ELEG404/604: Imaging & Deep Learning

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Chapter IV

Chapter V: Imaging Fundamentals

- Human visual system
  - For the design of imaging systems it is beneficial to have understanding of the mechanism of human vision system (HVS)
  - The HVS can be utilized to develop conceptual models of the human visual process
  - Models are vital in the construction of measures of image fidelity and intelligibility
- Color representation
  - Understanding of color perception is fundamental to develop image acquisition and display systems
  - Adequate color spaces in which distances model color mismatches

Light and EM Spectrum

Light: Radiant energy enables sight

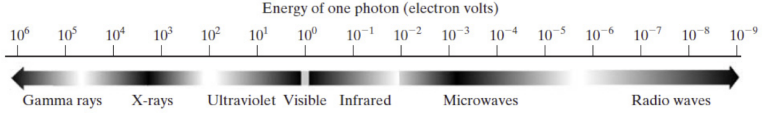


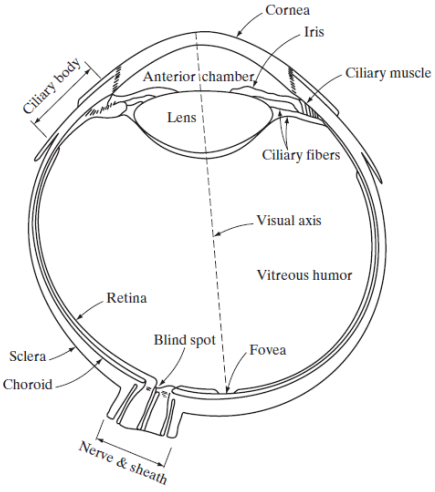
FIGURE 1.5 The electromagnetic spectrum arranged according to energy per photon.

Observed light

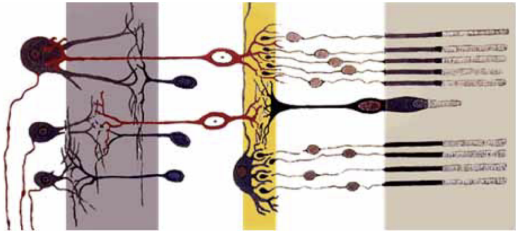
- To see an object the EM wavelength must be no bigger than the object
- To image molecules far ultraviolet or soft x-ray waves must be used

Eye Physiology

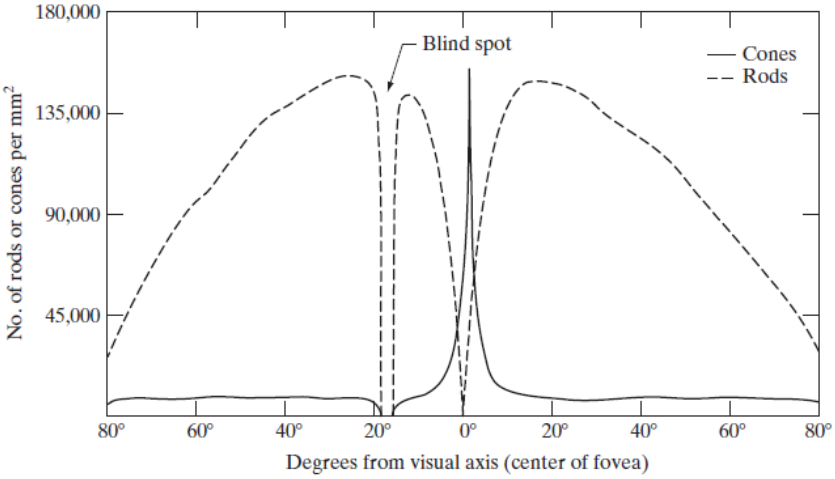
- Enclosing membranes
  - Outer-cornea, sclera
- Iris opening (2-8mm)
- Retina light receptors
  - Cones in fovea
    - 6-7 millions
    - Color sensitive
    - Photopic (bright-light) vision
  - Rods
    - 75-150 million
    - Not color sensitive
    - Scotopic (low-light) vision



- The retina is a light-sensitive tissue lining the inner surface of the eye.
- Events trigger nerve impulses.that are sent to centers of the brain through the fibers of the optic nerve.
- Retina is a layered structure of neurons interconnected by synapses. Neurons that are sensitive to light are the photoreceptor cells. These are of two types: the rods and cones.



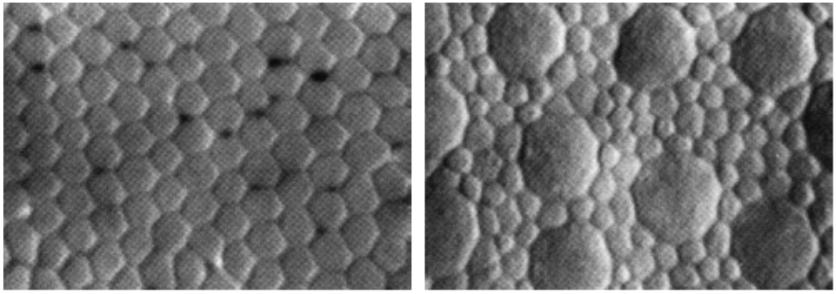
Distribution of Cones and Rods in the Retina



