

ISETBio: Software for the foundations of vision science

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QUANTITATIVE MEASUREMENTS

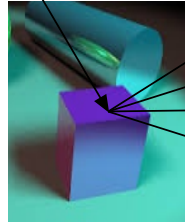
∞

COMPUTATIONAL MODELS

∞

CHECK AND SHARE

Image systems simulation for biology (ISETBio)



Scene spectral radiance



Physiological optics

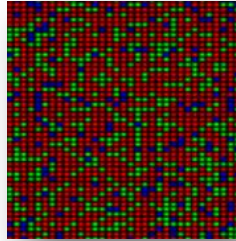
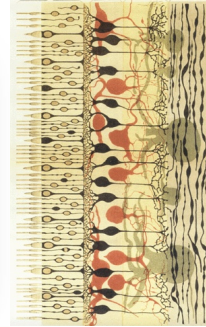
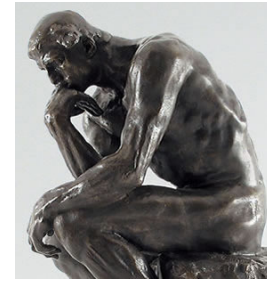


Photo transduction



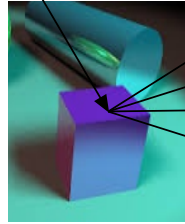
Retinal processing



Inference

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 ...

Image systems simulation for biology (ISETBio)



Scene spectral radiance



Physiological optics

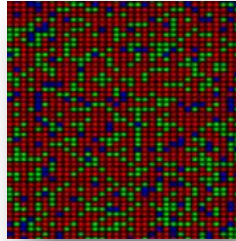
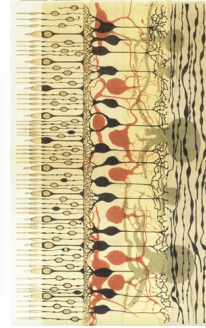
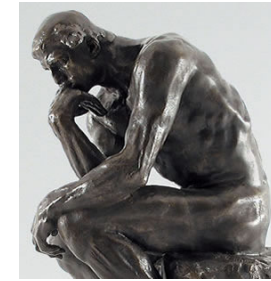


Photo transduction



Retinal processing



Inference

- **What:** Software to calculate how light from a scene is transmitted through the optics and processed by the visual circuitry
- **Goal:** Image-computable models to clarify and quantify the impact of the eye and neural processing on visual perception
- **Who:** Designed to support both basic and applied vision research



Imaging systems simulation for cameras (ISETCam)

The Image Systems Engineering Toolbox for cameras (**ISETCam**) provides an extensive software environment that engineers use to simulate and predict the imaging systems performance.



Optics



Display



Imaging systems simulation for cameras (ISETCam)

More than 500 users in
80 companies,
9 research institutes,
65 universities,
in 24 countries

Open Source

<https://github.com/iset/isetcam>

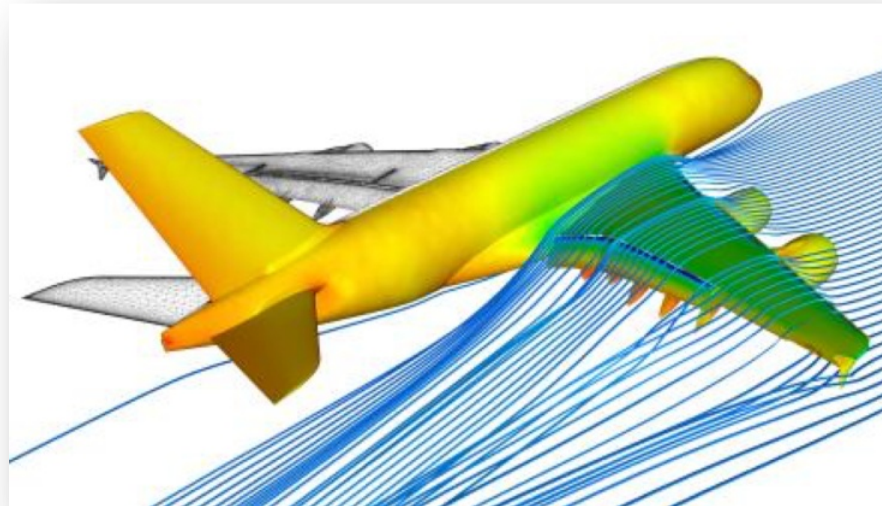


Systems simulation is important

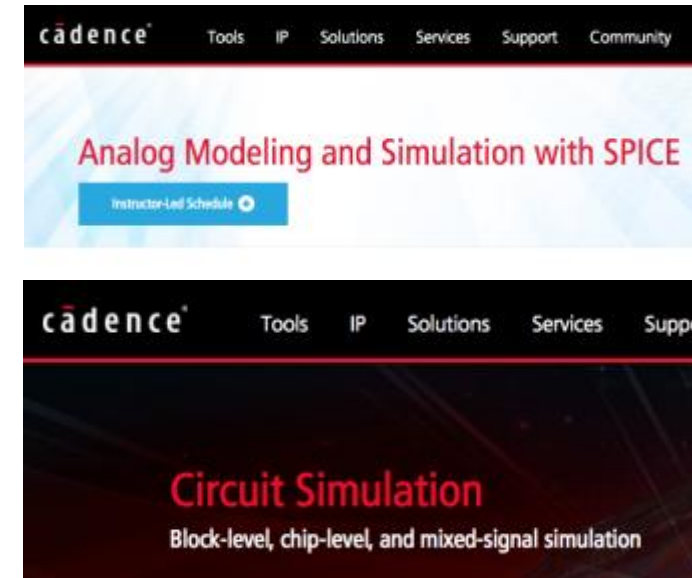
System simulation is important in many mature industries



ECU (Electronic Control Unit) Simulation for Automobiles



Numerical flow simulation on an Airbus A380



Integrated circuitry

First point

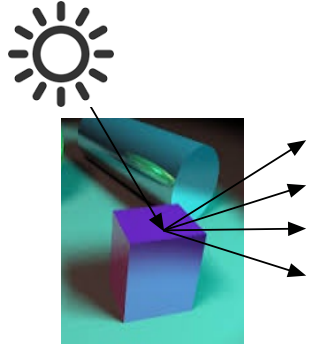
Image systems simulation software that is trusted by key stakeholders in industry and academia can speed the development of next generation image sensors, camera arrays, displays

First point

Image systems simulation software that is trusted by industry and academia can speed the development of next generation image sensors, camera arrays, displays

Simulations trusted by vision scientists can speed the development of reproducible models of visual neurobiology and perception.

The ISETBio project



Scene spectral radiance



Physiological optics

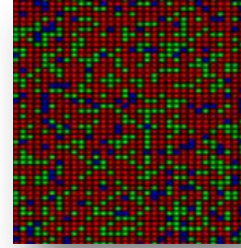
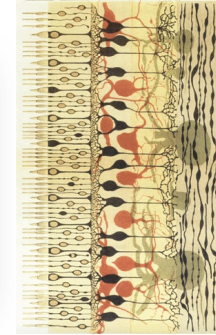
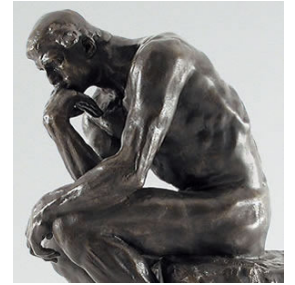


Photo transduction



Retinal processing



Inference

- Stimulus modeling
- Physiological optics
- Encoding and inference



Brian Wandell



David Brainard



Joyce Farrell



Trisha Lian



Nicolas Cottaris



Fred Rieke



E.J. Chichilnisky



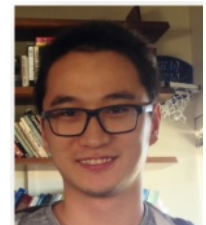
James Golden



Jon Winawer



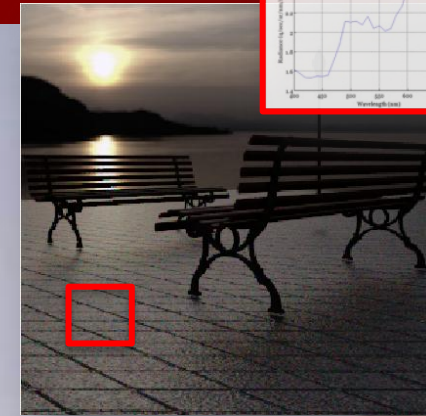
Xiaomao Ding



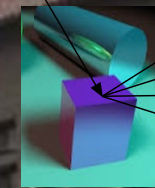
Haomiao Jiang

Today's presentation

- Stimulus modeling
- Physiological optics
- Retinal encoding and inference



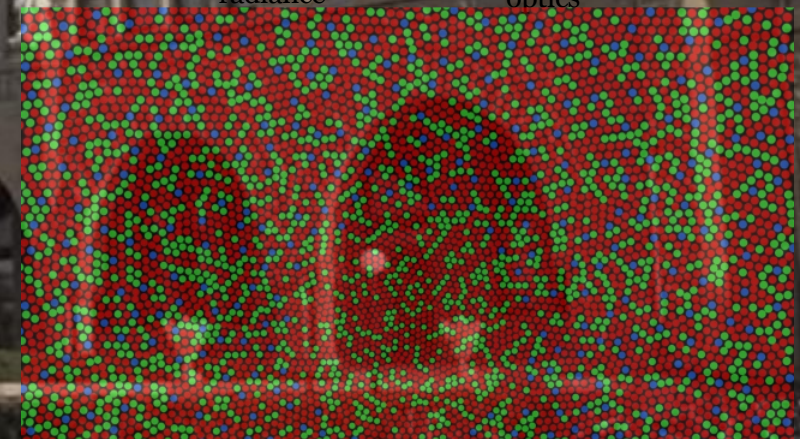
$q/s/sr/nm/m^2$



Scene spectral radiance

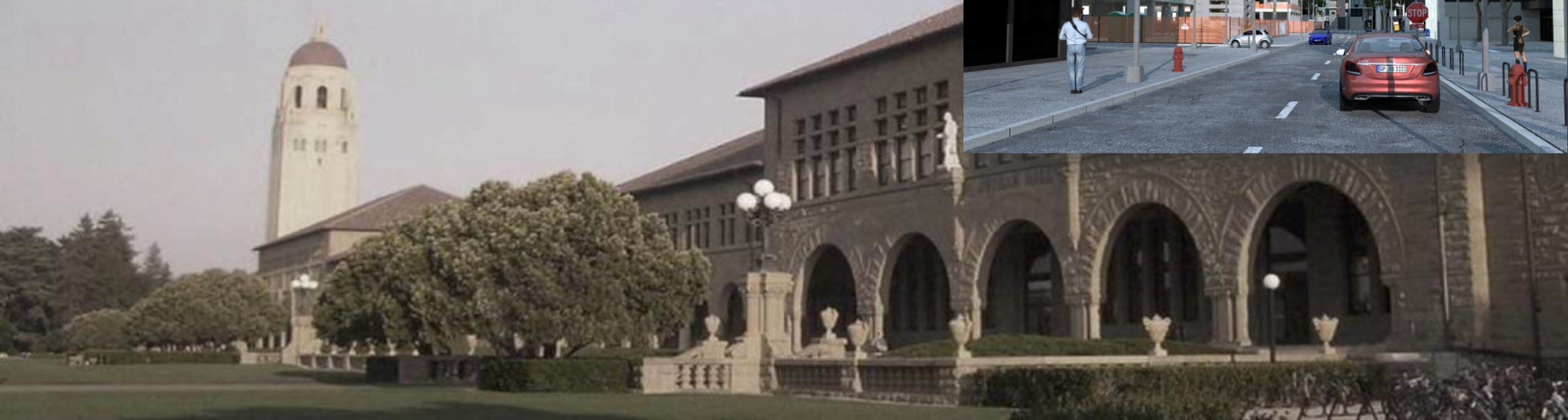


Physiological optics



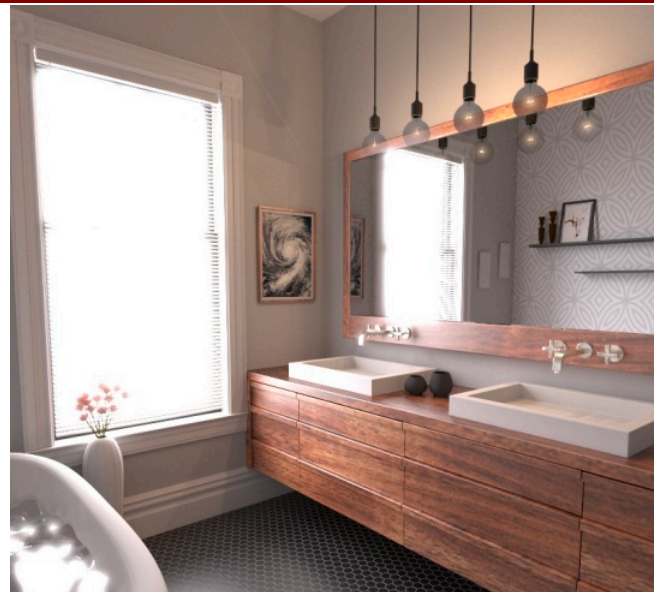
Modeling the stimulus

- Stimulus modeling
- Physiological optics
- Retinal encoding and inference



Computer graphics for vision science

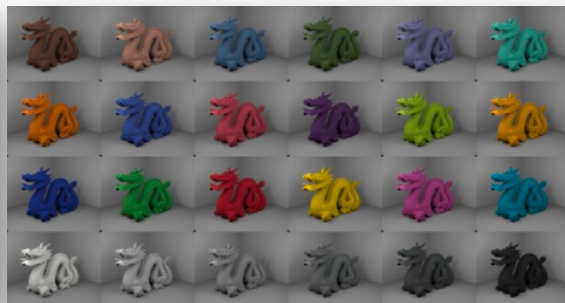
- Progress in computer graphics enables us to create highly realistic synthetic images
- Brainard's lab (RenderToolbox3/4) and others have developed tools that use computer graphics to generate complex but controlled experimental stimuli



Journal of Vision (2014) 14(2)8, 1-22 <http://www.journalofvision.org/content/14/2/8>

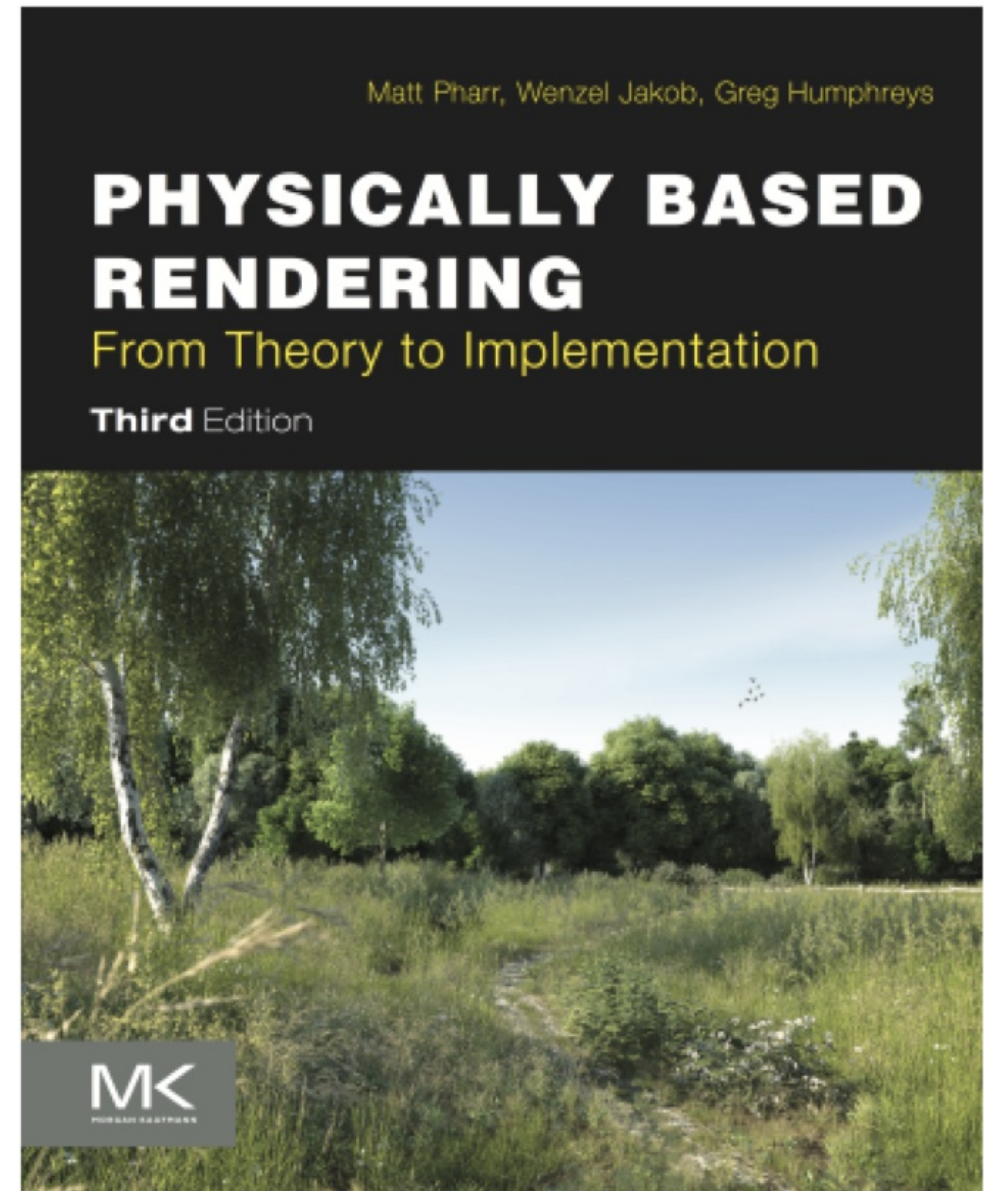
RenderToolbox3: MATLAB tools that facilitate physically based stimulus rendering for vision research

Benjamin S. Heasly Department of Psychology, University of Pennsylvania, Philadelphia, PA, USA ✉
Nicolas P. Cottaris Department of Psychology, University of Pennsylvania, Philadelphia, PA, USA 🏠 ✉
Daniel P. Lichtman Department of Psychology, University of Pennsylvania, Philadelphia, PA, USA ✉
Bei Xiao Department of Computer Science, American University, Washington, DC, USA 🏠 ✉
David H. Brainard Department of Psychology, University of Pennsylvania, Philadelphia, PA, USA 🏠 ✉



