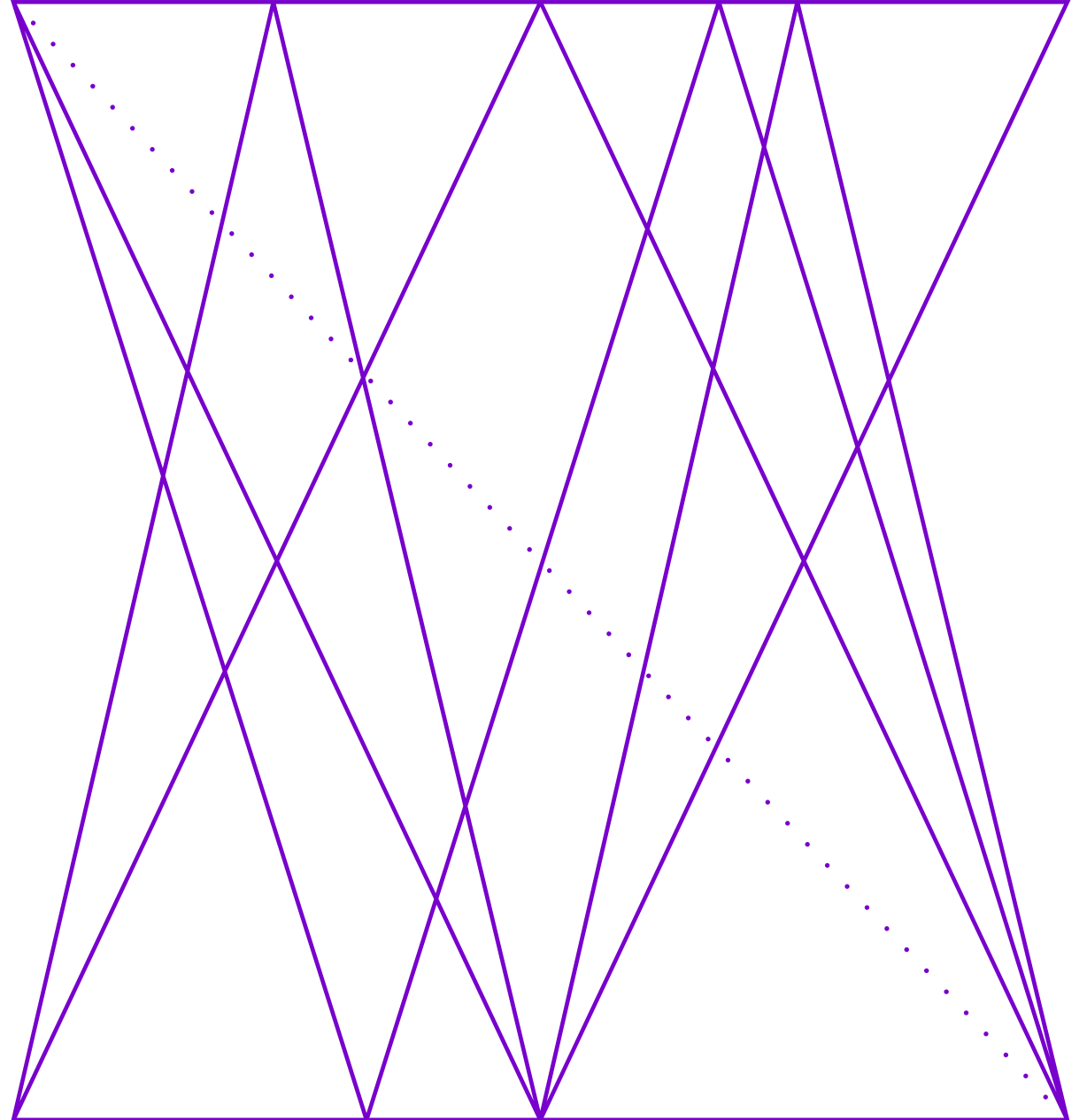


Color Mechanisms: A Progress Report

27 June 2023 | 11:00-12:00 EDT



Technical Group Executive Committee



Francisco Imai
*Chair of the OSA Color
Technical Group*



Javier Hernandez-Andres
*Universidad
de Granada*



Rigmor C. Baraas
*University of South-
Eastern Norway*



Yoko Mizokami
Chiba University



Allie Healey
University of Oxford

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 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 coffee breaks
- Incubator meetings

Connect with our Technical Group

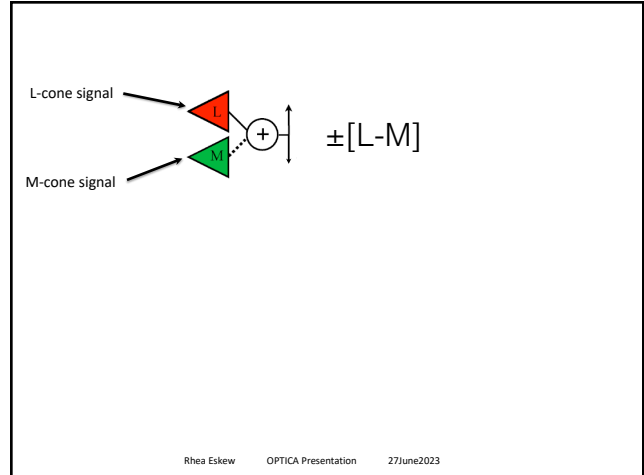
Join our online community to stay up to date on our group's activities. You also can share your ideas for technical group events or let us know if you're interested in presenting your research.

Ways to connect with us:

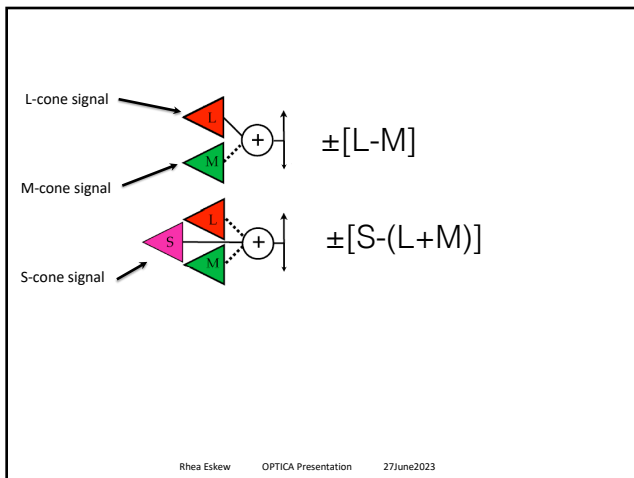
- Our website at www.optica.org/vc
- On Twitter at [#ColorTG](https://twitter.com/ColorTG)
- On LinkedIn at www.linkedin.com/groups/13573604
- Email us at TGactivities@optica.org



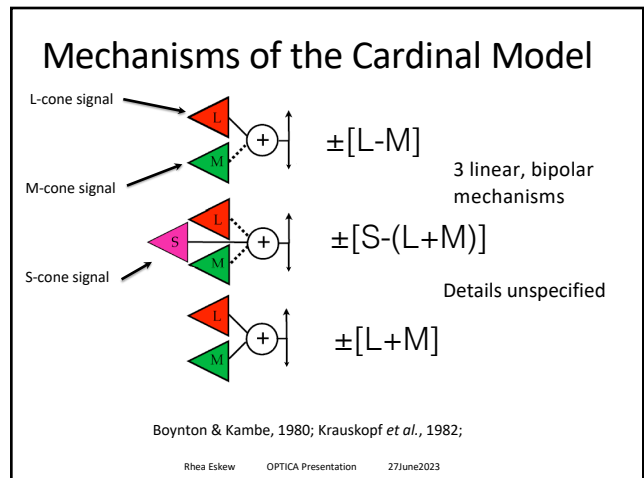
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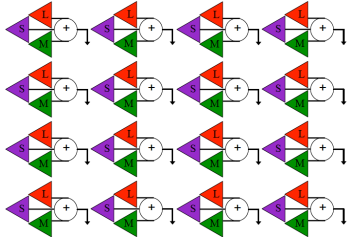


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Higher-order Model



- Multiple mechanisms
- Recombinations of signals from cardinal mechanisms
- Details unspecified
- No consensus on a computable model

Krauskopf *et al.*, 1986

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Postreceptoral Color Mechanisms: a **working definition**

