

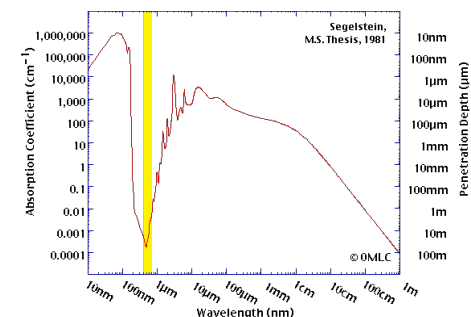
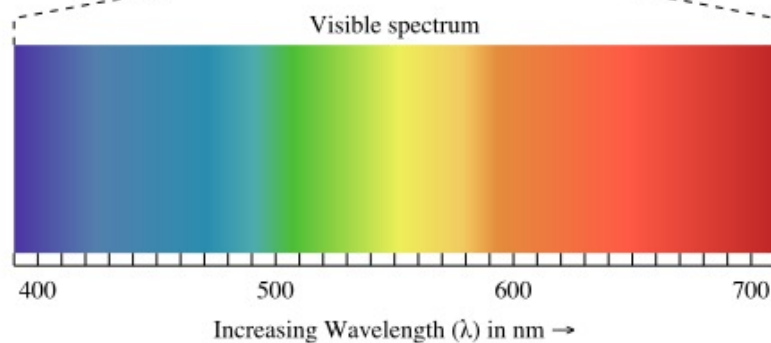
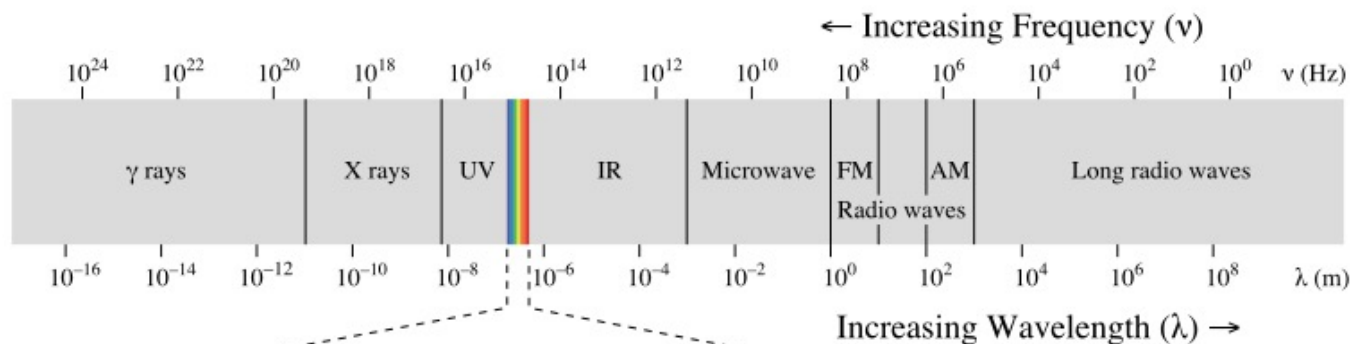
Computer Graphics

The Human Visual System (HVS)

Philipp Slusallek

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



EM absorption in water

Plenoptic Function

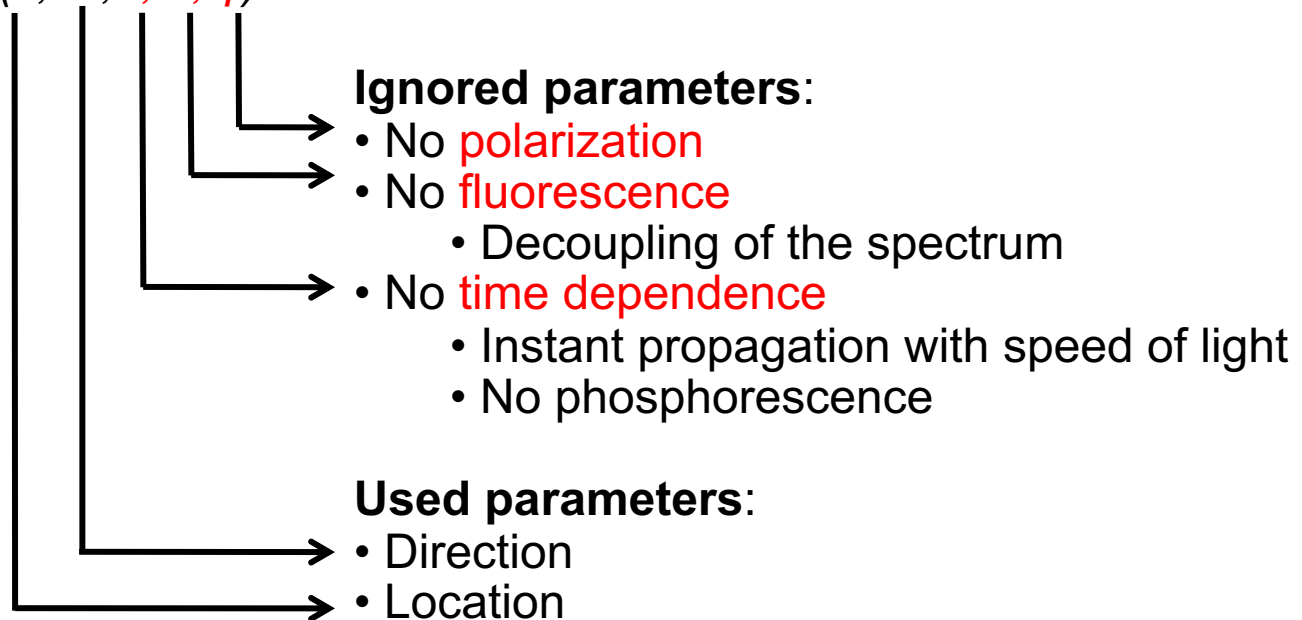
- **Physical model for light**

- Wave/particle-dualism

- Electromagnetic radiation wave model
- Photons: $E_{ph} = h\nu$ → particle model & ray optics (h: Planck constant)

- *Plenoptic function* defined at any point in space

- $L = L(x, \omega, t, \nu, \gamma)$ → 5 dimensional



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	$dQ/d\omega dt$	I_e	[W/sr]	Radiant intensity
	$dQ/dA d\omega dt$	L_e	[W/(m ² · sr)]	Radiance

Photometry

- **Equivalent units to radiometry**

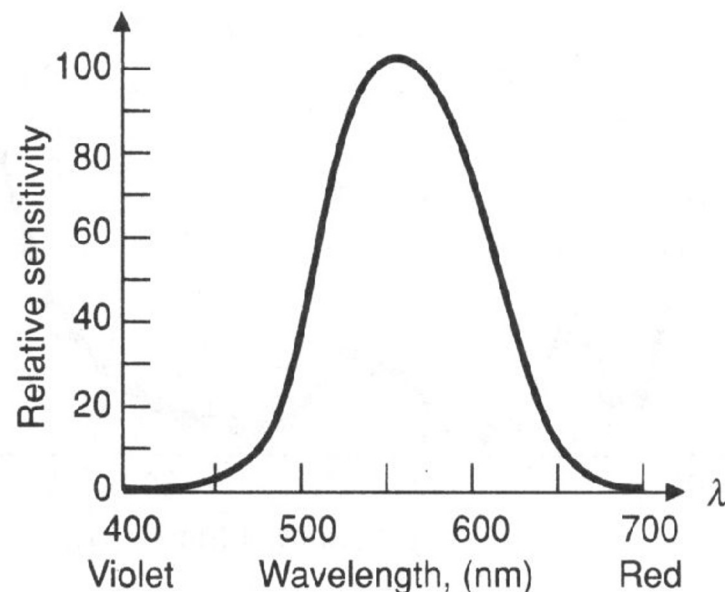
- Weighted with luminous efficiency function $V(\lambda)$
- Considers the spectral sensitivity of the human eye
 - Measured across different sets of humans
- Spectral or (typically) “total” units
 - Integrate over the entire spectrum and deliver a single scalar value

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

$$K_m = 680 \text{ lm/W}$$

- Simple distinction (in English!):

- Names of radiometric quantities contain “radi”
- Names of photometric quantities contain “lumi”



Luminous efficiency function $V(\lambda)$

Photometric Units (total)

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 (e.g., illumination on desk)
Flux density	dQ/dAdt	B_v	[lx = lm/m ²] (lux)	Luminosity (e.g., reflection off desk)
Intensity	dQ/d ω dt	I_v	[cd = lm/sr] (candela)	Luminous intensity (e.g., intensity of a point light)
	dQ/dAd ω dt	L_v	[lm/(m ² · sr)] (nits)	Luminance (e.g., brightness of a monitor)

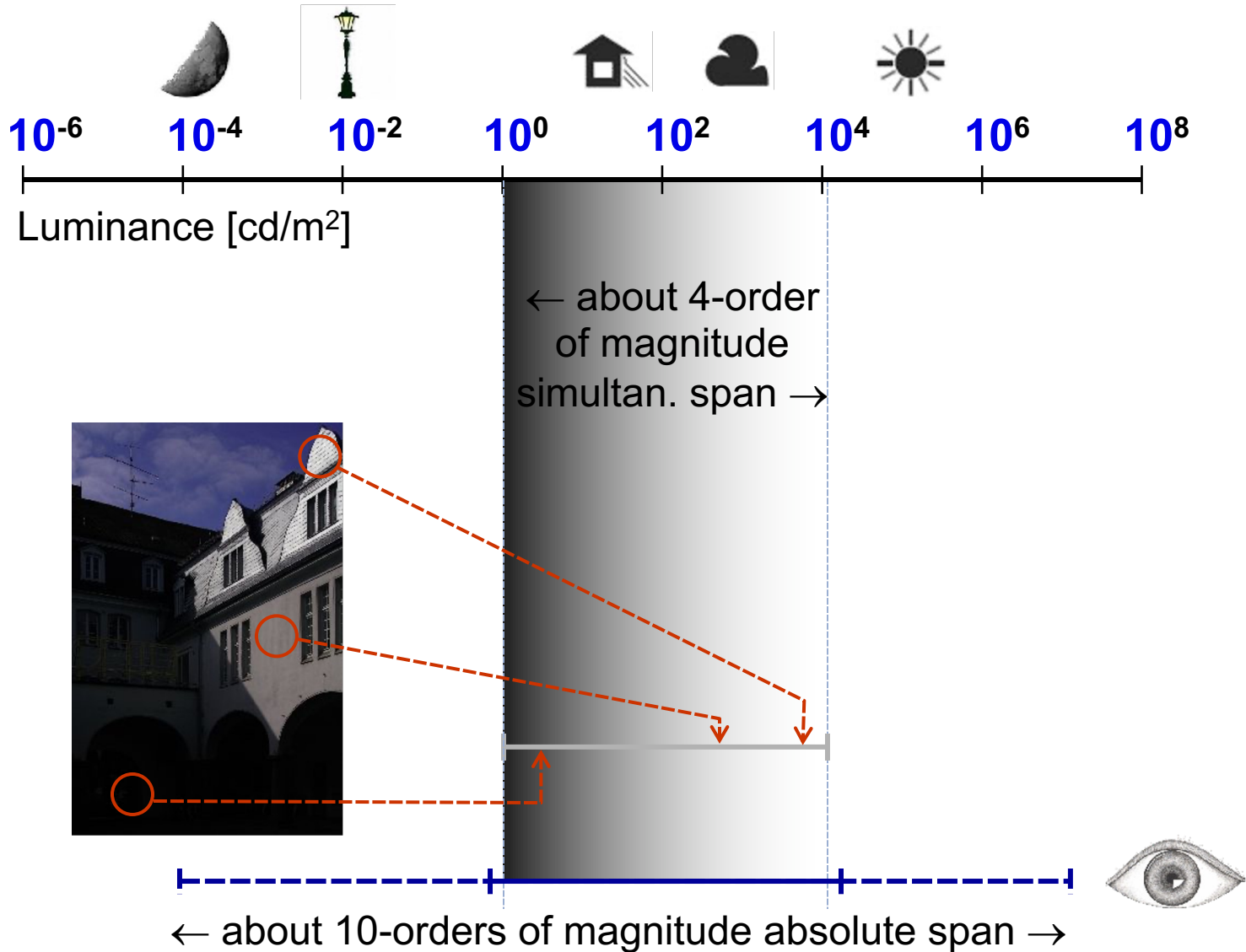
With luminous efficiency function weighted units

Illumination: Examples

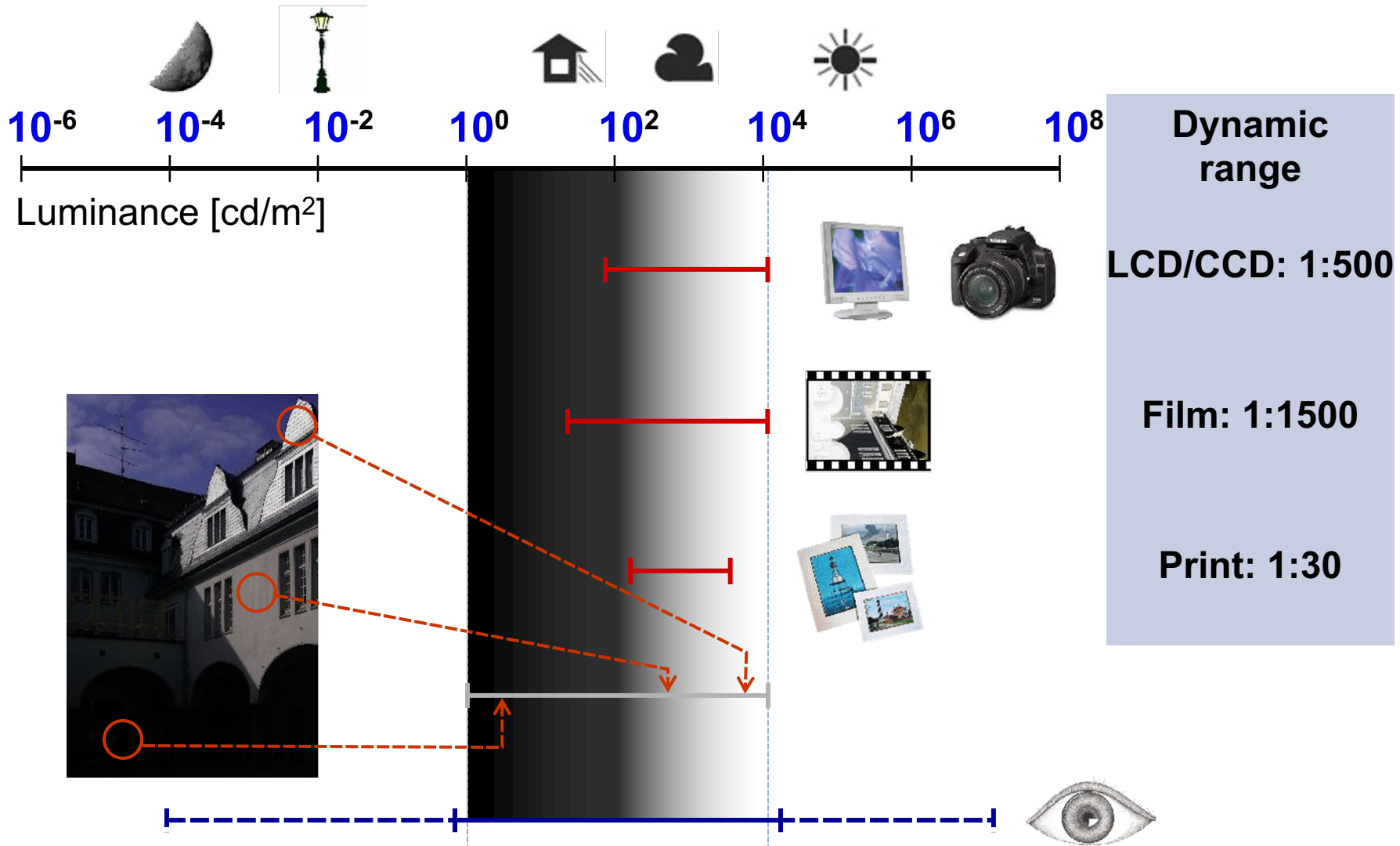
- **Typical illumination intensities**

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

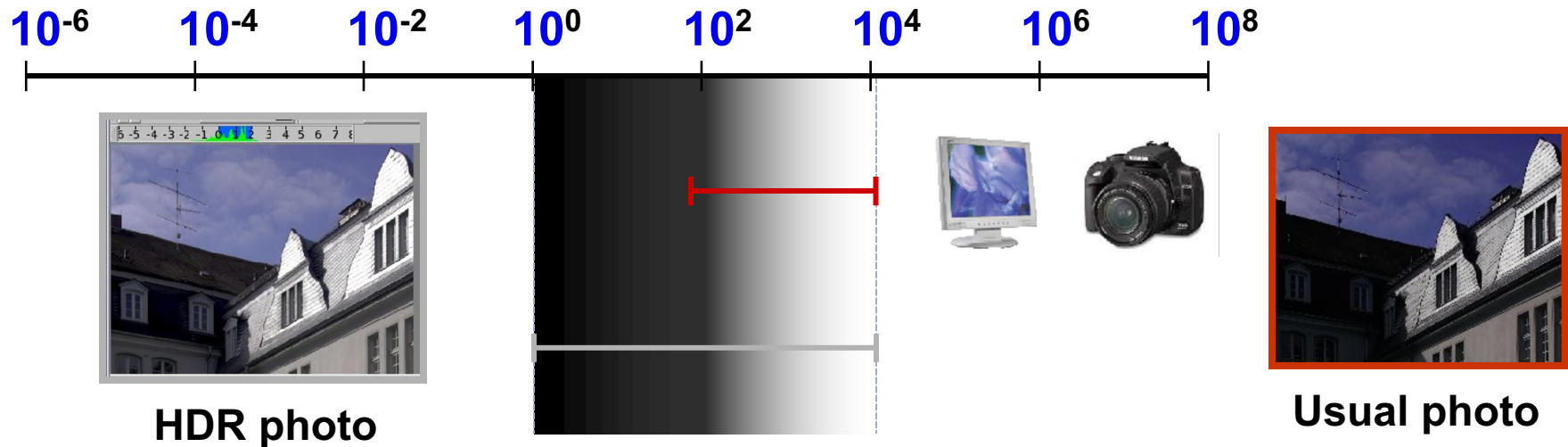
Luminance Range



Contrast (Dynamic Range)

