

Image systems simulation

Prof. Brian Wandell
Stein Family Professor

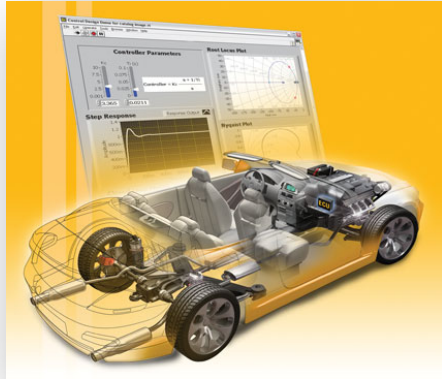
Stanford's Center for Cognitive and Neurobiological Imaging
Founding Director

Stanford Neurosciences Institute
Deputy Director

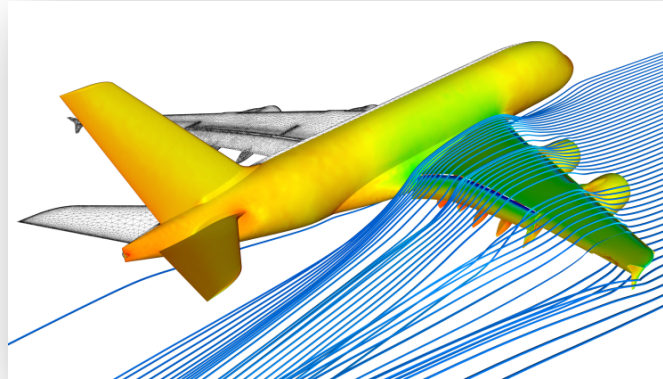


Image systems simulation

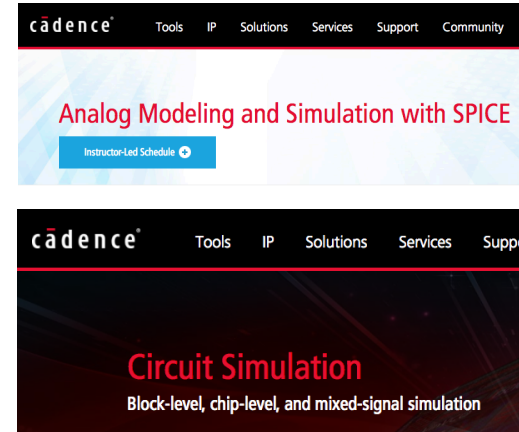
System simulation is important in many mature industries



ECU (Electronic Control Unit) Simulation for Automobiles



Numerical flow simulation on an Airbus A380



Integrated circuitry

Imaging industry is large and very innovative, spanning cameras, displays and processing



Multiple lens



RGB-depth



360 Surround Video

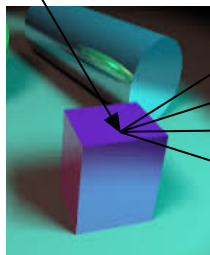


VR, AR and MR HMDs

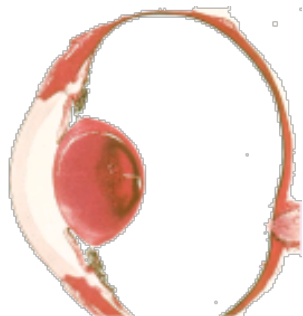


Light field

Image systems simulation for biology



Scene spectral radiance



Physiological optics

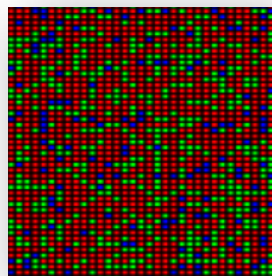
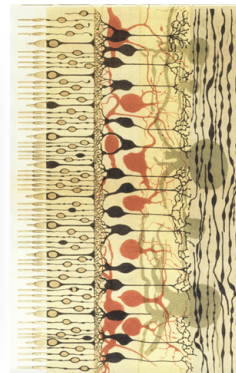


Photo transduction



Retinal processing



Inference



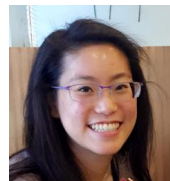
Brian Wandell



David Brainard



James Golden



Trisha Lian



Nicolas Cottaris



Fred Rieke



E.J. Chichilnisky



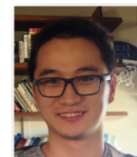
Xiaomao Ding



Jon Winawer



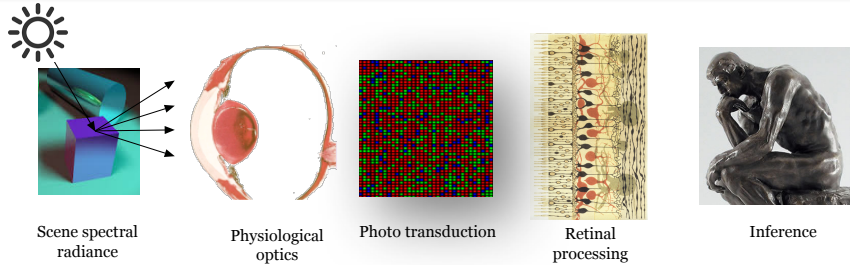
Joyce Farrell



Haomiao Jiang

Image systems simulation for biology

- ISETBIO is a set of computational tools to calculate and model how light from a scene is encoded and processed in the visual circuitry
- The goal is to clarify the impact of the different elements of the eye and neural processing in the retina and brain on visual perception
- The tool is designed to support both basic and applied vision research

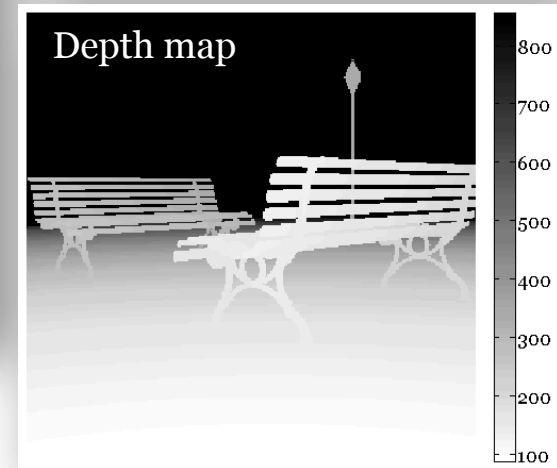
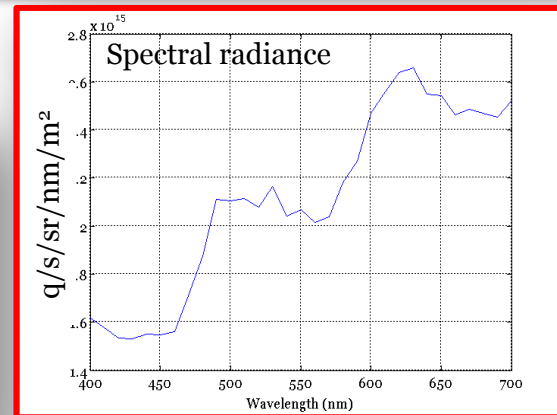


Spectral radiance, refraction, optics, Snell's law, diffraction, Airy disk, photons, energy, Planck's constant, chromatic aberration, retinal irradiance, pupil aperture, eye movements (tremor, drift, saccade), plenoptic function, wavefront aberrations, macular pigment, lens pigment, photopigments, rod and cone absorptions, color-matching functions, transduction, photocurrent, receptive fields, convolution, normalization, linear-nonlinear models, linear classifier theory, ideal observer

Essential technologies for image systems simulation

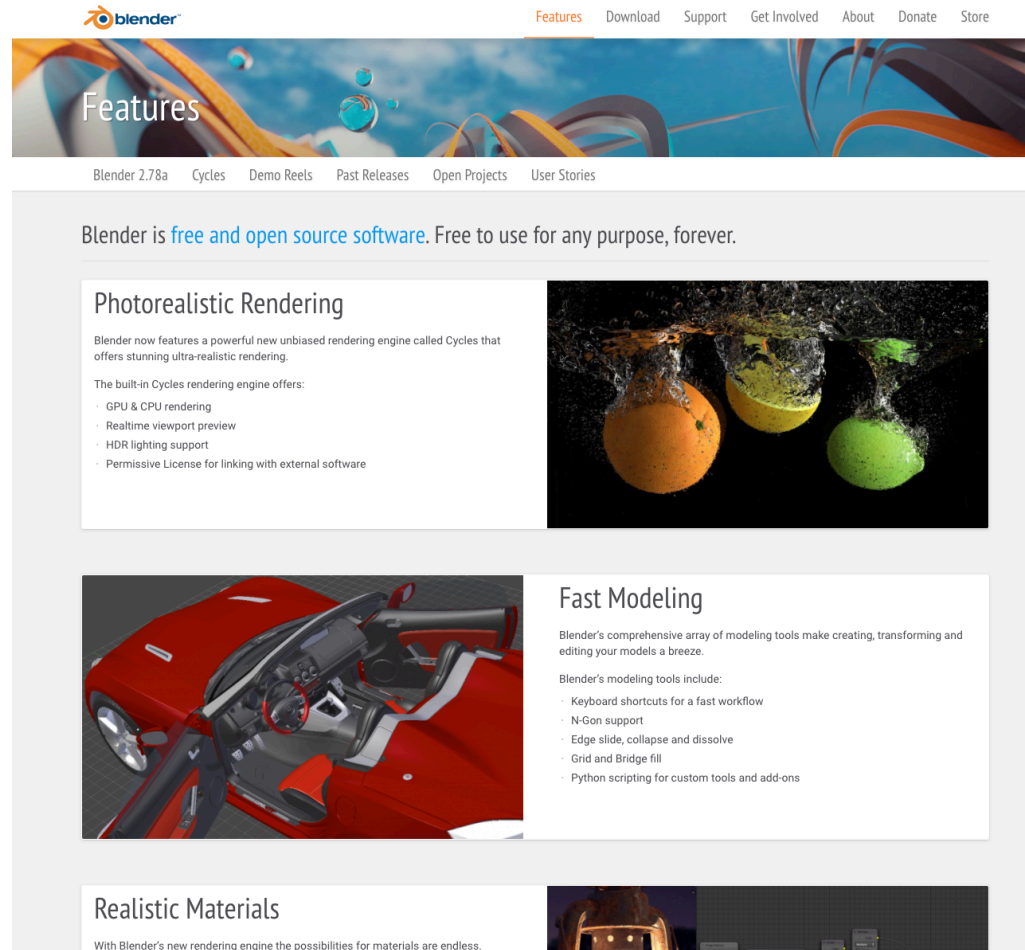
- Scene spectral radiance data are critical; depth information is important for many natural images
- Acquiring such data for natural images has been a limitation; some valuable cases are extremely difficult to obtain (e.g. high dynamic range, under water, inside the body, automotive)

Quantitative computer graphics



Tools for modeling shapes, lights, material geometry

- Progress in computer graphics enables us to create synthetic and yet highly realistic input data.
- We want simulations with meaningful units; quantitative computer graphics
- Challenges remain to complete this work, but there are some encouraging successes



The screenshot shows the Blender website homepage. At the top, there is a navigation bar with the Blender logo and links for Features, Download, Support, Get Involved, About, Donate, and Store. Below the navigation bar is a large banner image with the word "Features" overlaid. Underneath the banner, there are links for Blender 2.78a, Cycles, Demo Reels, Past Releases, Open Projects, and User Stories. The main content area features a headline: "Blender is free and open source software. Free to use for any purpose, forever." Below this, there are three main sections: "Photorealistic Rendering" with a list of features and a corresponding image of fruit splashing in water; "Fast Modeling" with a list of modeling tools and a corresponding image of a red sports car; and "Realistic Materials" with a corresponding image of a car's interior.

blender

Features Download Support Get Involved About Donate Store

Features

Blender 2.78a Cycles Demo Reels Past Releases Open Projects User Stories

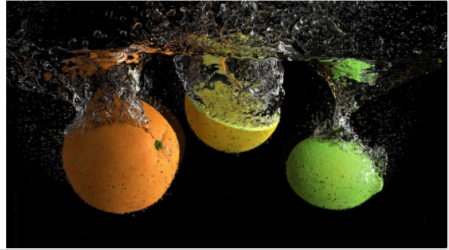
Blender is [free and open source software](#). Free to use for any purpose, forever.

Photorealistic Rendering

Blender now features a powerful new unbiased rendering engine called Cycles that offers stunning ultra-realistic rendering.

The built-in Cycles rendering engine offers:

- GPU & CPU rendering
- Realtime viewport preview
- HDR lighting support
- Permissive License for linking with external software

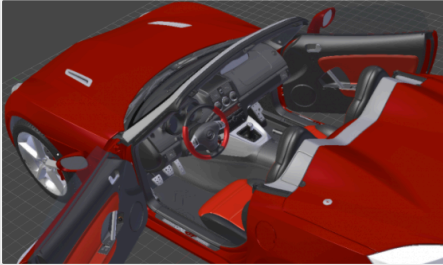


Fast Modeling

Blender's comprehensive array of modeling tools make creating, transforming and editing your models a breeze.


Blender's modeling tools include:

- Keyboard shortcuts for a fast workflow
- N-Gon support
- Edge slide, collapse and dissolve
- Grid and Bridge fill
- Python scripting for custom tools and add-ons



Realistic Materials

With Blender's new rendering engine the possibilities for materials are endless.



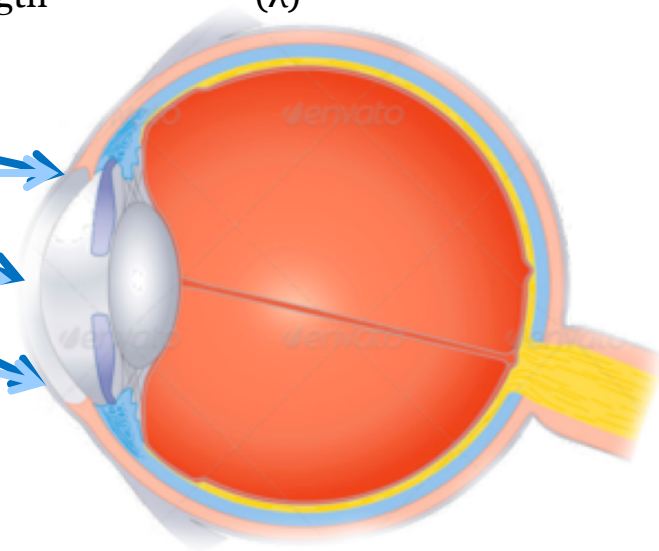
Ray trace methods yield light fields (plenoptic function)

(Adelson and Bergen, 1991; Levoy and Hanrahan, 1996)

$L(u,v,\alpha,\beta,\lambda)$ – light field at the eye



Position (u,v)
Azimuth and elevation (α, β)
Wavelength (λ)



Human encoding overview



Physiological
optics

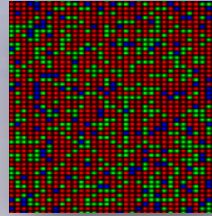
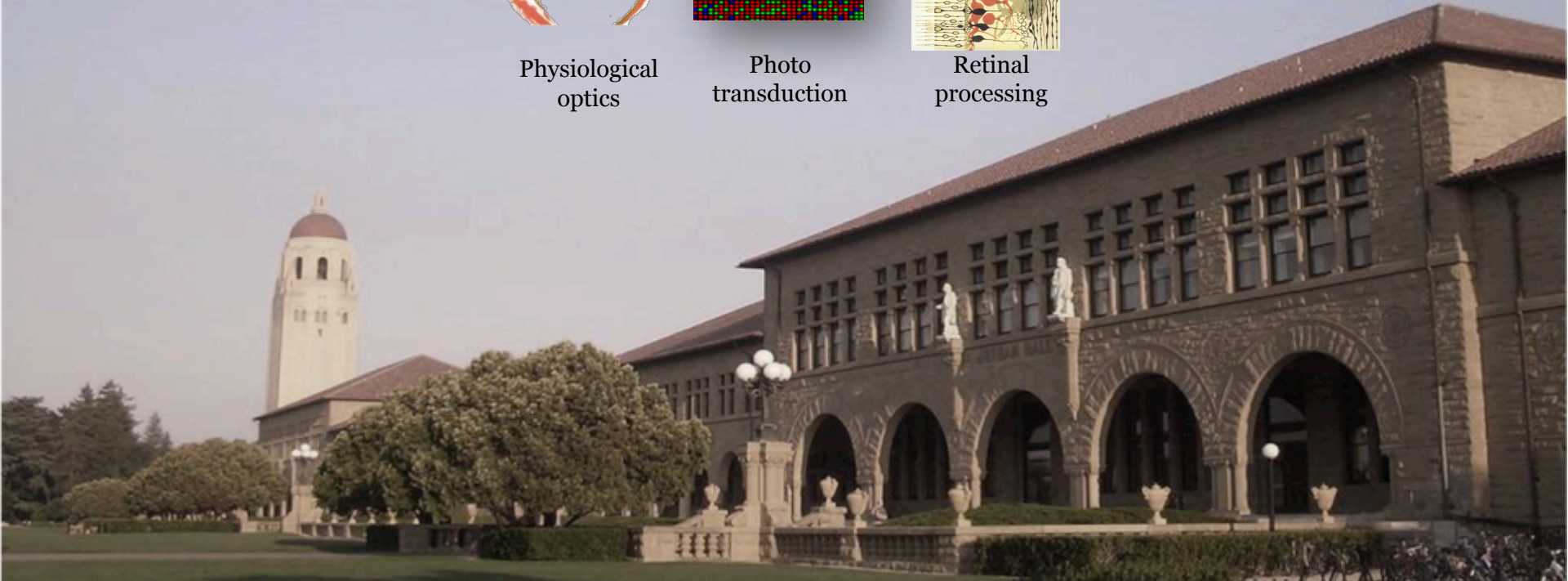


