The Photoreceptor Mosaic

Aristophanis Pallikaris
IVO, University of Crete

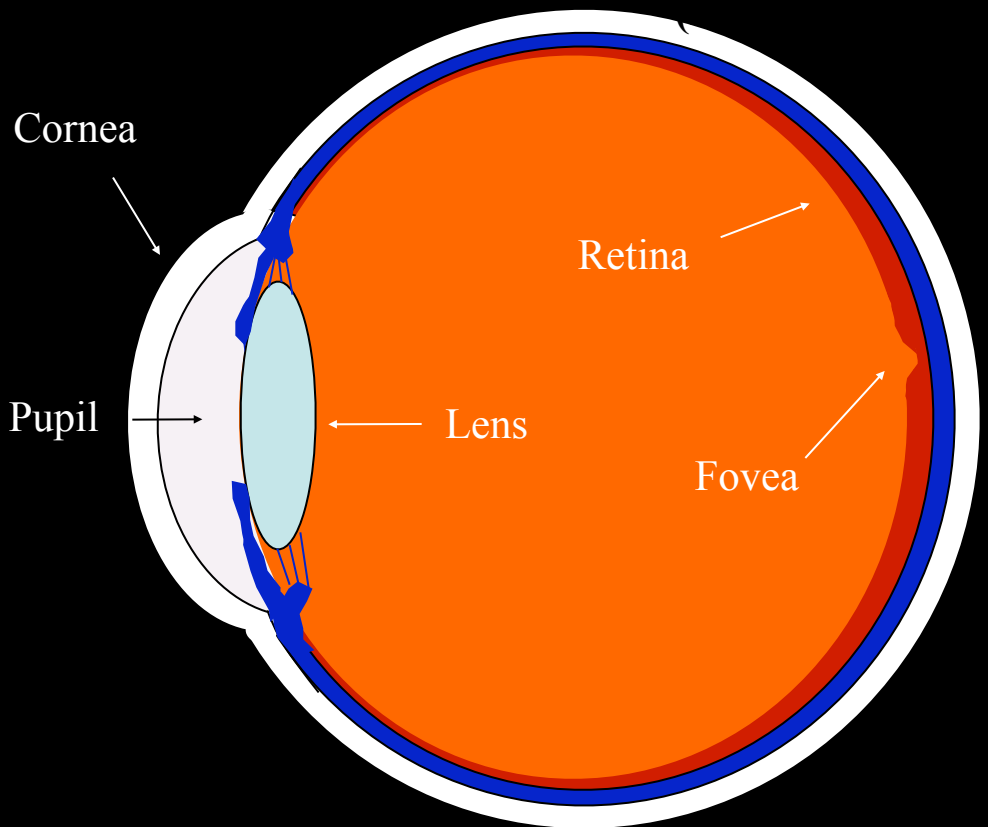
Institute of Vision and Optics
10th Aegean Summer School

Overview

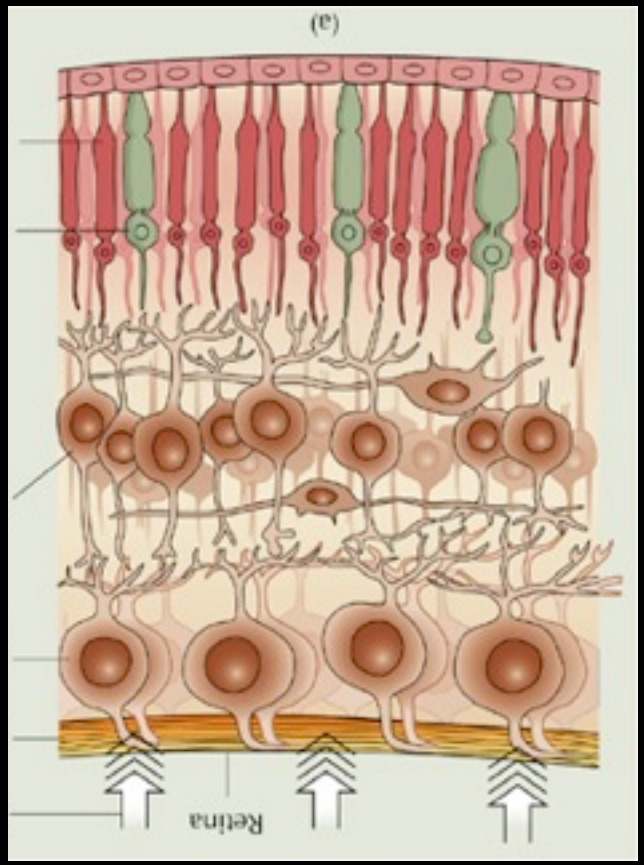
- Brief Anatomy
- Photoreceptors
  - Categorization
  - Visual Function
- Photoreceptor Mosaic
  - Density
  - Size
  - Spatial Regularity
- Sampling Resolution Limits

- Conclusions & Discussion

Eye Anatomy



Retinal Anatomy



Pigmented cells

Photoreceptors

Horizontal, Amacrine, Bipolar Cells

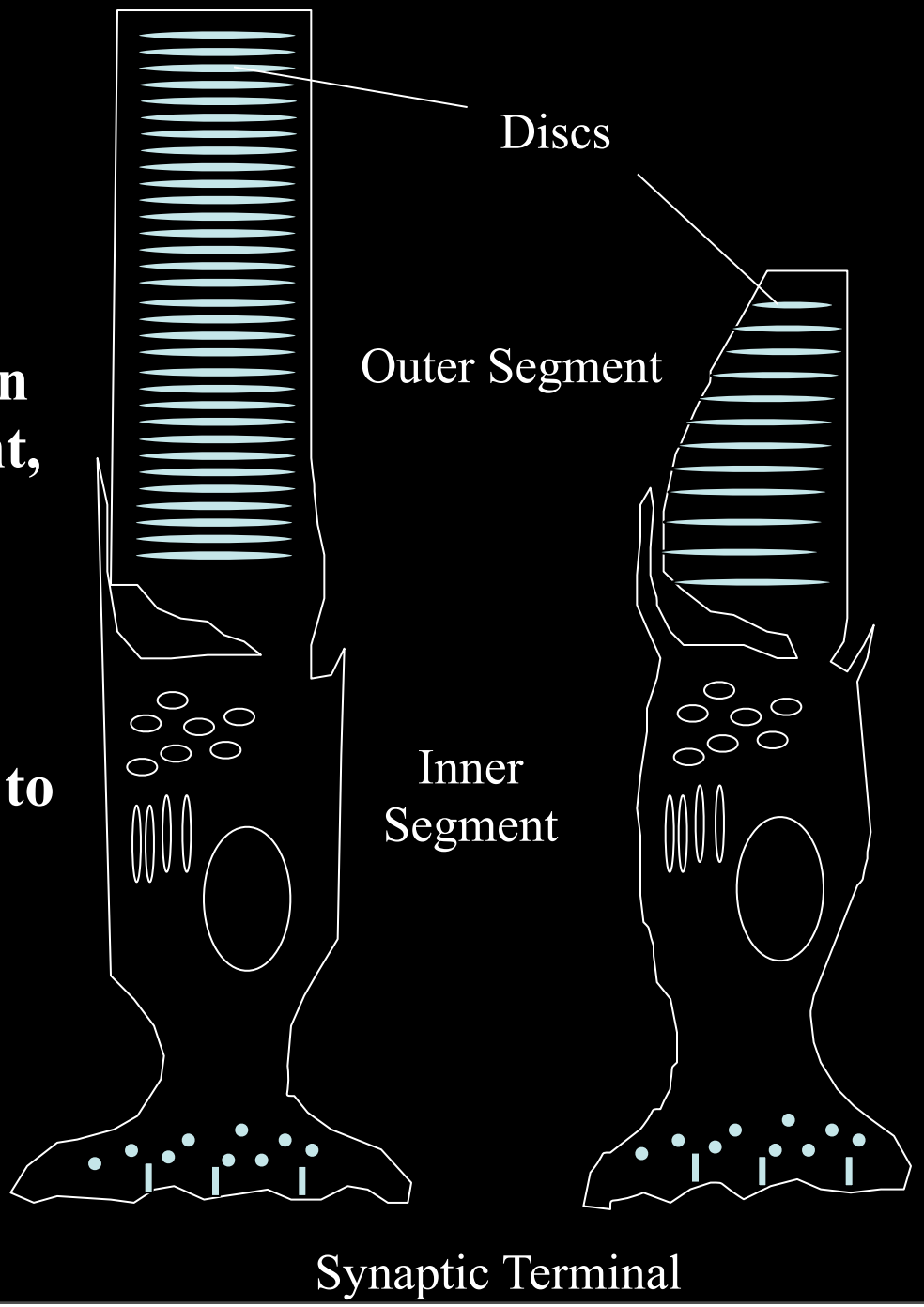
Ganglion cells

PUPIL

2004, John Willey & Sons, Inc
Huffman: PSYCHOLOGY IN ACTION, 7E

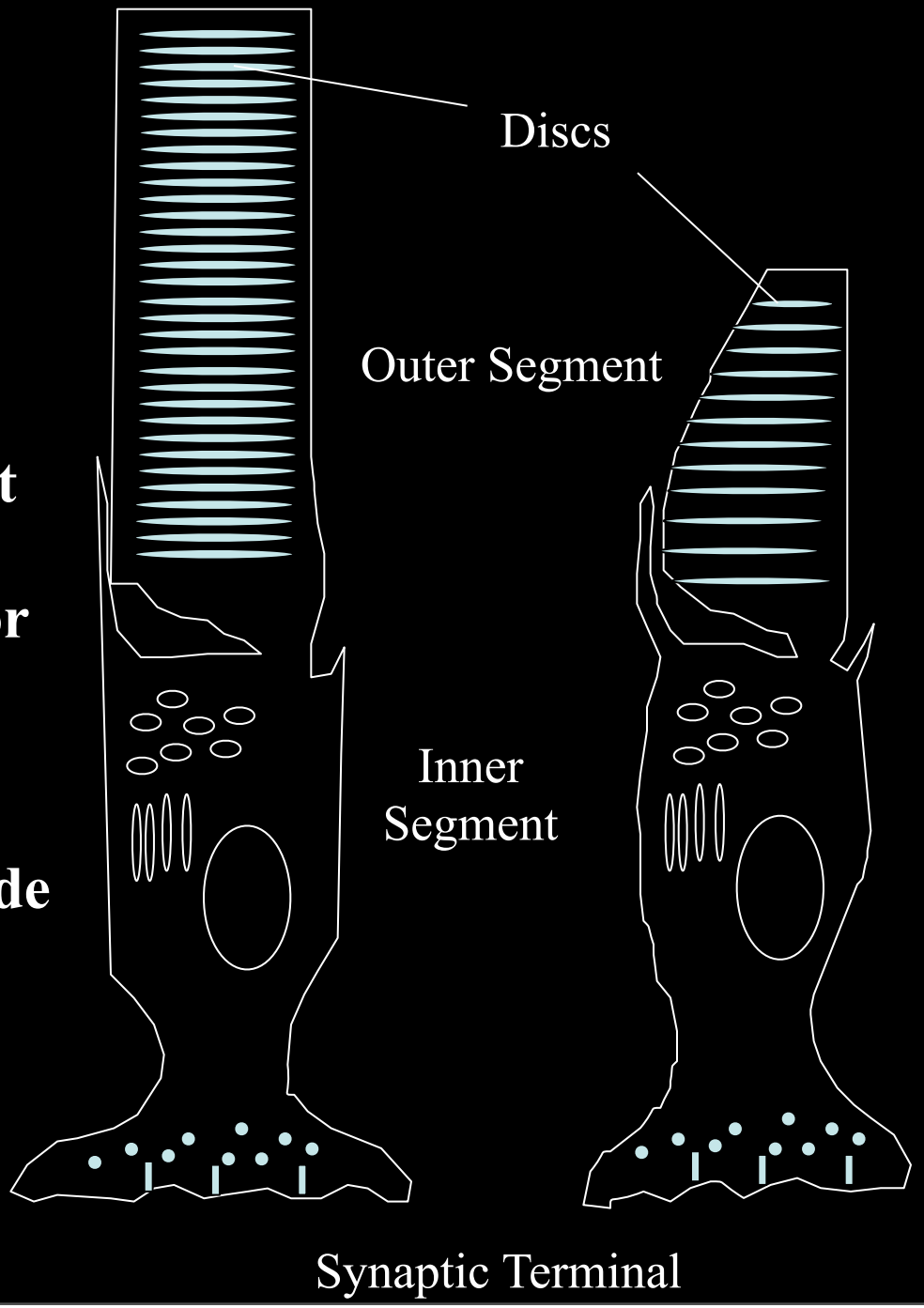
Photoreceptor's Characteristics

The photoreceptors consist of an outer segment, an inner segment, a cell body, and a synaptic terminal.
Cones have conical shaped structure and the discs of the outer segment remain attached to the outer segment membrane.
Rods have slim rod-shaped structure and the discs of the outer segment are free floating inside the outer segment disc.

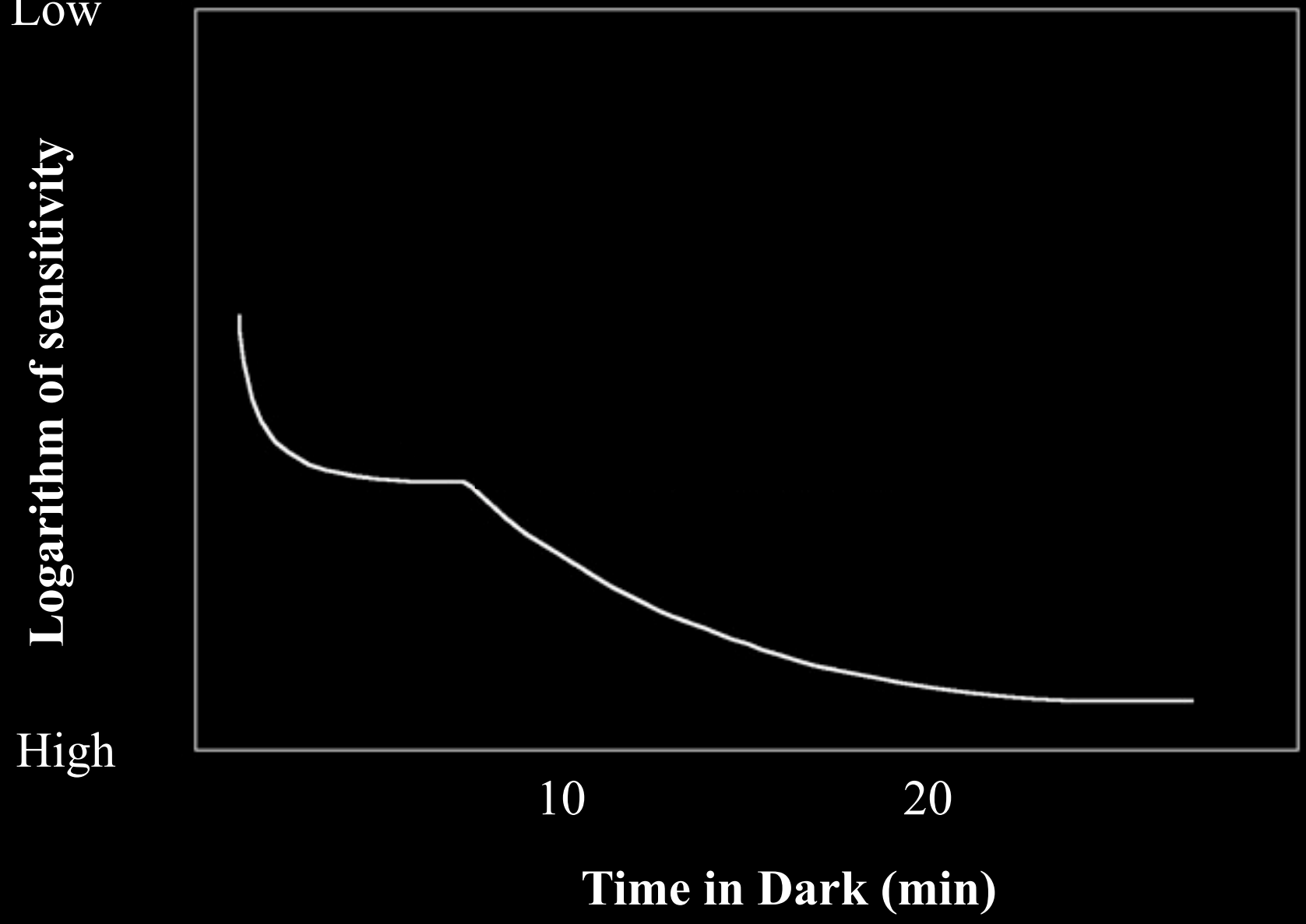


Photoreceptor's Characteristics

Rods contain the visual pigment rhodopsin, are highly sensitive photoreceptors, and are used for vision under dark-dim conditions.
Cones contain cone opsins, are used for color vision, and provide the highest acuity during high light levels.

