OPTICA
Advancing Optics and Photonics Worldwide

Technical Groups

Color Vision at a Cellular Level

Featuring Katrin Franke and William Tuten
10 December 2021

Technical Group Executive Committee

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Chair of the Color Technical Group

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University of South-Eastern Norway

About the Color Technical Group

Our technical group focuses on all aspects related to the physics, physiology, and psychology of color in biological and machine vision.

Our mission is to connect the 900+ members of our community through technical events, webinars, networking events, and social media.

Our past activities have included:

- Special webinar on display calibration
- Vision science in times of social distancing bi-weekly coffee breaks
- Incubator meetings

Connect with the Color Technical Group

Join our online community to stay up to date on our group's activities. You also can share your ideas for technical group events or let us know if you're interested in presenting your research.

Ways to connect with us:

- Our website at www.optica.org/VC
- On Twitter at #OSAColorTG
- On LinkedIn at www.linkedin.com/groups/13573604
- Email us at TGactivities@optica.org

Upcoming Webinar

OPTICA
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Color

WEBINAR

Sky Optics: Colors and Spectra of Clear Daytime and Twilight Skies

13 January 2022 | 14:00 — 15:00 EST (UTC-05:00)

Vision Technical Group Executive Committee

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Vyas Akondi
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Instituto de Optica, CSIC

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Clerio Vision, Inc.

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About the Vision Technical Group

Our technical group focuses on optics of the eye and of ophthalmic lenses and devices; physiological optics; and mechanisms of transduction, transmission, coding, detection and analysis of visual information.

Our mission is to connect the 1000+ members of our community through technical events, webinars, networking events, and social media.

Our past activities have included:

- Virtual Vision Science Seminar
- Vision and Color Data Blast Series
- Workshop on Chromatic Aberrations in Vision

Connect with the Vision Technical Group

Join our online community to stay up to date on our group's activities. You also can share your ideas for technical group events or let us know if you're interested in presenting your research.

Ways to connect with us:

- Our website at www.optica.org/VV
- Email us at TGactivities@optica.org

Upcoming Webinar: Grant Writing for Vision Scientists

- January 26, 2022 12:00-13:00 EST
- Speakers: David Williams and Pablo Artal

Today's Speakers

Katrin Franke

Tübingen University

William Tuten

University of California, Berkeley

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Vision

Behavioral state tunes mouse (color) vision to ethological features through pupil dilation

Katrin Franke
Bernstein Center for Computational Neuroscience Tübingen
Institute for Ophthalmic Research
Center for Integrative Neuroscience

Optica Joint Colour & Vision Technical Groups Webinar

@kfrankelab

CIN
Werner Reichardt
Centrum für Integrative Neurowissenschaften

Forschungsinstitut für Augenheilkunde
Universitätsklinikum Tübingen

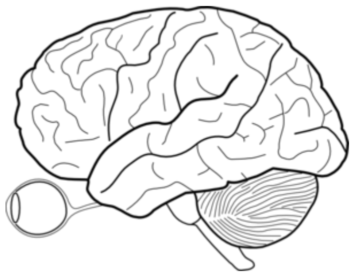
Bernstein Center for Computational Neuroscience Tübingen

Visual information processing is modulated by behavioral state

Visual input

10^9 bits/second

Information processing



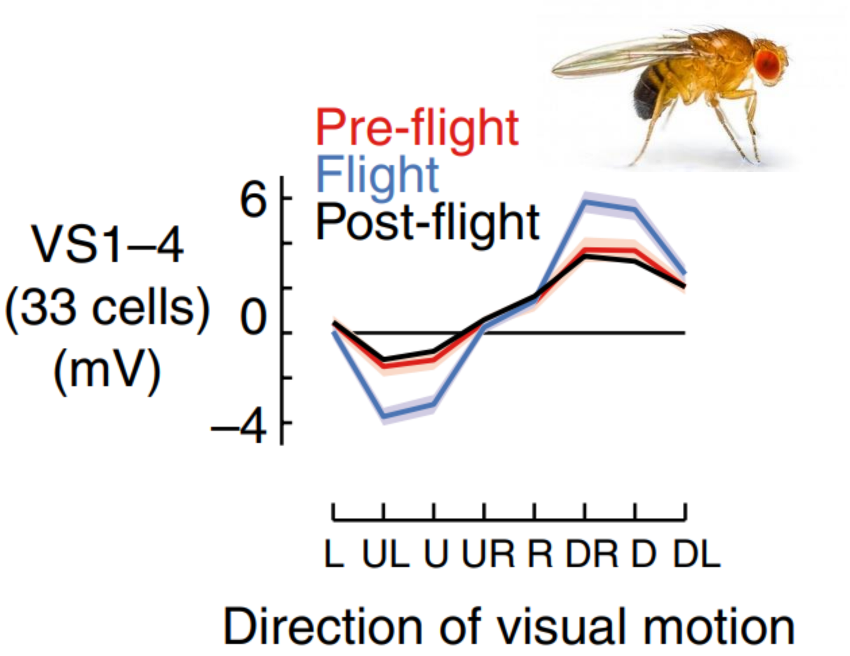
Behavioral output

A few bits/second

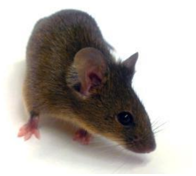
Modulation of visual processing via neuromodulatory feedback!

Inspired by Pitkow and Meister, 2014

Visual information processing is modulated by behavior & brain state



Maimon et al. 2010 Nat Neuro



Niell & Stryker 2010 Neuron
Erisken et al. 2014 Curr Biol

Treue & Maunsell 1996 Nature
McAdams & Maunsell 1996 J Neurosci

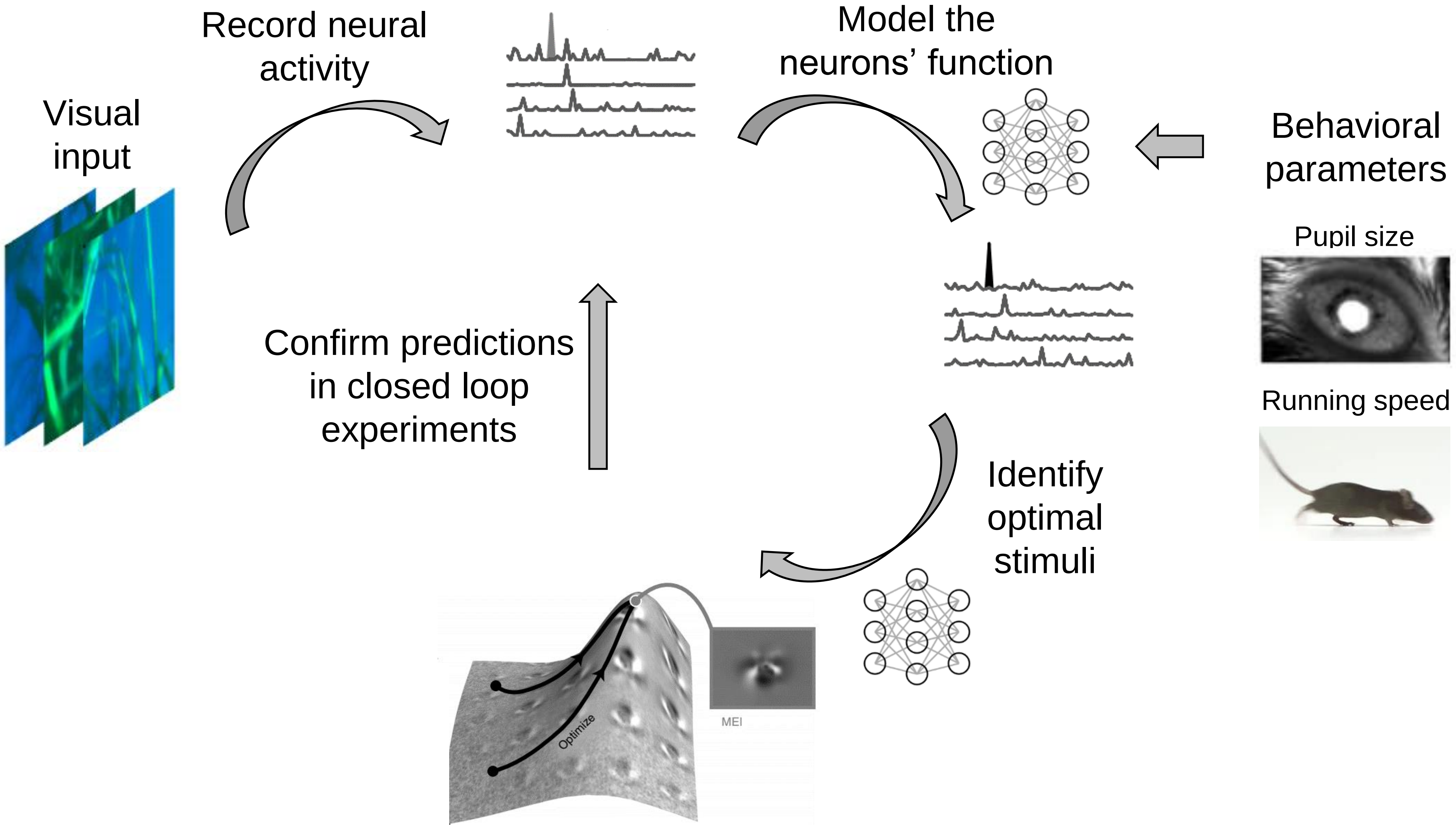
→ Enhancement of visual responses and signal to noise ratio in an active behavioral/brain state

→ Stimulus selectivity remains largely unchanged

But: Simple stimuli, few visual features tested and quantifying relationship between function and behavior challenging

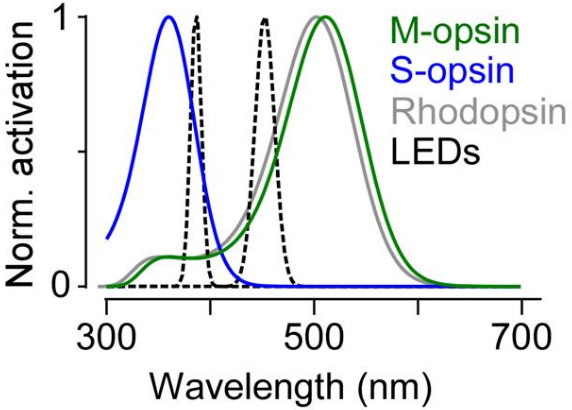
→ How does behavioral state modulate stimulus selectivity in the context of colored naturalistic scenes?

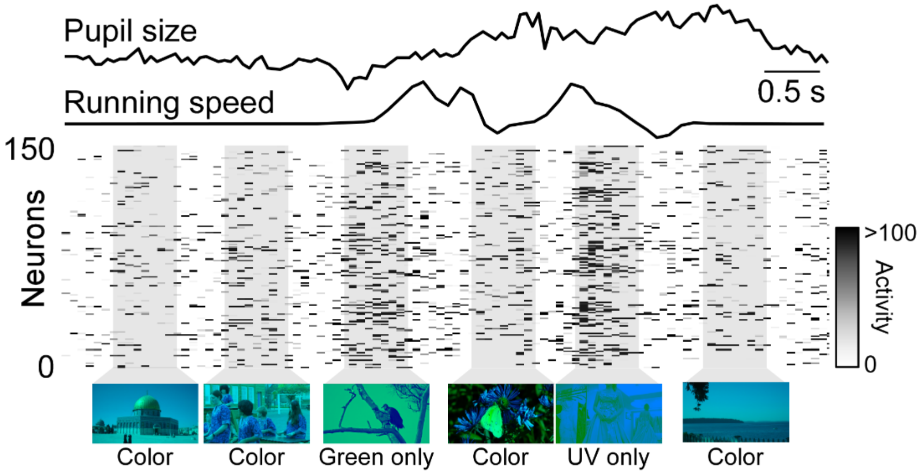
Studying visual processing of colored natural scenes in the context of behavior

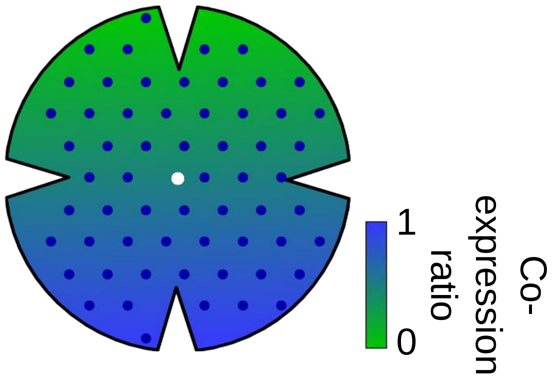


Adapted from Walker et al., Nat Neuro 2019

Recording visual responses to colored natural scenes in mouse visual cortex

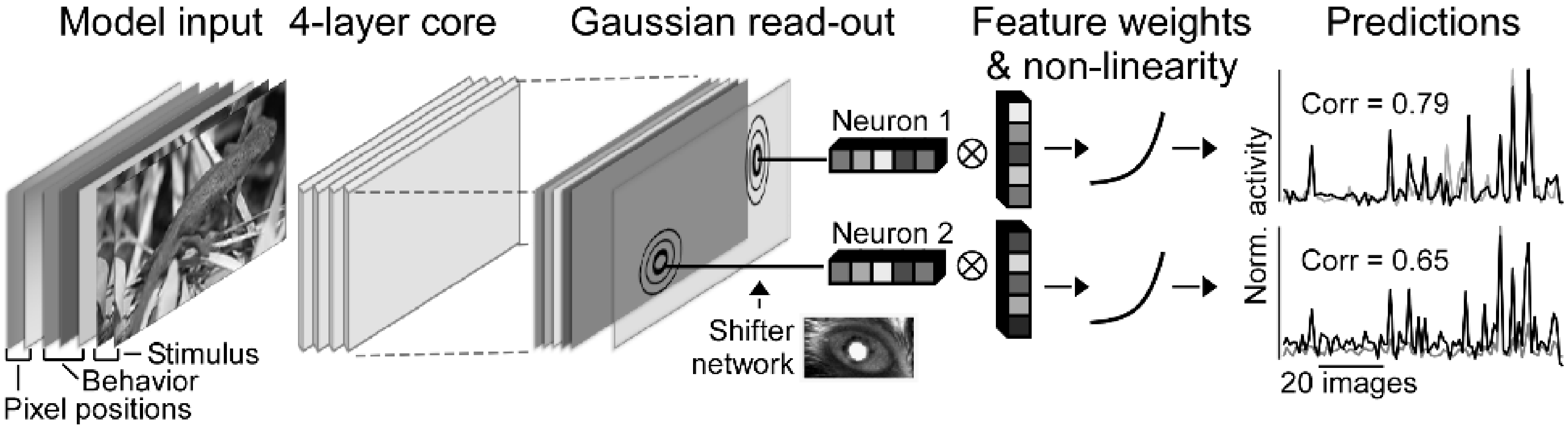






Franke*, Willeke*, Ponder, Galdamez, Muhammad, Froudarakis, Reimer, Sinz, Tolias. *Behavioral state tunes mouse vision to ethological features through pupil dilation*. bioRxiv 2021