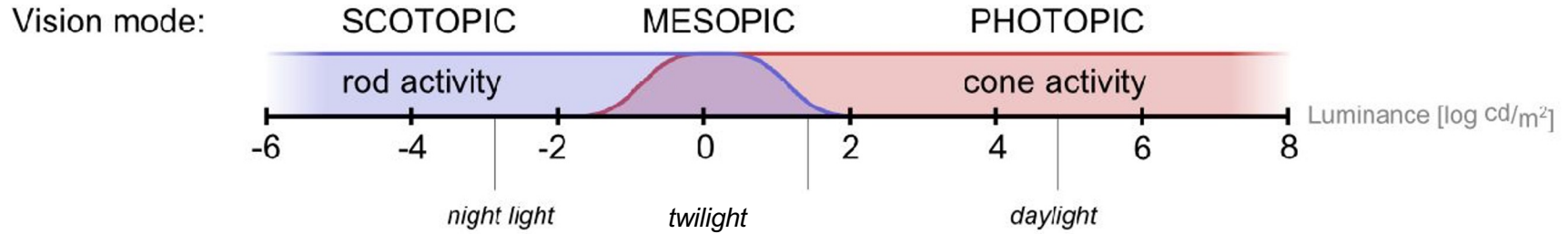


High Dynamic Range (HDR)



- **How to display computed/measured HDR values on an LDR device ?**
 - Tone mapping (→ RIS course)

Percept. Effects: Vision Modes



Mode properties: monochromatic vision
 limited visual acuity

 good color perception
 good visual acuity



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

Visual Acuity and Color Perception

Photopic vision

Mesopic/photopic transition



a) daylight: 1000 cd/m²

b) interior: 10 cd/m²

Scotopic/mesopic transition

Scotopic vision

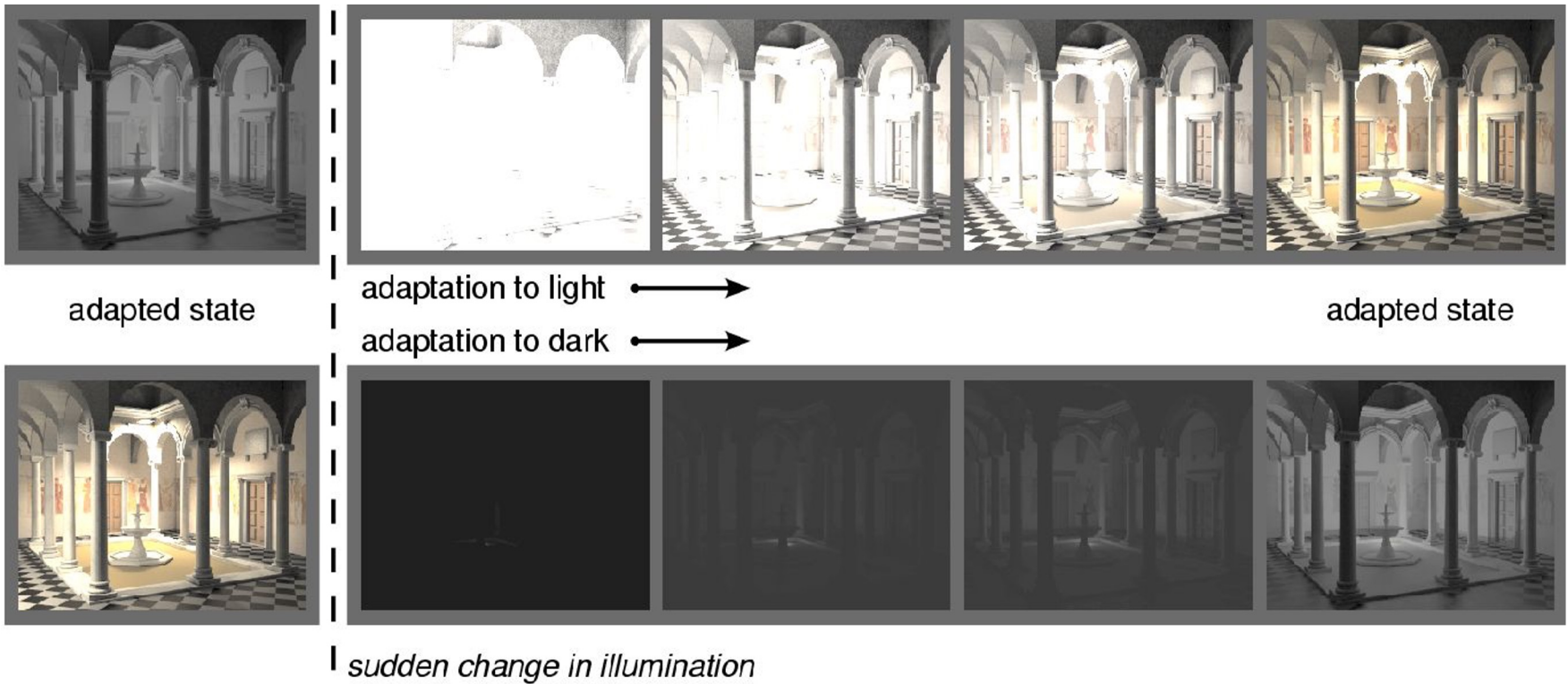


c) moonlight: 0.04 cd/m²

d) starlight: 0.001 cd/m²

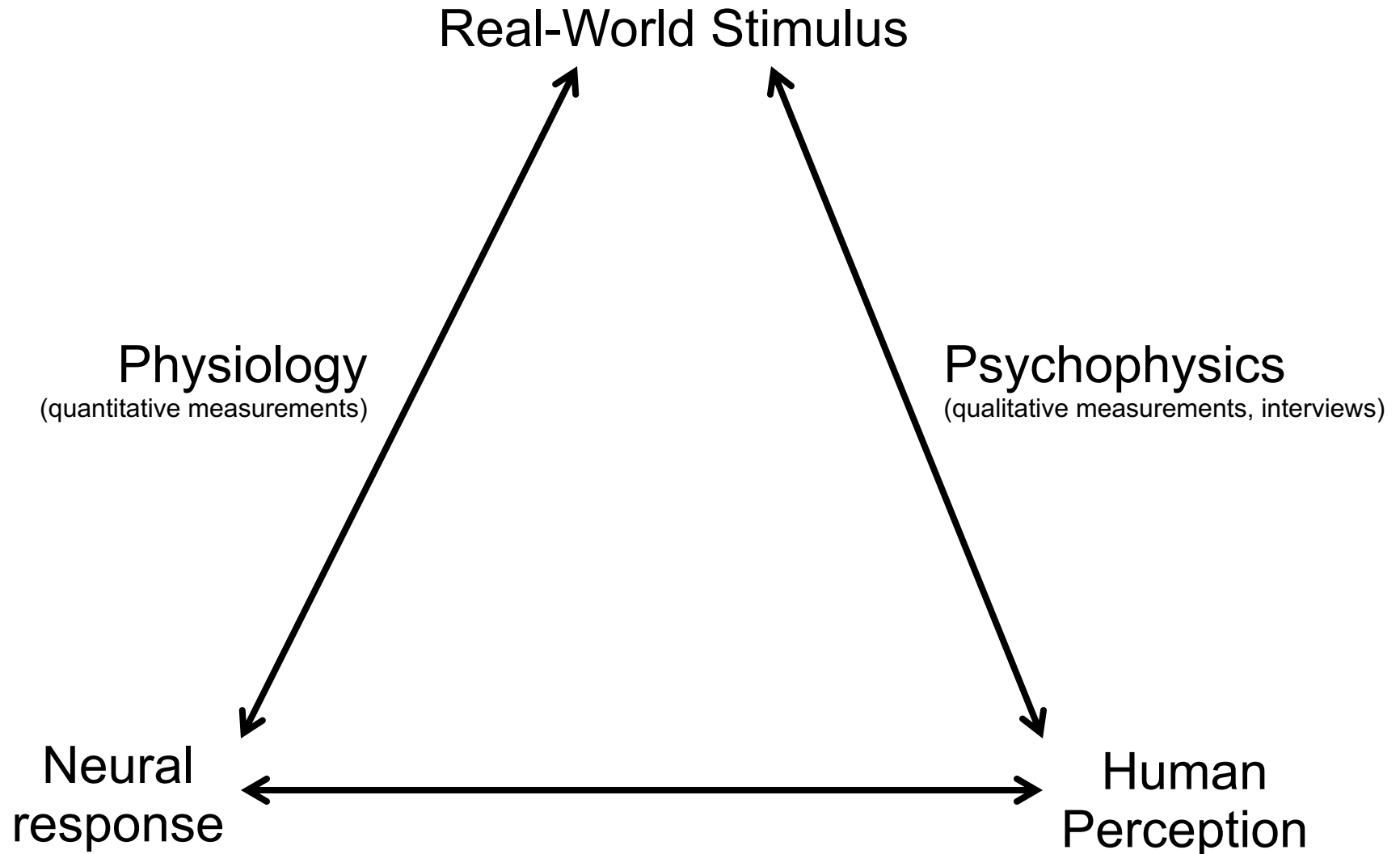
Percept. Effects: Temp. Adaptati.

- Adaptation to dark much slower



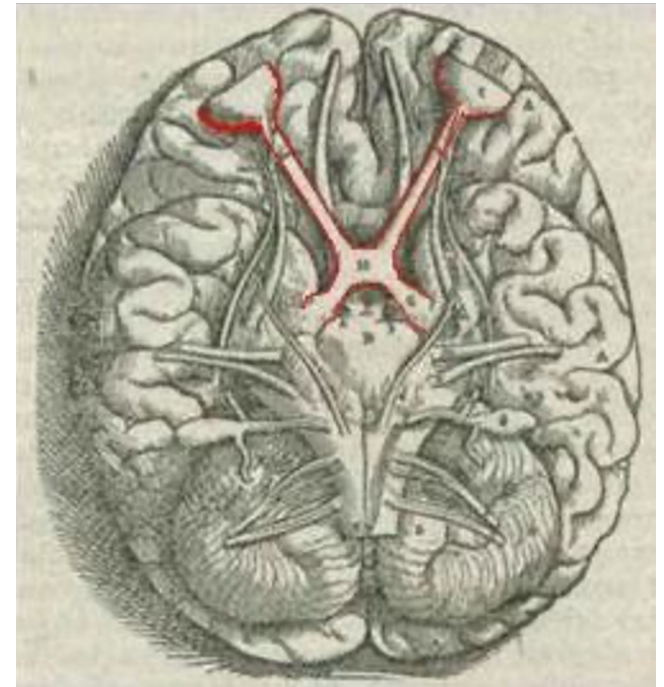
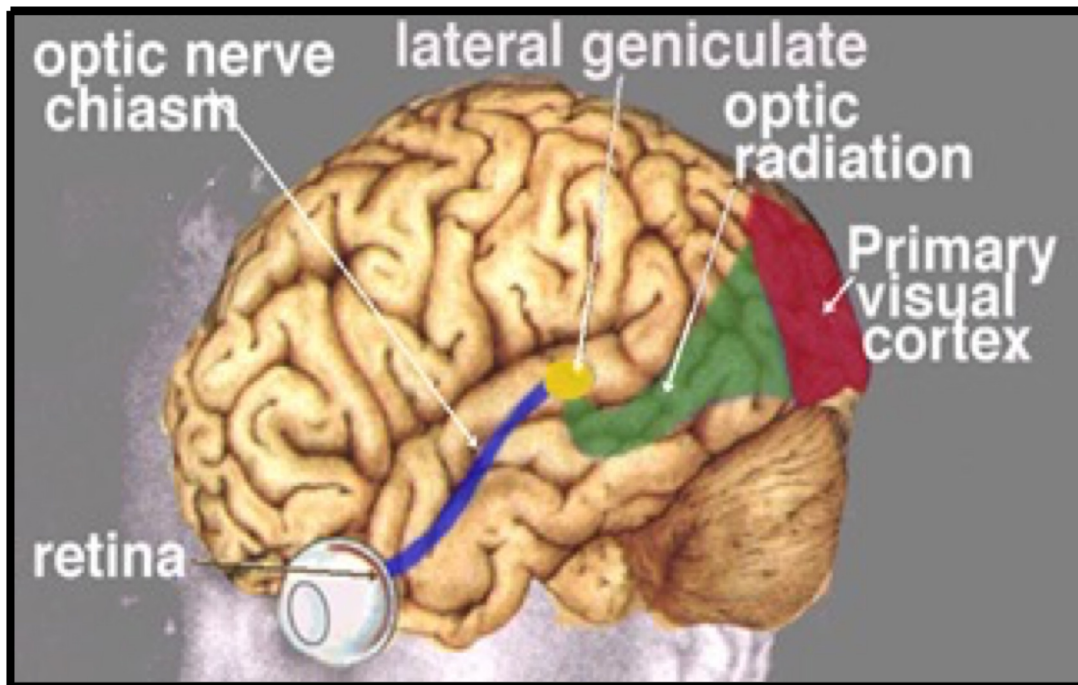
- **Simulation requires:**
 - Time-dependent filtering of light adaptation

HVS - Relationships



Human Visual System

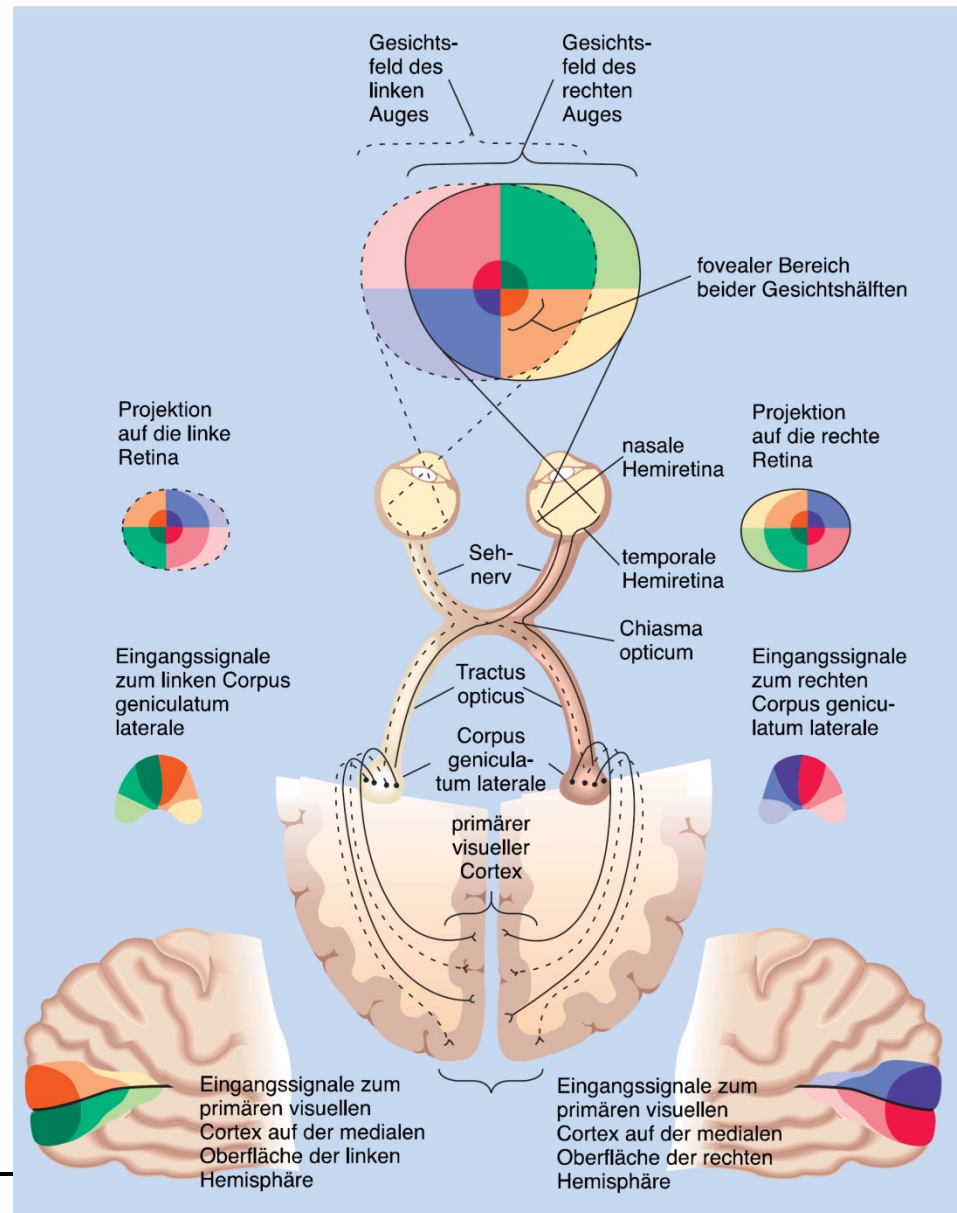
- Physical structure well established
- Percept. behavior complex & less understood process