- A combination of cone signals that covaries with observer behavior
 - in more than a single task

Cole *et al.* 1990; Eskew *et al.*, 1999; Eskew, 2008, 2009; Graham, 1989; Sankeralli & Mullen, 1997; Stiles, 1967)

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Postreceptoral Color Mechanisms: a **working definition**

- **Labeled line** (Graham, 1989; Watson and Robson, 1981; Müller, 1835): quale associated with a mechanism
 - Müller's Law of Specific Nerve Energies
 - Representation (hue or brightness)
- **Univariance** (Rushton, 1972): single response dimension (a scalar magnitude)
 - Failure of representation — information loss (e.g, wavelength, cone of origin, color angle)

Cole *et al.* 1990; Eskew *et al.*, 1999; Eskew, 2008, 2009; Graham, 1989; Sankeralli & Mullen, 1997; Stiles, 1967)

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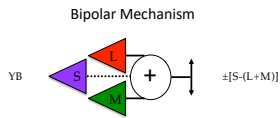
Implication of Univariance and Labeled Line Assumptions

- "Red" and "Green" are distinct qualia
- Must be two separate mechanisms -- unipolar
- Empirically:
 - Two complimentary polarities are independently manipulable
 - Two complimentary polarities are discriminable at threshold

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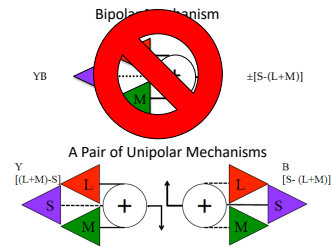
Rectified Mechanisms



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Rectified Mechanisms



Our model has 'quasi-paired' mechanisms

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Postreceptoral Color Mechanisms: a working definition

- A combination of cone signals that is correlated with observer behavior
 - not task specific
 - rectified: a single chromatic polarity
- Mechanisms are stochastically independent, but not necessarily orthogonal
- Fixed relative "strengths" of cone inputs
 - constant relative spectral sensitivity (after taking cone-independent adaptation into account)

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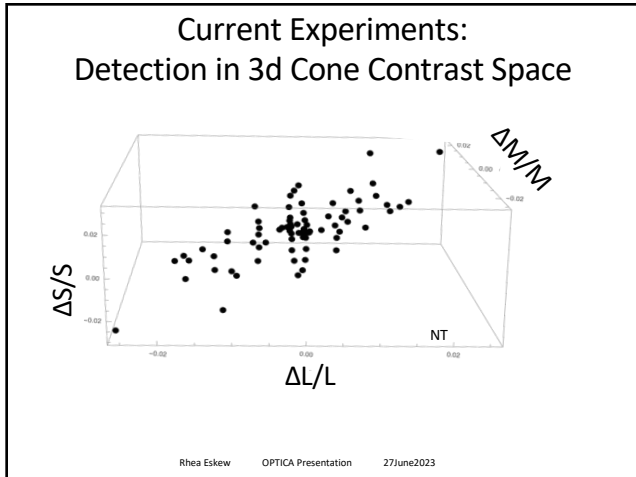
11

Experiments

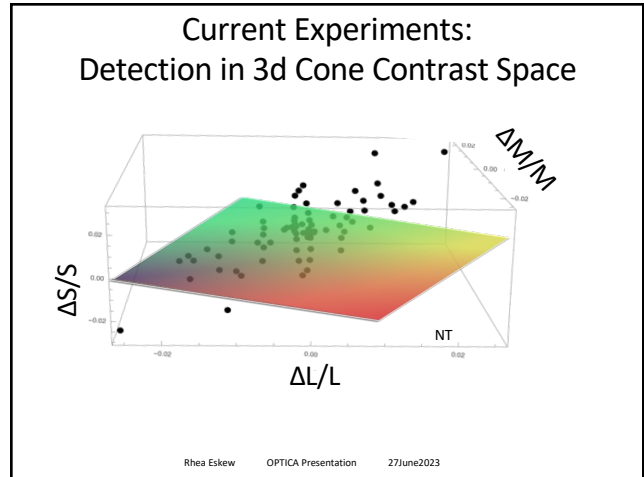
Procedures	LM Plane	LMS Space
Forced-Choice Detection	✓	~✓
Asymmetric Color Matching at Threshold	✓	In Progress
Forced-Choice Discrimination at Threshold	✓	In Progress

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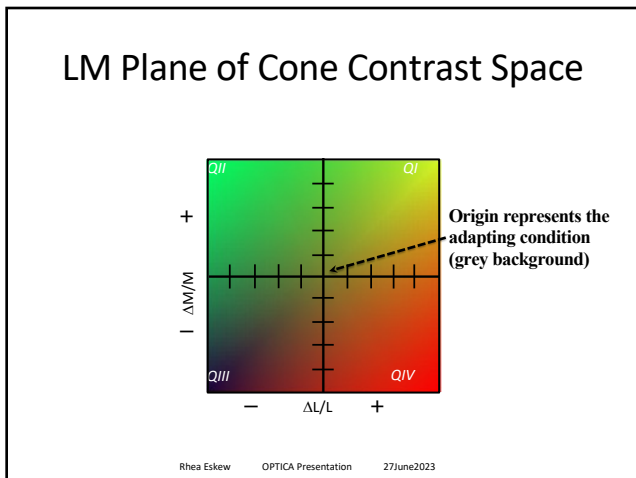
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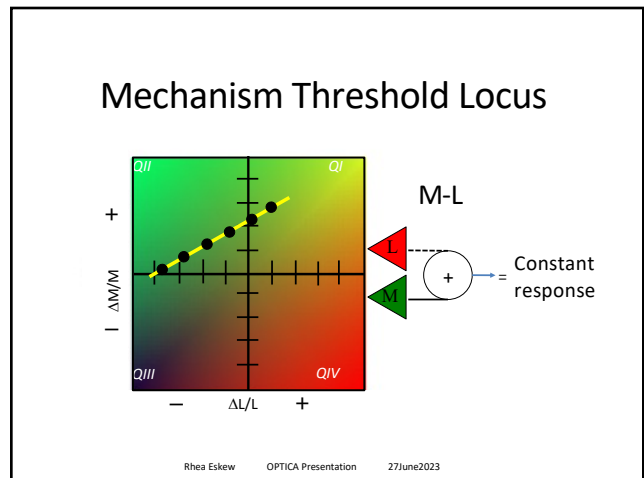
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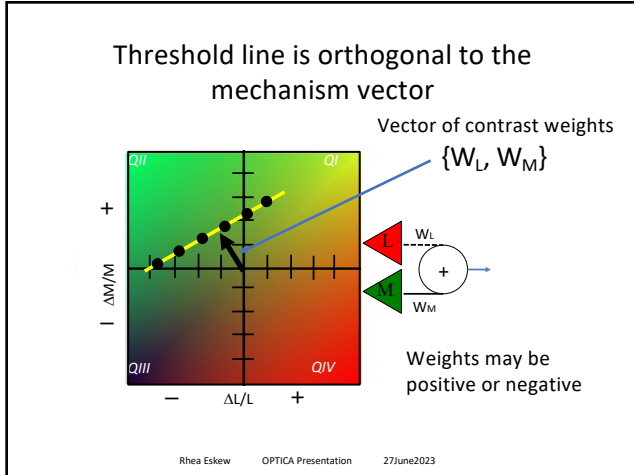
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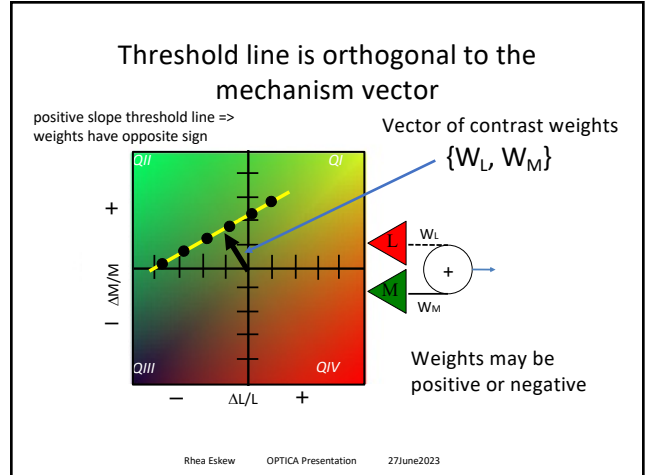
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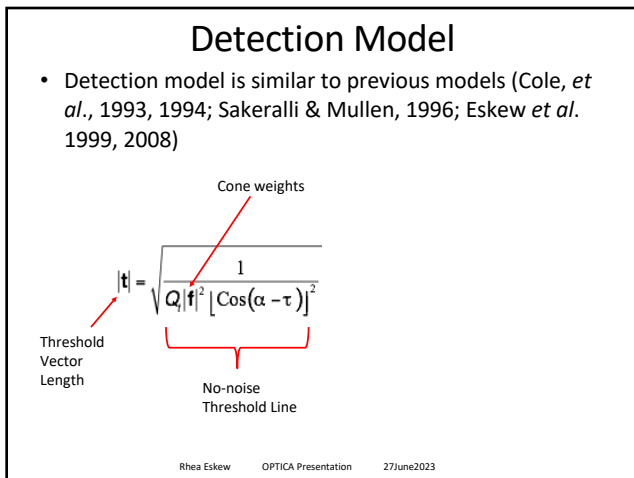
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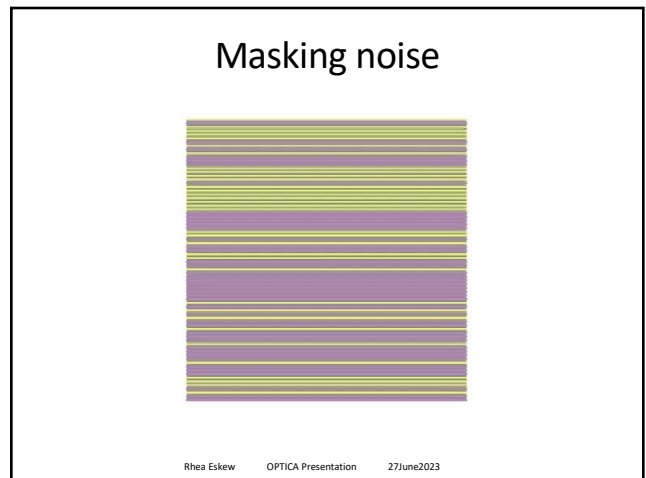
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Noise Masking Model

