Lecture 9:

The Human Visual System

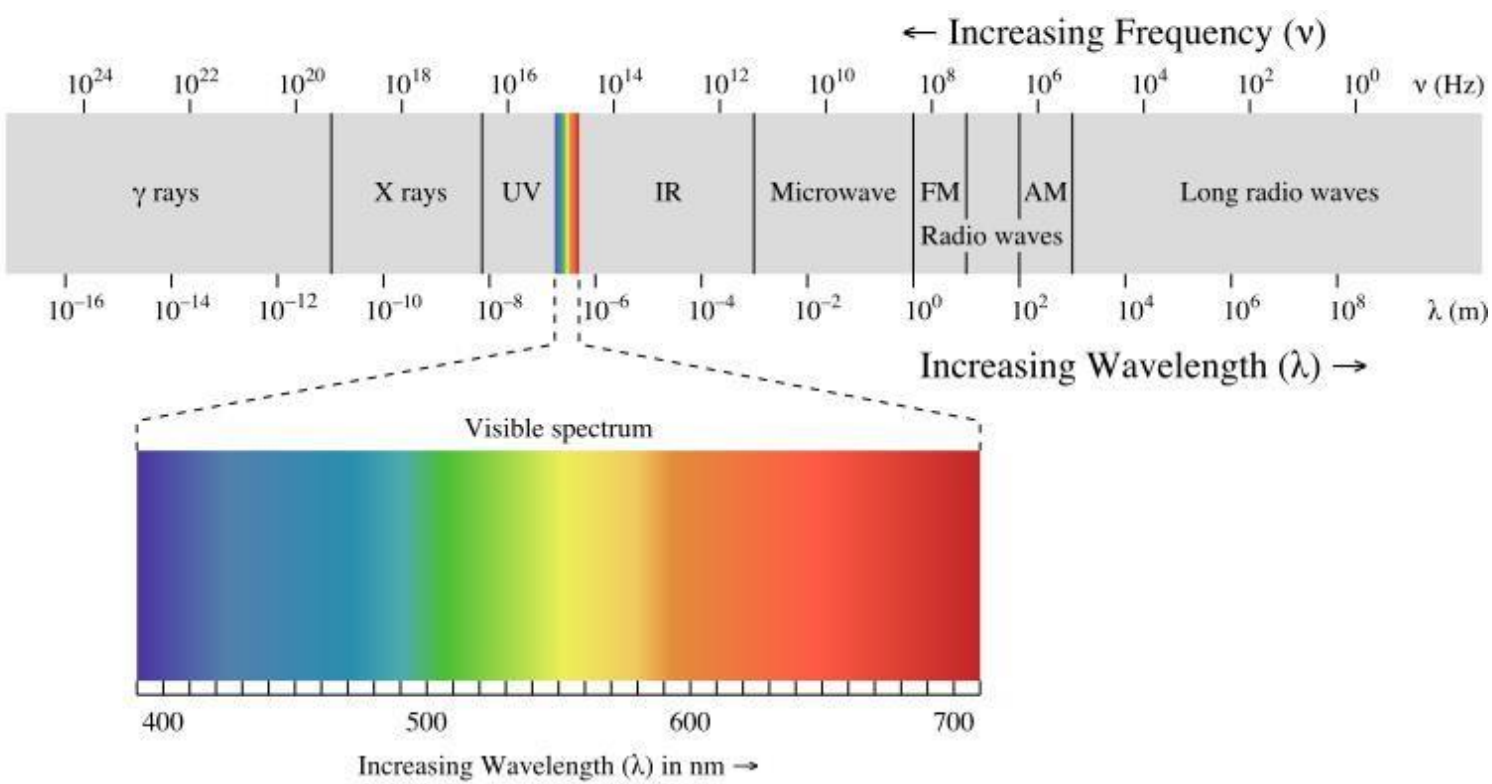
Contents

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



Physical model for light

- Wave / particle – dualism
    - Electromagnetic radiation wave model
    - Photons: $E_{ph} = hv$ → particle model & ray optics (h: Planck constant)
- *Plenoptic function* defined at any point in space
    - $L = L(x, \omega, t, v, \gamma)$ → 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

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 (radian exitance)
Intensity	$dQ/d\omega dt$	I_e	[W/sr]	Radiant intensity
	$dQ/dAd\omega dt$	L_e	[W/(m^2·sr)]	Radiance

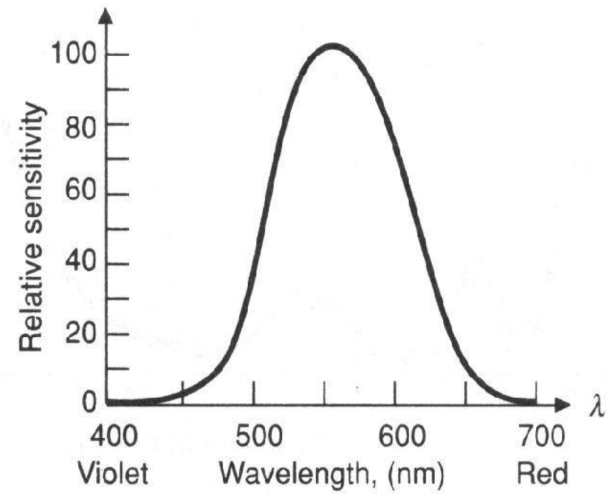
Equivalent units to radiometry

- Weighted with *luminosity function* $V(\lambda)$ (a.k.a. *luminous efficiency function*)
- 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

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

$$K_m = 680\ {}^{lm}/_{W}$$

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



luminosity function $V(\lambda)$

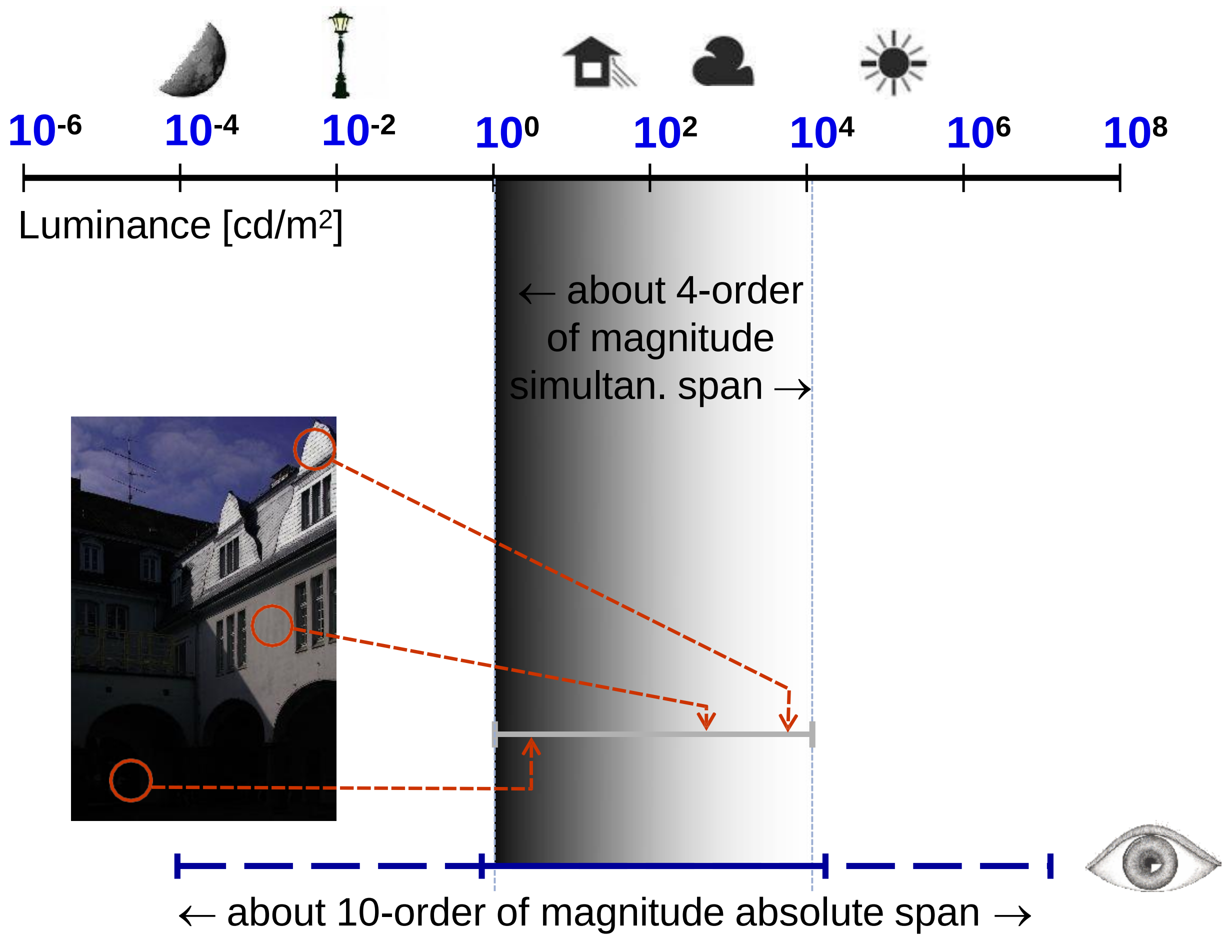
Photometric Units

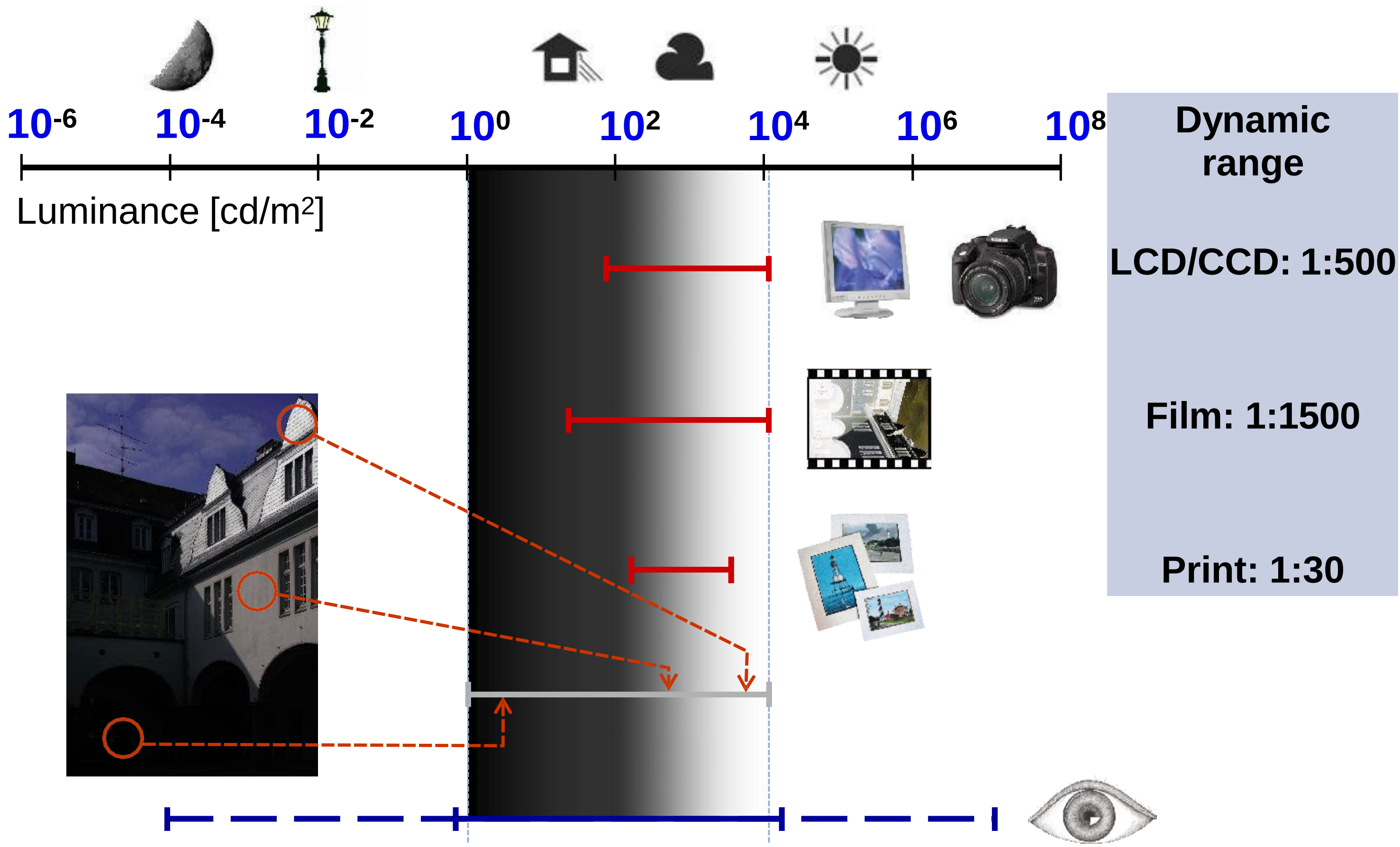
Specification	Definition	Symbol	Unit	Quantity
Energy		Q_v	[T = lm·s] (talbot)	Luminous energy
Power, flux	dQ/dt	Φ_v	[lm = T/s] (lumen)	Luminous flux (*e.g.* emitted power of lamp)
Flux density	$dQ/dAdt$	E_v	[lx = lm/m^2] (lux)	Illuminance
Flux density	$dQ/dAdt$	B_v	[lx = lm/m^2] (lux)	Luminosity (*e.g.*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

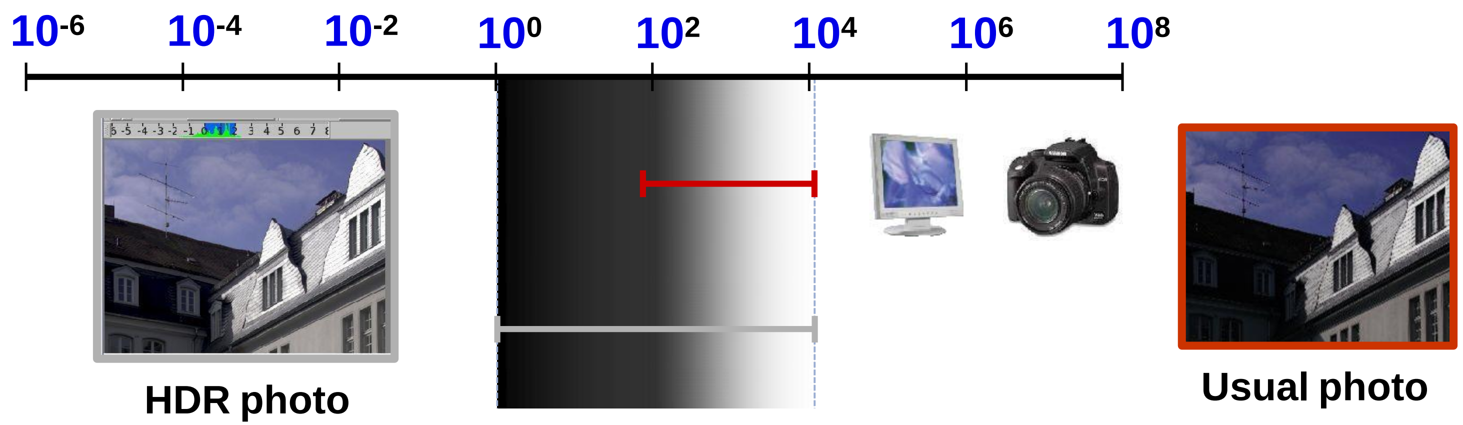
Typical illumination intensities:

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

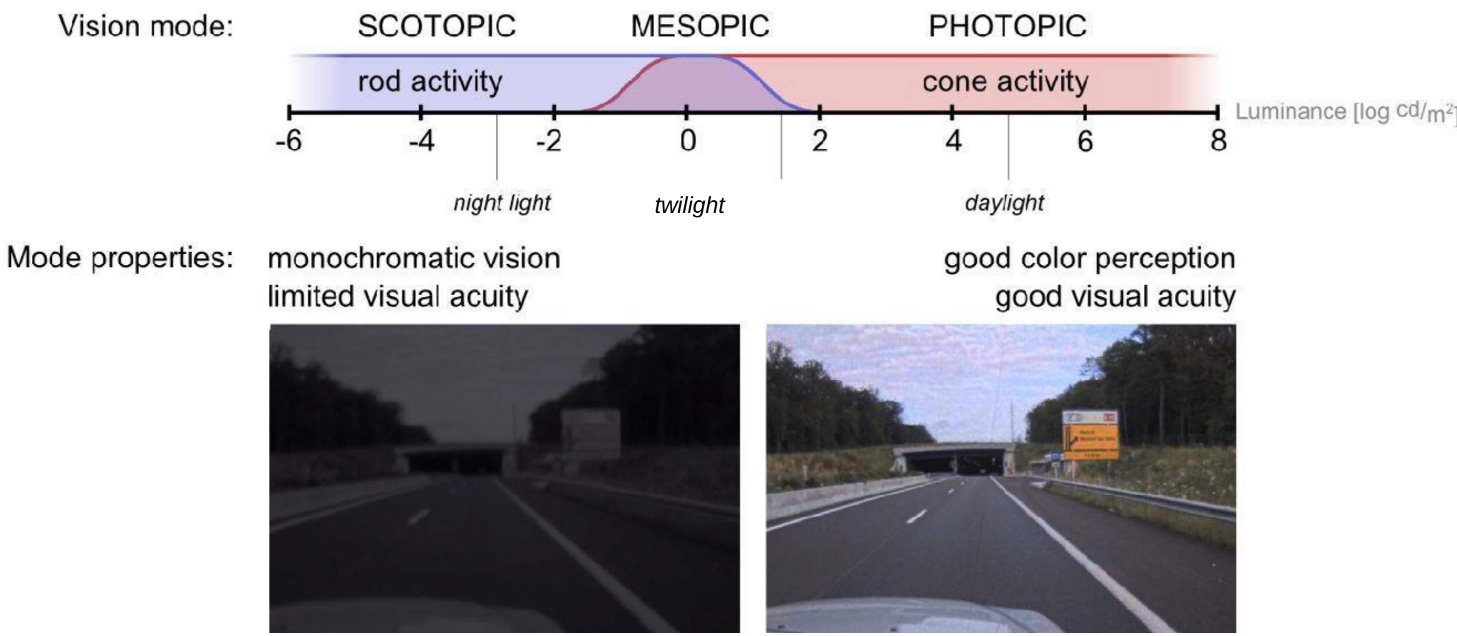



10-6
10-4
10-2
100
102
104
106
108
Luminance [cd/m2]
Dynamic range
LCD/CCD: 1:500
Film: 1:1500
Print: 1:30



How to display computed / measured HDR values on an LDR device ?