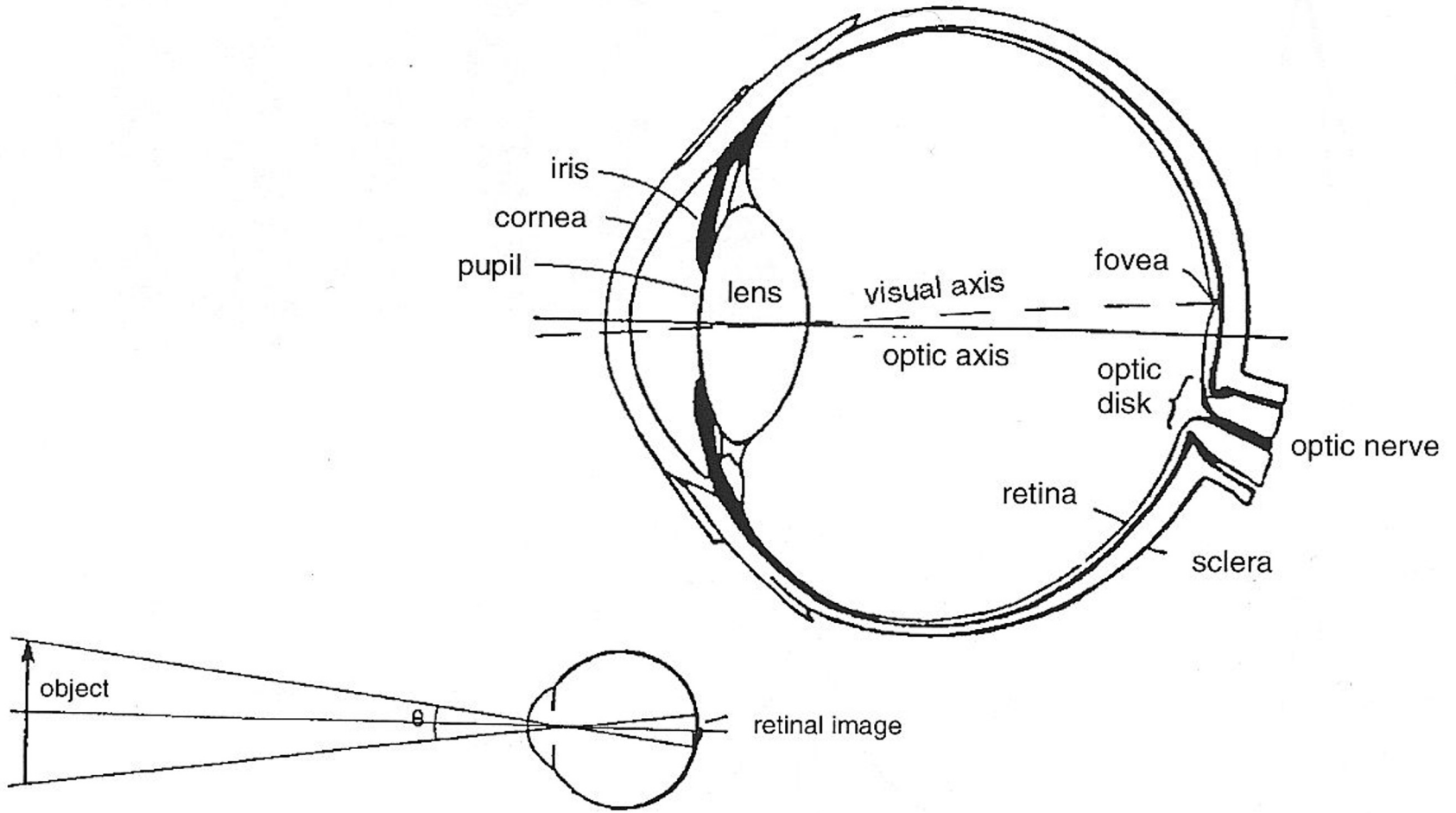
Optic chiasm

Optical Chiasm

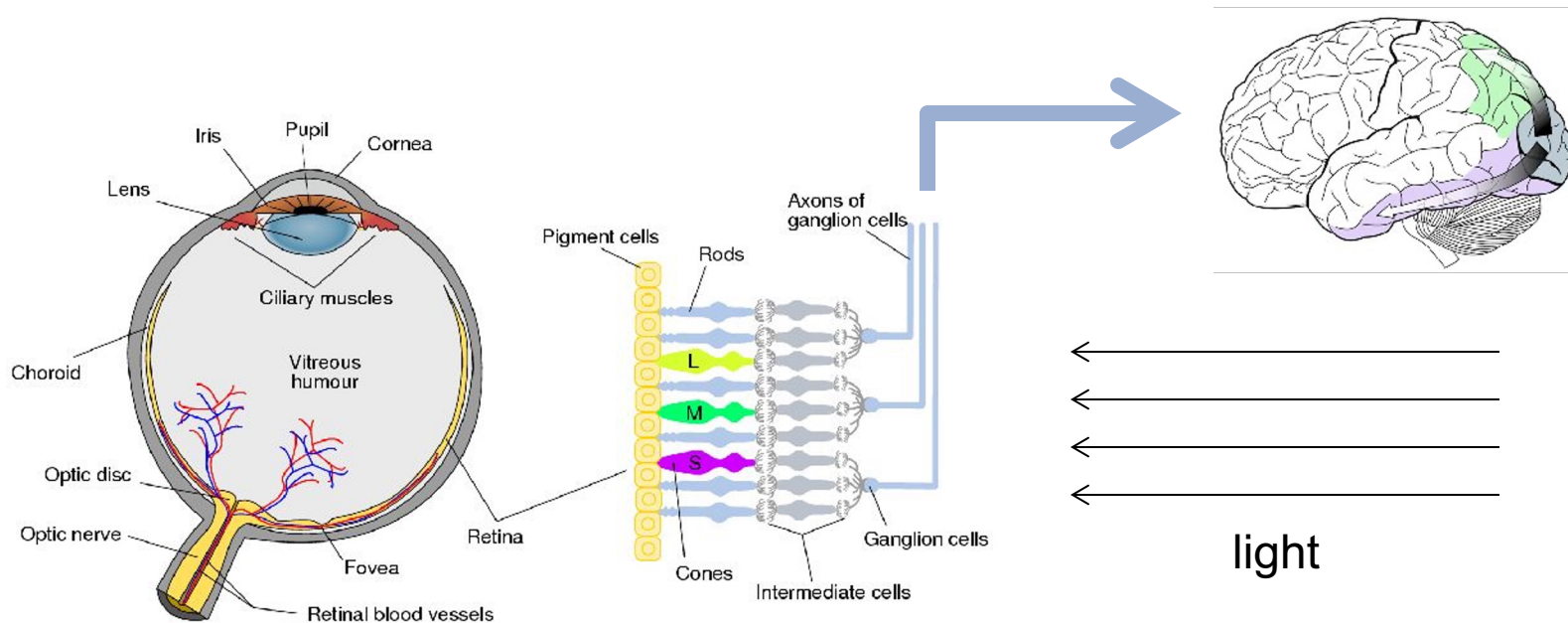
- **Right half of the brain operates on left half of the field of view**
 - From both eyes!!
- **And vice versa**
 - Damage to one half of the brain can result in loss of one half of the field of view



Perception and Eye



Human Visual Perception



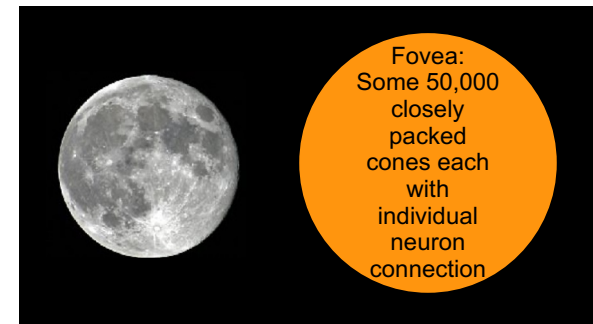
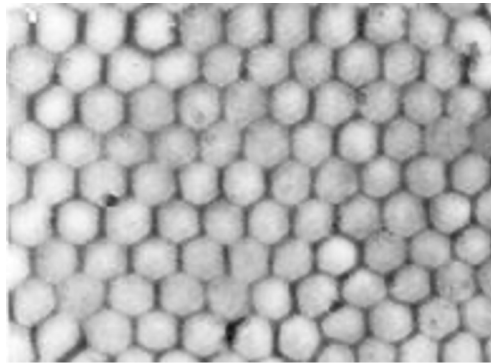
early vision (eyes)

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

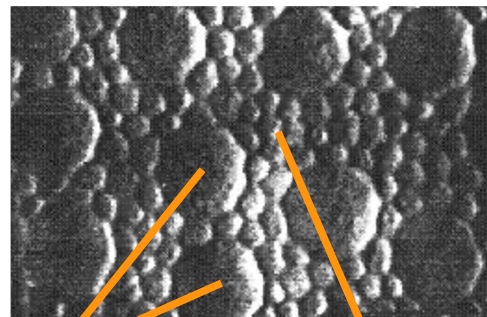
Distribution of Rods and Cones

- 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

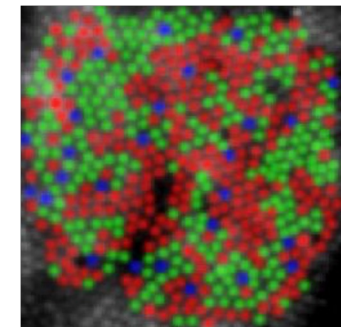
L-cones

~

M-cones

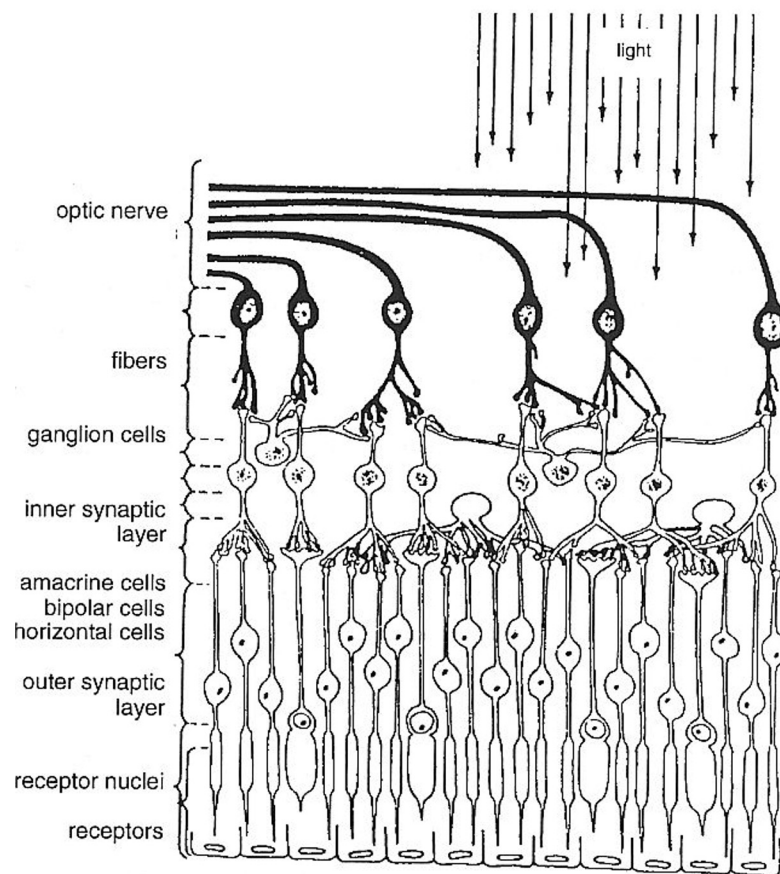
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S-cones



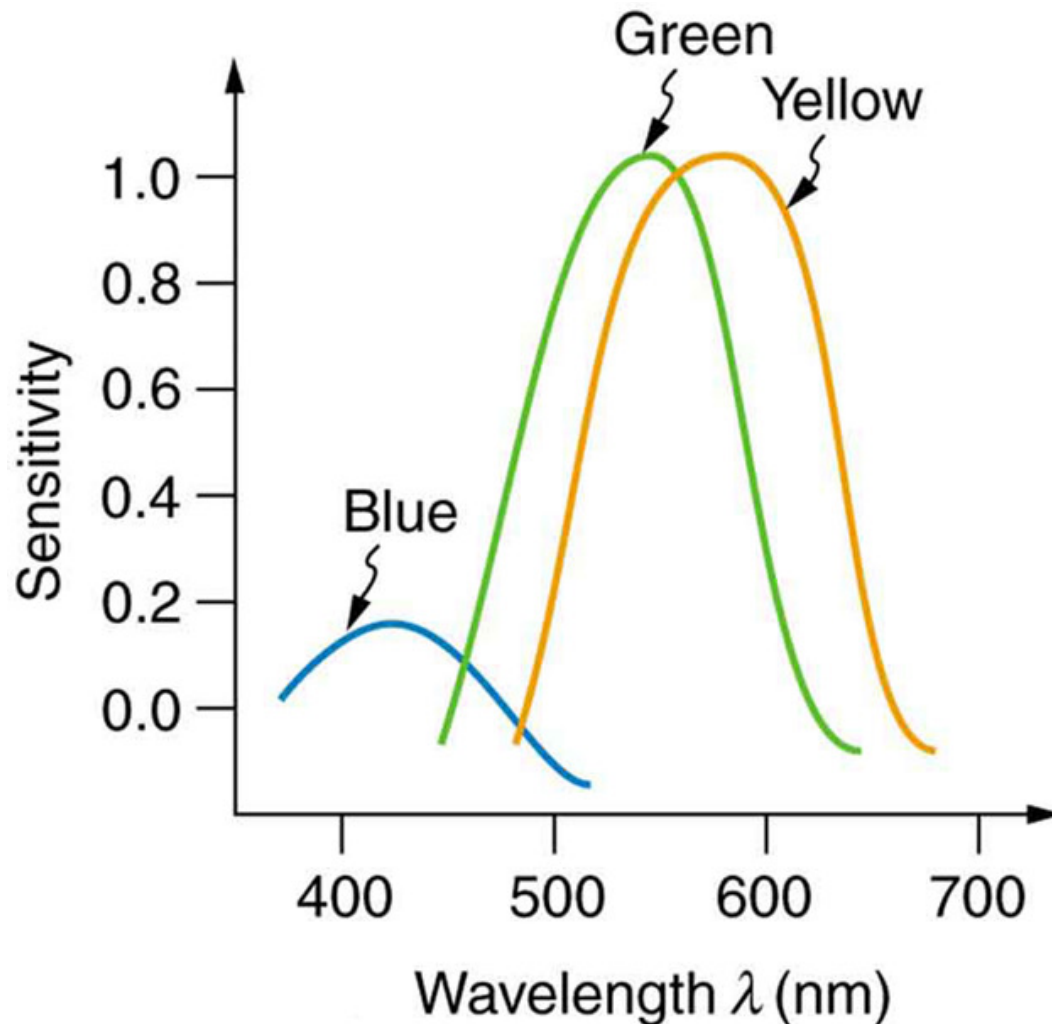
Retina

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



Eye as a Sensor

- Relative sensitivity of cones to photons



Eye

- **Fovea (centralis):**

- Ø 1-2 visual degrees
- 50,000 **cones** each covering ~0.5 arcminutes angle (~2.5 µm wide)
- No rods in central fovea, but three different cone types:
 - **L**(ong, 64%), **M**(edium, 32%), **S**(hort wavelength, 4%), varies individ.
 - ⇒ Varying resolution: 10 arcminutes for S vs. 0.5 arcminutes for L & M
- Mostly linked directly with optical nerves and visual cortex (1:1),
 - 1% of retina area but covers 50% of visual cortex in brain
- Adaptation to light intensity only through cones

- **Periphery:**

- 75-150 M. **rods**: night vision (B/W)
 - 5-7 M. cones (color)
 - Rods: Response to stimuli by even a single photon (@ 500 nm)
 - 100x better than cones, integrating over 100 ms
 - Signals from many rods are combined before linking with nerves
 - Bad resolution, high flicker 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

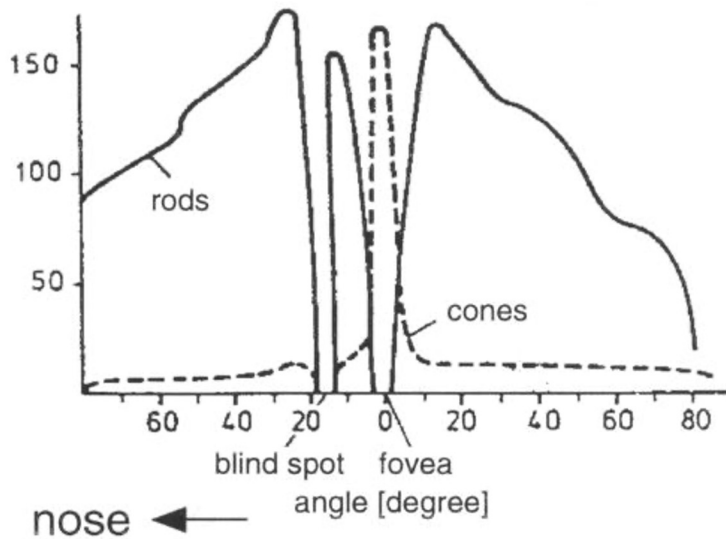
This is a text in red

This is a text in green

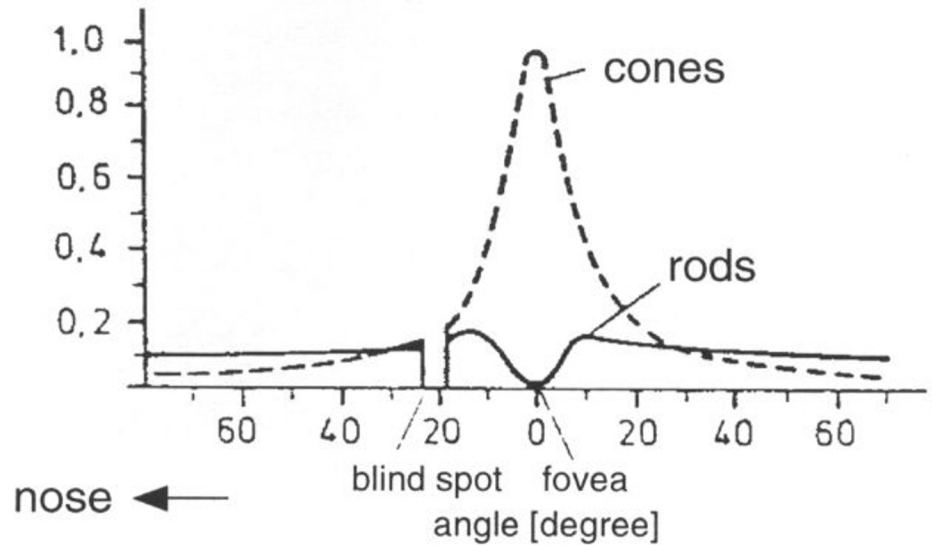
This is a text in blue

Visual Acuity

receptors
in 1000/mm²



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)

