

# Einführung in die Farbwissenschaft

## Human Perception

### Overview

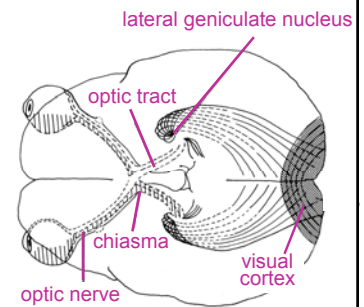
- eye anatomy
- human visual system
- monochromatic and color vision
- luminous efficiency
- contrast sensitivity
- adaptation
- color constancy

### Human Visual System

- principal sensory organ: the eyes
- by far the most data-intensive sense: estimates rank **80% of all input** as visual
- substantial post-processing of raw data necessary to yield insights
- only exterior (processing) parts of the human visual system are reasonably well understood
- fortunately, these are those which are of immediate interest to color science

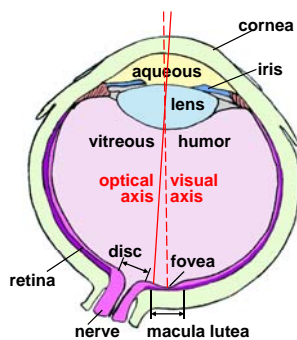
### Visual Centers in the Brain

- visual cortex located at rear of the skull
- optical nerves cross once
- exact functions of inner brain regions still not entirely clear



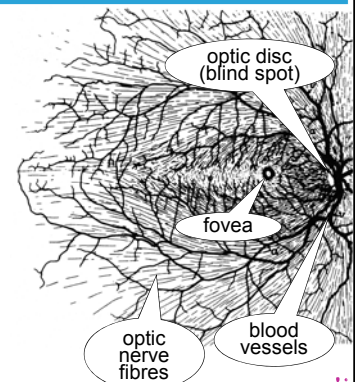
### Human Eye Anatomy

- principle: inverted image focused on retina
- simple optical system
- large chromatic aberration
- powerful retinal processing



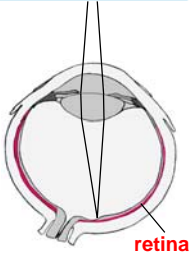
### Retinal Blood Vessels

- pattern of blood vessels in the retina is as characteristic as a fingerprint
- used in modern biometric authentication systems



### Retina

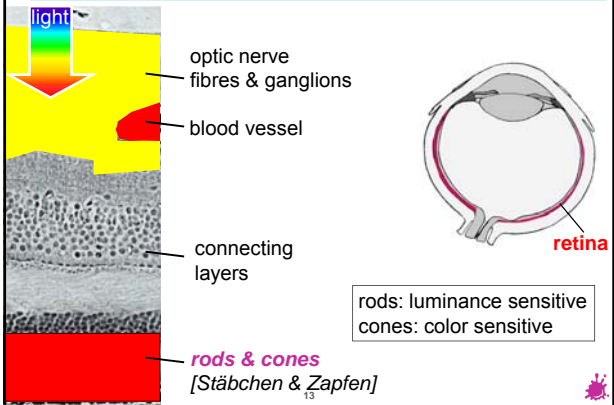
- light-sensitive tissue onto which an image is projected
- $0.25 \text{ mm} \times 1.1 \text{ cm}^2 = 200 \text{ million nerve cells}$
- 2 types of light-sensitive cells: **rods & cones**
- rods & cones are supported by
  - large neural infrastructure gathering their input
  - support systems such as connecting tissue and blood vessels



retina

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### Retina



light

optic nerve fibres & ganglions

blood vessel

connecting layers

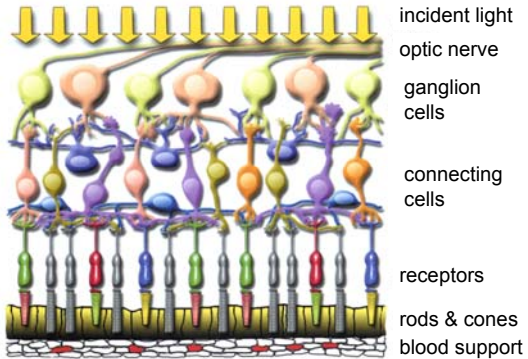
rods & cones [Stäbchen & Zapfen]

rods: luminance sensitive  
cones: color sensitive

retina

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### Retinal Structure Scheme



incident light

optic nerve

ganglion cells

connecting cells

receptors

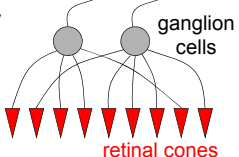
rods & cones

blood support

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### Neural Processing in the Retina

