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The Limits of Natural and Artificial Compensation in Abnormal Color Vision

Featuring Kenneth Knoblauch

07 December 2022

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Color Technical Group

The Limits of Natural and Artificial Compensation in Abnormal Color Vision

Kenneth Knoblauch

December 07 2022 | 11:00 - 12:00 EDT (UTC-04:00)

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Color Technical Group

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 1,000+ 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

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Ways to connect with us:

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

Next webinar

March 1 2023

Color Inconstancy, Chromatic Adaptation and Scales of C

Mark Fairchild, RIT

Today's Speaker

OPTICA
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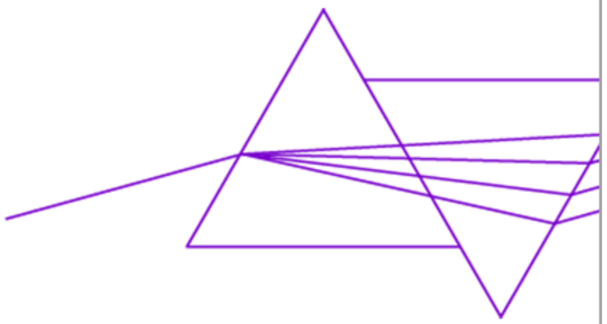
Color

WEBINAR

The Limits of Natural and Artificial Compensation in Abnormal Color Vision

07 December 2022 | 11:00 — 12:00 EST (UTC-05:00)



About the Presenter: Kenneth Knoblauch from the Stem Cell and Brain Research Institute at INSERM

Kenneth Knoblauch is a research director at the Stem Cell and Brain Research Institute at INSERM in France and holds a part-time professor position at the University of Southeast Norway. Knoblauch is interested in the neural basis of perception and uses methods from psychophysics, functional imaging and modeling neural mechanisms and cortical connectivity. Knoblauch has recently worked on the development of quantitative tools to measure visual appearance and used these to characterize a color filling-in phenomenon, infant color perception, contrast response in normal and anomalous color vision and multi-modal integration in gender perception.

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The Limits of Natural and Artificial Compensation in Anomalous Color Vision

Kenneth Knoblauch

Université Claude Bernard, Lyon 1
Inserm U 1208
Stem-cell and Brain Research Institute
Bron, France

National Centre for Optics, Vision and Eye Care
Faculty of Health and Social Sciences,
University of South-Eastern Norway
Kongsberg, Norway