- Detection model is similar to previous models (e.g., Cole, *et al.*, 1993, 1994; Sankeralli & Mullen, 1996; Eskew *et al.* 1999, 2008)
- but now add additional features to incorporate noise masking quantitatively (e.g., Legge *et al.*, 1987; Pelli, 1990)

$$|t| = \sqrt{\frac{1}{Q_i |t|^2 [\text{Cos}(\alpha - \tau)]^2} + b \frac{Q_n |n|^2 [\text{Cos}(\alpha - \nu)]^2}{Q_i [\text{Cos}(\alpha - \tau)]^2}}$$

Threshold Vector Length

No-noise Threshold Line

Masked Threshold Line Intercept

Shepard *et al.*, 2016

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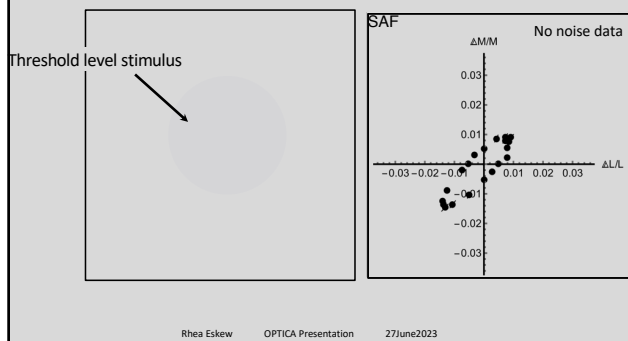
Detection Model

- There are three (four) free parameters per mechanism:
 - L cone weight
 - M cone weight
 - S cone weight (not in LM Plane)
 - proportionality constant related to relative spatio-temporal sensitivity
 - (all are constant across noise conditions)

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Method: No-Noise Condition



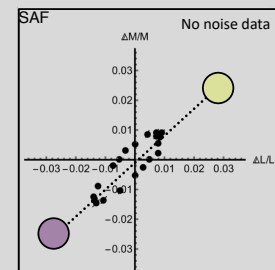
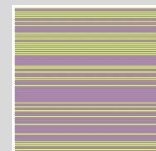
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Masking Noise Near the Corner

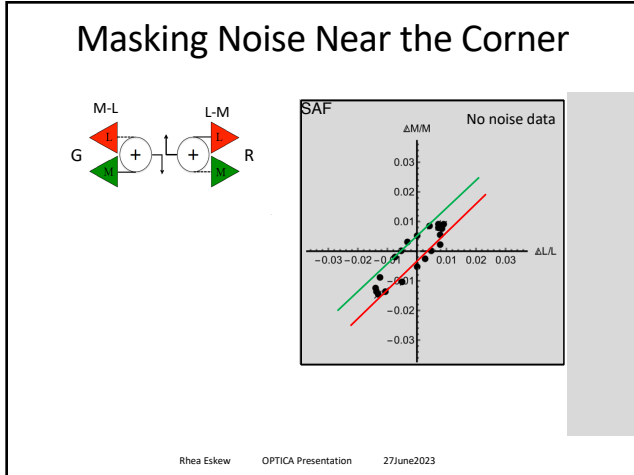
Hansen & Gegenfurtner (2013)

Masking was selective

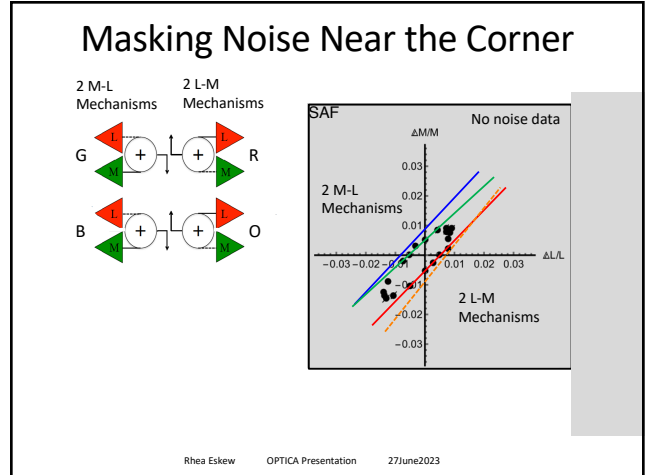
Detection contour tilted to align with the noise direction



