Human Visual System

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Objectives

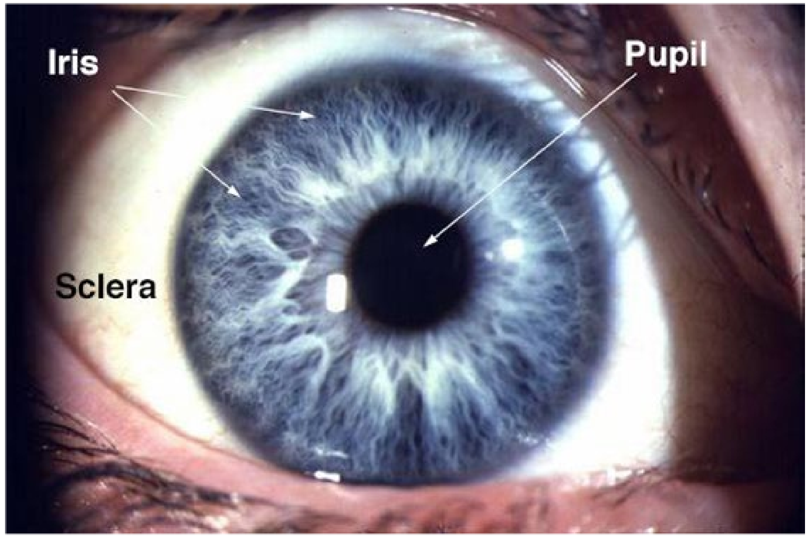
- In this lecture we discuss:
  - Structure of human eye
  - Mechanics of human visual system (HVS)
  - Brightness adaptation and discrimination
  - Perceived brightness and simultaneous contrast
  - Topics of image formation and acquisition, such as the pinhole camera model, lenses, sampling, and quantization

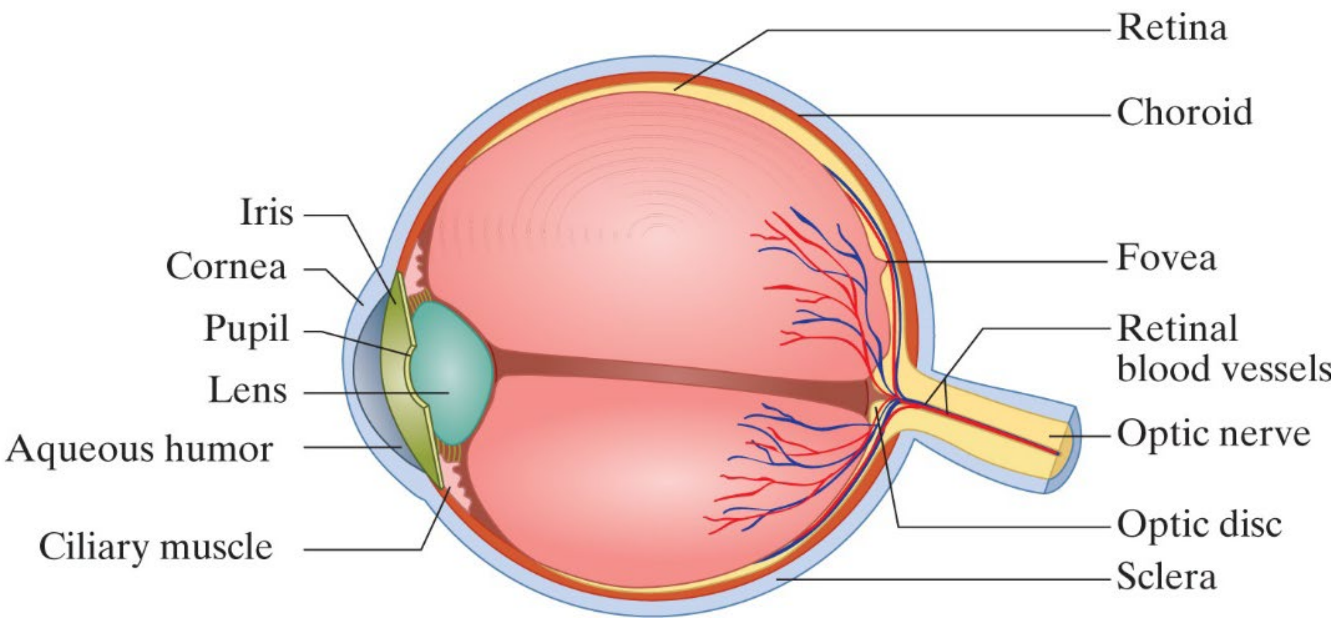
Human and Computer Vision

- 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?

Structure of the Human Eye

- Shape is nearly spherical
- Average diameter = 24mm
- 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. It is the white part of the eye.

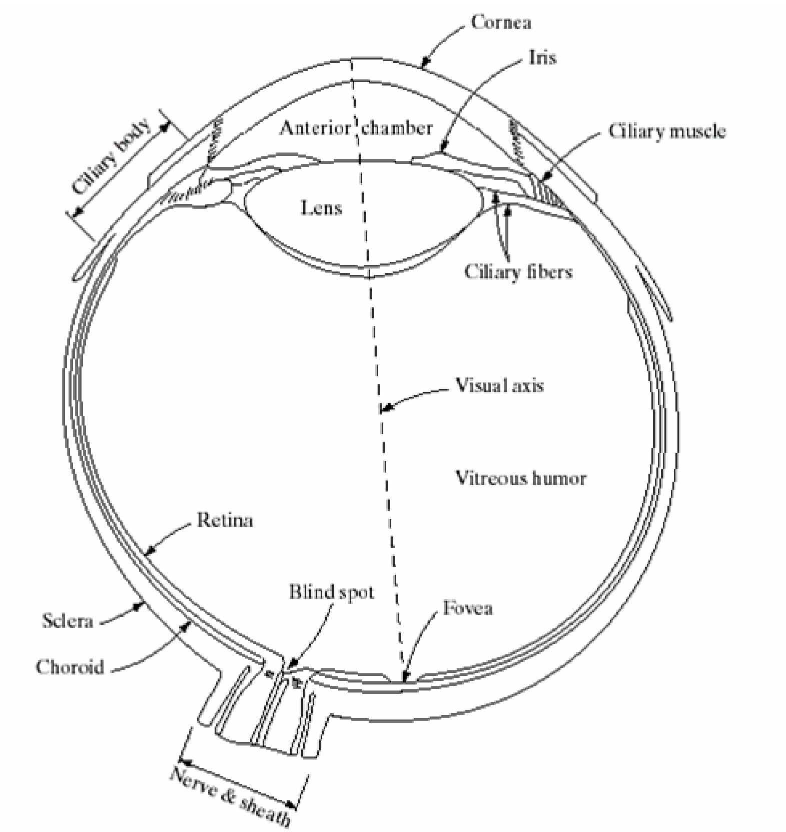


FIGURE 2.1 Simplified diagram of a cross section of the human eye.

