

# Image systems simulation

Prof. Brian Wandell  
Stein Family Professor

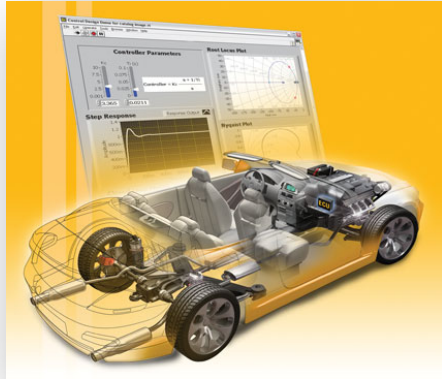
Stanford's Center for Cognitive and Neurobiological Imaging  
Founding Director

Stanford Neurosciences Institute  
Deputy Director

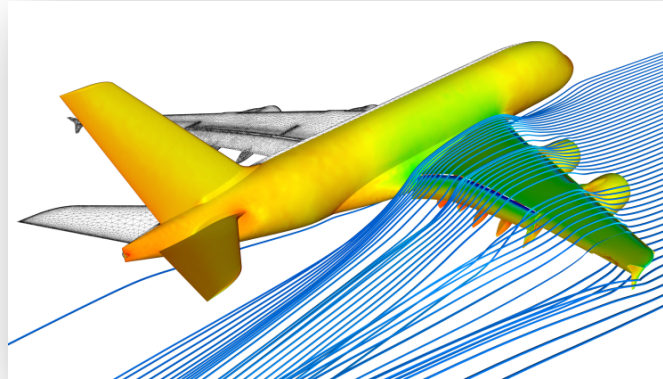


# Image systems simulation

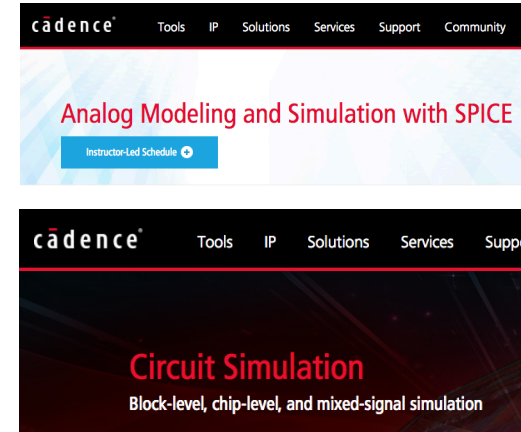
System simulation is important in many mature industries



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

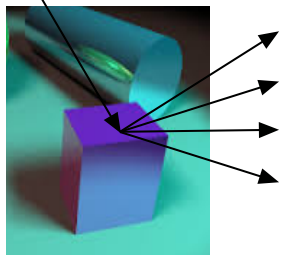


VR, AR and MR HMDs

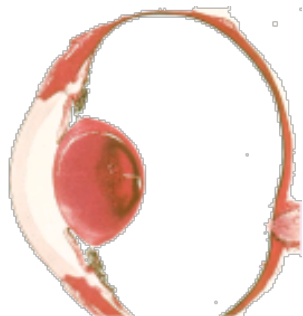


Light field

# Image systems simulation for biology



Scene spectral radiance



Physiological optics

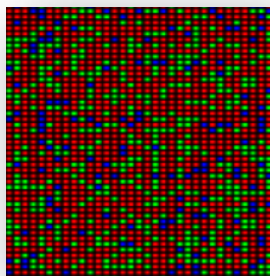
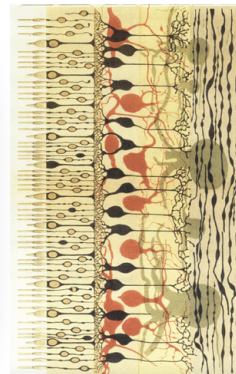


Photo transduction



Retinal processing



Inference



Brian Wandell



David Brainard



James Golden



Trisha Lian



Nicolas Cottaris



Fred Rieke



E.J. Chichilnisky



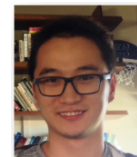
Xiaomao Ding



Jon Winawer



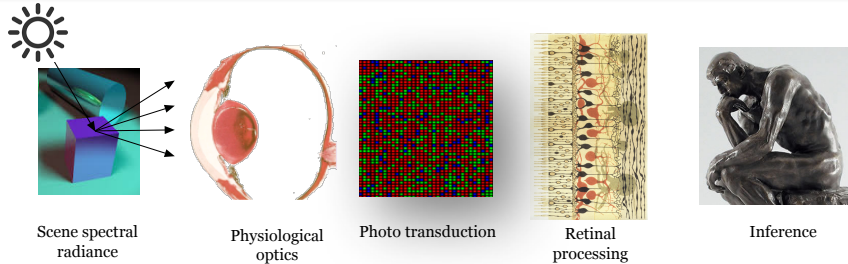
Joyce Farrell



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

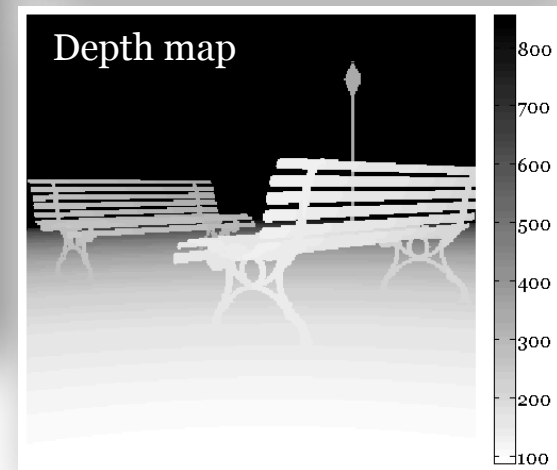
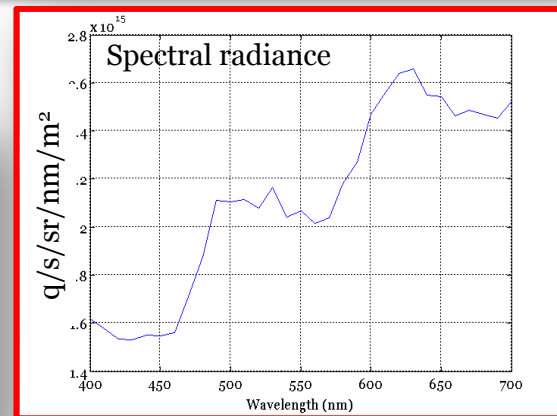


Spectral radiance, refraction, optics, Snell's law, diffraction, Airy disk, photons, energy, Planck's constant, chromatic aberration, retinal irradiance, pupil aperture, eye movements (tremor, drift, saccade), plenoptic function, wavefront aberrations, macular pigment, lens pigment, photopigments, rod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

