- **Apparent contrast between inner and outer shades**

A

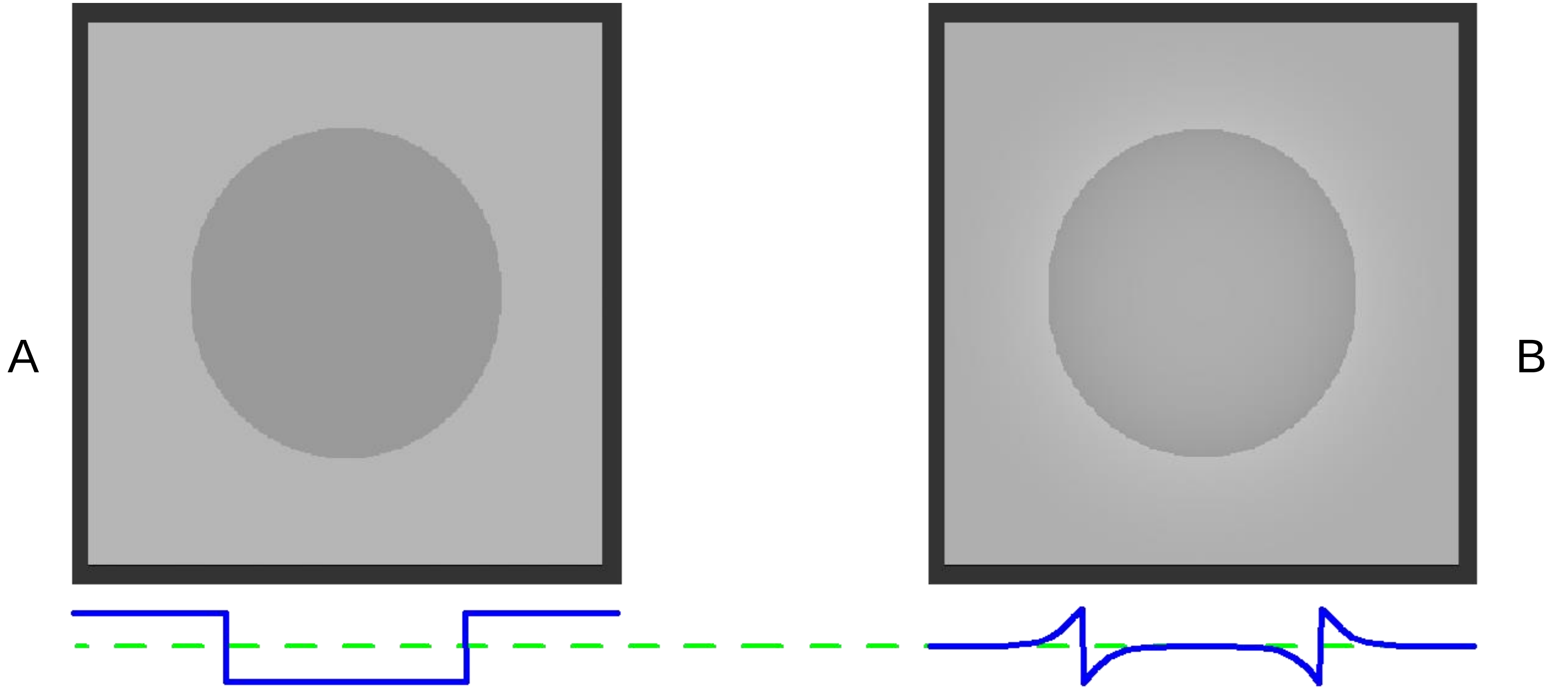




B

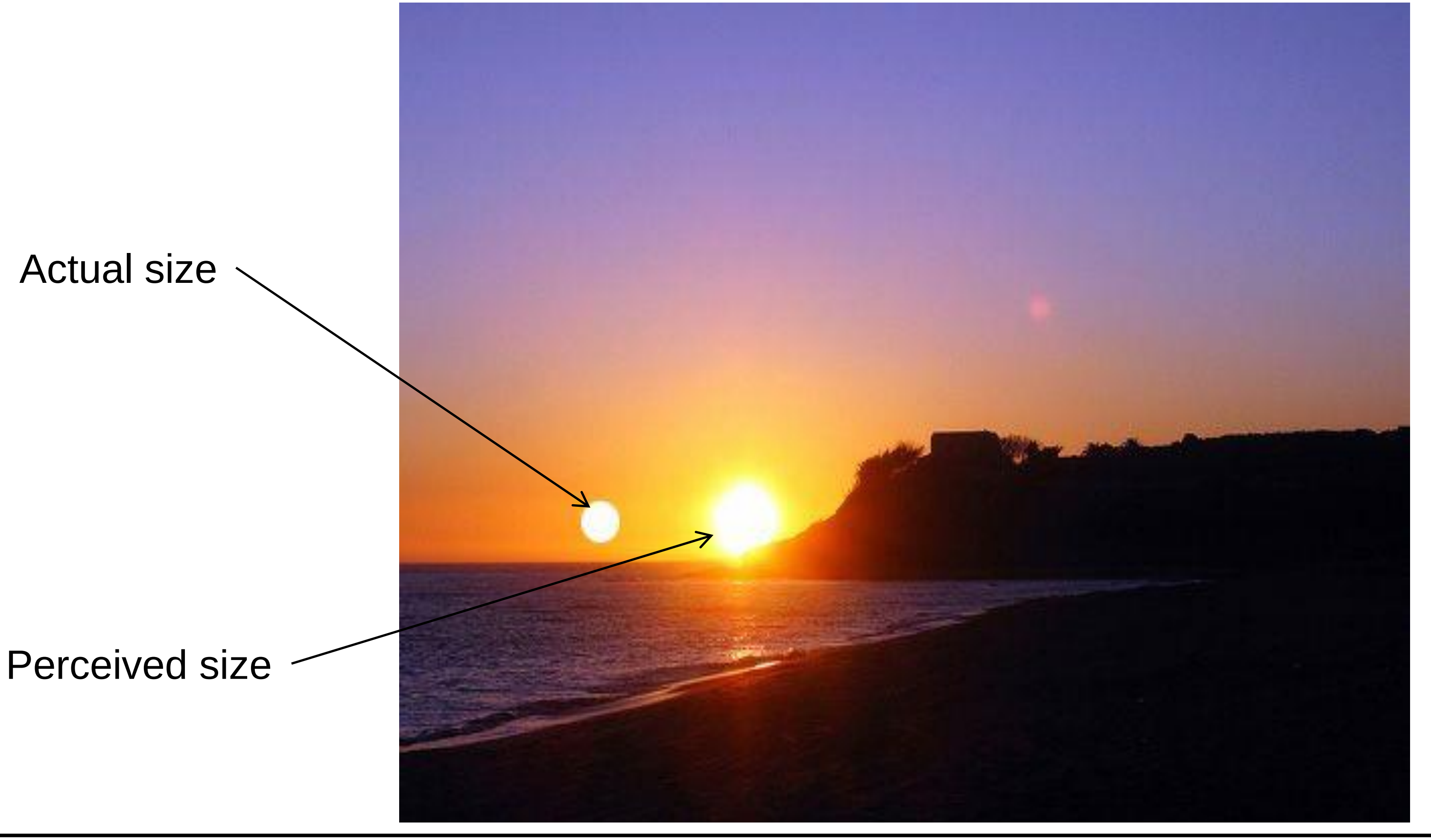
Cornsweet Illusion

- **Apparent contrast between inner and outer shades**
  - Due to gradual darkening/brightening towards a contrasting edge
