Vision: the human eye

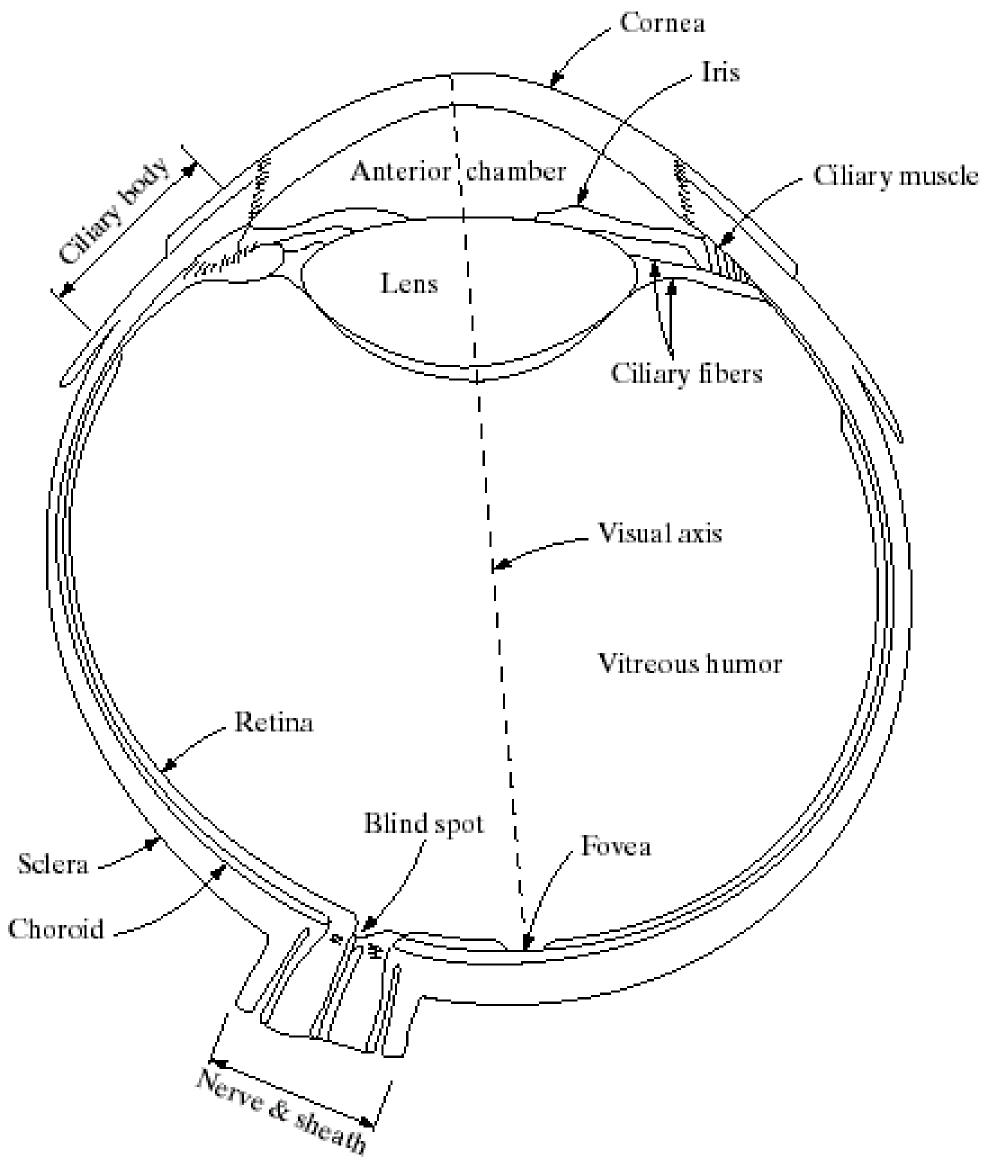


FIGURE 2.1
Simplified diagram of a cross section of the human eye.

Subsystems:
- Optical
- Mechanical
- Transduction
- Signal processing
- Data compression

The human eye

- Three types of cones: L,M,S (R,G,B)
- "Panchromatic" rods

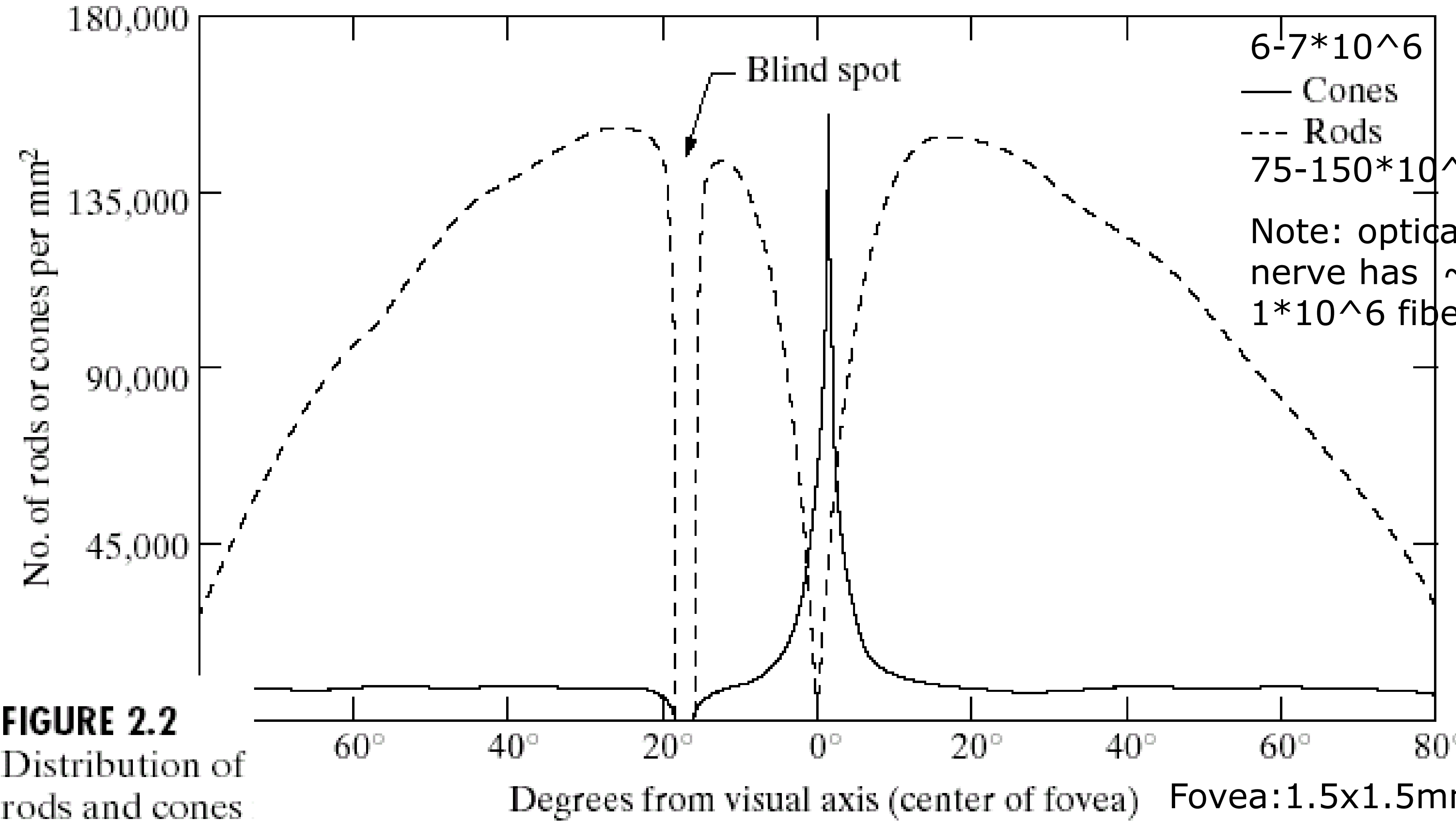


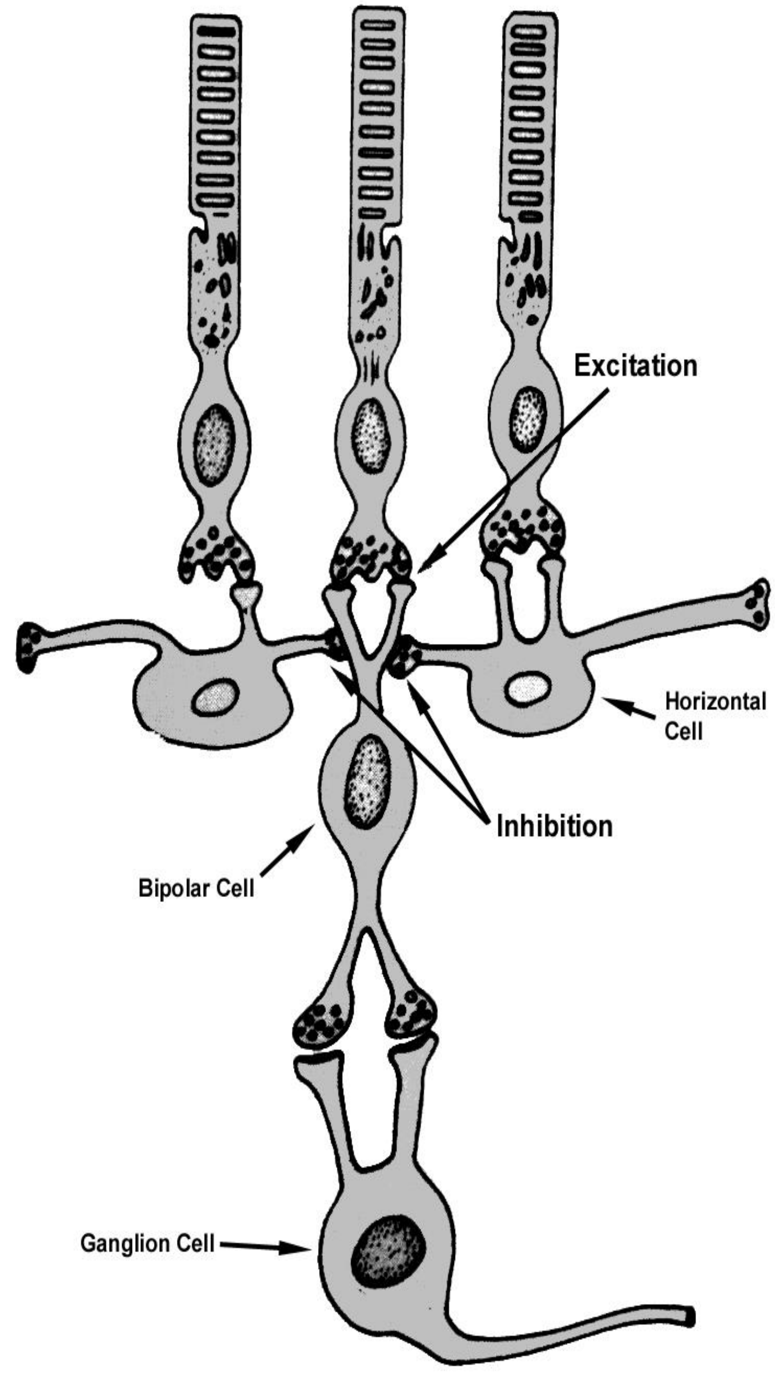
FIGURE 2.2
Distribution of rods and cones

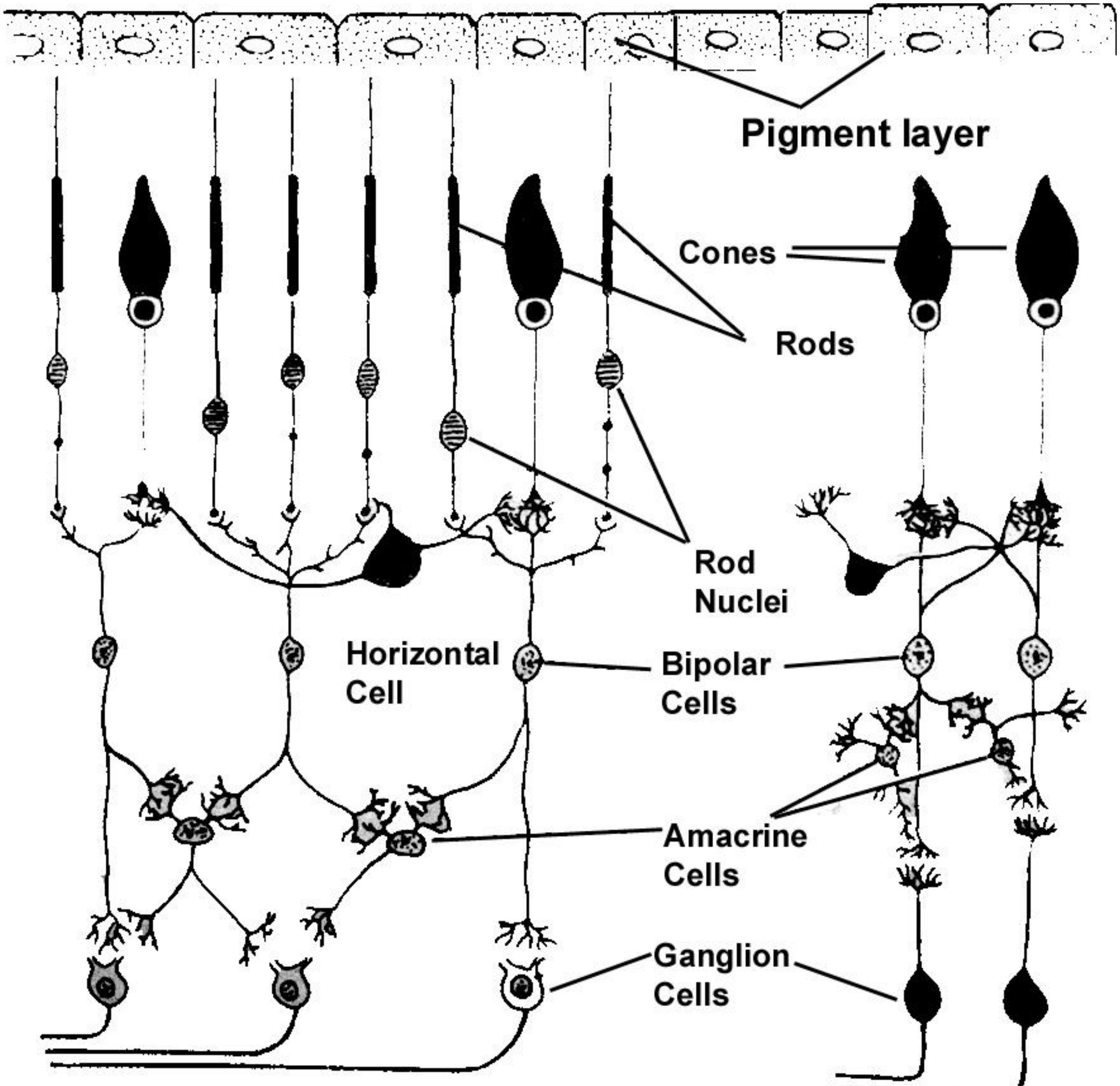
The human eye

Synapses connect different parts (**dendrites, body, axon**) of pairs of cells

Bipolar cells can receive signals from the rods and cones directly, or via the mediation of a **horizontal cell**. Their axons synapse with other integrators, specifically **amacrine cells** and **ganglion cells**

Amacrine cells mediate signals between bipolar cells, other amacrine cells, and ganglion cells. Ganglion cells are the final element in the chain



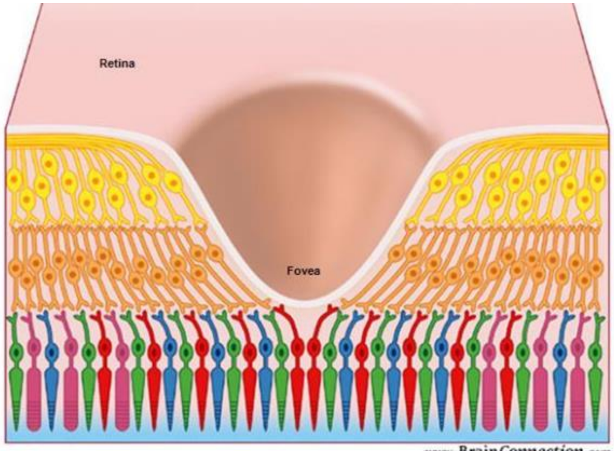


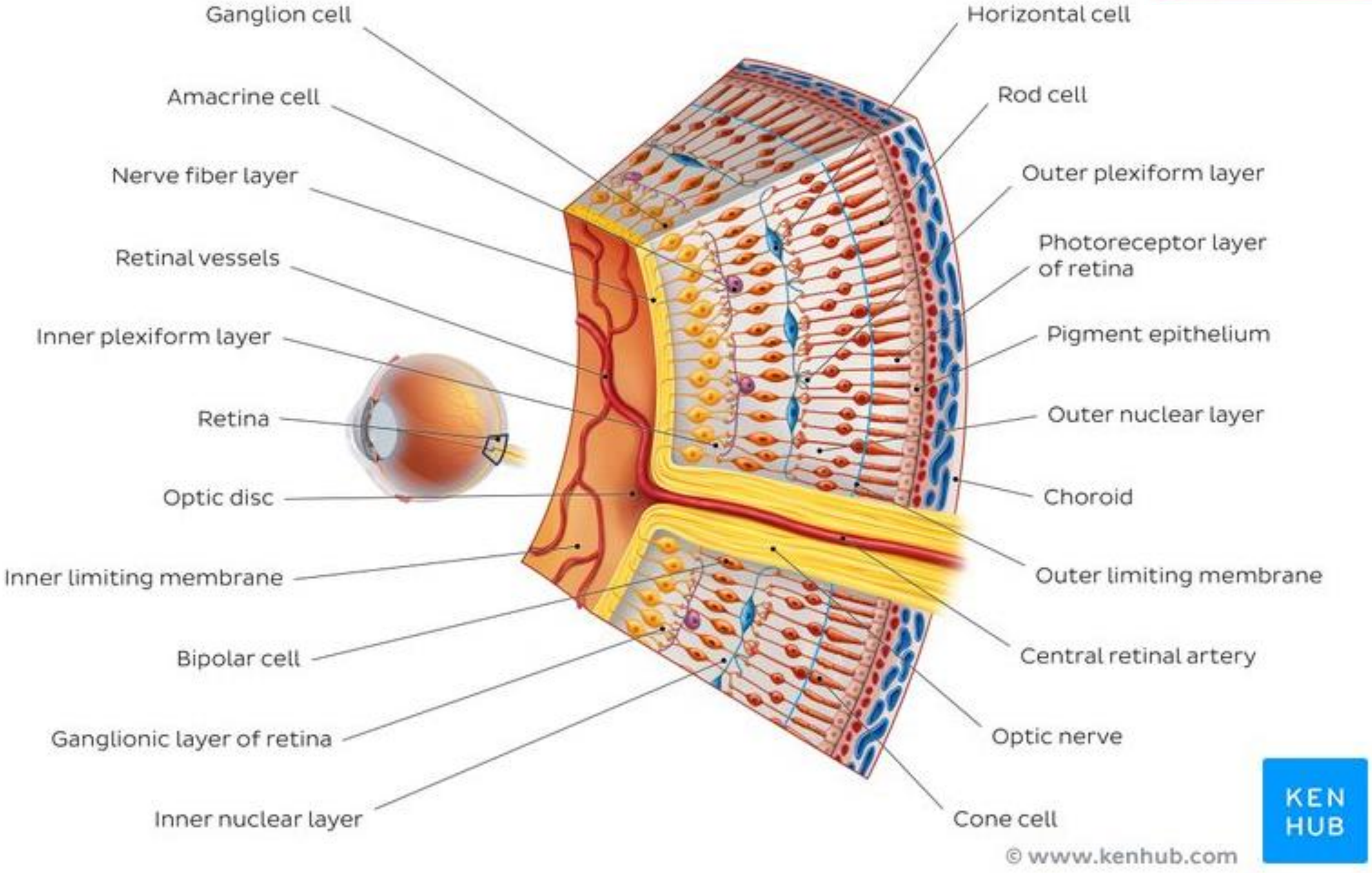
There is large flexibility in the actual route of information through the retina.

Lateral connections between two rods and cones, bipolar cells, etc., are all possible and the number of possible combinations is huge