- rods & cones are mutually interconnected (neural network) to perform pre-processing tasks:
  - edge enhancement
  - color separation (spectral inhibition)
  - separate „wiring“ for rods and cones
- >100M rods & cones versus 1M ganglion cells



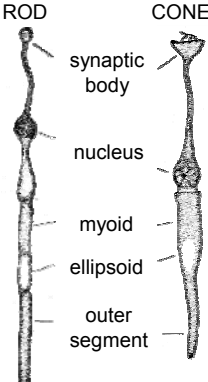
ganglion cells

retinal cones

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### Rods & Cones

- specialized nerve cells with light-sensitive tips
- can register single photons (!)
- a dark adapted observer can see a 100 ms flash if it contains on average 90 photons at the cornea or 9 at the retina.  $\approx$  a candle at 50 km in a clear night.



ROD

CONE

synaptic body

nucleus

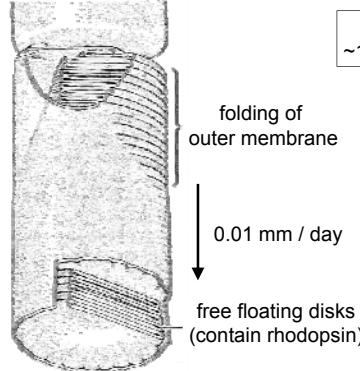
myoid

ellipsoid

outer segment

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### Photoreceptors Details: Rods



folding of outer membrane

0.01 mm / day

free floating disks (contain rhodopsin)

$10^8$  rods contain  $\sim 10^{15}$  rhodopsin molecules

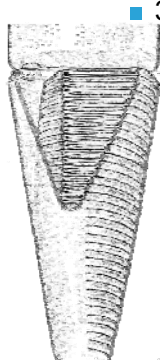
rod sensitivity: maximum at 496 nm

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### Photoreceptors Details: Cones

3 types of cones:

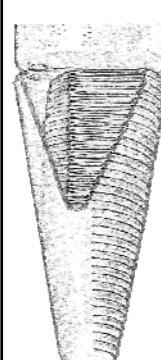
- ◆ **L-cones**
  - long wavelength-sensitive pigment max. ~558 nm (red)
- ◆ **M-cones**
  - medium wavelength-sens. pigment
  - max. ~531 nm (green)
- ◆ **S-cones**
  - short wavelength-sens. pigment
  - max. ~419 nm (blue)