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

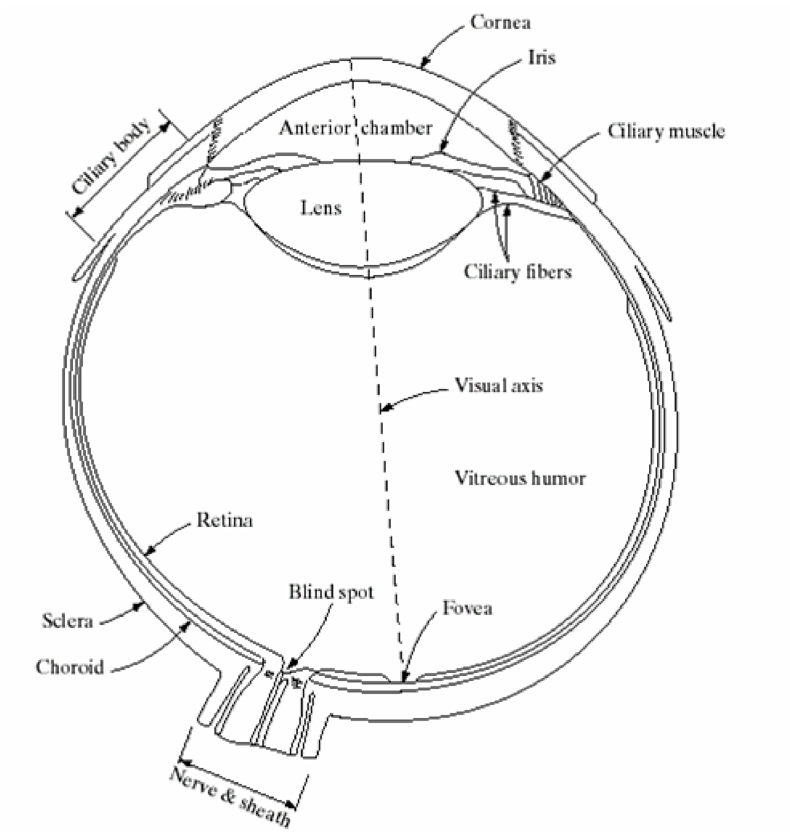


FIGURE 2.1 Simplified diagram of a cross section of the human eye.

Structure of the Human Eye: 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.

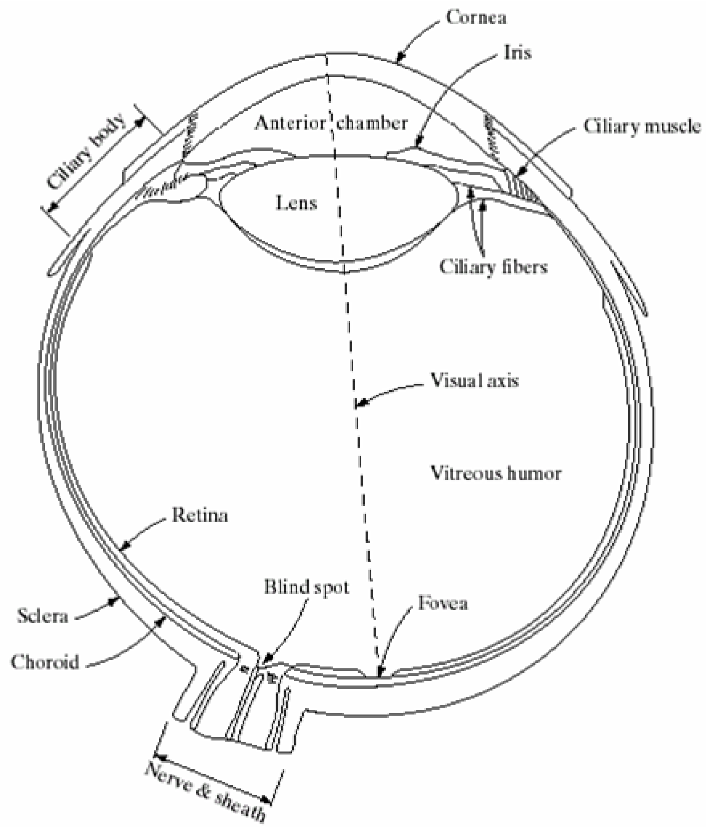
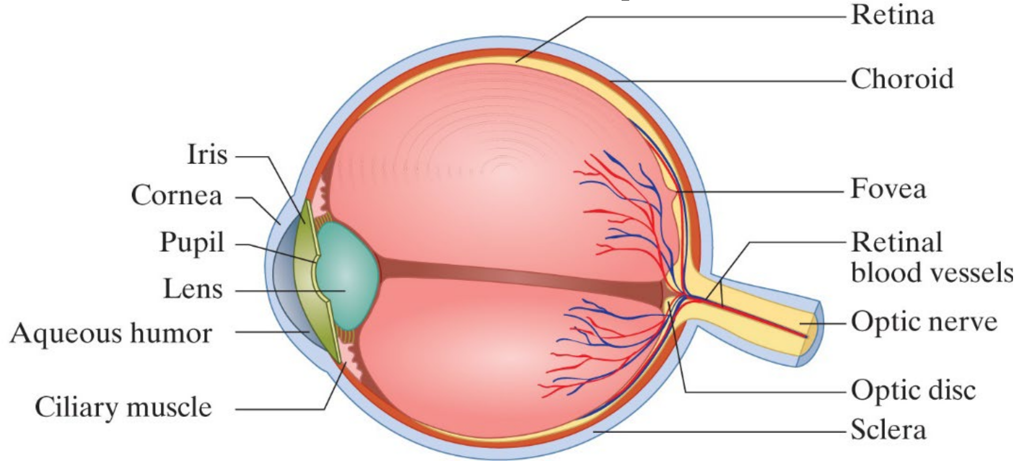


FIGURE 2.1 Simplified diagram of a cross section of the human eye.

Transmission of Light

- Light rays enter the eyeball through the cornea, where they are bent before they pass through the aqueous humor, where they are bent again.
- These rays then pass through the small aperture known as the pupil, whose size is controlled by muscles attached to the iris, the colored circular region surrounding the pupil.
- The rays are bent again by the lens, whose thickness is controlled by the ciliary muscle.
- The lens provides only about 1/3 of the refractive power of the eyeball, the rest being achieved by the cornea and aqueous humor.
- The lens focuses the light to form an image on the retina at the back of the eyeball.
- After absorbing a photon, the photoreceptors in the retina are nourished by the choroid, the layer between the sclera and the retina.



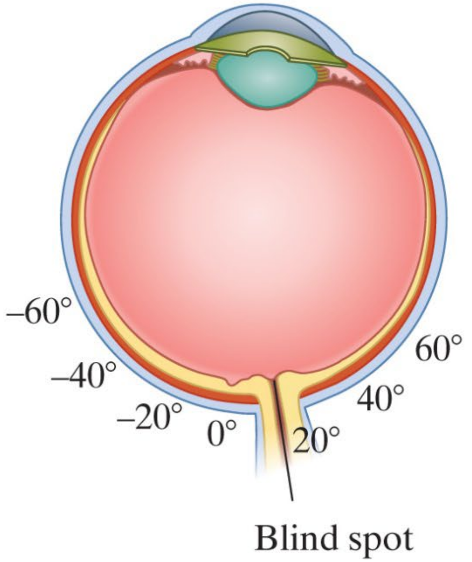
Receptors

- The retina consists of two types of light receptors: 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.
  - L-, M-, and S-cones respond to long-, middle-, and short-wavelength light (RGB cones).