Fovea

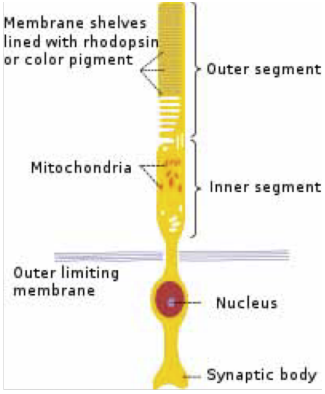
- Size: approximately 1.5mm×1.5mm
- Cone density: approximately 150.000 elements per mm^2

The photoreceptor mosaic on the retina

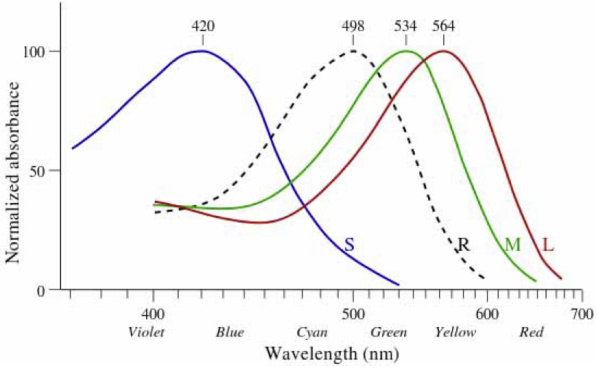


(a) In the fovea, the cones are densely packed on a hexagonal sampling array. (b) In the periphery, their size and separation grows, and rods fill in the spaces. Each image shows an area of 35×25 μm^2. ©1990 John Wiley & Sons.

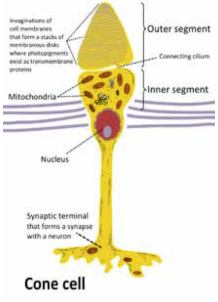
- Rod cells responds to a single photon of light (100 times more sensitive than cones). Rods are concentrated at the outer edges of the retina providing peripheral vision.
- Rod cells are almost entirely responsible for night vision (scotopic vision).
- Multiple rod cells converge on a single interneuron (amplifies but decreases resolution).
- Cone cells require tens to hundreds of photons to become activated.



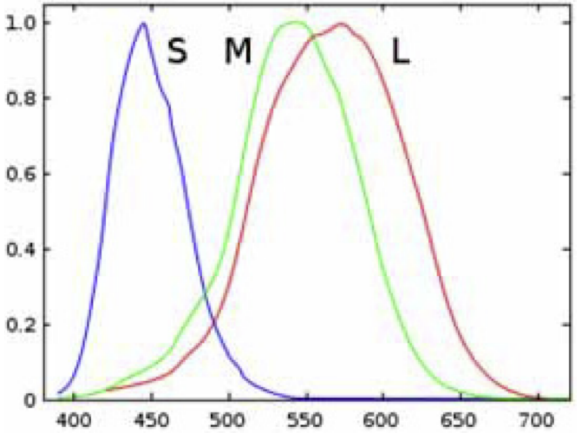
- Convergence of rod cells tends to make peripheral vision very sensitive to movement.
- Rods are most sensitive to wavelengths around 498 nm (green-blue). As intensity dims at twilight, the rods take over, and color disappears completely, peak sensitivity of vision shifts towards the rods' peak sensitivity (blue-green).



- Cone cells are responsible for color vision. Function best in bright light.
- Cone cells are densely packed in the fovea, but gradually become sparser towards the periphery of the retina.
- About 4.5 million cone cells and 90 million rod cells in the human retina.
- Cones perceive finer detail and more rapid changes in images.



- Humans have three kinds of cones. With peak wavelengths near 564-580 nm, 534-545 nm, and 420-440 nm.
- Cone cells are shorter than rods, but wider and tapered, and are much less numerous than rods.