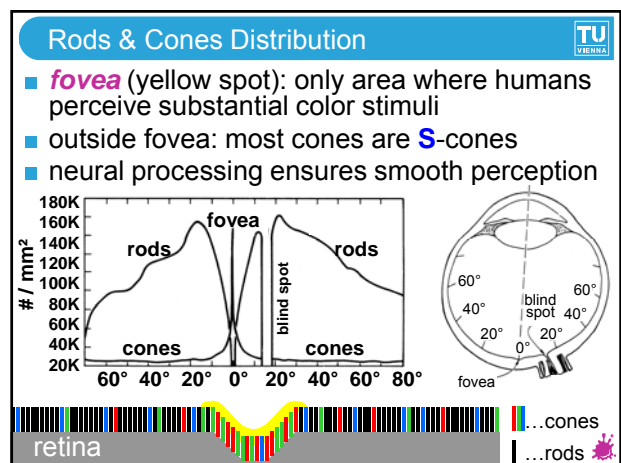
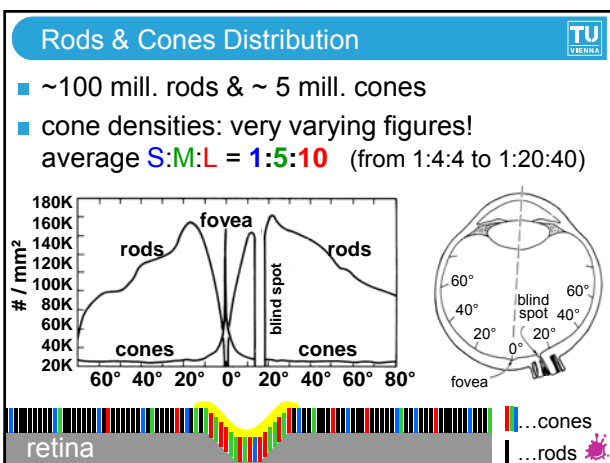
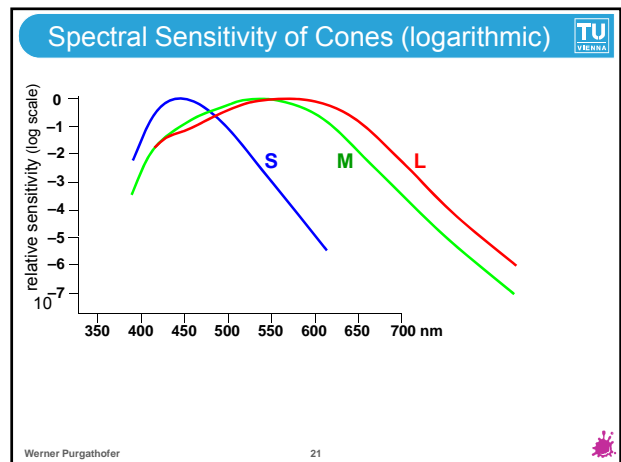
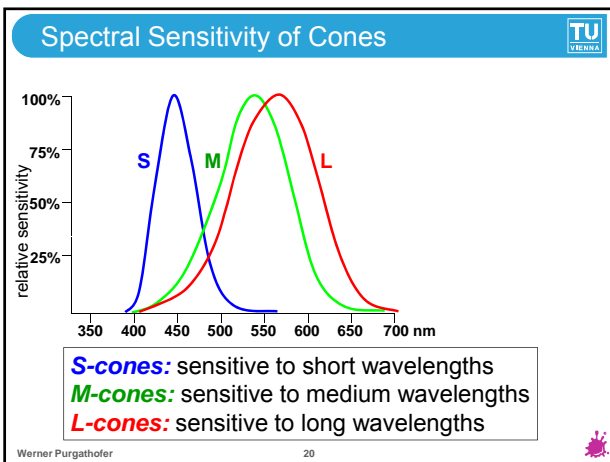
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### Photoreceptors Details: Cones

- ◆ photopigments trigger a series of *chemical reactions* within cone cells („bleaching“)
- ◆ these reactions ultimately *alter* the cell's *electrical charge*, generating a signal that is transmitted to the brain
- ◆ *brain combines* input from all three types of cones to produce *normal color vision*



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### Blind Spot

close left eye & look at this point

at the right distance this point will vanish

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### Equivalence of Stimuli

- stimuli generate electric nerve signals proportional to input signal and sensitivity
- e.g. for blue cones: weak blue light generates same result as strong red light

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### Relative Luminous Efficiency

- photopic** – adapted to bright light (cones)
- scotopic** – adapted to the dark (rods)
- mesopic** – intermediate

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### Relative Luminance Efficiency Bandwidth

- response curves of “standard observer” are typically not exactly valid for all humans
- a wide gamut of „healthy“ RLE values exists

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### Rod vs. Cone Sensitivity

- rods and cones serve two purposes:
- rods are slower, but more sensitive to low light conditions
- cones are capable of color vision, but not at night

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### Rod vs. Cone Firing Characteristics

- cones**
  - less sensitive to light
  - fire four times faster
  - generate shorter signal
- rods**
  - more sensitive to light
  - slower
  - generate longer signal

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## Temporal Behaviour: Adaptation



- photo-pigments are bleached by photons
- chemical reaction has to be reversed in order for a particular molecule to fire again
- rods and cones have a certain regeneration speed for their pigments which is matched to the illumination
- a retina where a state of equilibrium w/r to use and regeneration of pigments has been reached is called *adapted* to the illumination

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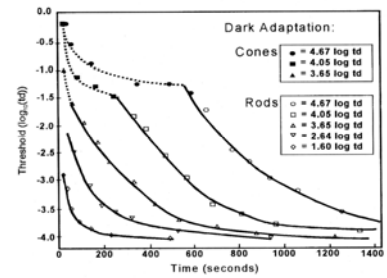
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## Dark Adaptation



- cones are initially faster, but have a higher threshold
- rods slowly take over after some time.