- Tone mapping



Simulation requires:

- Control over color reproduction
- Local reduction of detail visibility (computationally expensive)

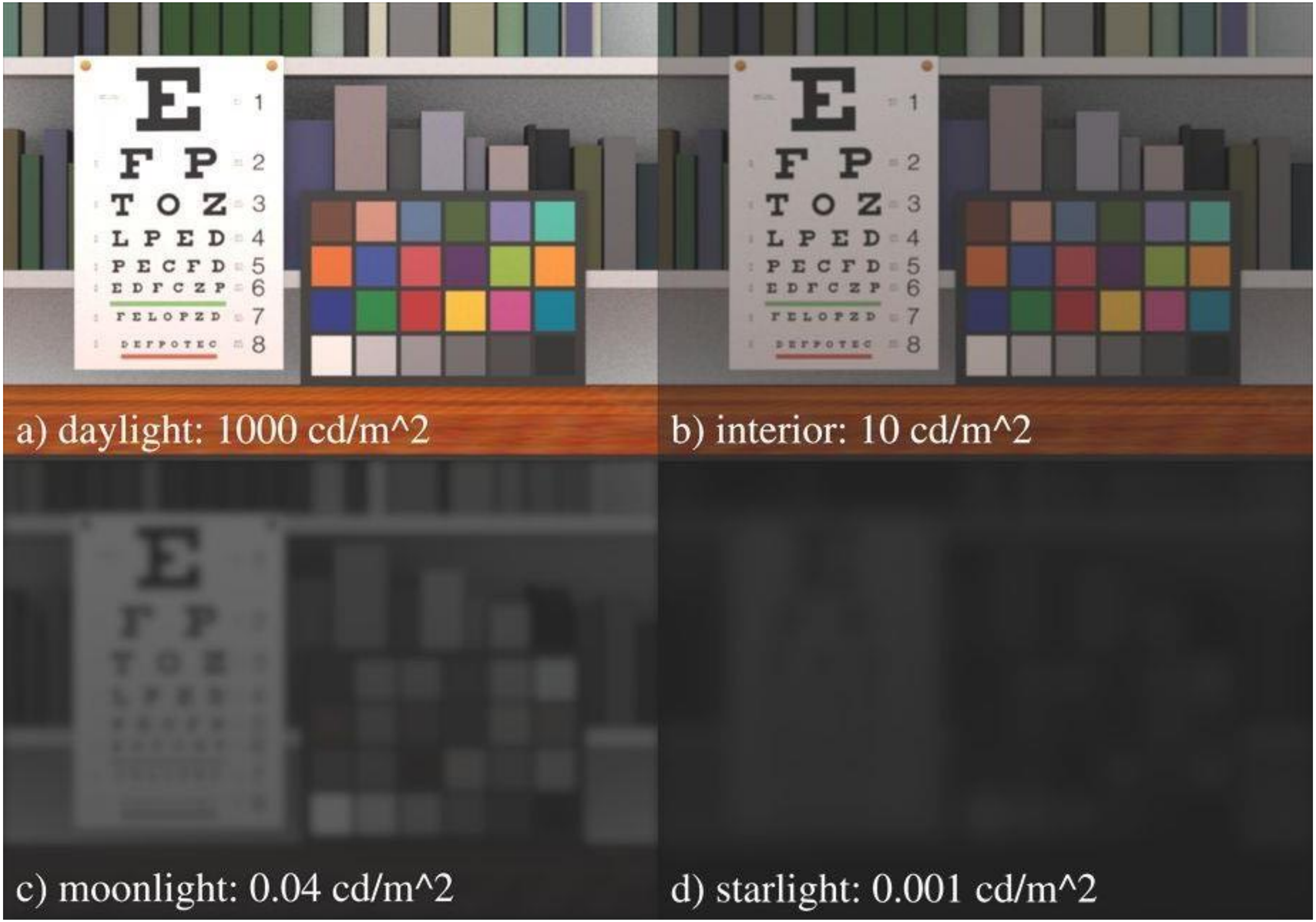
Visual Acuity and Color Perception

Photopic vision

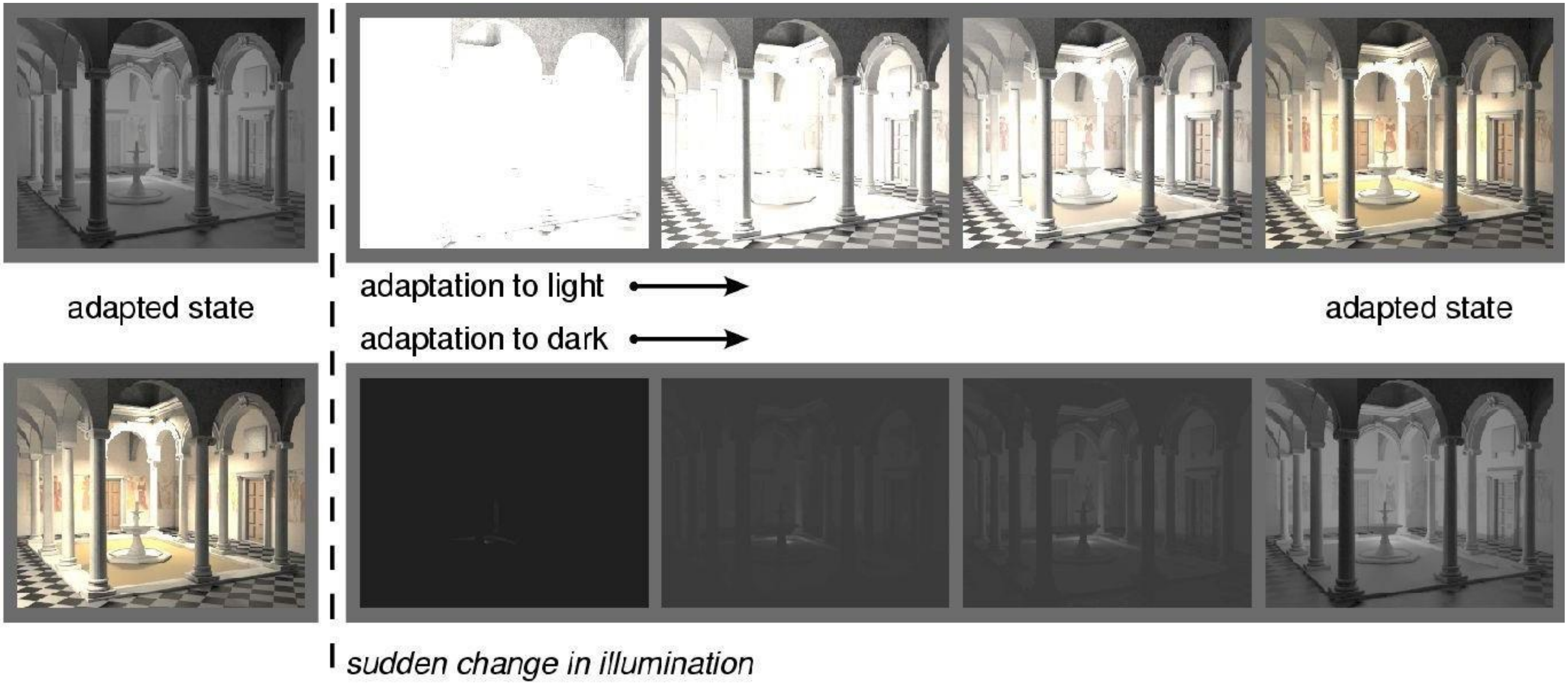
Mesopic / photopic transition

Scotopic / mesopic transition

Scotopic vision

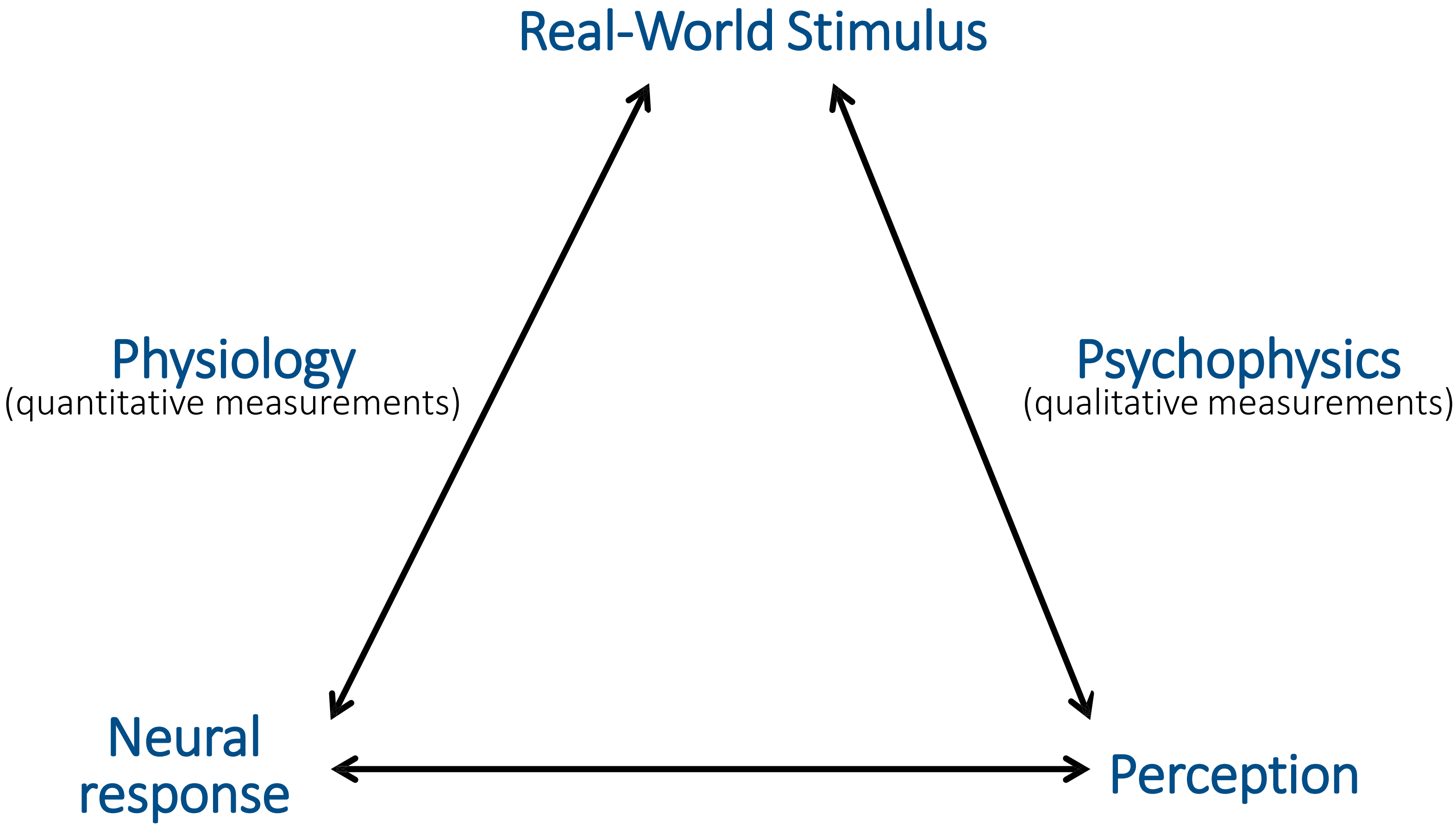


Adaptation to dark much slower



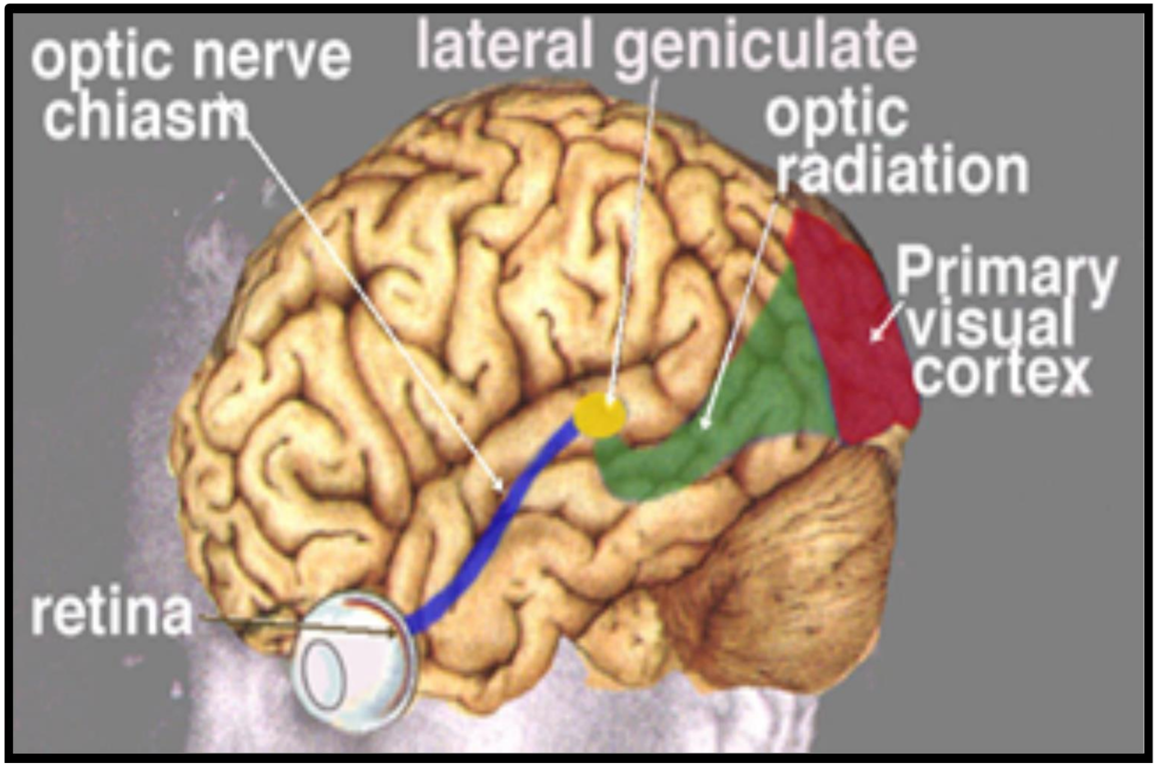
Simulation requires:

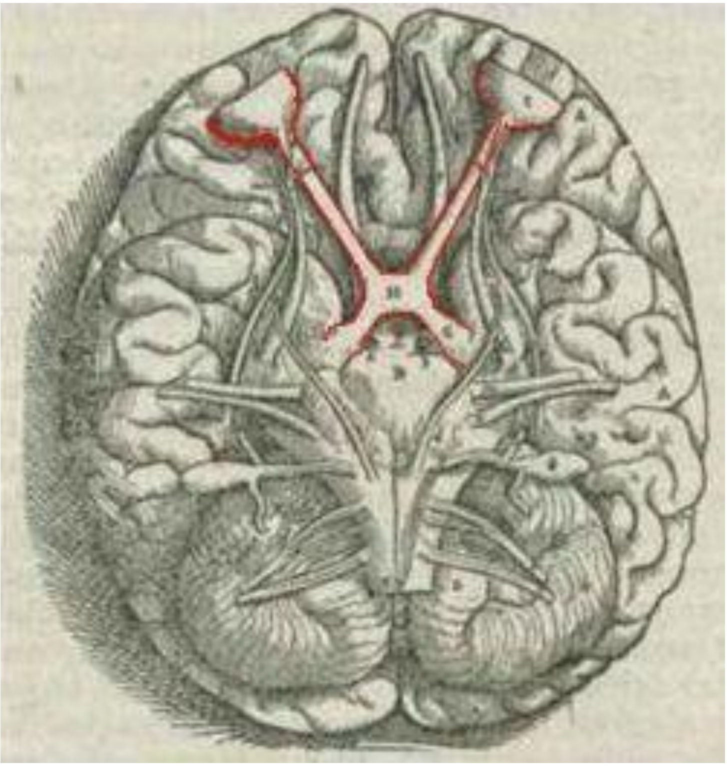
- Time-dependent filtering of light adaptation


Real-World Stimulus
Physiology
(quantitative measurements)
Psychophysics
(qualitative measurements)
Neural response
Perception