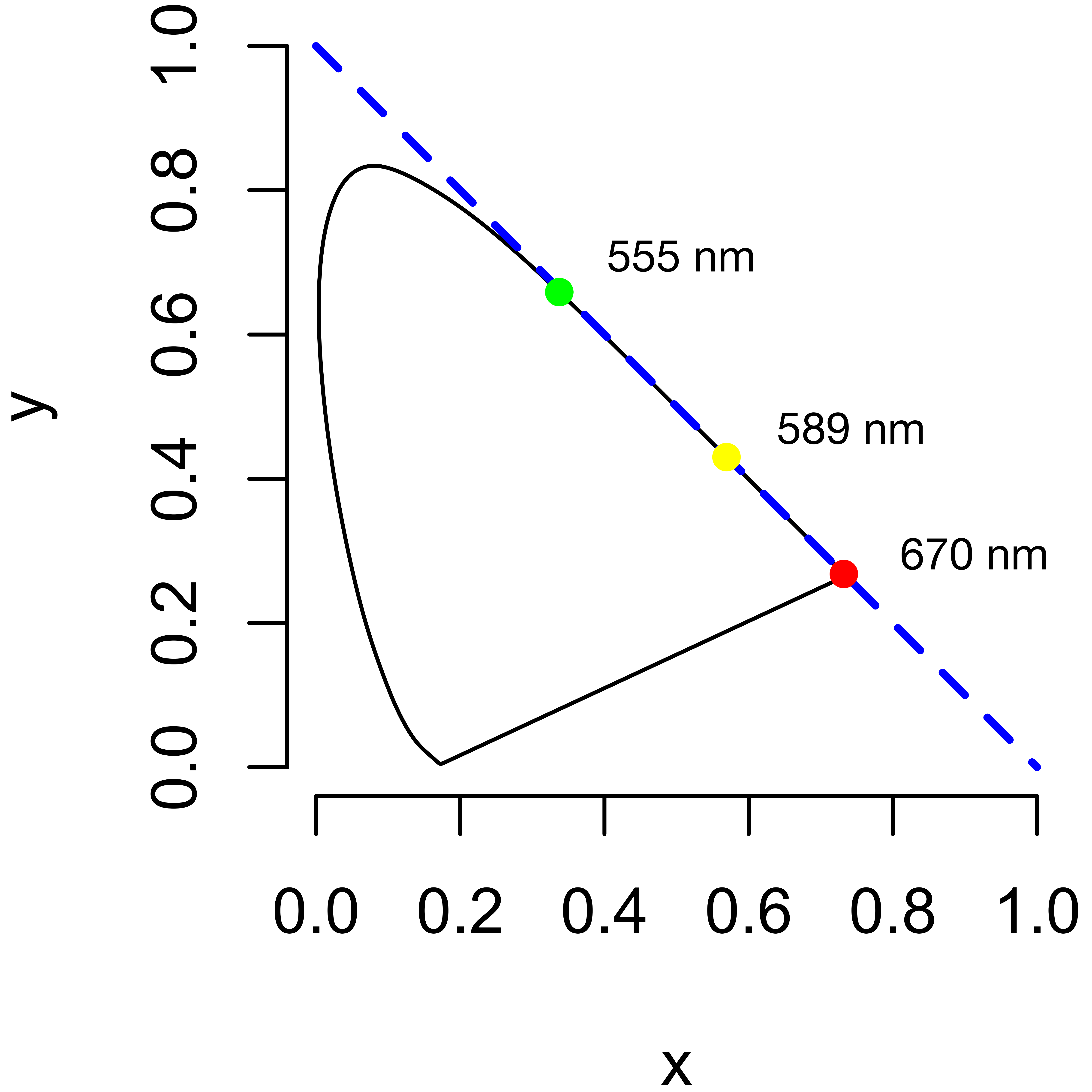
Brennan Marsh-Armstrong

John S. Werner

Department of Ophthalmology and Vision Science,
University of California, Davis, USA