# Essential technologies for image systems simulation

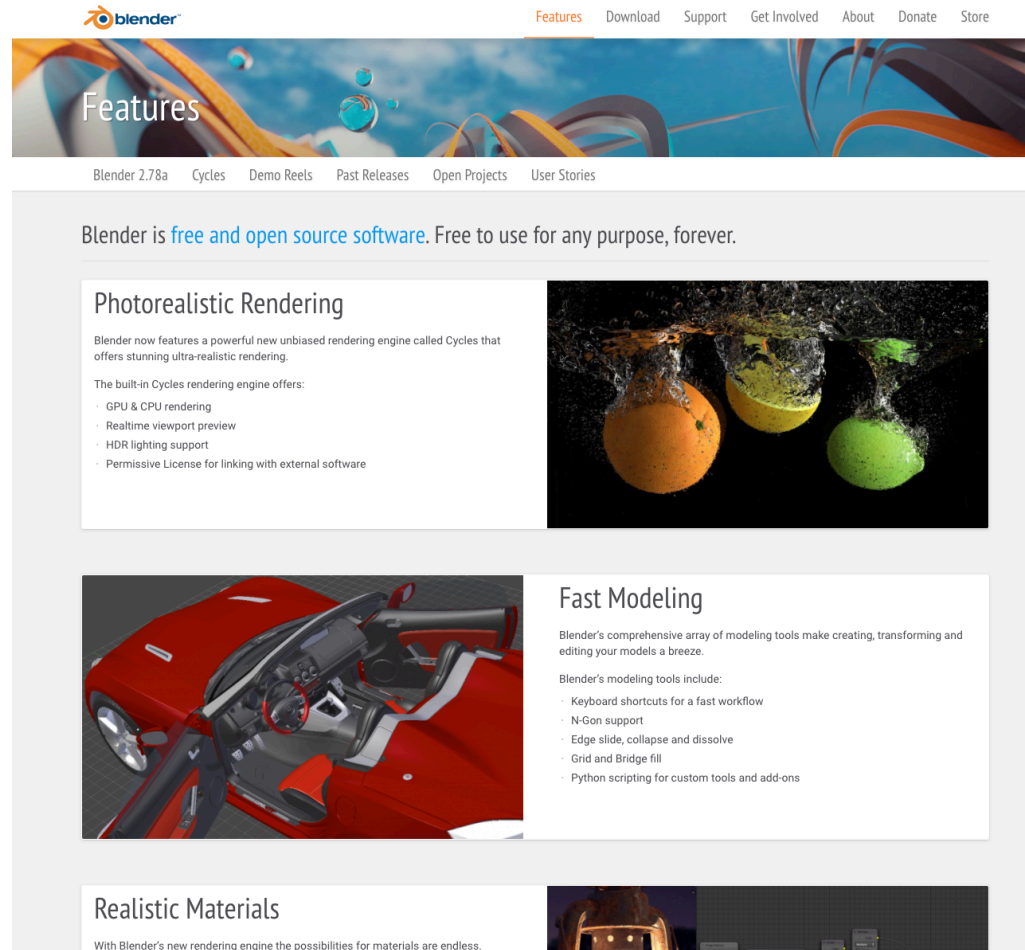
- Scene spectral radiance data are critical; depth information is important for many natural images
- Acquiring such data for natural images has been a limitation; some valuable cases are extremely difficult to obtain (e.g. high dynamic range, under water, inside the body, automotive)

## 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

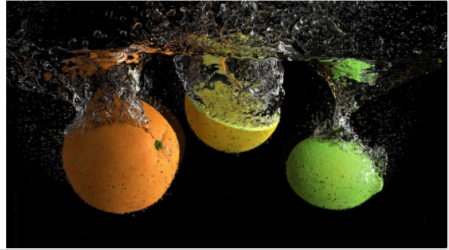
Blender is [free and open source software](#). Free to use for any purpose, forever.

### 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

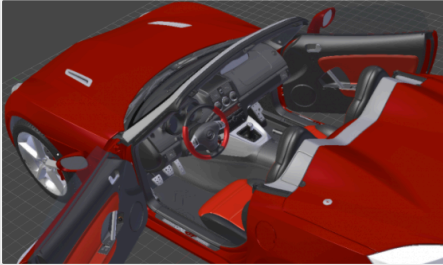


### Fast Modeling

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.



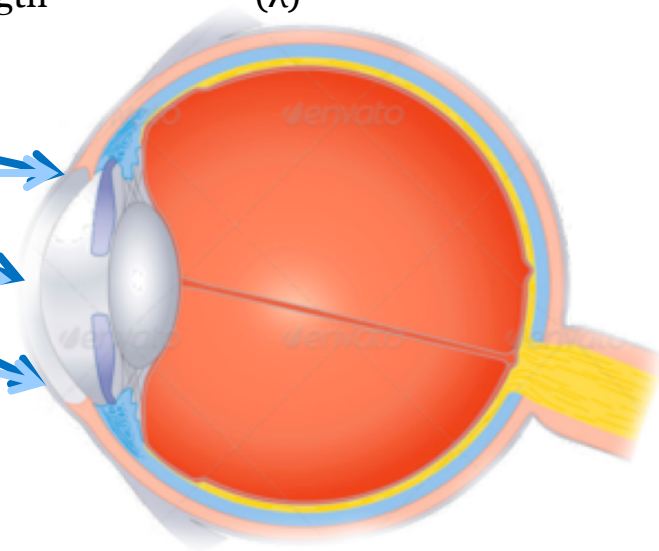
# Ray trace methods yield light fields (plenoptic function)

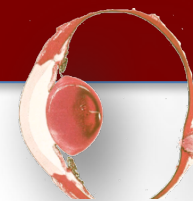
(Adelson and Bergen, 1991; Levoy and Hanrahan, 1996)

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

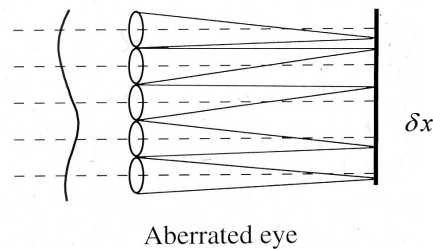
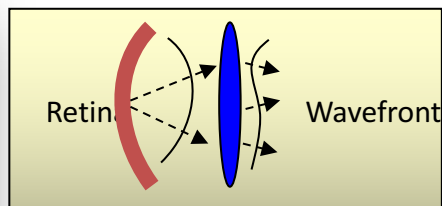
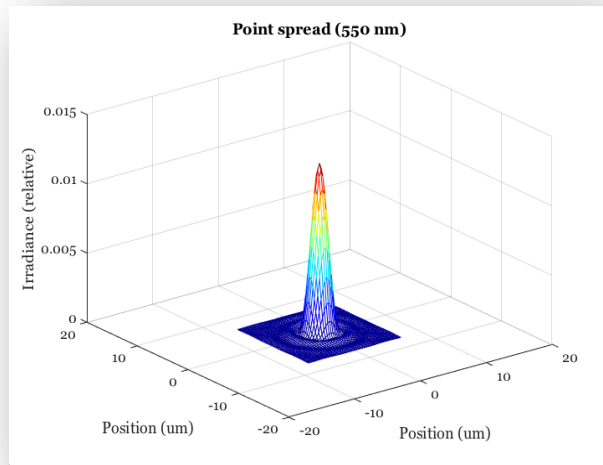


Position  
Azimuth and elevation  $(\alpha, \beta)$   
Wavelength  $(\lambda)$

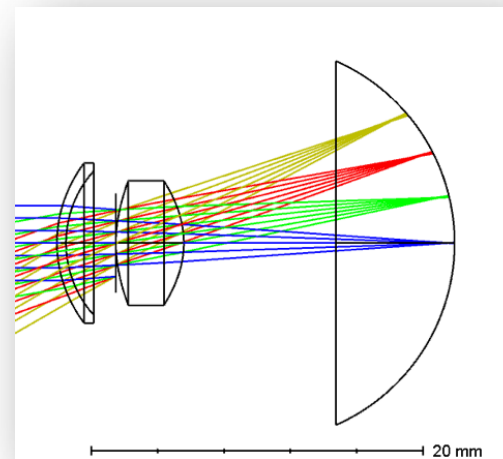




Shift-invariant models from diffraction to  
AO wavefront measures  
(Zernike polynomial)