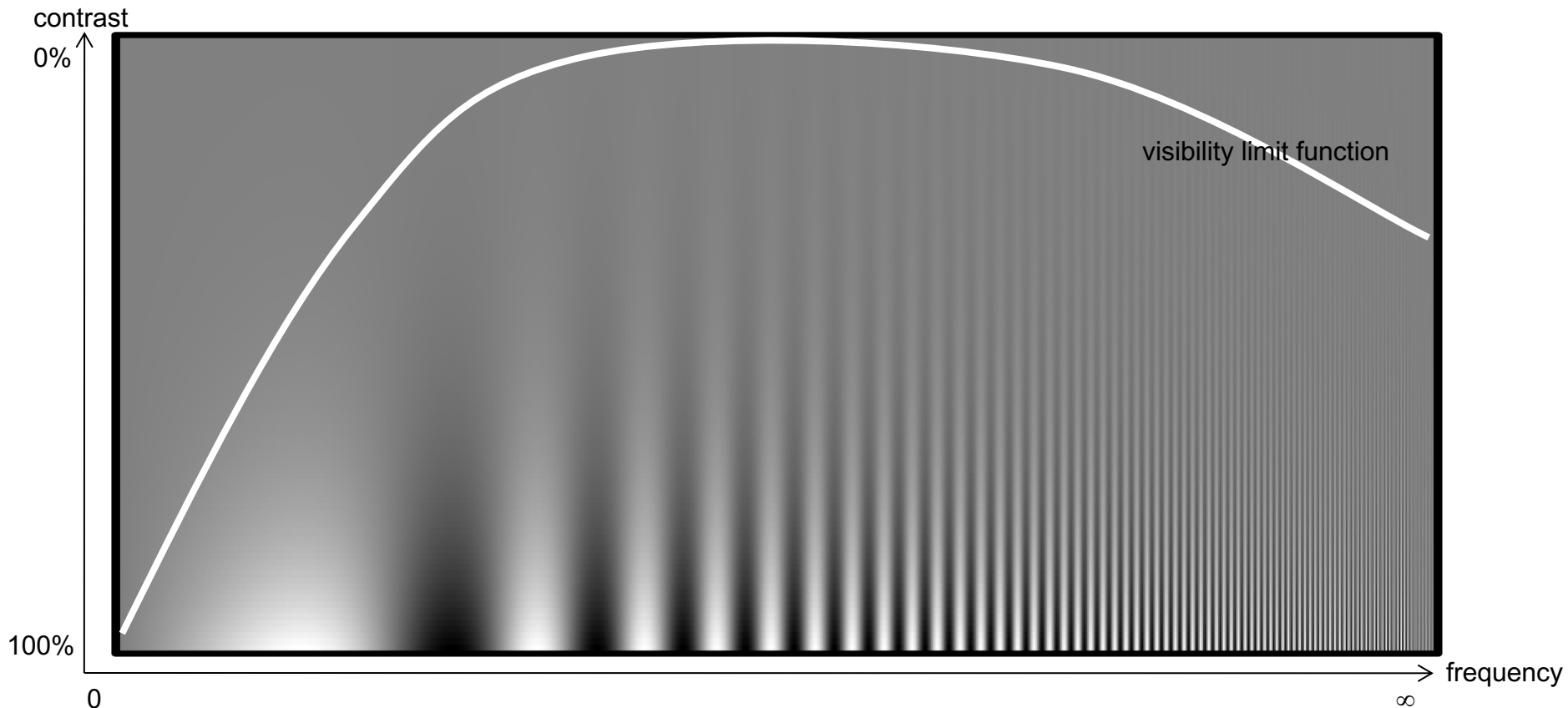


- Eye micro-tremor: 60-100 Hz, 5 μm (2-3 photoreceptor spacing)
 - Allows to create super-resolution (w/ Poisson pattern)
 - Together corresponds to 19" display at 60 cm away from viewer:
3,000² without hyperacuity – 18,000² pixels with hyperacuity
- **Fixation of eye onto (moving) region of interest**
 - Automatic gaze tracking, autom. compensation of head movement
 - Apparent overall high resolution of fovea
 - **Visual acuity increased by**
 - Brighter objects and high contrast
-

Contrast Sensitivity

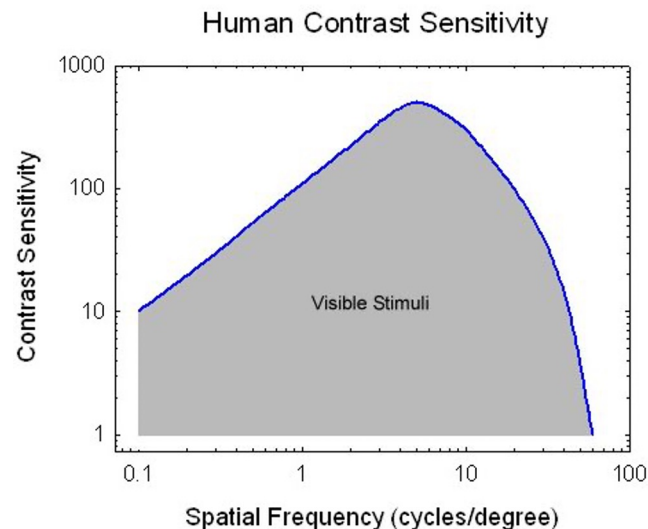
- **Human visual system**

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



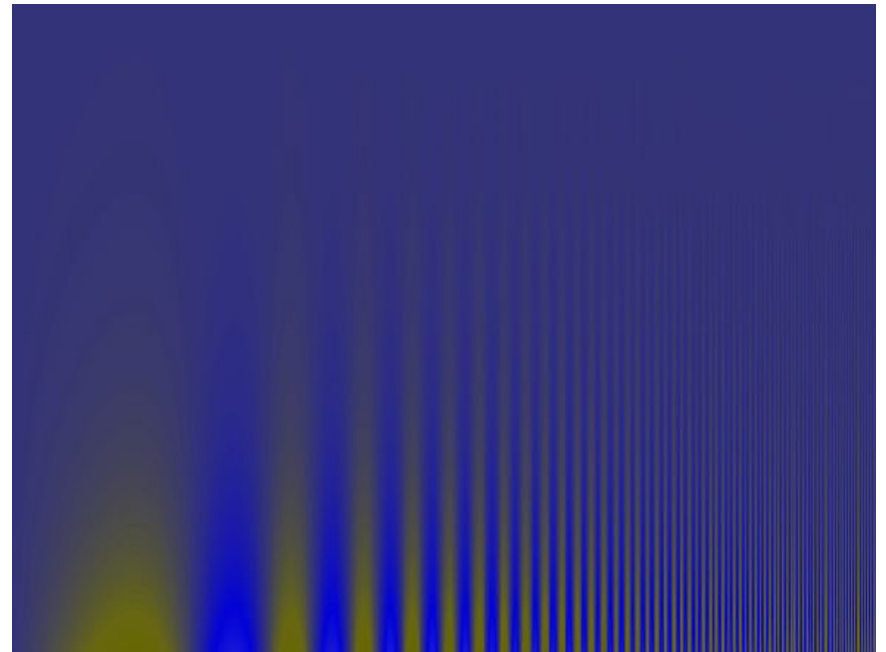
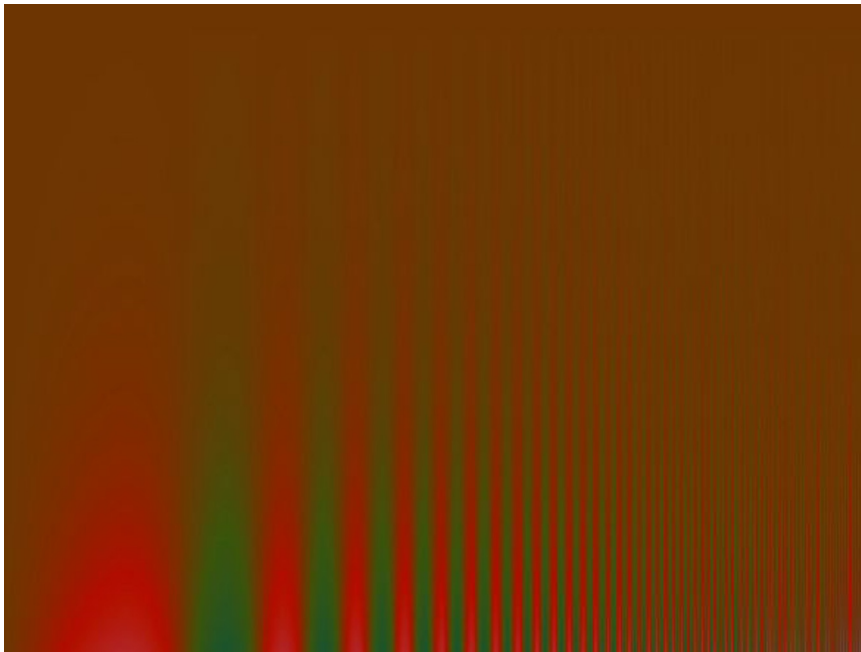
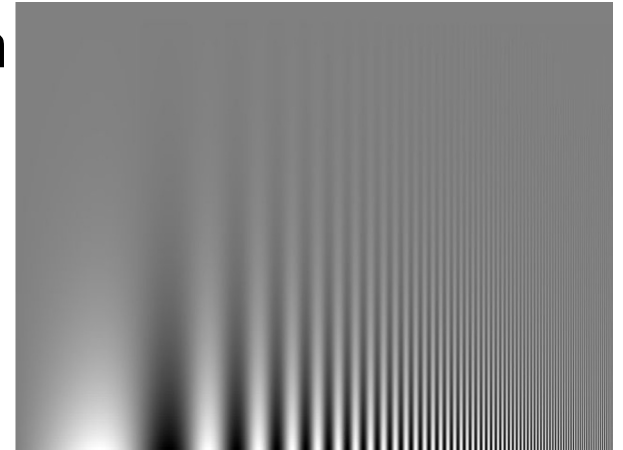
Luminance Contrast Sensitivity

- **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)



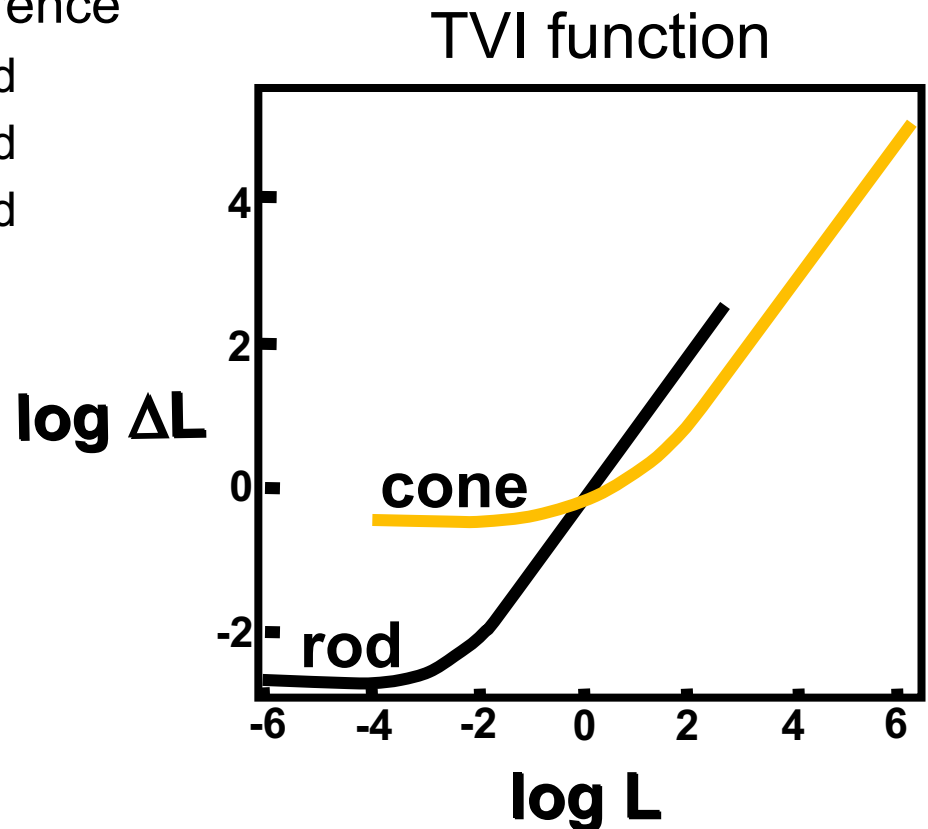
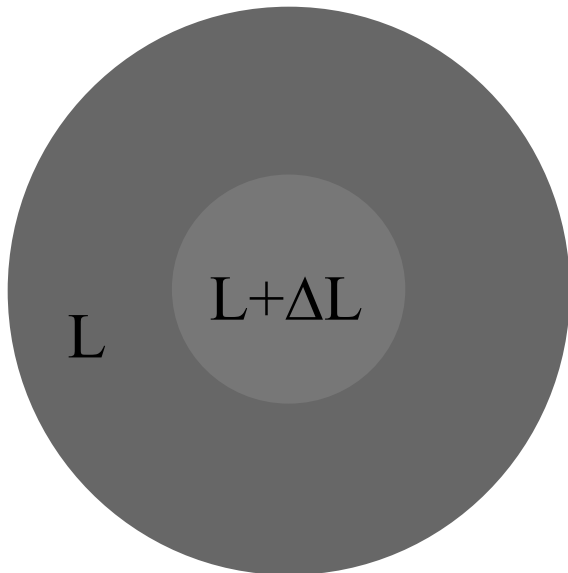
Color Contrast Sensitivity

- **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.

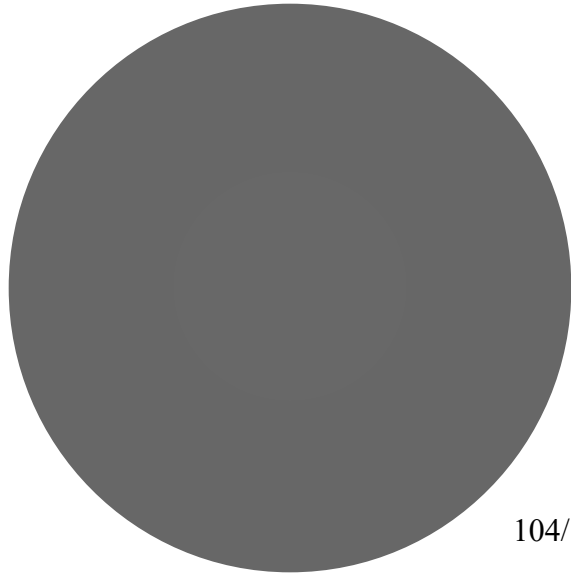


Threshold Sensitivity Function

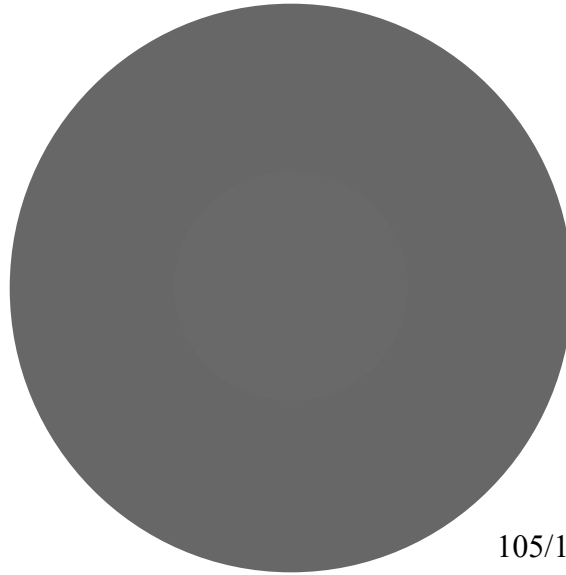
- **Weber-Fechner law (Threshold Versus Intensity, TVI)**
 - Perceived brightness varies linearly with $\log(\text{radiant intensity})$
 - $E = K + c \log I$
 - Perceivable intensity difference
 - 10 cd vs. 12 cd: $\Delta L = 2$ cd
 - 20 cd vs. 24 cd: $\Delta L = 4$ cd
 - 30 cd vs. 36 cd: $\Delta L =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