- Rods
  - 100-150 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



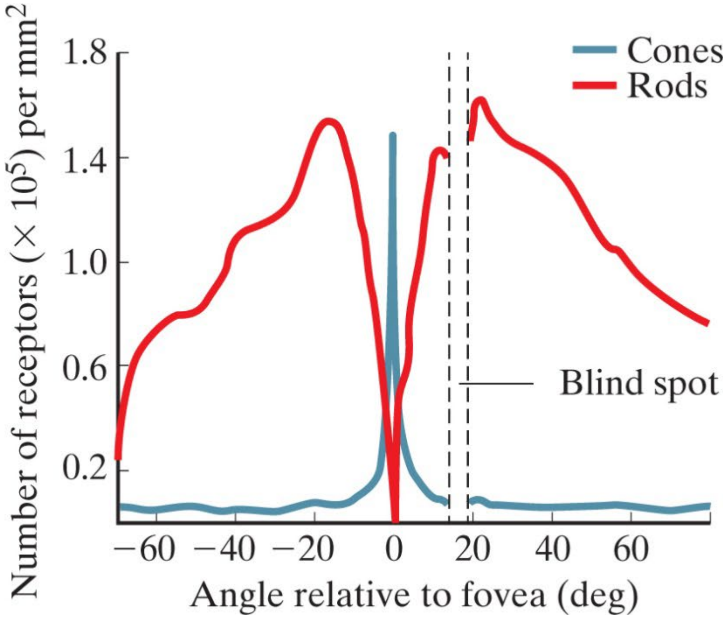
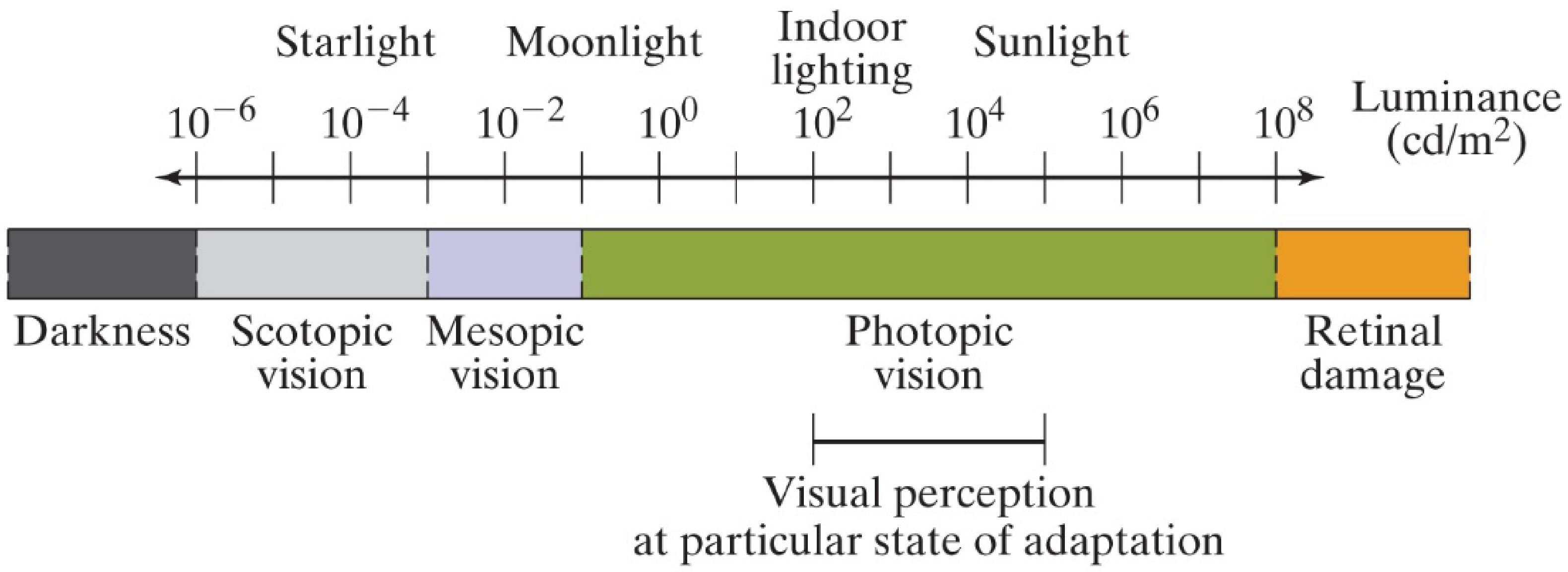


Figure 2.3 Distribution of cones and rods in the retina. Based on B. A. Wandell. *Foundations of Vision*. Sunderland, Mass., Sinauer Associates, Inc., 1995.

Human Visual Perception (1)

- The human visual system can respond to levels of light ranging an astounding 14 orders of magnitude.
- The eye cannot process this range simultaneously but instead adapts using the different types of photoreceptors and by adjusting the size of the pupil

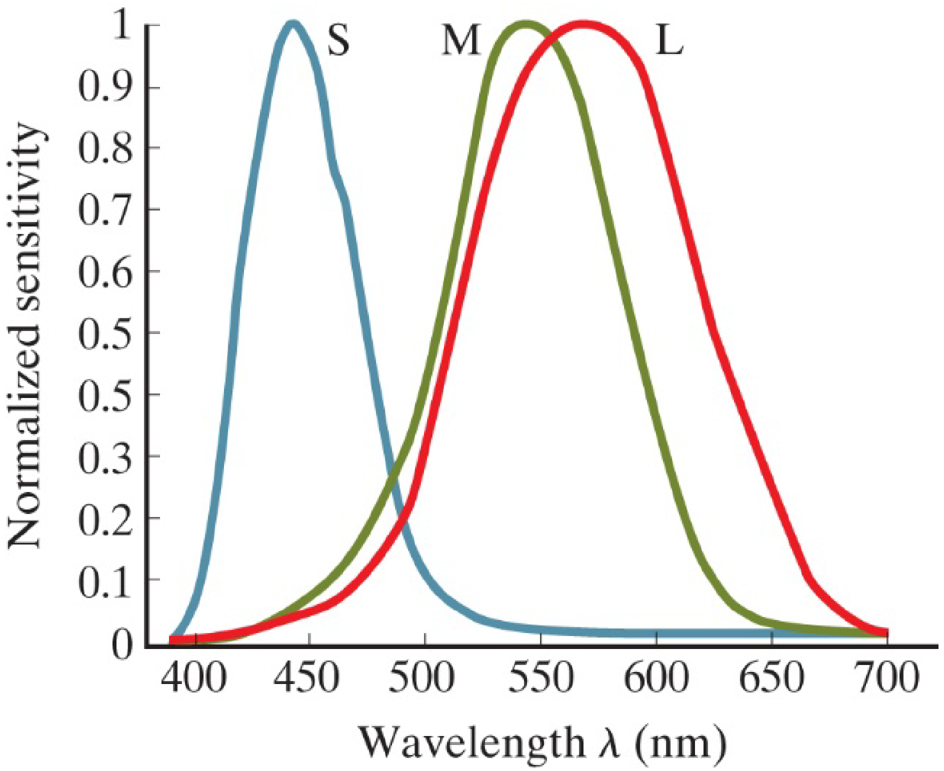
Figure 2.8 Scotopic, mesopic, and photopic vision at different light levels. While the human visual system is capable of sensing light in approximately a range of 10^{14} overall (from 10^{-6} to 10^{8} cd/m²), light can be sensed in a range of 10^{3}, at any particular state of adaptation.



