EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

FACULTY OF
SCIENCE
Computer Graphics

Computer Graphics (Graphische Datenverarbeitung)

- The Human Visual System –

Hendrik Lensch

WS 2021/2022

Corona

- Regular random lookup of the 3G certificates

- Contact tracing: We need to know who is in the class room
  - New ILIAS group for every lecture slot
  - Register via ILIAS or this QR code (only if you are present in this room)

What do you see?

What do you see?

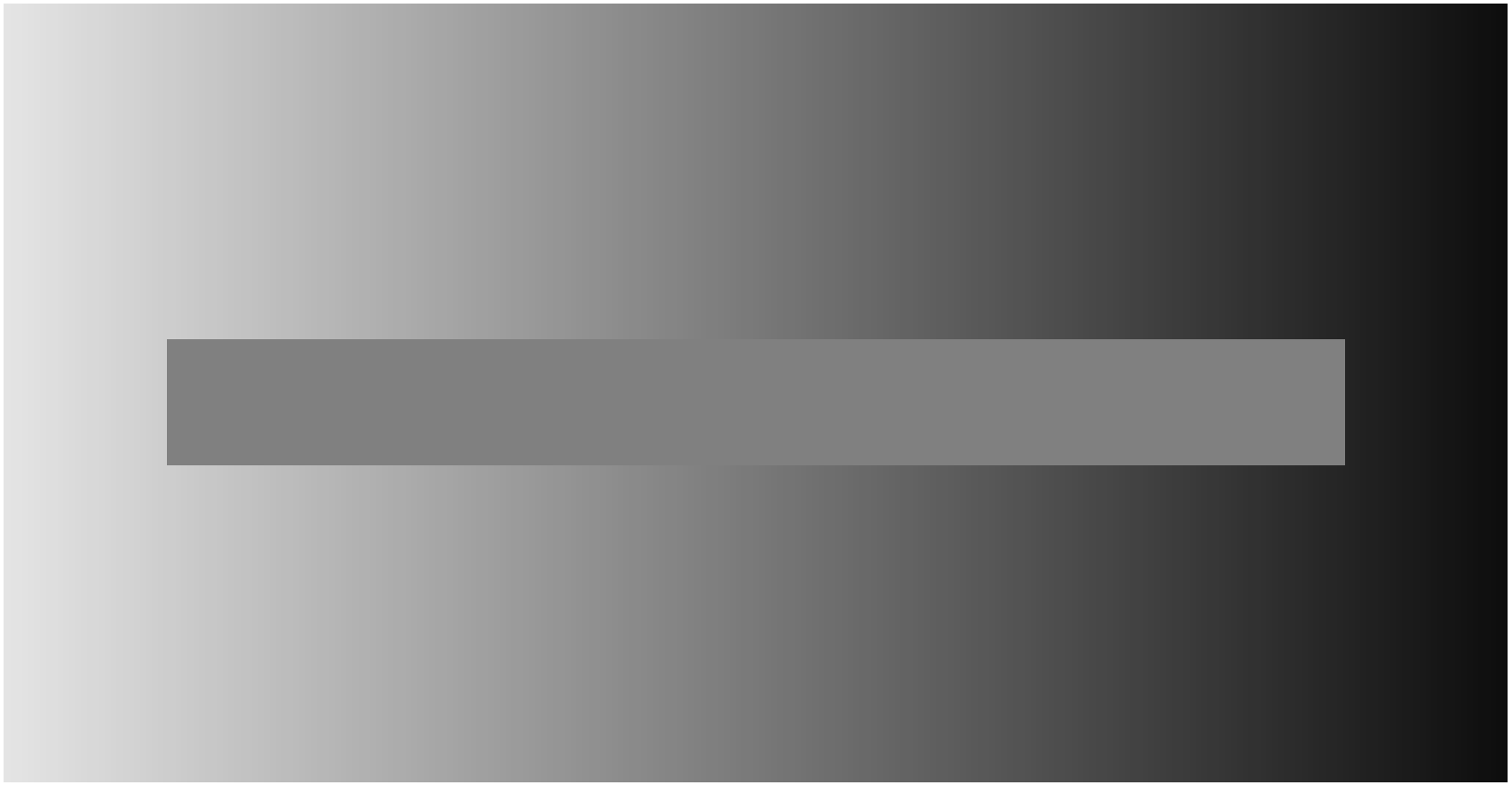
Where is the ball?

Where is the ball? – 1

Where is the ball? – 2

Where is the ball?

Constant Color? Gradients?



What you should learn

- The setup of the human eye.
- What is displayed and what we “see” is not necessarily the same. Be aware.

Overview

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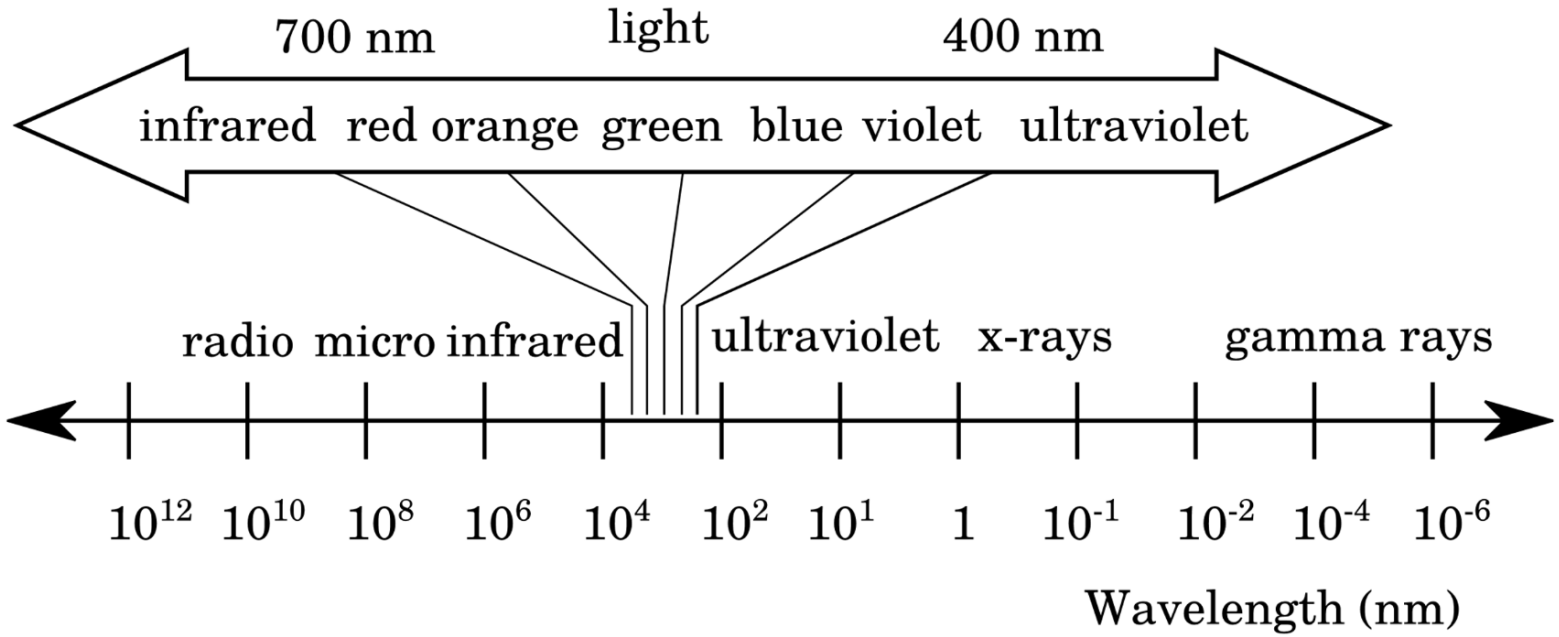
- Previous
  - Antialiasing
  - Super-Sampling
  - Image Filters
- Today
  - The Human Visual System
    - The eye
    - Early vision
    - High-level analysis
    - Color perception
- Next lecture
  - Color spaces

Light

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



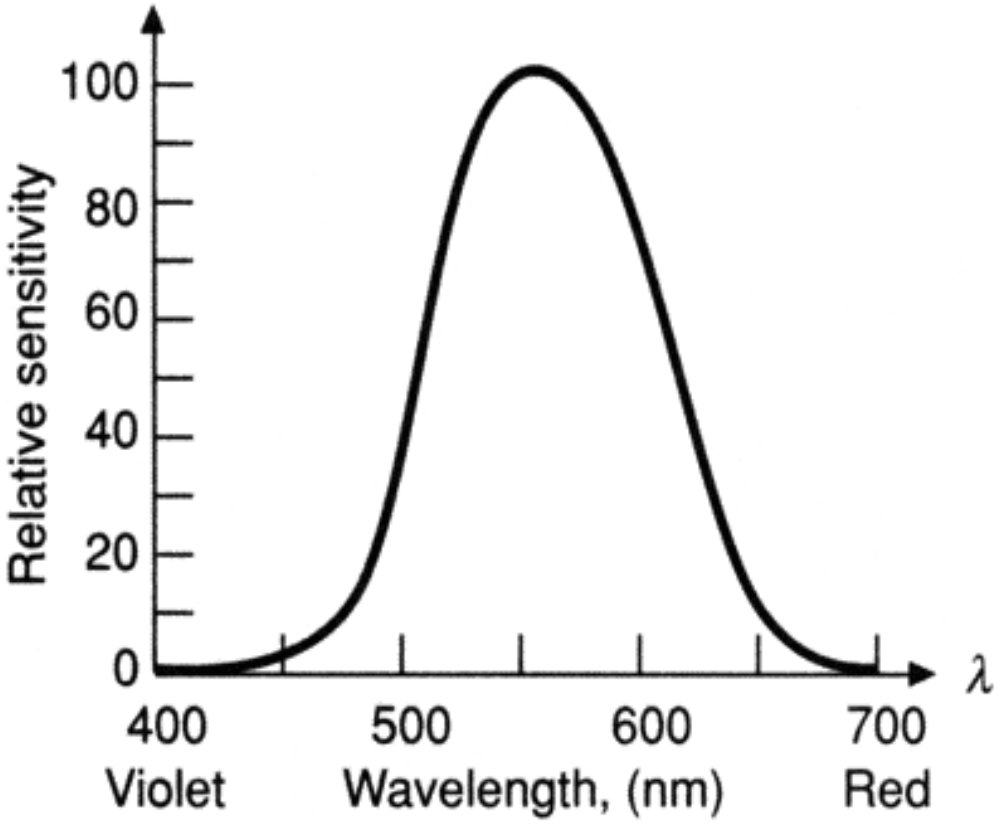
Photometry

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

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

$$K_m = 683\ lm/W$$

  - Distinction in English simple:
    - “rad”: radiometric unit
    - “lum”: photometric unit



Radiometric Units

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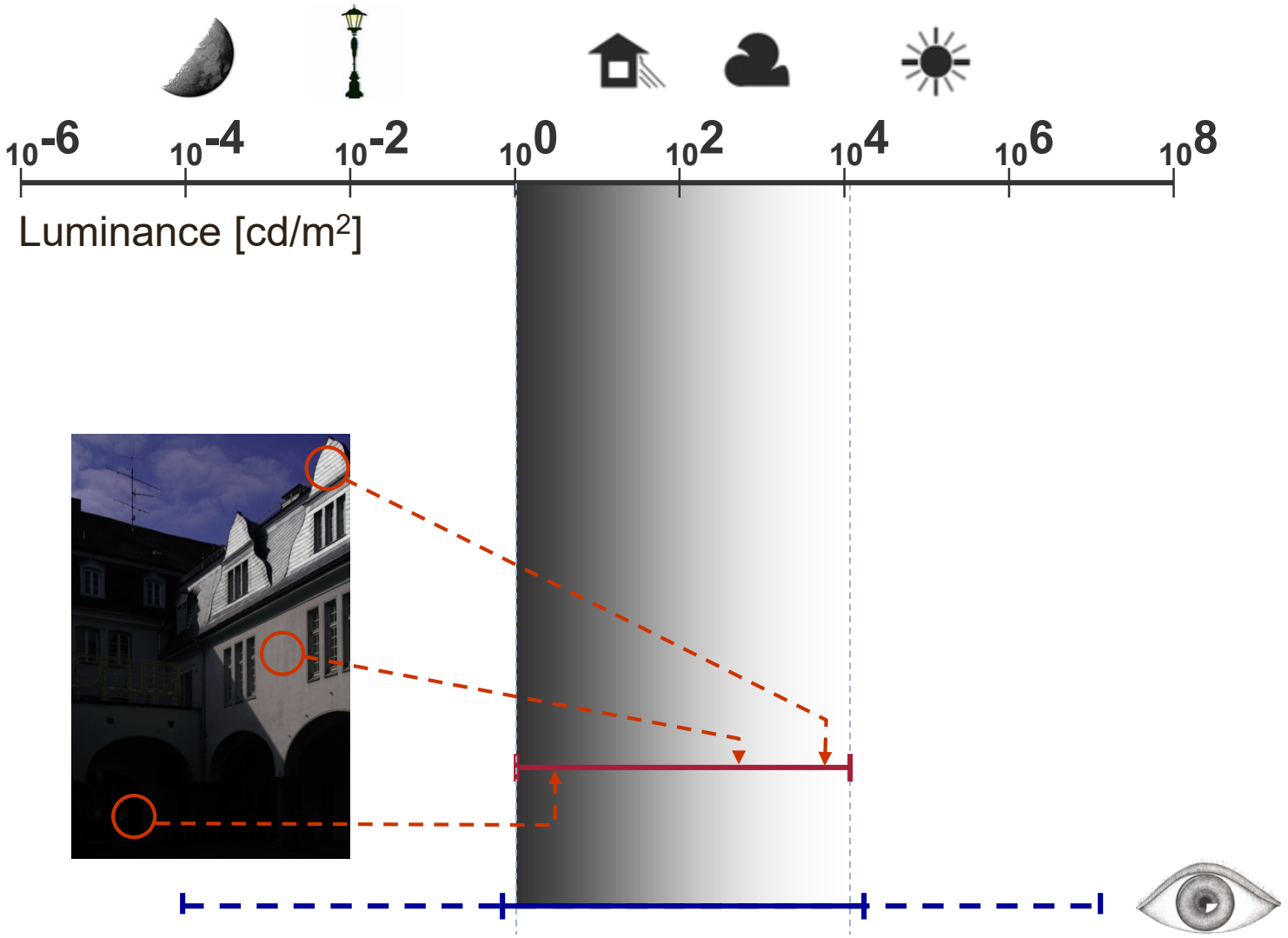
Specification	Definition	Symbol	Unit	Notation
Energie energy		Q_e	[J= Ws] Joule	Strahlungsenergie radiant energy
Leistung, Fluß power, flux	dQ/dt	Φ_e	[W= J/s]	Strahlungsfluß radiant flux
Flußdichte flux density	dQ/dAdt	E_e	[W/m^2]	Bestrahlungsstärke Irradiance
Flußdichte flux density	dQ/dAdt	$M_e = B_e$	[W/m^2]	Radiom. Emissionsvermögen Radiosity
	dQ/dA$^{\Phi}$dωdt	L_e	[W/m^2/sr]	Strahlungsdichte Radiance
Intensität intensity	dQ/dωdt	I_e	[W/sr]	Strahlungsstärke radiant intensity

Photometric Units

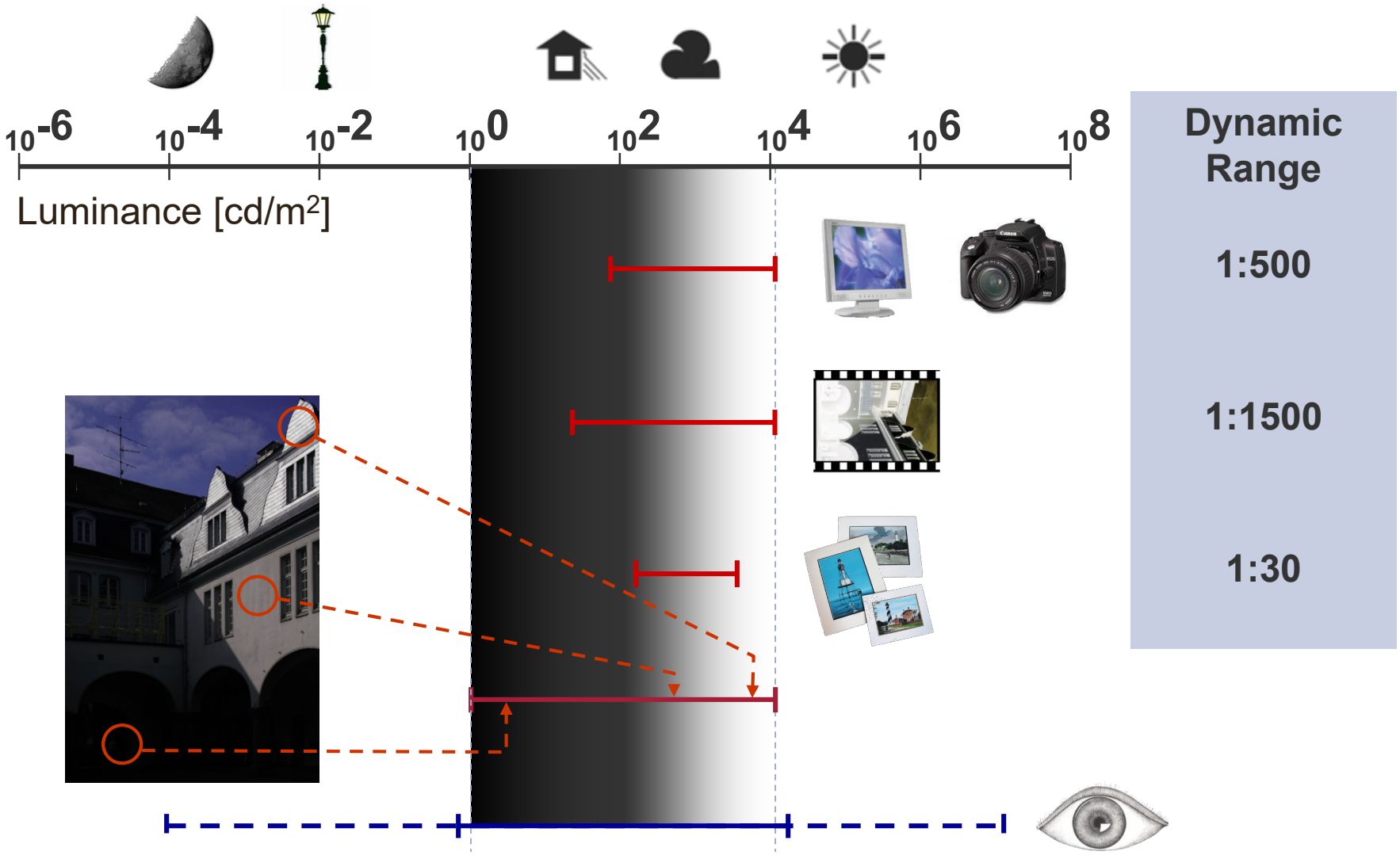
- With luminous efficiency function weighted units

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/m^2]	Beleuchtungsstärke Illuminance
Flußdichte flux density	dQ/dAdt	[M_v=] B_v	[lux]	Photom. Emissionsvermögen Luminosity
	dQ/dA$^{\Phi}$dωdt	L_v	[lm/m^2/sr]	Leuchtdichte Luminance
Intensität intensity	dQ/dωdt	I_v	[cd (candela) = lm/sr]	Lichtstärke radiant intensity