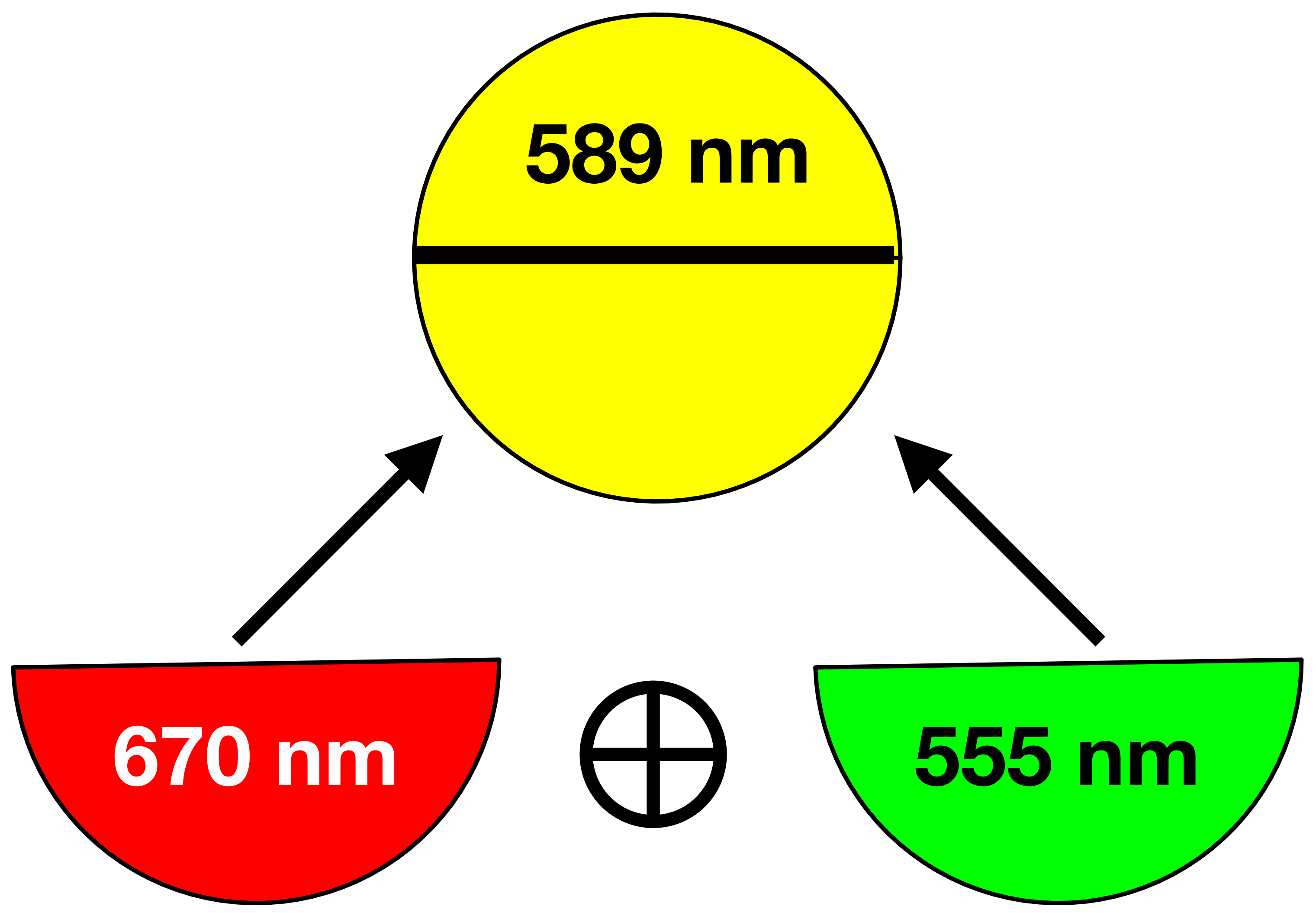
CIE 1931 xy chromaticity diagram

Human trichromatic color vision
becomes dichromatic along the
the long-wavelength limb of the
CIE xy chromaticity diagram.



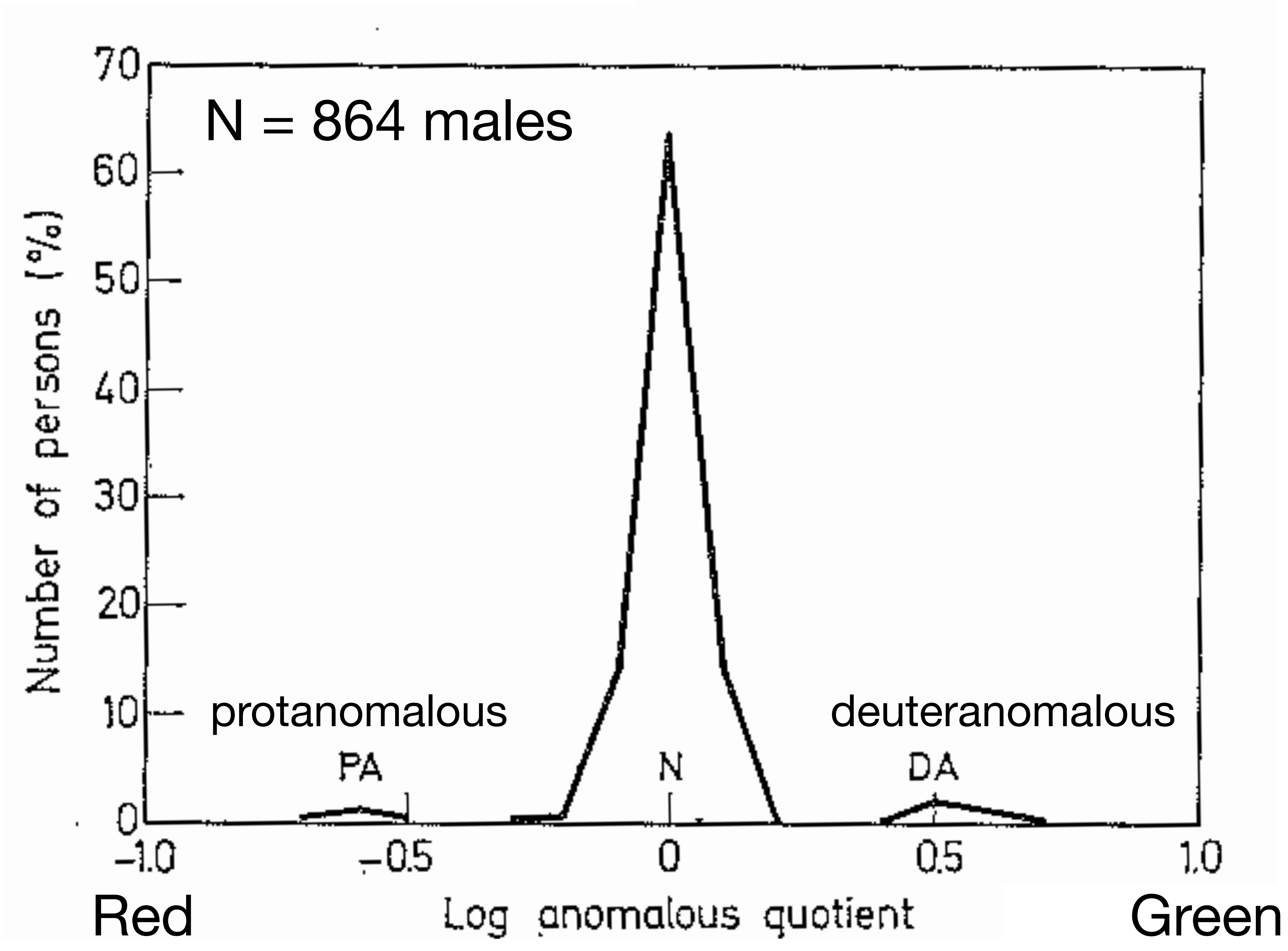
How is anomalous trichromacy defined?