Human Visual Perception (2)

- **Luminous efficiency function (LEF):** captures the relative sensitivity of the visual system to different wavelengths.

Figure 2.2 Relative sensitivity of the S-, M-, and L-cones of the human visual system to different wavelengths. These functions are also known as the cone fundamentals. Based on data from http://www.cvrl.org.



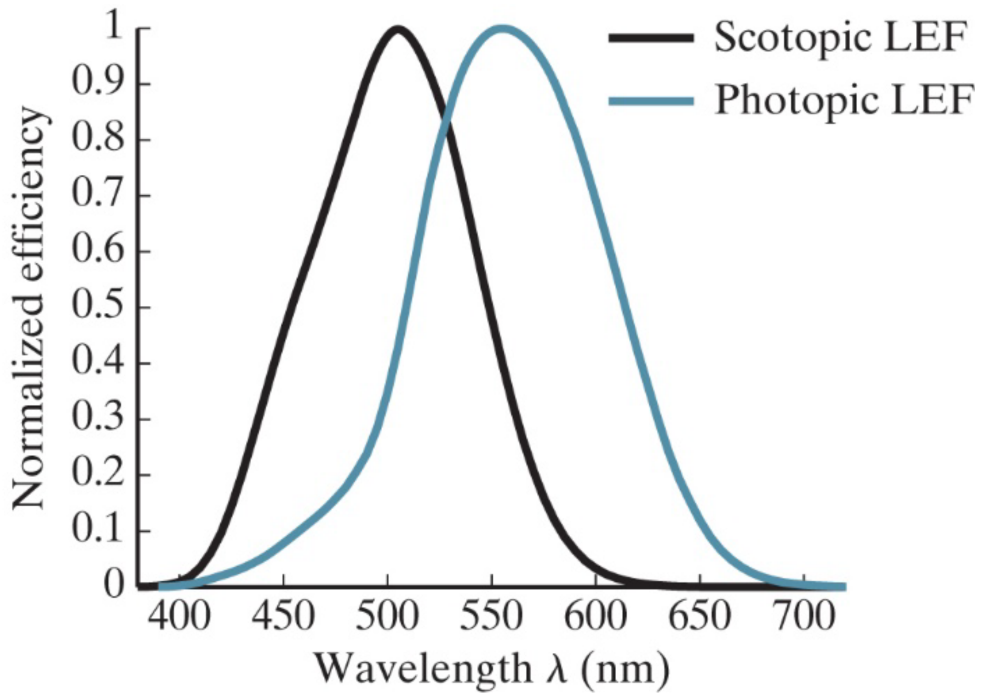
Luminous Efficiency Functions (1)

- **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.

Luminous Efficiency Functions (2)

- The scotopic LEF closely matches the spectral sensitivity function, and the photopic LEF is well approximated as a weighted contribution of the S-, M-, and L-cones.

Figure 2.9 Photopic and scotopic luminous efficiency functions (LEFs). Based on data from http://www.cvrl.org.



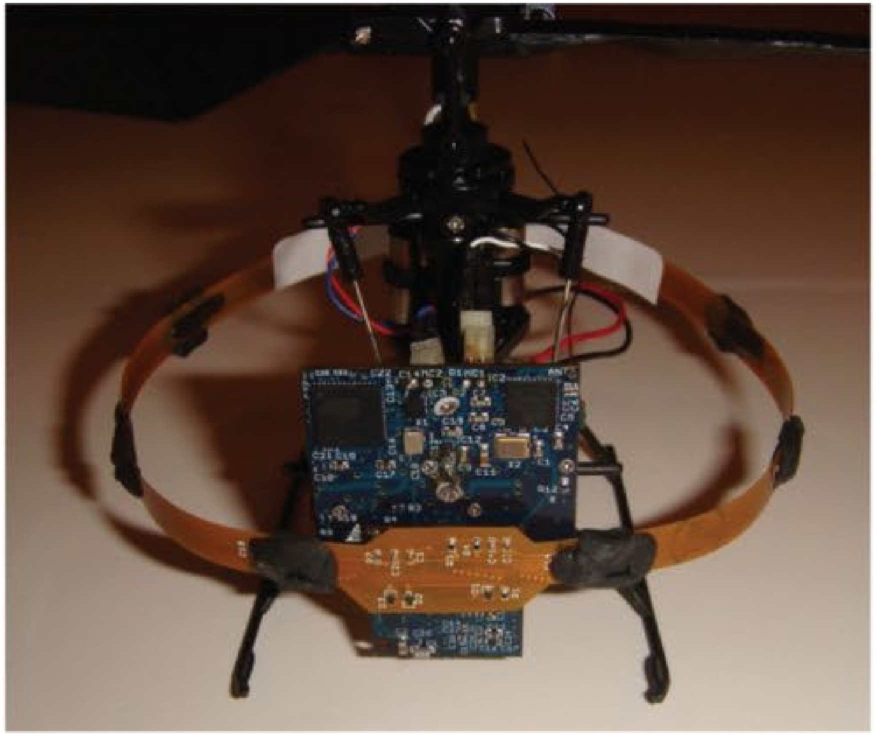
Animal Vision (1)

- 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)

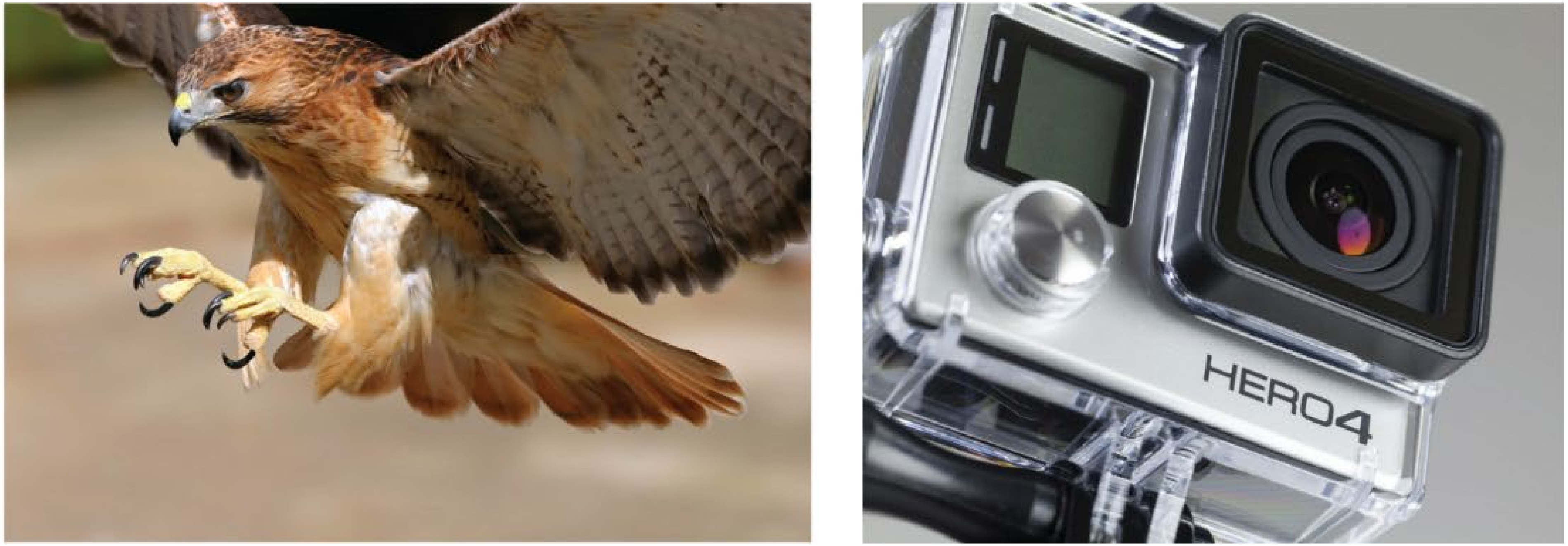
Figure 2.10 The common housefly has the fastest visual response of any animal, leading to extreme maneuverability in flight. Tiny flying robots (such as this one from Centeye) have been inspired to mimic the housefly's navigation ability based on optic flow.