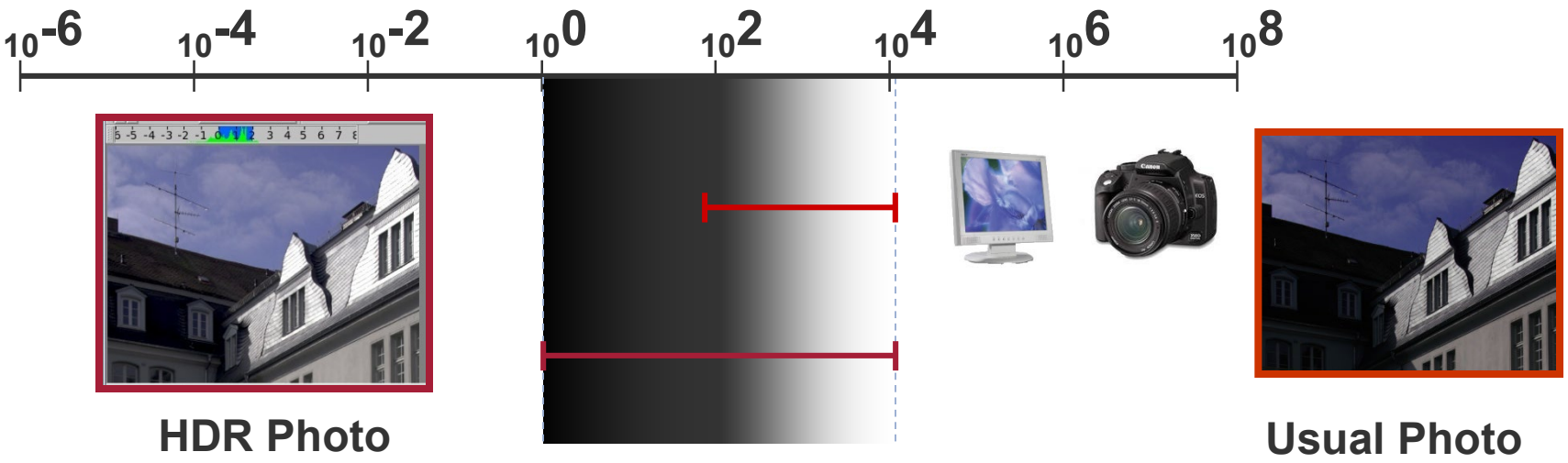
Luminance Range



Contrast (Dynamic Range)



High Dynamic Range (HDR)



Illumination: samples

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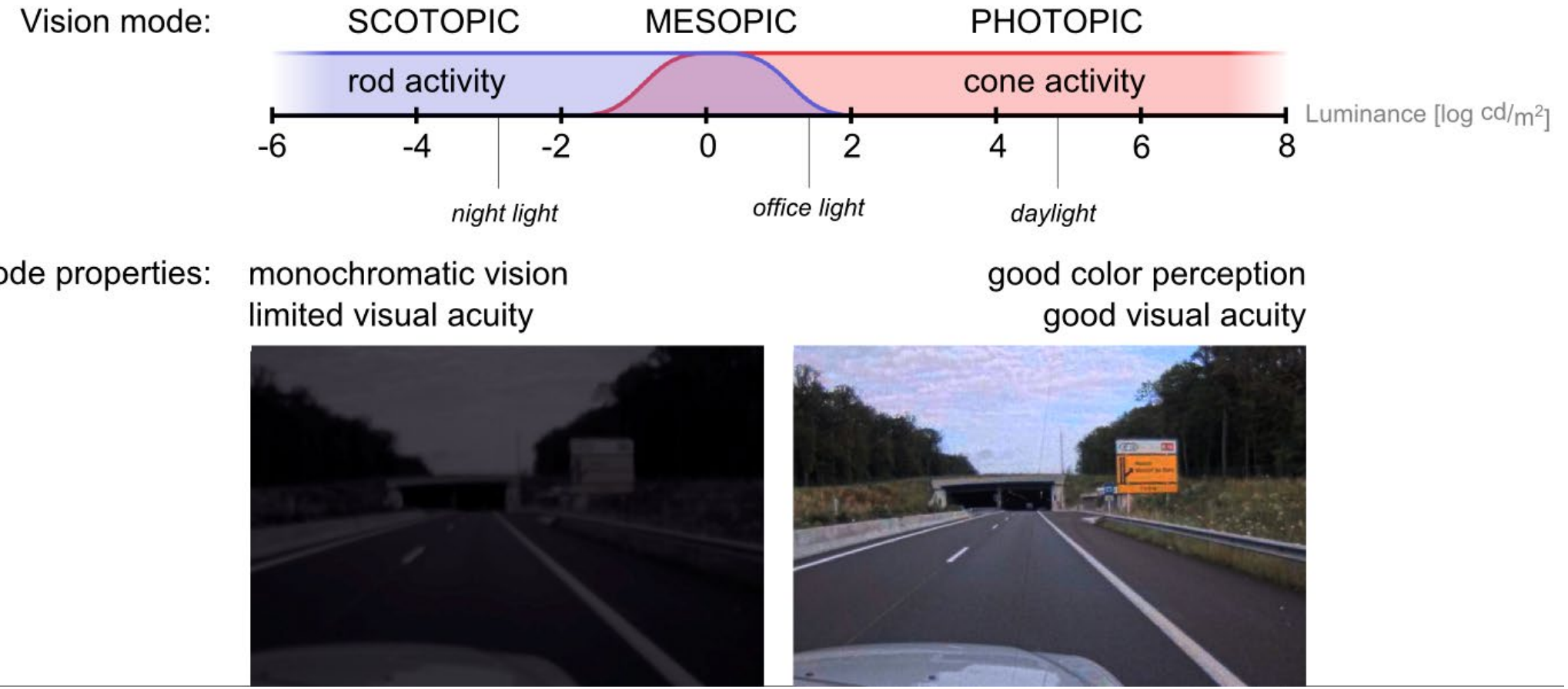
- Typical illumination intensities

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

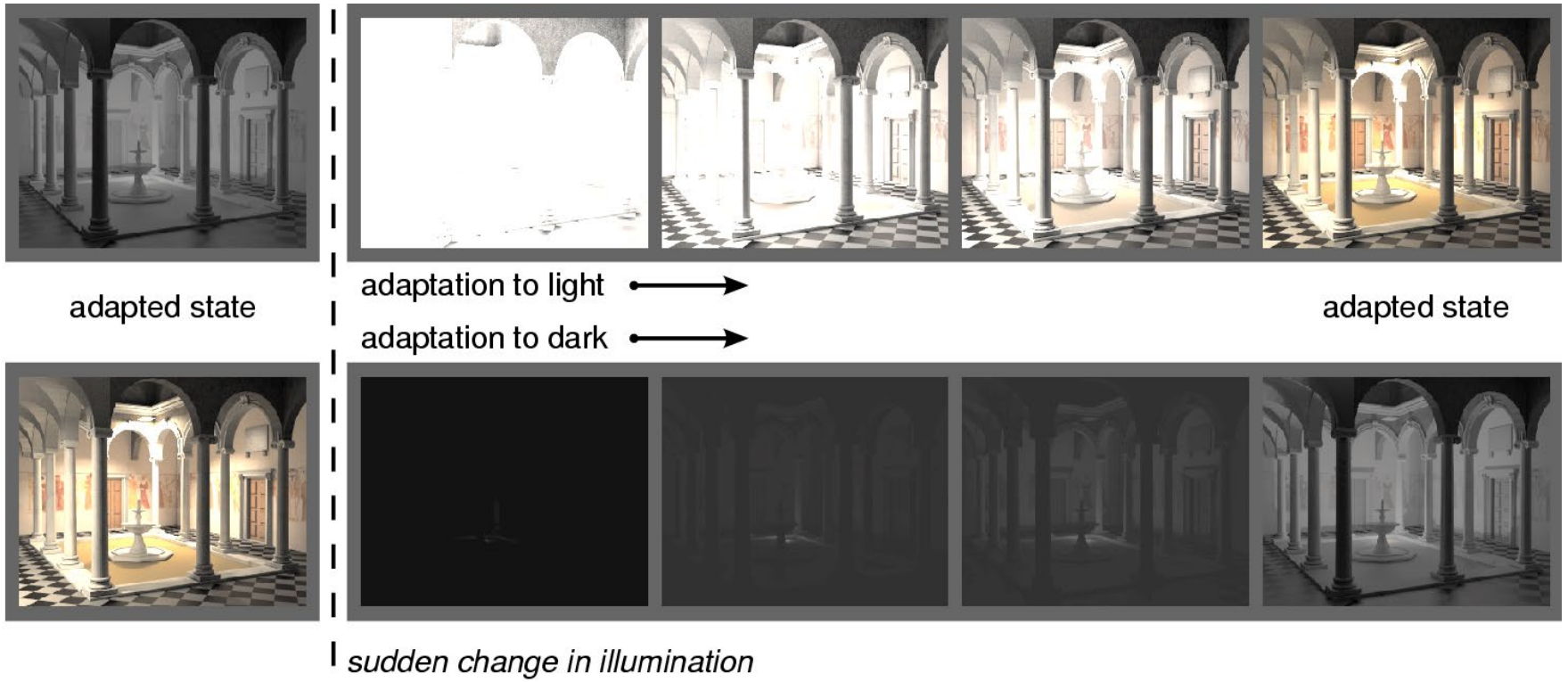
Percept. Effects – Vision Modes



Simulation requires:

- control over color reproduction
- local reduction of detail visibility
  (computationally expensive)

Percept. Effects – Light Adaptation



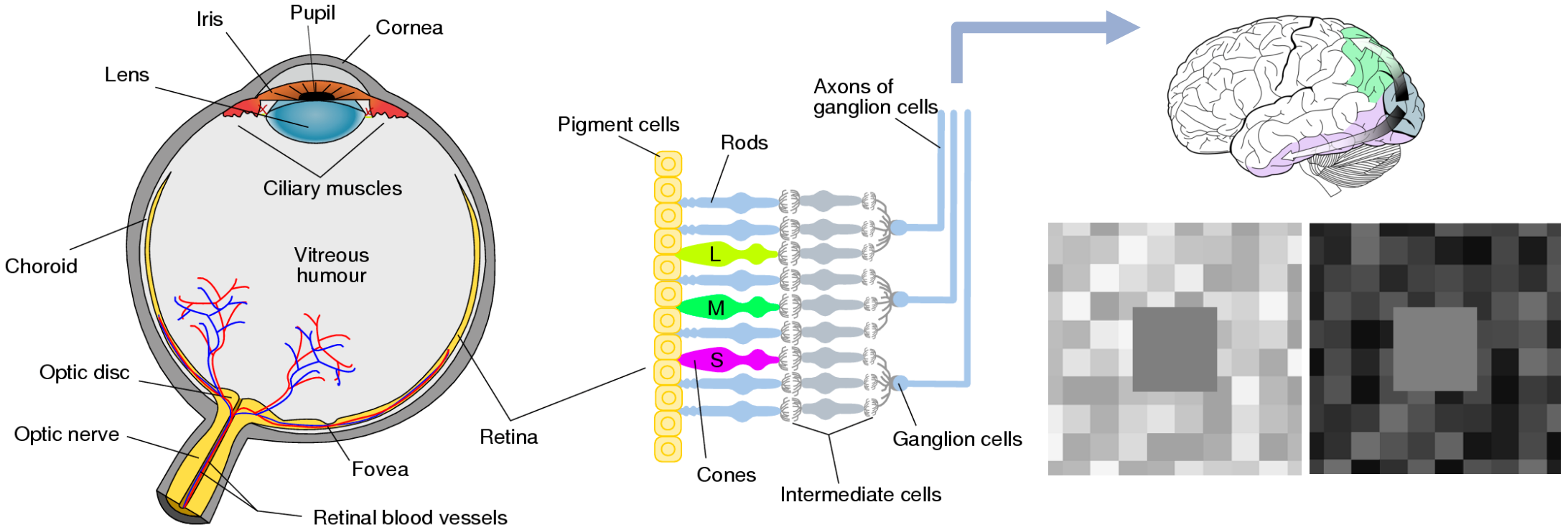
Adaptation to dark much slower

Simulation requires:

- time-dependent filtering of light adaptation

HVS & Color Vision

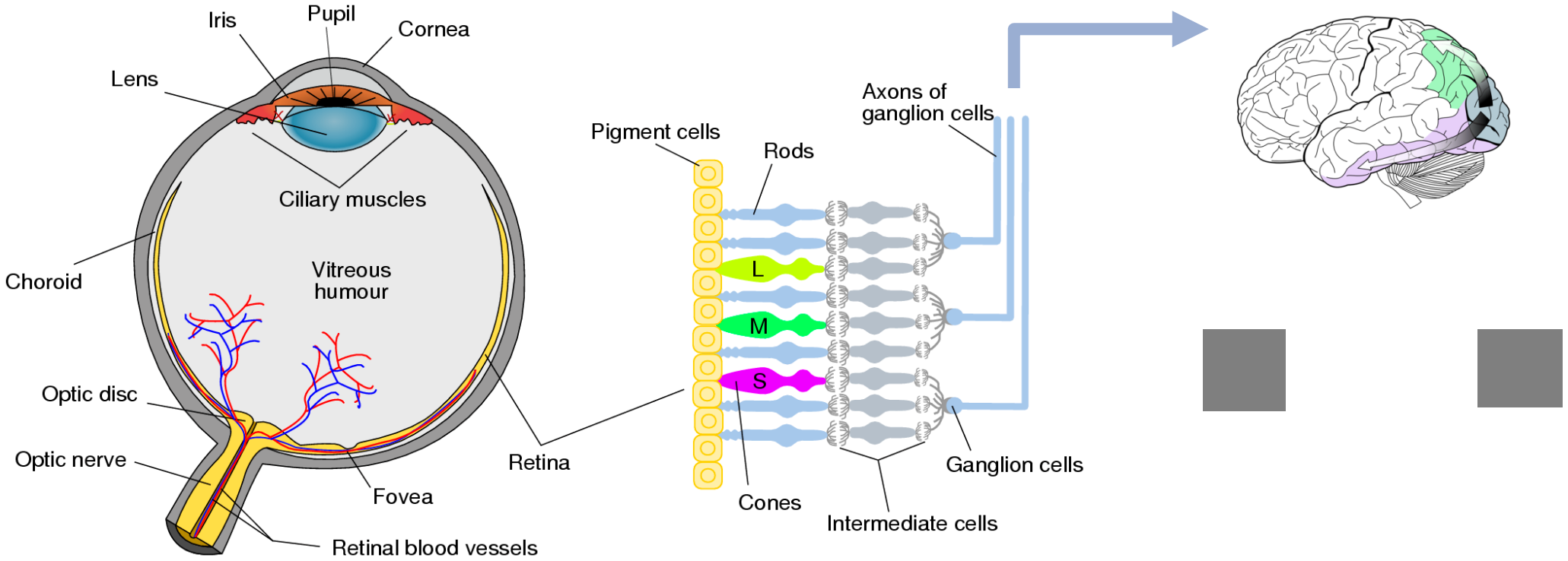
Human Visual Perception



early vision (eyes) **image appearance**

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

Human Visual Perception

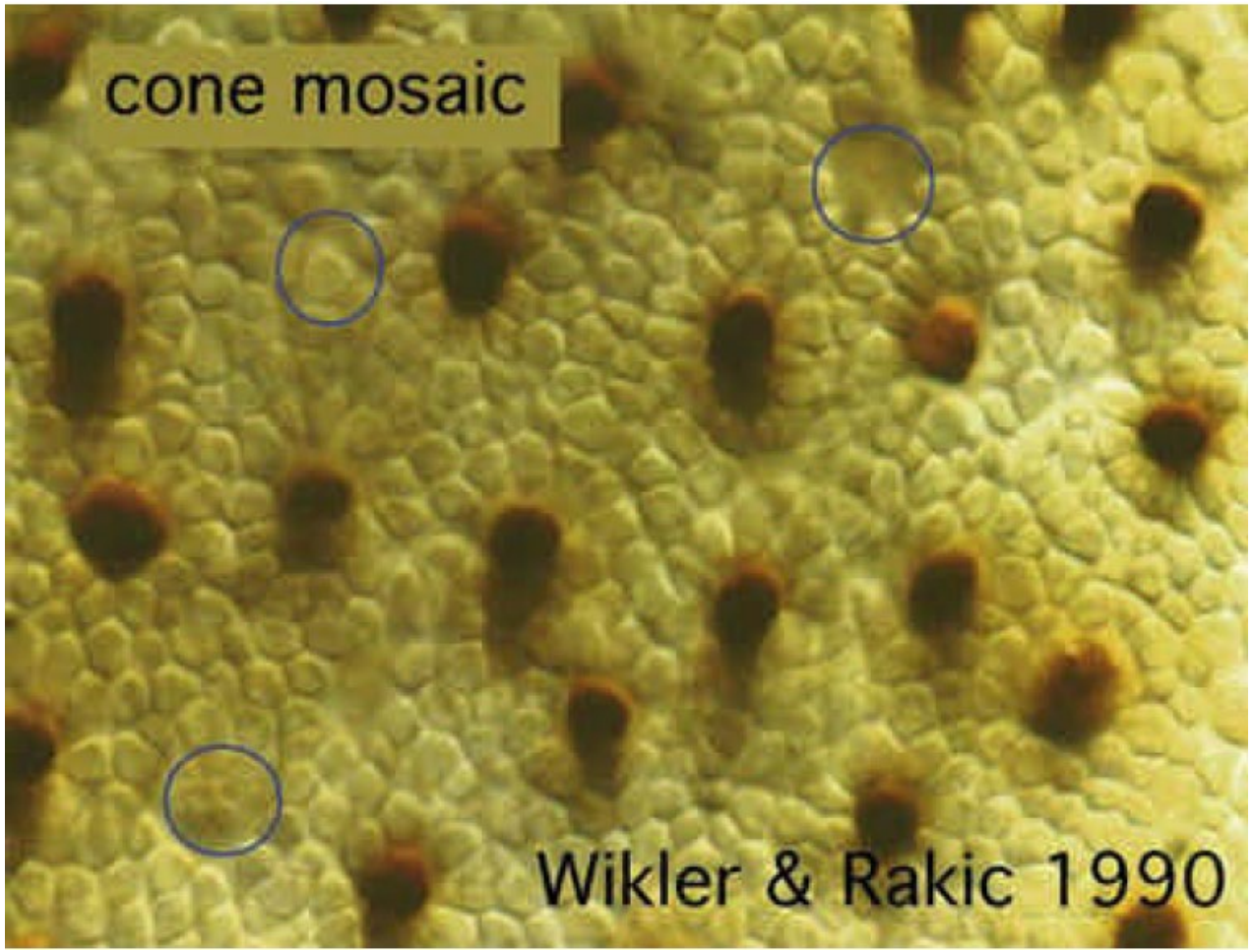


early vision (eyes) **image appearance**

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

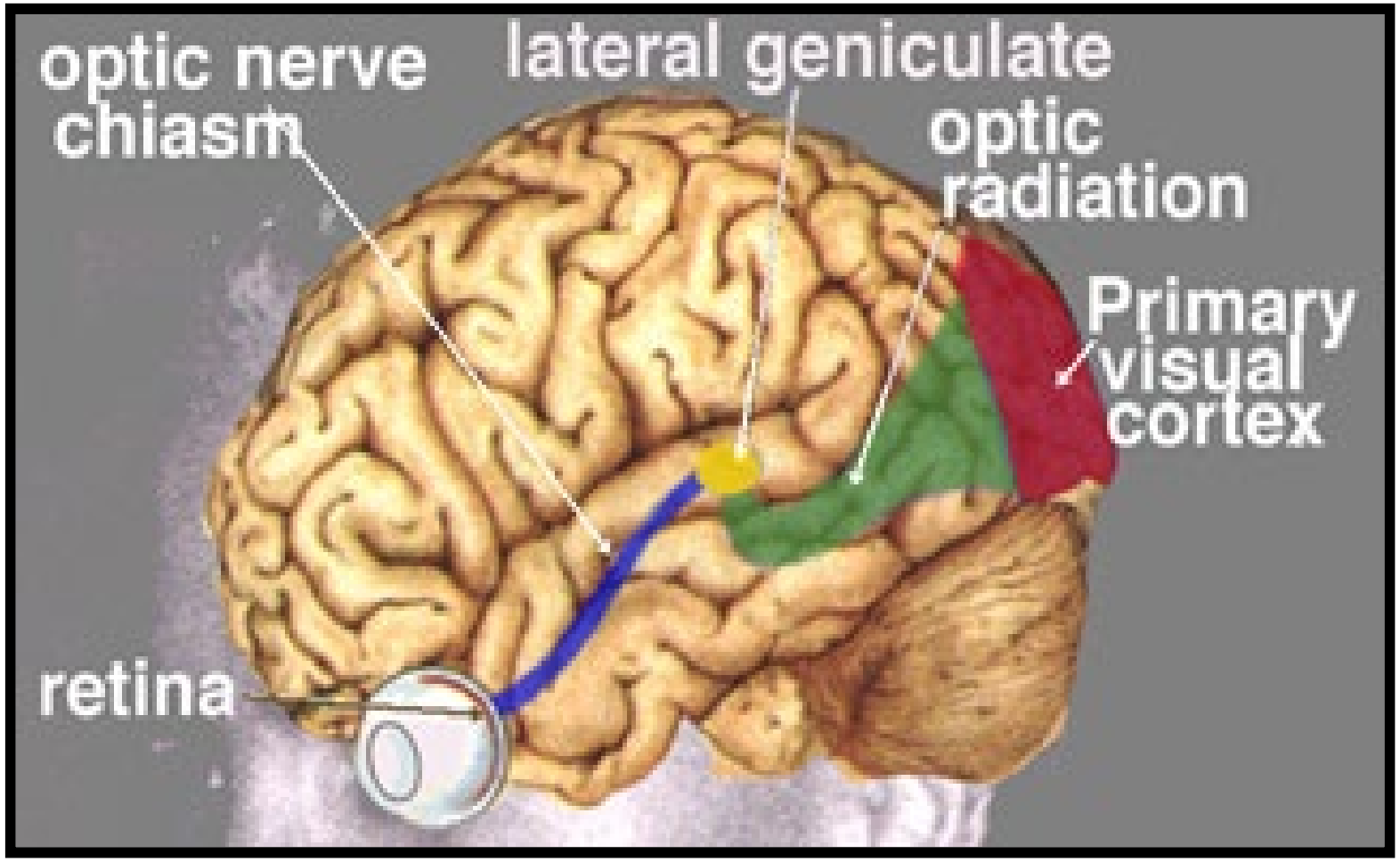
Distribution of Rods and Cones

- approximate a Poisson disc distribution



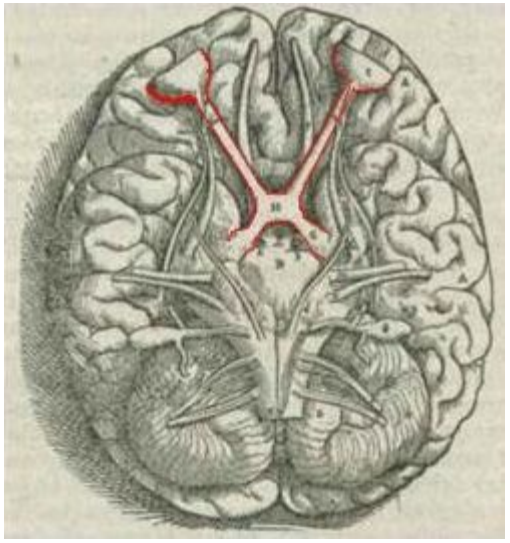
Human Visual System

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

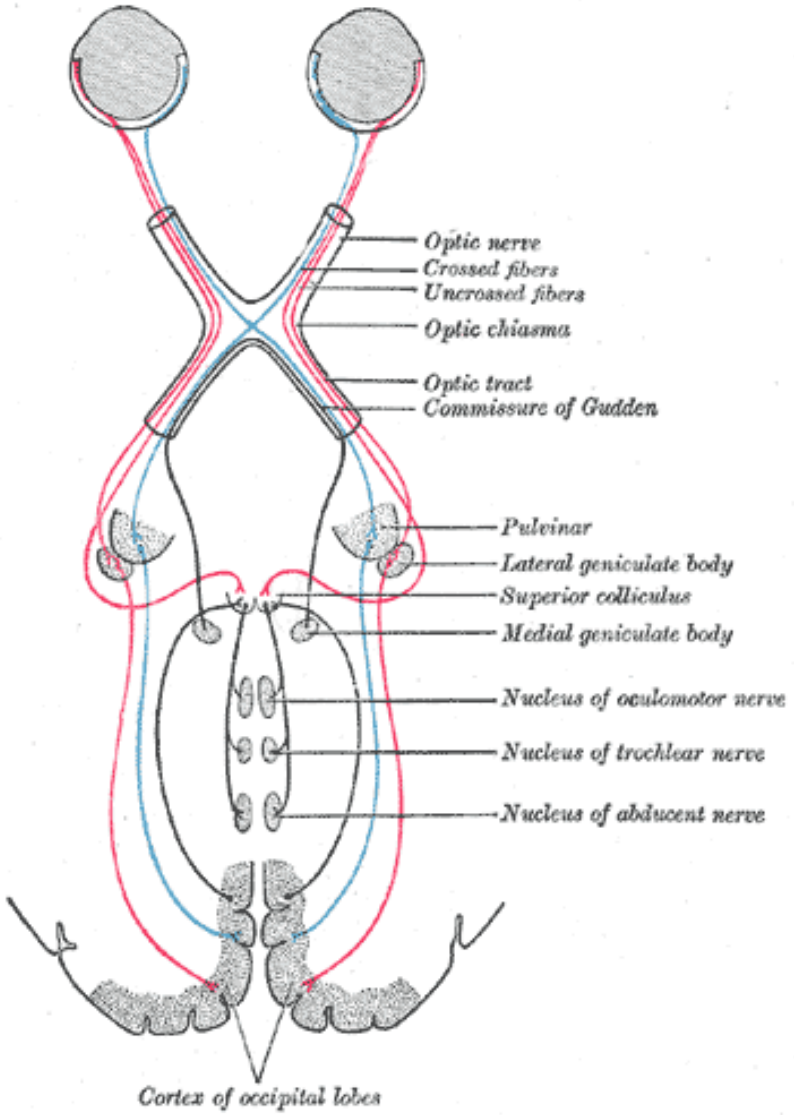


Human Visual System

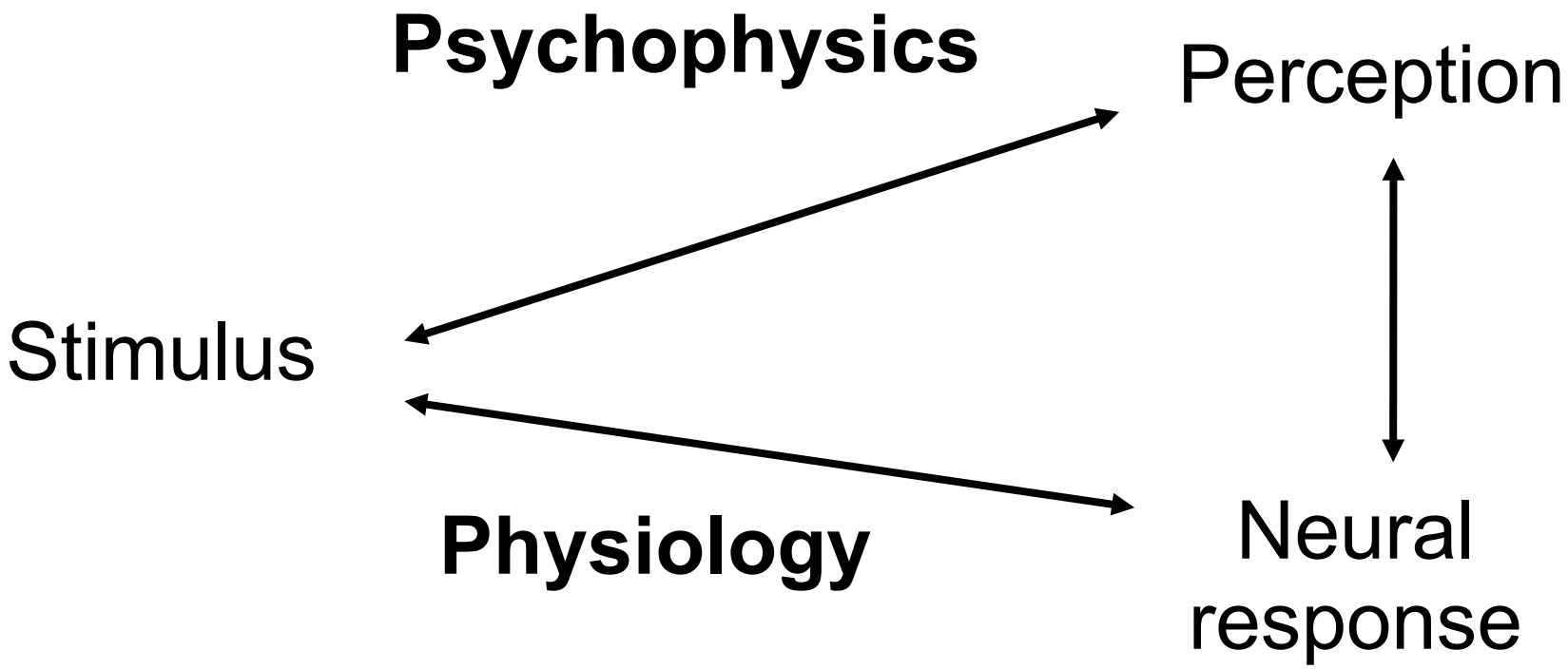
- Physical structure well established
- Perceptual behaviour is a complex process
- Chiasm: crossing of nerve bundles.
  - right temporal visual field of right eye
    -> left brain
  - left temporal field of left eye -> right brain



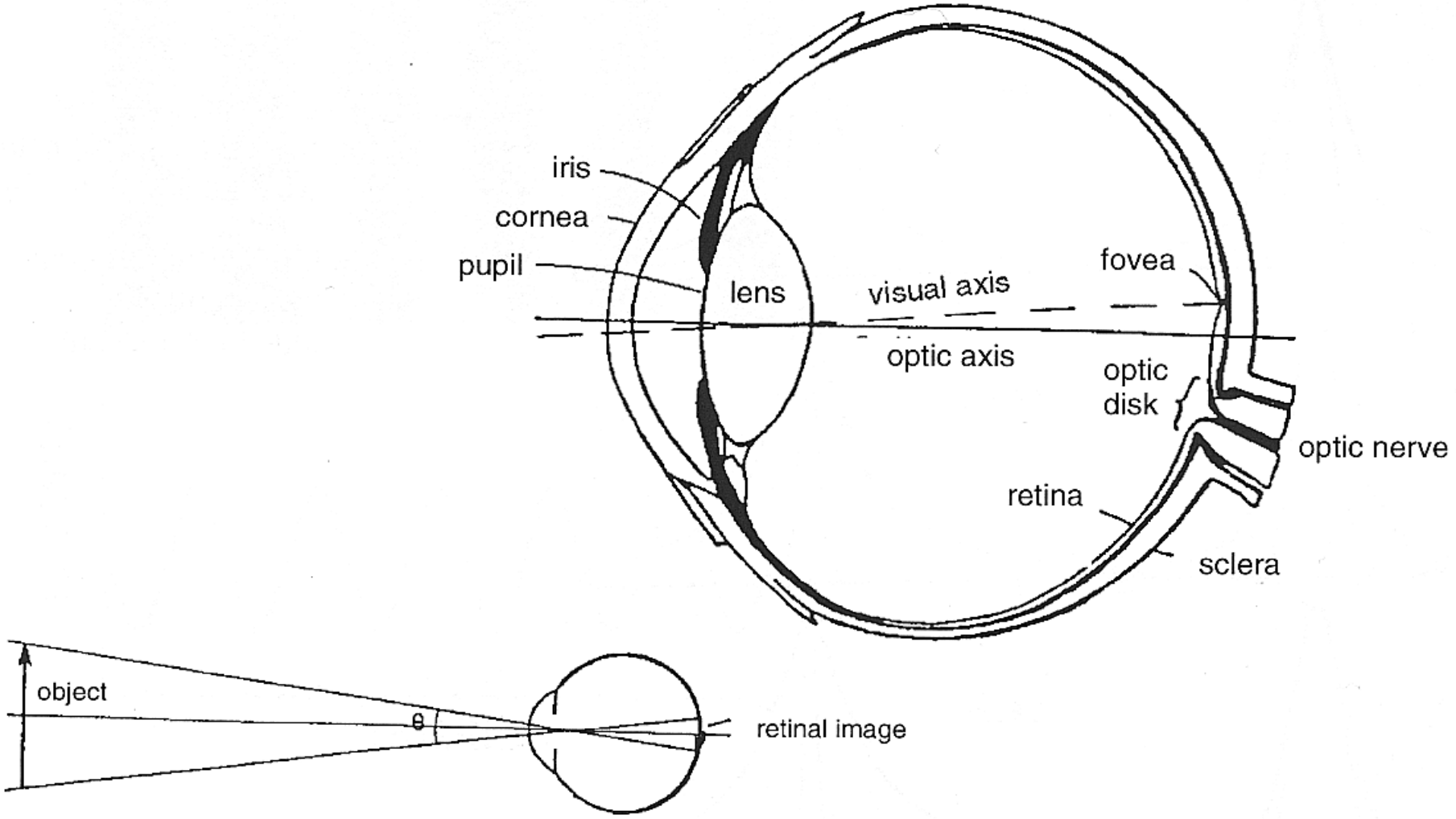
optic chiasm



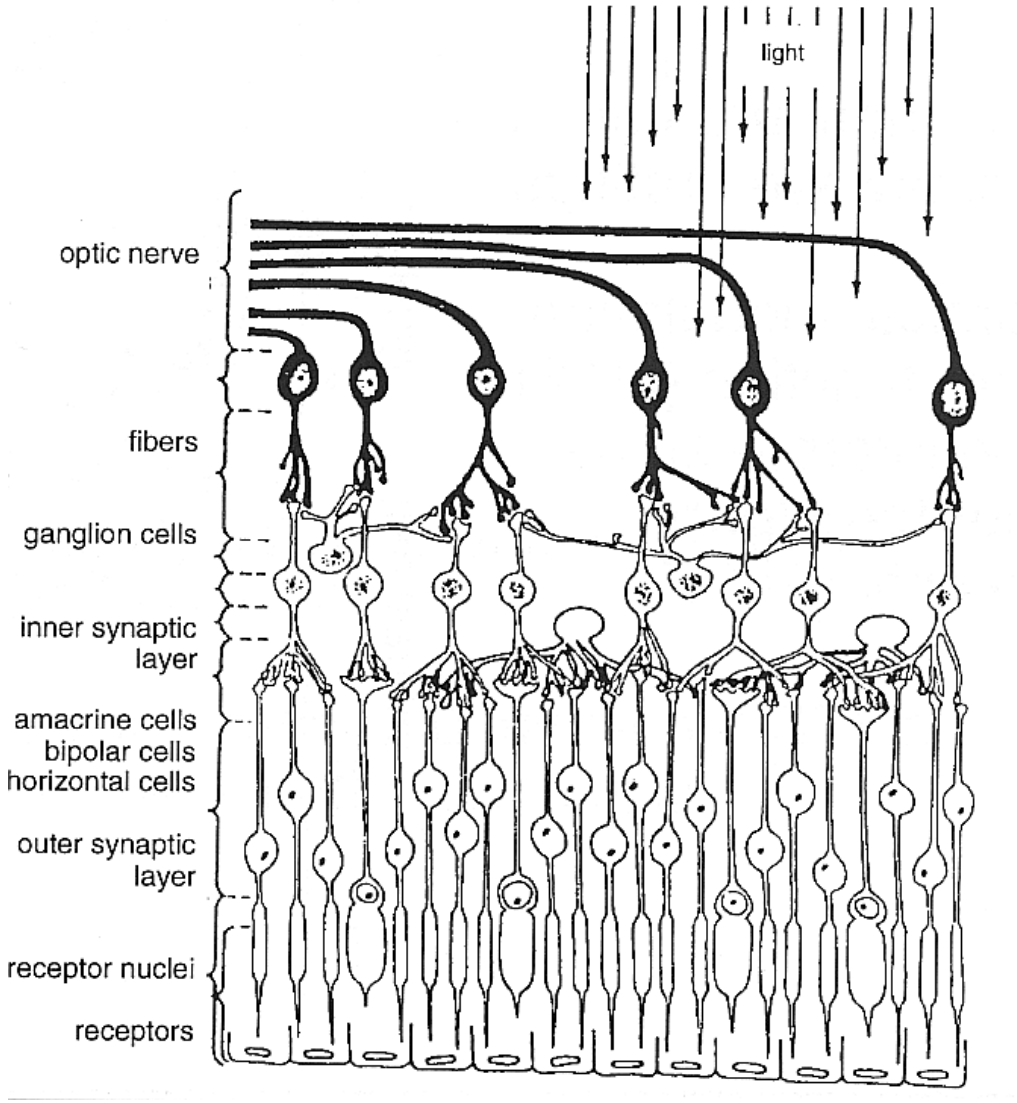
HVS - Relationships



Perception and Eye

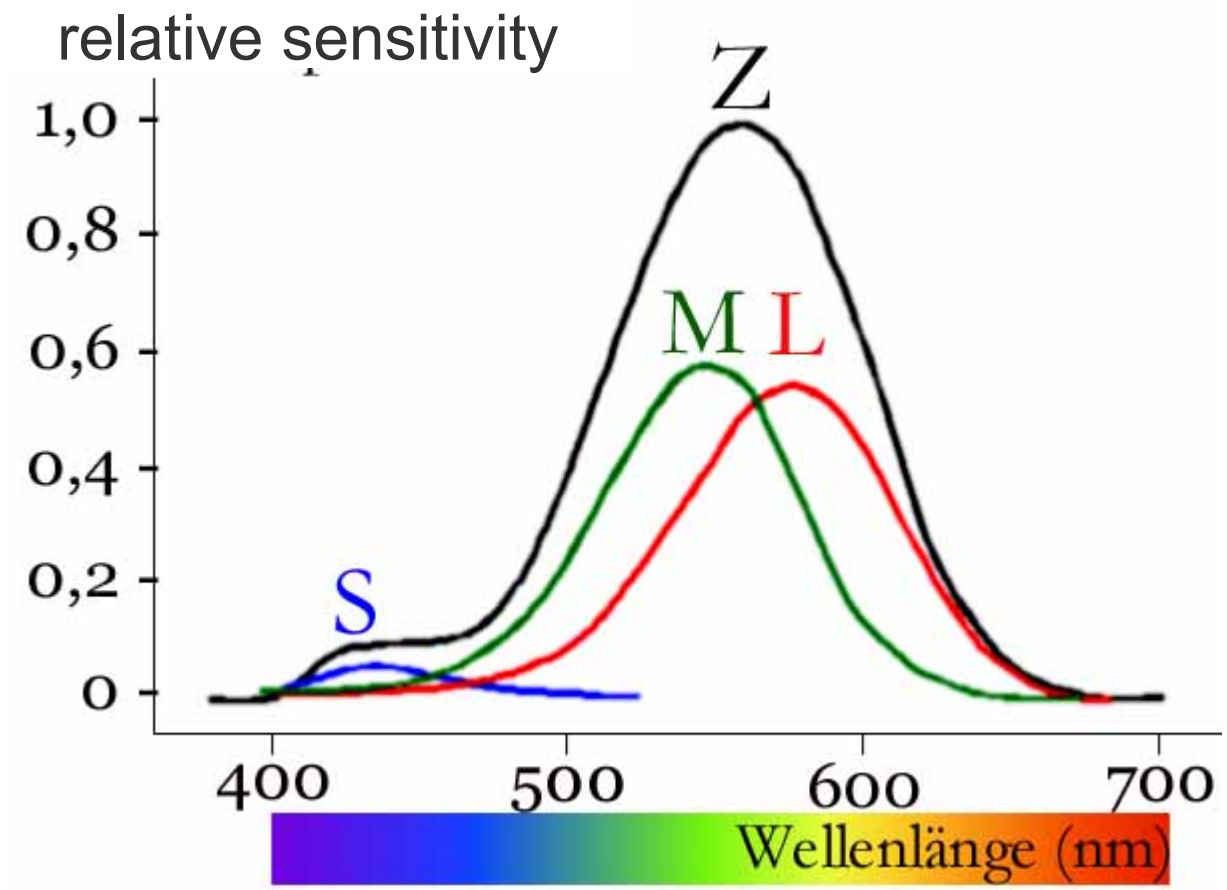


Retina


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 and Rods
  - S scaled by 3x
  - Z (Stäbchen – rods) total sensitivity