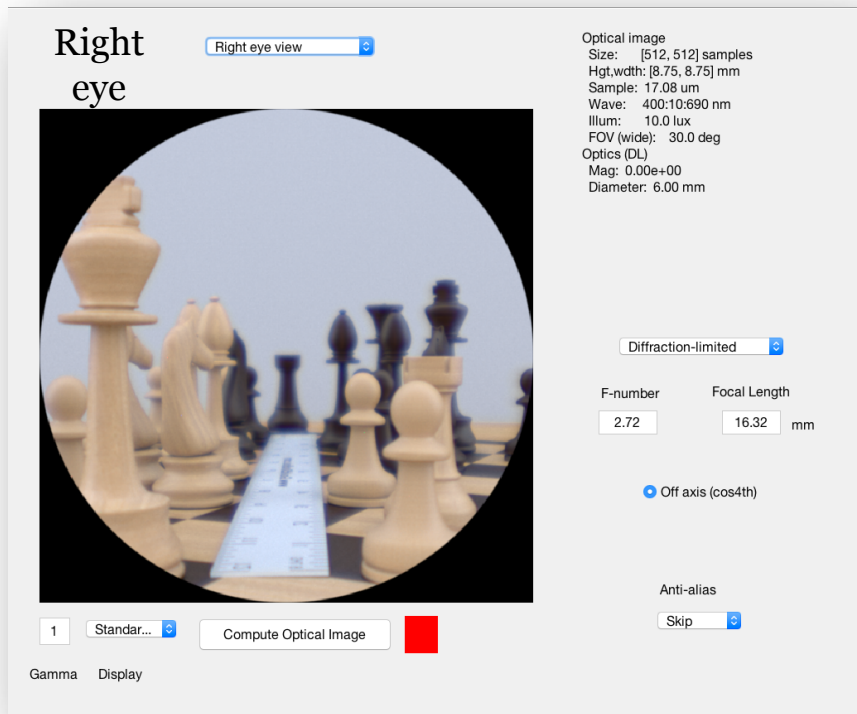


Ray trace with diffraction  
model (e.g. Navarro eye m  
model)

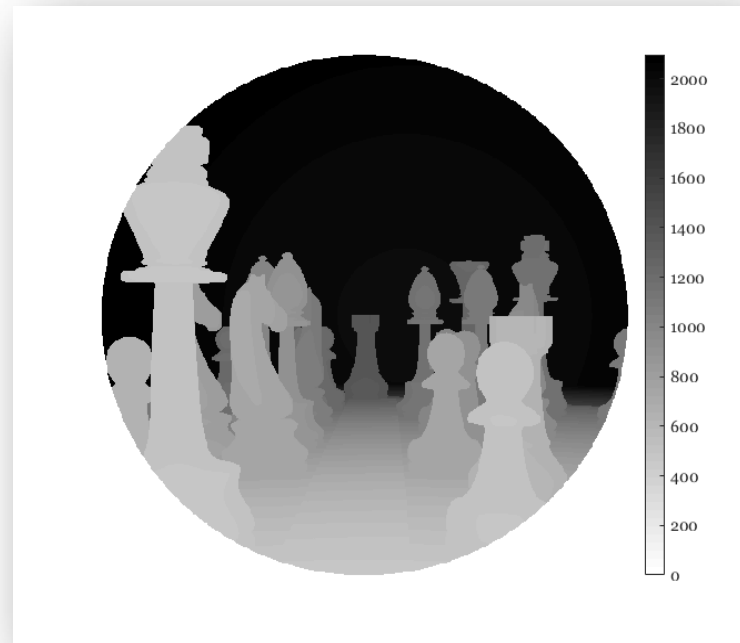


# Natural images - Image formation (optics) models and quantitative graphics

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

Diffraction-limited

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,wdth: [8.75, 8.75] mm  
Sample: 17.08  $\mu\text{m}$   
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,wdth: [8.75, 8.75] mm  
Sample: 17.08  $\mu\text{m}$   
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

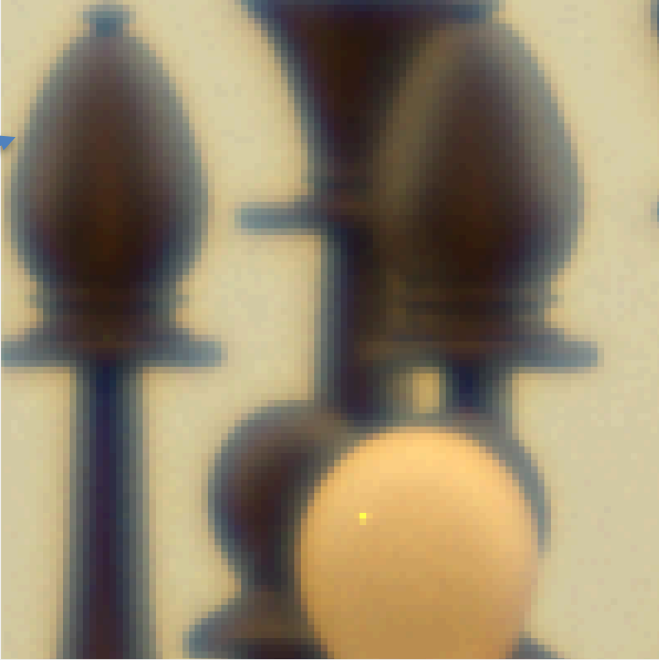
Gamma    Display

# 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,wdth: [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

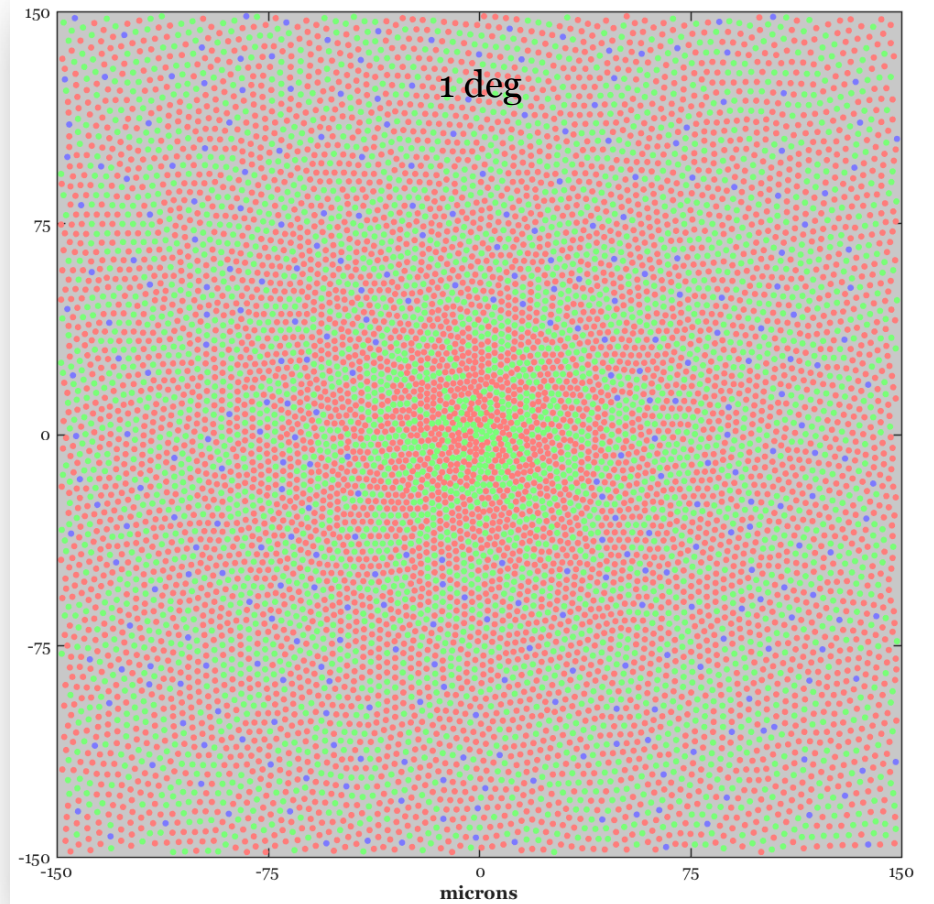
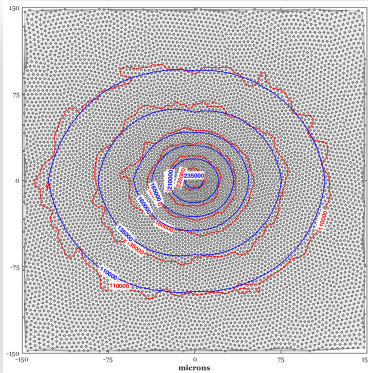
1    Standar...    Compute Optical Image    ■

