Single Cell Limits of Vision

Adam M Dubis, PhD

4 February 2020

NEUR 0017
Visual
Neuroscience

Learning Objectives

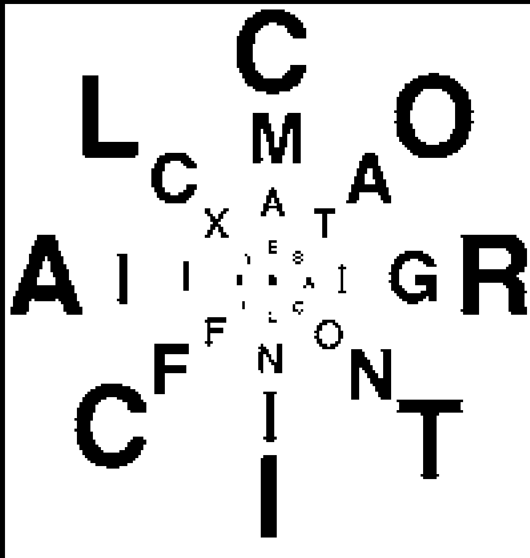
- Understand the difference, with regards to the human visual system between acuity and sensitivity

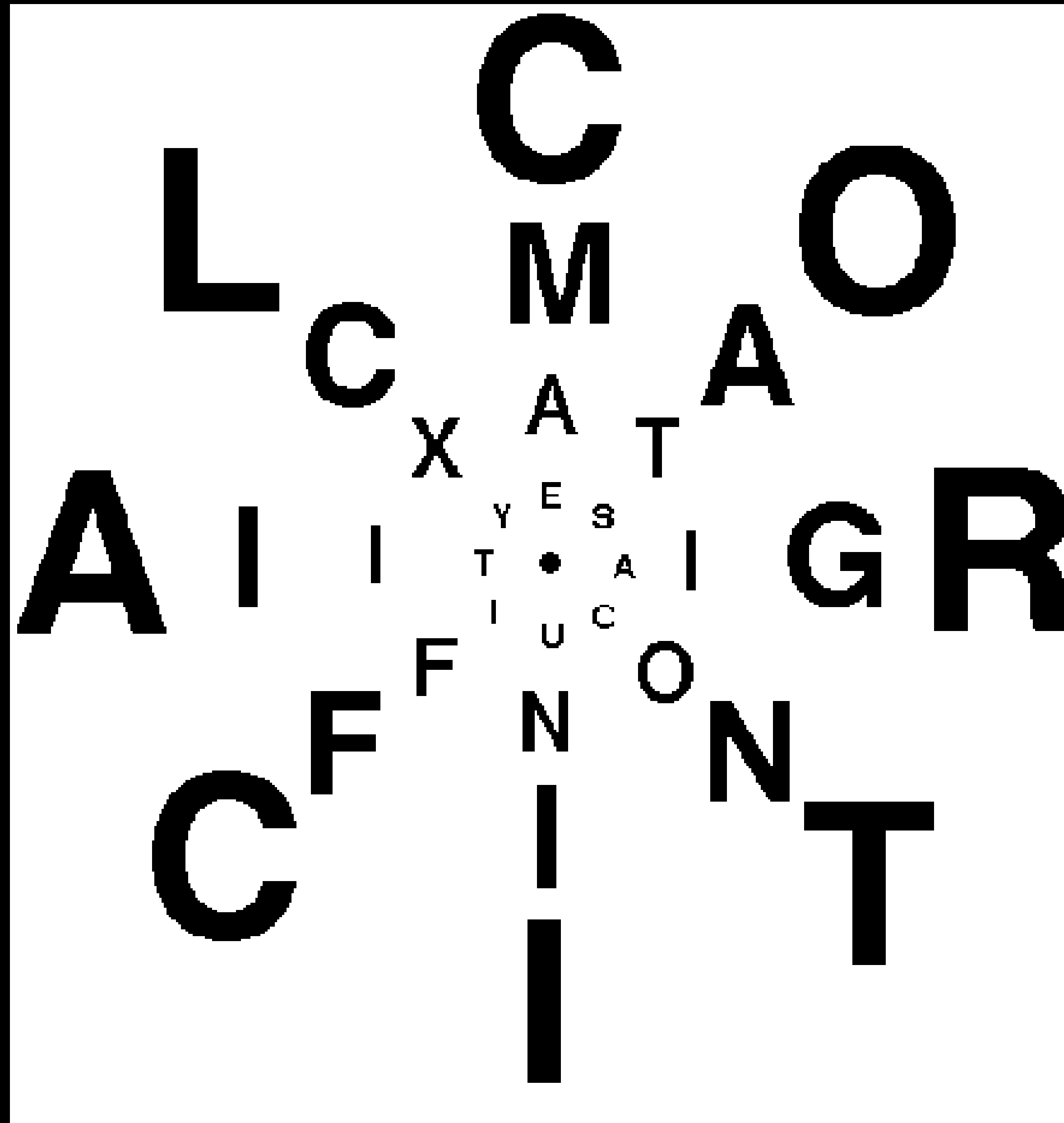
- Understand what the limit of the rod photoreceptor system is and how it is tested

- Understand the limits of visual acuity and how this changes across the retina

-Understand the limits of retinal sensitivity

-Understand our evolving understanding about the limits of colour vision





Visual acuity gets much poorer with eccentricity

Credit: Stuart Anstis, UCSD

The human visual system is a foveating system

Simulation of what we see when we fixate with cone vision.

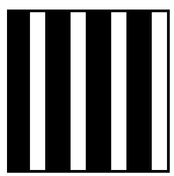
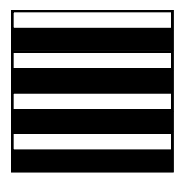
Credit: Stuart Anstis, UCSD

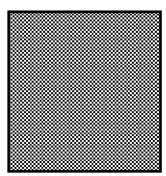
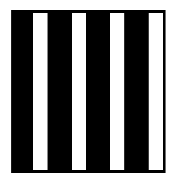
Visual Acuity: four standard methods

Letter acuity (Snellen)

Can the subject correctly identify the letter or the letter orientation?

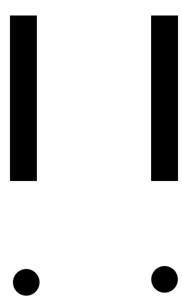
Grating acuity

 vs.  Orientation resolution acuity

 vs.  Detection acuity

2-line resolution

2-point resolution

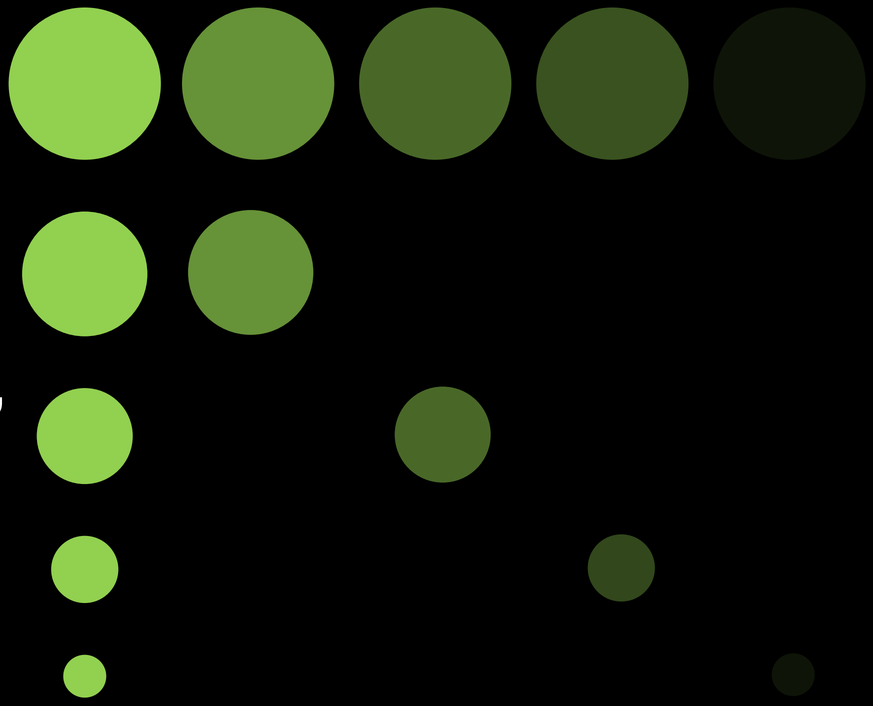


Can the subject see two lines or points rather than one?

Borrowed from Arthur Bradley

Testing Visual Sensitivity

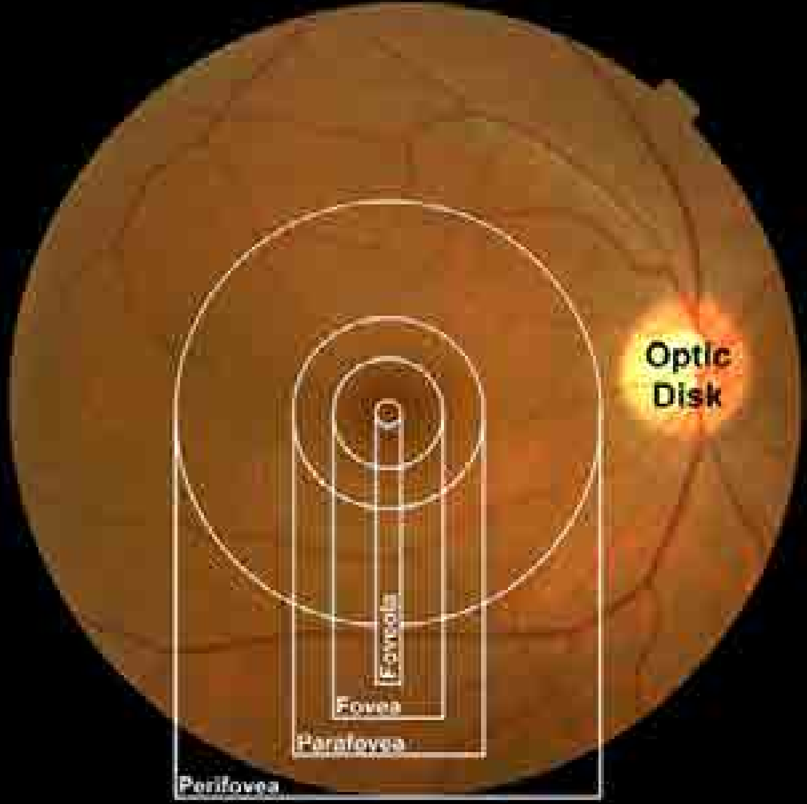
- Sensitivity is the ability to detect an object in space
- It is usually reported in relation to a background illumination specification
- Can be tested as an intensity, size or both
- Carefully managed testing parameters are important to understand limits of experiment

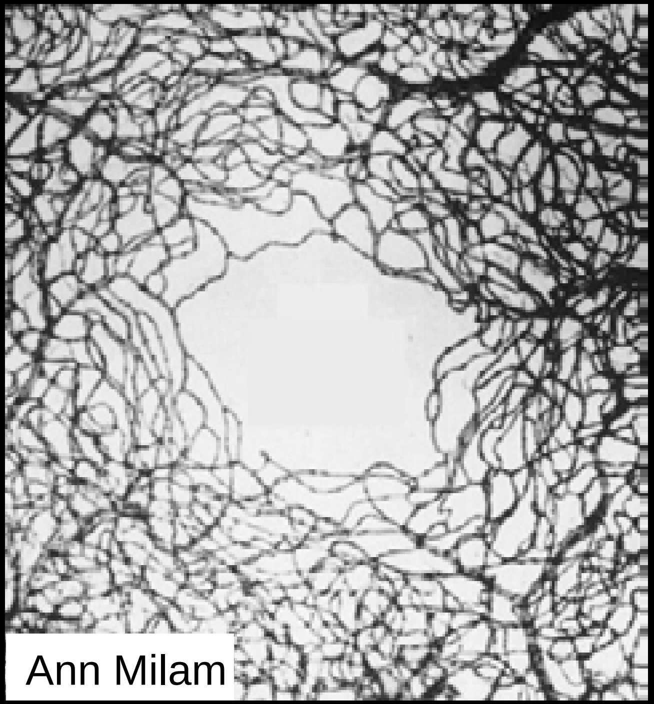


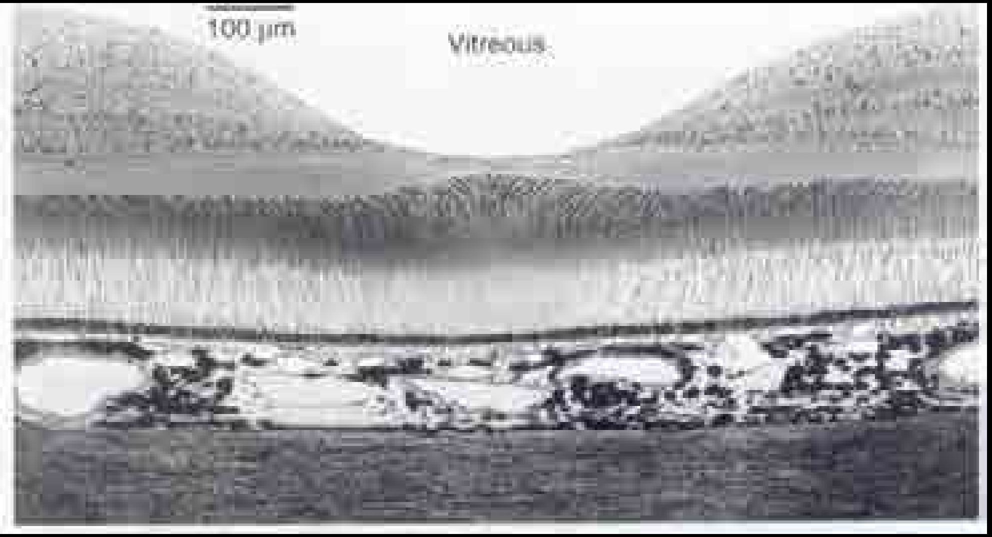
What do we need to know to test rod sensitivity?

Limits of Rod Photoreceptors

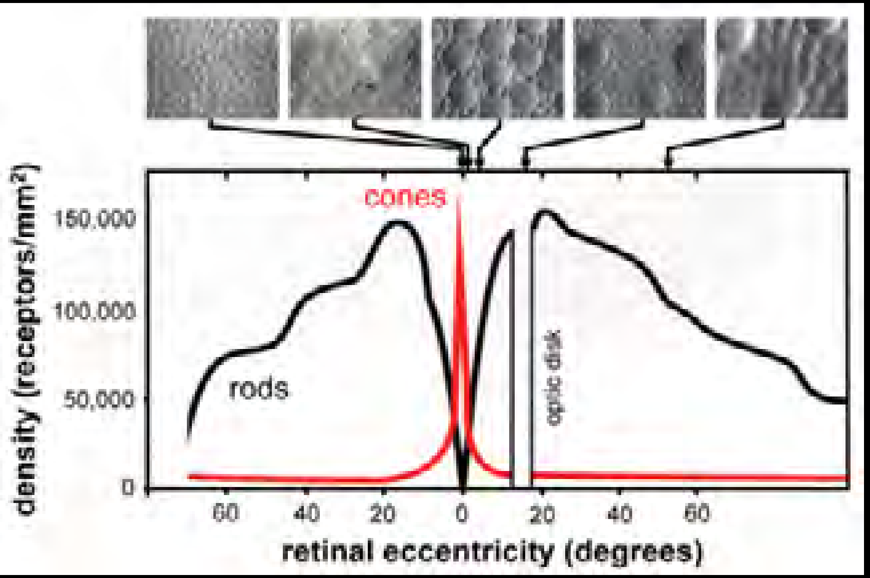
- Where in the eye are you testing?
- What is the dark adaptation status of the eye?
- How big is your stimulus?
- How does light propagate through the eye, how layers interact with the eye and how?
- How do you determine whether a person saw the stimulus?





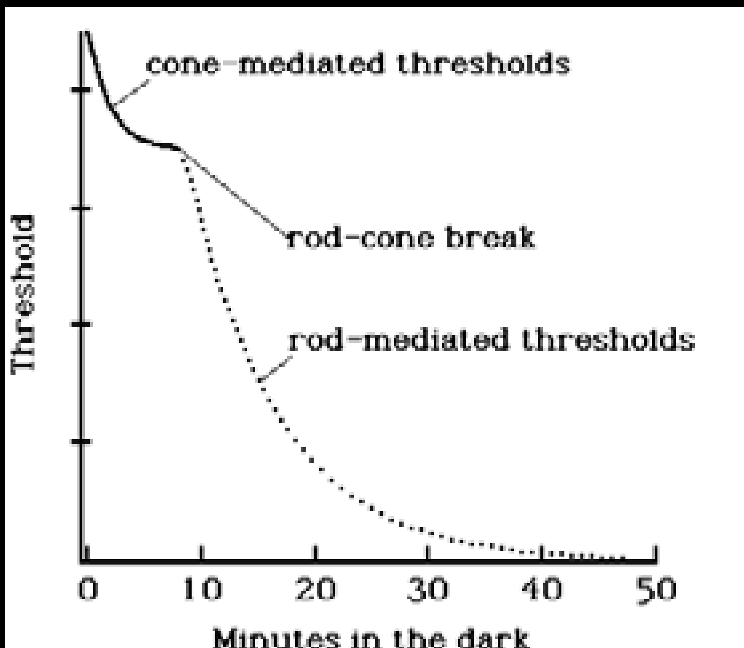


Fine & Yanoff (1979)

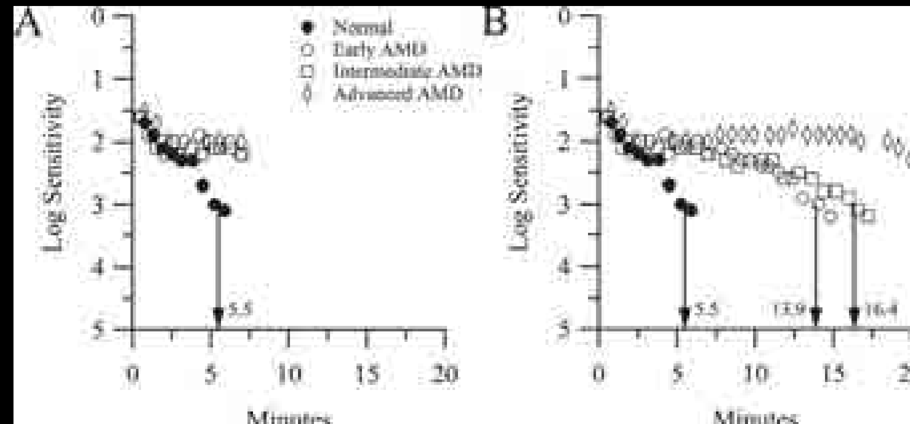


Carroll, Yoon, Williams (2008)

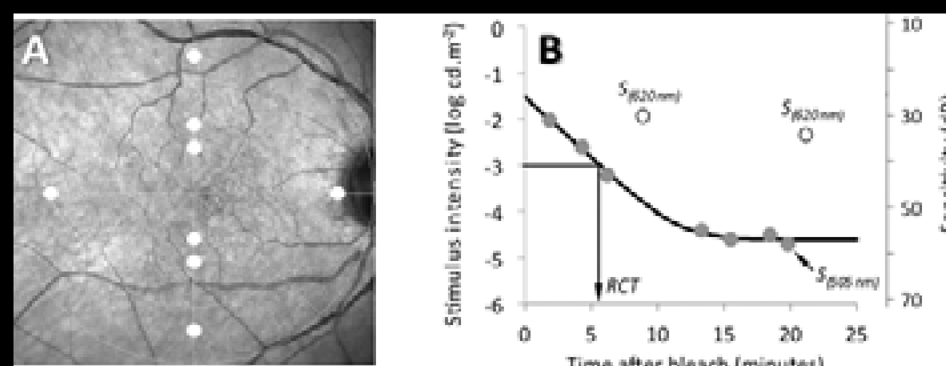
Dark Adaptation Methods



(Sample DA Curve)

