
Human Visual System

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Objectives

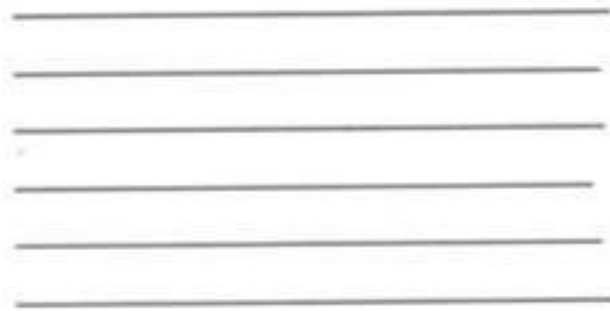
- In this lecture we discuss:
 - Structure of human eye
 - Mechanics of human visual system (HVS)
 - Brightness adaptation and discrimination
 - Perceived brightness and simultaneous contrast

Human and Computer Vision

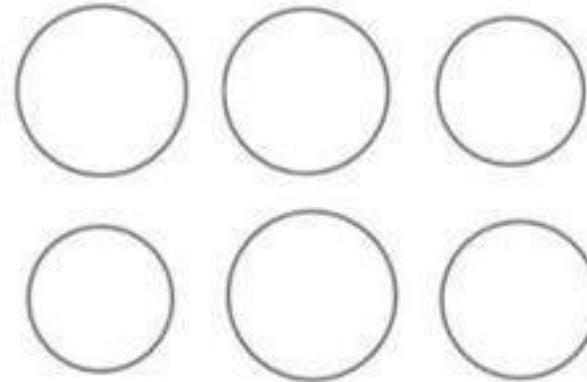
- We observe and evaluate images with our visual system
- We must therefore understand the functioning of the human visual system and its capabilities for brightness adaptation and discrimination:
 - What intensity differences can we distinguish?
 - What is the spatial resolution of our eye?
 - How accurately do we estimate distances and areas?
 - How do we sense colors?
 - By which features can we detect/distinguish objects?

Examples

a Parallel lines : <5% variation in length



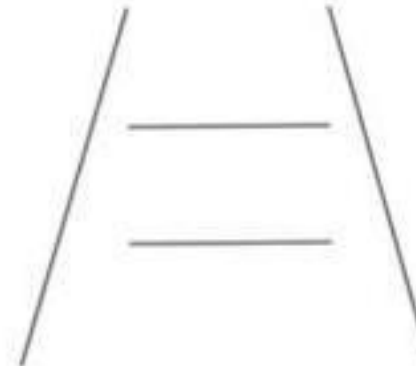
b Circles: <10% variation in radii



c Vertical line falsely appears longer

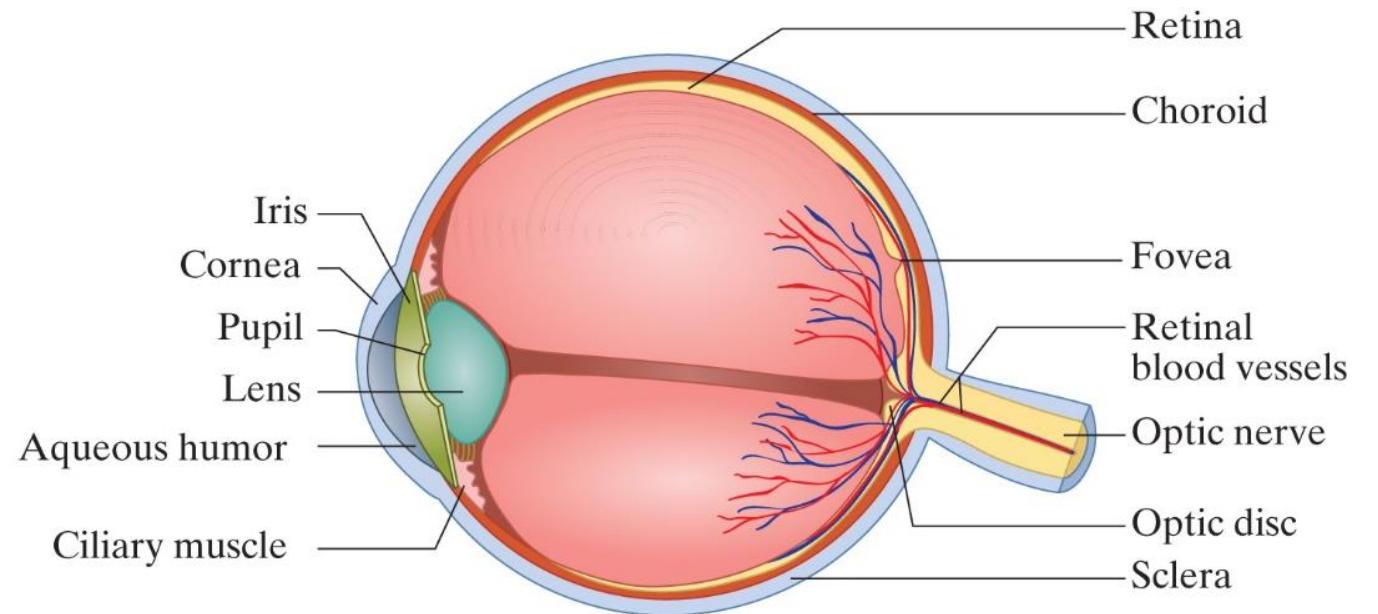
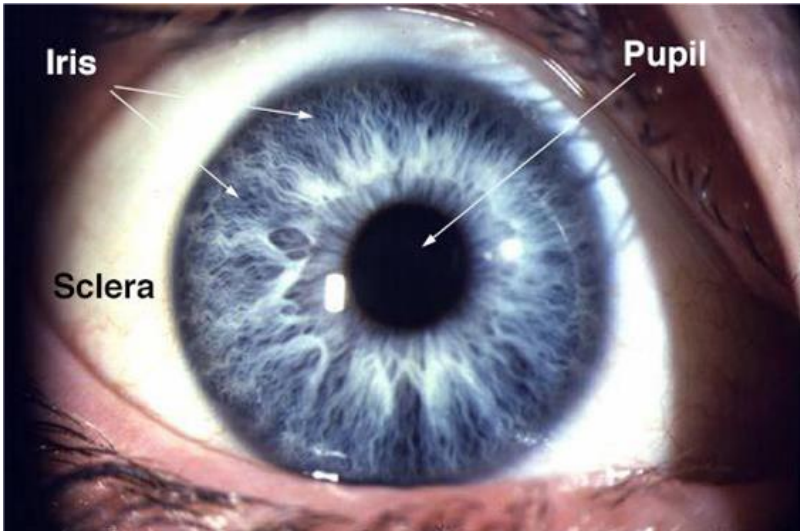