mrfiza / 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.



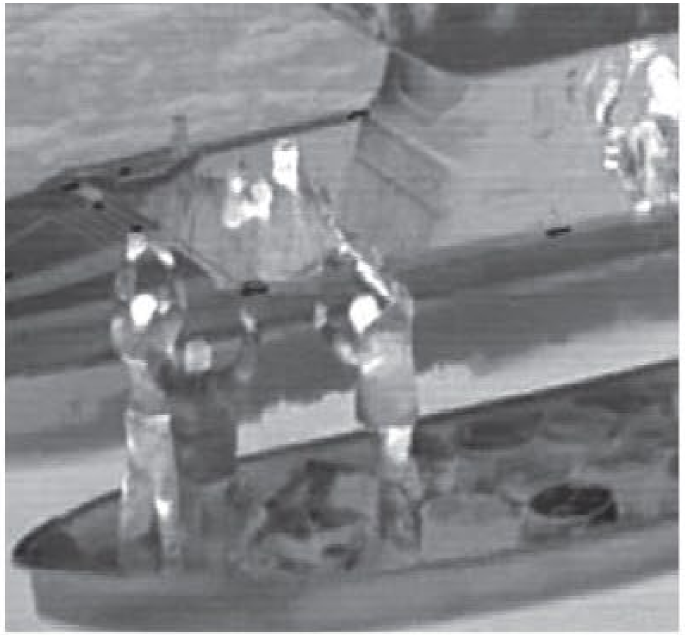
Animal Vision (4)

Figure 2.12
Predators such as this tiger have two eyes facing forward, so that it can estimate the distance to its intended prey via stereo vision. Prey such as this rabbit have eyes on the sides of the head, providing a much wider field of view to detect danger.

Dariush M / Shutterstock.com, Eric Isselee / Shutterstock.com

Animal Vision (5)

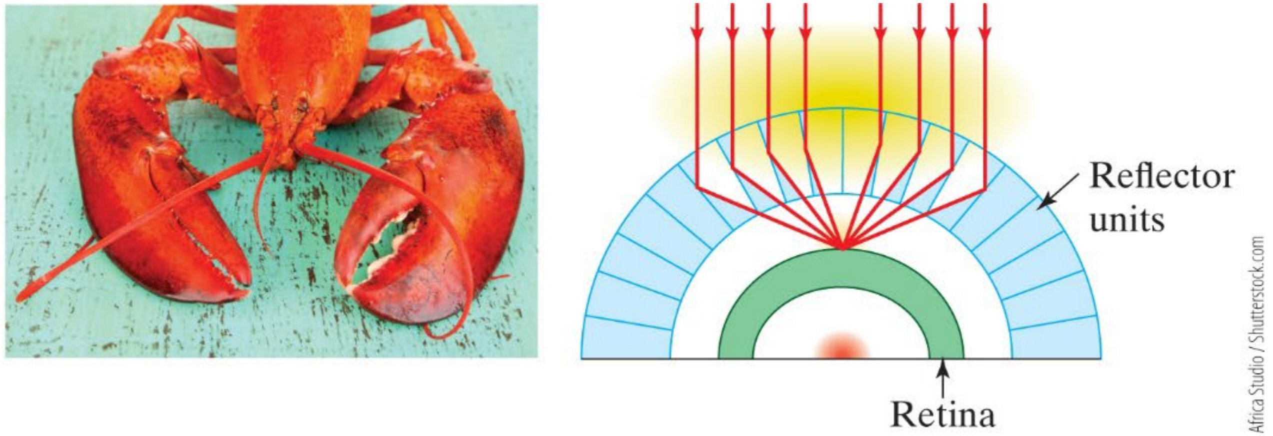
Figure 2.13 The loreal pit between the eye and nostril on a pit viper leads to an organ that detects heat via infrared light. Forward-looking infrared (FLIR) cameras detect warm bodies by examining the infrared portion of the spectrum, as seen in this thermal image.



Animal Vision (6)

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).

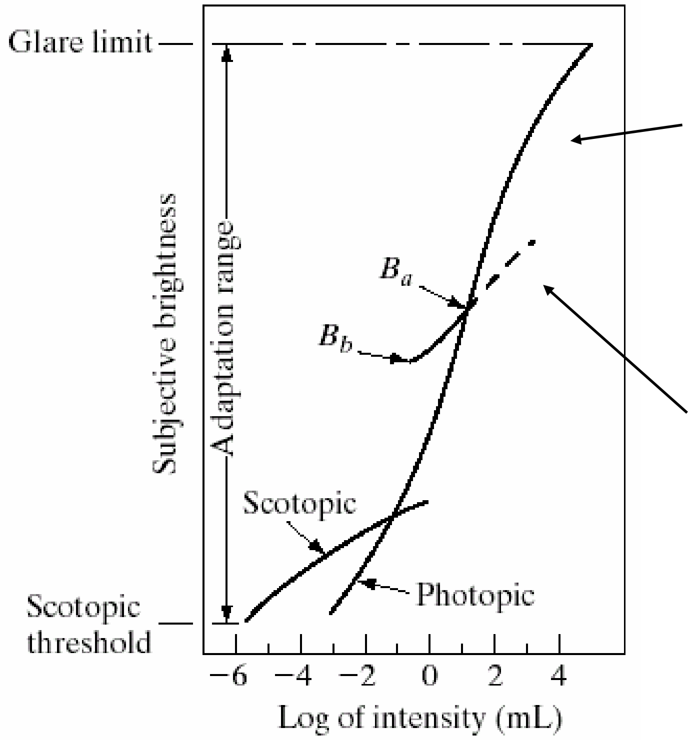
Figure 2.16 The lobster eye focuses by reflection, not refraction, and is the inspiration for a new generation of telescope. Based on *Trilobite Eyes—Ultimate Optics* by Kurt Wise https://answersingenesis.org/extinct-animals/trilobite-eyes-ultimate-optics/



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.