Physical structure well established

Perceptional behavior complex and less understood process





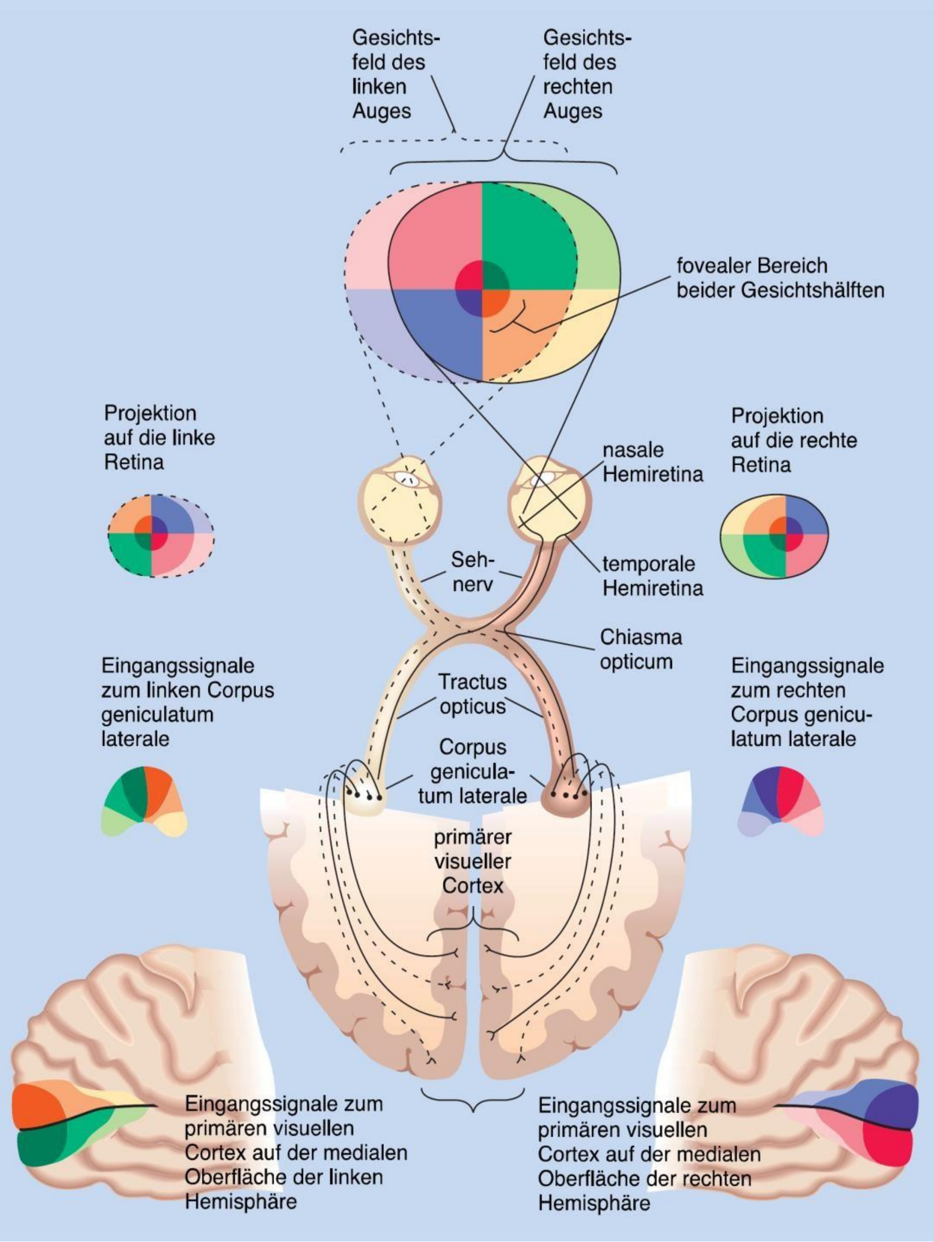
Optic chiasm

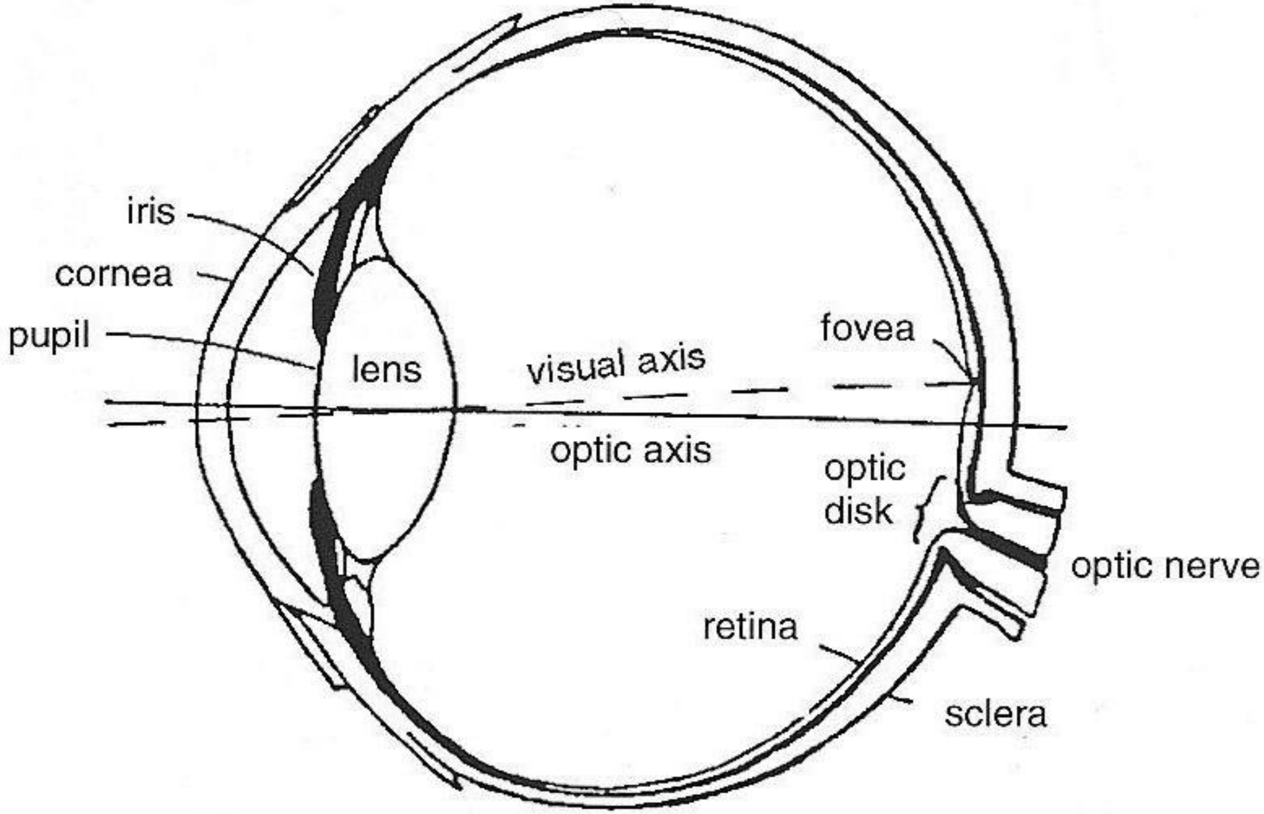
Right half of the brain operates on left half of the field of view

- 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




iris
cornea
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visual axis
optic axis
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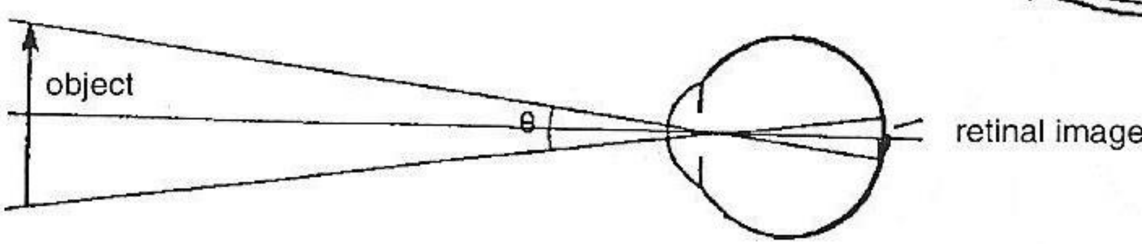
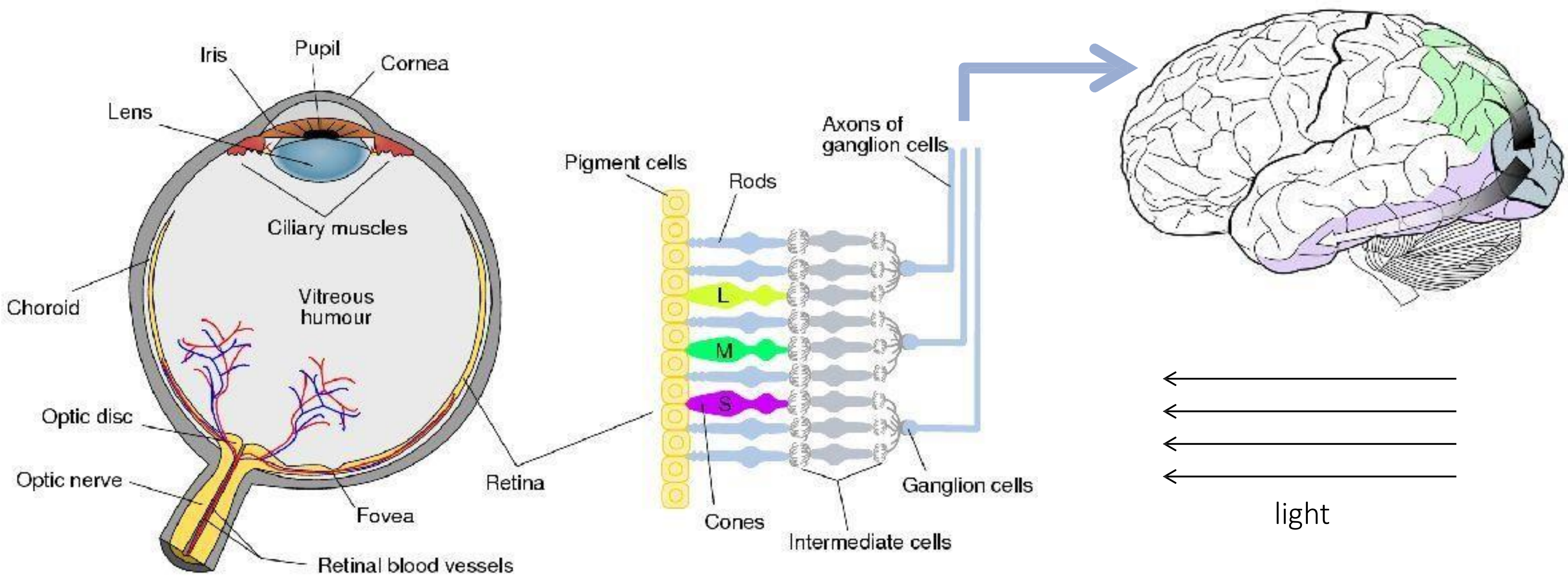
optic nerve
retina
sclera


object
θ
retinal image

Human Visual Perception



early vision (eyes)

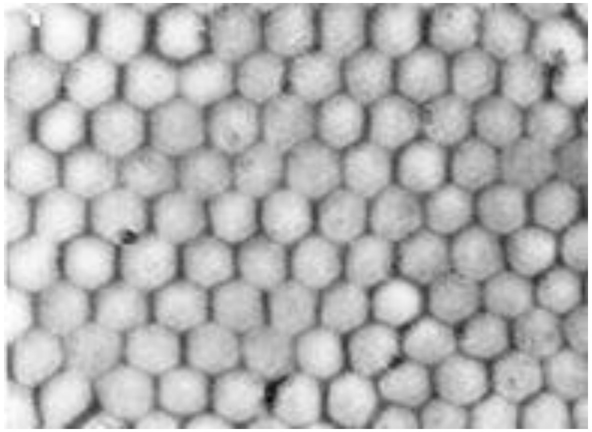
Determines how real-world scenes appear to us

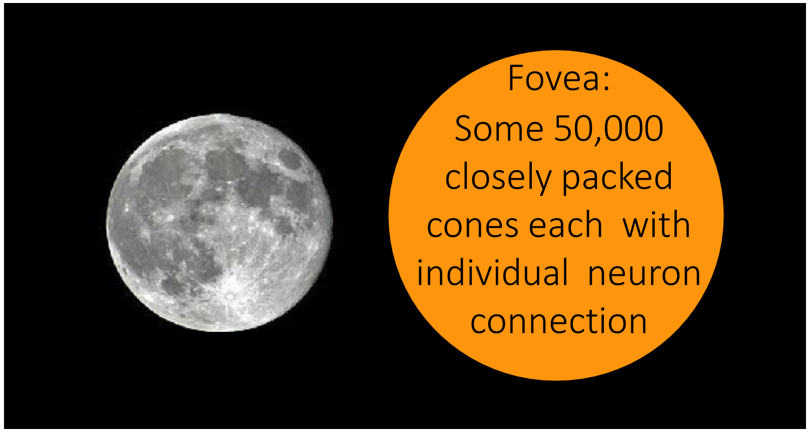
Understanding of visual perception is necessary to reproduce appearance, *e.g.* in tone mapping

High-resolution foveal region with highest cone density

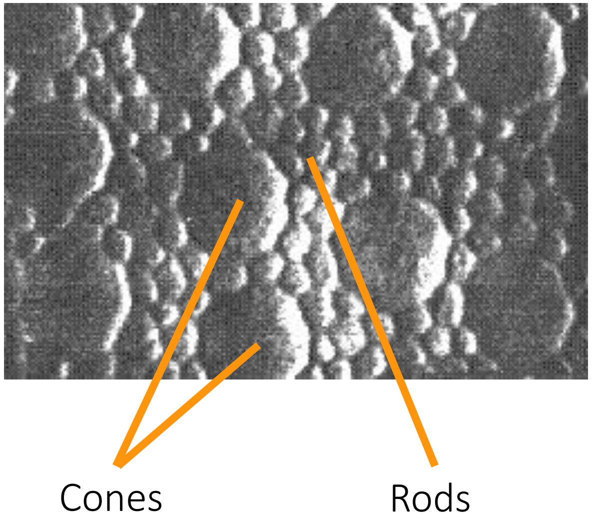
Poisson-disc-like distribution

Cone mosaic in fovea which subtends small solid angle

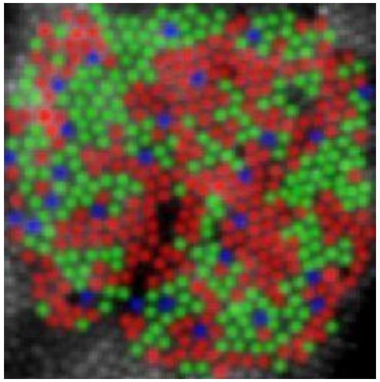




Cone mosaic in periphery with almost 180° field of view



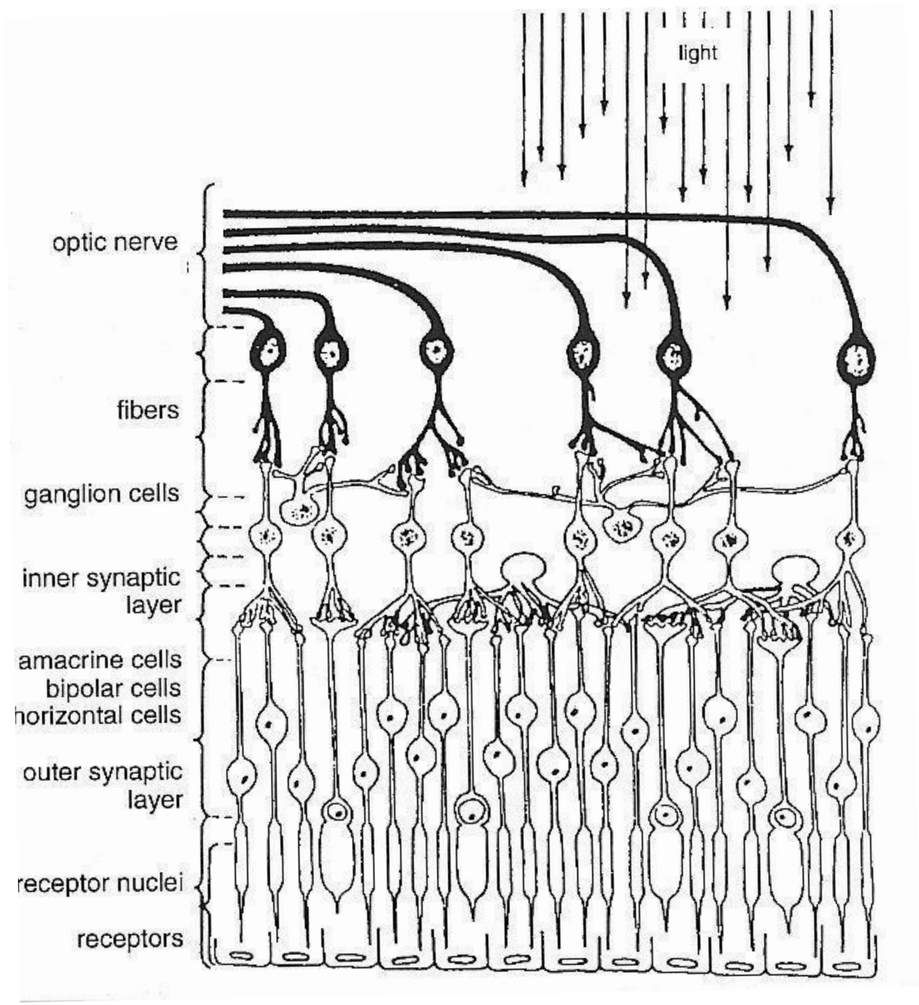
L-cones ~ M-cones >> S-cones



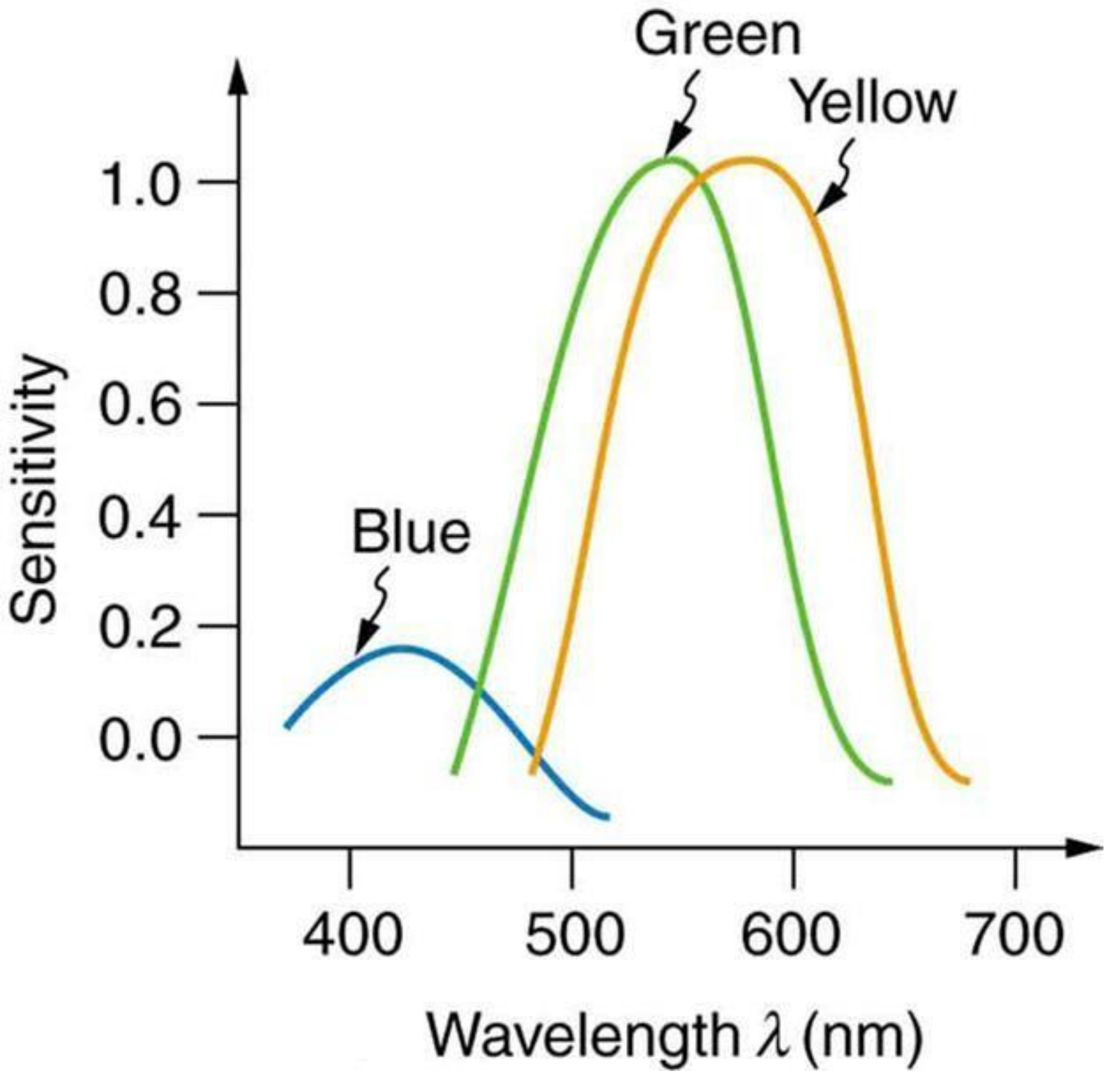
Receptors on opposite side of incoming light