  - Causes B to be perceived similarly to A



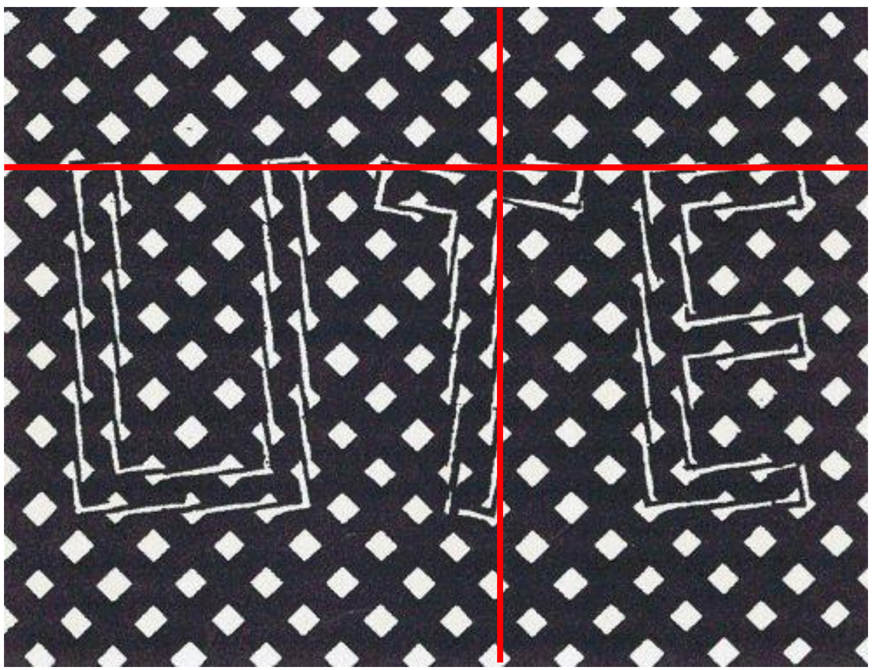
Optical Effects – Veiling Glare

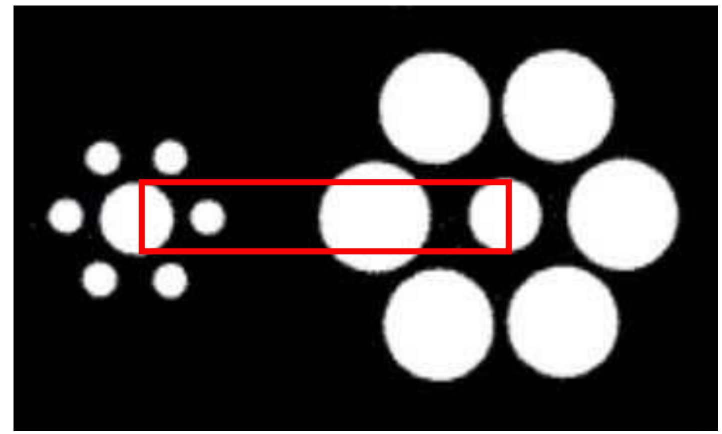
- **Internal scattering/blur of sources of high luminance**
- **Computationally expensive to simulate**