Rayleigh Match



Strutt, J. W. (1881) "Experiments on colour." *Nature*

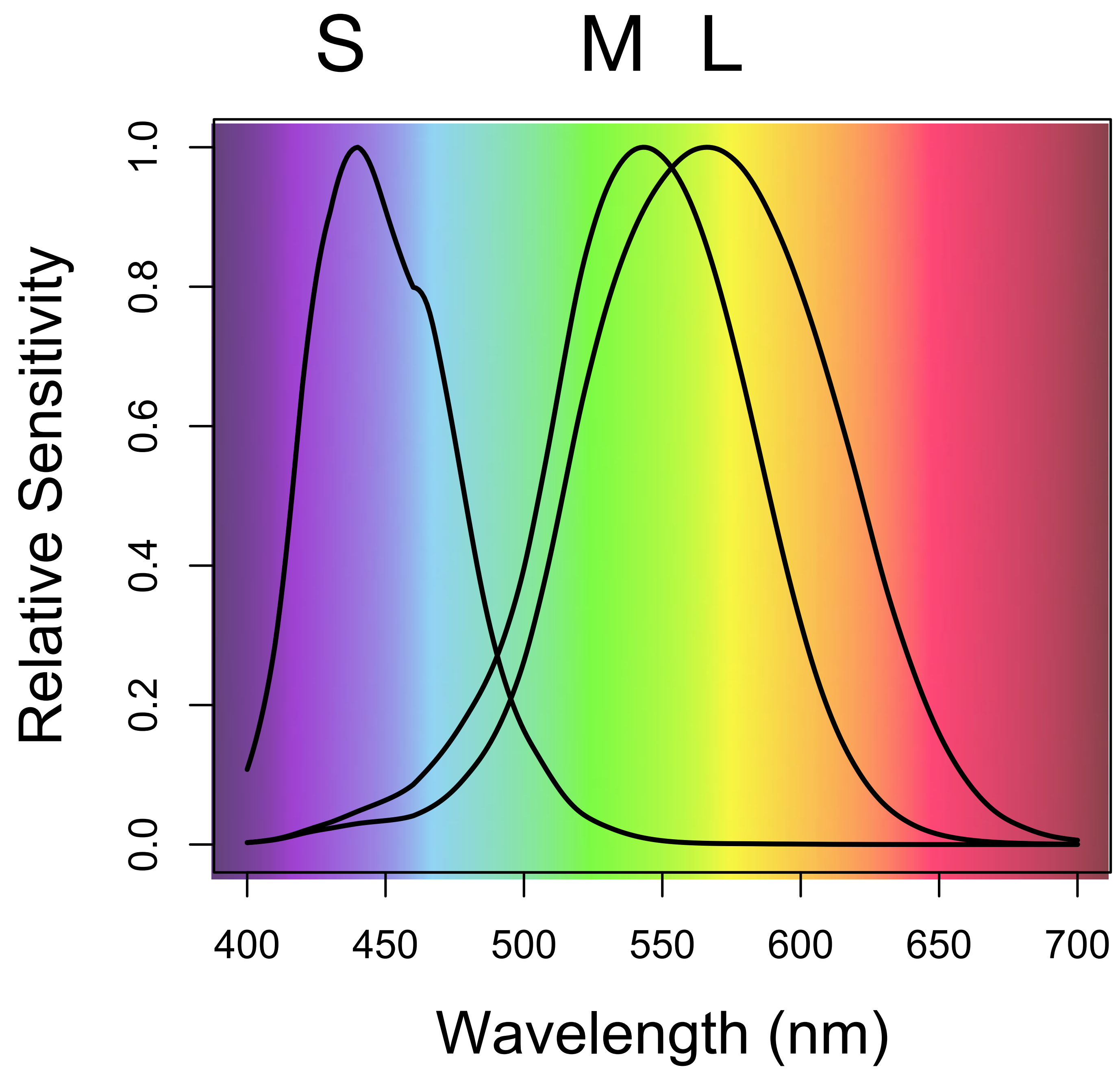
Anomaloscope Matches