Gamma    Display

# Cone absorptions and eye movements

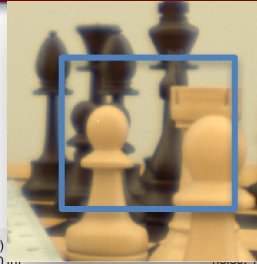
- Uniform and space-varying cone density representations (Nicolas Cottaris)
- Incorporates parameters that specify how cone spacing and cone aperture size vary with distance from the fovea
- Removes S-cones in very central fovea

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/mm<sup>2</sup>): 84379.2  
Duration: 0.5 sec (100 samps)

Linear  
random

Cone size  
( $\mu\text{m}$ )

3.442 3.442

Pigment  
density

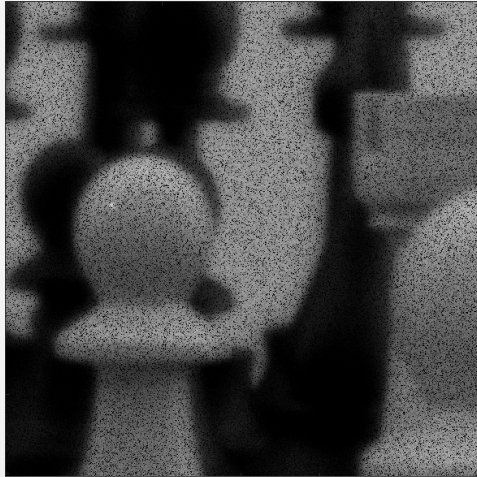
[0.5, 0.5, 0.4]

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  
( $\mu\text{m}$ )

11.32 11.32

Pigment  
density

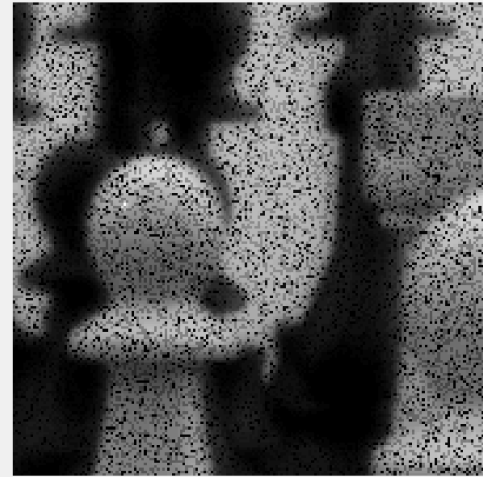
[0.5, 0.5, 0.4]

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/mm<sup>2</sup>): 7803.75  
Duration: 0.5 sec (100 samps)

Absorptions per integration time

12000

Row Col

184 184

Integration

5.0 (ms)

Eccentricity

9

Blank-LMS

[0.0, 0.6, 0.3]

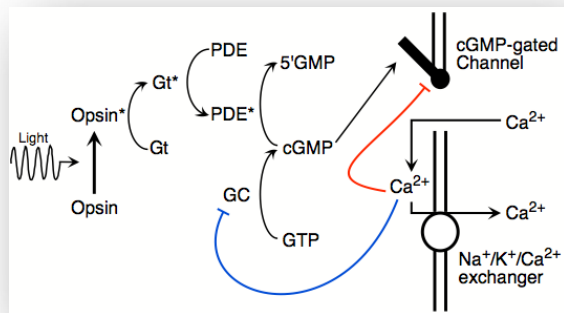
8000

6000

4000

2000

# We have an implementation of photocurrent (Rieke Lab)

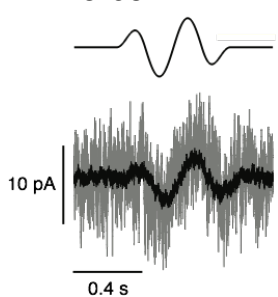


$$dR(t)/dt = s(t) - \sigma R(t)$$

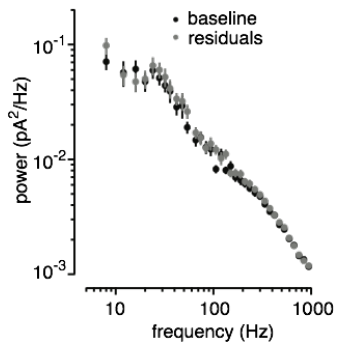
$$dP(t) = \gamma R(t) + \eta - \phi P(t)$$

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

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 ]

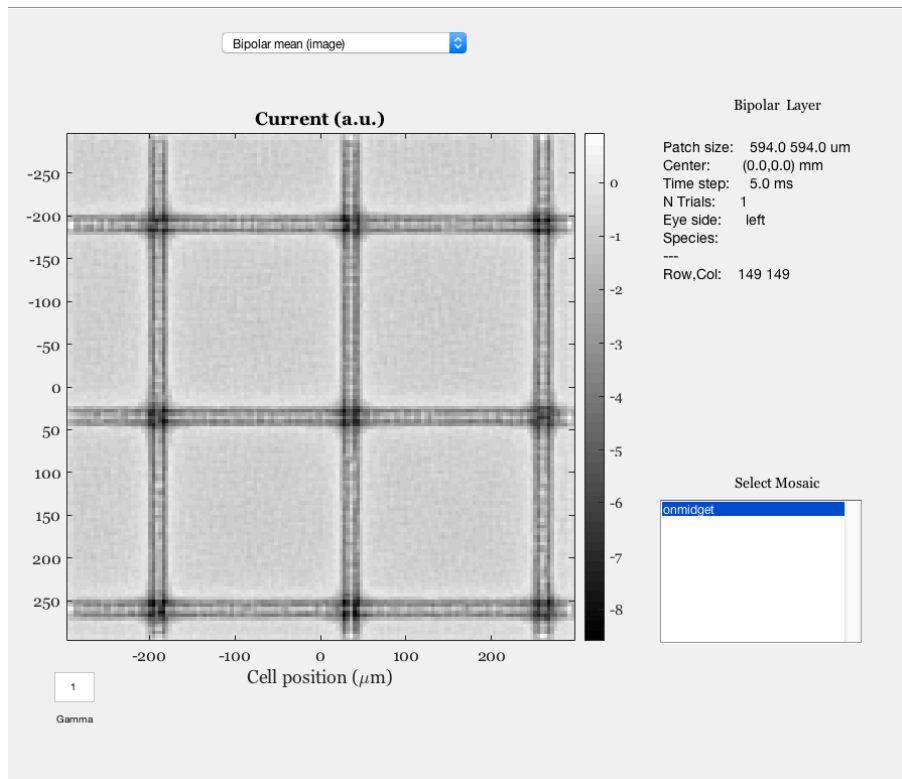
Integration  
[ 5.0 ] (ms)