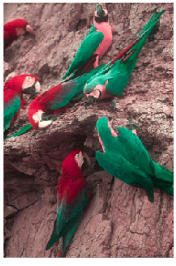
Color Blindness

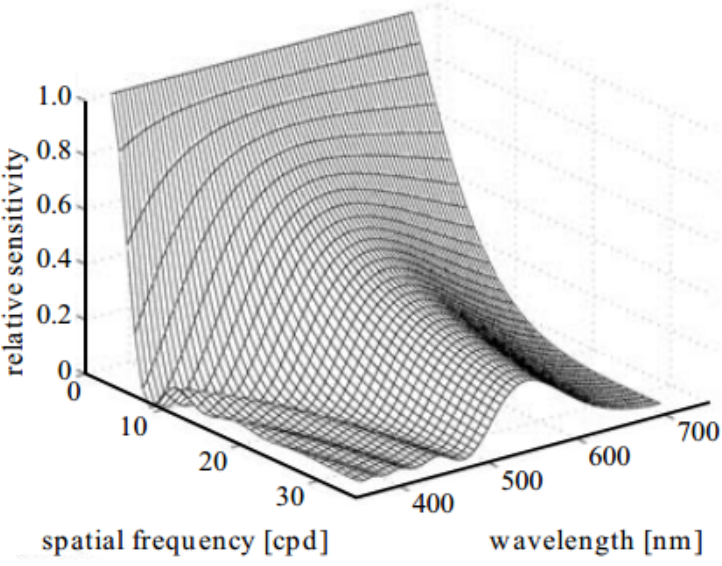
Normal

Deuteranomaly

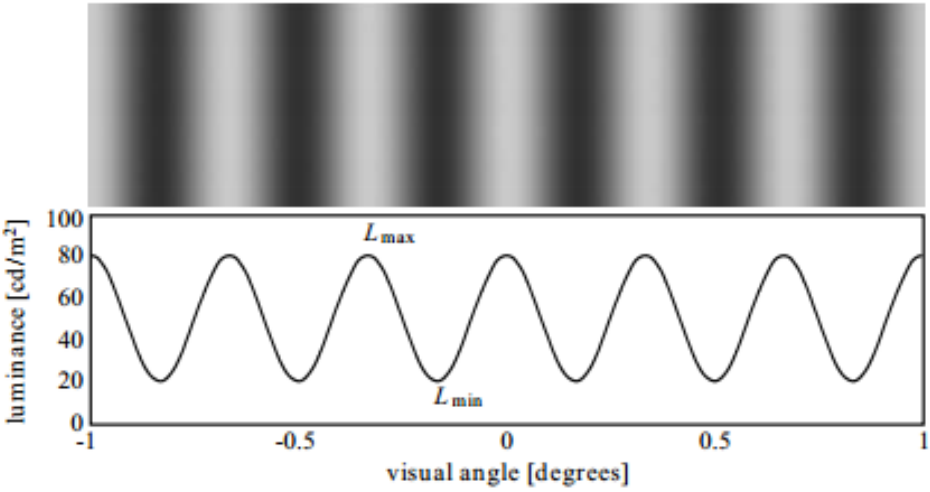
Protanomaly

Tritanomaly



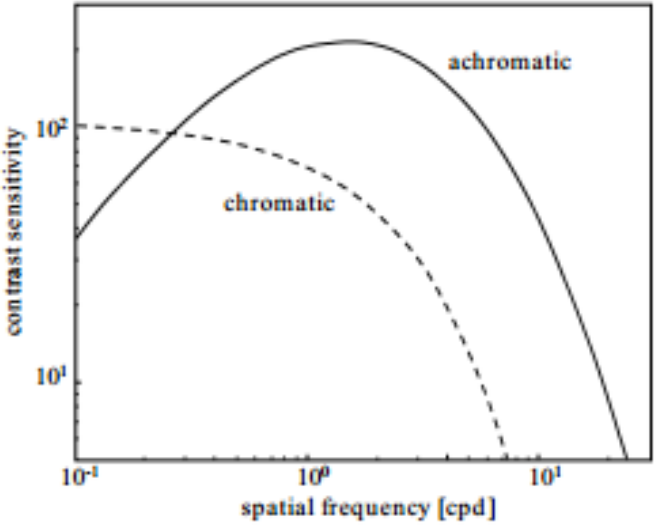


Variation of the modulation transfer function of a human eye model with wavelength. (cpd) cycles per degree



Sinusoidal grating with contrast of $C_M = 0.6$ and its luminance profile.

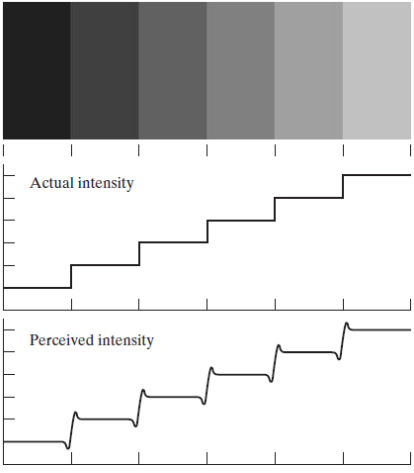
$$C_M = \frac{L_{max} - L_{min}}{L_{max} + L_{min}}$$



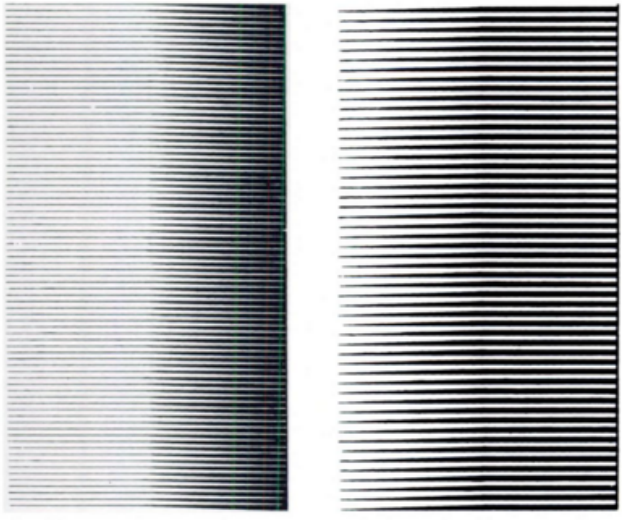
Approximations of achromatic and chromatic contrast sensitivity functions.