Model architecture



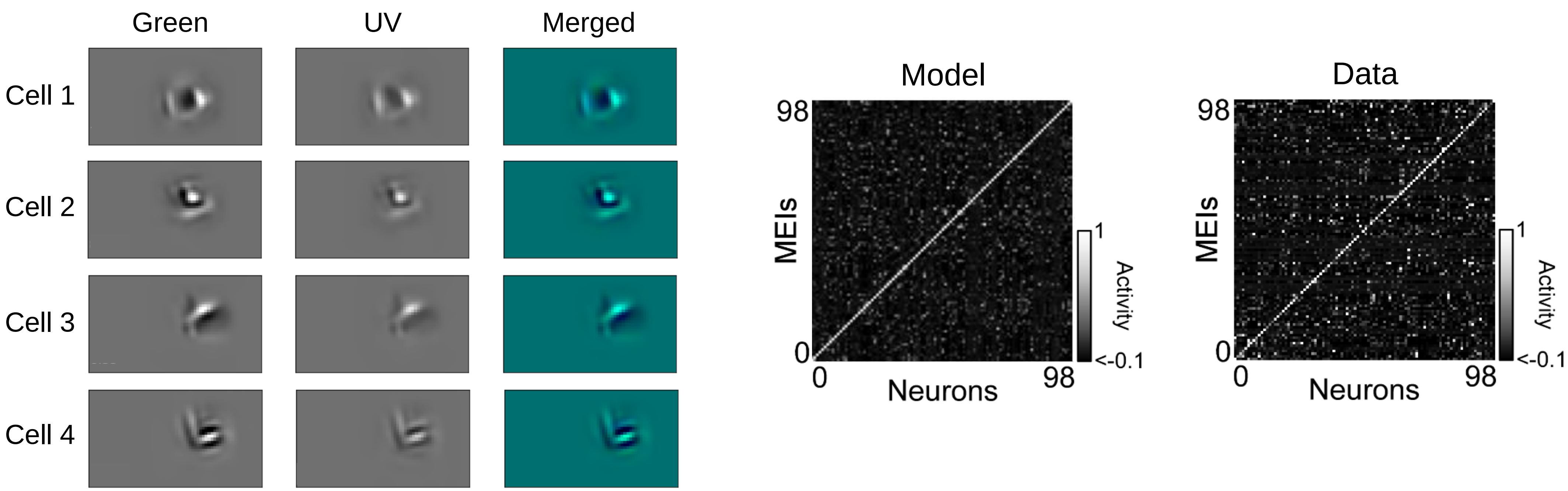
Behavior channels:

- Pupil size
- Change in pupil size
- Running speed

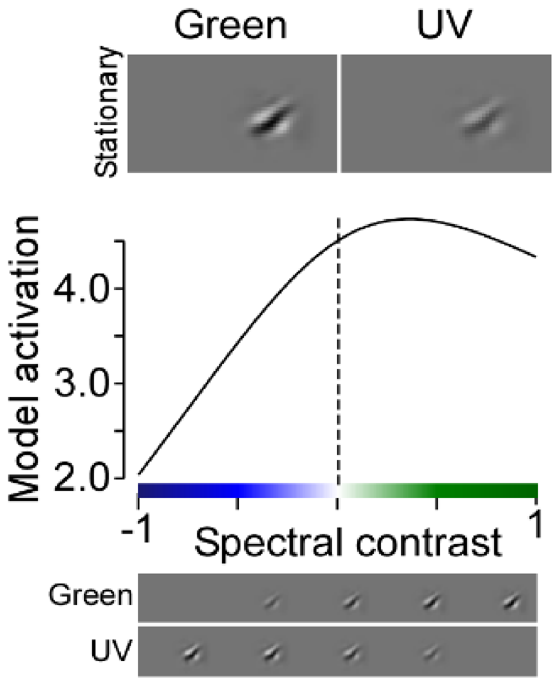
→ Predict neural responses as a function of both visual input and behavior

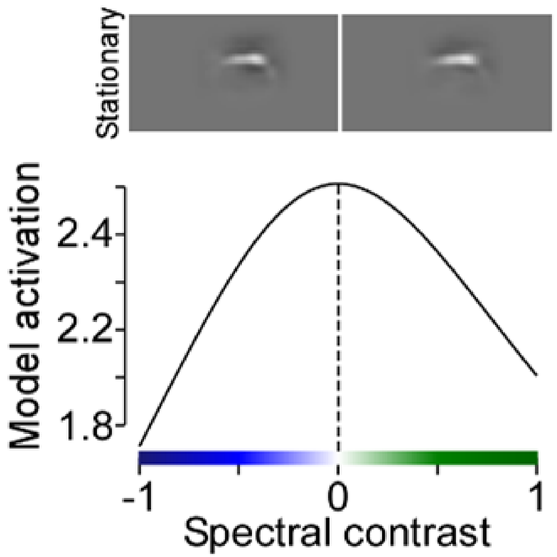
Most exciting images and closed loop confirmation

Modeling framework allows to systematically investigate chromatic processing and test predictions experimentally

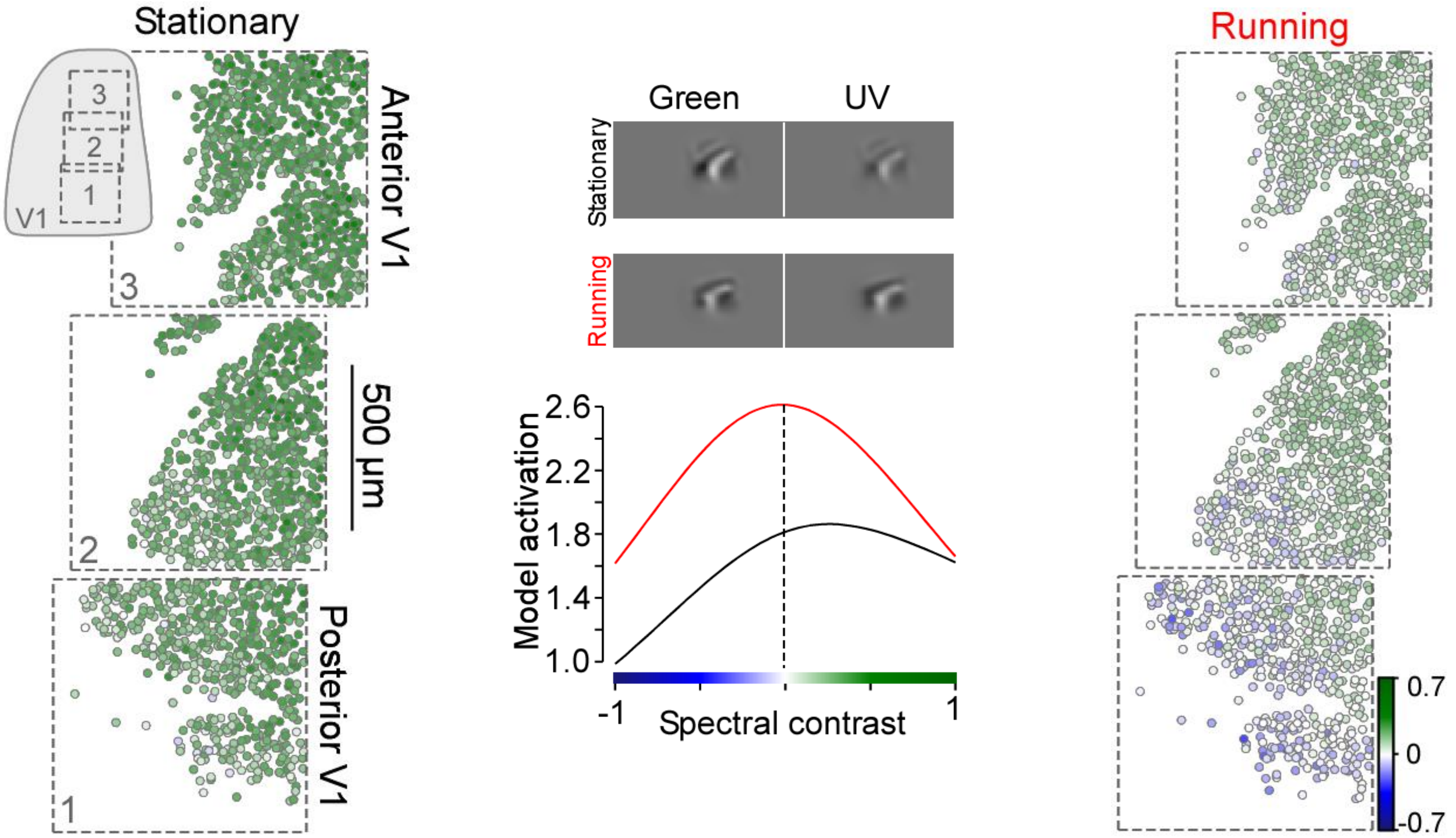


Generating in silico color tuning curves

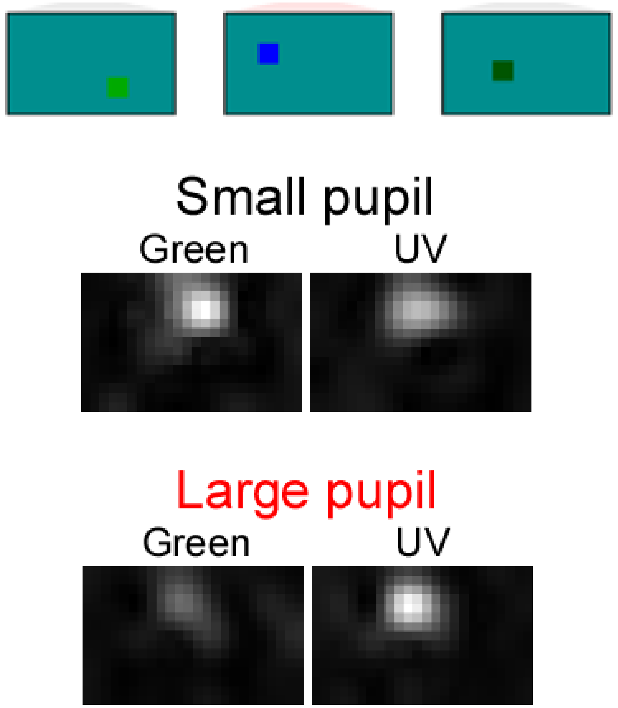


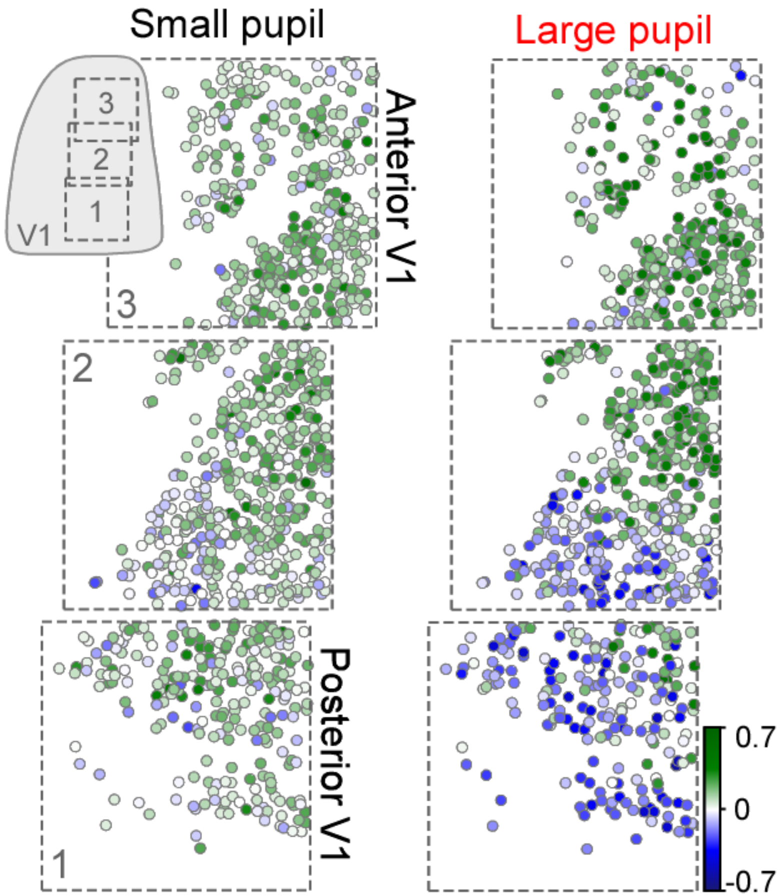


Color preference across mouse primary visual cortex

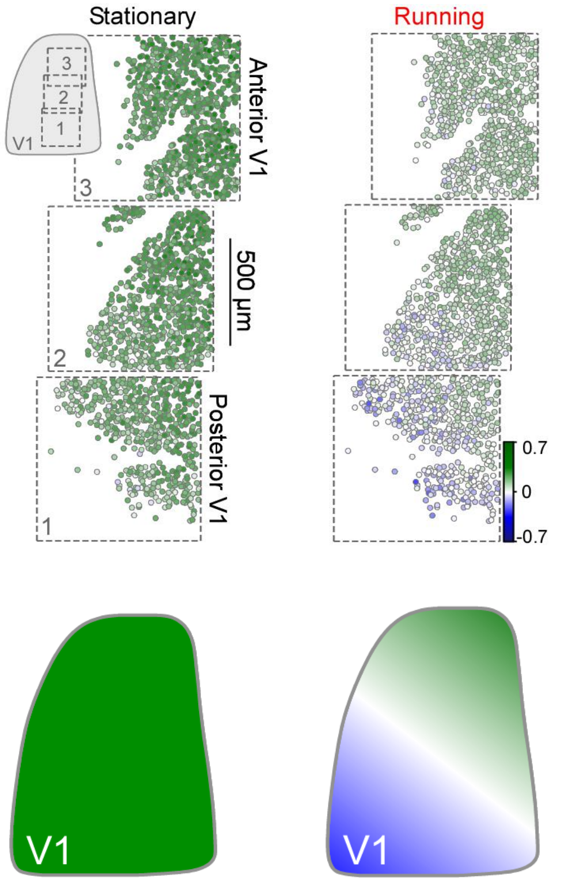


Confirmation of behavioral modulation using a colored dotmap



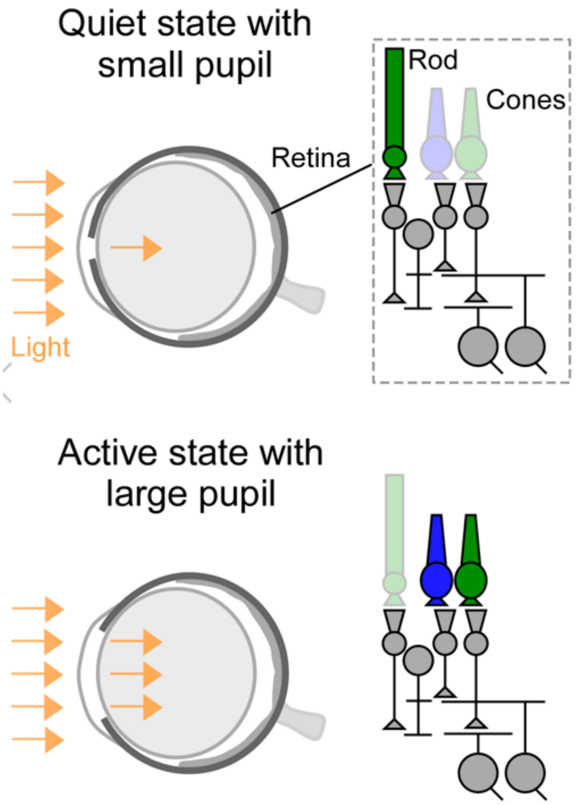


Mechanism underlying behavioral shift in stimulus selectivity – pupil size?