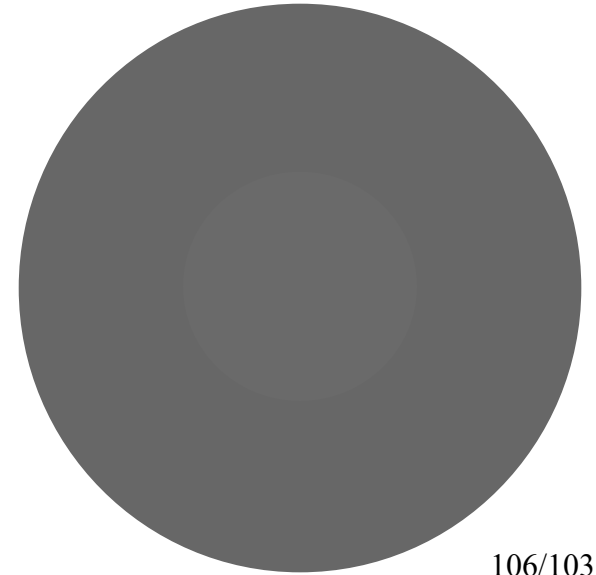
Weber-Fechner Examples



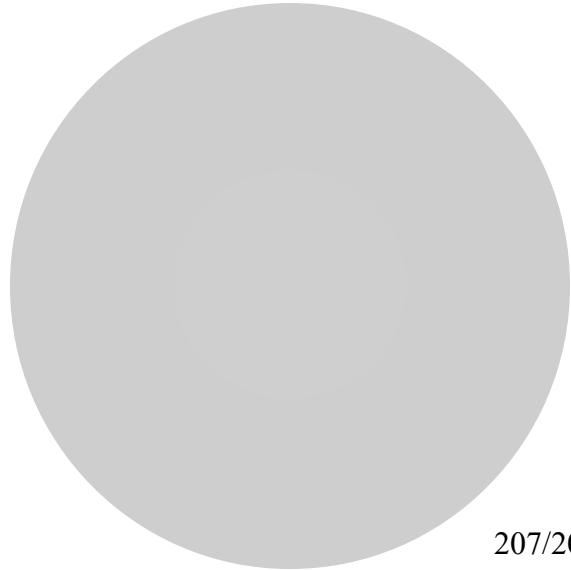
104/103



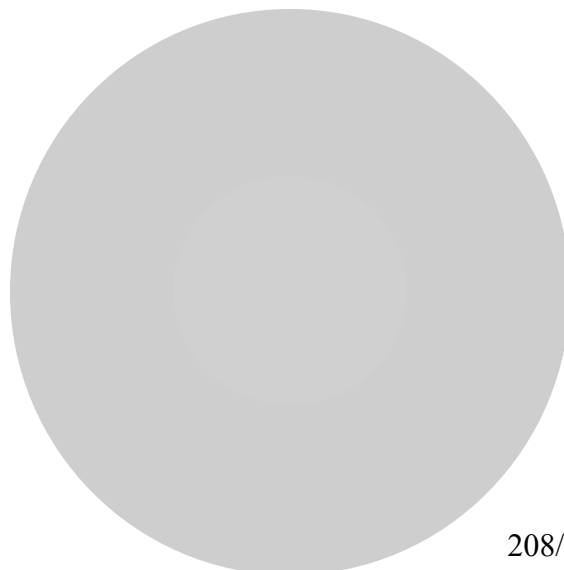
105/103



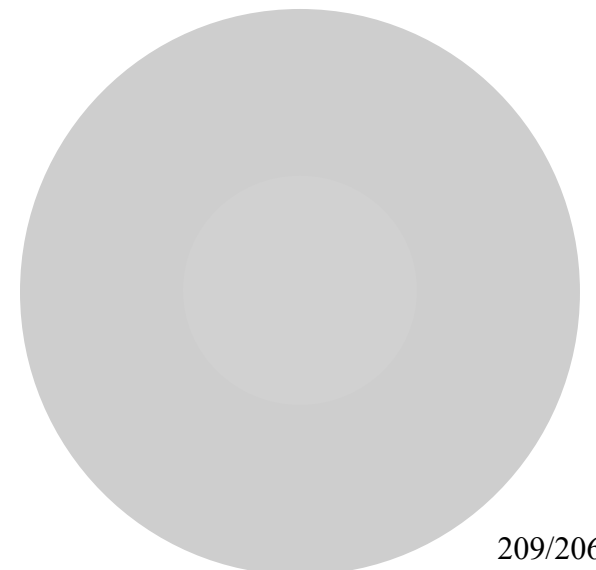
106/103



207/206



208/206

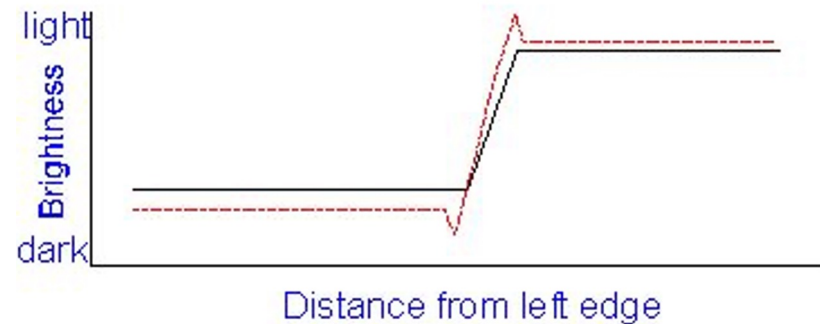
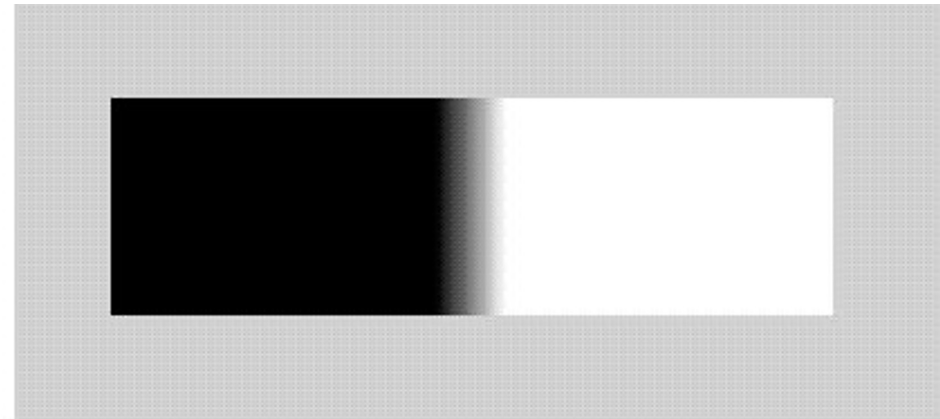


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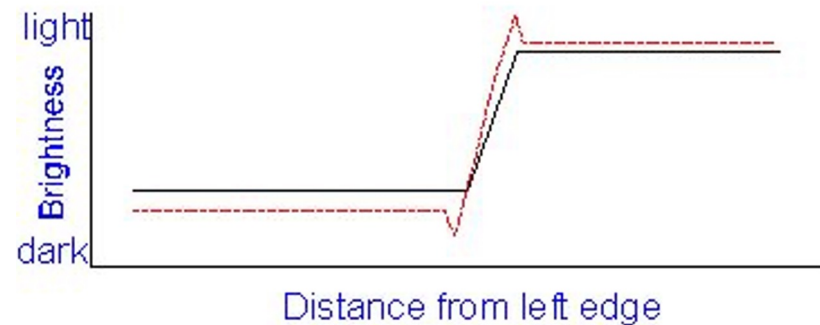
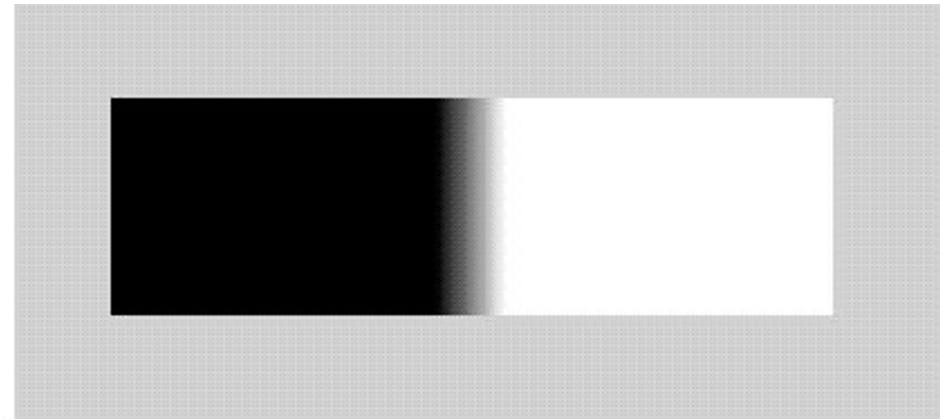
Mach Bands

- **“Overshooting” along edges**
 - Extra-bright rims on left sides
 - Extra-dark rims on right sides
- **Due to “lateral inhibition”**



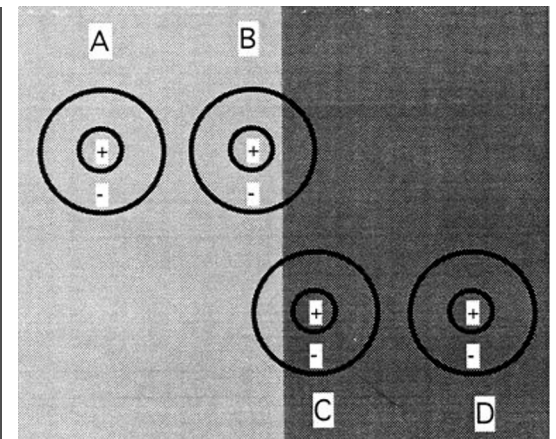
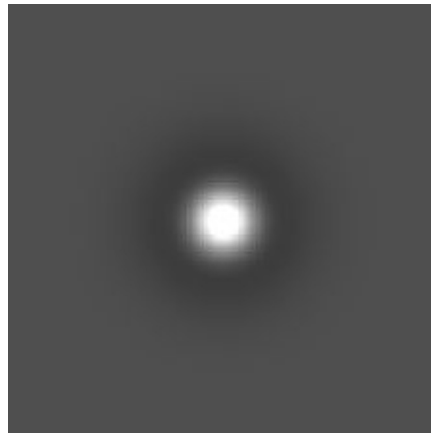
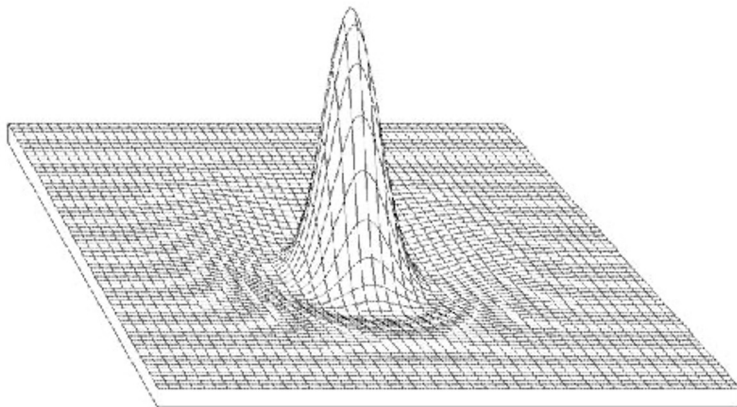
Mach Bands

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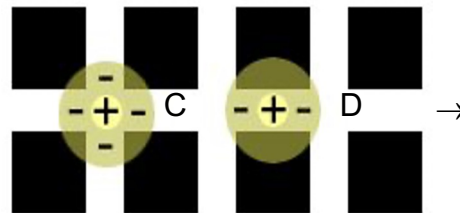
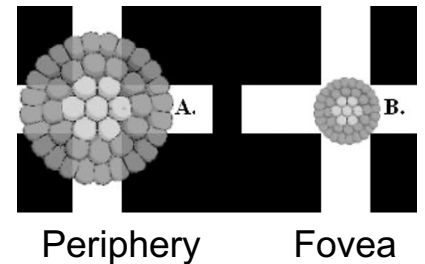
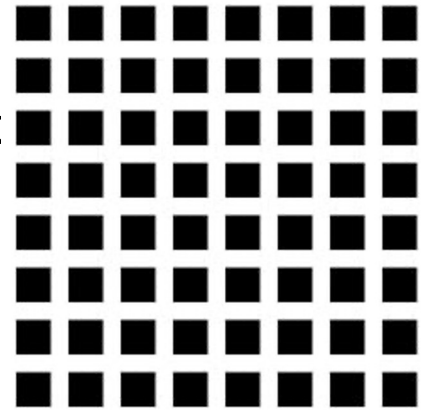
Lateral Inhibition

- **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 two Gaussian)

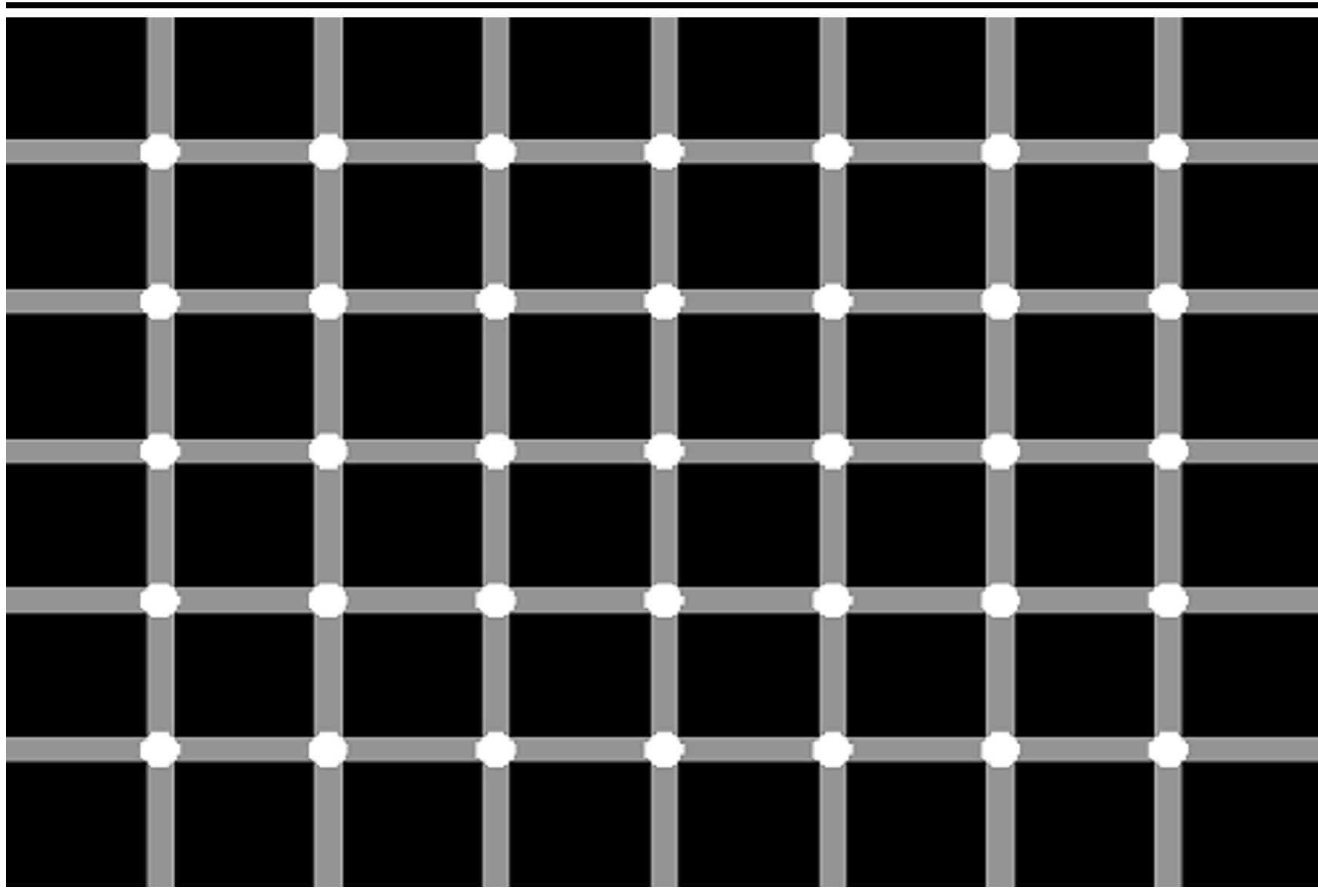


Lateral Inhibition: Hermann Grid

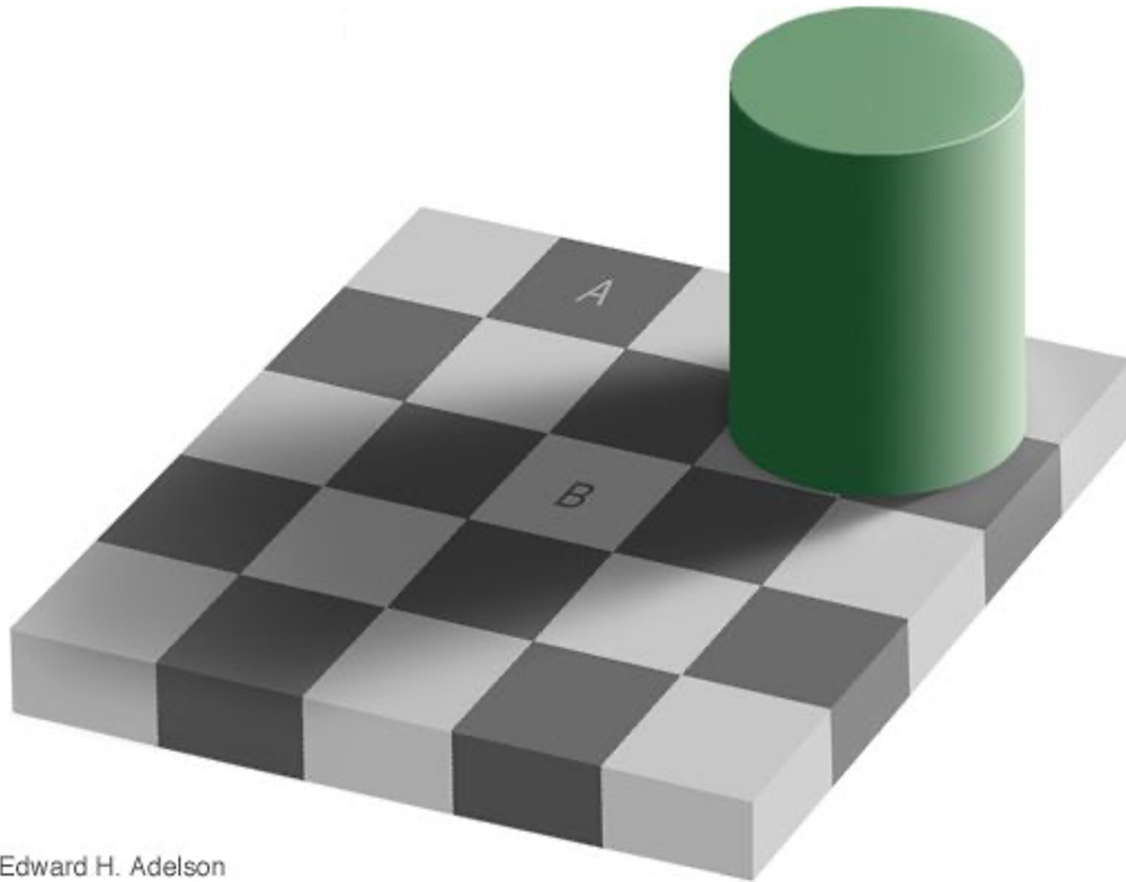
- **Apparent dark spots at perip. crossings**
 - Weakly if within foveal Ω (B): smaller filter extent
 - Strongly within periphery (A): larger filter extent
- **Explanation**
 - Crossings (C): more surround stimulation
 - More inhibition \Rightarrow weaker response
 - Streets (D): less surround stimulation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