The human eye

Retina & fovea





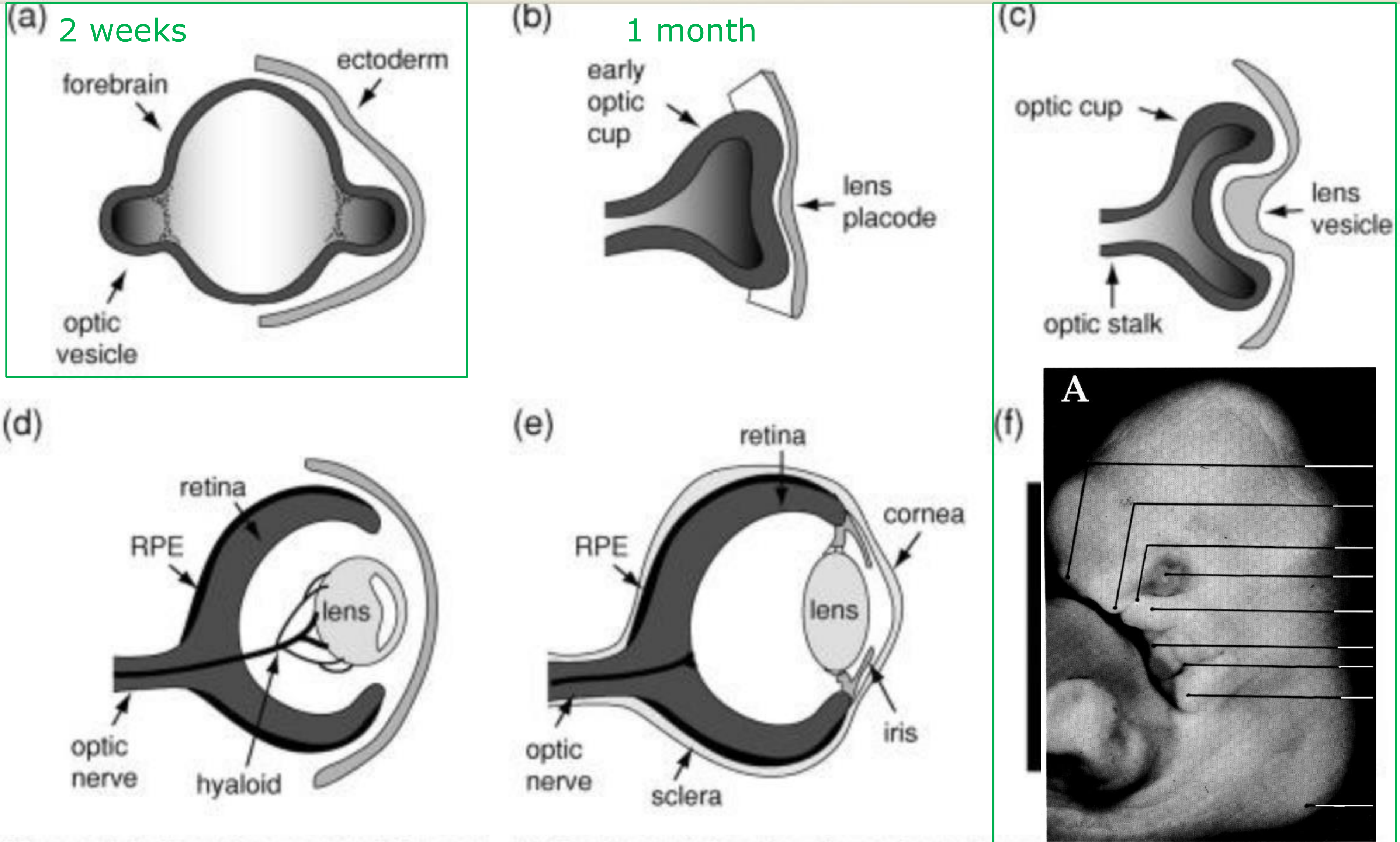
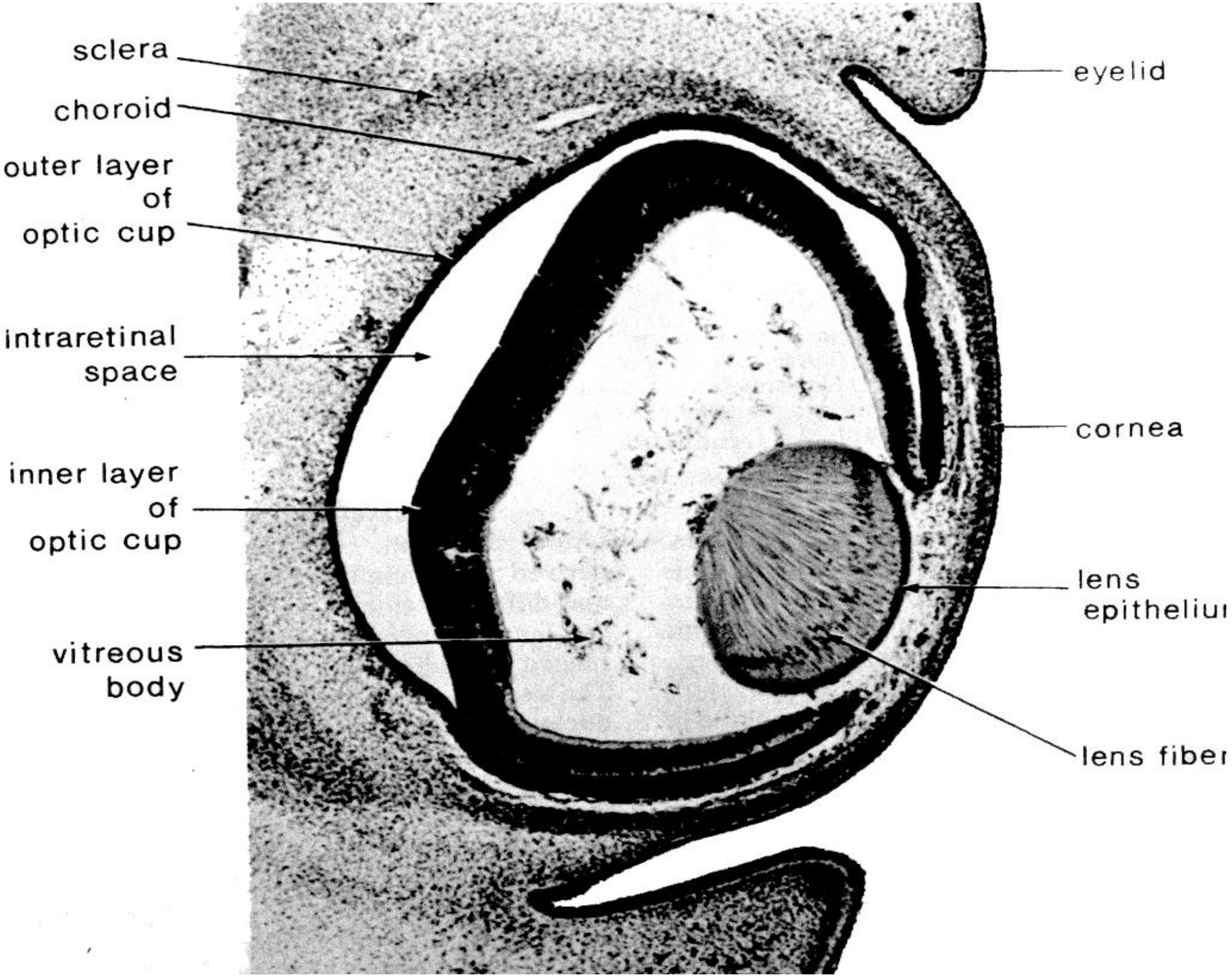


Figure 1.1 Development of the eye. (a) Optic vesicles that form from the neural tube give rise to the two eyes. (b) Contact between the optic vesicles and the surface ectoderm produces a lens placode. (c) The lens placode pushes into the optic vesicle, resulting in the formation of an optic cup and a lens vesicle. (d) The outer surface of the optic cup becomes the retinal pigment epithelium (RPE), and the inner surface becomes the retina. (e) Location of the retina within the mature eye. (f) Example of a

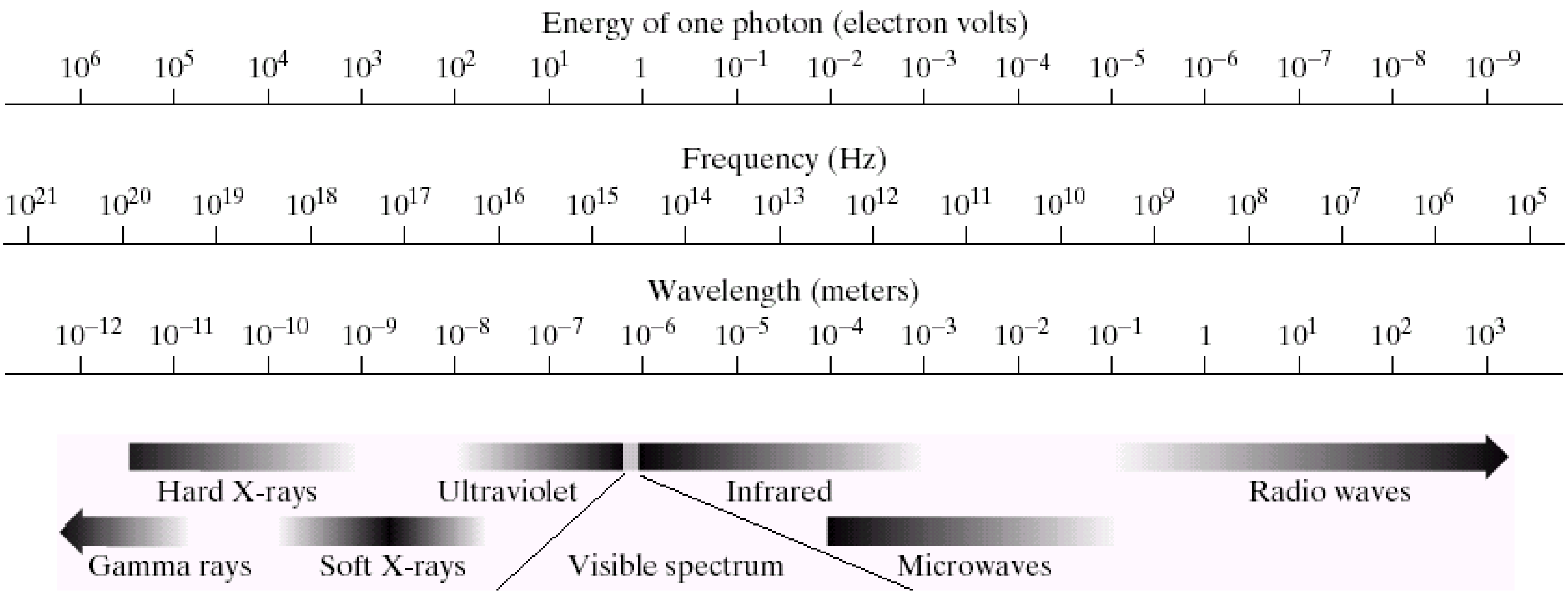
The human eye

Optical-microscopy image of the eye in a 41-day-old human embryo.

The retina has begun to develop; the intraretinal space will eventually be obliterated. The lens has detached from the surface and the cornea is forming from the thickened ectoderm



Photometry: radiometric definitions



$$E = h\nu = hc/\lambda$$

$$h = 4.135\times10\text{^}{-15}\ \mathrm{eV}\cdot\mathrm{s} = 6.626\times10\text{^-}34\ \mathrm{J}\cdot\mathrm{s}\ \ (Planck)$$

$$c = 3\cdot10^{8}\ \mathrm{m/sec}$$

Photometry: radiometric definitions

QUANTITY	DEFINITION	SI UNITS
Radiant energy	The amount of energy transferred in the form of electromagnetic radiation	Joules (J)
Radiant flux	The rate of flow of energy per unit time. This is sometimes called *optical power* or *radiant power*	Watts (W)
Radiant flux density	The radiant flux per unit area on a surface. There are two cases: **Irradiance** — the radiant flux *incident* on the surface per unit area **Radiant exitance** — the radiant flux exiting from a unit area on the surface in all directions. *Radiant emittance* and *radiosity* are older terms (no longer used) for radiant exitance	Watts per square metre ($\mathrm{W\,m^{-2}}$)
Radiant intensity	The radiant power emitted from a point source per unit solid angle	Watts per steradian ($\mathrm{W\,sr^{-1}}$)
Radiance	The radiant power per unit solid angle per unit projected source area	Watts per steradian per square metre ($\mathrm{W\,sr^{-1}\,m^{-2}}$)

Radiometric quantity → CIE *spectral luminous efficiency function* for photopic vision, *V(λ)* → photometric quantity

$$\Phi_{\mathrm{v}} = \int_{\lambda} \Phi(\lambda) V(\lambda) \mathrm{d}\lambda$$

… conversion …

Spectral Luminous Efficiency: sensitivity as a function of frequency

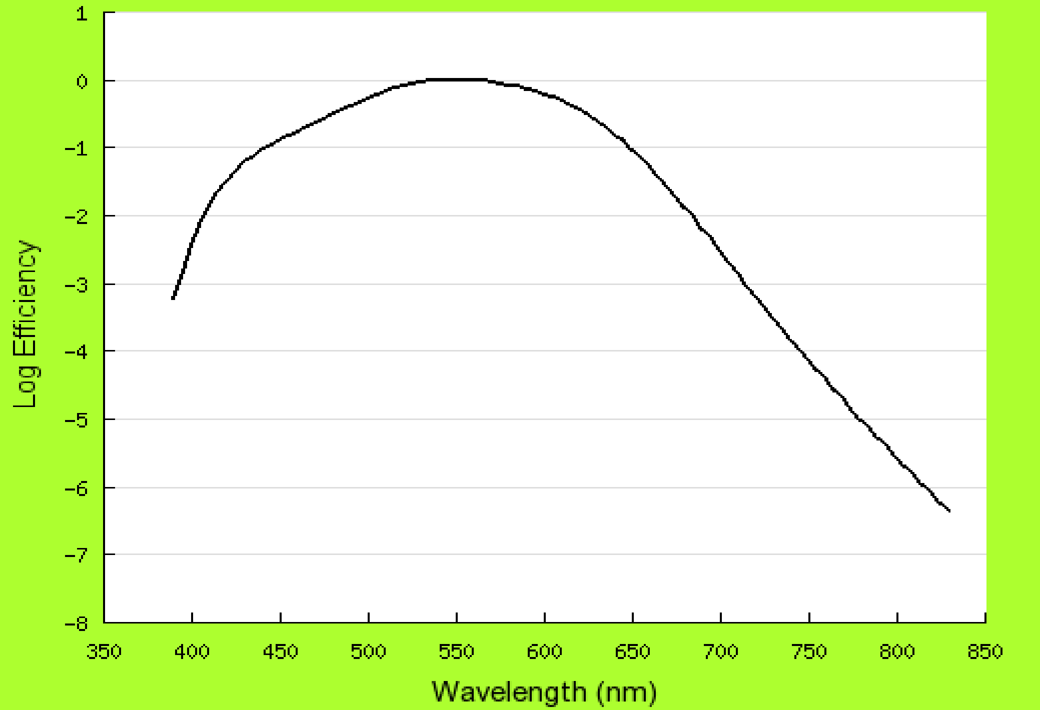
- **photopic**, 10 deg. field, "physiologically relevant", CIE 2008

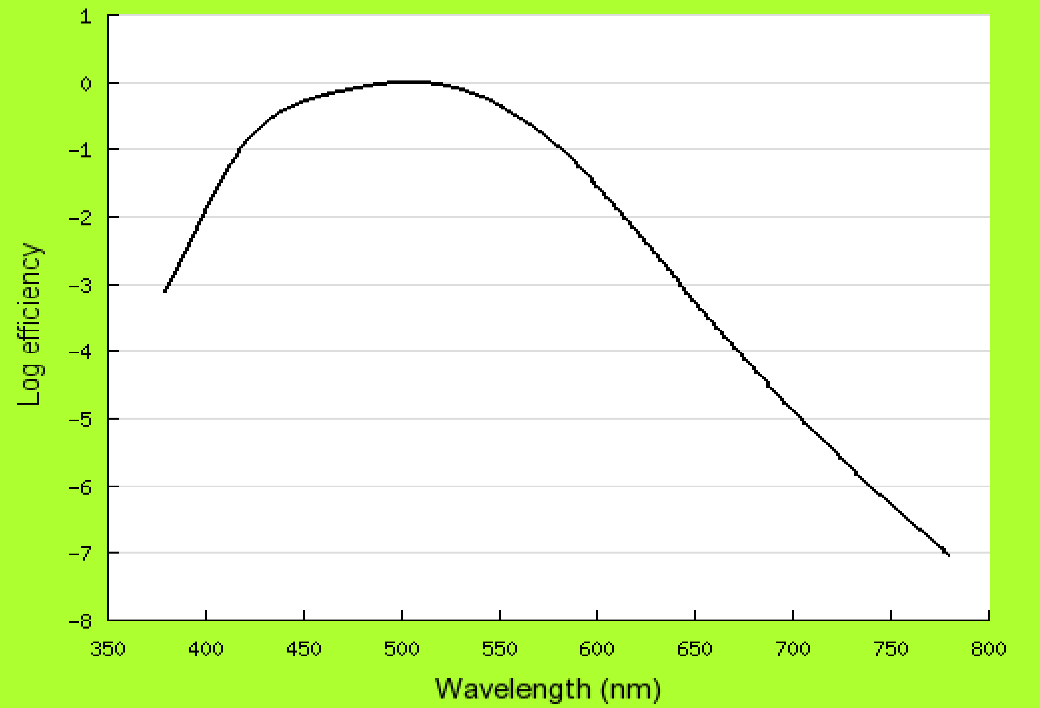
- **scotopic**, CIE 1951

units: lumen/watt (see later)

Tabular values available:

www.cvrl.org/lumindex.htm





Photometric definitions

Table 2.2 Photometric definitions and units

QUANTITY	DEFINITION	SI UNITS
Luminous energy	The amount of electromagnetic energy that is part of the visible spectrum	Lumen second (lm s)
Luminous flux	The rate of flow of energy (weighted for visible wavelengths only) per unit time, emitted by a source in all directions. Also called *luminous power* (e.g., power of an electric lamp)	Lumen (lm)
Luminous flux density	The photometrically weighted radiant flux per unit area on a surface. There are two cases: **Illuminance** – the total amount of visible light *incident* on a point on the surface per unit area. *Illumination* is an older term (no longer used) for illuminance **Luminous exitance** – the visible light exiting from a unit area on the surface in all directions. *Luminous emittance* is an older term (no longer used) for luminous exitance	Lux (lx) (lumens per square metre, lm m^{-2}) [lm/cm2 = Lambert]
Luminous intensity	The luminous flux emitted from a point source per unit solid angle in a particular direction	Candela (cd), also expressed as lumen per steradian (lm sr^{-1})
Luminance	The luminous power per unit solid angle per unit projected source area	Candela per square metre (cd m^{-2}) [also called "nit"]

Photometric definitions

QUANTITY	PHOTOMETRIC UNITY
power (luminous flux)	lumen (lm)
power per unit area (density of lum. flux)	lm/m^2 = lux (lx)
	[lm/cm^2 = Lambert]
power per unit solid angle (lum. intensity)	lm/sr = candela (cd)
power per unit area per unit solid angle	$lm/(m^2 sr) = cd/m^2$ = nit

The **candela** is one of the seven base units of the SI system:

the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} Hz (555 nm) and that has a radiant intensity in that direction of 1/683 W/sr.

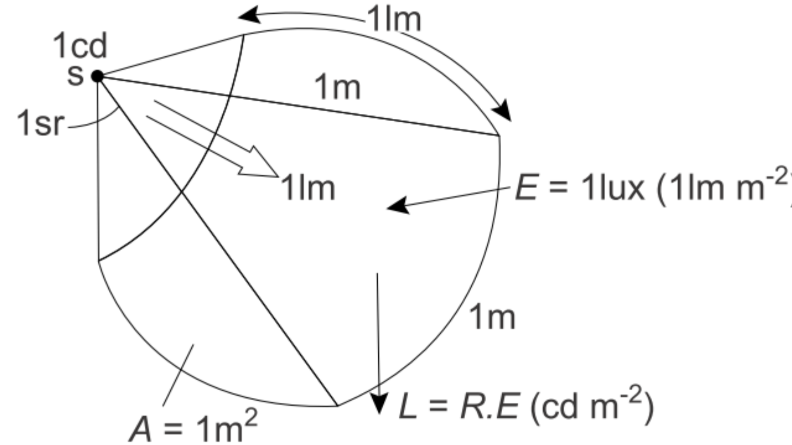
General Conference on Weights and Measures (CGPM), 1979

Luminance is the rate at which light is *emitted from* a surface: cd/m^2

Illuminance is the rate at which light *strikes* a surface: lm/m^2 = lx

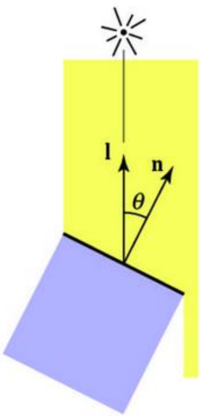
Photometric definitions

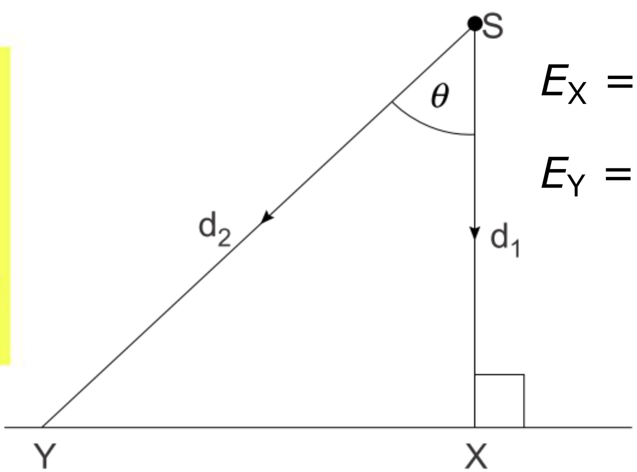
Photometric units derived from source S with intensity I of 1 cd at centre of sphere of radius 1 m. Flux (power) emitted into 1 sr is 1 lm. Area A (1 m2) has illuminance E of 1 lx and luminance L cd/m2 due to reflection coeff. R



The illuminance decreases with the square of the distance (applies only to point sources; approx. true for any source that is small in proportion to its distance from the object; not applicable e.g. to a spotlight, due to the optical system used to direct the light beam)

Lambert’s cosine law (1760): the illuminance on an inclined surface is proportional to the cosine of the angle of incidence of the light rays





$$E_X = I / d_1^2$$

$$E_Y = I \cos(\theta) / d_2^2$$

Lambertian surface:
formed by isotropic point sources, emits uniformly in all directions (typ. of matte and smooth surfaces)

Polarization in plane waves

Polarization describes the direction of oscillation of the electric field in a plane perpendicular to the direction of propagation.
We describe the electric field only, since the magnetic field is perpendicular to it and their amplitudes are proportional.

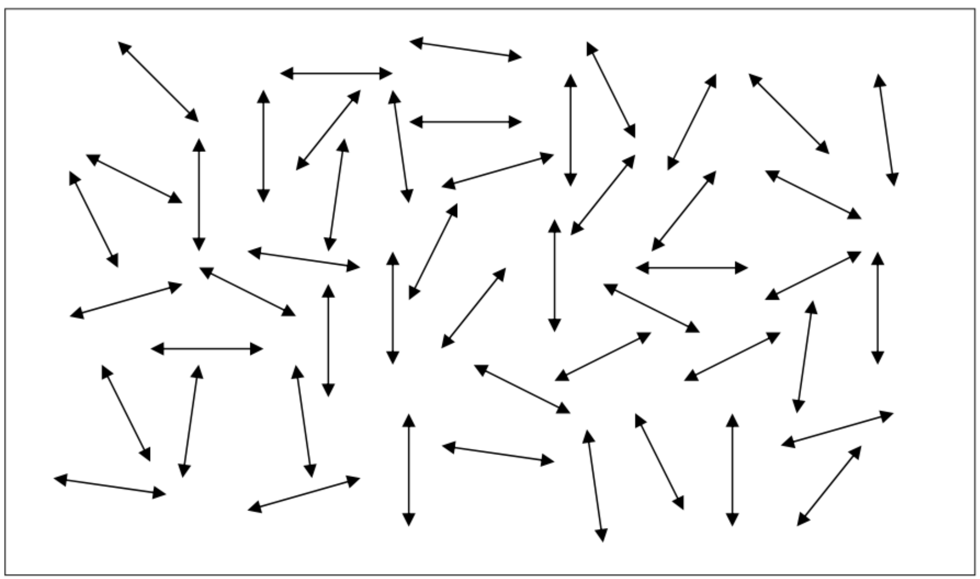


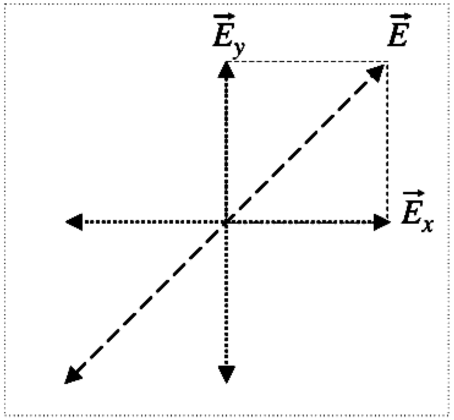
Figure 2.10 A head-on view of an approaching wavefront of unpolarized light at a fixed instant in time. At each position the direction of vibration in the plane of polarization is randomly aligned.