Match Band

- Brightness perception is not strictly a function of intensity
- The visual system introduces under shoot and over shoot at boundaries



Mach Band Effect



Vertical lines are an ilussion created by nonlinear response of the visual system to spatial frequency

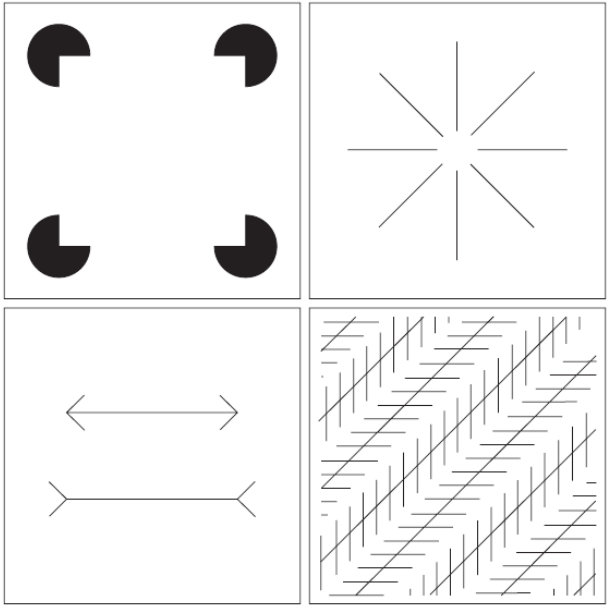
Simultaneous Contrast

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.

- The perceived brightness depends on the background

Human Perception Influences

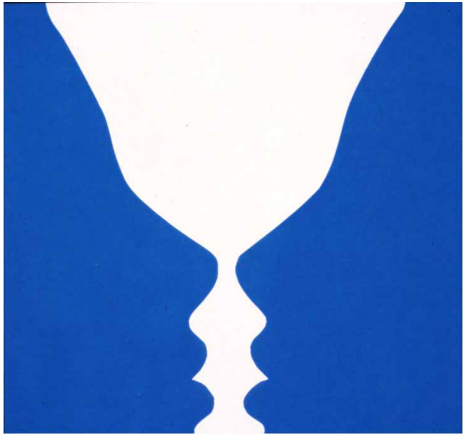


a b
c d

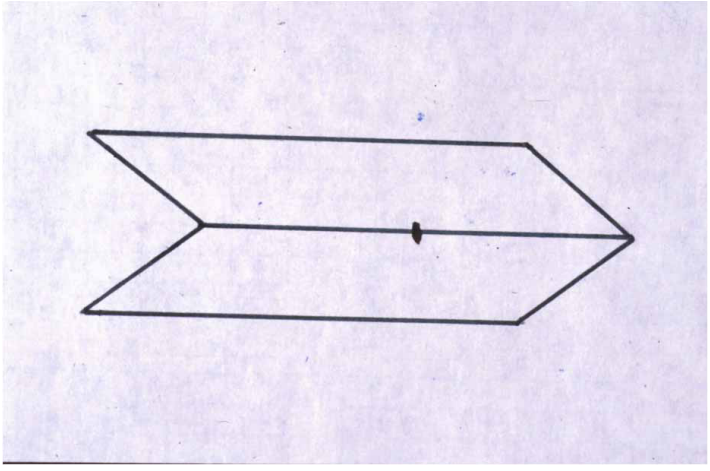
FIGURE 2.9 Some well-known optical illusions.

Visual Perception

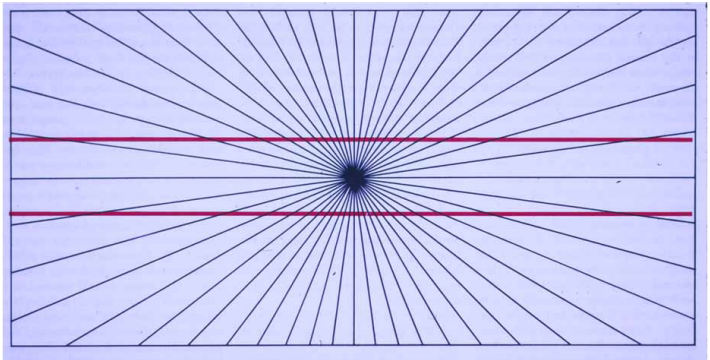
- Although both the blue area and white area are in our visual field, we cannot see figure and ground simultaneously.



- Illusion. Where is the dot located?

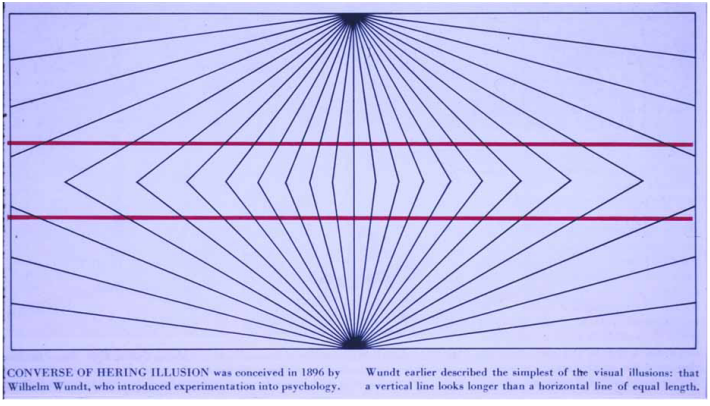


- The background in an image cannot be discovered from the foreground.
- Question: Are the red horizontal lines parallel or bowed outward?