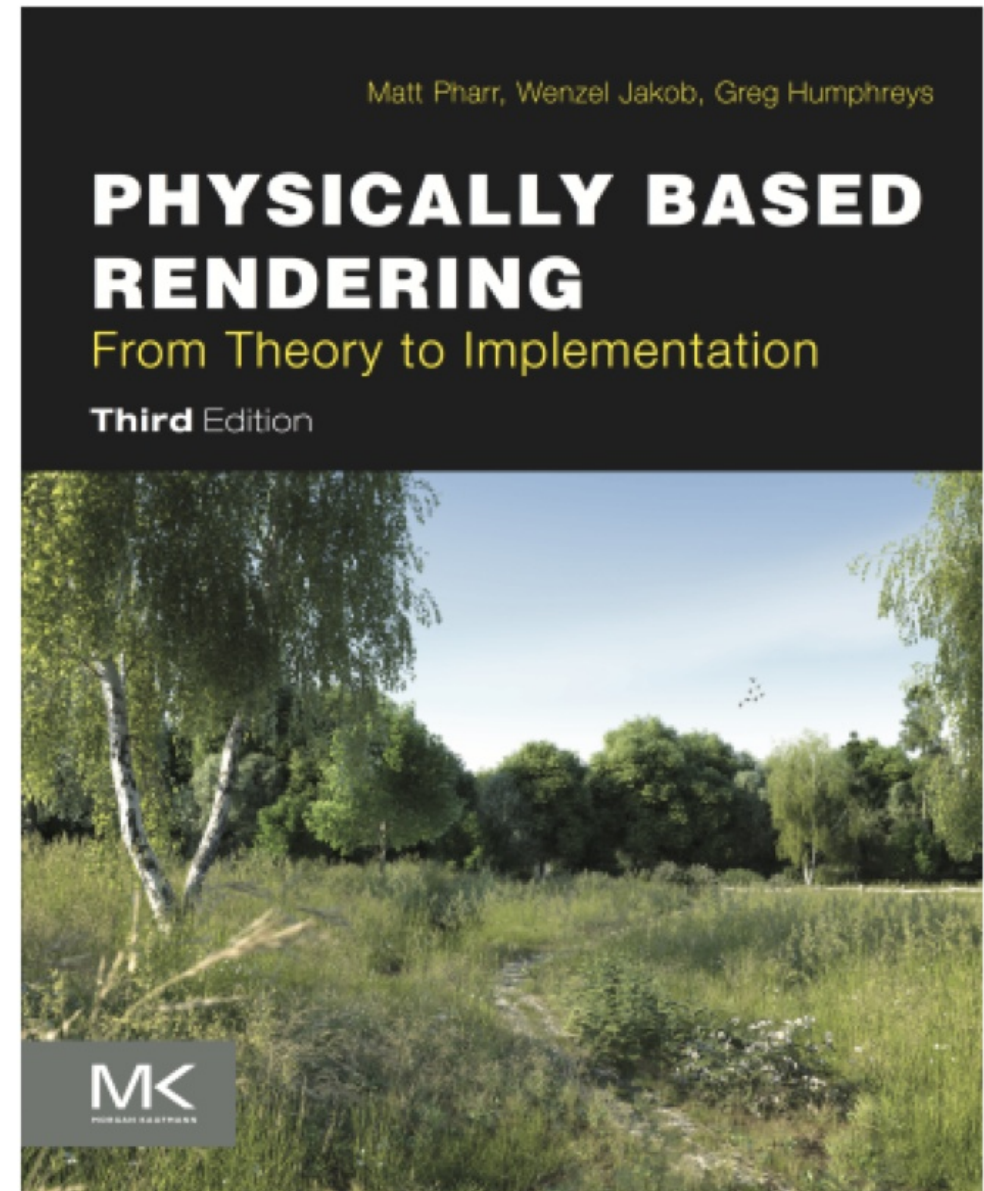
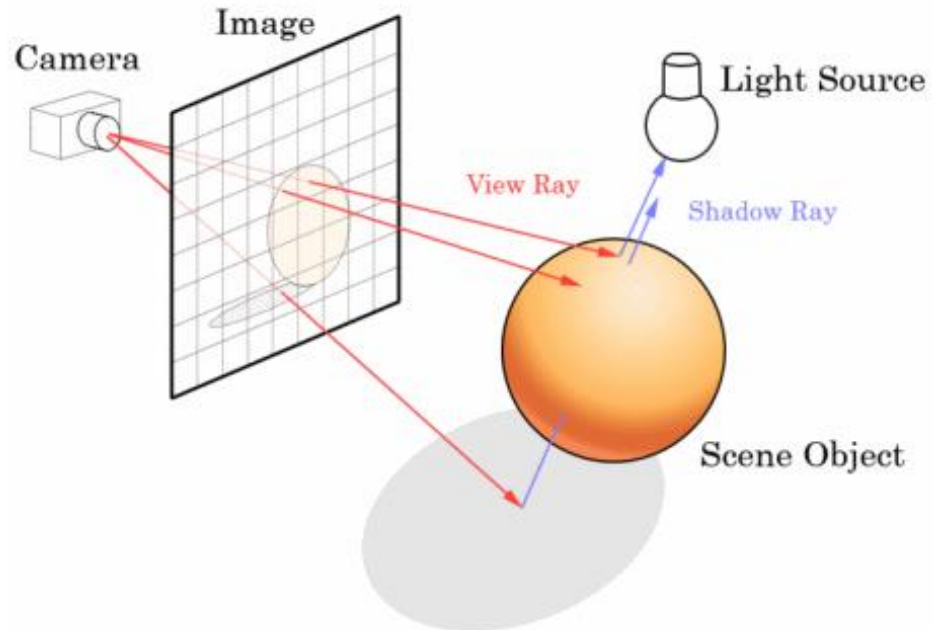
Quantitative computer graphics is necessary for vision modeling

- Scientific and engineering applications need simulations with meaningful units; **quantitative computer graphics**
- Many of the methods you might have seen, using game engines, create images by visual effects that are designed for speed and not for physics



Tools for modeling shapes, lights, materials, geometry

Physically Based Rendering (PBRT) uses physical principles of ray tracing - from the sensor through a camera model into the scene – and is based on physical models of optics, surfaces and lights





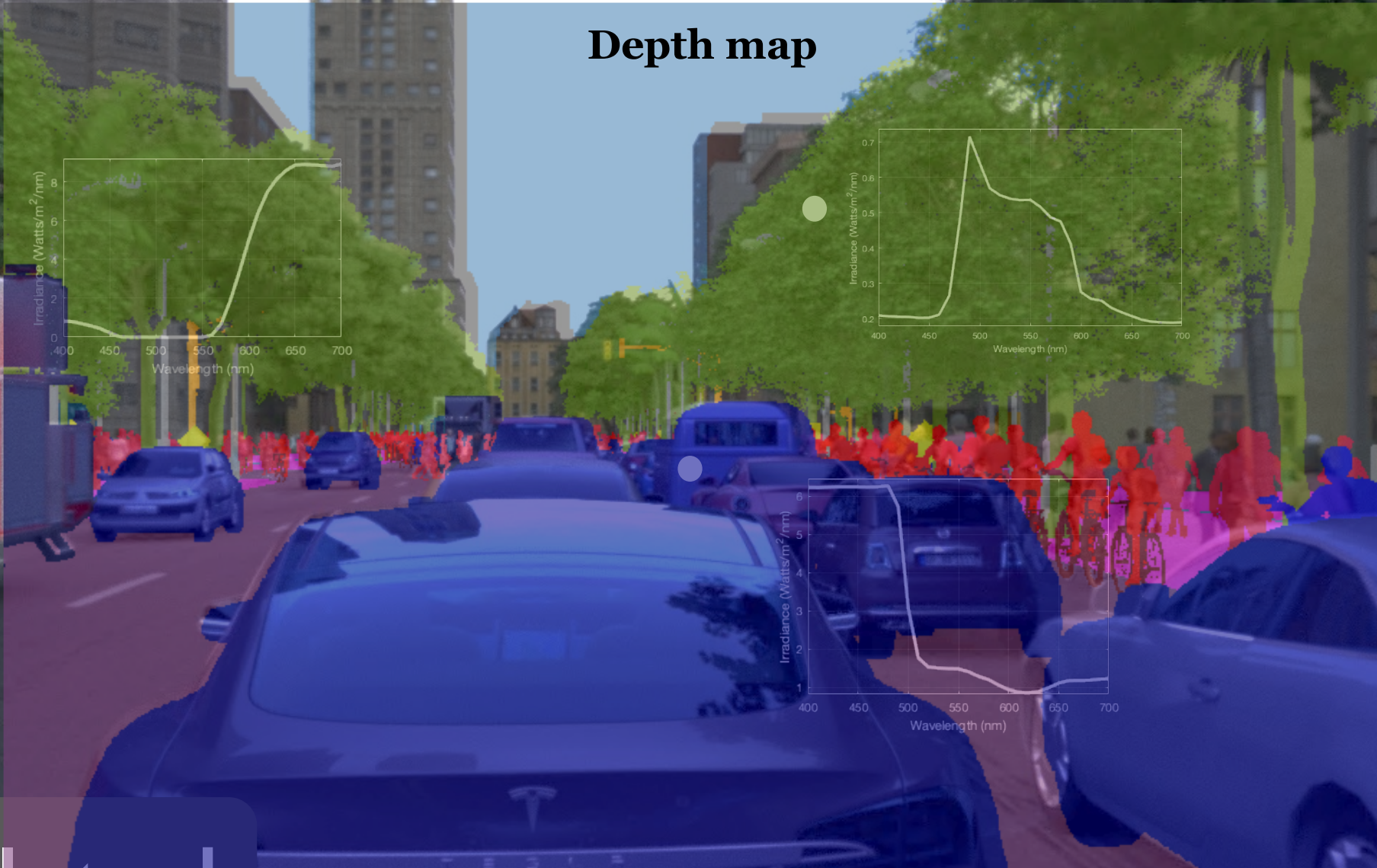
Rendering single assets is straightforward

**Set Pivot Point to
Move object freely**



Scene generation

Depth map



Simulated

VISTALAB2018

Second point

Vision science modeling can benefit from quantitative descriptions of complex visual stimuli. We are building and sharing quantitative computer graphics tools to produce such images (ISET3d).

Modeling the retinal image

- Stimulus modeling
- Physiological optics
- Retinal encoding and inference



Trisha Lian

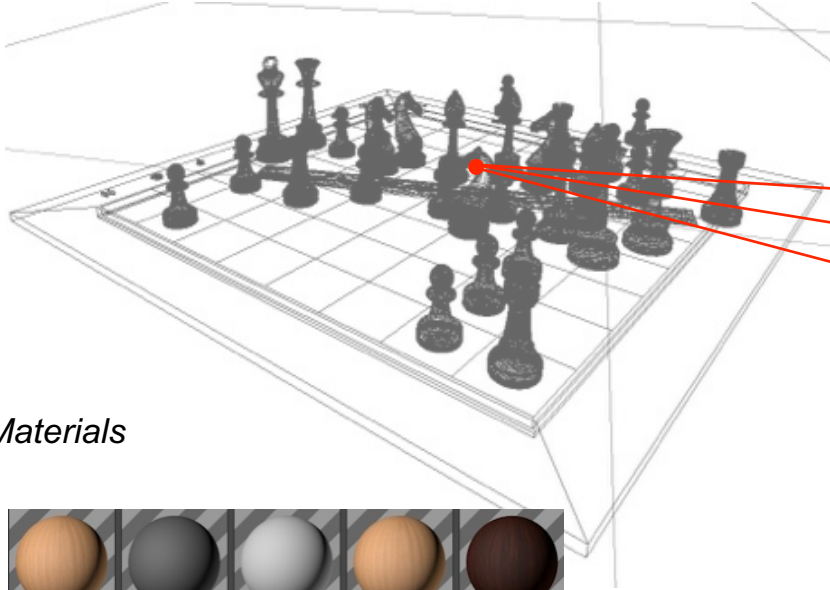


ISETBio and ISET3d – Physiological optics

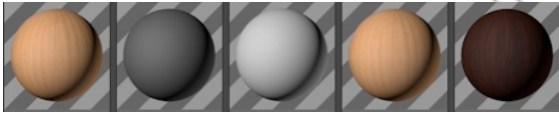
Ray tracing 3D spectral scenes through human optics models
Lian et al., JoV, 2019

Quantitative computer graphics

Geometry



Materials



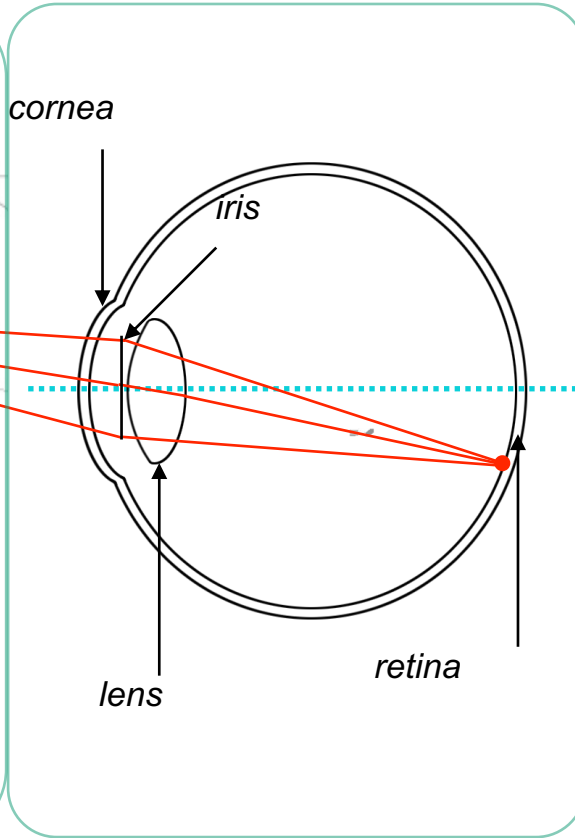
Physiological optics

cornea

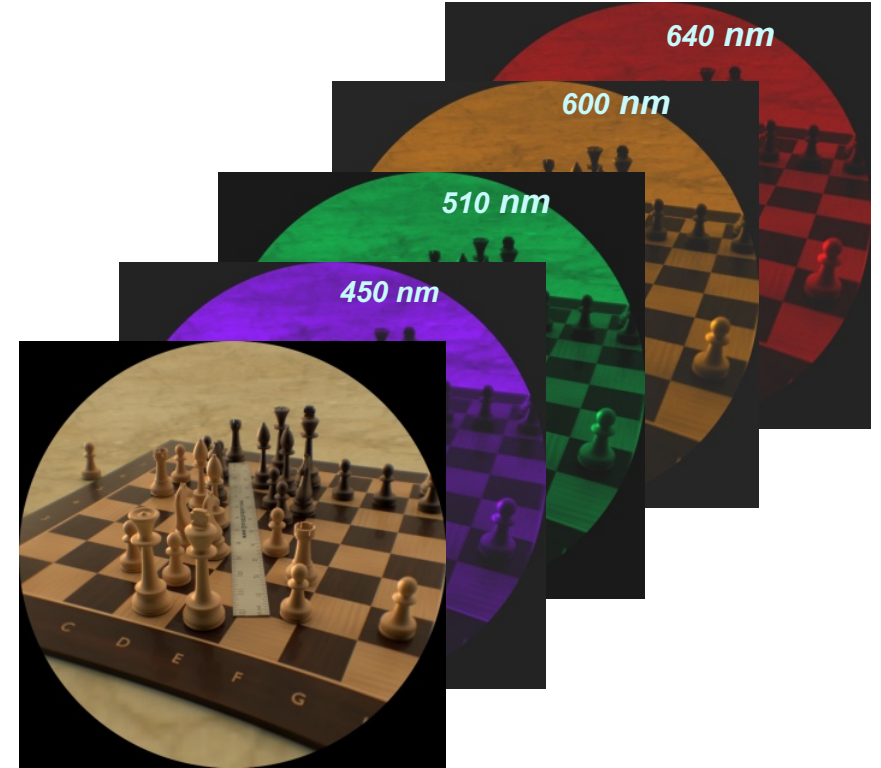
iris

lens

retina



Retinal irradiance



Physiological optics models

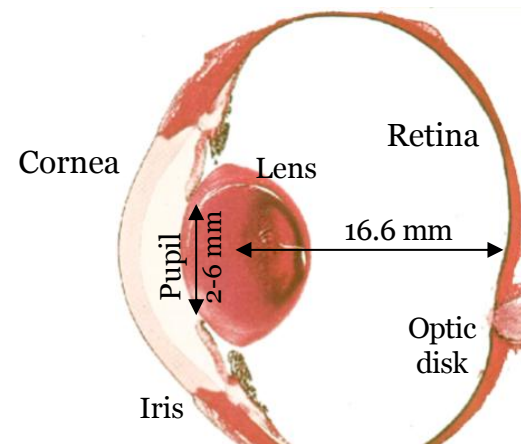
- Physiological optics models are specified by the surface shapes and refractive indices; the typical model description is a table
- The PBRT modifications we implemented converts the spherical and biconic surfaces with wavelength-dependent indices of refraction data into a computable form
- PBRT ray traces the scene rays through the surfaces of the eye model to calculate the retinal image

Ray tracing 3D spectral scenes through human optics models
Lian et al., JoV, 2019

Table 3: Le Grand Full Theoretical Eye (Artal, 2017)

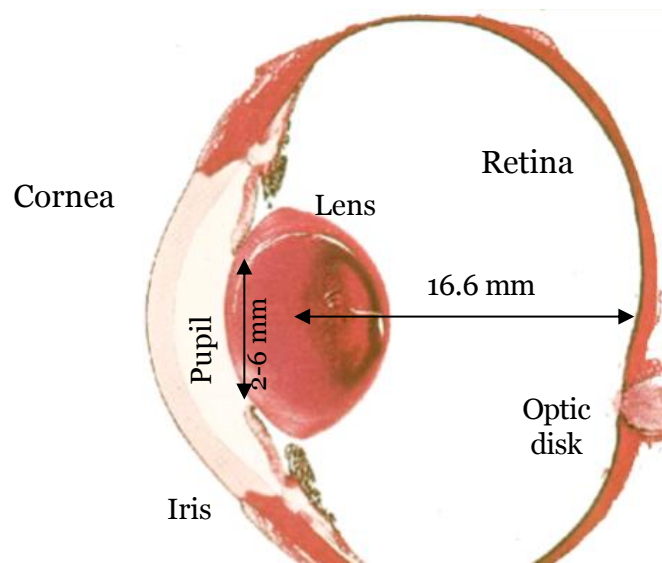
Surface	Radius (mm)	Ocular Media (to next surface)	Conic Constant	Thickness (mm) (to next surface)
Cornea Anterior	7.8	Cornea	0	0.55
Cornea Posterior	6.50	Aqueous	0	3.05
Lens Anterior	10.20	Lens	0	4.00
Lens Posterior	-6.00	Vitreous	0	16.5966
Retina	-13.4			

Refractive Indices (Atchison & Smith, 2005)



Physiological optics models

- This framework, in ISETBio, is adequate to calculate the most widely used physiological optics models
- We visualize the effects on complex scenes and calculate fundamental metrics including the MTF, LCA, TCA and point spread functions



Navarro Eye Model

Surface	Radius (mm)	Ocular Media (to next surface)	Conic Constant	Thickness (mm) (to next surface)
Cornea Anterior	7.72	Cornea	-0.26	0.55
Cornea Posterior	6.50	Aqueous	0	3.05
Lens Anterior	10.20	Lens	-3.1316	4.00
Lens Posterior	-6.00	Vitreous	-1.0	16.3203
Retina	-12			
Refractive Indices		(Escudero-Sanz & Navarro, 1999)		