"Natural" light in free space, far from source, is a TEM wave

Both the direction and the amplitude of the vectors vary along time or space

Polarization in plane waves

Linear polarization:
the E vector describes a line with fixed orientation



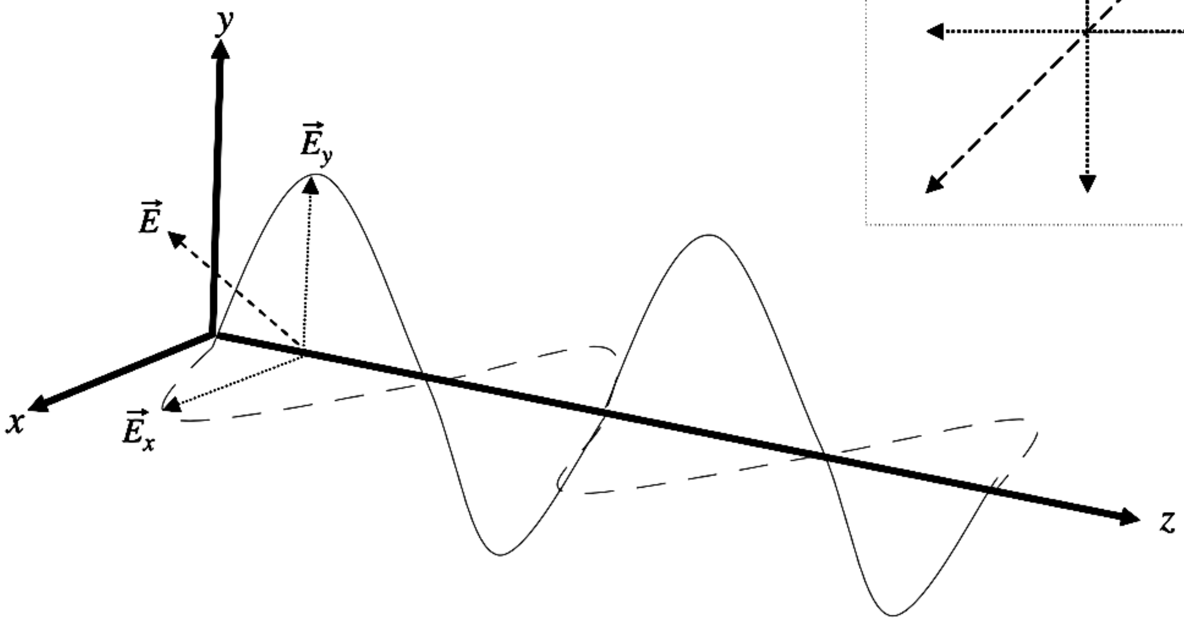
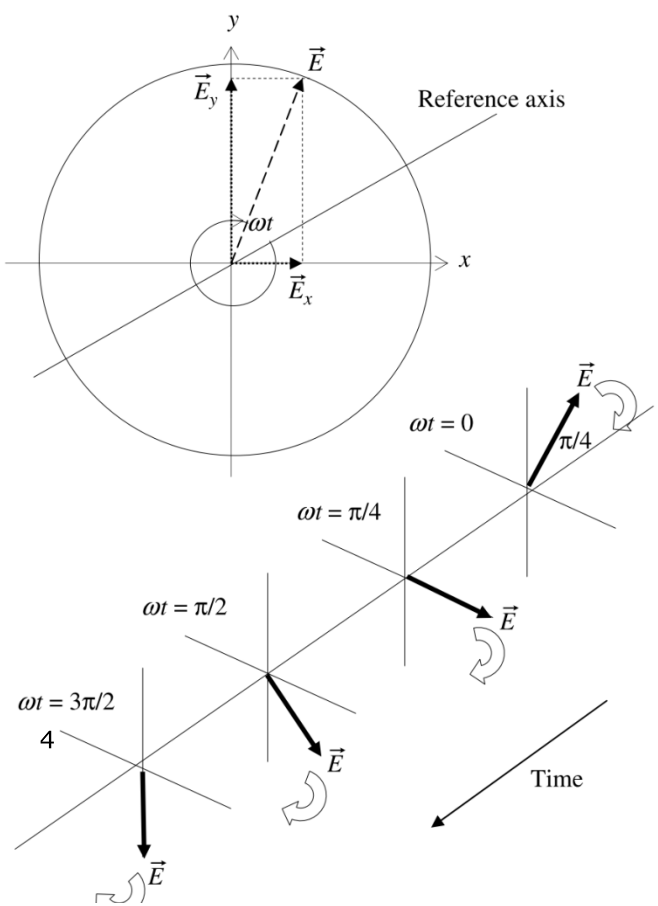


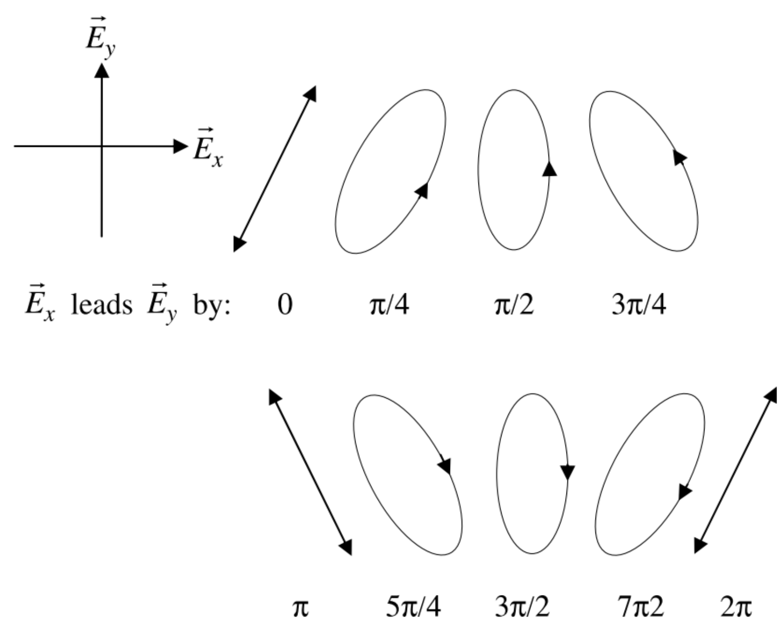
Figure 2.11 Linear light. The two wave components with electric fields $\vec{E}_x$ and $\vec{E}_y$ are in phase. The wave's electric field, $\vec{E}$, is linearly polarized in the first and third quadrants.

Polarization in plane waves

Circular polarization: the tip of the *E* vector describes a circle.
Can be obtained using a "quarter-wave" optical filter that delays *Ex (Ey)* by $\pi/2$ wrt *Ey (Ex)*



Linear and circular polarization are special cases of *elliptic polarization*, depending on specific amplitude and phase differences between *Ex* and *Ey*



Elements of visual perception

The eye can adapt to an enormous range (in the order of 10^10) of light intensities, from **scotopic** threshold to the glare limit.

Subjective **brightness** (i.e. perceived intensity) is a function of the log light intensity incident on the eye.

In **photopic** vision alone, the range is about 10^6(-2 to 4 in a log scale).

The transition from scotopic to photopic vision is gradual over the range (0.001, 0.1) millilambert (-3 to -1 mL in the log scale).

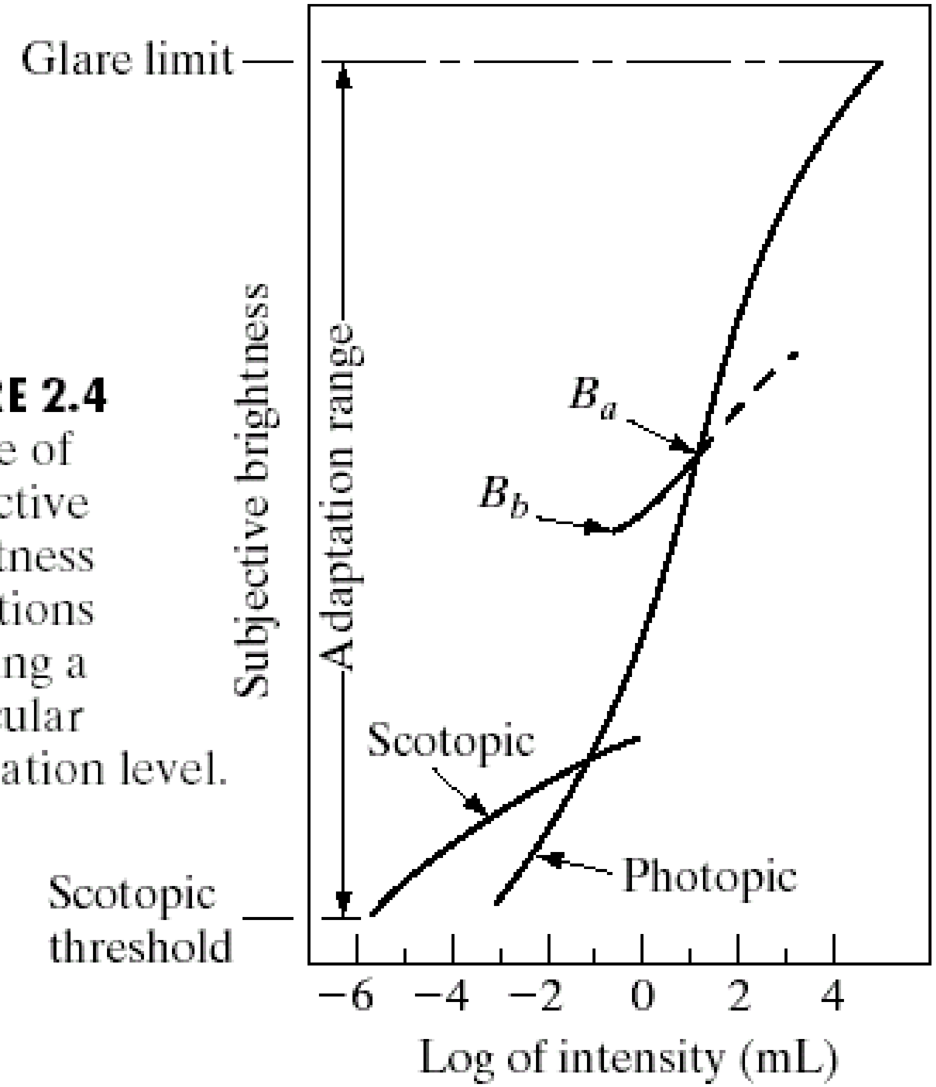


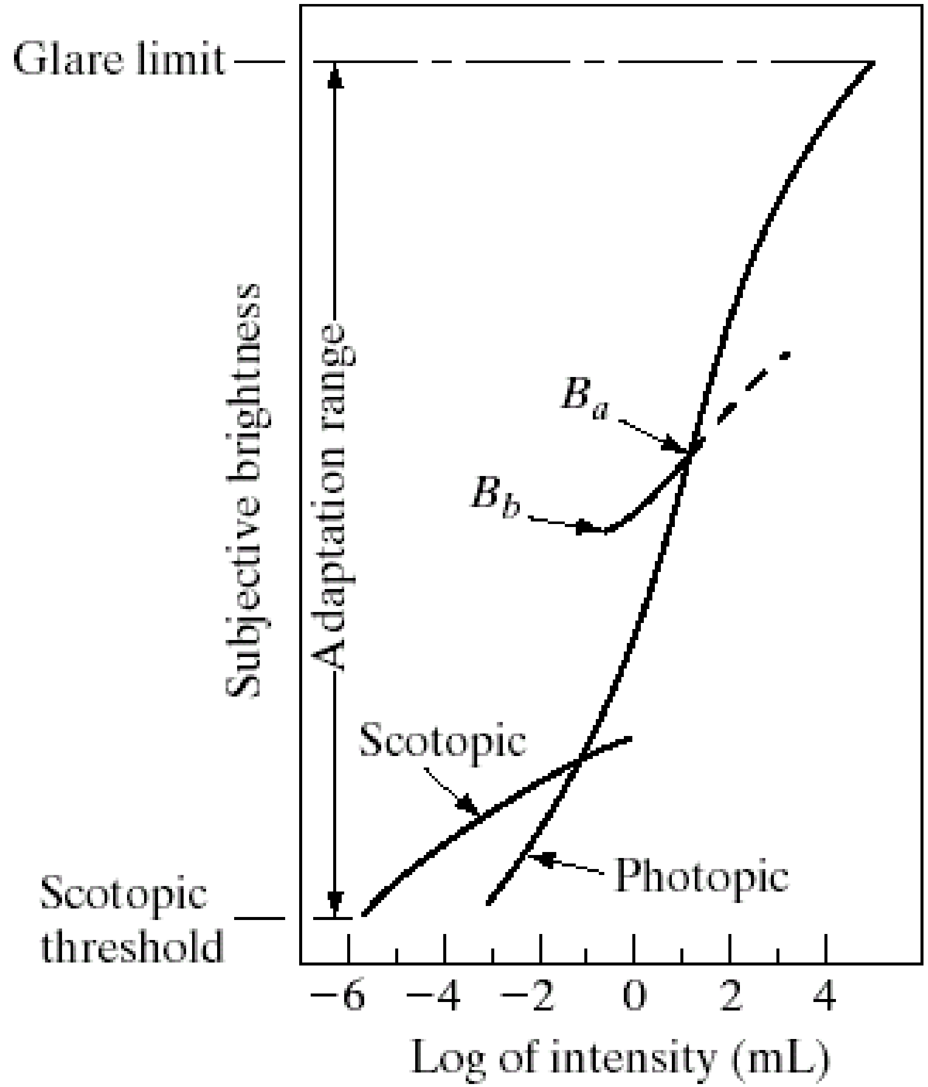
FIGURE 2.4 Range of subjective brightness sensations showing a particular adaptation level.

Elements of visual perception

The visual system cannot operate over such a huge range simultaneously; instead, it changes its overall sensitivity. This phenomenon is called **brightness adaptation**.

E.g.: if the eye is adapted to brightness level *Ba*, the short intersecting curve represents the range of subjective brightness perceived by the eye. The range is rather restricted, i.e. below level *Bb* all stimuli are perceived as black.

The upper part of the curve (dashed) is not restricted, but when extended too far it looses its meaning since the adaptation level becomes higher than *Ba*.



Elements of visual perception

Psychophysics studies the relationship between (physical) stimuli and the sensations and perceptions they evoke

1. Bernoulli argued that the perceived increment of satisfaction *dy* for a change *dx* in possessed money is directly proportional to *dx*, and inversely proportional to the overall fortune *x*
2. Weber formalized an empirical law for the minimum perceivable amplitude of stimuli of different types: ***dx / x* = constant**. Now known as **Weber law**
3. Fechner reformulated the same relationship as

   $$dy = k\, dx / x \quad \rightarrow \quad y = k \log x + C$$

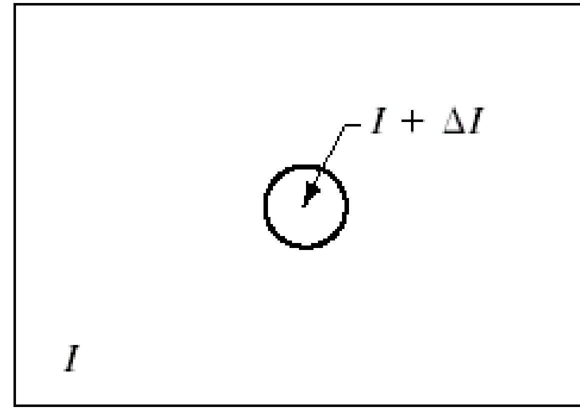
   i.e. the **Weber-Fechner law**

[1] Bernoulli, D. (1738). Specimen theoriae novae de mensura sortis. Commentarii Academiae Scientiarum Imperialis Petropolitanae, 5

[2] Weber, E.H. (1834). De pulsu, resorptione, auditu et tactu. Annotationes anatomicae et physiologicae. Leipzig: Koehler

[3] Fechner, G.T. (1860). Elemente der Psychophysik. Leipzig: Breitkopf und Härtel

Elements of visual perception



Contrast sensitivity and **Weber ratio**

Contrast is defined as $\Delta I/I$

i.e. $(I_2-I_1)/I_1$ or $(I_2-I_1)/(I_2+I_1)$

Experiment for **brightness discrimination**:

- Look at a flat, uniformly illuminated large area, e.g. a large opaque glass illuminated from behind by a light source, having intensity I.
- Add an increment ΔI, in the form of a short-duration circular flash in the middle (J. Ferwerda, 1996)
- Or, add a static sinusoidal grating of amplitude ΔI (P. Barten, 1992)
- Vary ΔI.

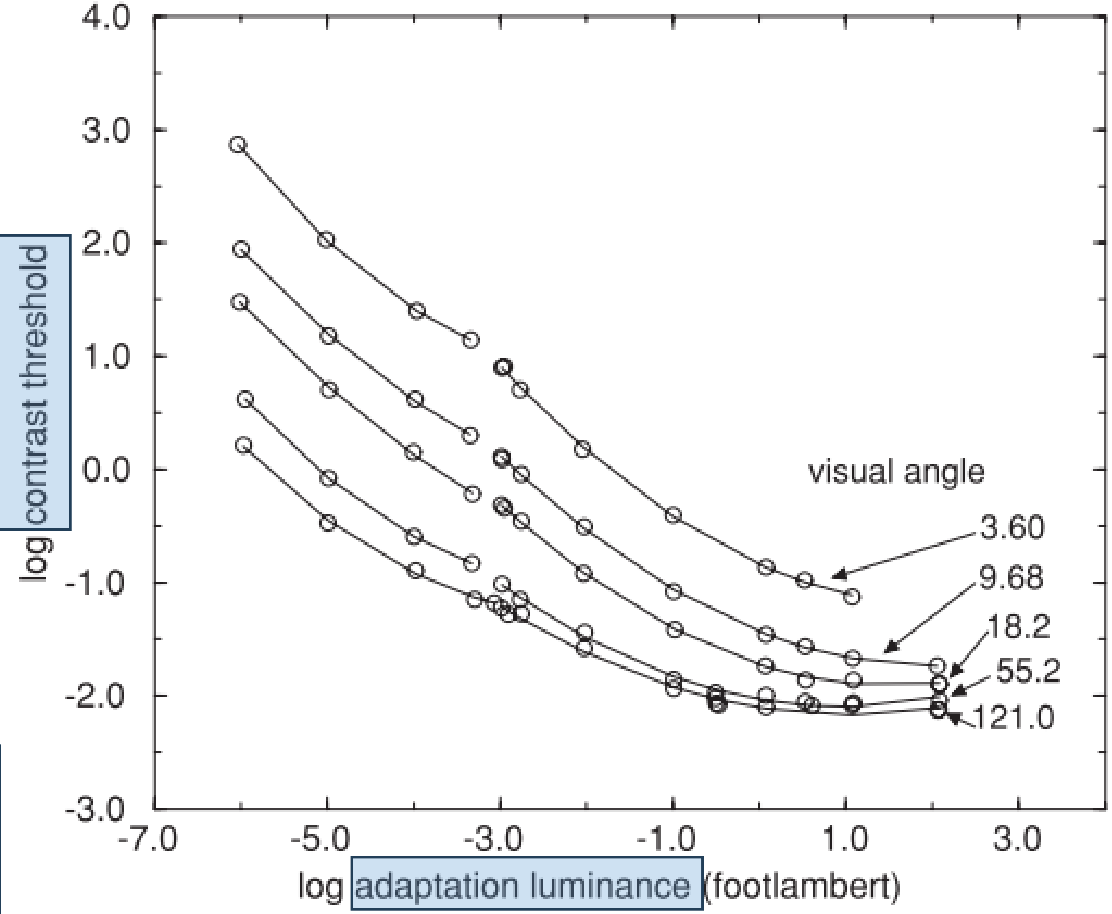
The fraction $\boldsymbol{\Delta I_C/I}$ for which ΔI_C produces a ***Just Noticeable Difference (JND)*** is called the **Weber ratio**.

Elements of visual perception

Experiments show that brightness discrimination is poor (large Weber ratio) at low level of illumination, and it improves significantly as I increases.

At low levels of illumination vision is carried out by the rods, whereas at high levels (better discrimination), cones are at work

For a large target at high luminance (flat portion of the plots, above 1 cd/m2), **Weber's law** is a good approximation



1 ft-L = 3.426 cd/m2

H.-C. Lee 2005, Fig.13.2

Elements of visual perception

Large quantization steps can generate *false contours*

Problem: how finely should we quantize the luminance *L* when we design a display?

Let's count the **no. of JNDs**

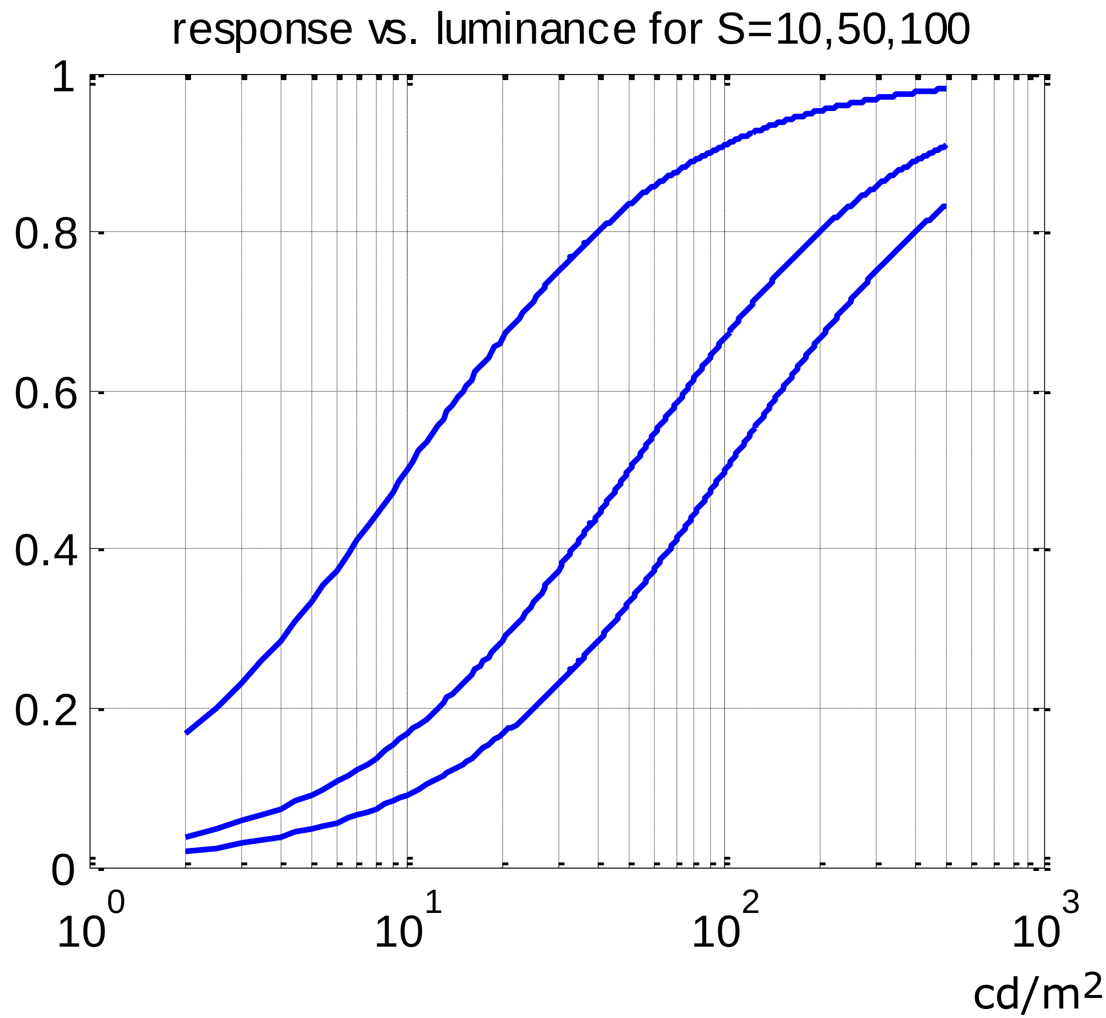
The human photoreceptors response *P* can be approximated by

$P(L,S) = L / (L+S)$

(Naka-Rushton model)