Eye

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- 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

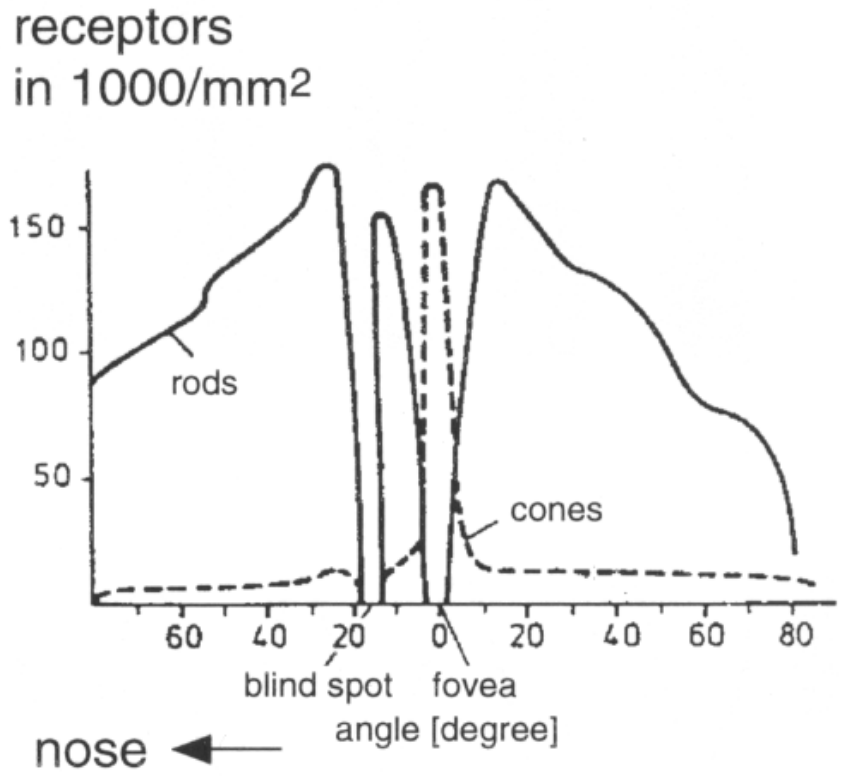
This is a text in red

This is a text in green

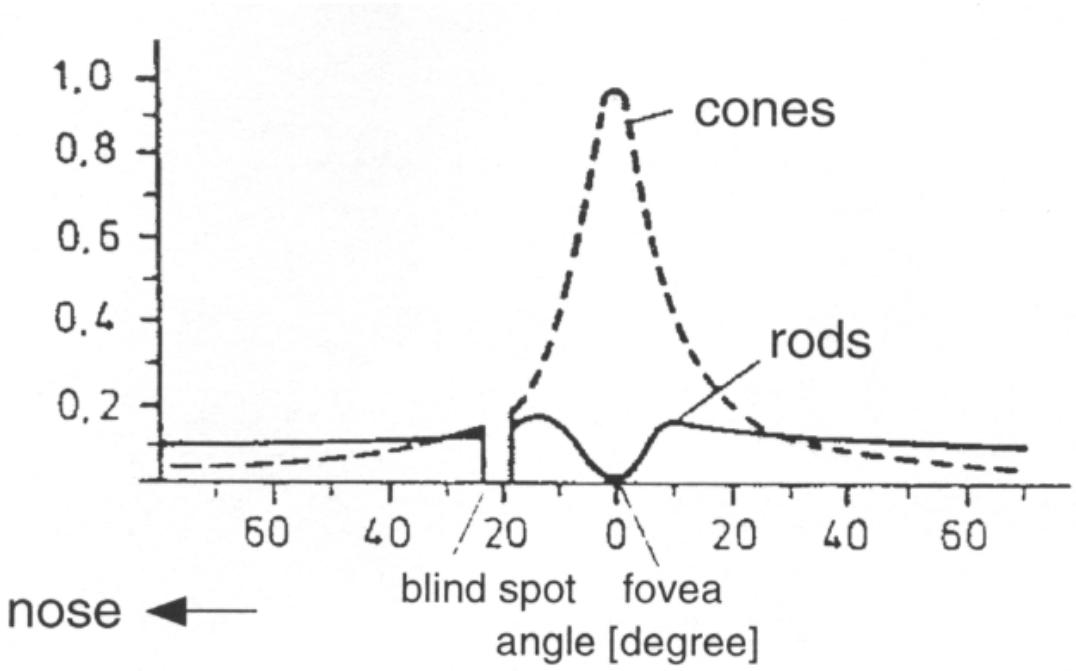
This is a test in blue

Contrast and Resolution

Visual Acuity

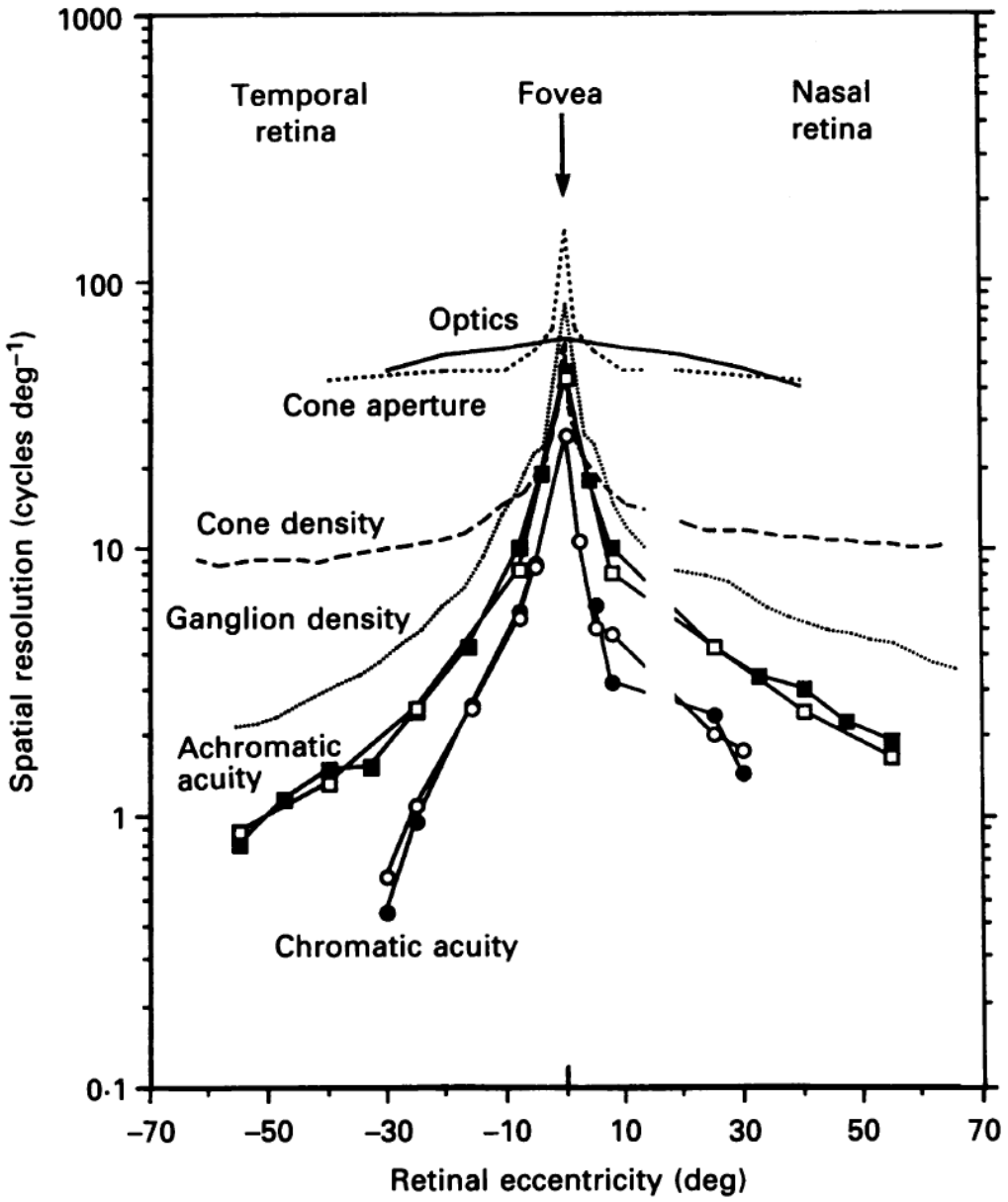


Receptor density



Resolution in line-pairs/arc minute

Effective Spatial Resolution

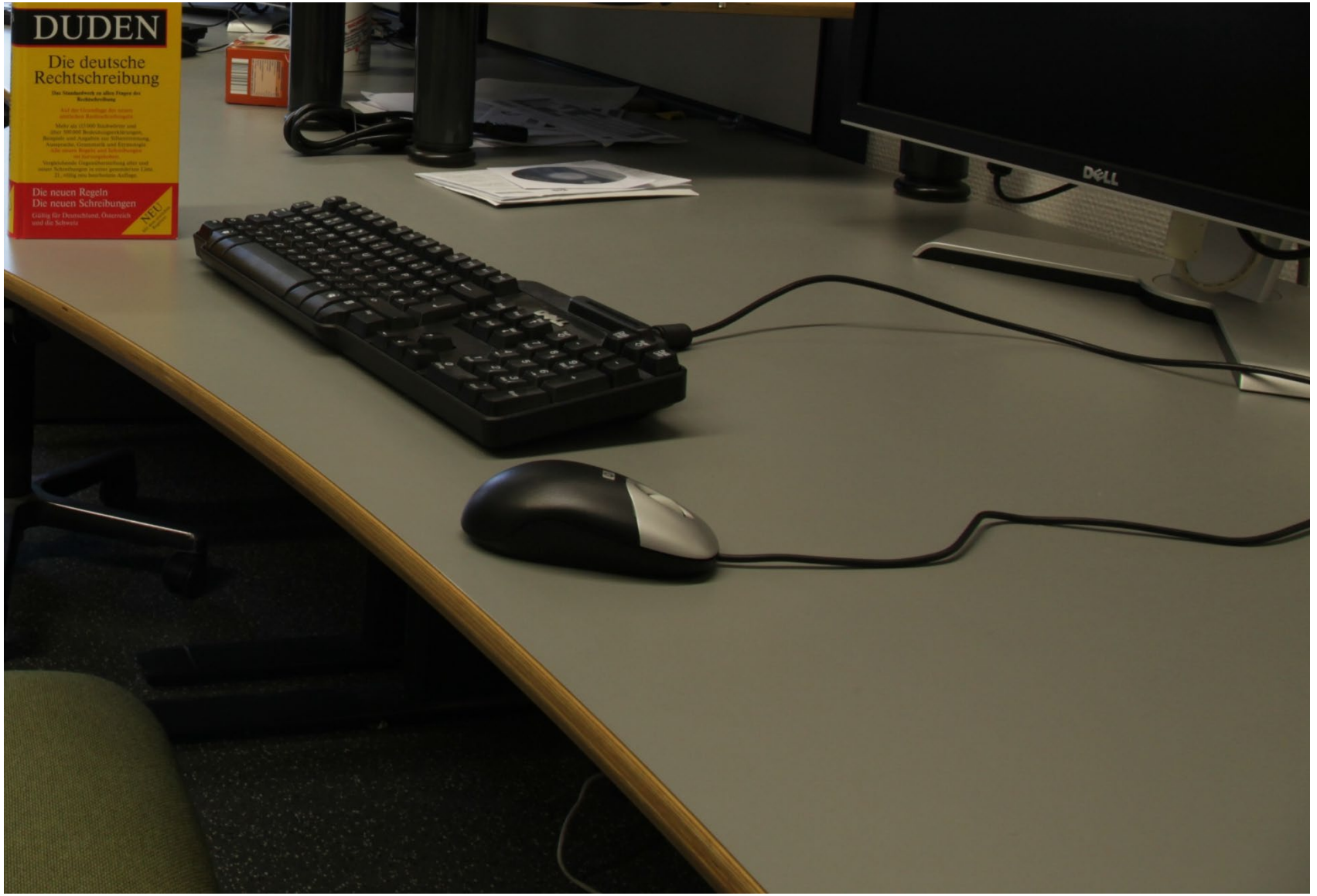


[Stephen et al. 1991]

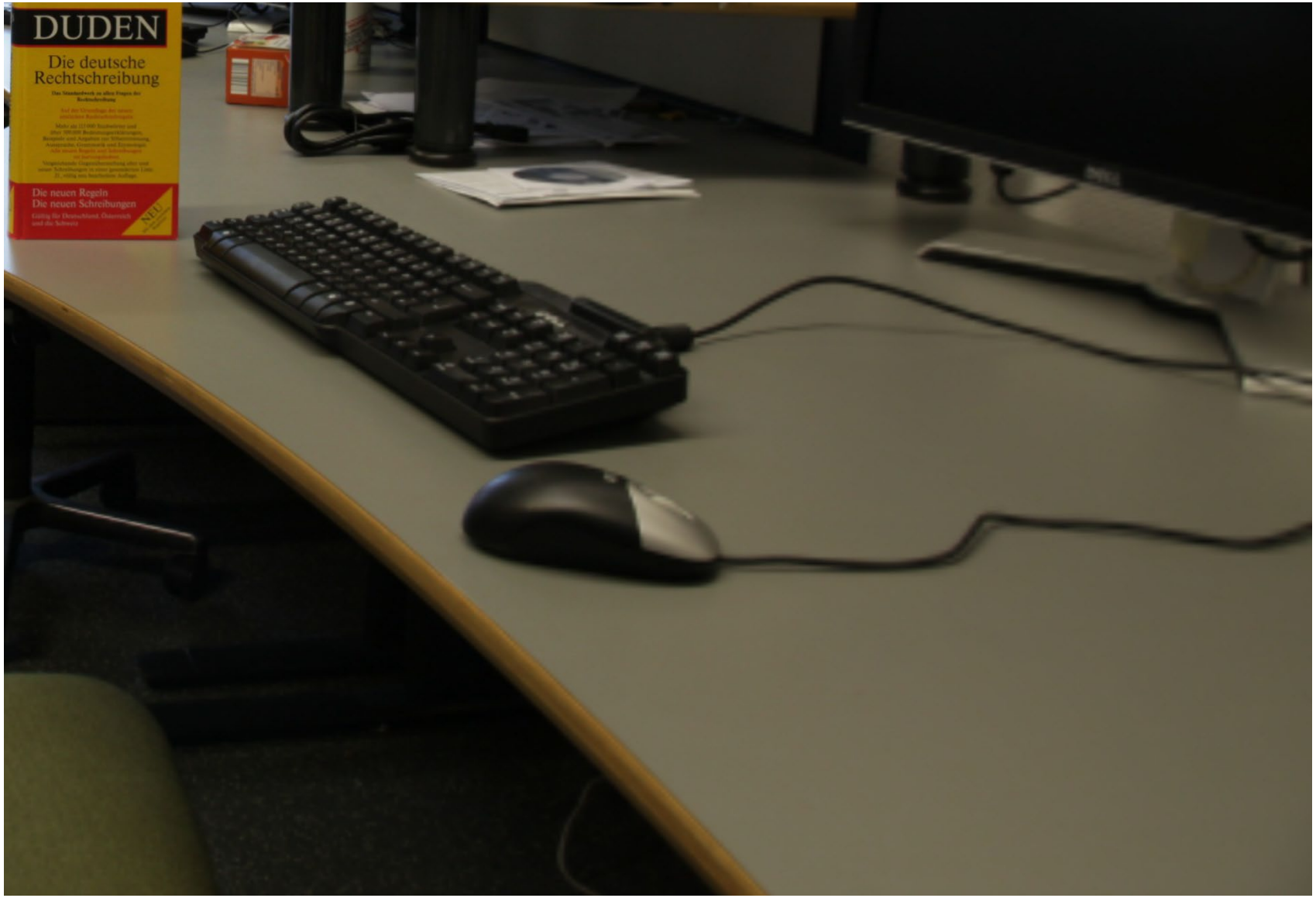
Effect of Resolution – Sharp

Effect of Resolution – Considered

Effect of Resolution – Sharp



Effect of Resolution – Considered



Resolution of the Eye

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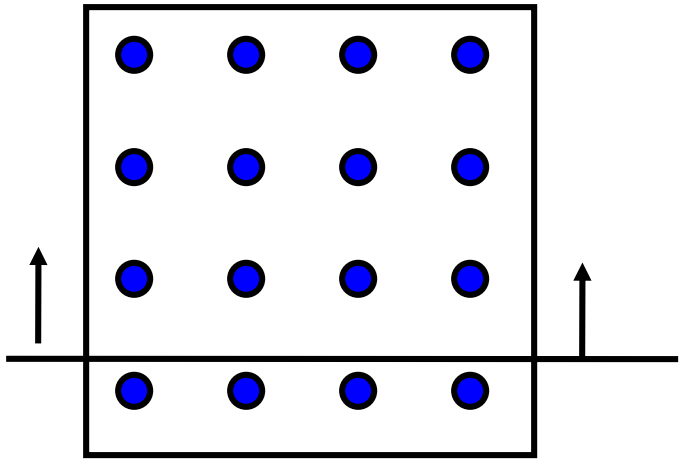
- Resolution-experiments
  - Line pairs: 50-60/degree → resolution .5 arc minutes
  - Line offset: 5 arc seconds (hyperacuity)

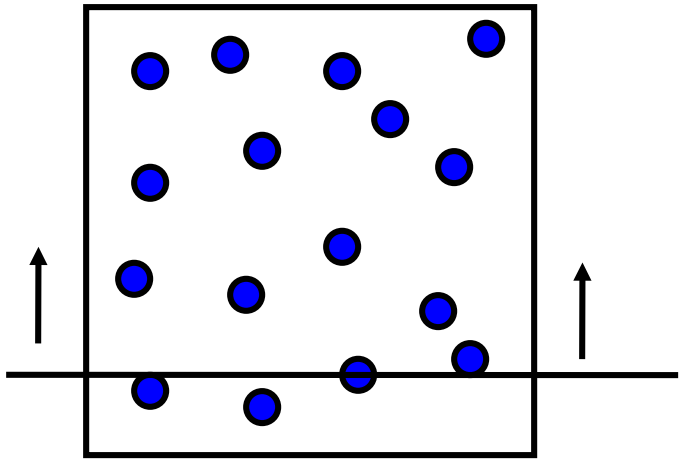
  - Eye micro-tremor: 60-100 Hz, 5 μm (2-3 photoreceptor spacings)
    - Allows to reconstruct from super-resolution
  - Together corresponds to
    - 19“ display at 60 cm: 18.000^2 Pixel (3000^2 w/out hyperacuity)
- Automatic fixation of eye onto region of interest
  - Automatic gaze tracking
  - Apparent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

Super-Sampling in Practice

- Problems with regular super-sampling
  - Expensive: 4-fold to 16-fold effort
  - Non-adaptive: Same effort everywhere
  - Too regular: Apparent reduction of number of levels
- Introduce irregular sampling pattern