Early cellular processing between receptors & nerves

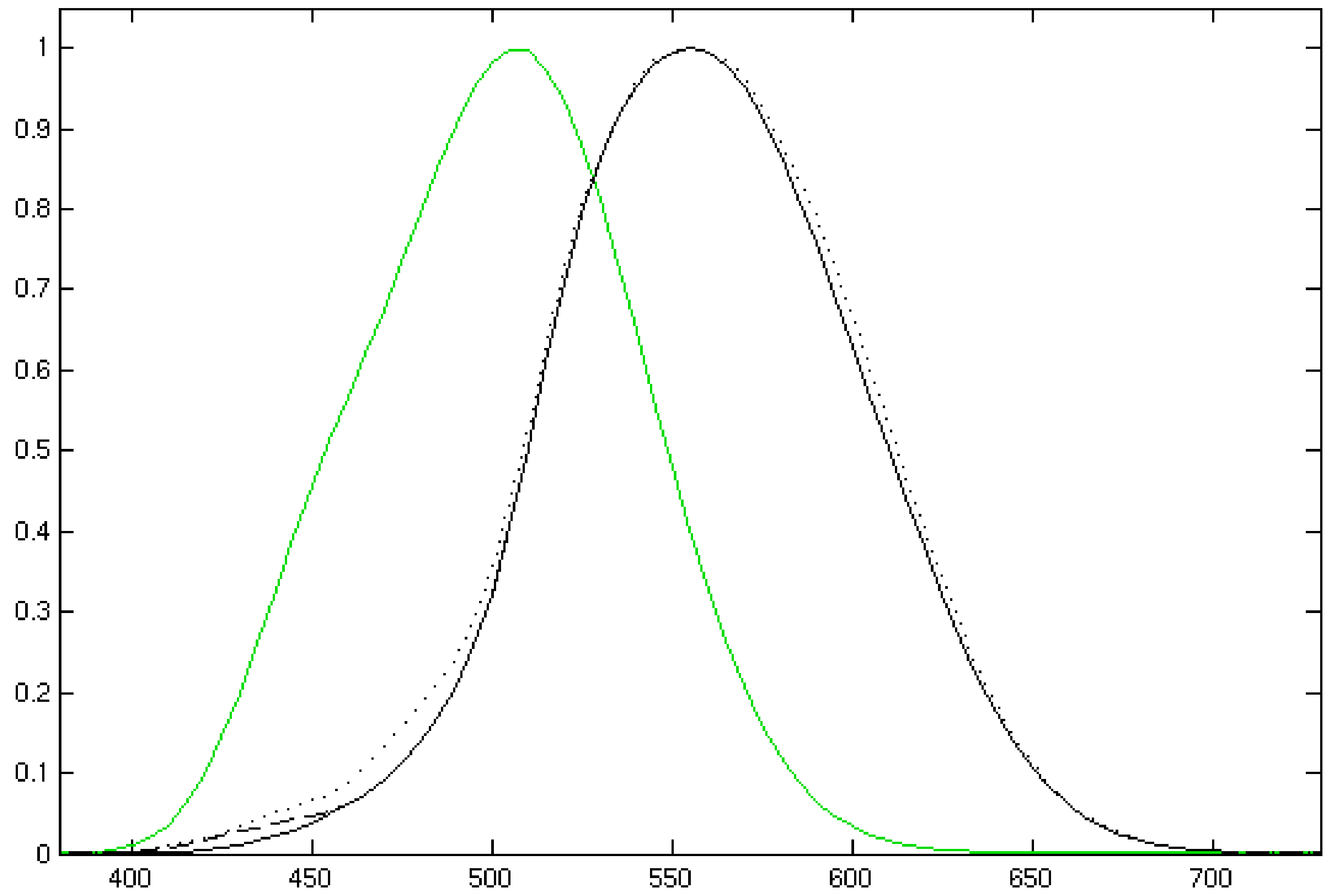
- Mainly for rods



Relative sensitivity of cones



Different for cones (black) & rods (green)



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

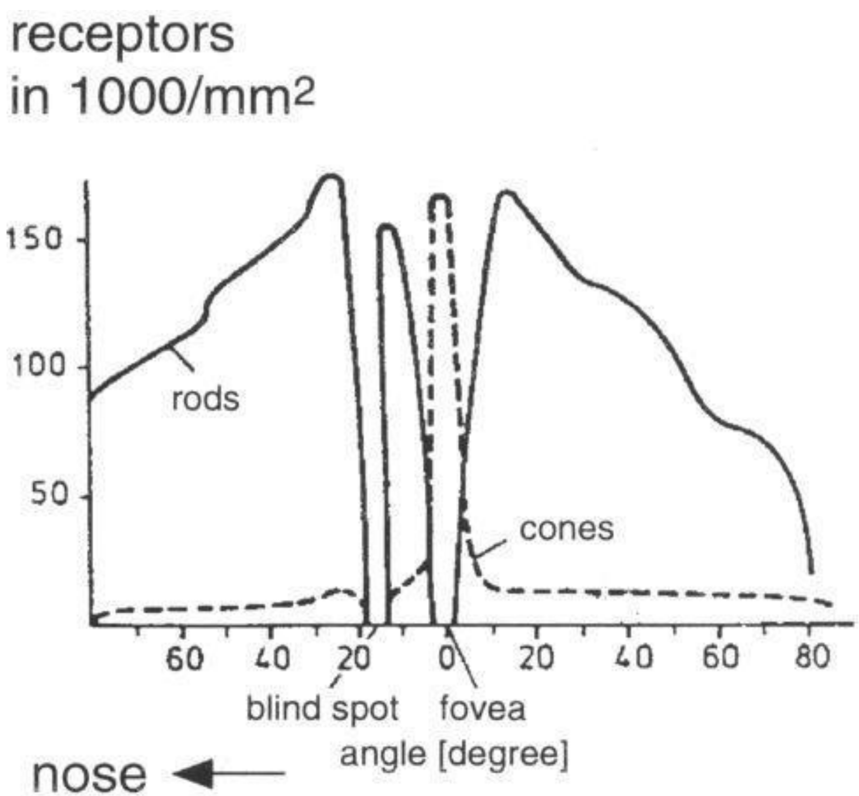
This is a text in green

This is a text in blue

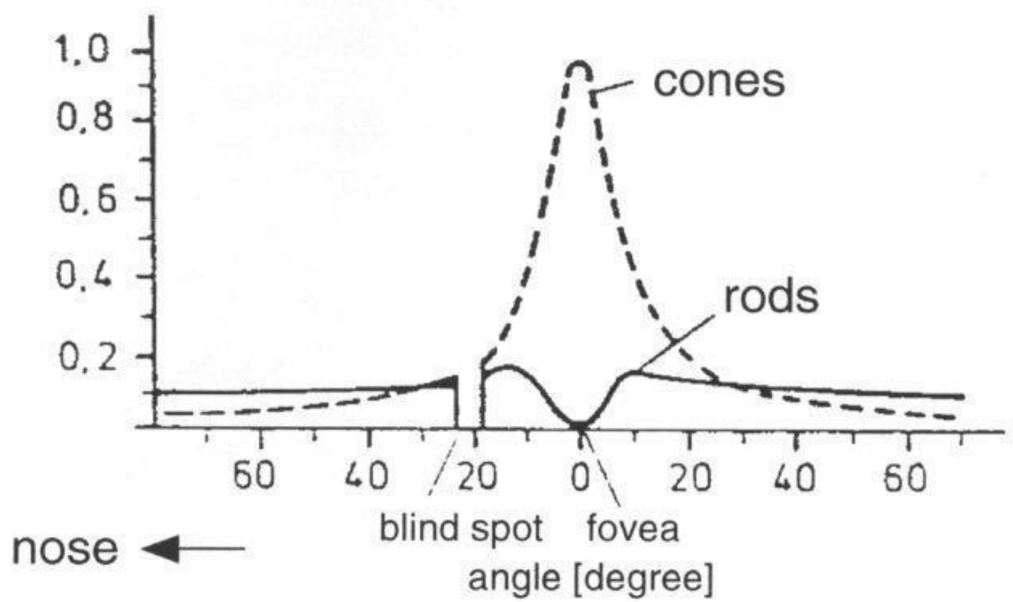
This is a text in red

This is a text in green

This is a test in blue



Receptor density



Resolution in line-pairs/arcminute

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

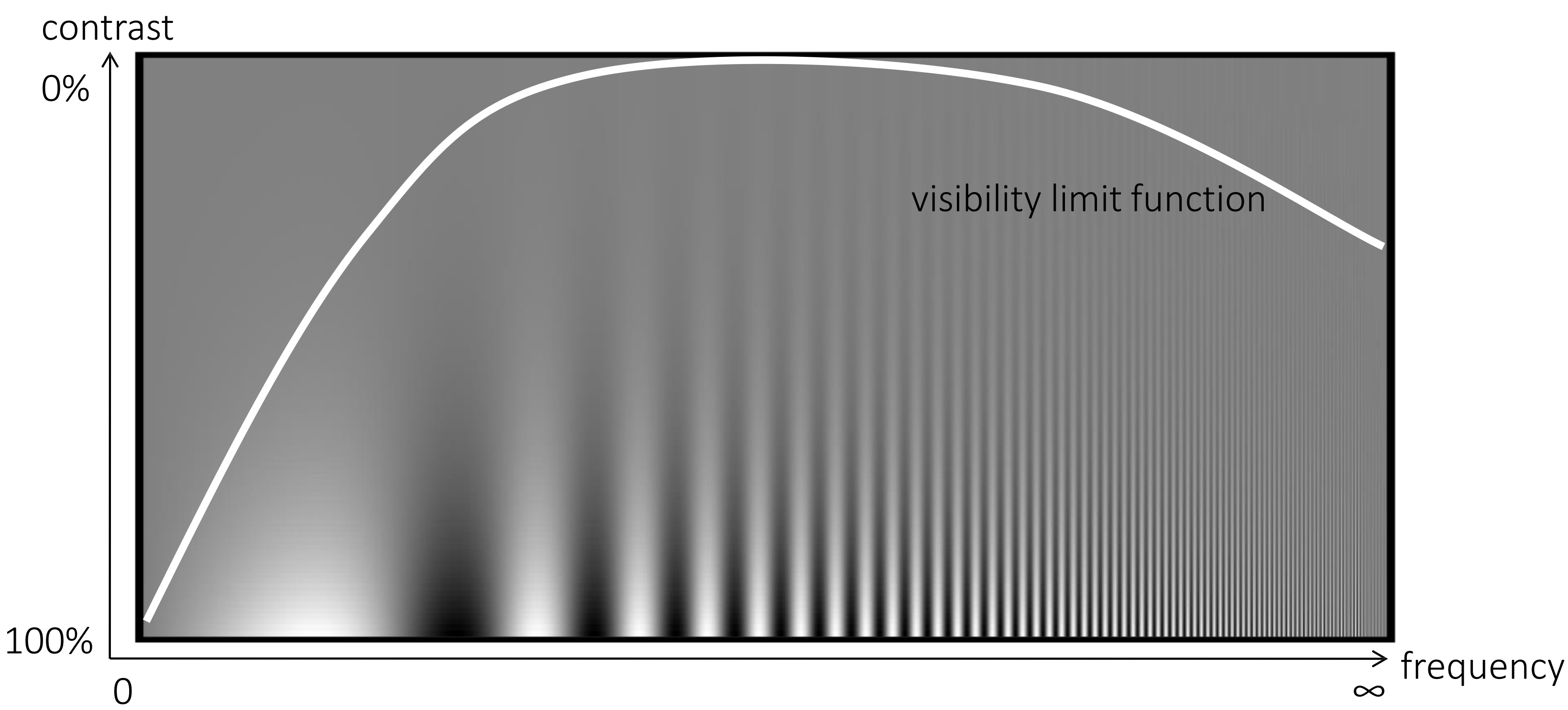
- Automatic gaze tracking, automatic compensation of head movement
- Apparent overall high resolution of fovea

Visual acuity increased by

- Brighter objects
- High contrast

Human visual system

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



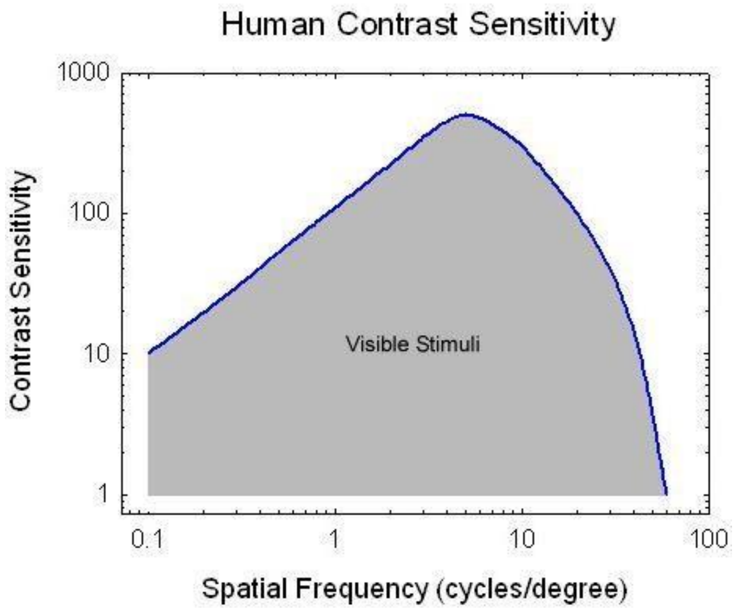
Contrast sensitivity: is a measure of the ability to discern between luminances of different levels in a static image

Maximum acuity at 5 cycles per degree

- Varies between individuals, reaching a maximum at approximately 20 years of age, and at angular frequencies of about 2–5 cycles per degree.

It can decline with age and also due to other factors such as

- Glaucoma (affects peripheral vision: low frequencies)
- Multiple sclerosis (affects optical nerve: notches in contrast sensitivity)
- Cataracts and diabetic retinopathy.



Color vs. luminance vision system

- Similar but slightly different curves
- Higher sensitivity at lower frequencies
- High frequencies less visible

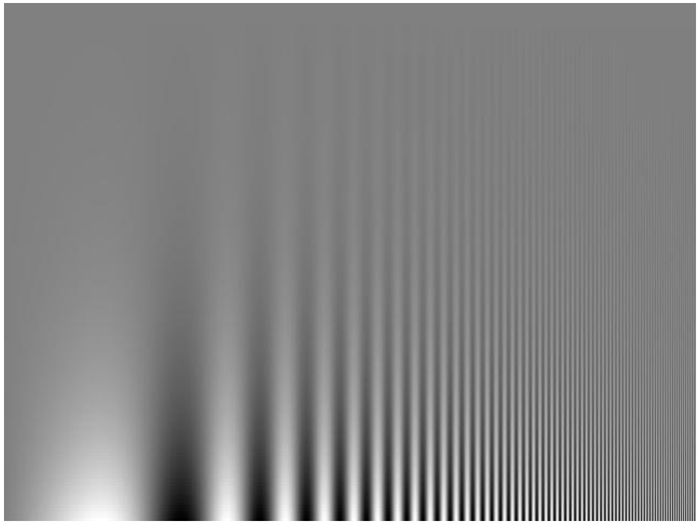
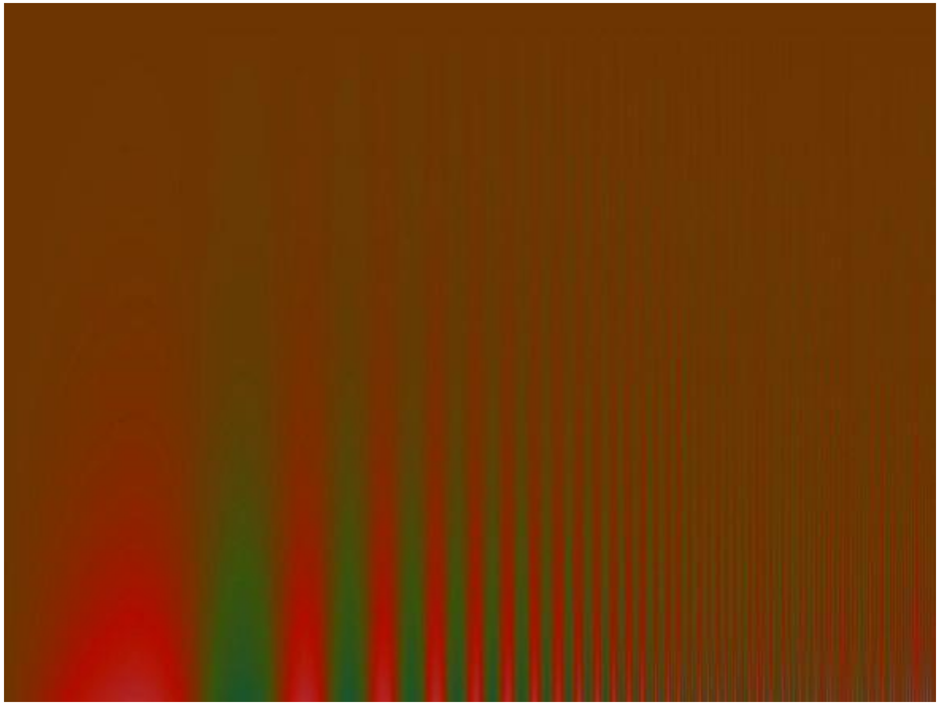
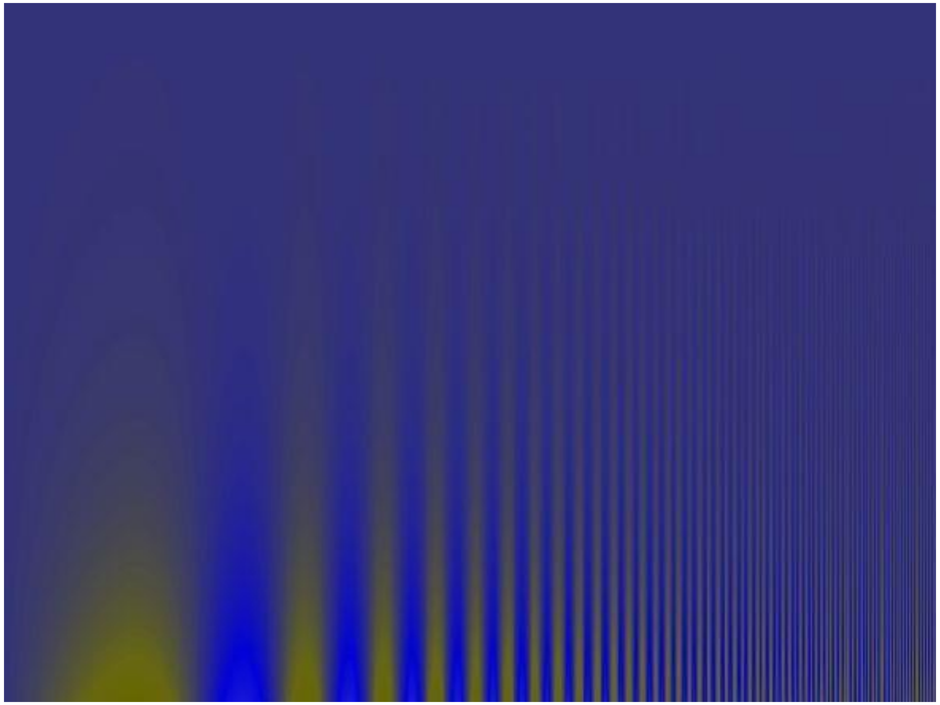