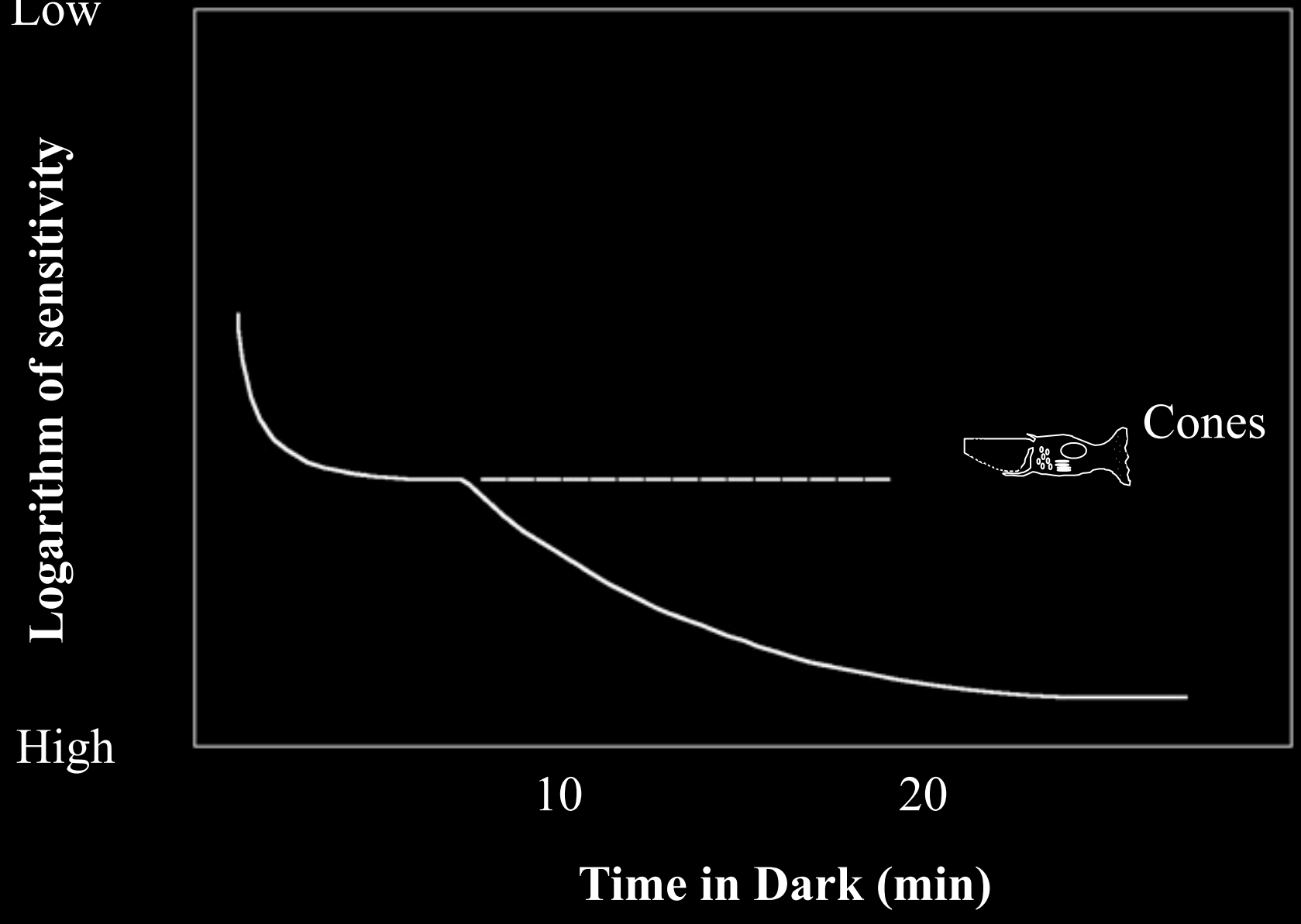


Dark Adaptation of Photoreceptors



McFarland et al 1960

Dark Adaptation of Photoreceptors



McFarland et al 1960

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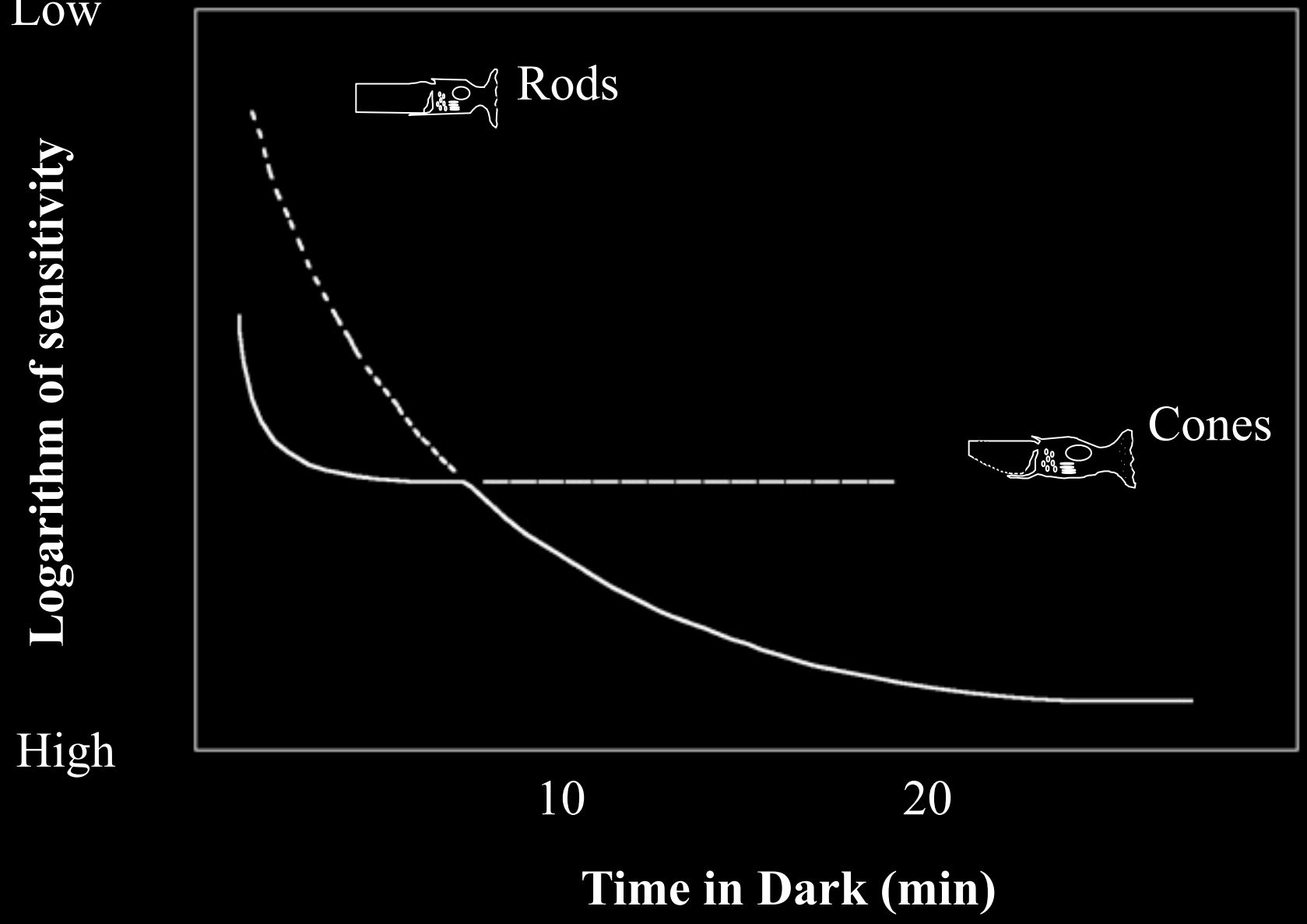
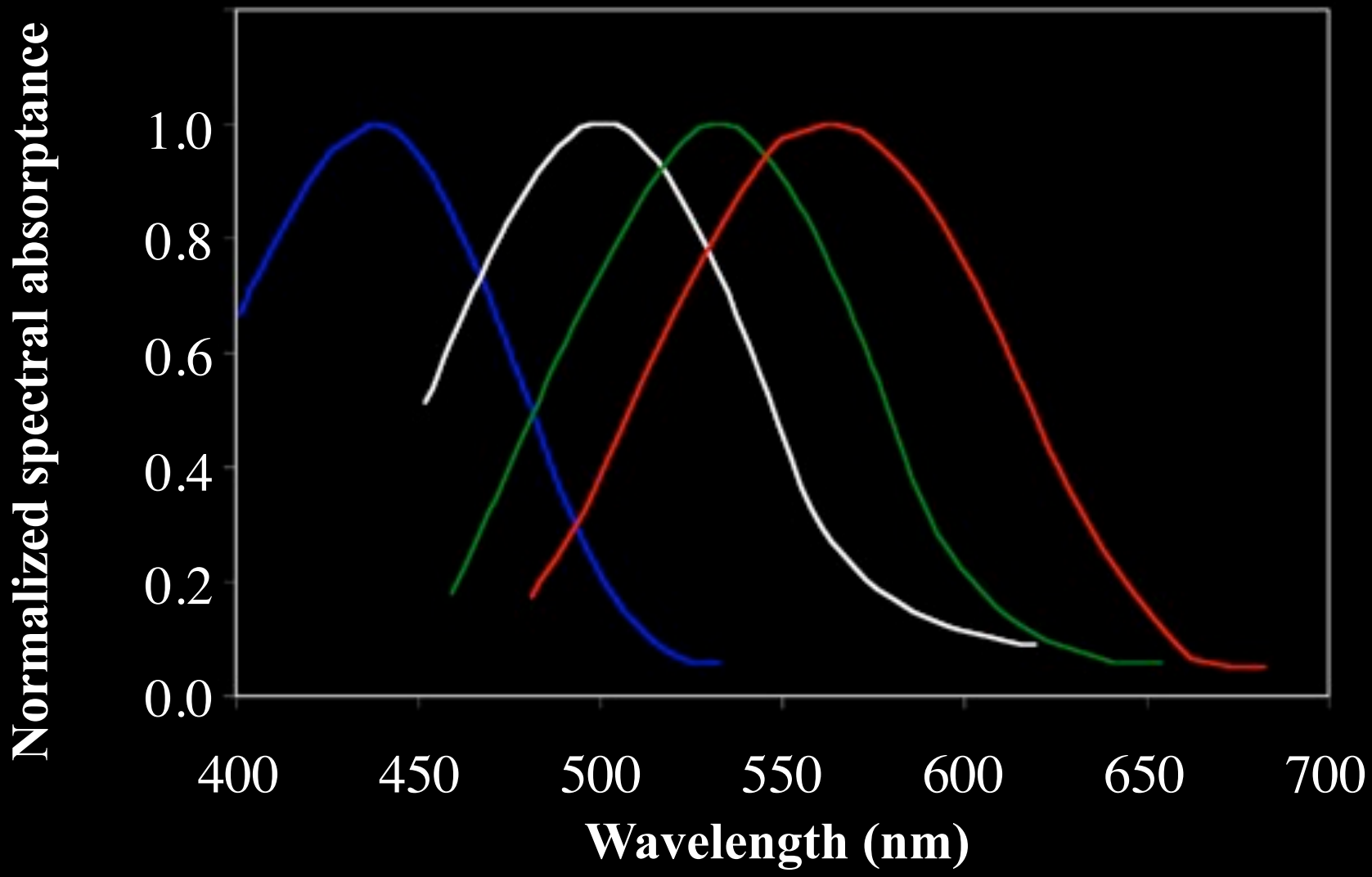


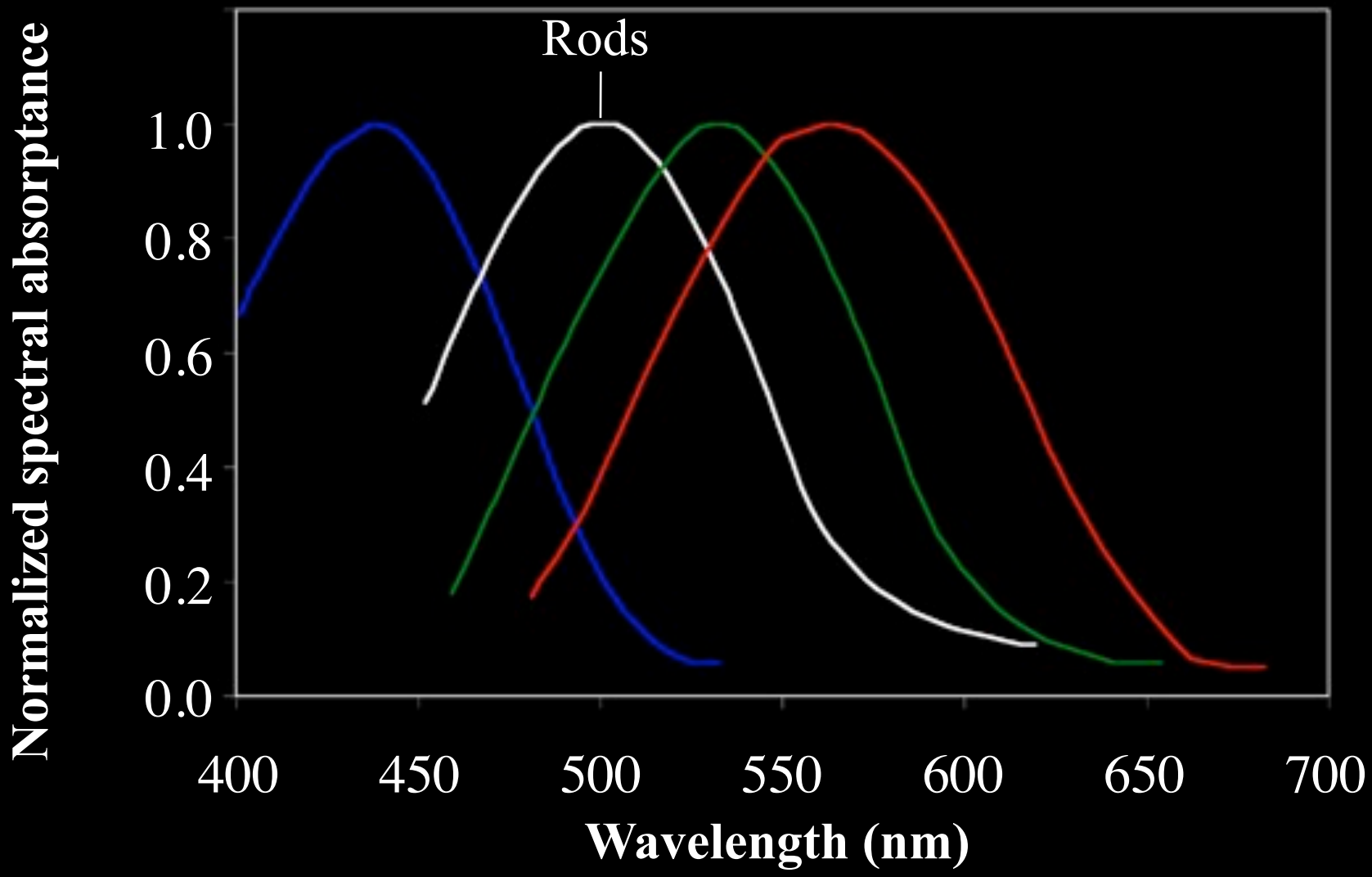
McFarland et al 1960

Spectral Absorptance of Cone Opsins



Brown & Wald 1964,

Spectral Absorptance of Cone Opsins



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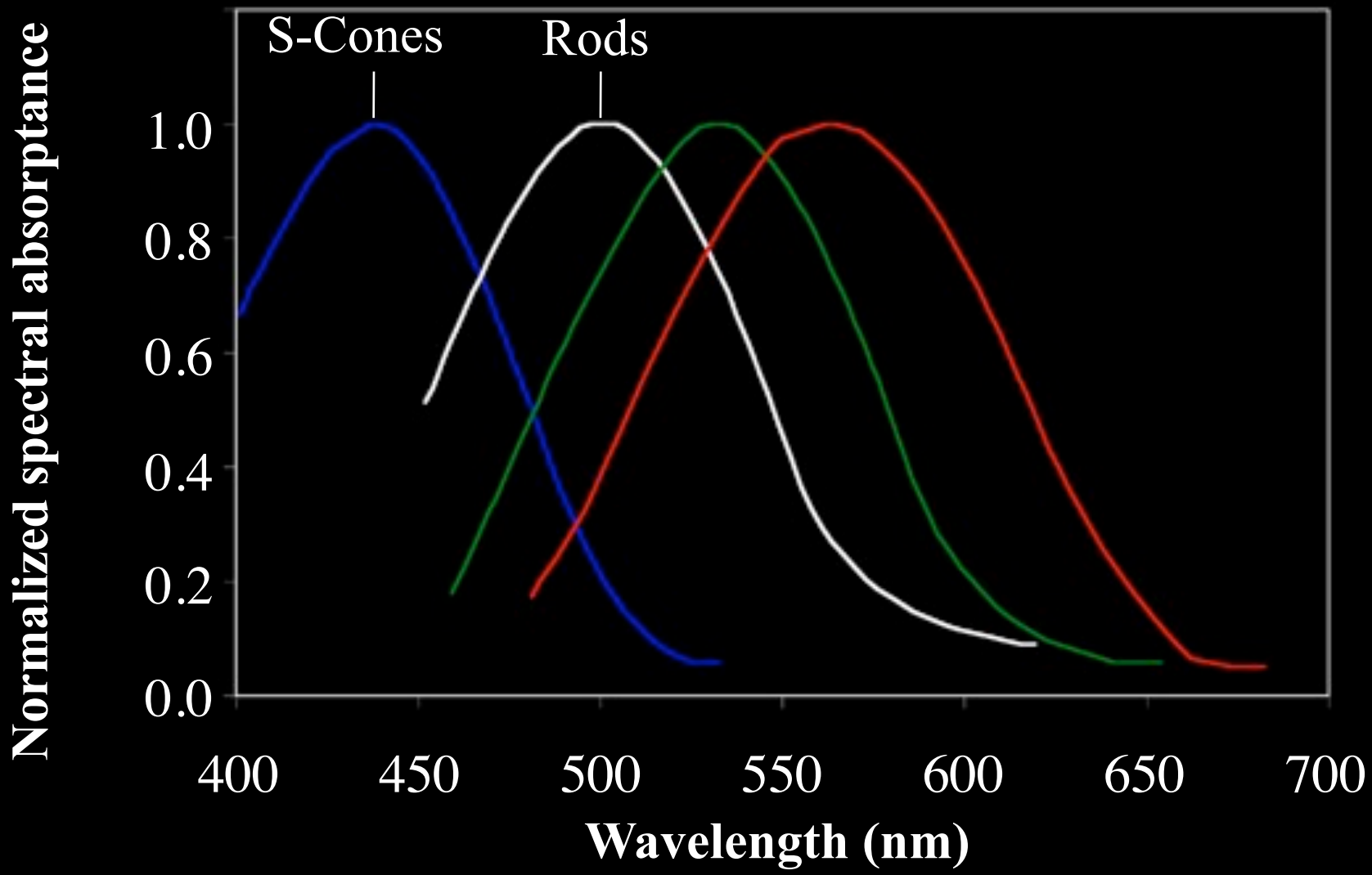
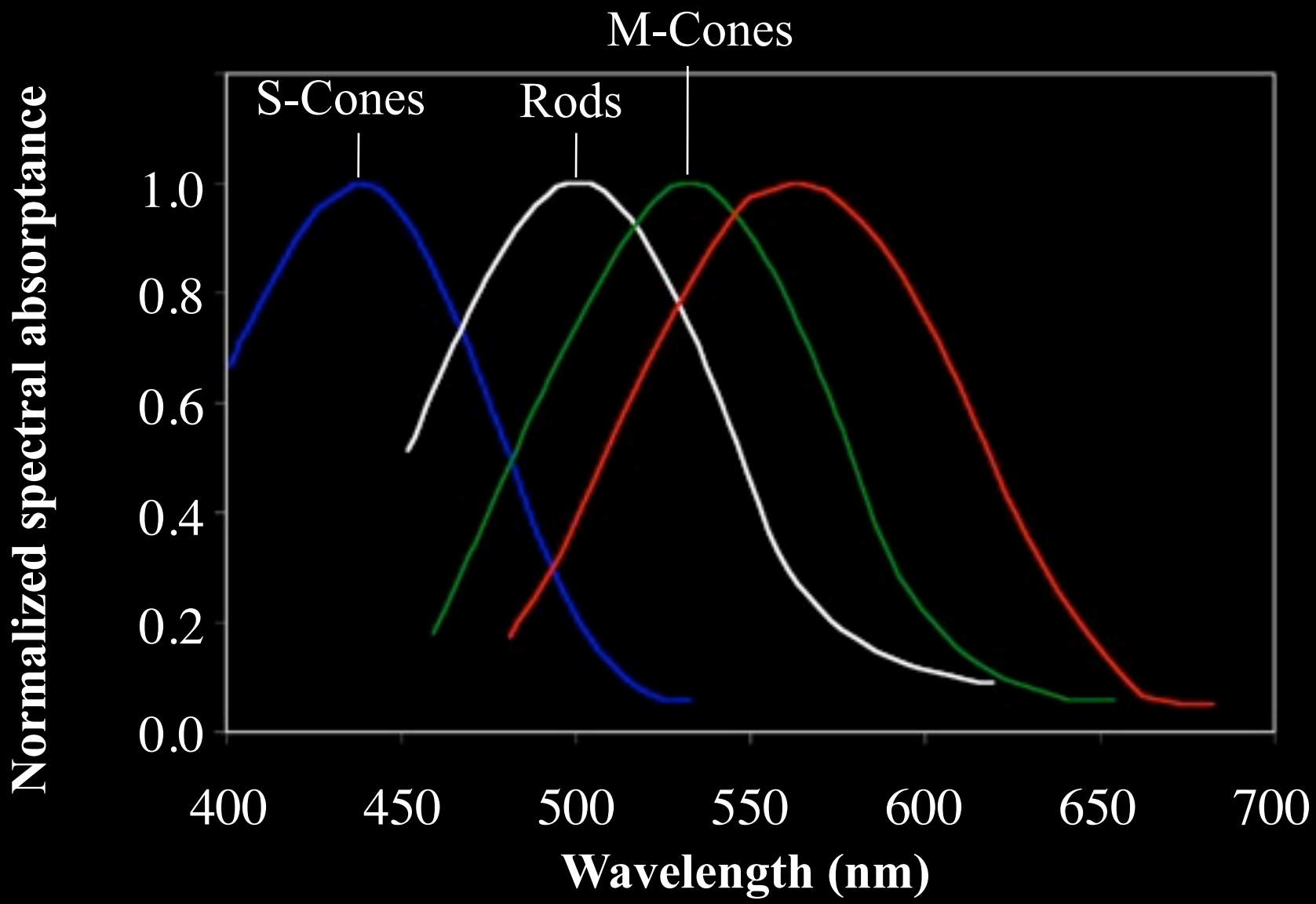