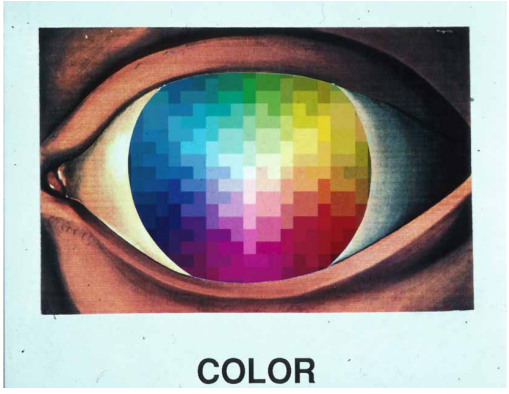
HERING ILLUSION was published in 1861 by Ewald Hering. The horizontal lines are of course straight. Physicists and astronomers of that period took a lively interest in illusions, being concerned that visual observations might sometimes prove unreliable.

- Change the background and you change the foreground. Now the red lines look bowed inward.

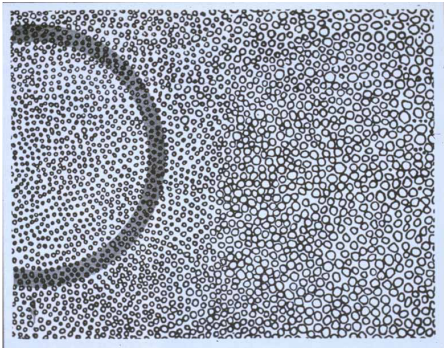


CONVERSE OF HERING ILLUSION was conceived in 1896 by Wilhelm Wundt, who introduced experimentation into psychology. Wundt earlier described the simplest of the visual illusions: that a vertical line looks longer than a horizontal line of equal length.

- Subjective contours are related to the idea of closure.


COLOR

Retina: Cons (Color) and Rods (Movement, Low brightness)



"GRAIN" of the human retina is made up of cones and rods (*dots at far right*). Semicircle indicates fovea.

Are the two small rings the same physical color.

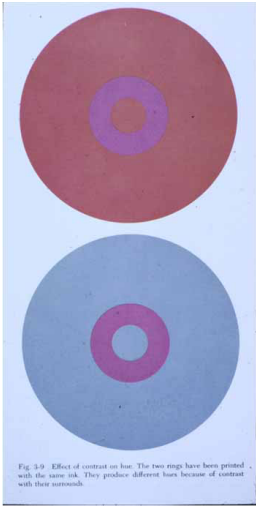


Fig. 3-9 Effect of contrast on hue. The two rings have been printed with the same ink. They produce different hues because of contrast with their surrounds.

The color in the red and blue bars changes as dark and light patterns are superimposed

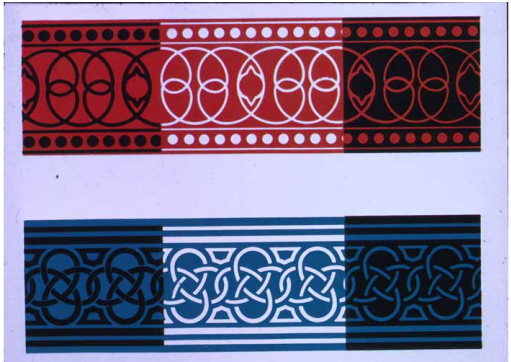
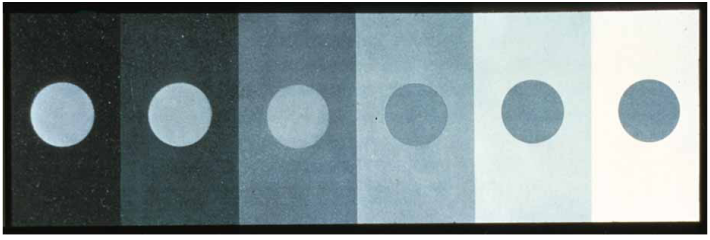
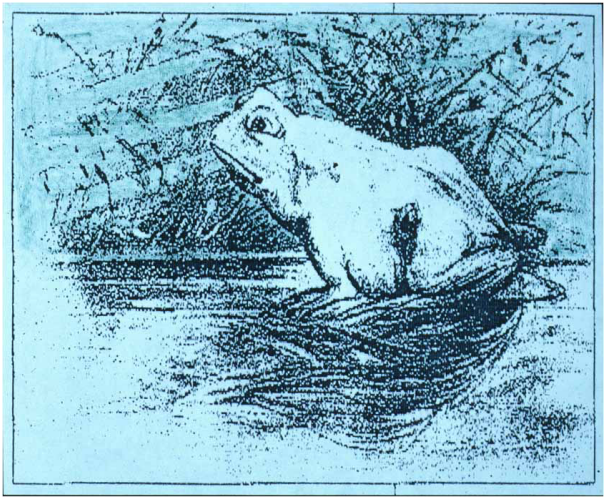
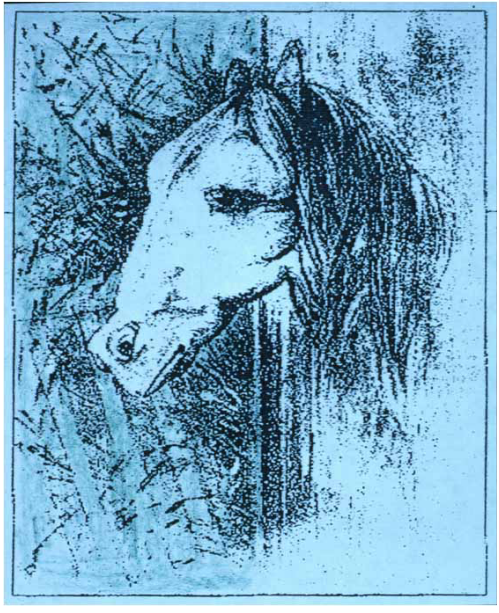