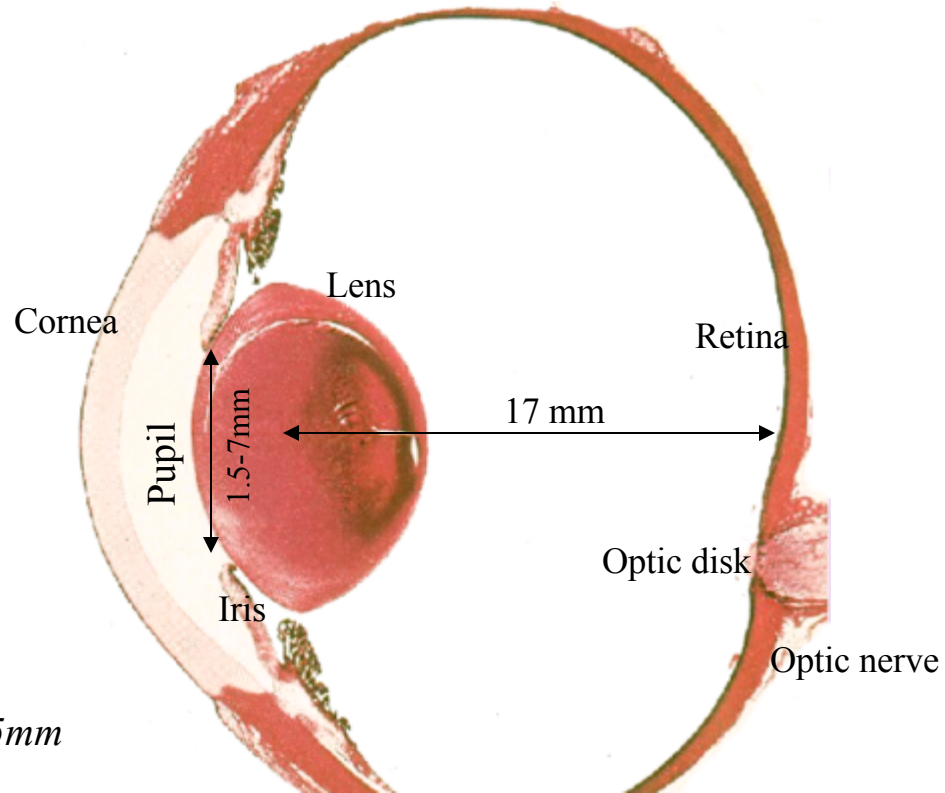
Photo
transduction



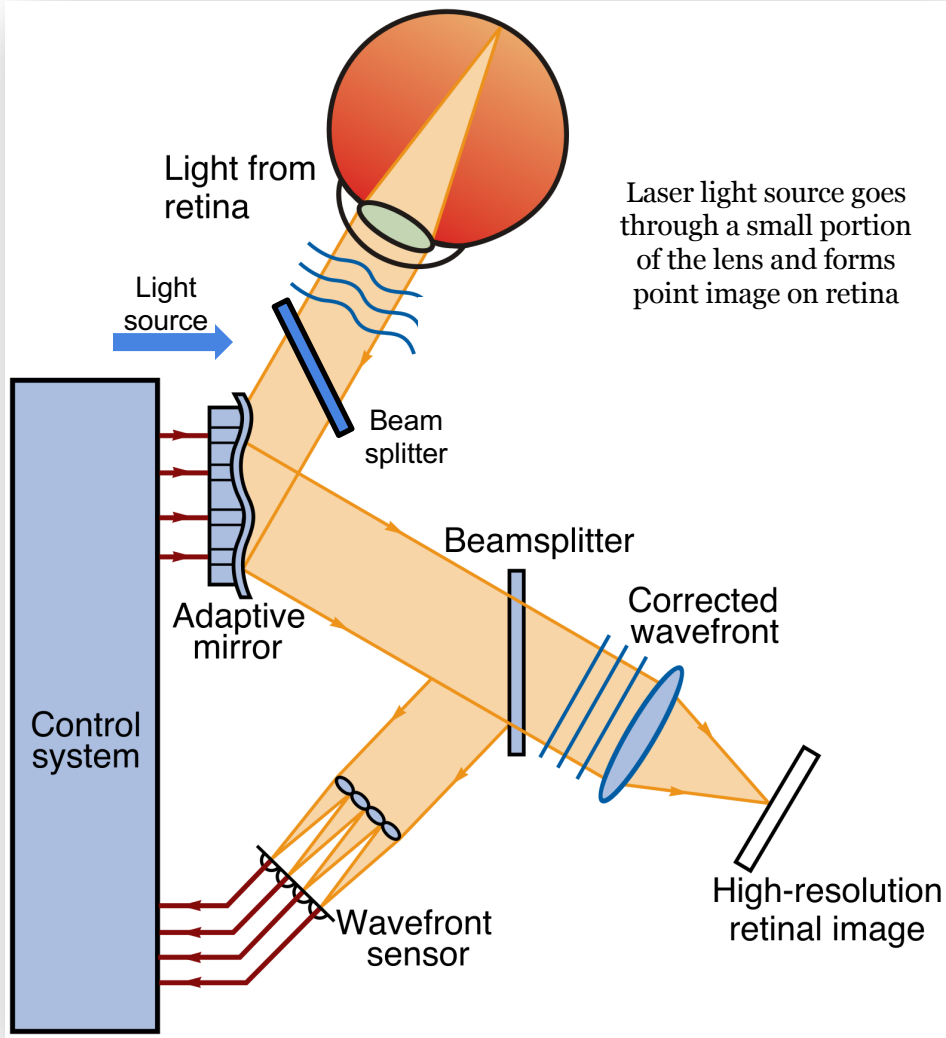
Retinal
processing



Human eye in cross- section



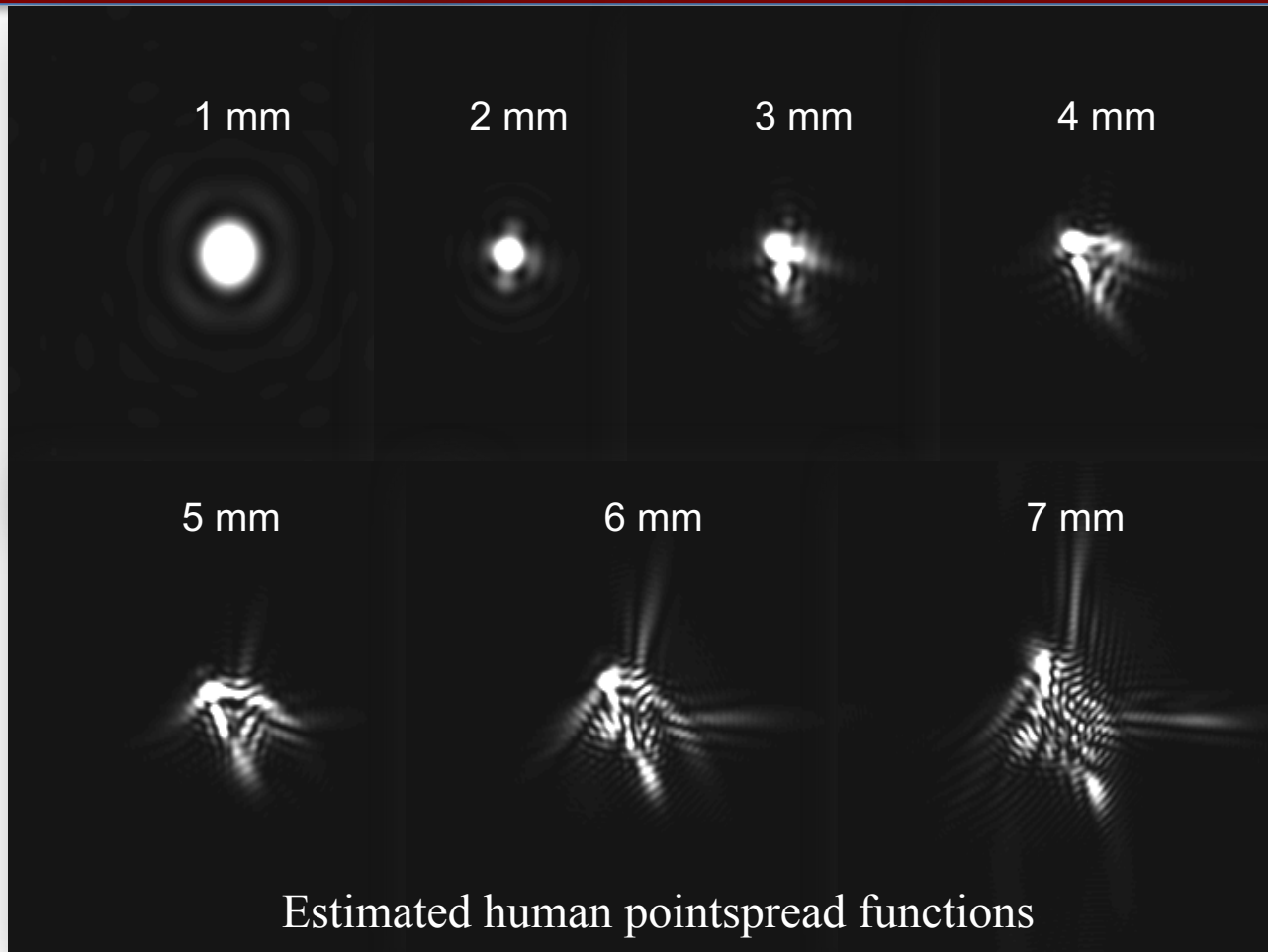
F-number ~ 2.4-11
Retinal thickness ~ 0.5mm



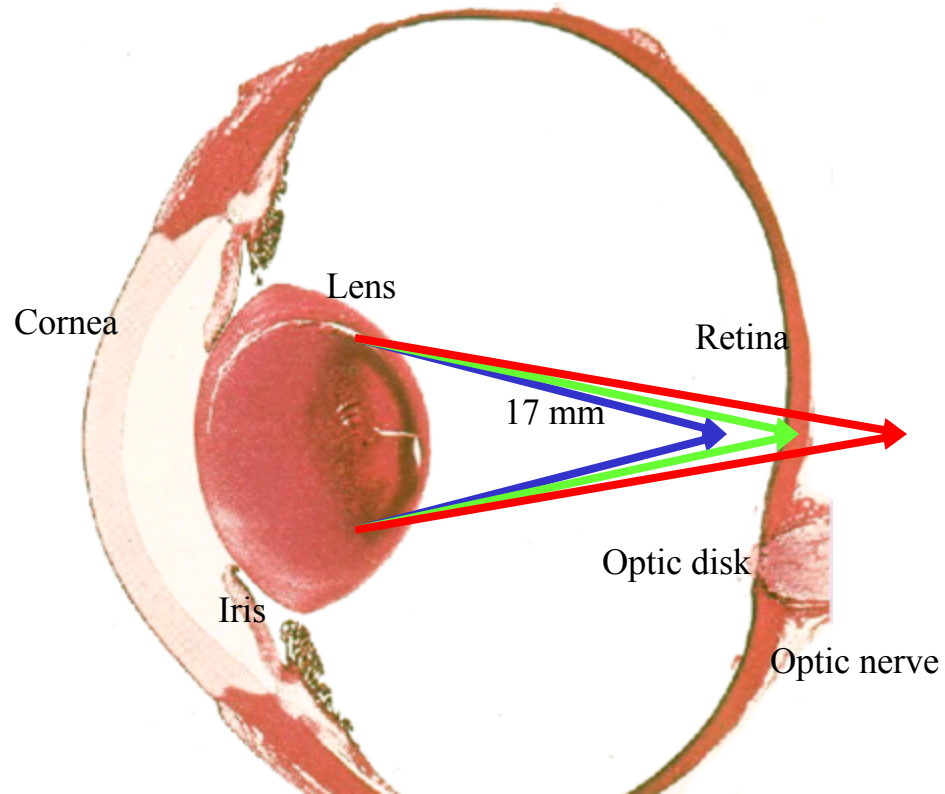
Adaptive optics corrects retinal wavefront aberrations

J. Carroll, D. Gray, A. Roorda, D. R. Williams (2005)

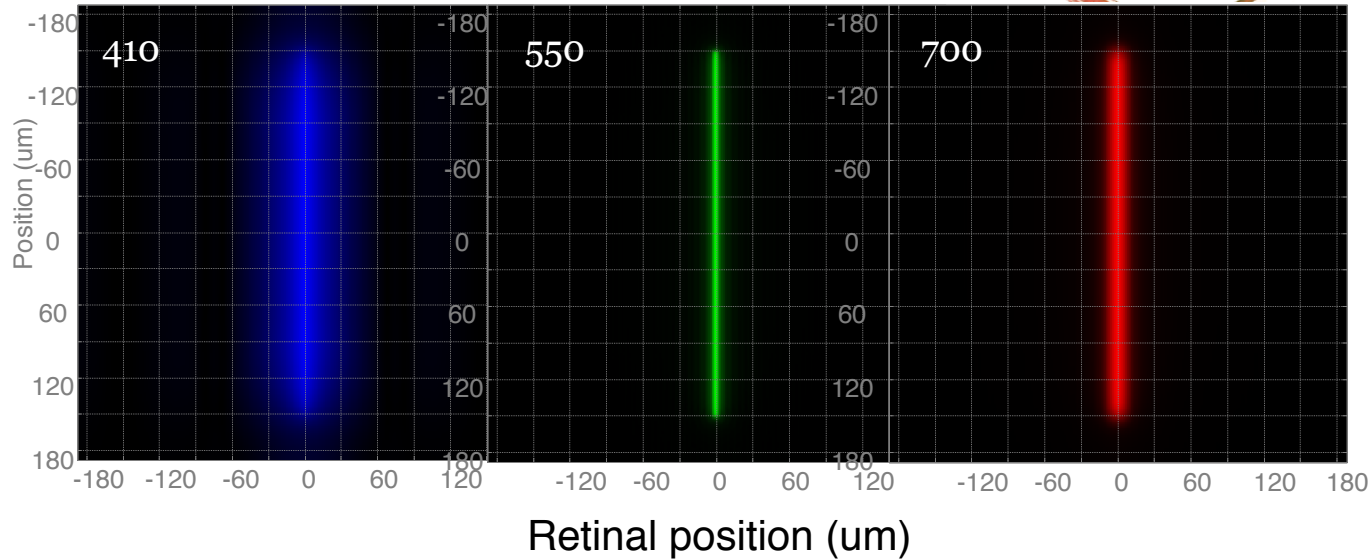
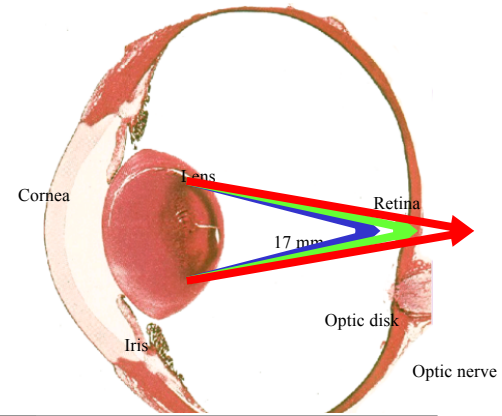
Visual acuity is worse as pupils dilate (Faber, 2001, CFAO)