Eccentricity  
[ 0 ]

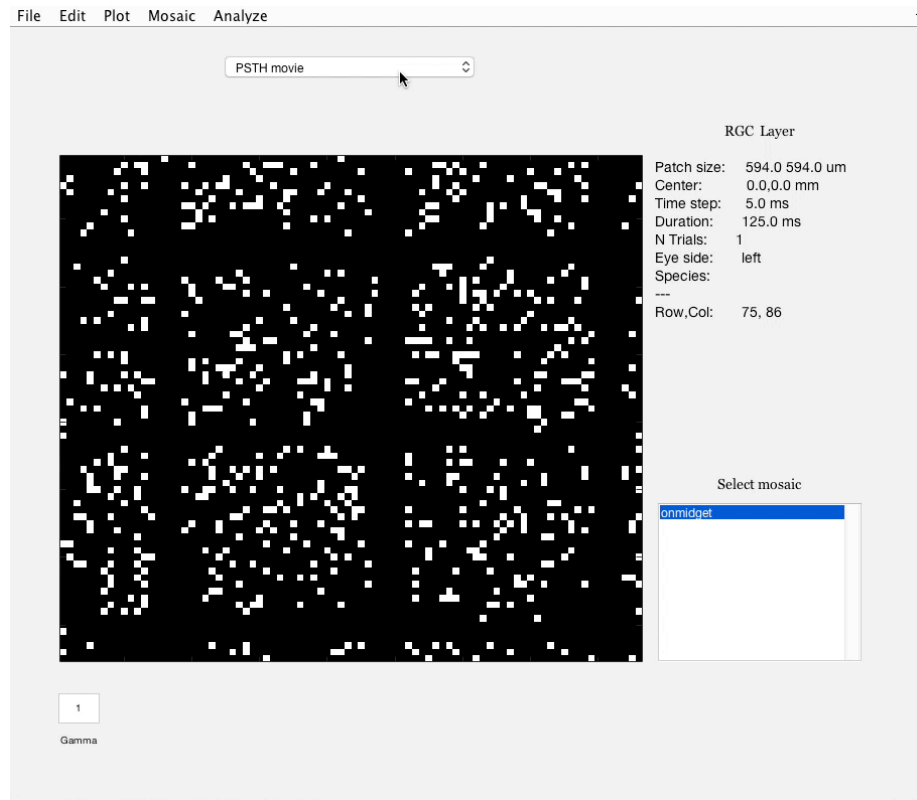
Blank-LMS  
[ 0.0, 0.6, 0. ]

# We are working on bipolar and ganglion cell models

## Bipolar current

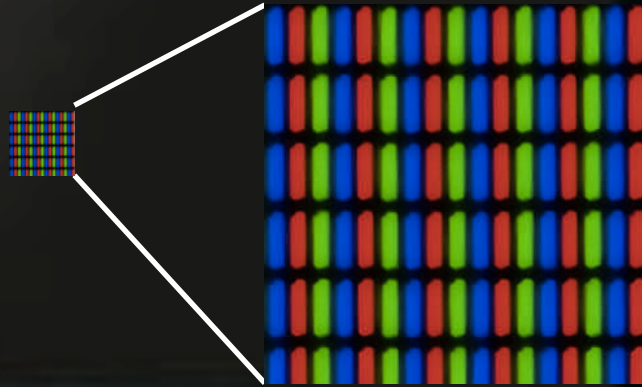


## On midget spikes



# Laboratory experiments display devices

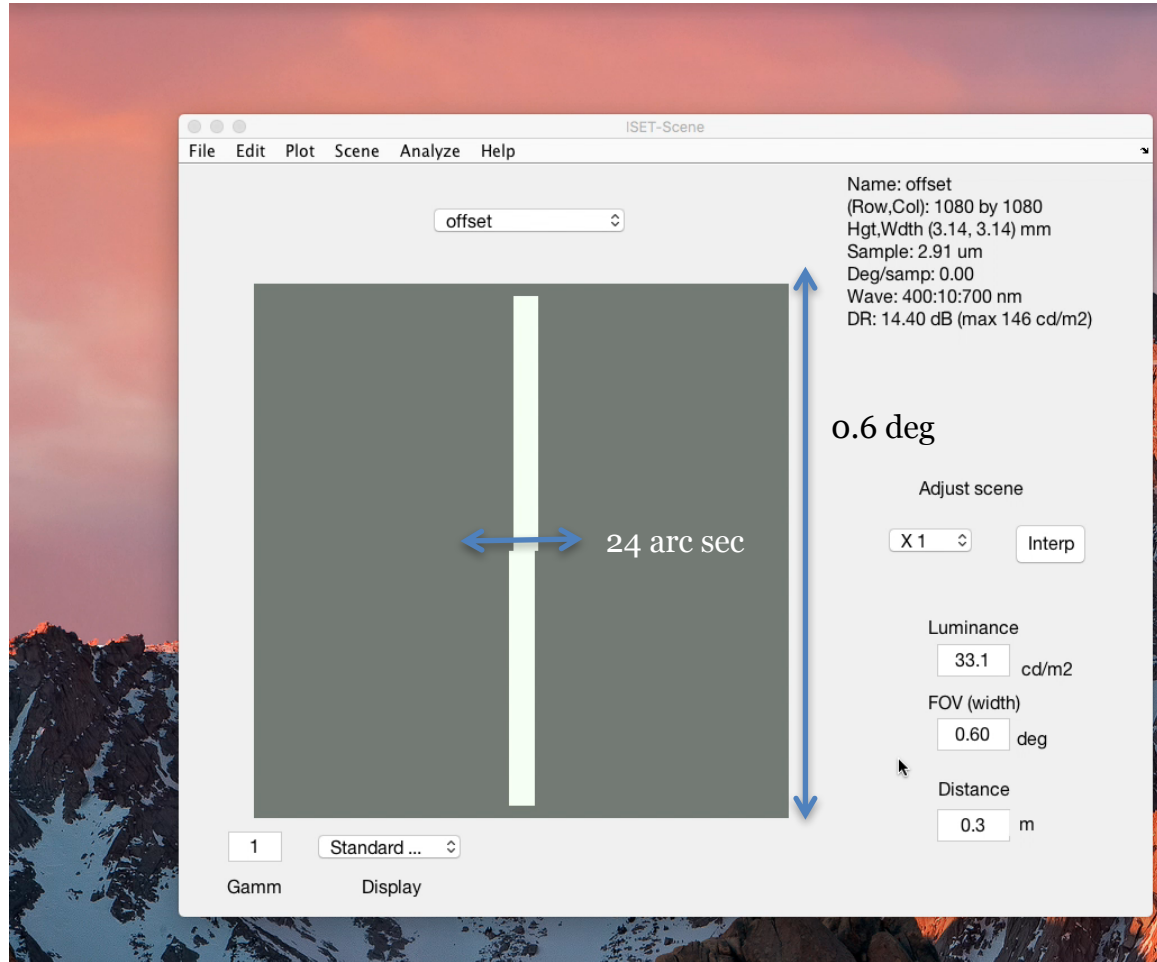
Display models are part of the ISETBIO code –  
this converts images to scene spectral radiance;  
such models are necessary for modeling  
psychophysical experiments and industrial  
applications