Some Further Weirdness

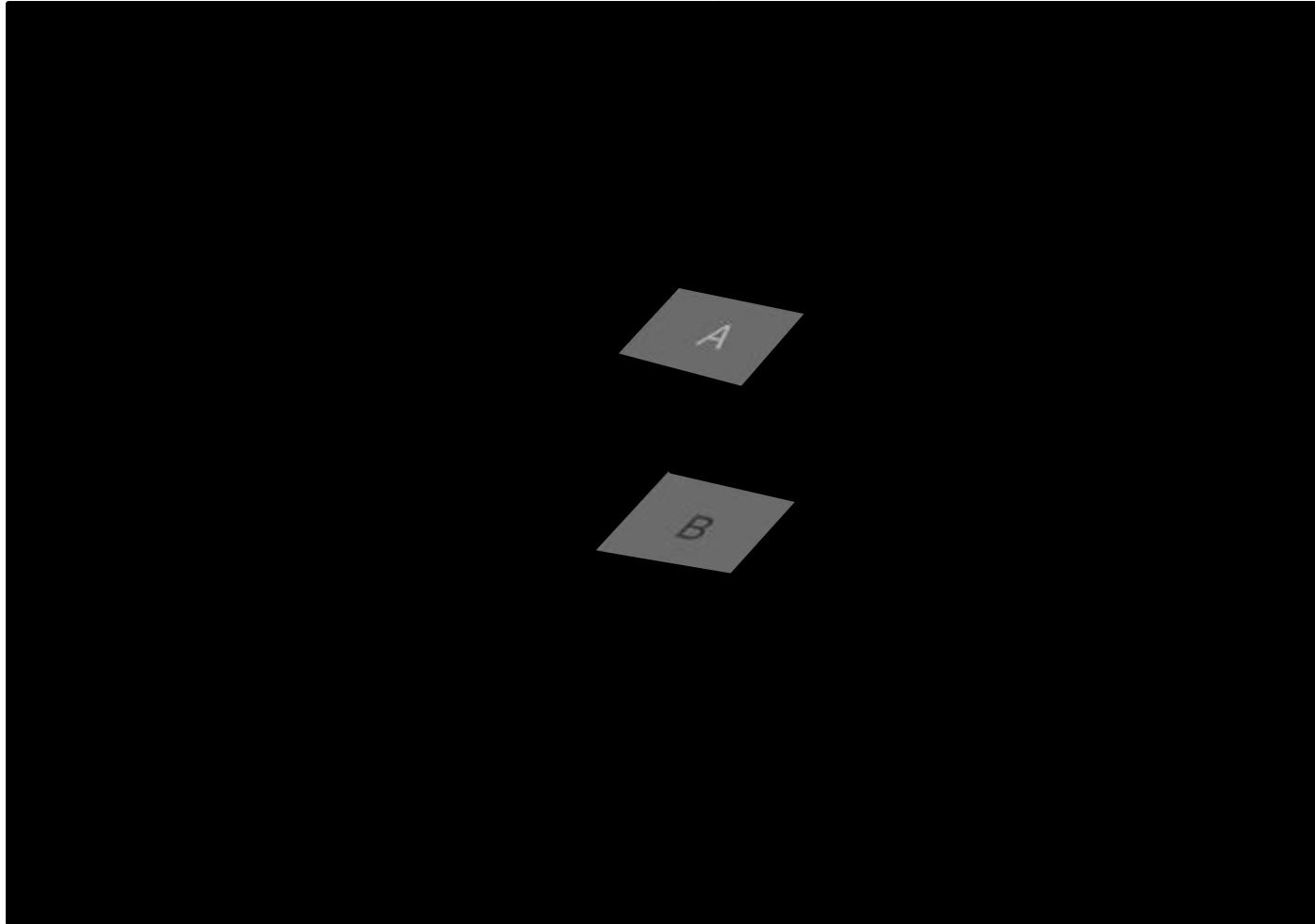


High-Level Contrast Processing



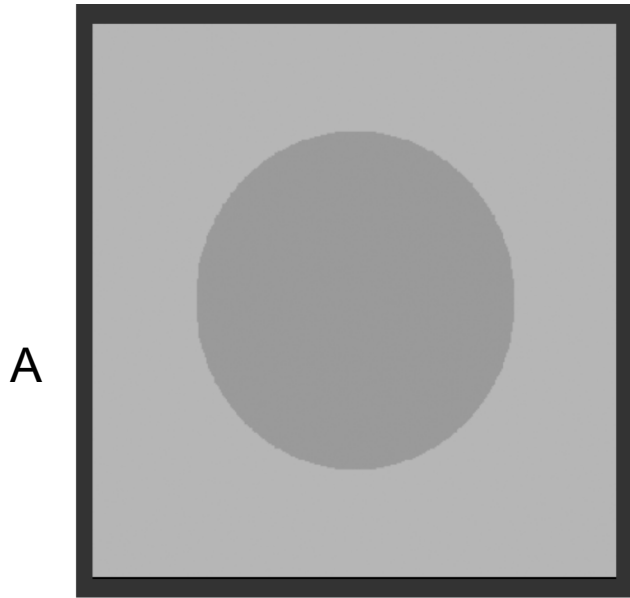
Edward H. Adelson

High-Level Contrast Processing



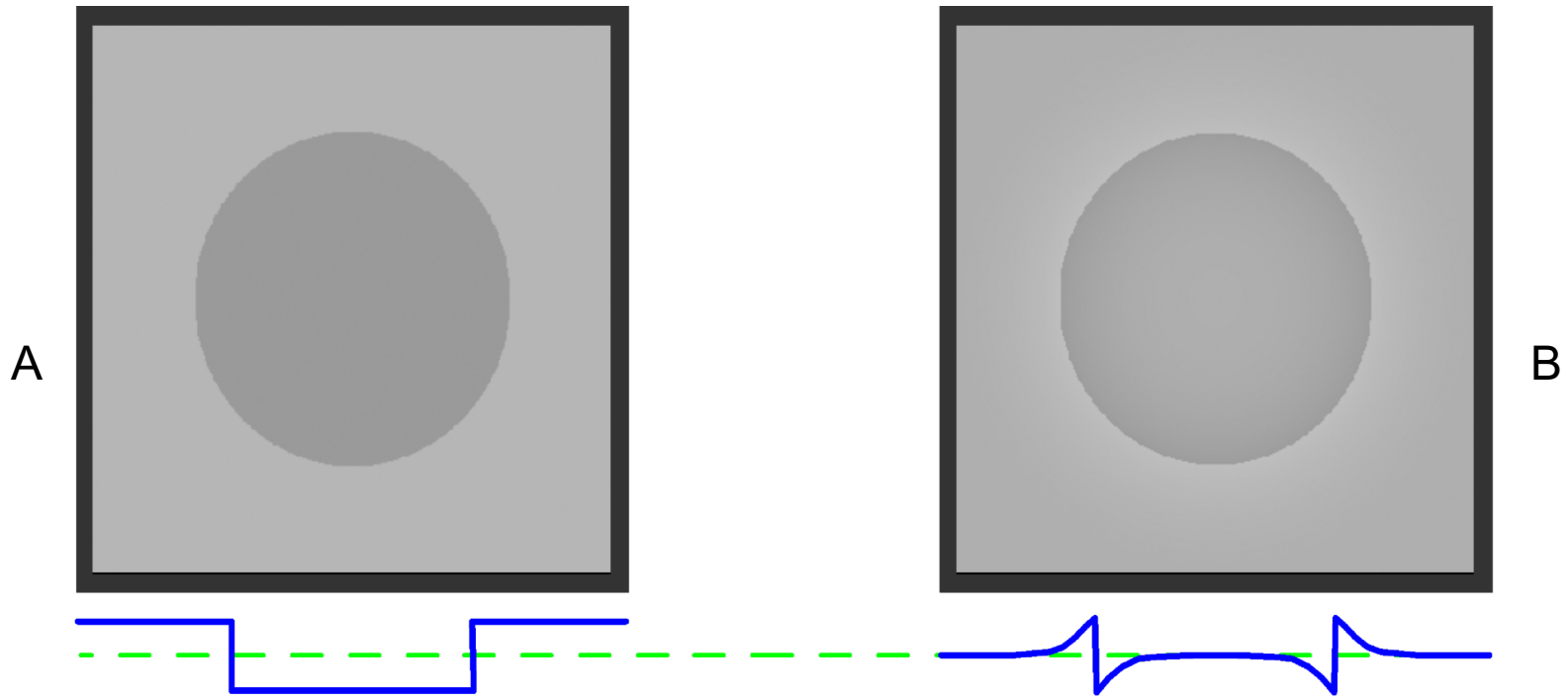
Cornsweet Illusion

- Apparent contrast between inner and outer shades



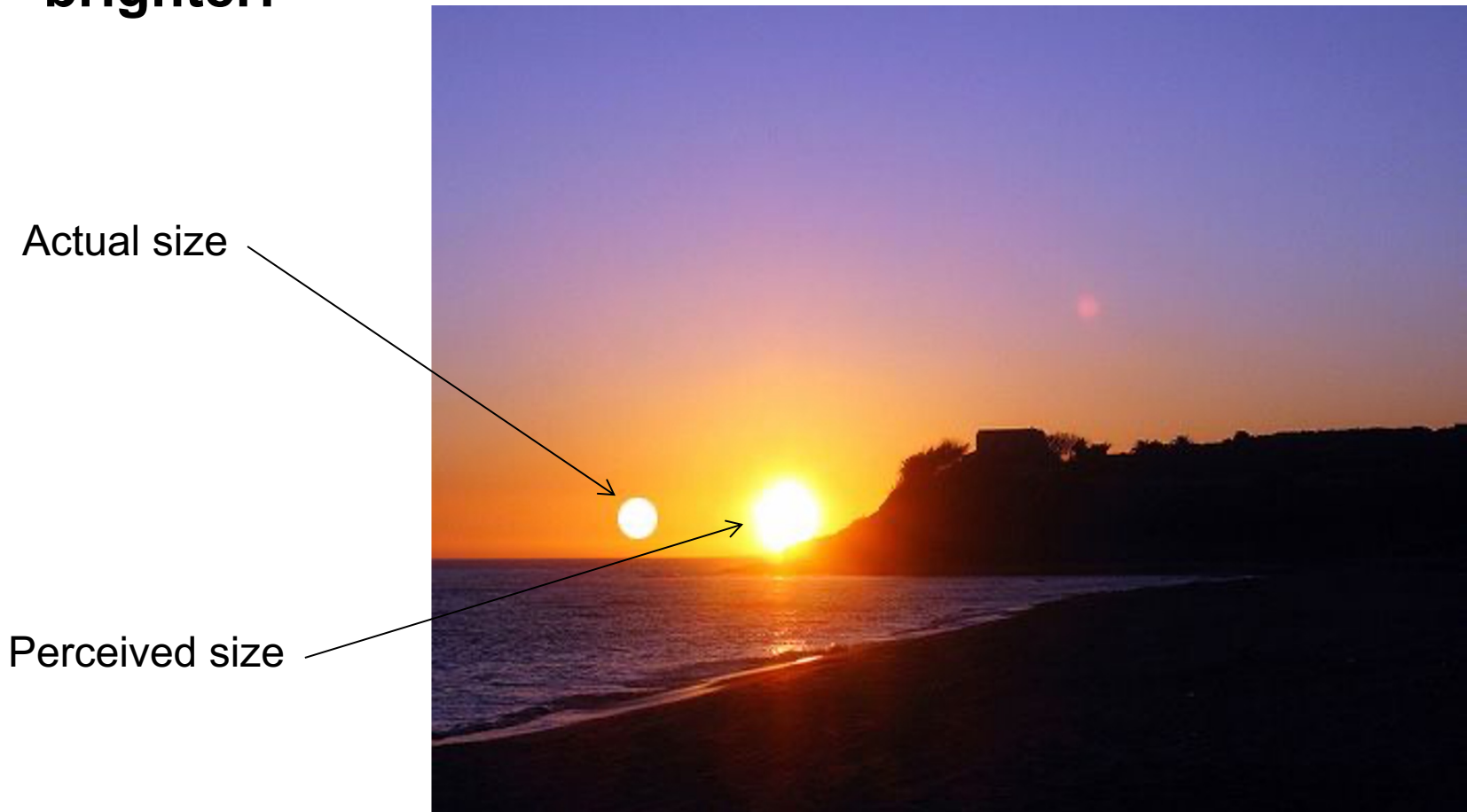
Cornsweet Illusion

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



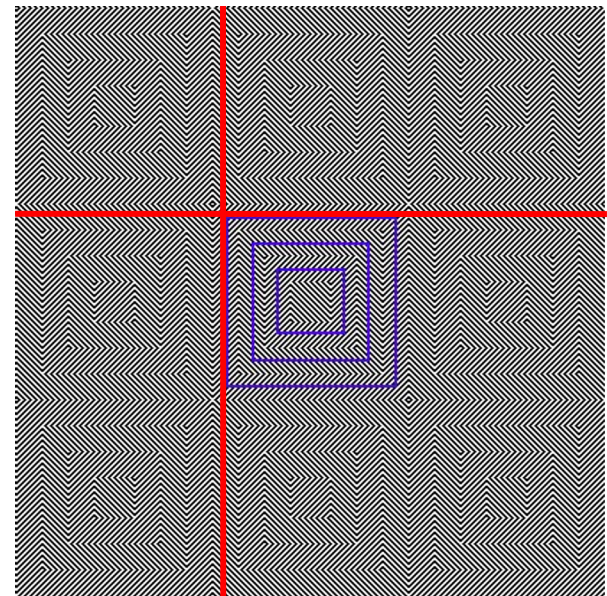
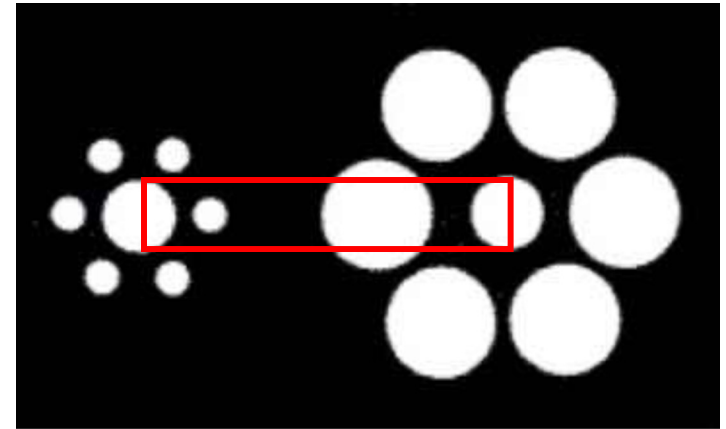
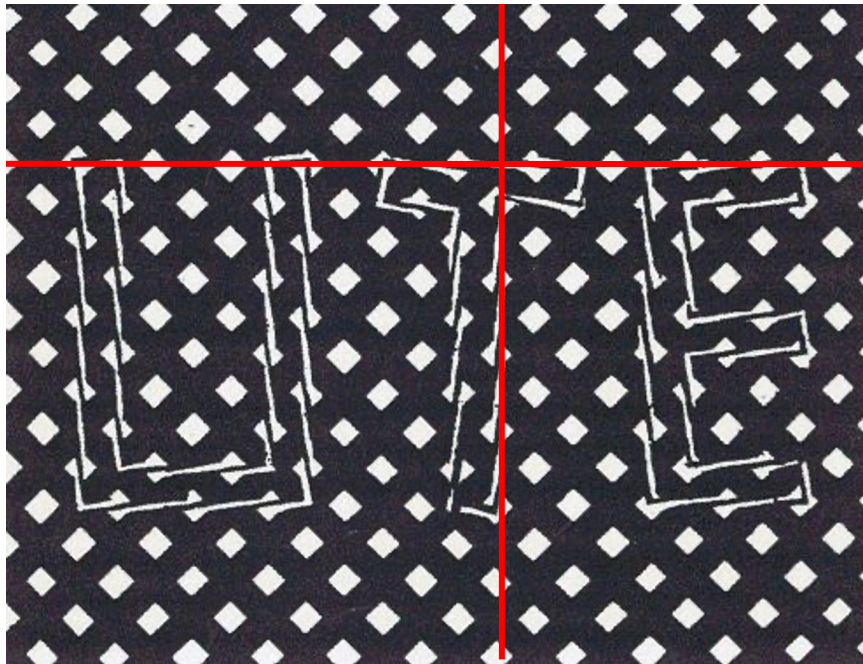
Optical Effects – Veiling Glare

- **Internal scattering/blur of sources of high luminance**
- **Blur around the bright object makes it appear brighter!**



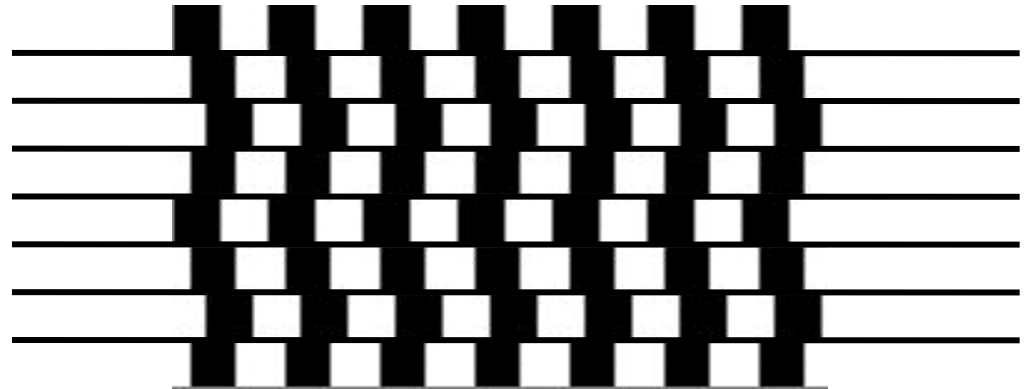
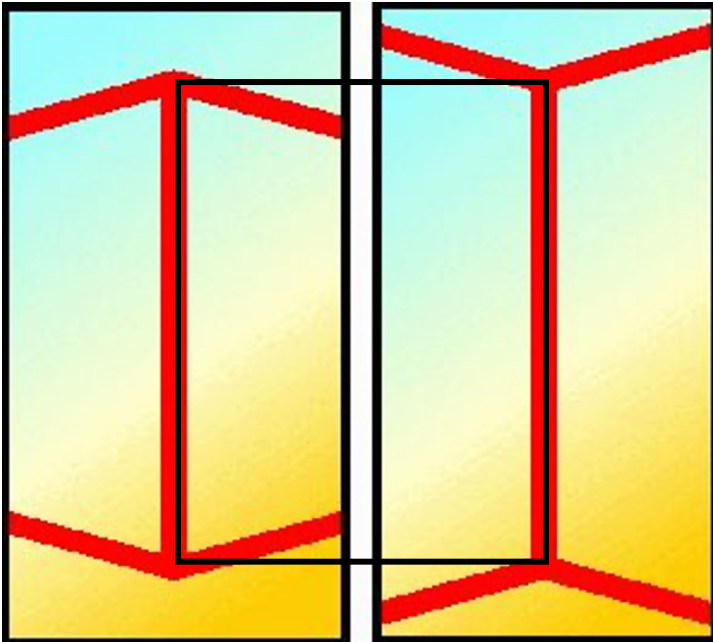
Shape Perception