Image compression

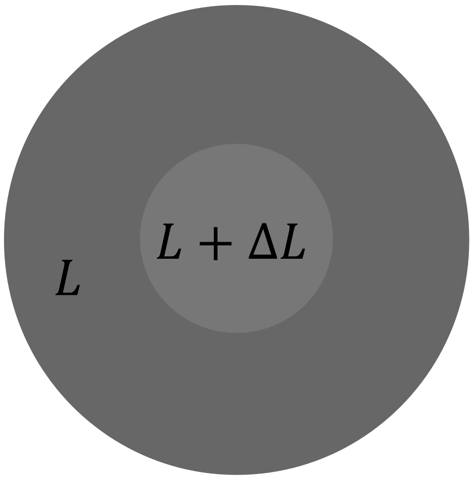
- Exploit color sensitivity in lossy compression

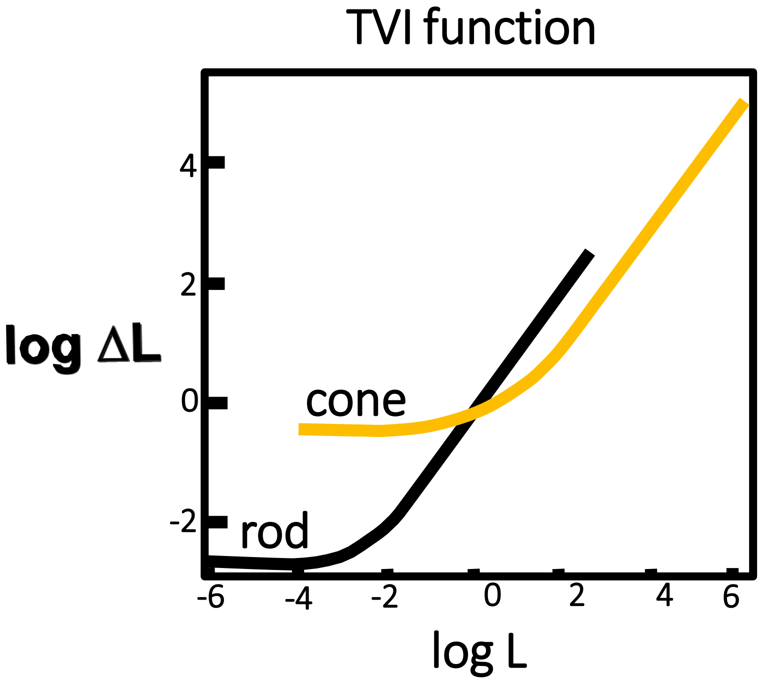


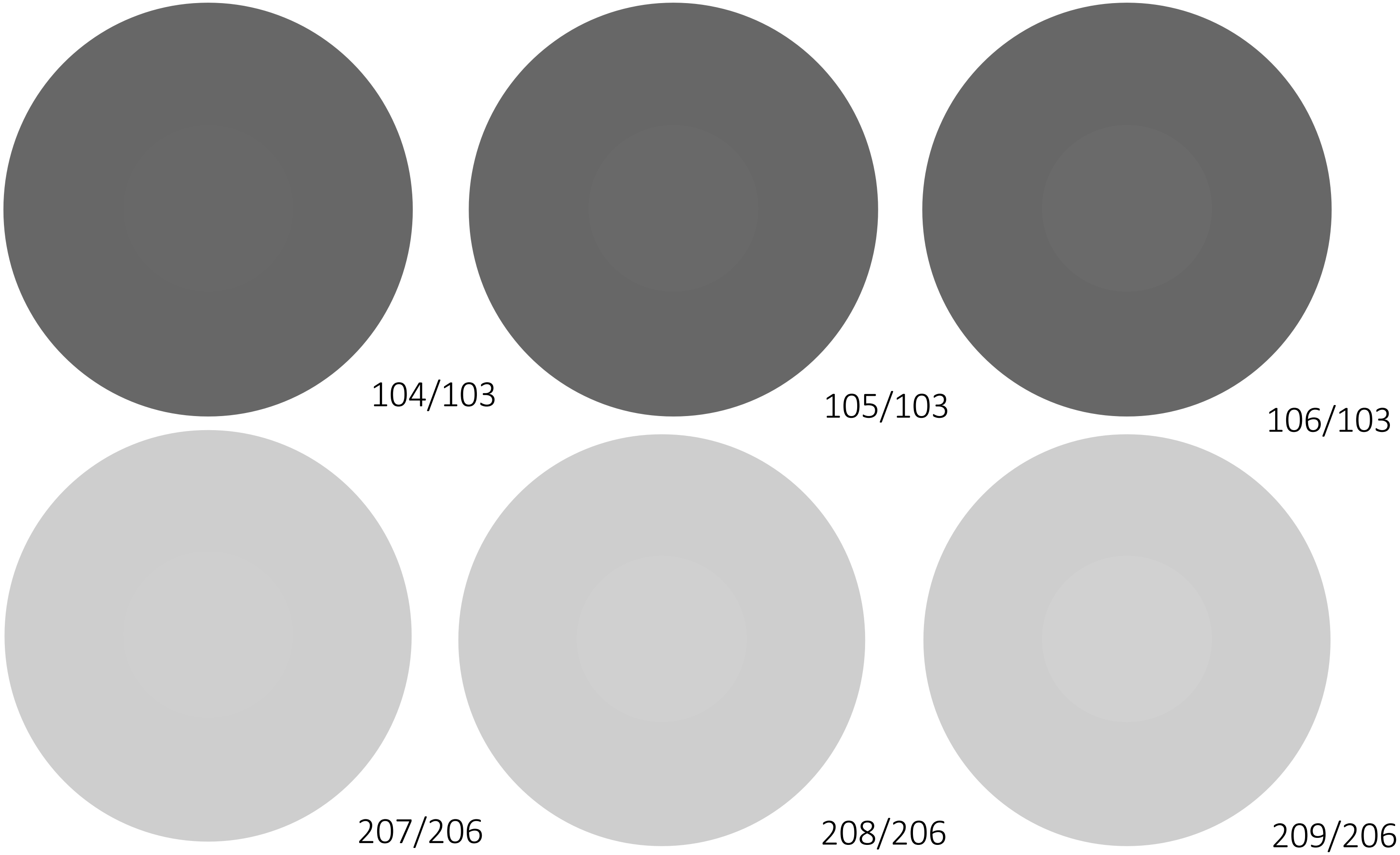


Weber-Fechner law (Threshold Versus Intensity, TVI)

- 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





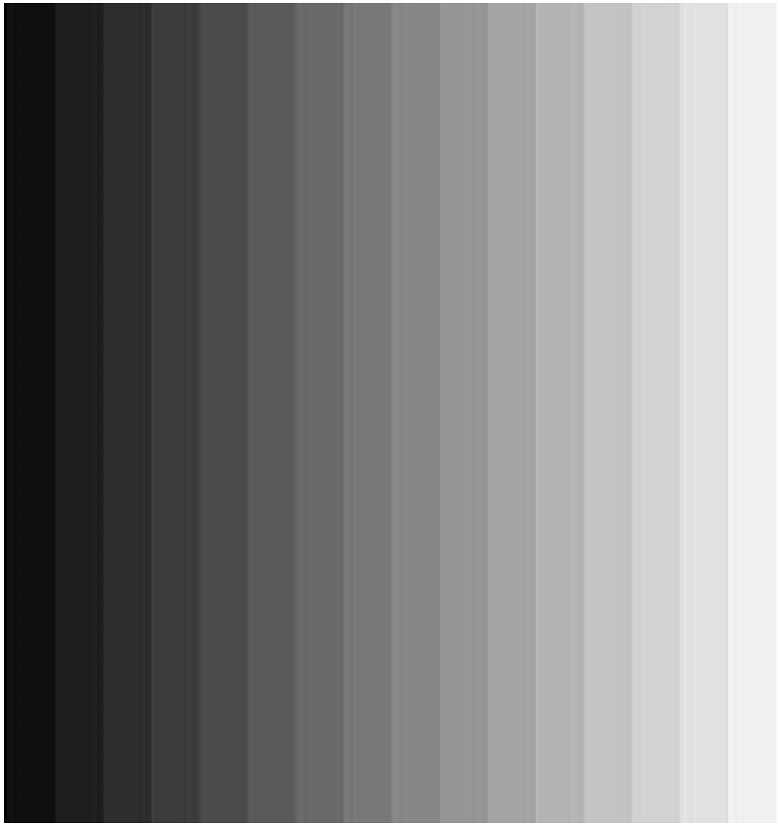

104/103
105/103
106/103
207/206
208/206
209/206

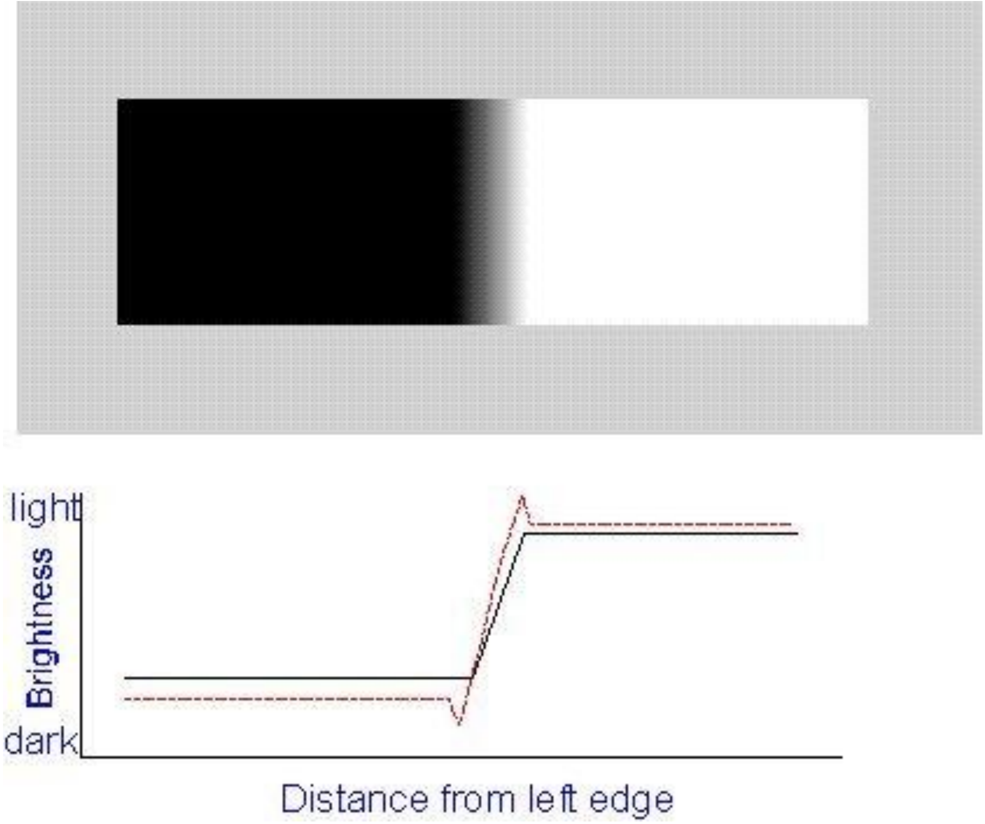
Due to *lateral inhibition*

- the capacity of an excited neuron to reduce the activity of its neighbors

"Overshooting" along edges

- Extra-bright rims on bright sides
- Extra-dark rims on dark sides





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“Overshooting” along edges

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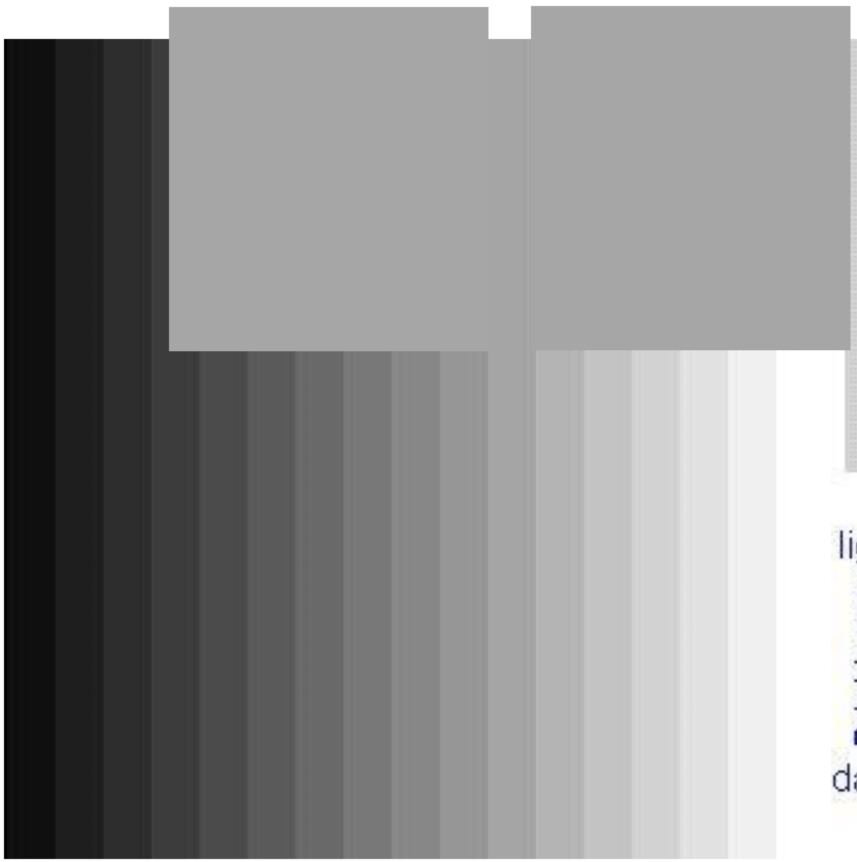
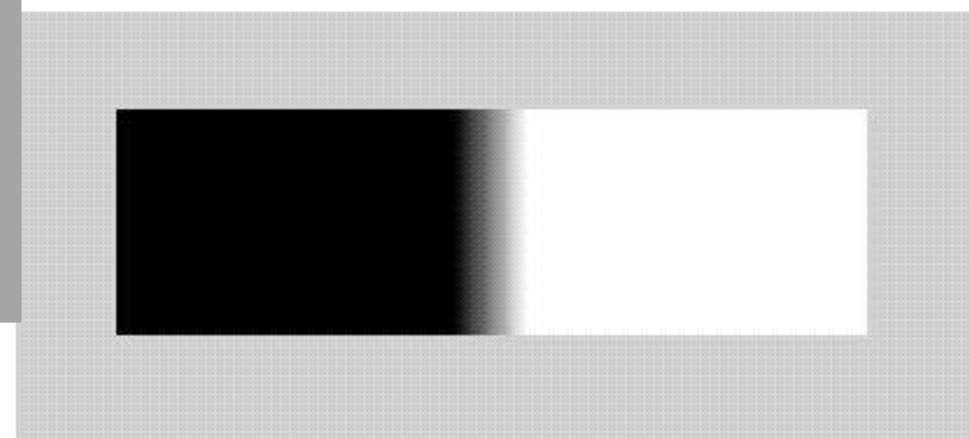
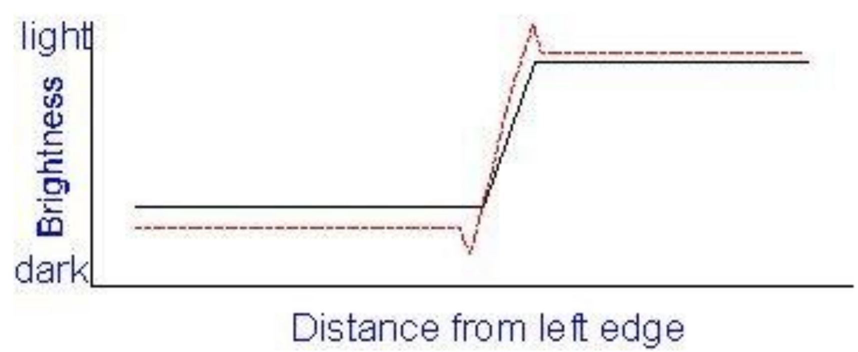




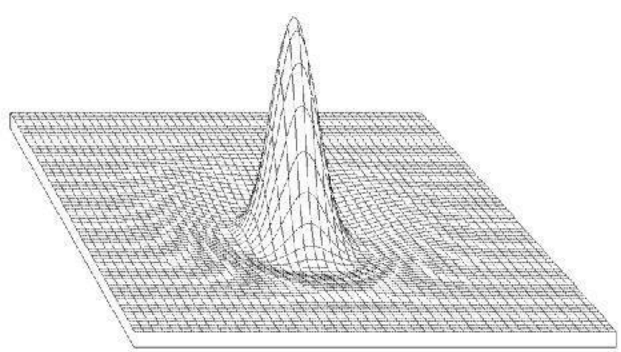


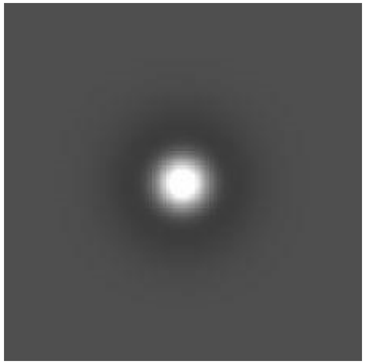
Pre-processing step within retina

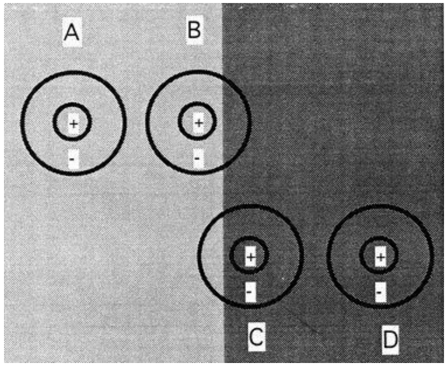
- Surrounding brightness level weighted negatively
  - A: high stimulus, maximal bright inhibition
  - B: high stimulus, reduced inhibition → stronger response
  - D: low stimulus, maximal dark inhibition
  - C: low stimulus, increased inhibition → weaker response