d Upper line falsely appears longer



Structure of the Human Eye

- Shape is nearly spherical
- Average diameter = 20mm
- Three membranes:
 - Cornea and Sclera
 - Choroid
 - Retina



Structure of the Human Eye: Cornea and Sclera

- Cornea
 - Tough, transparent tissue that covers the anterior surface of the eye
- Sclera
 - Opaque membrane that encloses the remainder of the optical globe

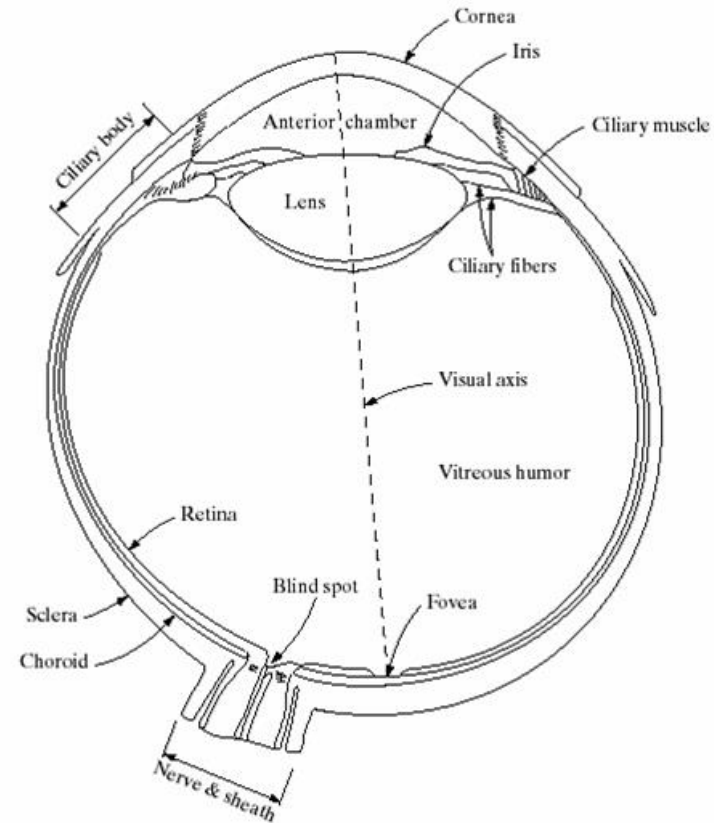


FIGURE 2.1
Simplified
diagram of a cross
section of the
human eye.

Structure of the Human Eye: Choroid

- Choroid
 - Lies below the sclera
 - Contains network of blood vessels that serve as the major source of nutrition to the eye.
 - Choroid coat is heavily pigmented and hence helps to reduce the amount of extraneous light entering the eye and the backscatter within the optical globe

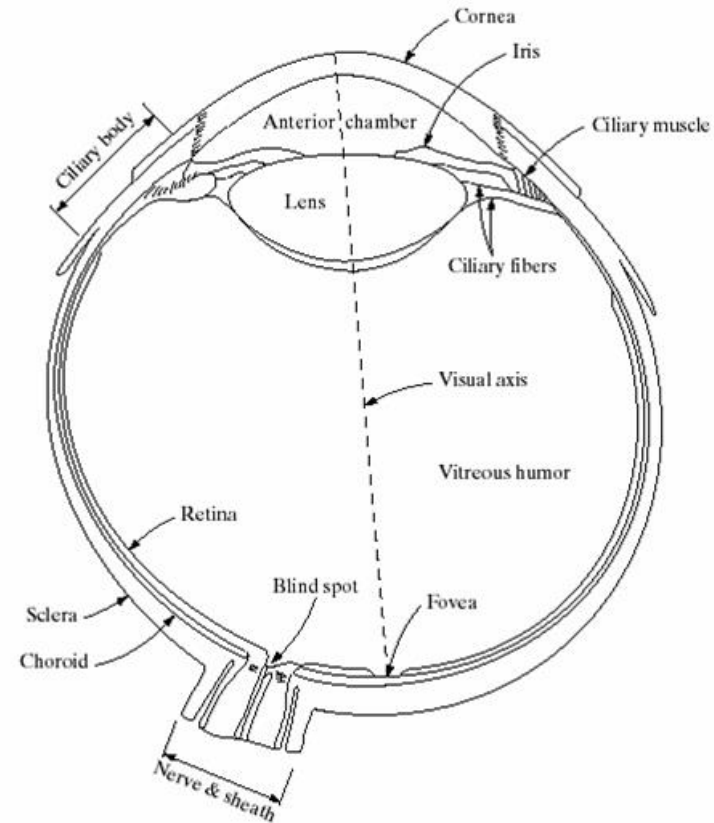


FIGURE 2.1
Simplified
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Lens and Retina

- Lens
 - Both infrared and ultraviolet light are absorbed appreciably by proteins within the lens structure and, in excessive amounts, can cause damage to the eye
- Retina
 - Innermost membrane of the eye which lines the inside of the wall's entire posterior portion. When the eye is properly focused, light from an object outside the eye is imaged on the retina.