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



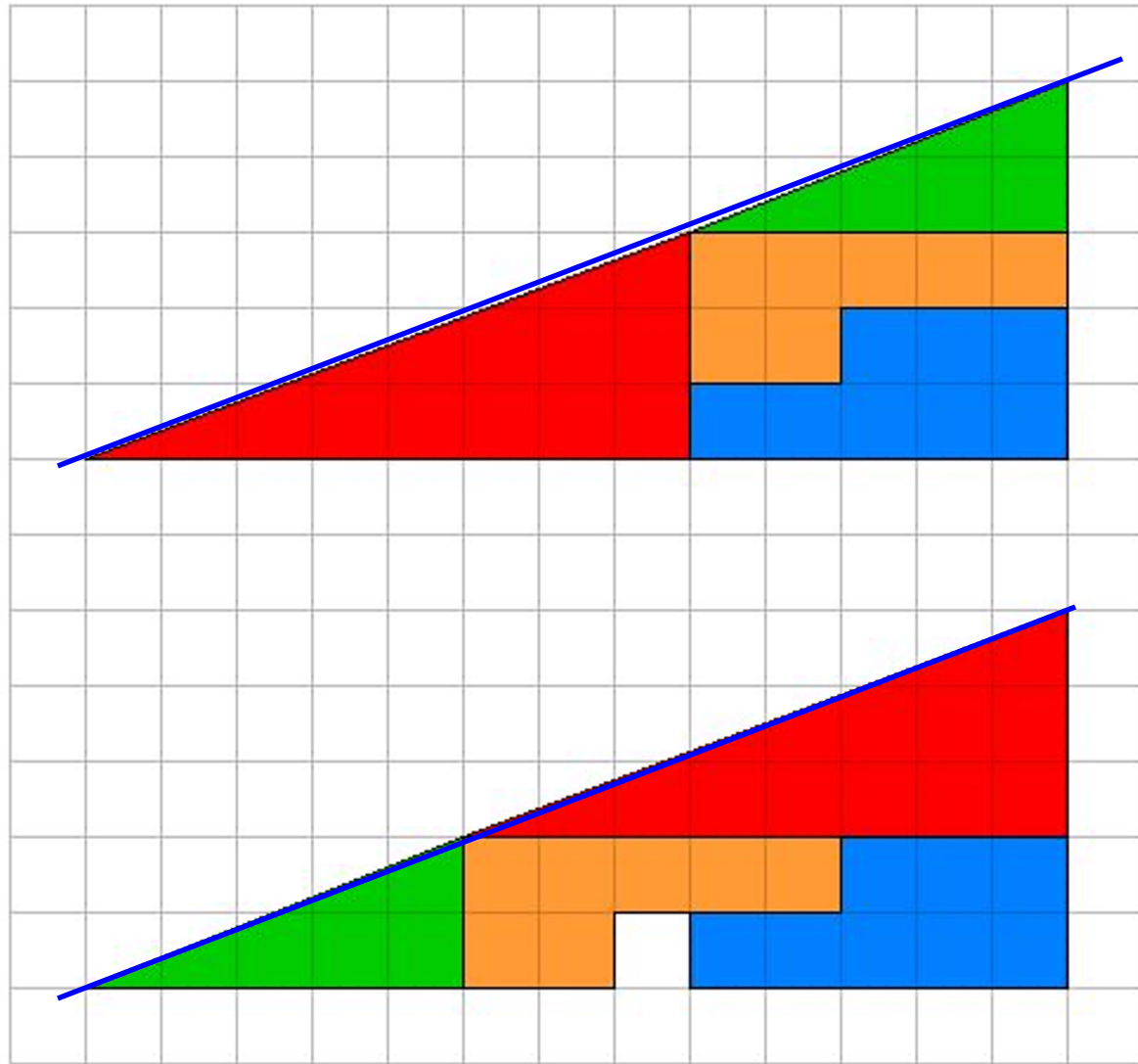
Geometric Cues

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



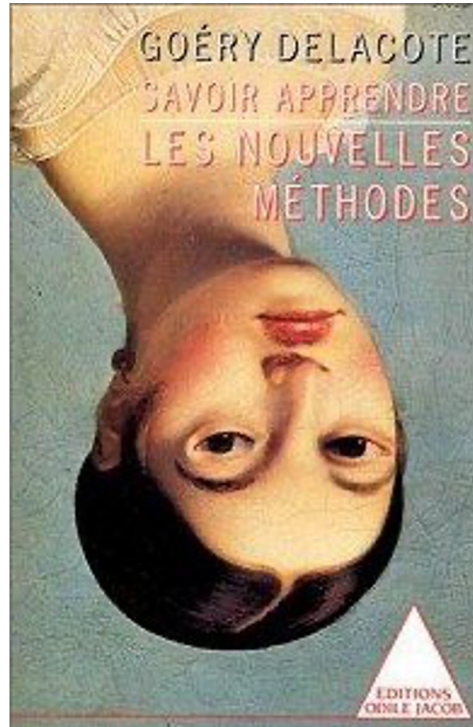
<http://www.panoptikum.net/optischetaeusungen/index.html>

Visual “Proofs”



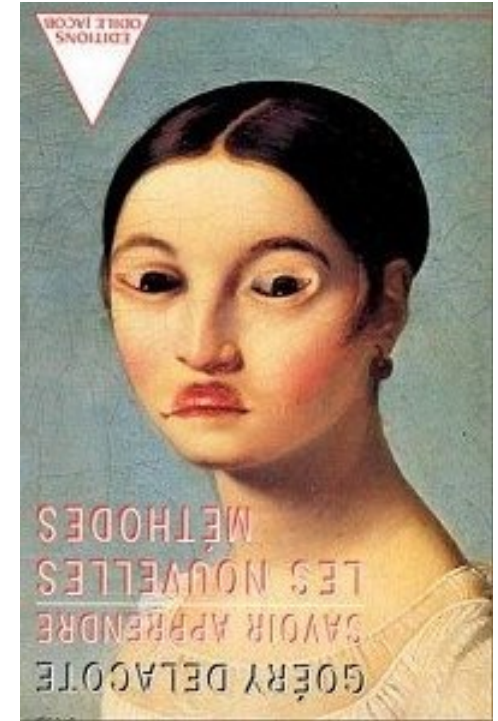
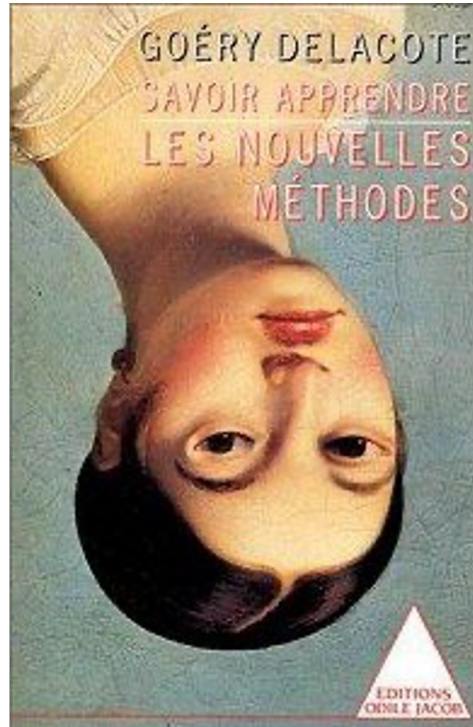
HVS: High-Level Scene Analysis

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



HVS: High-Level Scene Analysis

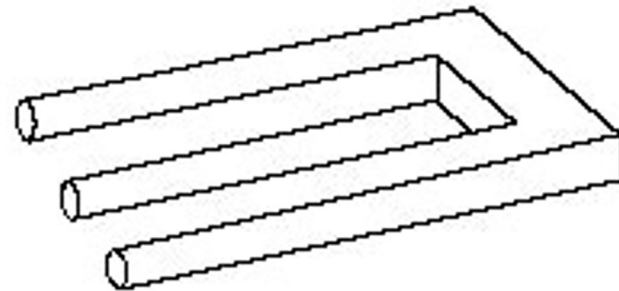
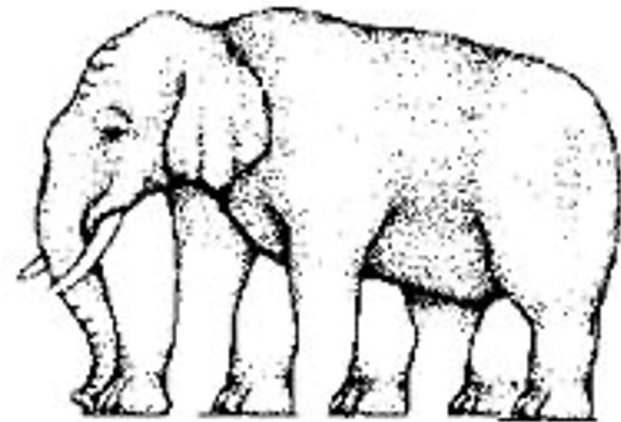
- **Experience & expectation**
 - Pictures usually horizontal
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Impossible Scenes

- **Escher et al.**

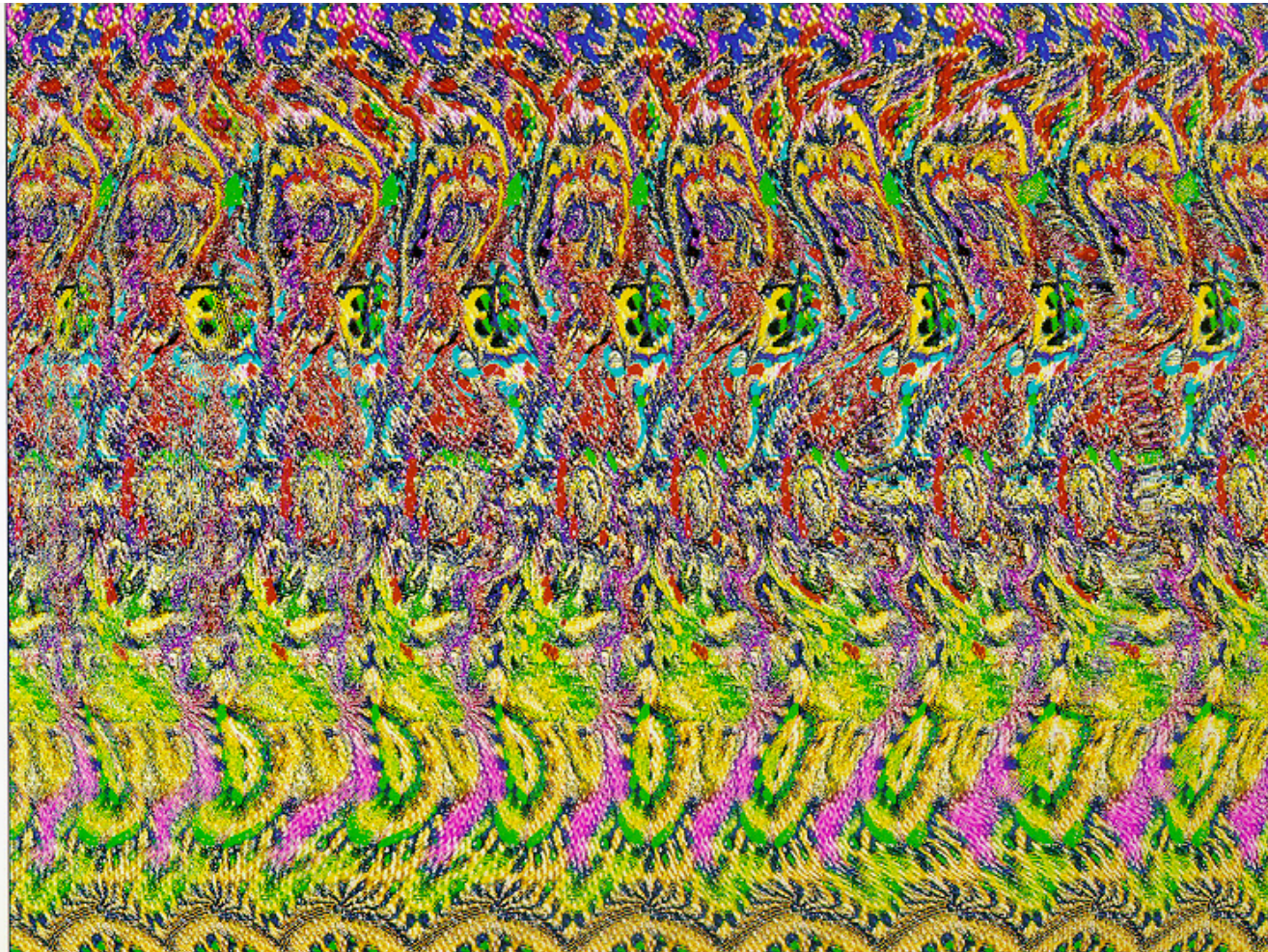
- Confuse HVS by presenting contradicting visual cues
- Locally consistent but not globally