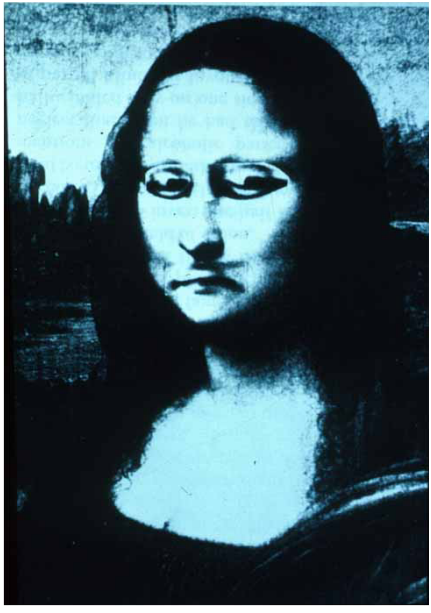
Fig. 3-12 Von Bezold spreading effect. The appearance of any area of red or blue depends largely on the colors of the adjacent areas. The appearance shifts are opposite to those that would be predicted on the basis of contrast. The phenomenon is referred to as spreading or assimilation. (*From:* Evans, R. M., *An Introduction to Color,* New York, John Wiley & Sons, Inc., 1948, Plate XI.)

Simultaneous contrast

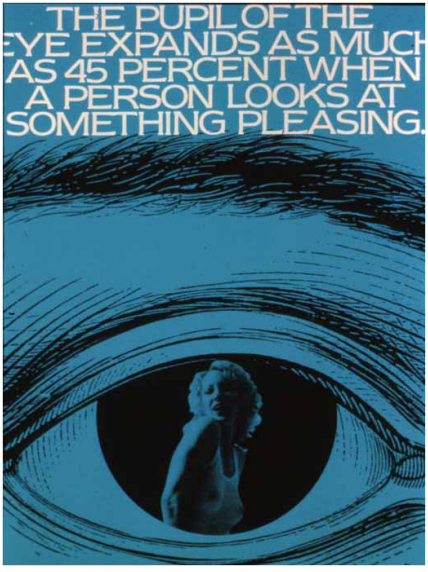


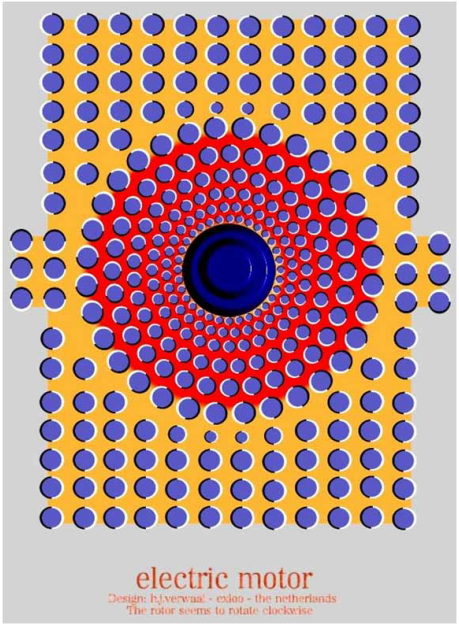




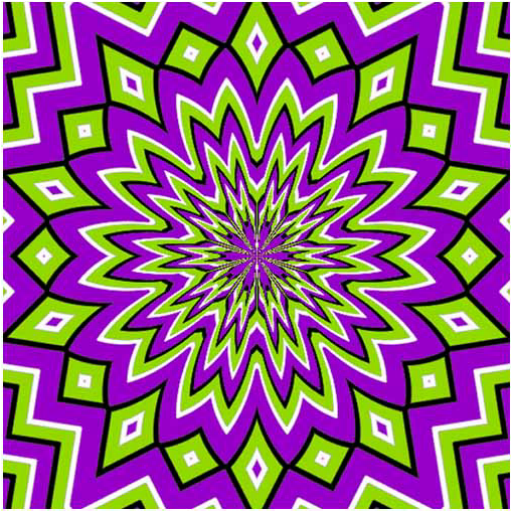


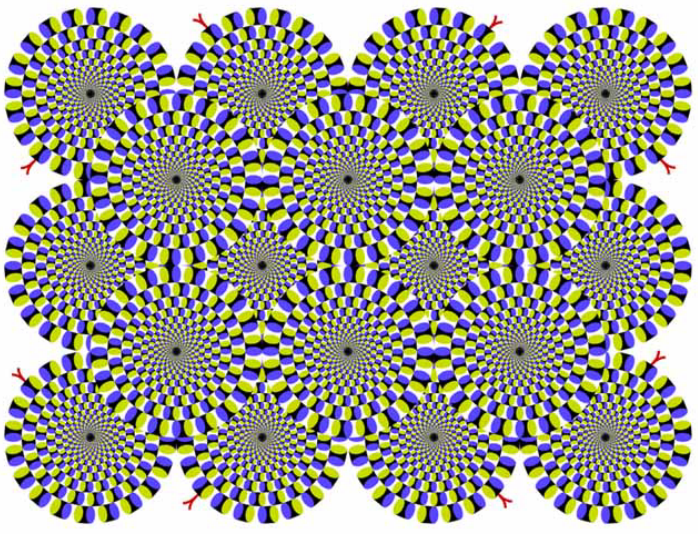
Pupillometrics

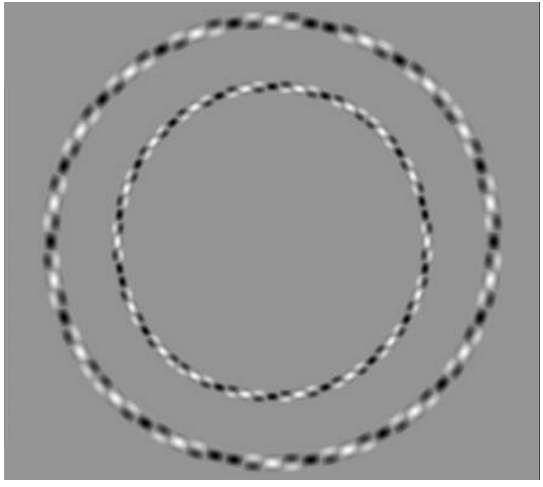



electric motor
Design: h.j.verwaal - exloo - the netherlands
The rotor seems to rotate clockwise