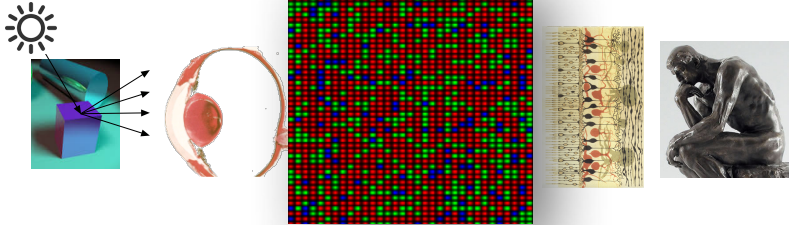
# Analyzing psychophysical tasks

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/mm<sup>2</sup>): 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

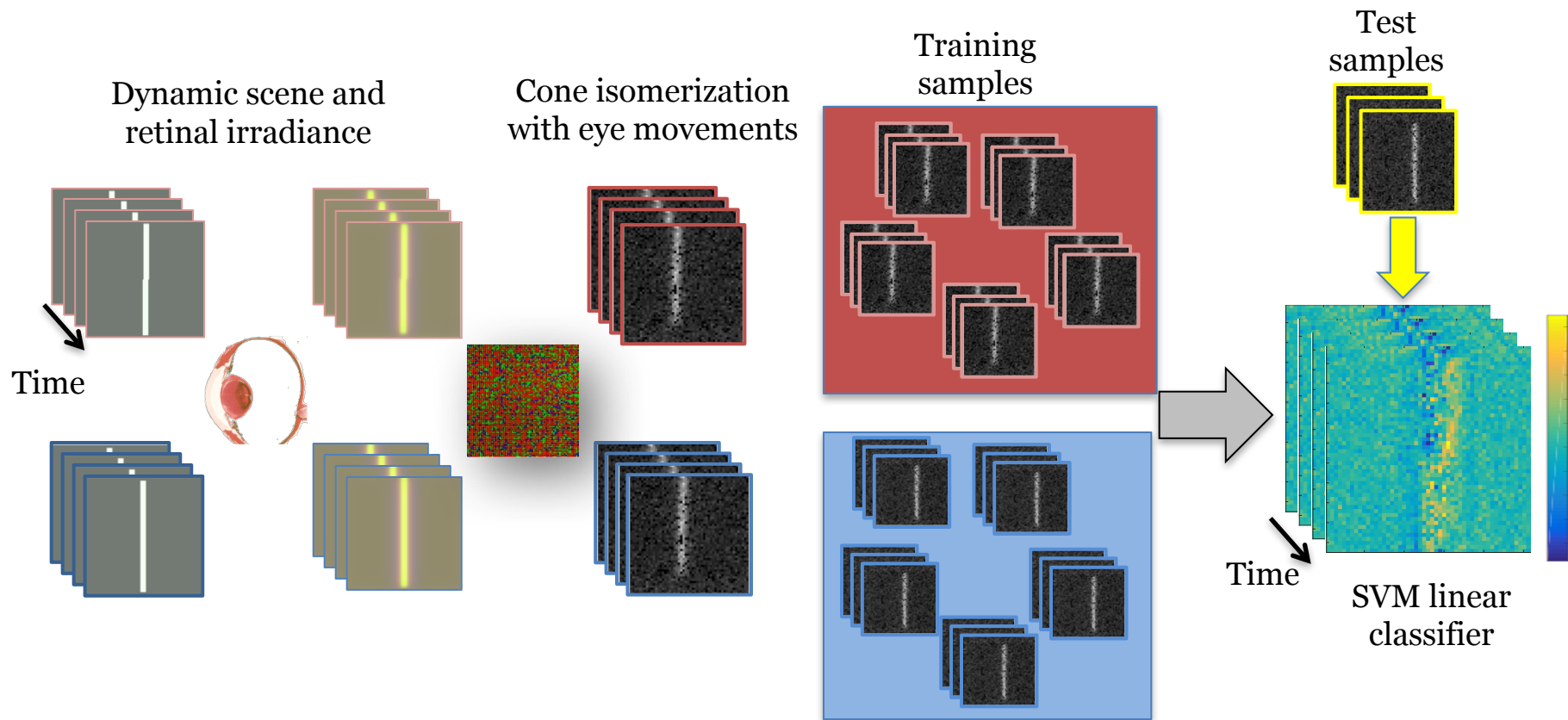
Blank-LMS  
[0.0, 0.6, 0.6]

0

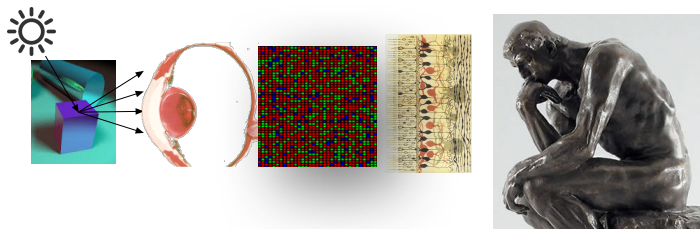
1  
Gam

Compute cone absorptions

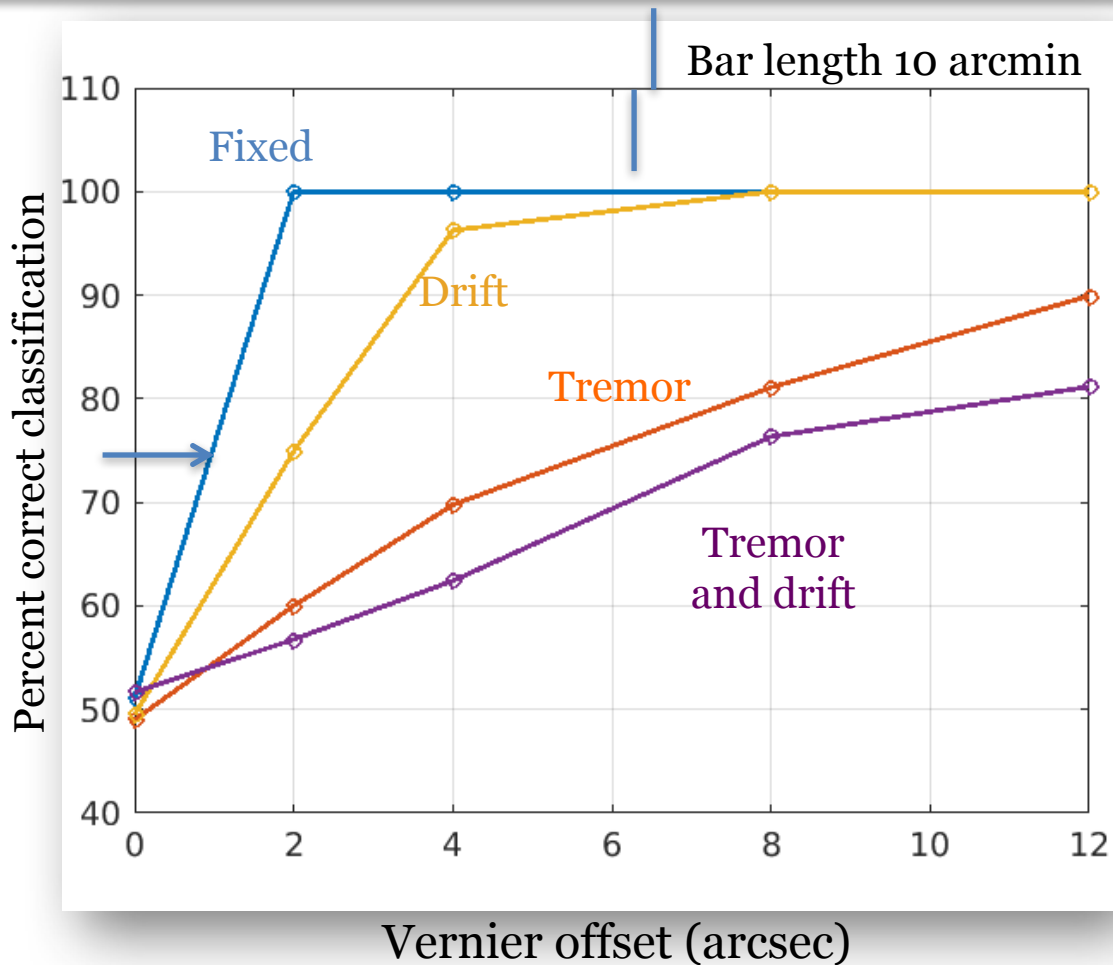
# Computational observer pipeline for the Vernier task