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

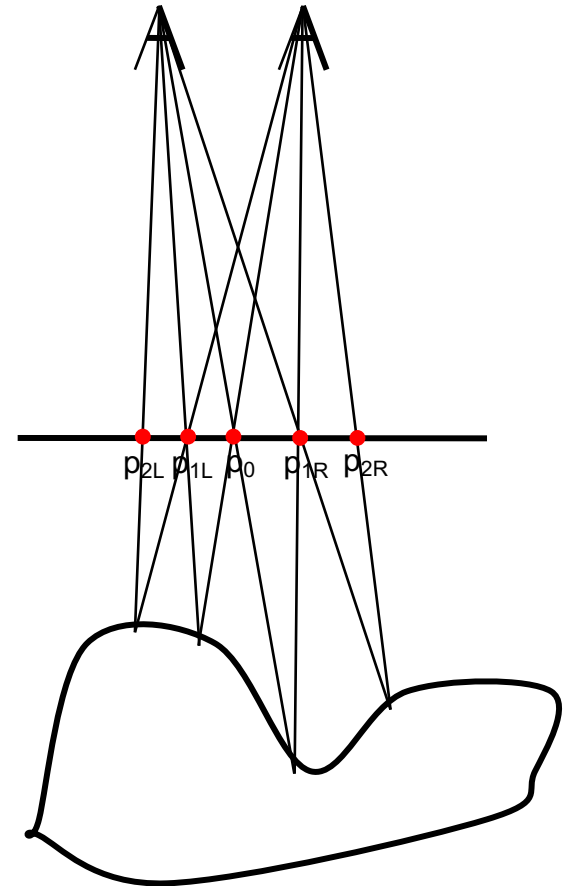
Single Image Random Dot Stereograms

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

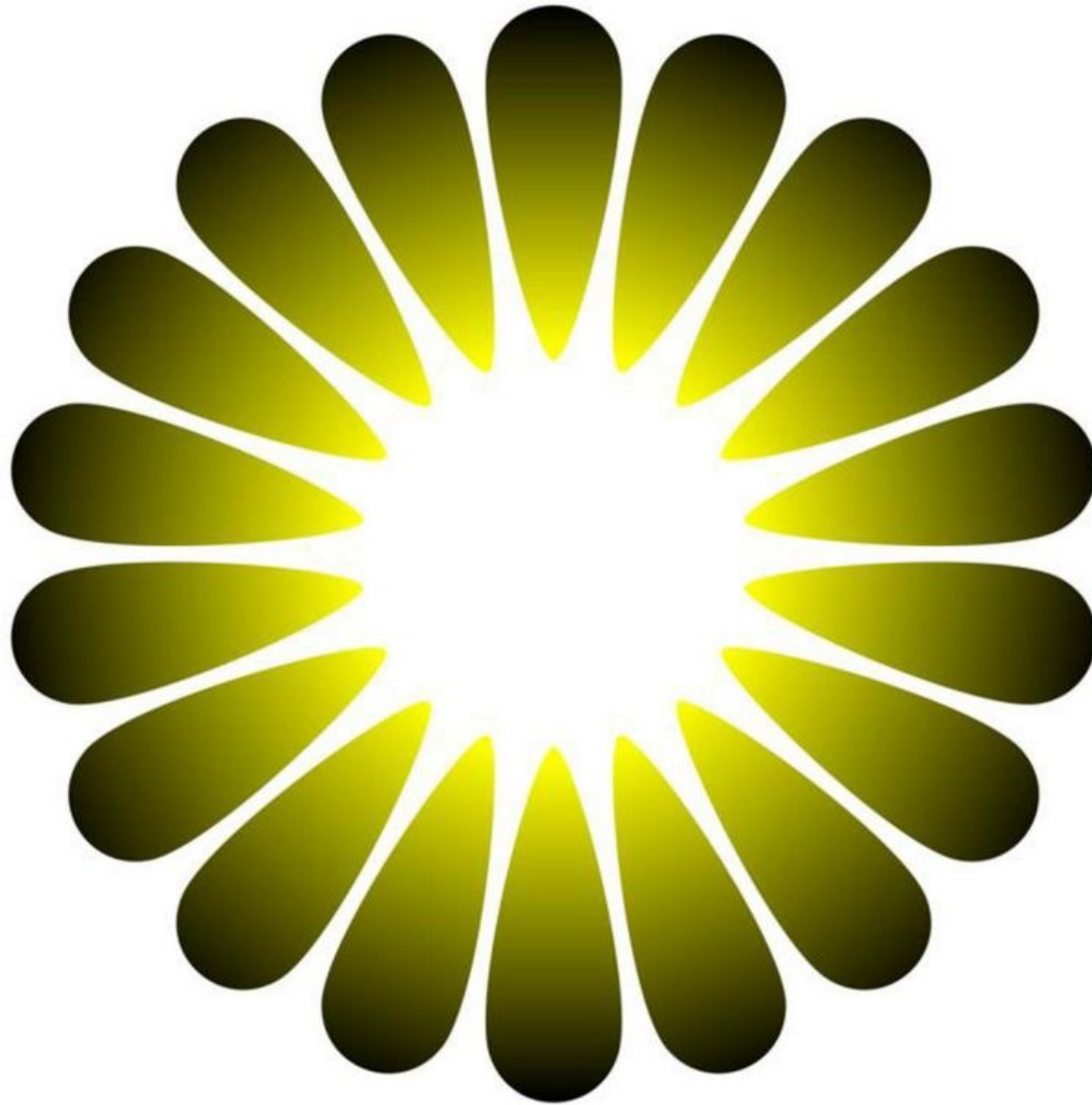


SIRDS Construction

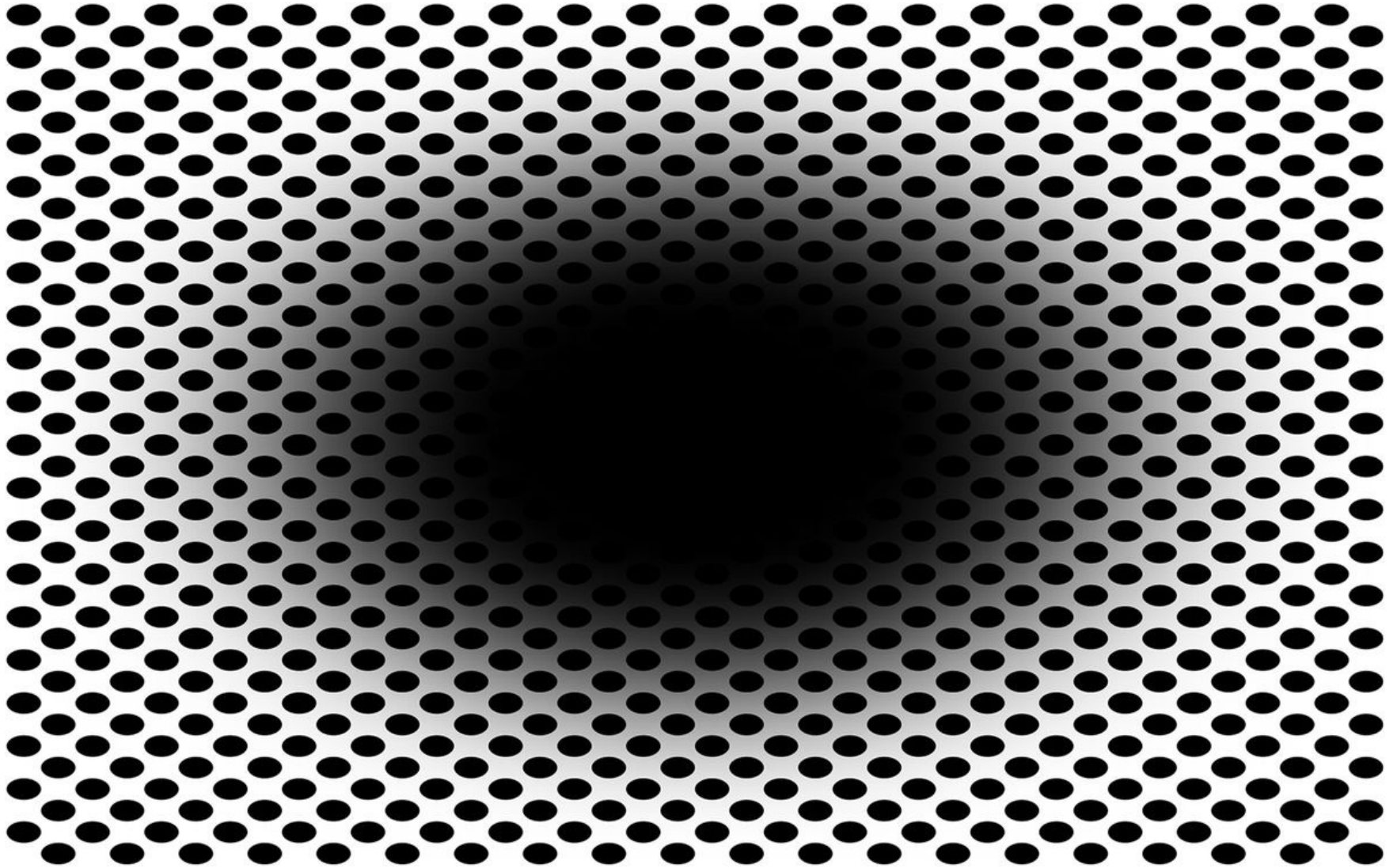
- Assign arbitrary color to pixel p_0 in image plane
- Trace from eye points through p_0 to object surface
- Trace back from object to corresponding other eye
- Assign color at p_0 to intersection points p_{1L}, p_{1R} with image plane
- Trace from eye points through p_{1L}, p_{1R} to object surface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



Asahi Illusion

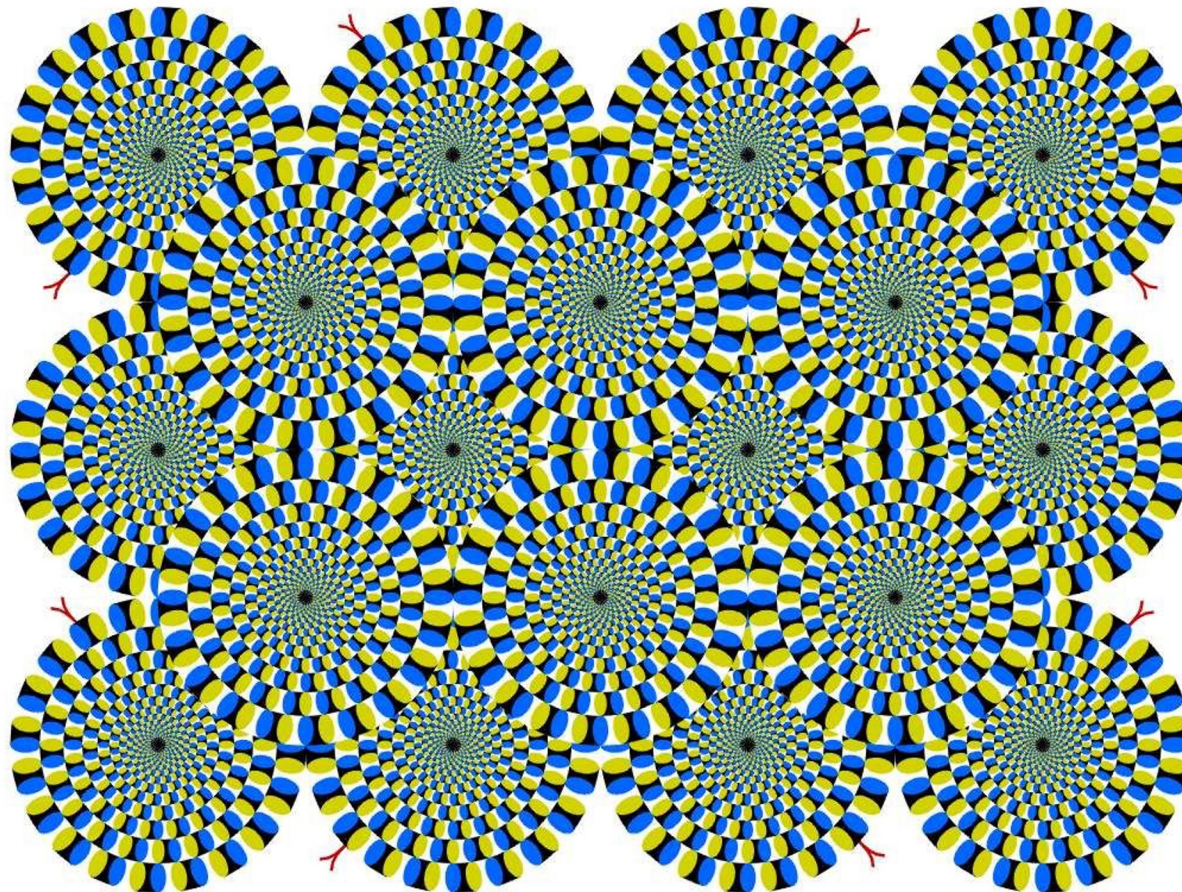


Asahi Illusion

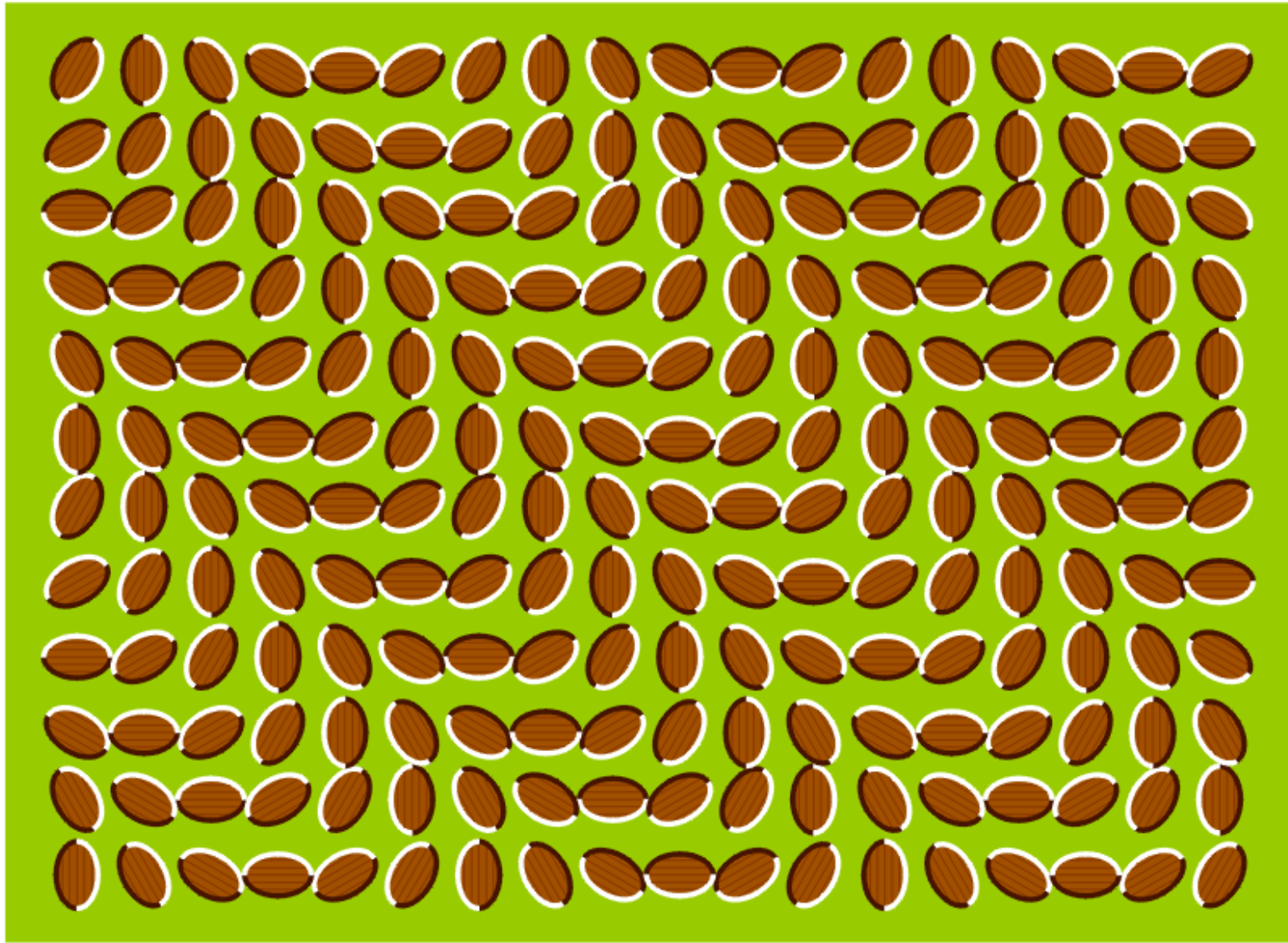


Motion Illusion

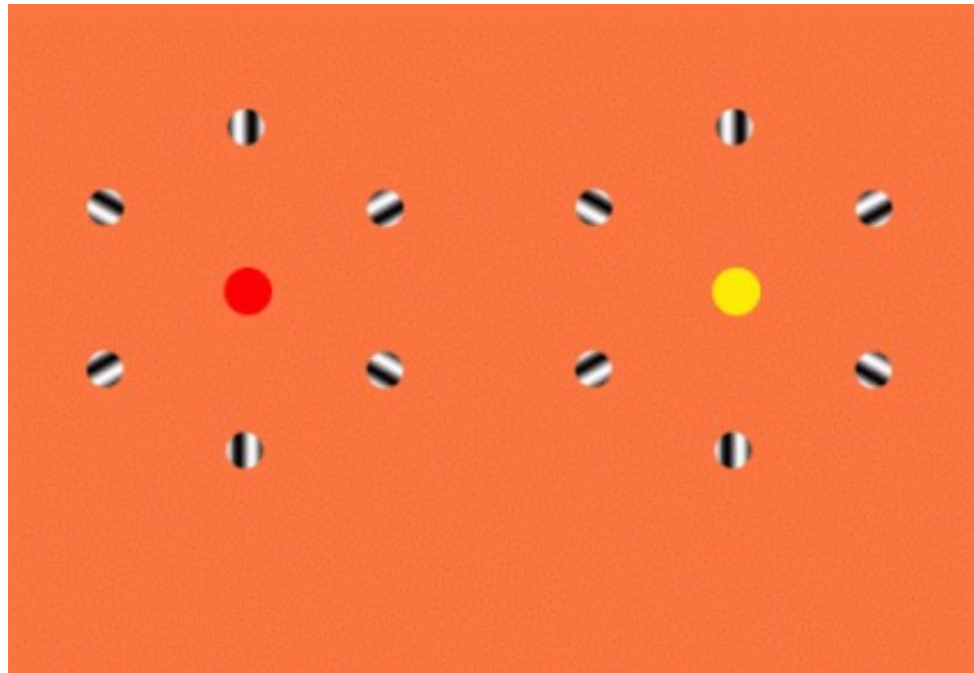
- **Appearance of movement in static image**
 - Due to cognitive effects of interacting color contrast & shape pos.
 - Saccades → diff. in neural signals between dark and bright areas



Motion Illusion

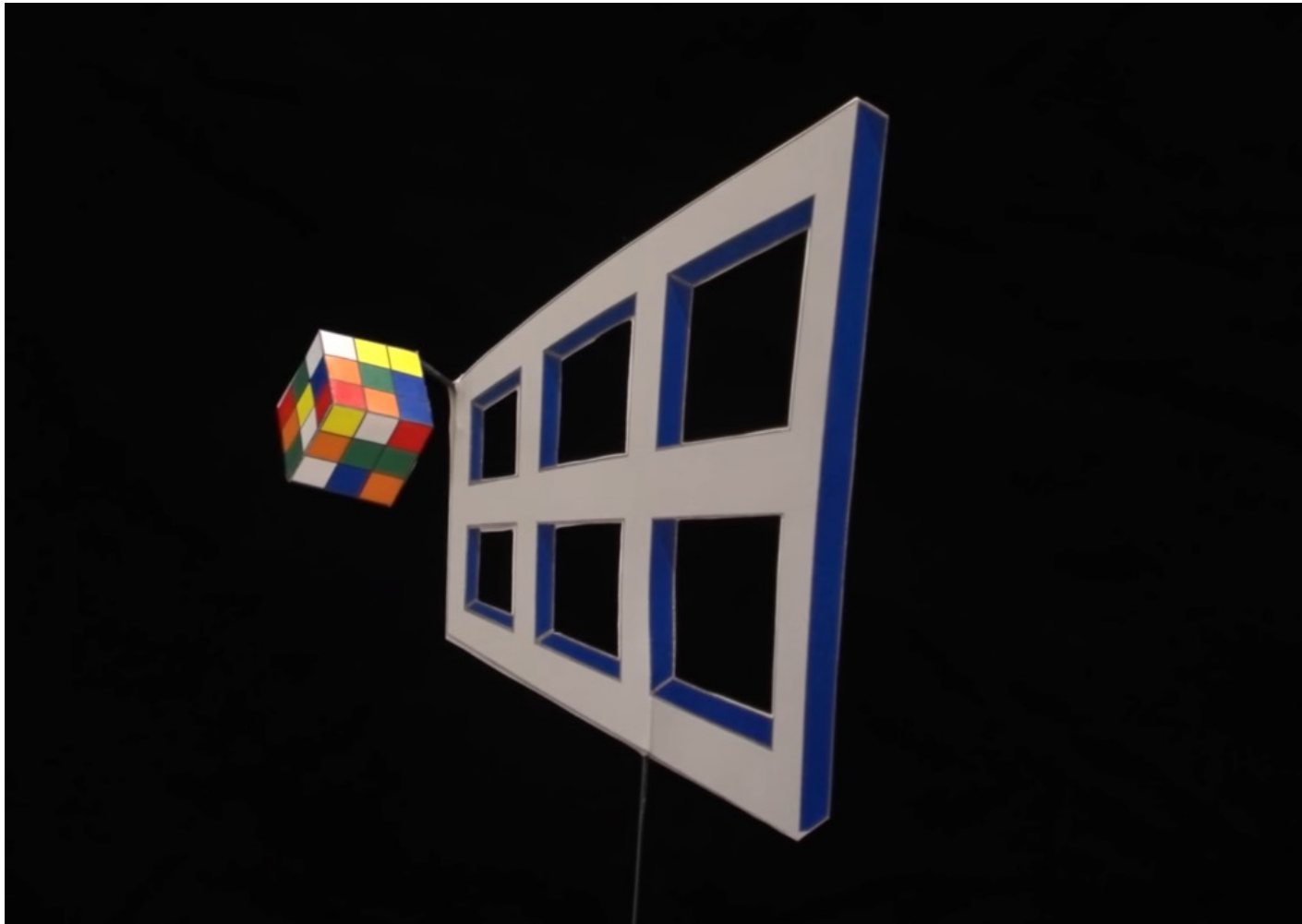


Motion Illusion



Ames Window Illusion

- https://www.youtube.com/watch?v=dBap_Lp-0oc



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