Wide range of intensity levels to which HVS can adapt: from scotopic threshold to glare limit (on the order of 10^10)

Range of subjective brightness that eye can perceive when adapted to level B_a

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).

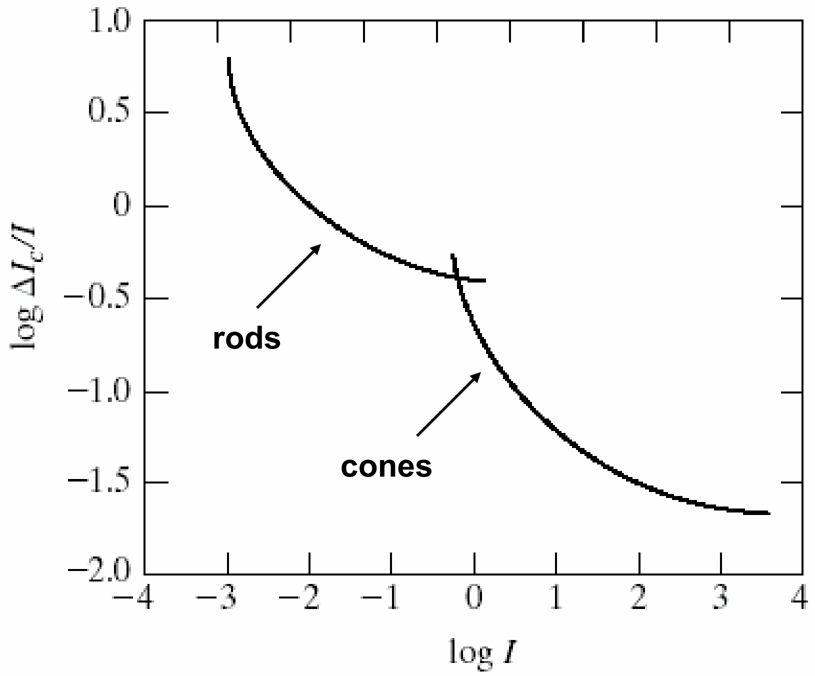
Brightness Discrimination (1)

- 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.
  - This area typically is a diffuser, such as opaque glass, illuminated from behind by a light source I
- Let ΔI be the change in object brightness required to just distinguish the object from the background.
  - The object is a short-duration flash that appears as a circle in the center of the uniformly illuminated field.
- 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)

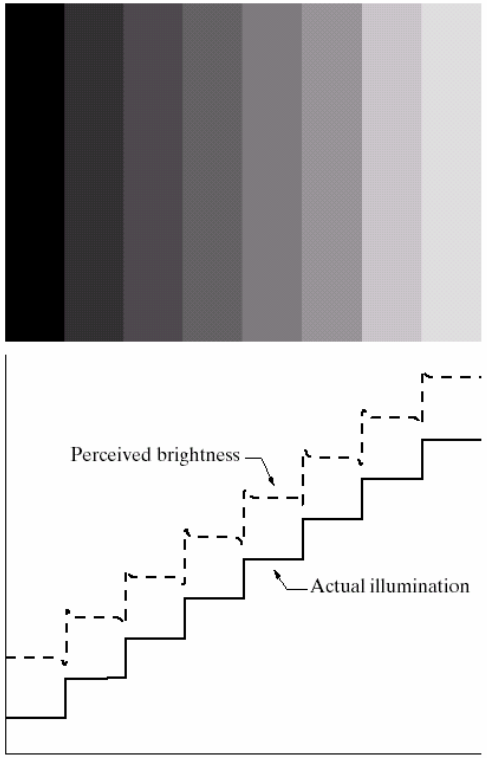
- Brightness discrimination is poor at low levels of illumination, where vision is carried out by rods. Notice Weber's ratio is large.
- Brightness discrimination improves at high levels of illumination, where vision is carried out by cones. Notice Weber's ratio is small.

FIGURE 2.6
Typical Weber ratio as a function of intensity.



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.



a
b

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.

