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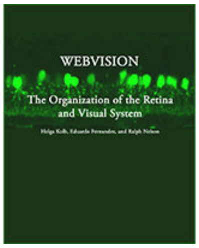

Facts and Figures Concerning the Human Retina

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Size of the Retina

- 32 mm from ora to ora along the horizontal meridian (1) (Kolb, unpublished measurements).
- The area of the human retina is 1,094 square mm (Bernstein, personal communication), calculated from the expectations that the average dimension of the human eye is 22 mm from anterior to posterior poles, and that 72% of the inside of the globe is retina (2). See also Penkhus (3).

Size of Optic Nerve Head or Disc

- 1.86 × 1.75 mm (Fig. 1)

Degrees and Distance in Micometers

- One degree of visual angle is equal to 288 µm on the retina without correction for shrinkage (4).

Foveal Position

- 11.8° or or 3.4 mm temporal to the optic disk edge

Cross Diameter of the Macula

- 3 mm of intense pigmentation, surrounded by a 1-mm-wide zone of less pigmentation (5).

Cross Diameter of the Central Fovea from Foveal Rim to Foveal Rim

- 1.5 mm (5)
- 1.2-1.5 mm (Ahnelt and Kolb, unpublished data) (Fig. 2a and Fig. 2b)

Cross Diameter of Central Rod-free Area

- 400-600 µm (5)
- 750 µm (6)
- 570 µm (7)