Brown & Wald 1964,

Spectral Absorptance of Cone Opsins



Brown & Wald 1964,

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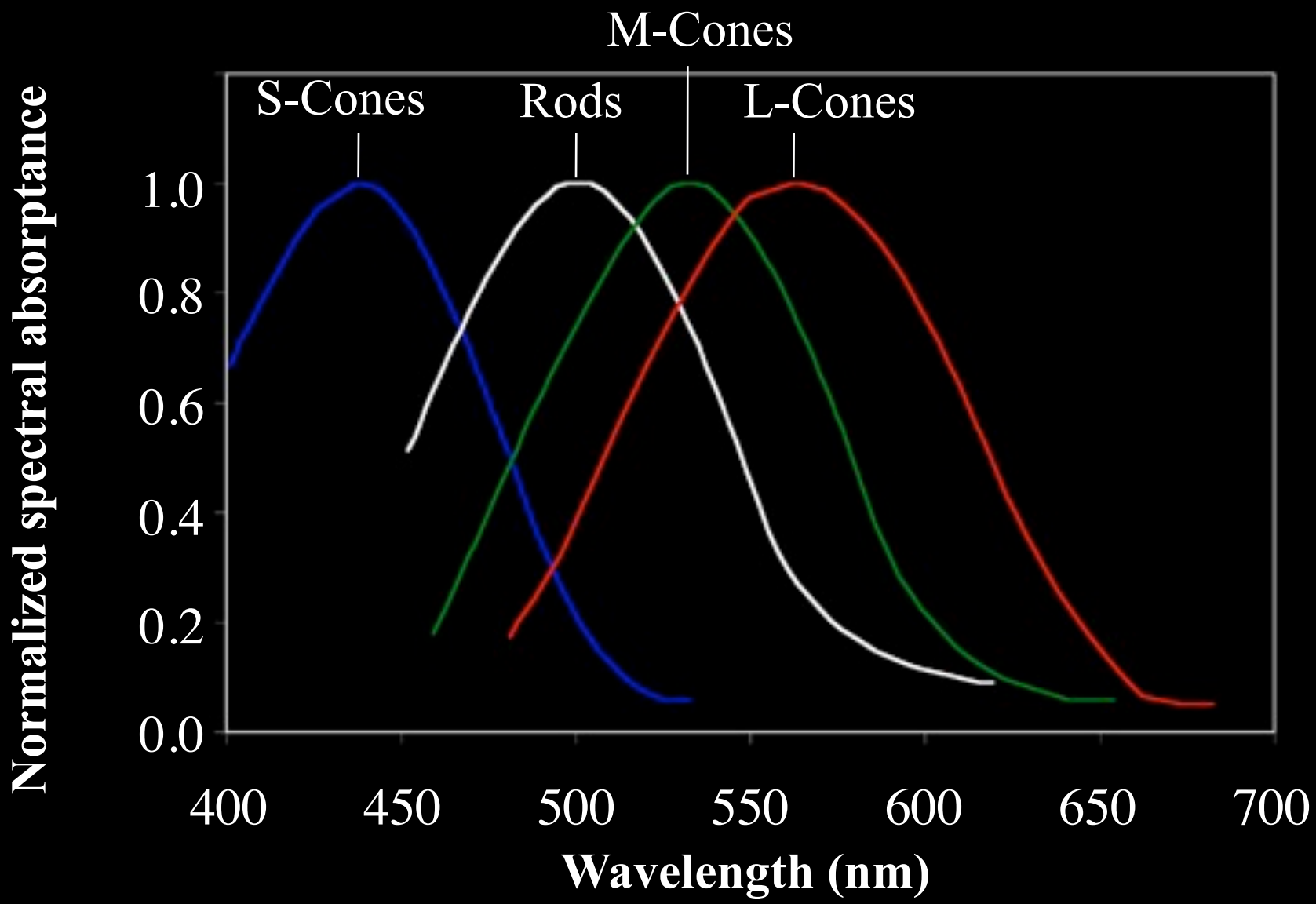
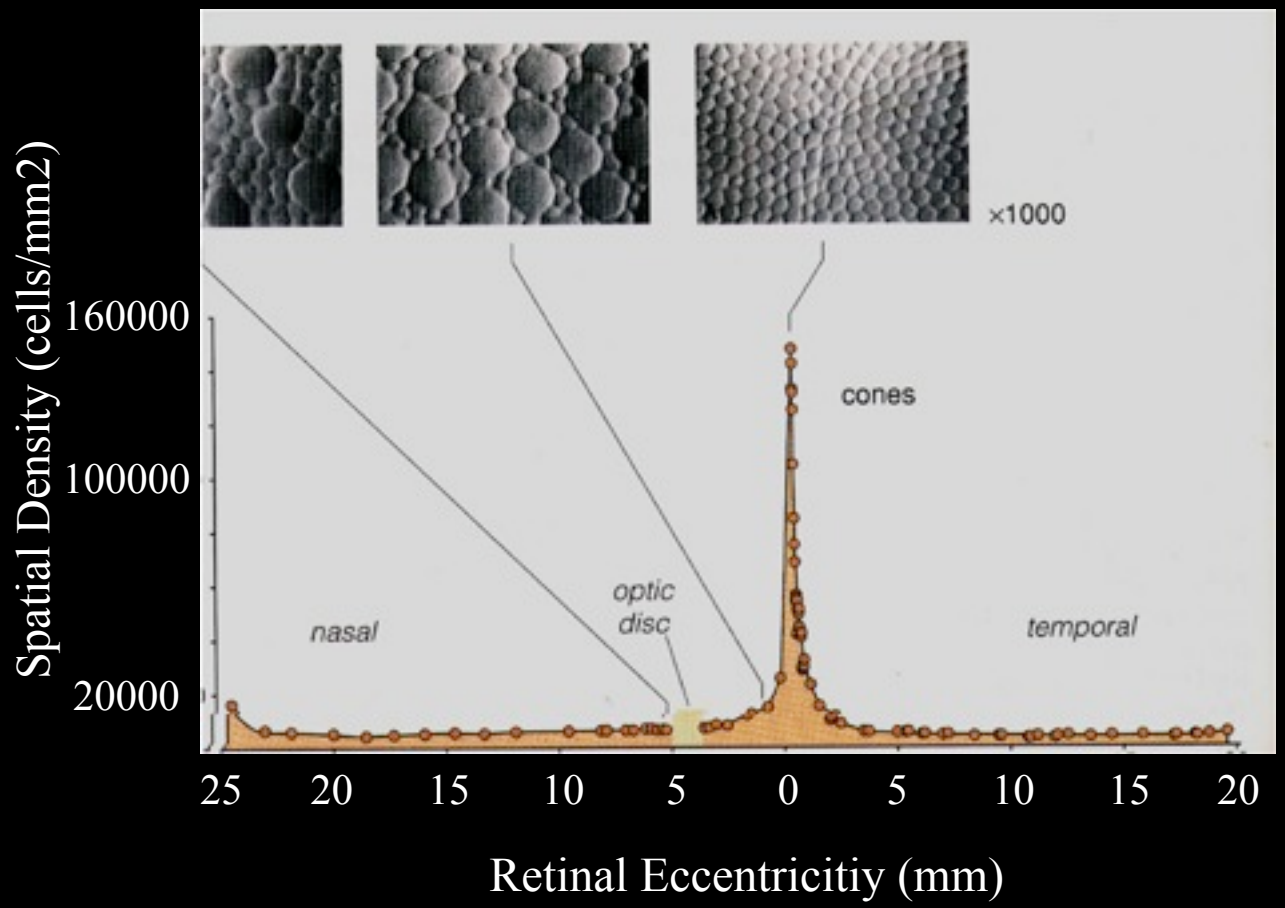


Brown & Wald 1964,

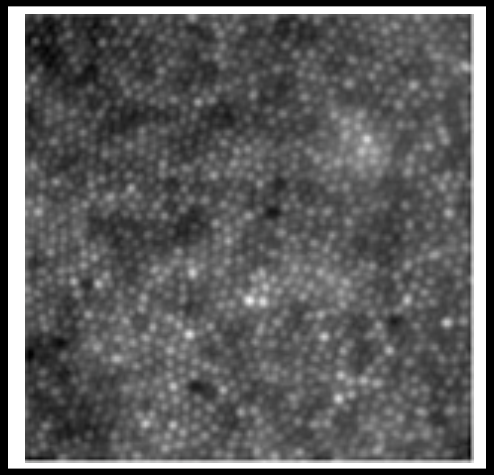
Spatial Density of Cones



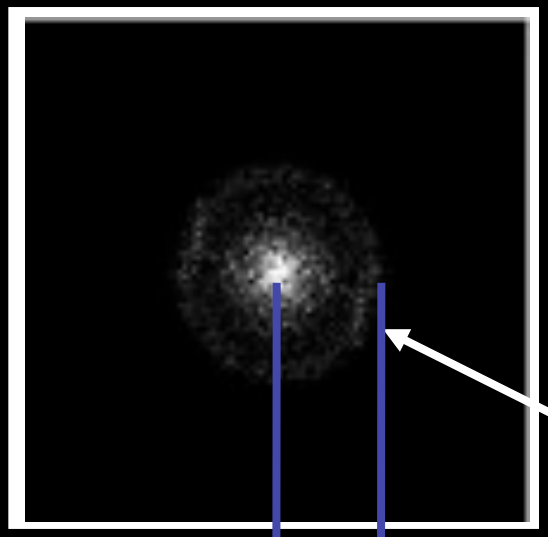
Cones are densely packed in the fovea and their density decreases abruptly with eccentricity.

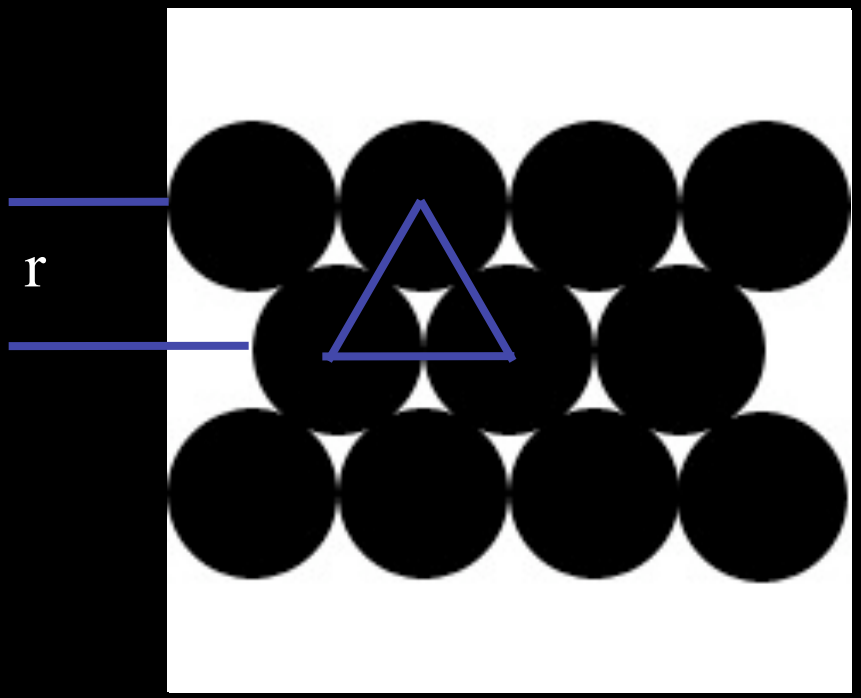
5 million cones

After Osterberg 1935, as modified by Rodieck 1988, micrographs from Curcio 1990

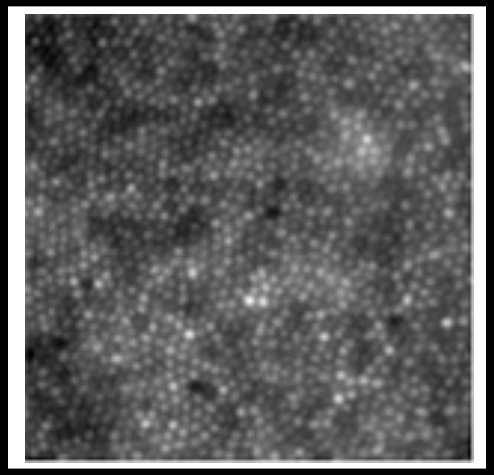


Power Spectrum

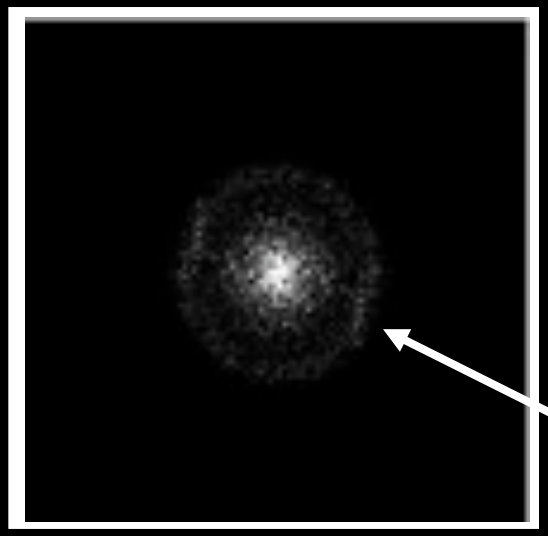




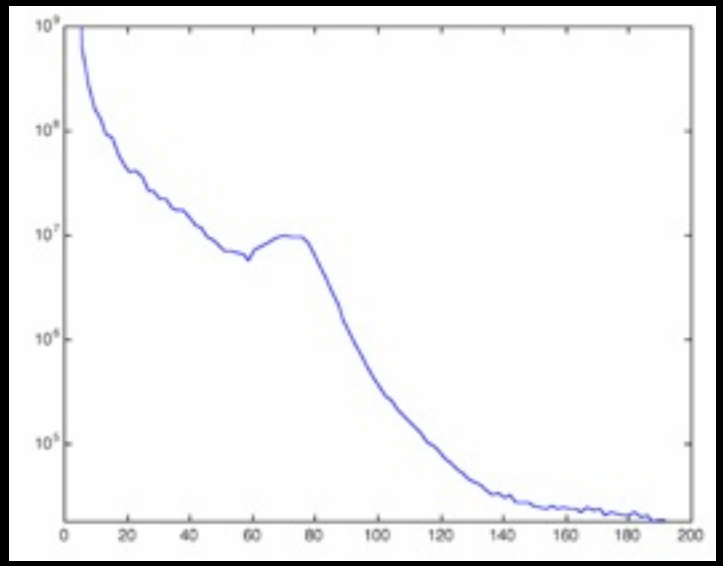
Triangular mosaic that is fairly regular
r = √3/2 * center-to-center spacing