High – pass filter

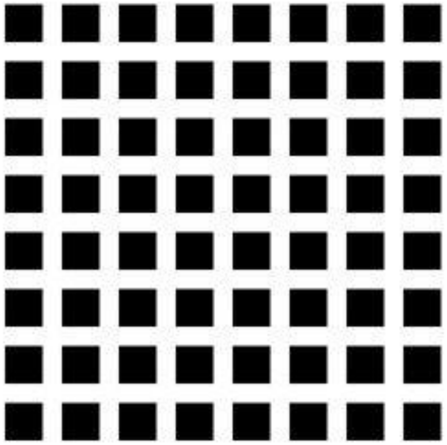
- Enhances contrast along edges
- Differential operator (Laplacian / difference of Gaussian)





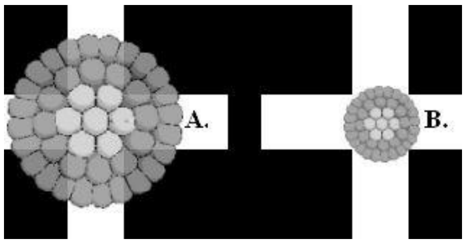


Lateral Inhibition: Hermann Grid



Apparent dark spots at peripherial crossings

- Weakly if within foveal Ω (B): smaller filter extent
- Strongly within periphery (A): larger filter extent



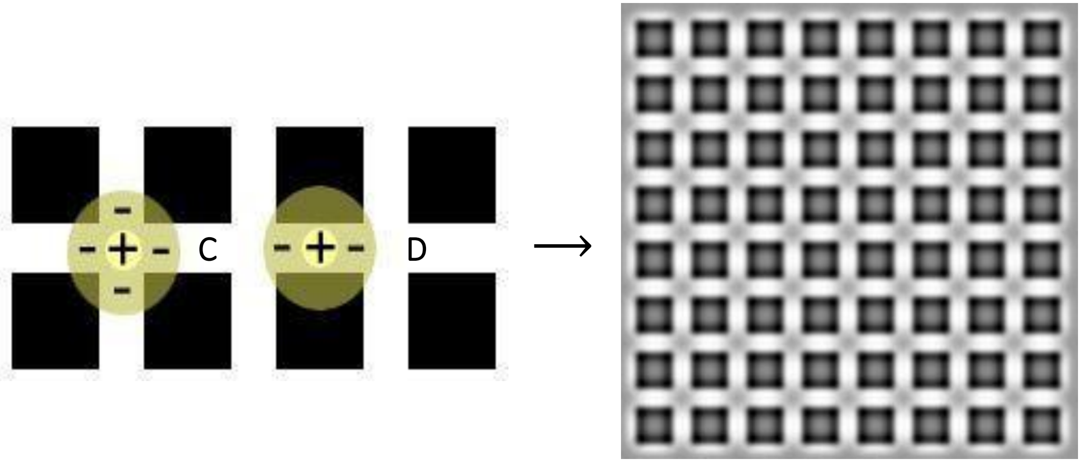
Periphery Fovea

Explanation

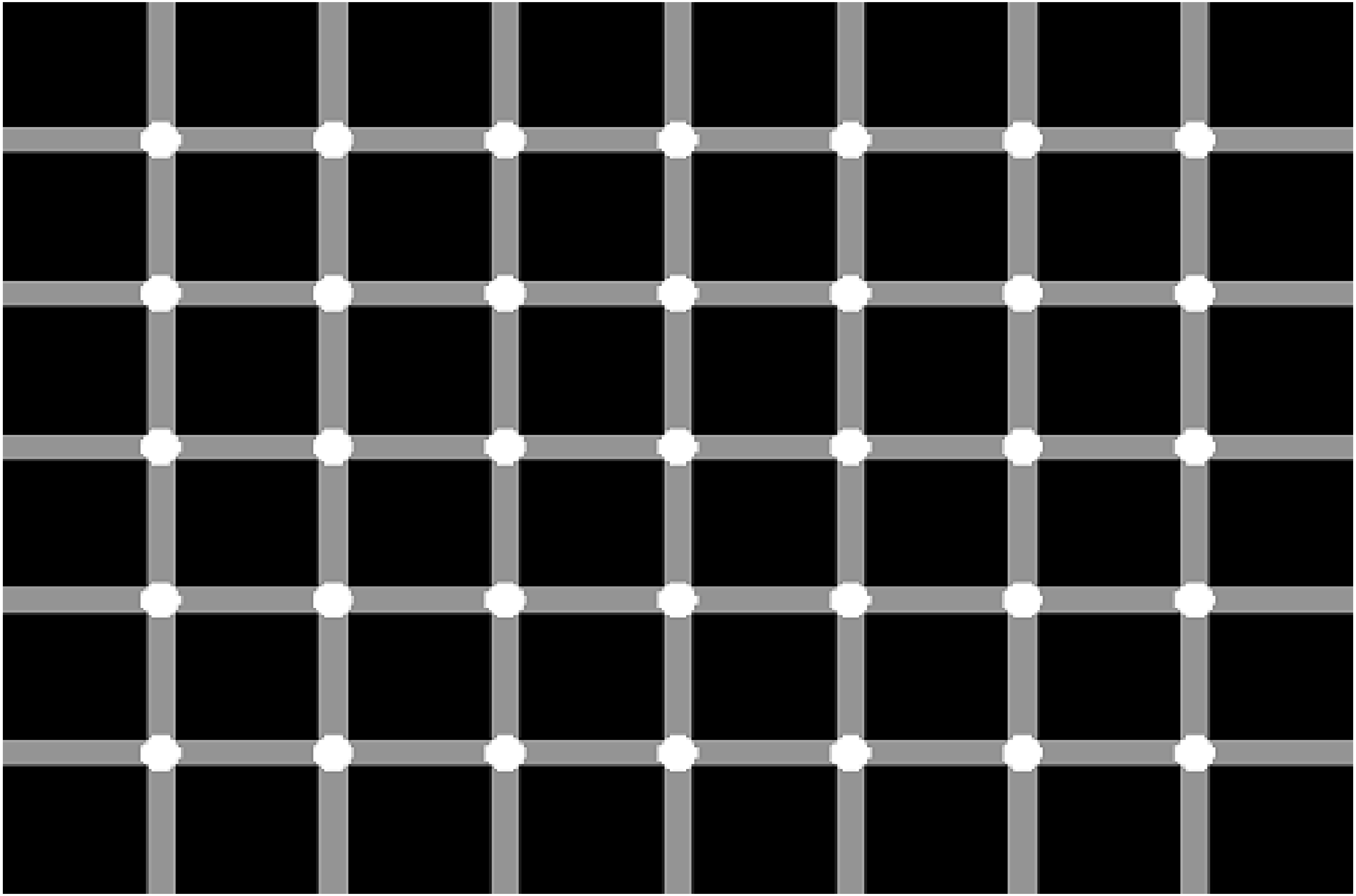
- Crossings (C): more surround stimulation
  - More inhibition ⇒ weaker response
- Streets (D): less surround stimulation
  - Less inhibition ⇒ greater response

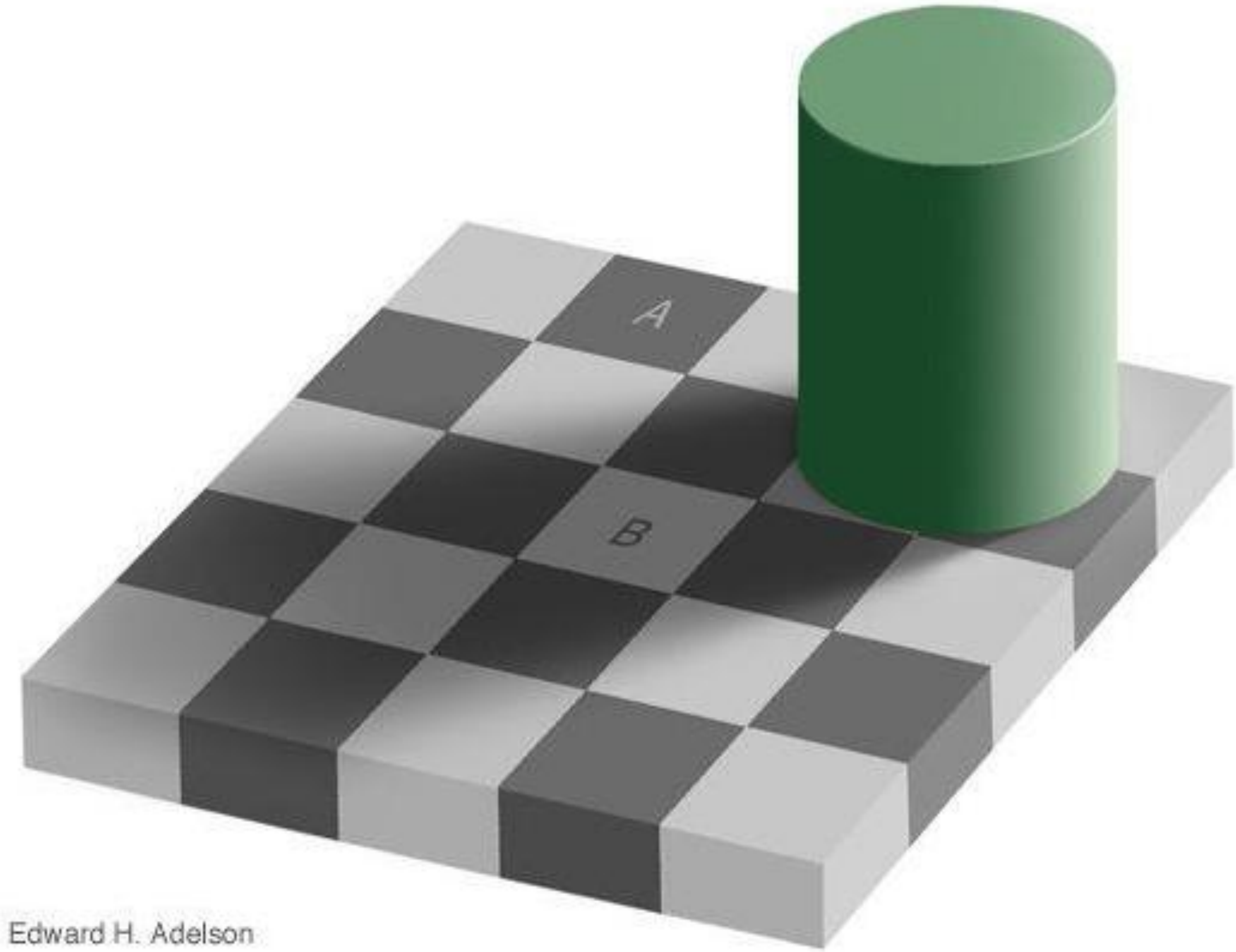
Simulation

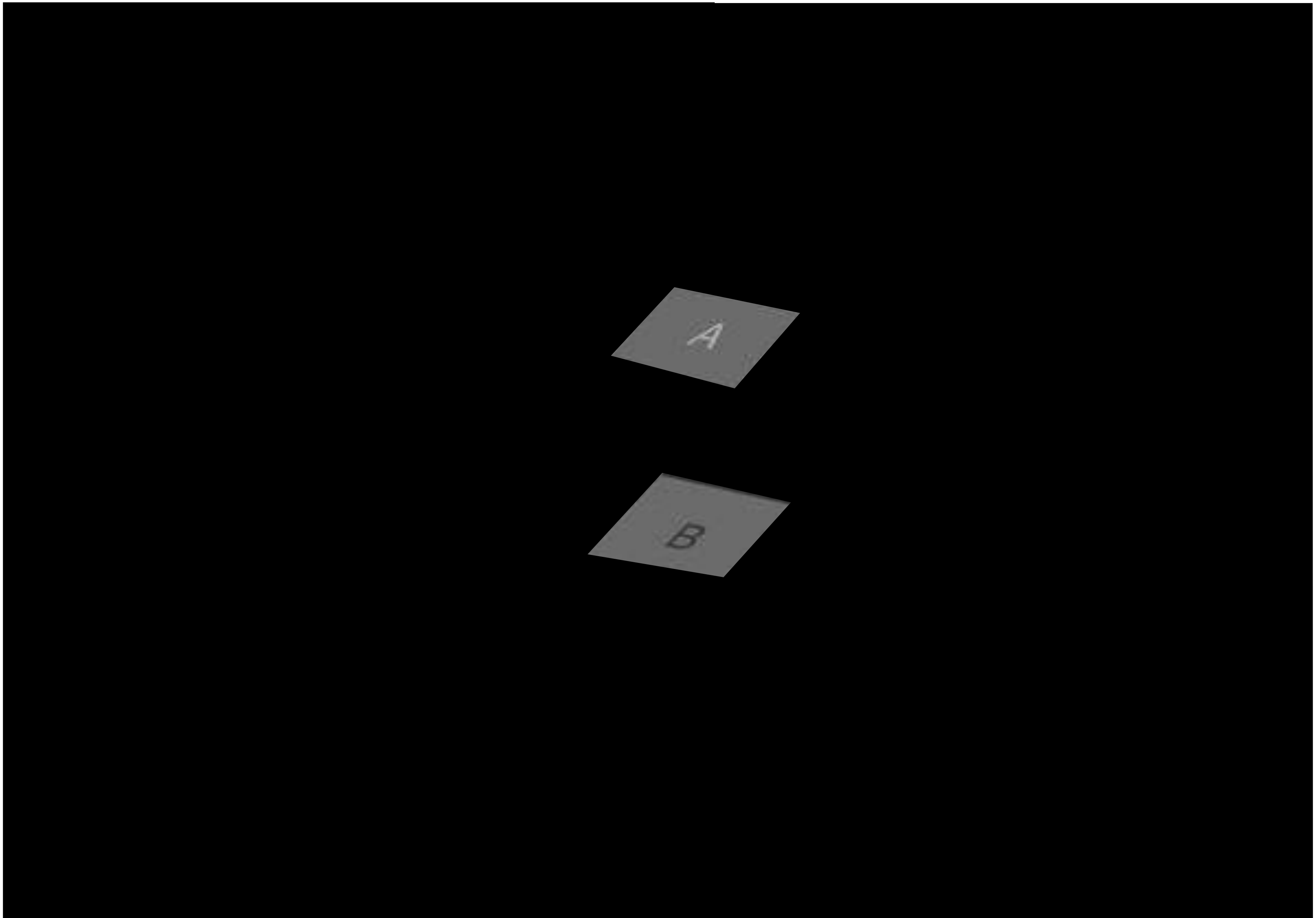
- Convolution with differential kernel
- Darker at crossings, brighter in streets
- Appears more steady
- What if inversed colors?