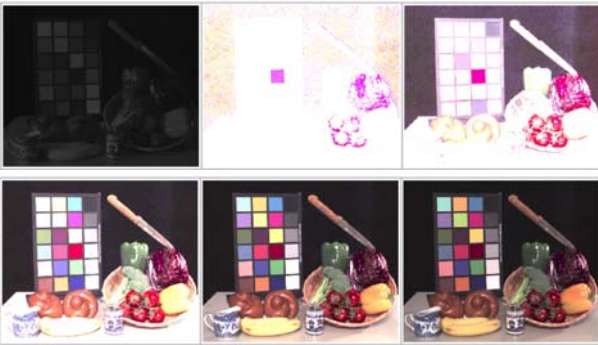


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## Time Dependent Perception



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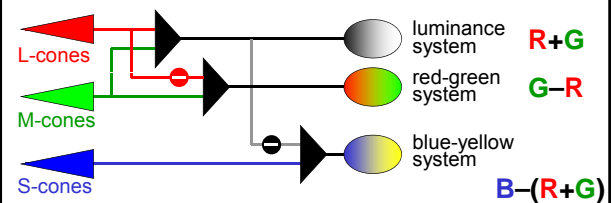
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## Post-processing System



- bridge between RGB sensors and separate perception of luminance and chroma ( $L^*a^*b^*$ )



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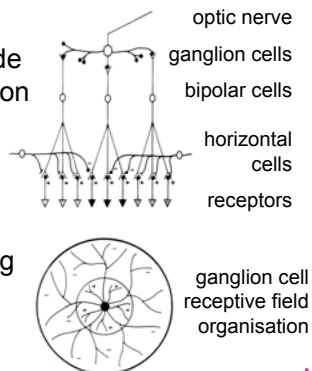
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## Ganglion Receptive Field



- groups of receptors are bundled to provide specific edge-detection capabilities
- opponency capabilities are particularly well developed for luminance processing



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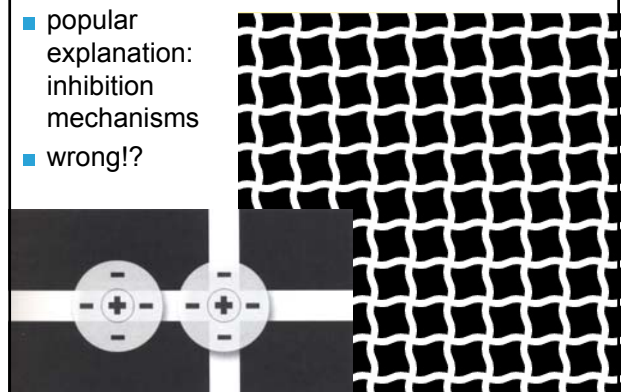
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## Hermann Grid



- popular explanation: inhibition mechanisms
- wrong!?



### Contrast Sensitivity

- dependent on density and arrangement of rods and cones in the retina
- peak at about 8 cycles/degree
- zero above 60 cycles/degree

$$A(f) = 2.6 \cdot (0.0192 + 0.114 \cdot f) \cdot e^{-f}$$

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### Visual Acuity

- the ability to discern detail in a scene is dependent of the absolute intensity of the illumination
- at low light levels, rods take over

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### Rod vs. Cone Vision

rod vision: colorless, blurred

cone vision: sharp, color

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### HL Neural Processing: Color Constancy

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### Perceiving Polarization: Haidinger's Brush

- [Haidinger-Büschel]
- some people can see polarization of light
- weak blue-yellow pattern ~2-3° across
- probable cause: weak radial orientation preference in the cones of the fovea centralis

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