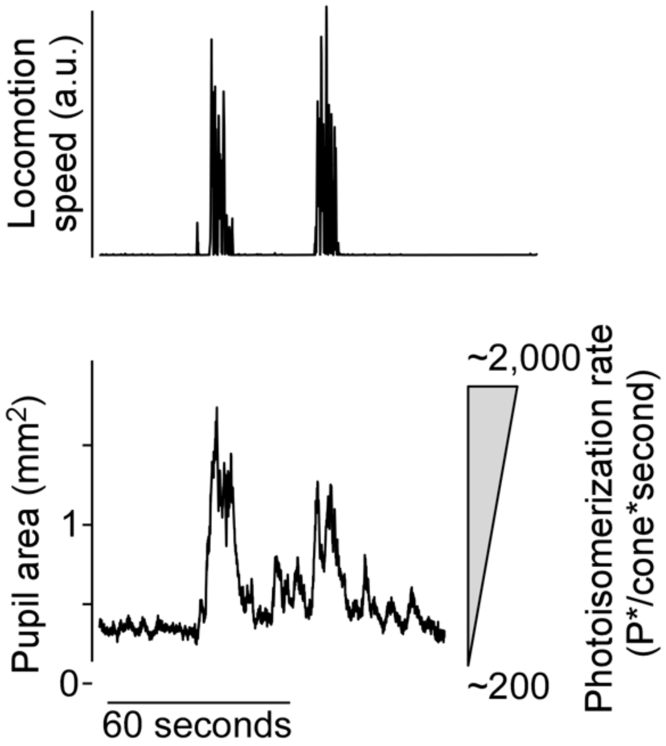


→ Rod-driven respones?

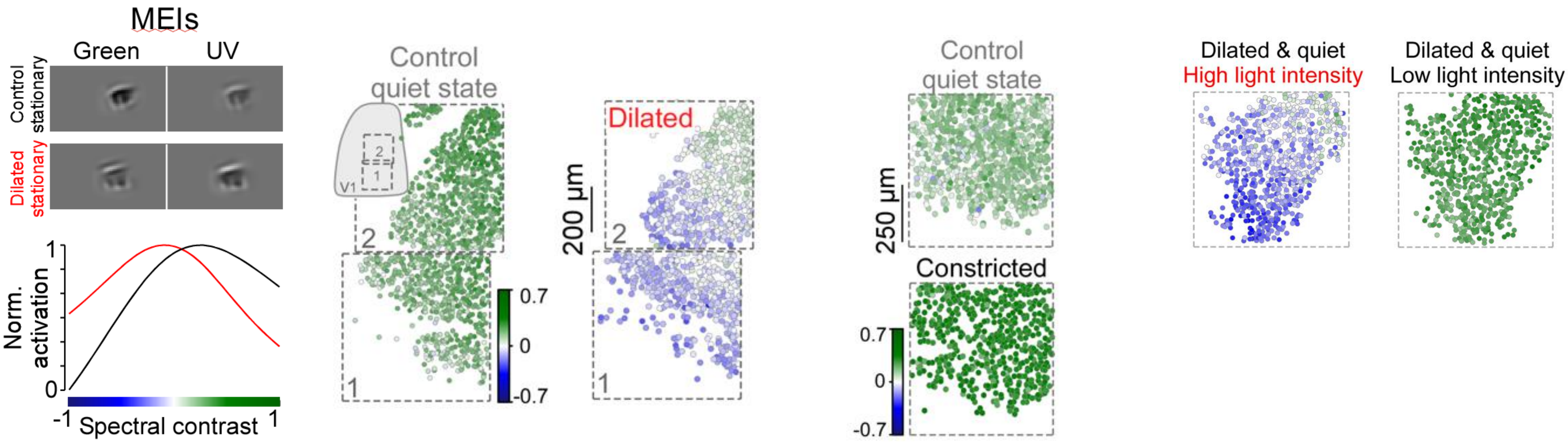
→ Cone-driven respones?



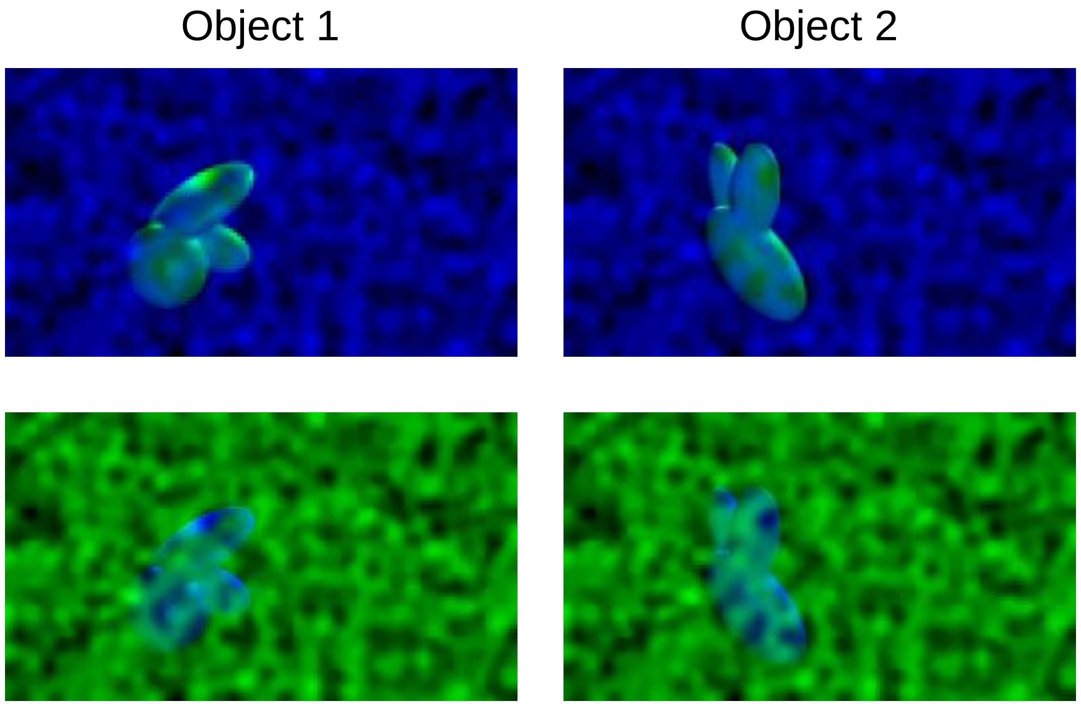
See also Rhim et al. 2021 Scientific Reports

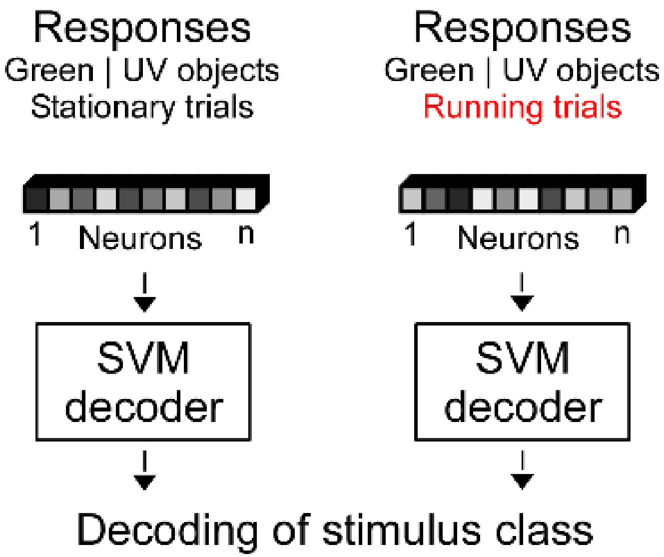


Mechanism underlying behavioral shift – changes in pupil size?



Decoding of colored objetcs





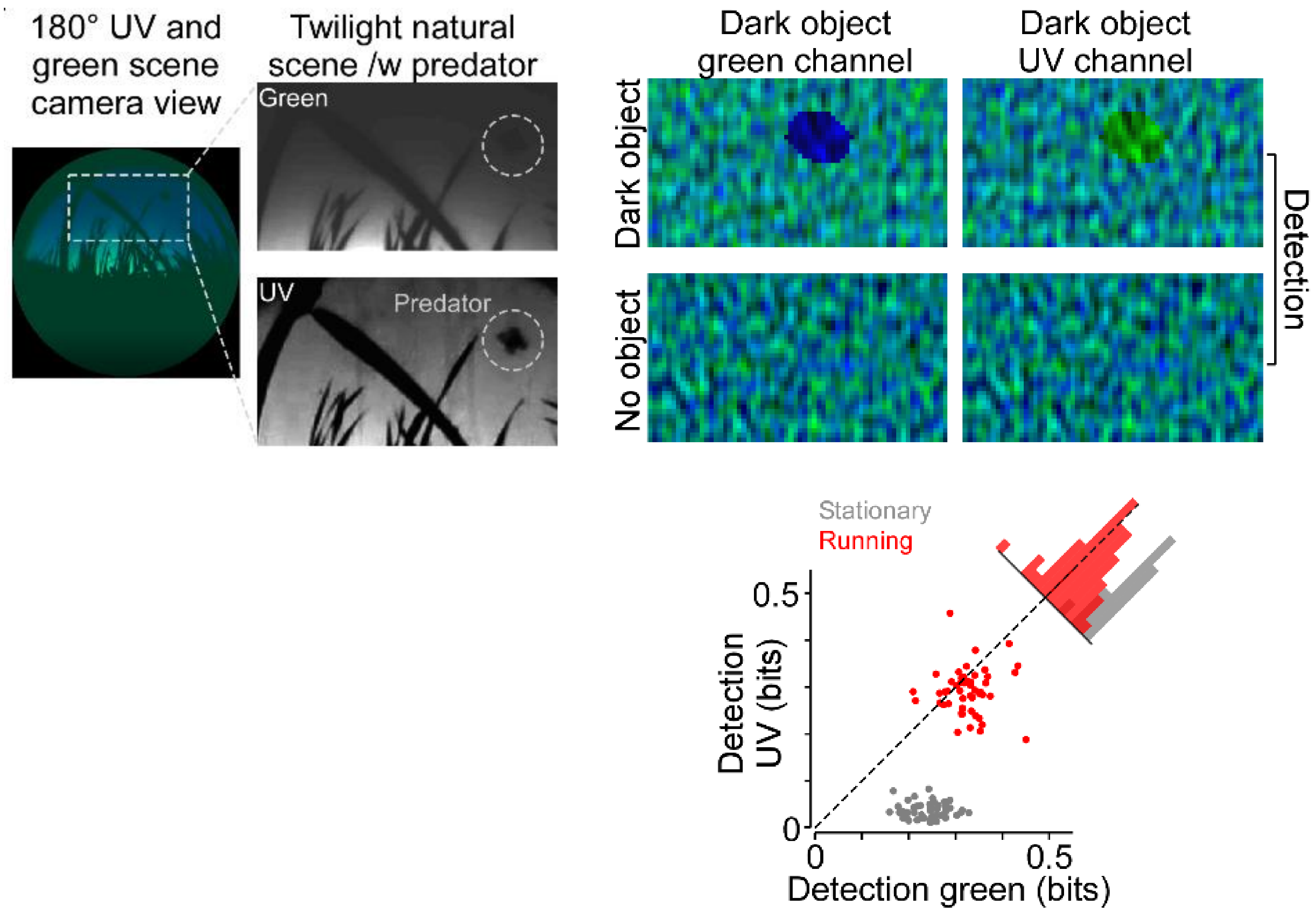
Hypothesis: Improved decoding for UV objects during running compared to stationary

Functional & behavioral relevance of shift in color preference?

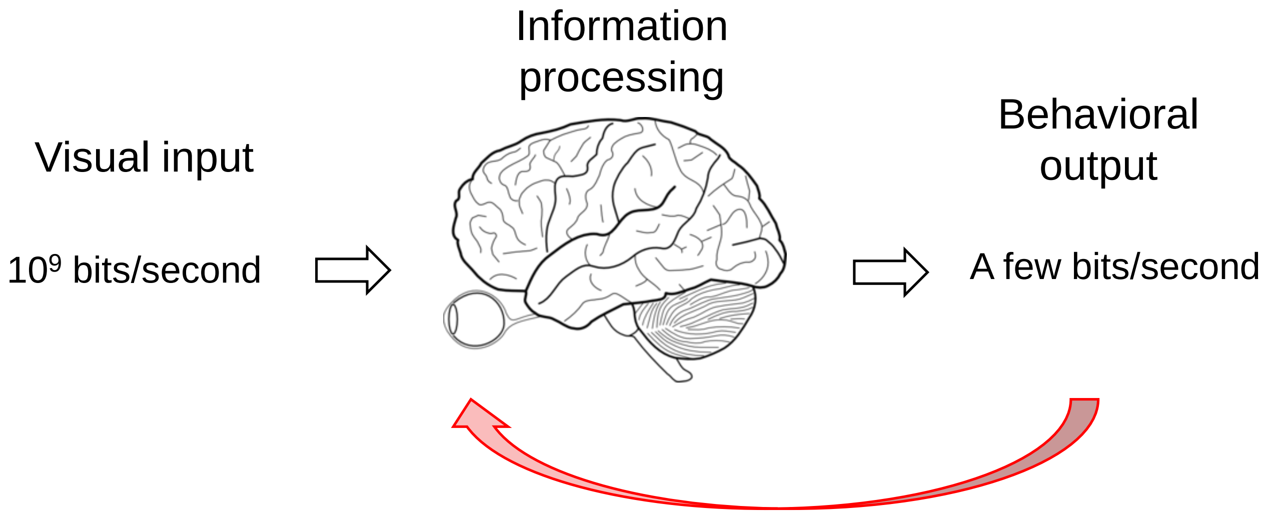
Qiu, Zhao, Klindt, Kautzky, Szatko, Schaeffel, Rifai, Franke, Busse, Euler. *Mouse retinal specializations reflect knowledge of natural environment statist*ics. Current Biology 2021

→ Higher UV sensitivity during arousal might facilitate the detection of aerial predators during dusk and dawn

Functional & behavioral relevance of shift in color preference?