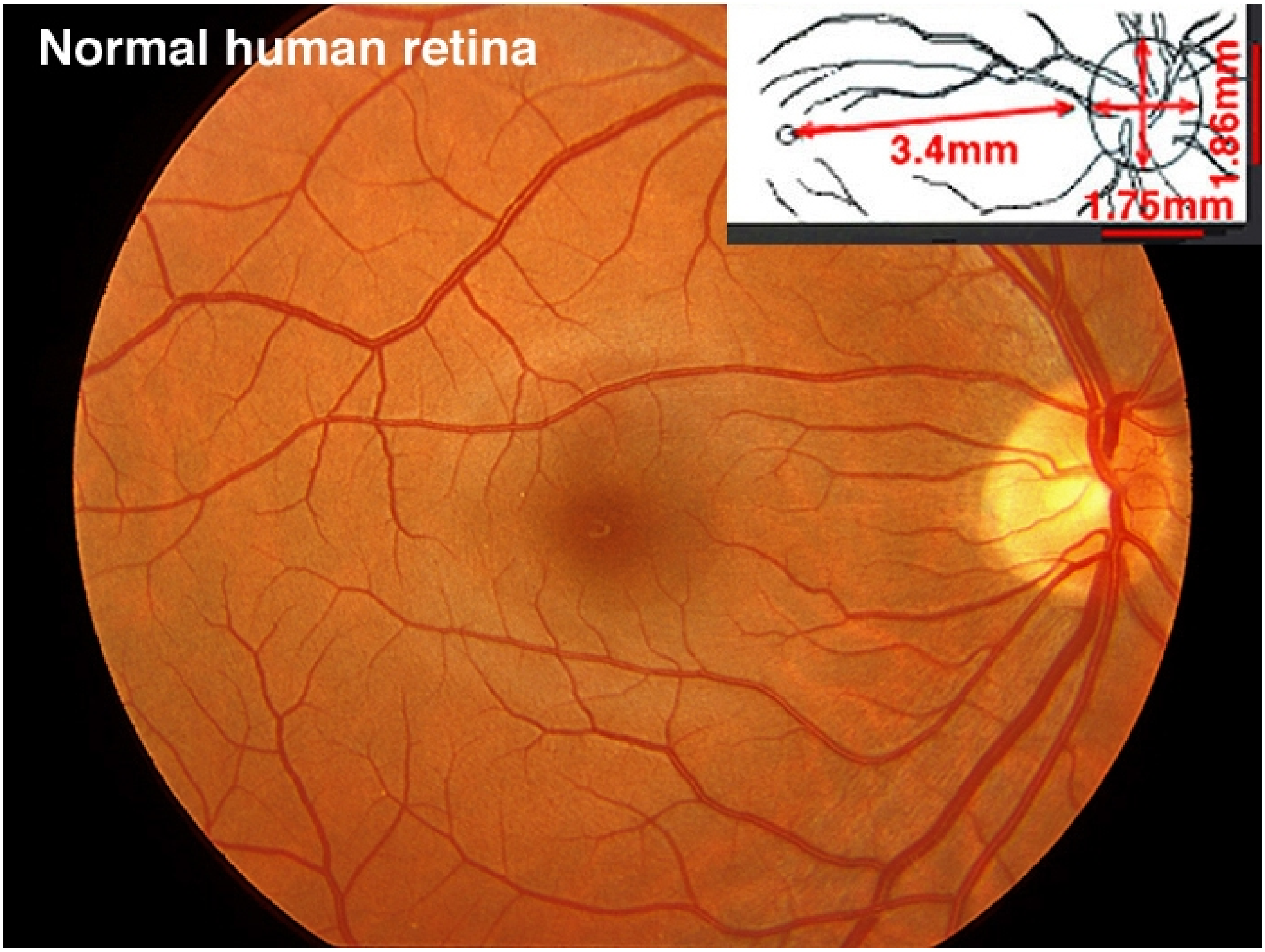

Figure 1. Topography and dimensions of optic nerve and fovea.

- 250 µm (8)

Vertical Thickness of the Fovea from Inner Limiting Membrane (ILM) to ELM

- in the foveal pit, 150 µm (7)
- foveal rim, 400 µm

Central Region of Fovea Where There Are No Cone Pedicles

- 250 µm (7)
- 200 µm (6)
- 300 µm (9)

Length of Foveal Axons (Henle Fibers)

- 150-300 µm (9)