Receptors

- Two classes of light receptors on retina: cones and rods
- Cones
 - 6-7 million cones lie in central portion of the retina, called the fovea.
 - Highly sensitive to color and bright light.
 - Resolve fine detail since each is connected to its own nerve end.
 - Cone vision is called photopic or bright-light vision.
- Rods
 - 75-150 million rods distributed over the retina surface.
 - Reduced amount of detail discernable since several rods are connected to a single nerve end.
 - Serves to give a general, overall picture of the field of view.
 - Sensitive to low levels of illumination.
 - Rod vision is called scotopic or dim-light vision.

Distribution of Cones and Rods

- Blind spot: no receptors in region of emergence of optic nerve.
- Distribution of receptors is radially symmetric about the fovea.
- Cones are most dense in the center of the retina (e.g., fovea)
- Rods increase in density from the center out to 20° and then decrease

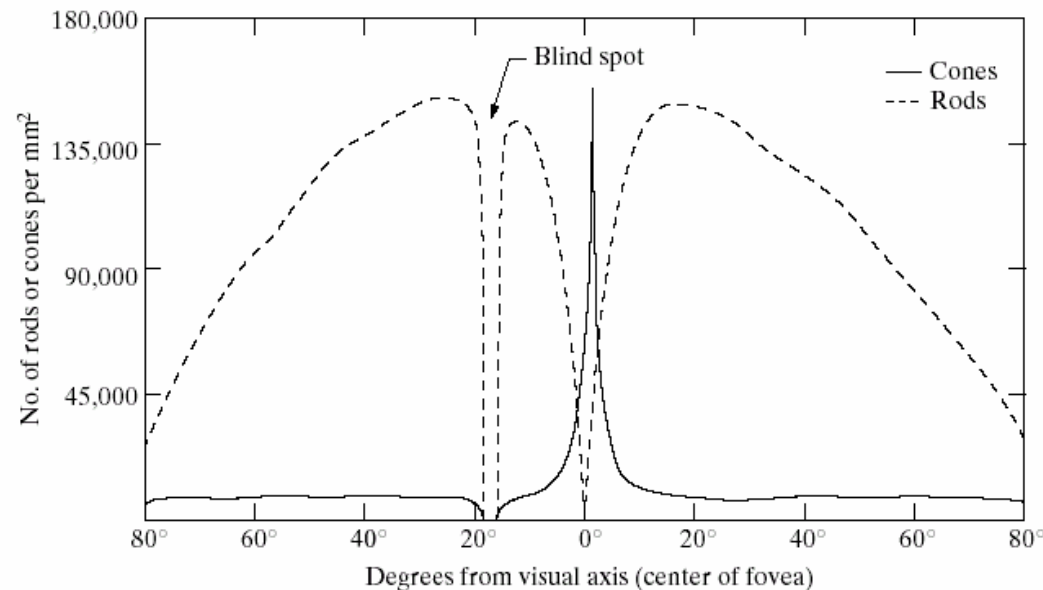
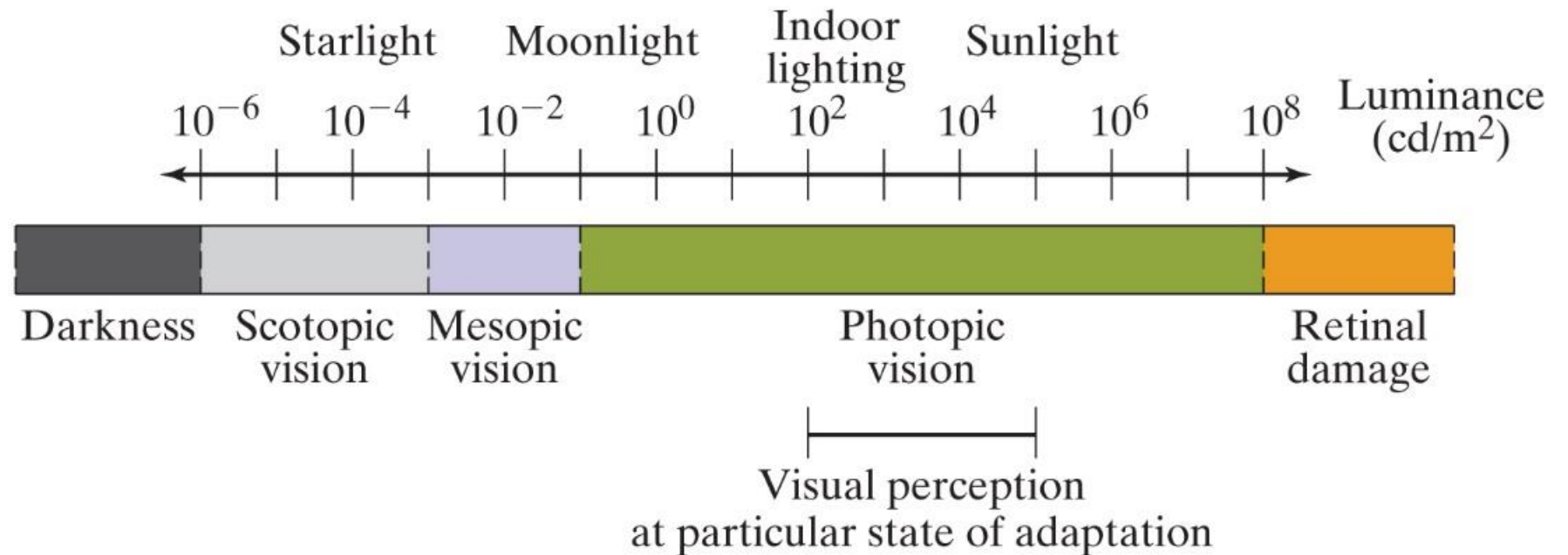