Visual processing is modulated by behavior & brain state through pupil dilation



State-dependent modulation of pupil size changes photoreceptor recruitment, thereby dynamically tuning visual representations on short timescales

Acknowledgments

Konstantin Willek

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Andreas Tolias

Manolis Froudarakis

Jake Reimer

Mario Galdamez

Taliah Muhammad

Kayla Ponder

Saumil Patel

CIN
Werner Reichardt
Centrum für Integrative Neurowissenschaften

Forschungsinstitut für Augenheilkunde
Universitätsklinikum Tübingen

Bernstein Center for Computational Neuroscience Tübingen

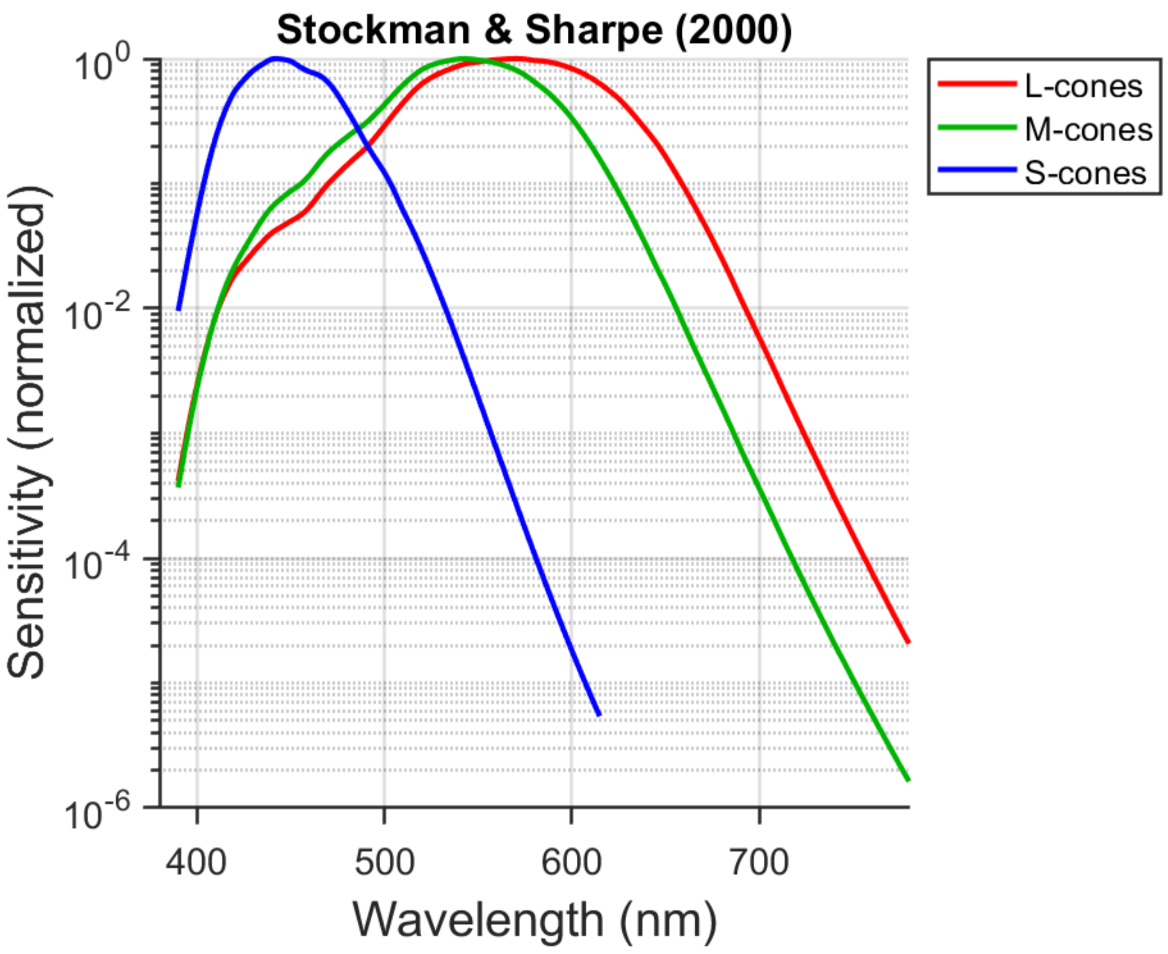
Cone spectral topography and vision at the cellular scale

William Tuten, OD PhD
Herbert Wertheim School of Optometry & Vision Science
University of California, Berkeley, USA
wtuten@berkeley.edu

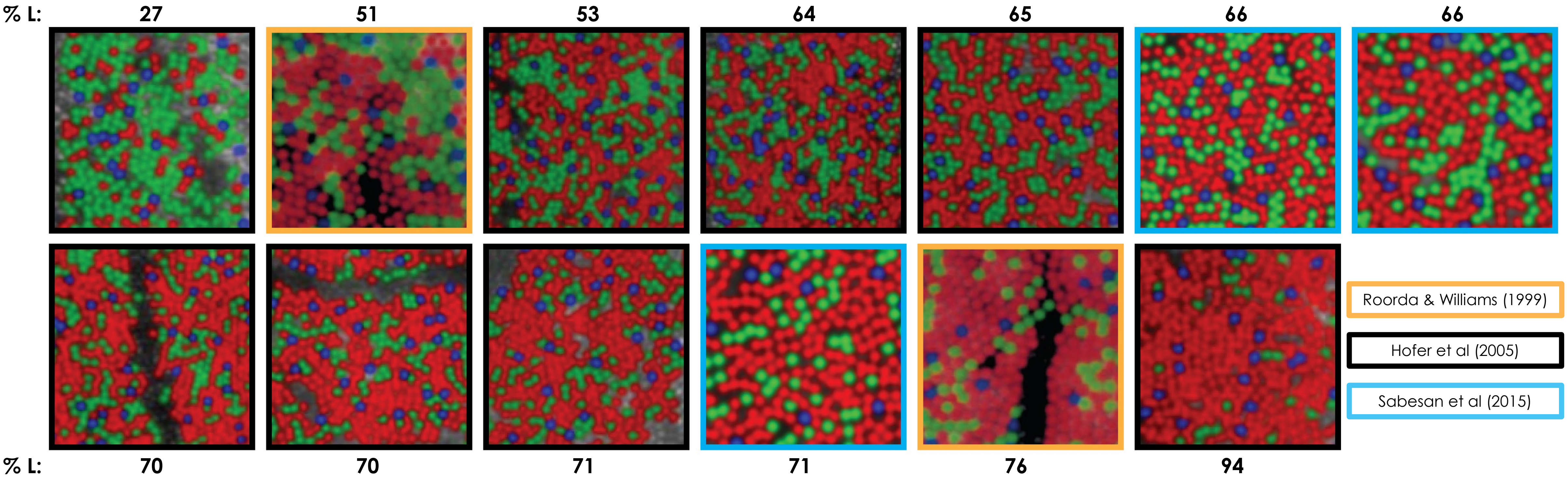
Optica webinar – 10 Dec 2021
No disclosures.

Berkeley Herbert Wertheim School of Optometry & Vision Science

Human color vision is trichromatic



The spectral topography of cones is nonuniform and the relative number of L and M cones varies substantially between individuals



How does vision depend on the spectral topography of the cone mosaic?

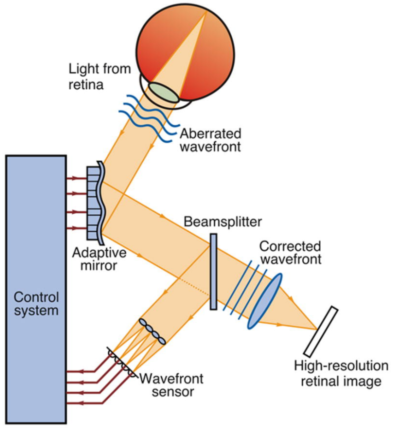
Answering this question definitively requires:

1. Knowledge of how the L, M, and S cones are arranged in the receptor lattice
2. Control over how those cones sample the retinal image

Retinal stimulation with adaptive optics scanning laser ophthalmoscopy (AOSLO)

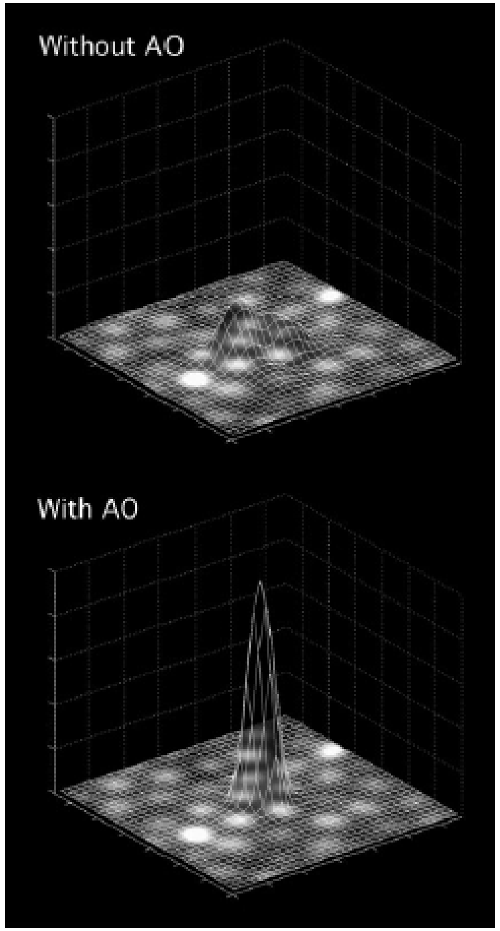
Key features

- Adaptive optics (AO):
  - measurement and correction of ocular aberrations
    - including chromatic aberrations
  - improved retinal image quality



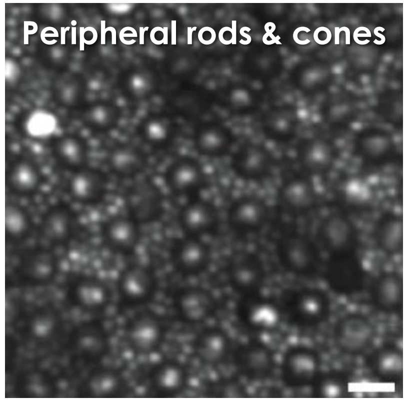
Godara et al. (2010)

Point spread functions

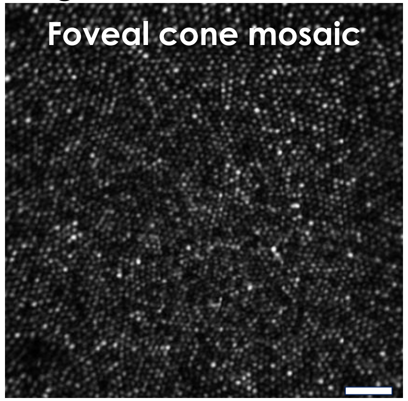


Makous et al. (2006)

Retinal images



Dubra & Sulai (2011)

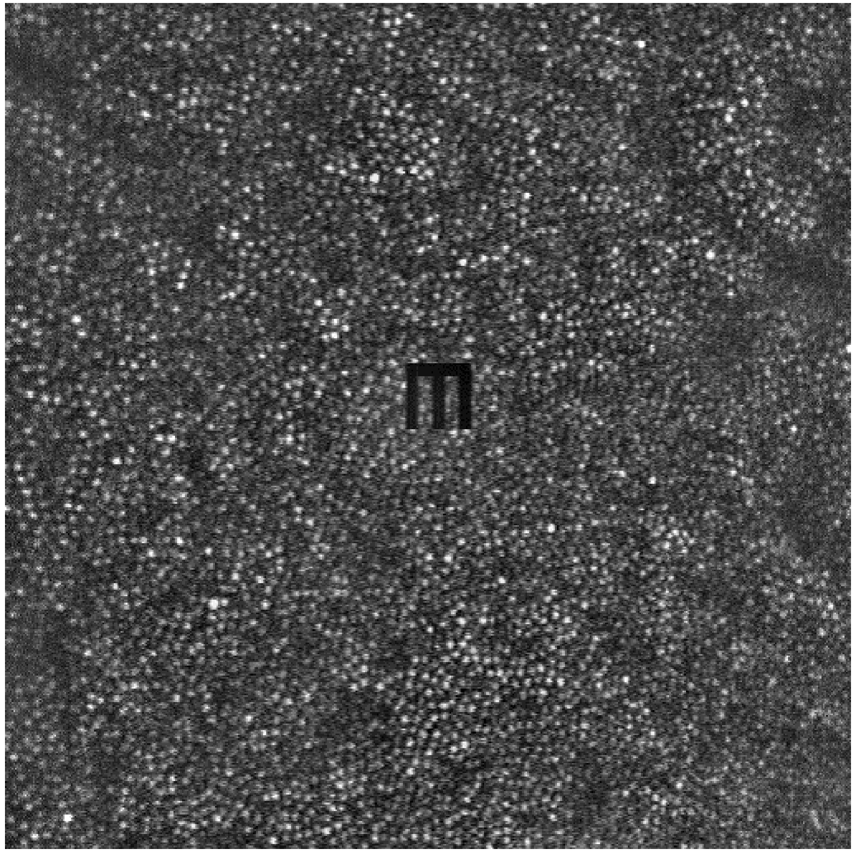


Dubra et al. (2011)

Retinal stimulation with adaptive optics scanning laser ophthalmoscopy (AOSLO)

Key features

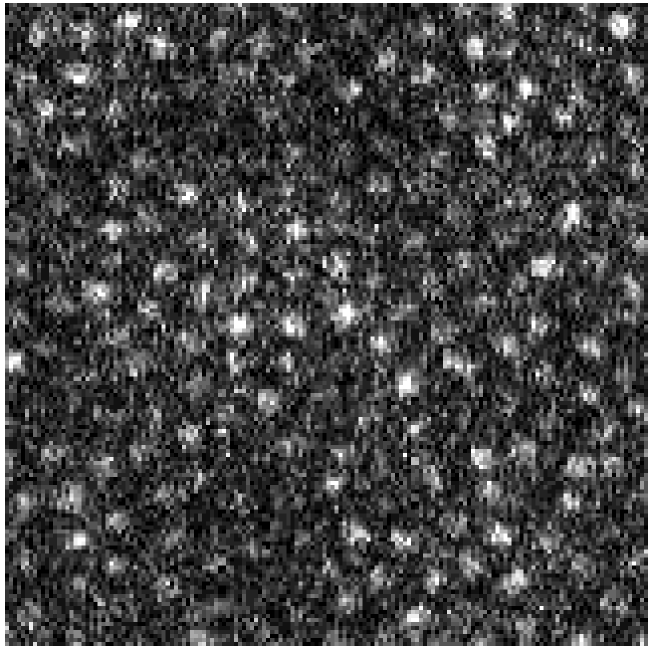
- Adaptive optics (AO):
  - measurement and correction of ocular aberrations
    - including chromatic aberrations
  - improved retinal image quality
- SLO imaging:
  - video-rate (30 Hz) imaging (**840** nm)
  - real-time eye tracking
  - dynamic, multi-λ (**543** & **680** nm) stimulus delivery via high-speed laser modulation



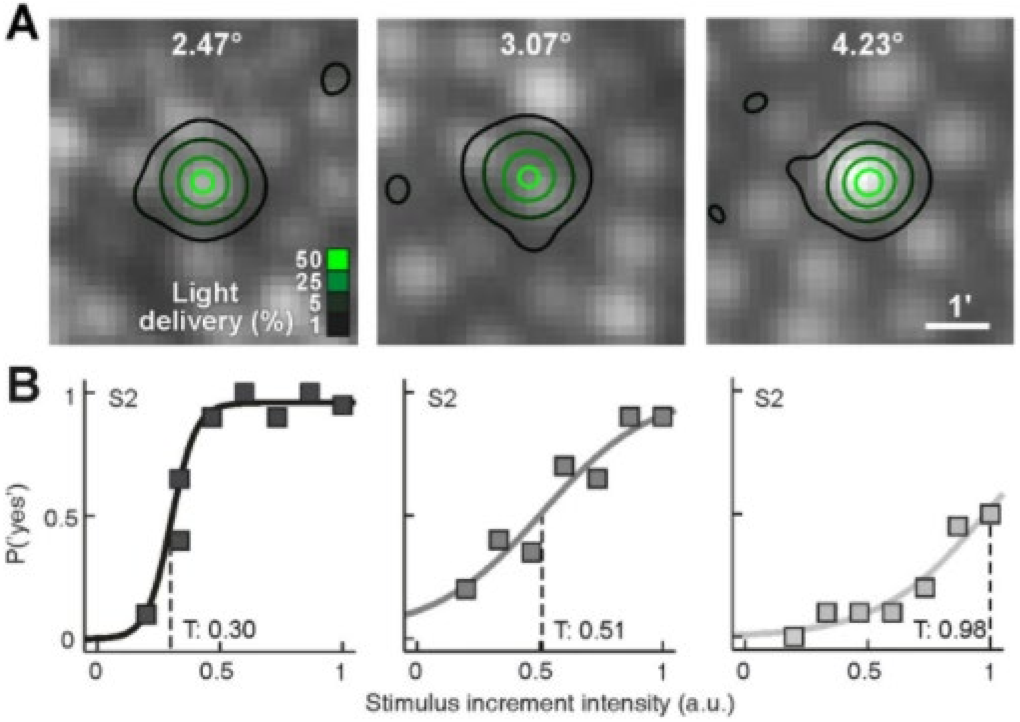
Roorda et al. (2002)
Poonja et al. (2006)
Grieve et al. (2006)
Arathorn et al. (2007)
Tuten et al. (2012)
Harmening et al. (2012)

Single-cone psychophysics

Single-cone stimulation (λ = **543 nm**)