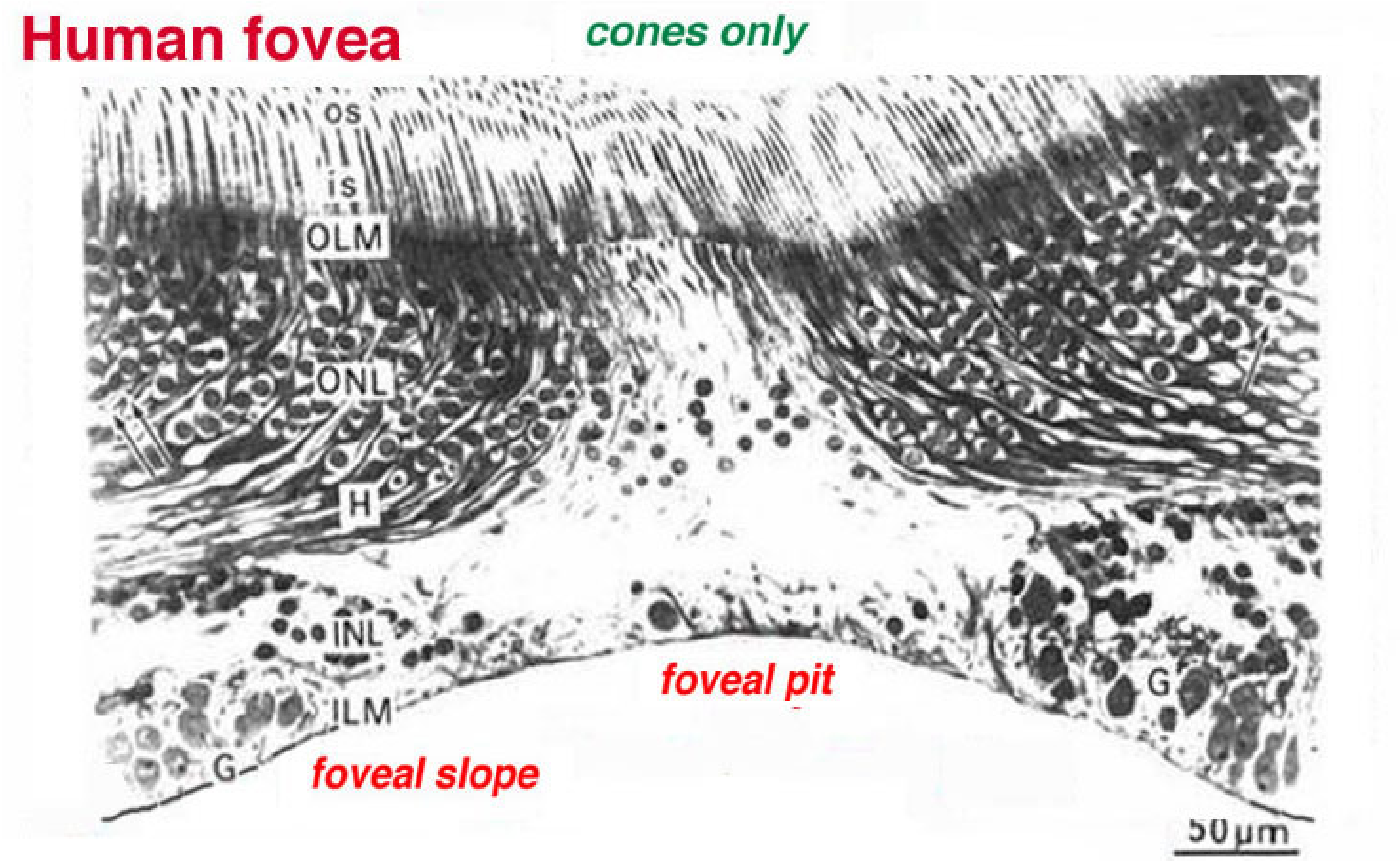

Figure 2a. Vertical section of the human fovea. os, outer segments; is, inner segments; OLM, outer limiting membrane; ONL, outer nuclear layer; H, Henle fibers; INL, inner nuclear layer; ILM, inner limiting membrane; G, ganglion cells. From Yamada (7).

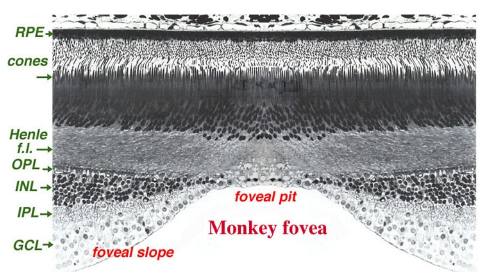

Figure 2b. Vertical section of the monkey fovea. From Hagerman and Johnson (19).

Vertical Thickness of the Retina in Different Areas

The vertical extent of the retina across the horizontal meridian at different eccentricities is shown in Fig. 3. This is taken from data given by Sigelman and Ozanics (20). The small black numbers are the originals from Sigelman and Ozanics which were measured in typical histological preparations where there is a great deal of shrinkage. The figures in red are those recently measured by Ahnelt (personal communication) in well fixed EM quality material where there is little or no shrinkage. Hence the latter numbers are larger. The numbers are in mm.

Age When Fovea Is Fully Developed

- not before 4 years of age (6)