Chromatic
aberration is
a difference in
optical focus
across
wavelength



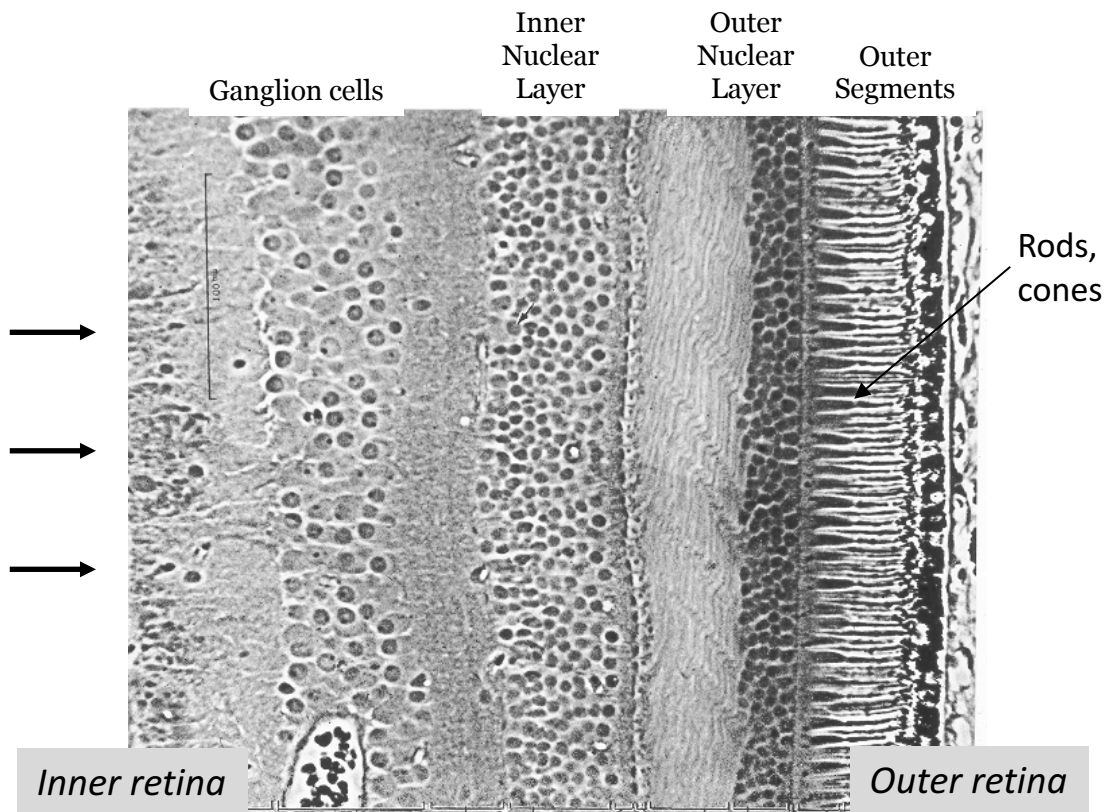
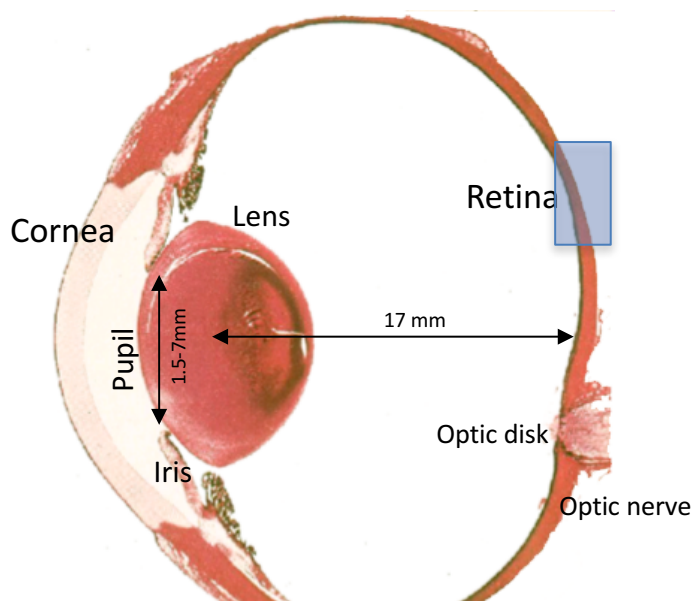
At the retina,
the line spread
differs by
wavelength



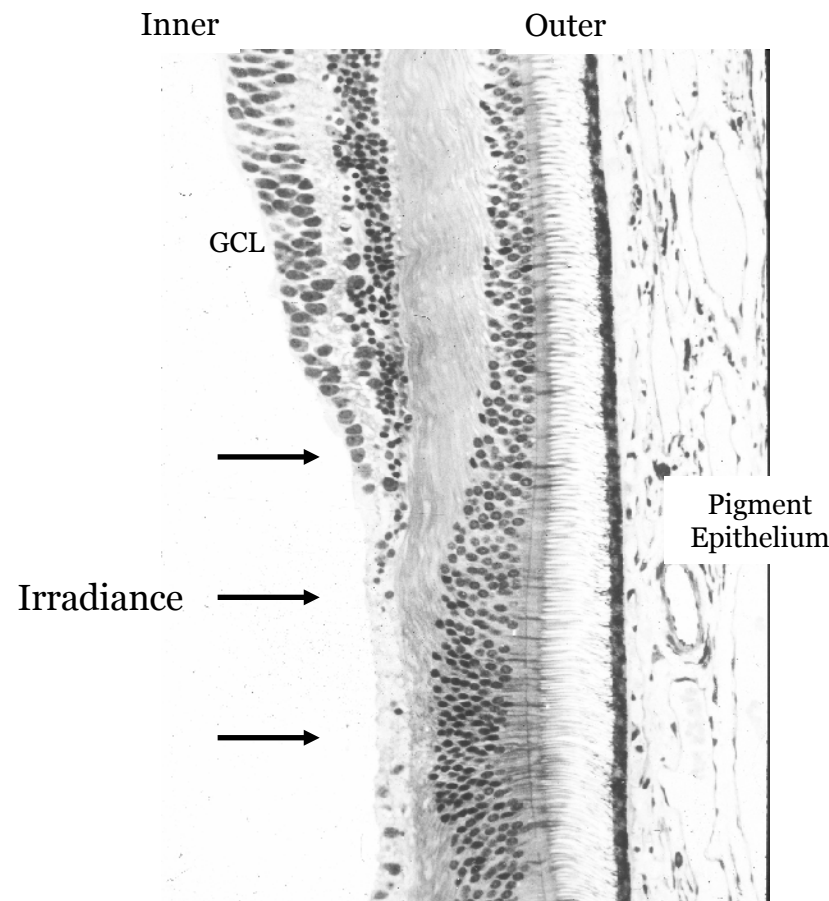
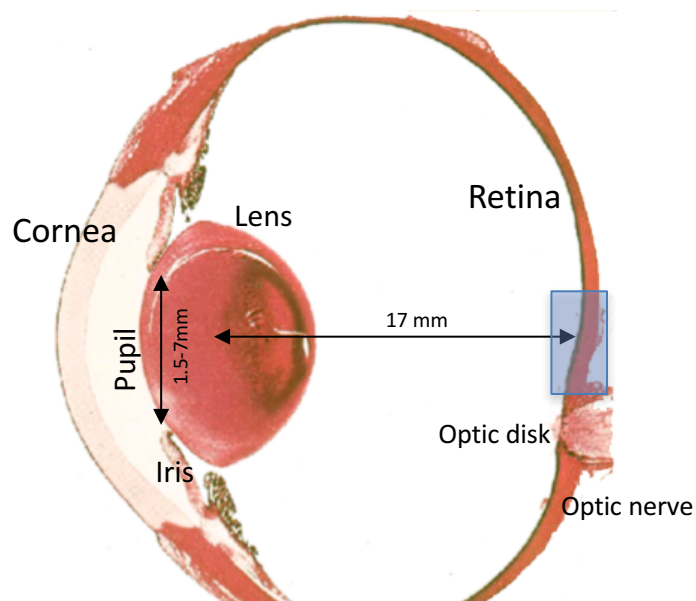
Human eye in cross-section

F-number $\sim 2.4-11$

Retinal thickness $\sim 0.4\text{mm}$



The primate fovea (pit) contains mainly cones and is specialized for high acuity and color



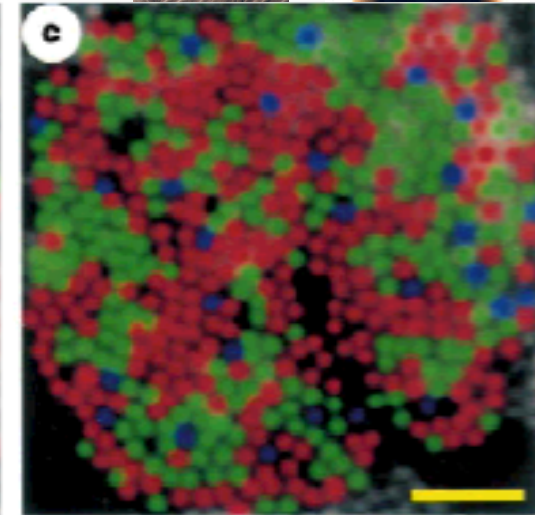
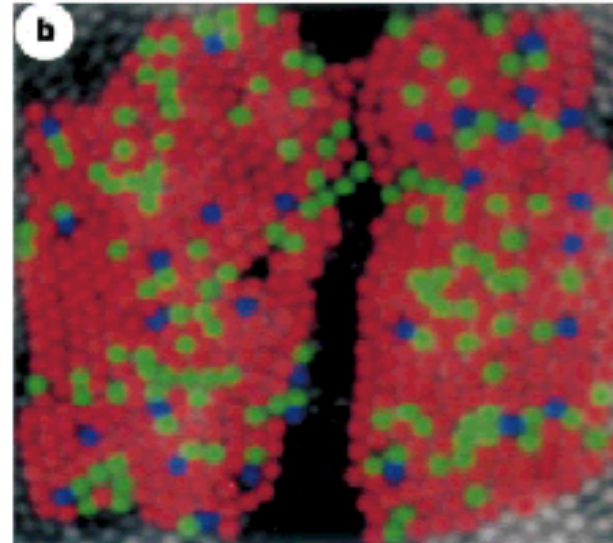
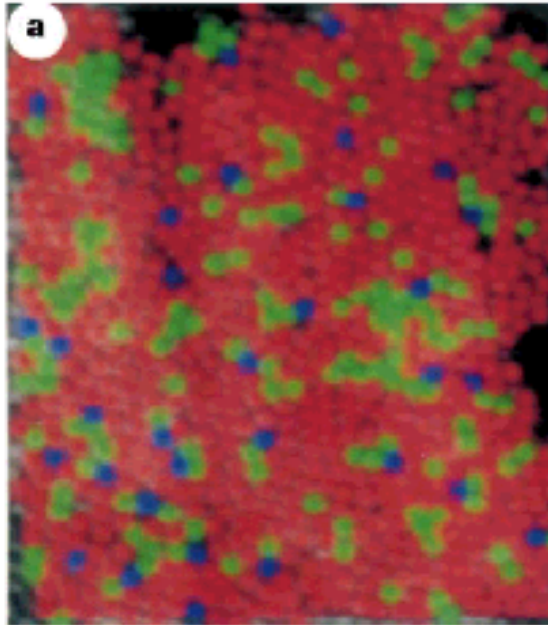
Application: Seeing The Arrangement of Cone Classes in the Human Eye (Roorda and Williams et al., 1999)

Austin Roorda

Heidi Hofer



letters to nature



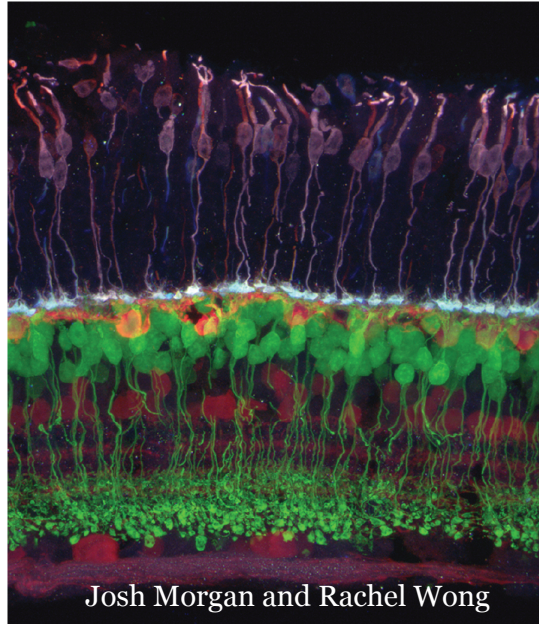
Retinal overview

Photoreceptors

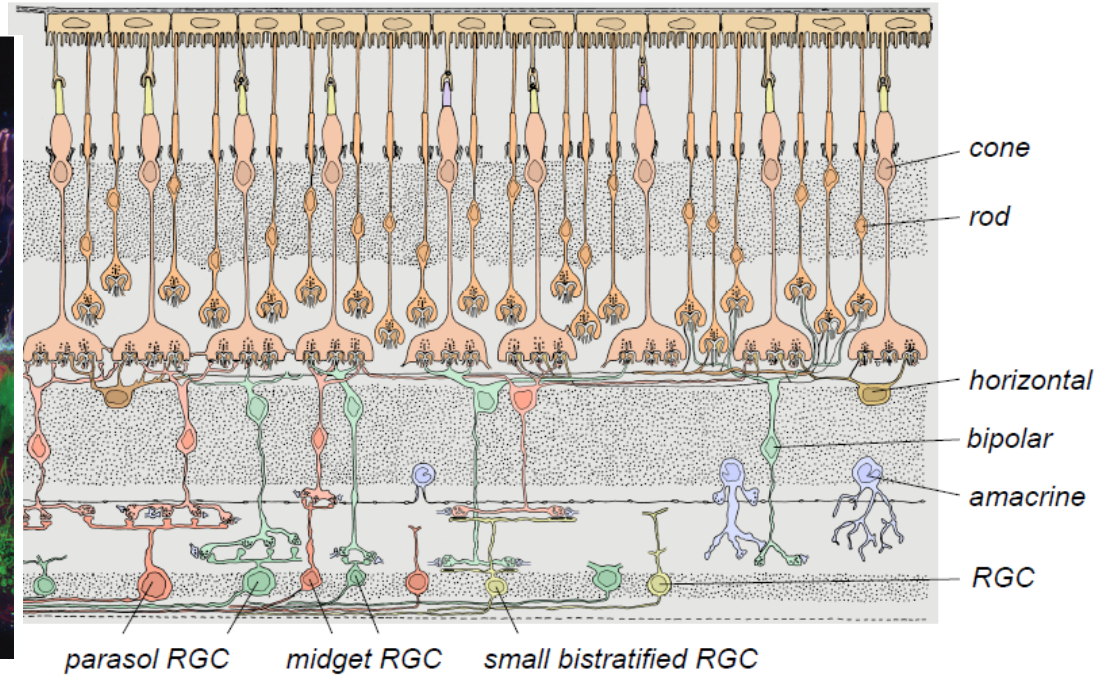
Horizontal
Bipolar

Amacrine

Ganglion

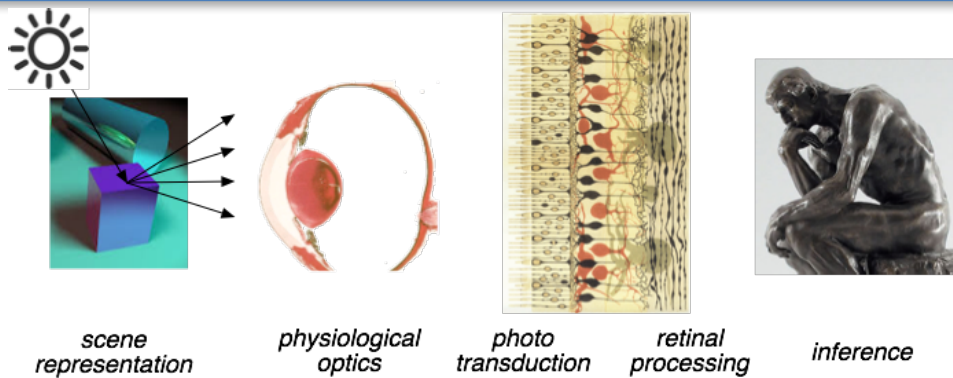


Pigment epithelium



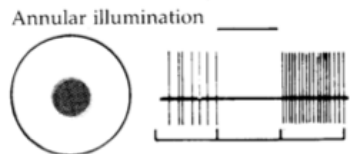
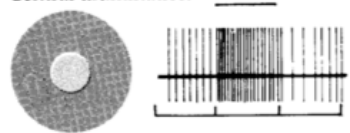
(Chichilnisky and Field, Annual Reviews of Neuroscience)