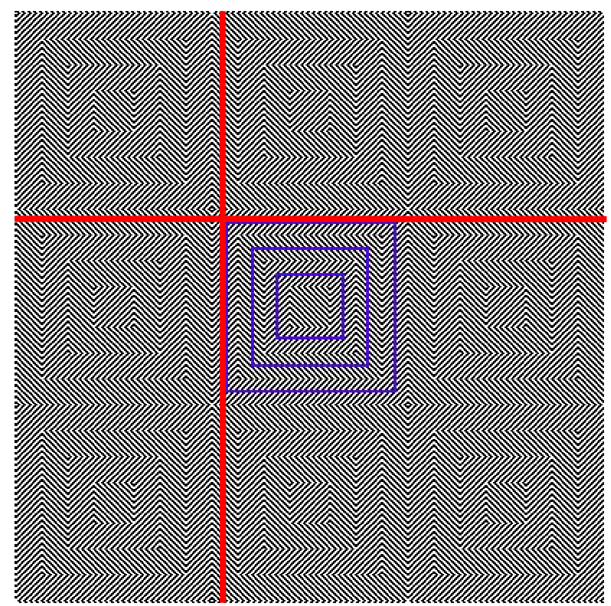


Shape Perception

- **Depends on surrounding primitives**
  - Size emphasis
  - Directional emphasis