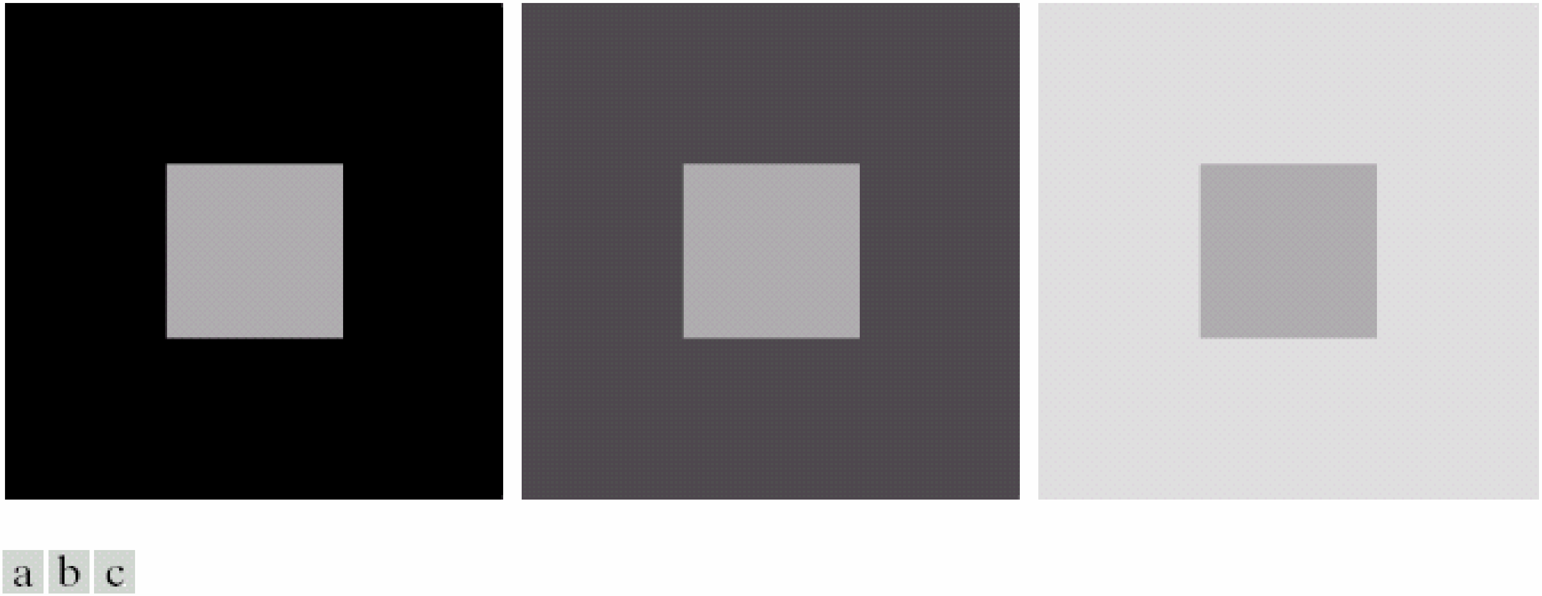
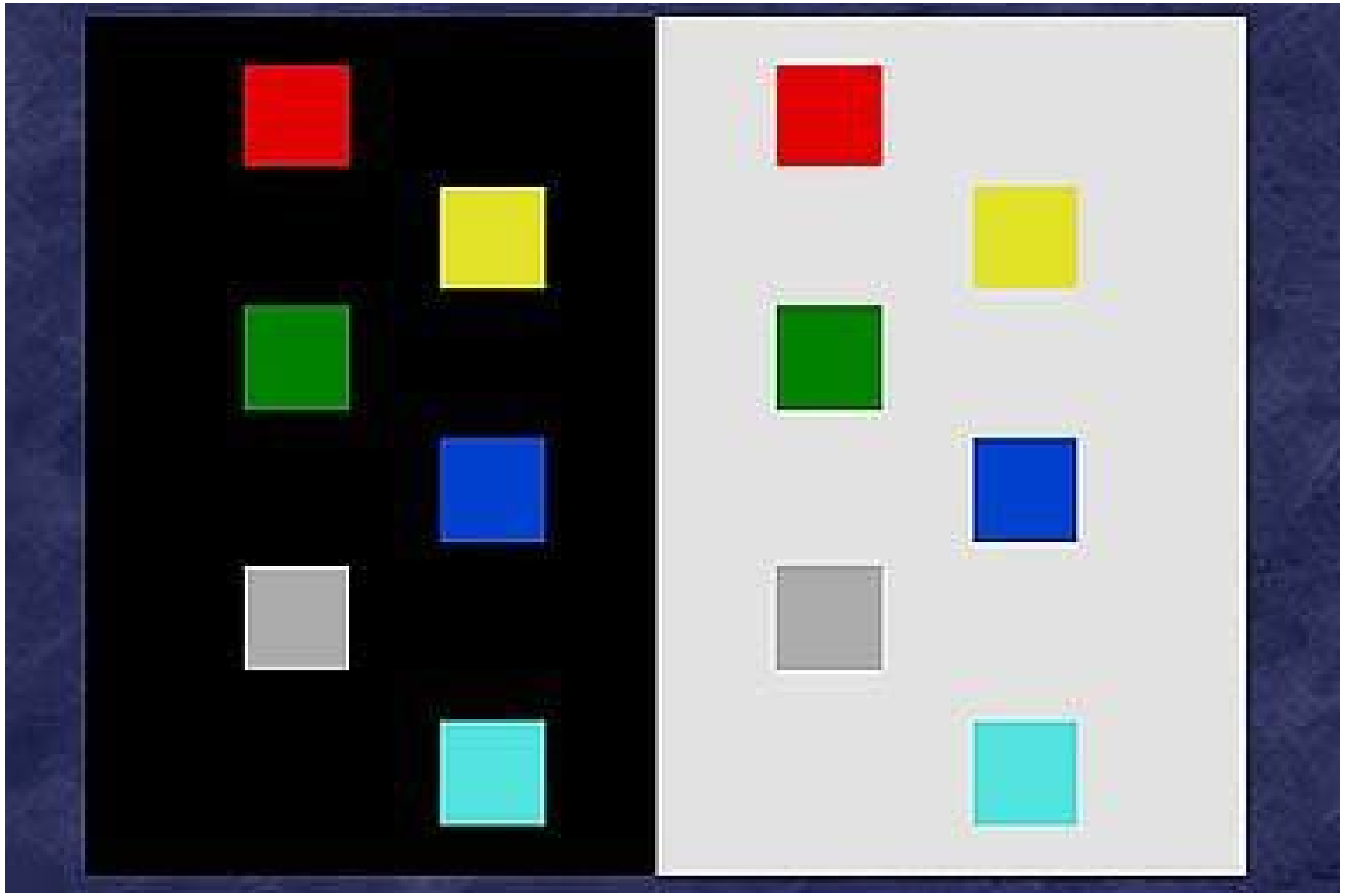


FIGURE 2.8 Examples of simultaneous contrast. All the inner squares have the same intensity, but they appear progressively darker as the background becomes lighter.

Simultaneous Contrast (2)

- An example with colored squares.



Choice of Grayscales (1)

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

Choice of Grayscales (2)

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

  $I_0, \; I_1 = rI_0, \; I_2 = rI_1 = r^2 I_0, \; I_3 = rI_2 = r^3 I_0, \; \ldots, \; I_{255} = r^{255} I_0 = 1,$

  where I_0 is the lowest attainable intensity.
- $r = (1/I_0)^{1/255},$
- $I_i = r^i I_0 = (1/I_0)^{i/255} I_0 = I_0^{(1-i/255)} = I_0^{(255-i)/255}$
- In general, for n+1 intensities:

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

  $I_i = I_0^{(n-i)/n}$ for $0 \leq i \leq n$

Choice of Grayscales (3)

- Example: let $n=3$ and $I_0=1/8$:
  - $r = 2$
  - $I_0 = (1/8)^{(3/3)}$
  - $I_1 = (1/8)^{(2/3)} = ¼$
  - $I_2 = (1/8)^{(1/3)} = ½$
  - $I_3 = (1/8)^{(0/3)} = 1$
  - Typically, $1/200 < I_0 < 1/40$.
  - Linear grayscale is close to logarithmic for large number of graylevels (256).

Code to Evaluate Grayscales

```
#include <cstdio>
#include <iostream>
#include <cmath>

using namespace std;
int main() {
        int    n = 255;                              // max graylevel; total graylevels = n+1
        double I0 = 0.01;                            // minimum intensity (e.g., black)
        double r  =  pow((1.0/I0), 1.0/n);           // ratio between adjacent graylevels
        double I[n+1];                               // array of graylevels

        // print ratio r
        cout << "r = " << r << endl;

        // for every index i, compute grayscale based on logarithmic spacing; scale by n for display
        for(int i=0; i<n+1; i++) {
                I[i] = n * pow(I0, (double) (n-i)/n);
                cout << i << ": " << I[i] << endl;
        }

        return 0;
}
```

Grayscale Example (1)

- Example: n = 255 and I_0=1/100; r = 1.0182280.