0 → 4/16 → 8/16 → 12/16 → 16/16

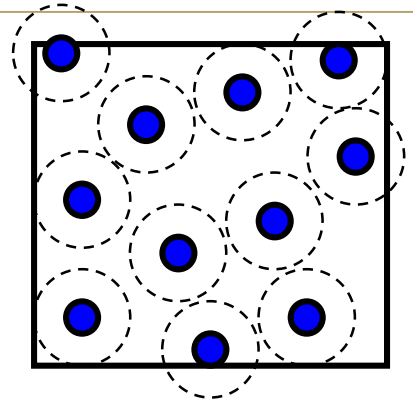


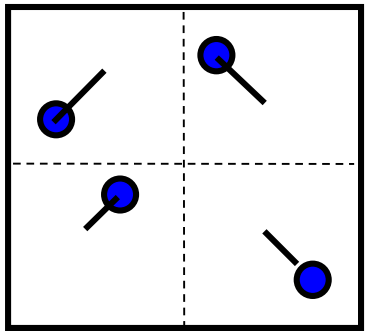
Better, but noisy

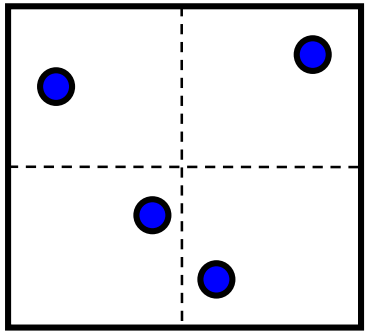
- Stochastic super-sampling
  - Or analytic computation of pixel coverage and pixel mask

Stochastic Sampling

- Requirements
  - Even distribution
  - Little correlation between samples
  - Incremental generation
- Generation of samples
  - Poisson-disk sampling
    - Fixes a minimum distance between samples
    - Random generation of samples
      - Rejection, if too close to other samples
  - Jittered sampling
    - Random perturbation from regular positions
  - Stratified Sampling
    - Subdivision into areas with one random sample each
    - Improves even distribution
  - Quasi-random numbers (Quasi-Monte Carlo)
    - E.g. Halton Sequence
    - Advanced feature

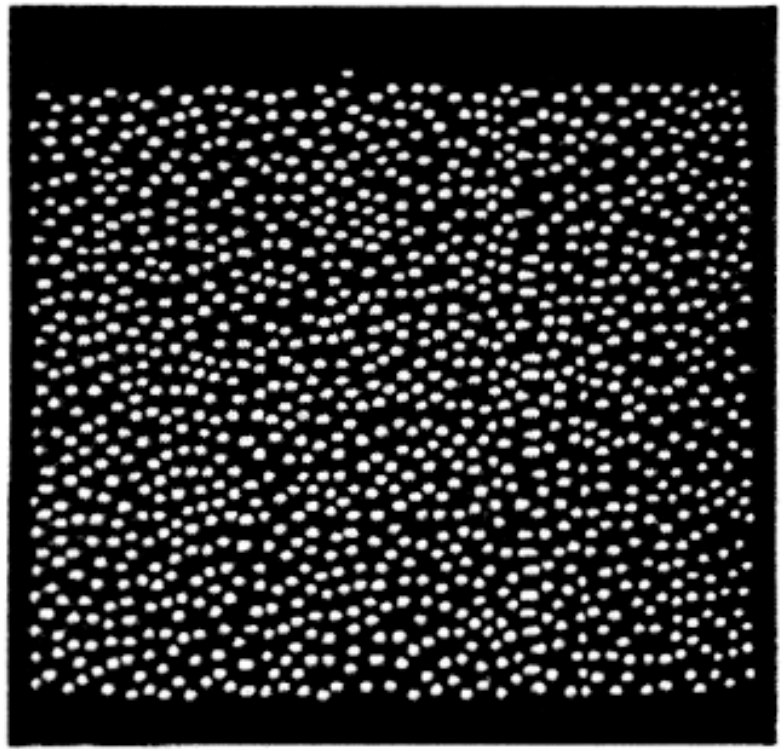




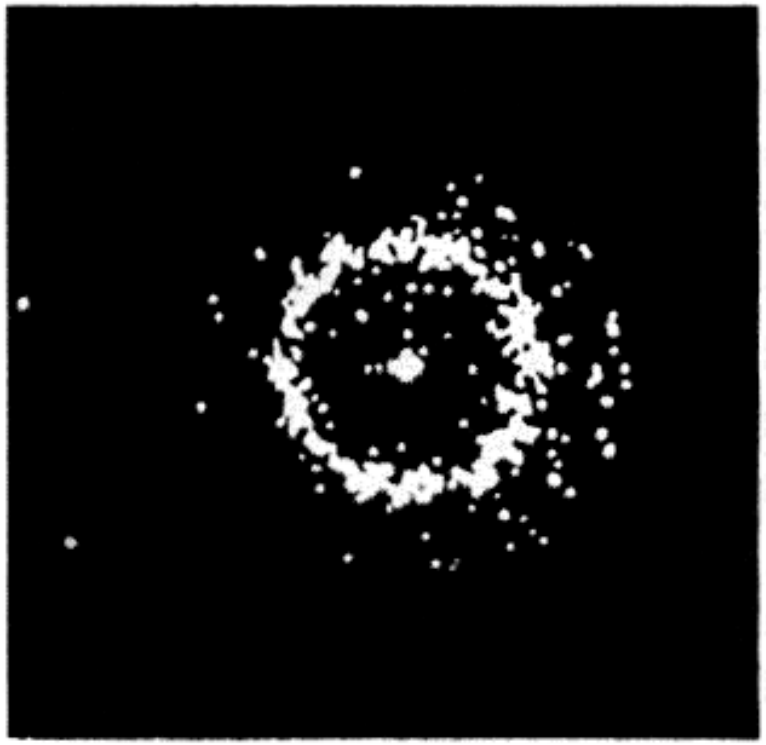


Poisson-Disk Sample Distribution

- Motivation
  - Distribution of the optical receptors on the retina (here: ape)



Distribution of the receptors

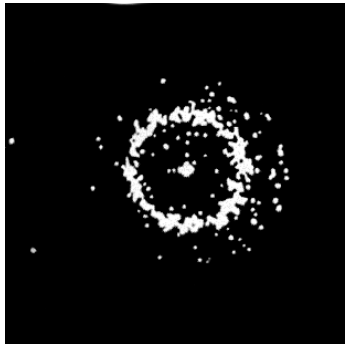


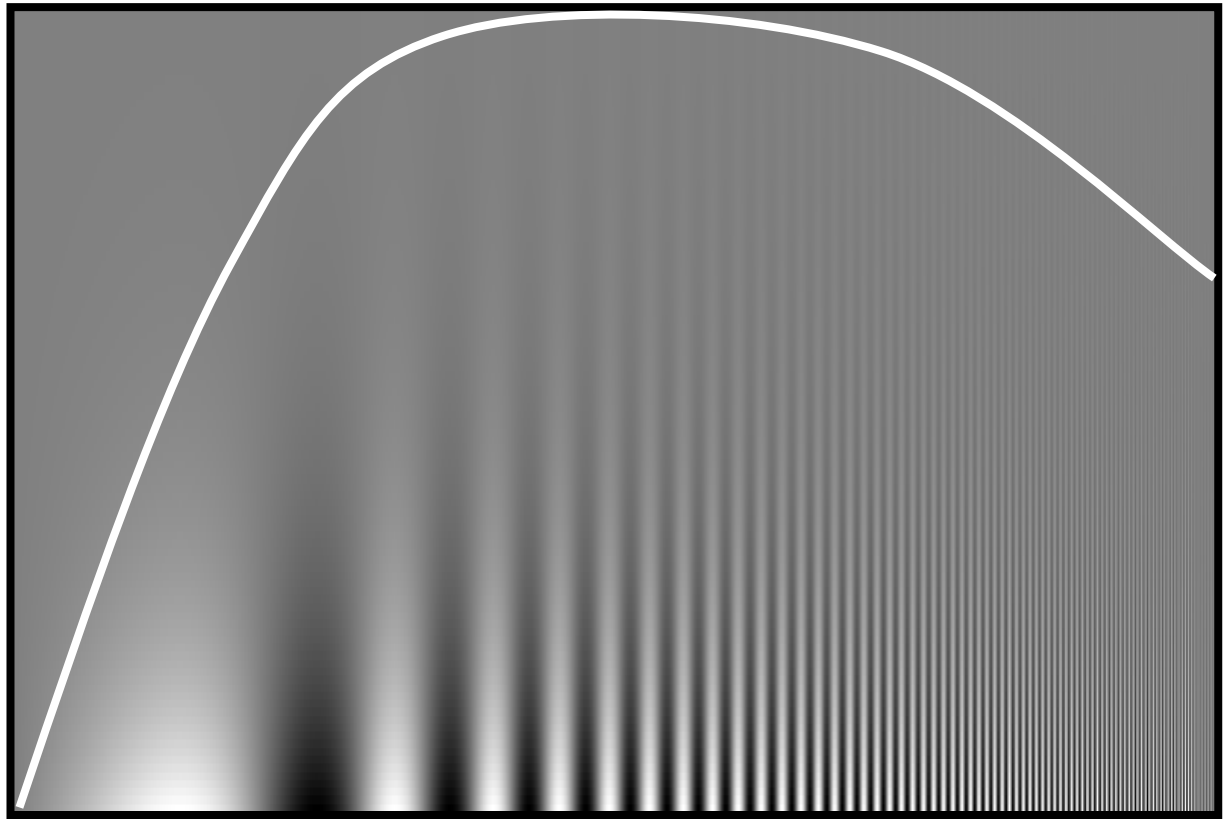
Fourier analysis

© Andrew Glassner, Intro to Raytracing

HVS: Poisson Disk Experiment

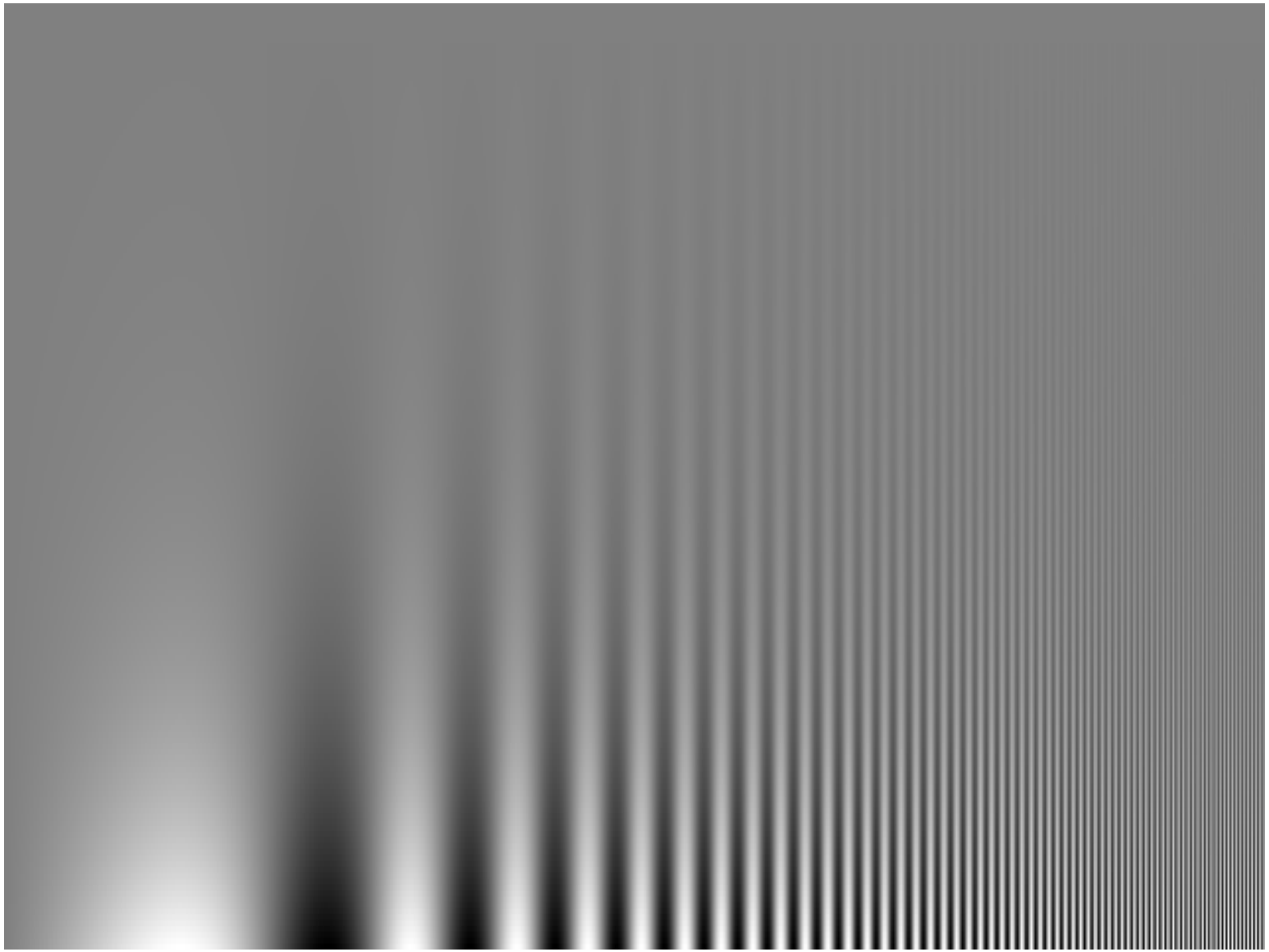
- Human Perception
  - Very sensitive to regular structures
  - Insensitive against (high frequency) noise





Campbell-Robson contrast sensitivity chart

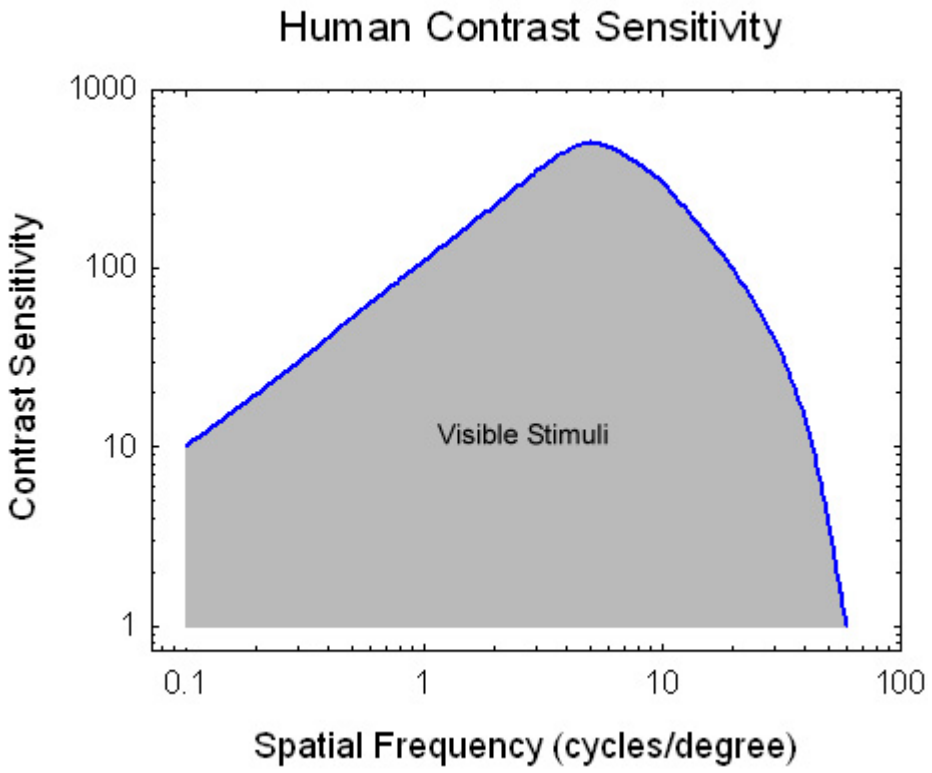
Luminance Contrast Sensitivity



Campbell-Robson contrast sensitivity chart

Contrast Sensitivity

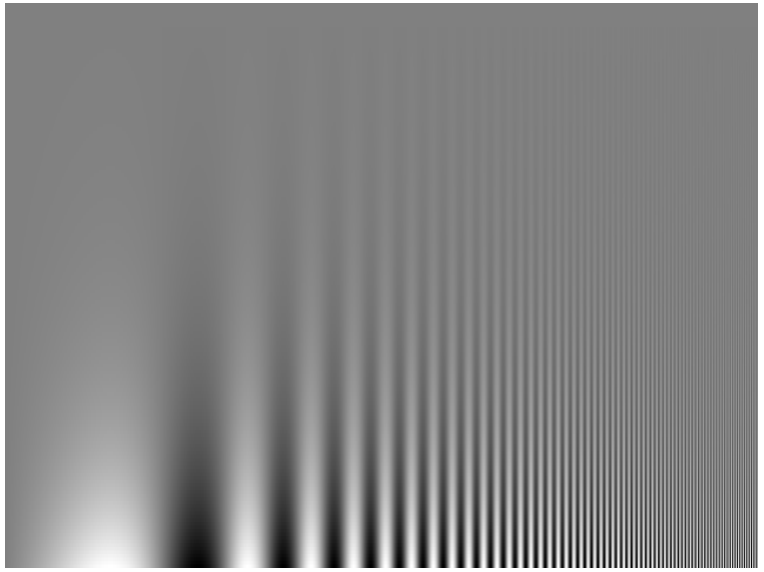
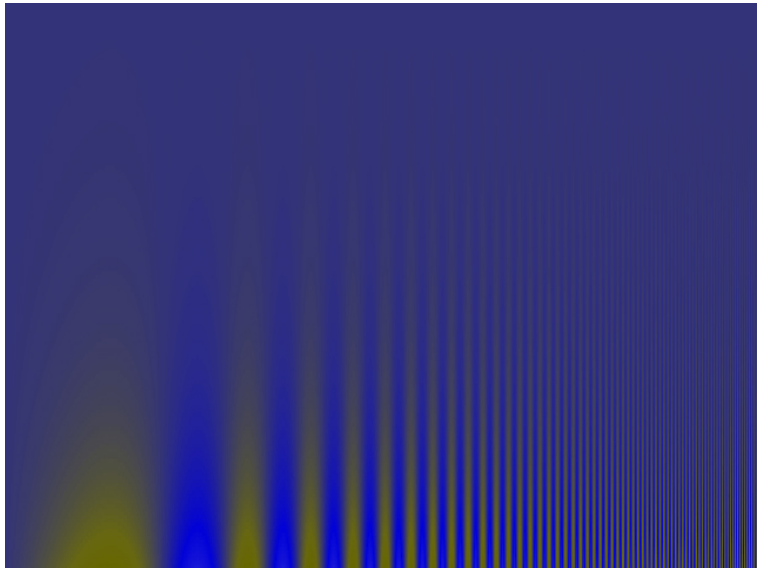
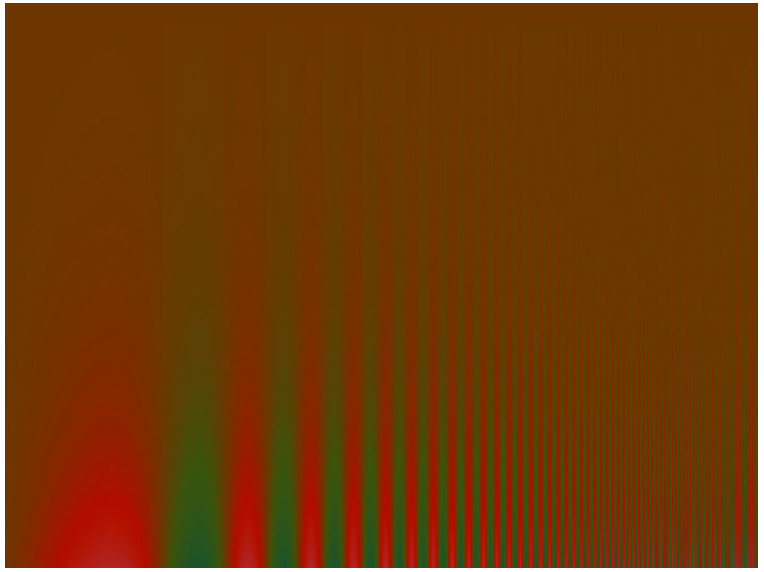
- Sensitivity:
  1 / threshold contrast
- Maximum acuity at
  5 cycles/degree (0.2 %)
  - Decrease toward low frequencies: lateral inhibition
  - Decrease toward high frequencies: sampling rate (Poisson disk)
  - Upper limit: 60 cycles/degree