Arizona Eye Model

Surface	Radius (mm)	Ocular Media (to next surface)	Conic Constant	Thickness (mm) (to next surface)
Cornea Anterior	7.8	Cornea	-0.25	0.55
Cornea Posterior	6.50	Aqueous	-0.25	2.97
Lens Anterior	12.0	Lens	-7.518749	3.767
Lens Posterior	-5.224557	Vitreous	-1.353971	16.713
Retina	-13.4			
Refractive Indices		(Schwiegerling, 2004)		

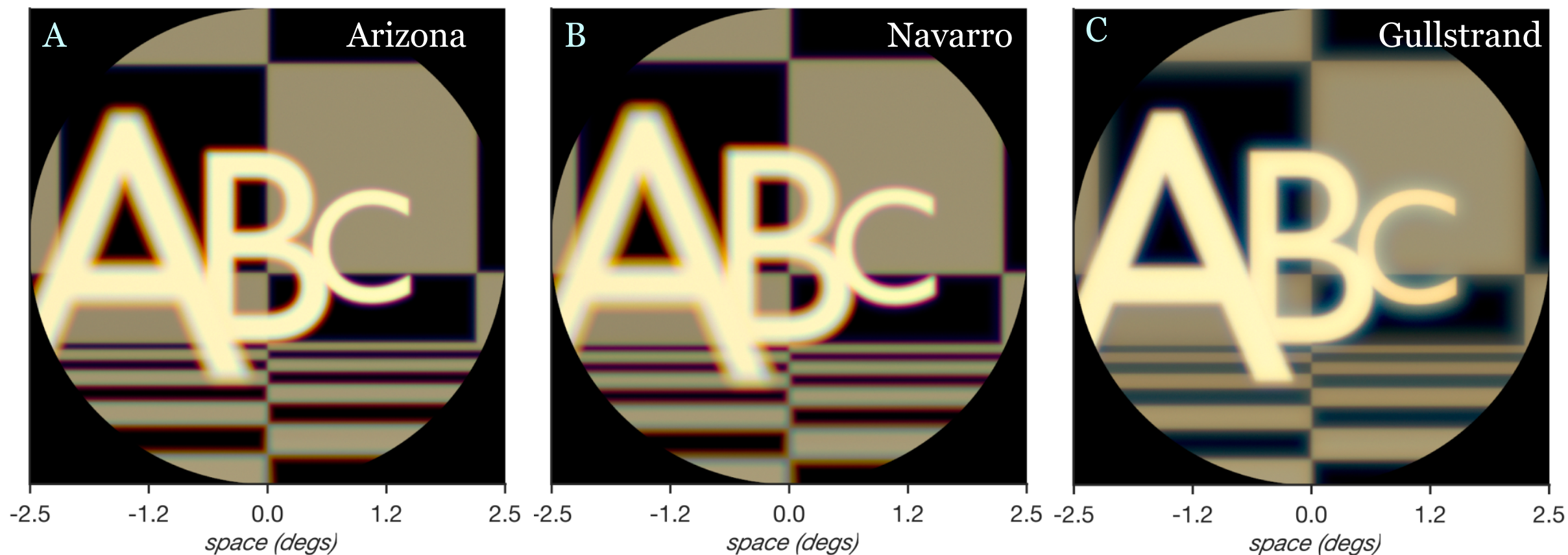
Gullstrand, Le Grand, Artal

Surface	Radius (mm)	Ocular Media (to next surface)	Conic Constant	Thickness (mm) (to next surface)
Cornea Anterior	7.8	Cornea	0	0.55
Cornea Posterior	6.50	Aqueous	0	3.05
Lens Anterior	10.20	Lens	0	4.00
Lens Posterior	-6.00	Vitreous	0	16.5966
Retina	-13.4			
Refractive Indices		(Atchison & Smith, 2005)		

Eye models differ – and sometimes significantly

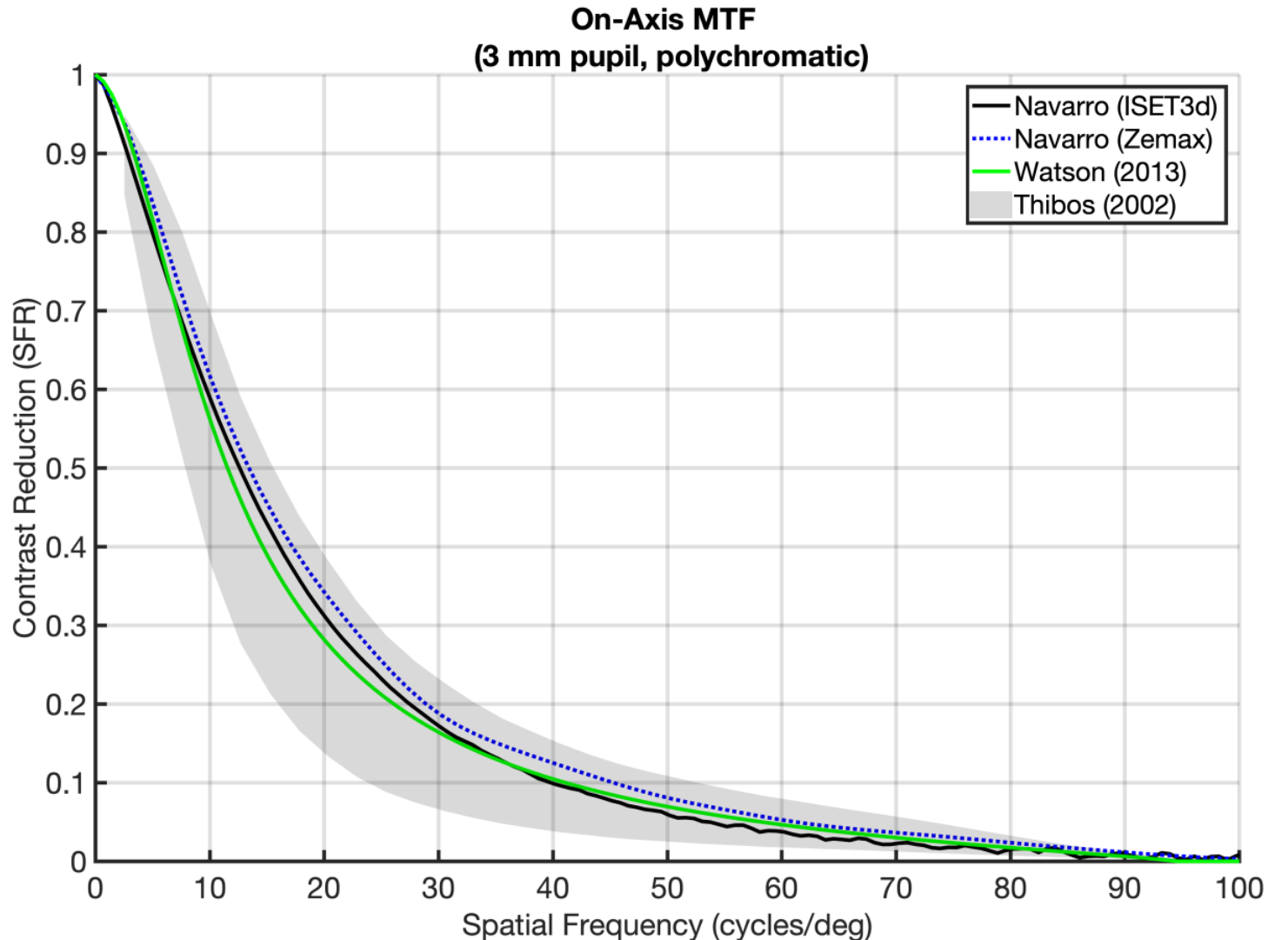
Three major human eye models

Ray tracing 3D spectral scenes through
human optics models
Lian et al., JoV, 2019



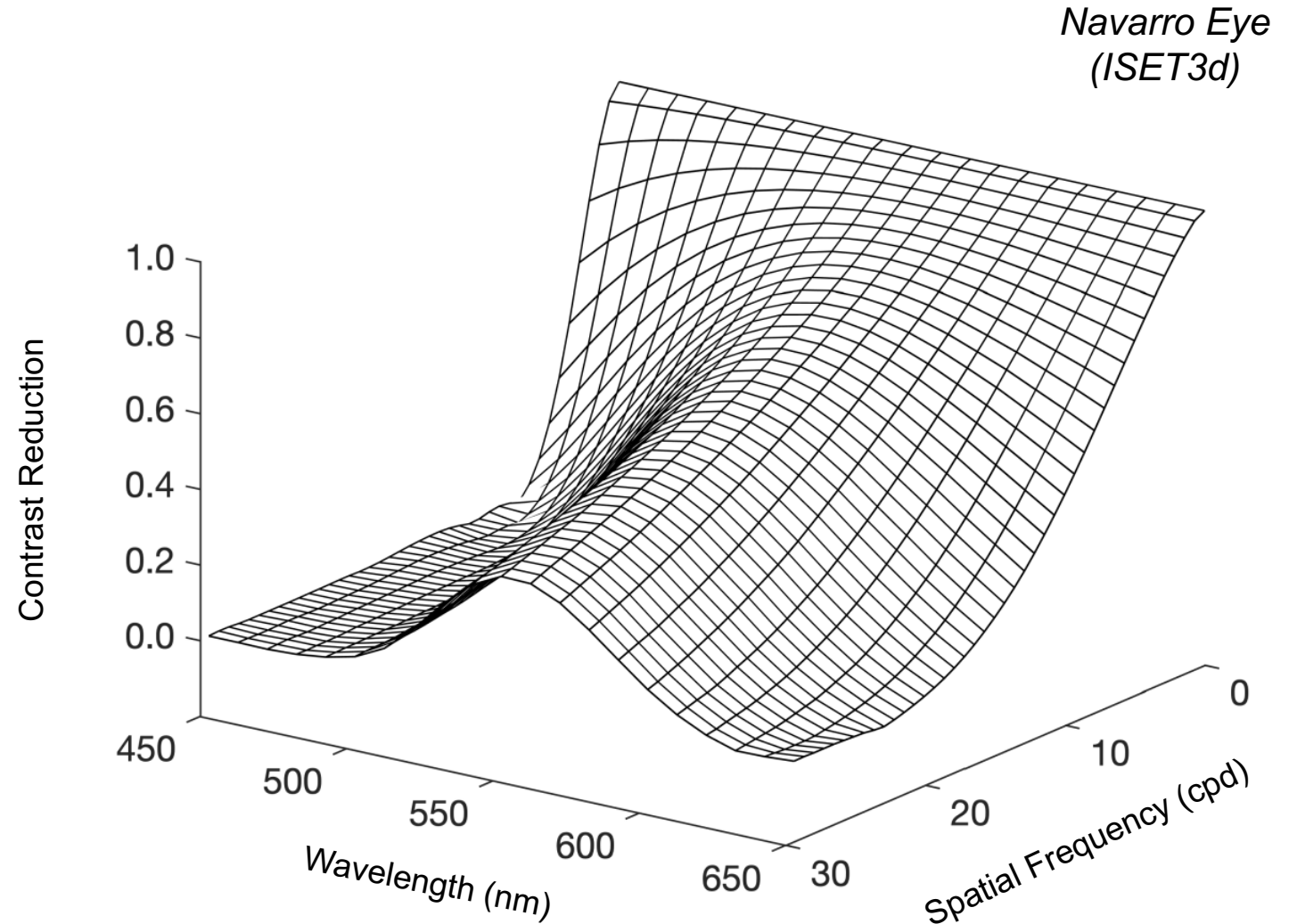
Validation of the ISETBio implementation

- **System validation:** Make sure that the code accurately reflects the intentions of the original authors. This validation is an important part of the development process in ISET related tools
- These curves show that ISETBio matches the MTF computed using Zemax for the Navarro eye and estimated by Watson (2013).
- The MTF differences are much smaller than the variation in measured eyes (shaded gray).



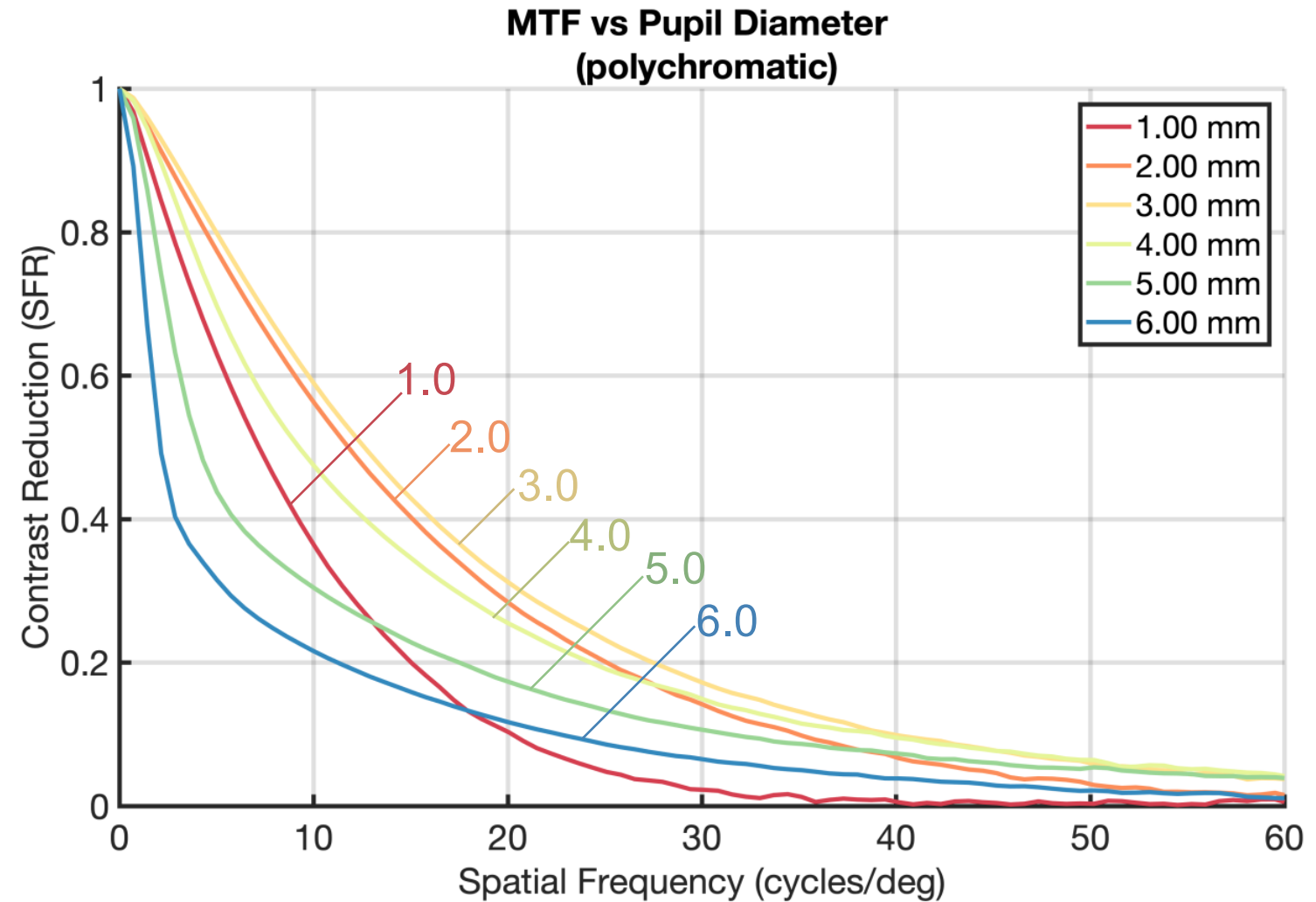
Validation of the ISETBio implementation

- Having these eye models implemented and image-computable enables us to to compute other metrics
- **This examples shows the MTF as a function of wavelength**



Pupil diameter and the modulation transfer function (MTF)

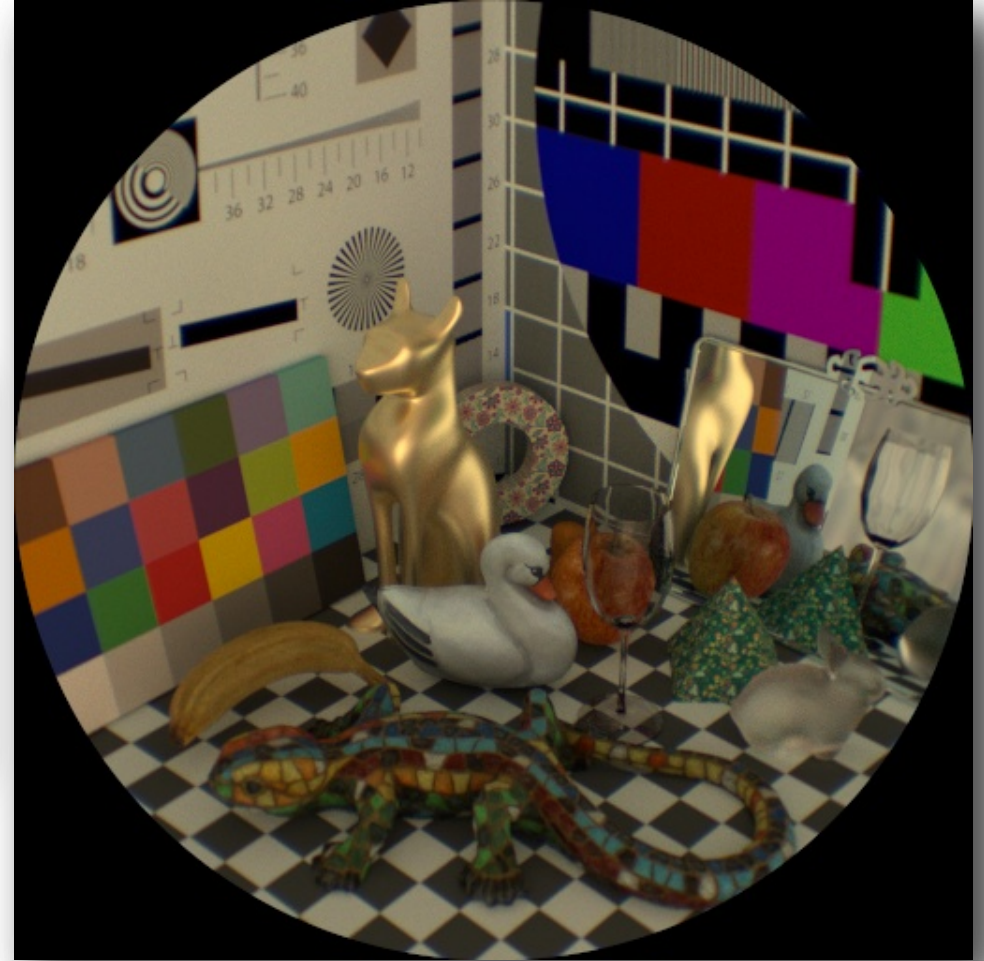
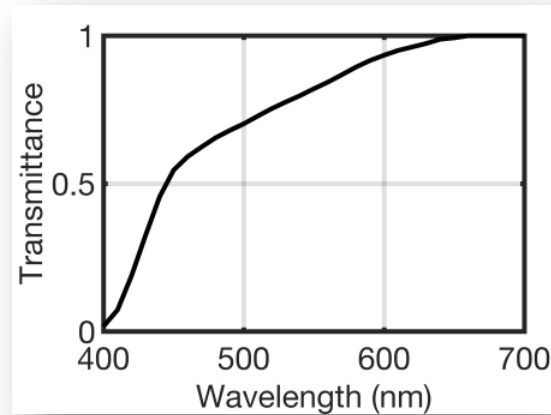
- Having these eye models implemented and image-computable enables us to compute other metrics
- **This example shows the MTF as a function of pupil diameter**