S is the adaptation state, at which the response is 0.5

Note Weber-law response [y = k log x] if stimulus is close to adaptation state



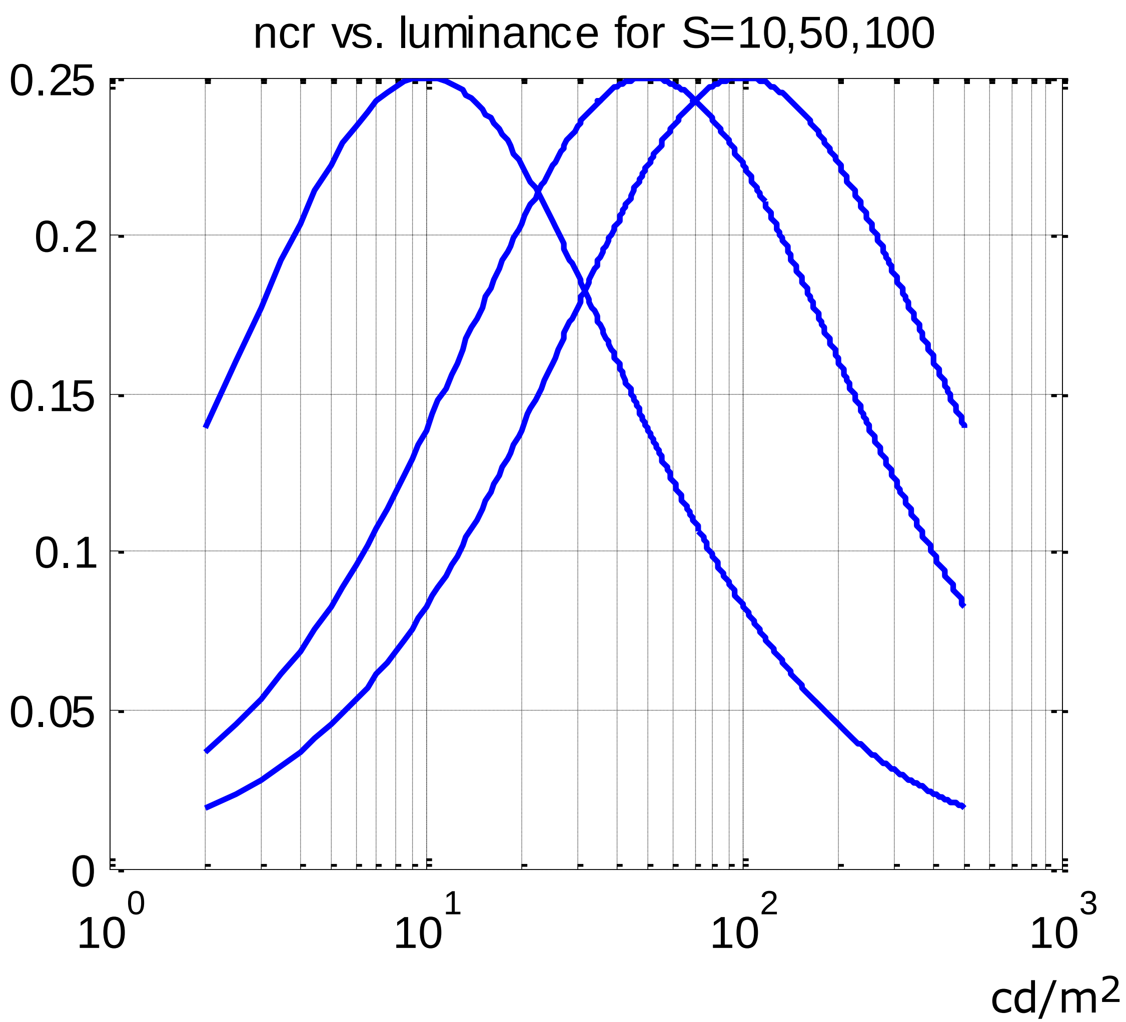
Elements of visual perception

The normalized contrast response ***ncr*** can be derived:

$$ncr(L,S) =$$

$$= dP/(dL/L)$$

$$= (L*S) / (L+S)^2$$



Elements of visual perception

The normalized contrast threshold ***nct*** is then

$nct(L,S) = 1 / ncr = (L+S)^2 / (L*S)$

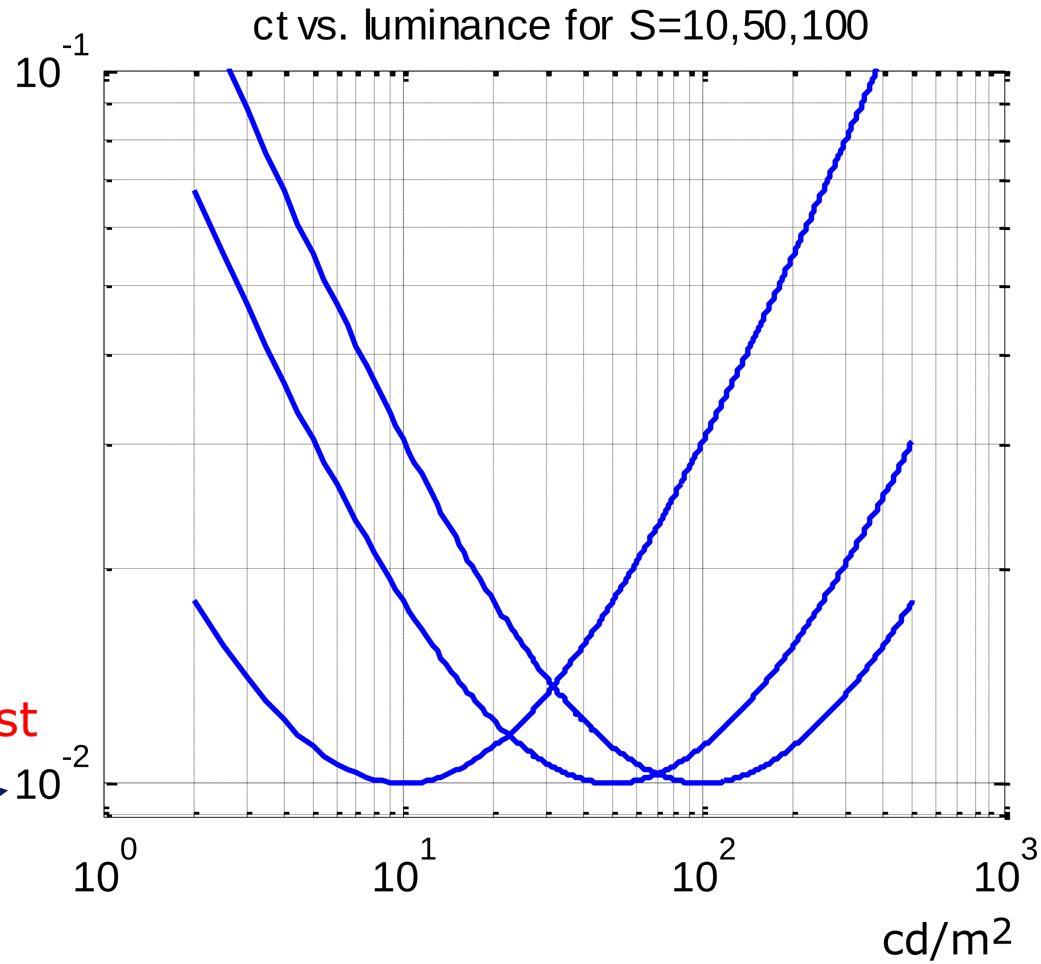
Taking as a reference the perfect adaptation case:

$nct(L=S) = (2S)^2 / S^2 = 4$

we get the (denormalized) contrast threshold ***ct***:

$ct(L,S,cto) = (cto/4) * nct =$
$= (cto/4) * (L+S)^2 / (L*S)$

where ***cto*** is the optimal contrast threshold
Barten: $cto = 0.01$
(Ferwerda: $cto = 0.1$)



Elements of visual perception

In the **varied adaptation** case, the total number of JNDs (***Njnd***) in a given luminance range (*Lmn,Lmx*) can be estimated as the largest integer exponent *N* that satisfies

$$(1+cto)^N \le Lmx/Lmn$$

Indeed:

$$cto = (Lmx-L1)/L1 = Lmx/L1 - 1 \rightarrow Lmx/L1 = 1+cto$$

$$\ldots \quad cto = (L7-L8)/L8 = L7/L8 - 1 \rightarrow L7/L8 = 1+cto \quad \ldots$$

i.e.:

$$Lmx/Lmn = (Lmx/L1)(L1/L2)(L2/L3) \ldots (L[N-1]/Lmn) \quad [N \text{ factors}]$$

E.g.: $cto=0.01$, $Lmn=2$ cd/m^2, $Lmx=500$ cd/m^2, $\rightarrow$ $Njnd = 554$

In the **fixed adaptation** case, *Njnd* is the largest *N* that satisfies

$$Prod\_[k=1,N] \; (1+ct(L(k))) \le Lmx/Lmn$$

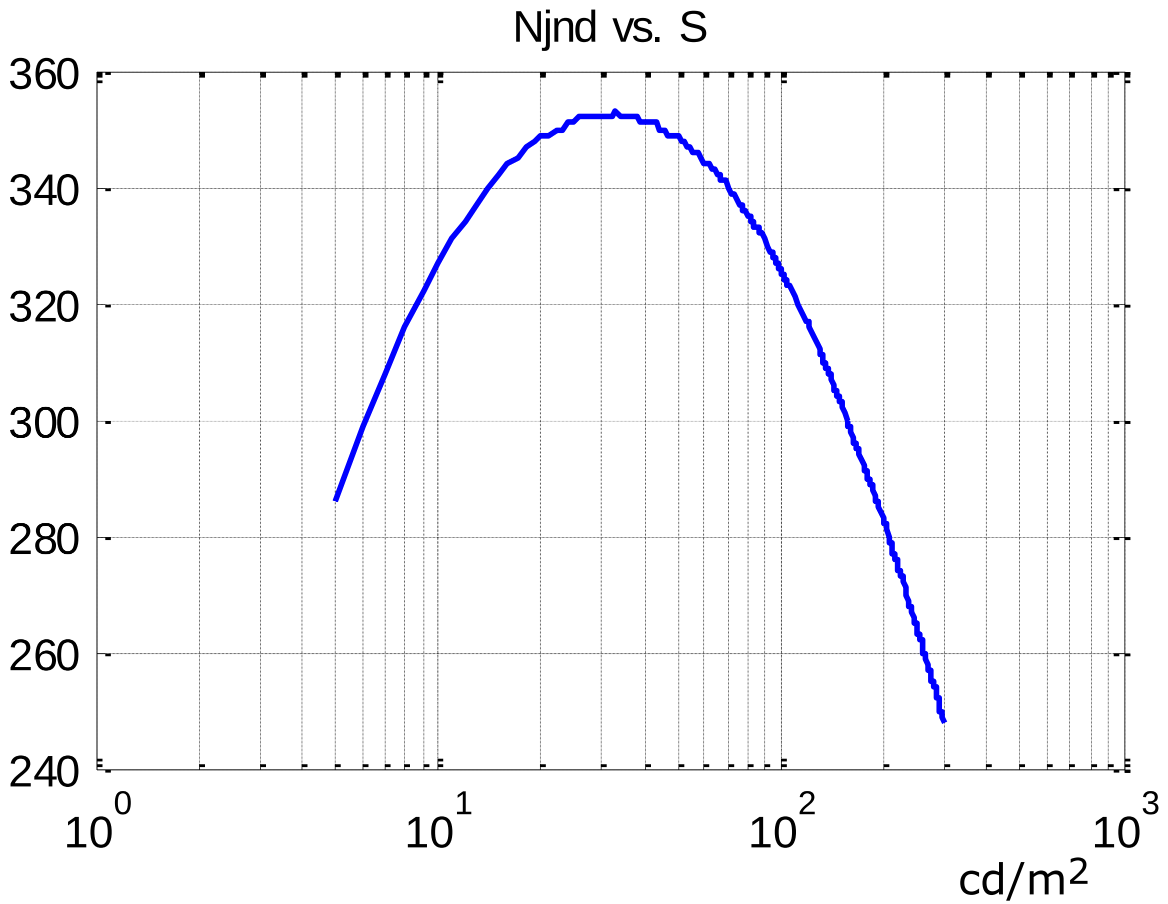
where $L(1) = Lmn; \; L(k+1) = L(k)*(1+ct(L(k)))$

Since *ct* is always larger than *cto*, *Njnd* is now smaller.

E.g.: $Njnd = 350$ if $S = 50$

Elements of visual perception

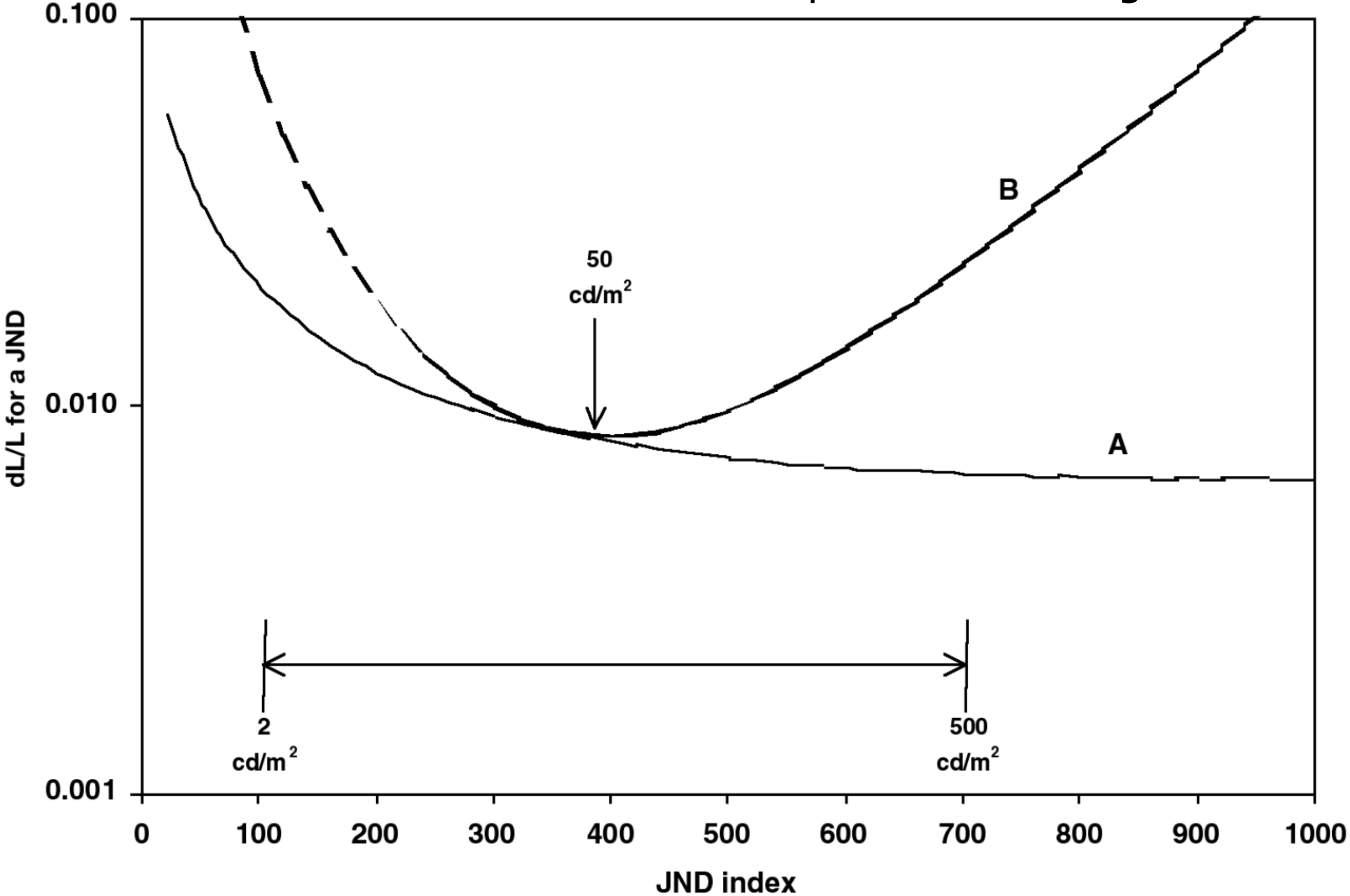
Fixed adaptation case:
Njnd in a [2-500] cd/m^2 display, as a function of the adaptation level *S*



(see also G. Ward 2008, 'Defining dynamic range')

Elements of visual perception

Reference: AAPM TG-18 Report No.03 - Fig.3



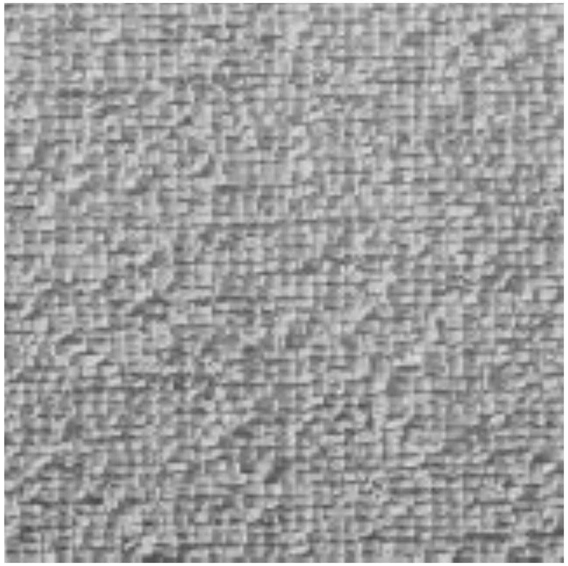
Contrast threshold for varied (A) and fixed (B, Flynn et al. 1999) visual adaptation.

Elements of visual perception

Example Brodatz texture D84

($mean$, std) = (158.6, 28.6)

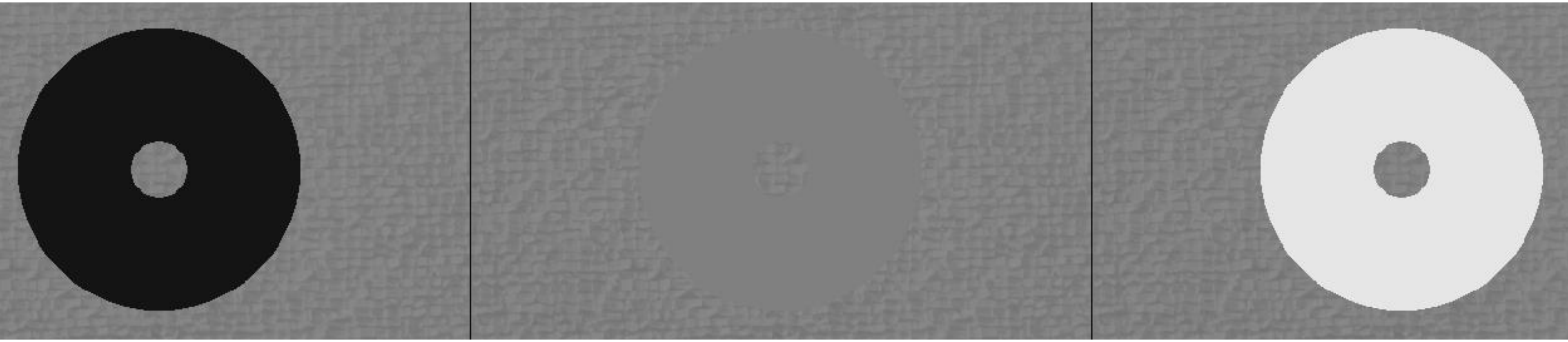
gray levels range: (70, 222)



scaled to ($mean$, std) = (128, 5)

gray levels range: (112, 139)

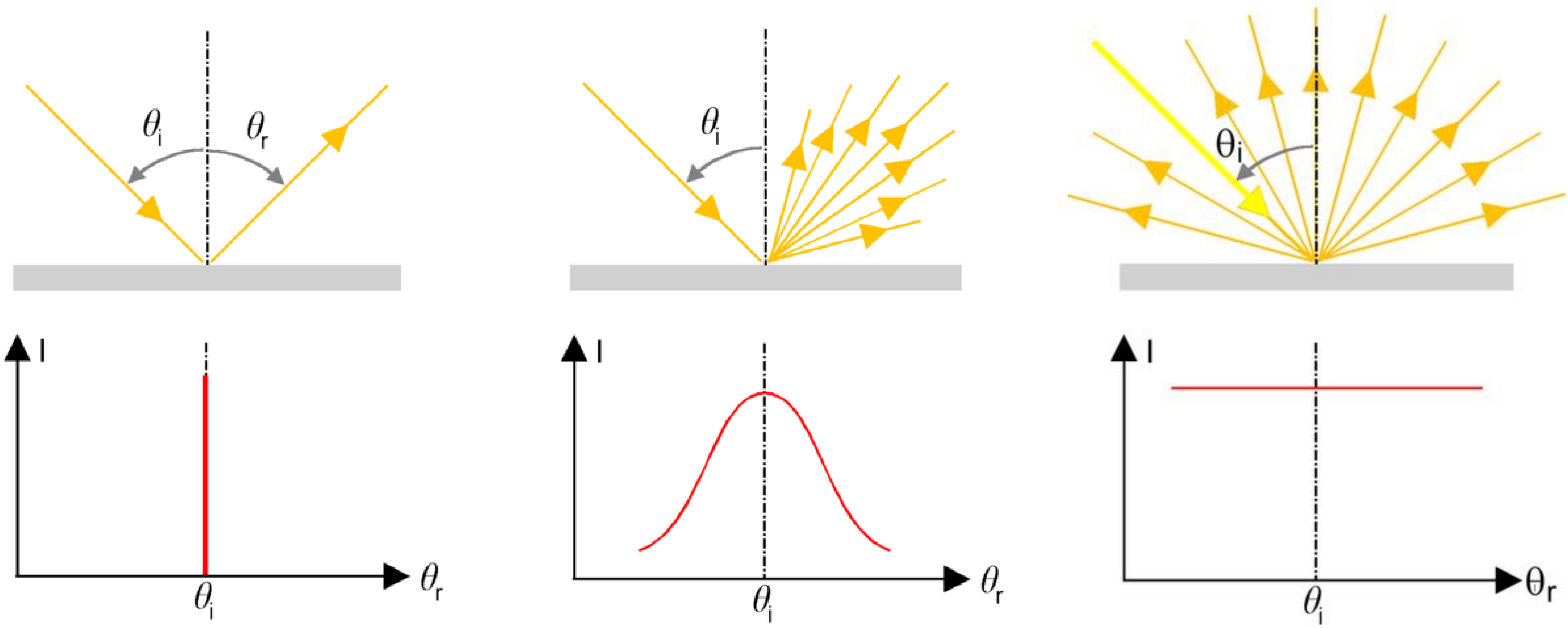
Ring gray levels: Gr = 20, 128, 230



Elements of visual perception

...But we should take into account also the **luminance of a screen caused by ambient illumination**

specular, haze, diffuse (Lambertian) reflection:



https://commons.wikimedia.org/w/index.php?curid=4518625

Elements of visual perception

Changes in *Njnd* due to **ambient illumination**

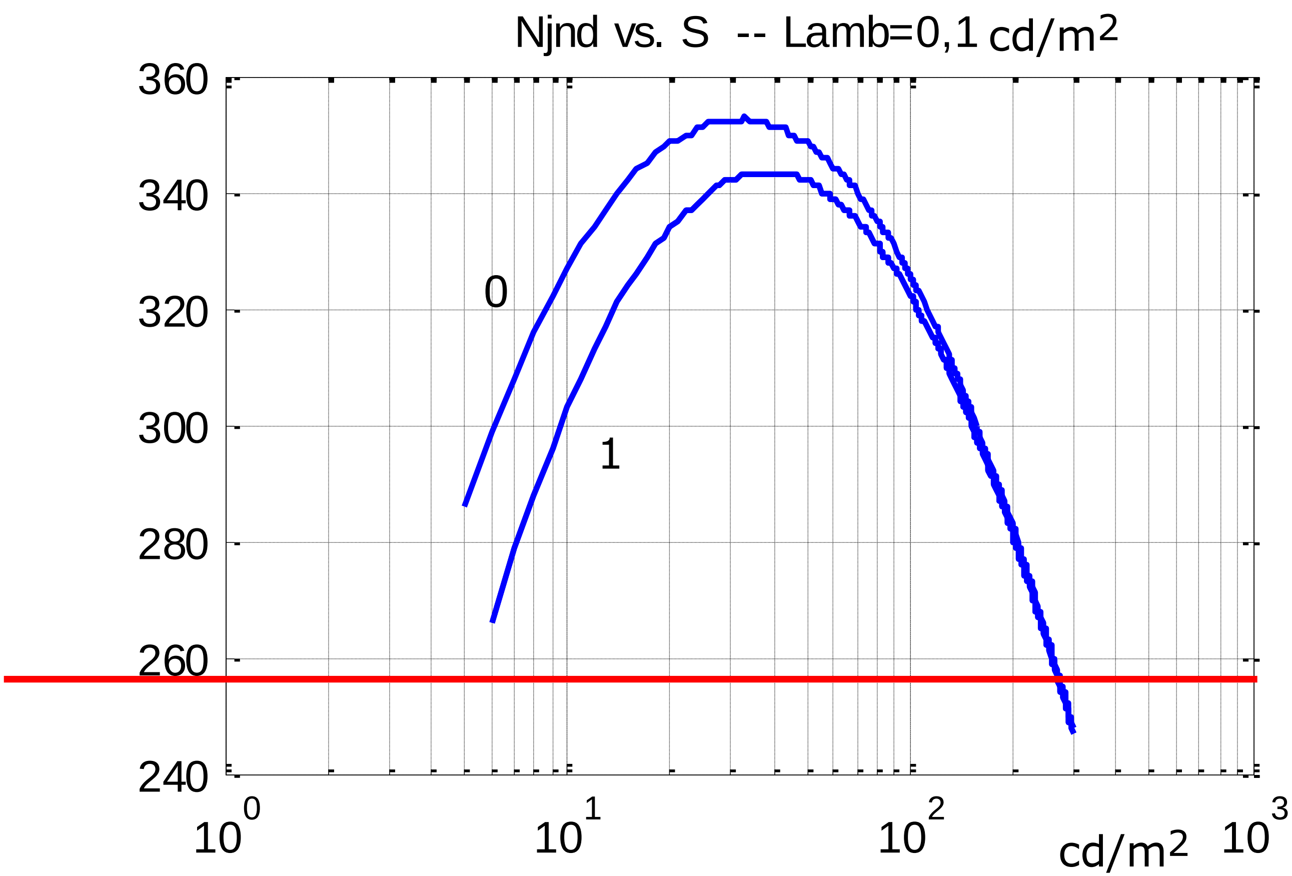
Luminance diffused by a display having *Rd* = 0.02 1/sr (diffuse reflection coeff.) in a reading room with *I* = 30 Lux:

→ *Lamb* = *I***Rd* = 0.6 cd/m^2

- The *effective* dynamic range is: $\frac{(Lmx+Lamb)}{(Lmn+Lamb)}$

- *S* changes too

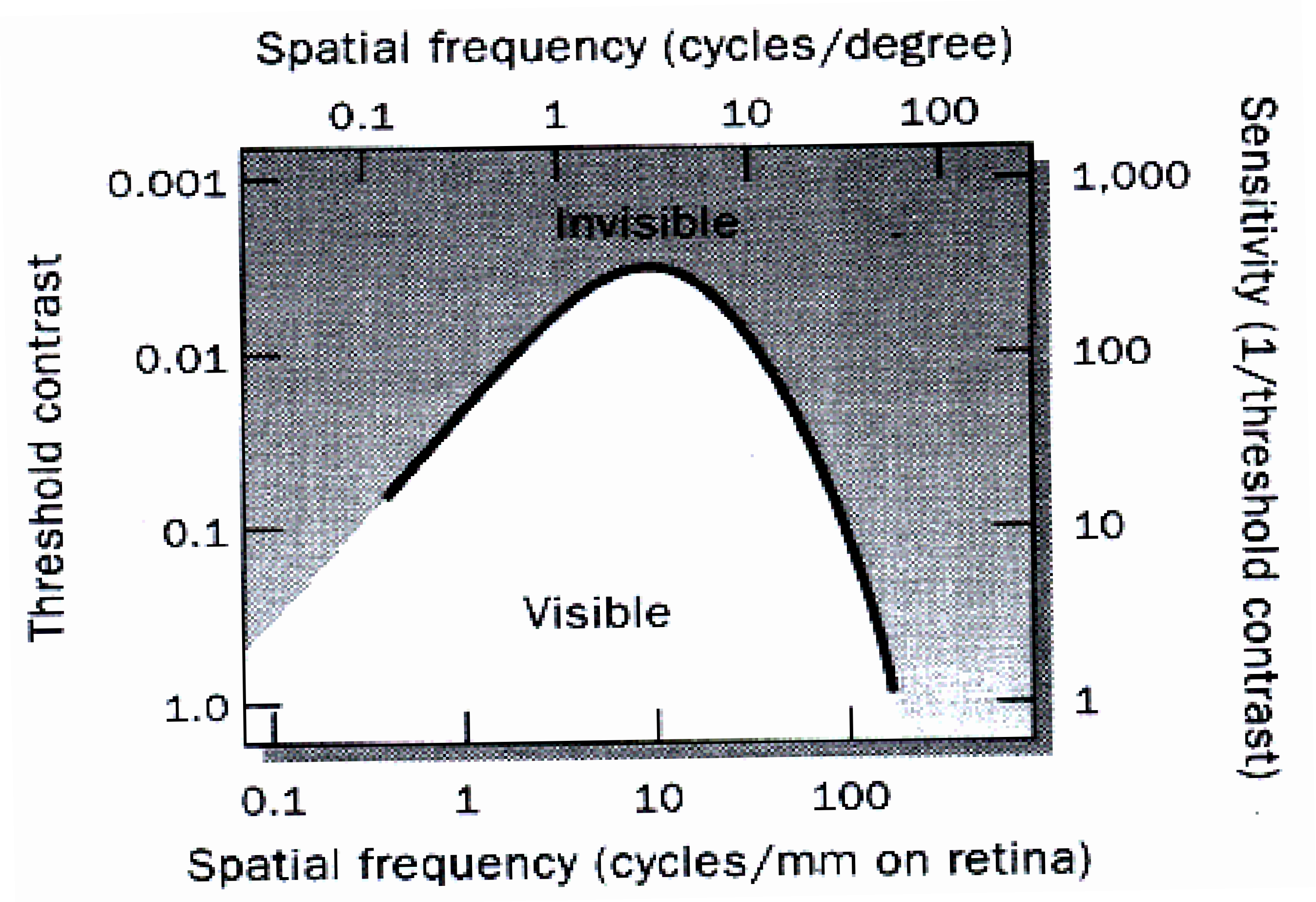
Note: An 8-bit quantization of the luminance permits to generate only 256 levels



Elements of visual perception

Contrast Sensitivity Function (CSF):

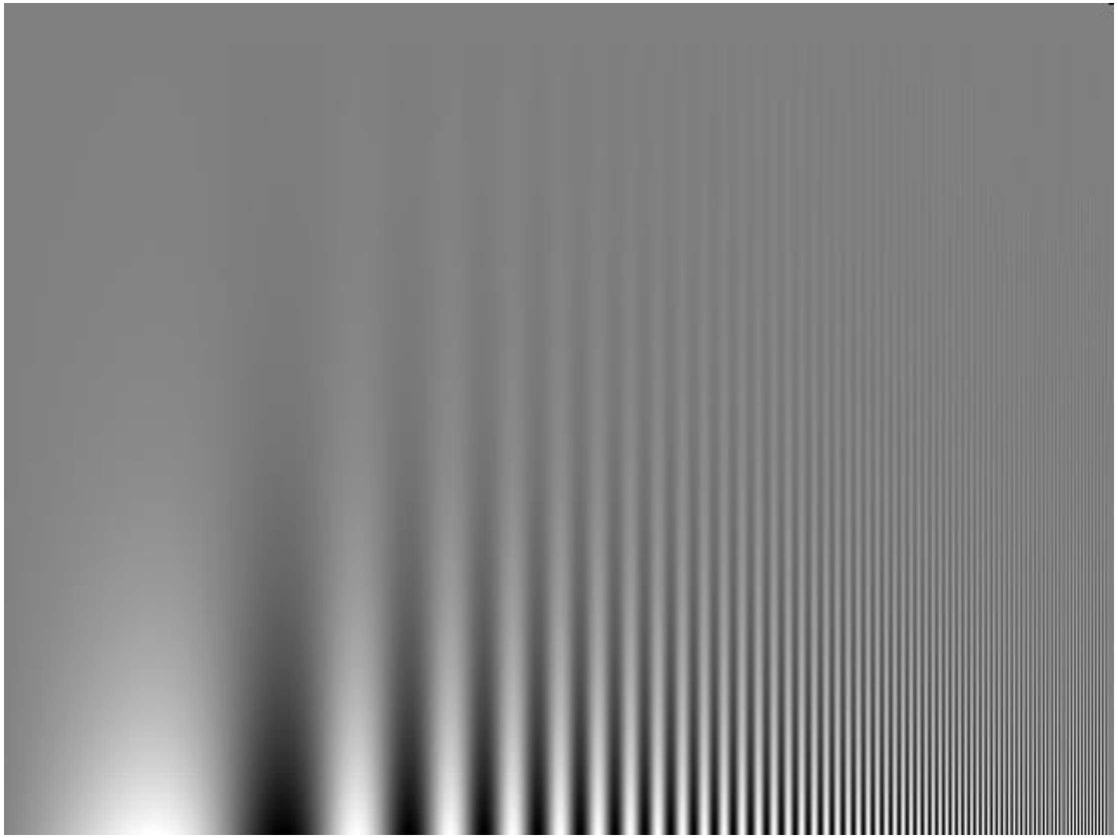
sensitivity as a function of **spatial frequency**

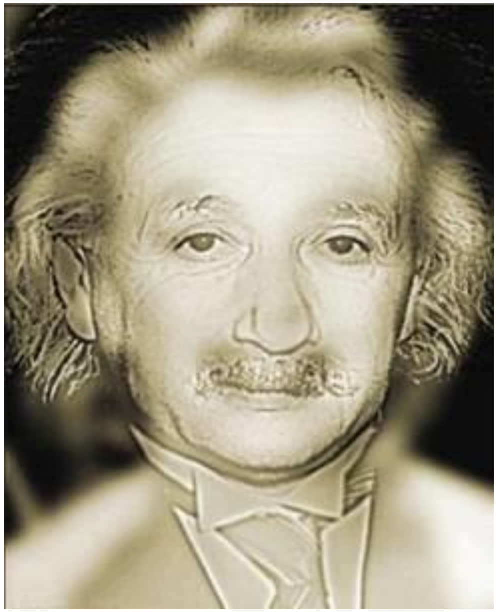


The threshold of a perceivable contrast is a function of the spatial frequency. Maximum sensitivity at a few cycles/degree

Elements of visual perception

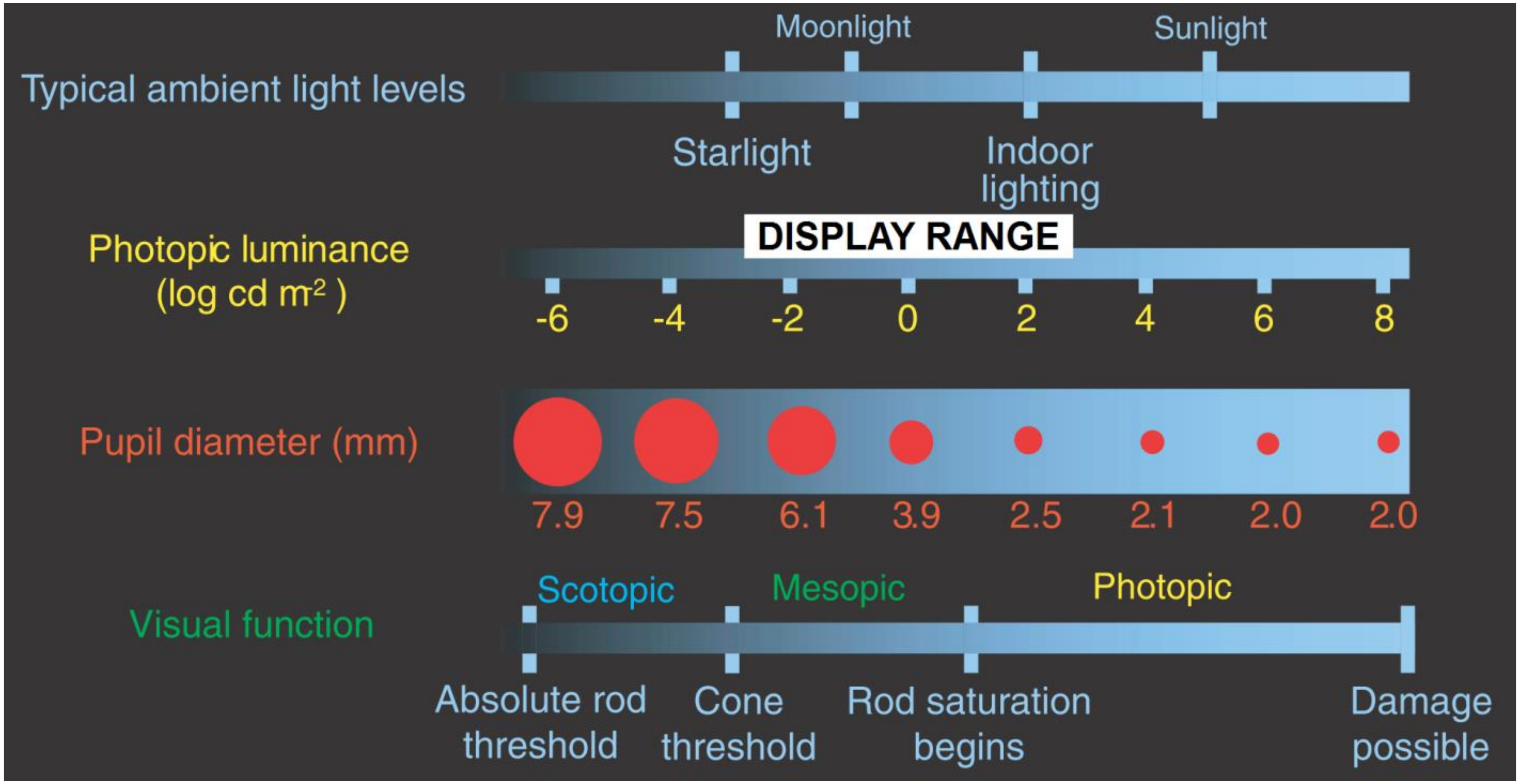
Sinusoidal grating, exponential increase in frequency from left to right, exponential increase in contrast from top to bottom [Campbell and Robson 1968]





Elements of visual perception

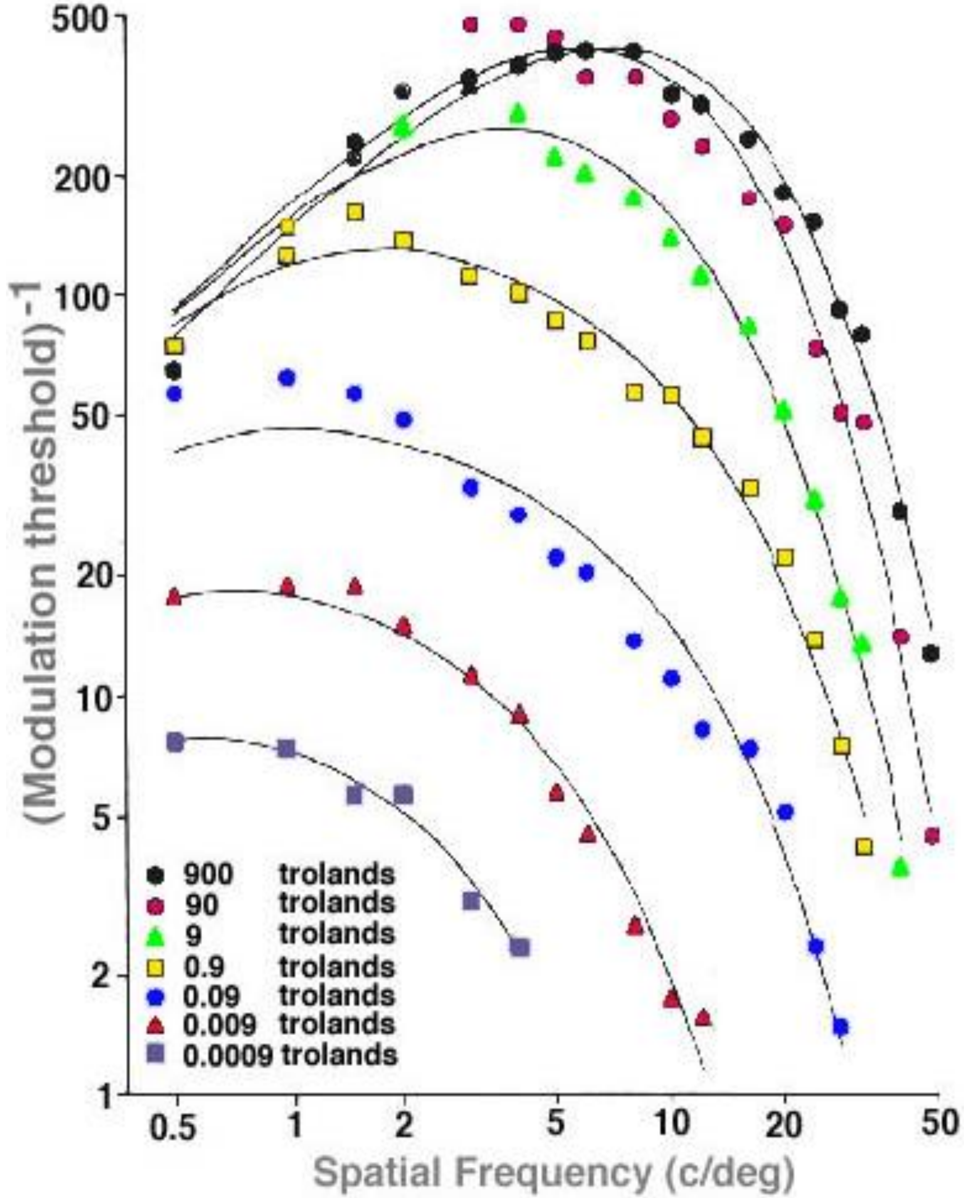
Can we exploit the lowest part of the luminance range?



Elements of visual perception

CSF, as a function of retinal illumination

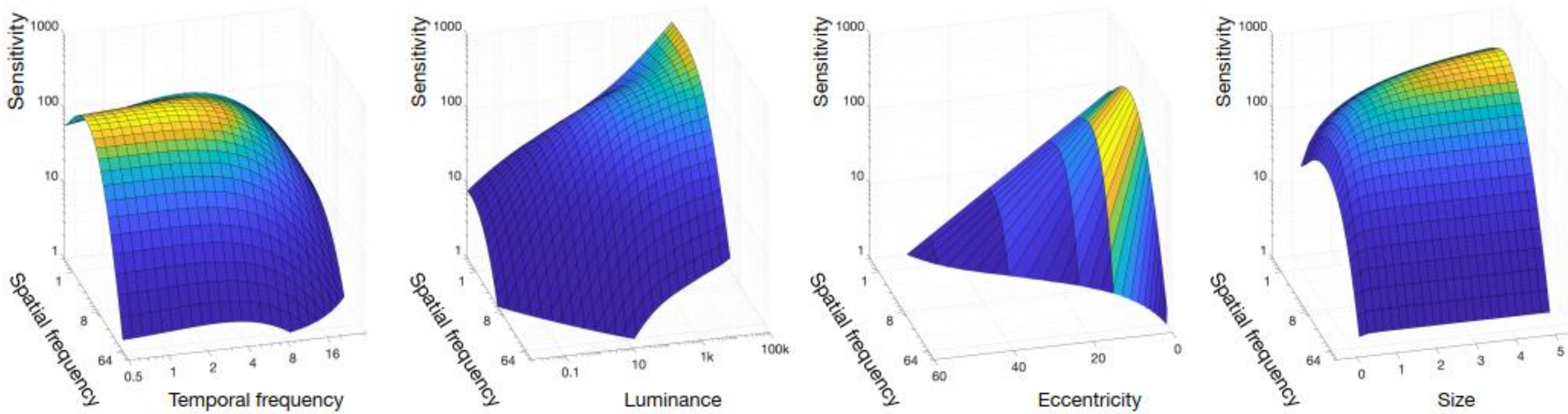
Simple formula for luminous flux incident on the retina:
$T = LS$
where L is the luminance of the stimulus in cd/m^2 and S is the area of the pupil in mm^2. The luminous intensity on the retina, T, is then given in *trolands*



stelaCSF - A Unified Model of Contrast Sensitivity as the Function of Spatio-Temporal Frequency, Eccentricity, Luminance and Area

RAFAŁ K. MANTIUK, University of Cambridge, UK
MALIHA ASHRAF, University of Liverpool, UK
ALEXANDRE CHAPIRO, Reality Labs, USA

ACM Trans. Graph., Vol. 41, No. 4, July 2022



"CSFs account for spatial frequency, but equally important is the background luminance and size of the stimulus. For moving patterns, we also need to account for temporal frequencies. If the pattern is not fixated (i.e., is projected outside fovea), a CSF depends on the position in the visual field, described by the eccentricity."

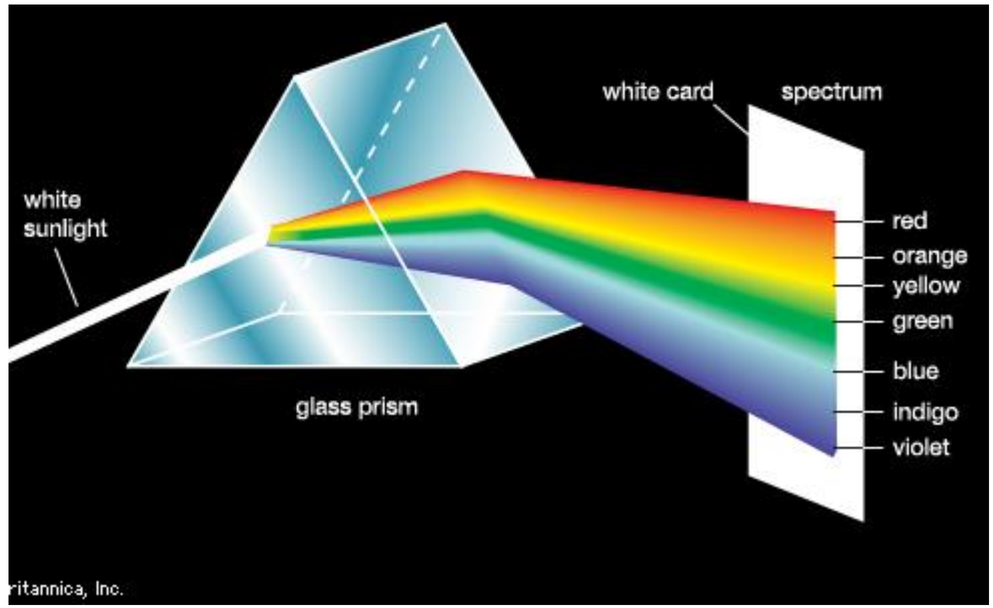
Applications:

- Flicker detection
- Foveated rendering
- 3-D perception in stereoscopic vision

Colors: physics

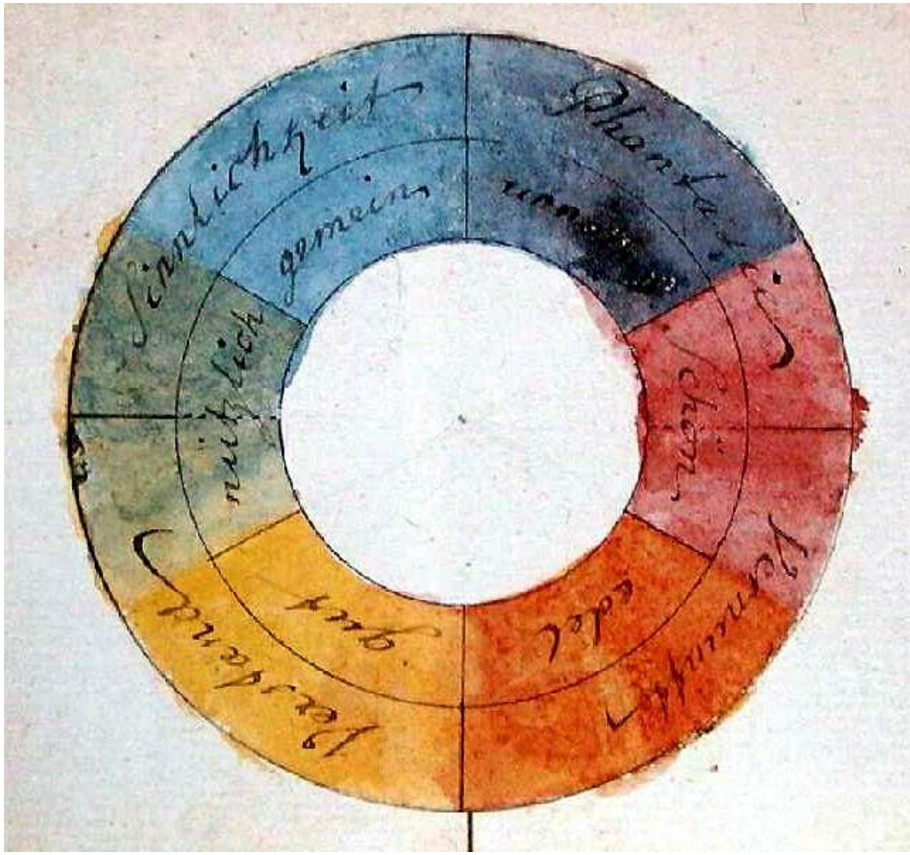
Sir Isaac Newton experimenting in the 1660s with a prism.