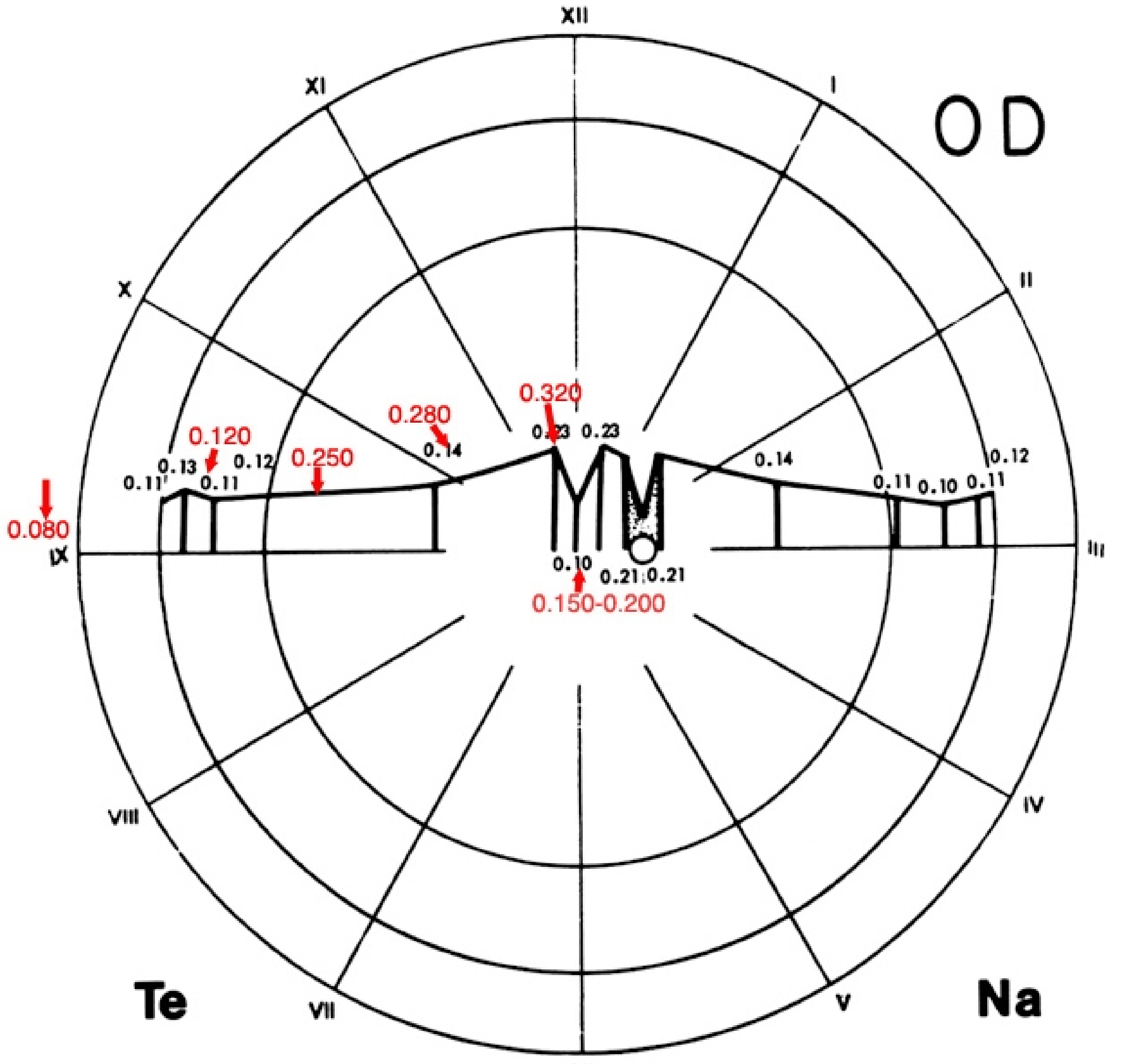

Figure 3. The retinal thickness shows greatest variations in the center. The retina is thinnest at the foveal floor (0.10, 0.150-0.200 mm) and thickest (0.23, 0.320 mm) at the foveal rim. Beyond the fovea the retina rapidly thins until the equator. At the ora serrata the retina is thinnest of all (0.080 mm).

Highest Density of Cones at Center of the Fovea (50 × 50 µm)

- 147,000/mm^2 (10)
- 178,000-238,000/mm^2 (8)
- 96,900-281,000/mm^2; mean, 161,900/mm^2 (11) (Fig. 4)

Total Number of Cones in Fovea

- approximately 200,000. 17,500 cones/degree^2. Rod-free area is 1°; thus, there are 17,500 cones in the central rod-free fovea.

Total Number of Cones in the Retina

- 6,400,000 (10)