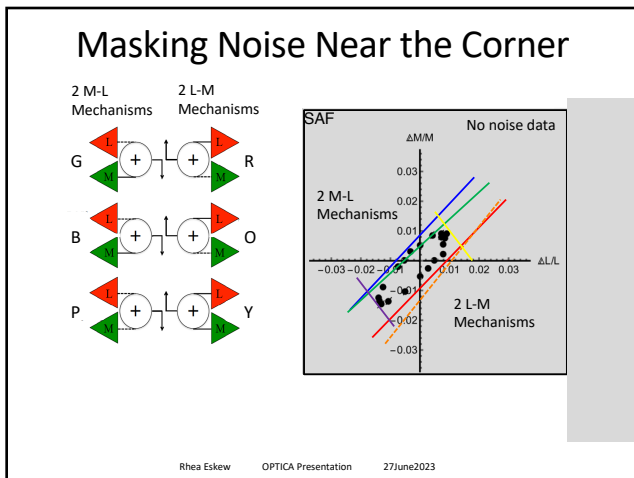
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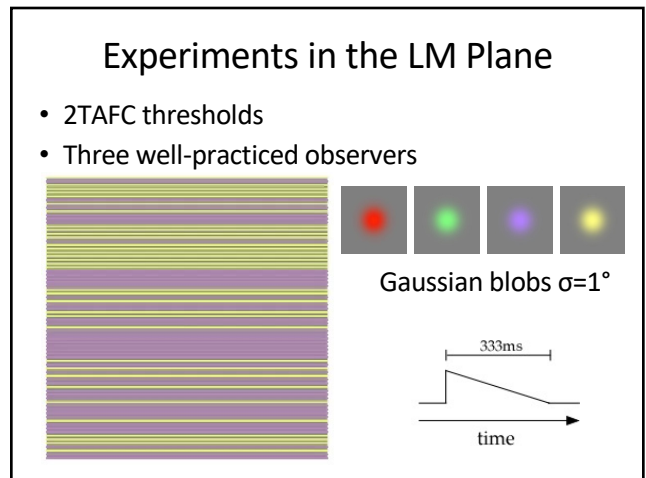
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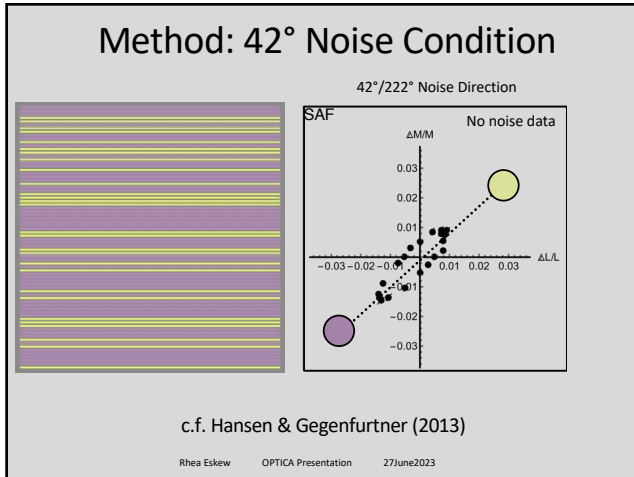
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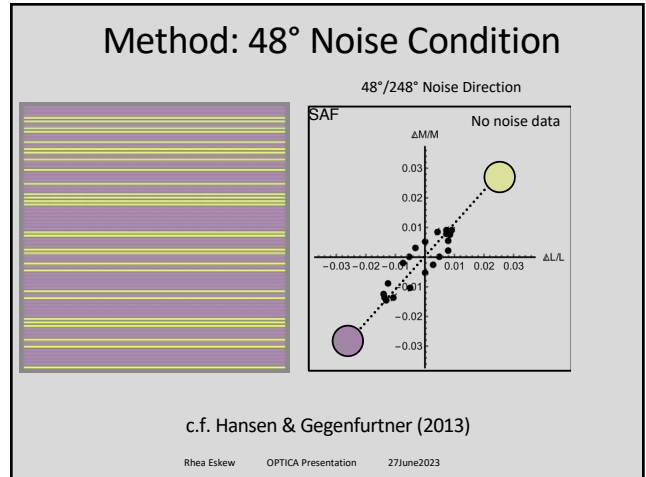
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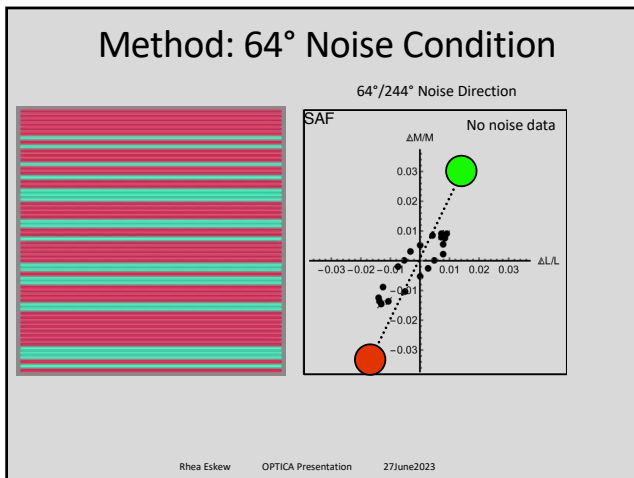
28



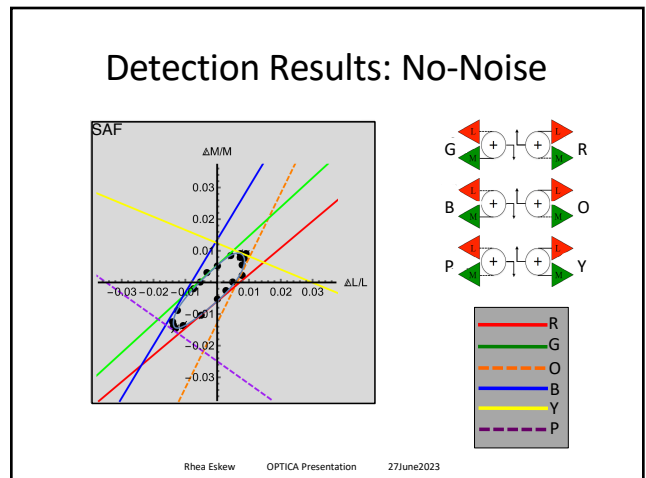
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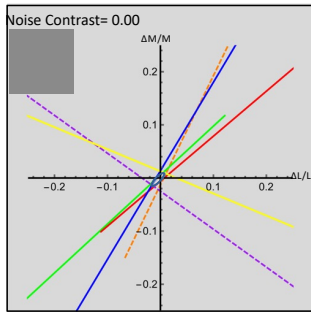


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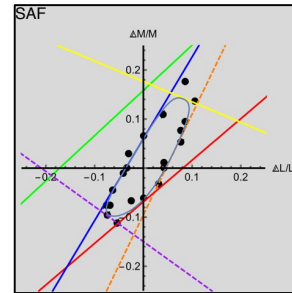
Six Mechanism Model: No Noise



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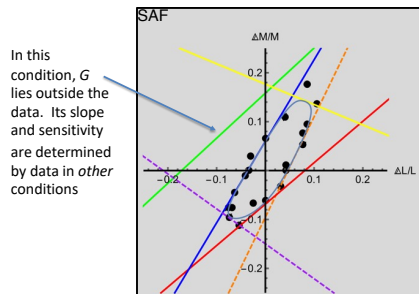
64° Noise Condition



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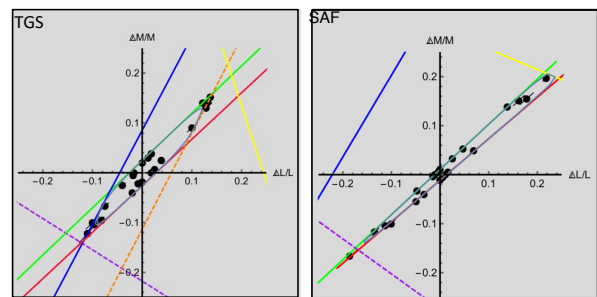
64° Noise Condition



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Detection Results: 42° Noise Condition

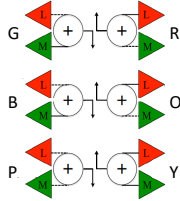


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Summary: Detection

- 6 mechanism model of detection in (L, M) plane (Shepard et al., 2016)
 - Selective masking & tilts of detection contours
 - Adding mechanisms did not significantly improve the fit

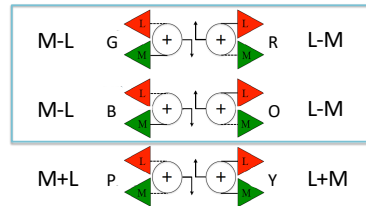


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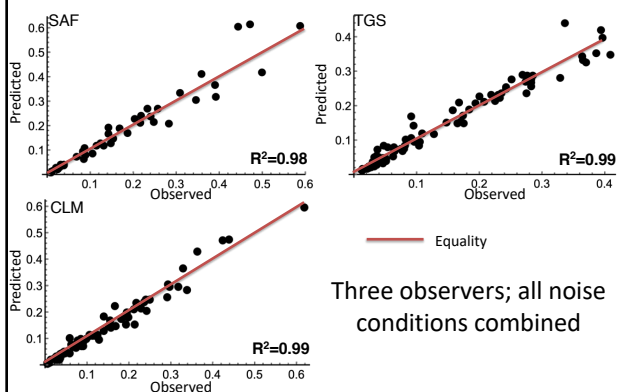
Summary: Detection

- Two pairs (G & R, B & O) take the difference of L and M cones
 - Similar cone contrast weights
 - Highly correlated responses



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Observed vs. Predicted Thresholds



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Summary: Detection

- Model accounts for the data:
 - but it has 18 free parameters
 - is it *correct*?
- Test it:
 - compare with other procedures
 - color matching
 - chromatic discrimination