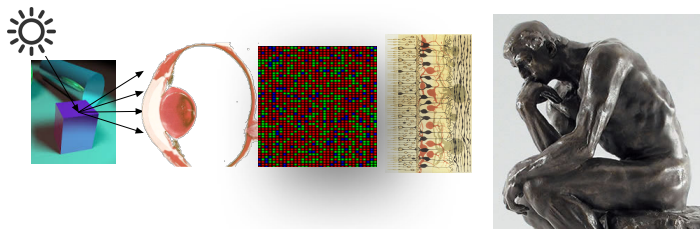
# Tremor and drift limit classification accuracy



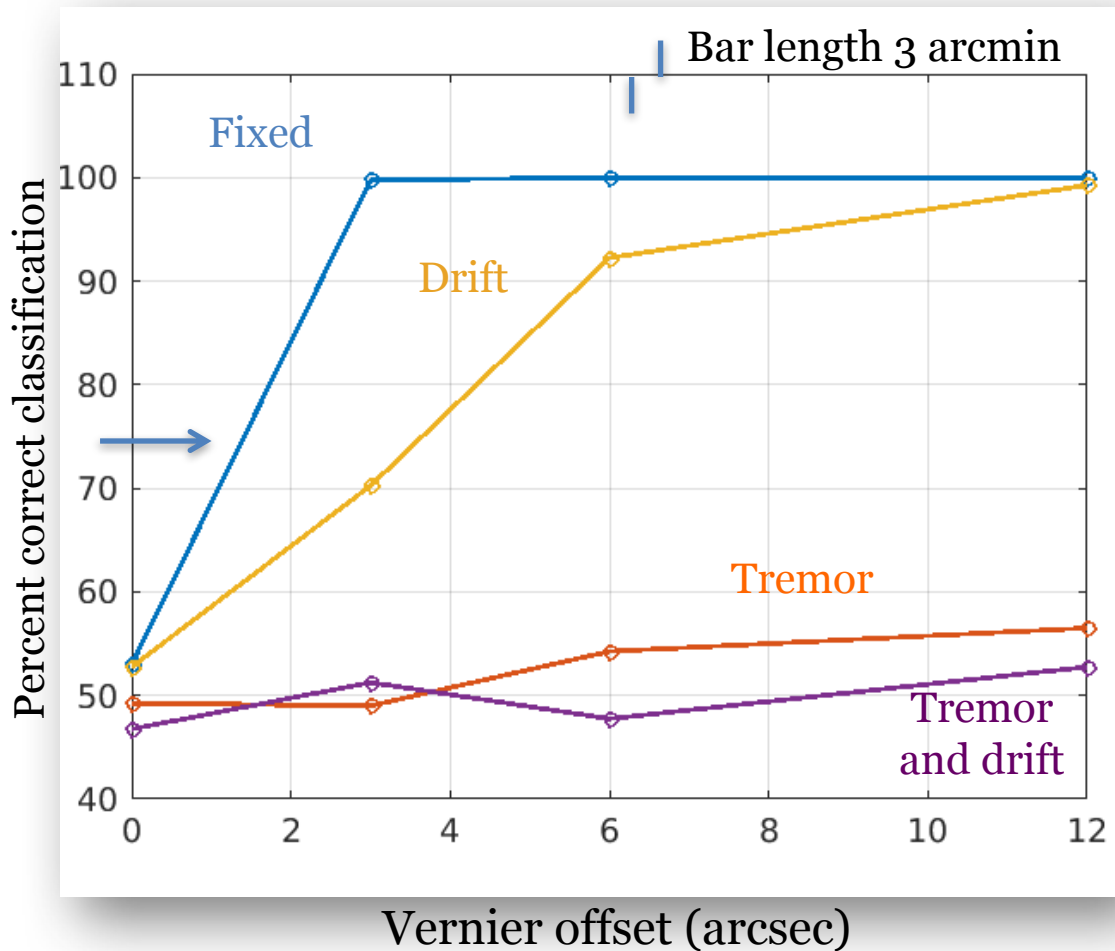
- The SVM linear classifier separates aligned and offset stimuli at very high resolution when we turn off eye movements
- Drift and tremor both degrade performance.



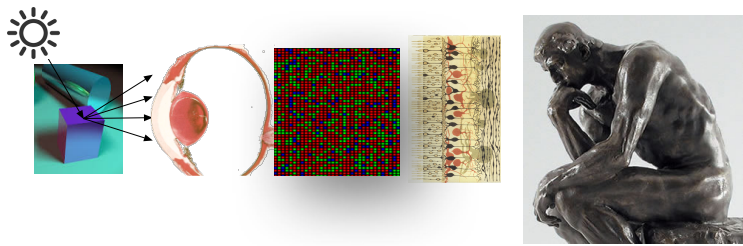
# Tremor and drift limit classification accuracy