As your vision moves back and forth the center area seems to be moving toward the center (contracting).





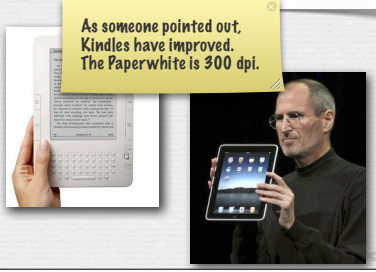


Spatial Resolution of Display Media

pitch = Δx  density = $1/\Delta x$

- Example #1: Macbook Air (laptop)
  - 900 pixels on 7" high display
  - Δx = 7"/ 900 pixels = 0.0078"/pixel
  - $1/\Delta x$ = 129 dpi (dots per inch)
- Example #2: Kindle 2
  - 800 pixels on 4.8" high display
  - $1/\Delta x$ = 167 dpi
- Example #3: iPad ~~iPad~~ iPad3
  - 1024 ~~pixels~~ 2048 on 7.8" high display
  - $1/\Delta x$ = 132 ~~dpi~~ 263

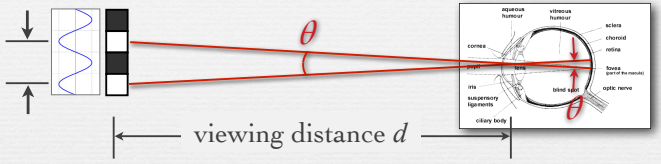
Line printers are 300 dpi. This is why we don't like reading on laptops.



© Marc Levoy

Spatial Frequency on the Retina

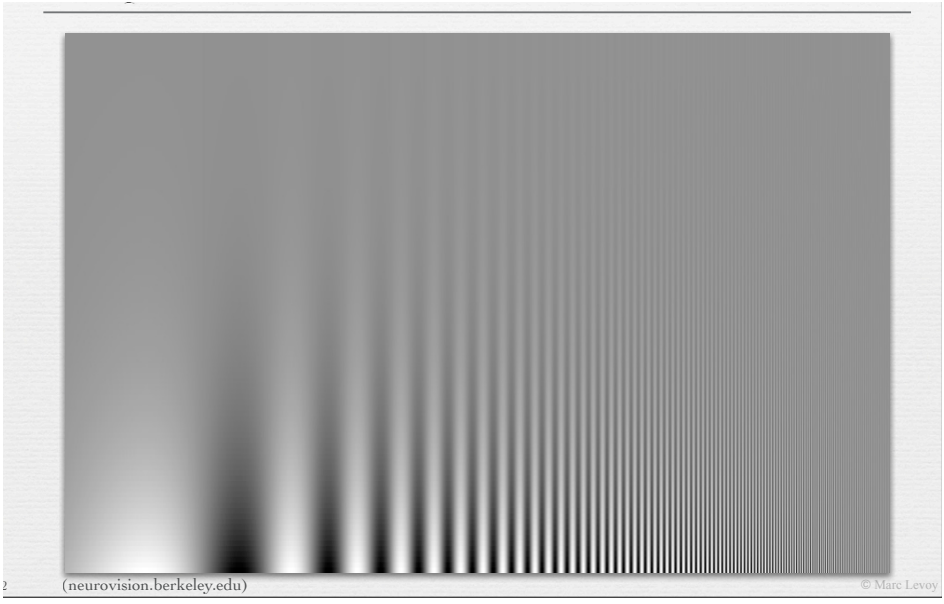
assume the minimum period p of a sine wave is a black-white pixel pair ("line pair")