FIGURE 2.2
Distribution of
rods and cones in
the retina.

Human Visual Perception (1)

- The human visual system can respond to levels of light ranging an astounding 14 orders of magnitude.

Figure 2.8 Scotopic, mesopic, and photopic vision at different light levels. While the human visual system is capable of sensing light in approximately a range of 10^{14} overall (from 10^{-6} to 10^8 cd/m^2), light can be sensed in a range of 10^3 , at any particular state of adaptation.



Human Visual Perception (2)

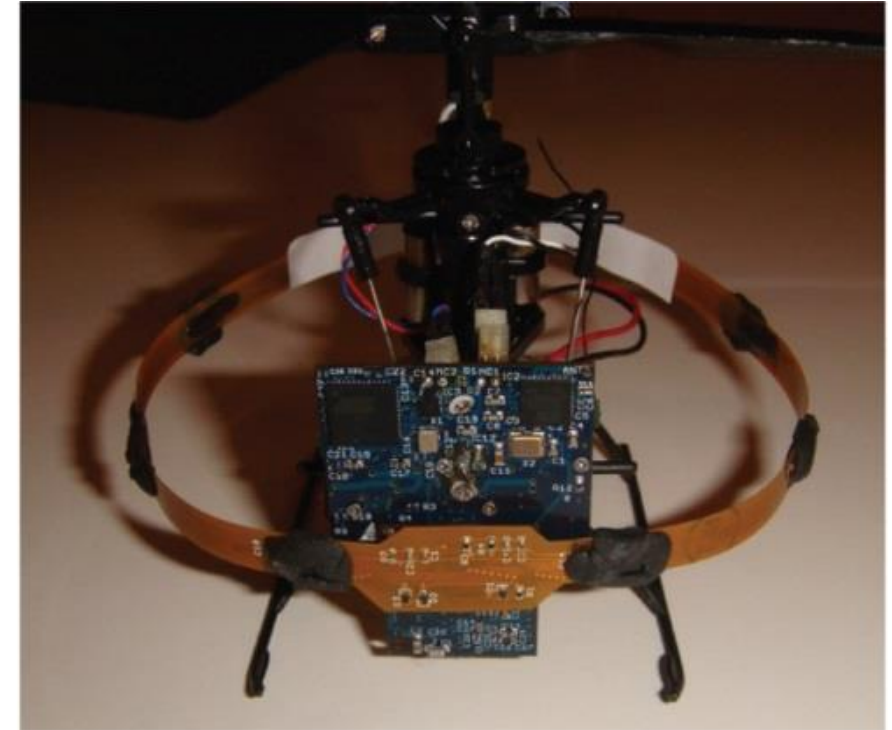
- **Luminous efficiency function (LEF):** captures the relative sensitivity of the visual system to different wavelengths.
- **Photopic LEF:** corresponds to normal light levels where the cones dominate due to the saturation of the rods.
- **Scotopic LEF:** corresponds to low light levels where the rods dominate due to the lack of sensitivity of the cones.
- **Purkinje effect:** the difference in peak wavelength.
 - It explains why objects appear to have a more bluish tint as the light dims.

Animal Vision (1)

- The imitation of natural systems is known as **biomimicry** (or *biomimetics*).
 - It is an important approach to discovering novel solutions in both software and hardware.
- In a compound eye, the photoreceptors are arranged in small groups called **ommatidia**.
 - Each ommatidium views the world from a different direction, yielding a mosaic of images providing a fairly low-resolution representation of the scene.

Animal Vision (2)

Figure 2.10 The common housefly has the fastest visual response of any animal, leading to extreme maneuverability in flight. Tiny flying robots (such as this one from Centeye) have been inspired to mimic the housefly's navigation ability based on optic flow.



mrifiza / Shutterstock.com, Courtesy of Centeye

Animal Vision (3)

Figure 2.11 Raptors, such as this hawk, have the highest visual acuity of any animal. Megapixel video cameras with similar ability are now commercially available.