Retinal light spread & psychometric functions

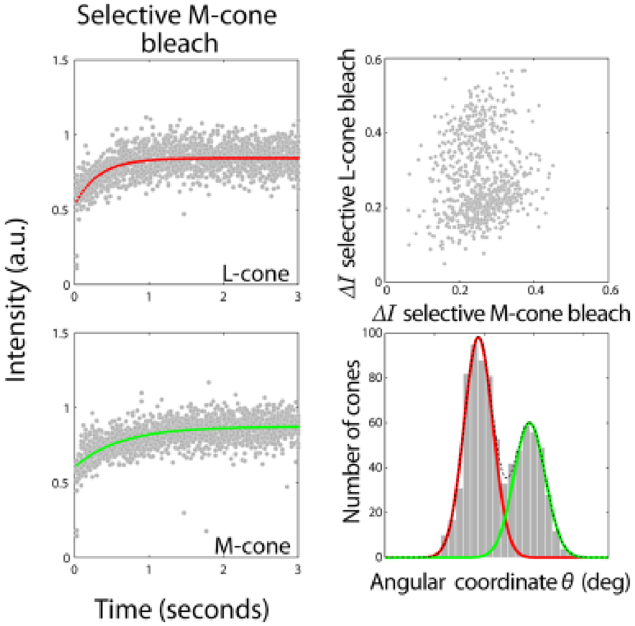


Harmening*, Tuten*, Roorda, Sincich. *J Neurosci. (2014)*

Spectral classification of human cones: two approaches

AO densitometry:

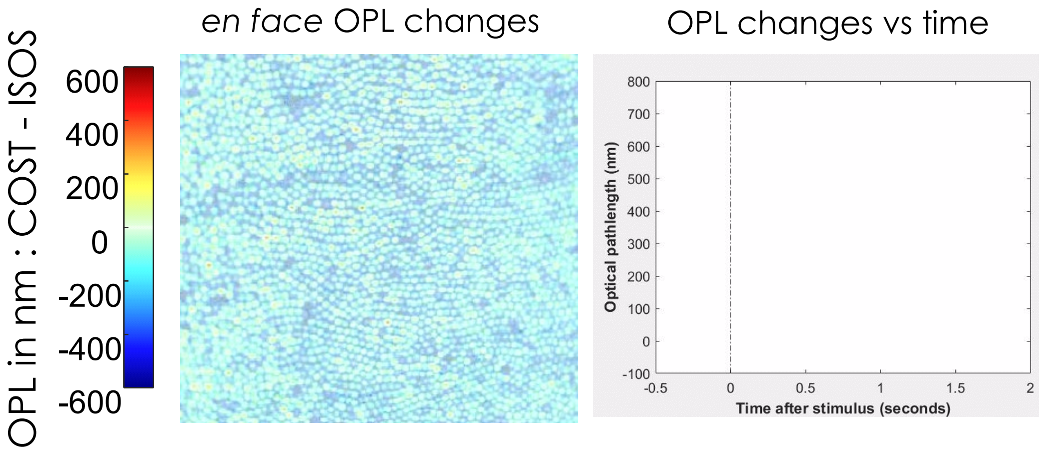
Dynamic photoreceptor **intensity changes** during reflectance imaging are indicative of cone type



Sabesan et al. (2015)
Hofer et al. (2005)
Roorda & Williams (1999)

AO optoretinography:

Stimulus-induces changes in outer segment **optical path length (OPL)** measured using AO-OCT delineate cone types



Pandiyan et al. (2020)
Zhang et al. (2019)

ORG videos courtesy of Ram Sabesan, Univ. of Washington

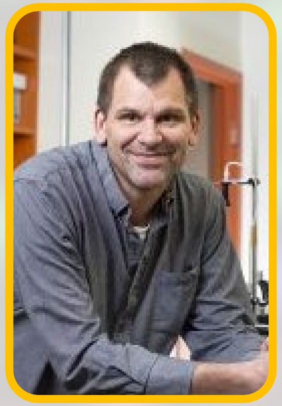
How does vision depend on the spectral topography of the cone mosaic?

1. Detection

2. Color appearance

Wolf Harmening, PhD
Univ. of Bonn

Ramkumar Sabesan, PhD
Univ. of Washington

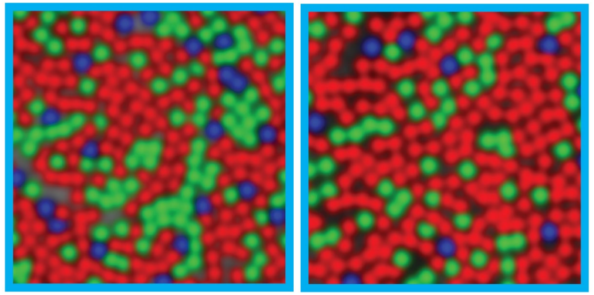


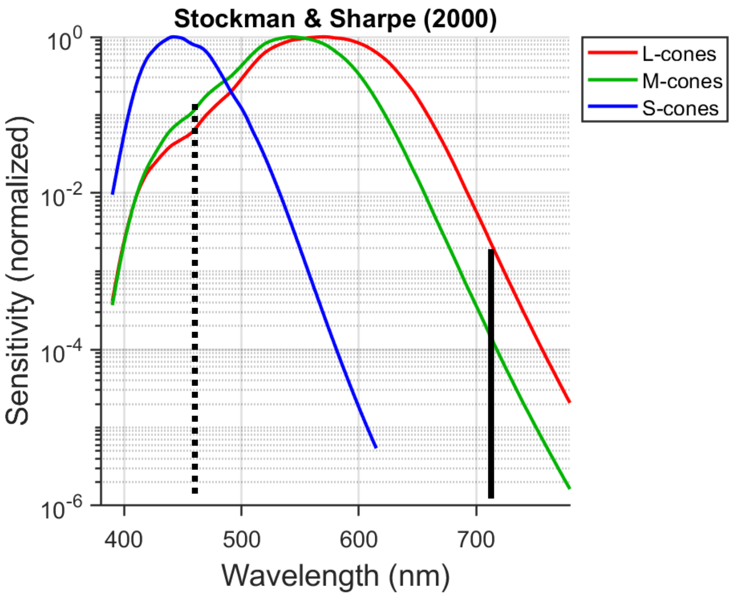
Austin Roorda, PhD
UC Berkeley

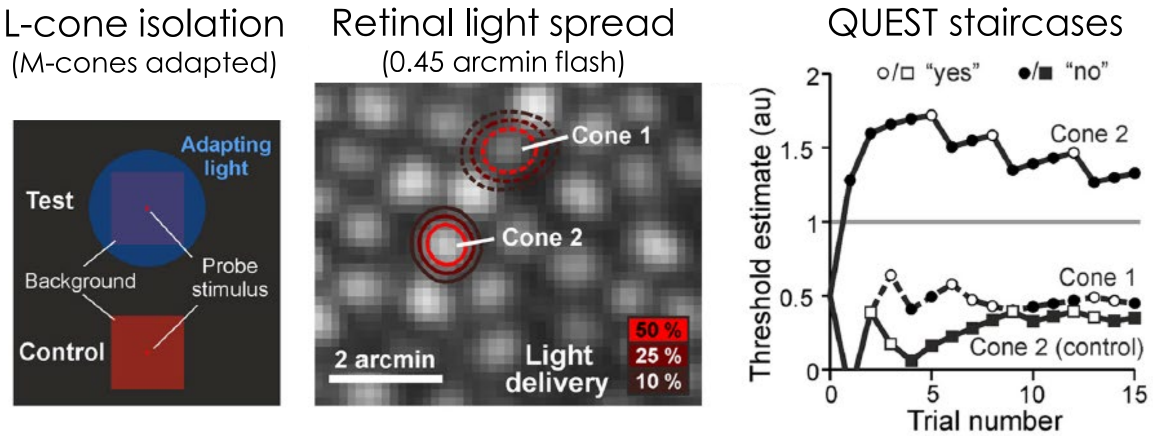
Lawrence Sincich, PhD
UAB

Goal: psychophysical classification of single-cones

Densitometric classification (**ecc = 1.5°**)
Sabesan et al (2015)







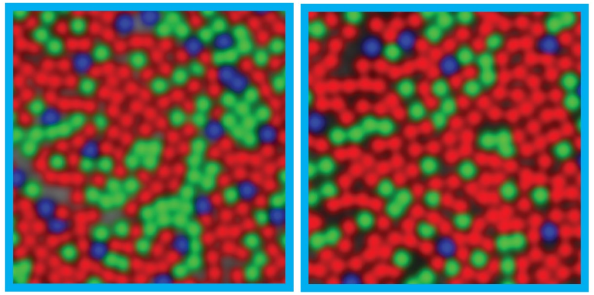
Worse sensitivity

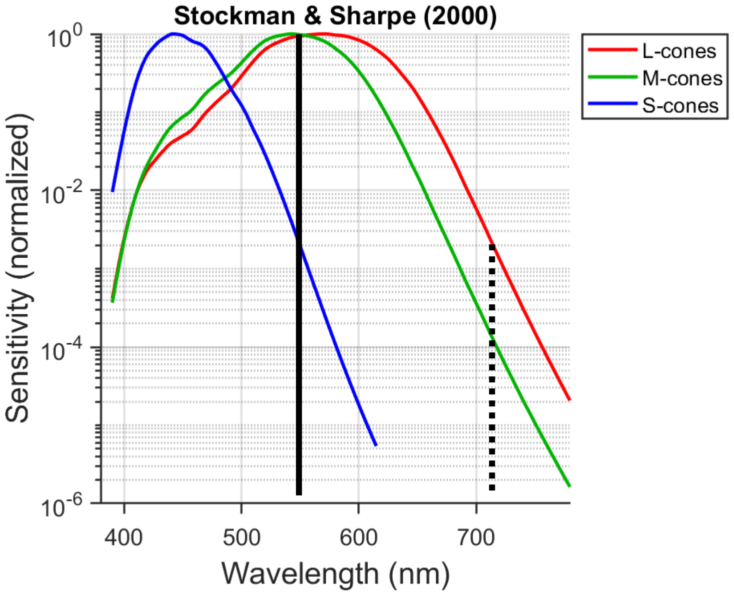
Better sensitivity

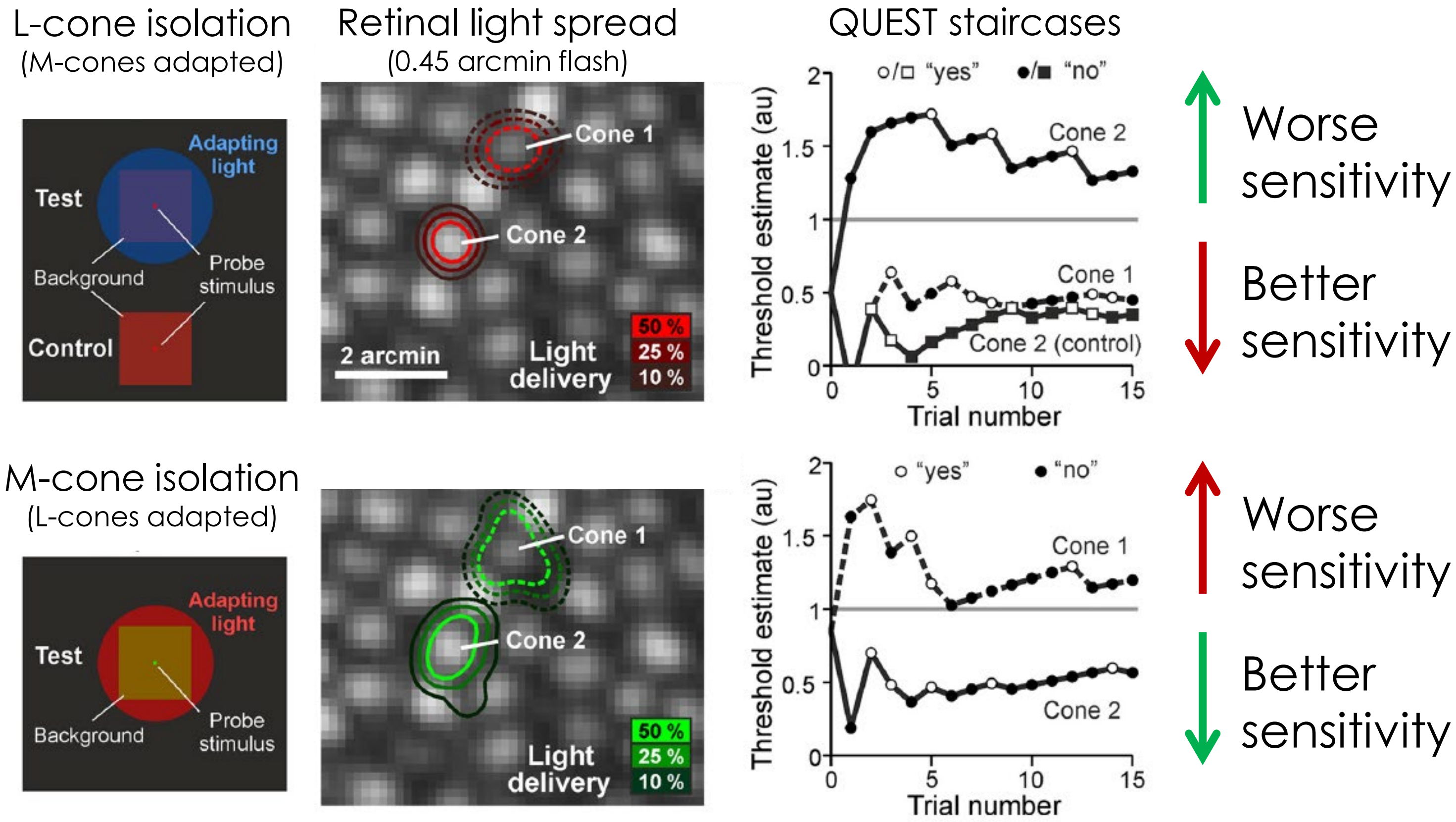
Tuten*, Harmening*, Sabesan, Roorda, Sincich. *J Neurosci.* (2017)

Goal: psychophysical classification of single-cones

Densitometric classification (**ecc = 1.5°**)
Sabesan et al (2015)