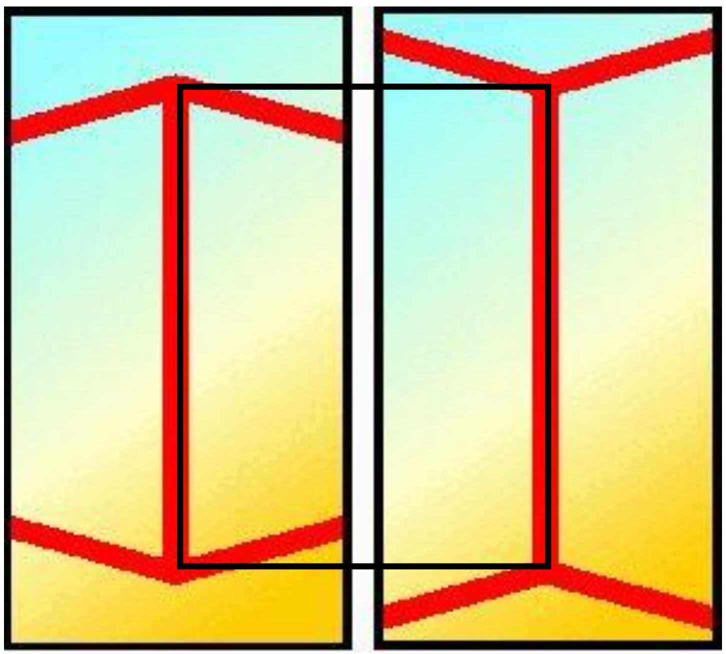


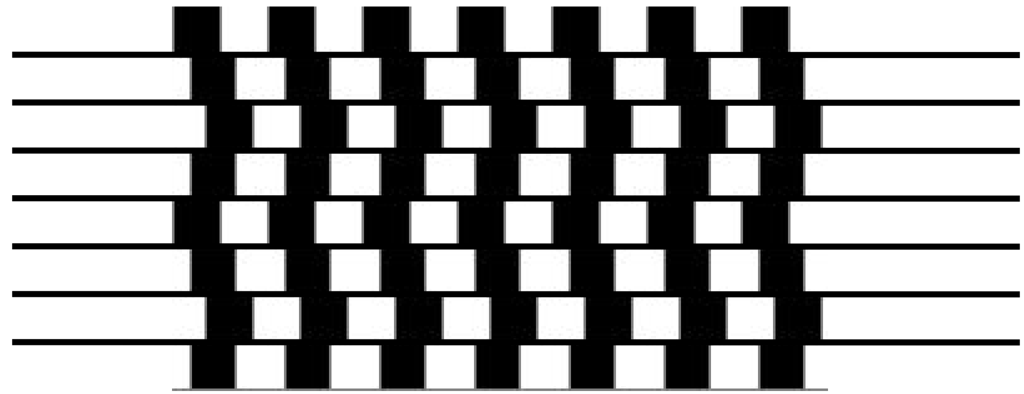


http://www.panoptikum.net/optischetaeuschungen/index.html

Geometric Cues

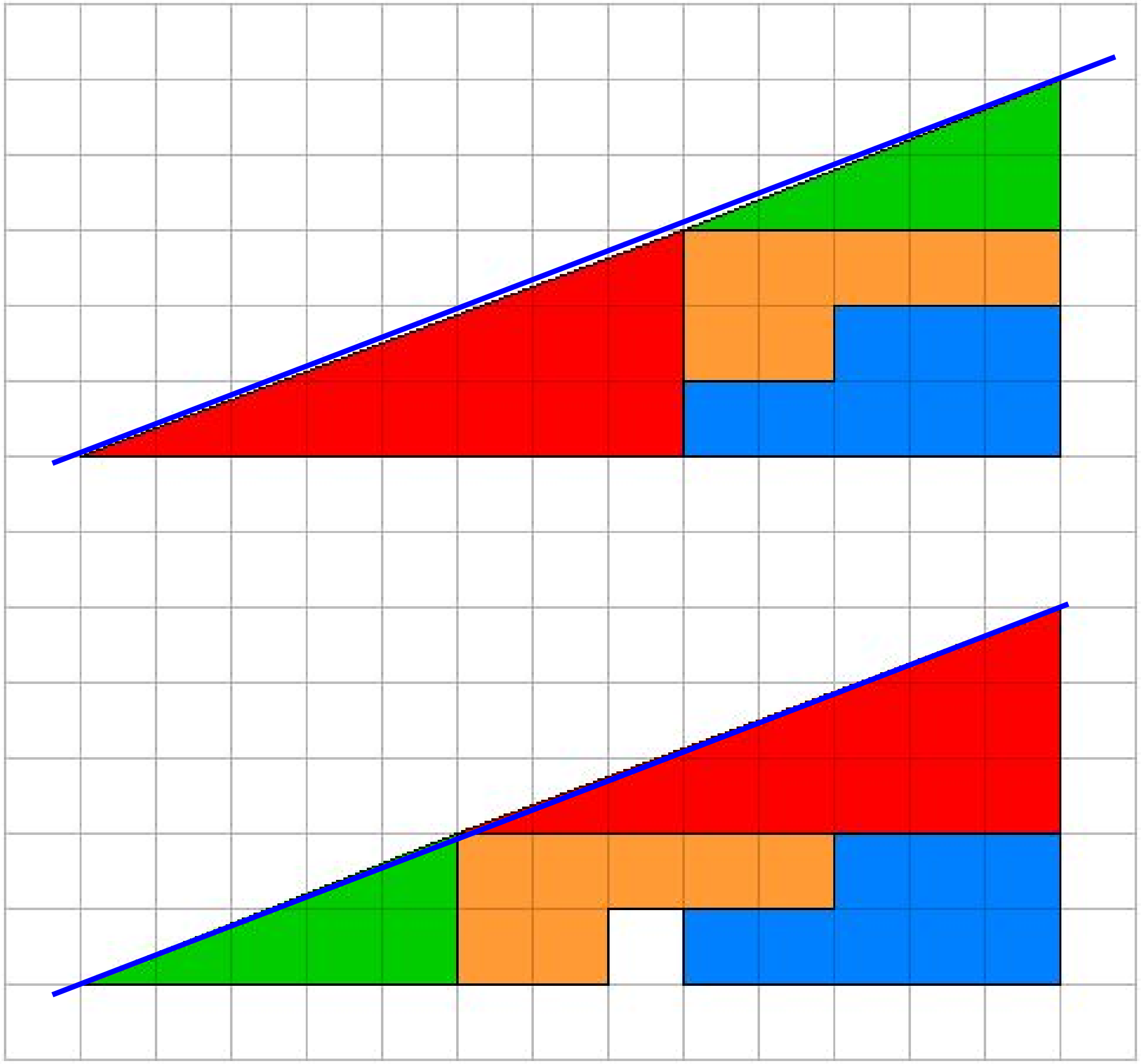
- **Automatic geometrical interpretation**
  - 3D perspective
  - Implicit scene depth





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

Visual “Proofs”



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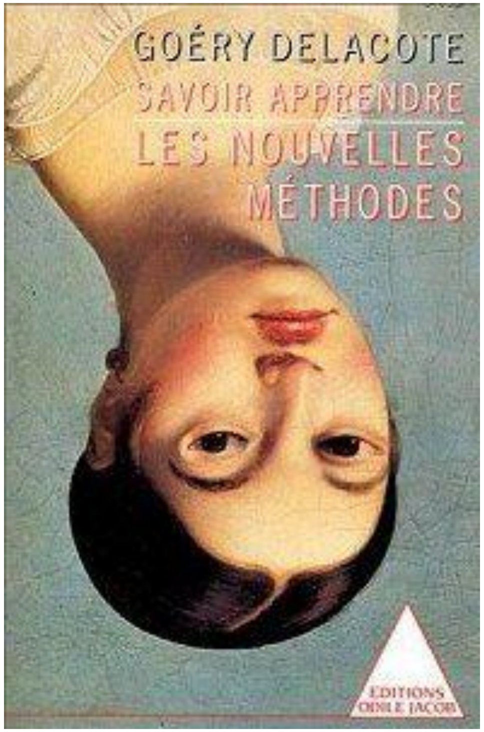
HVS: High-Level Scene Analysis