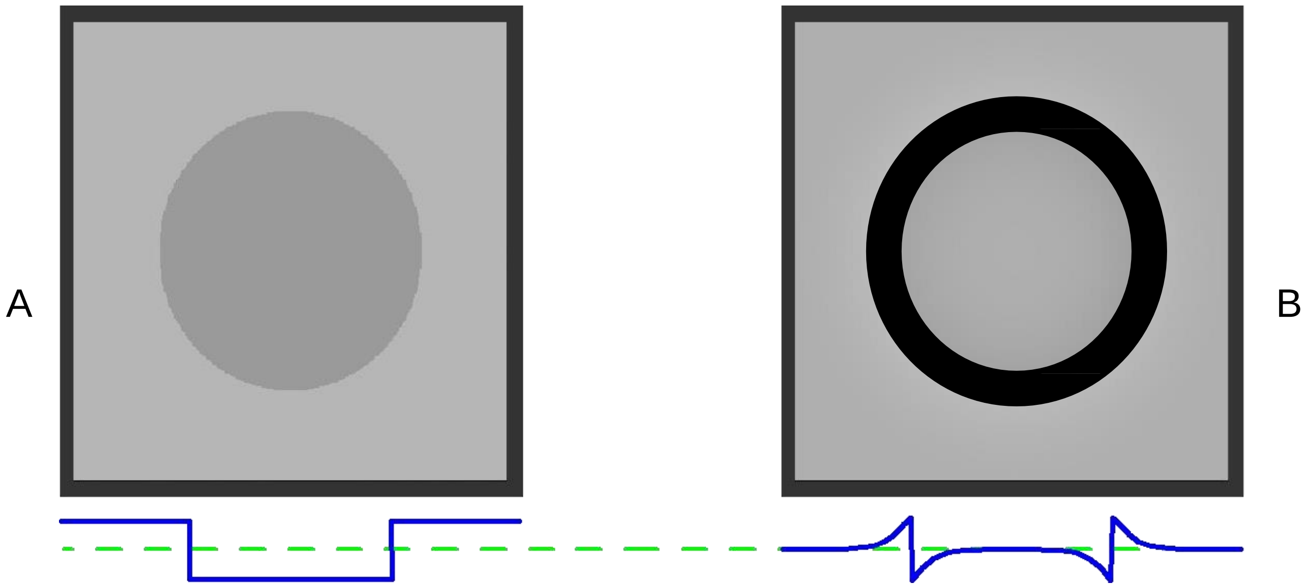
Some Further Weirdness




A
B
Edward H. Adelson

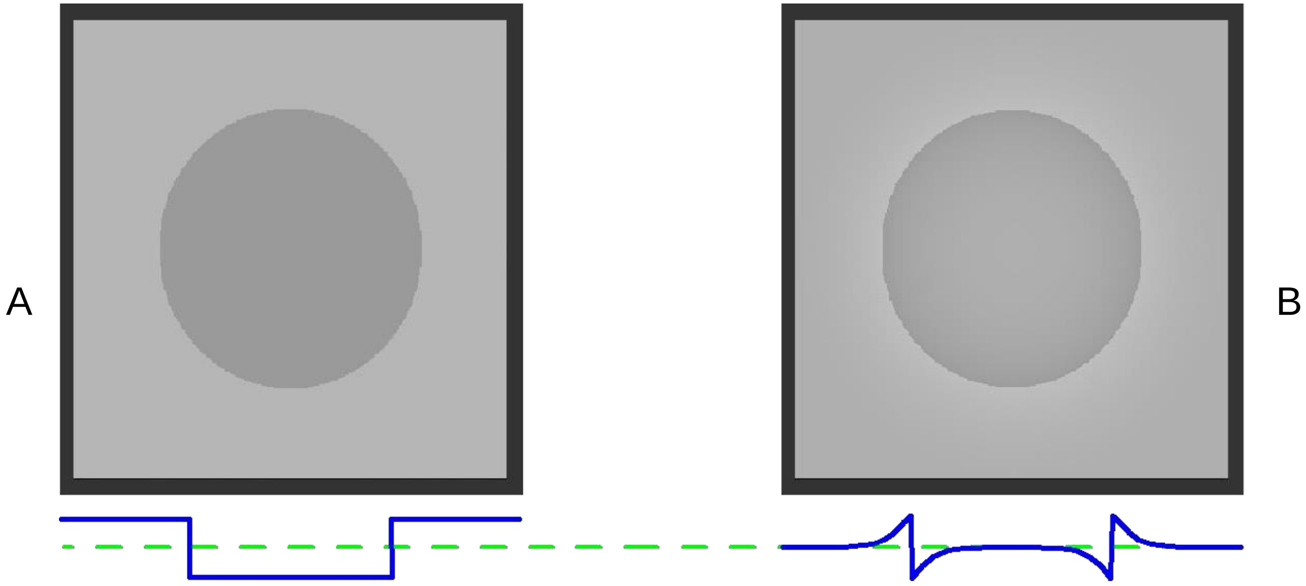

A
B

Apparent contrast between inner and outer shades



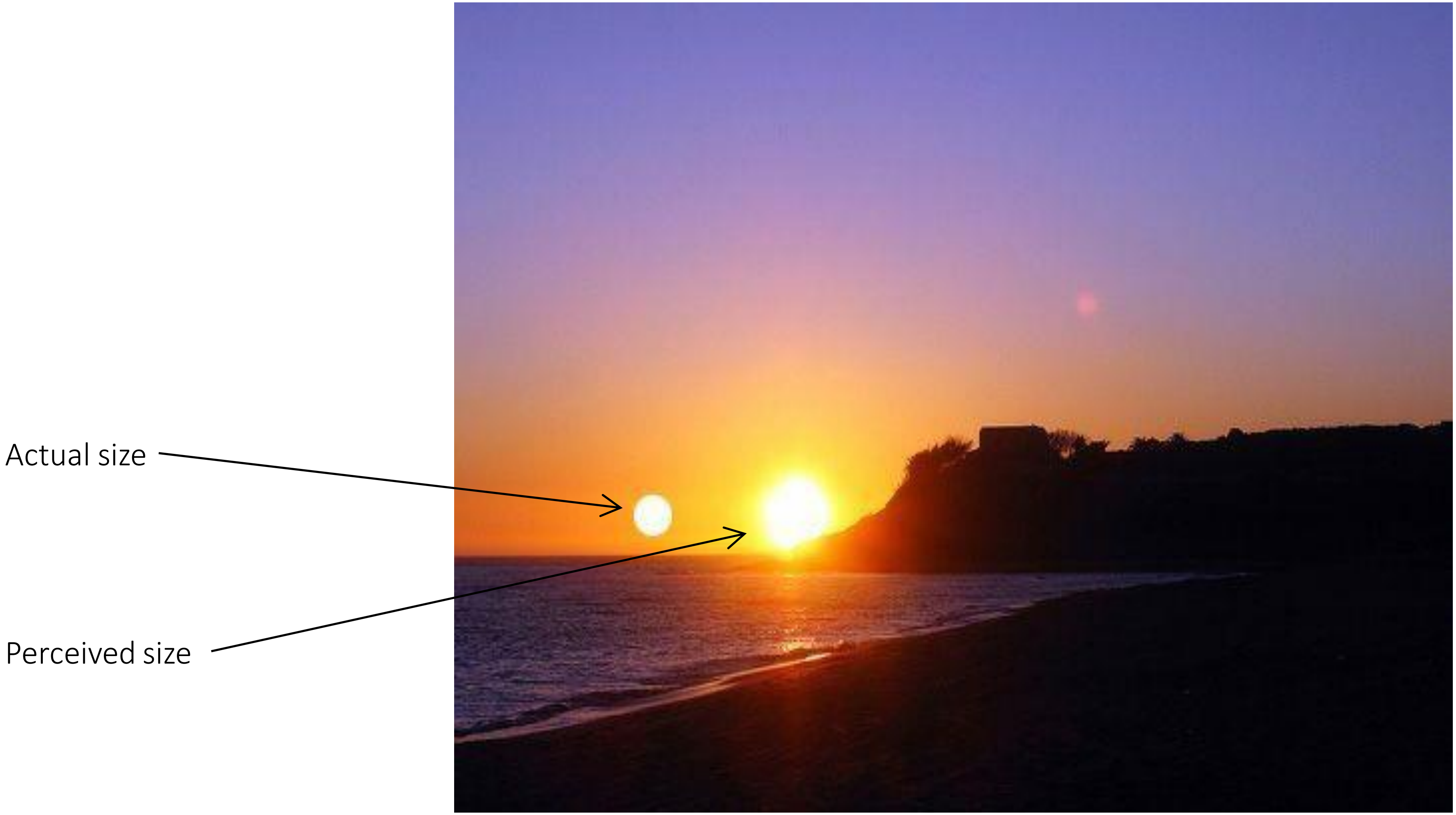
Apparent contrast between inner and outer shades

- Due to gradual darkening / brightening towards a contrasting edge
- Causes B to be perceived similarly to A



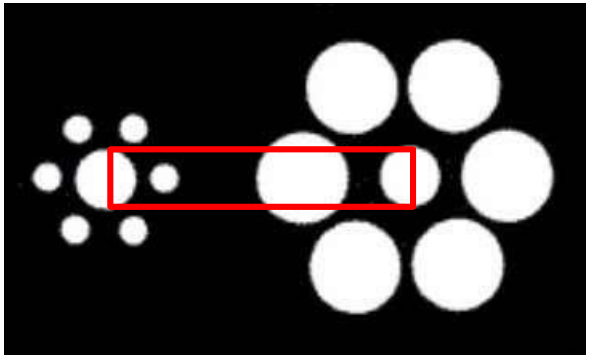
Internal scattering / blur of sources of high luminance

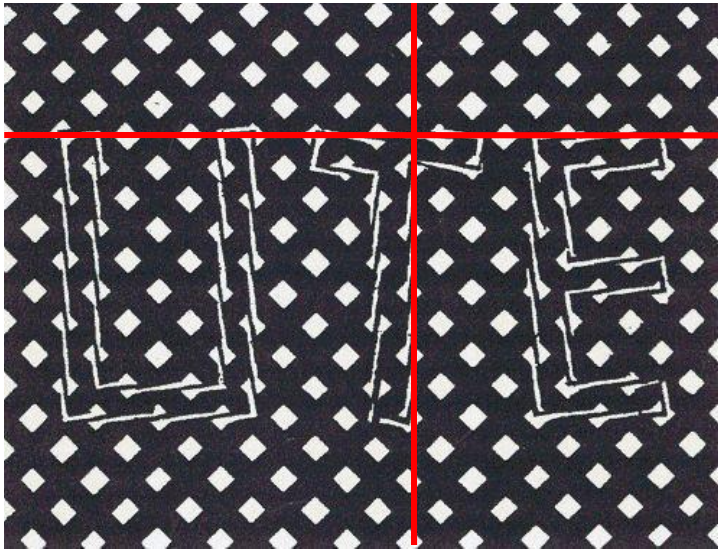
Computationally expensive to simulate



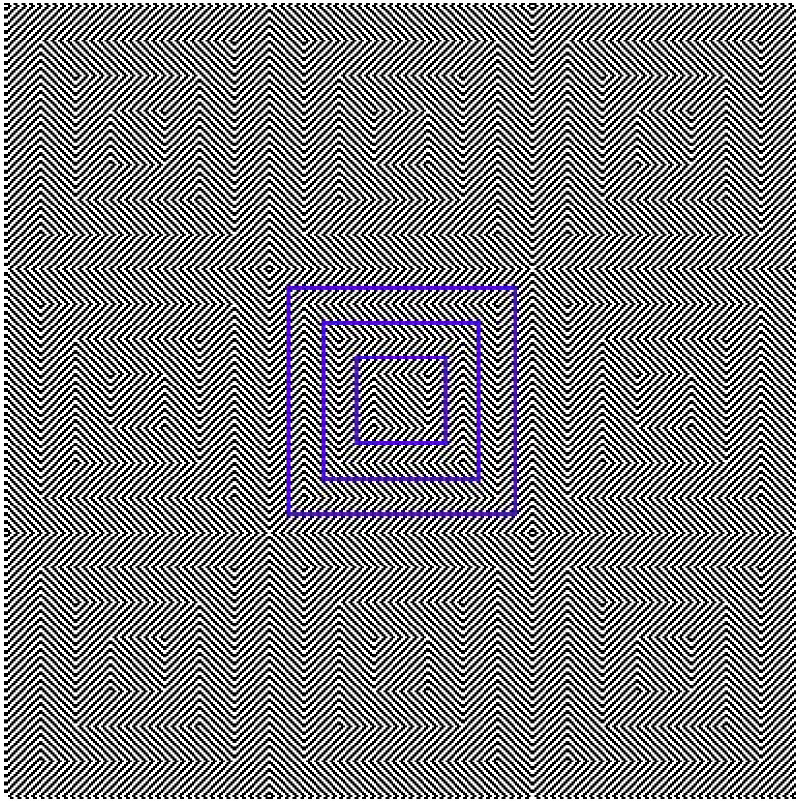
Depends on surrounding primitives

- Size emphasis
- Directional emphasis



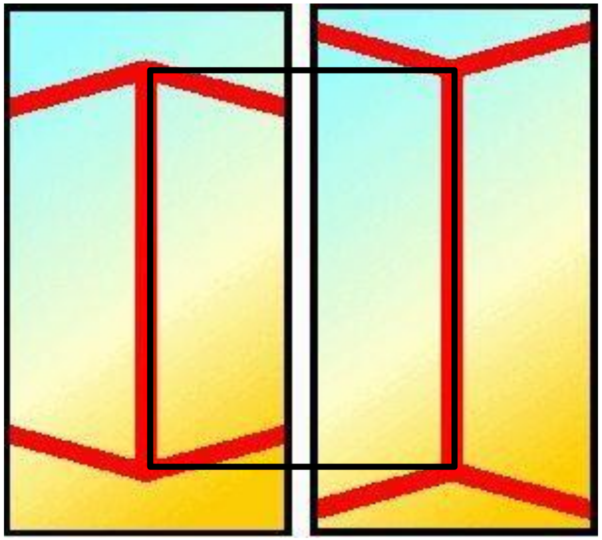


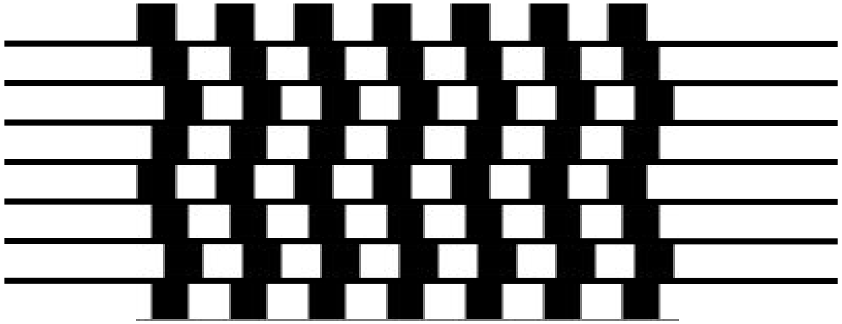
http://www.panoptikum.net/optischetaeuschungen/index.html



Automatic geometrical interpretation

- 3D perspective
- Implicit scene depth





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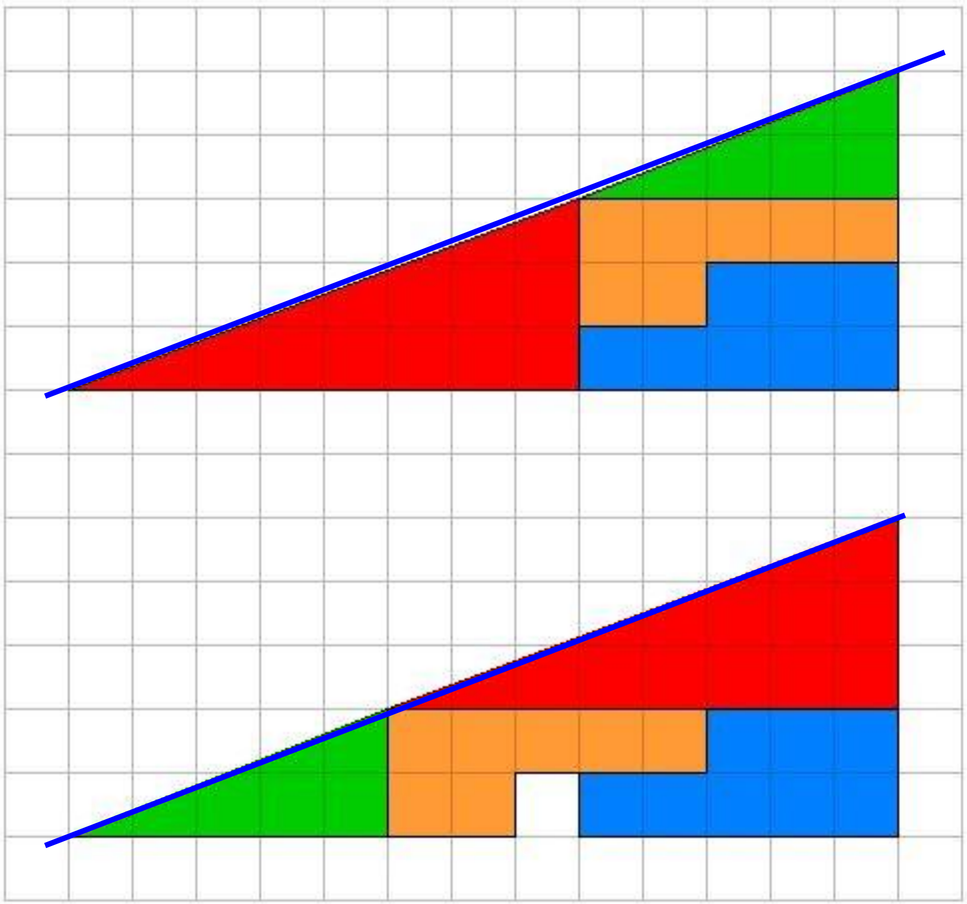

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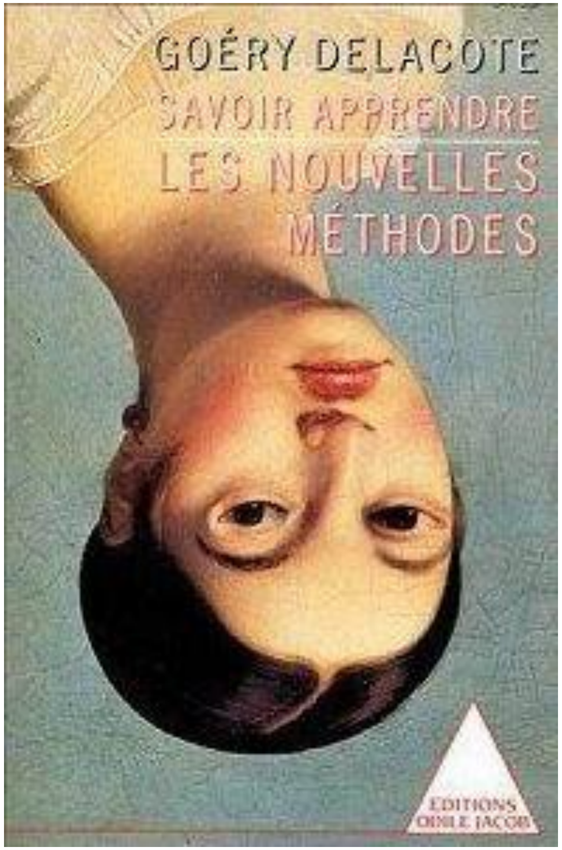
Experience & expectation

- Pictures usually horizontal

Local cue consistency

- Eyes and mouth look right, but actually are upside-down



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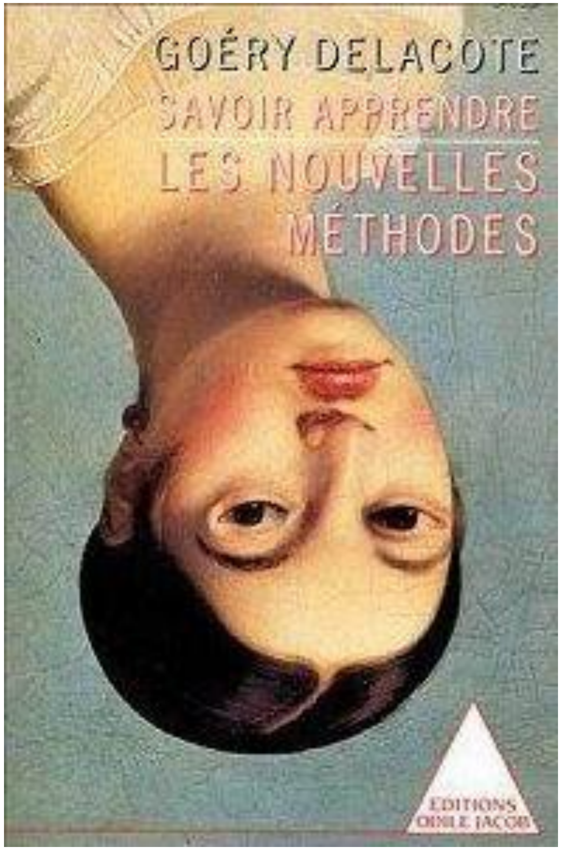
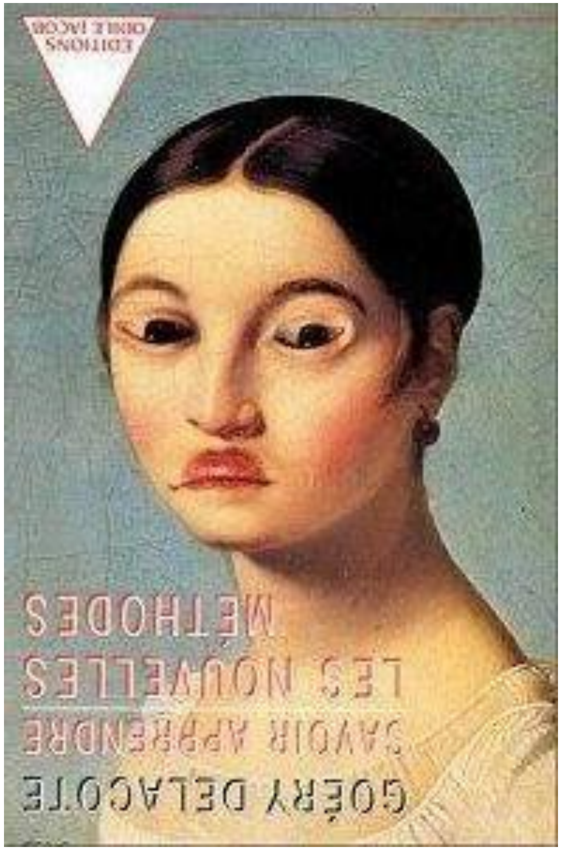
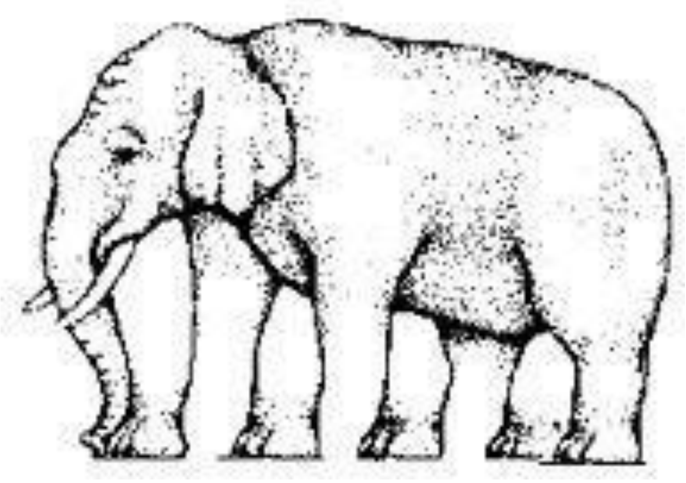