0: 2.55	20: 3.65934	40: 5.25129	60: 7.53578	80: 10.8141	100: 15.5186	120: 22.2698
1: 2.59647	21: 3.72603	41: 5.34698	61: 7.67311	81: 11.0112	101: 15.8015	121: 22.6757
2: 2.64379	22: 3.79393	42: 5.44442	62: 7.81294	82: 11.2119	102: 16.0894	122: 23.0889
3: 2.69197	23: 3.86307	43: 5.54364	63: 7.95532	83: 11.4162	103: 16.3826	123: 23.5096
4: 2.74102	24: 3.93347	44: 5.64467	64: 8.1003	84: 11.6242	104: 16.6812	124: 23.9381
5: 2.79097	25: 4.00515	45: 5.74753	65: 8.24791	85: 11.8361	105: 16.9852	125: 24.3743
6: 2.84184	26: 4.07814	46: 5.85227	66: 8.39822	86: 12.0517	106: 17.2947	126: 24.8185
7: 2.89362	27: 4.15245	47: 5.95892	67: 8.55127	87: 12.2714	107: 17.6099	127: 25.2708
8: 2.94636	28: 4.22813	48: 6.06751	68: 8.7071	88: 12.495	108: 17.9308	128: 25.7313
9: 3.00005	29: 4.30518	49: 6.17809	69: 8.86577	89: 12.7227	109: 18.2575	129: 26.2002
10: 3.05472	30: 4.38363	50: 6.29067	70: 9.02734	90: 12.9546	110: 18.5903	130: 26.6777
11: 3.11039	31: 4.46352	51: 6.40531	71: 9.19185	91: 13.1906	111: 18.929	131: 27.1638
12: 3.16707	32: 4.54486	52: 6.52204	72: 9.35936	92: 13.431	112: 19.274	132: 27.6589
13: 3.22479	33: 4.62768	53: 6.64089	73: 9.52992	93: 13.6758	113: 19.6252	133: 28.1629
14: 3.28355	34: 4.71202	54: 6.76191	74: 9.70359	94: 13.925	114: 19.9829	134: 28.6761
15: 3.34339	35: 4.79789	55: 6.88514	75: 9.88042	95: 14.1788	115: 20.347	135: 29.1987
16: 3.40432	36: 4.88532	56: 7.01061	76: 10.0605	96: 14.4371	116: 20.7178	136: 29.7308
17: 3.46636	37: 4.97435	57: 7.13837	77: 10.2438	97: 14.7002	117: 21.0954	137: 30.2726
18: 3.52953	38: 5.065	58: 7.26846	78: 10.4305	98: 14.9681	118: 21.4798	138: 30.8243
19: 3.59385	39: 5.1573	59: 7.40091	79: 10.6206	99: 15.2409	119: 21.8712	139: 31.386

Grayscale Example (2)

- Example: n = 255 and I_0=1/100; r = 1.0182280.

140: 31.958	160: 45.8609	180: 65.812	200: 94.4425	220: 135.528	240: 194.488
141: 32.5404	161: 46.6966	181: 67.0113	201: 96.1636	221: 137.998	241: 198.032
142: 33.1334	162: 47.5476	182: 68.2325	202: 97.9161	222: 140.513	242: 201.641
143: 33.7372	163: 48.4141	183: 69.4759	203: 99.7004	223: 143.074	243: 205.316
144: 34.352	164: 49.2963	184: 70.742	204: 101.517	224: 145.681	244: 209.057
145: 34.978	165: 50.1947	185: 72.0312	205: 103.367	225: 148.336	245: 212.867
146: 35.6154	166: 51.1094	186: 73.3439	206: 105.251	226: 151.039	246: 216.746
147: 36.2645	167: 52.0408	187: 74.6804	207: 107.169	227: 153.792	247: 220.696
148: 36.9253	168: 52.9892	188: 76.0414	208: 109.122	228: 156.594	248: 224.718
149: 37.5983	169: 53.9548	189: 77.4271	209: 111.111	229: 159.448	249: 228.813
150: 38.2834	170: 54.9381	190: 78.8381	210: 113.136	230: 162.354	250: 232.983
151: 38.9811	171: 55.9393	191: 80.2748	211: 115.197	231: 165.312	251: 237.229
152: 39.6915	172: 56.9587	192: 81.7377	212: 117.297	232: 168.325	252: 241.552
153: 40.4148	173: 57.9967	193: 83.2273	213: 119.434	233: 171.392	253: 245.954
154: 41.1513	174: 59.0536	194: 84.744	214: 121.611	234: 174.516	254: 250.436
155: 41.9012	175: 60.1297	195: 86.2883	215: 123.827	235: 177.696	255: 255
156: 42.6648	176: 61.2255	196: 87.8608	216: 126.083	236: 180.934	
157: 43.4423	177: 62.3412	197: 89.4619	217: 128.381	237: 184.231	
158: 44.234	178: 63.4773	198: 91.0922	218: 130.721	238: 187.589	
159: 45.0401	179: 64.6341	199: 92.7523	219: 133.103	239: 191.007	

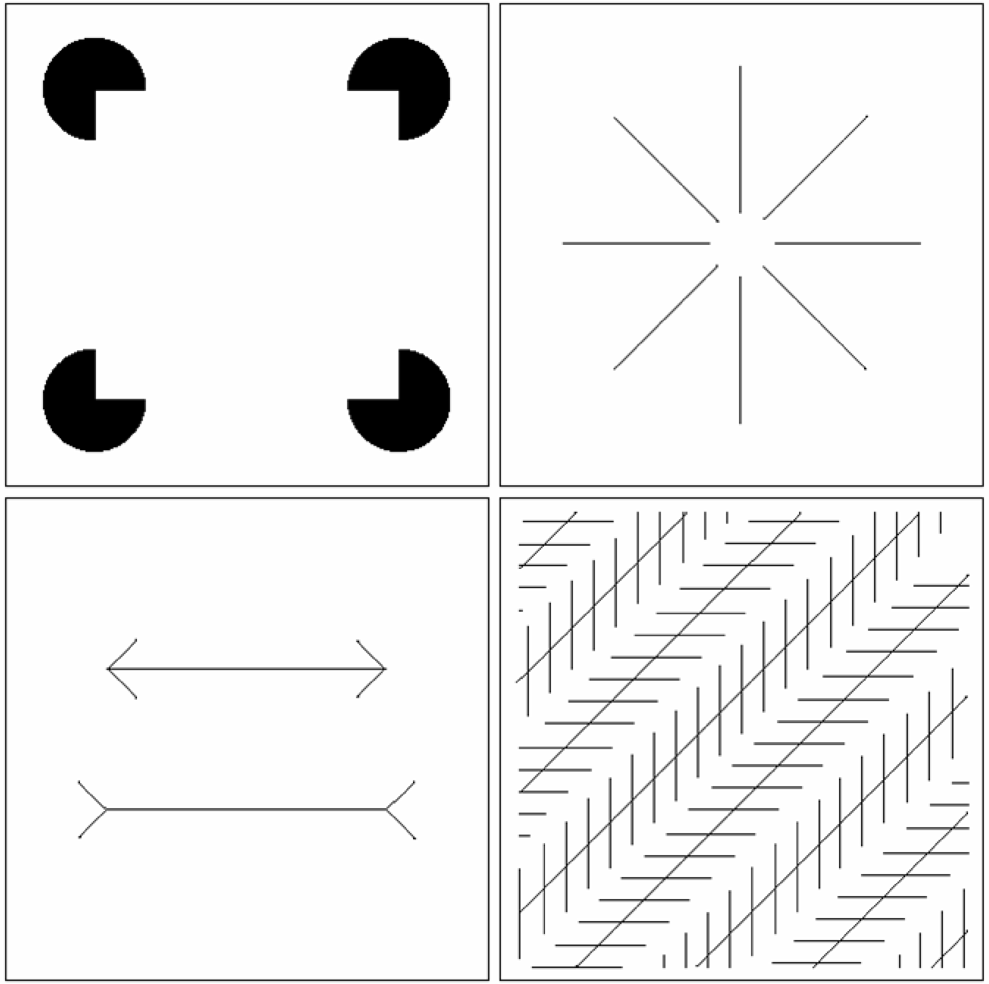
Projectors

- Why are projection screens white?
  - Reflects all colors equally well to create contrast that you can see
- 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