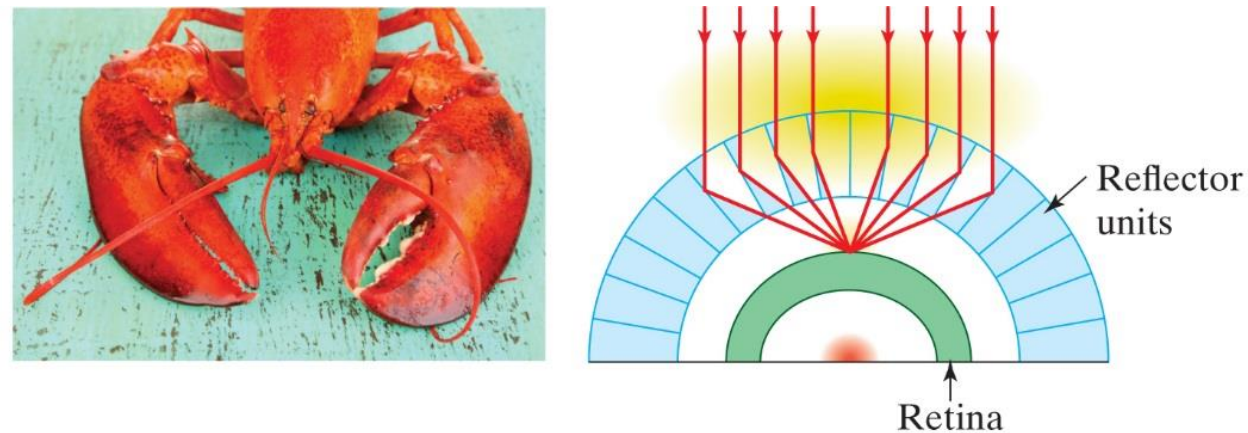
Ronnie Howard / Shutterstock.com, ymgerman / Shutterstock.com

Animal Vision (4)

Figure 2.14 Bees have ultraviolet filters enabling them to detect the flower center, which is helpful for pollinization. The middle image shows the flower (left) as it appears to a bee. Ultraviolet cameras are also used to detect heavenly bodies, such as the sun (right).



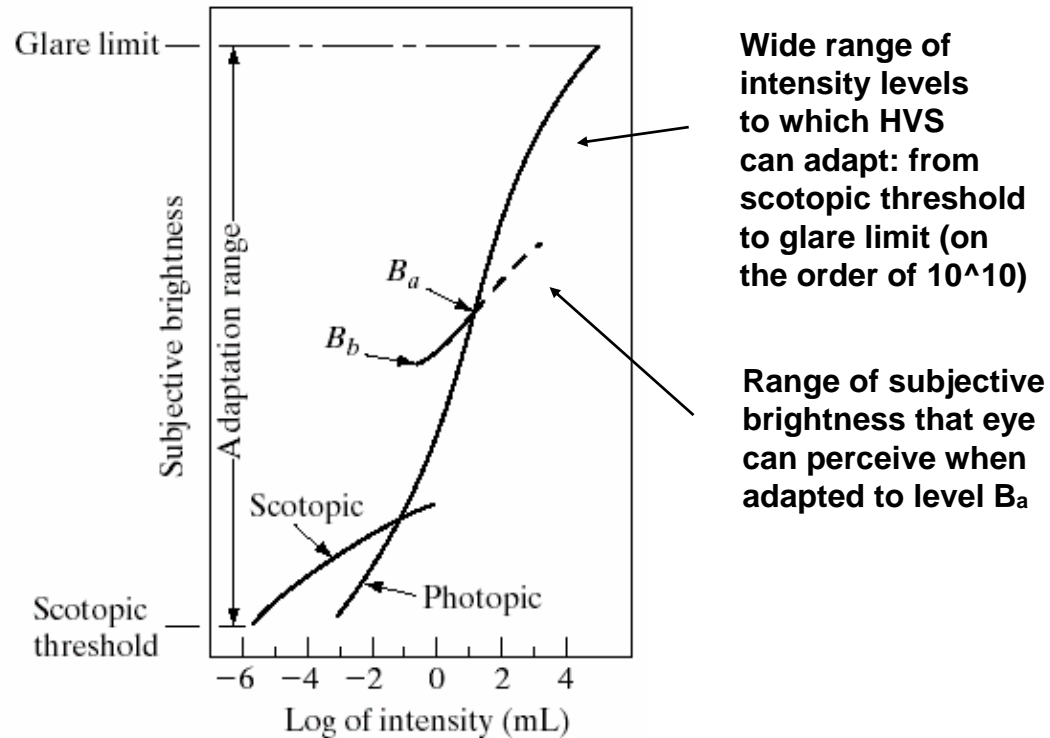
Figure 2.16 The lobster eye focuses by reflection, not refraction, and is the inspiration for a new generation of telescope. Based on *Trilobite Eyes—Ultimate Optics* by Kurt Wise <https://answersingenesis.org/extinct-animals/trilobite-eyes-ultimate-optics/>



Brightness Adaptation (1)

- The human eye's ability to discriminate between intensities is important.
- Experimental evidence suggests that subjective brightness (perceived) is a logarithmic function of light incident on eye. Notice approximately linear response in log-scale below.

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



Brightness Adaptation (2)

- Essential point: the HVS cannot operate over such a large range *simultaneously*.
- It accomplishes this large variation by changes in its overall sensitivity: *brightness adaptation*.
- The total range of distinct intensity levels it can discriminate simultaneously is rather small when compared with the total adaptation range.
- For any given set of conditions, the current sensitivity level of the HVS is called the *brightness adaptation level* (B_a in figure).