Lens transmittance

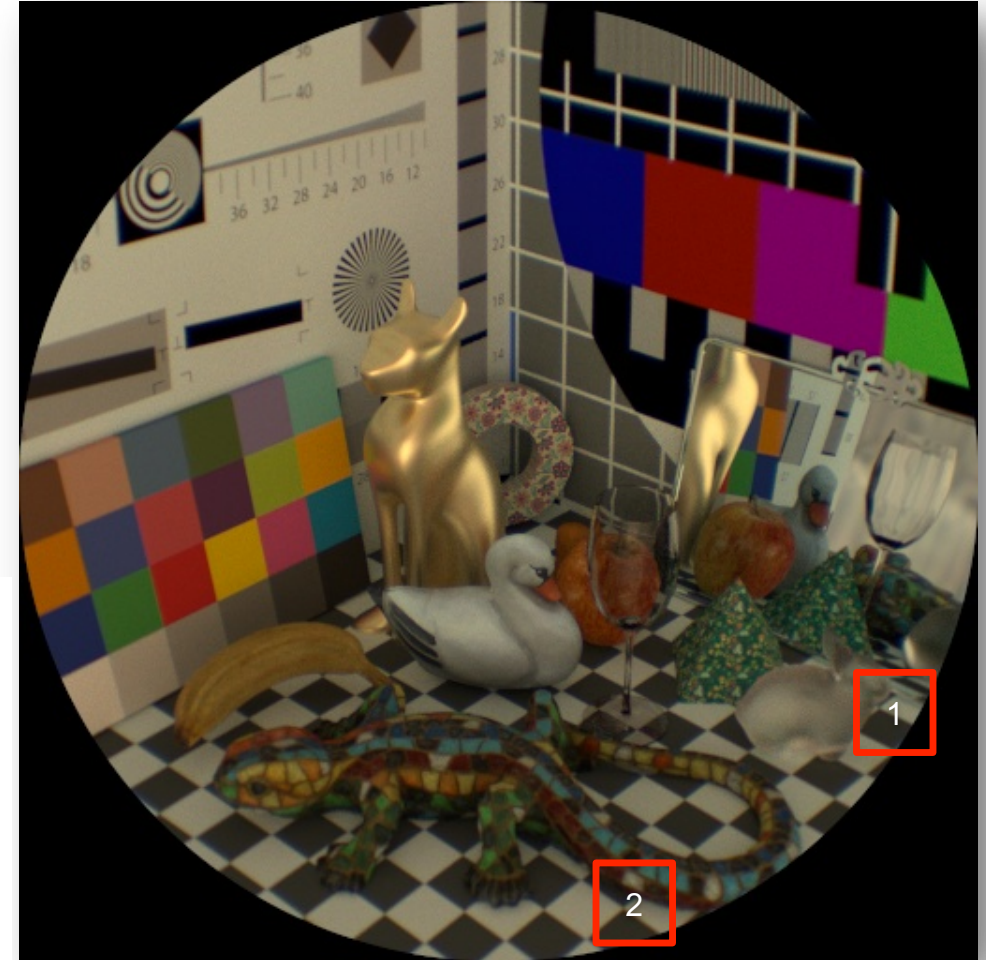
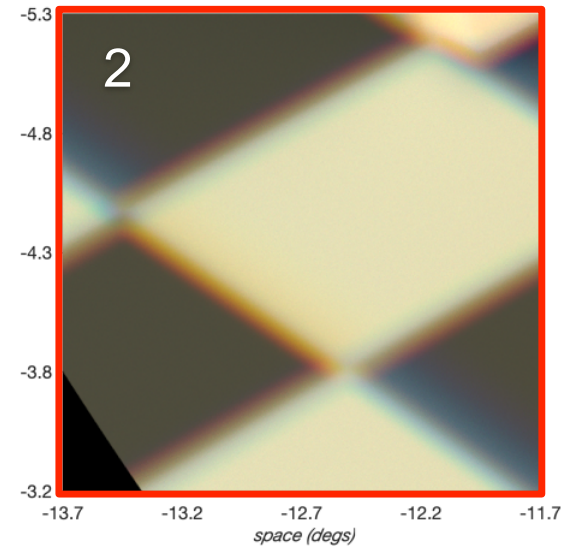
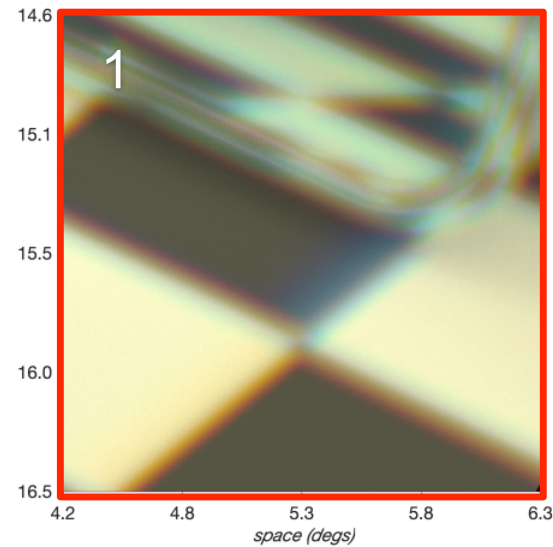
- Having these eye models implemented and image-computable enables us to compute full scenes
- **This example includes lens transmission, longitudinal and transverse chromatic aberration**

Lens transmittance

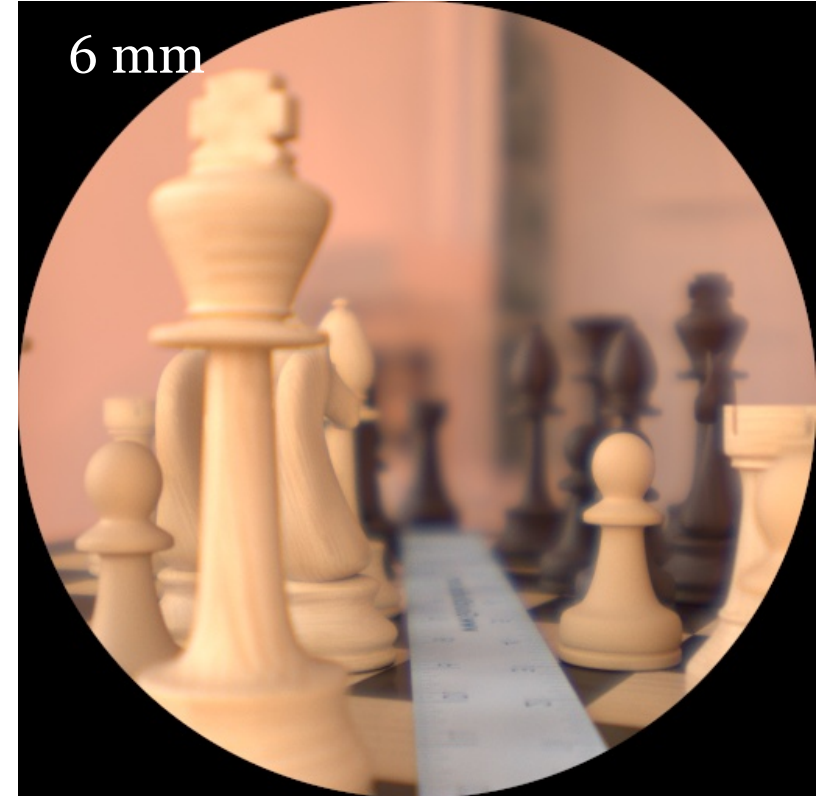
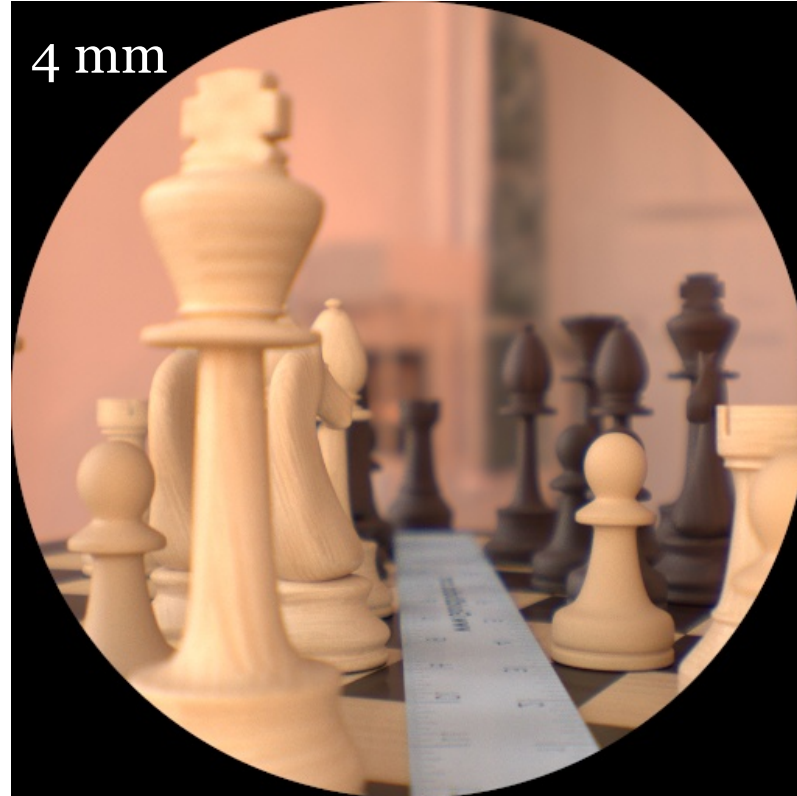
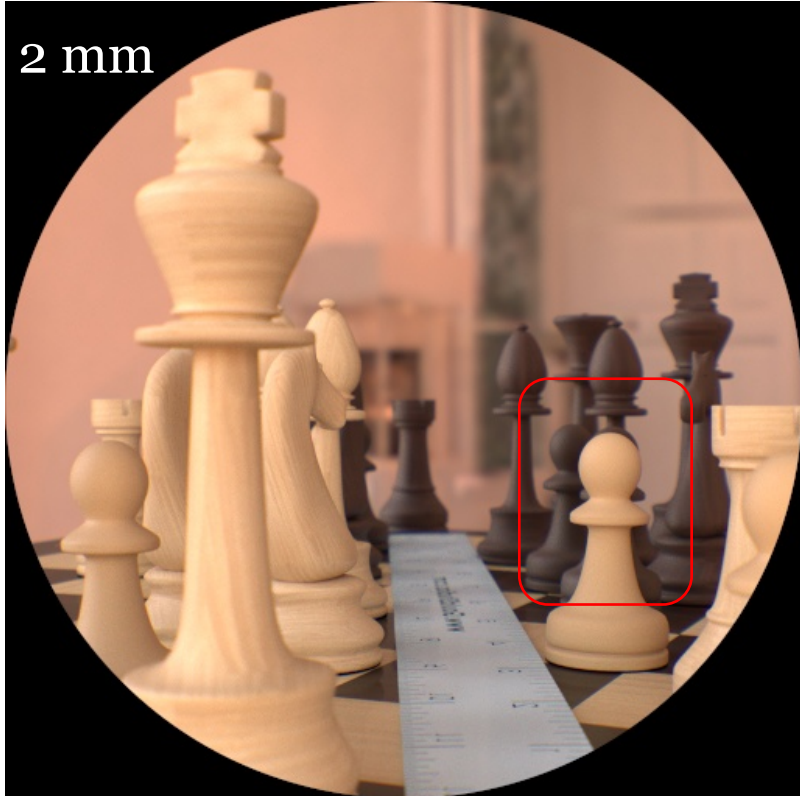


Depth dependent chromatic aberration

- Because the methods are image-computable we can expand from engineering and optics metrics to full image rendering
- **This example includes lens transmission, longitudinal and transverse chromatic aberration**



Pupil diameter and depth of field

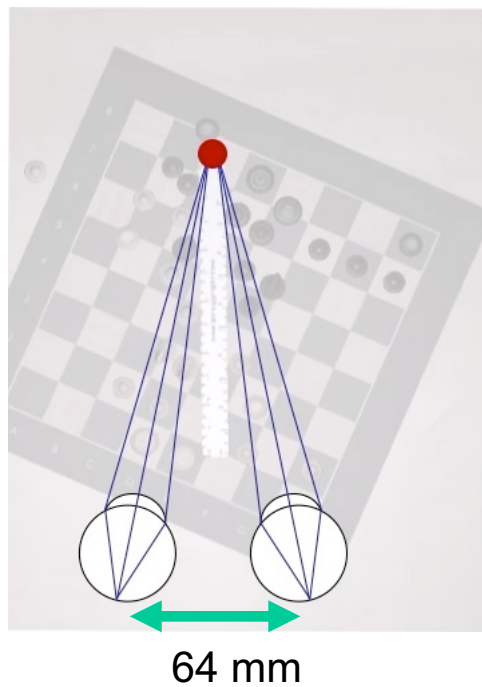


Vergence and accommodation

1.66 diopters (Left)

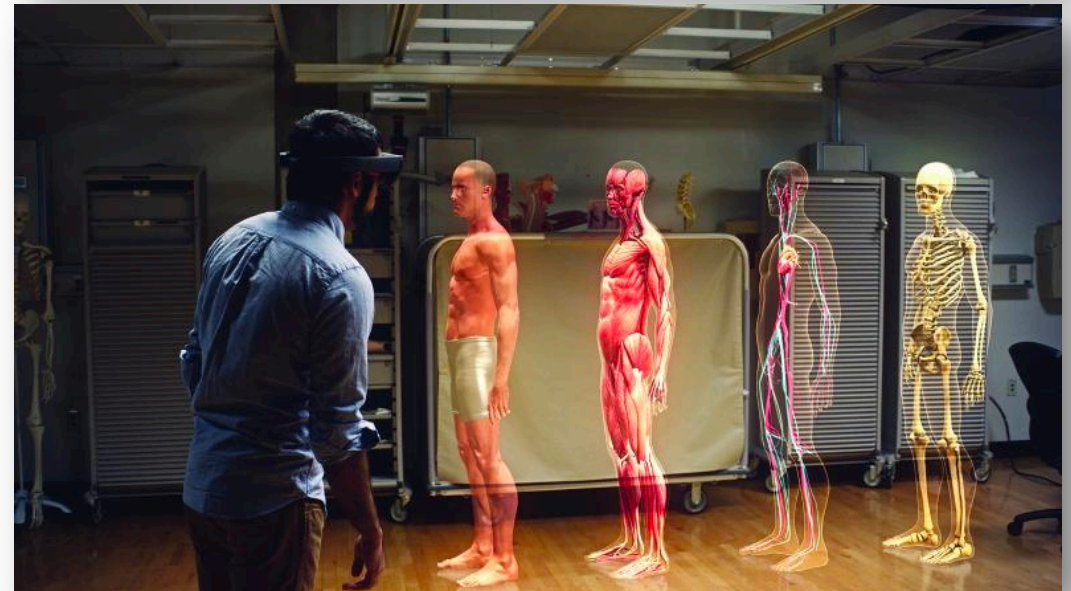


1.66 diopters (Right)



Applications: next generation displays metrics

- Image quality metrics for the next generation of displays requires a new approach because ...
- Some rendered images are mixtures of the display photons and natural image photons (**mixed reality**)
- Other displays include transparent elements at multiple focal planes (**multi-focal**) or emit rays at multiple angles (**light field**)
- These displays are not simply 'RGB' data



Advanced display simulation for image quality metrics

- Current image quality metrics work on the classic model of display technology
 - Images are controlled by RGB input
 - Quality is measured using these input referred values: the **ideal RGB** input vs. the **actual RGB** values delivered by a camera or algorithm
- For example, the image quality metric, SSIM, which has been cited more than 20,000 times and was awarded a Television Emmy, uses this approach

SSIM, PSNR, MS-SSIM



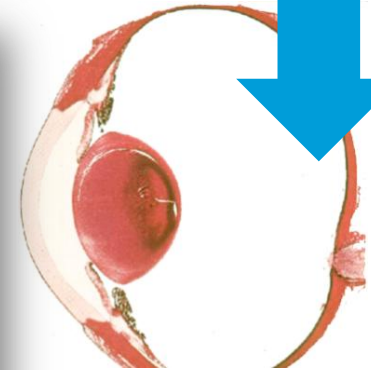
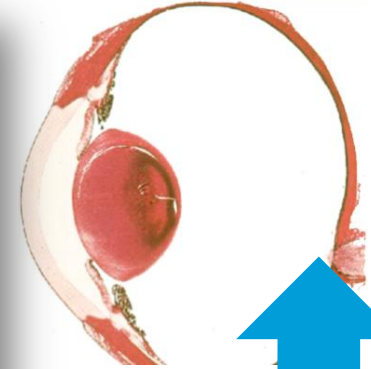
Advancing display simulation for image quality metrics

- A better framing: calculate metrics quality using the photons absorbed by the photoreceptors
- Many advantages; ISET3d is a tool that calculates the photoreceptor excitations from complex scenes including AR/VR scenarios

Ideal RGB



Actual RGB



Compare here

Third point

ISETBio makes physiological optics accessible in vision science and engineering. The ability to incorporate lens models will find applications for questions about stereo, depth of field, near field displays, and augmented reality