Power Spectrum

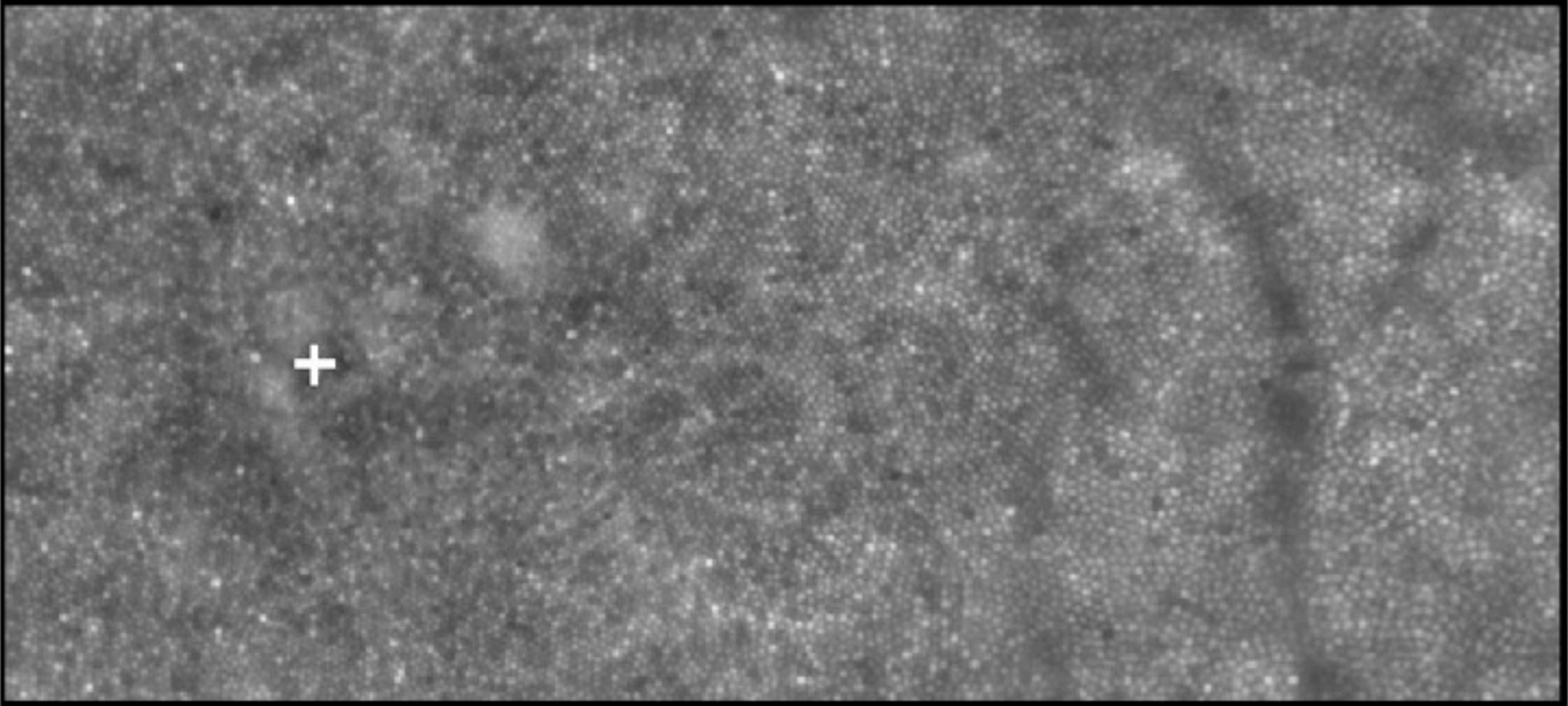


Average Radial Power Spectrum



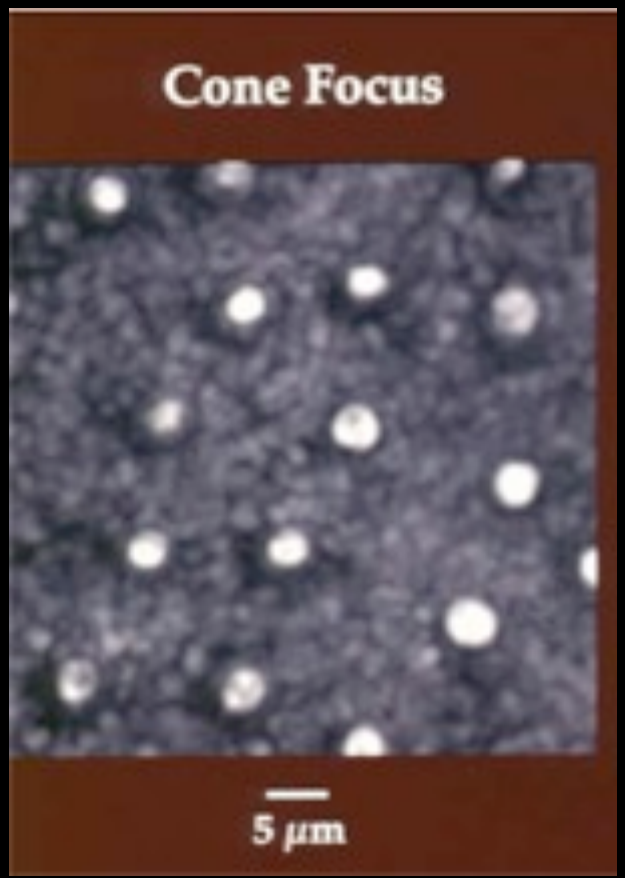
Spatial Frequency (cycles/degree)

High Resolution Retinal Images



Heidi Hofer and Matt McMahon

Cone Mosaic in the Extrafoveal Retina

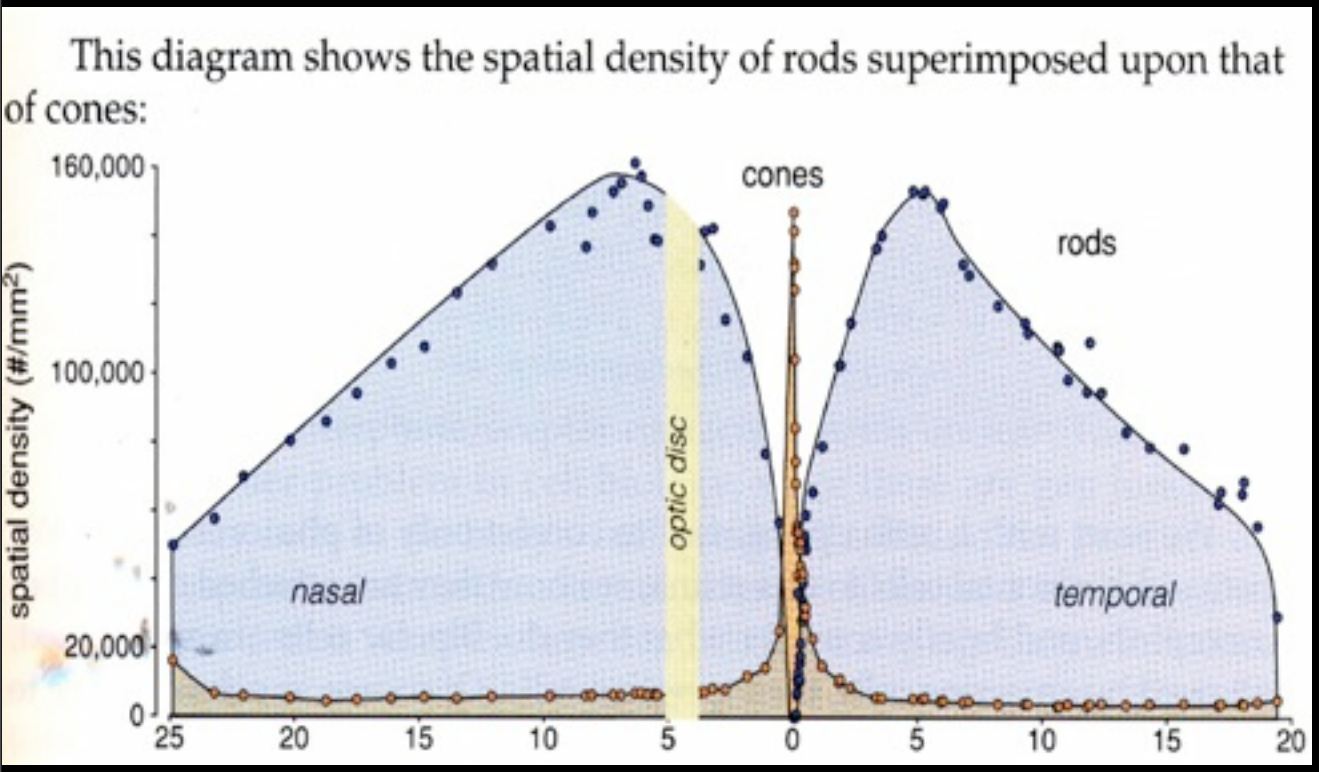


Irregular Lattice

Regularity degenerates with eccentricity approaching an asympotic amount of dissaray at 2-3 deg

Packer et al 1996

Spatial Density of Rods

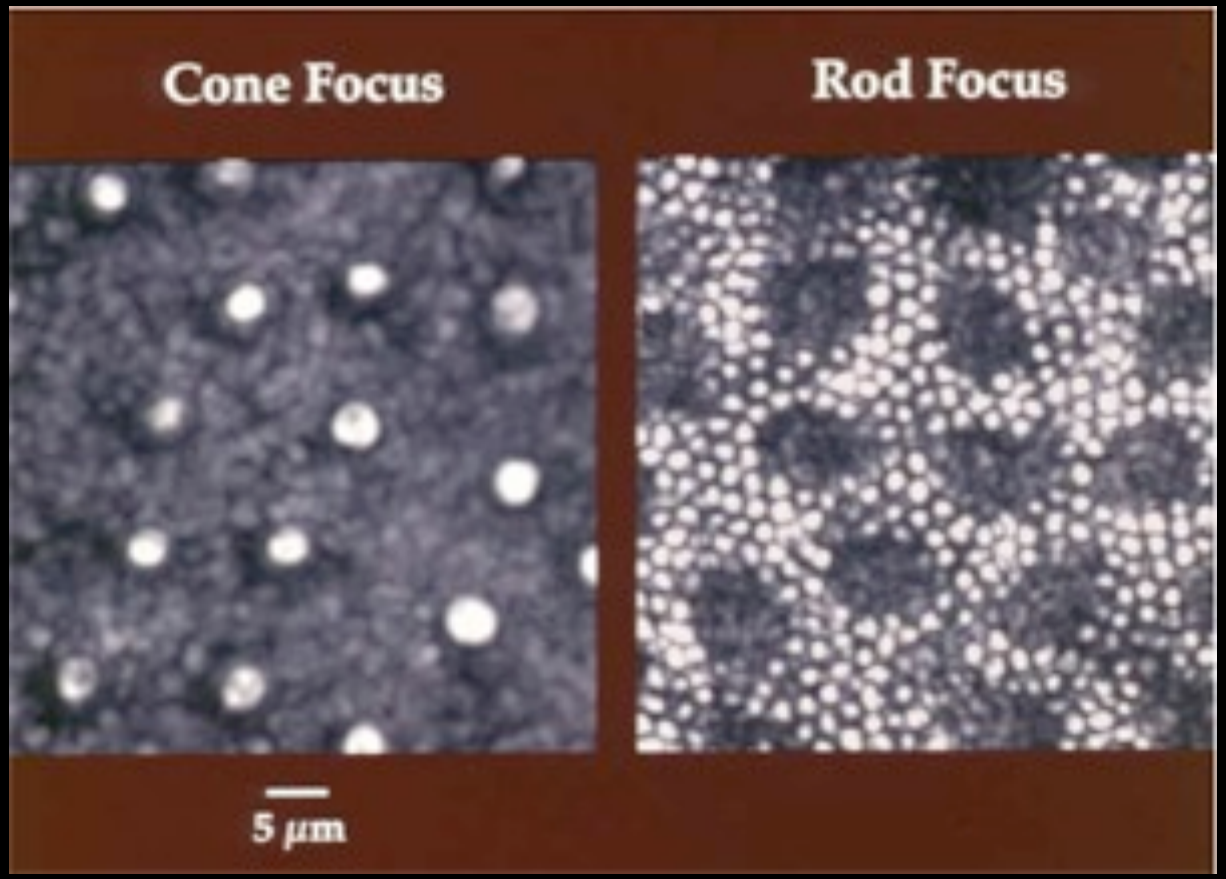


Rods are absent from the center of the fovea, their density reaches a maximum at around 20 deg and decreases again toward the periphery.

200 million

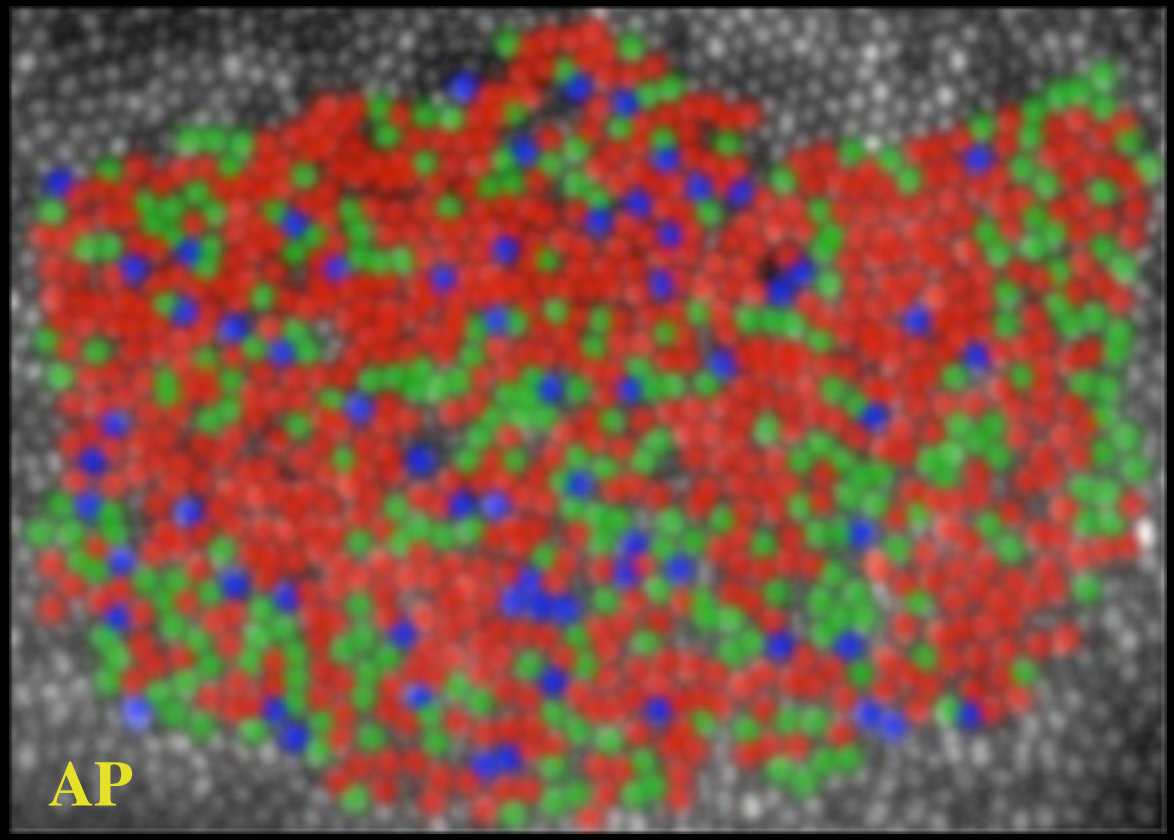
After Osterberg 1935, as modified by Rodieck 1988, micrographs from Curcio 1990