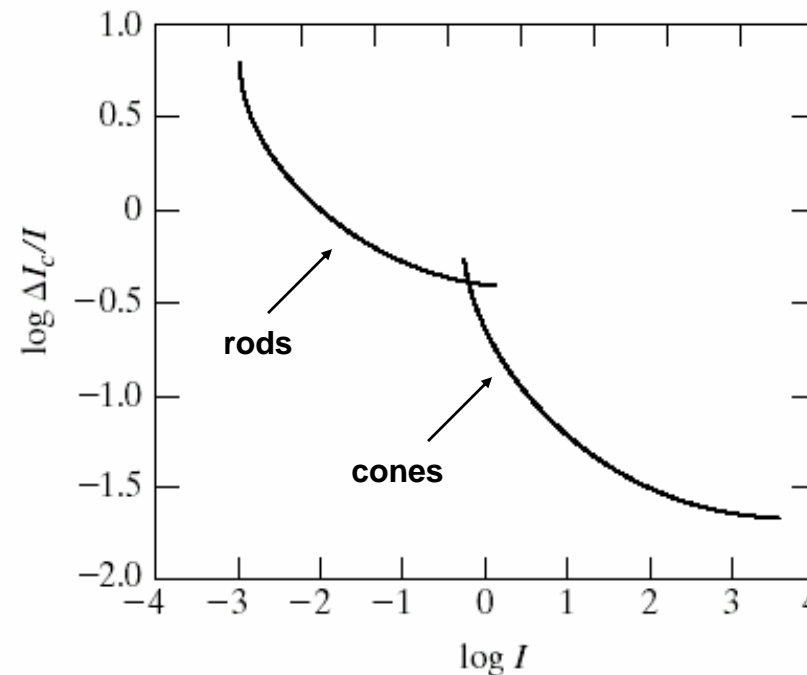
Brightness Discrimination (1)

- The ability of the eye to discriminate between intensity *changes* at any adaptation level is of considerable interest.
- Let I be the intensity of a large uniform area that covers the entire field of view.
- Let ΔI be the change in object brightness required to just distinguish the object from the background.
- Good brightness discrimination: $\Delta I / I$ is small.
- Bad brightness discrimination: $\Delta I / I$ is large.
- $\Delta I / I$ is called Weber's ratio.

Brightness Discrimination (2)

- Brightness discrimination is poor at low levels of illumination, where vision is carried out by rods. Notice Weber's ratio is large.
- Brightness discrimination improves at high levels of illumination, where vision is carried out by cones. Notice Weber's ratio is small.

FIGURE 2.6
Typical Weber
ratio as a function
of intensity.



Choice of Grayscale (1)

- Let I take on 256 different intensities:
 - $0 \leq I_j \leq 1$ for $j = 0, 1, \dots, 255$.
- Which levels we use?
 - Use eye characteristics: sensitive to *ratios* of intensity levels rather than to absolute values (Weber's law: $\Delta B/B = \text{constant}$)
 - For example, we perceive intensities .10 and .11 as differing just as much as intensities .50 and .55.

Choice of Grayscale (2)

- Levels should be spaced logarithmically rather than linearly to achieve equal steps in brightness:

$I_0, I_1 = rI_0, I_2 = rI_1 = r^2I_0, I_3 = rI_2 = r^3I_0, \dots, I_{255} = r^{255}I_0 = 1,$
where I_0 is the lowest attainable intensity.

- $r = (1/I_0)^{1/255},$
- $I_j = r^j I_0 = (1/I_0)^{j/255} I_0 = I_0^{(1-j/255)} = I_0^{(255-j)/255}$
- In general, for $n+1$ intensities:

$$r = (1/I_0)^{1/n},$$

$$I_j = I_0^{(n-j)/n} \quad \text{for } 0 \leq j \leq n$$

Choice of Grayscale (3)

- Example: let $n=3$ and $I_0=1/8$:
 - $r = 2$
 - $I_0 = (1/8)^{(3/3)}$
 - $I_1 = (1/8)^{(2/3)} = 1/4$
 - $I_2 = (1/8)^{(1/3)} = 1/2$
 - $I_3 = (1/8)^{(0/3)} = 1$
 - For CRTs, $1/200 < I_0 < 1/40$.
 - $I_0 \neq 0$ because of light reflection from the phosphor within the CRT.
 - Linear grayscale is close to logarithmic for large number of graylevels (256).

Perceived Brightness

- Perceived brightness is not a simple function of intensity.
- The HVS tends to over/undershoot around intensity discontinuities.
- The scalloped brightness bands shown below are called *Mach bands*, after Ernst Mach who described this phenomenon in 1865.

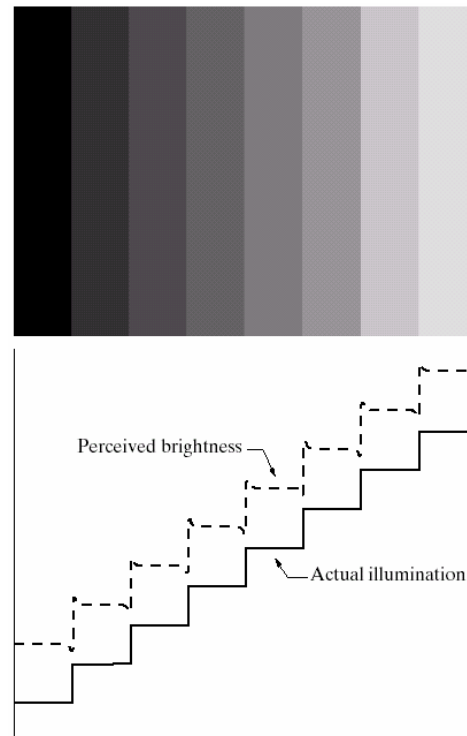


FIGURE 2.7
(a) An example showing that perceived brightness is not a simple function of intensity. The relative vertical positions between the two profiles in (b) have no special significance; they were chosen for clarity.

Simultaneous Contrast (1)

- A region's perceived brightness does not depend simply on its intensity. It is also related to the surrounding background.