Modeling the encoding and decision

- Stimulus modeling
- Physiological optics
- Retinal encoding and inference

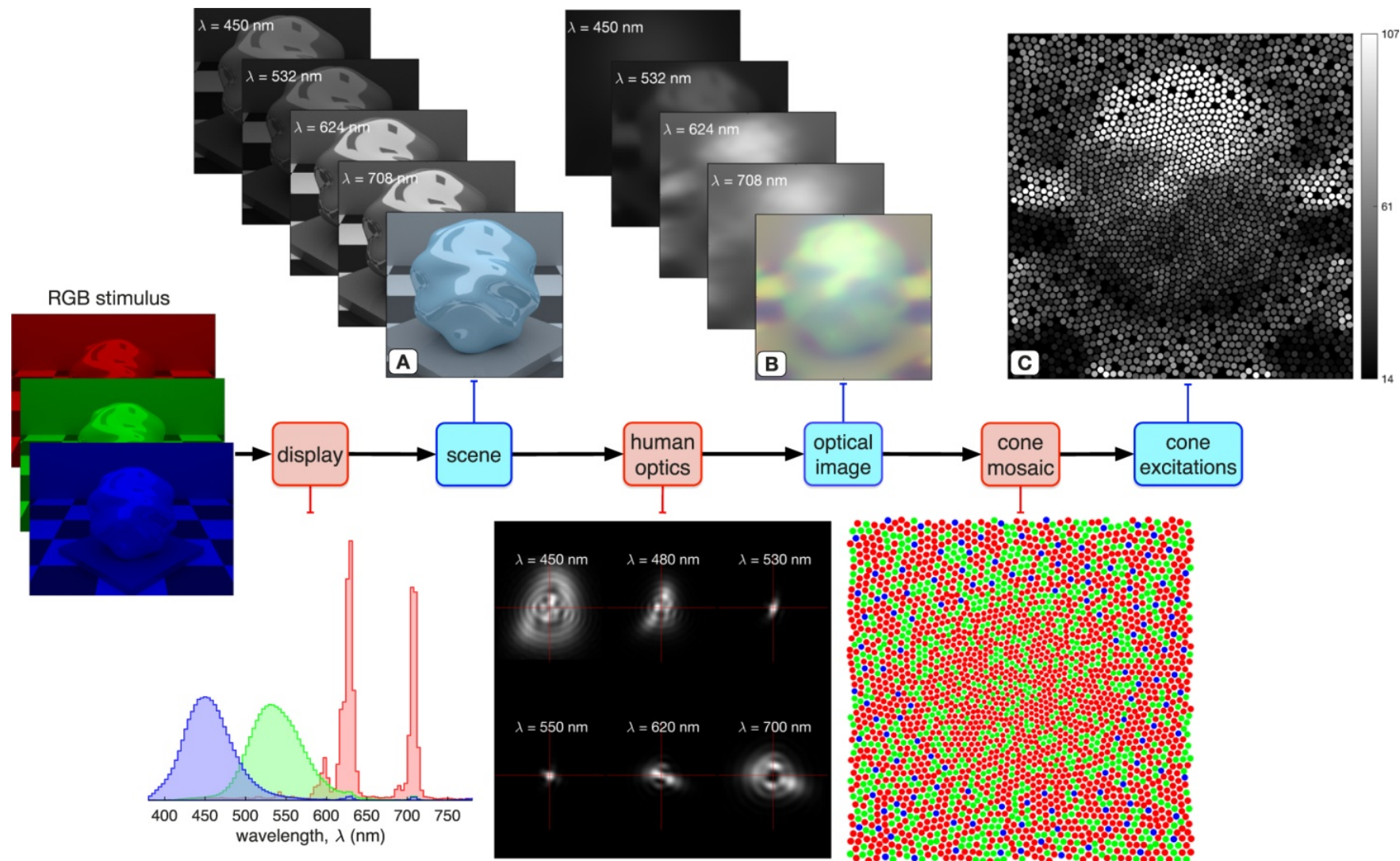


Nicolas Cottaris



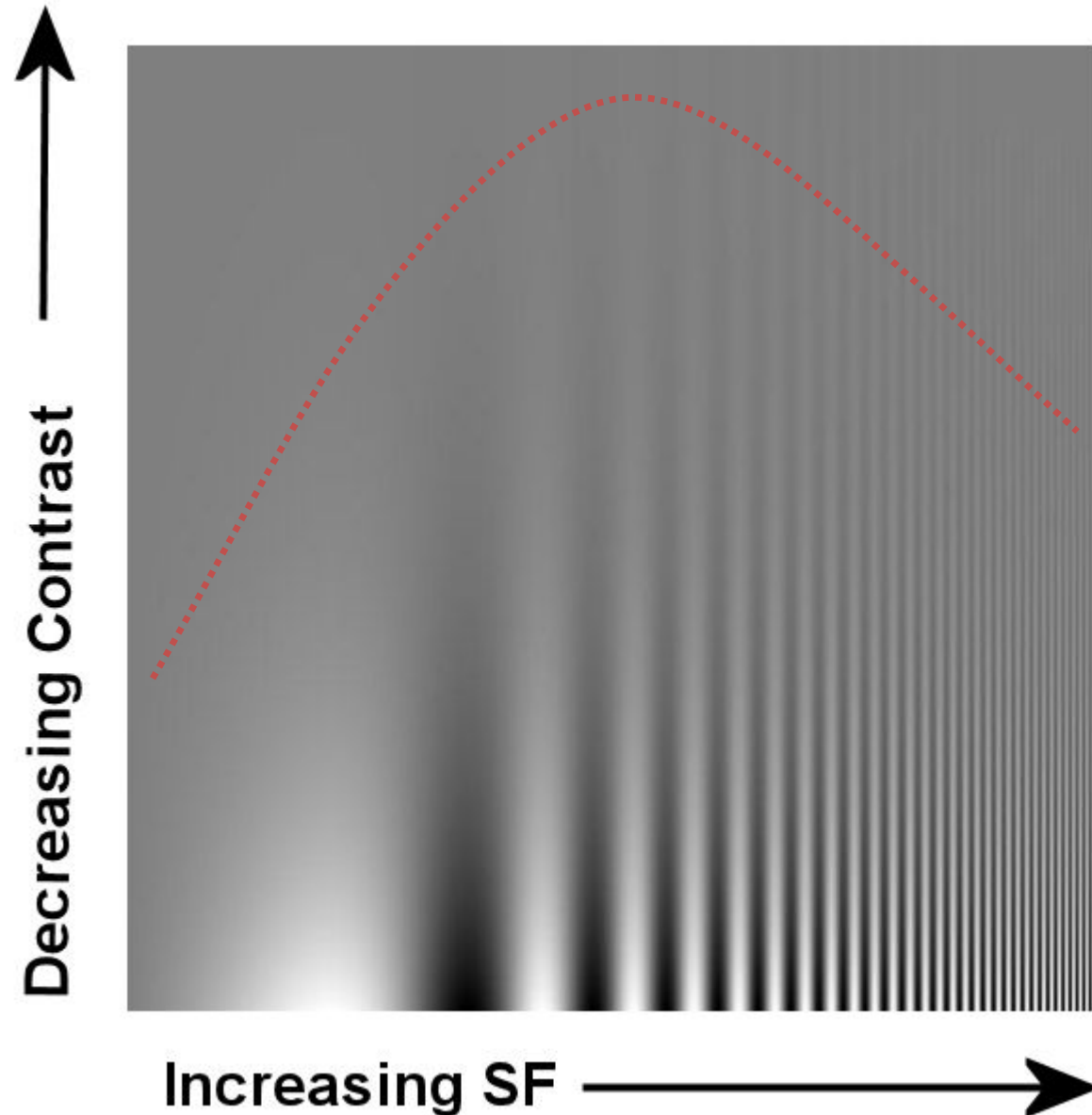
Vision modeling: From display to photocurrent

- ISETBio also models calibrated planar displays, wavefront aberrations, space-varying cone mosaics, fixational eye movements, cone excitations, and cone photocurrent
- Cottaris et al. (JoV, 2019) and (in preparation) is exploring the impact of many biological factors on contrast sensitivity



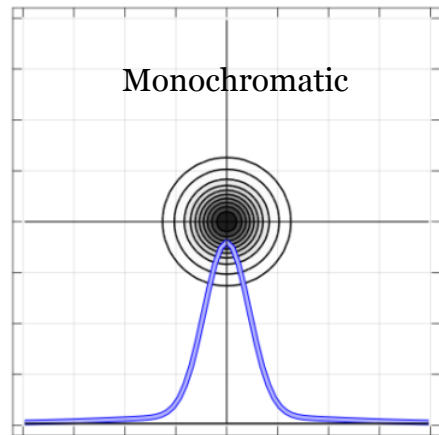
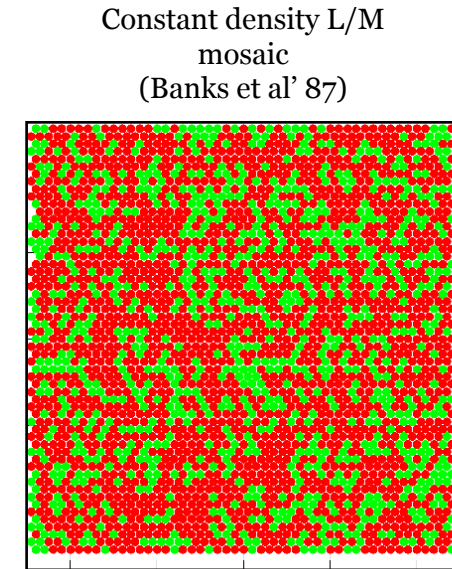
Contrast Sensitivity Function (CSF)

- The reduced sensitivity to large uniform fields (low frequency) suggests that the visual system detects contrast patterns, not absolute levels
- Relative measurements matter a lot; absolute levels matter much less and are often not perceptible

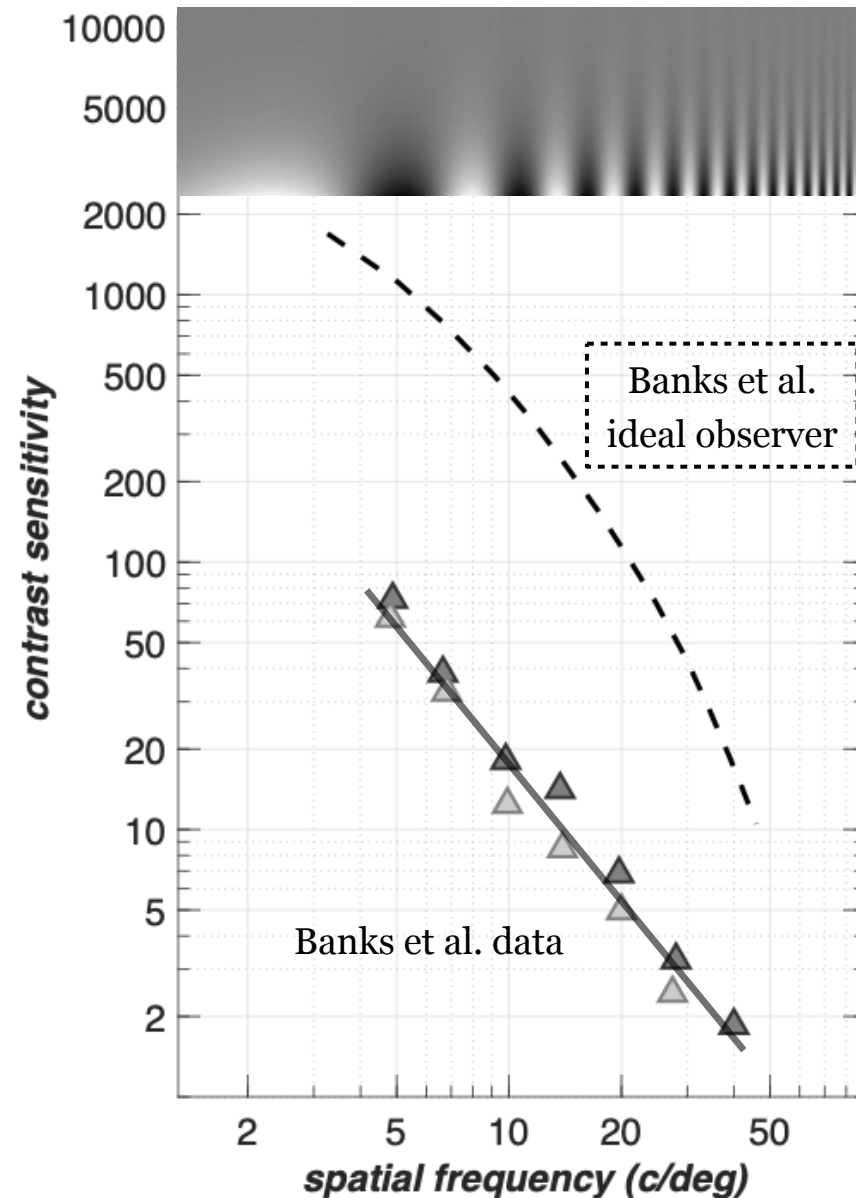


Validation: Comparison with the Banks et al. 1987

- **System validation.**
Banks et al. 1987 is a classic paper that uses an ideal observer calculation to understand the factors limiting the CSF
- We tested the ISETBio implementation by comparing our calculations with their formula-based calculation

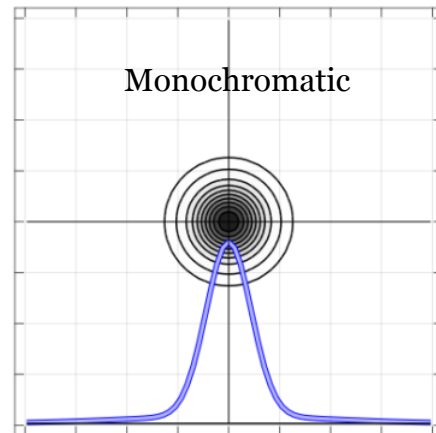
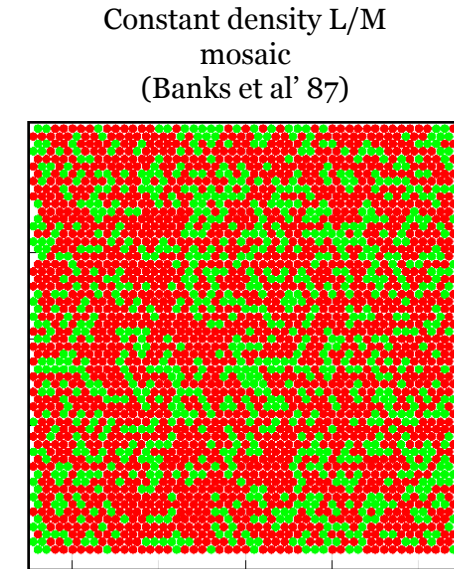


Banks '87 based on
Campbell & Gubisch '66
2 mm pupil

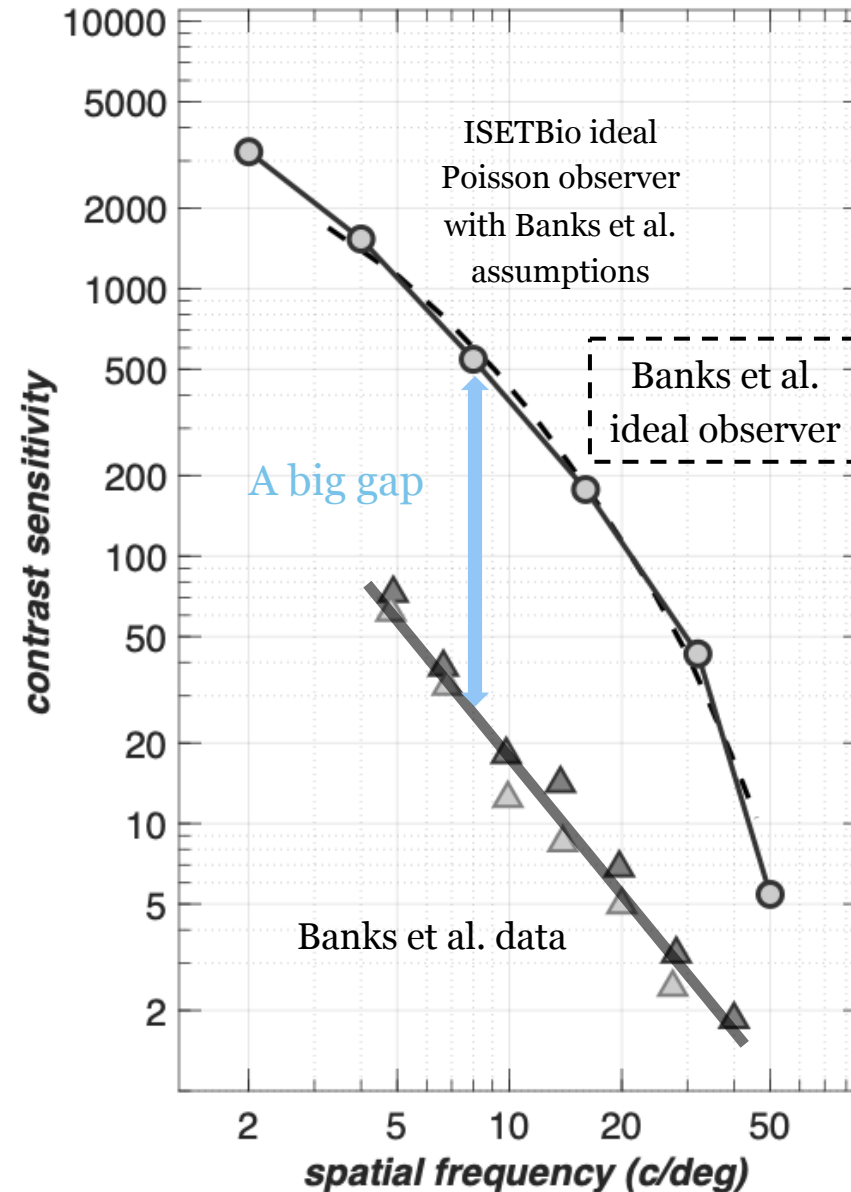


Validation: Comparison with the Banks et al. 1987

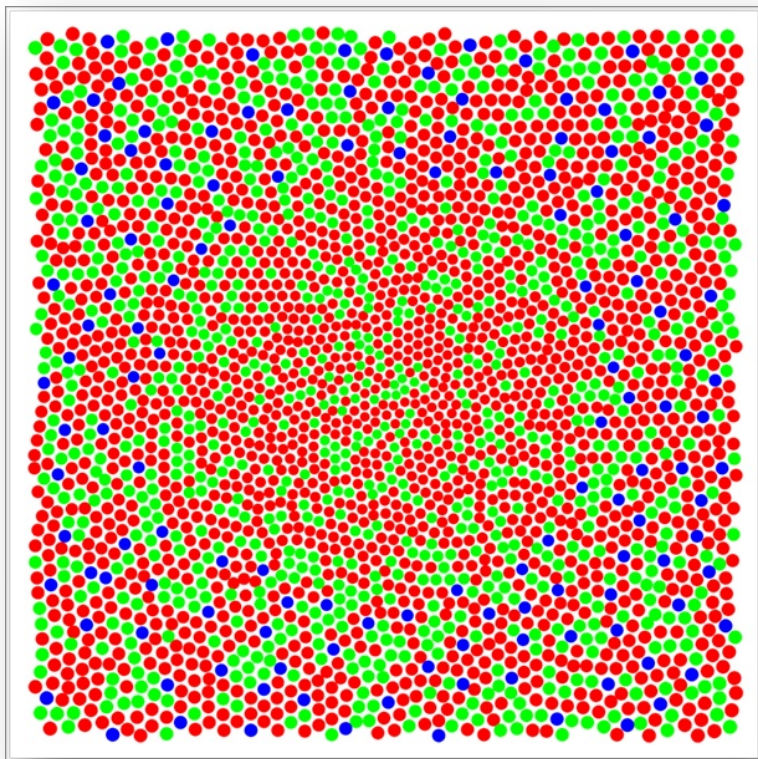
- This **system validation** test of ISETBio matches Banks et al. '87 calculation closely
- One value of the computational approach is that **we can continue to investigate more complex assumptions**