Rod Mosaic in the Extrafoveal Retina

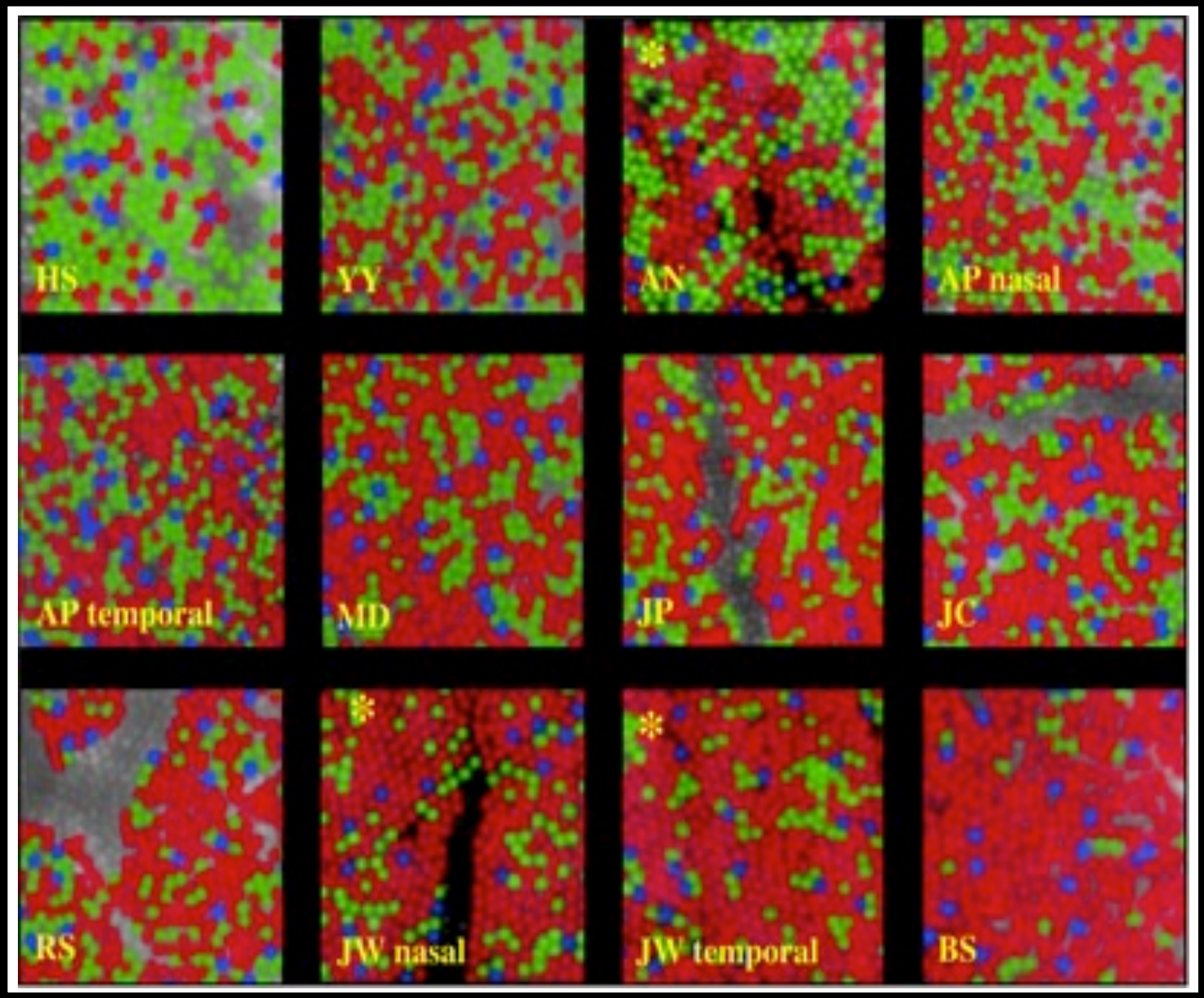


Packer et al 1996

Trichromatic Cone Mosaic in the Fovea



Trichromatic Cone Mosaic in the Fovea

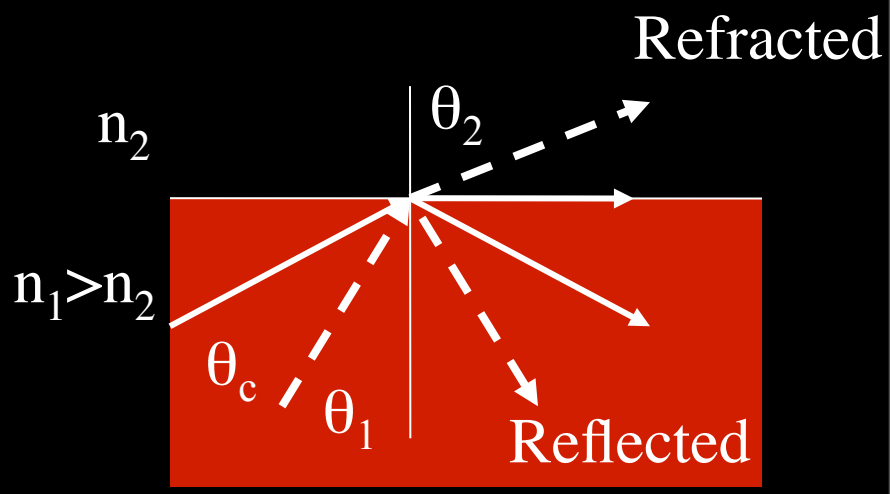


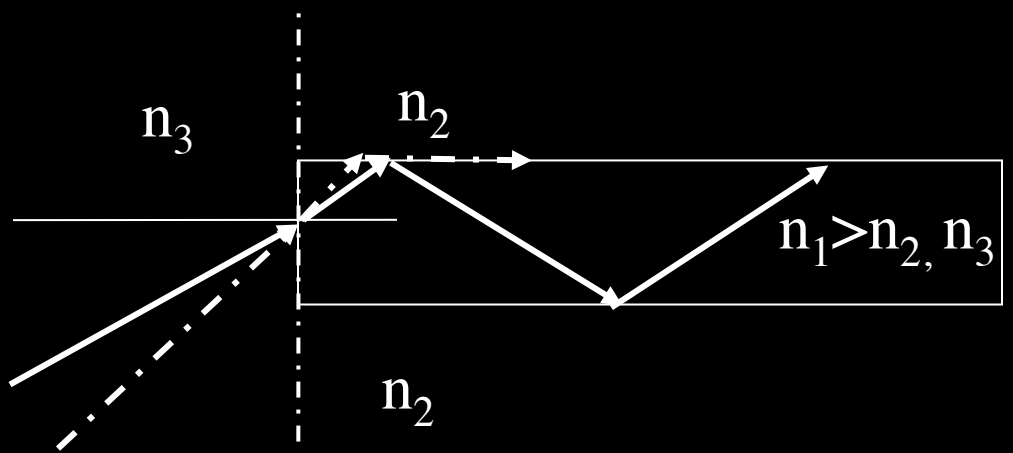
Average L:M = 2:1

Roorda & Wiliams, 1999, Hofer et al 2005

Waveguide Properties

The individual photoreceptors behave as a classic fiber-optic element which capture the incident light and channel the electromagnetic to sites of visual absorption.

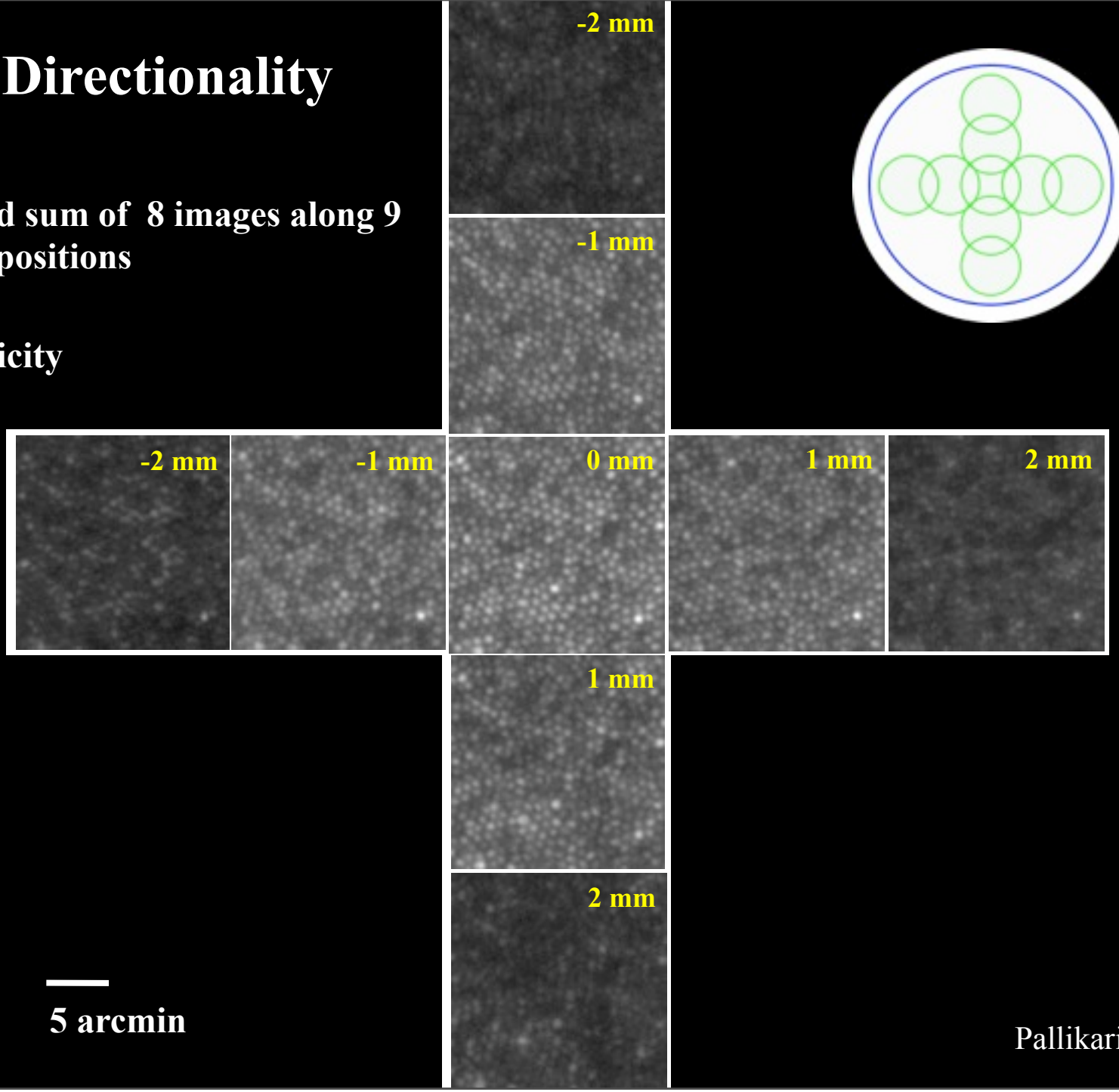




Cone Directionality

Registered sum of 8 images along 9 different positions

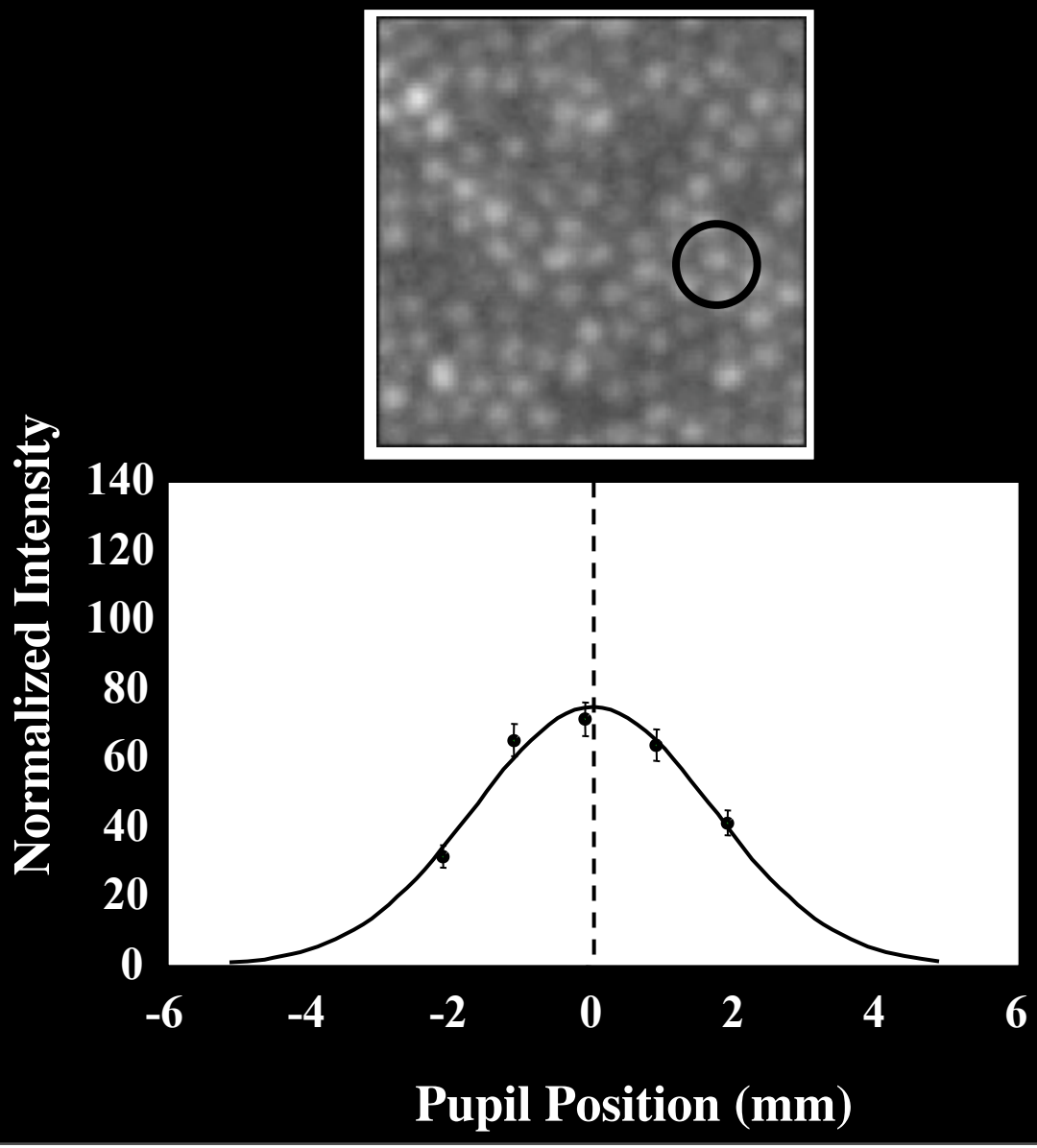
1°eccentricity



5 arcmin

Pallikaris et al 2003

Cone Directionality



Pallikaris et al 2003

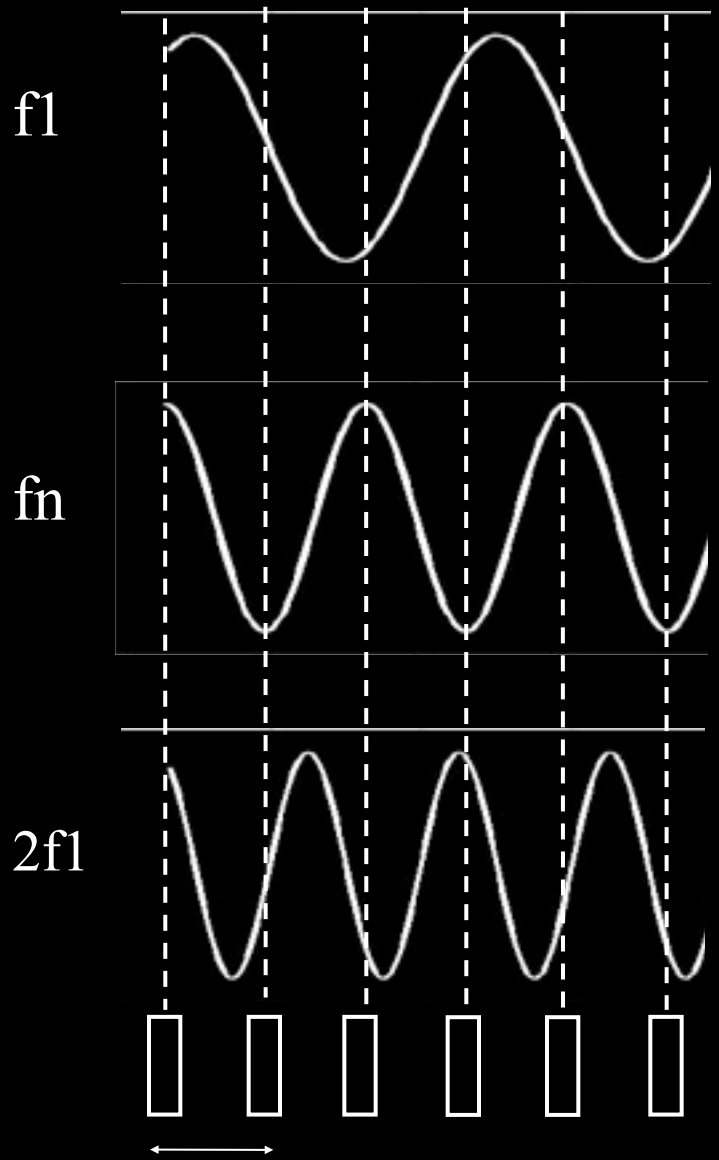
Sampling Resolution

The Sampling Theorem:

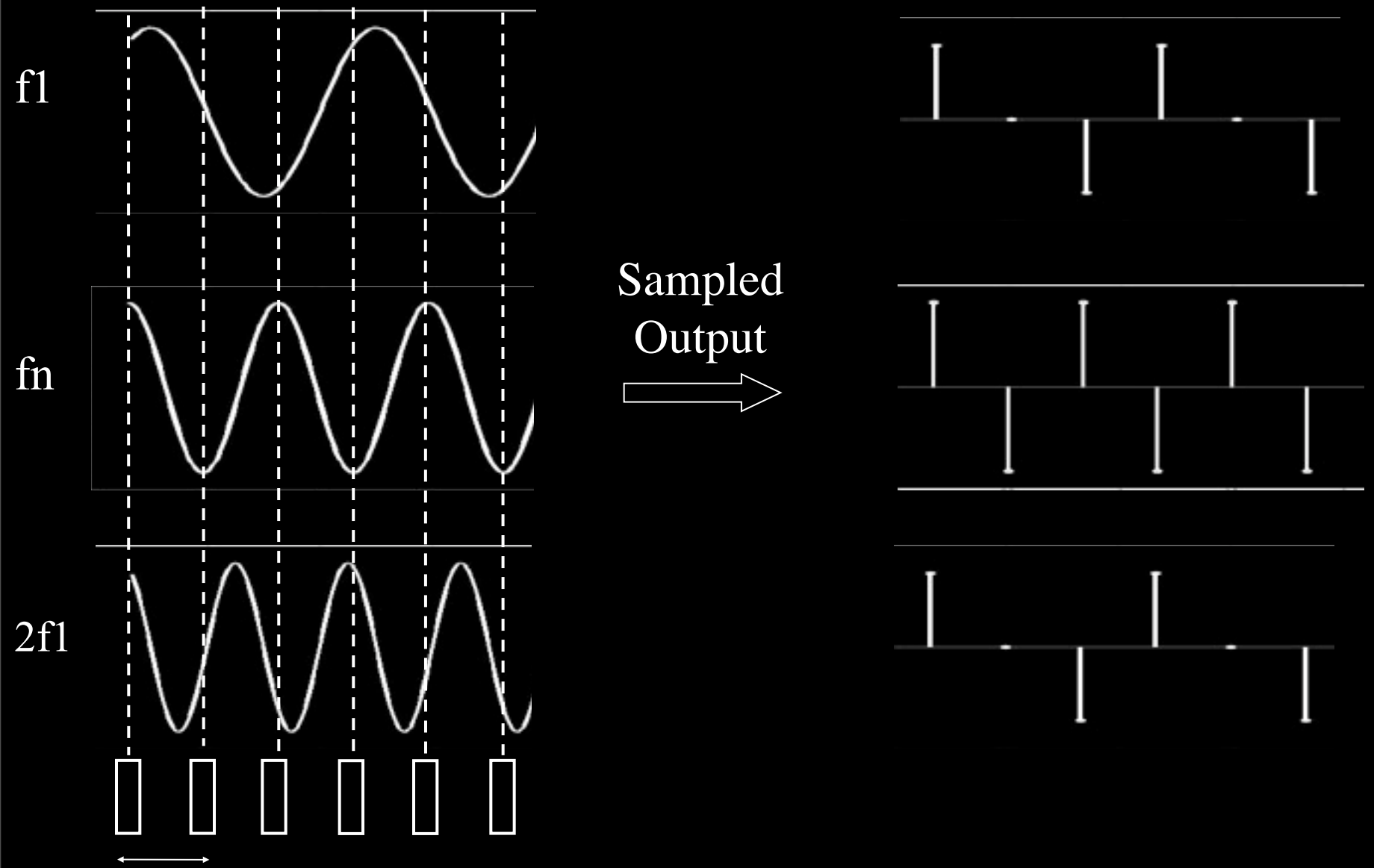
Helmholtz (1911): “When the widths of two luminous objects used in the test are vanishingly small as compared with the interval between them, they cannot be seen as separate unless there is an unstimulated retinal element between the retinal elements on which
their images fall. In other words, the diameter of such an element must certainly be less than the interval between the two images.”