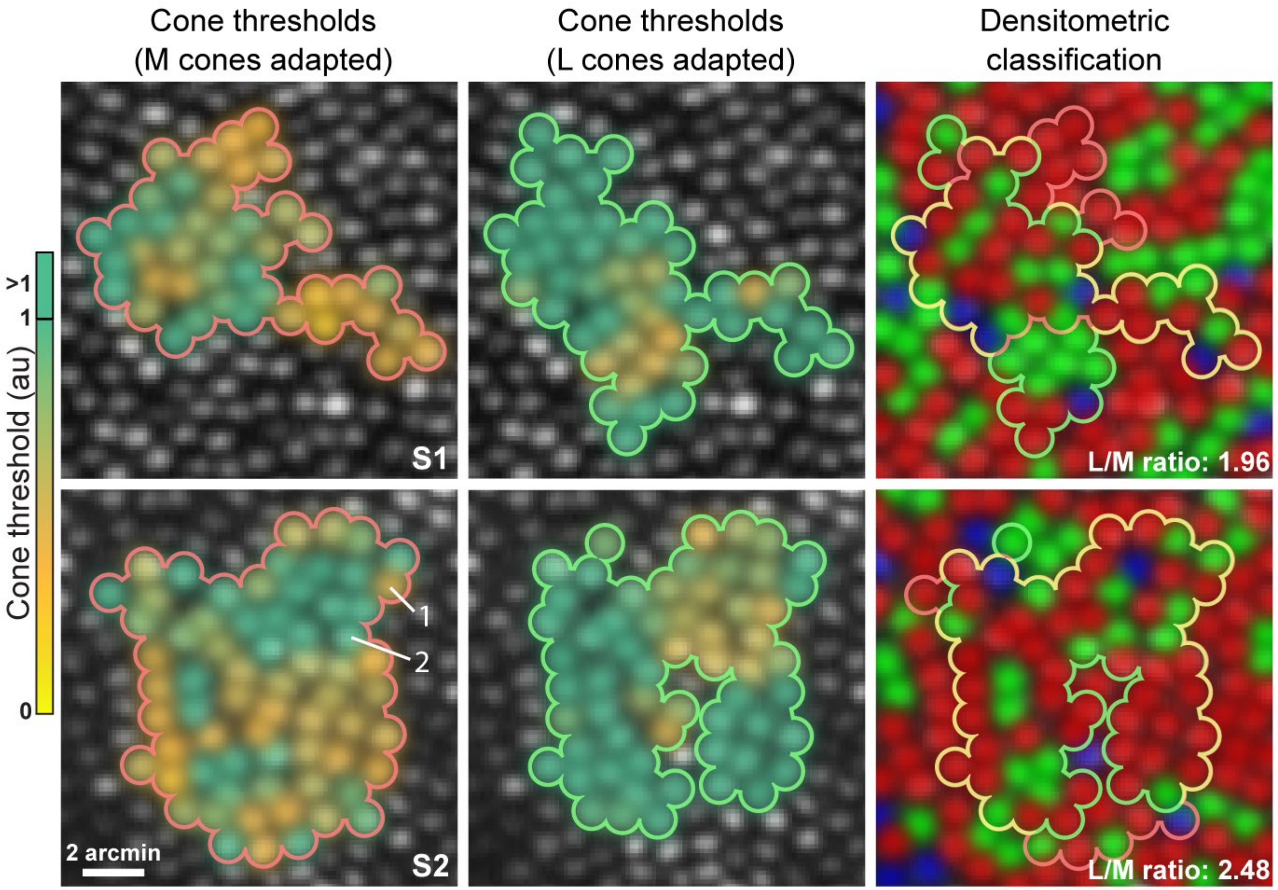




Tuten*, Harmening*, Sabesan, Roorda, Sincich. *J Neurosci.* (2017)

Result: cone thresholds do not cluster into distinct groups

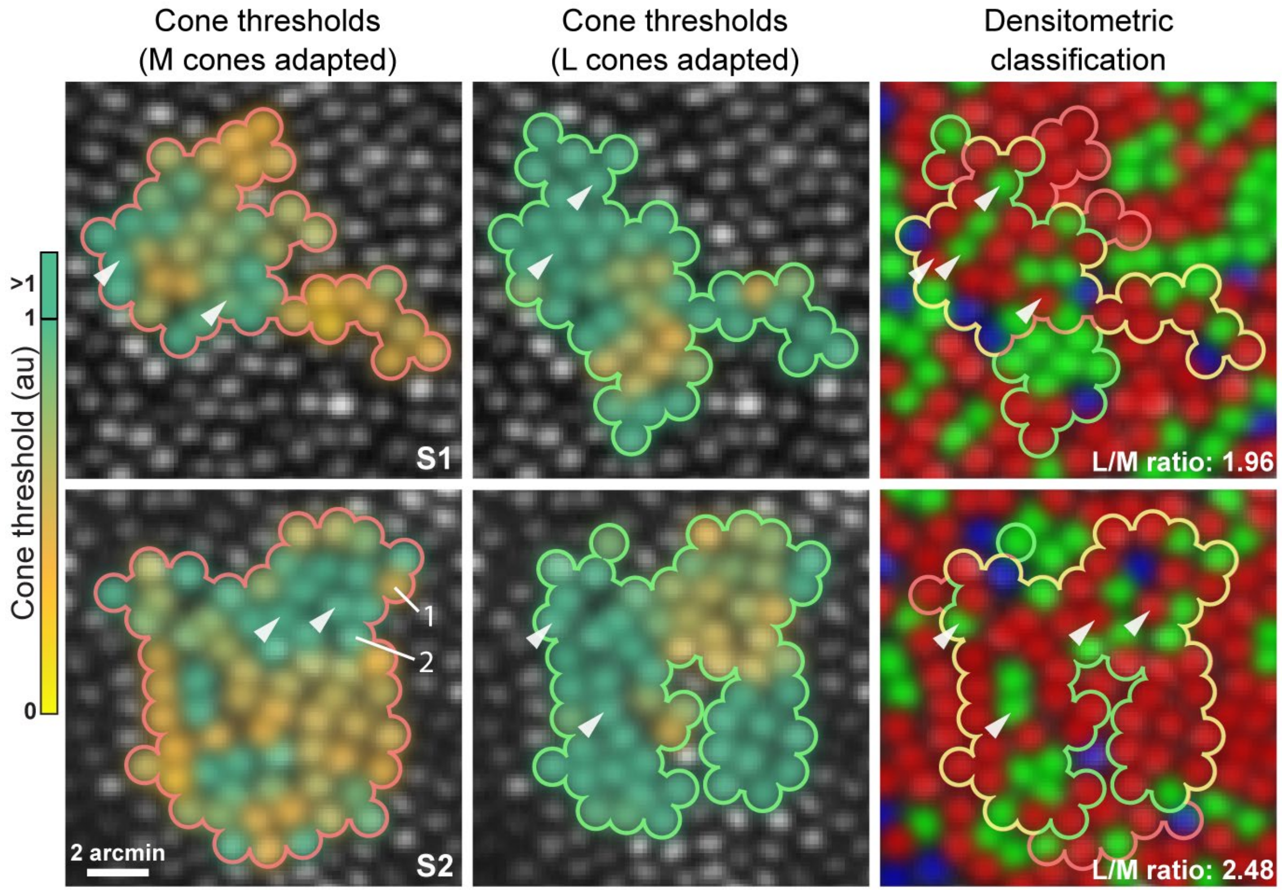
77% agreement between psychophysical and densitometric classifications.



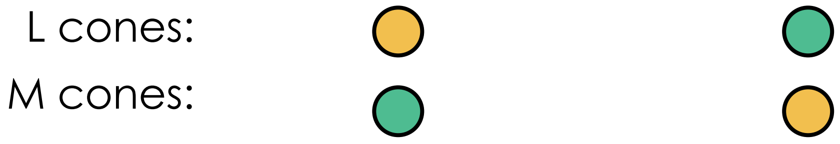
Predicted thresholds L cones:
M cones:

Tuten*, Harmening*, Sabesan, Roorda, Sincich. *J Neurosci*. (2017)

Result: cones surrounded by receptors sensitive to the adapting wavelength exhibit high thresholds

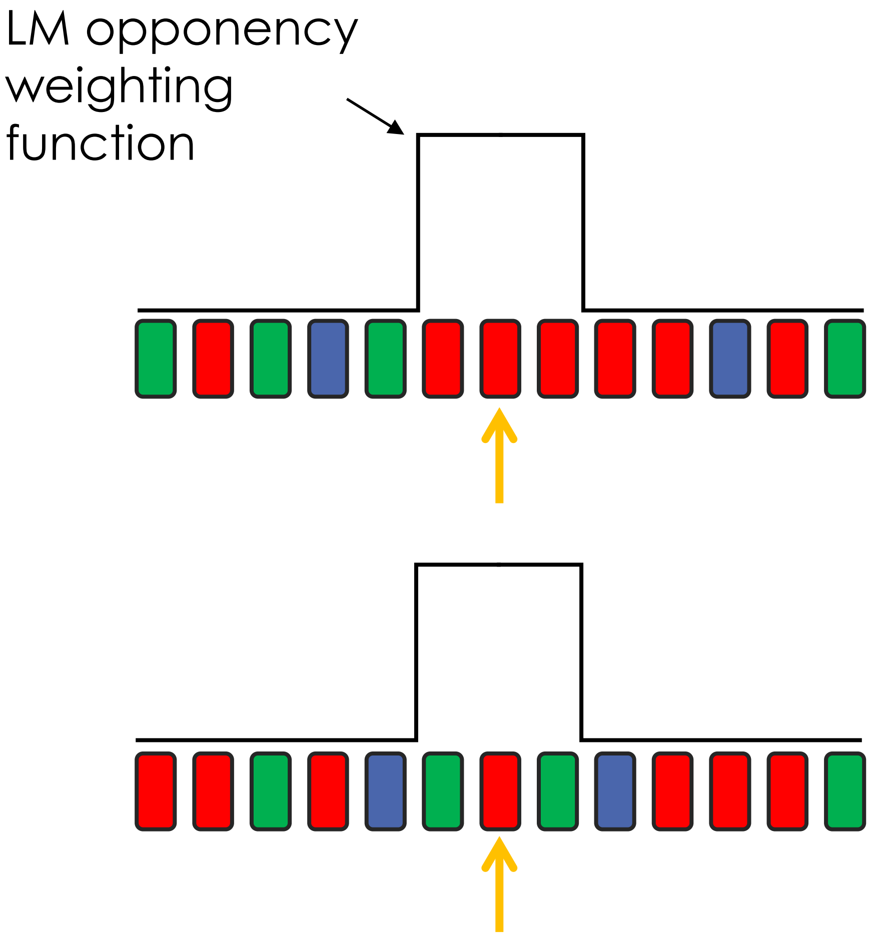


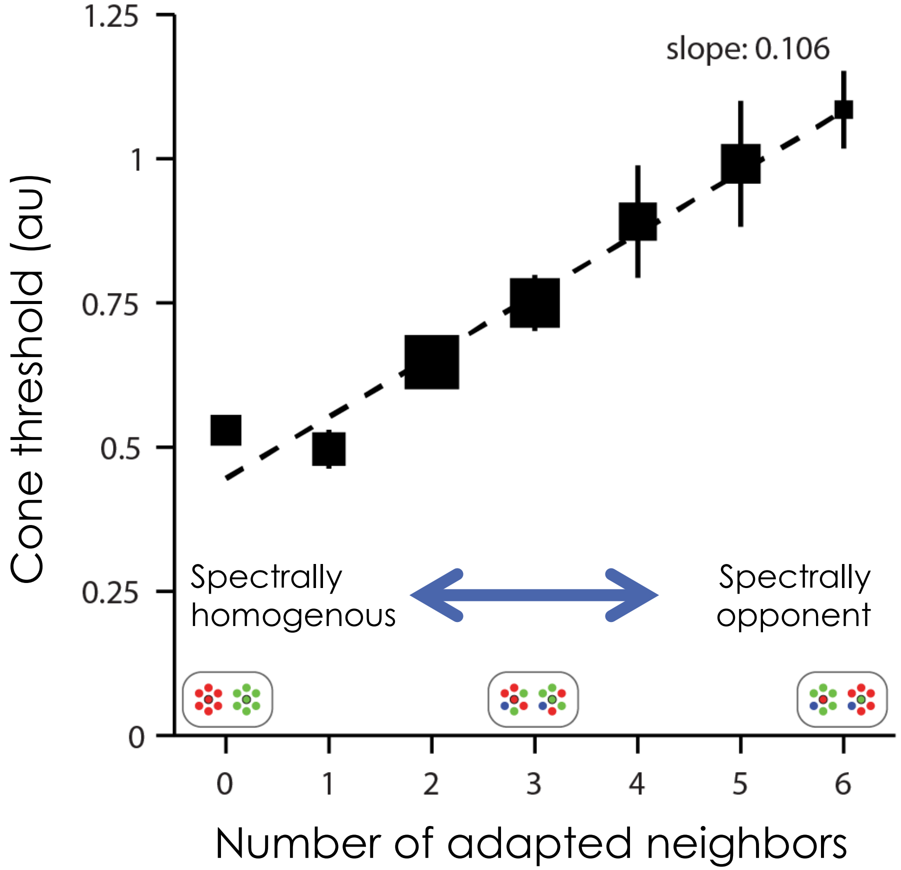
Predicted thresholds



Tuten*, Harmening*, Sabesan, Roorda, Sincich. *J Neurosci*. (2017)

Cone thresholds correlate with local spectral demographics

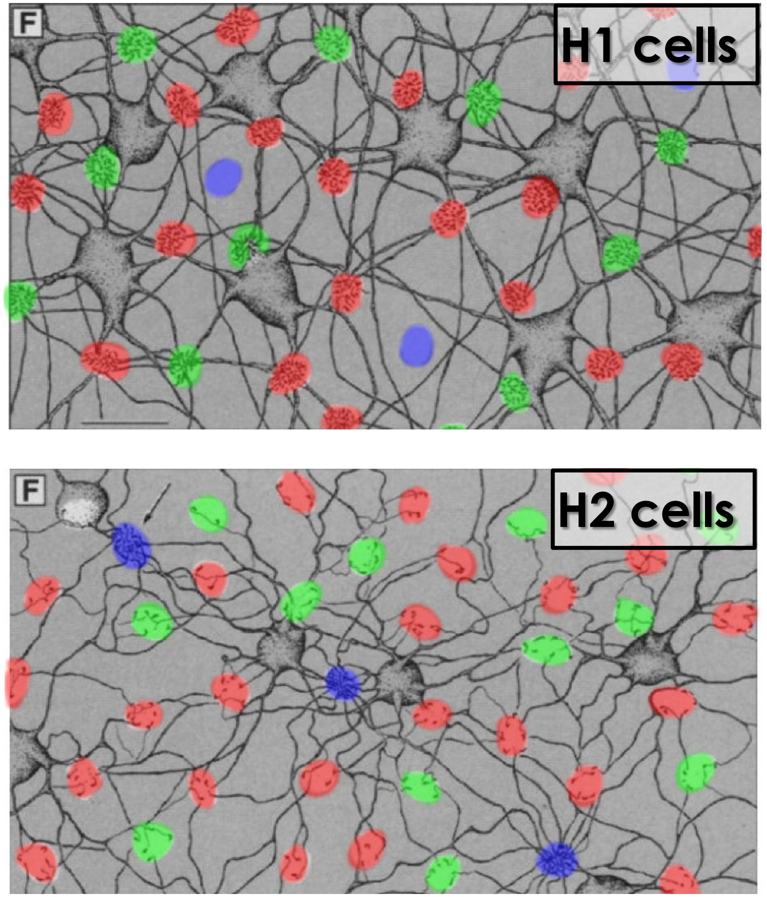




Tuten*, Harmening*, Sabesan, Roorda, Sincich. *J Neurosci*. (2017)

Summary, Pt 1 – Detection

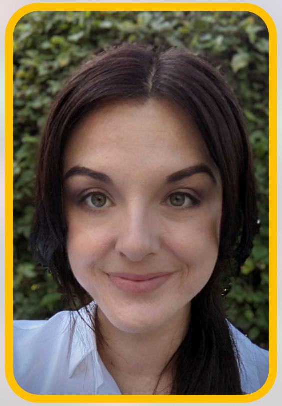
- Measured against chromatic adapting fields, single-cone thresholds depend on both the photopigment of the targeted cone and the spectral makeup of the immediate neighborhood
- The spatial and spectral pattern of the lateral interactions resemble the anatomical dimensions and cone-type wiring patterns of H1 and H2 horizontal cells, suggesting a potential neural basis for the inhibitory effects we observed



adapted from Dacey et al, 1996

How does vision depend on the spectral topography of the cone mosaic?