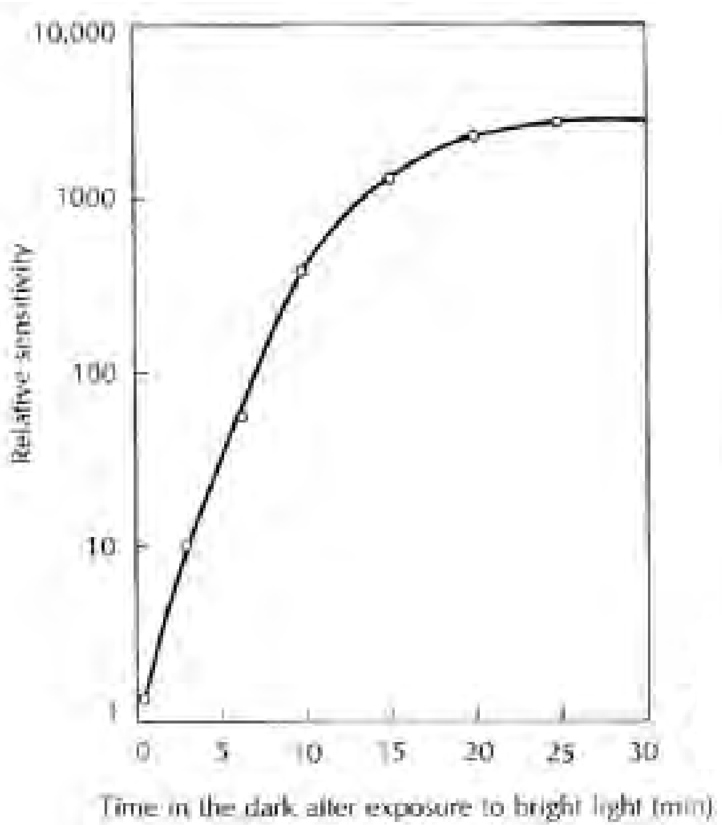


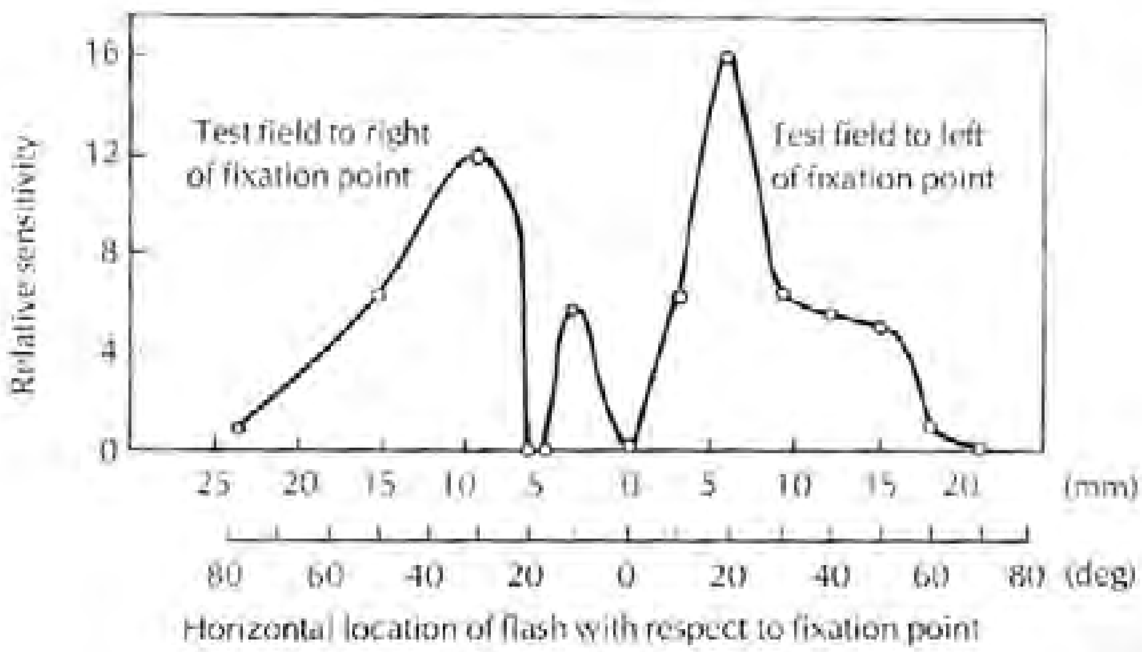
Jackson et al 2014, IOVS



Fraser et al 2016, IOVS

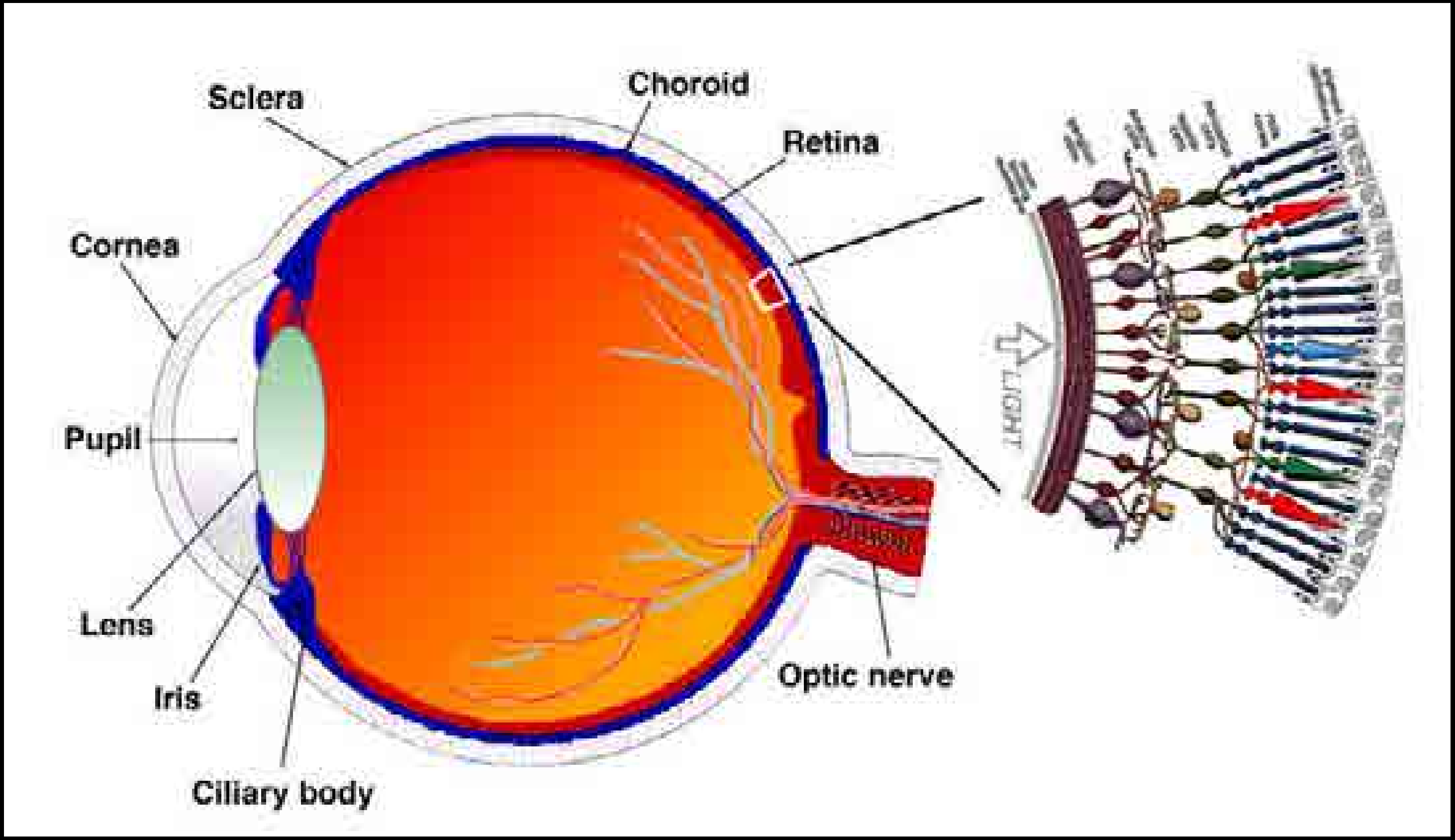
Meaning for Retinal Sensitivity





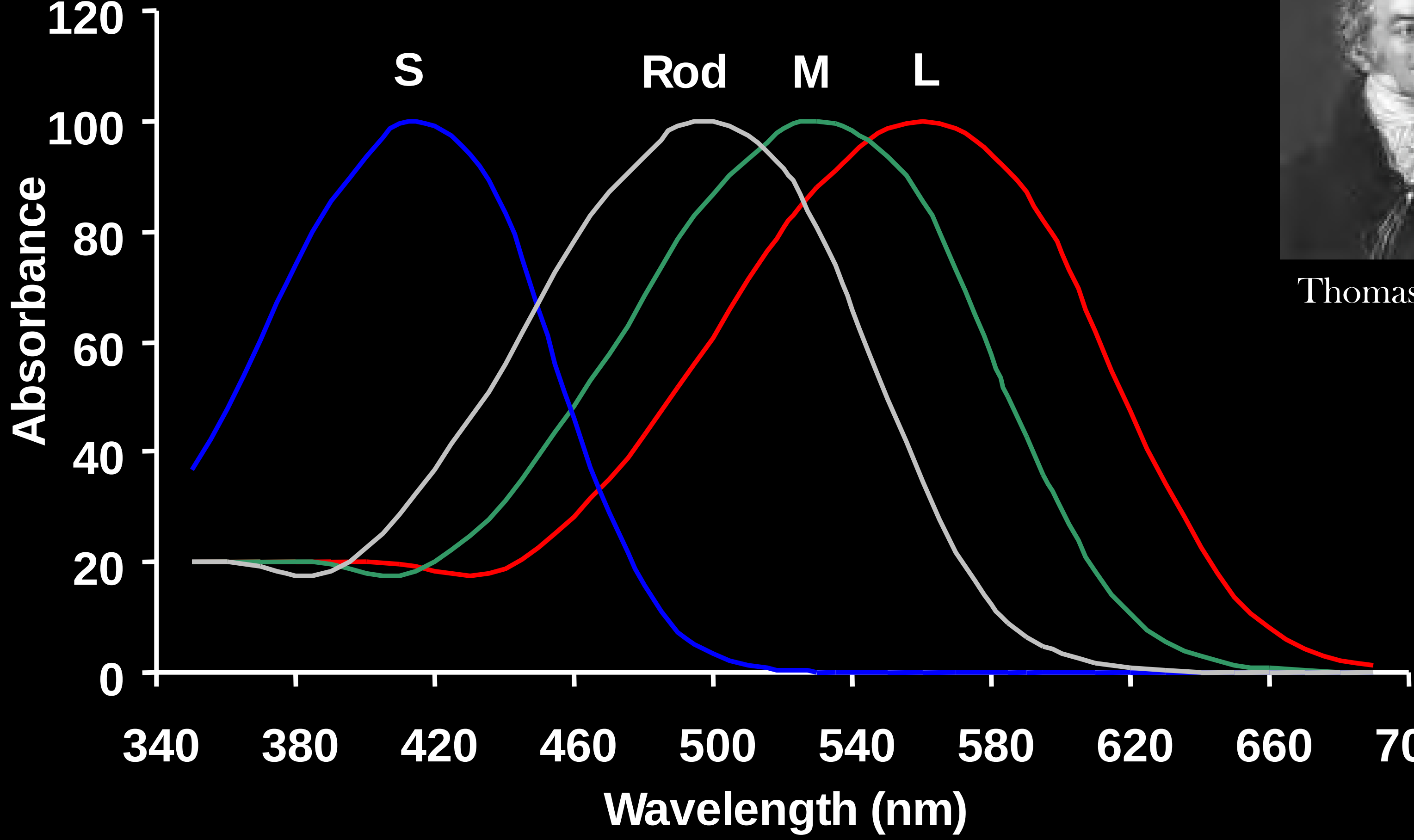
Cornsweet, 1987 'Experiment of
Hecht, Schlaer and Pirenne'

The Human Eye



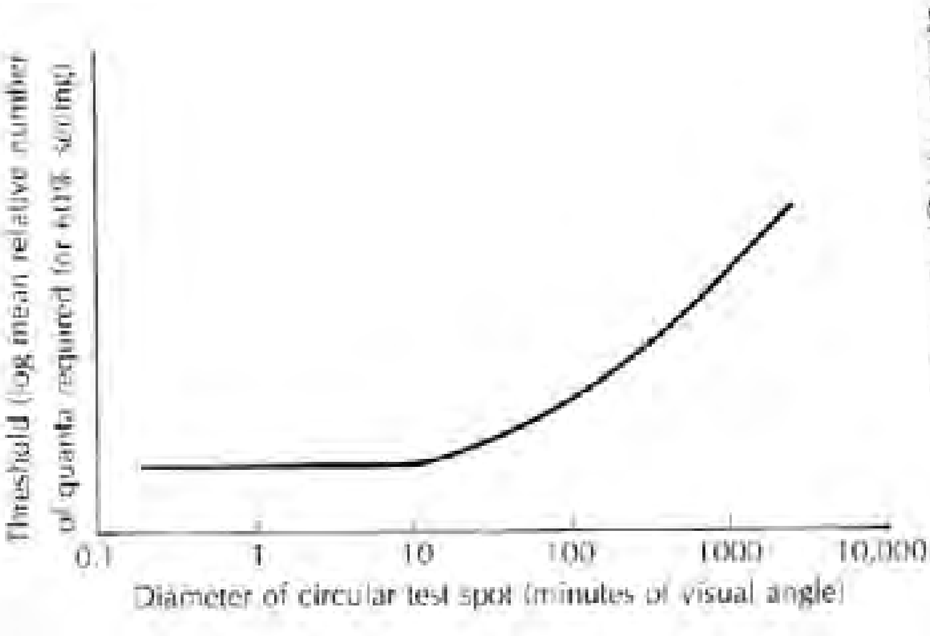
Webvision.med.utah.edu

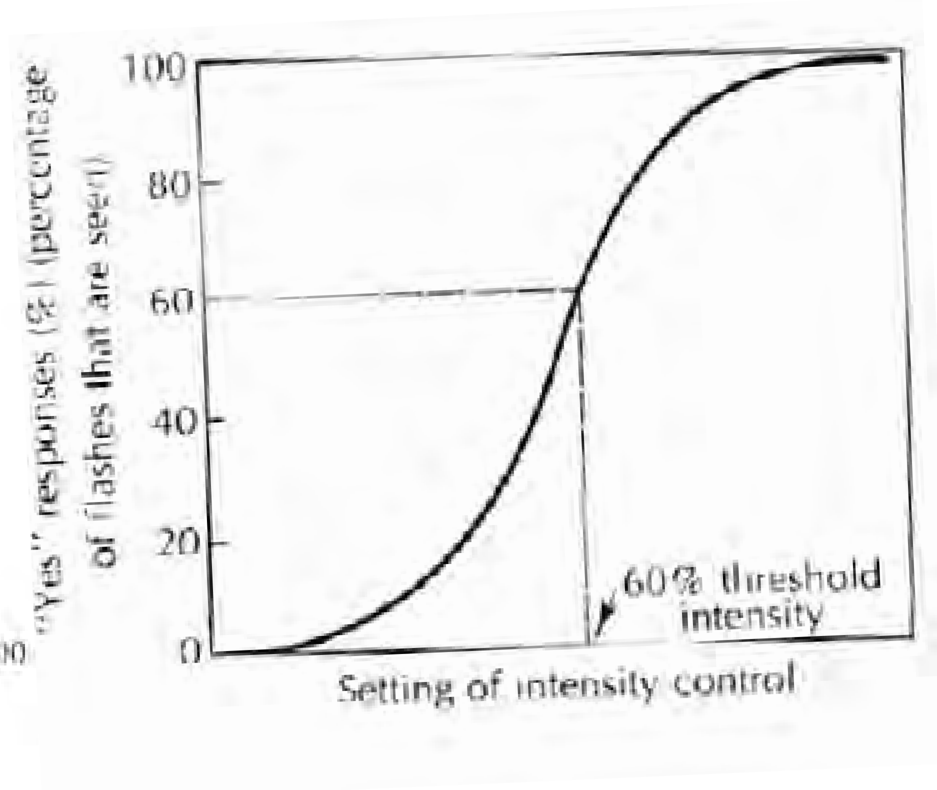
Photopigments can be characterized according to the efficiency with which they absorb light...



Thomas Young

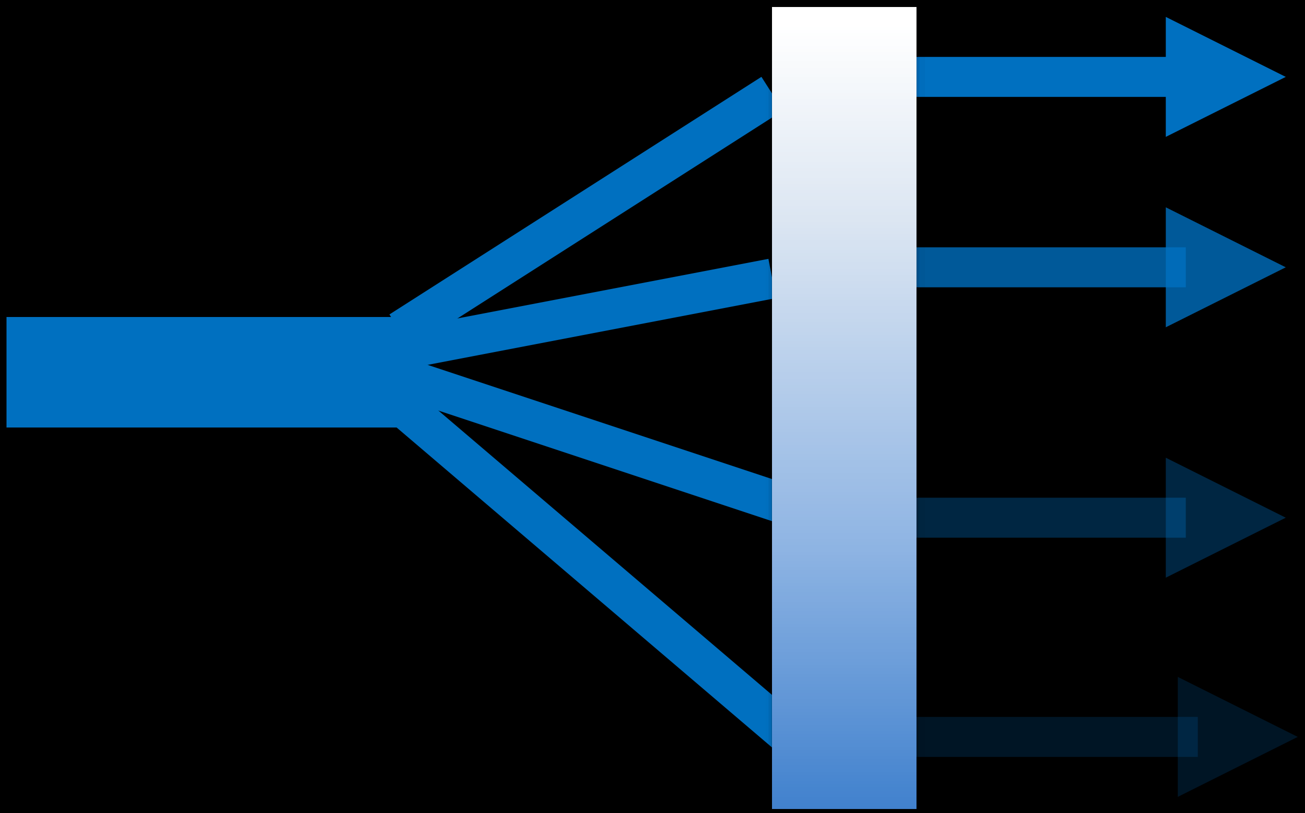
Defining Stimulus Parameters





Cornsweet, 1987 'Experiment of Hecht, Schlaer and Pirenne'