Goodman (1968): a band-limited signal that is sampled at regular intervals can be completely recovered from the sample values without aliasing if the highest frequency of the signal does not exceed 1/2S where S is the spacing between samples.

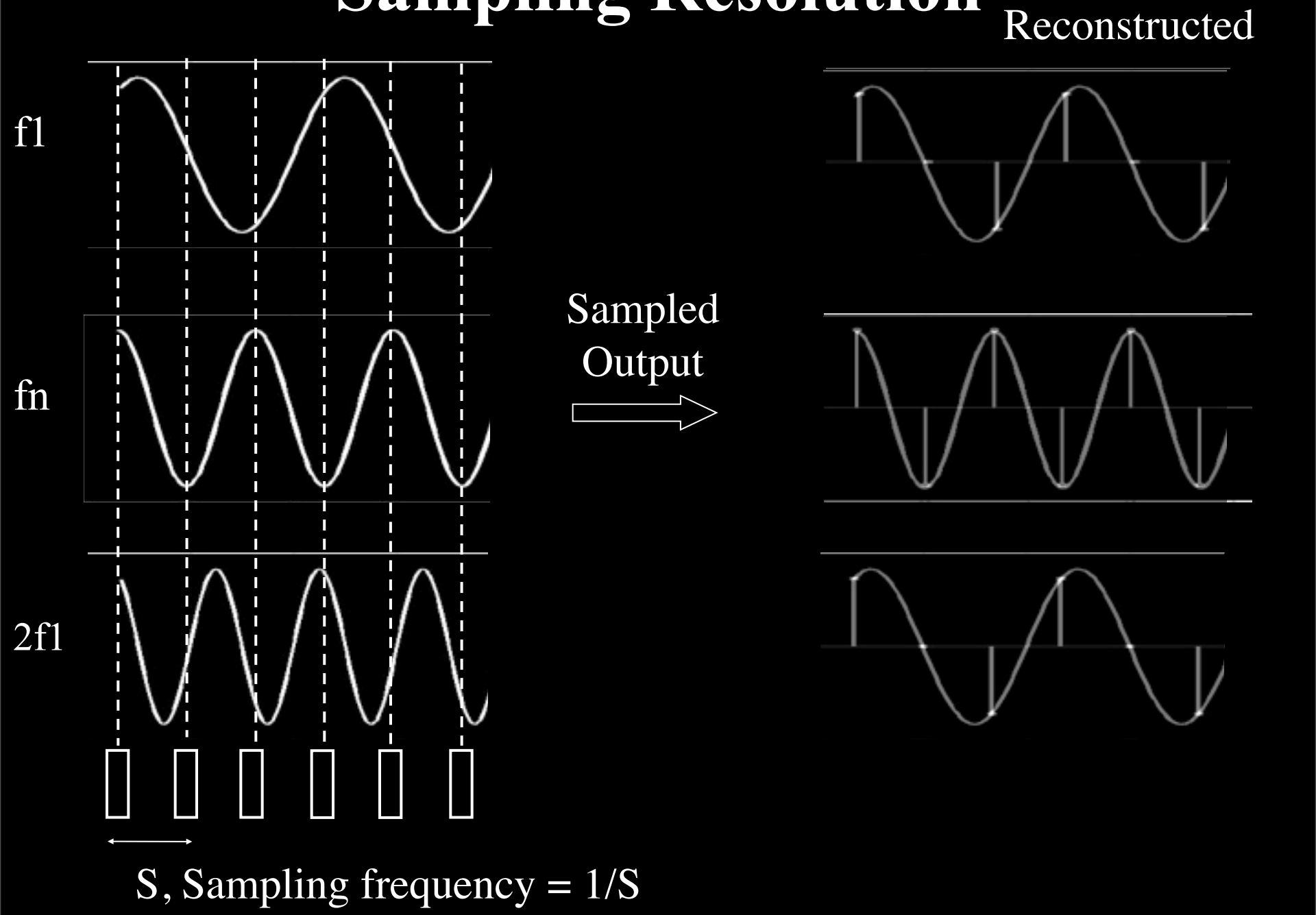
Sampling Resolution



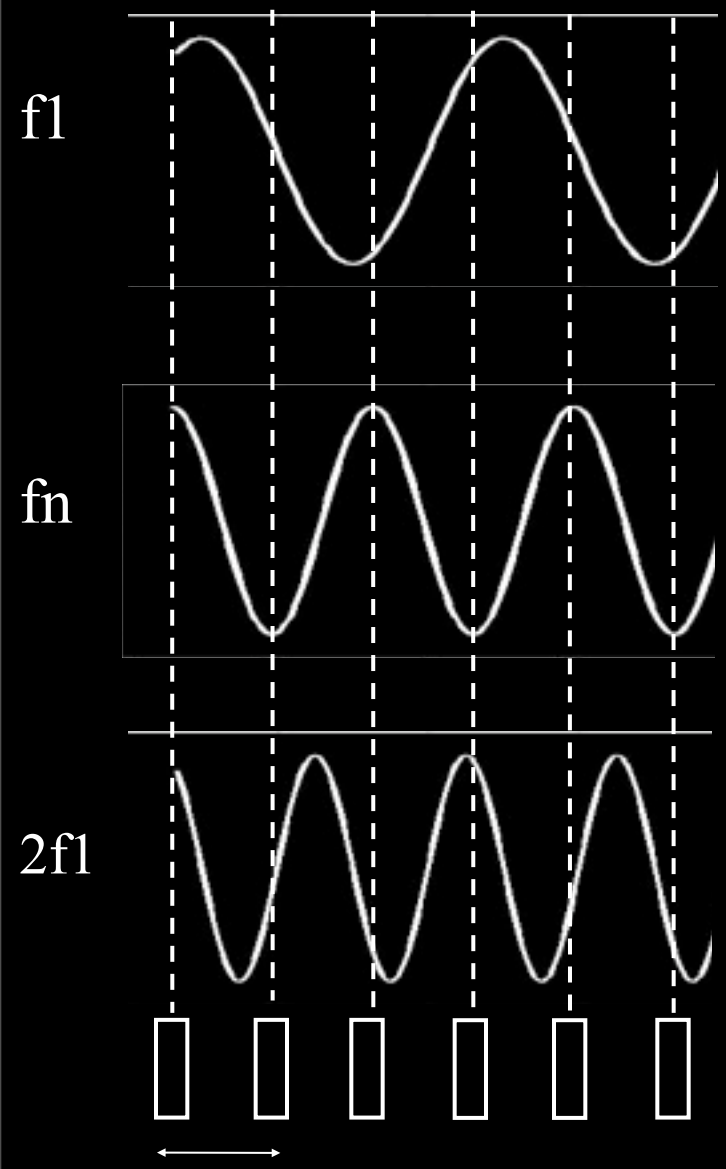
Sampling Resolution



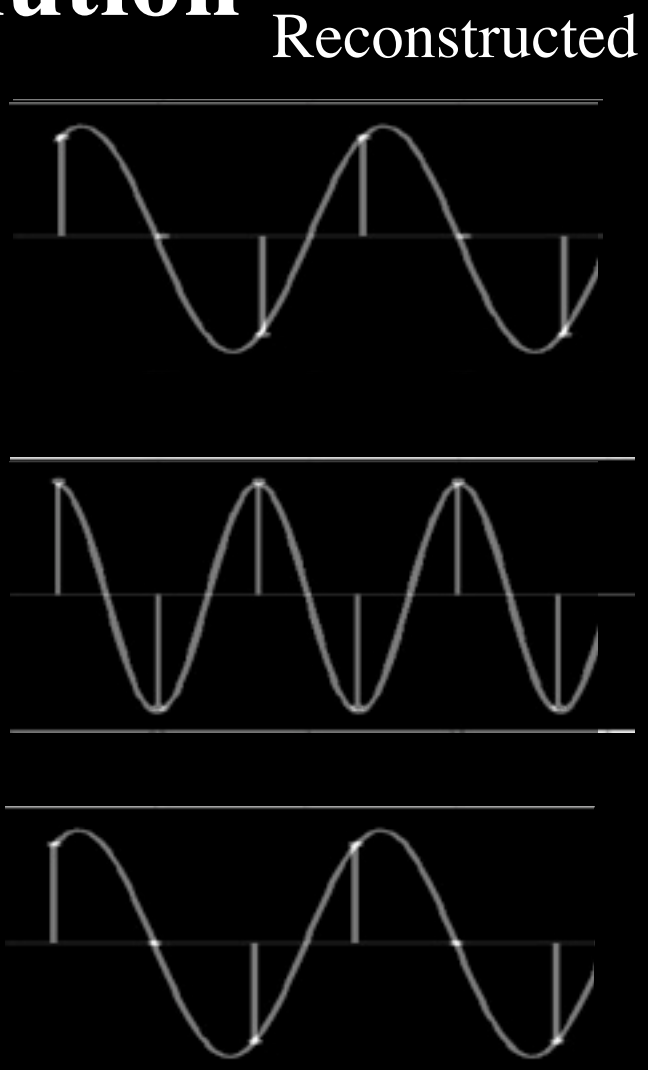
Sampling Resolution



Sampling Resolution

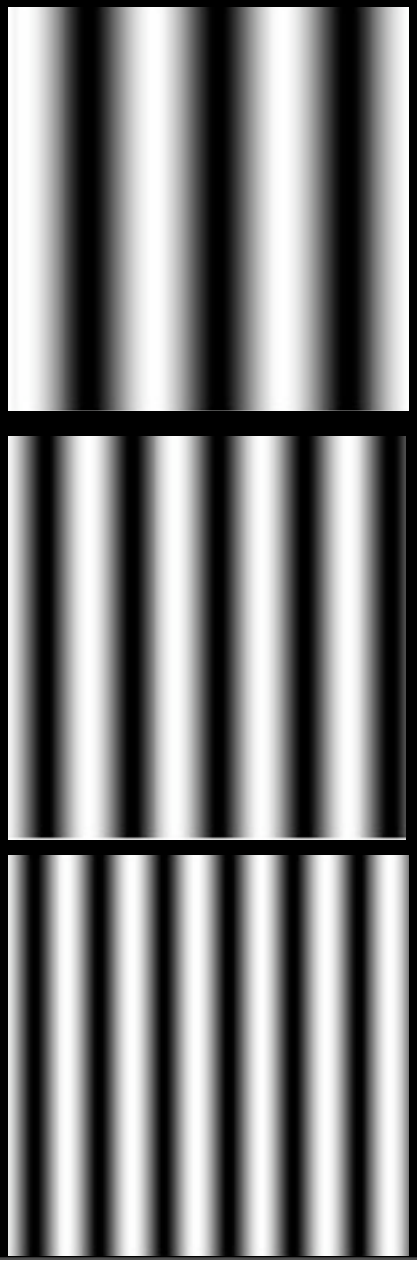


Sampled Output

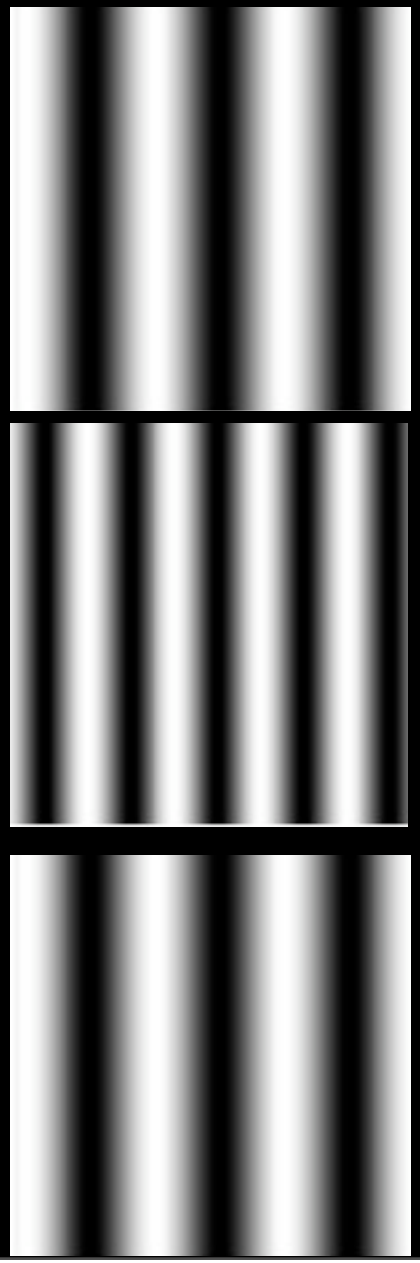


fn=1/2S Nyquist Frequency (maximum resolvable frequency

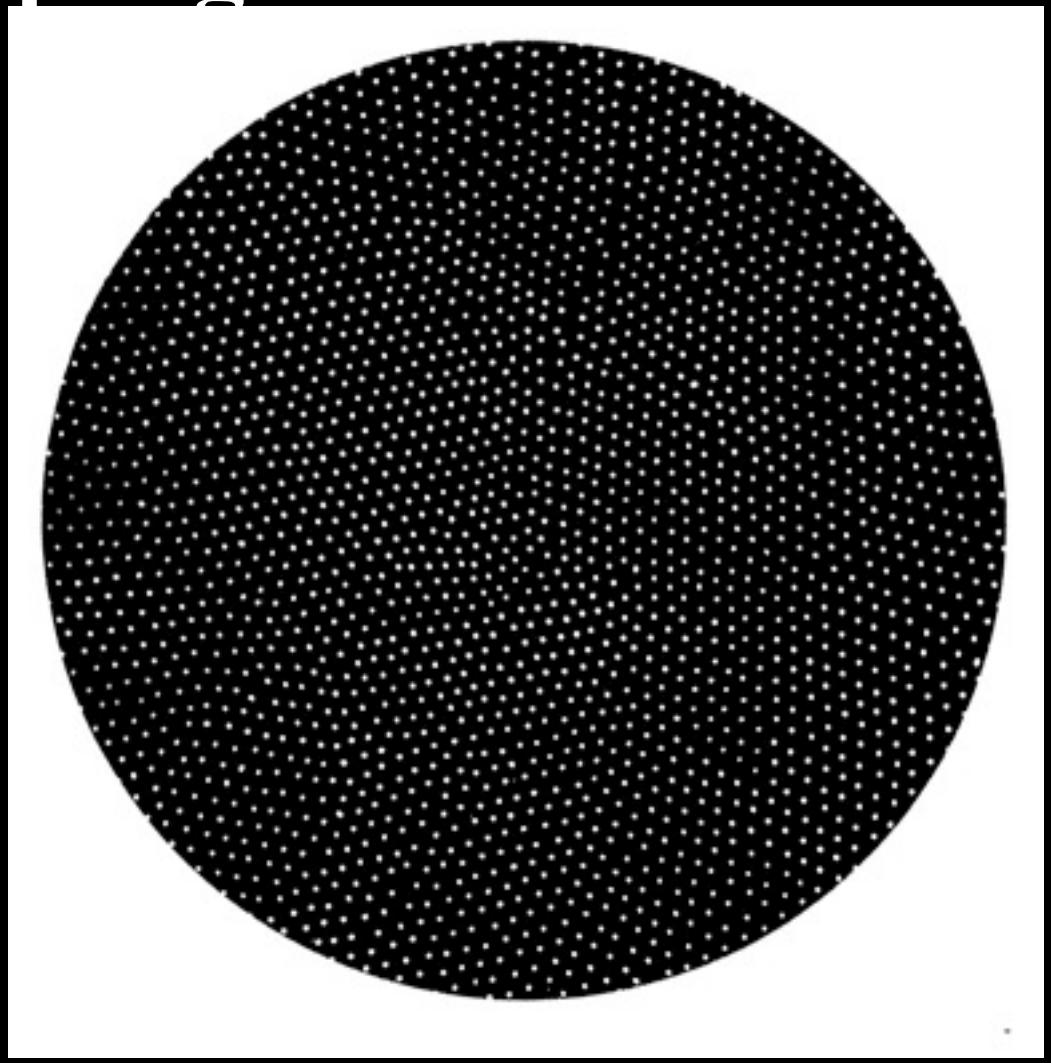
Sampling Resolution



Sampled and Reconstructed
Sine Grating