- **Experience & expectation**
  - Pictures usually horizontal
- **Local cue consistency**
  - Eyes and mouth look right, but actually are upside-down



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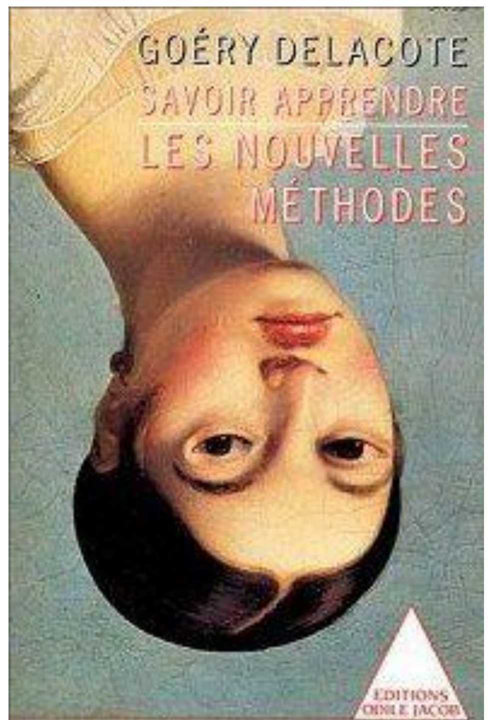

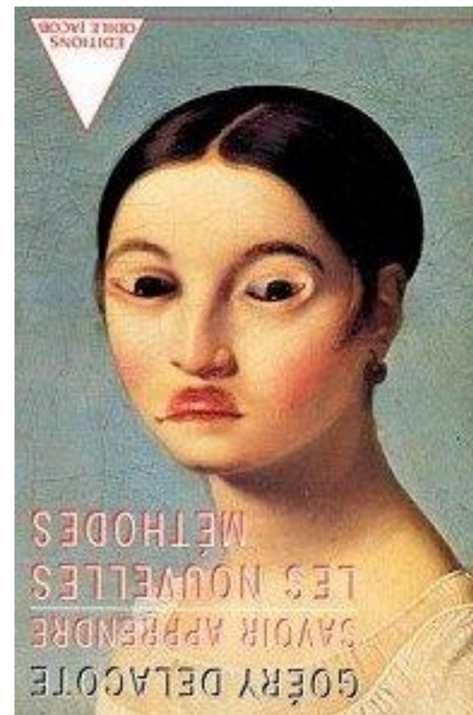

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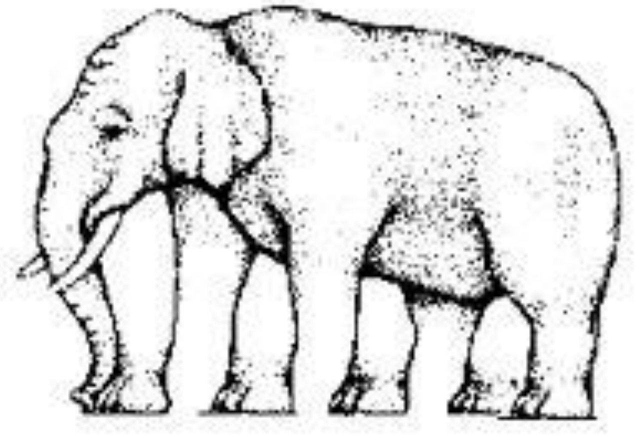
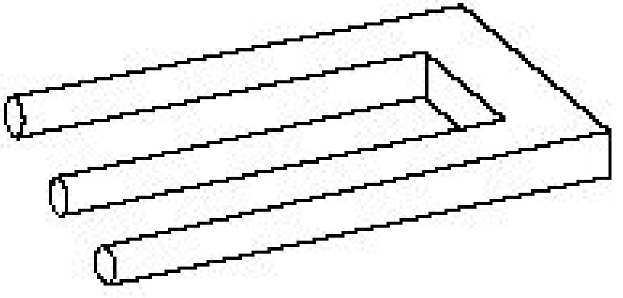
Impossible Scenes

- **Escher et al.**
  - Confuse HVS by presenting contradicting visual cues
  - Locally consistent but not globally