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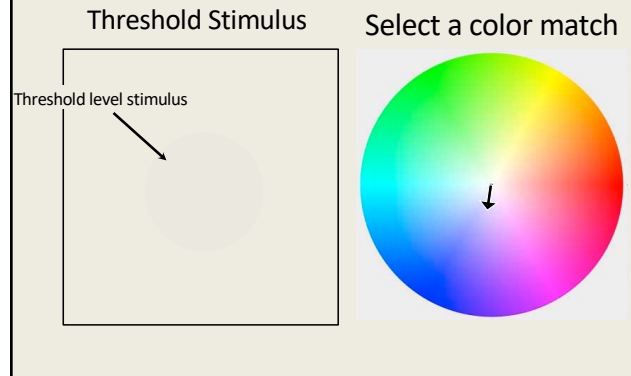
40

Experiment 2: Color Matching at Threshold

- The same three observers
- Presented threshold-level tests, in the same noise conditions
- Matched each threshold level test with a suprathreshold color
- Within a noise condition, test angles were presented in random order
- Observer did not know which tests were presented

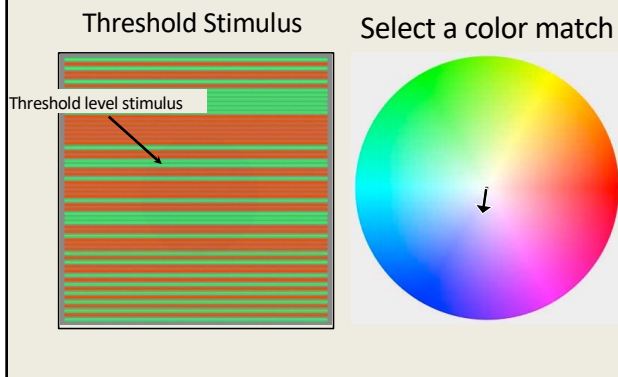
41

Method: Asymmetric Color Matching



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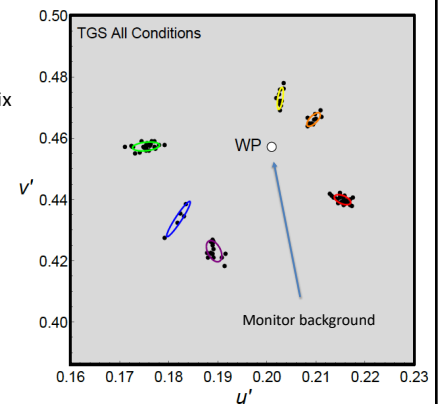
Method: Asymmetric Color Matching



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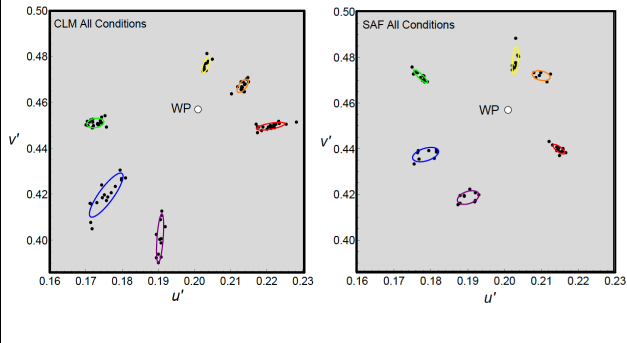
Results

- Across noise conditions, the matches fall into six clusters
- 95% error ellipses around the centroids were computed



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Results



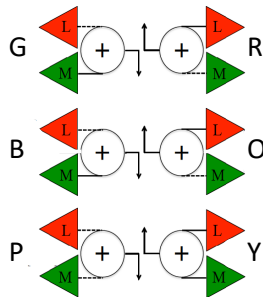
45

How do the color matches correspond to the detection mechanisms?

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Summary: Detection Model

- Detection model was fit to thresholds
 - prior to collecting color matches
 - and not altered by color match results
 - => independent test of the model



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Definition: Color Mechanism

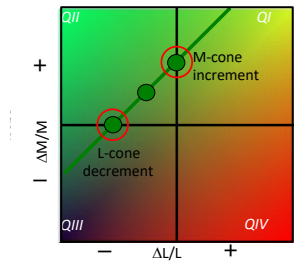
Two hypothesized properties of mechanisms:

- Univariance (Rushton, 1972)
- Labeled Lines (Graham, 1989; Watson and Robson, 1981; Müller, 1835)

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Applying the Principles to Color Matching: Univariance

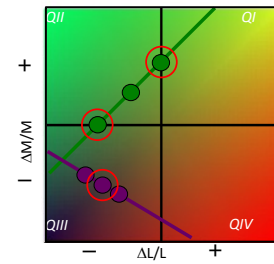
Physically-different stimuli that lie along one mechanism threshold line should produce the same color match



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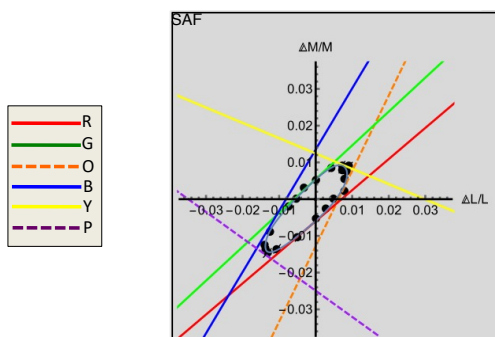
Applying the Principles to Color Matching: Labeled Lines

Tests that lie on two different mechanism lines should be matched with two different colors



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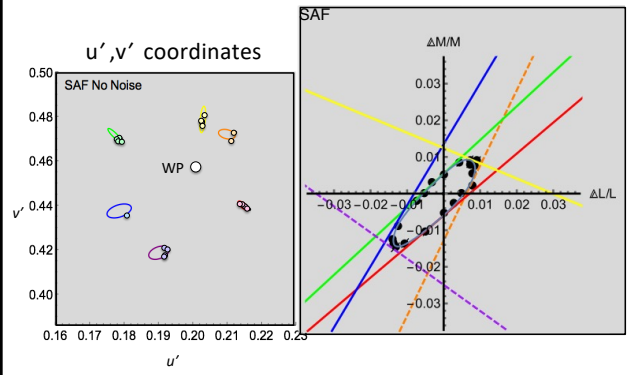
Detection Results: No-Noise



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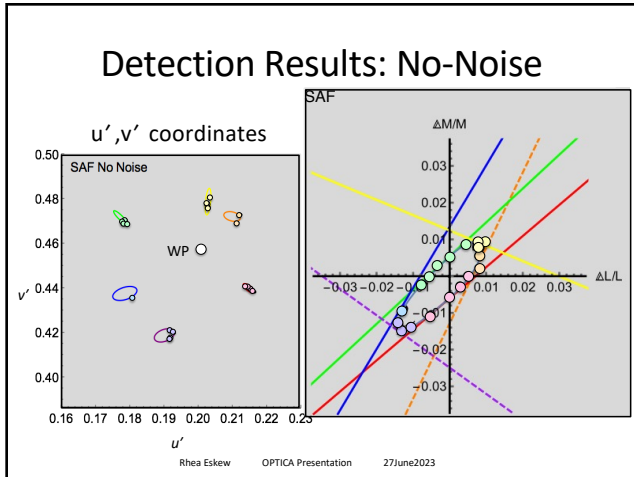
51

Detection Results: No-Noise

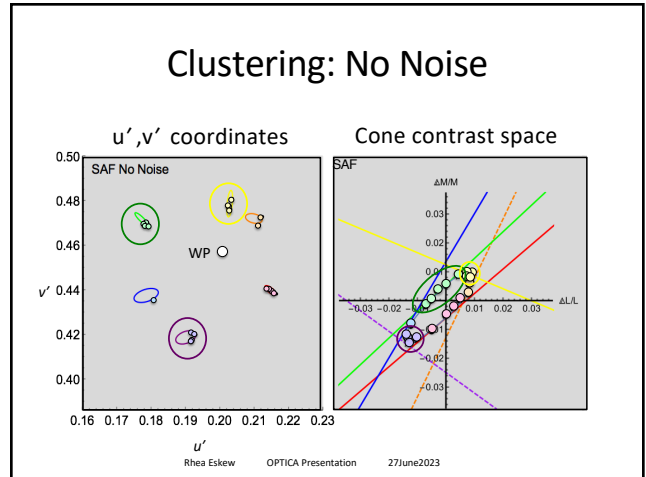


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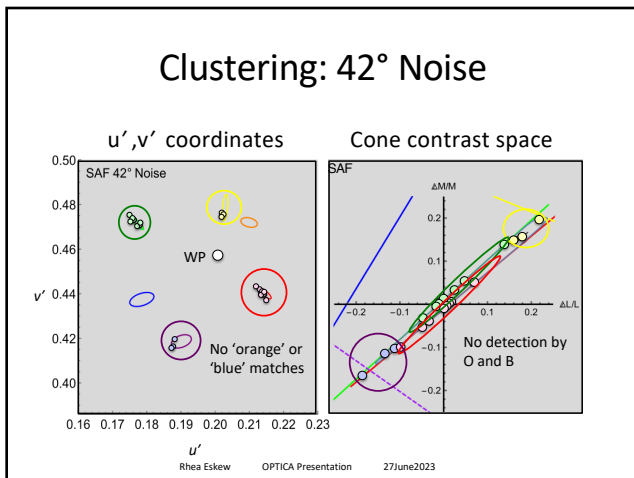
52