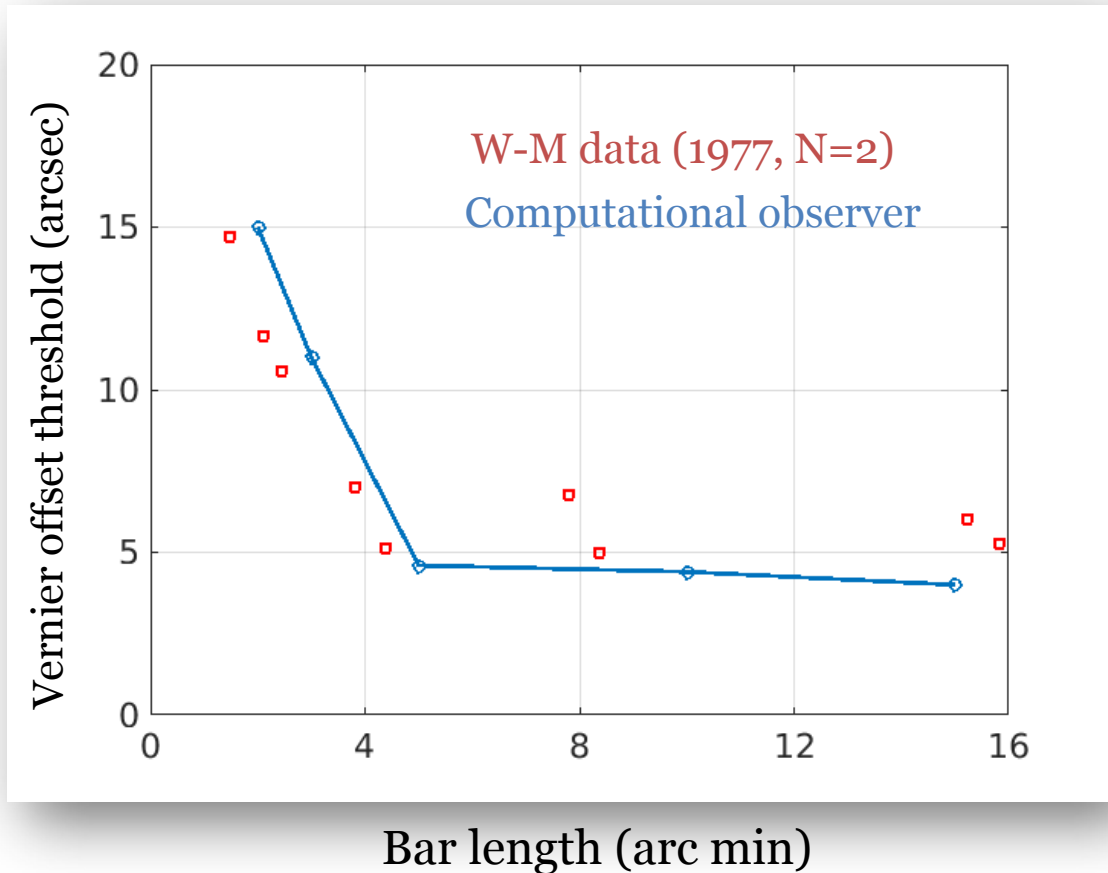
- The SVM linear classifier separates aligned and offset stimuli at very high resolution when we turn off eye movements
- Drift and tremor both degrade performance
- Particularly for small stimuli



# A phenomenological description of Westheimer and McKee



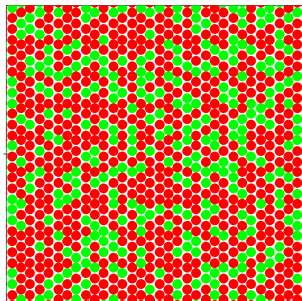
- By choosing to limit the Computational Observer (e.g., size of the cone mosaic), we can make a computational description that matches some properties of the human psychophysics



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

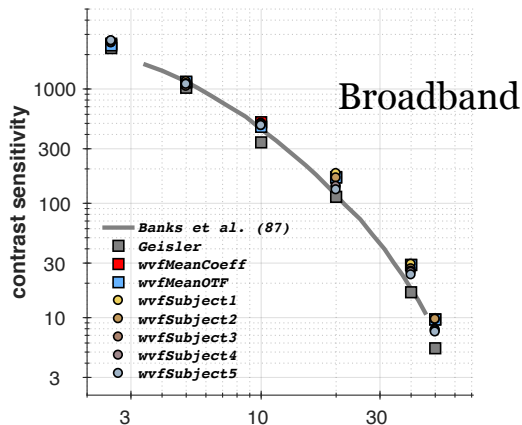
## Comparison with Banks et al. 1987

Cone spacing 3.0  $\mu\text{m}$   
Cone aperture 3.0  $\mu\text{m}$   
Pupil 2 mm  
L,M cones  
Broadband stimulus

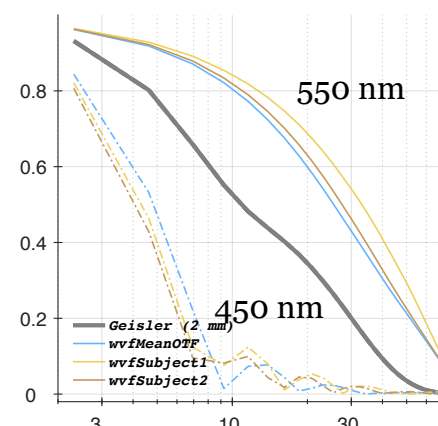
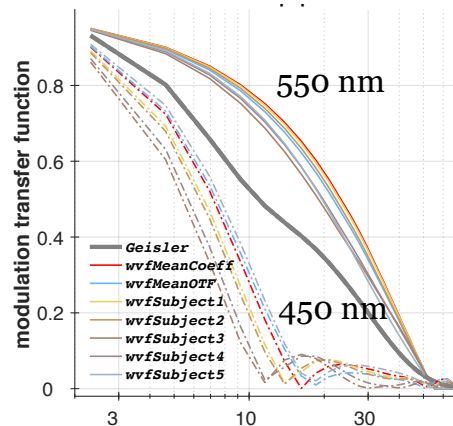
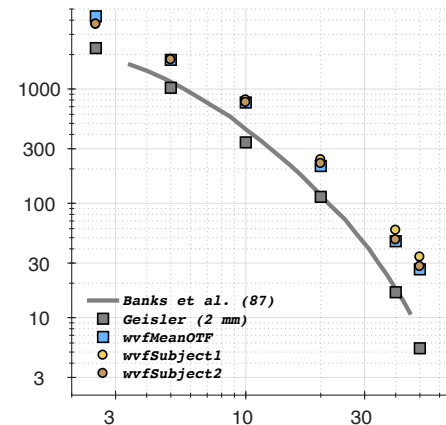


wvfSubjects are samples of wave front measurements

2 mm pupil



3 mm pupil



# 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

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

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

## 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
```

File Edit Plot Cones Help

cone mosaic

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<sup>2</sup>): 250000  
Duration: 0.05 sec (1 sampls)

Cone size (um): 2 2

Pigment density

Flow Coil: 72 88

Integration: 50.0 (mm)

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- Home
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- Numerical utility functions
- ISETBIO Data
- ISETBIO Videos
- Validation
- For Developers

Clone this wiki locally

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

Clone in Desktop

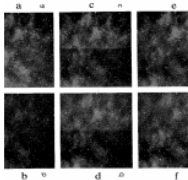
# Video tutorials and data resources

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TALKS **TUTORIALS** SERVICES LOGIN SUPPORT ABOUT

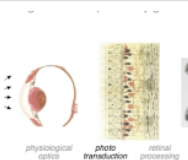
## Tutorials



### Image Systems

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

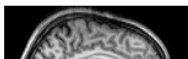
**Start watching now!**



### 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

Stanford | VISTA Data Repository

## 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.



# Image systems engineering tools for biology: ISETBIO

20+5 FVM, Washington D.C.

For more than two centuries scientists have developed theories and made measurements that characterize how the visual system converts light into neural signals. This knowledge is contained in a distributed set of textbooks and research papers. We are developing an open-source Matlab toolbox, ISETBIO, that integrates this knowledge into a set of computations that convert 3D scene spectral radiance into retinal irradiance and neural responses. At this time, ISETBIO models the physiological optics, inert ocular pigments, eye movements, photoreceptor sampling and photopigment absorptions, cone photocurrent, bipolar cell responses, and retinal ganglion cell responses. One benefit of the project is that it clarifies which parts of our understanding are secure and which need further definition; a second benefit is that assembling the diverse sources of information into a single integrated package clarifies the contributions from different visual system components. We hope our colleagues will check and extend our work - we are particularly eager to develop models that characterize responses deeper in the nervous system and models that can be applied to animal visual systems. I will explain how the current computations, which characterize the initial stages of visual encoding, can be helpful to research scientists and engineers who aim to understand how information available in the nervous system limits fundamental perceptual judgments, such as Vernier acuity, contrast sensitivity, and color and motion sensitivity.