Modeling the Retinal Output

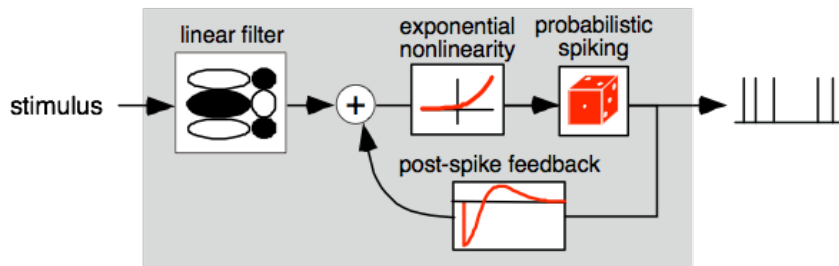


classical models

Central illumination

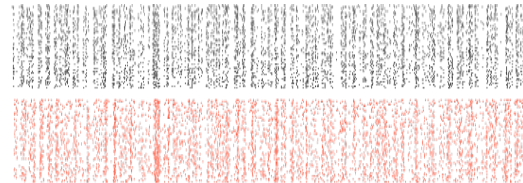


pseudo-linear models

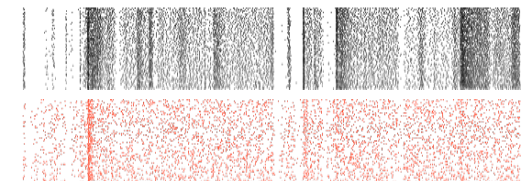


Paninski (2004)
Truccolo et al (2004)

white noise data & model



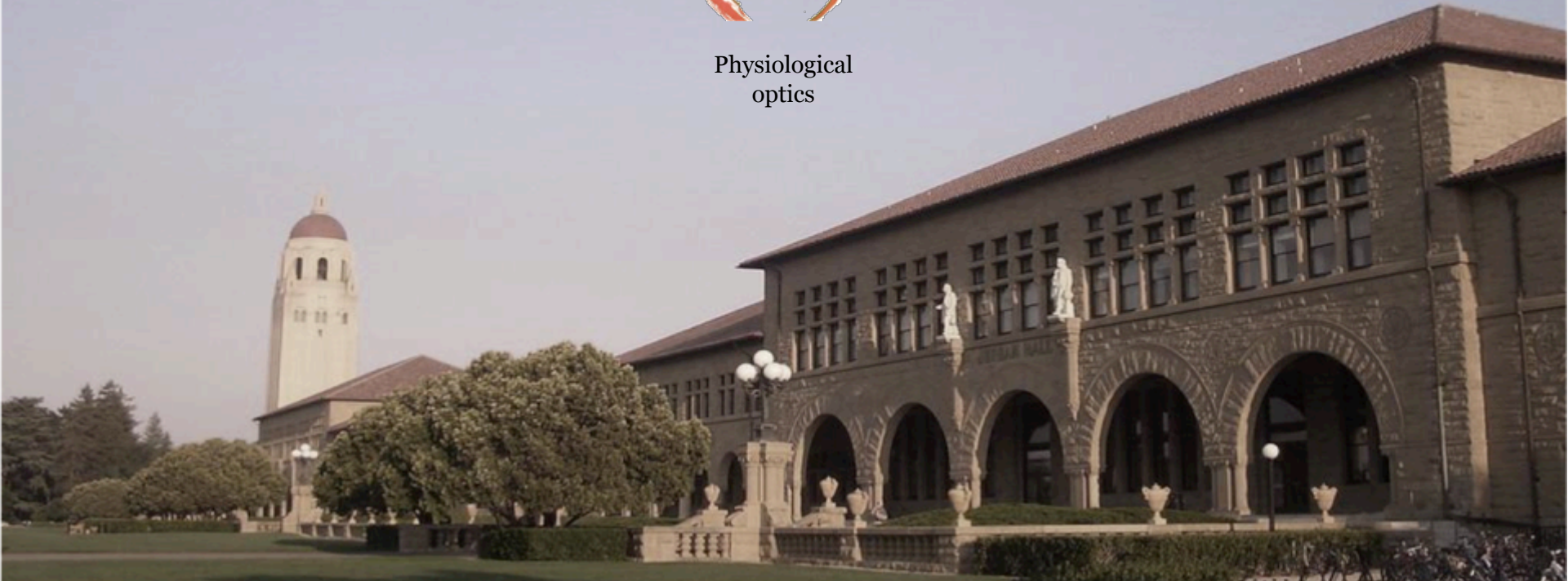
natural stimuli data & model



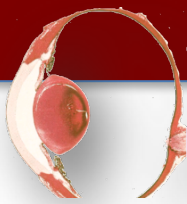
Human image formation



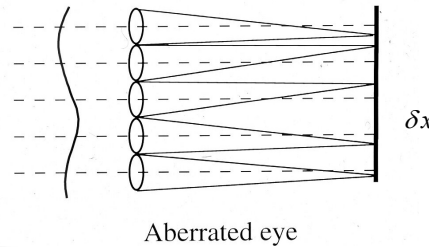
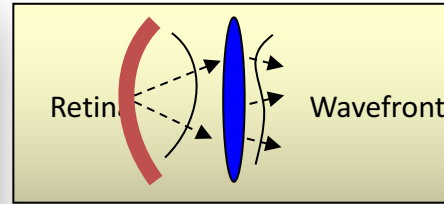
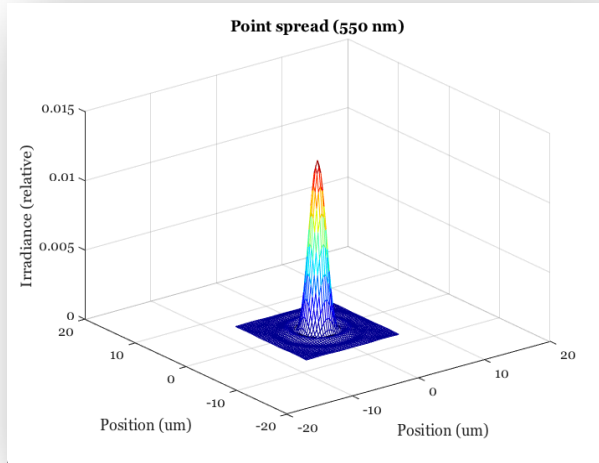
Physiological
optics



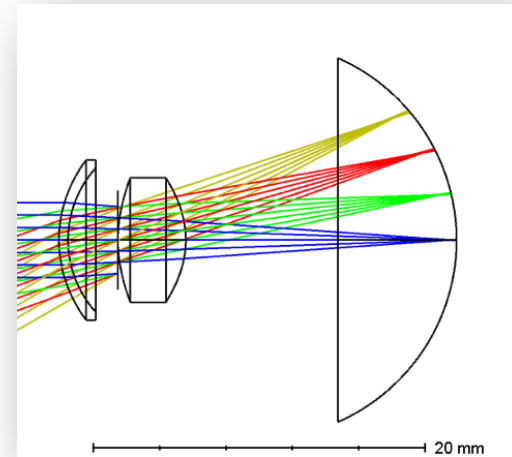
ISETBIO - Ray trace and wavefront optics models



Shift-invariant models from diffraction to
AO wavefront measures
(Zernike polynomial)

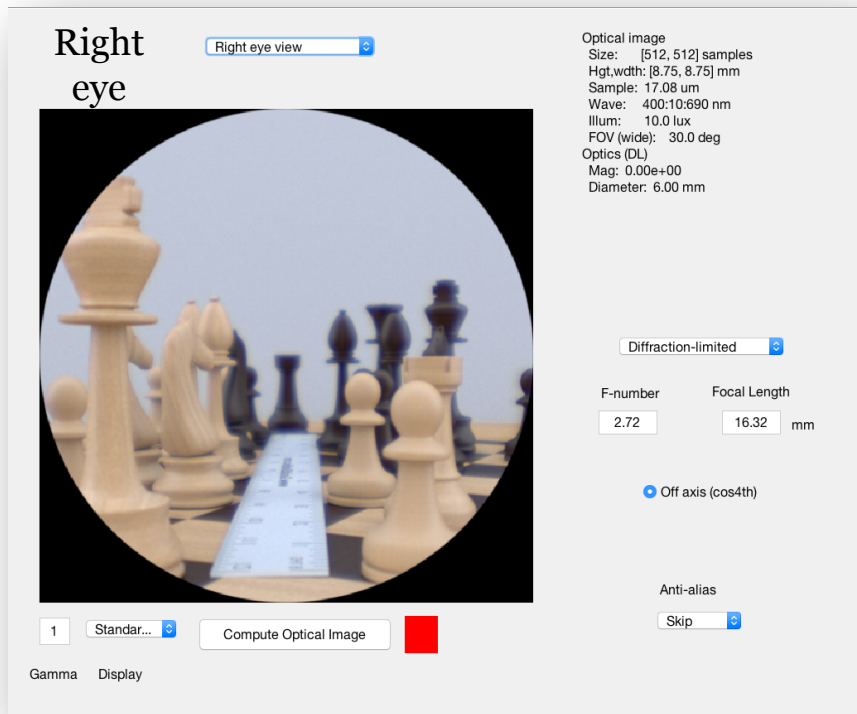


Ray trace with diffraction
model (e.g. Navarro eye m
model)



Natural images - Image formation (optics) models and quantitative graphics

Quantitative computer graphics implementation (PBRT) of the Navarro eye model (Trisha Lian)



Depth map (mm)

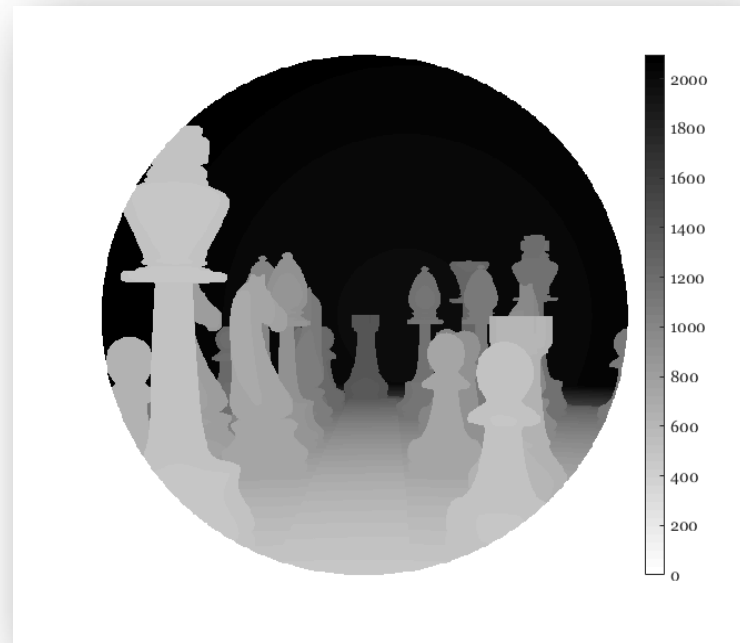



Image formation (optics) models and quantitative graphics

Stereo pairs are straightforward to compute

Right eye

Right eye view



Optical image
Size: [512, 512] samples
Hgt,width: [8.75, 8.75] mm
Sample: 17.08 um
Wave: 400:10:690 nm
Illum: 10.0 lux
FOV (wide): 30.0 deg
Optics (DL)
Mag: 0.00e+00
Diameter: 6.00 mm

Diffraction-limited

F-number Focal Length
2.72 16.32 mm

Off axis (cos4th)


Anti-alias
Skip

1 Standar... Compute Optical Image

Gamma Display

Left eye

Left eye view



Optical image
Size: [512, 512] samples
Hgt,width: [8.75, 8.75] mm
Sample: 17.08 um
Wave: 400:10:690 nm
Illum: 10.0 lux
FOV (wide): 30.0 deg
Optics (DL)
Mag: 0.00e+00
Diameter: 6.00 mm

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F-number Focal Length
2.72 16.32 mm

Off axis (cos4th)

Anti-alias
Skip


1 Standar... Compute Optical Image

Gamma Display

Natural images - Image formation (optics) models and quantitative graphics

Inert pigments (e.g. lens transmission)

Left eye



Optical image
Size: [512, 512] samples
Hgt,wtdh: [8.75, 8.75] mm
Sample: 17.08 μm
Wave: 400:10:690 nm
Illum: 10.0 lux
FOV (wide): 30.0 deg
Optics (DL)
Mag: 0.00e+00
Diameter: 6.00 mm


F-number Focal Length
 mm

Off axis (cos4th)

Anti-alias

Gamma Display

Left with Lens



Optical image
Size: [512, 512] samples
Hgt,wtdh: [8.75, 8.75] mm
Sample: 17.08 μm
Wave: 400:10:690 nm
Illum: 8.4 lux
FOV (wide): 30.0 deg
Optics (DL)
Mag: 0.00e+00
Diameter: 6.00 mm

F-number Focal Length
 mm

Off axis (cos4th)

Anti-alias

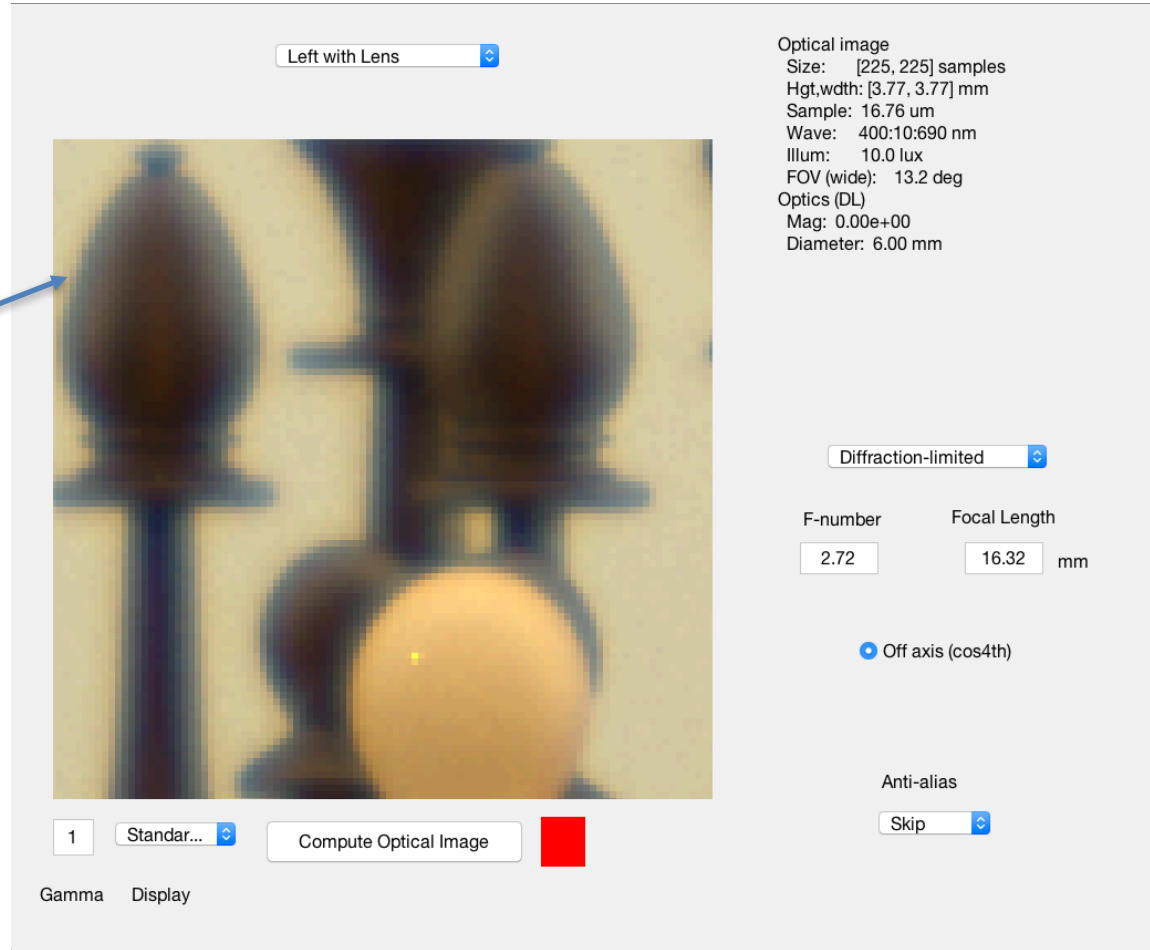
Gamma Display

Longitudinal and transverse chromatic aberration

Zoomed view

Notice the spread of the short-wavelength light

Chromatic aberration (and diffraction) are included in both the ray trace calculation and shift-invariant models



Left with Lens

Optical image
Size: [225, 225] samples
Hgt,width: [3.77, 3.77] mm
Sample: 16.76 um
Wave: 400:10:690 nm
Illum: 10.0 lux
FOV (wide): 13.2 deg
Optics (DL)
Mag: 0.00e+00
Diameter: 6.00 mm

Diffraction-limited

F-number Focal Length
2.72 16.32 mm

Off axis (cos4th)

Anti-alias
Skip

1 Standar... Compute Optical Image ■

Gamma Display

Cone absorptions

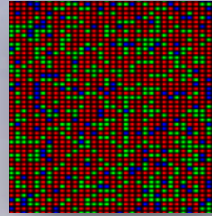
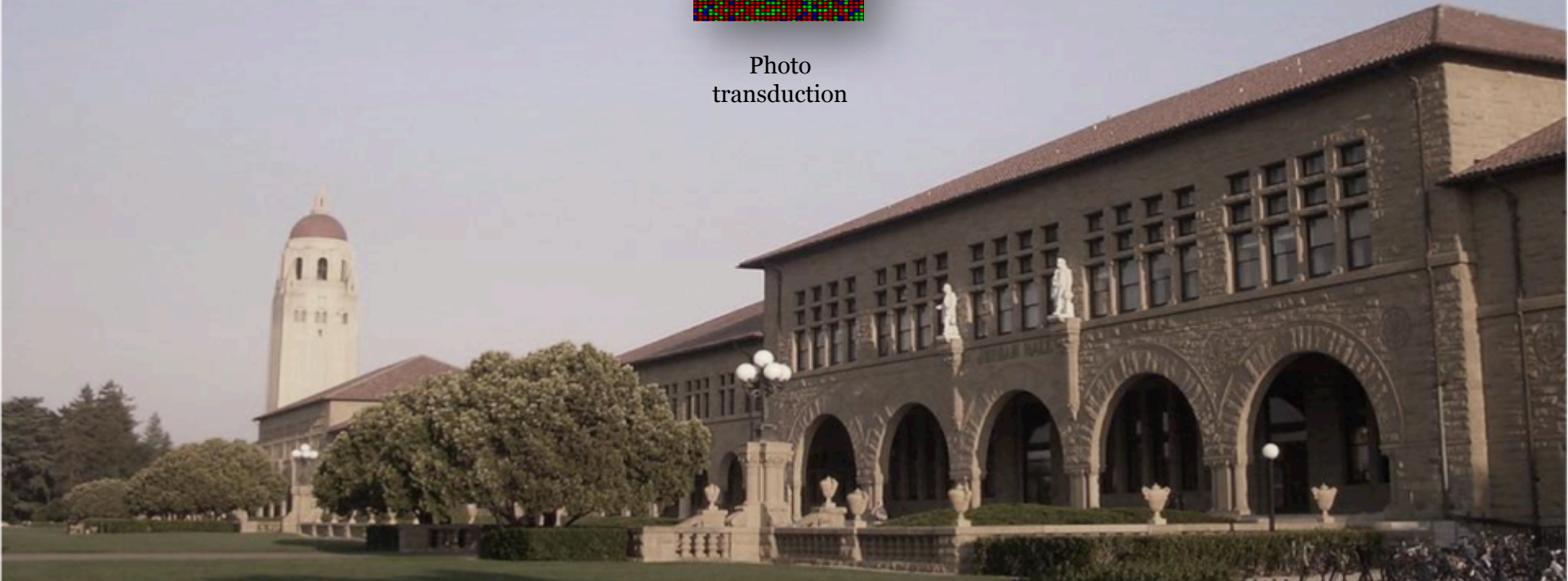