Engraving after a picture by J.A. Houston, ca. 1870 - ©Smithsonian Libraries



© Encyclopædia Britannica

Colors: psychology



Wolfgang Goethe: Zur Farbenlehre (1810) [To a color theory]: a large set of experiments also in opposition to Newton's theory - ©Smithsonian Libraries

Schön (beautiful)
Edel (noble)
Gut (good)
Nützlich (useful)
Gemein (mean, common)
Unnöthig (unnecessary)

…"allegorical, symbolic, mystic use of colour" (*Allegorischer, symbolischer, mystischer Gebrauch der Farbe*). He associated red with the "beautiful", orange with the "noble", yellow to the "good", green to the "useful", blue to the "common", and violet to the "unnecessary". These six qualities were assigned to four categories of human cognition, the rational (*Vernunft*) to the beautiful and the noble (red and orange), the intellectual (*Verstand*) to the good and the useful (yellow and green), the sensual (*Sinnlichkeit*) to the useful and the common (green and blue) and, closing the circle, imagination (*Phantasie*) to both the unnecessary and the beautiful (purple and red) ©Wikipedia

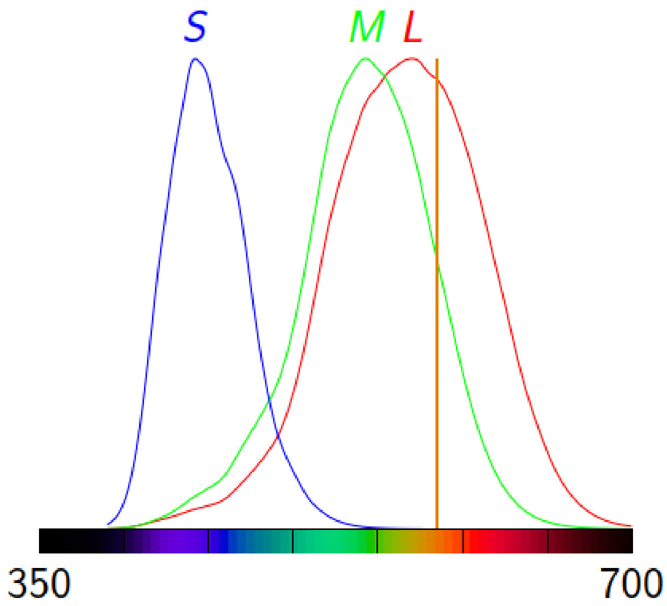
See also Kandiskij or Mondrian

Colors: perception

Photopic sensitivity comes from a combination of different sensor types

Normalized sensor response =

= intensity of the stimulus * relative sensitivity of cones

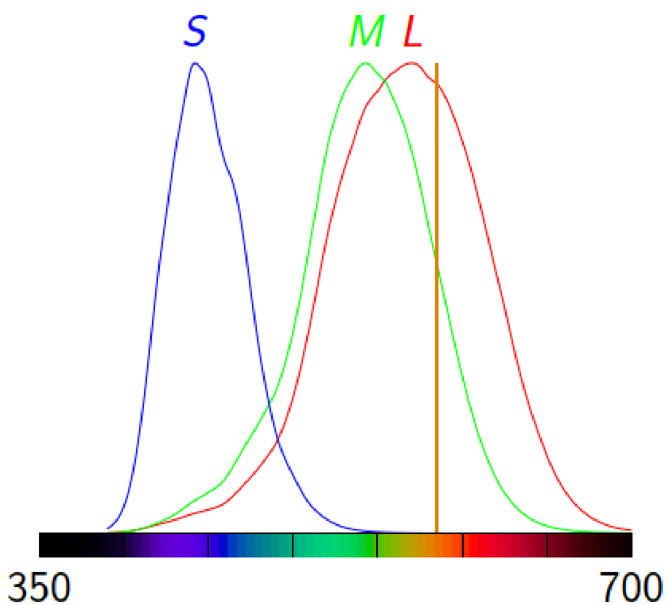


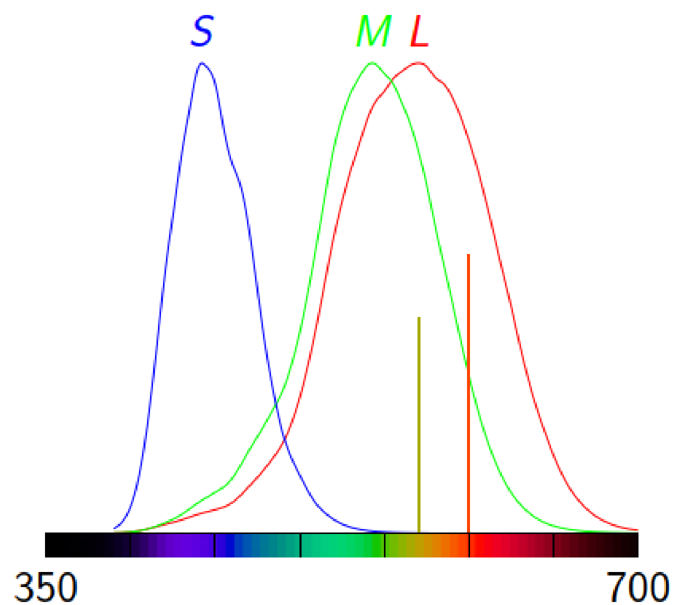
$R_L = 1*0.95$
$R_M = 1*0.60$
$R_S = 1*0.00$

For non-monochromatic stimuli, the visual system evaluates the integral of the response in the relevant wavelength interval

Colors: perception

Metamerism: different spectral contents may give same perception



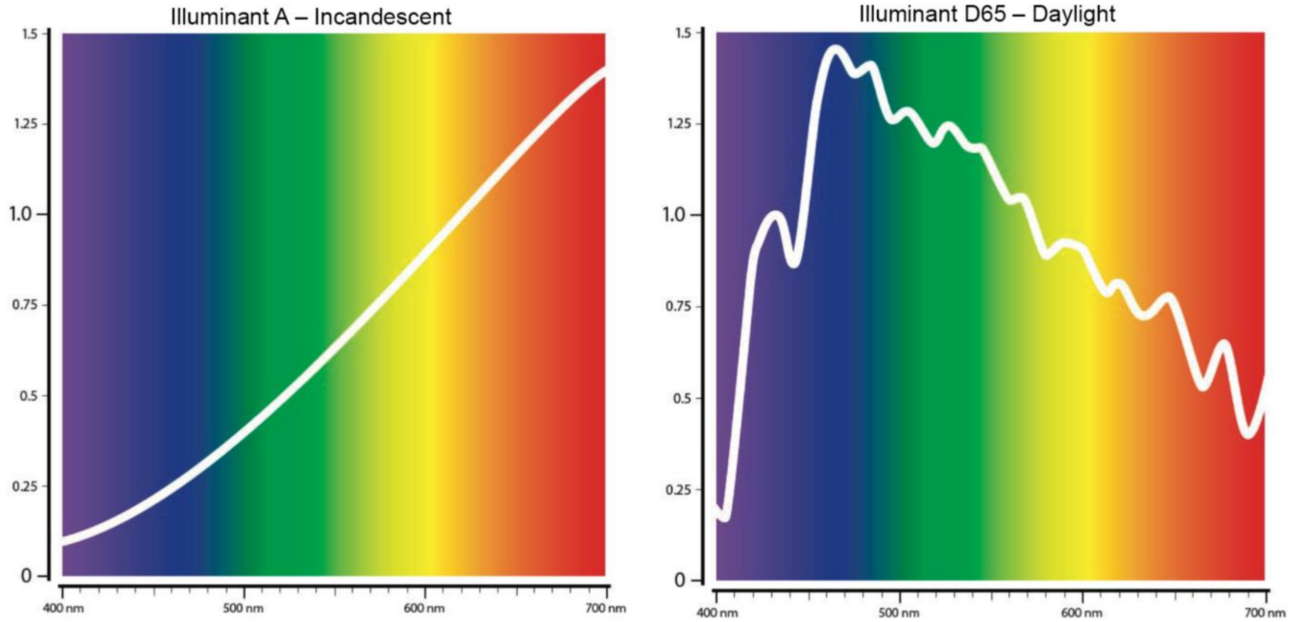


$R_L = 1*0.95$
$R_M = 1*0.6$
$R_S = 1*0$

$R_L = 0.5*1 + 0.6*0.75 = 0.95$
$R_M = 0.5*0.8 + 0.6*0.33 = 0.6$
$R_S = 0.5*0 + 0.6*0 = 0$

Colors: perception

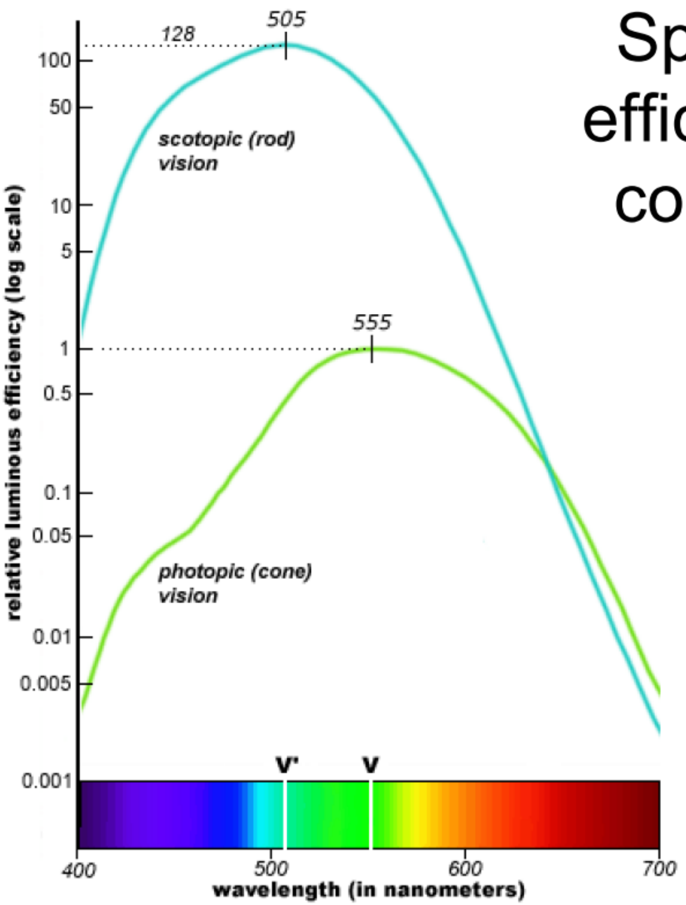
Illuminant-elicited metamerism: in the real world, the stimulus is produced by the product between the spectral reflectance of the object and the spectrum of the illuminant



"Metamerism is common when a product is assembled using different materials. Automakers struggle with this phenomenon all the time. Even though the body paint is made from pigments different from those used on the bumpers and rear-view mirrors, and the interior fabric is colored with dyes that are not anywhere near the fingerprints of the pigments used for the plastic dashboard, the assembled car has to match under virtually all types of illumination."
https://www.xrite.com/blog/what-is-metamerism

Colors: perception

Relative luminous sensitivity of different sensors



Spectral luminous efficiency of rod and cone based vision

These curves represent the sensitivity of the eye to light of varying wavelengths. The shapes of these functions depend on several factors:

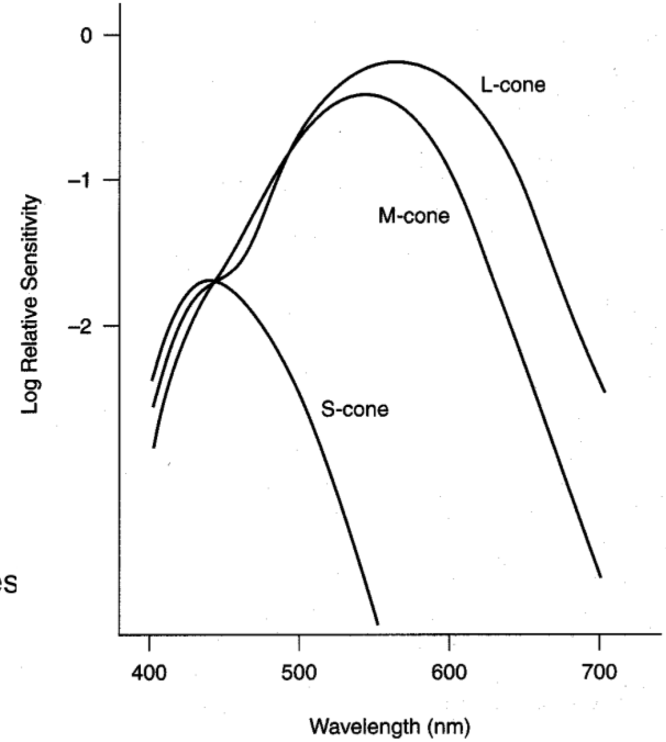
Pre-retinal absorption in the eye

The pigment absorption curves

Neural interactions among receptors

The relative population of the various receptor types.

(Note the logarithmic scale on the vertical axis.)



https://www.opt.uh.edu/onlinecoursematerials/stevenson-5320/

The pitfalls of vision: **illusions**

- **Optical** (physical)
- **Perceptual**
- **Cognitive**

The pitfalls of vision: illusions

Simultaneous contrast (perceptual illusion):

a region's perceived brightness does not depend simply on its intensity.

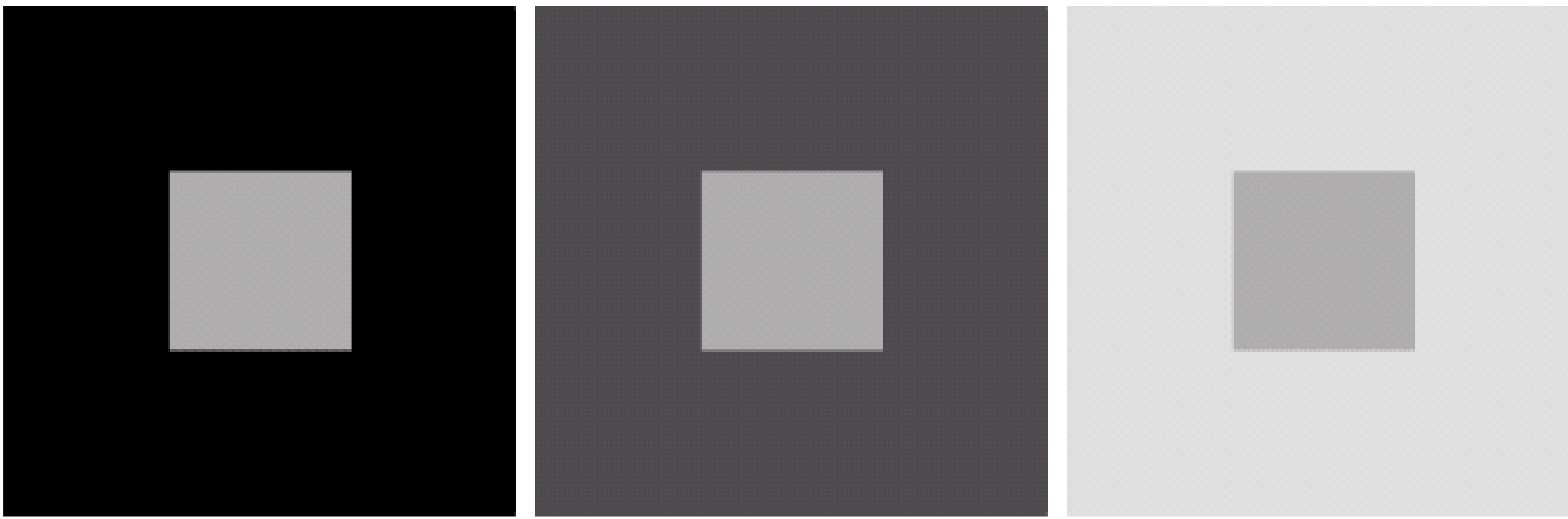
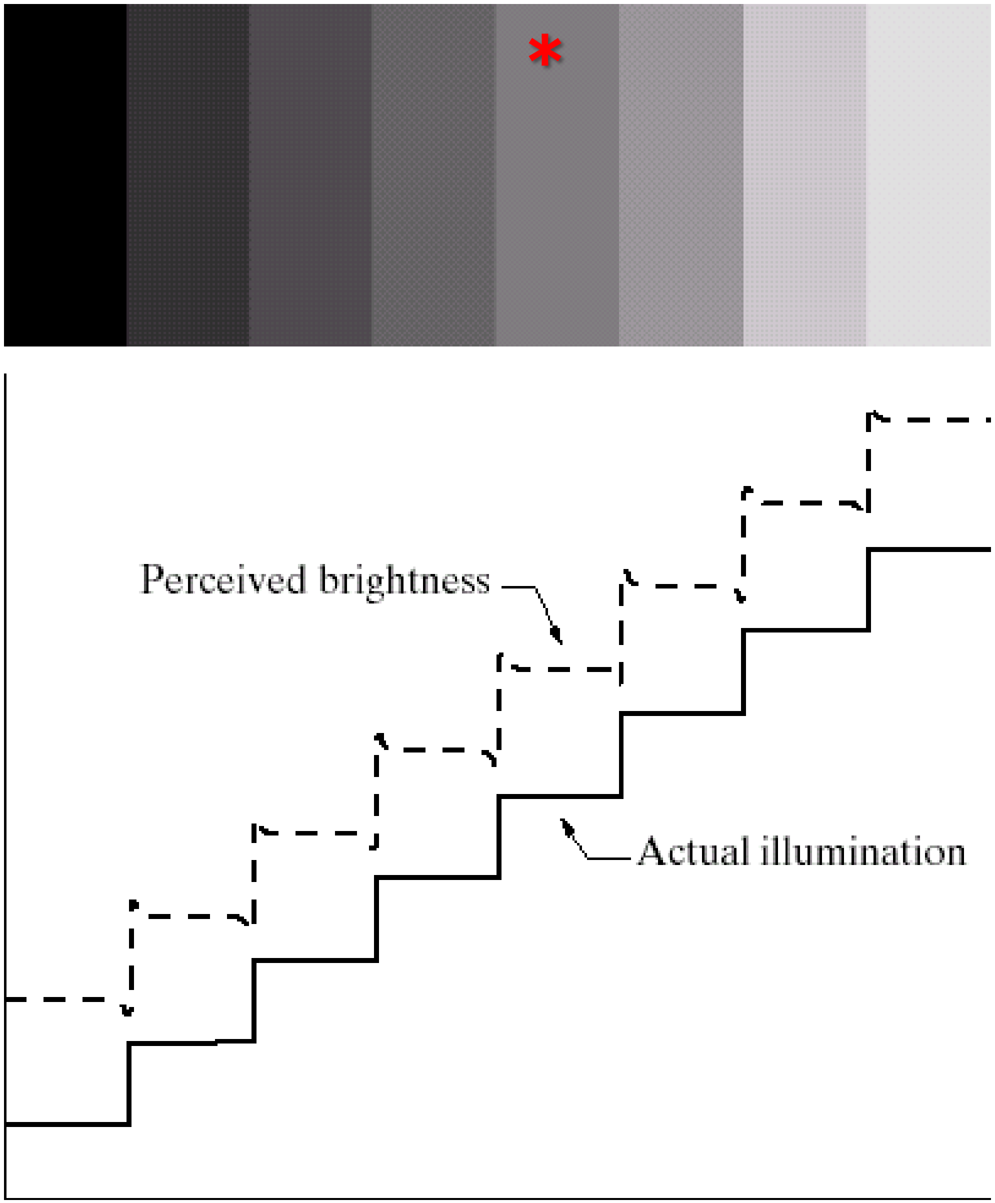
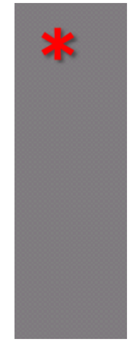


FIGURE 2.8 Examples of simultaneous contrast. All the inner squares have the same intensity, but they appear progressively darker as the background becomes lighter.

The pitfalls of vision: illusions





Mach band effect

(perceptual illusion)

FIGURE 2.7
(a) An example showing that perceived brightness is not a simple function of intensity. The relative vertical positions between the two profiles in (b) have no special significance; they were chosen for clarity.