Banks '87 based on
Campbell & Gubisch '66
2 mm pupil

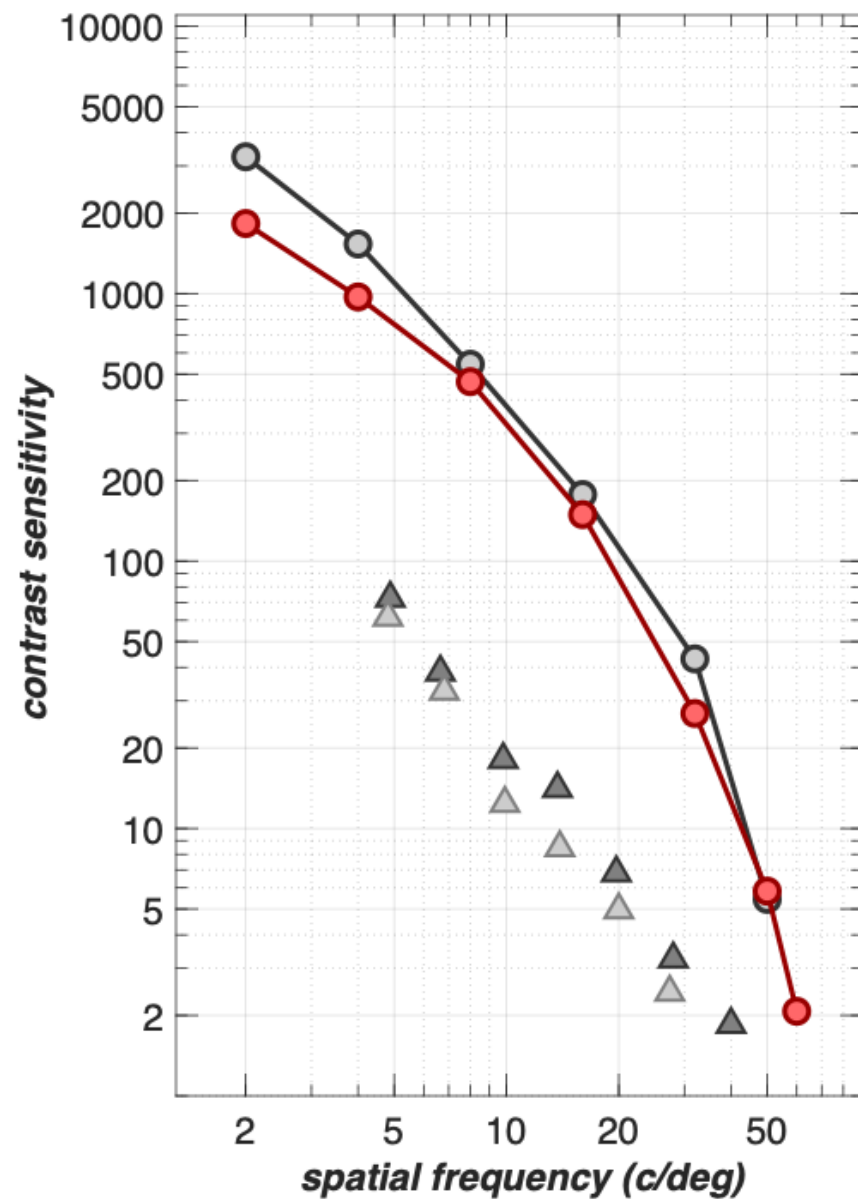


A realistic mosaic, wavelength-dependent and empirical PSF



ISETBio ideal
Poisson observer
with Banks et al.
assumptions

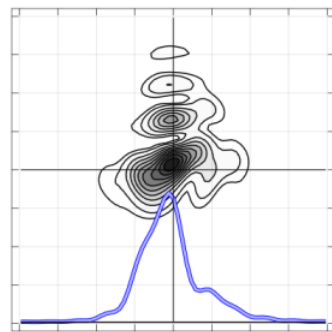
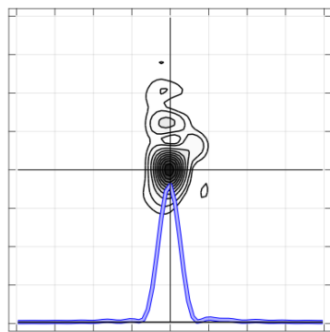
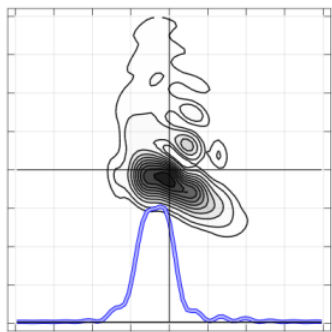
ISETBio ideal
Poisson observer
with realistic
mosaic and blur



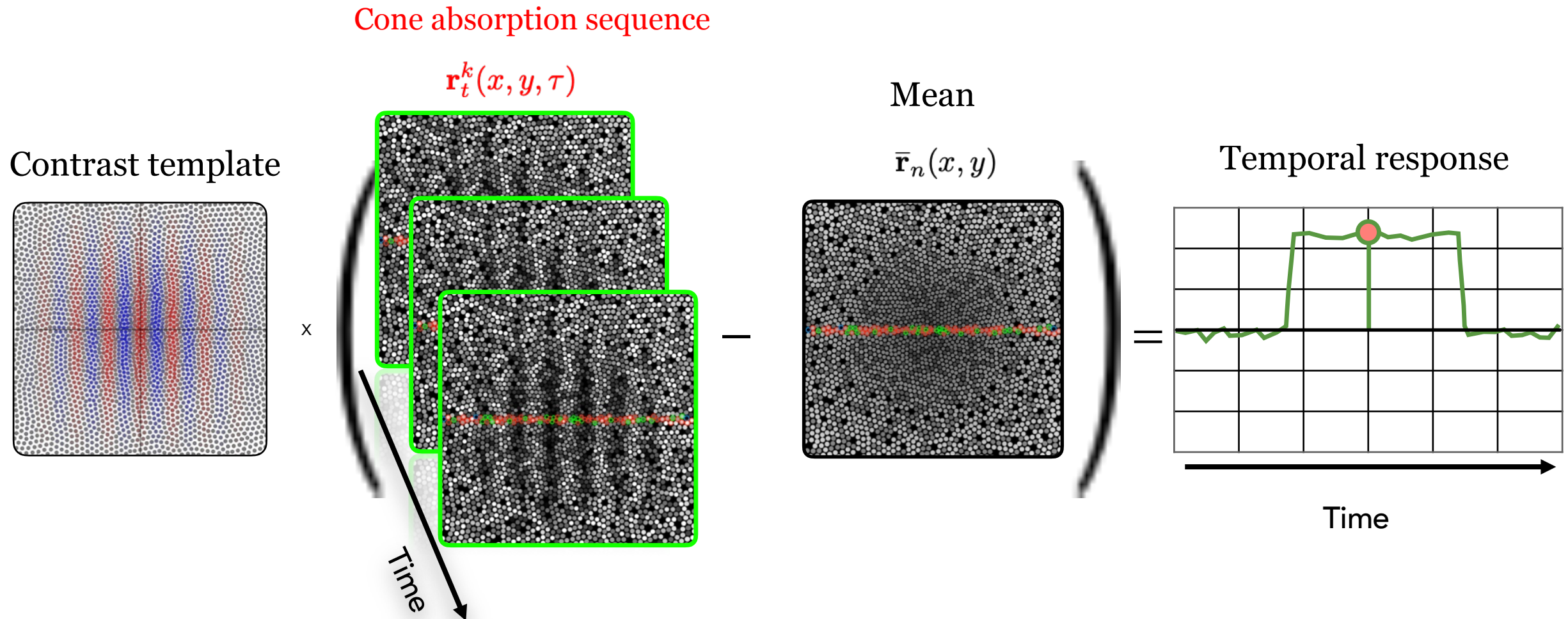
500nm

550nm

600nm



SVM – Linear template model



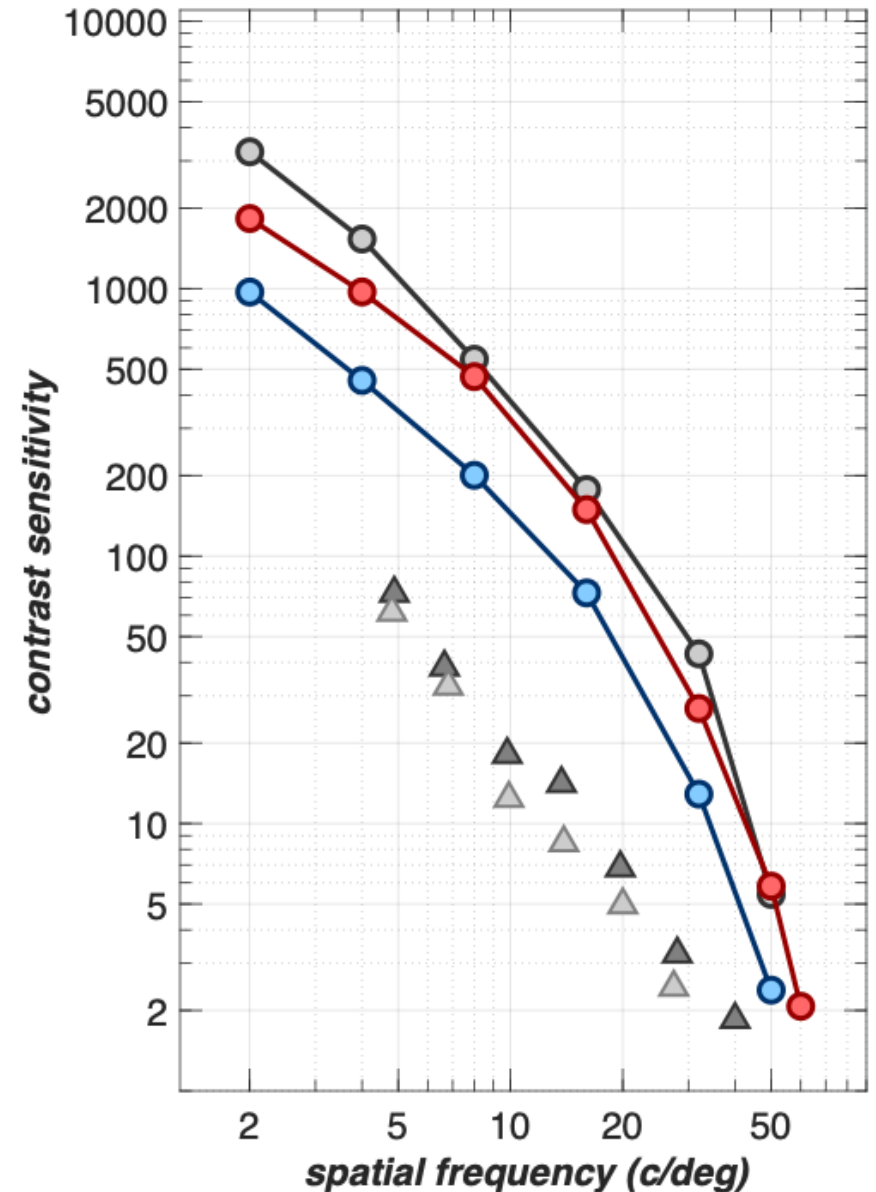
The impact of a sub-optimal inference engine

- The SVM-Linear template model, using a realistic mosaic and blur assumptions, reduces sensitivity by about a factor of two from the ideal Poisson observer
- The general shape of the CSF is preserved

ISETBio ideal
Poisson observer
with Banks et al.
assumptions

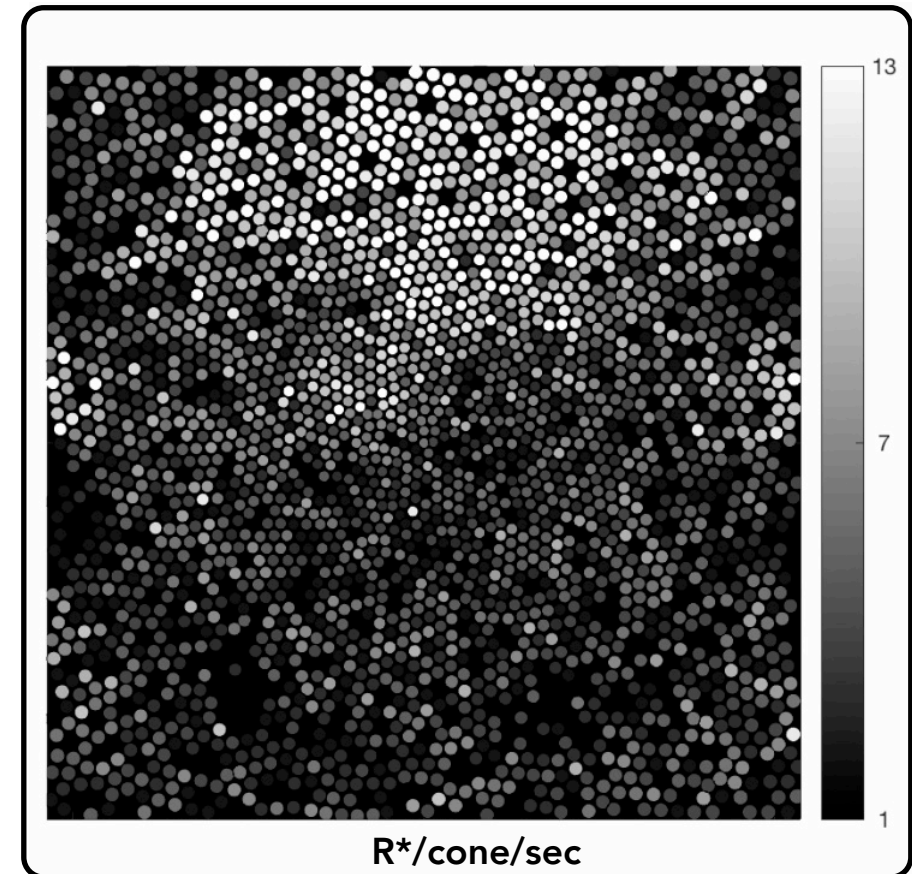
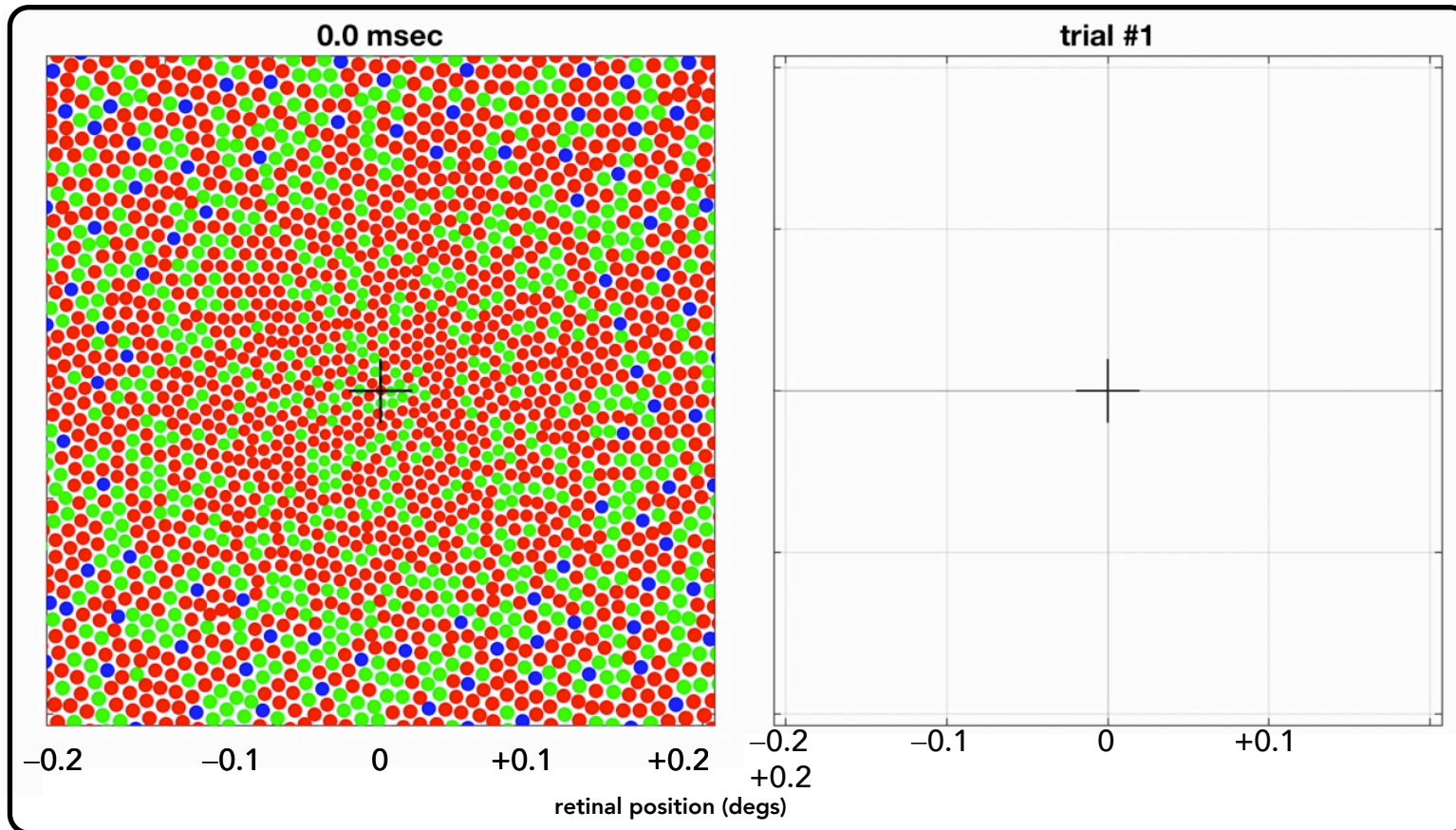
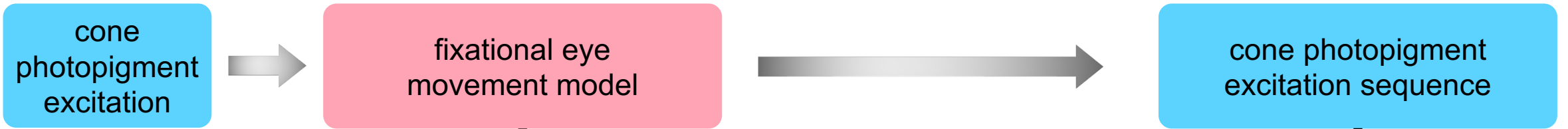
ISETBio ideal
Poisson observer
with realistic
mosaic and blur

ISETBio SVM-
Linear template



Cone mosaic and fixational eye movements

Mergenthaler and Engbert (2007)