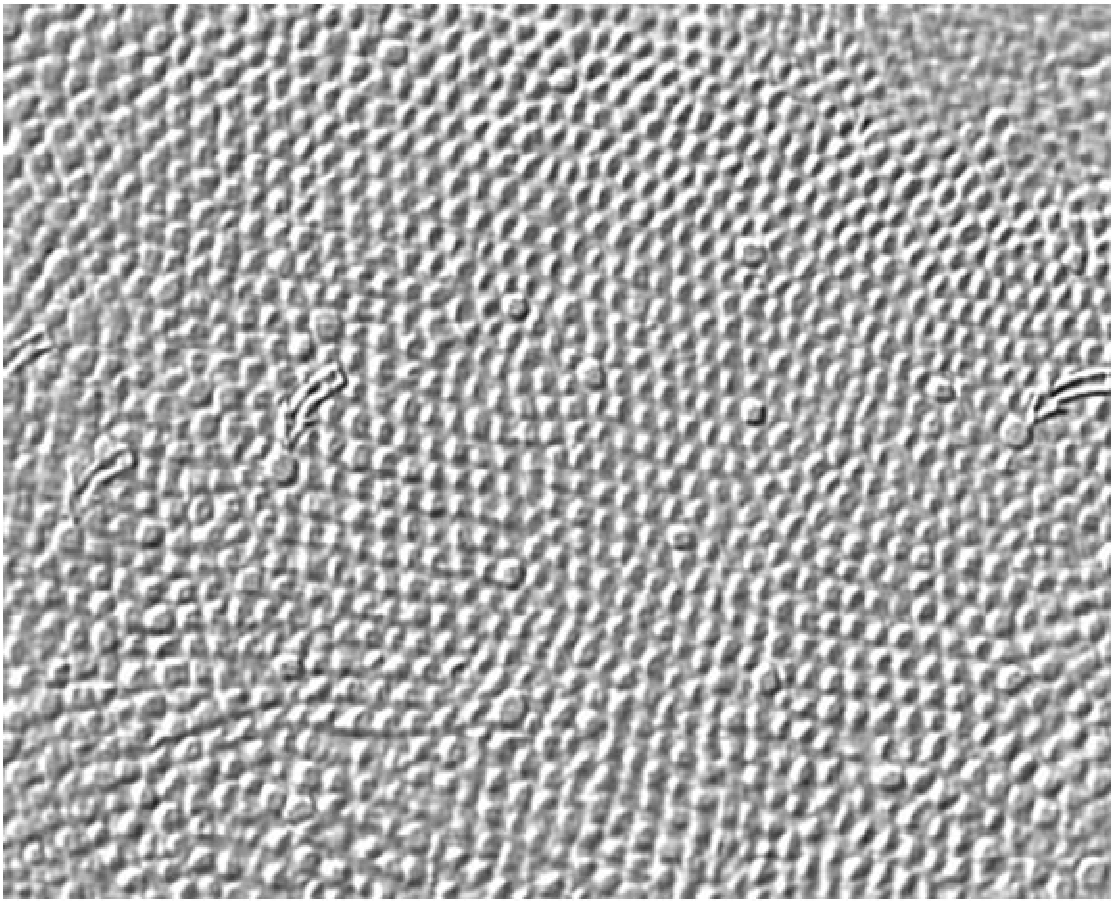

Figure 4. Tangential section through the human fovea. Larger cones (arrows) are blue cones.

Total Number of Rods in the Retina

- 110,000,000 to 125,000,000 (10)

Rod Distribution

- Rods peak in density 18° or 5 mm out from the center of the fovea, in a ring around the fovea at 160,000 rods/mm^2
- No rods in central 200 µm
- Average 80-100,000 rods/mm^2.
- Rod acuity peak is at 5.2° or 1.5 mm from foveal center, where there are 100,000 rods/mm^2 (12) (Fig. 5)

Number of Axons in the Optic Nerve

- 564,776-1,140,030 (13)
- 800,000-1,000,000 (5)
- 1,200,000 (14, 15)

Number of Cones to Ganglion Cells in the Fovea

- 1 cone to 2 ganglion cells out to about 2.2° (16)

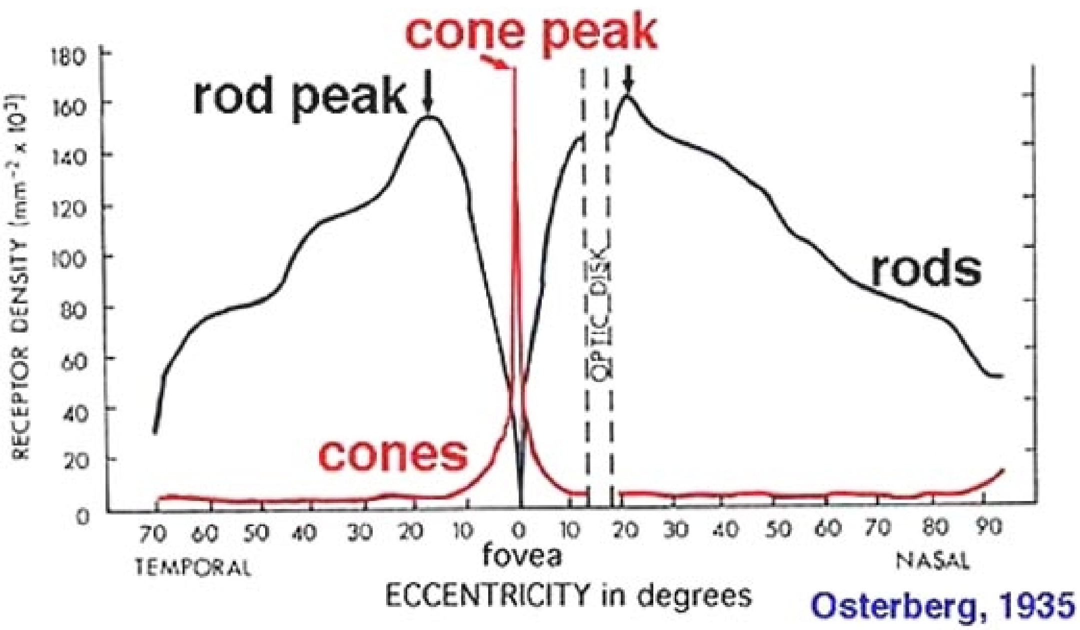

Figure 5. Graph to show rod and cone densities along the horizontal meridian.