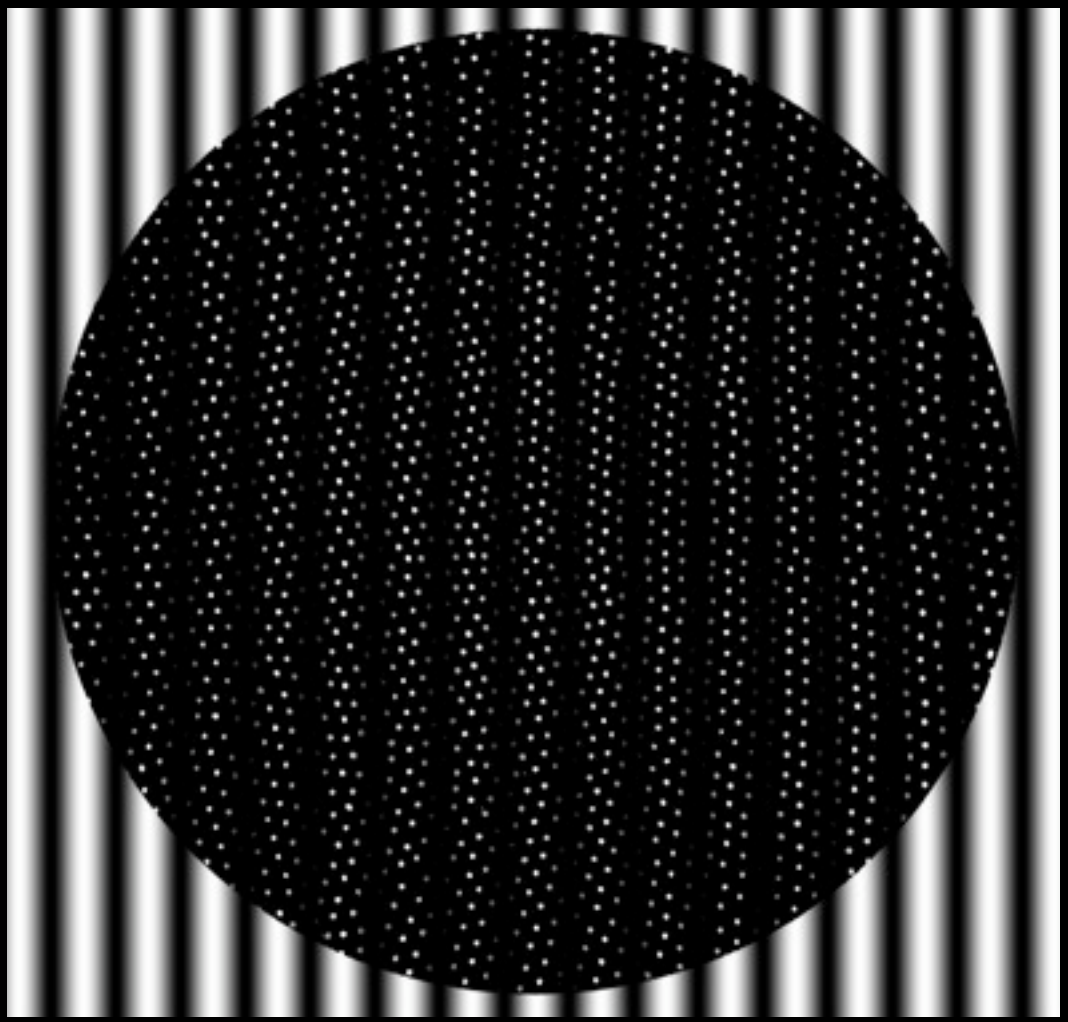
Sampling in the Central Retina

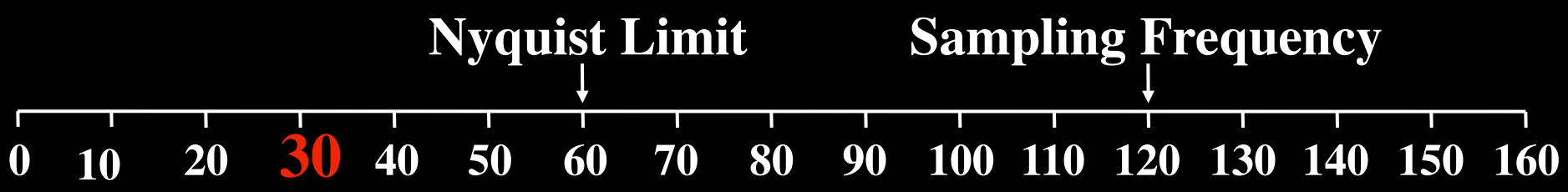


Primate Central Fovea (0.5 deg)

Slide courtesy David R. Williams

Slide courtesy David R. Williams





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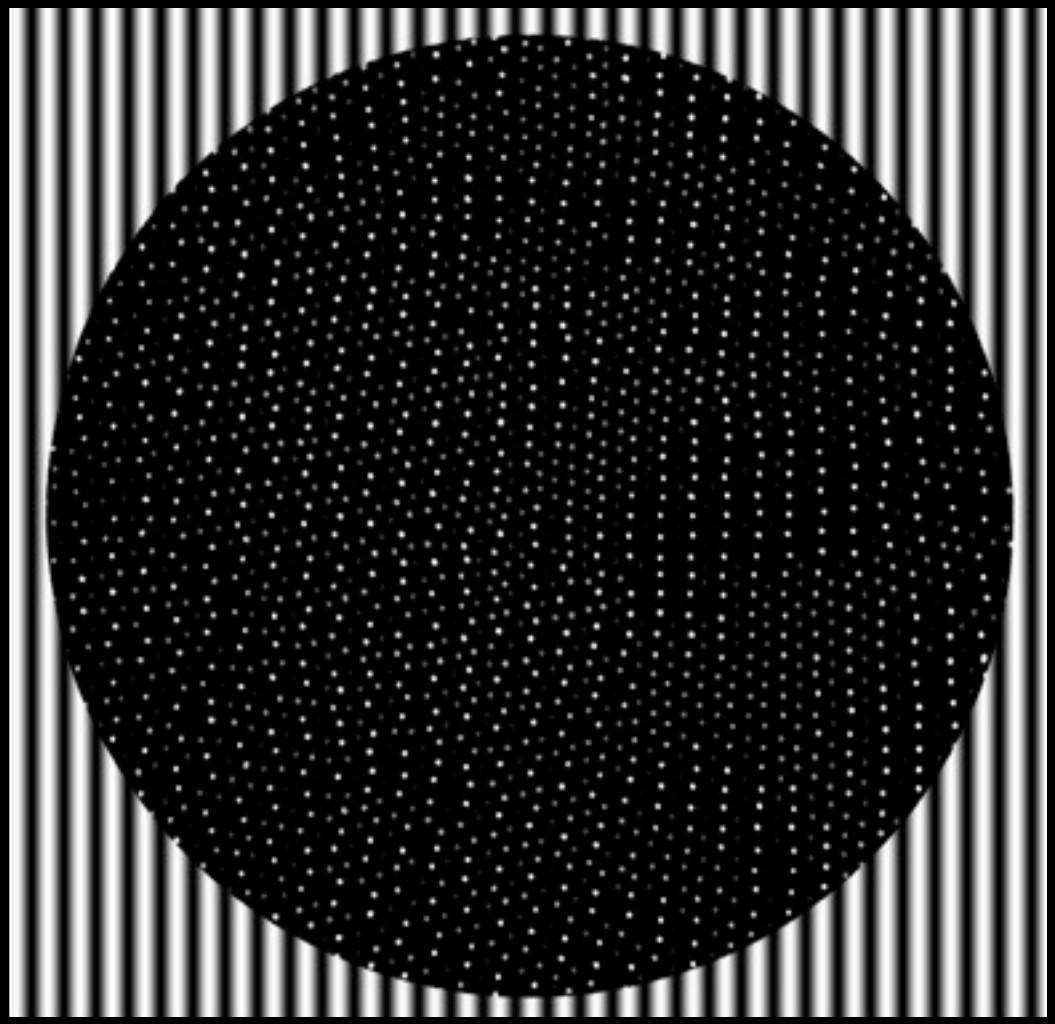

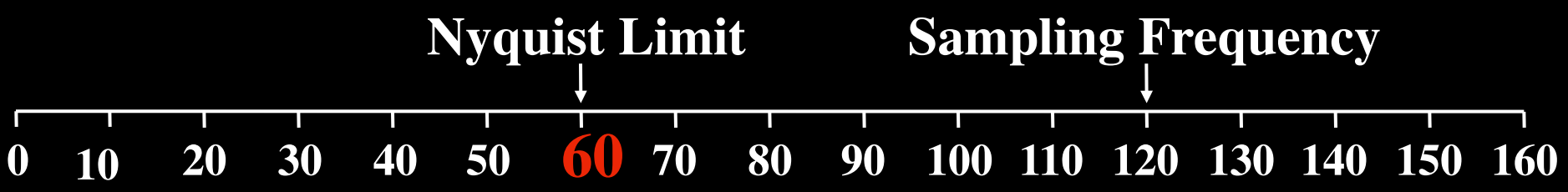

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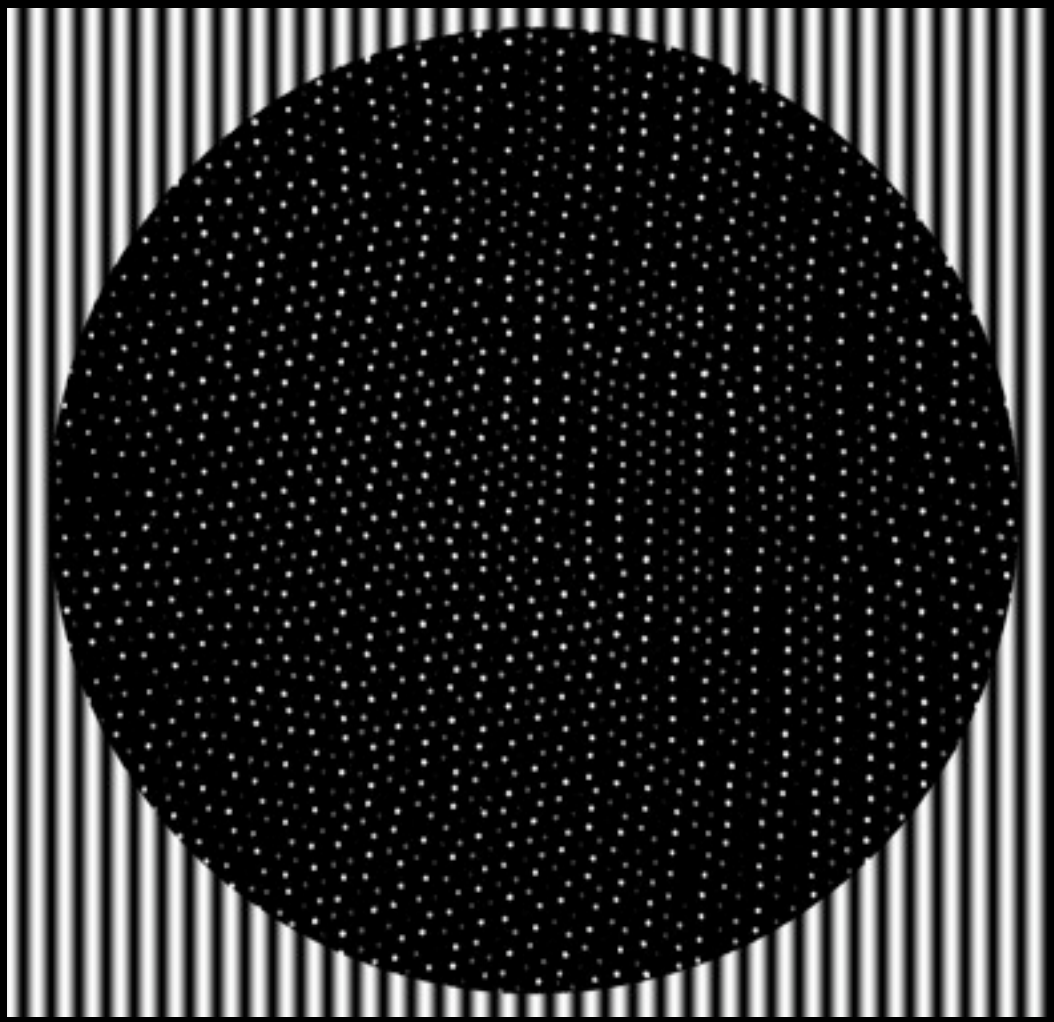

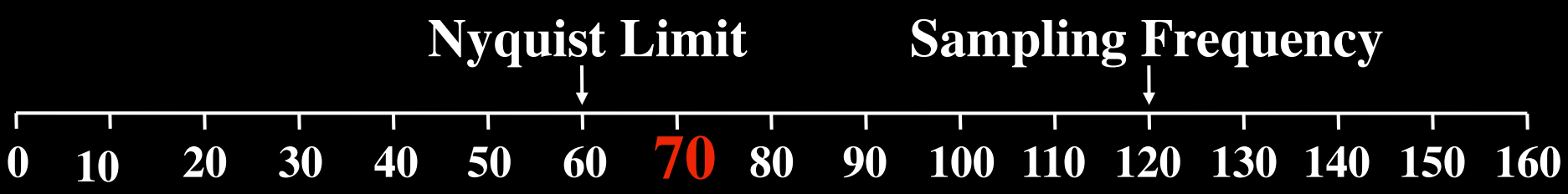

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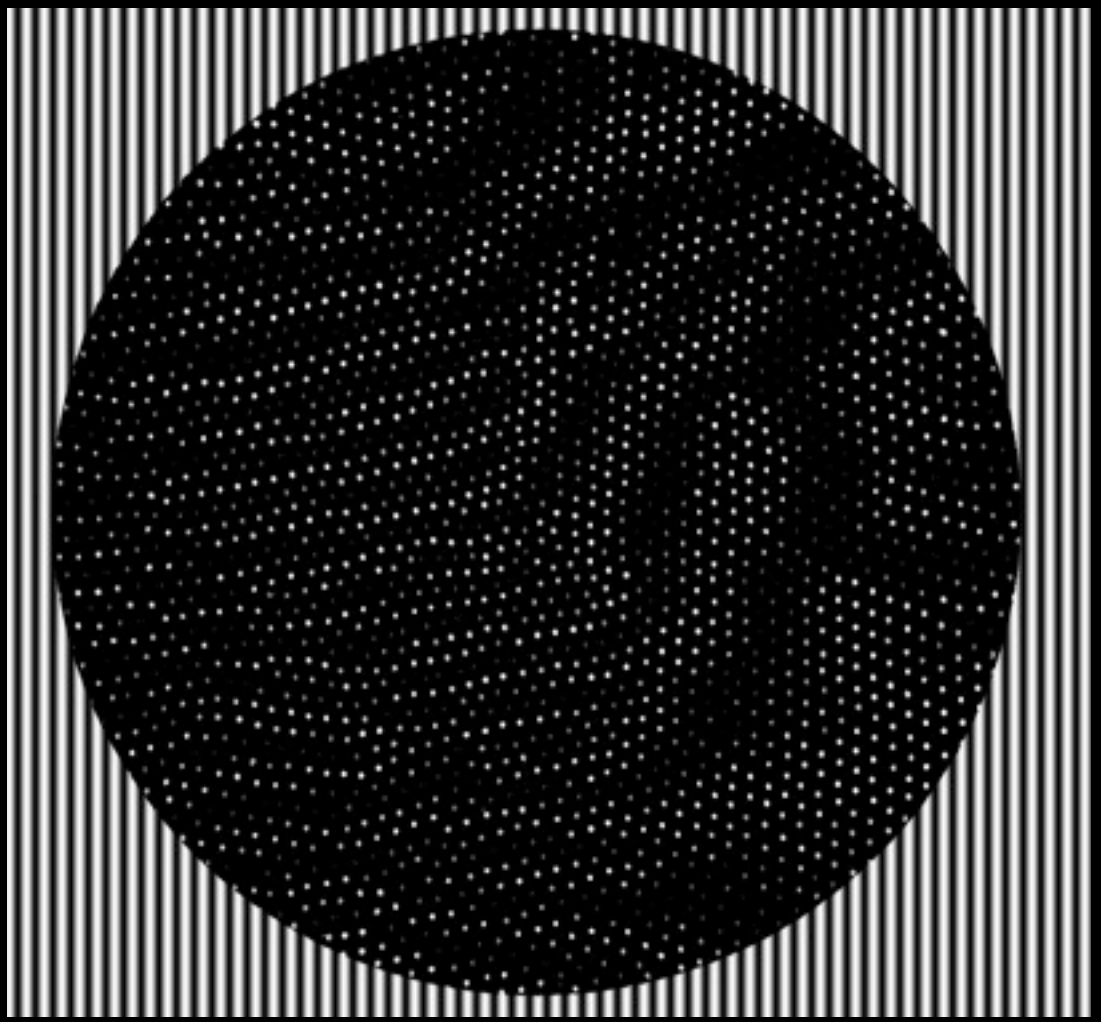
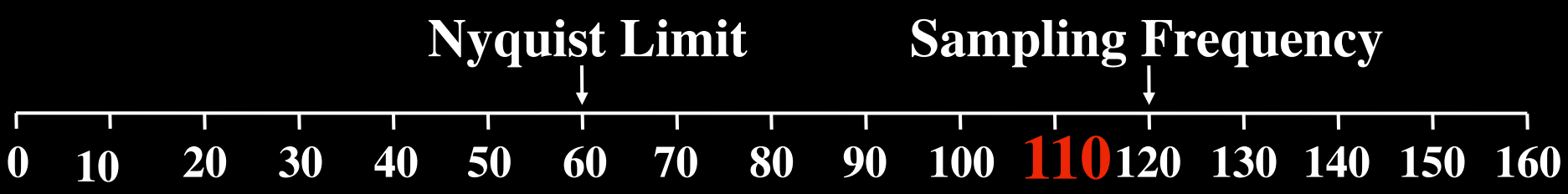
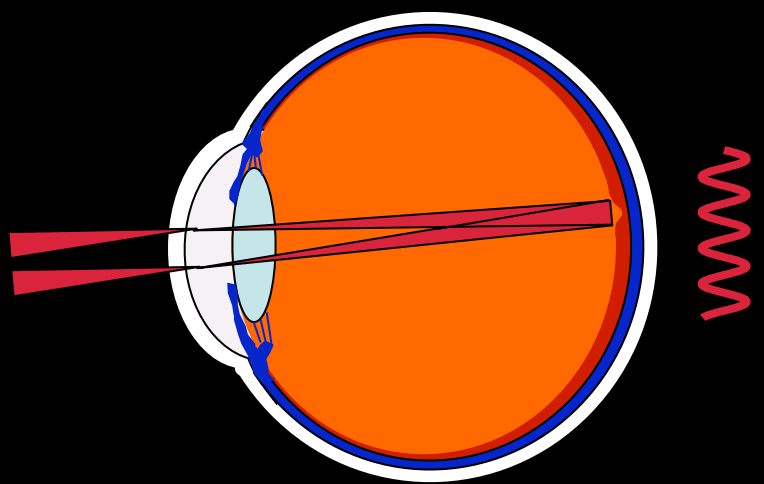
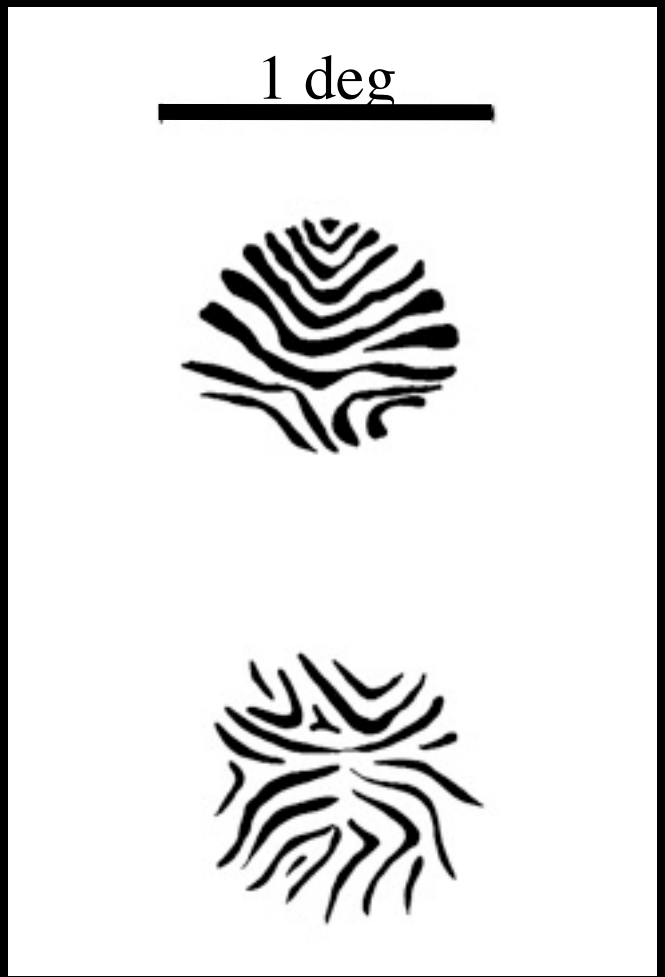