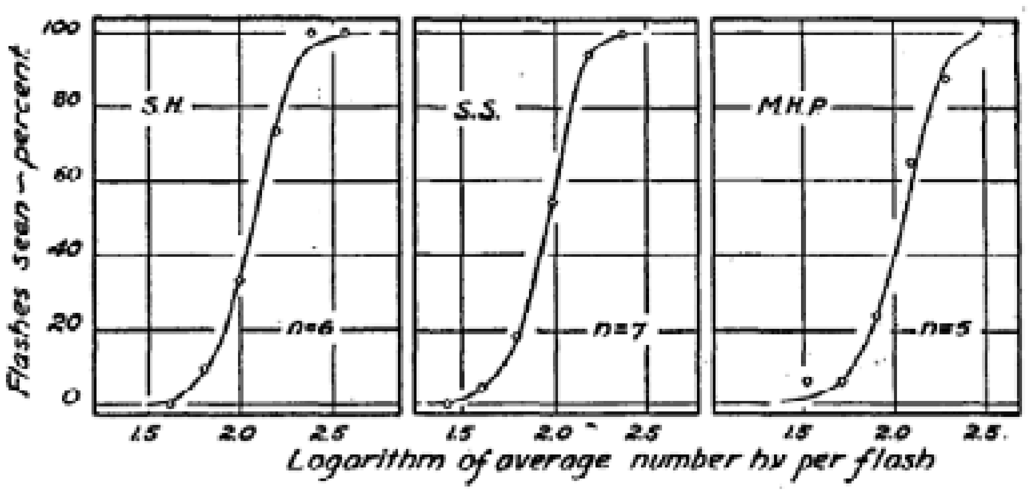
Controlling Intensity Level



Use of a gradient filter

Final Rod System Sensitivity

S. H.		S. H.		S. S.		S. S.		M. H. P.	
No. of quanta	Frequency	No. of quanta	Frequency	No. of quanta	Frequency	No. of quanta	Frequency	No. of quanta	Frequency
	per cent		*per cent*		*per cent*		*per cent*		*per cent*
46.9	0.0	37.1	0.0	24.1	0.0	23.5	0.0	37.6	6.0
73.1	9.4	58.5	7.5	37.6	4.0	37.1	0.0	58.6	6.0
113.8	33.3	92.9	40.0	58.6	18.0	58.5	12.0	91.0	24.0
177.4	73.5	148.6	80.0	91.0	54.0	92.9	44.0	141.9	66.0
276.1	100.0	239.3	97.5	141.9	94.0	148.6	94.0	221.3	88.0
421.7	100.0	386.4	100.0	221.3	100.0	239.3	100.0	342.8	100.0



' This small number of quanta, in comparison with the large number of rods (500) involved, precludes any significant two quantum absorptions per rod, and means that in order to produce a visual effect, one quantum must be absorbed by each of 5-14 rods in the retina'

Hecht, Schlaer and Pirenne (1943)

What limits our ability to stimulate individual photoreceptors?

What limits our ability to stimulate individual photoreceptors?

- Optical aberrations – light scatter caused by liquid in eye and alignment of cells of eye
- Chromatic aberration- the human cornea and lens do not treat all wavelengths equally
- Eye motion – the eye is constantly moving, when imaging at the cellular scale this is a challenge

The Human Eye is Highly Aberrated

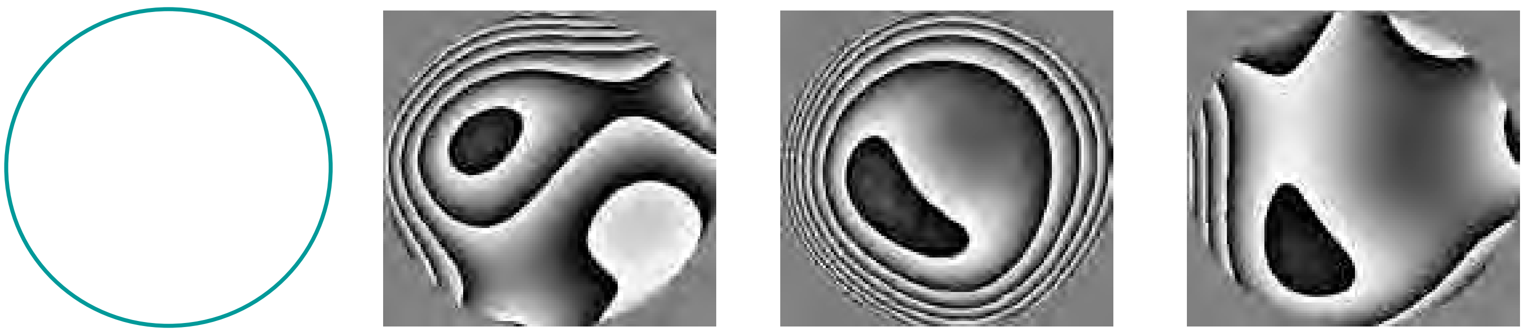
Wave Aberration (High order)

Perfect eye (diffraction-limited)