Number of Cones/Retinal Pigment Epithelial Cell (RPE)

- 30 cones/RPE in fovea (17)

Number of Rods/Retinal Epithelial Cell (RPE)

- in periphery, 22 rods/RPE cell
- in rod, peak (4-5 mm from foveal center), 28 rods/RPE cell (17)

Number of Neural and Glial Types in the Retina

The retina consists of many millions of cell types packed together in a tightly knit network spread over the surface of the back of the eye fundus as a thin film of tissue only 1/2 millimeter thick. The retina is like a three-layered cake with three layers containing cell bodies of neurons and two filling layers where synapses between the neurons occur. There are two basic kinds of photoreceptors—rods and cones. The cones are further subdivided into two types (long- and short-wavelength sensitive) in the majority of mammals, i.e., most mammals, which are dichromats and have divariant color vision. In primates, a third wavelength-sensitive cone has developed closely related to the long-wavelength cone type but a little more sensitive in the middle wavelength (i.e., green cone). Thus, primates including humans are trichromats and have trivariant color vision. Many reptiles, birds, and fish have four or even five types of cone, each sensitive to a slightly different peak wavelength.

The second-order neurons, postsynaptic to the photorecepors in the first synaptic (filling layer) (outer plexiform layer), are bipolar cells and horizontal cells. There are nine types of bipolar cell and two to four types of horizontal cell in species from mammals to fish. The third-order neurons are amacrine cells and ganglion cells that synapse in the inner synaptic filling layer (inner plexiform layer). There are two types of interplexiform cells stretching between both plexiform layers, in most vertebrate retinas. There are approximately 22 types of amacrine cell and 20 types of ganglion cell in the typical mammalian retina. There may be 30 or more amacrine cell types in fish and reptilian retinas and 22 or so ganglion cell types. The increased number of third-order neurons is attributable to the greater information processing taking place in the non-mammalian retinas than in mammalian retinas.

All vertebrate retinas also contain large numbers of glial cells. The radial Muller cells stretch from outer to inner limiting membranes and surround and isolate all neural cell types from each other except at synapses. Microglia arise in times of injury and are blood-borne cell types. Astrocytes surround ganglion cell axons and inner retinal blood vessels.

Fig. 6 shows a drawing of the human retina close to the fovea, where all of the cell types that have been studied in detail are depicted in their intricate and marvellous network.

Useful Units in Vision Science

From Wandell (18):

- Radiometric units represent a physical measurement, e.g., radiance is measured in watts sr$-^{1}$ m$-^{2}$.
- Calorimetric units adjust radiometric units for visual wavelength sensitivity, e.g., luminance is measured in candela per square meter, cd/m^2.
- Lux are units of illumination. Thus, a light intensity of 1 candela produces an illumination of 1 lux at 1 meter.
  - Scotopic luminance units are proportional to the number of photons absorbed by rod photoreceptors to give a criterion psychophysical result.
  - Photopic luminance units are proportional to a weighted sum of the photons absorbed by L- and M-cones to give a criterion psychophysical result.
- Typical ambient luminance levels (cd/m^2):
  - Starlight: 0.001
  - Moonlight: 0.1
  - Indoor lighting: 100
  - Sunlight: 10.000
  - Maximum intensity of common CRT monitors: 100
- One Troland (Td) of retinal illumination is produced when an eye with a pupil size of 1 mm^2 looks at a surface whose luminance is 1 cd/m^2.
- Lens focal length: f (meters); lens power= 1/f (diopters).