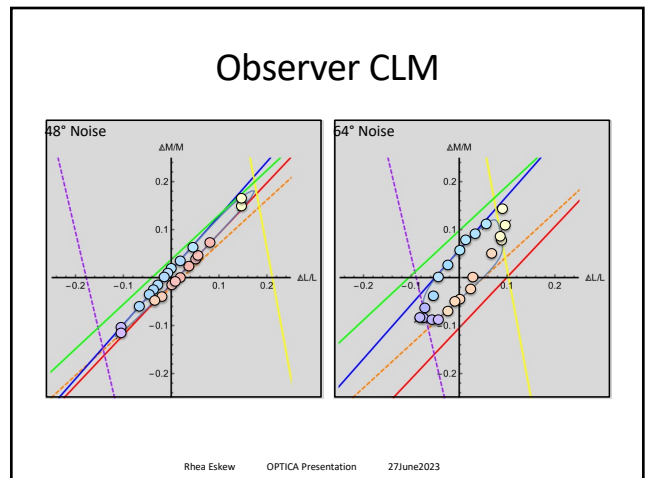
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Differential Masking

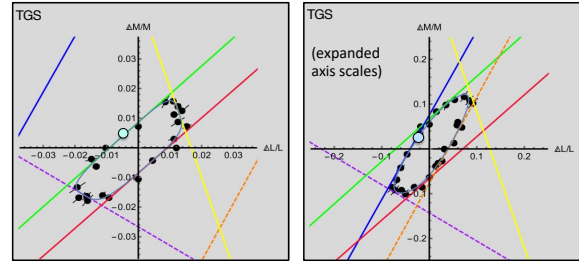
- A given test angle has the same relative L and M cone excitations, across noise conditions
- Detection model asserts that a given test angle may be detected by different mechanisms in different noise conditions
- Therefore, that test angle should be matched with different colors under those conditions (Labeled Line Principle)

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Differential Masking: 135° test

(cf. Webster & Mollon, 1994; Giulianini & Eskew, 1998)



No Noise

64° Noise



L/M contrast = -1

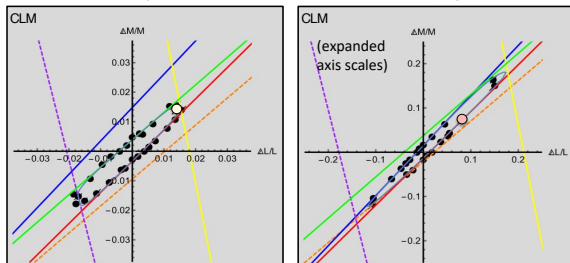


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Differential Masking: 45° test

(cf. Webster & Mollon, 1994; Giulianini & Eskew, 1998)



No Noise

48° Noise



L/M contrast = +1

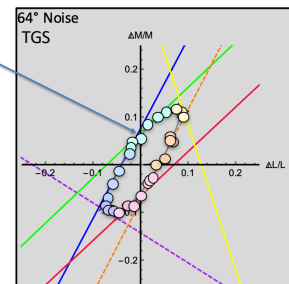


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Single cone hues

e.g., M cone increment detected by G; B is **almost** as sensitive. Suggests supra-threshold M stimulus might be cyan (Drum, 1989; Schirillo & Reeves, 1991)

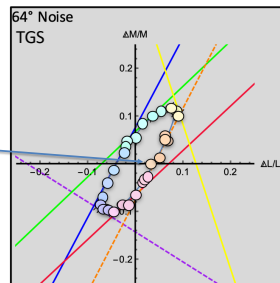


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Single cone hues

Similarly, L cone increment could be detected by O or R



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Potential Issue with Color Matches

- Observers knew we *expected* 6 matching clusters in the experiment
 - Tests chosen randomly
 - Couldn't affect correspondence with mechanisms
 - But influenced the number of matching cluster?

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Potential Issue with Color Matches

- Model actually predicts 4, 5, or 6 clusters
 - Unknown to observers
 - Yet this is what we obtained
- Not ideal

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Summary

- Color Matching
 - Provides insight into the subjective experience resulting from these mechanisms
 - Overall, excellent correspondence of matches to detection by particular mechanisms
 - Correspondence changes appropriately with noise
 - Shifts in color appearance with masking/habituation (e.g., Giulianini & Eskew, 1988; Webster & Mollon, 1994)

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Discrimination

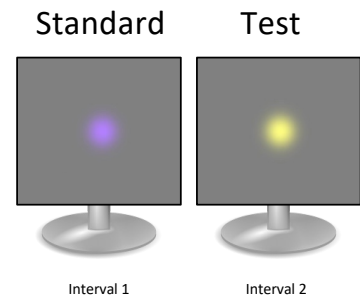
- Pairs of threshold-level stimuli
- Prediction based upon 6 mechanism model
- Forced-choice method

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Method: One Discrimination Trial

- Two temporal intervals were presented
- All stimuli at threshold
- Standard and test presented in random order

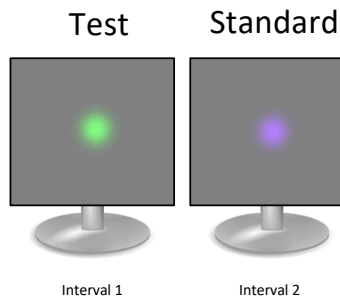


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Method: One Discrimination Trial

- Two temporal intervals were presented
- Standard and test presented in random order
- Task: select standard interval

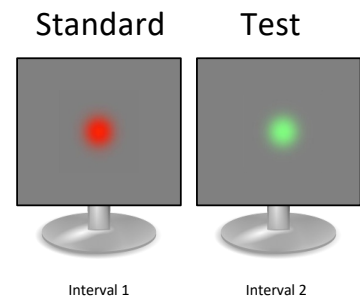


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Method: One Discrimination Trial

- Runs were blocked by standard angle



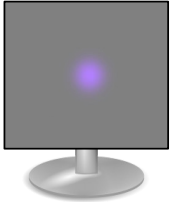
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Method: One Discrimination Trial

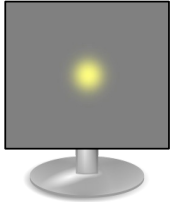
- Tests chosen at random
- Observer did not know which test was being presented

Standard



Interval 1

Test



Interval 2

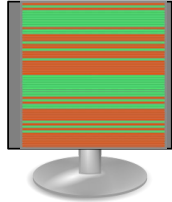
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Method: One Discrimination Trial

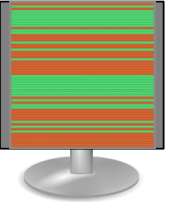
- Same noise conditions as in the detection experiment