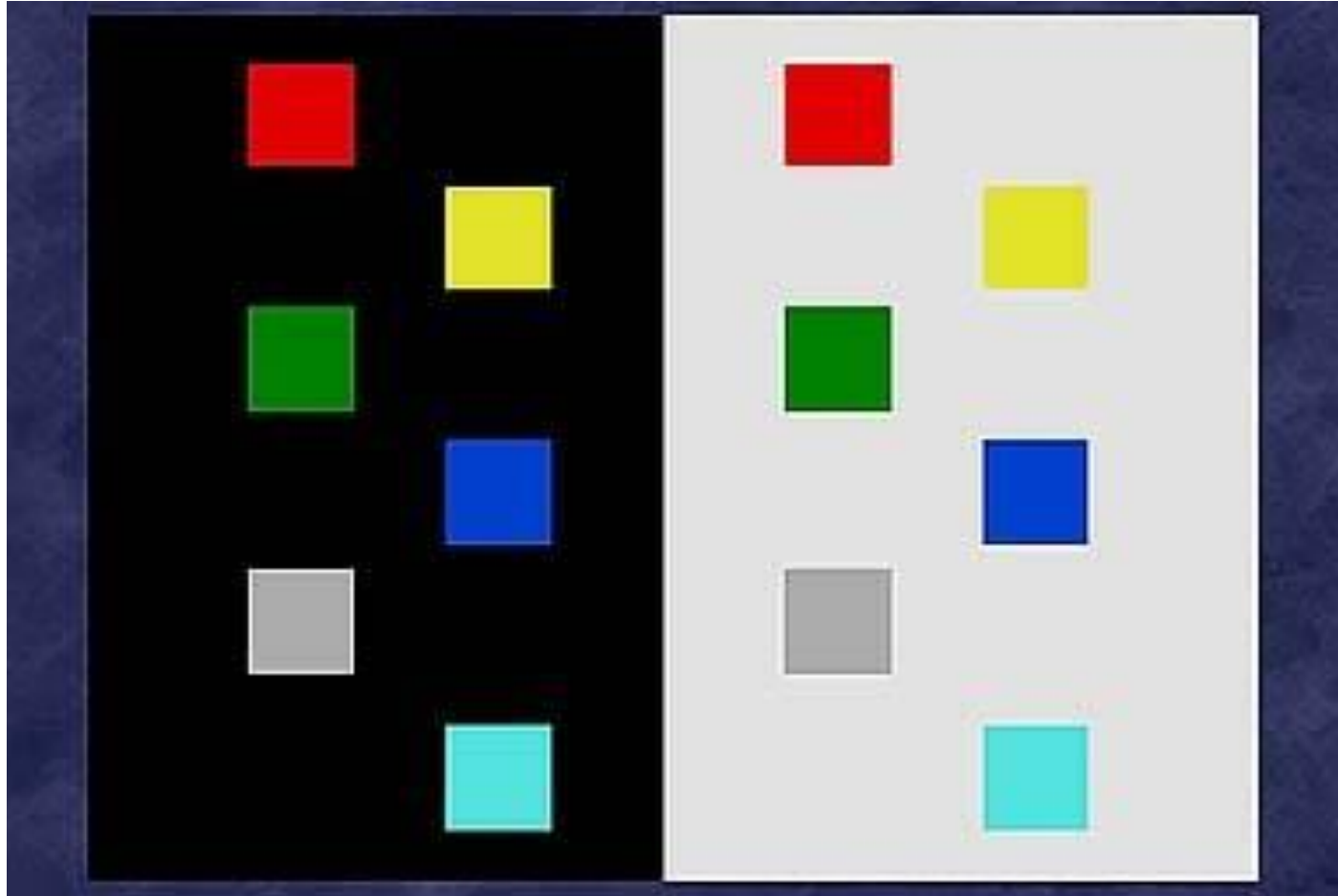


a b c

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.

Simultaneous Contrast (2)

- An example with colored squares.