- 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

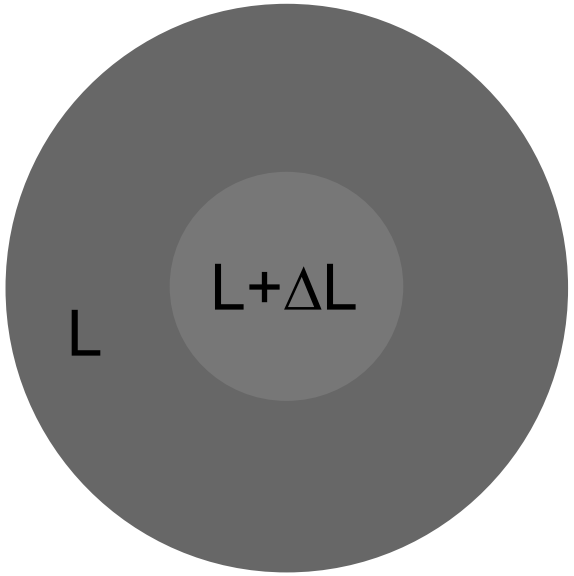
- Color vs. luminance
  vision system
  - Higher sensitivity at lower frequencies
  - High frequencies less visible
- Image compression

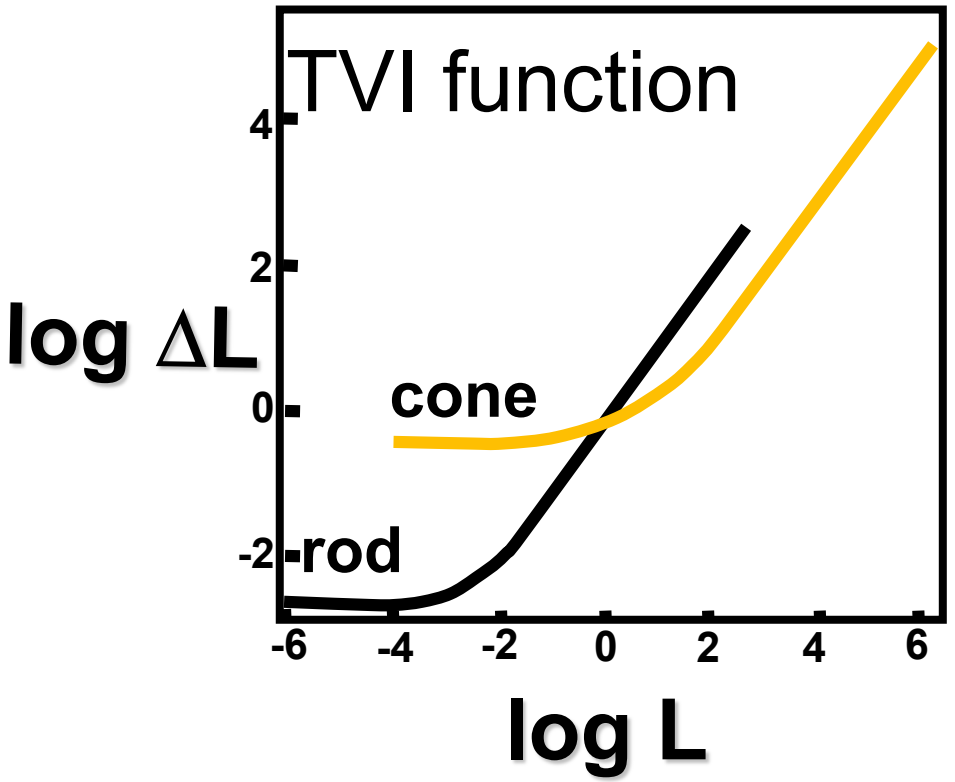
Threshold Sensitivity Function

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

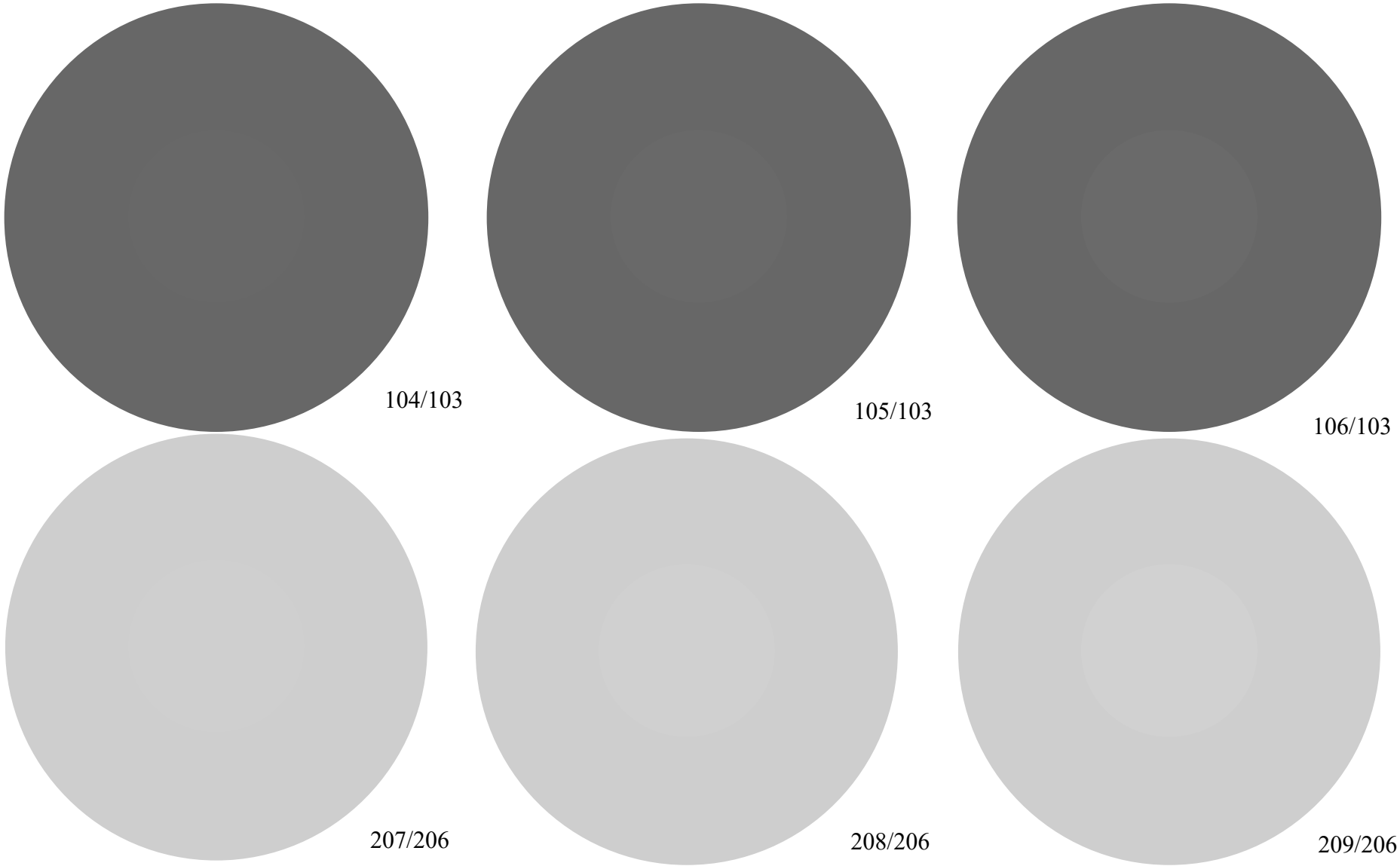
$$E=K+c \log I_v$$

  - Perceivable intensity difference
    - 10 cd vs. 12 cd: **$\Delta L=2cd$**
    - 20 cd vs. 24 cd: **$\Delta L=4cd$**
    - 30 cd vs. 36 cd: **$\Delta L=6cd$**