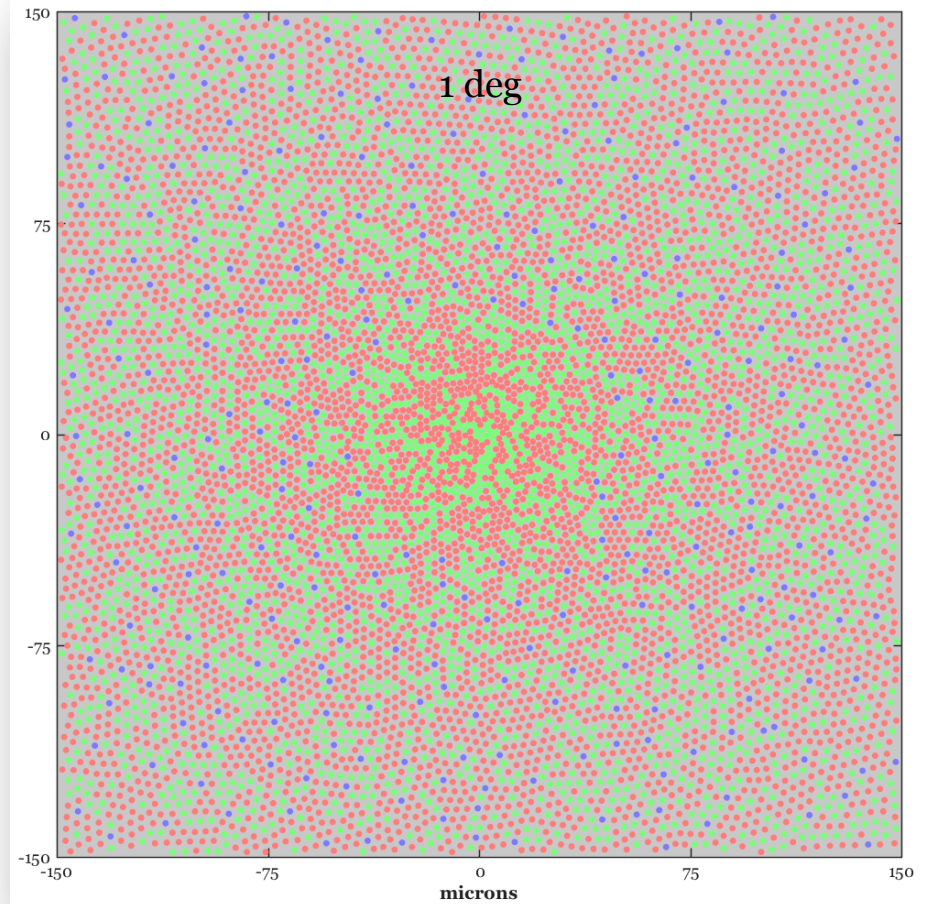
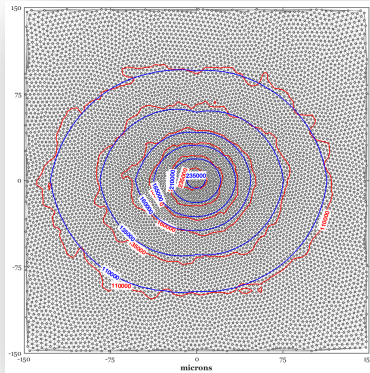
Photo
transduction



Cone absorptions and eye movements

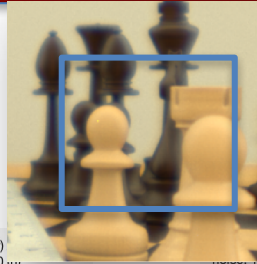
- Uniform and space-varying cone density representations (Nicolas Cottaris)
- Incorporates parameters that specify how cone spacing and cone aperture size vary with distance from the fovea
- Removes S-cones in very central fovea

Iso-density lines



Cone mosaic absorptions and eye movements

Eye movements (tremor, drift, saccade)
Photo and inert pigment properties (e.g., density)
Cone aperture variations with eccentricity



OS: osLinear
noise: random

0.5 deg ecc

Absorption m...

Showing absorption movie

Mosaic size (mm): 2.1 (w) x 2.1 (h)
FOV (deg): 7.00 (w) x 7.00 (h)
Aperture (um): 3.44 (w) x 3.44 (h)
Active cones: 364816
Density (cones/mm²): 84379.2
Duration: 0.5 sec (100 sampls)

Linear
random

Cone size
(um)

3.442 3.442

Pigment
density

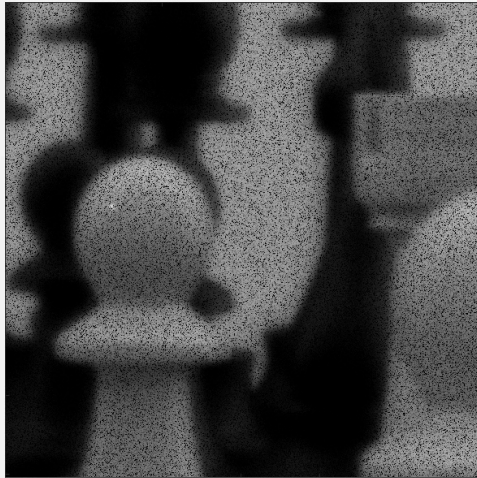
[0.5, 0.5, 0.4]

Peak

[0.67, 0.67, 0.67]

Macular
density

0.35



1
Gam

Compute cone absorptions

Row Col

604 604

Integration

5.0 (ms)

Eccentricity

0.45

Blank-LMS

[0.0, 0.6, 0.3]

Cone size
(um)

11.32 11.32

Pigment
density

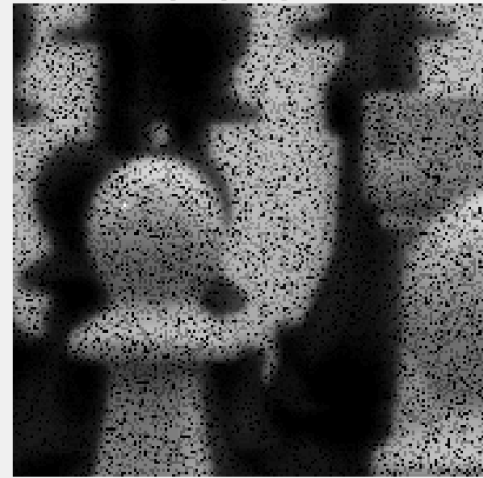
[0.5, 0.5, 0.4]

Peak

[0.67, 0.67, 0.67]

Macular
density

0.35



1
Gam

Compute cone absorptions

10 deg ecc

Mean absorpt...

Mosaic size (mm): 2.1 (w) x 2.1 (h)
FOV (deg): 7.01 (w) x 7.01 (h)
Aperture (um): 11.32 (w) x 11.32 (h)
Active cones: 33856
Density (cones/mm²): 7803.75
Duration: 0.5 sec (100 sampls)

Absorptions per integration time

12000

Row Col

184 184

Integration

5.0 (ms)

Eccentricity

9

Blank-LMS

[0.0, 0.6, 0.3]

8000

6000

4000

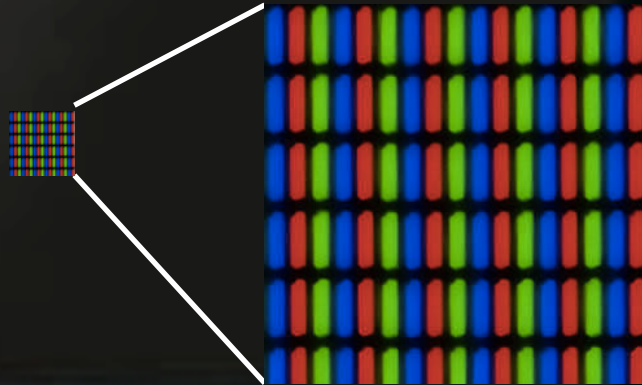
2000

Information analysis



Laboratory experiments display devices

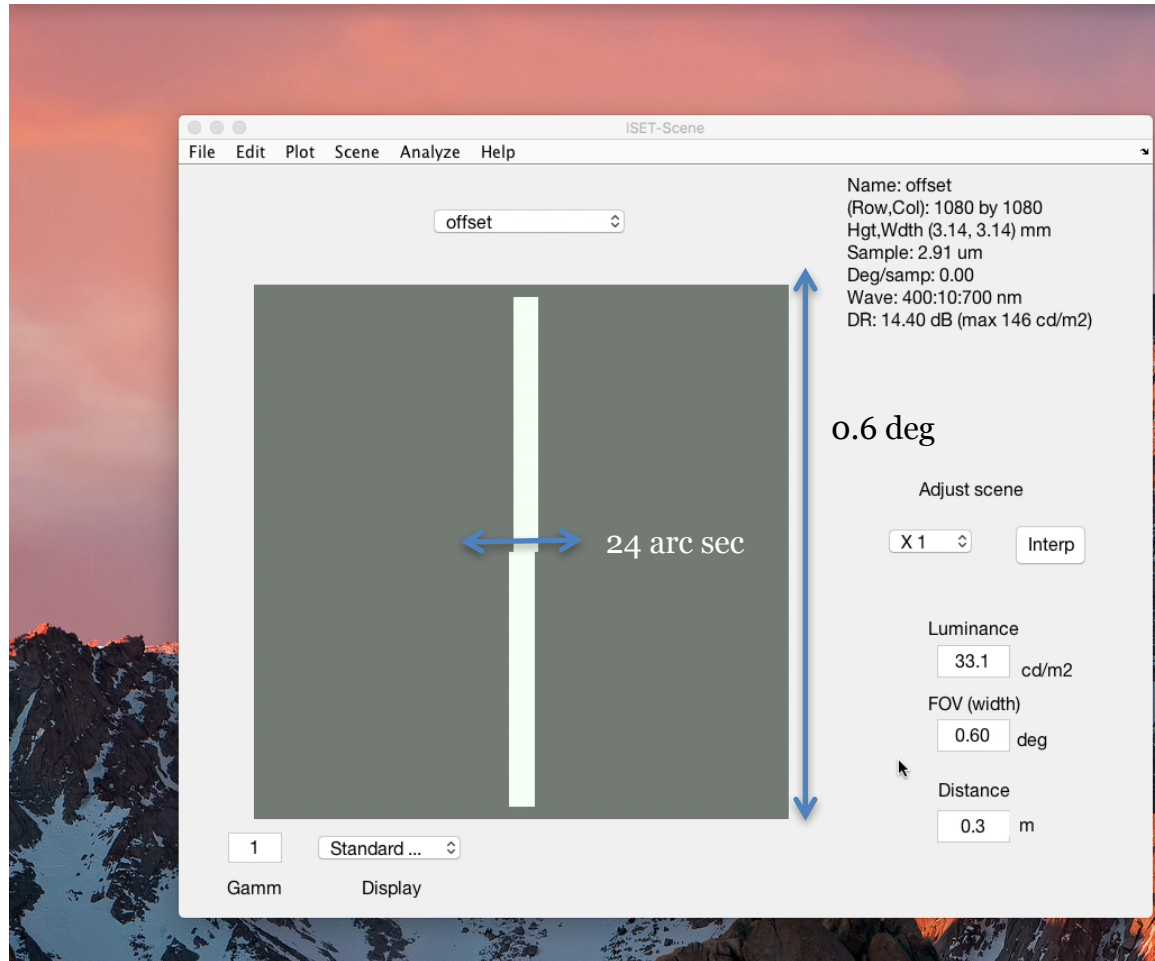
Display models are part of the ISETBIO code –
this converts images to scene spectral radiance;
such models are necessary for modeling
psychophysical experiments and industrial
applications



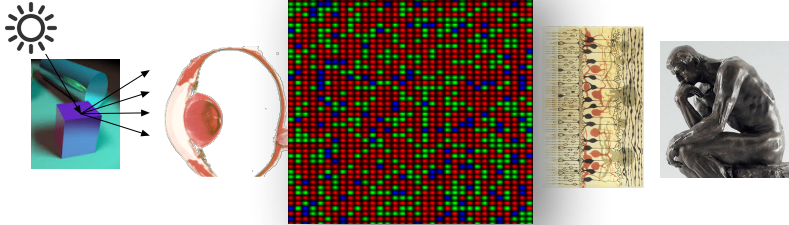
Analyzing psychophysical tasks

Two examples chosen for software validation and applications to industrial issues

- Vernier acuity (Wandell et al.)
- Contrast sensitivity (Cottaris et al.)



Cone absorptions accounting for eye movements



- The calculations here are on a rectangular grid;
- The cone photopigment properties were the standard templates

OS: osLinear
noise: random

cone mosaic

Cone mosaic ▾

Mosaic size (mm): 0.3 (w) x 0.3 (h)
FOV (deg): 1.00 (w) x 1.00 (h)
Aperture (um): 2.00 (w) x 2.00 (h)
Active cones: 22201
Density (cones/mm²): 250000
Duration: 0.5 sec (100 samps)

Cone size (um)
2 2

Pigment density
[0.5, 0.5, 0.4]

Peak
[0.67, 0.67, 0.6]

Macular density
0.35

Row Col
149 149

Integration
5.0 (ms)

Eccentricity
0

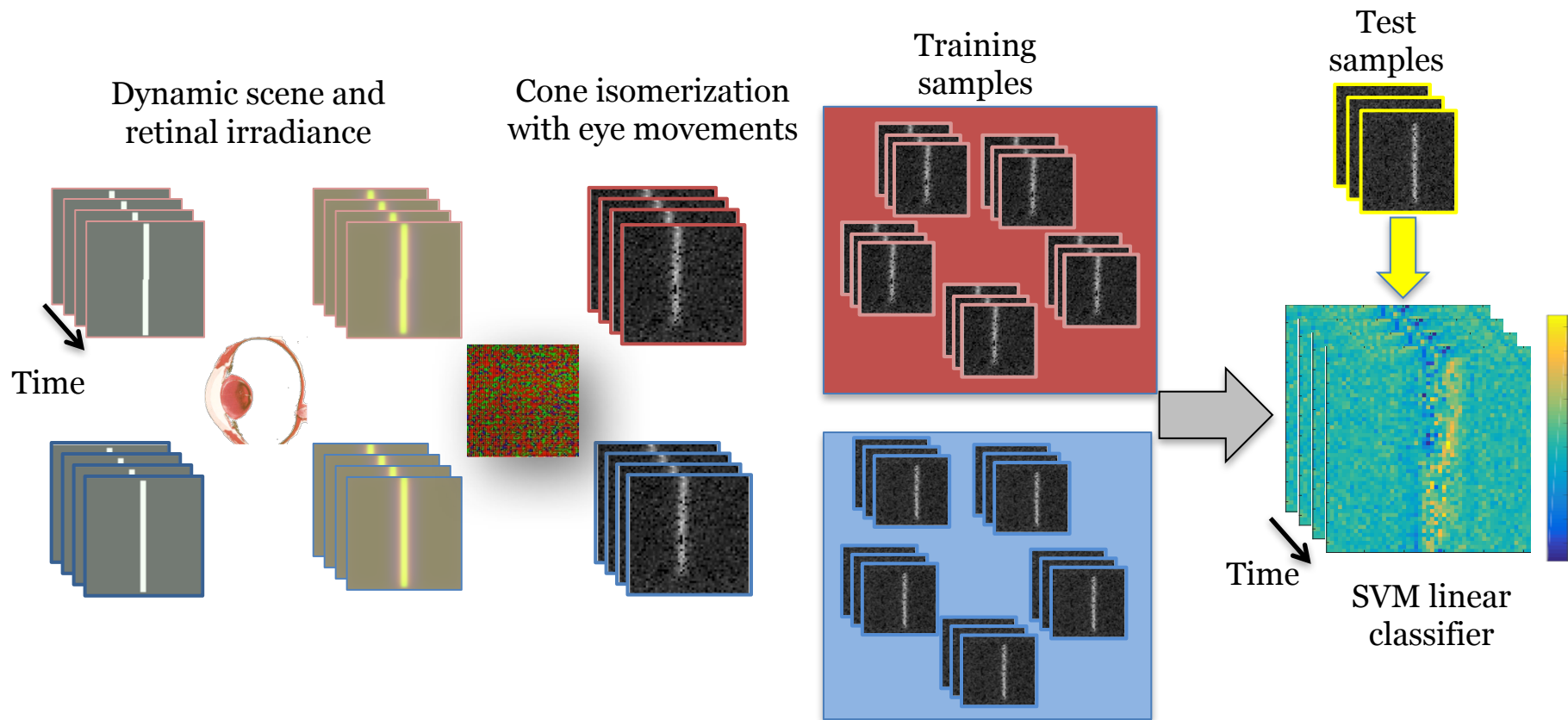
Blank-LMS
[0.0, 0.6, 0.6]