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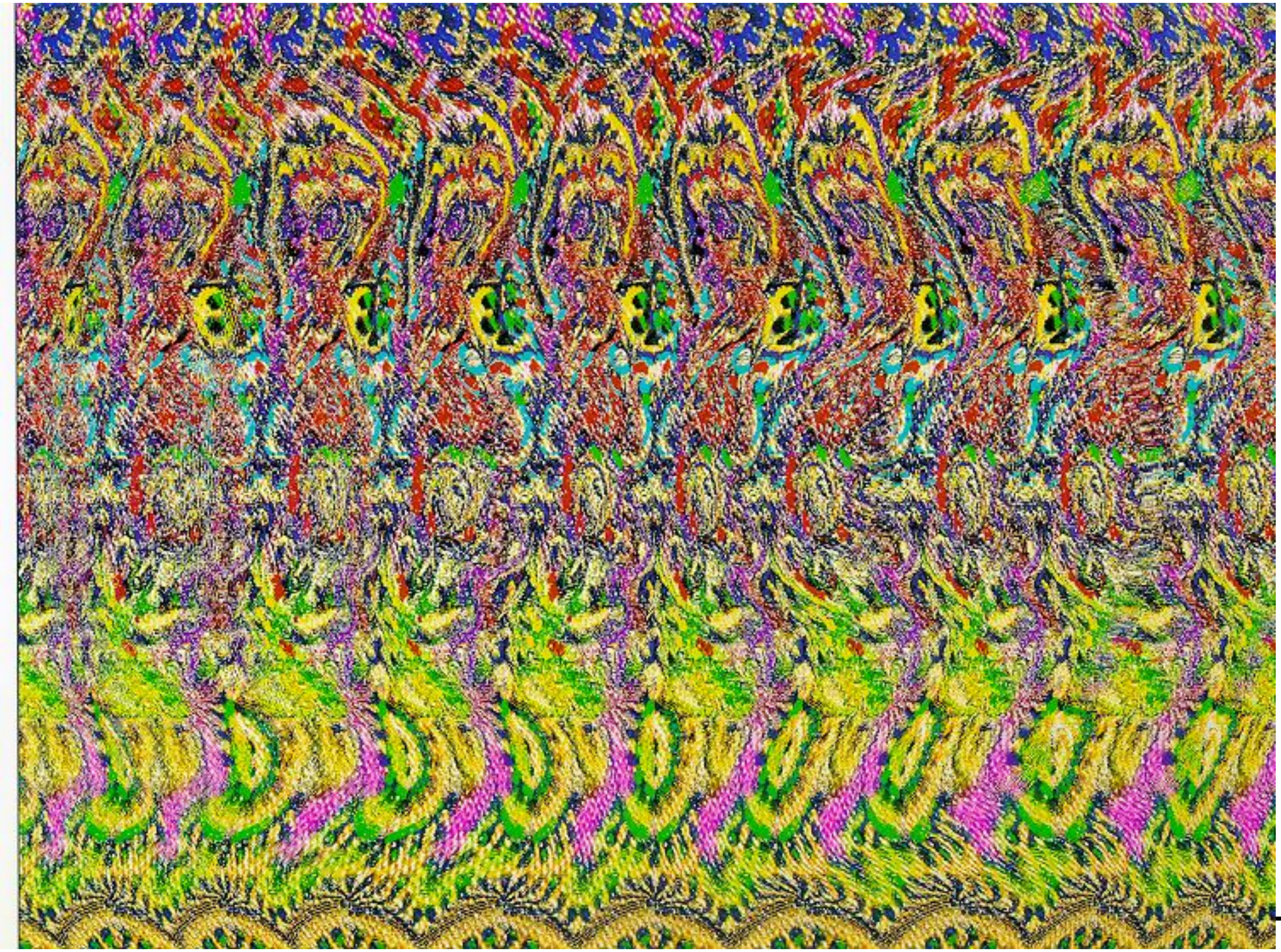
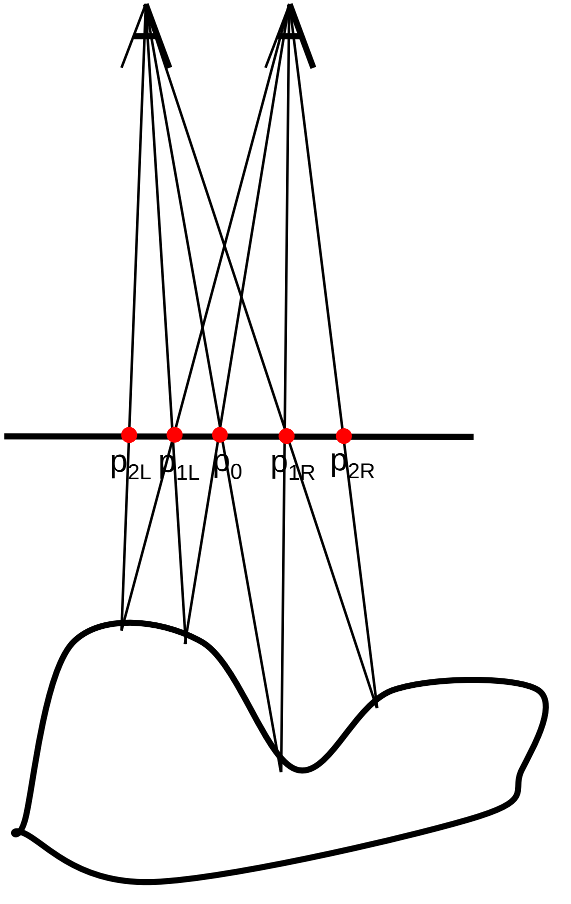
Single Image Random Dot Stereograms

- **Vergence: Cross eyers to look at the same 3D spot**
- **Accommodation: Focusing at a particular depth plane**