MRB

GYY

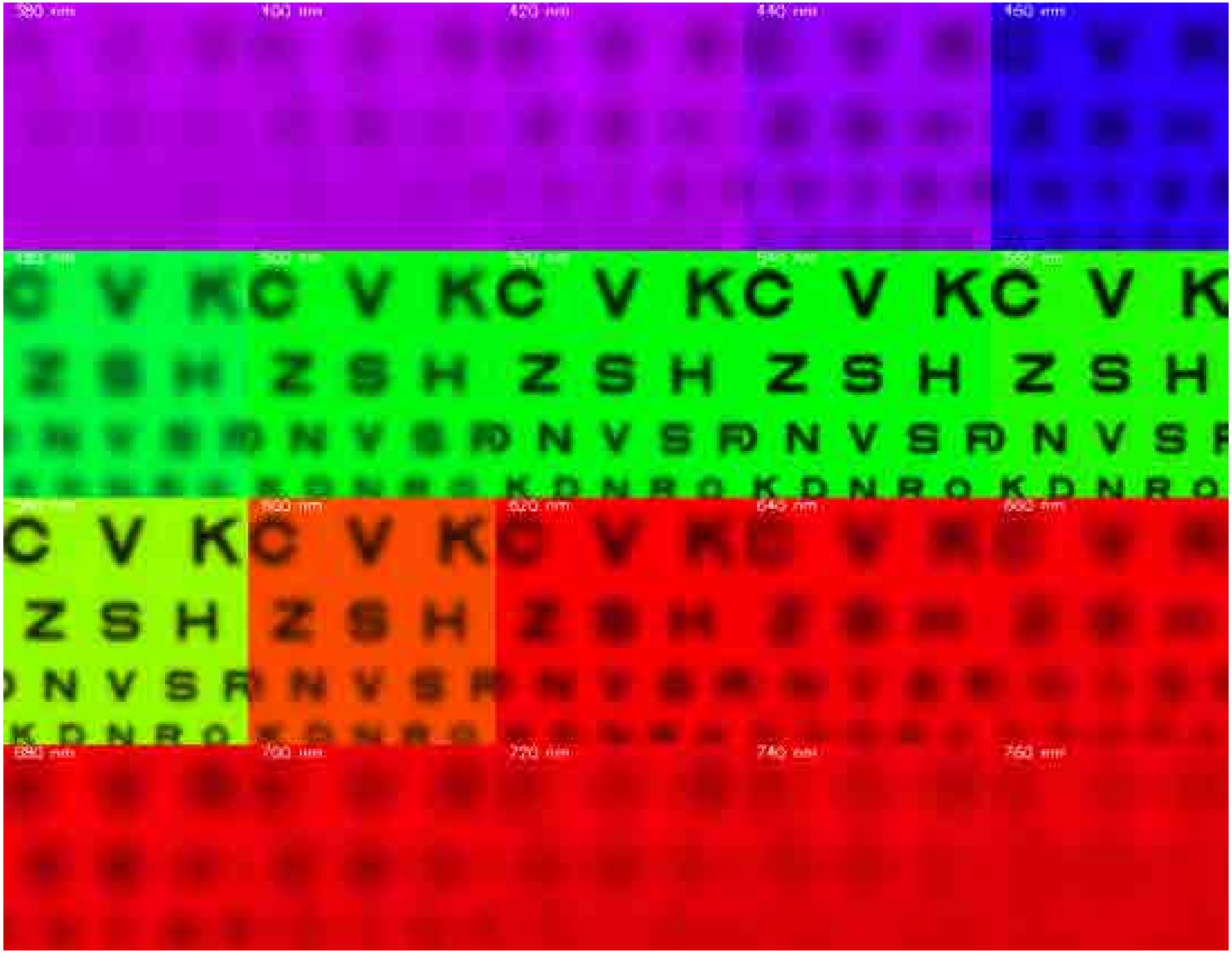
MAK



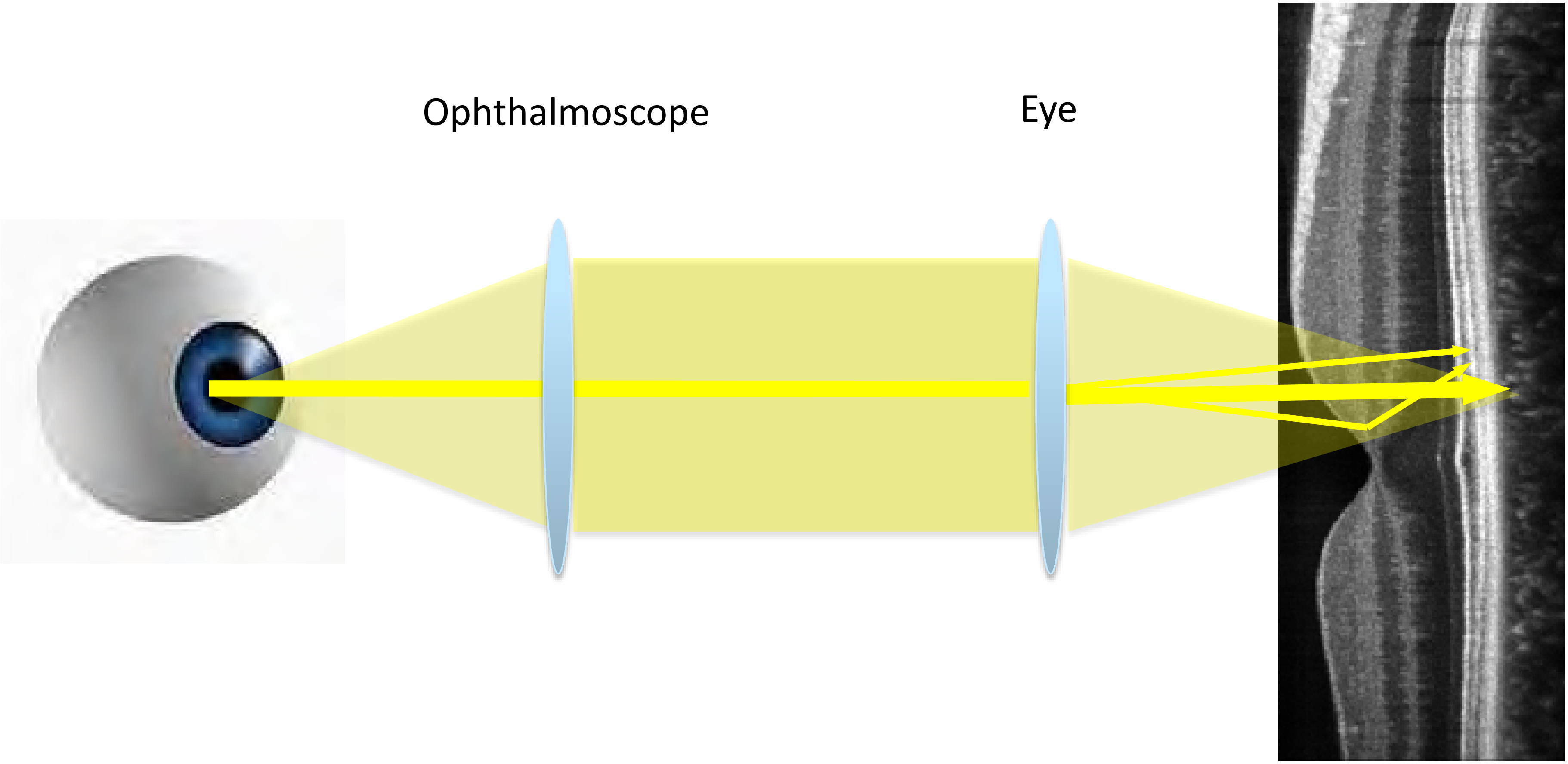
5.7-mm pupil

Courtesy: Jason Porter

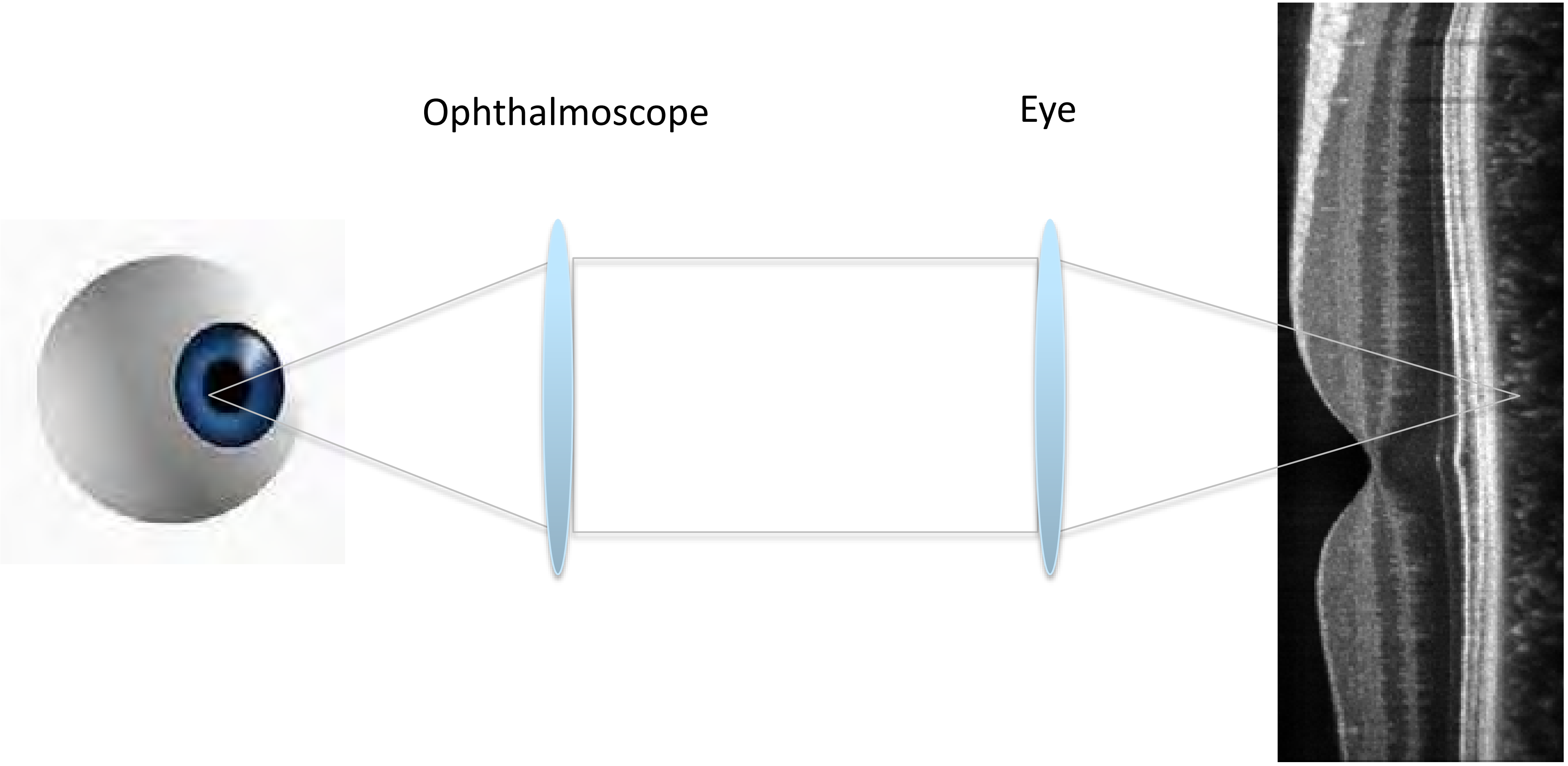
Effect of chromatic blur on eye chart



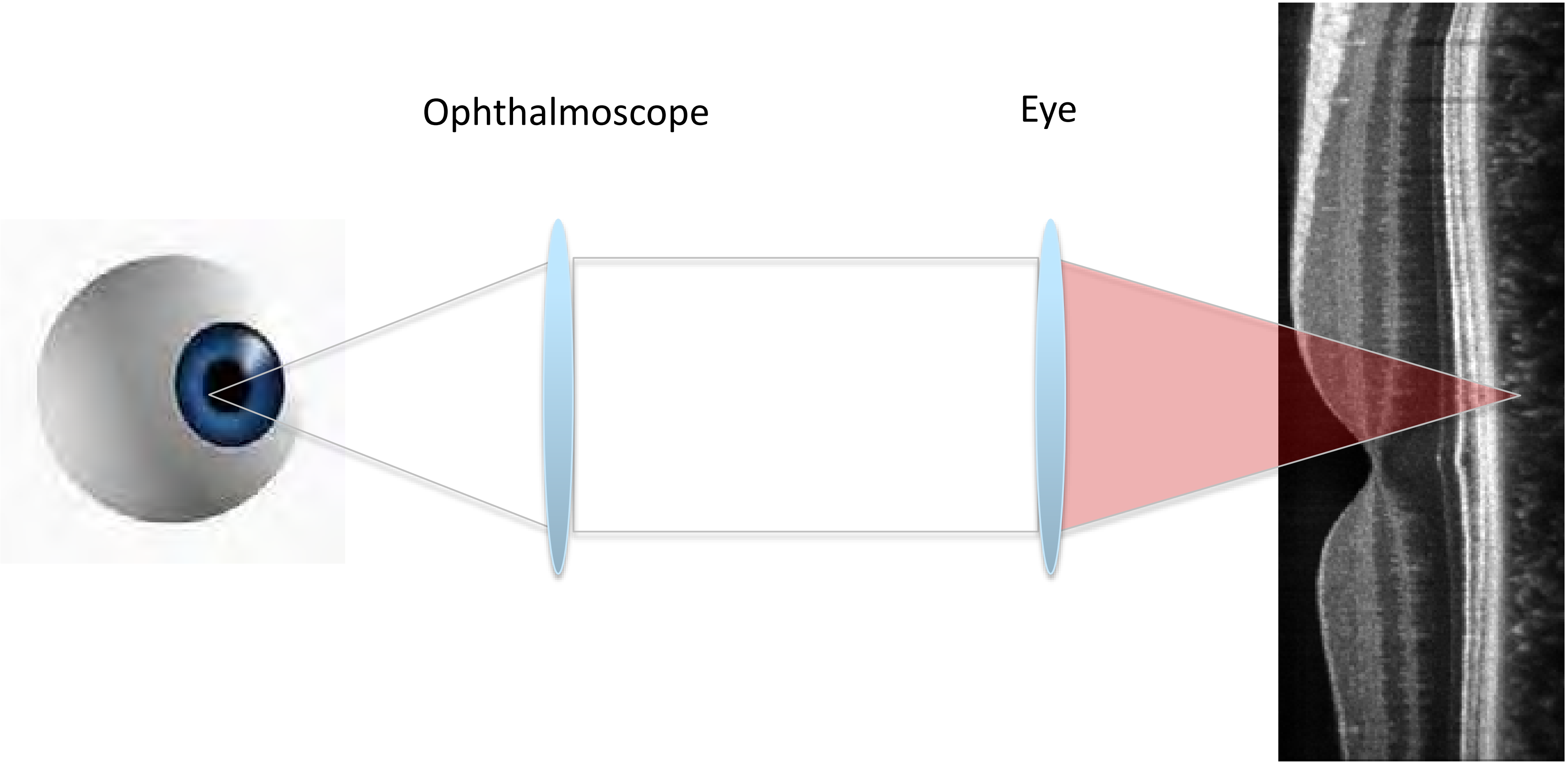
Ray Tracing: Light to Image



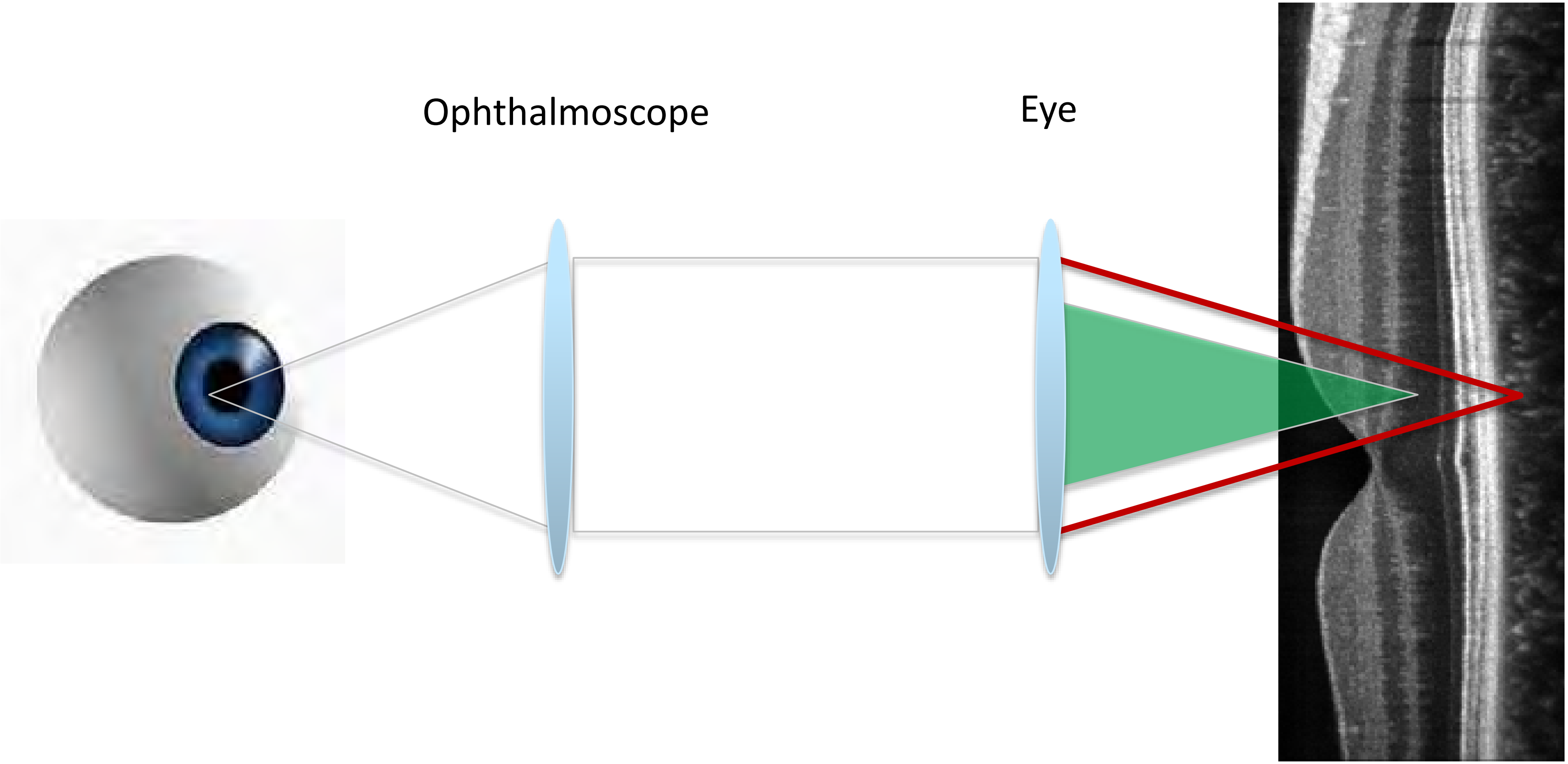
Ray Tracing: Light to Image



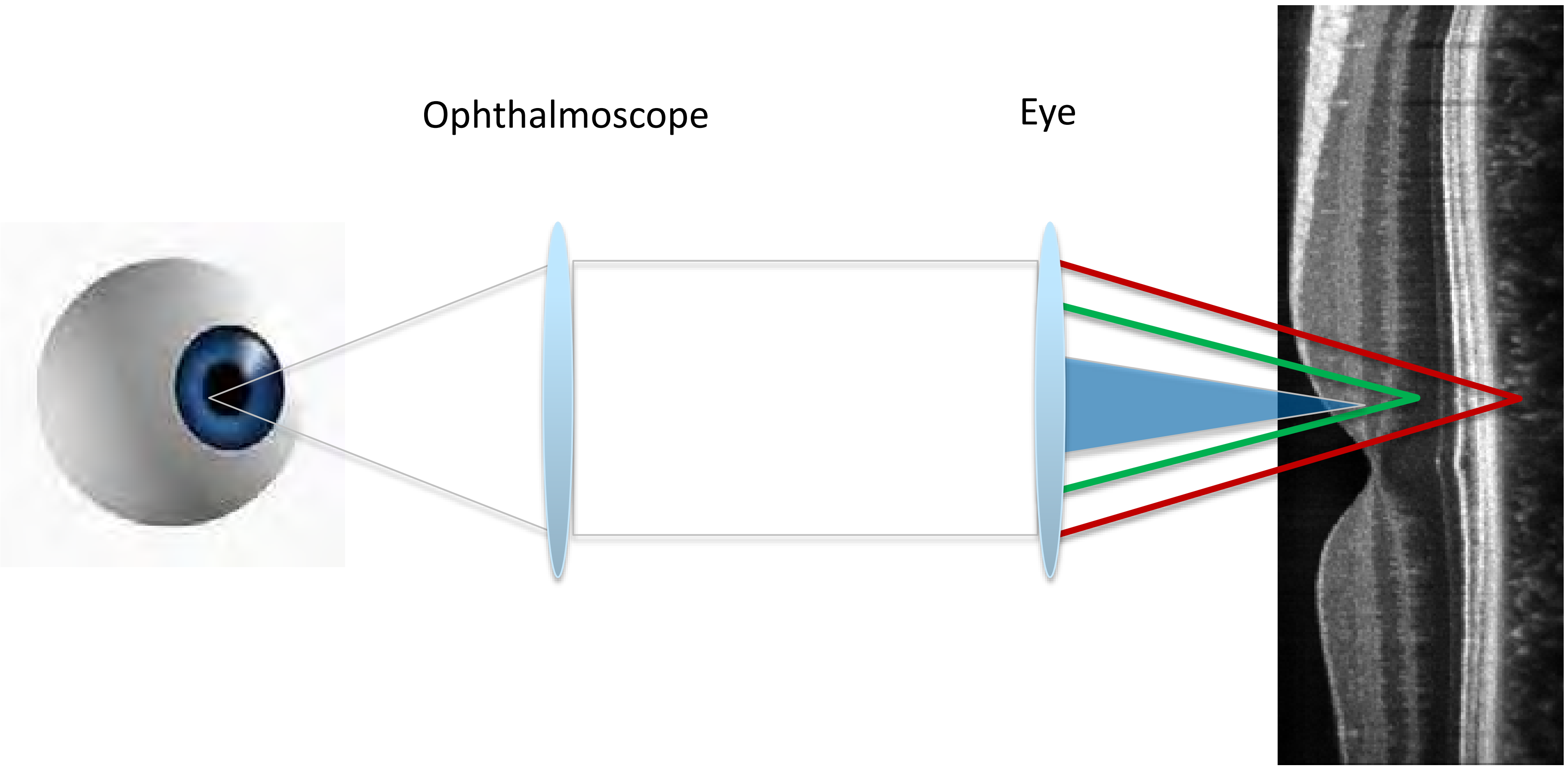
Ray Tracing: Light to Image



Ray Tracing: Light to Image

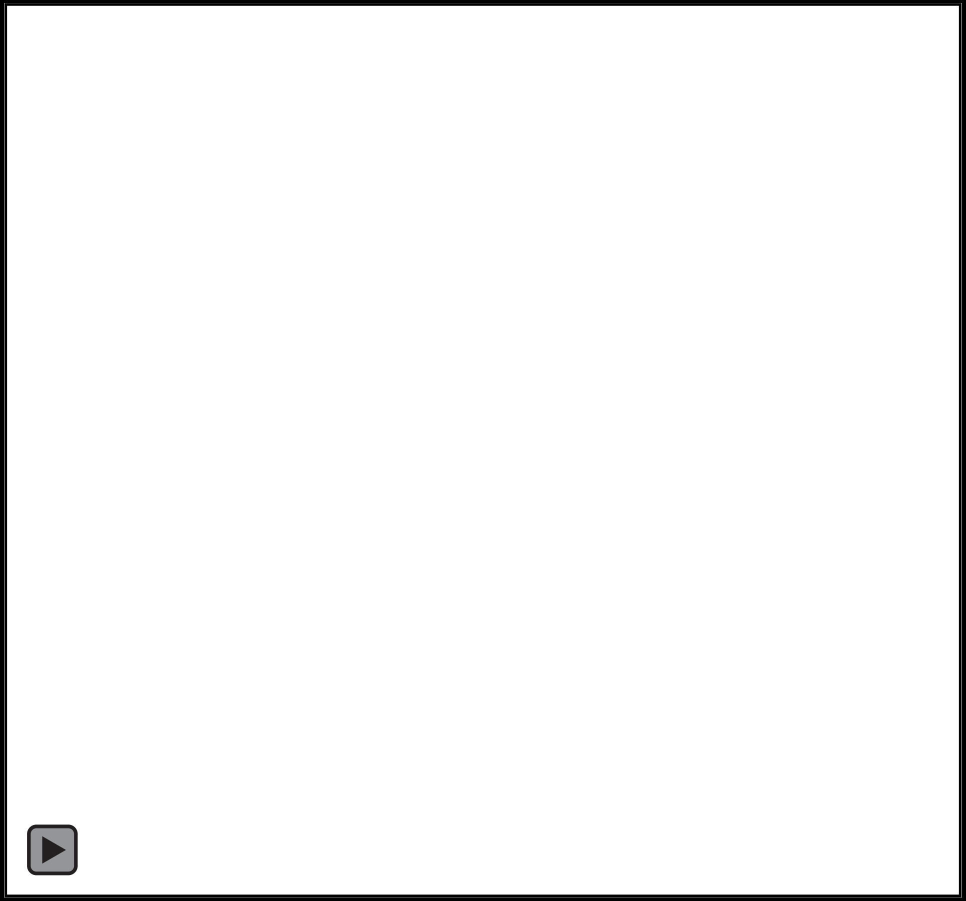


Ray Tracing: Light to Image

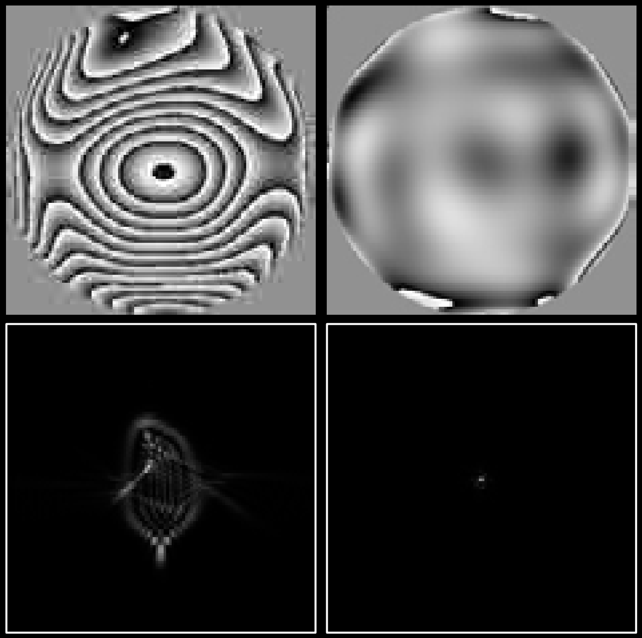


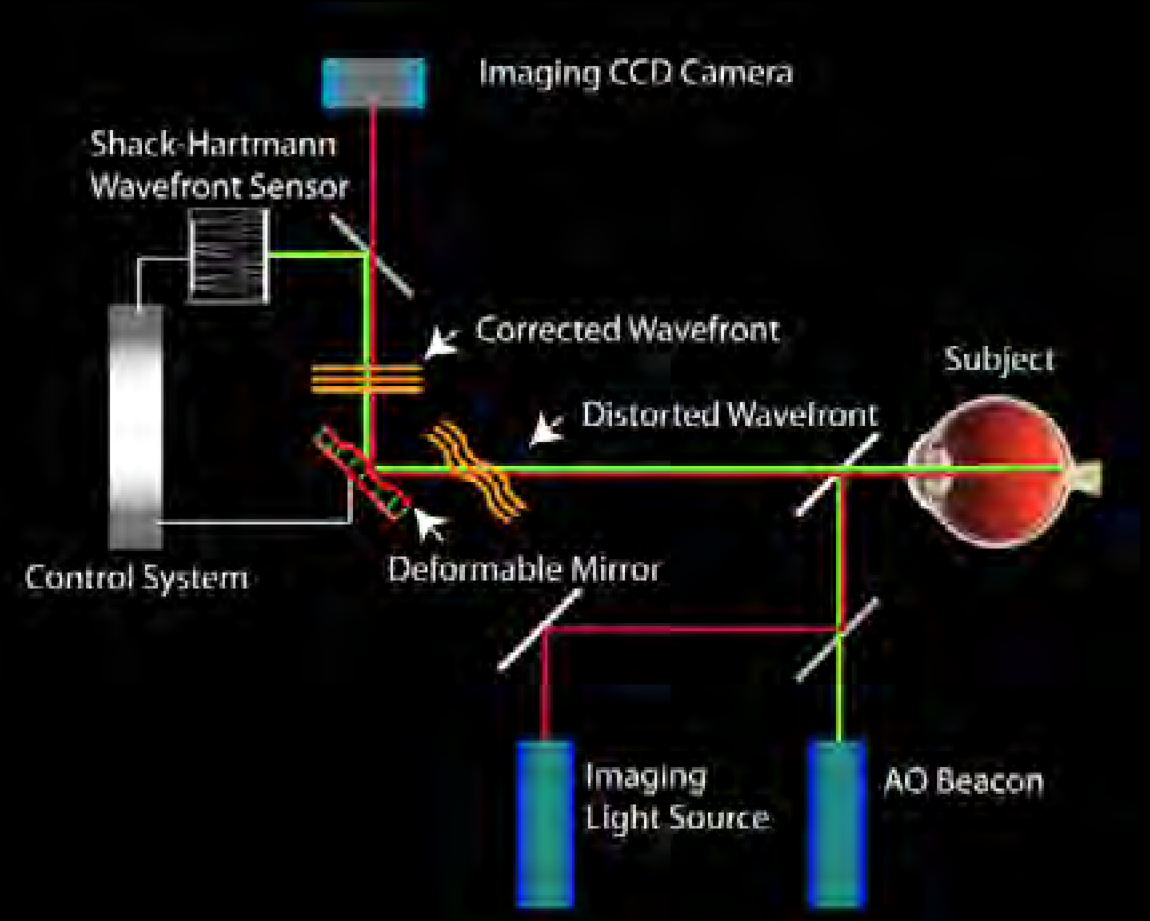
Effects of Eye Motion

- The eye is constantly moving
- This ensures the photoreceptors detection information in visual space are always ready
- This motion usually covers an area of 75-125µm
- This is different than nystagmus or large saccades which you will learn about



Adaptive Optics (AO) Retinal Imaging

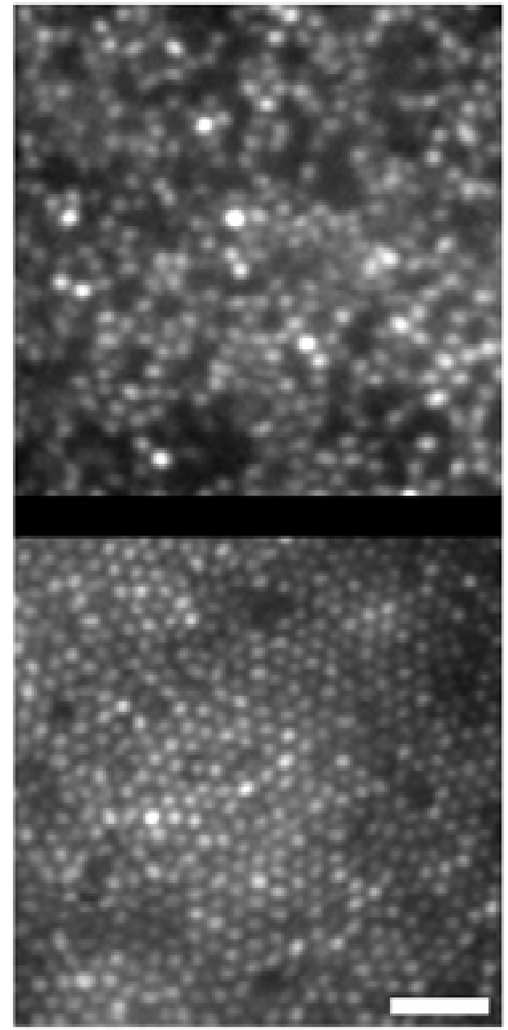




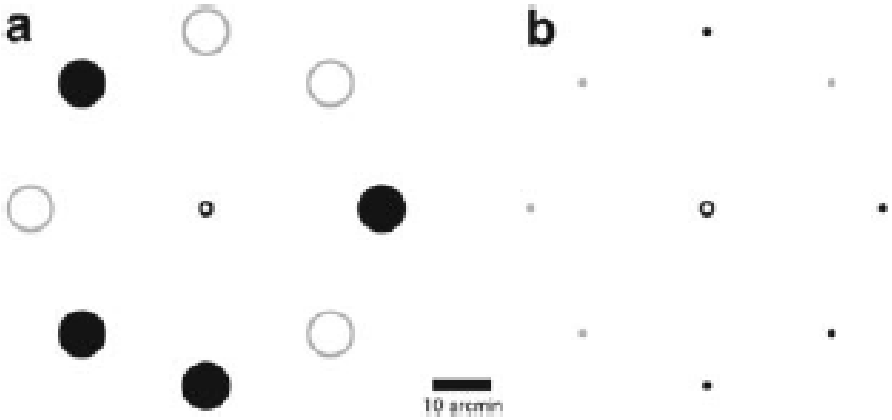
Retinal Microscotomas Revealed with Adaptive-Optics Microflashes