0

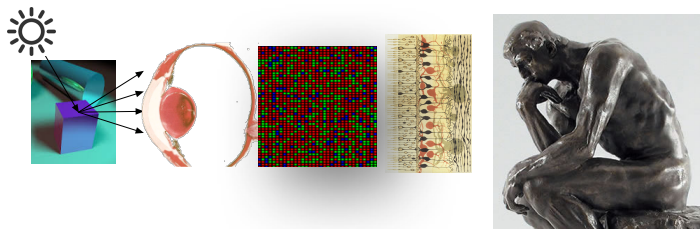
1
Gam

Compute cone absorptions

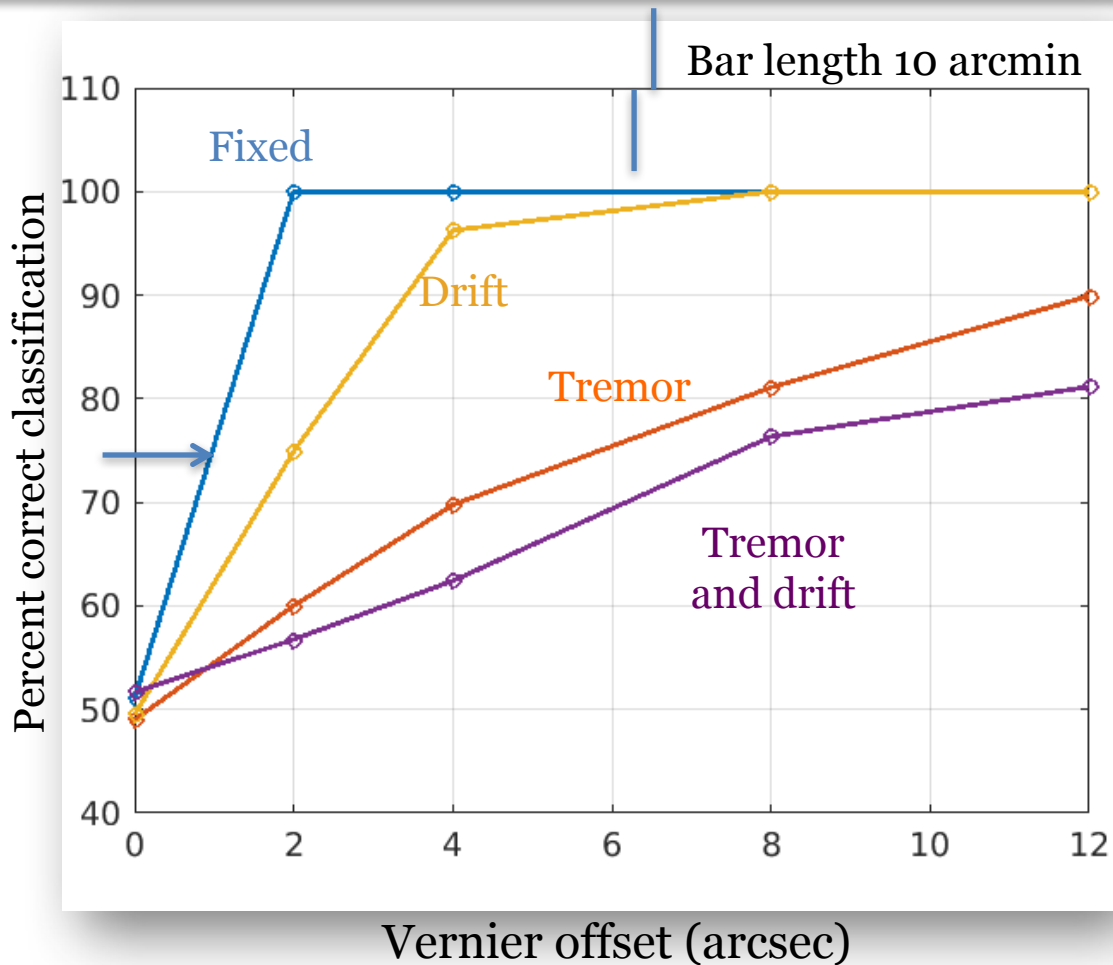
Computational observer pipeline for the Vernier task



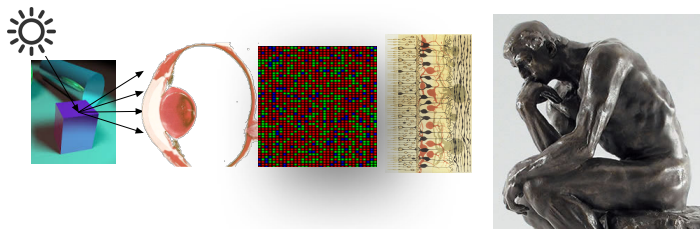
Tremor and drift limit classification accuracy



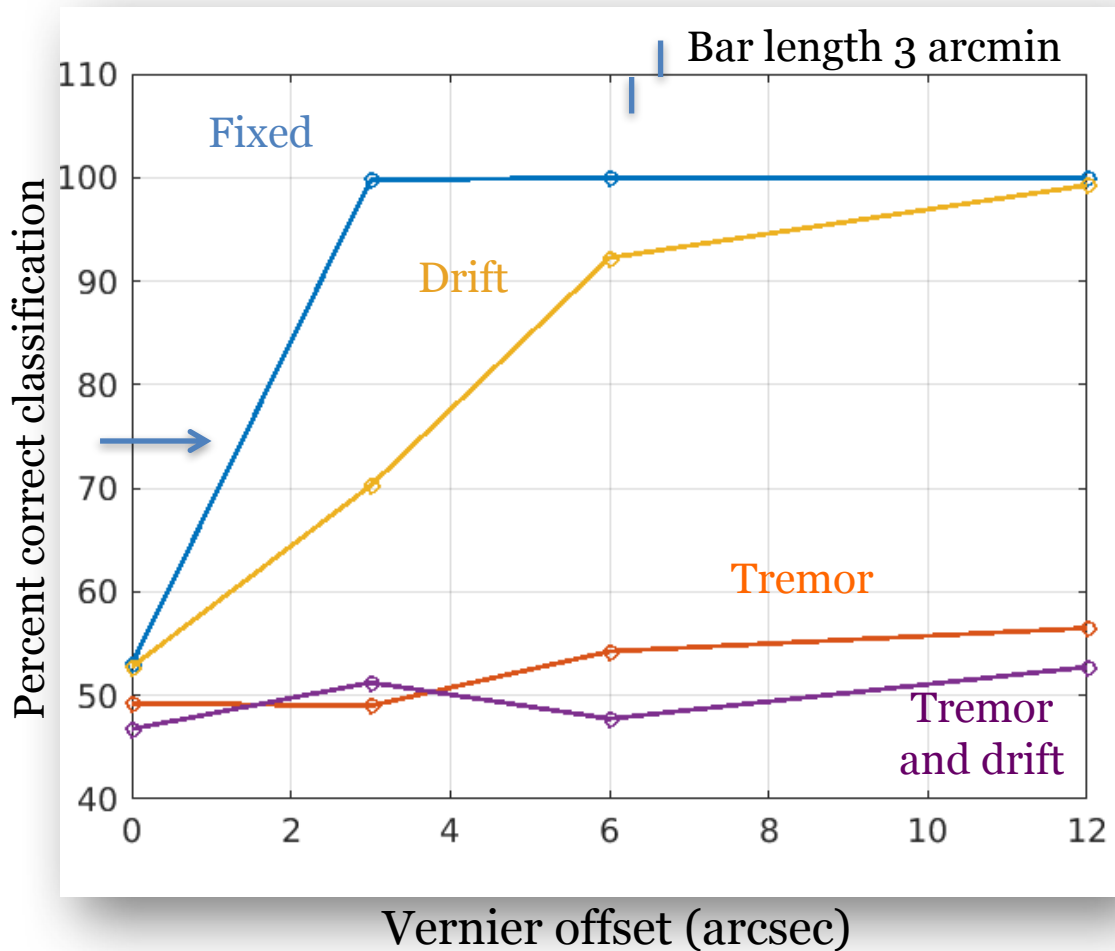
- The SVM linear classifier separates aligned and offset stimuli at very high resolution when we turn off eye movements
- Drift and tremor both degrade performance.



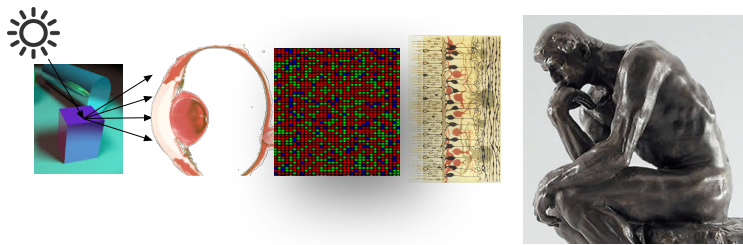
Tremor and drift limit classification accuracy



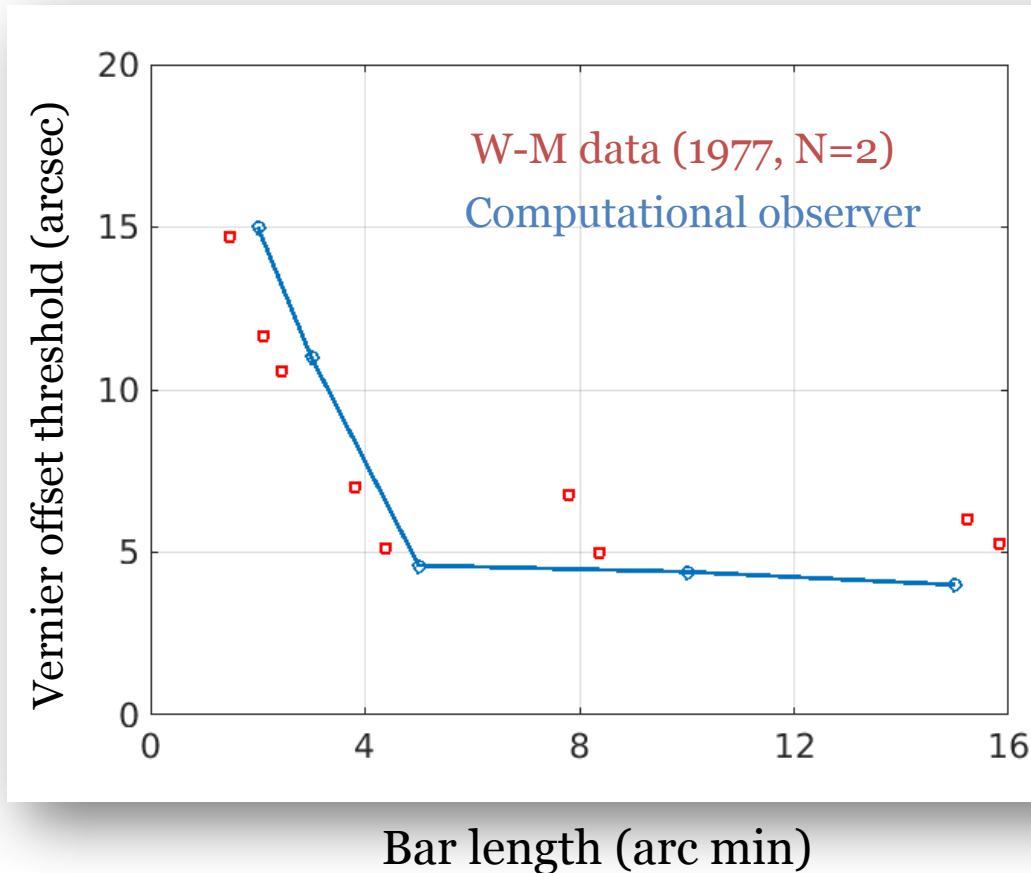
- The SVM linear classifier separates aligned and offset stimuli at very high resolution when we turn off eye movements
- Drift and tremor both degrade performance
- Particularly for small stimuli



A phenomenological description of Westheimer and McKee

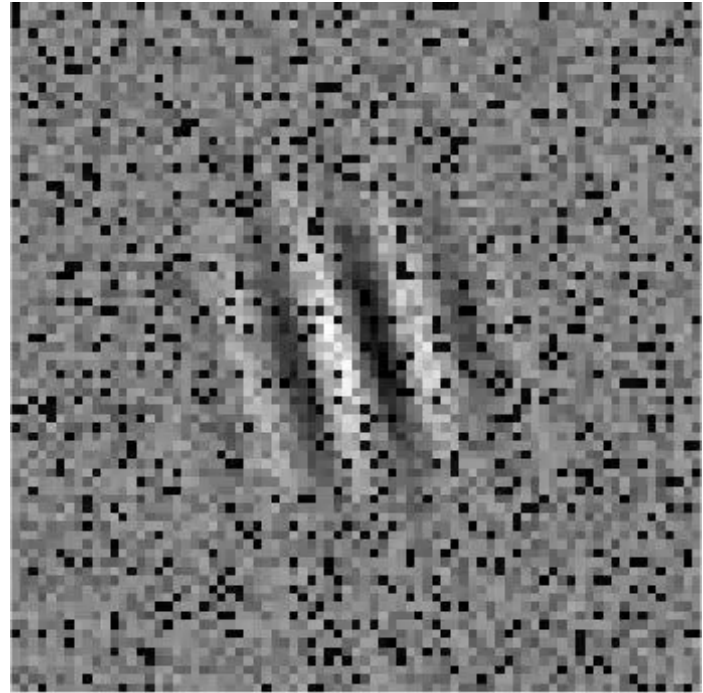
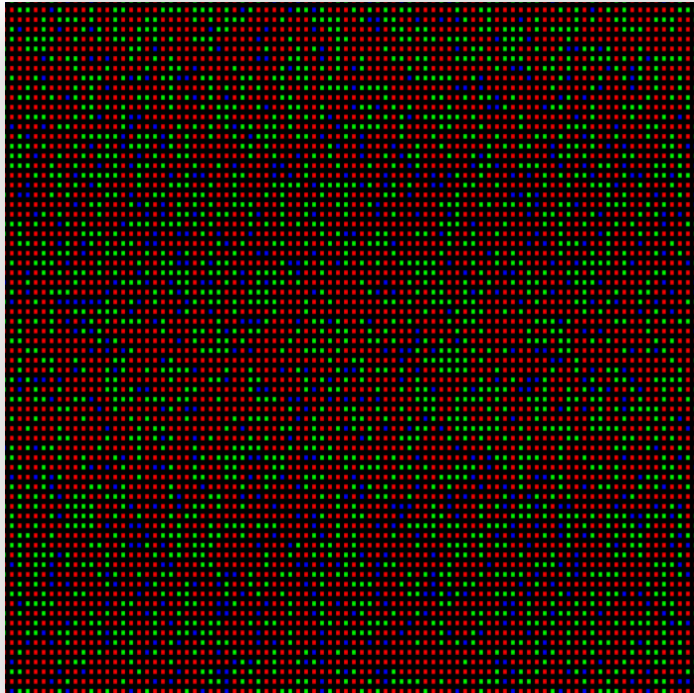


- By choosing to limit the Computational Observer (e.g., size of the cone mosaic), we can make a computational description that matches some properties of the human psychophysics



Contrast sensitivity functions

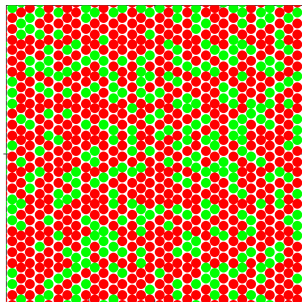
Limits of contrast sensitivity as a function of spatial frequency



ISETBIO replicates classic measurements in the literature (Cottaris et al., in prep)