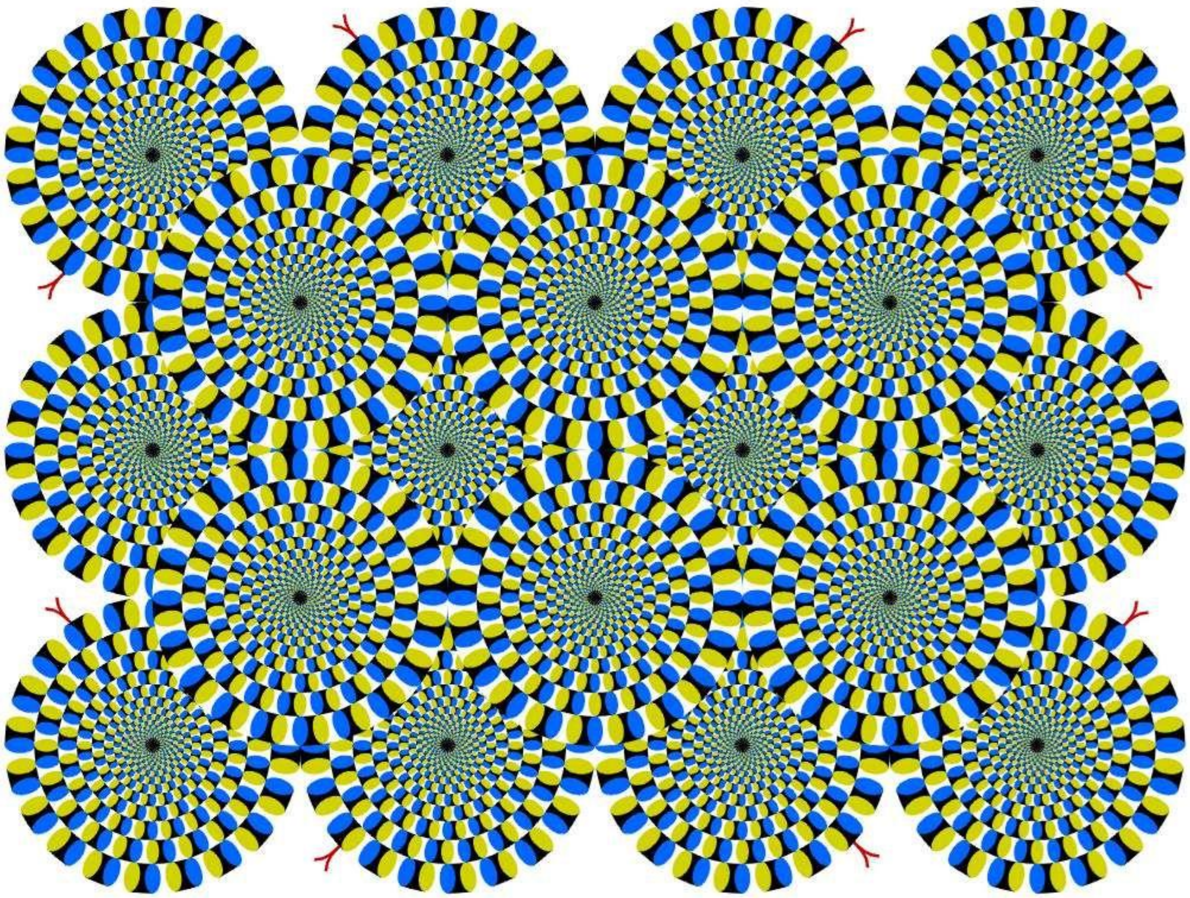
SIRDS Construction

- Assign arbitrary color to pixel 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