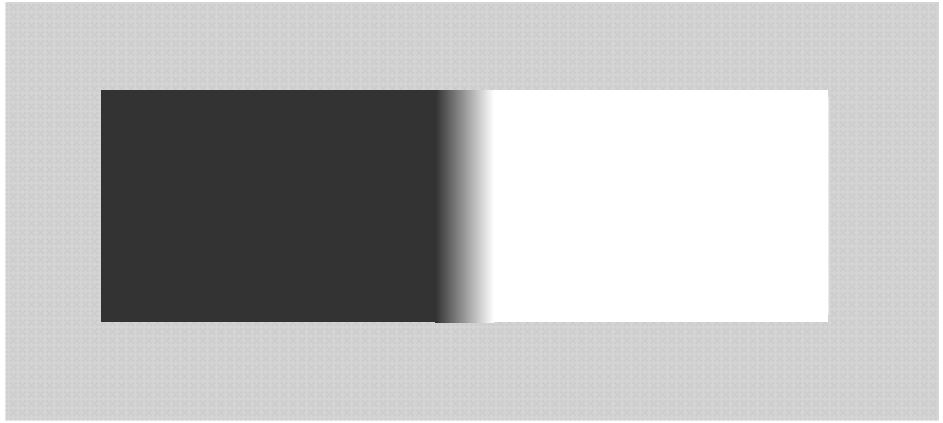


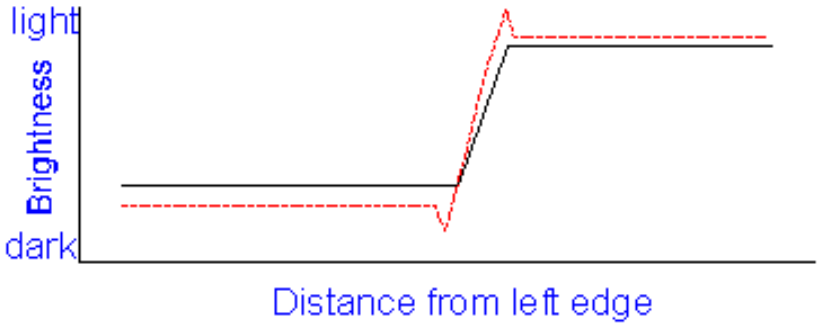
Weber-Fechner Examples

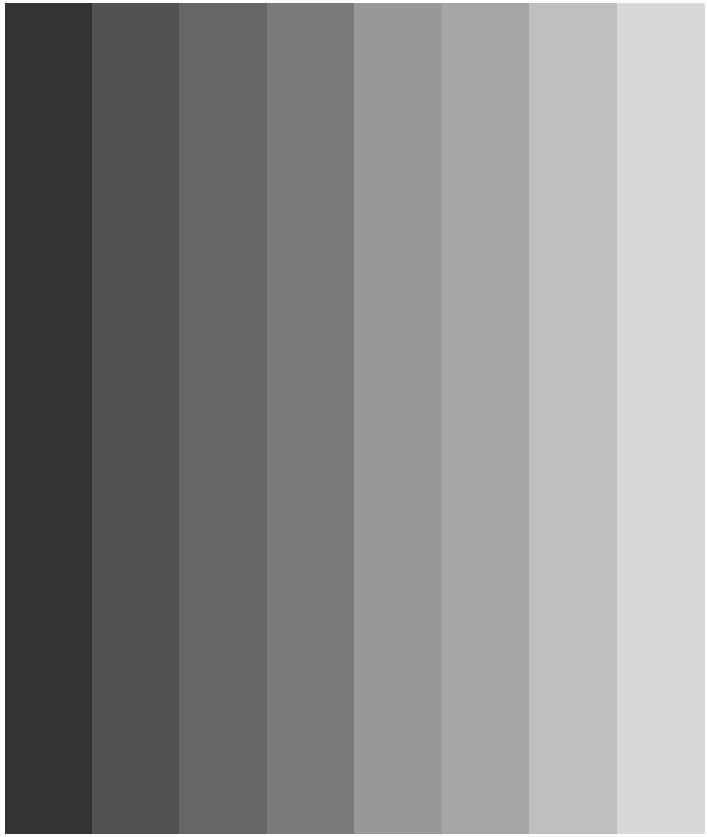


Mach Bands

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

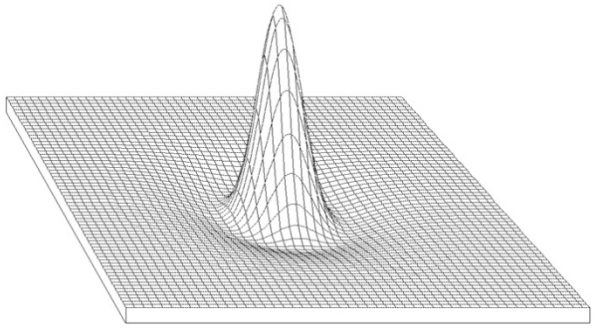


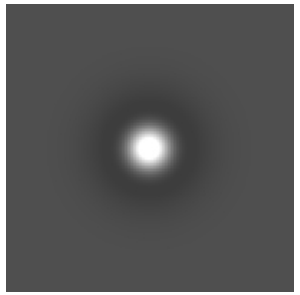


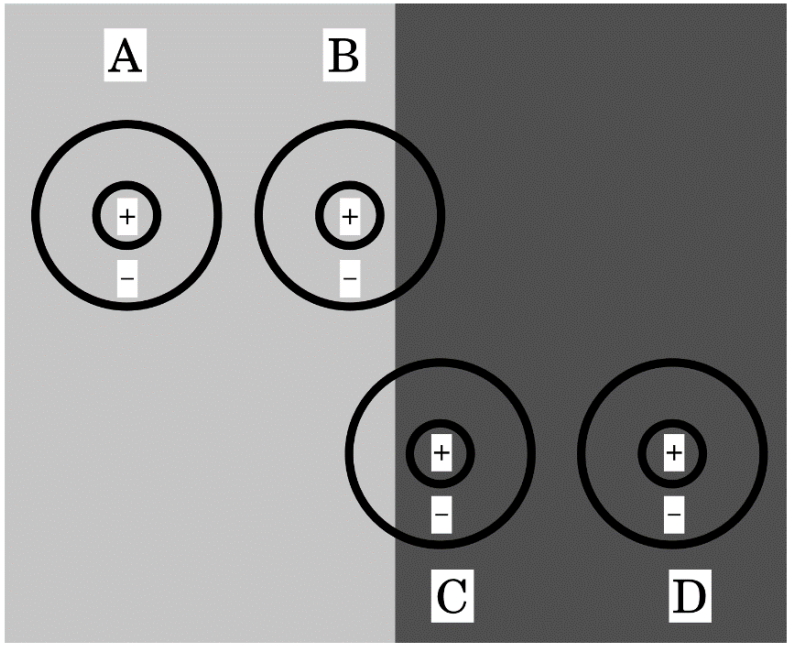


Lateral Inhibition

- 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

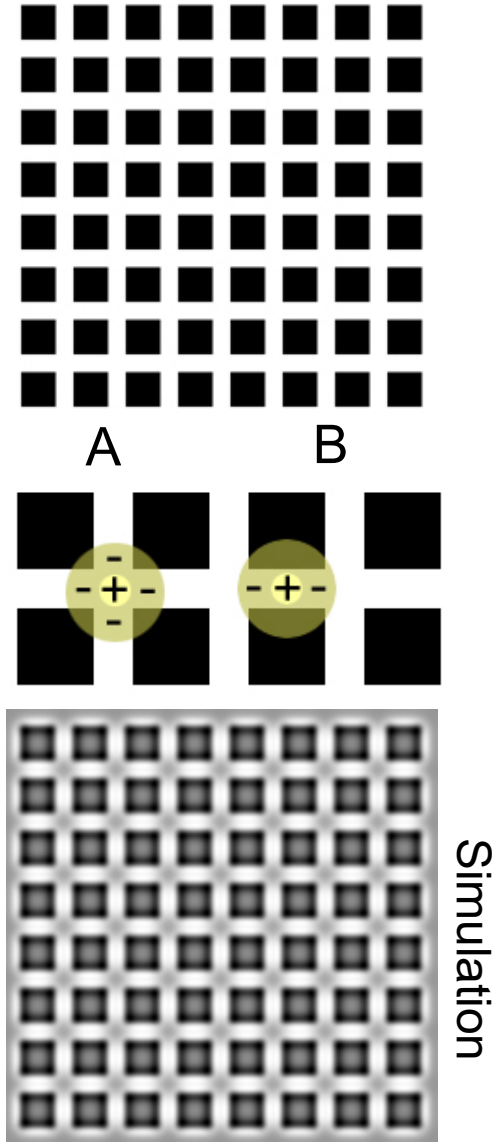


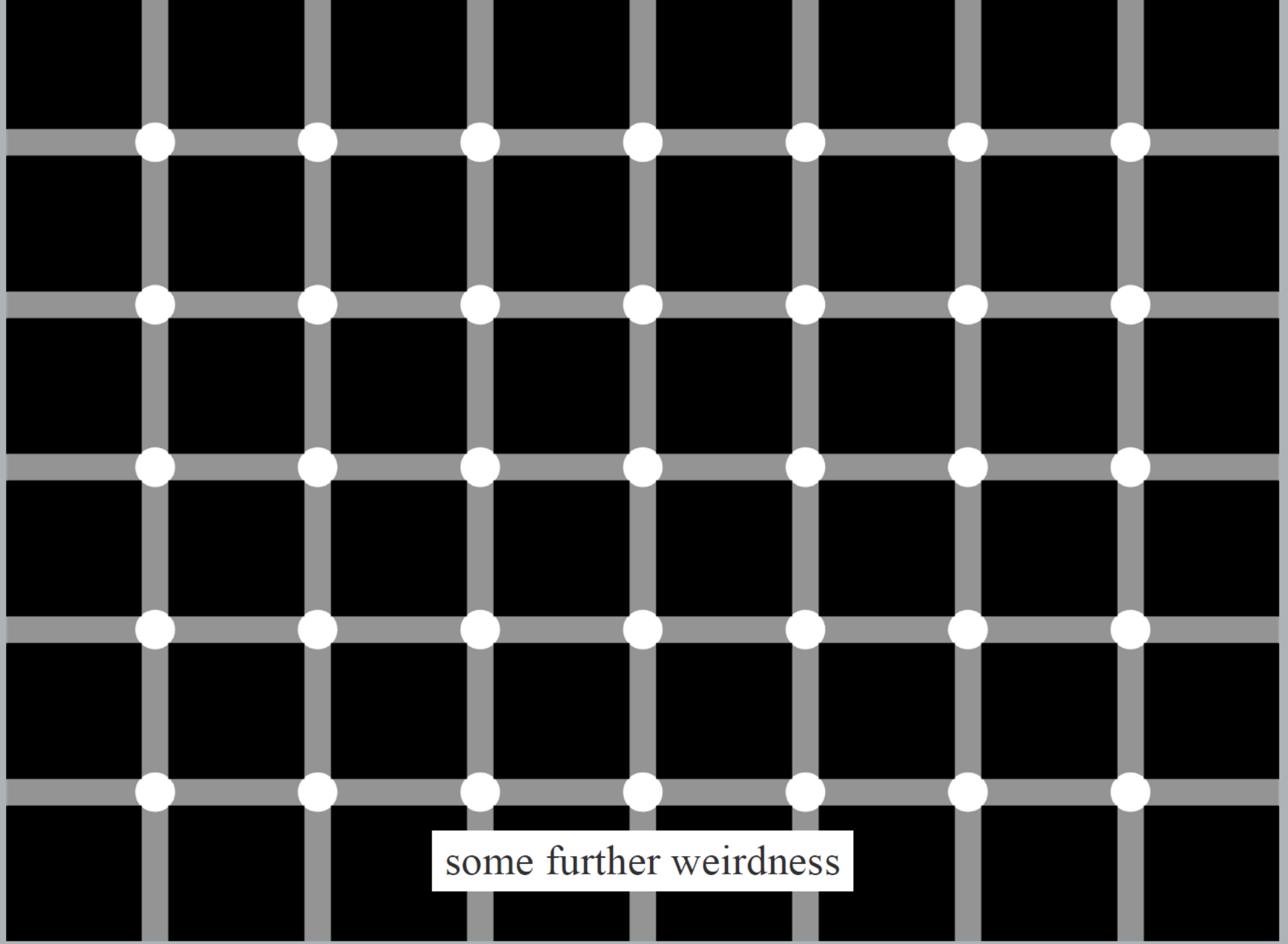




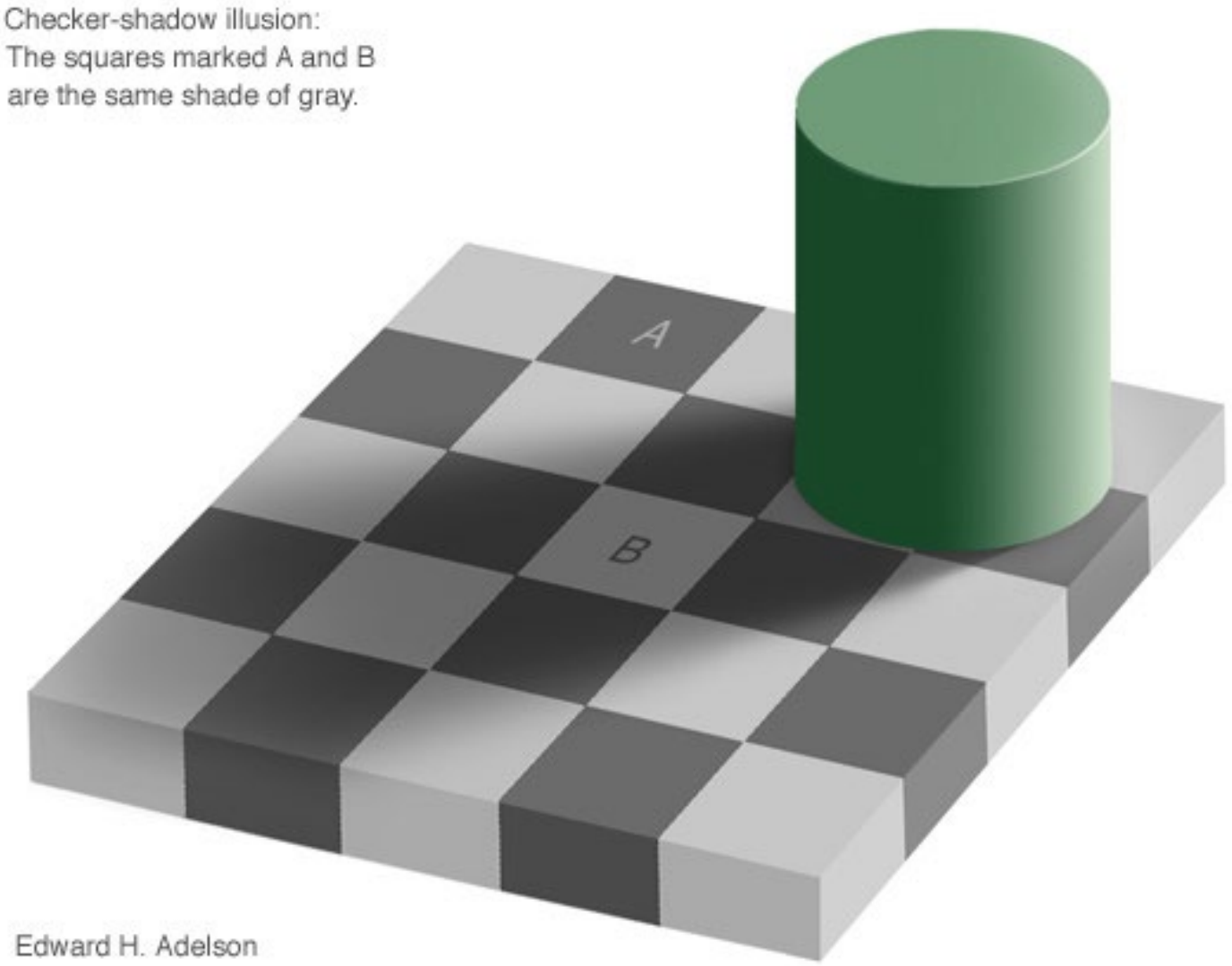
Lateral Inhibition: Hermann Grid

- 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
- Simulation
  - Darker at crossings, brighter in streets
  - Appears more steady
  - What if reversed ?

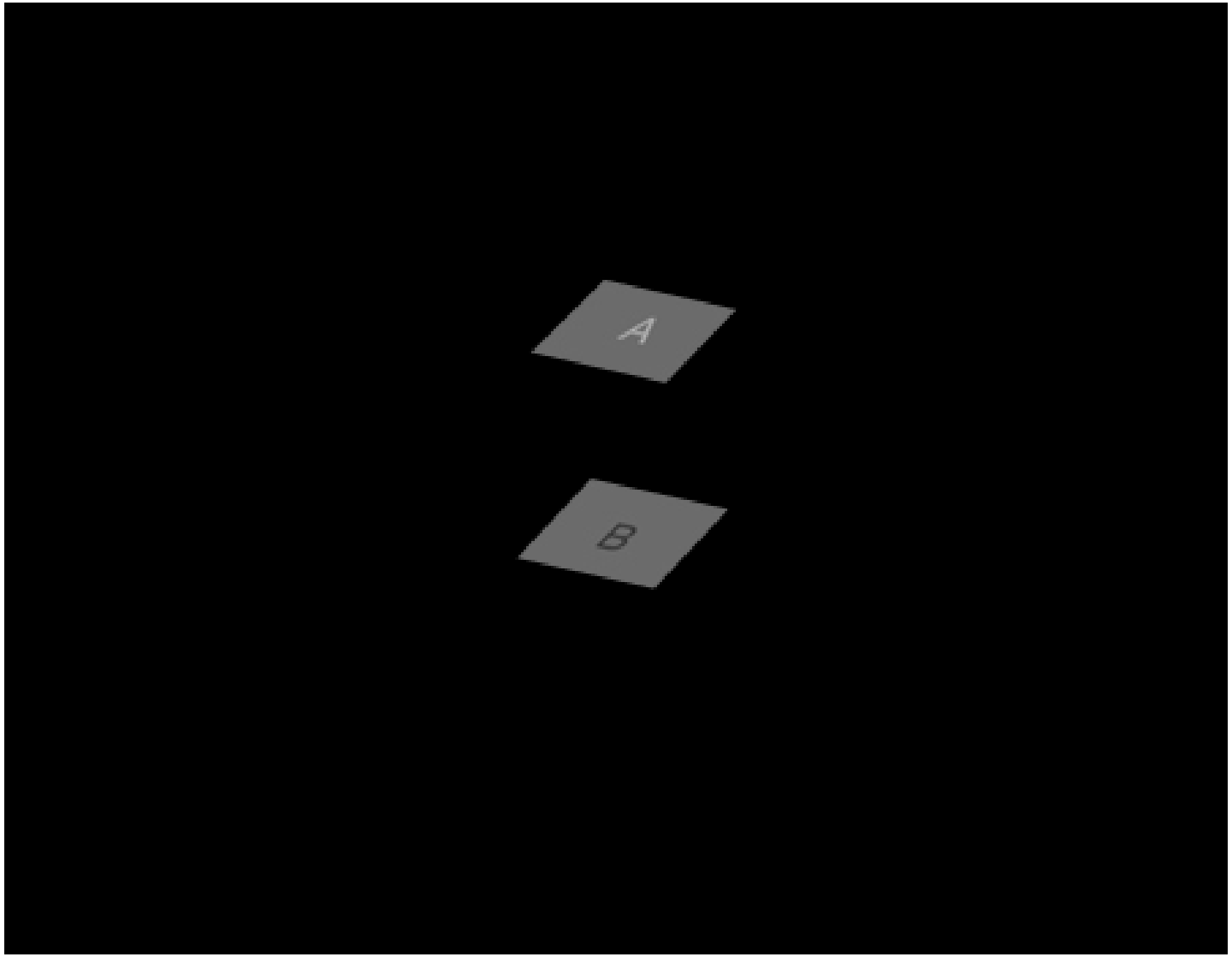



some further weirdness

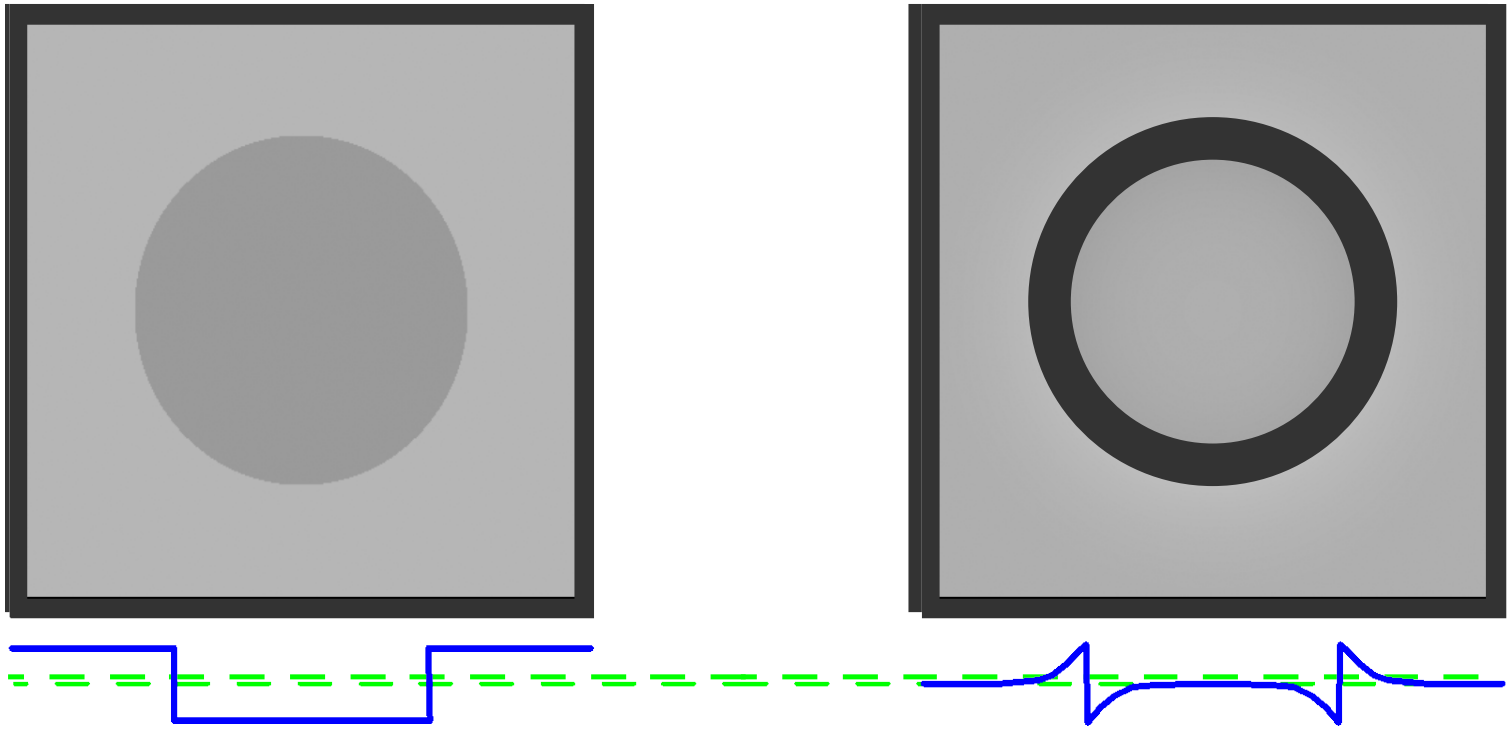
High-Level Contrast Processing



High-Level Contrast Processing

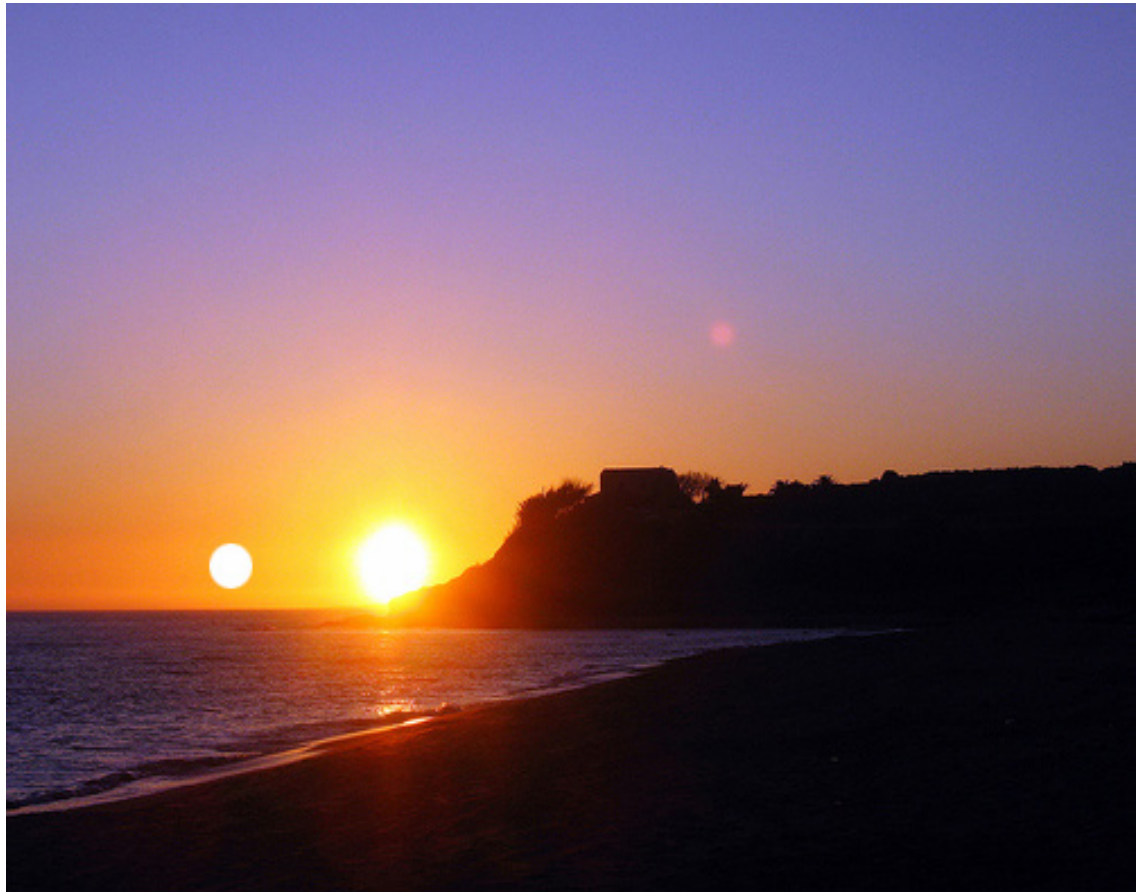


Cornsweet Illusion



- Apparent contrast due to gradual darkening / brightening towards a contrasting edge

Percept. Effects – Veiling Glare

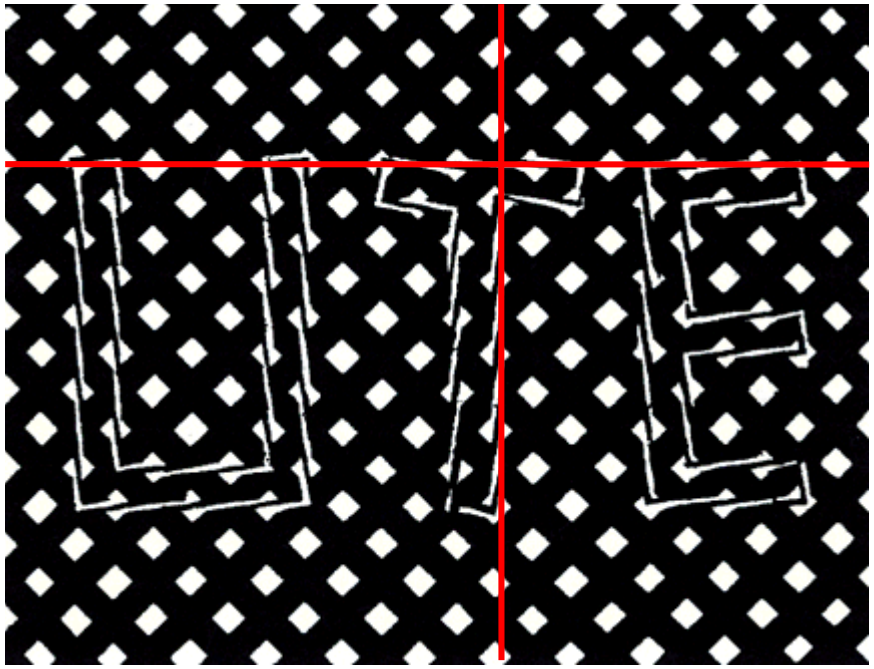


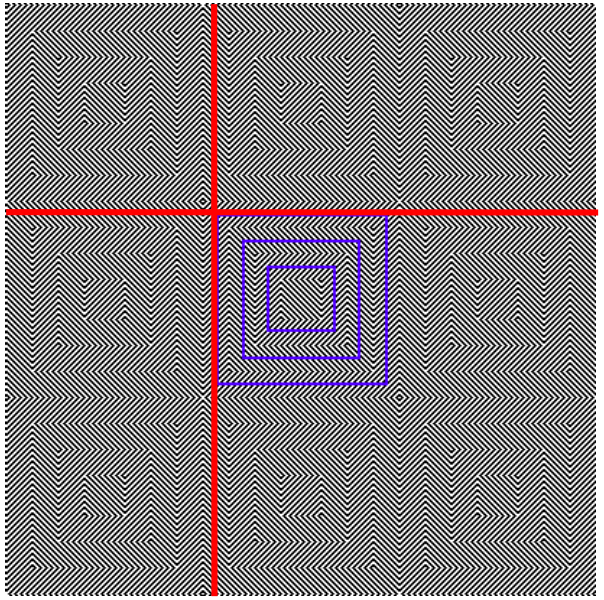
Simulation requires:

- scatter (blur) of sources of high luminance
  (computationally expensive)

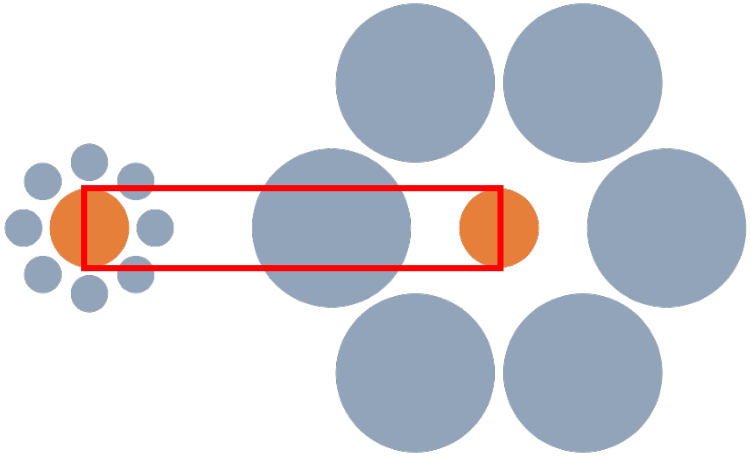
Optical Illusions

Shape Perception





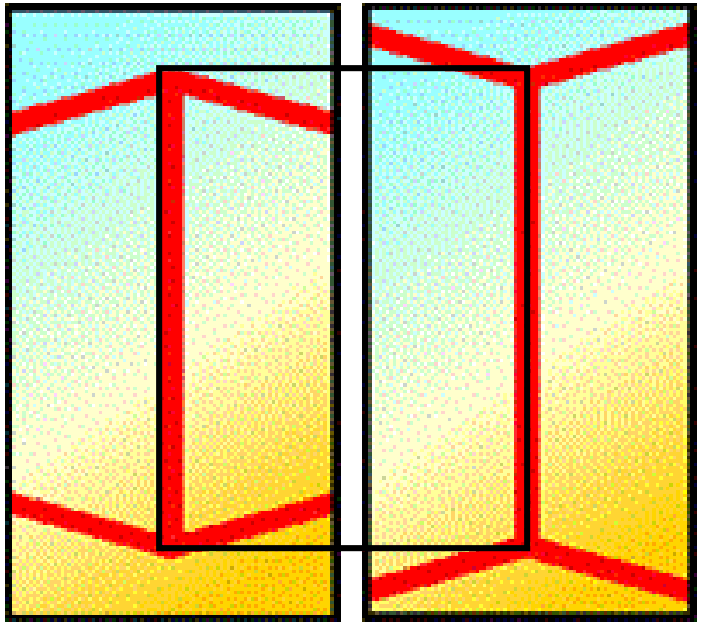
- Depends on surrounding primitives
  - Directional emphasis
  - Size emphasis

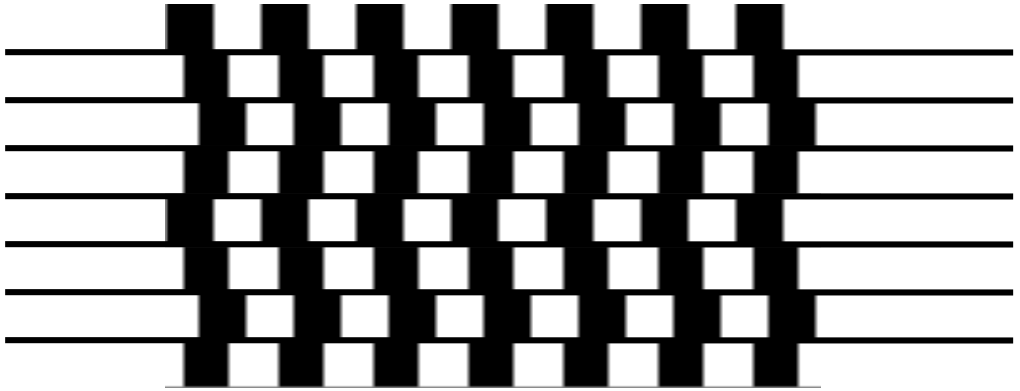


http://www.panoptikum.net/optischetaeuschungen/index.html

Who wants to live here?