Standard



Interval 1

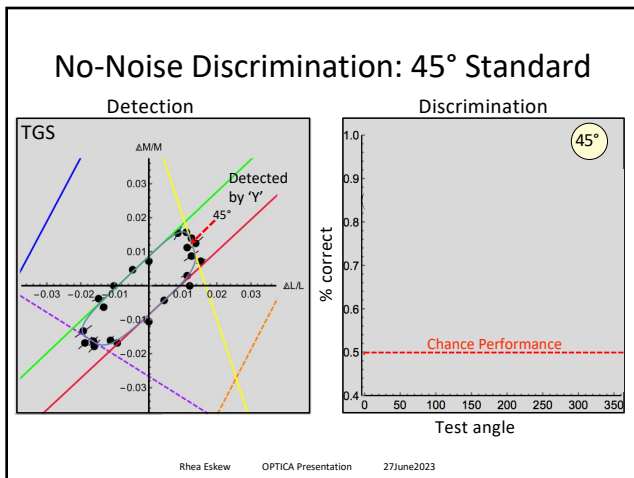
Test



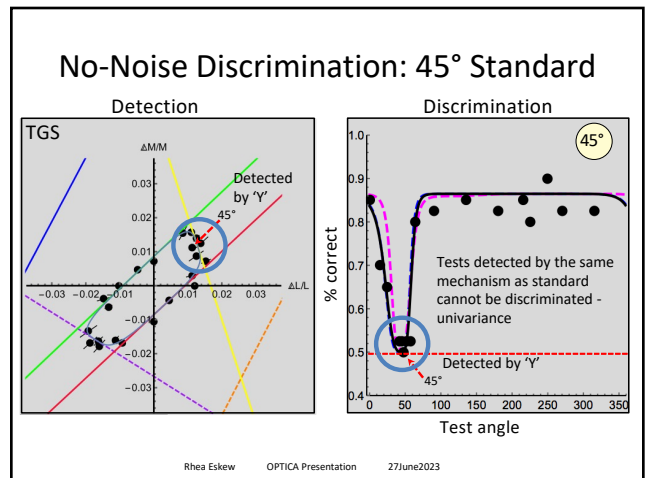
Interval 2

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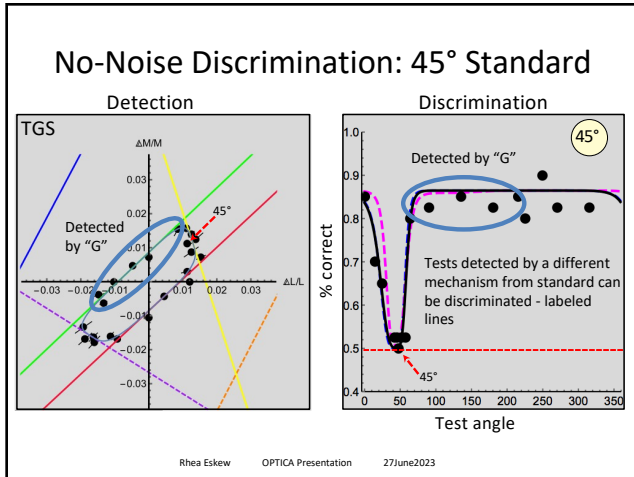
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Modeling discrimination

- Bayesian Classifier (Eskew *et al.*, 2001)
- Inputs are the six mechanism responses
- Output is an optimal decision
- **No free parameters**
 - For each observer, the prediction for every noise condition, for every standard, and for every test is made without any model-fitting

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hmmm.....

6 mechanism model

G R

B O

P Y

Joint Psychometric Functions:

$P(6 \text{ mechanisms} | \text{test})$

$P(6 \text{ mechanisms} | \text{standard})$

Given by detection model

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$$P(\text{test} | 6 \text{ mechanisms}) = \frac{P(6 \text{ mechanisms} | \text{test})}{P(6 \text{ mechanisms} | \text{test}) + P(6 \text{ mechanisms} | \text{standard})}$$

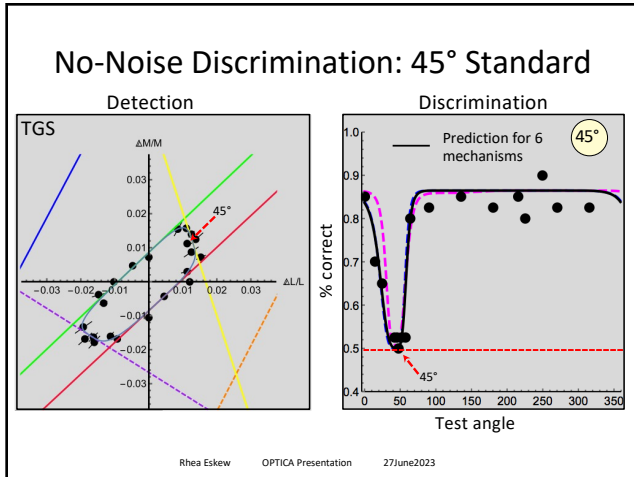
Posterior probability

Choose 'standard' if $P(\text{standard} | 6 \text{ mechanisms}) > P(\text{test} | 6 \text{ mechanisms})$

For each observer, across all noise conditions, prediction is made with **no free parameters**

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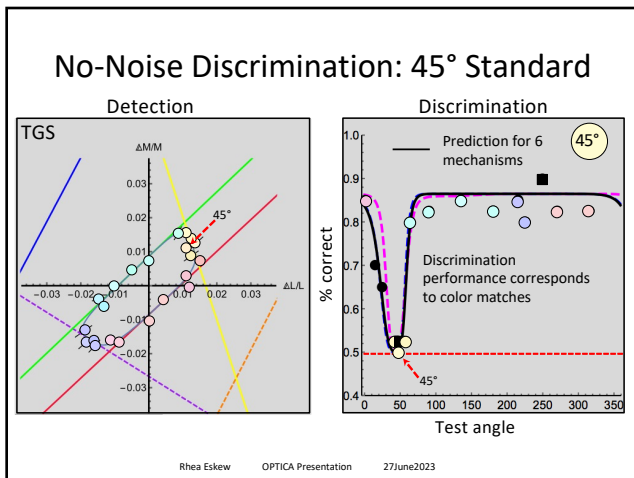
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Correspondence across tasks

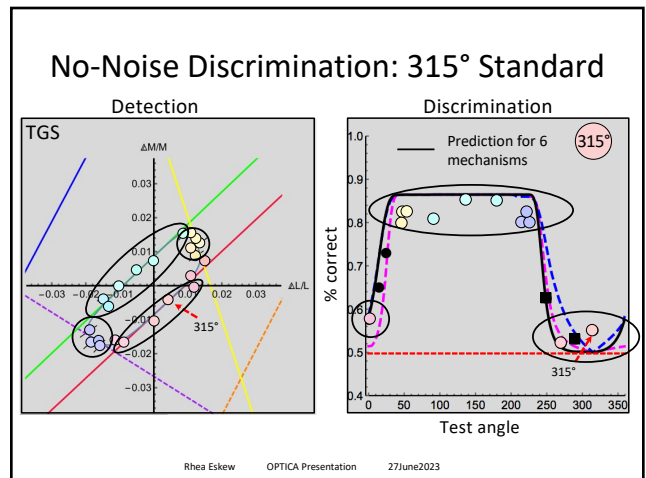
- Detection mechanisms correspond to color matches
- Detection mechanisms correspond to discrimination performance
- So we expect discrimination performance to also correspond to color matches

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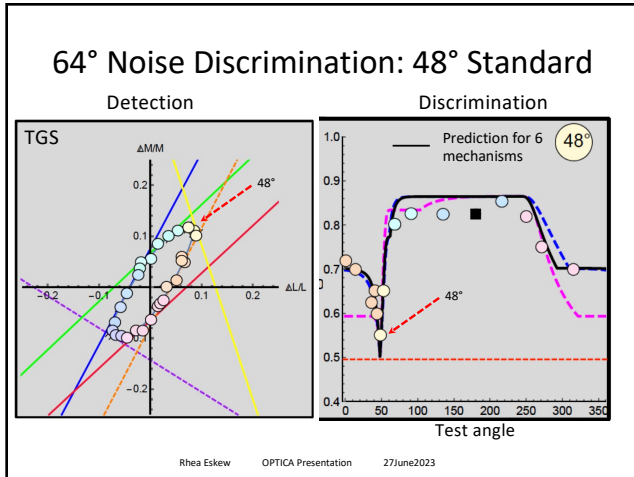
78