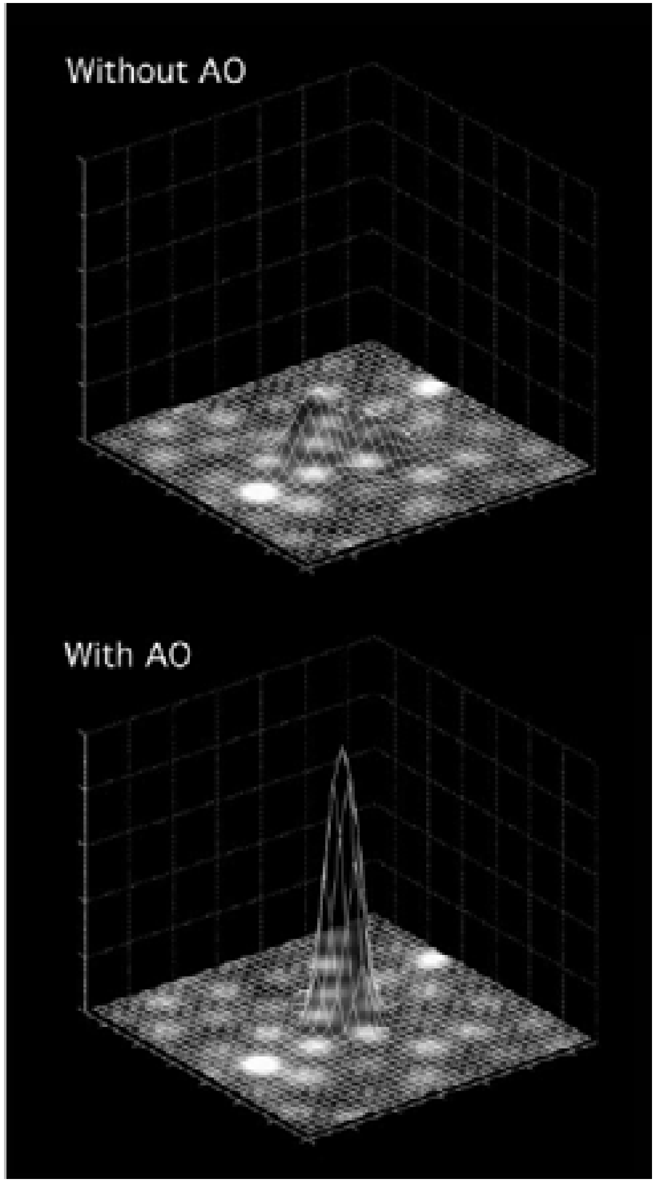
Walter Makous,[1,2] *Joseph Carroll,*[1,3] *Jessica I. Wolfing,*[1,4] *Julianna Lin,*[1] *Nathan Christie,*[5] *and David R. Williams*[1,2,4]

- Williams et al had just recently applied adaptive optics to the human eye, which gave near diffraction limited views of the back of the eye
- Carroll et al had recently identified people with unusual L/M opsin genes with slightly reduced visual acuity
- The team came together to try testing the limits of cone sensitivity



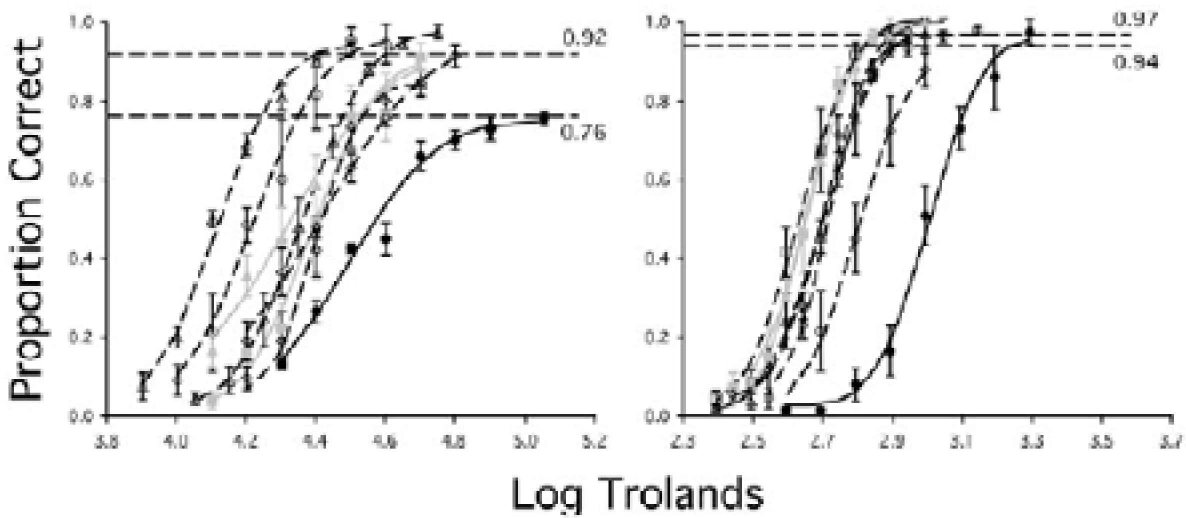
AO- Corrected Stimuli





Limits of Cone Sensitivity?

- Using the AO corrected stimuli, they showed that the patient had reduced sensitivity, even at the highest intensities
- This suggested that there were gaps in this persons sensitivity
- The team was not able to exactly localize each trial



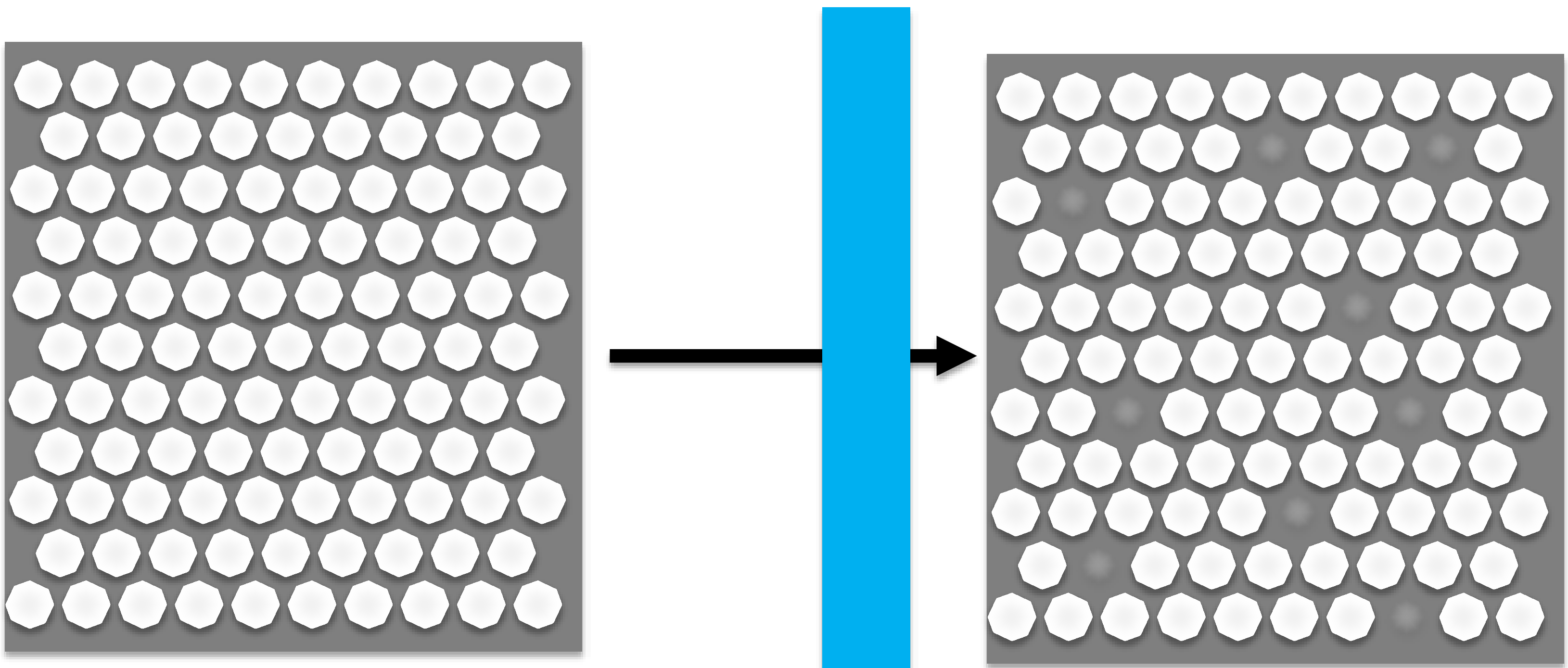
Journal of Vision (2005) 5, 444-454 http://journalofvision.org/5/5/5/ 444

Different sensations from cones with the same photopigment

Heidi Hofer Center for Visual Science, University of Rochester, Rochester, NY, USA

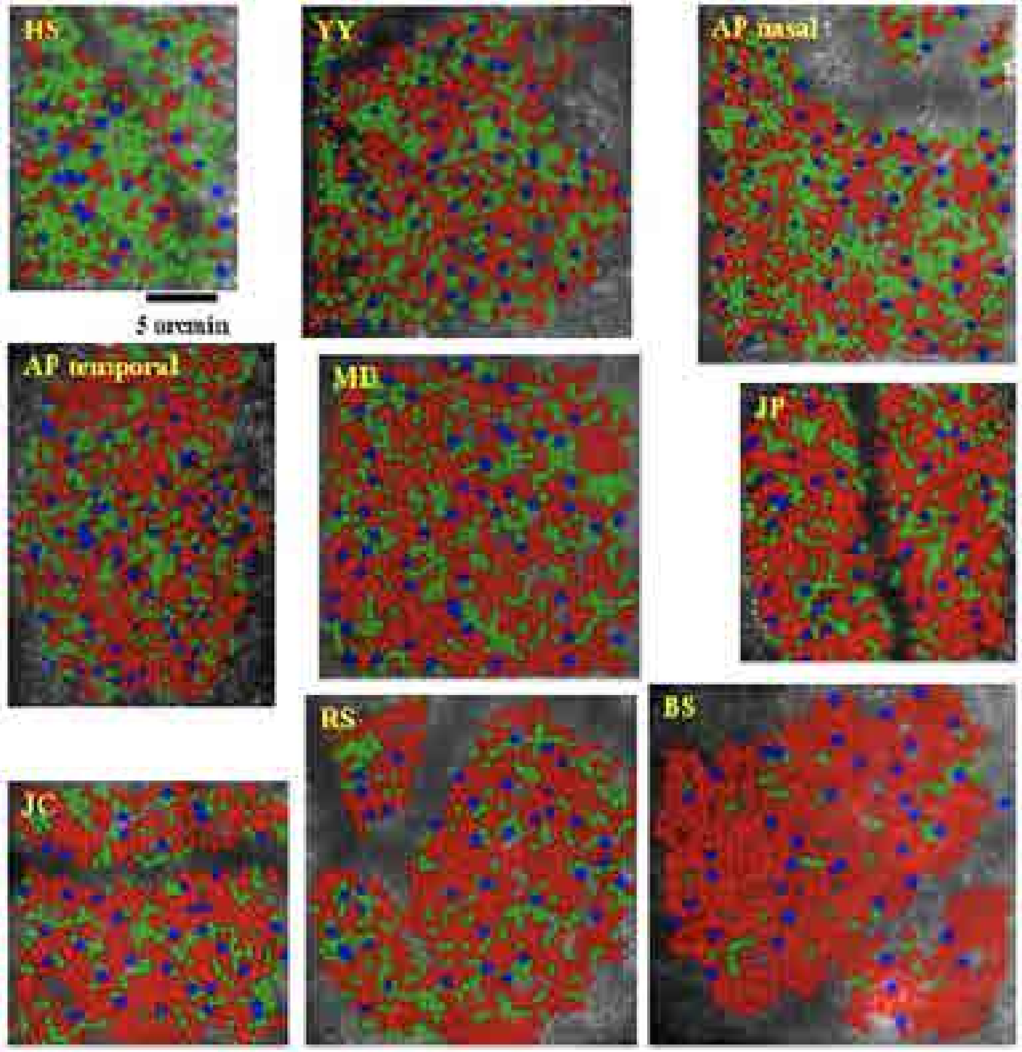
Ben Singer Center for Visual Science, University of Rochester, Rochester, NY, USA, & Center for the Study of Brain, Mind, and Behavior, Princeton University, Princeton, NJ, USA

David R. Williams Center for Visual Science, University of Rochester, Rochester, NY, USA



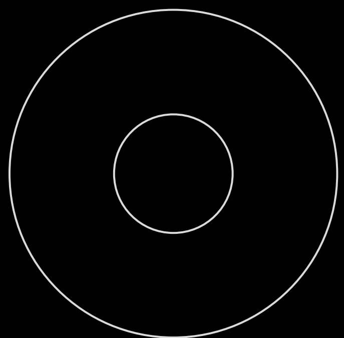
Variability in Cone Ratio

- Sets of images under different bleach states were acquired to determine cone type by densitometry
- Images shown as pseudocolour based in densitometry results
- Subjects were found to have highly skewed cone ratios



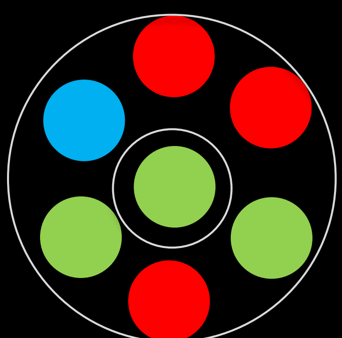
Hofer et al (2005a)

Spectral Opponency



- Centre vs surround activation and repression signals are combined to create chromatic percept

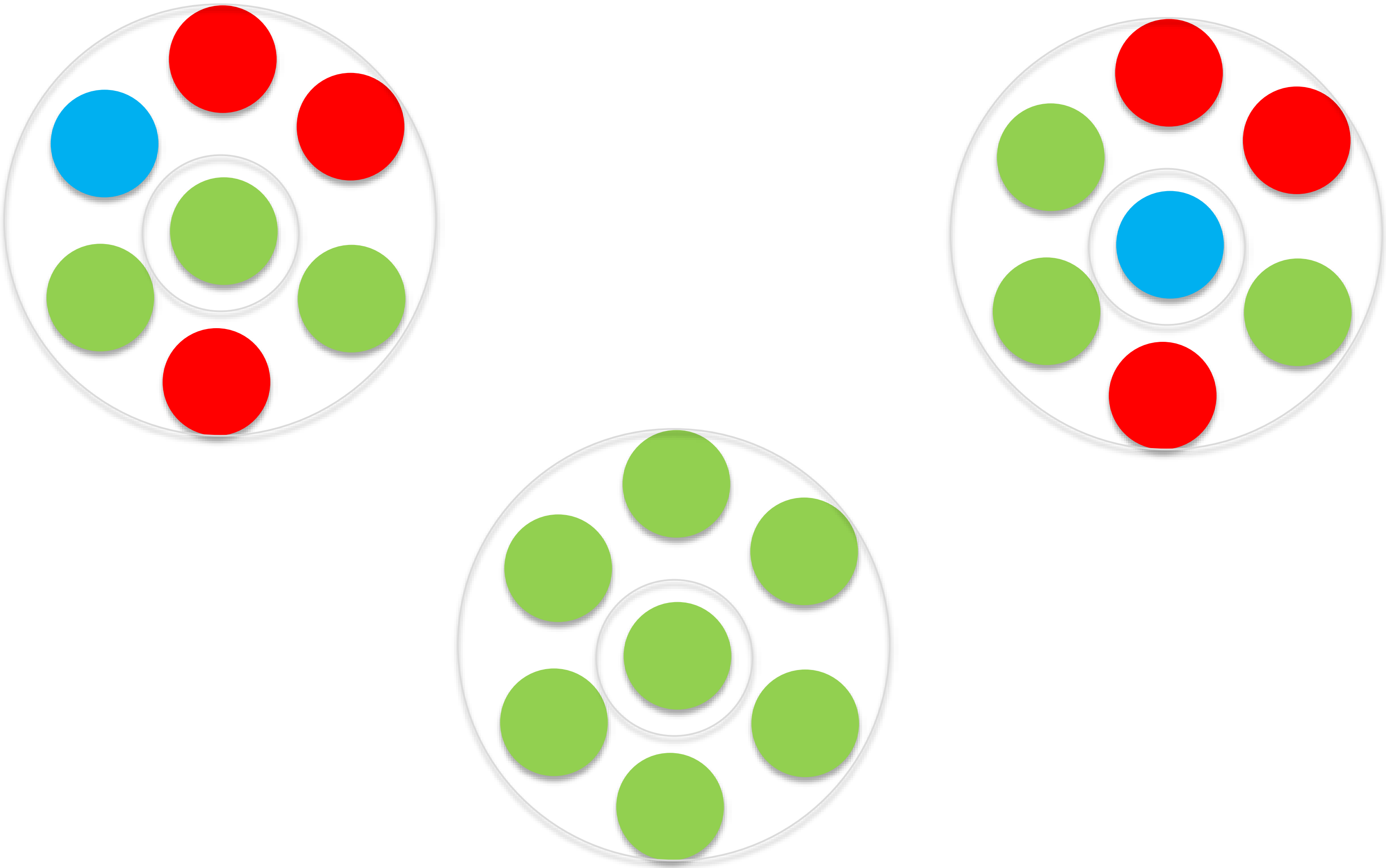
- Evolutionary the same photoreceptors must also encode an achromatic, intensity channel



- Intensity channel is believed to follow midget pathways and contribute to acuity

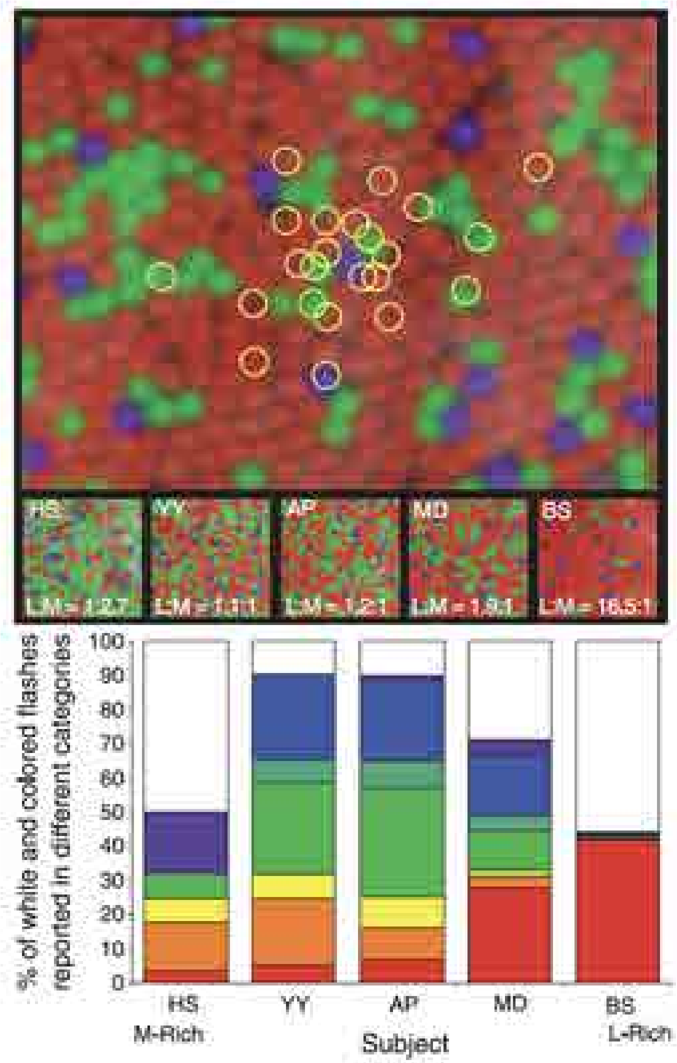
- How can these systems work together?