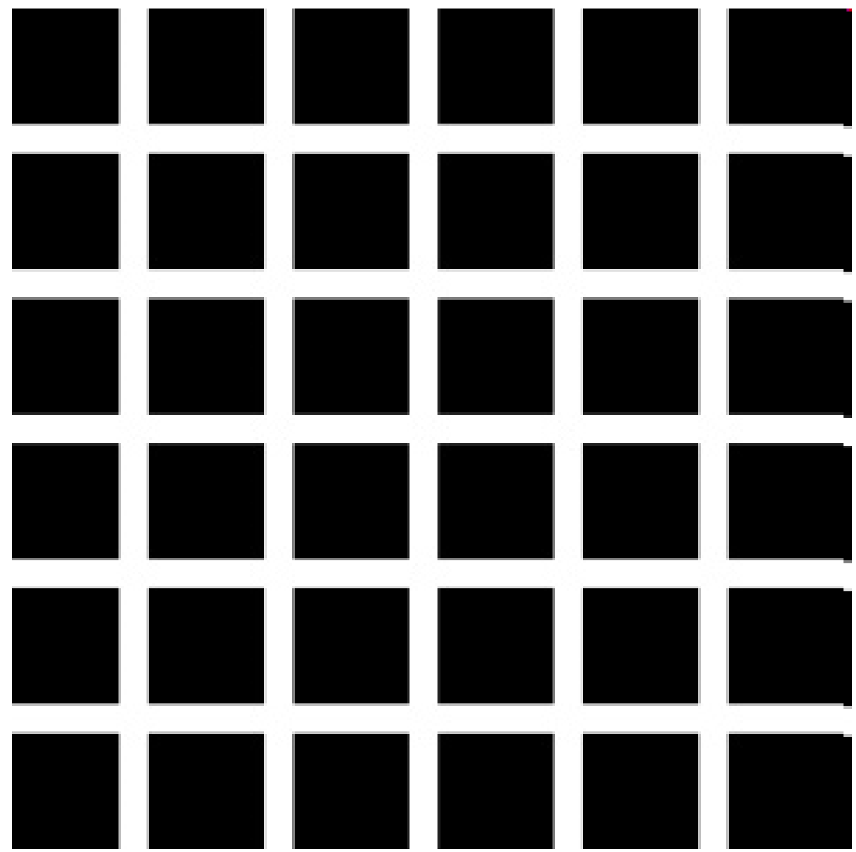
The pitfalls of vision: illusions

(Perceptual? illusion)

Hermann grid (L. Hermann, 1870)

Caused by lateral inhibition on out-of-fovea ON-center ganglion cells with large receptive fields

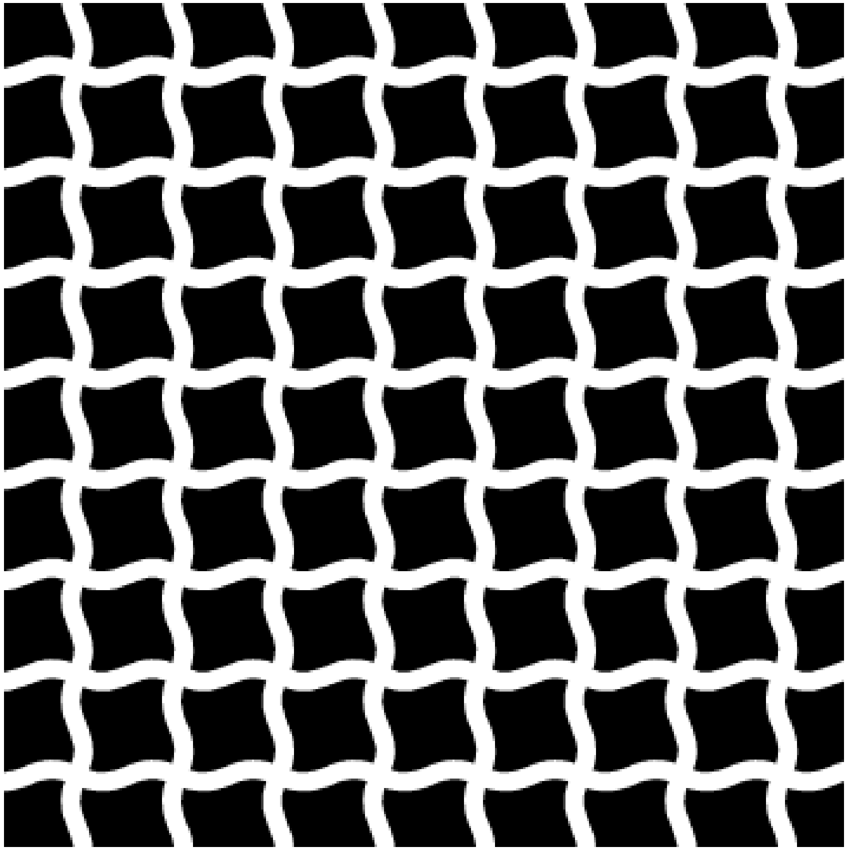
wrong



The pitfalls of vision: illusions

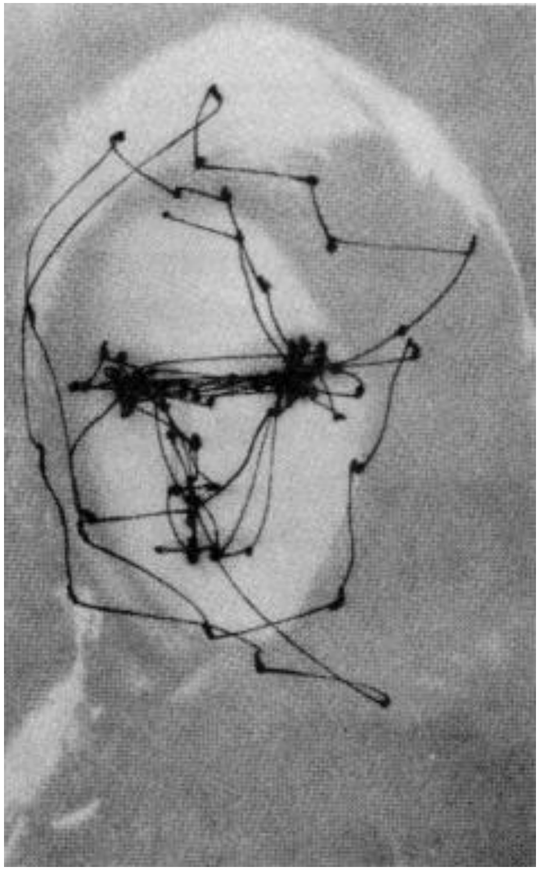
The classical explanation is untenable:

One alternative explanation is that the illusion is due to S1 type simple cells in the visual cortex.



The pitfalls of vision: illusions

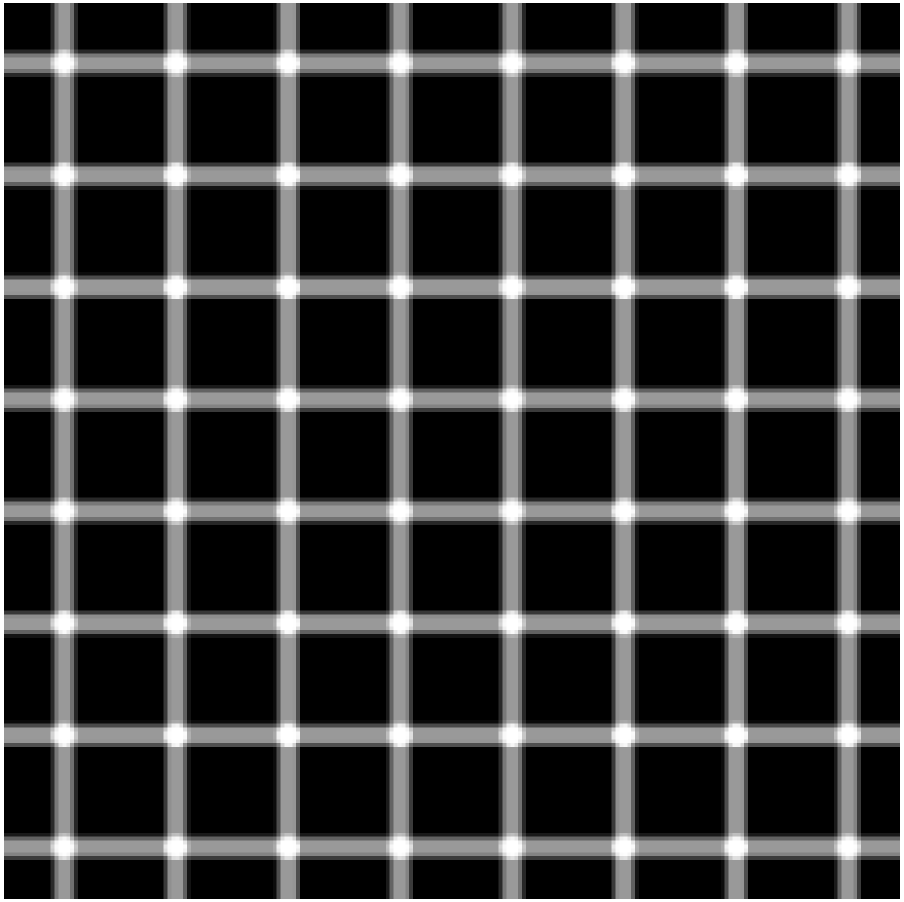
We perform ***saccadic eye movements*** (average rate 250 ms) when looking at a scene. *Saccadic suppression* (~50 ms) avoids motion blur perception



and this is made visible by the...

The pitfalls of vision: illusions

Scintillating grid illusion
(Lingelbach 1994)



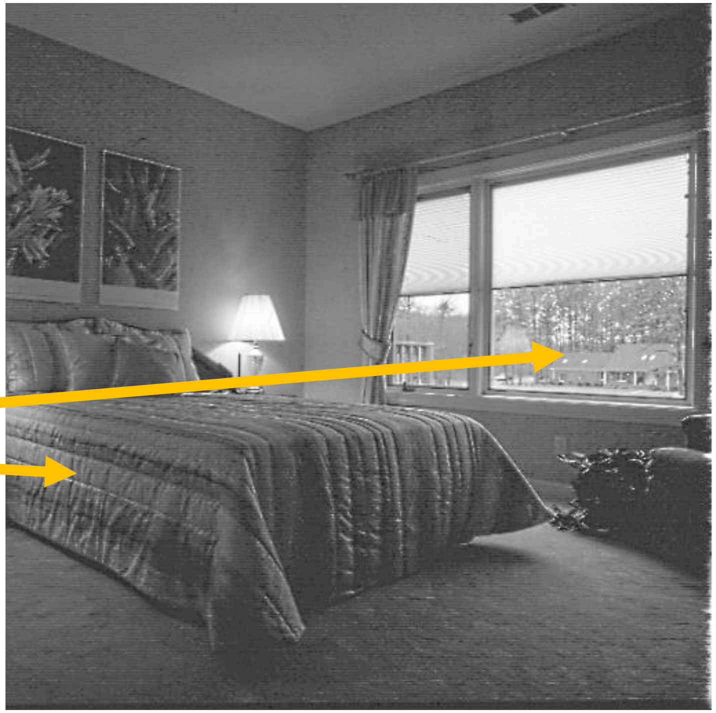
The pitfalls of vision: illusions

The HVS adapts as we look from place to place: this enhances our ability to see in high dynamic range (HDR) scenes

The pitfalls of vision: illusions

Our mental image is construed from what we are able to see as we look around

Different stimuli are perceived as having the same intensity

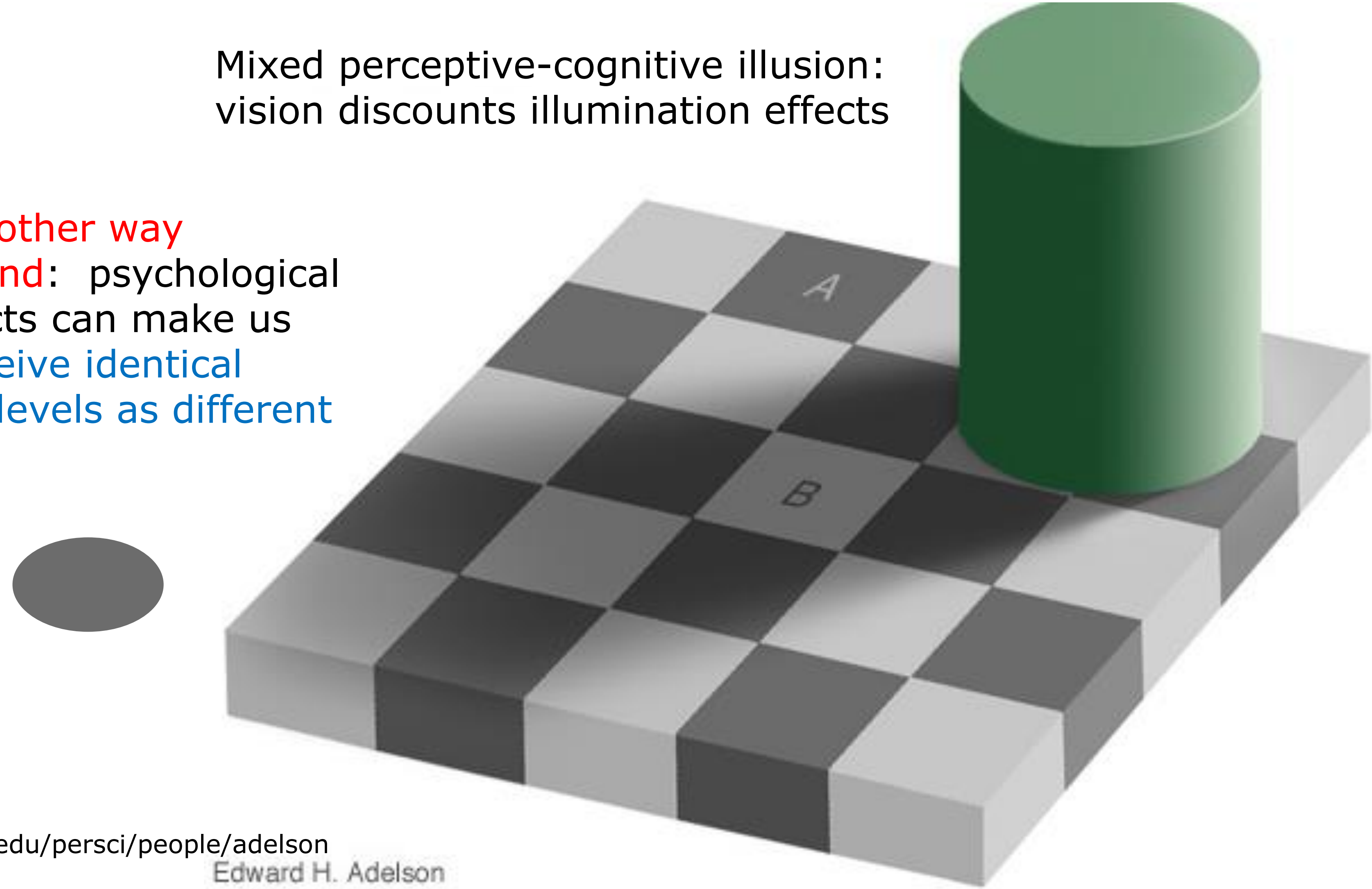


→ **Local tone mapping**, and even **contrast reversal** between "distant" regions, can be used for image enhancement

The pitfalls of vision: illusions

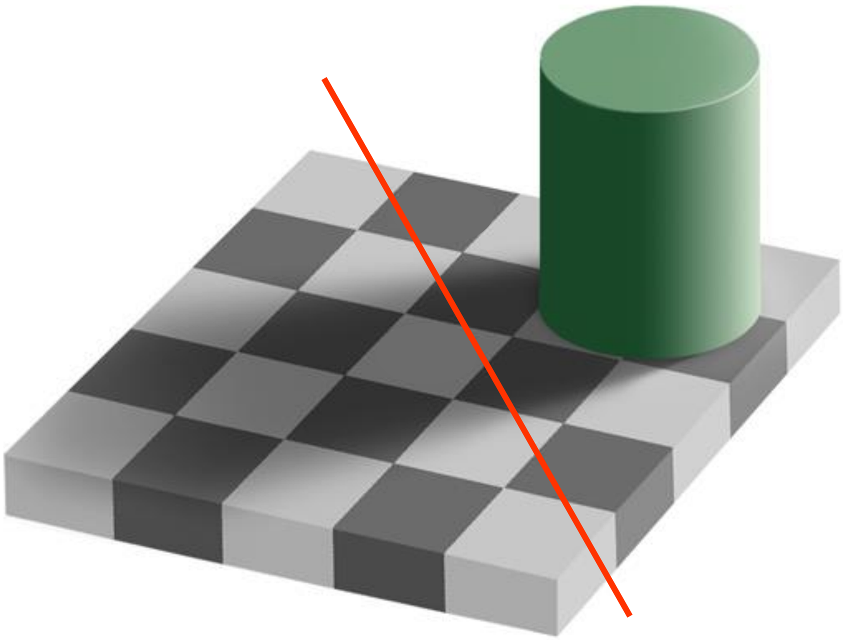
Mixed perceptive-cognitive illusion:
vision discounts illumination effects

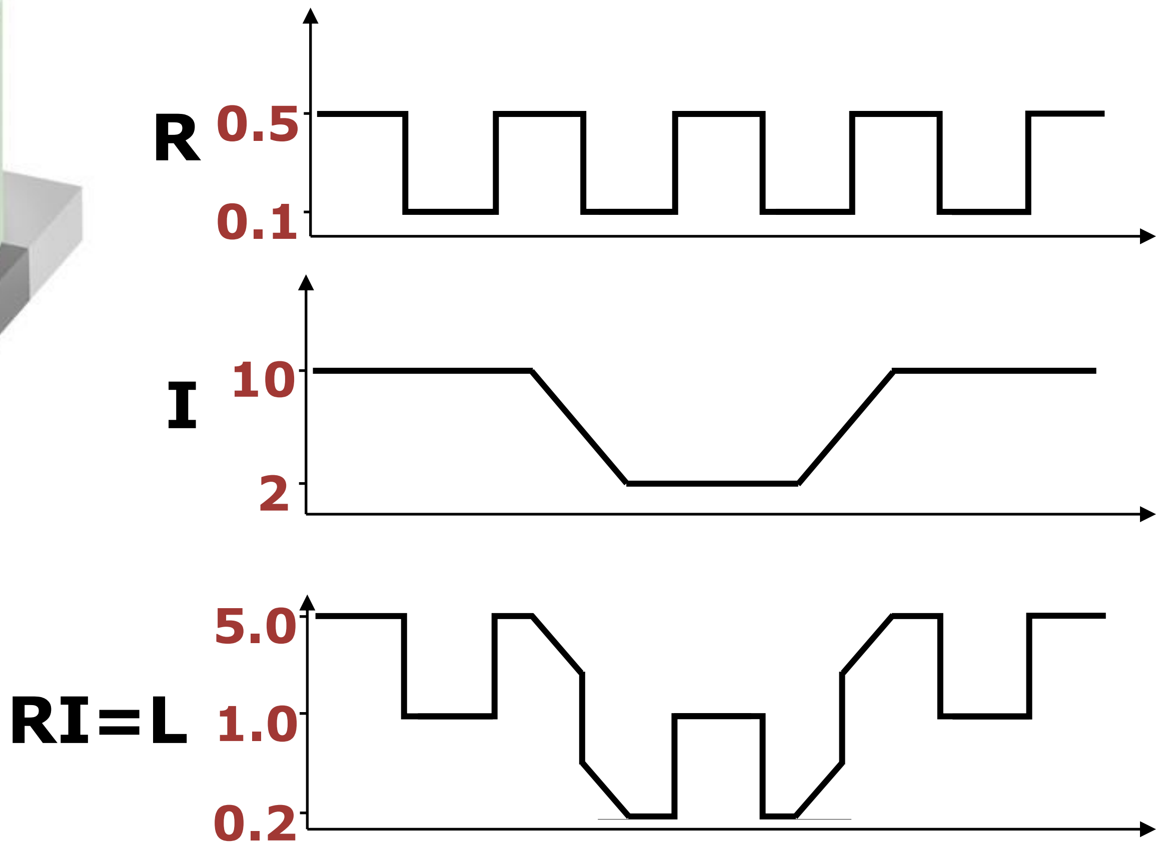
The other way around: psychological effects can make us perceive identical graylevels as different



web.mit.edu/persci/people/adelson

The pitfalls of vision: illusions





The pitfalls of vision: illusions

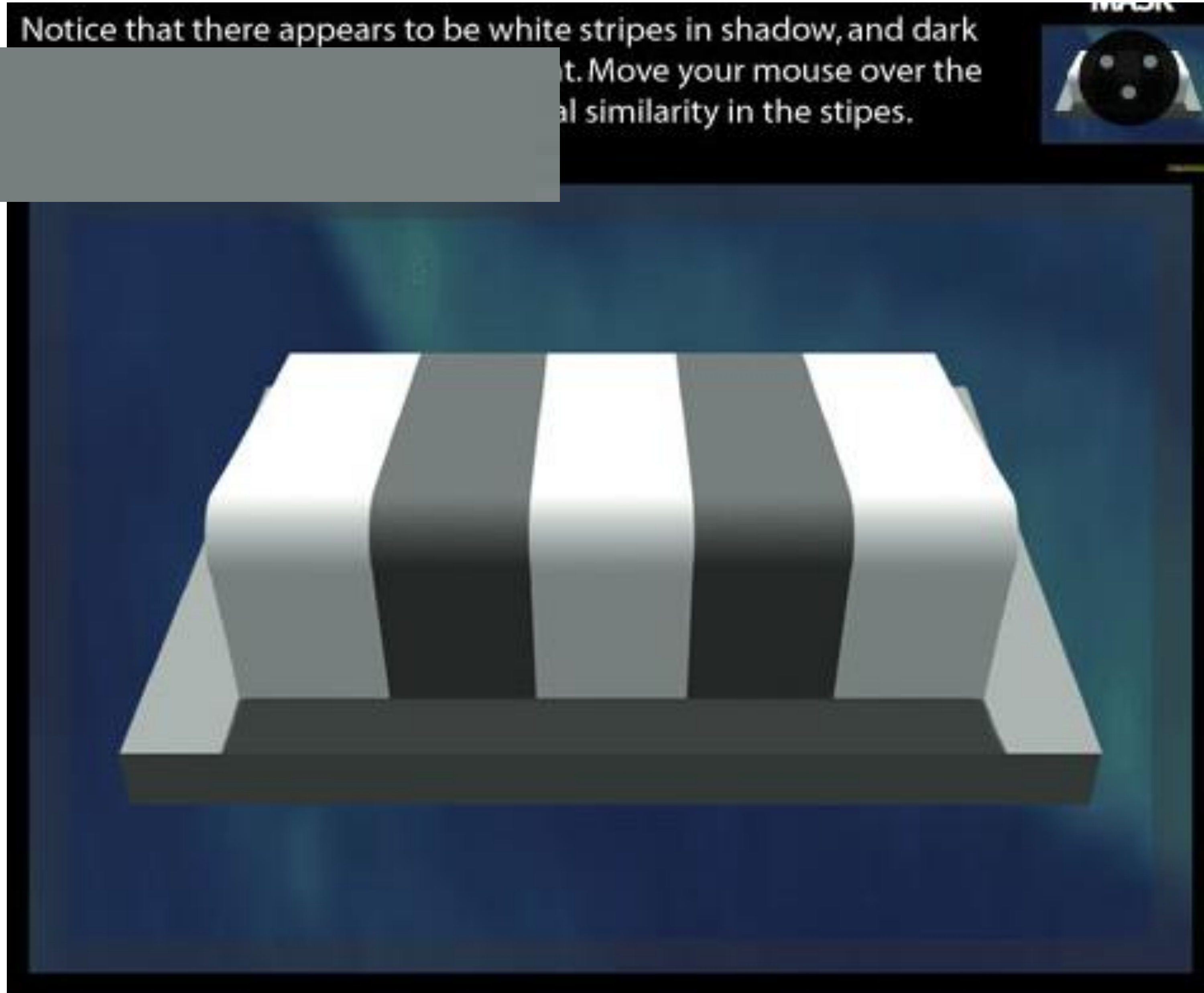
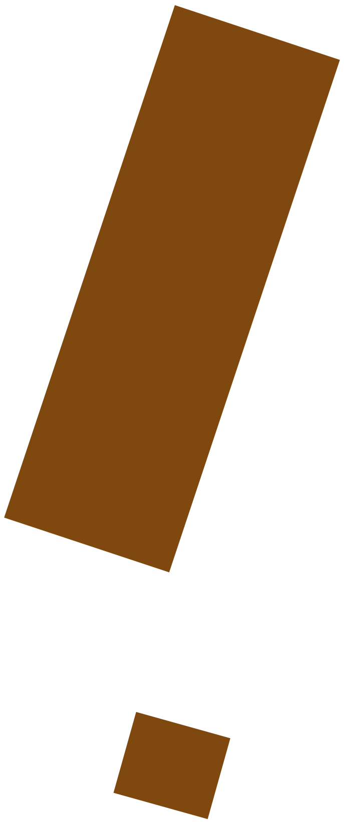