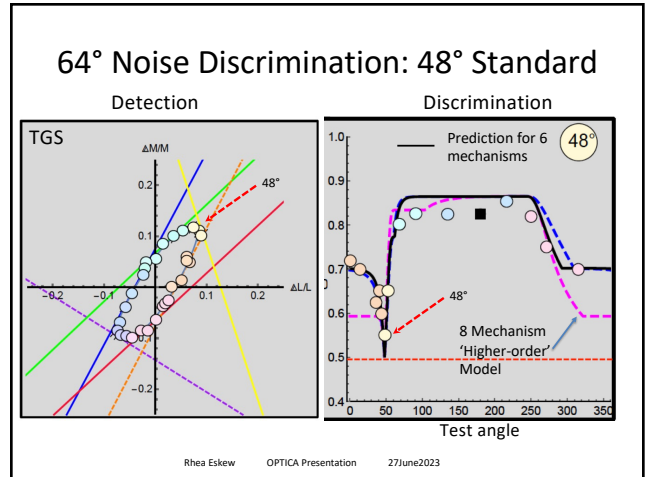
79



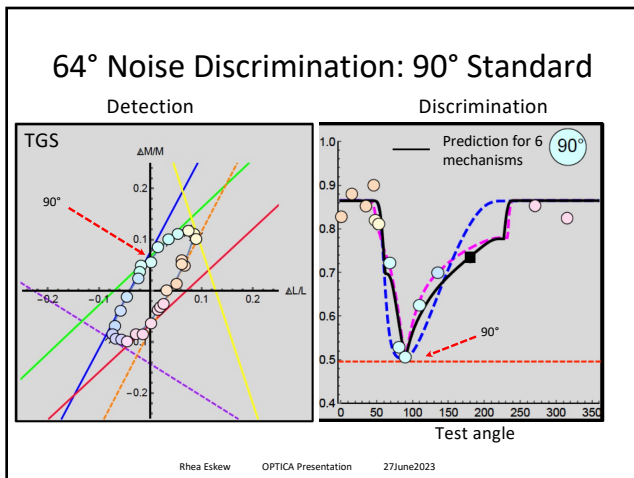
80



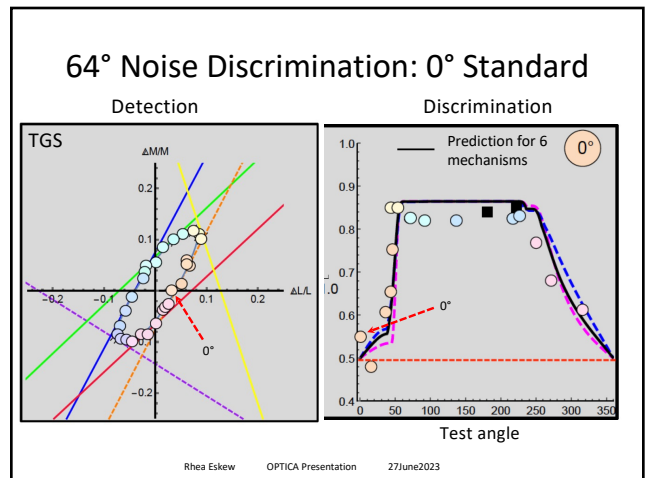
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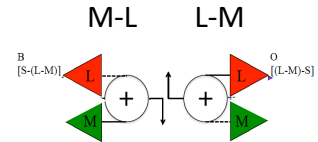
Summary: Six Mechanism Detection Model

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Summary: Six Mechanism Detection Model

- B and O
 - Nearly symmetric weights
 - S cone input likely but not measured in this study

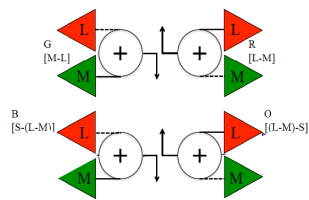


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Summary: Six Mechanism Detection Model

- Four mechanisms with opposed L and M signals
 - Allows selective masking & tilts of detection contours

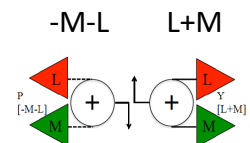


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Summary: Six Mechanism Detection Model

- Two mechanisms sum L and M signals
 - Possibly asymmetric
 - Weights not-well determined by data



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Postreceptoral Color Mechanisms: a working definition and **current results**

- A combination of cone signals that is correlated with observer behavior
 - not task specific
 - same color model for detection, discrimination, and color matching
 - rectified: a single chromatic polarity
 - more masking of increments than decrements
- Mechanisms are stochastically independent, but not necessarily orthogonal:
 - R and G are correlated with B and O
- Fixed relative “strengths” of cone inputs
 - threshold contours are always the same slope

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Postreceptoral Color Mechanisms: a working definition and **current results**

- **Labeled line** (Graham, 1989; Watson and Robson, 1981; Müller, 1835):
 - Representation (hue)
 - discrimination and color matches both agree with detection mechanisms
- **Univariance** (Rushton, 1972):
 - Failure of representation — information loss
 - stimuli that isolate a mechanism are not discriminable

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Categorical Perception

- Liberman(1954)
 - Within a category, stimuli are indiscriminable
 - Between categories, stimuli are perfectly discriminable
- Univariance and labeled line properties make mechanisms into proto-categorical representations

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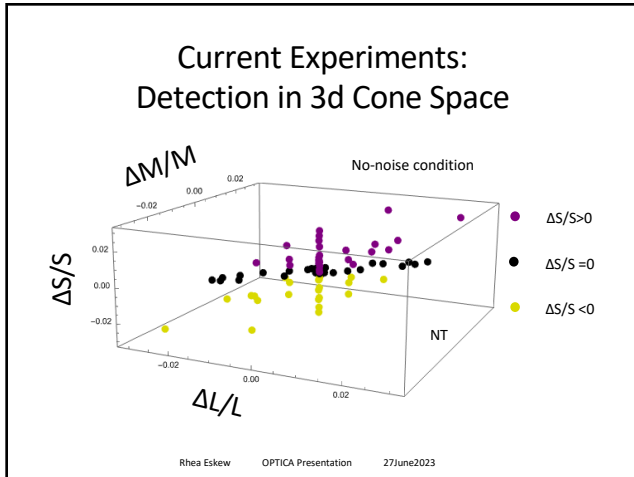
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Current Experiments: Detection in 3d Cone Space

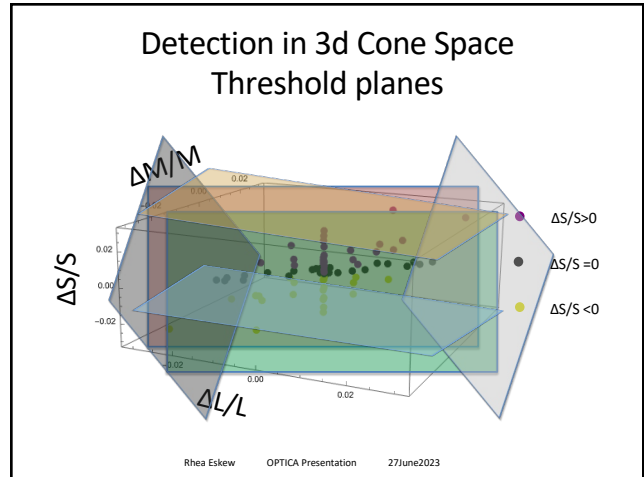
Procedures	LM Plane	LMS Space
Forced-Choice Detection	✓	~✓
Asymmetric Color Matching at Threshold	✓	In Progress
Forced-Choice Discrimination at Threshold	✓	In Progress

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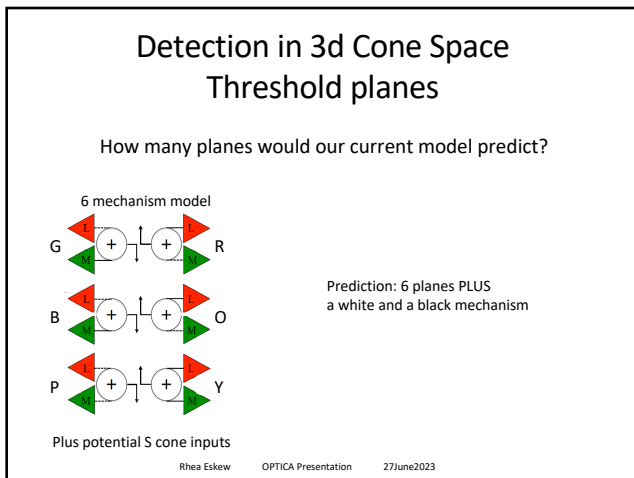
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- ### Detection in 3d Cone Space
- Results to date:
 - Six mechanisms account for the data
 - Achromatic mechanisms are weak or missing
 - Masking of increments > decrements
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Conclusions

- More mechanisms?
- Mechanism concept not useful if too many mechanisms

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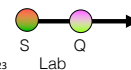
Thank you!



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