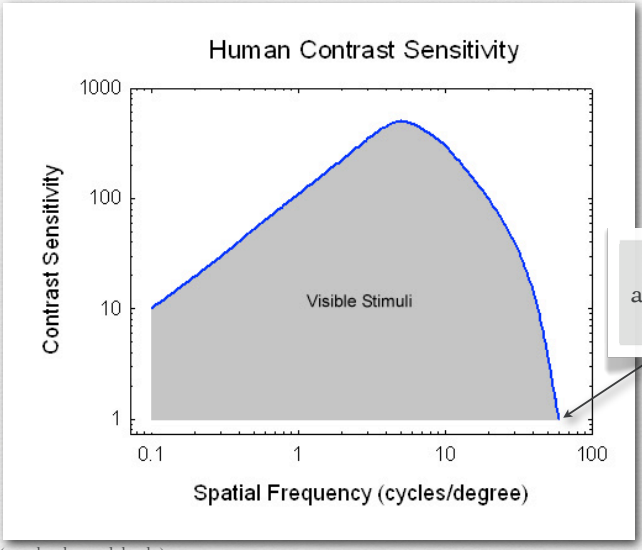
- Example #1: Macbook Air viewed at $d = 18$"
  - 900 pixels on 7" high display, $p = 2 \times 0.0078$"
  - retinal arc $\theta = 2 \arctan(p / 2d) = 0.05°$
  - spatial frequency on retina $1/\theta = 20$ cycles per degree

Q. What is the acuity of the human visual system?

Human Spatial Sensitivity (Campbell-Robson Chart)



Human Spatial Sensitivity



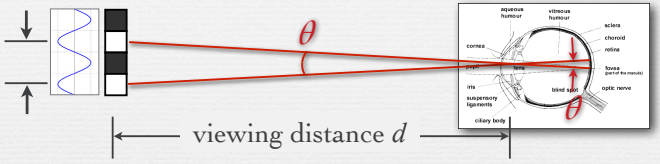
(horizontal axis not comparable to image on previous slide)

cutoff is at about 50 cycles per degree

(psych.ndsu.nodak.edu)

Spatial Frequency on the Retina

assume the minimum period p of a sine wave is a black-white pixel pair



- Example #1: Macbook Air viewed at $d = 18''$
  - 900 pixels on $7''$ high display, so $p = 2 \times 0.0078''$
  - retinal arc $\theta = 2 \arctan(p / 2d) = 0.05°$
  - spatial frequency on retina $1/\theta = 20$ cycles per degree

not nearly as high as human acuity

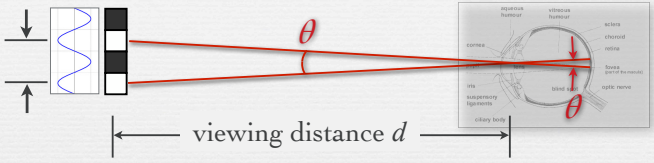
(Graham Flint)

Balboa Park, San Diego

(original is 40K × 20K pixels, Gates Hall print is 72" × 36")

Spatial Frequency on the Retina

assume the minimum period p of a sine wave is a black-white pixel pair

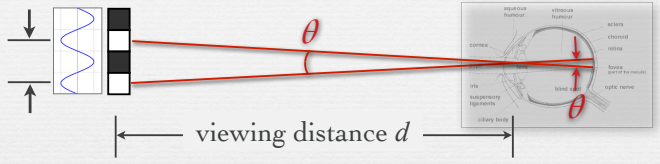


- Example #1: Macbook Air viewed at $d = 18$"
  - 900 pixels on 7" high display, $p = 2 \times 0.0078$"
  - retinal arc $\theta = 2 \arctan(p / 2d) = 0.05°$
  - spatial frequency on retina $1/\theta = 20$ cycles per degree
- Example #2: gigapixel photo viewed at $d = 48$"
  - 20,000 pixels on 36" high print, $p = 2 \times 0.0018$"
  - spatial frequency on retina $1/\theta = 232$ cycles per degree

much finer than human acuity

Spatial Frequency on the Retina

assume the minimum period p of a sine wave is a black-white pixel pair



- Example #2: gigapixel photo viewed at $d = 48$"
  - 20,000 pixels on 36" high print, $p = 2 \times 0.0018$"
  - spatial frequency on retina $1/\theta = 232$ cycles per degree

- Example #3: iPad Pro
  - 2048 pixels on 7.8" high display, $p = 2 \times 0.0038$"
  - $1/\Delta x = 263$ dpi
  - if viewed at 18", spatial frequency on retina = 41 cycles per degree

almost retina resolution

Spatial Frequency on the Retina

Studio Display

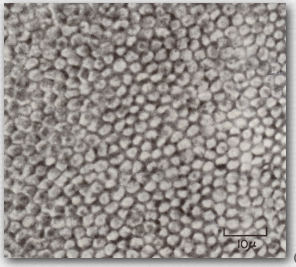
- 5120 by 2880 pixels (5k Display)
- 23.5" by 13.3"
- $1/\Delta x = 218$ pixels per inch
- d = 23", Spatial frequency = 43 cycles per degree
- 1 billion colors

Pro Display XDR

- 6016 by 3384 pixels (6k Display)
- 27.6" by 15.5"
- $1/\Delta x = 218$ pixels per inch
- d = 23", Spatial frequency = 43 cycles per degree
- 1073 billion colors

Spatial Frequency on the Retina

- the human retina consists of discrete sensing cells
- therefore, the retina performs sampling
- sampling theory says $f_{sampling} > 2 \times f_{cutoff}$
- if observed human cutoff is 50 cycles per degree, then its sampling rate must be > 100 samples per degree
- this agrees with observed retinal cell spacing!



(Cornsweet)

spacing between L,M cone cells is 1μ ≈ 30 arc-seconds (1/120°)