Image by R. Beau Lotto

www.lottolab.org

The pitfalls of vision: illusions



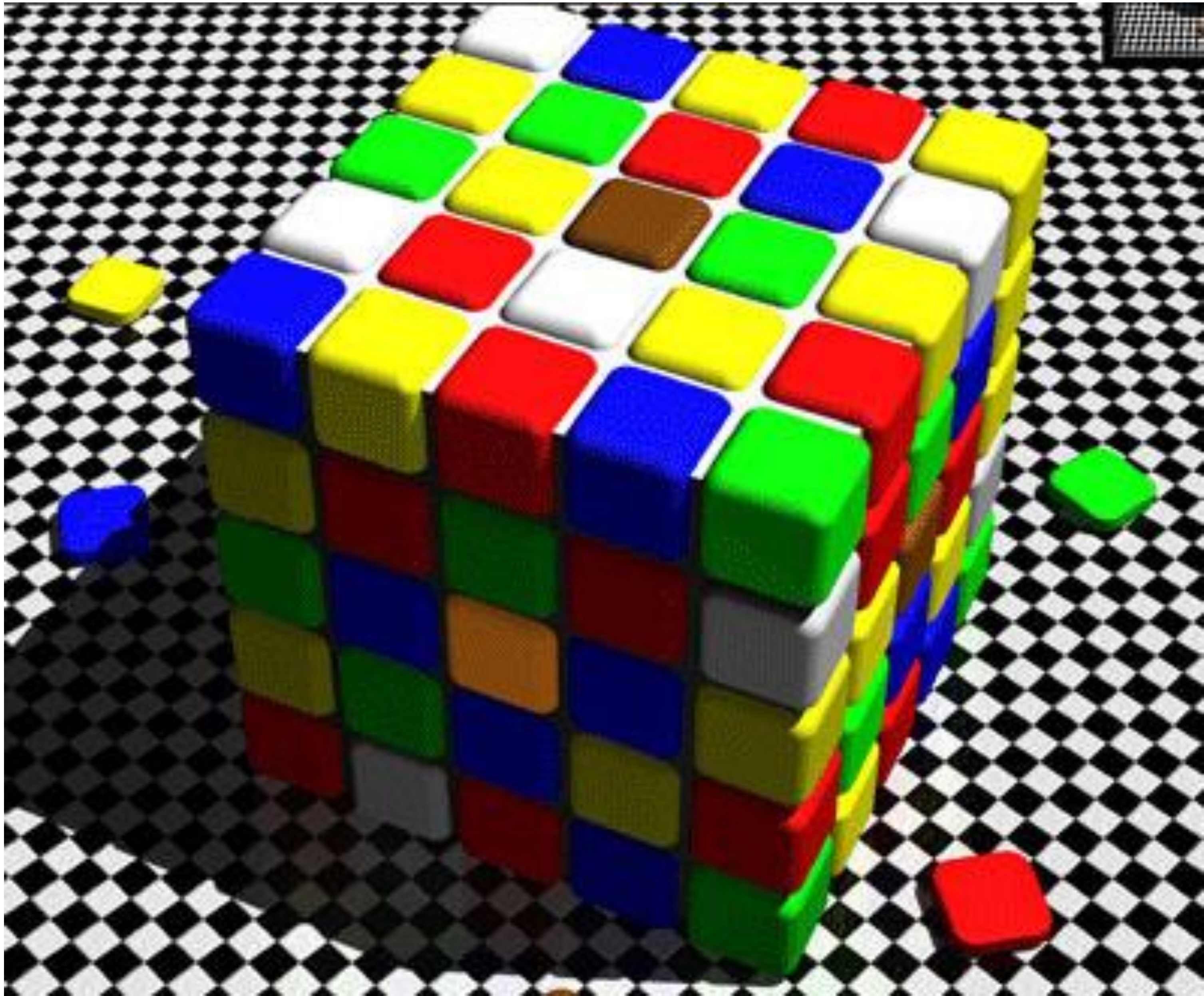
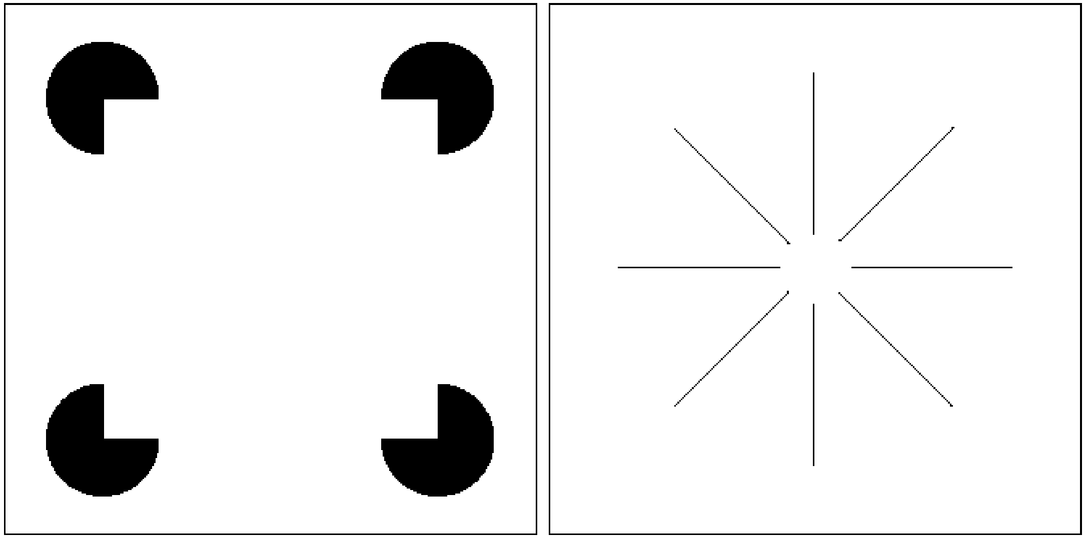


Image by R. Beau Lotto
www.lottolab.org

The pitfalls of vision: illusions

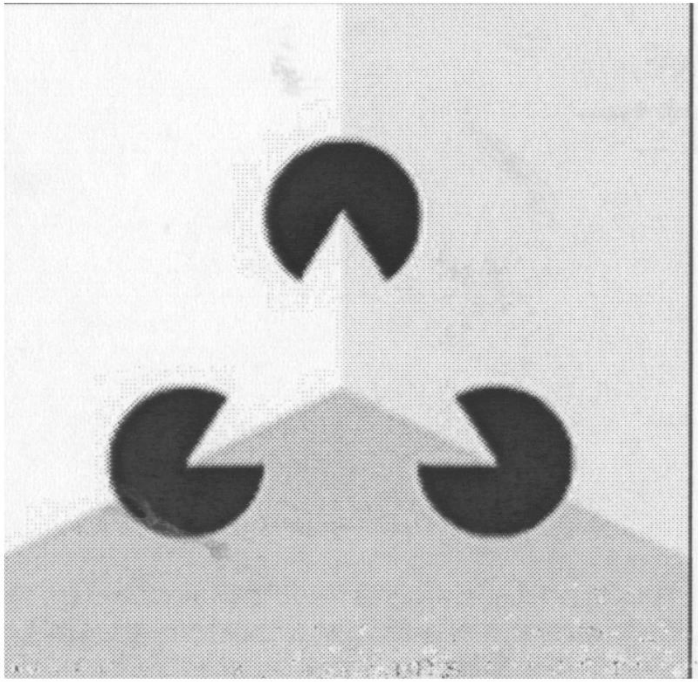
Abstraction of ideal shapes

(**cognitive** illusion)



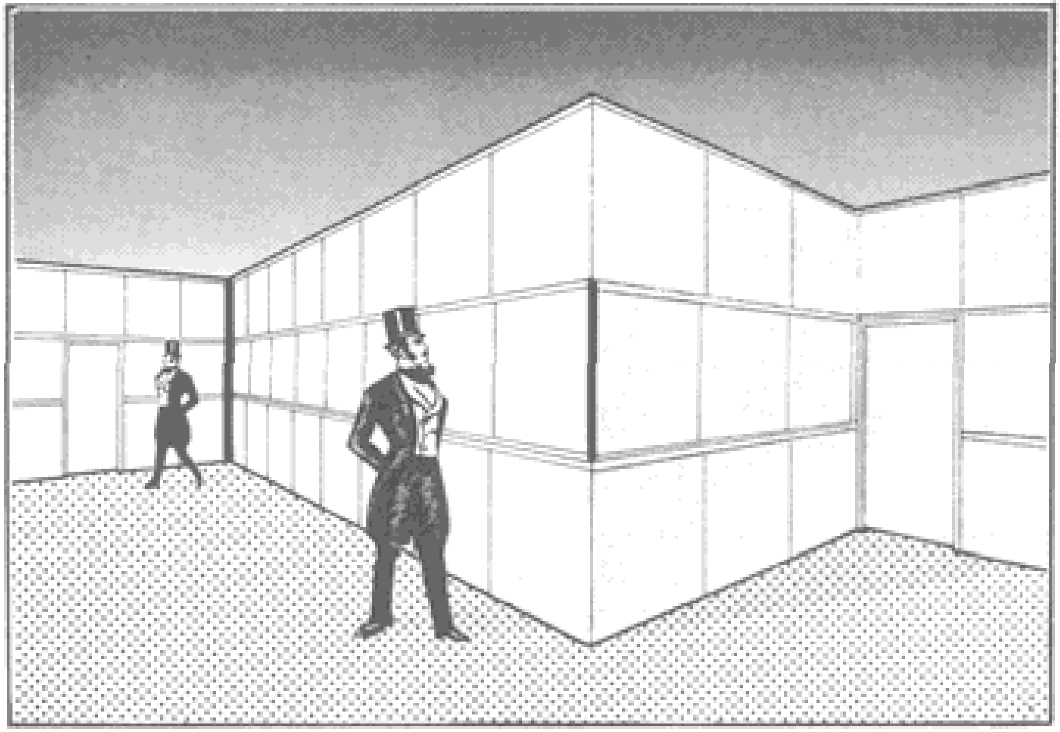
The pitfalls of vision: **3-D** illusions

3-D related cognitive illusions



Gaetano Kanizsa, psychologist,
Trieste 1913-1993

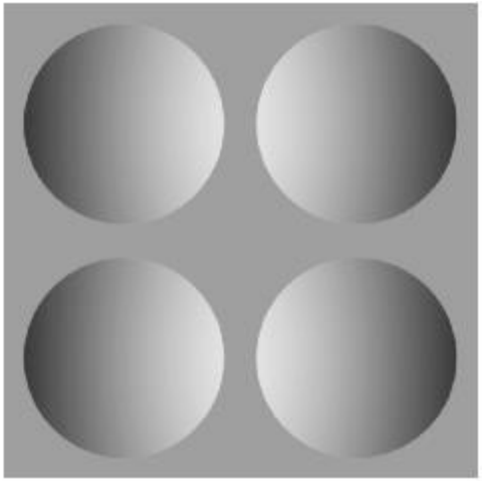
Jeremy Nathans
Johns Hopkins Medical School



3-D visual perception

Illumination-related 3-D perception

(a)

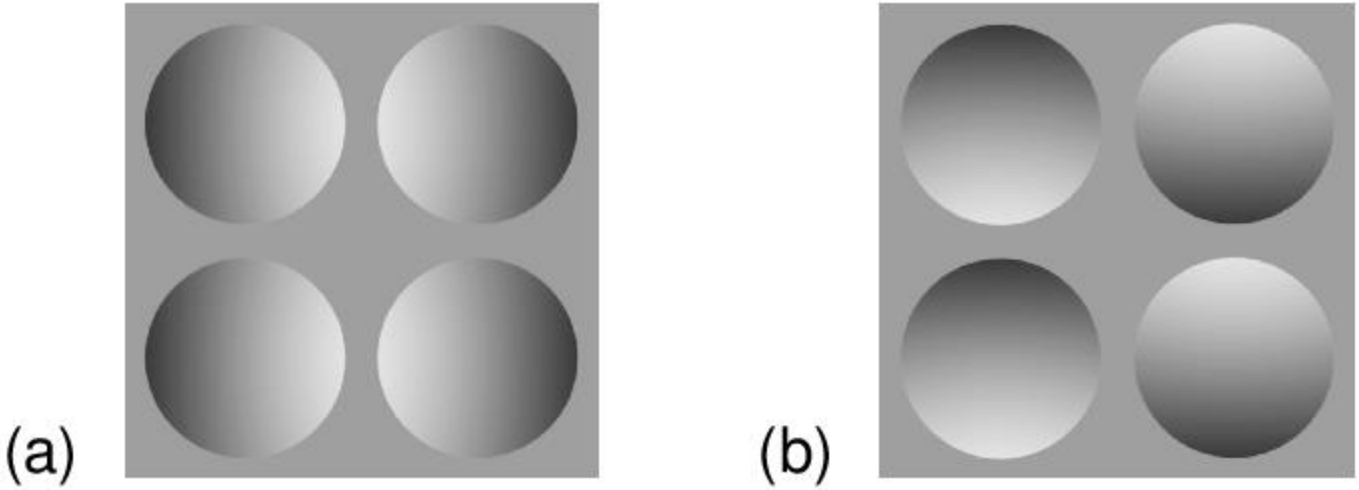


(a) Shading at the left-hand or right-hand side is ambiguous regarding the concavity or convexity of the disks.

(After Ramachandran, 1988)

3-D visual perception

Illumination-related 3-D perception



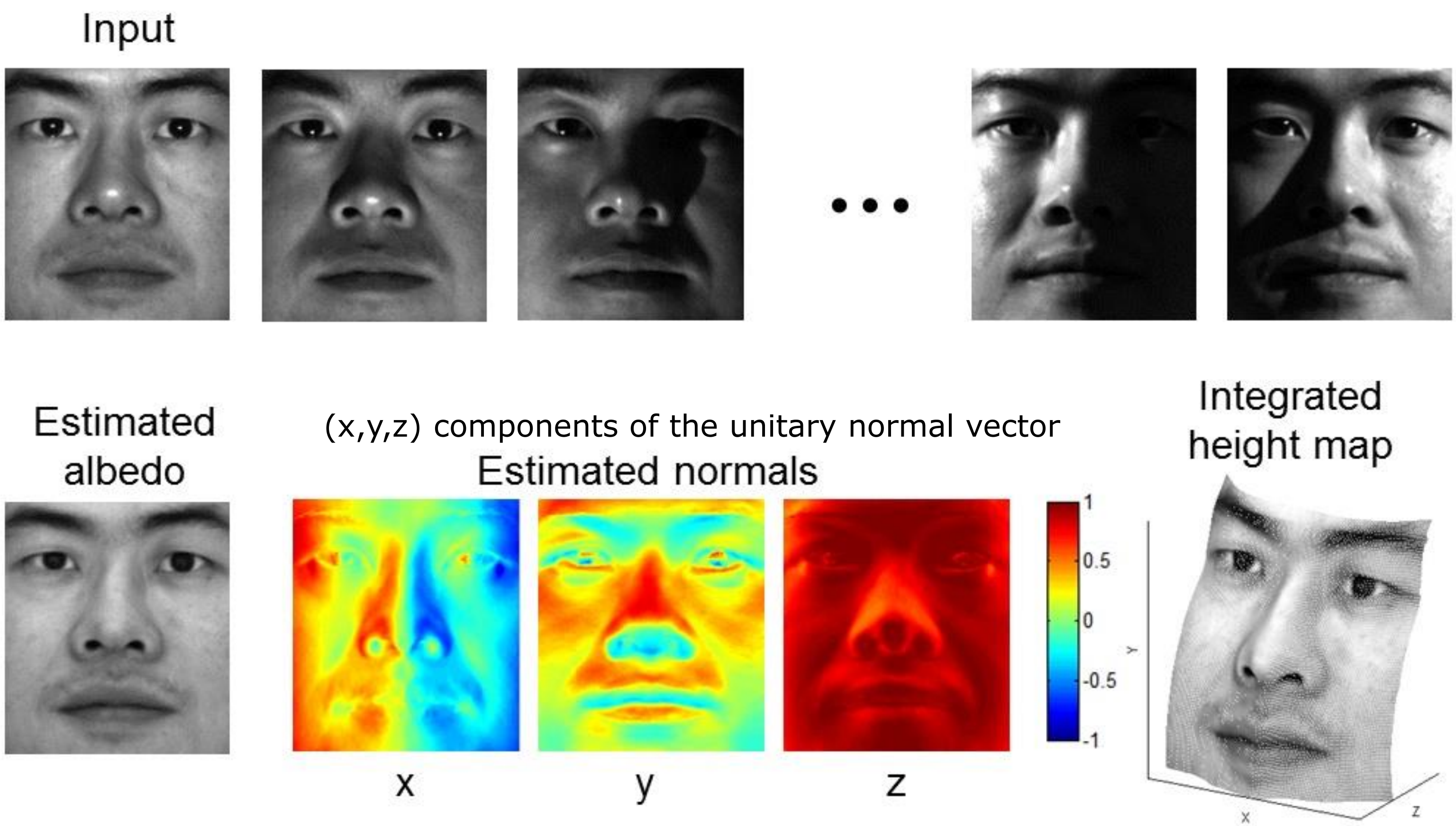
(a) Shading at the left-hand or right-hand side is ambiguous regarding the concavity or convexity of the disks.
(b) Shading at the top or bottom is fairly clear regarding concavity and convexity, respectively.

(After Ramachandran, 1988)

(3-D visual perception) – 3D modelling

Note that **shape from shading** is also a technique for image analysis: if the position of the illuminator is known, the shape of a uniform Lambertian surface can be determined using a single image

For non-uniform surfaces several projections are needed:



3-D visual perception

Clues for **depth perception**

- size of known objects
- focus (also exploited in photography)
- motion parallax
- binocular vision

construed depth perc.

deconstrued depth perc.

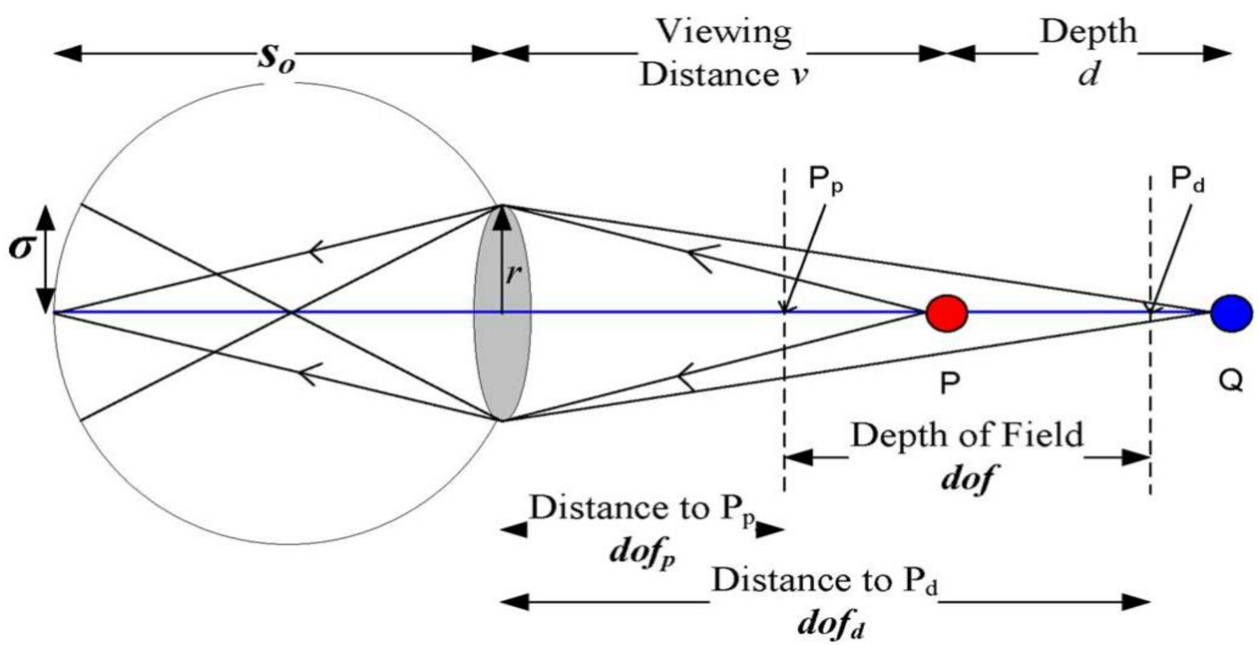
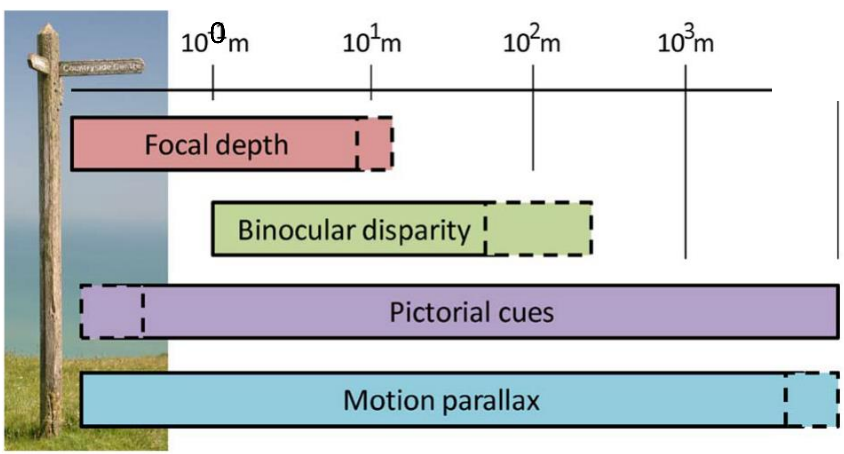


Fig. 2. Geometry of retinal blur.

3-D visual perception

PARALLAX: the apparent displacement of an object as seen from two different points not on a straight line with the object

Different clues are dominant at different distance ranges (Gotchev11)



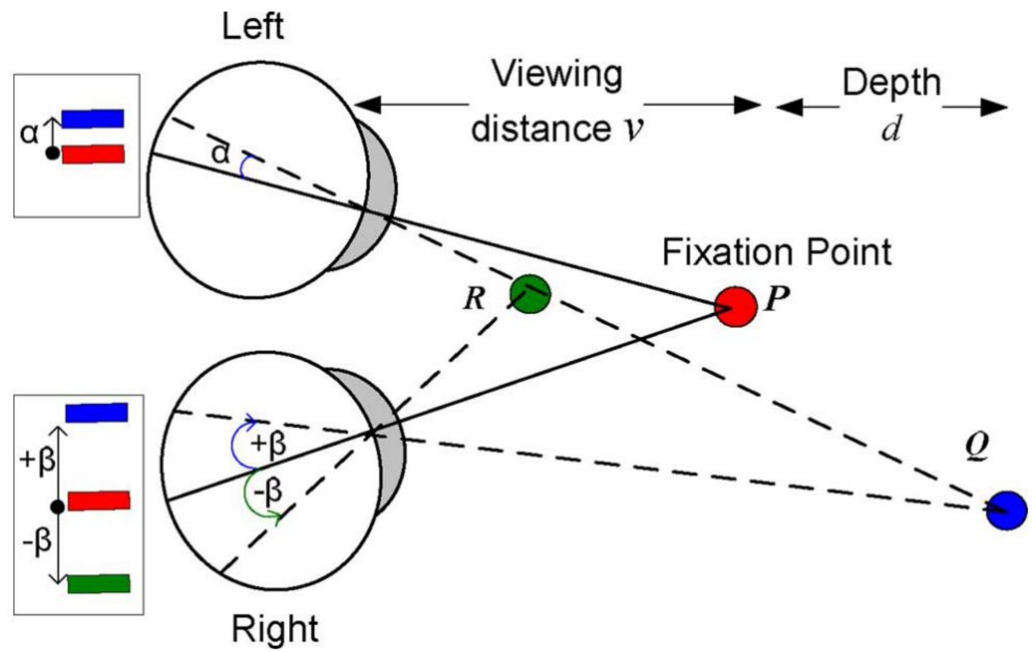


Fig. 1. Geometry of binocular stereopsis.