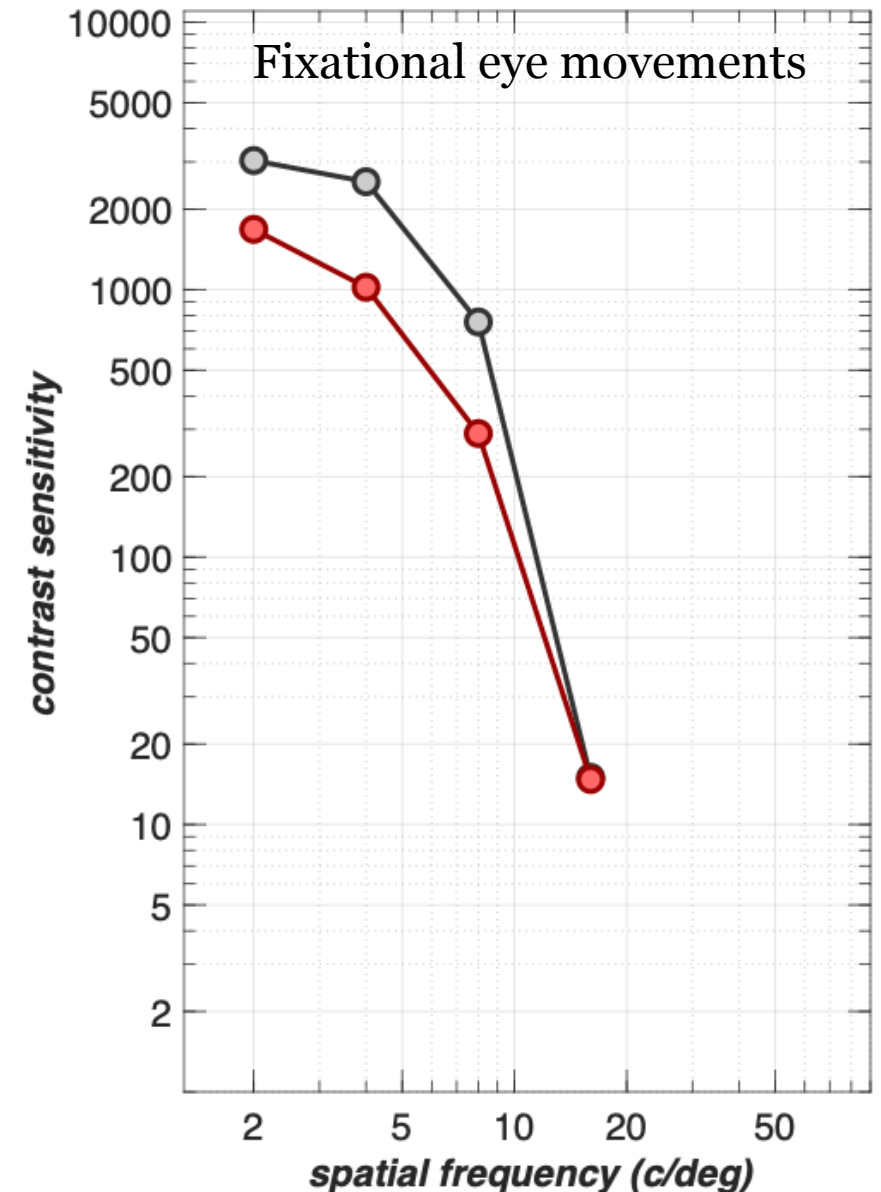


Fixational eye movements have a large impact

- Adding a realistic model of fixational eye movements reduces sensitivity and has a significant impact on the shape of the CSF
- The eye movements impact both the ideal observer and the SVM-Linear template inference calculations

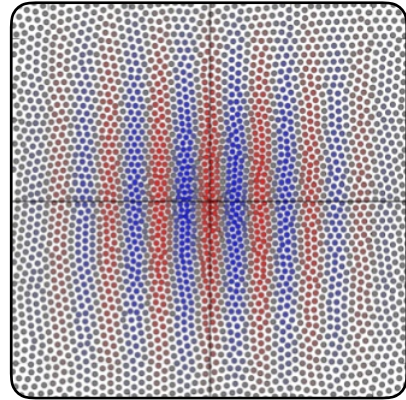
ISETBio ideal
Poisson observer
with Banks et al.
assumptions

ISETBio ideal
Poisson observer
with realistic
mosaic and blur

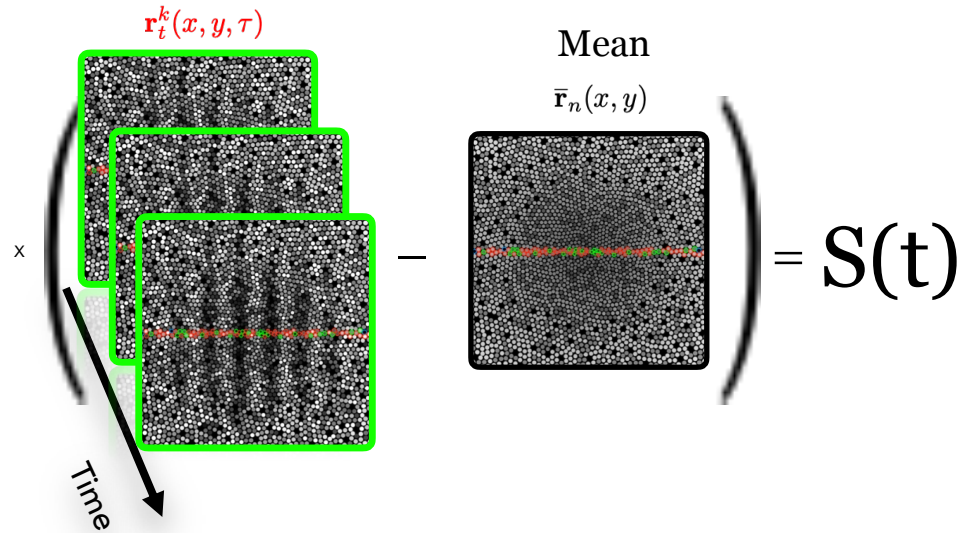


SVM – Quadrature model (motion-energy)

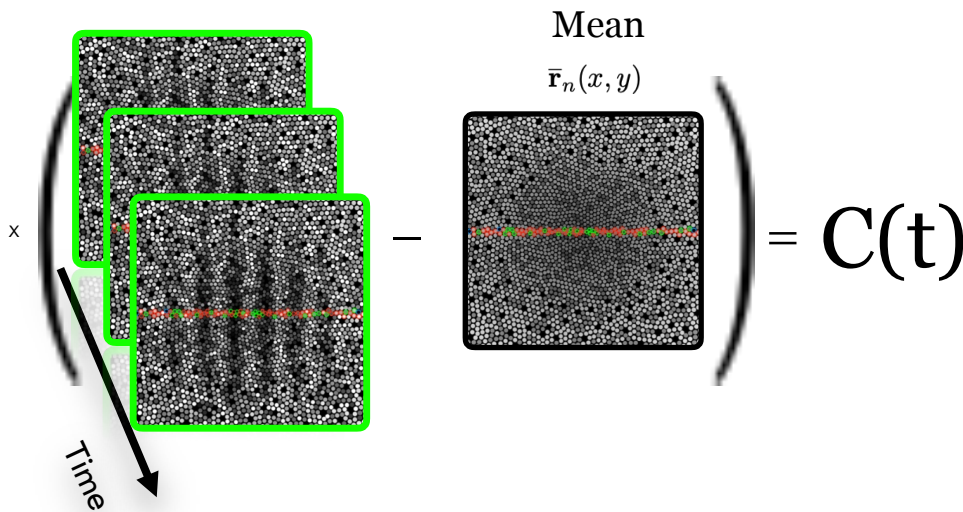
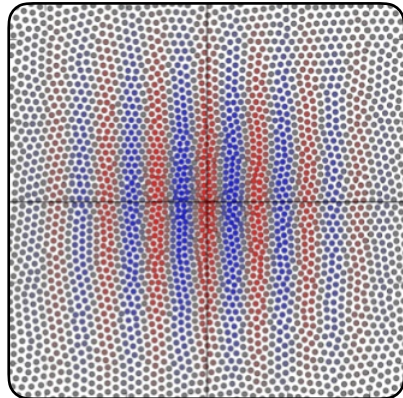
Sine-phase template



Cone absorption sequence



Cosine-phase template



The quadrature calculation (motion-energy) is a small-translation invariant calculation designed to reduce the impact of small movements

$$S(t)^2 + C(t)^2 = E$$

The CSF shape is preserved at the cost of a reduced sensitivity

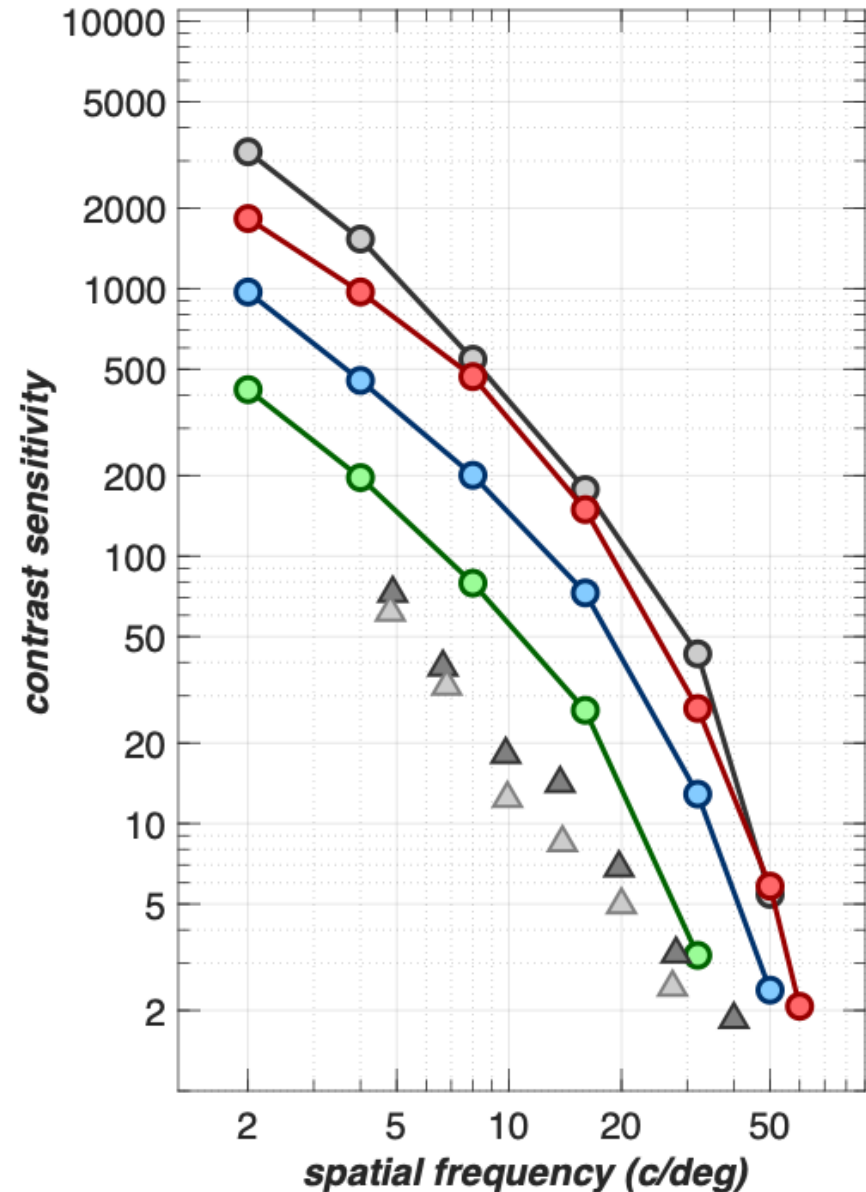
- Using the quadrature template preserves the shape of the CSF, but it costs another factor of two in sensitivity
- We conceive of this as part of the computational decision model; it is not tightly coupled to an implementation either in the retina or cortex
- There is still a gap of about a factor of two.

ISETBio ideal
Poisson observer
with Banks et al.
assumptions

ISETBio ideal
Poisson observer
with realistic
mosaic and blur

ISETBio SVM-
Linear template

ISETBio SVM-
Quadrature
template

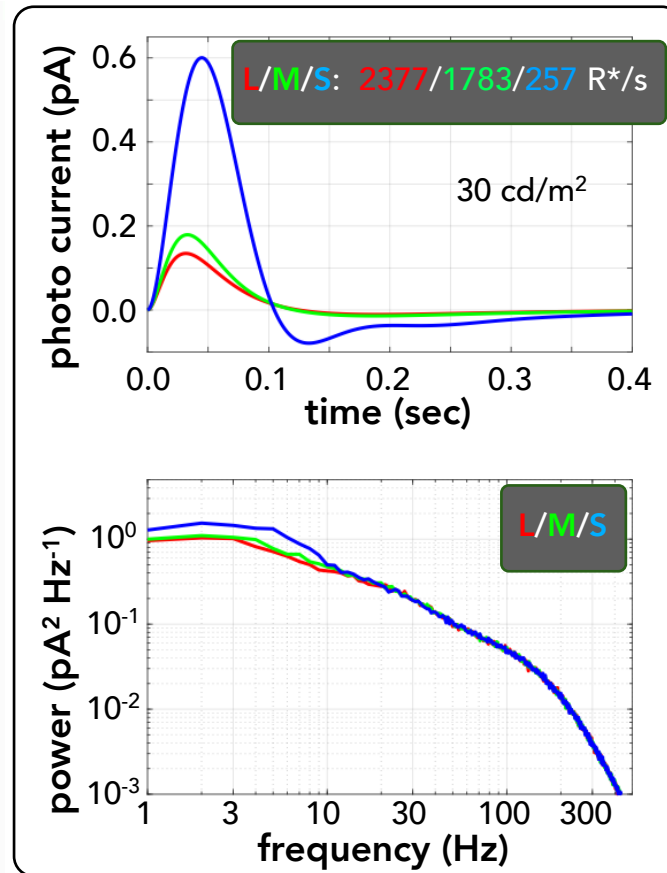
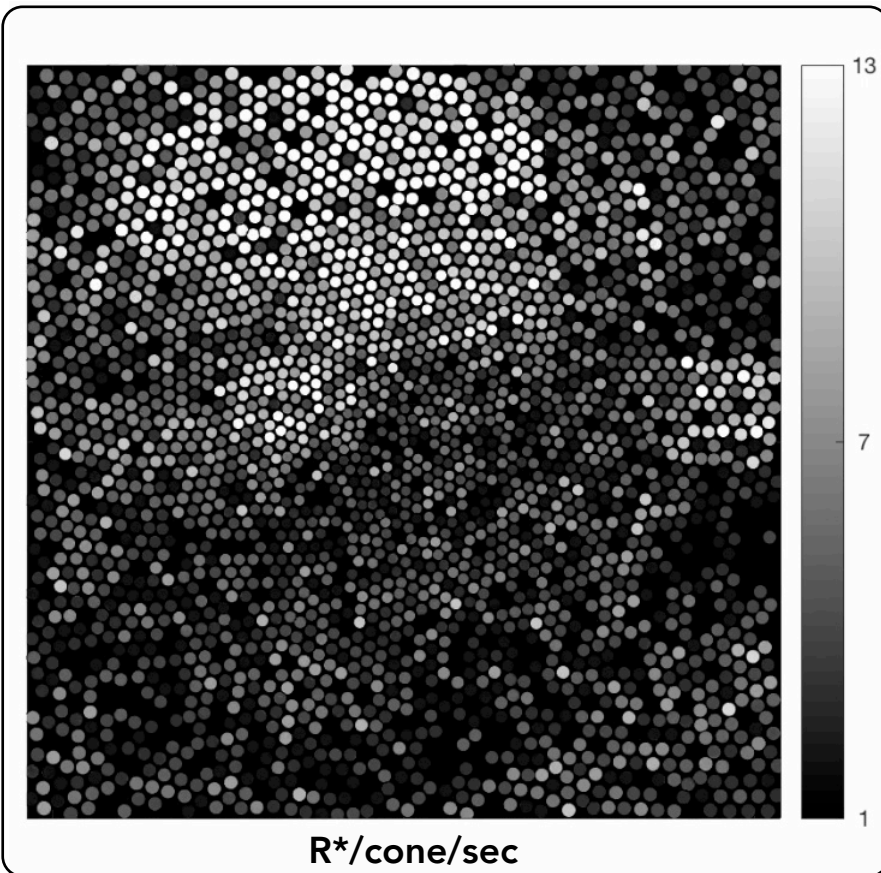


Photocurrent model (Rieke et al.)

cone photopigment
excitation sequence

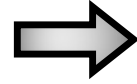


outer segment
photocurrent model

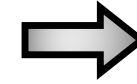


Photocurrent model (Rieke et al.)

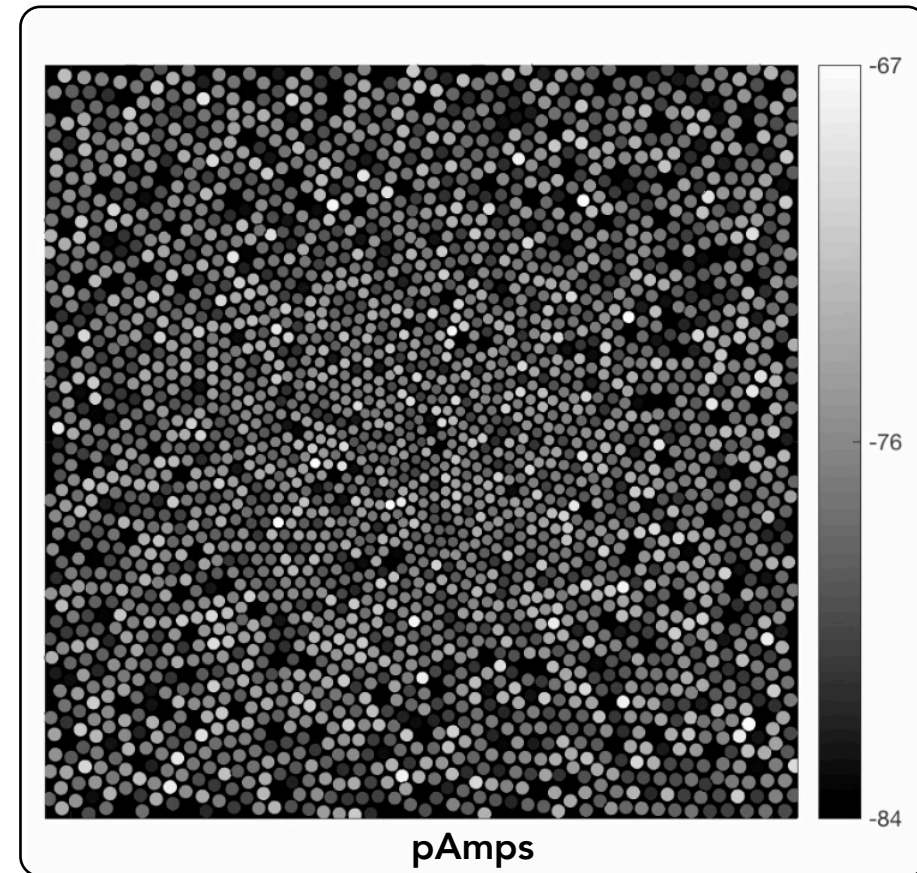
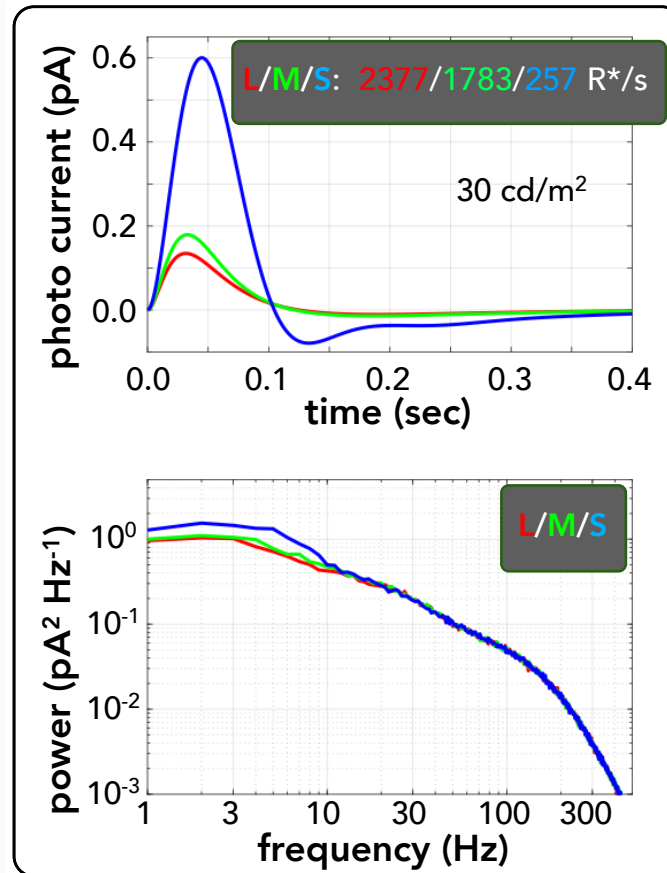
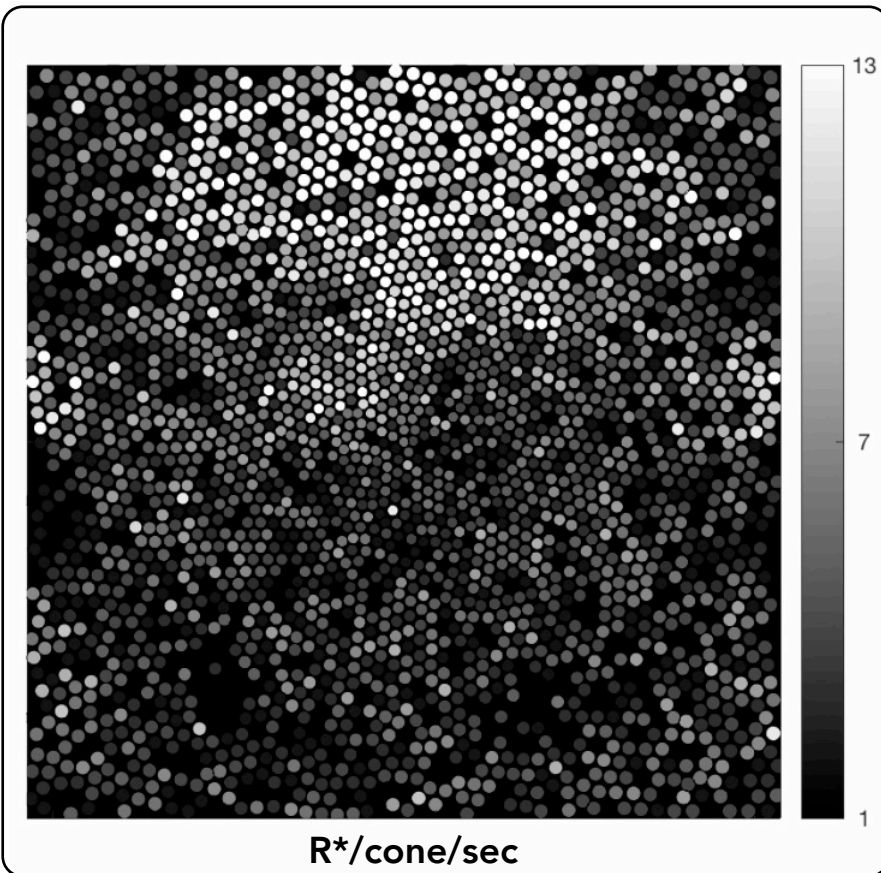
cone photopigment
excitation sequence