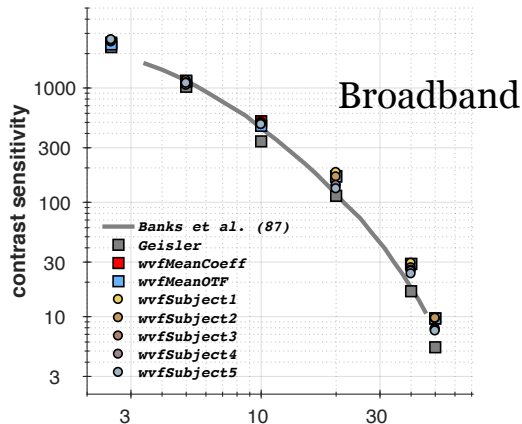
Comparison with Banks et al. 1987

Cone spacing 3.0 μm
Cone aperture 3.0 μm
Pupil 2 mm
L,M cones
Broadband stimulus

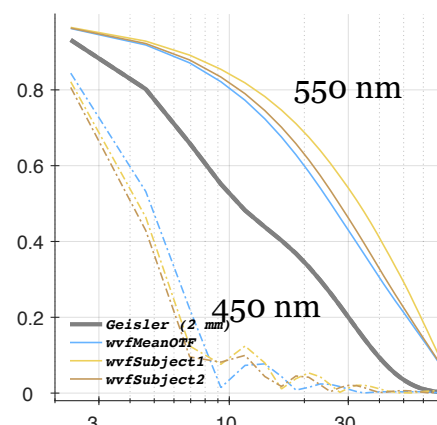
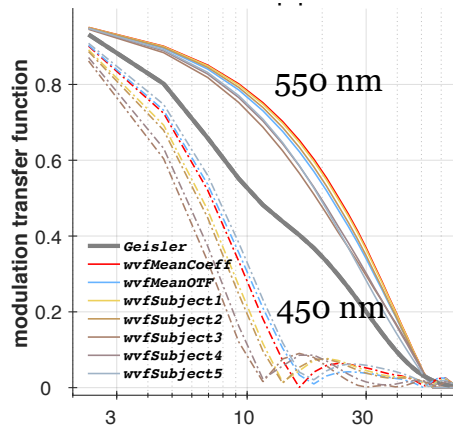
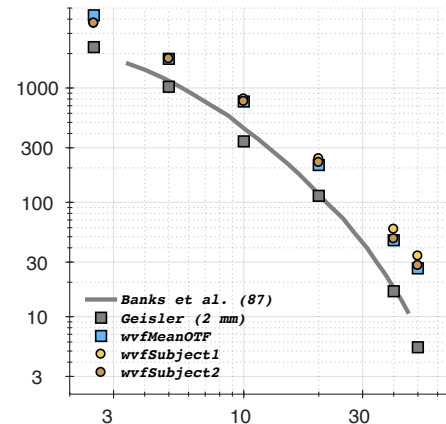


wvfSubjects are samples of
wave front measurements

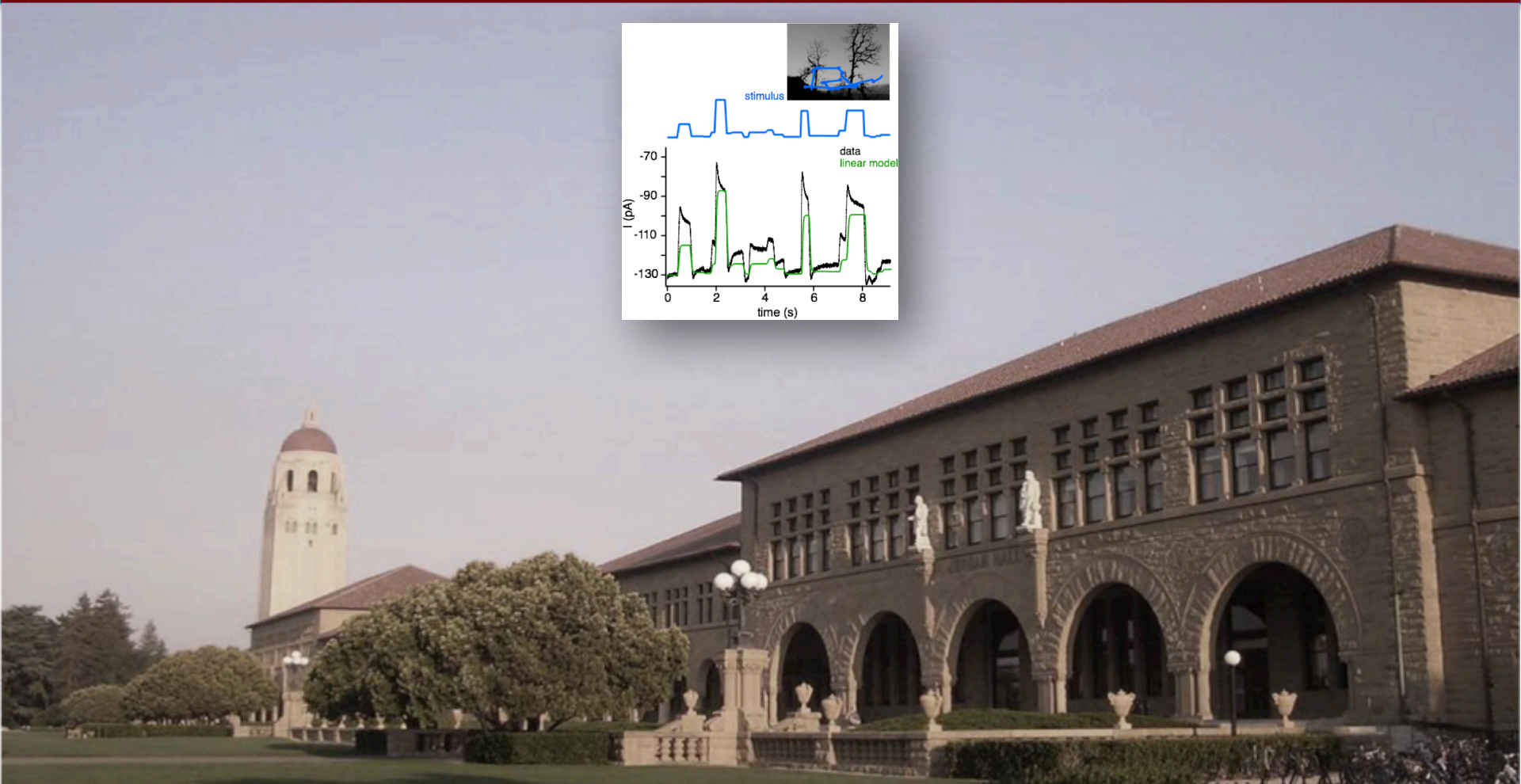
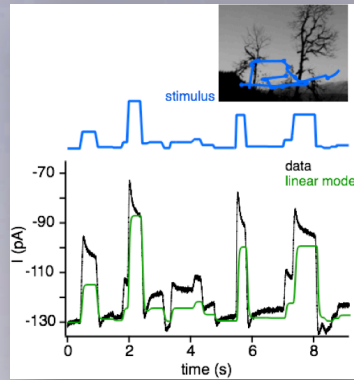
2 mm pupil



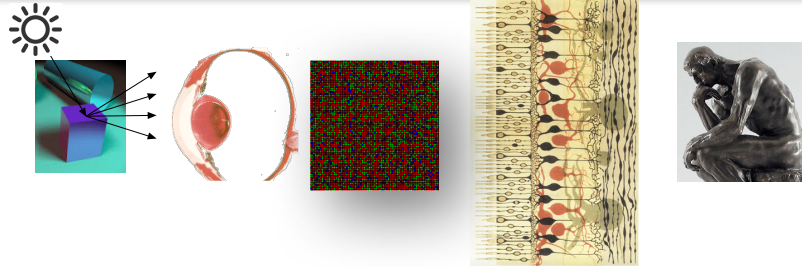
3 mm pupil



Photocurrent modeling

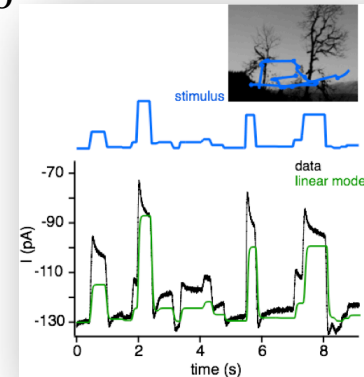


Photocurrent (Rieke model)

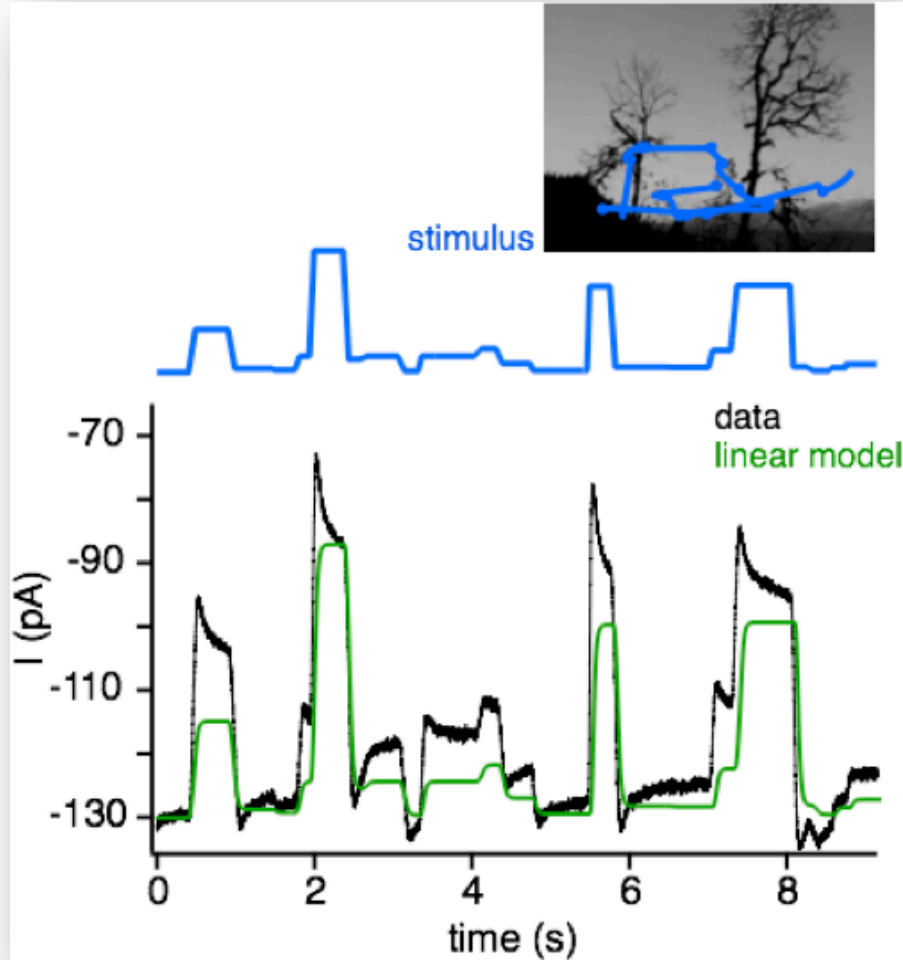


- The photocurrent model derived from electrophysiological measurements
- Comprises a set of differential equations and one nonlinear term
- Nonlinear implemented; linear approximation implemented too

Angueyra and Rieke
(2013, Nature Neuroscience)

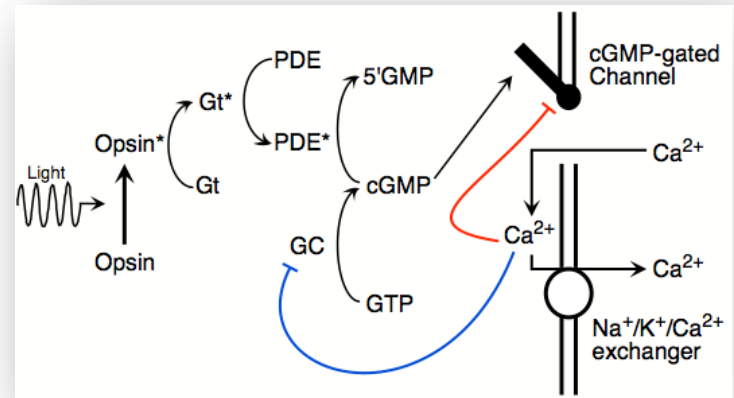
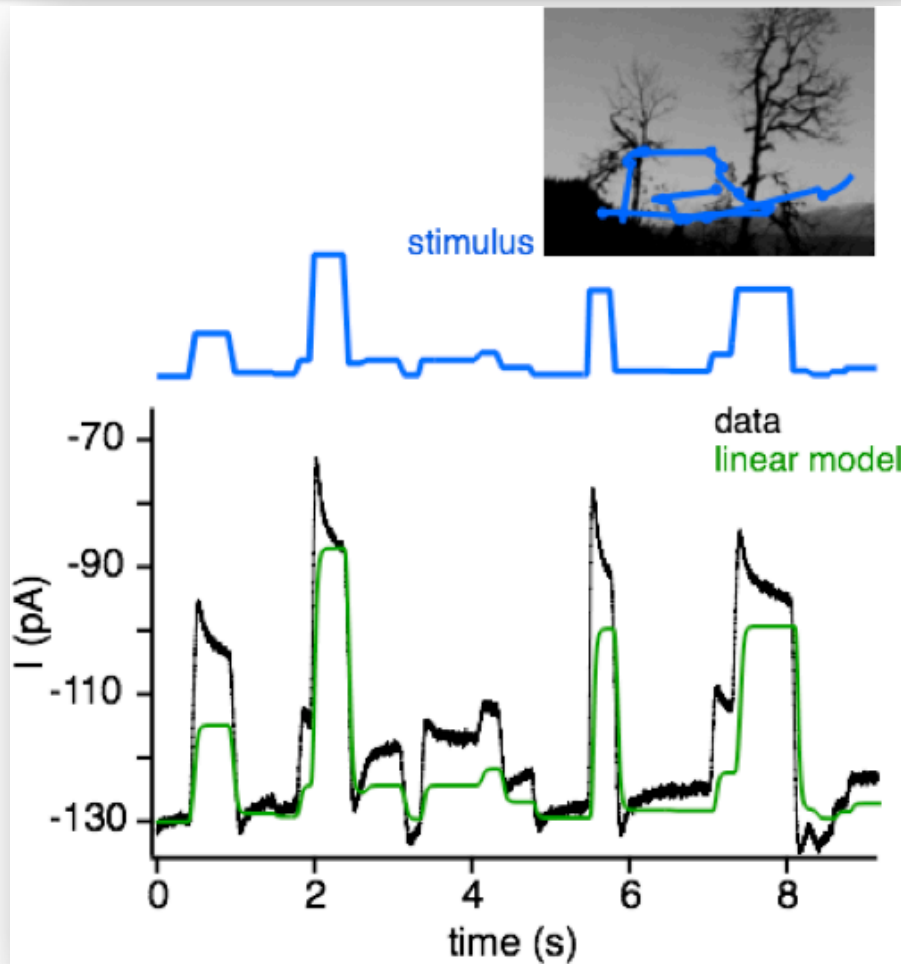


Cone responses exhibit strong time-dependent nonlinearities



- The transients at the transitions are not predicted by linear-nonlinear models
- There is a substantial nonlinear compression