Shape Processing: Geometrical Clues

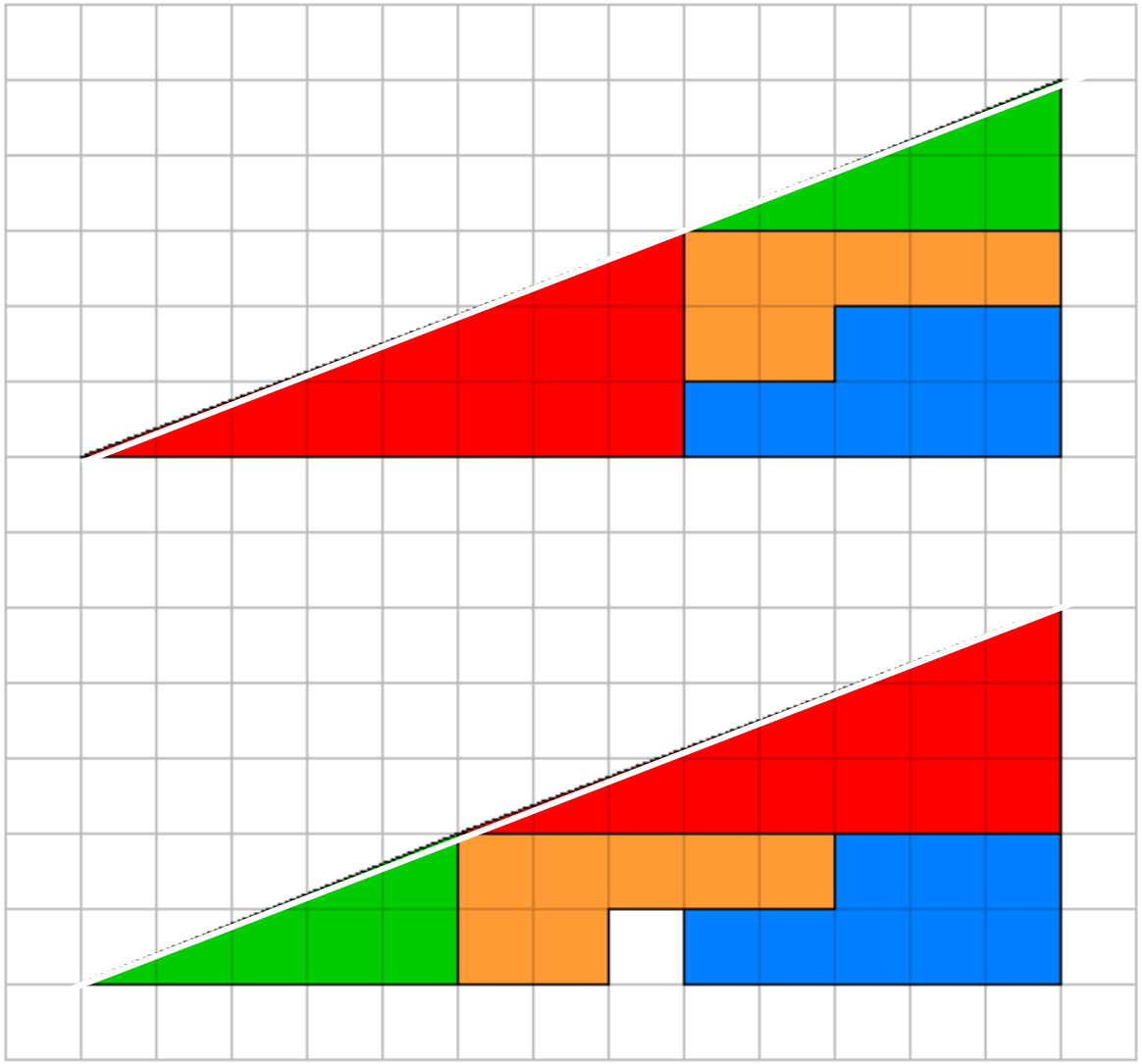




http://www.panoptikum.net/optischetaeuschungen/index.html

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

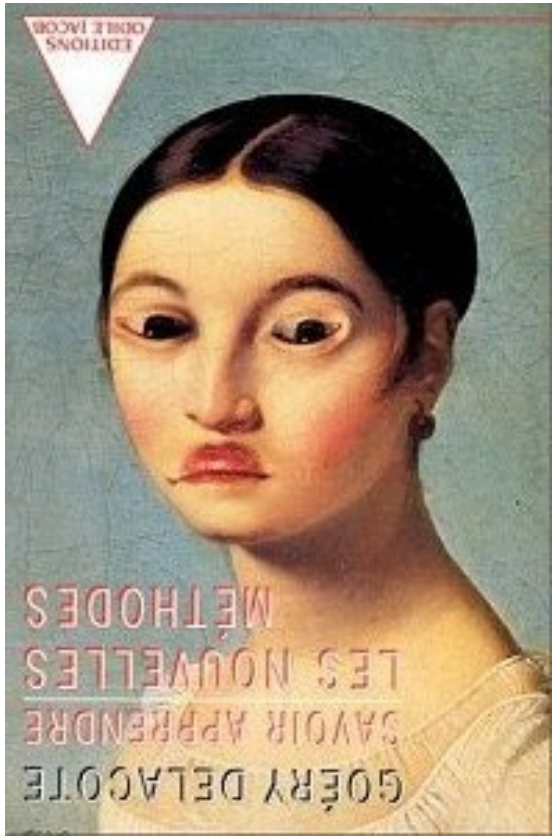
Visual “Proofs”



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

HVS: High-Level Scene Analysis

- Experience
- Expectation
- Local clue consistency



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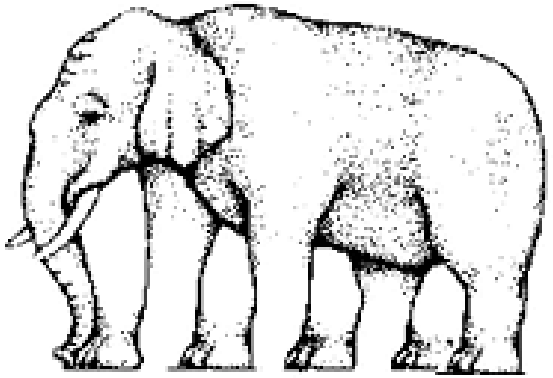
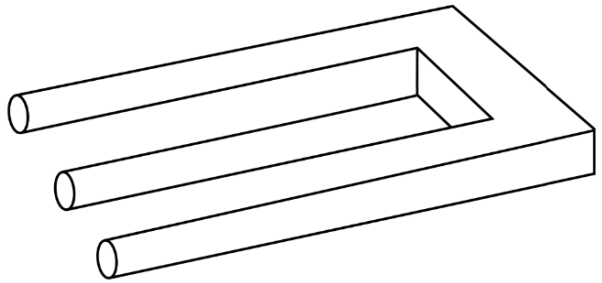
Impossible Scenes

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





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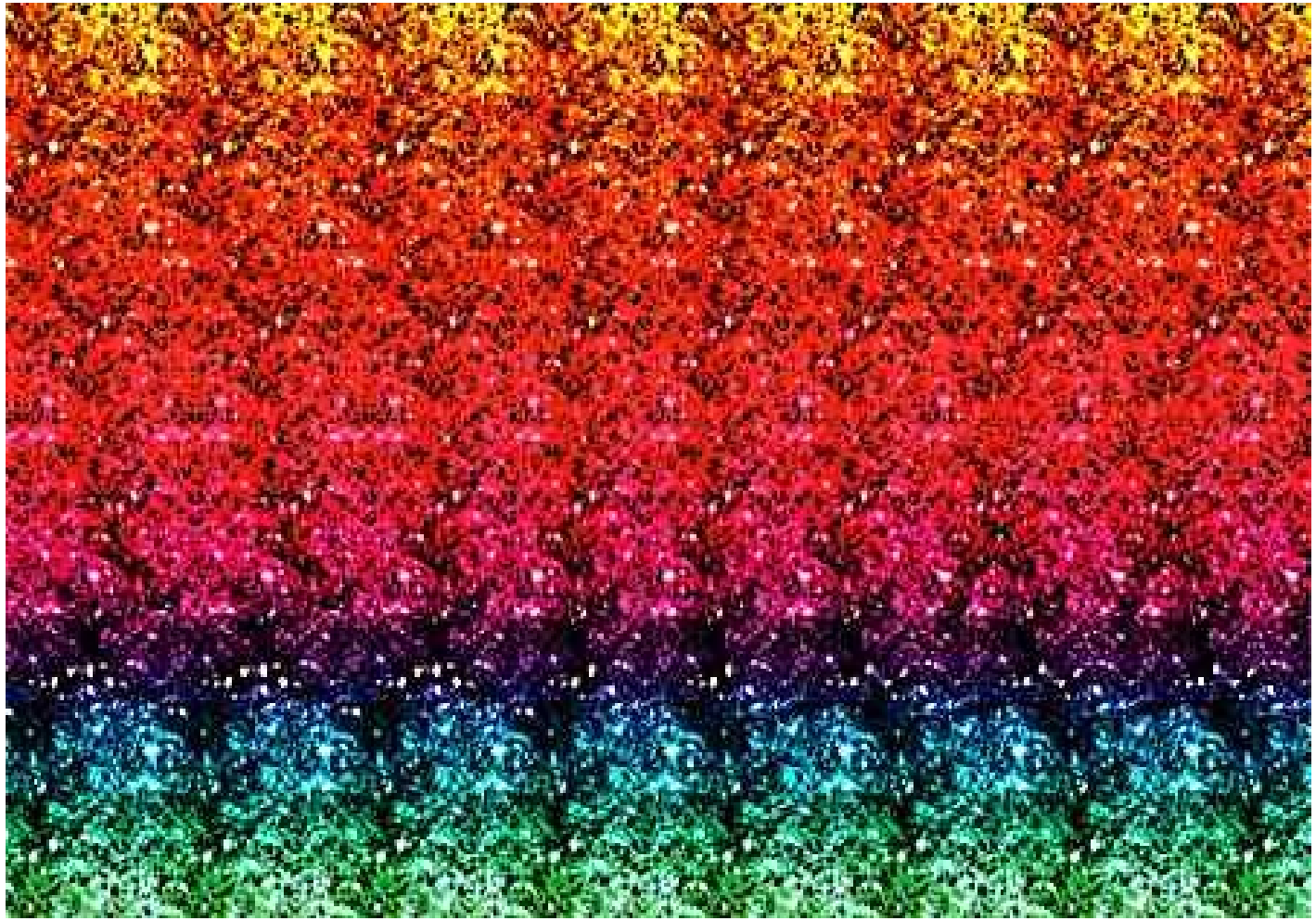
Who dunnit?

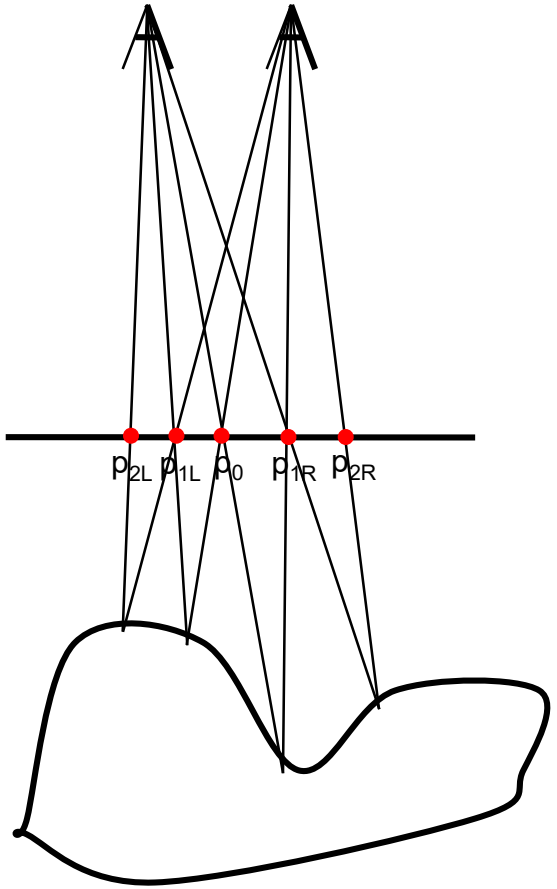
Single Image Random Dot Stereograms



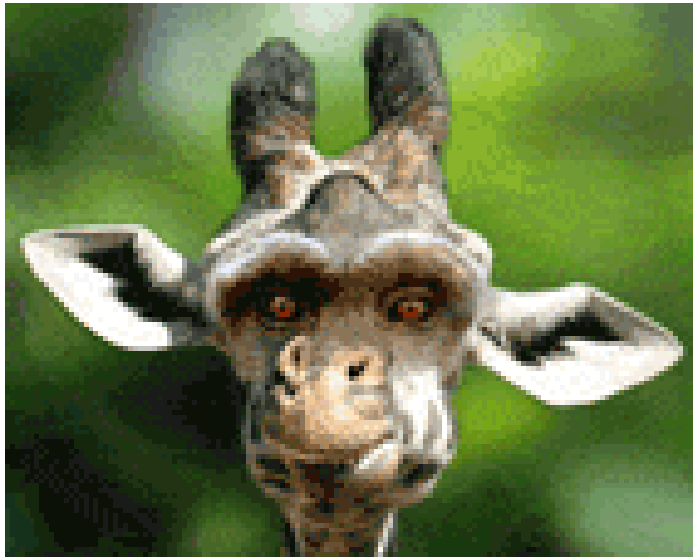
- Vergence: both eyes rotate to look at the same spot
- Accommodation: focusing at a particular depth plane

SIRDS Construction

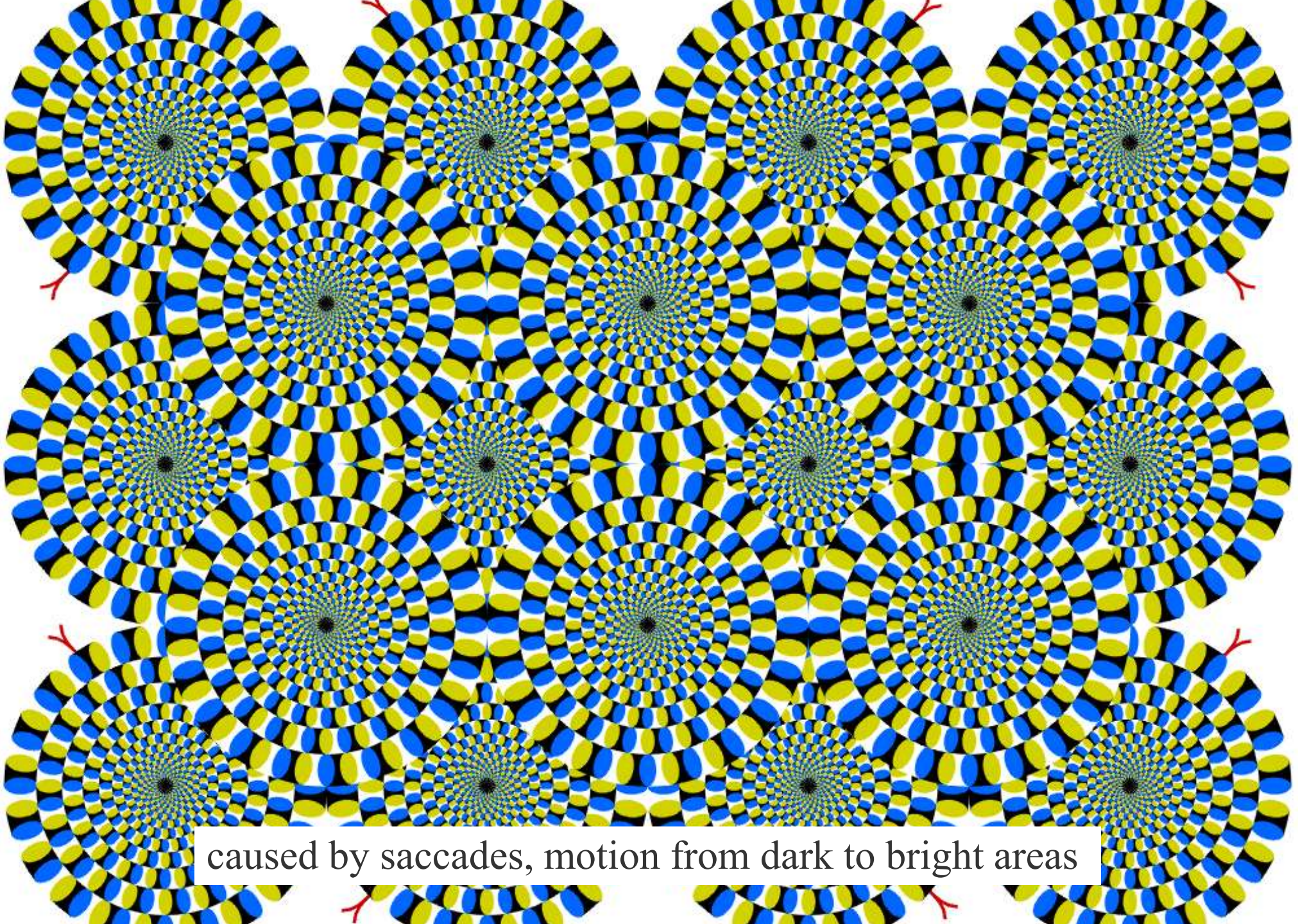
- Assign arbitrary color to p_0 in image plane
- Trace from eye points through p_0 to object surface
- Trace back from object to corresponding other eye
- Assign color at p_0 to intersection points p_{1L},p_{1R} with image plane
- Trace from eye points through p_{1L},p_{1R} to object surface
- Trace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



Another Optical Illusion



- If you stare for approx. 20 seconds some of you will actually see a giraffe.



caused by saccades, motion from dark to bright areas

Wrap-Up

Human Visual System

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- Physiologic parameters

- Perception is influenced on a number of levels
  - Intensity
  - Color
  - Shape
  - Distance
  - …

- Effects useful for rendering

Overview

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- Previous
  - Antialiasing
  - Super-Sampling
  - Image Filters
- Today
  - The Human Visual System
    - The eye
    - Early vision
    - High-level analysis
    - Color perception
- Next lecture
  - Color spaces