Image Formation

From Wandell (18):

- The eyes are 6 cm apart and halfway down the head.
- Visual angle of common objects (degrees, deg)
  - The sun or moon = 0.5 deg
  - Thumbnail (at arm's length) = 1.5 deg
  - Fist (at arm's length) = 8-10 deg
- Visual field (measured from central fixation)
  - Monocular: 160 deg (w) × 175 deg (h)
  - Binocular: 200 deg (w) × 135 deg (h)
  - Region of binocular overlap: 120 deg (w) × 135 deg (h)
- Range of pupil diameters: 1-8 mm
- Refractive indices
  - Air: 1.000

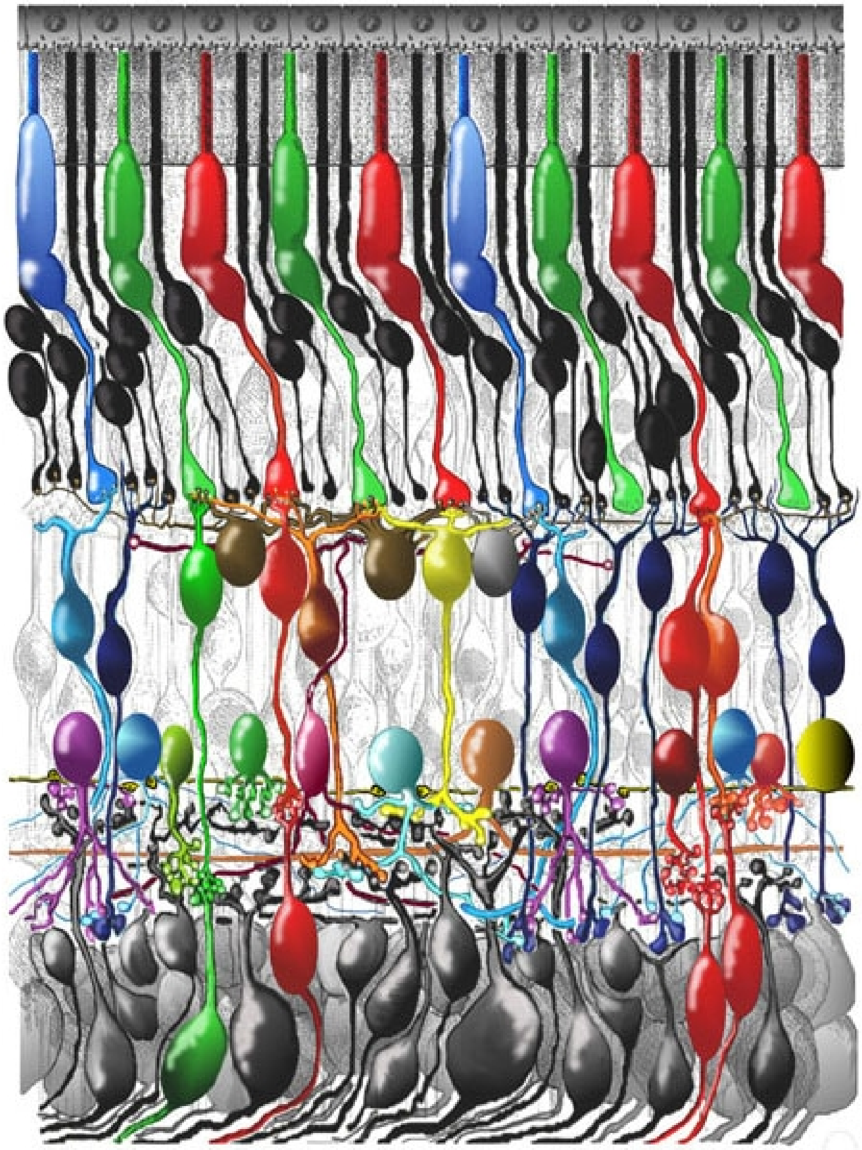

Figure 6. Drawing of a vertical section through the human retina to show the organization of the different neurons and glial cells constituting it.

    - Glass: 1.520
    - Water: 1.333
    - Cornea: 1.376
- Optical power (diopters)
    - Cornea: 43
    - Lens (relaxed): 20
    - Whole eye: 60
    - Change in power due to accomodation: 8
- Axial chromatic aberration over the visible spectrum: 2 diopters
- Visible spectrum: 370-730 nanometers (nm)
- Peak wavelength sensitivity
    - Scotopic: 507 nm
    - Photopic: 555 nm

- Spectral equilibrium hues
    - Blue: 475 nm
    - Green: 500 nm
    - Yellow: 575 nm
    - No spectral equilibrium: red

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