Spectral Opponency



Colour from a Single Cone

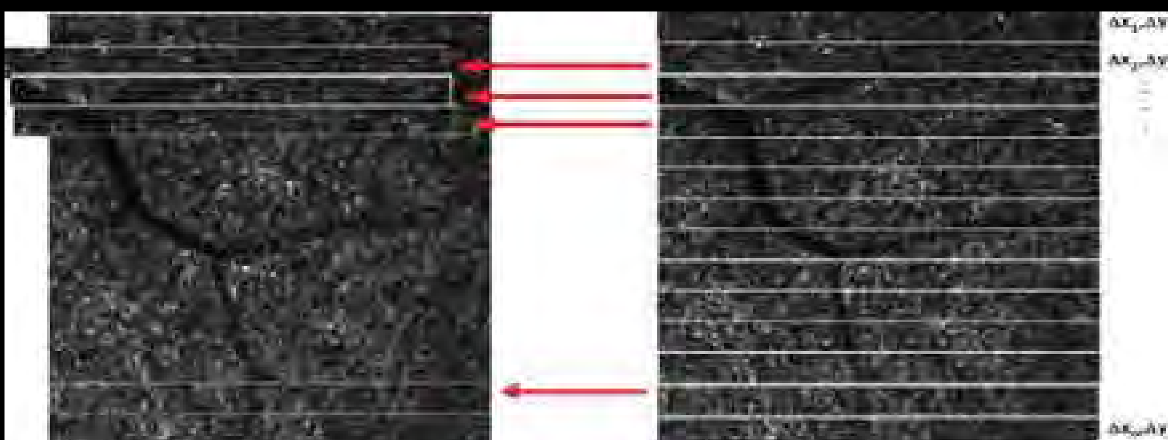
- Health controls had regions of there retina cone typed using retinal densitometry
- They were then shown 550 nm (green) spots, stimuli were 0.3 arcmin and ~4 msec
- Stimuli, if diffraction limited were ~1/3-1/2 cone diameter
- Highly variable responses, but all saw chromatic responses
- Were not able to localise stimuli to cone stimulated (exactly)

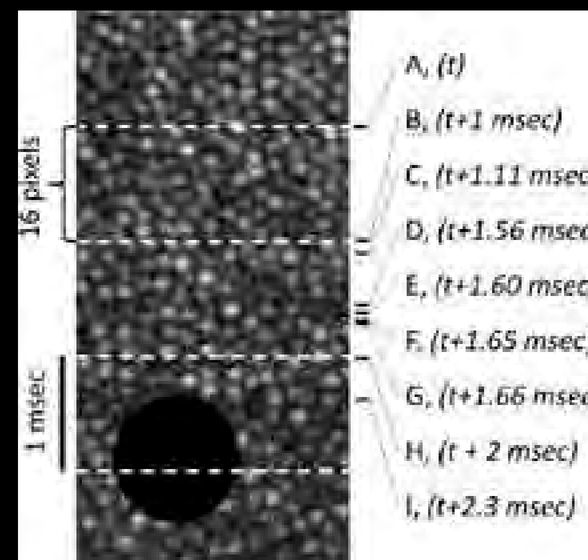


High-speed, image-based eye tracking with a scanning laser ophthalmoscope

Christy K. Sheehy,[1,*] Qiang Yang,[2] David W. Arathorn,[2] Pavan Tiruveedhula,[1] Johannes F. de Boer,[3] and Austin Roorda[1]

[1]School of Optometry, University of California, Berkeley; Berkeley, CA 94720, USA
[2]Montana State University, Bozeman, MT 59717, USA
[3]Rotterdam Ophthalmic Institute, Rotterdam, The Netherlands
*Christy.Sheehy@berkeley.edu





- What advantages could this provide, disadvantages?

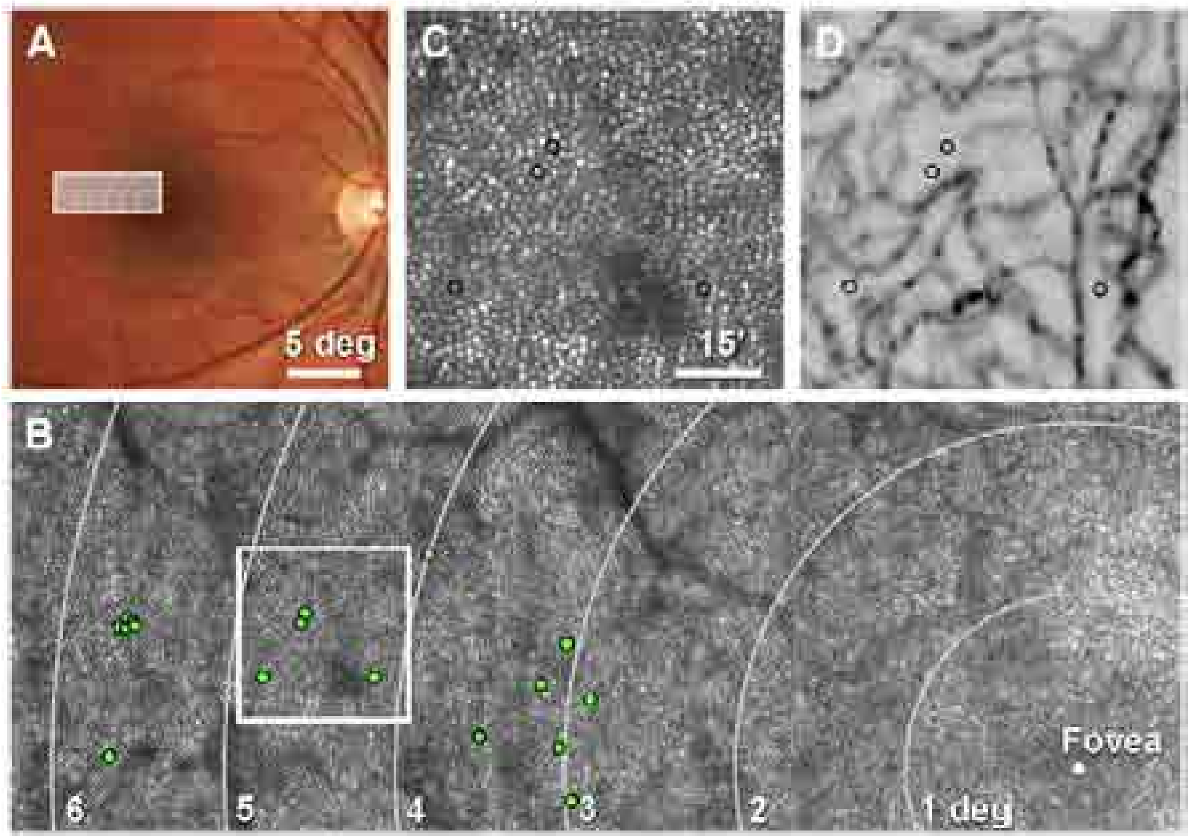
- Any other outstanding problems?

Behavioral/Cognitive

Mapping the Perceptual Grain of the Human Retina

Wolf M. Harmening,[1,2*] William S. Tuten,[1*] Austin Roorda,[1] and Lawrence C. Sincich[3]
[1]University of California, Berkeley, School of Optometry and Vision Science Graduate Group, Berkeley, California 94720, [2]University of Bonn, Department of Ophthalmology, 53127 Bonn, Germany, and [3]University of Alabama at Birmingham, Department of Vision Sciences, Birmingham, Alabama 35294

- Stimuli are now scanned in to retinally stabilized images
- Imaging at 842nm, with stimuli presented at 543nm
- Stimuli scanned in as 3x3 pixels (~2.9μm)
- Claim 1.5 px resolution for repeated stimuli



Measuring Light Energy and Sensitivity

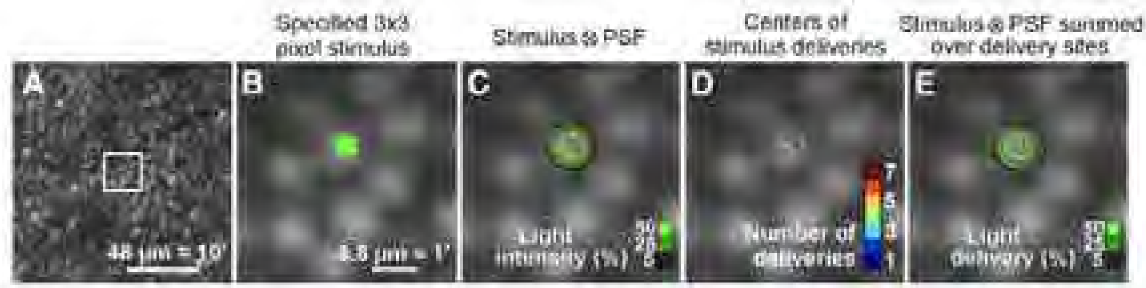


Figure 2

- As stimuli is scanned onto retina, you can assess where the stimuli falls with the residual wavefront to understand light distribution.
- There was some spill over, but was confined to a single cone space

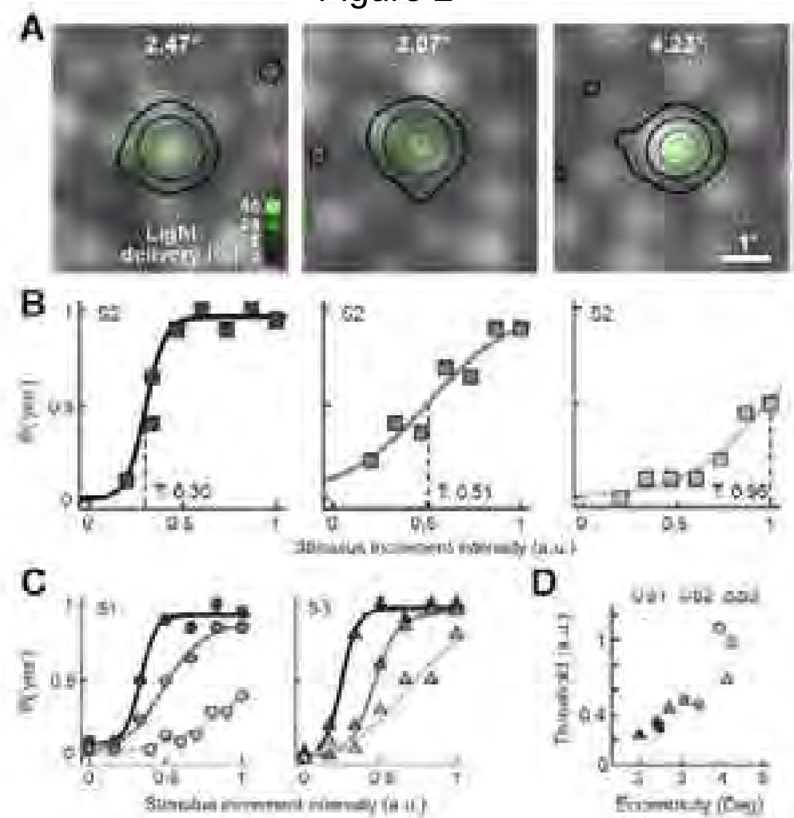
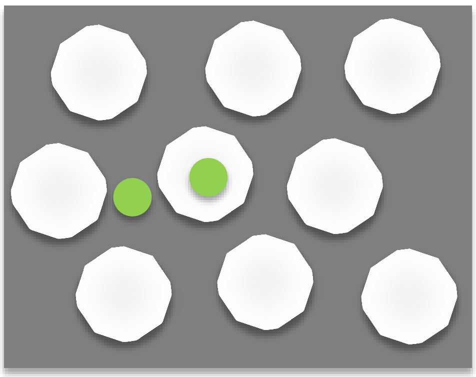


Figure 3

Gap vs Cone Sensitivity



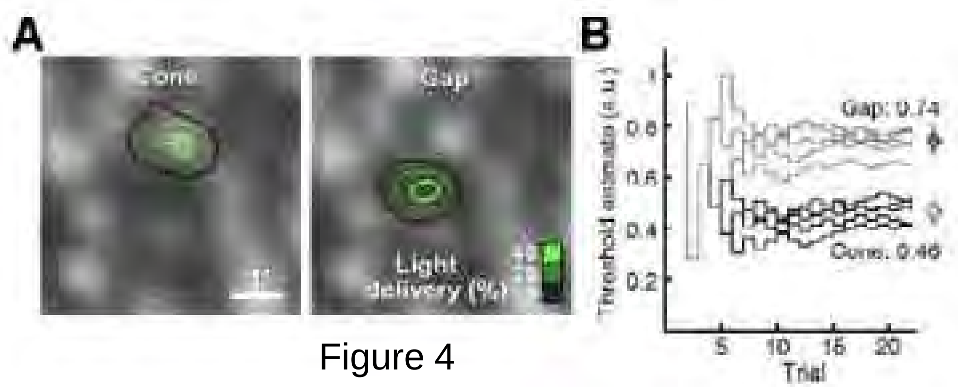


Figure 4

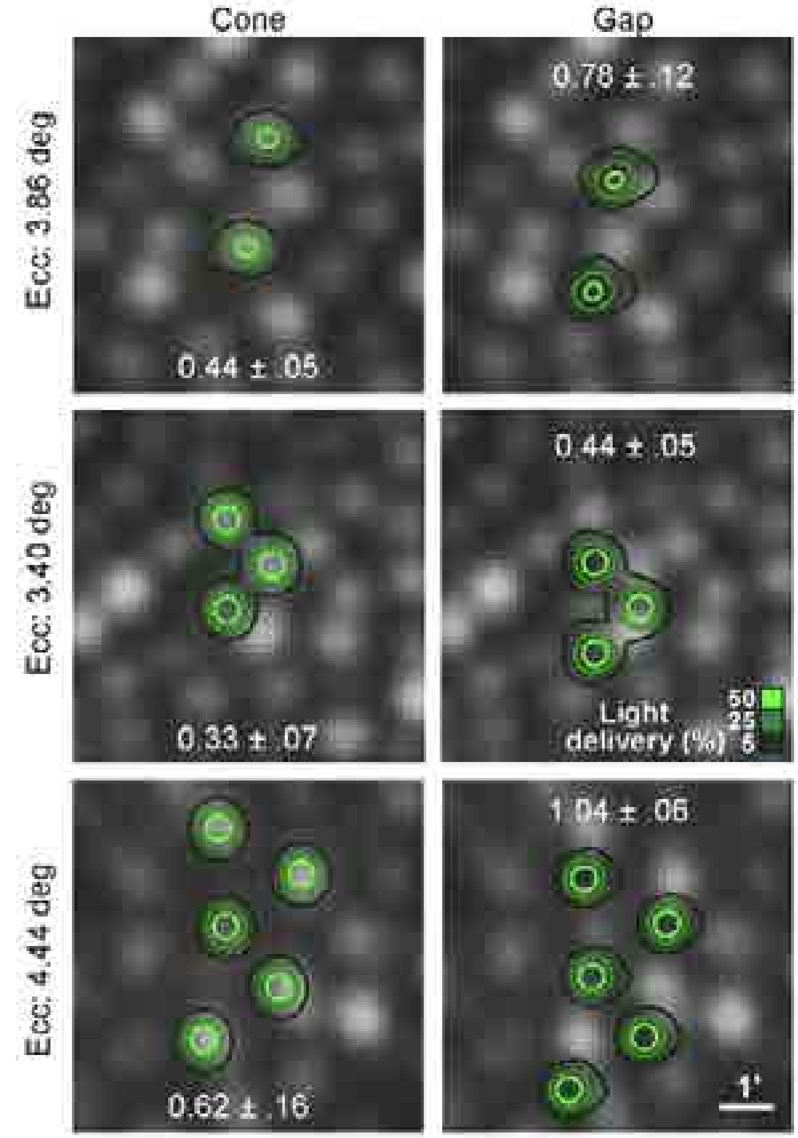


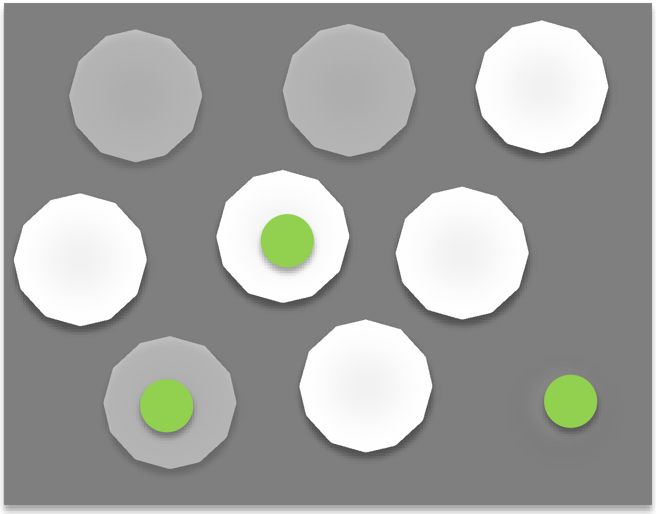
Figure 7

(Cooper, Dubis et al, 2011 – BoE)

Why may cone reflectance change?

Do you think some cones may stay always bright or always dark?

Does cone reflectance correlate with function?

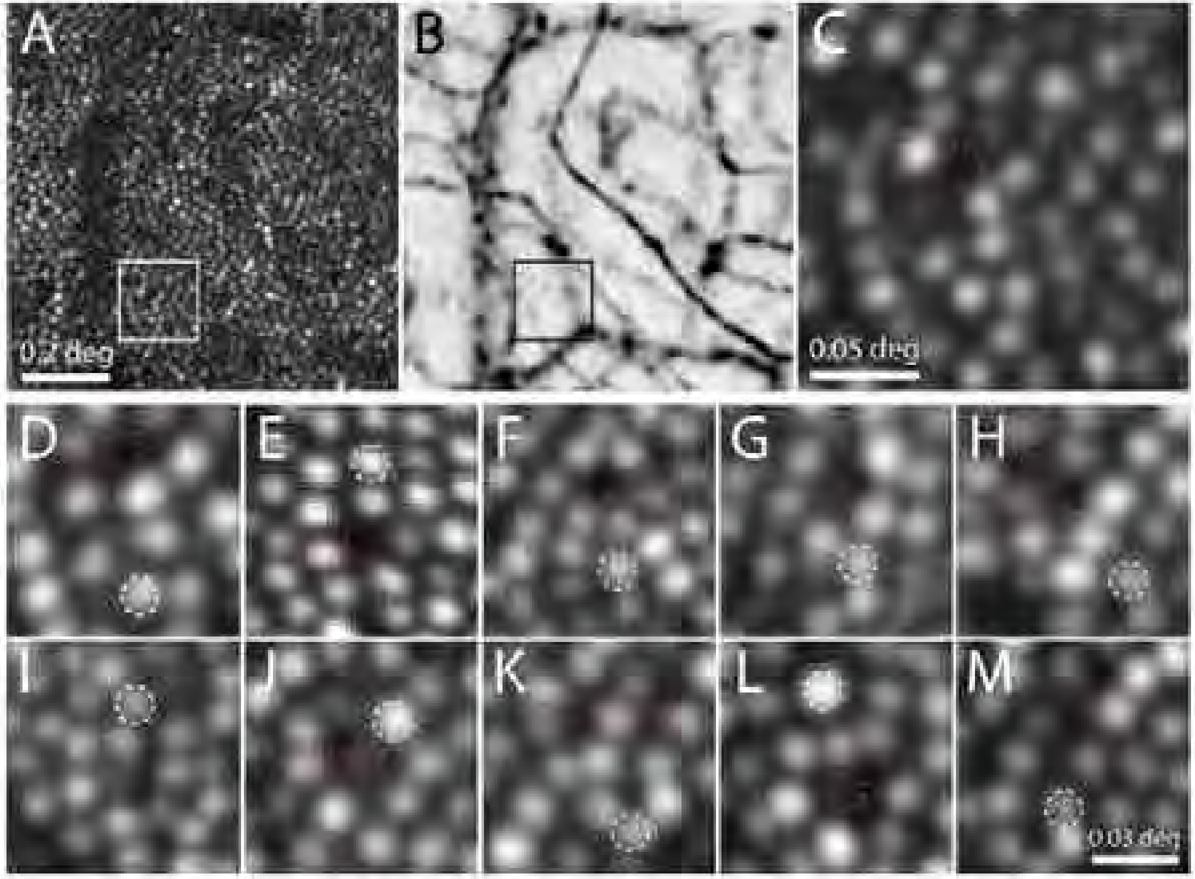


Visual Psychophysics and Physiological Optics

Normal Perceptual Sensitivity Arising From Weakly Reflective Cone Photoreceptors

Kady S. Bruce,[1] Wolf M. Harmening,[2] Bradley R. Langston,[3] William S. Tuten,[4] Austin Roorda,[4] and Lawrence C. Sincich[1]