1. Detection



Ally Boehm, PhD

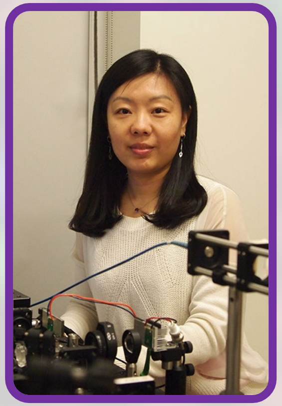
John Erik Vanston, PhD

Austin Roorda, PhD

UC Berkeley

2. Color appearance






Ramkumar Sabesan, PhD

Vimal Pandiyan, PhD

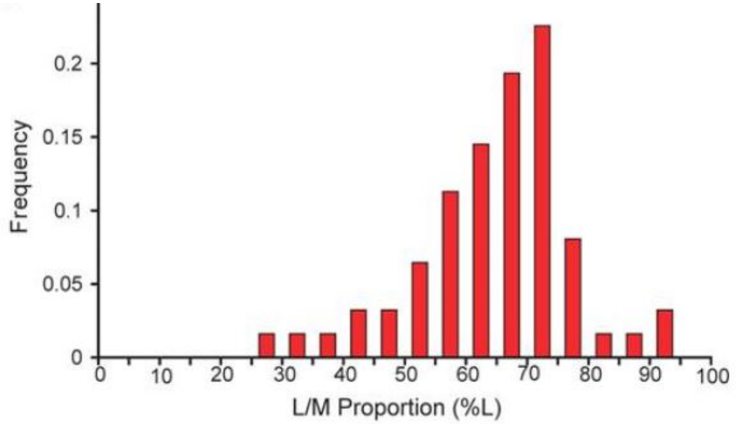
Xiaoyun Jiang, PhD

Sierra Schleufer

University of Washington

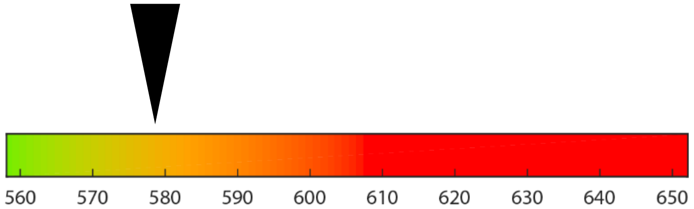
For large stimuli, the wavelength of unique yellow is remarkably robust to individual variations in L:M cone ratio

L:M numerosity estimated by ERG

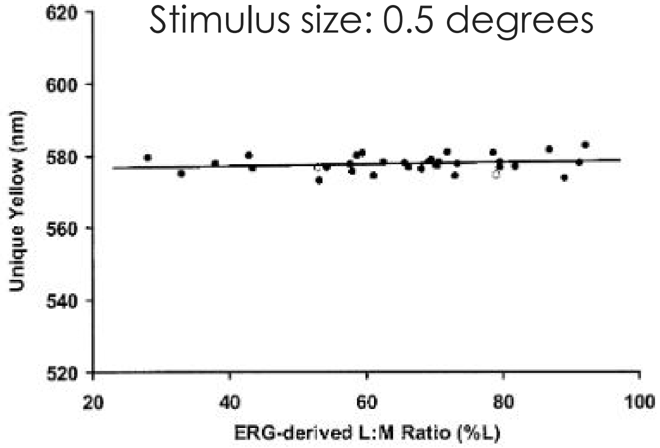


Carroll, Neitz, & Neitz. (2002)

<u>Unique yellow</u>: a yellow that contains no trace or redness or greenness



Wavelength (nm)



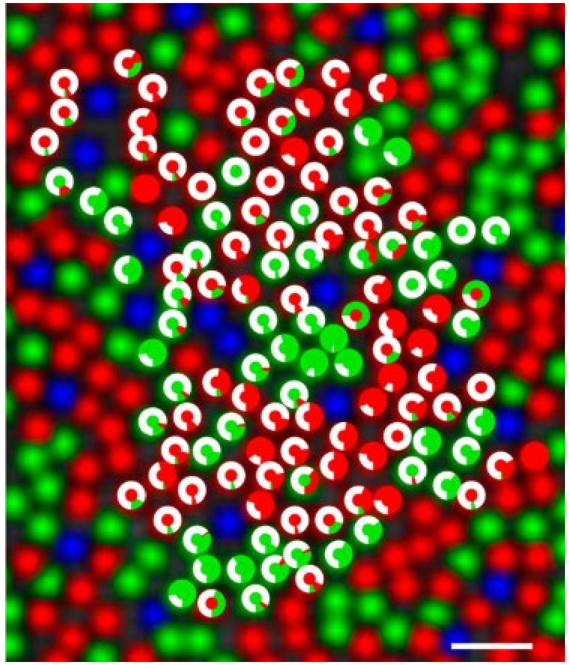
Neitz et al. (2002)
see also: Brainard et al. (2000)

Adaptation studies suggest the wavelength of unique yellow may reflect tuning to the spectral characteristics of the environment.

cf. Neitz et al. (2002) & Welbourne, Morland, Wade (2015)

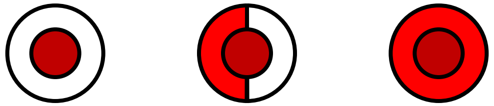
At the cellular scale, color signals are ambiguous and color perception can be highly non-veridical

Color naming data: λ = 543 nm

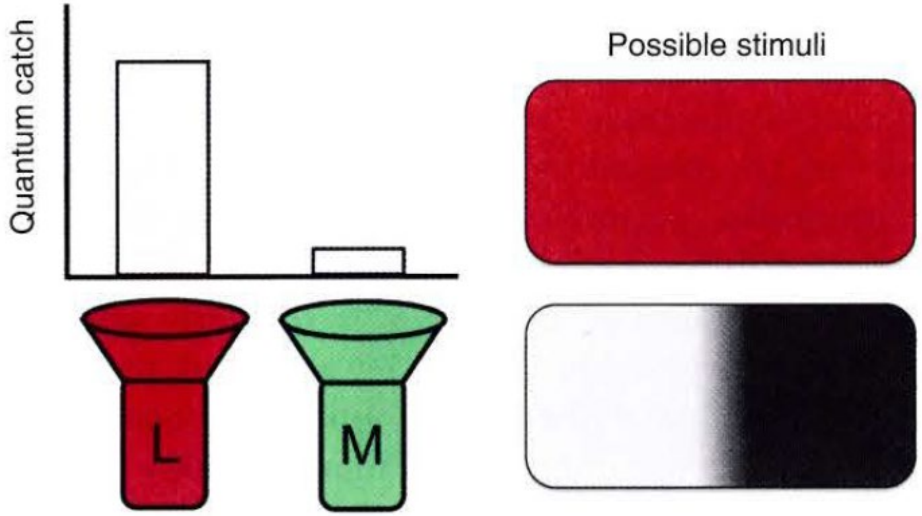


Response Options:

Donut Histograms:



100% white (achromatic) | 50% white 50% red | 100% red

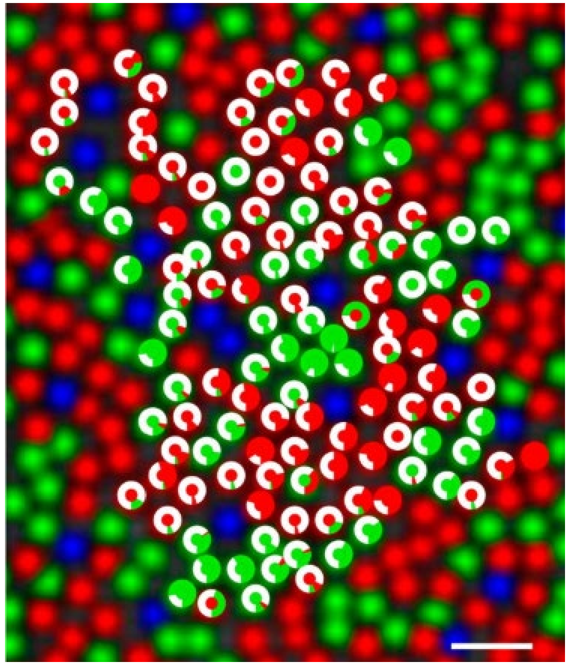


Hofer & Williams (2014)

Sabesan, et al. *Science Advances*. (2016)
see also: Hofer, Singer, Williams. *JOV*. (2005)

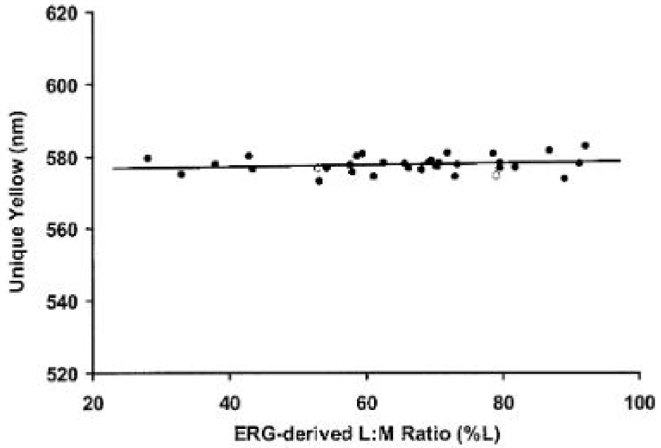
At what scale do the mechanisms that compensate for the L:M cone ratio operate?

Small spots (<1 arcmin)



Sabesan, et al. *Science Advances*. (2016)
see also: Hofer, Singer, Williams. *JOV*. (2005)

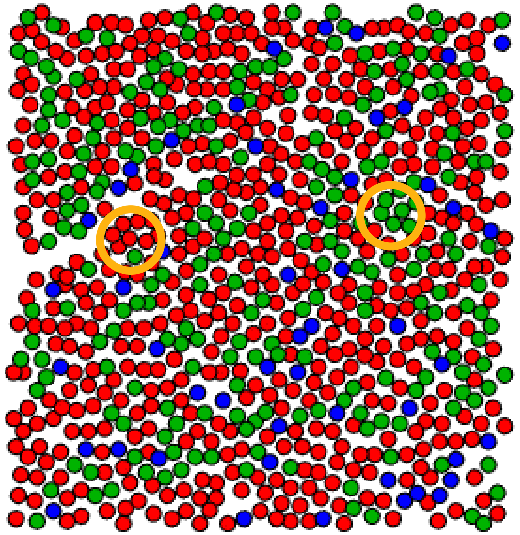
Larger spots (≥0.5 degrees)



Neitz et al. (2002)
see also: Brainard et al. (2000)

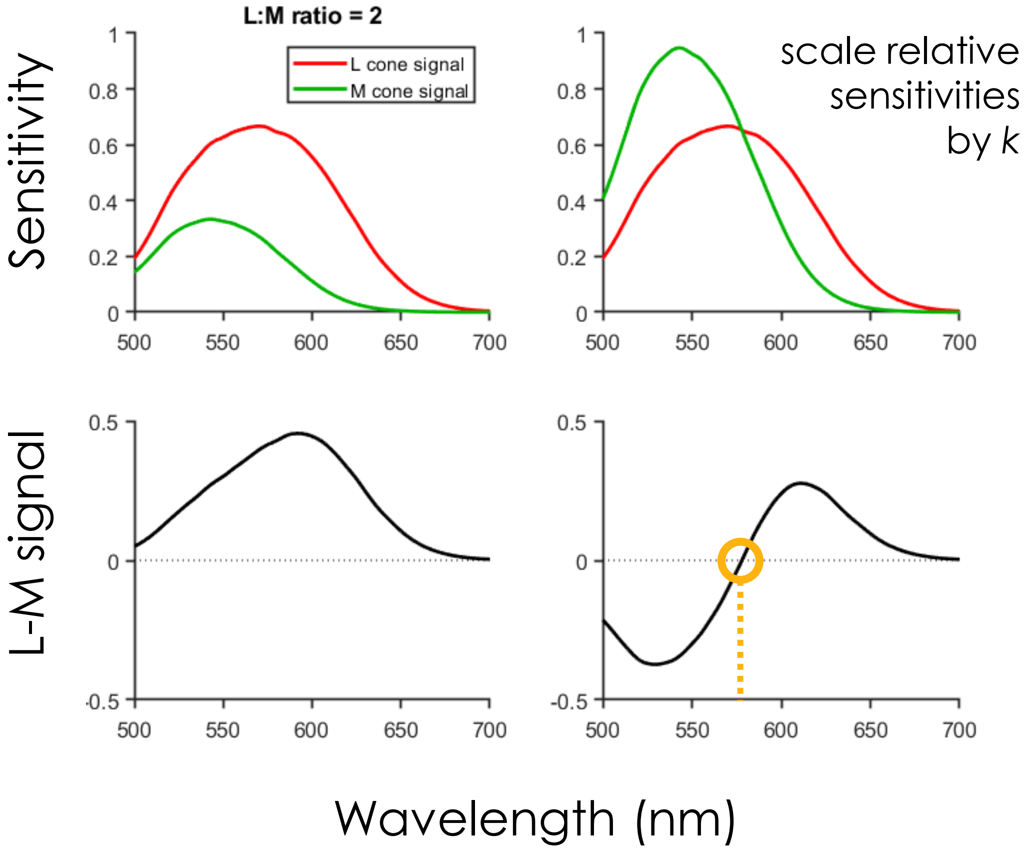
At what scale do the mechanisms that compensate for the L:M cone ratio operate?

L:M ratio = 2

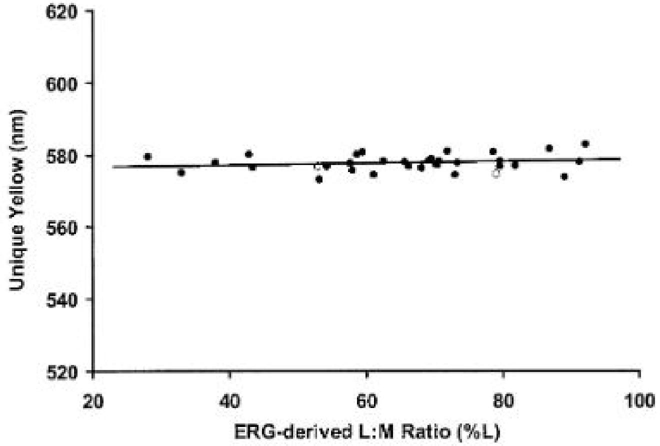


578 nm appears **too green**
(UY shifts to longer λ)

578 nm appears **too red**
(UY shifts to shorter λ)



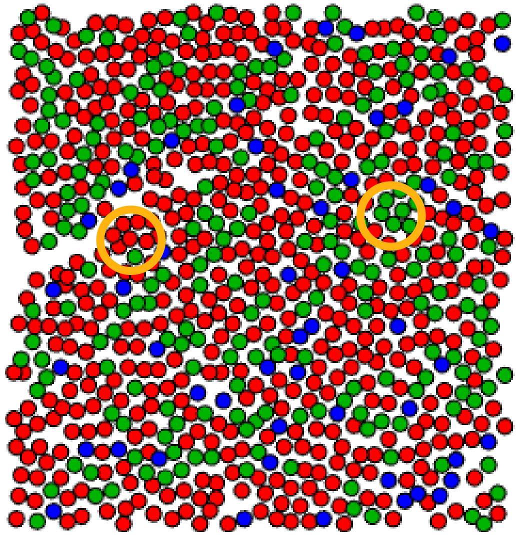
Larger spots (≥0.5 degrees)