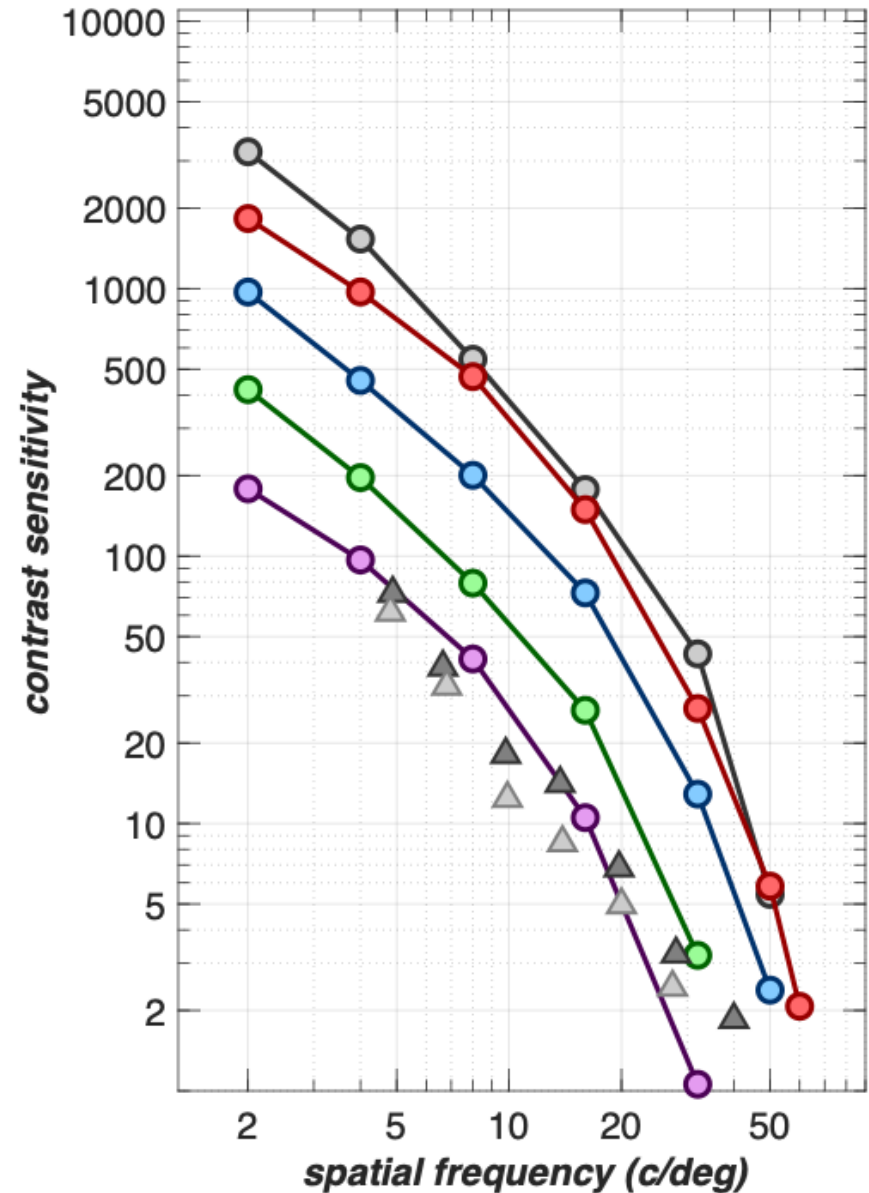
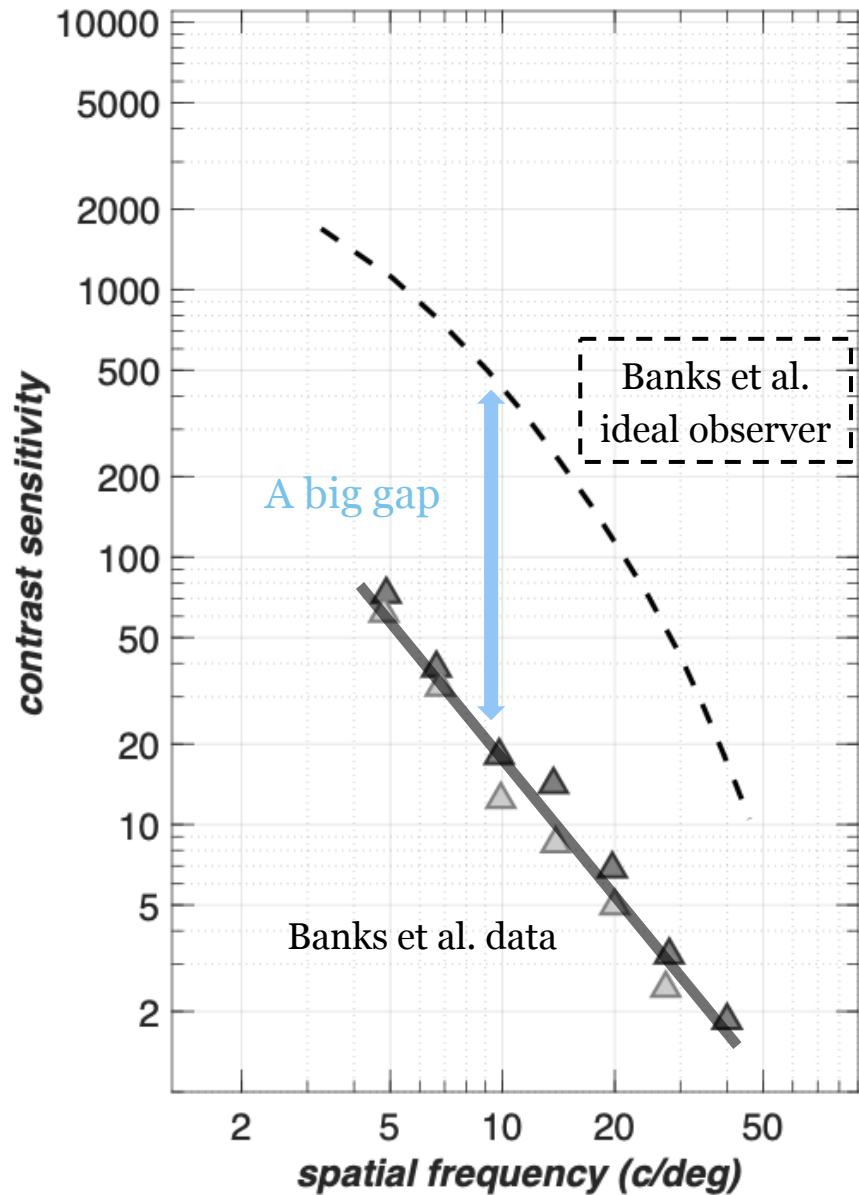
outer segment
photocurrent



cone outer-segment
photocurrent response



Combined encoding factors and inference engine



ISETBio ideal
Poisson observer
with Banks et al.
assumptions

ISETBio ideal
Poisson observer
with realistic
mosaic and blur

ISETBio SVM-
Linear template

ISETBio SVM-
Quadratic
template

ISETBio SVM-
Quadratic
template
applied to
photocurrent

Final point

A consensus (validated) platform will be beneficial to the vision science and vision engineering, enabling exploration of a complex system.

Additional methodologies can extend the value of these computations – databases, cloud-scaling, containers for platform independence.

ISETBIO software resources

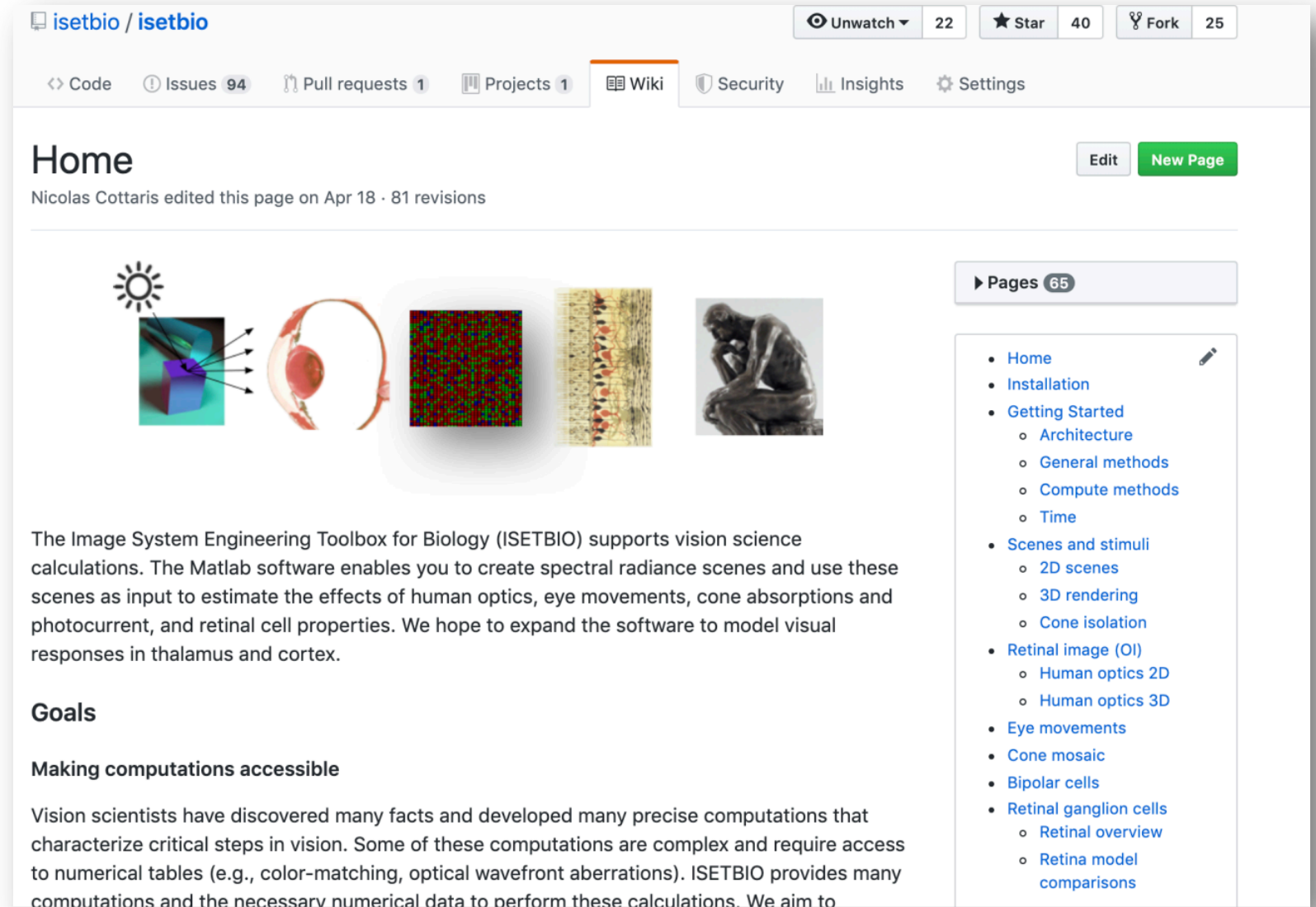
GitHub –

See our GitHub wiki
pages and multiple
repositories

Tutorials

ISET₃D

ISETBIOLiveScripts



isetbio / isetbio

Unwatch 22 Star 40 Fork 25

Code Issues 94 Pull requests 1 Projects 1 Wiki Security Insights Settings

Home

Nicolas Cottaris edited this page on Apr 18 · 81 revisions

Pages 65

- Home
- Installation
- Getting Started
 - Architecture
 - General methods
 - Compute methods
 - Time
- Scenes and stimuli
 - 2D scenes
 - 3D rendering
 - Cone isolation
- Retinal image (OI)
 - Human optics 2D
 - Human optics 3D
- Eye movements
- Cone mosaic
- Bipolar cells
- Retinal ganglion cells
 - Retinal overview
 - Retina model comparisons

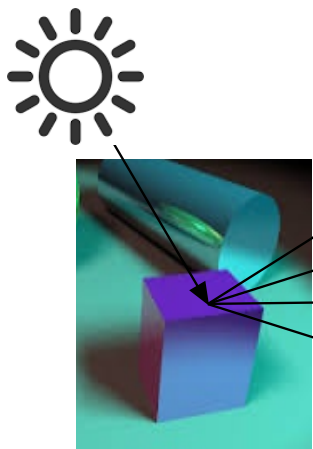
The Image System Engineering Toolbox for Biology (ISETBIO) supports vision science calculations. The Matlab software enables you to create spectral radiance scenes and use these scenes as input to estimate the effects of human optics, eye movements, cone absorptions and photocurrent, and retinal cell properties. We hope to expand the software to model visual responses in thalamus and cortex.

Goals

Making computations accessible

Vision scientists have discovered many facts and developed many precise computations that characterize critical steps in vision. Some of these computations are complex and require access to numerical tables (e.g., color-matching, optical wavefront aberrations). ISETBIO provides many computations and the necessary numerical data to perform these calculations. We aim to

Image systems simulation for biology (ISETBio)



Scene spectral radiance



Physiological optics

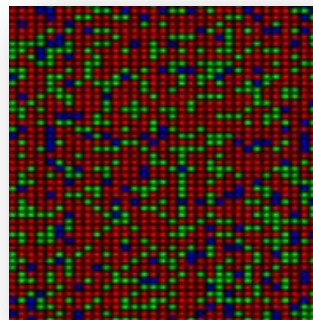
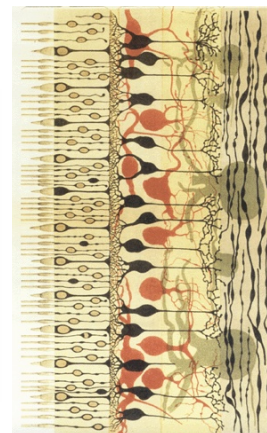
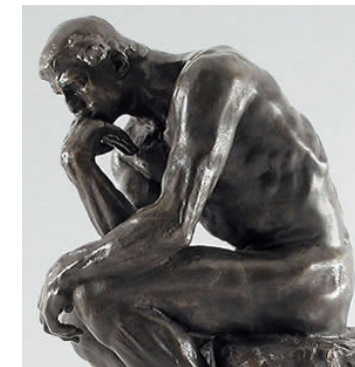


Photo transduction



Retinal processing



Inference



Brian Wandell



David Brainard



Joyce Farrell



Trisha Lian



Nicolas Cottaris



Fred Rieke



E.J. Chichilnisky



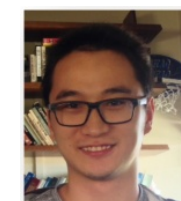
James Golden



Jon Winawer

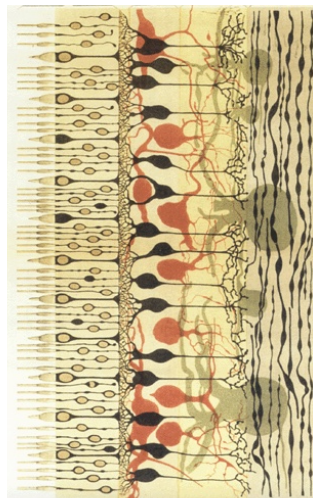
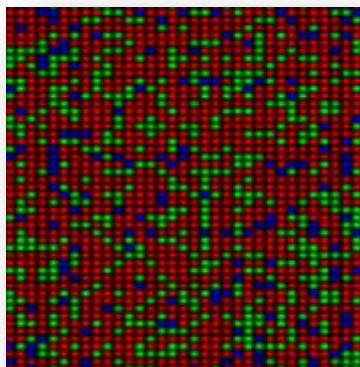
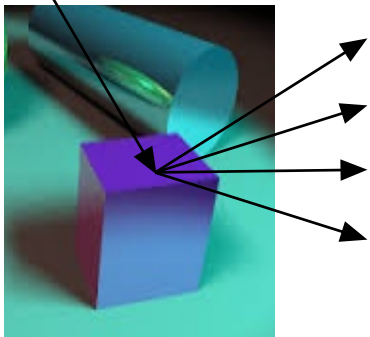


Xiaomao Ding



Haomiao Jiang

Image systems simulation for biology (ISETBio)



Scene spectral radiance

Physiological optics

Photo transduction

Retinal processing

Inference



Thanks to Simons Foundation
Oculus Research, Samsung,
Qualcomm