[1]Department of Vision Sciences, University of Alabama at Birmingham, Birmingham, Alabama, United States
[2]Department of Ophthalmology, University of Bonn, Bonn, Germany
[3]School of Medicine, University of Alabama at Birmingham, Birmingham, Alabama, United States
[4]School of Optometry, Vision Science Graduate Group, University of California at Berkeley, Berkeley, California, United States



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[2]Department of Ophthalmology, University of Bonn, Bonn, Germany
[3]School of Medicine, University of Alabama at Birmingham, Birmingham, Alabama, United States
[4]School of Optometry, Vision Science Graduate Group, University of California at Berkeley, Berkeley, California, United States

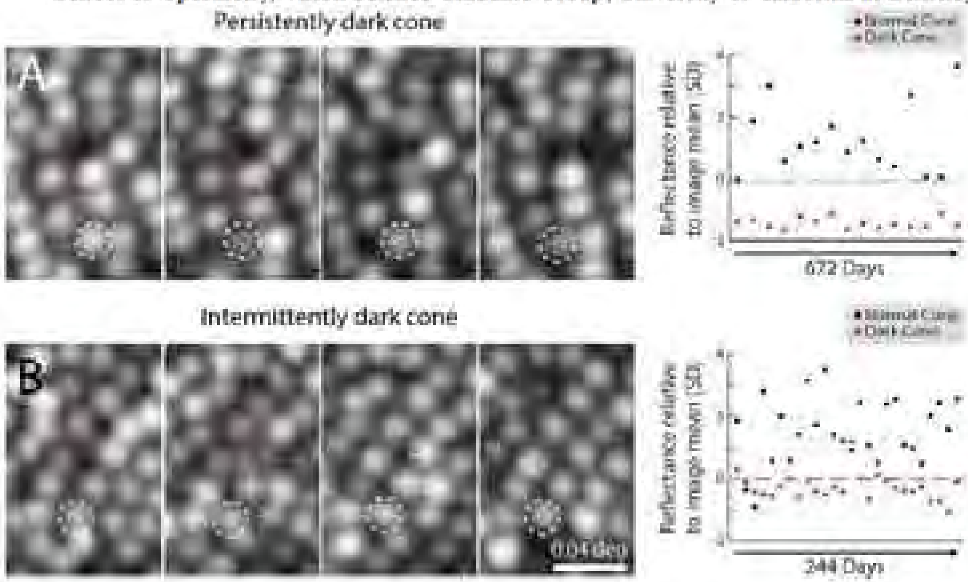

Figure 3

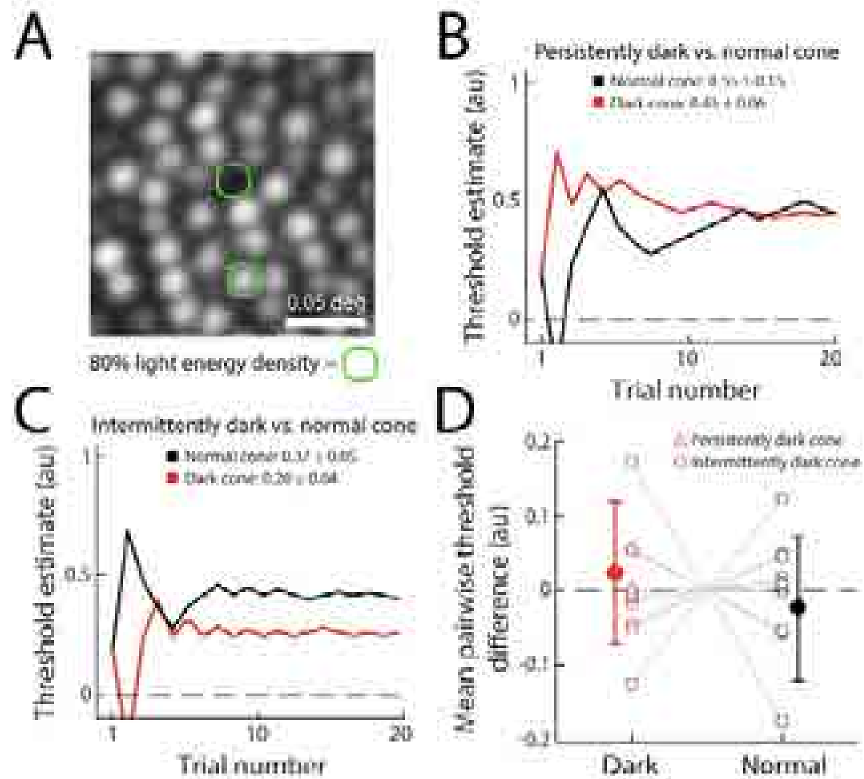

Figure 4

Visual Psychophysics and Physiological Optics

Normal Perceptual Sensitivity Arising From Weakly Reflective Cone Photoreceptors

Kady S. Bruce,[1] Wolf M. Harmening,[2] Bradley R. Langston,[3] William S. Tuten,[4] Austin Roorda,[4] and Lawrence C. Sincich[1]

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[2]Department of Ophthalmology, University of Bonn, Bonn, Germany
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- Tested 284 normally reflecting pairs, found no difference in threshold between these pairs and the dark/light pairs

- Hypothesized that the difference in intensity was due to waveguiding properties

- This would mean there is an anatomical basis for the difference, but does not disrupt function.

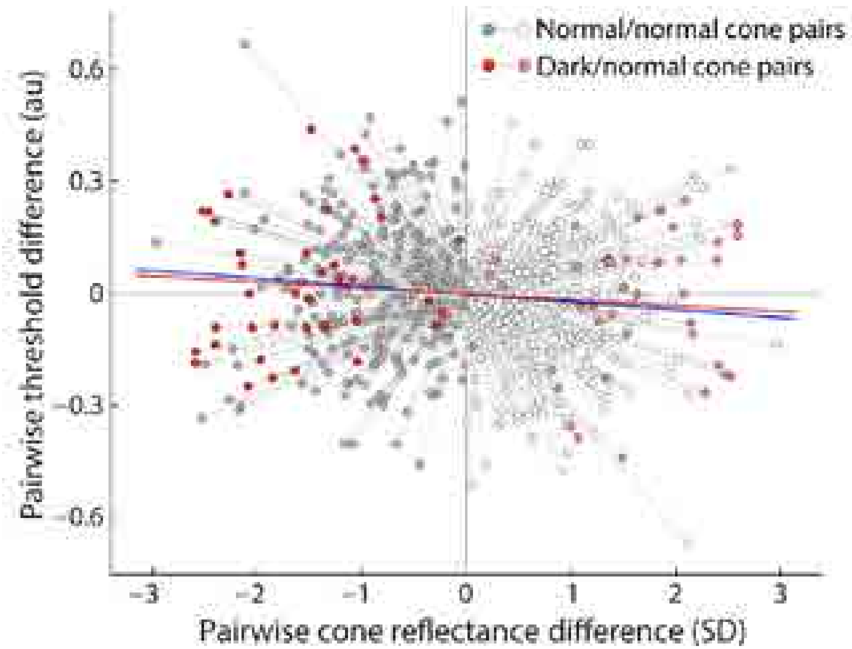


Figure 5

RESEARCH ARTICLE

NEUROSCIENCE

The elementary representation of spatial and color vision in the human retina

Ramkumar Sabesan,[1*†‡] Brian P. Schmidt,[2†] William S. Tuten,[1] Austin Roorda[1]

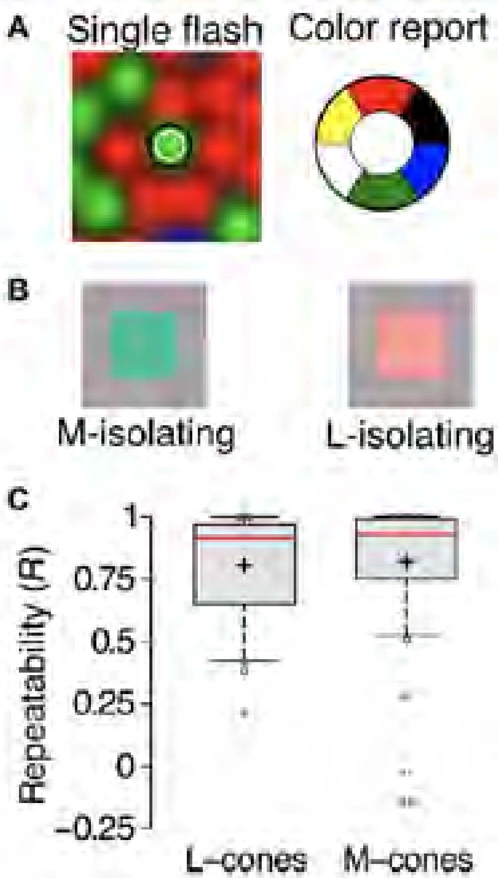


Figure 1

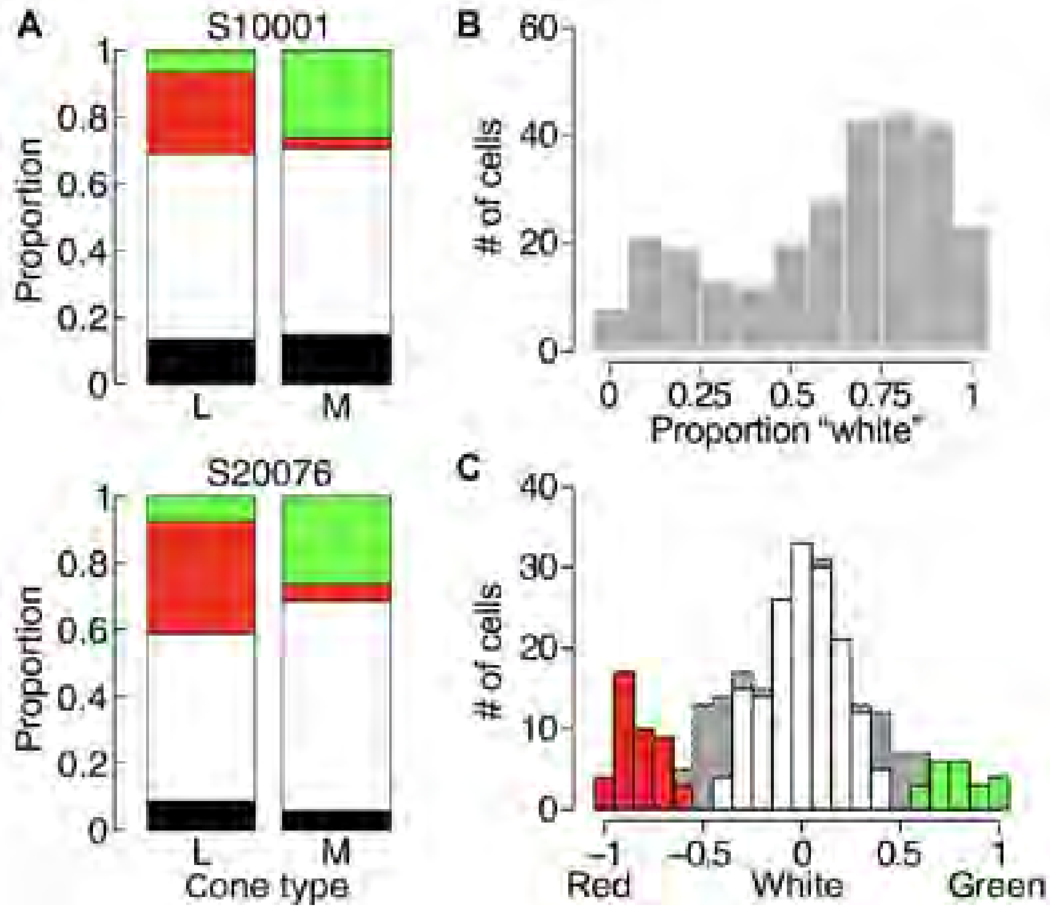
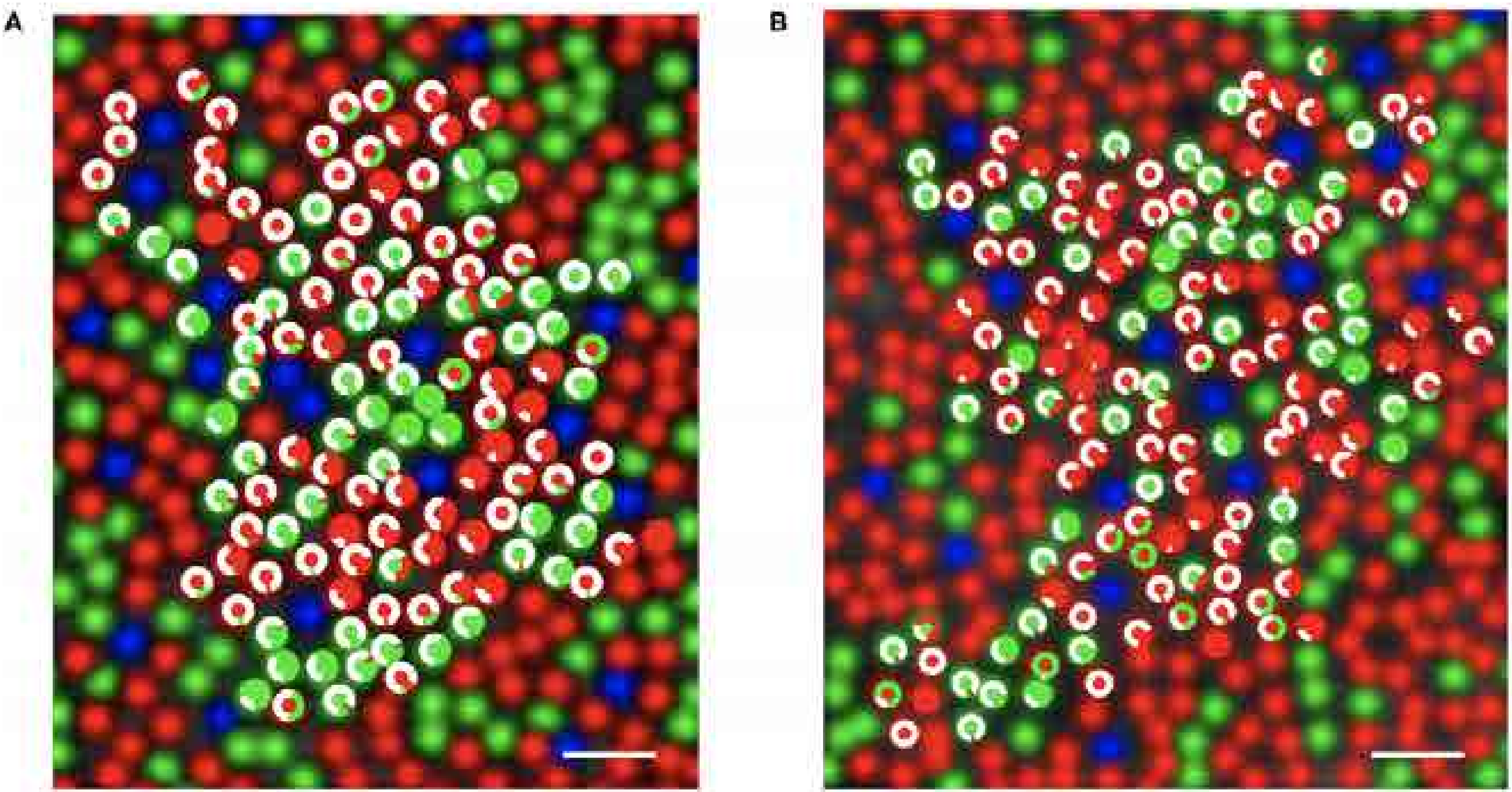


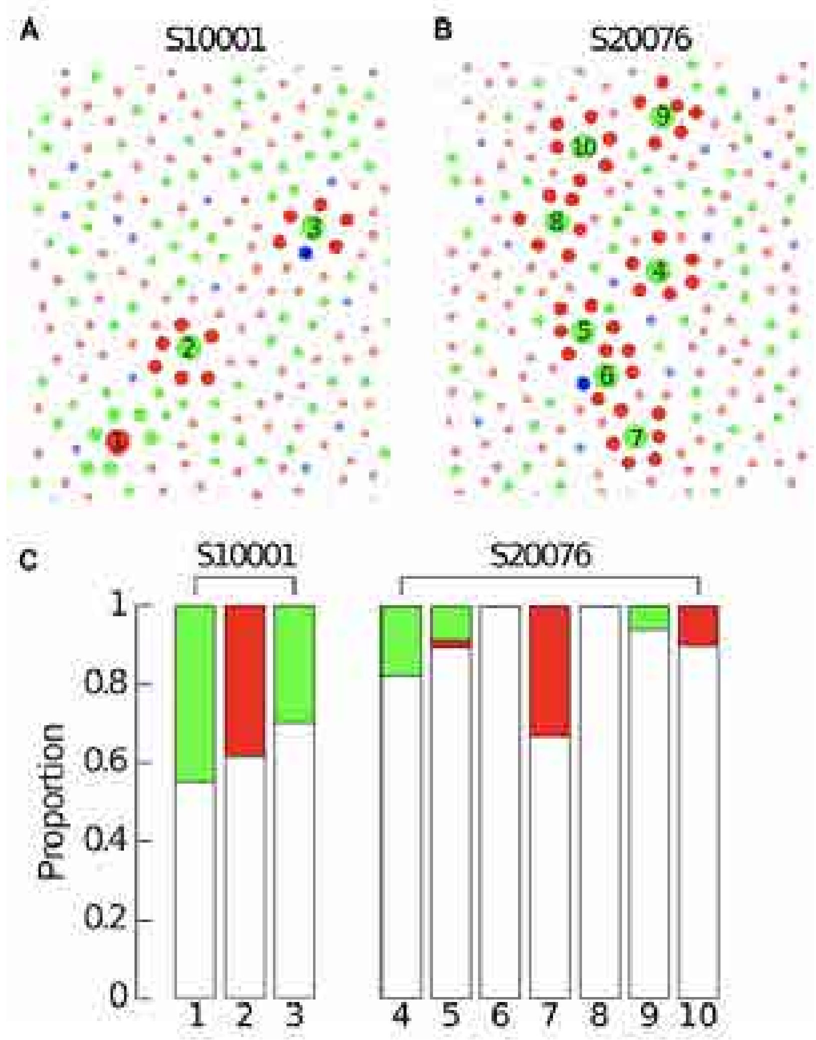
Figure 2

Colour Percept from a Single Cone



Does ‘Neighborhood’ Affect Percept

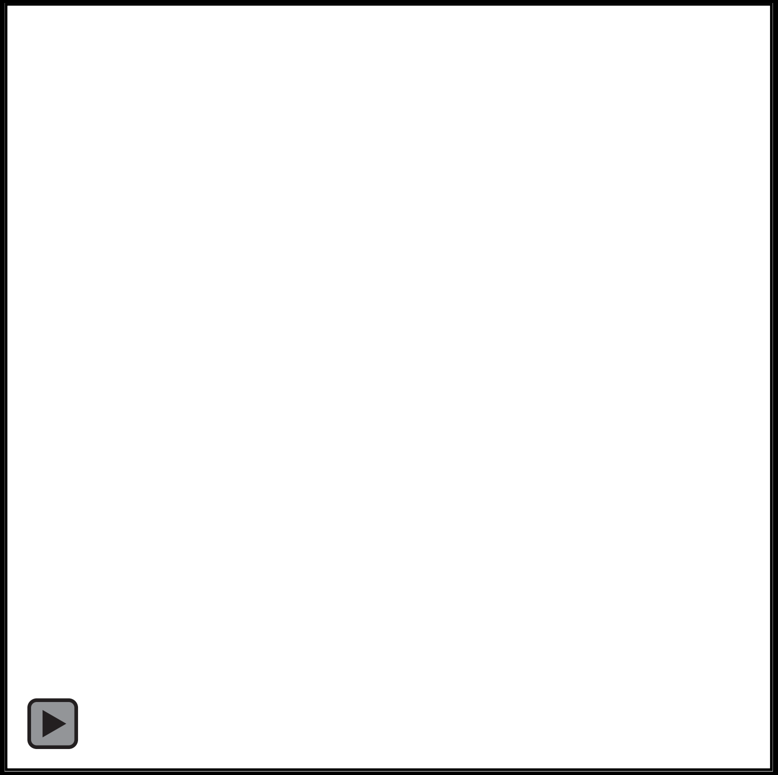
- Considerable variability in responses (compare 2,7,8)
- Cones surrounded by different classes tended to see more white than chromatic responses
- S cones presence did not appear to make a difference.