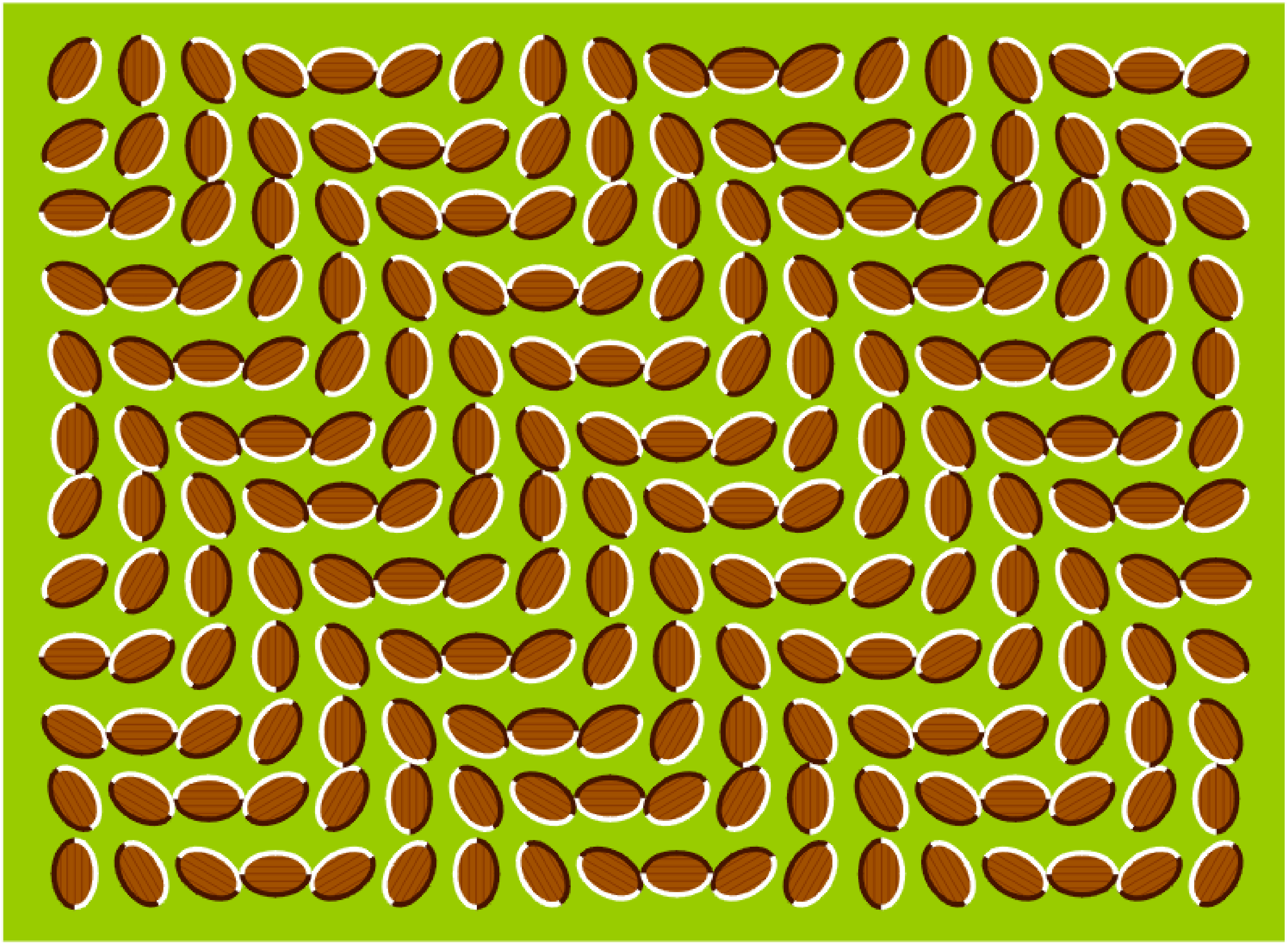


Motion Illusion

- **Appearance of movement in static image**
  - Due to cognitive effects of interacting color contrast & shape pos.
  - Saccades → diff. in neural signals between dark and bright areas

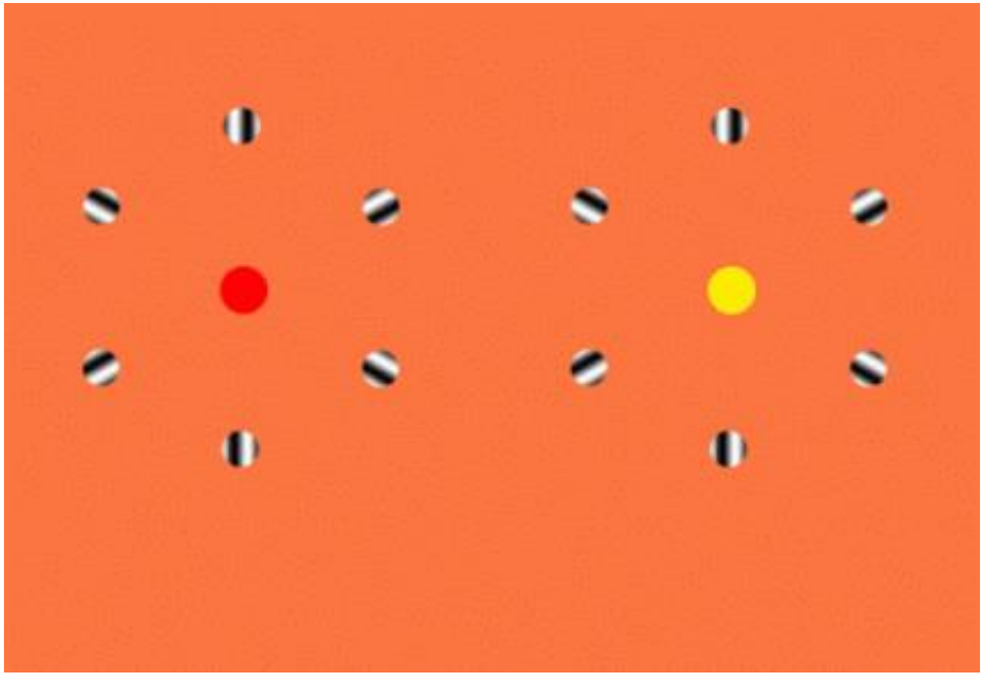


Motion Illusion



Motion Illusion

-



Negative Afterimages

- **Cones excited by color eventually lose sensitivity**
  - Photoreceptors adapt to overstimulation and send a weak signal

Negative Afterimages

- **When switching to grey background**
  - Colors corresponding to adapted cones remain muted
  - Other freshly excited cones send out a strong signal
  - Same perceived signal as when looking at the inverse color

Another Optical Illusion

- **If staring for ~ 15 sec., you may see a giraffe appear**