Cone responses exhibit strong time-dependent nonlinearities



$$dR(t)/dt = s(t) - \sigma R(t)$$

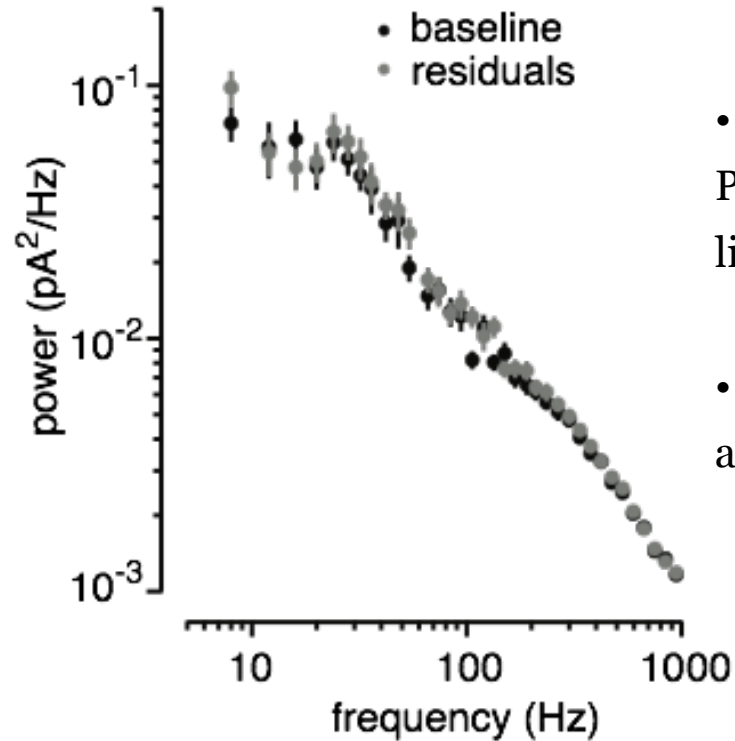
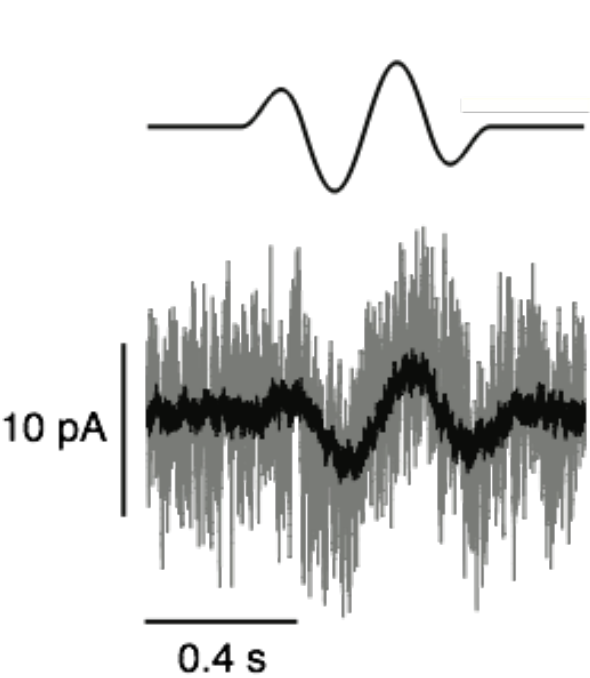
$$dP(t) = \gamma R(t) + \eta - \phi P(t)$$

$$dG(t)/dt = s(C) - P(t)G(t)$$

Five more equations and noise

Photocurrent noise

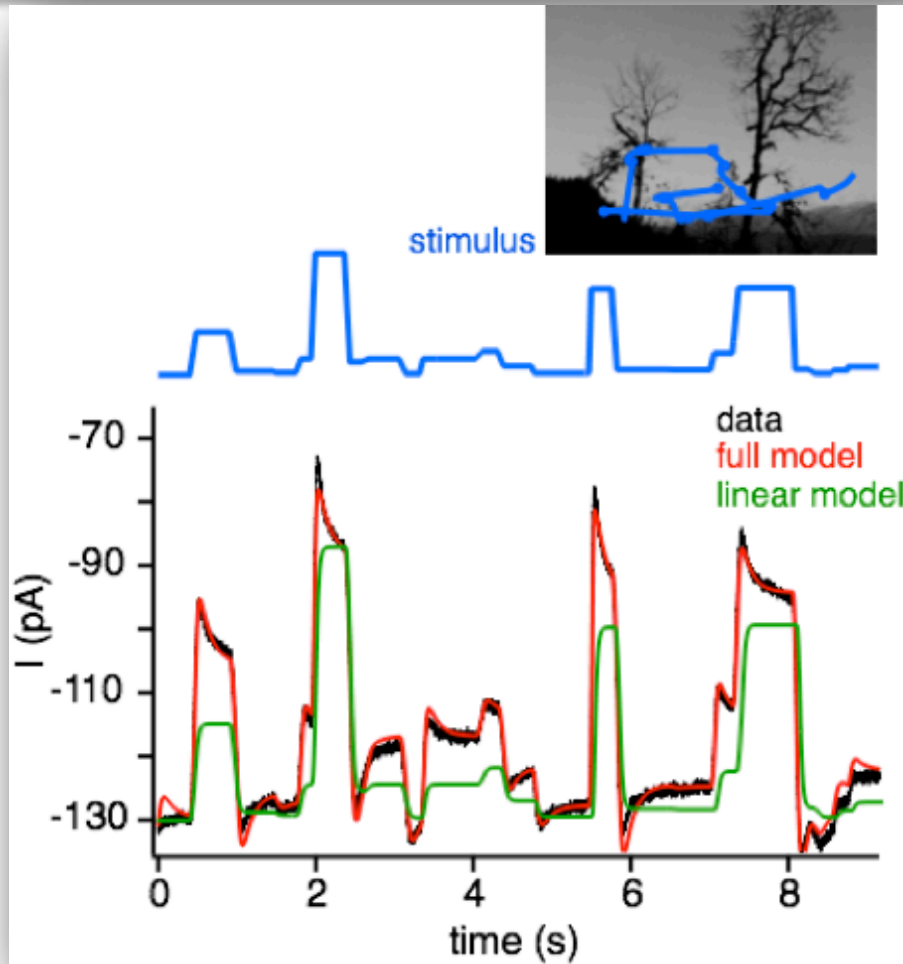
Rieke



- Cone noise exceeds the Poisson fluctuations at most light levels
- The noise is approximately additive

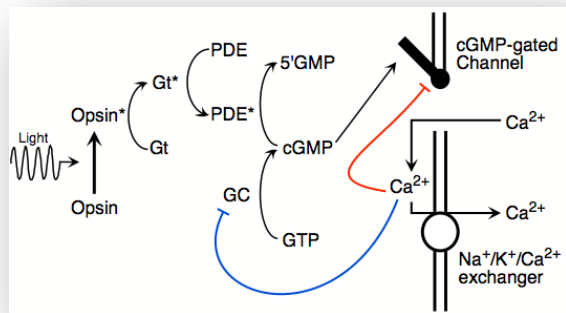
Charlie Hass
Juan Angueyra
Greg Horwitz

Cone responses exhibit strong time-dependent nonlinearities



- The ISETBIO implementation includes the photocurrent and noise model
- We will visualize the consequences in the next steps

We have an implementation of photocurrent (Rieke Lab)

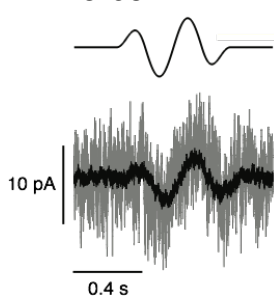


$$dR(t)/dt = s(t) - \sigma R(t)$$

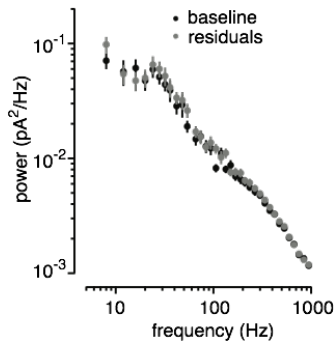
$$dP(t) = \gamma R(t) + \eta - \phi P(t)$$

$$dG(t)/dt = s(C) - P(t)G(t)$$

Noise



...



OS: osLinear
noise: random

Cone size
[2 | 2]

Pigment density
[0.5, 0.5, 0.4]

Peak
[0.67, 0.67, 0.6]

Macular density
[0.35]

cone mosaic

Photocurre... ▾

1
Gam

Compute cone absorptions

Mosaic size (mm): 0.6 (w) x 0.6 (h)
FOV (deg): 2.00 (w) x 2.00 (h)
Aperture (um): 2.00 (w) x 2.00 (h)
Active cones: 88209
Density (cones/mm^2): 250000
Duration: 0.125 sec (25 samps)

Row Col
[297 | 297]

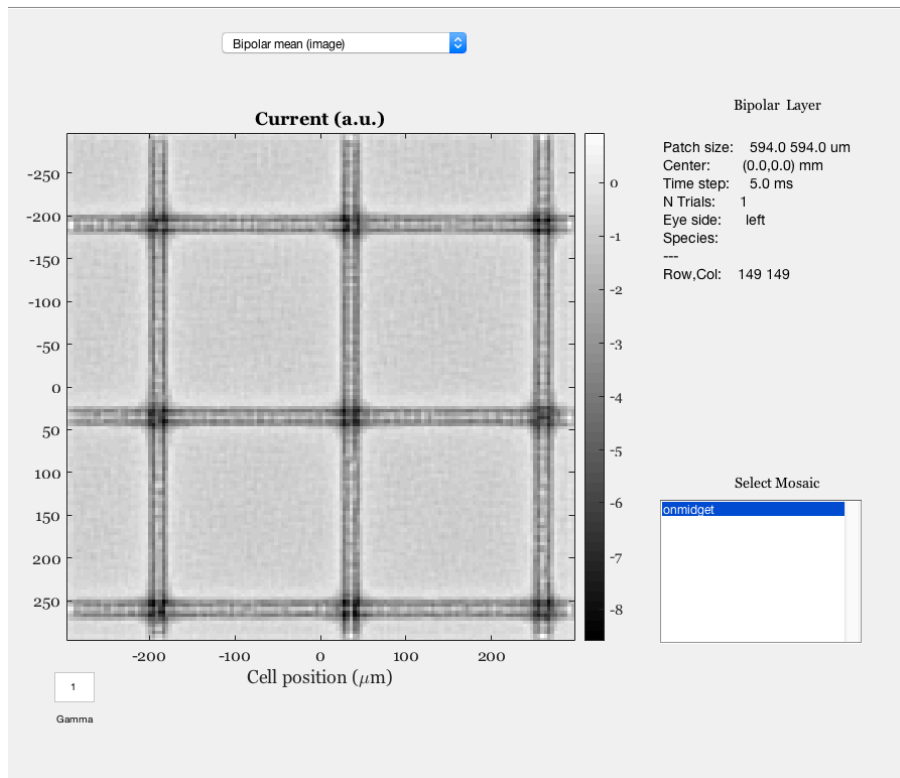
Integration
[5.0] (ms)

Eccentricity
[0]

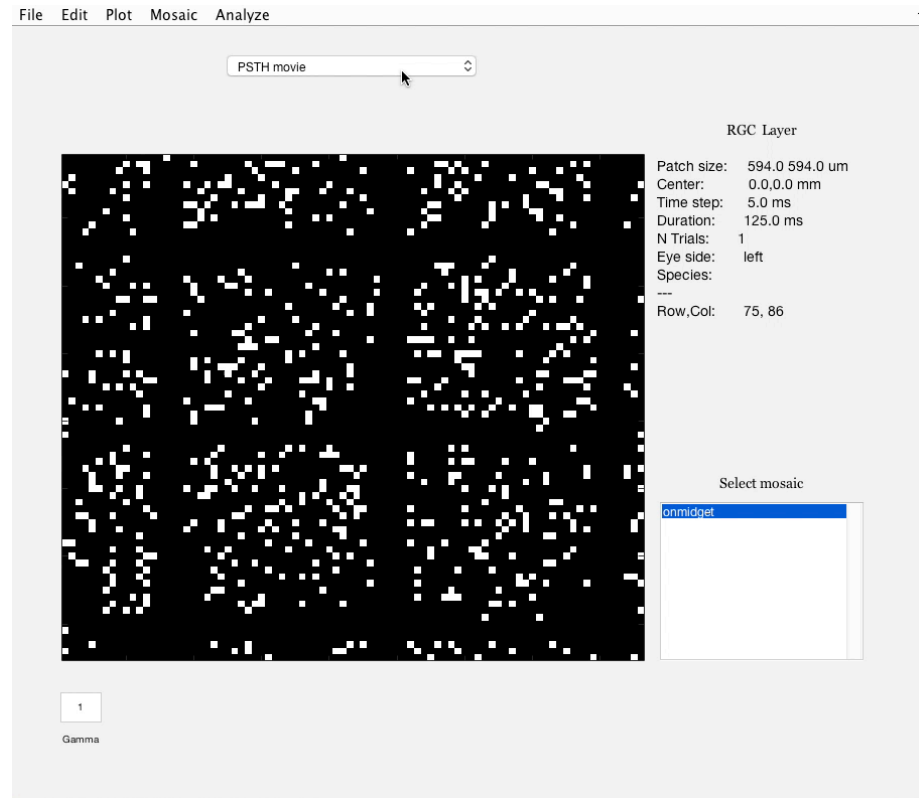
Blank-LMS
[0.0, 0.6, 0.]

We are working on bipolar and ganglion cell models

Bipolar current



On midget spikes



Github code and wiki – continuous integration

This repository | Search | Pull requests | Issues | Gist

isetbio / isetbio | Unwatch 18 | Star 12 | Fork 10

Code | Issues 54 | Pull requests 0 | Projects 0 | Wiki | Pulse | Graphs | Settings

Tools for modeling image systems engineering in the human visual system front end

1,702 commits | 3 branches | 2 releases | 8 contributors | MIT

Branch: master | New pull request | Create new file | Upload files | Find file | Clone or download -

Author	Commit Message	Latest commit	Time ago
benjamin-heasley	ieValidateFullAllAssert -> ieValidateFullAll('asAssertion', true)	256fa43	8 hours ago
	configuration	Fixed syntax error in IsetbioLocalHookTemplate	a month ago
	documentation/resources	Initial import of clean version of 0.1 dev branch, now the master bra...	2 years ago
	external	Added StructUtils from BrainardLabToolbox	19 days ago
	isettools	Took computeDensityMap out of visualizeGrid	a day ago
	scripts	Working still on tutorials.	2 months ago
	tutorials	Put t_eyeMovement in the right place	3 days ago
	utility	Pulled out as much as I could easily find that depends on sensor, pix...	2 months ago
	validation	ieValidateFullAllAssert -> ieValidateFullAll('asAssertion', true)	8 hours ago
	.ghignore	Updated for DS_STORE and local	2 months ago
	LICENSE	Initial import of clean version of 0.1 dev branch, now the master bra...	2 years ago
	README.md	Adding build status icon	6 days ago
	isetbioRootPath.m	Initial import of clean version of 0.1 dev branch, now the master bra...	2 years ago

build passing

The Image System Engineering Toolbox for Biology ISETBIO is a Matlab toolbox designed for calculating the properties of the front end of the visual system. This includes a description of the scene, the optics and retinal image, the capture of light by the photopigment, the photocurrent responses in the receptors, bipolar responses, and retinal ganglion cell responses.

This repository includes a **WIKI** that describes the software as well as many examples of how to perform computations to calculate the visual encoding of light in the eye. The **WIKI** also describes tools to view and and

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Cone mosaic

Brian Wandell edited this page 26 days ago · 51 revisions

The cone mosaic object converts the optical image irradiance into the cone absorptions and photocurrent. For details, please refer to

```
doc coneMosaic
```

The main top-level coneMosaic object commands are

```
cmosaic = coneMosaic; - Create cone mosaic. Many parameters can be set.
cmosaic.compute(o1); - Compute the absorptions from the optical image, o1
cmosaic.computeCurrent; - Compute the photocurrent using the attached outerSegment model
```

The coneMosaic class has an interactive window. This window differs from sceneWindow and oiWindow because like all of the newer ISETBIO concepts, the coneMosaic is a class. Also, there is a growing number of plotting methods.

```
cmosaic.window; - An interactive window to view the mosaic, absorptions and current
cmosaic.plot(); - Plotting methods
```

Cone Mosaic interface screenshot:

- File | Edit | Plot | Cones | Help
- OS: 64Linear, noise: off
- Mosaic size (mm): 0.2 (w) x 0.1 (h), FOV (deg): 0.59 (w) x 0.45 (h), Aperture (um): 2.00 (w) x 2.00 (h), Active cones: 6336, Density (cones/mm^2): 250000, Duration: 0.05 sec (1 sampls)
- Cone size (um): 2 x 2
- Pigment density
- Flow Coil: 72 x 88
- Integration: 50.0 (ms)

Pages 47

- Home
- Installation
- Getting Started
- Data types
 - Scenes
 - Retinal image
 - Cone mosaic
 - Bipolar cells
 - Retinal ganglion cells
- Compute overview
 - Retina model comparisons
- Tutorial scripts
- Numerical utility functions
- ISETBIO Data
- ISETBIO Videos
- Validation
- For Developers

Clone this wiki locally

<https://github.com/isetbio/>

Clone in Desktop

Video tutorials and data resources

Tutorials

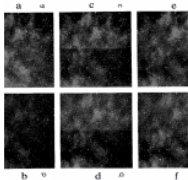
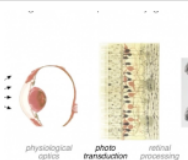


Image Systems

Tutorials in applied vision and image systems. Topics include image formation, optics and other fundamentals of vision science.

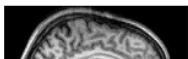
Start watching now!



ISETBIO

Tutorials on the ISETBIO software and its applications in neuroscience.

Start watching now!



Neuroimaging

SEARCH TUTORIALS

September 2015						
M	T	W	T	F	S	S
		1	2	3	4	
7	8	9	10	11		
14	15	16	17	18		
21	22	23	24	25		
28	29	30				

« Aug

SECTIONS

Tutorials

RECENT TUTORIALS

- » David Brainard: "ISETBIO: Computa modeling early human vision" (09/09)
- » Brian Wandell: "Photons and Energy"
- » Fred Rieke: "Modeling Cone Respon"
- » PSYCH 204A [Fall 2014]: MRI – Sig
- » PSYCH 204A [Fall 2014]: MRI – The

TOPICS

ISETBIO

VALIDATION » SCIEN » ISETBIO

ISETBIO datasets: [6]

5BANDPSF

- No description.

- [ReadMe](#)
- [TOC.jsn](#)

BLillumDiscrimCache

- No description.

HDR

- No description.

- [EurasianFemale_Office.mat](#)
- [EurasianFemale_shadow.mat](#)
- [EurasianFemale_window_illuminant.mat](#)
- [EurasianFemaleoffice_illuminant.mat](#)
- [TOC.jsn](#)

HYPERSPECTRAL

Hyperspectral scenes collected by JE Farrell using Hyspex and other radiometric devices.

VESA

These images were provided by David Hoffman for his VESA analysis. If you are not part of the SCIEN program, please download them from the VESA site which is <http://XXXXXX>

fullvalidation

- No description.