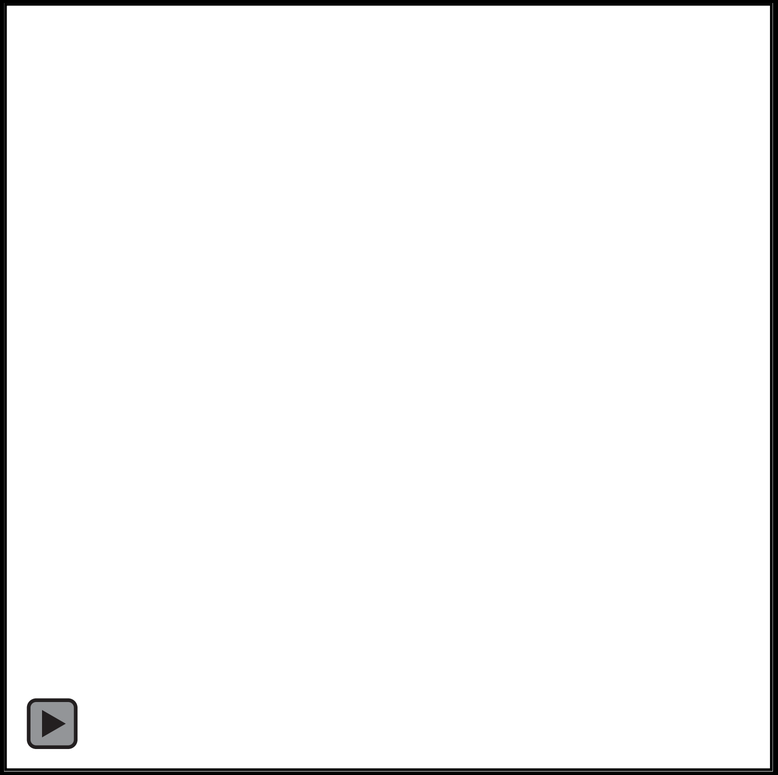


The relationship between visual resolution and cone spacing in the human fovea

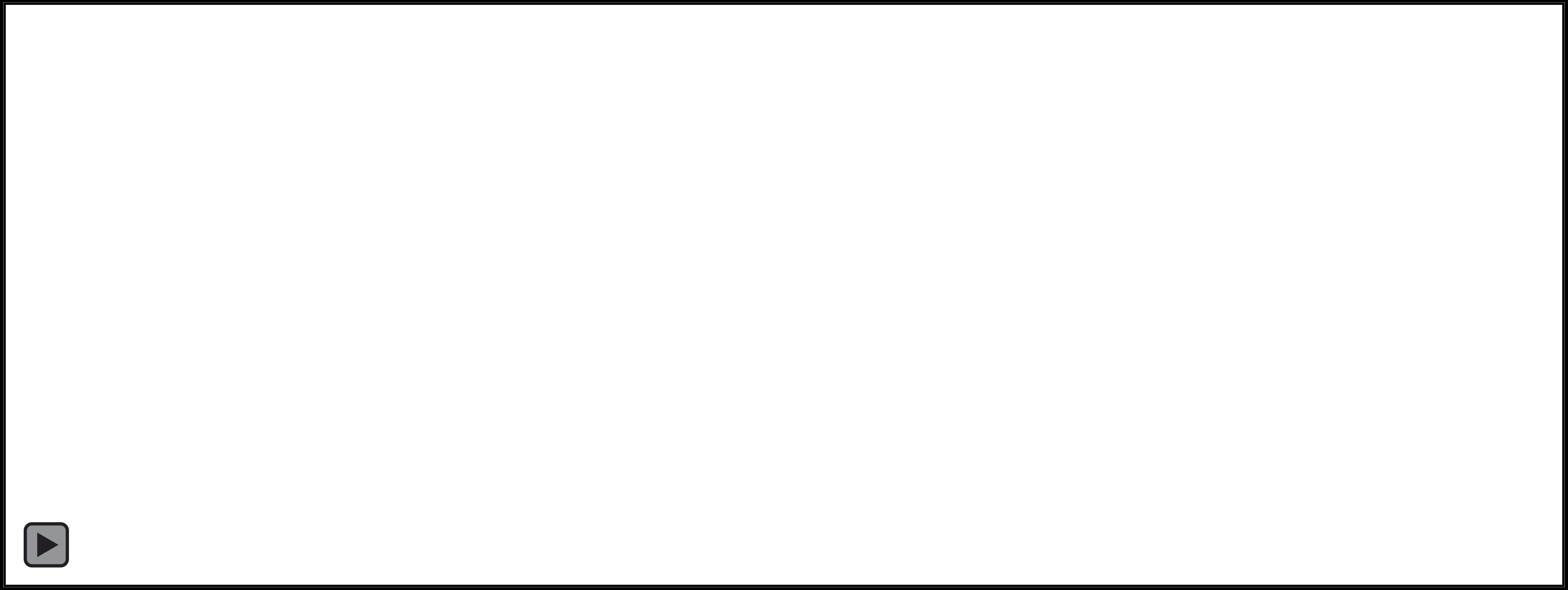
Ethan A Rossi[1] & Austin Roorda[1,2]

Visual resolution decreases rapidly outside of the foveal center. The anatomical and physiological basis for this reduction is unclear. We used simultaneous adaptive optics imaging and psychophysical testing to measure cone spacing and resolution across the fovea, and found that resolution was limited by cone spacing only at the foveal center. Immediately outside of the center, resolution was worse than cone spacing predicted and better matched the sampling limit of midget retinal ganglion cells.

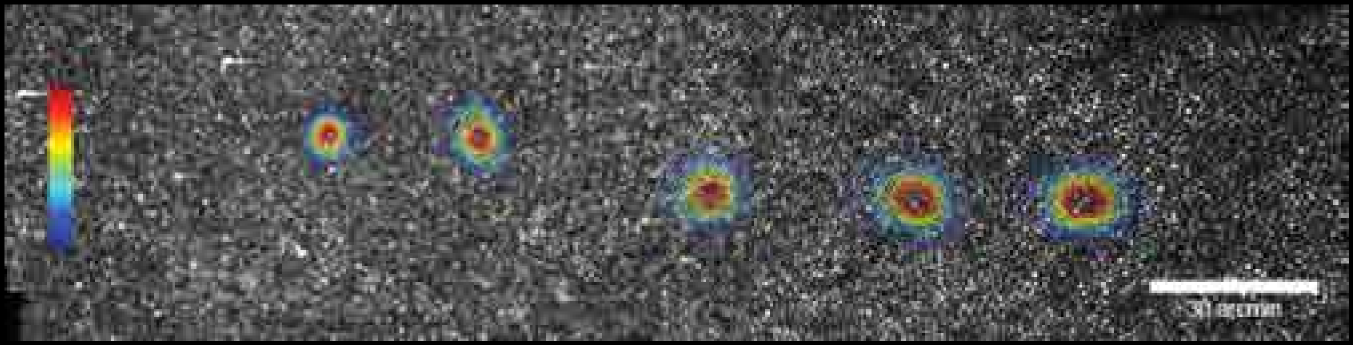




Cone Inputs and Visual Sensation

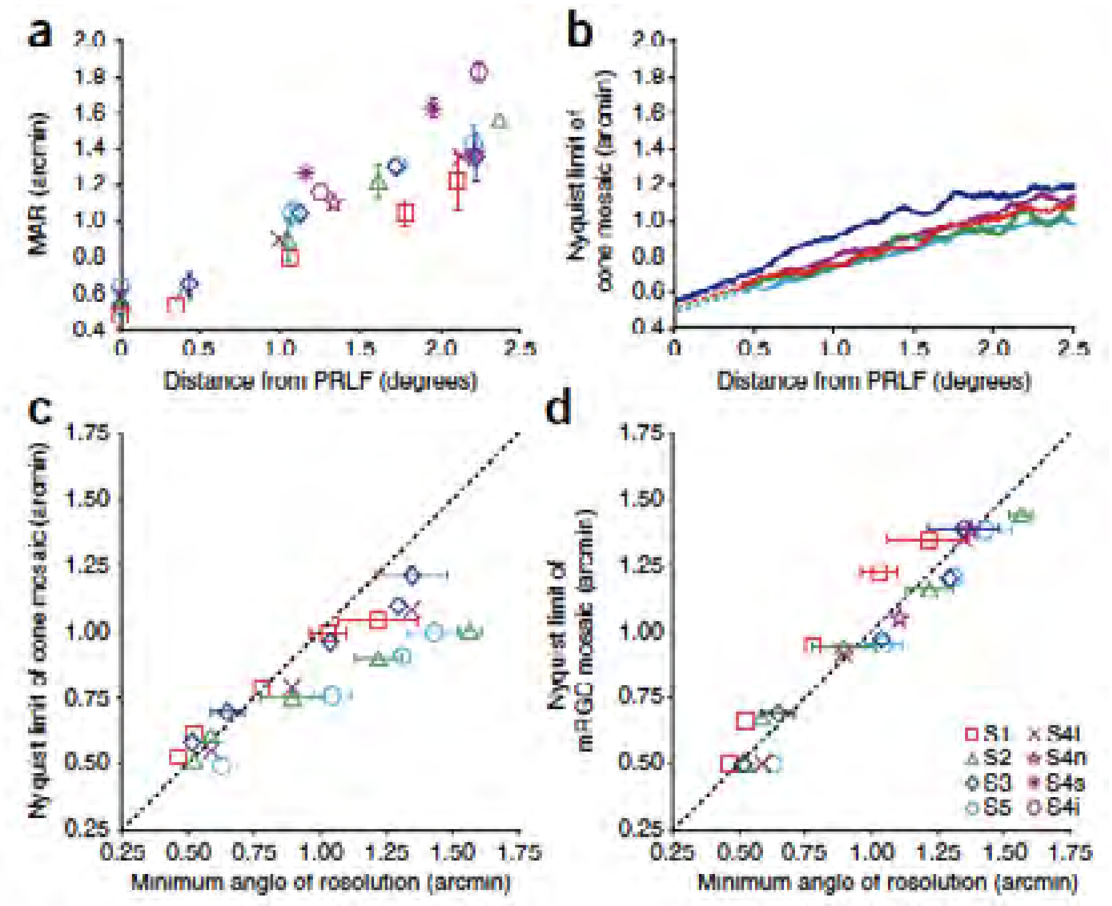


Cone Stimulation Map



Limits of Human Visual Resolution

- Evaluated the resolution at different distances from the preferred retinal location of fixation (PRLF)
- The experimenters could not see the exact fovea (started 0.25º)
- Evaluation of plots B &C suggest that cones limit at the centre but do not cover whole relationship
- Plot D shows that ganglion cell sampling, which varies over fovea better explains the entire relationship

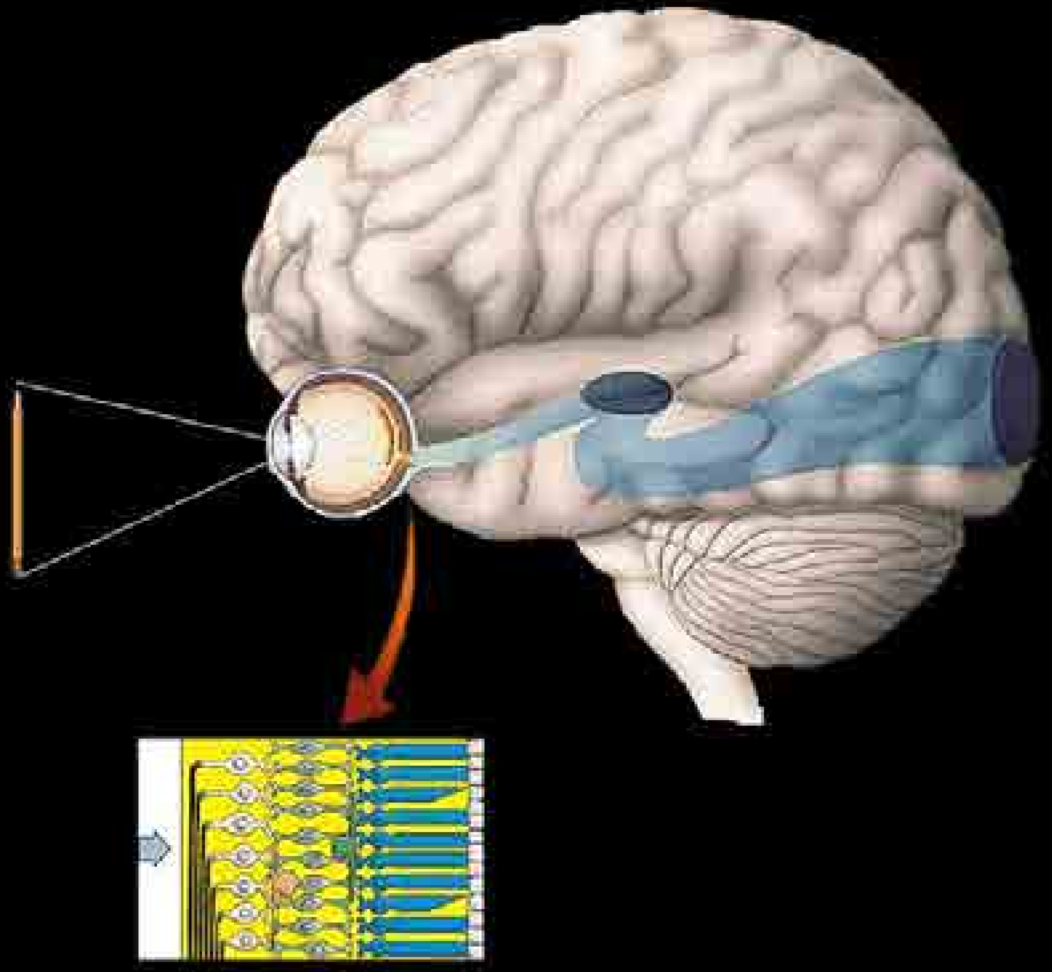


Resolving single cone inputs to visual receptive fields

Lawrence C Sincich[1], Yuhua Zhang[2,3], Pavan Tiruveedhula[2], Jonathan C Horton[1] & Austin Roorda[2]

With the current techniques available for mapping receptive fields, it is impossible to resolve the contribution of single cone photoreceptors to the response of central visual neurons. Using adaptive optics to correct for ocular aberrations, we delivered micron-scale spots of light to the receptive field centers of neurons in the macaque lateral geniculate nucleus. Parvocellular LGN neurons mapped in this manner responded with high reliability to stimulation of single cones.

The Human Visual System



(HHMI, 2009)

LGN Excitation Videos

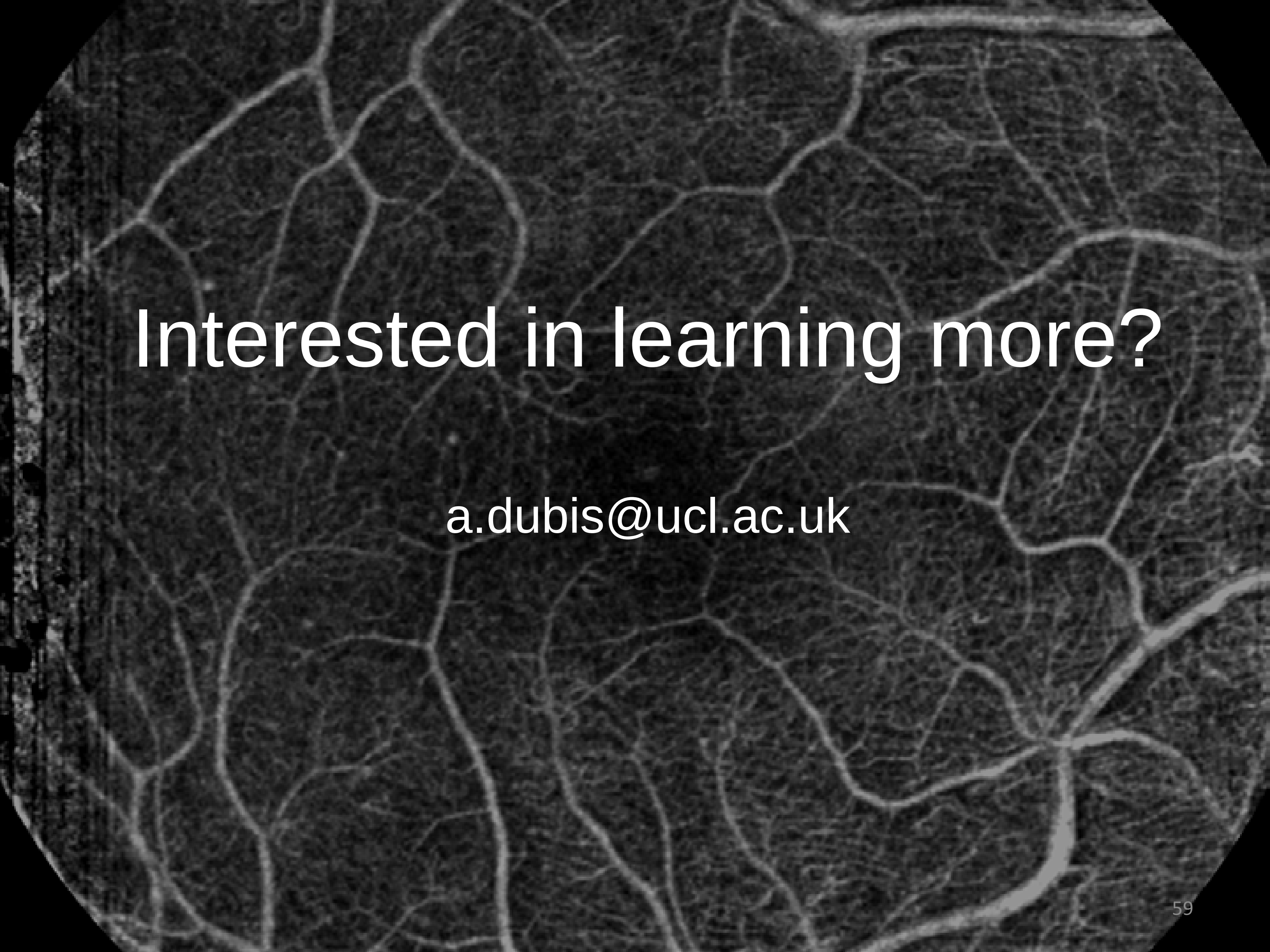
Conclusions

- Hecht, Schlaer and Pirenne showed that an individual rod only needs one opsin activation, but several within a receptive field to create a visual perception

- Makous et al (2006) and Hofer et al (2005) showed that individual cells can not facilitate a visual perception, but this signal will also have chromatic information

- Harmening et al (2014) and Sabesan et al (2016) showed that individual cell can be intentionally targeted and their responses mapped

- Rossi et al (2009) showed that ganglion cell sampling not photoreceptors limit visual acuity



Interested in learning more?

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