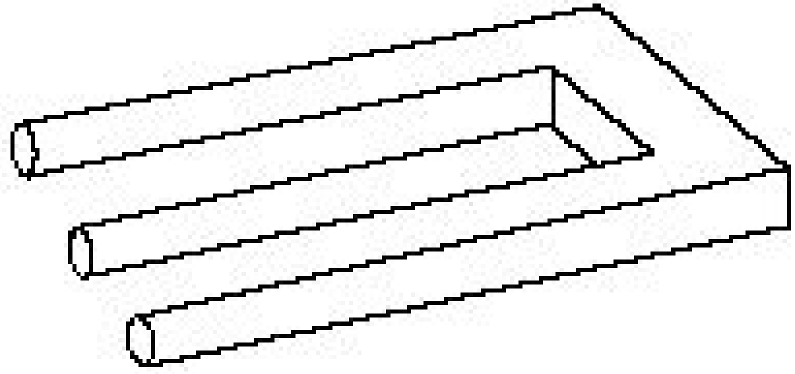


http://www.panoptikum.net/optischetaeuschungen/index.html

Escher *et al.*

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

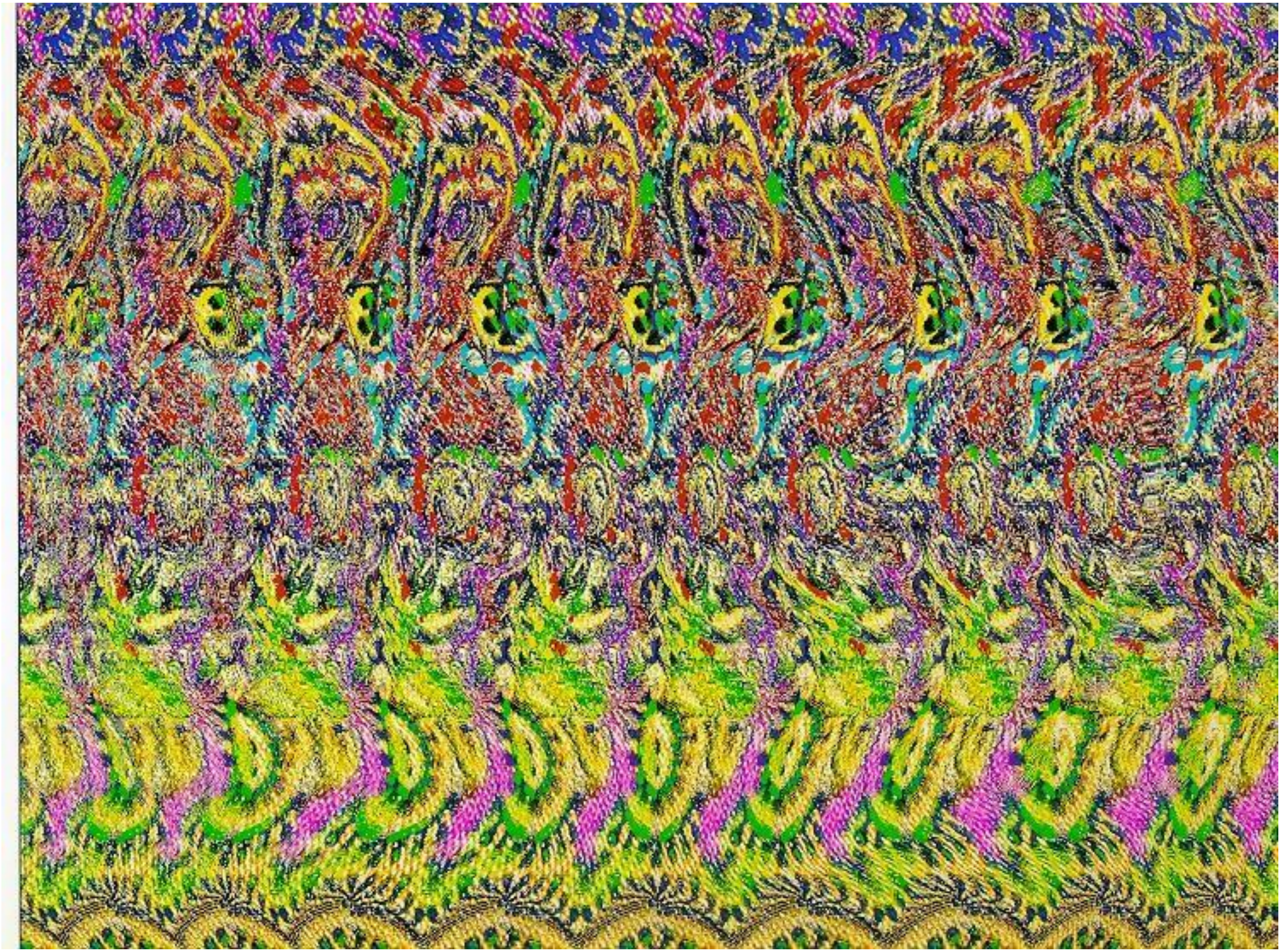




http://www.panoptikum.net/optischetaeuschungen/index.html

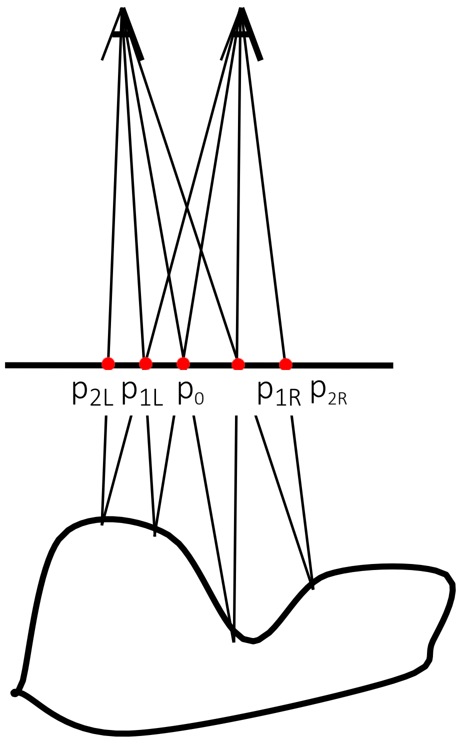
Vergence: Cross eyers to look at the same 3D spot

Accommodation: Focusing at a particular depth plane



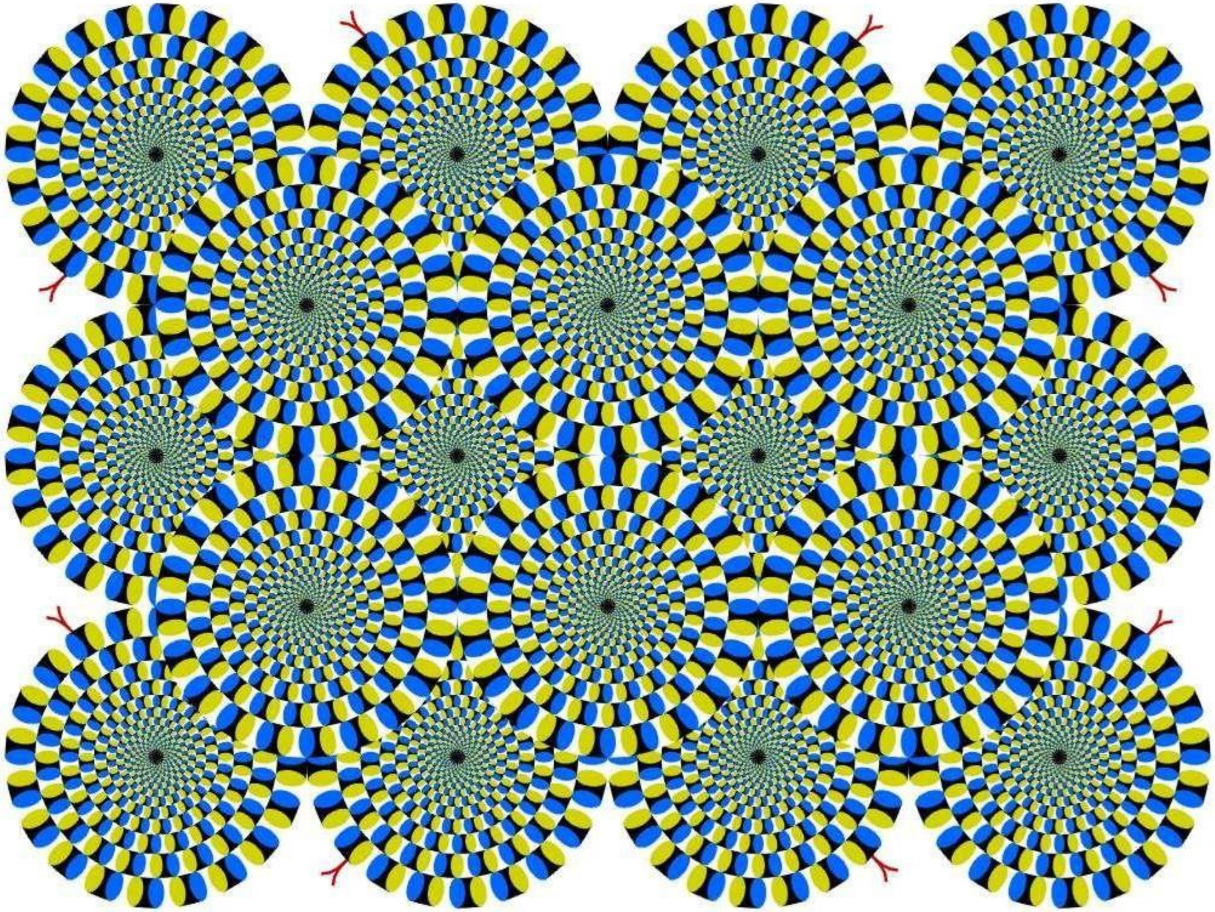
SIRDS Construction

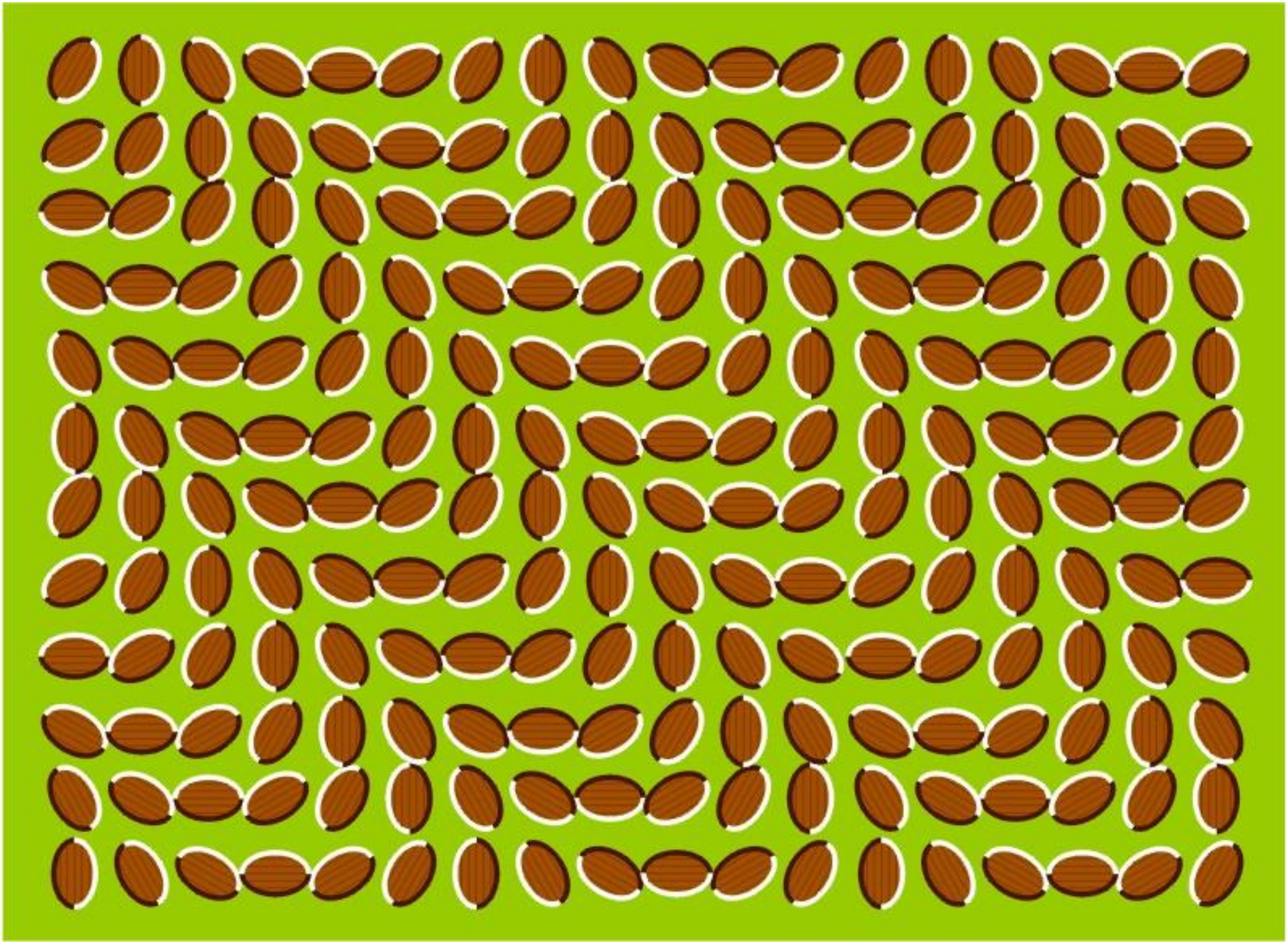
- Assign arbitrary color to pixel p_0 in image plane
- Trace from eye points through p_0 to object surface
- Trace back from object to corresponding other eye
- Assign color at p_0 to intersection points p_{1L}, p_{1R} with image plane
- Trace from eye points through p_{1L}, p_{1R} to object surface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

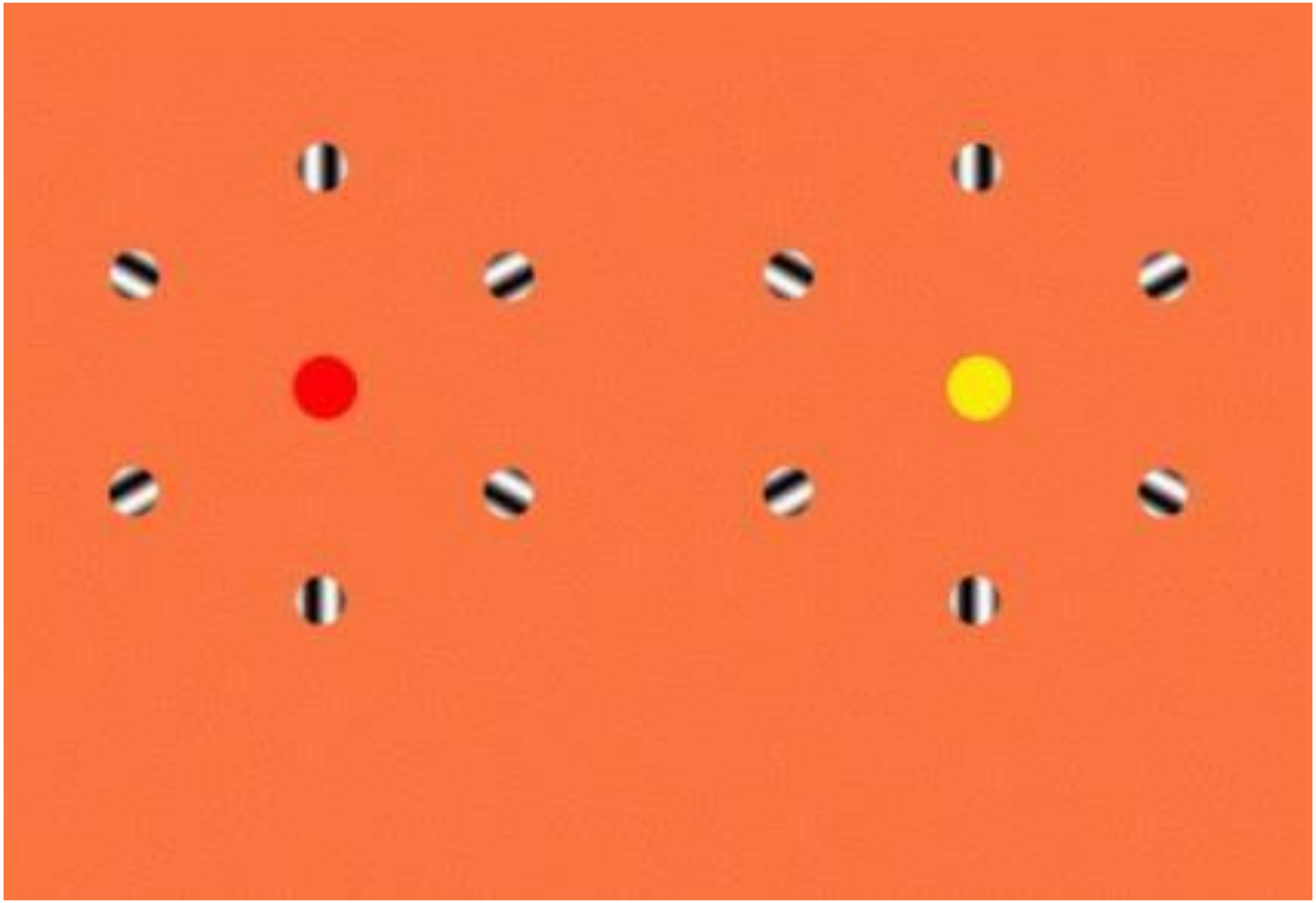


Appearance of movement in static image

- Due to cognitive effects of interacting color contrast & shape position
- Saccades → difference in neural signals between dark and bright areas







Cones excited by color eventually lose sensitivity

- Photoreceptors adapt to overstimulation and send a weak signal

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

If staring for ~15 seconds, you may see a giraffe appear