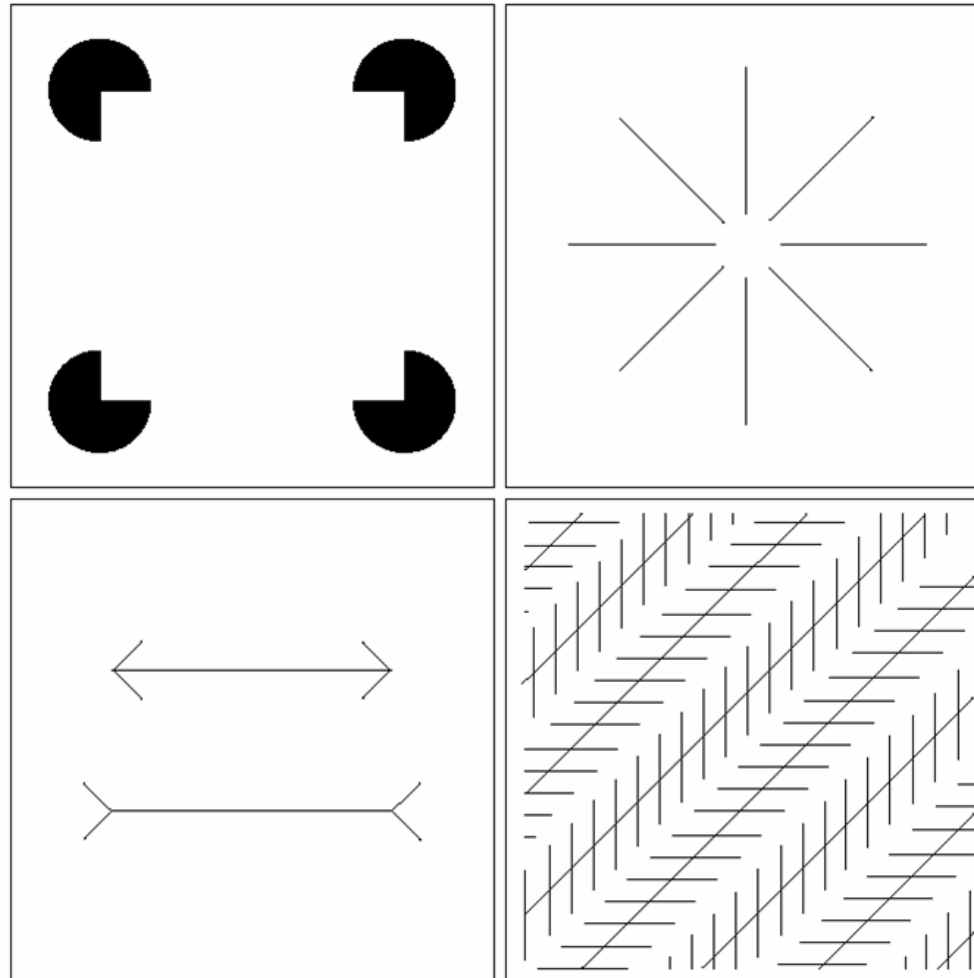
Projectors

- Why are projection screens white?
 - Reflects all colors equally well
- Since projected light cannot be negative, how are black areas produced?
 - Exploit simultaneous contrast
 - The bright area surrounding a dimly lit point makes that point appear darker

Visual Illusions (1)

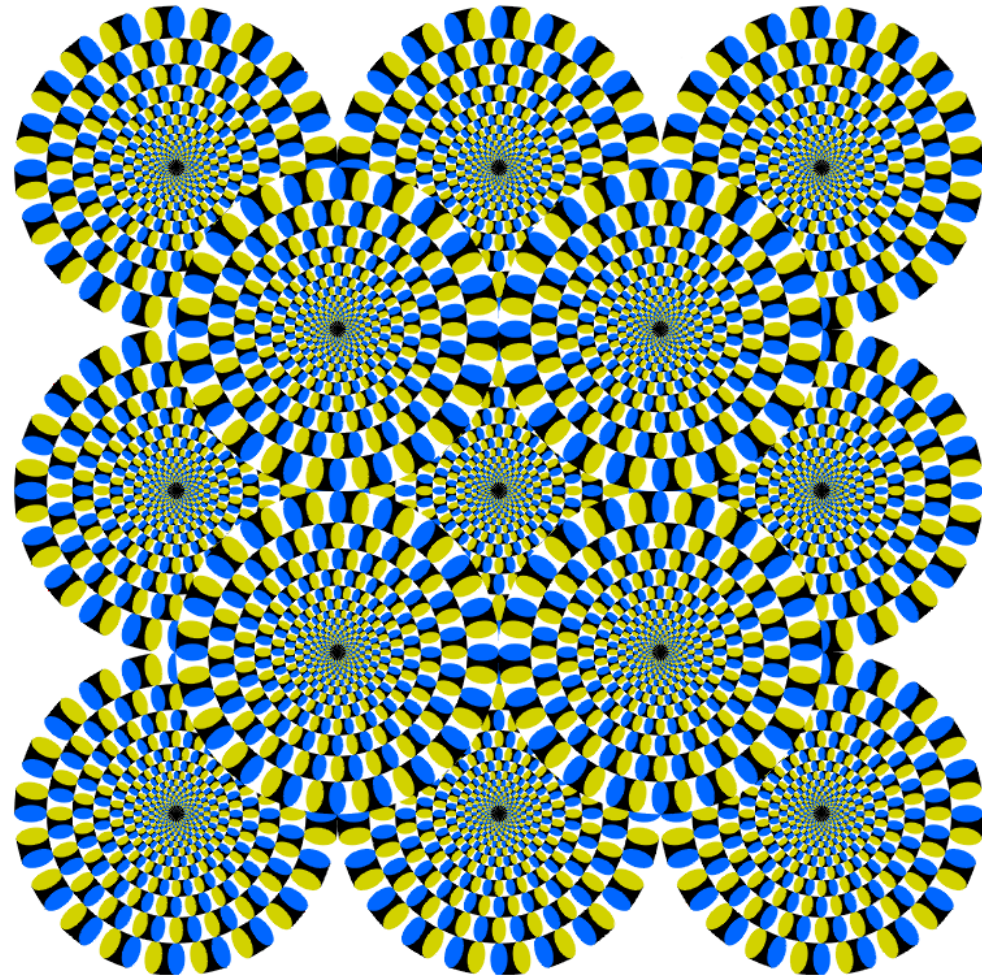
a b
c d

FIGURE 2.9 Some well-known optical illusions.



Visual Illusions (2)

- Rotating snake illusion
- Rotation occurs in relation to eye movement
- Effect vanishes on steady fixation
- Illusion does not depend on color
- Rotation direction depends on the polarity of the luminance steps
- Asymmetric luminance steps are required to trigger motion detectors



Stereo Vision

Figure 2.5 Retinal disparity is defined as the distance between corresponding points on the two retinas, after the retinas have been overlaid on top of one another and rotated so that their optical axes are coincident. Based on B. A. Wandell. *Foundations of Vision*. Sunderland, Mass., Sinauer Associates, Inc., 1995.