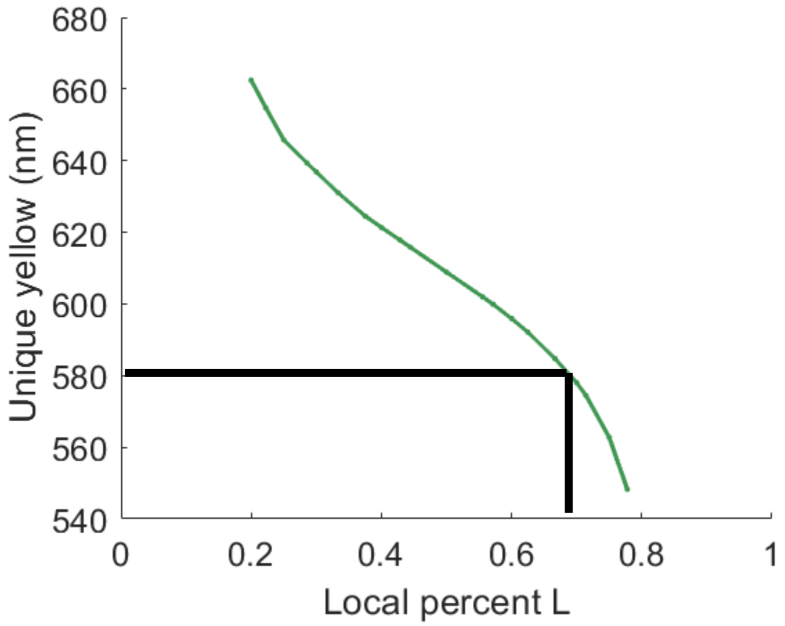
Neitz et al. (2002)
see also: Brainard et al. (2000)

L-M signal normalization: local vs global

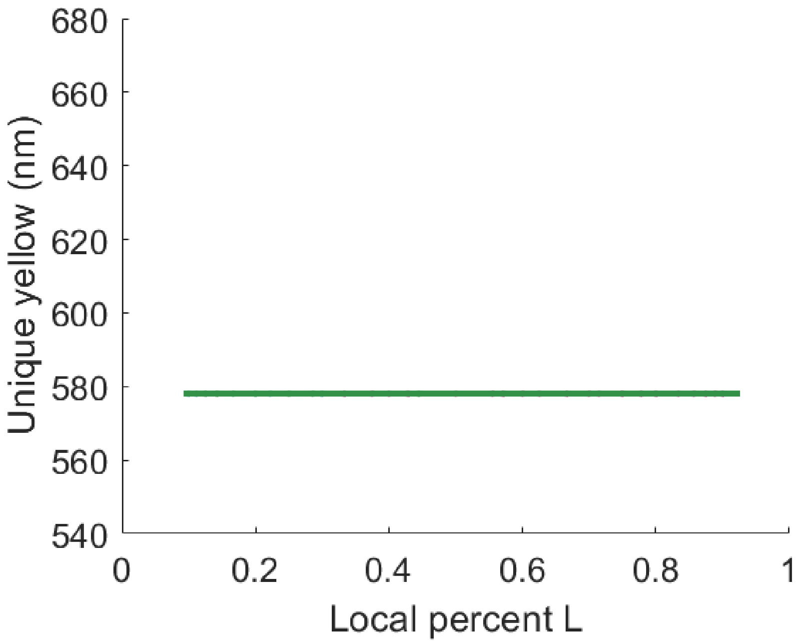
L:M ratio = 2



global compensation

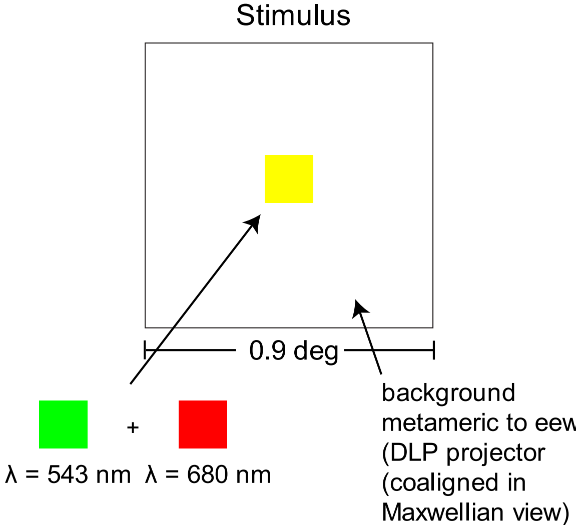


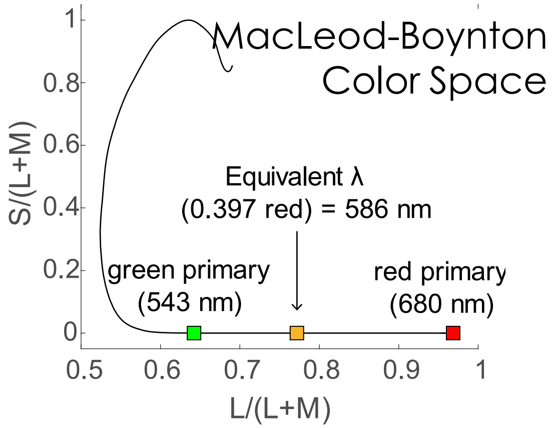
local compensation



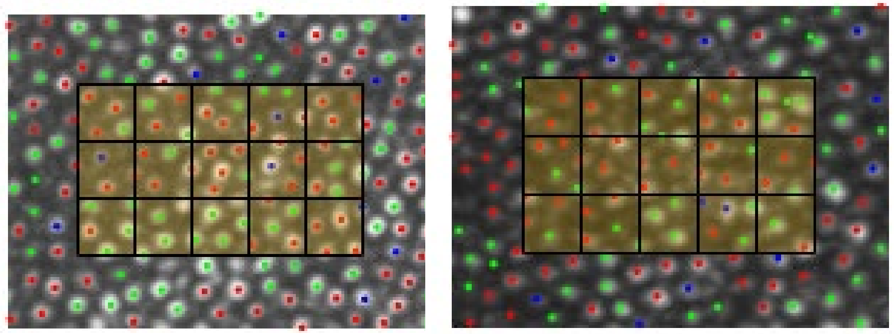
To distinguish between these hypotheses, we need to measure the topography of unique yellow with small stimuli

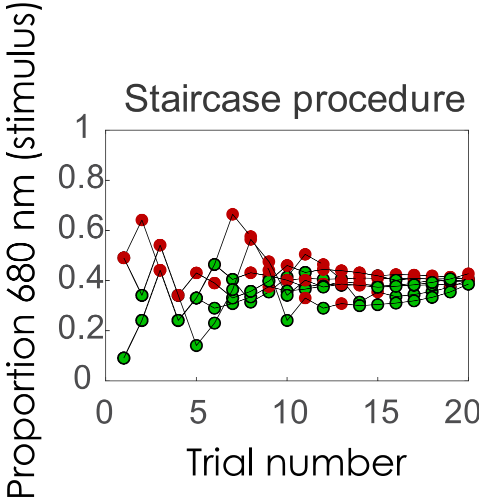
Methods

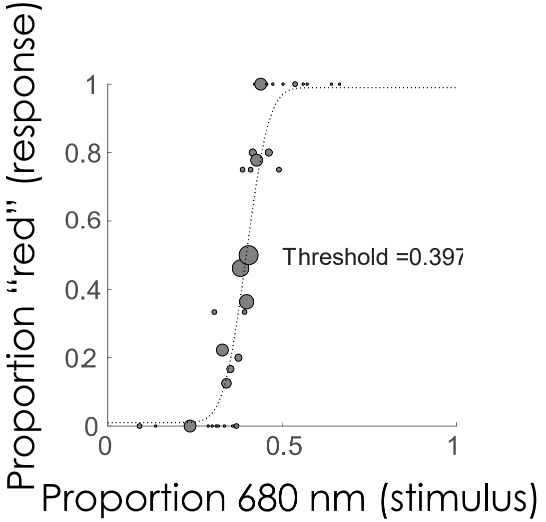




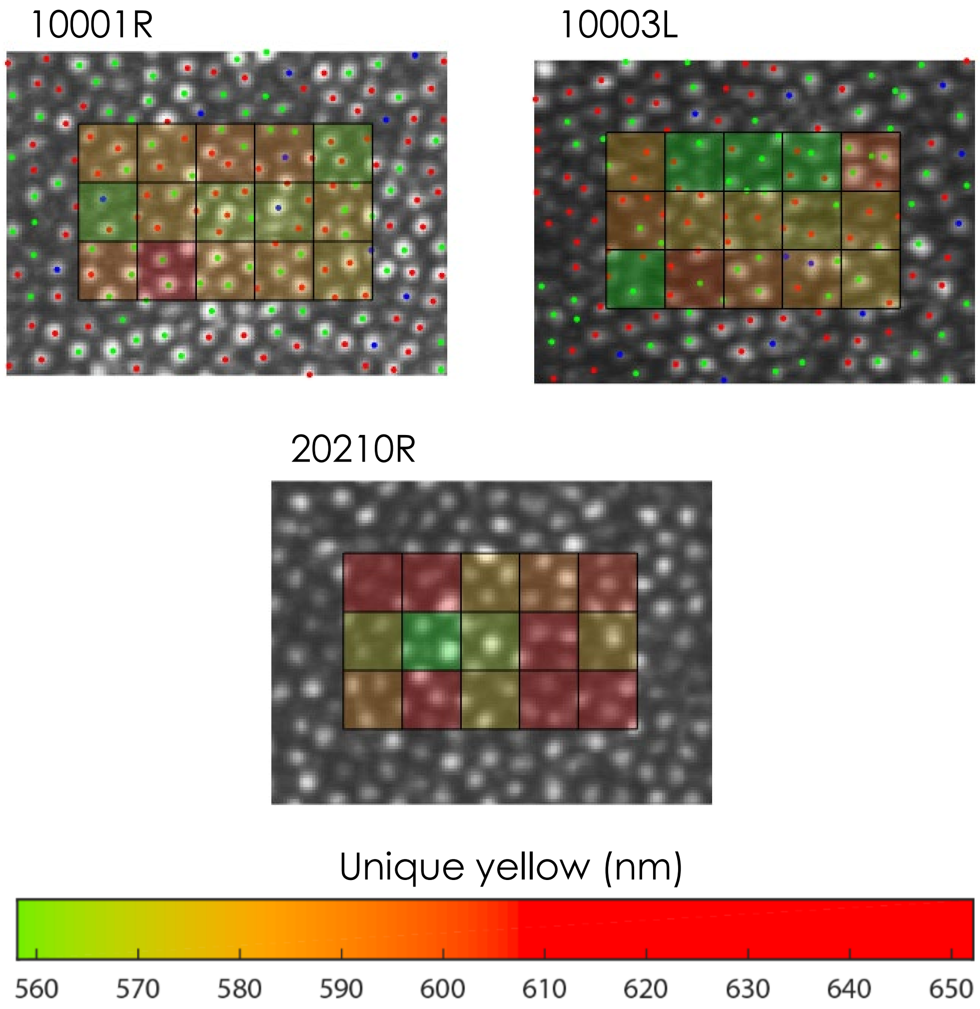
- Retinally-stabilized measurements of unique yellow using 2.2' x 2.2' stimuli
- 3 color-normal subjects (2 w/classed mosaics)
- 543 and 680 nm AOSLO primaries were mixed to create lights metameric to intermediate λ's
- 2AFC staircase ("redder" or "greener") was used to find red-green null point

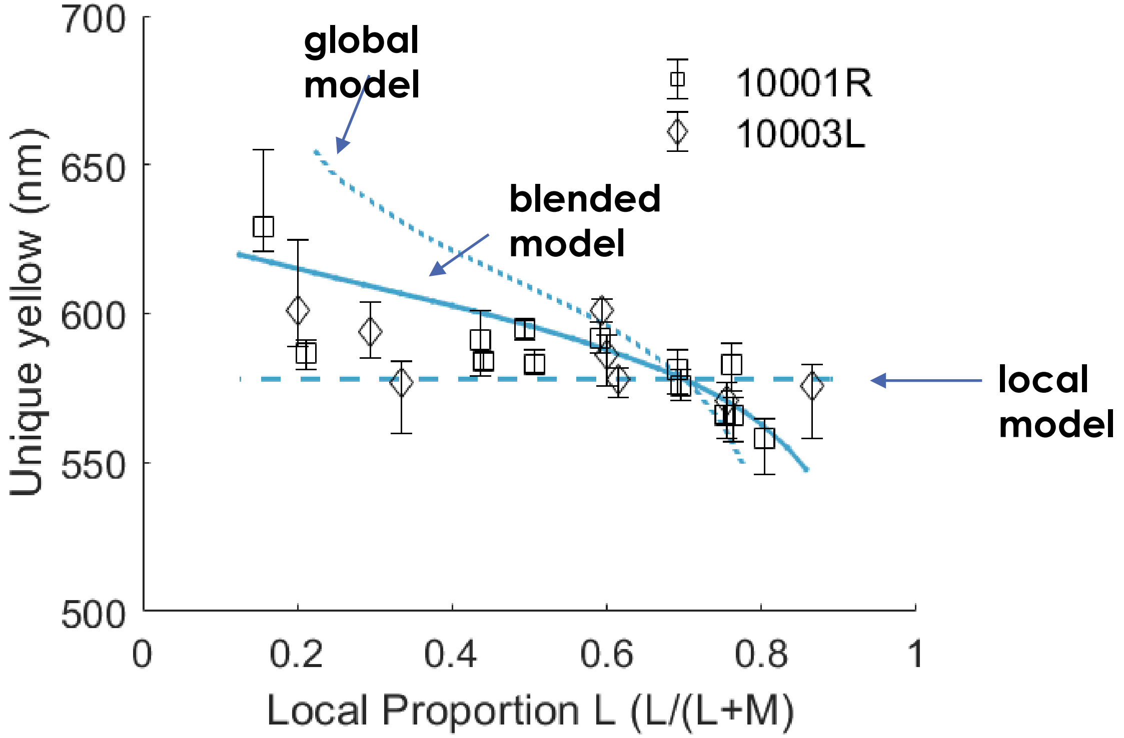






Results

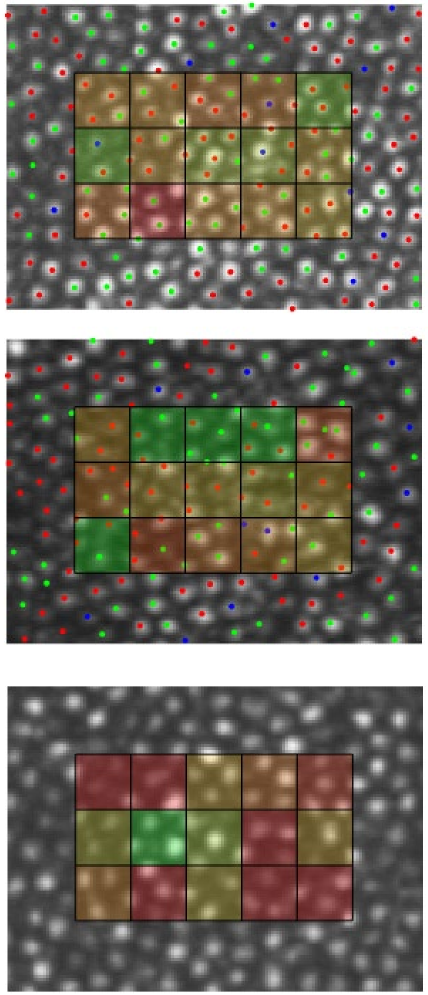

10001R
10003L
20210R
Unique yellow (nm)
560
570
580
590
600
610
620
630
640
650


global model
blended model
local model
10001R
10003L
Unique yellow (nm)
700
650
600
550
500
0
0.2
0.4
0.6
0.8
1
Local Proportion L (L/(L+M))

Summary, Pt 2 – Color Appearance

- Measured with small, retinally-stabilized stimuli, the wavelength of unique yellow varies across the parafoveal cone mosaic in accordance local variations in L:M cone ratio

- The amount of variation was less than predicted by a model that only included compensation for the global L:M cone ratio



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