Sampling Limits by Laser Interferometry

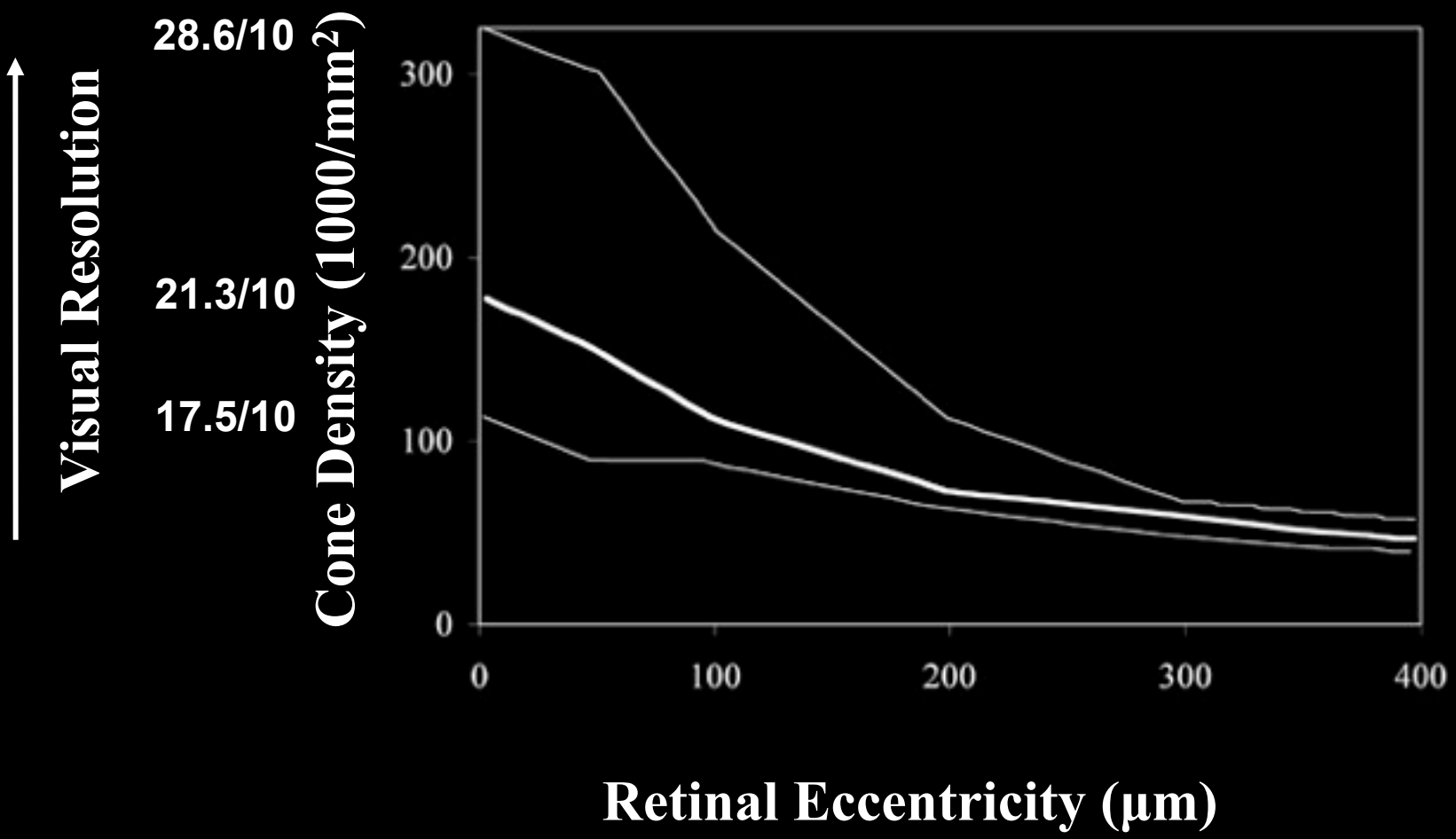




Drawings of appearance of 110 c/deg Interference Fringes

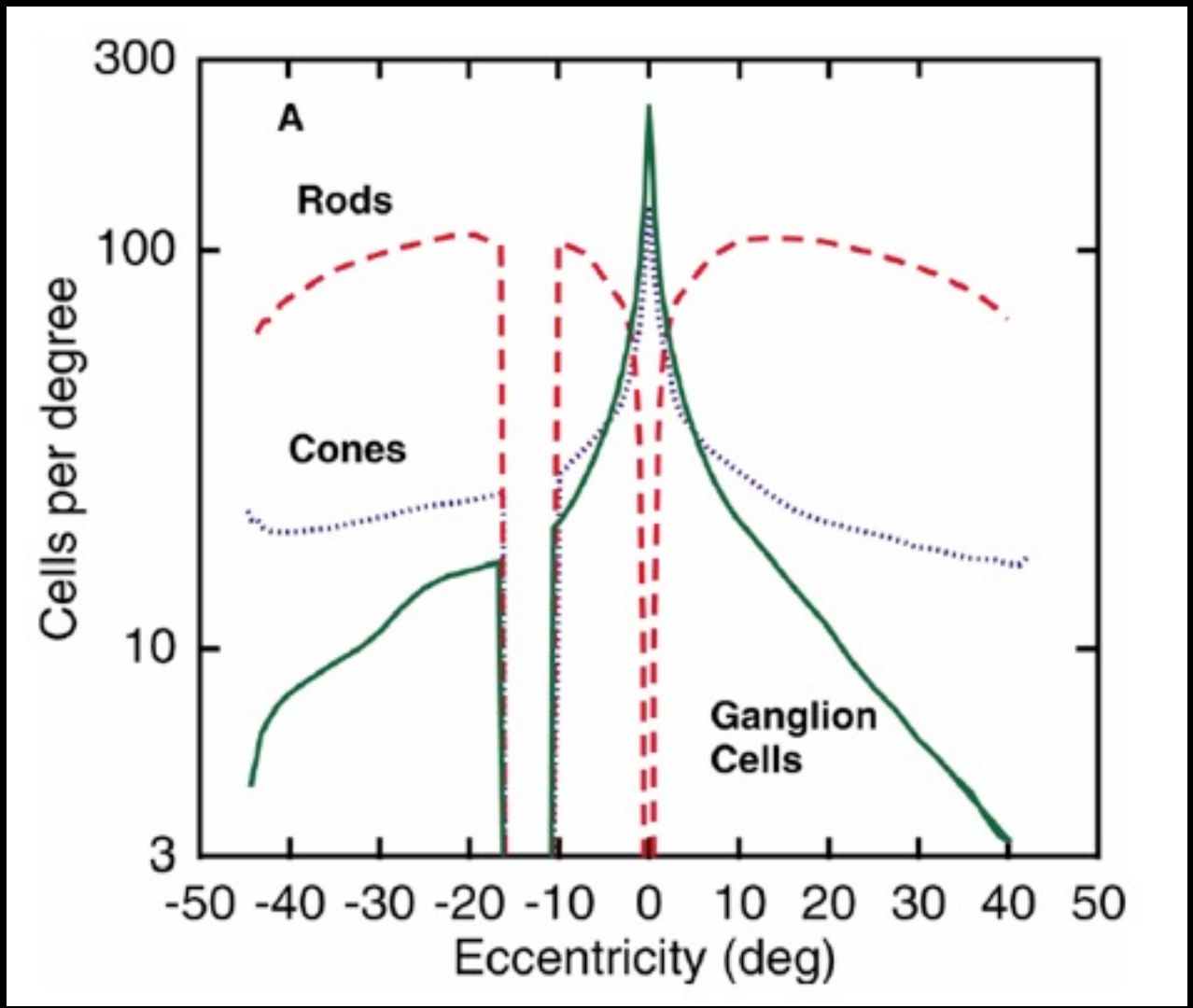
Williams et al. 1985

Cone Density and Resolution



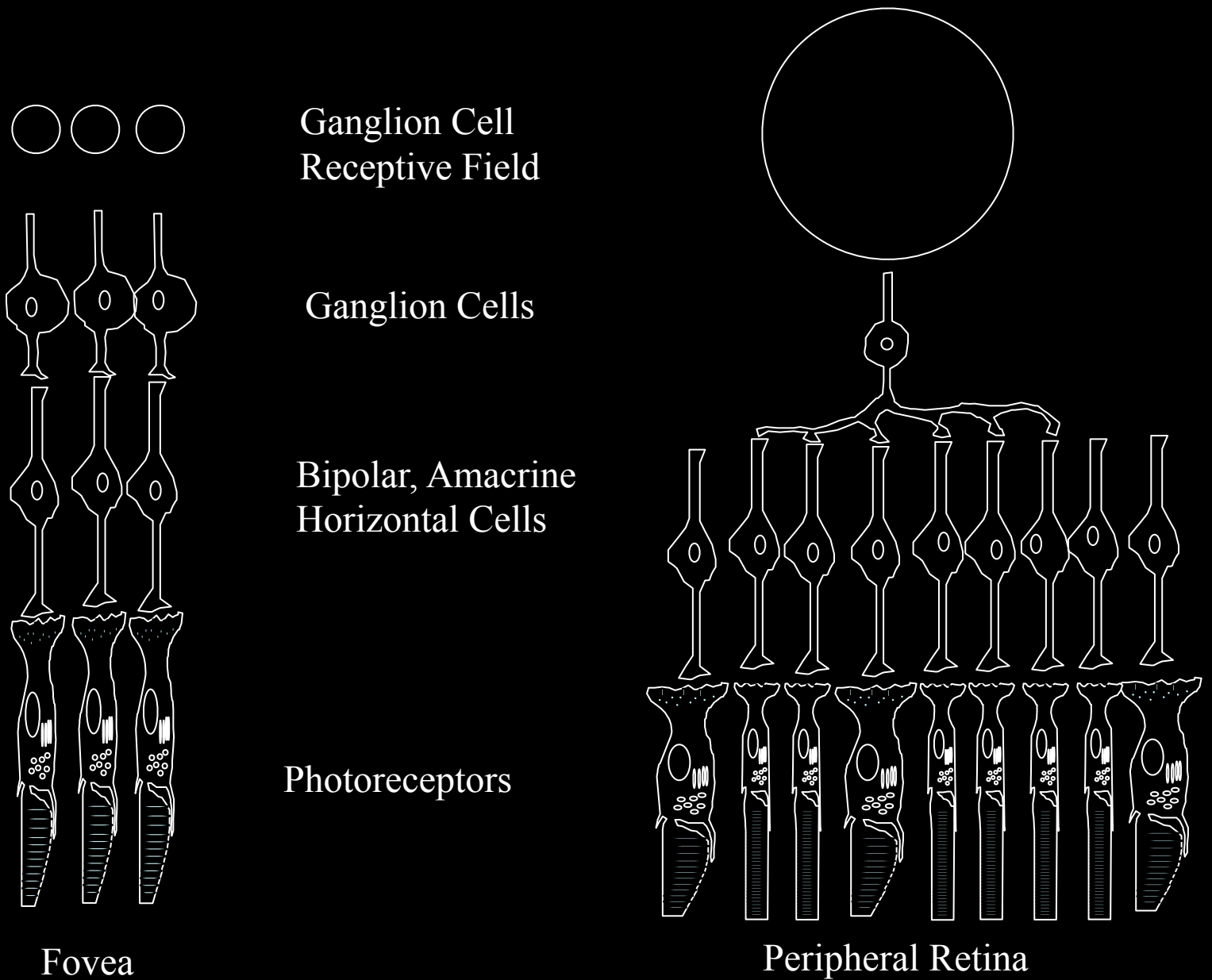
Curcio et al., 1990

Distribution of Photoreceptors and Ganglion Cells

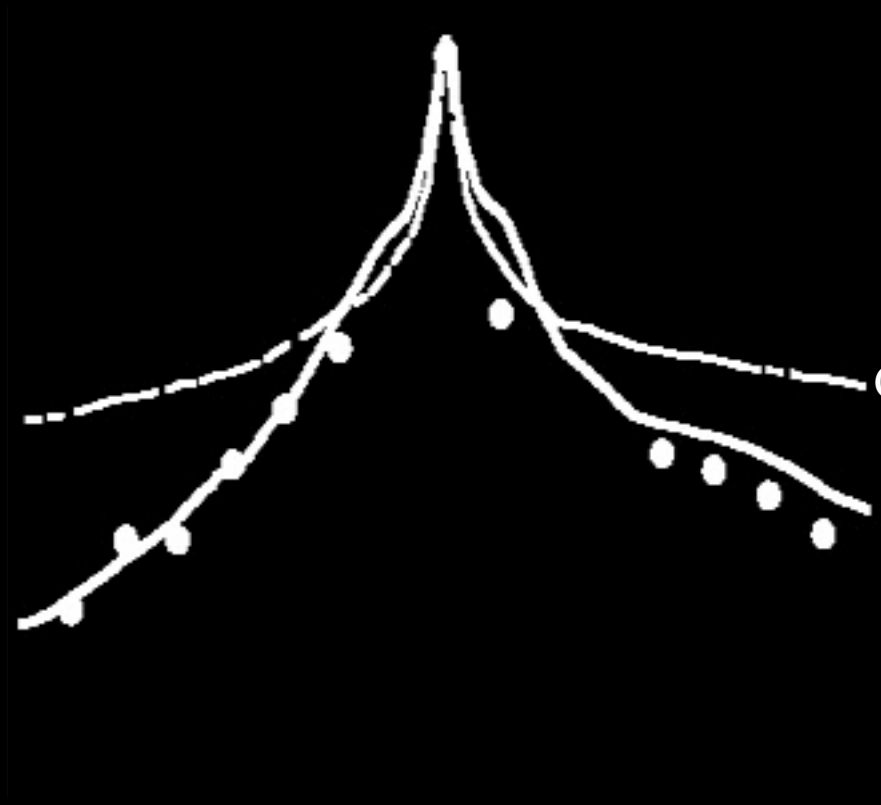


Geisler and Banks, 1995

Sampling in the Peripheral Retina



Resolution Acuity Matches RGC Sampling Density



LNT acuity (Thibos 1987)

Cones (Curcio 1990)

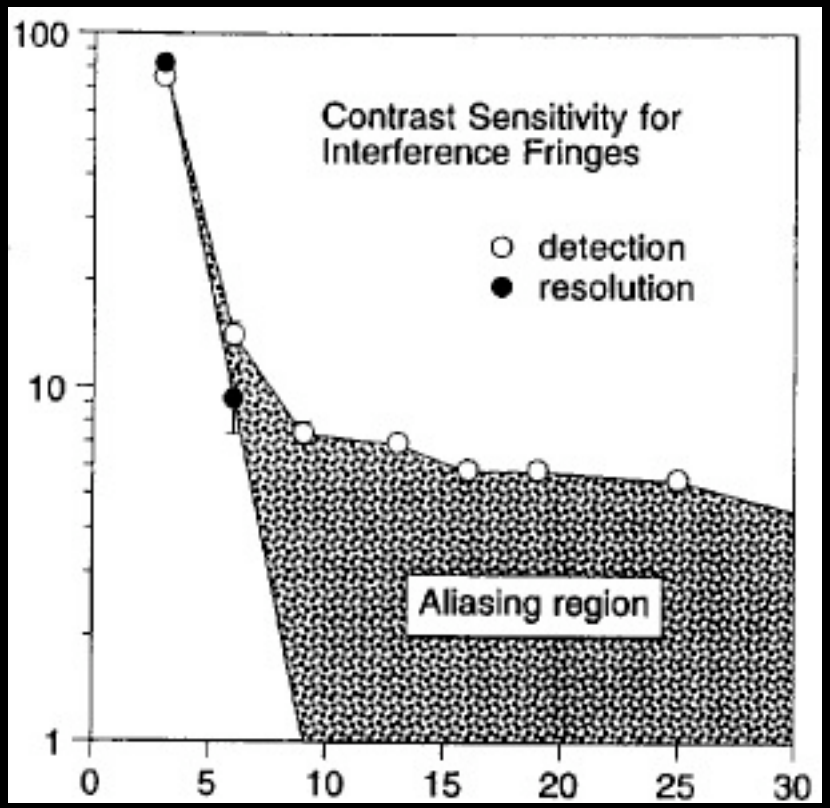
Gagglion Cells (Curcio 1990)

Neural Resolution (cycles/deg)

(Temporal field)

Eccentricity from fovea (deg)

Sampling in the Peripheral Retina



20 deg eccentricity

Williams et al 1996

Conclusions & Discussion

• There is a significant variation in the arrangement of the photoreceptors across the retina.

• There is a significant variation in the resolution limits related to the sampling properties of the photoreceptor mosaic across the retina.

• The peripheral retinal image is subject to retinal undersampling, which will cause perceptual aliasing of spatial frequencies greater than the resolution limit of the central fovea.

Thank you
for your attention