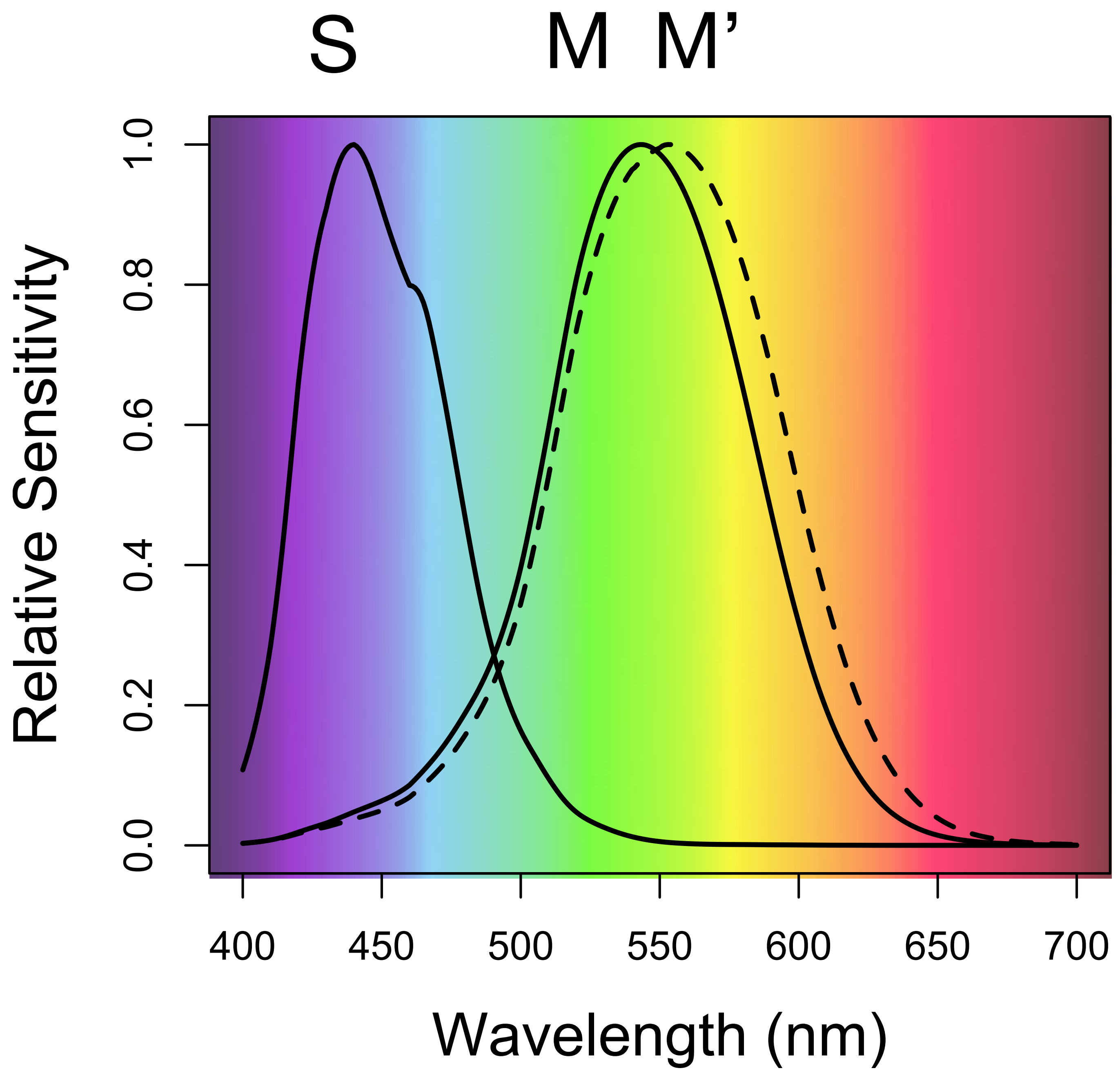
Schmidt I. (1955) *J Opt Soc Am*

DeMarco et al. average estimates of normal and anomalous cone spectral sensitivities

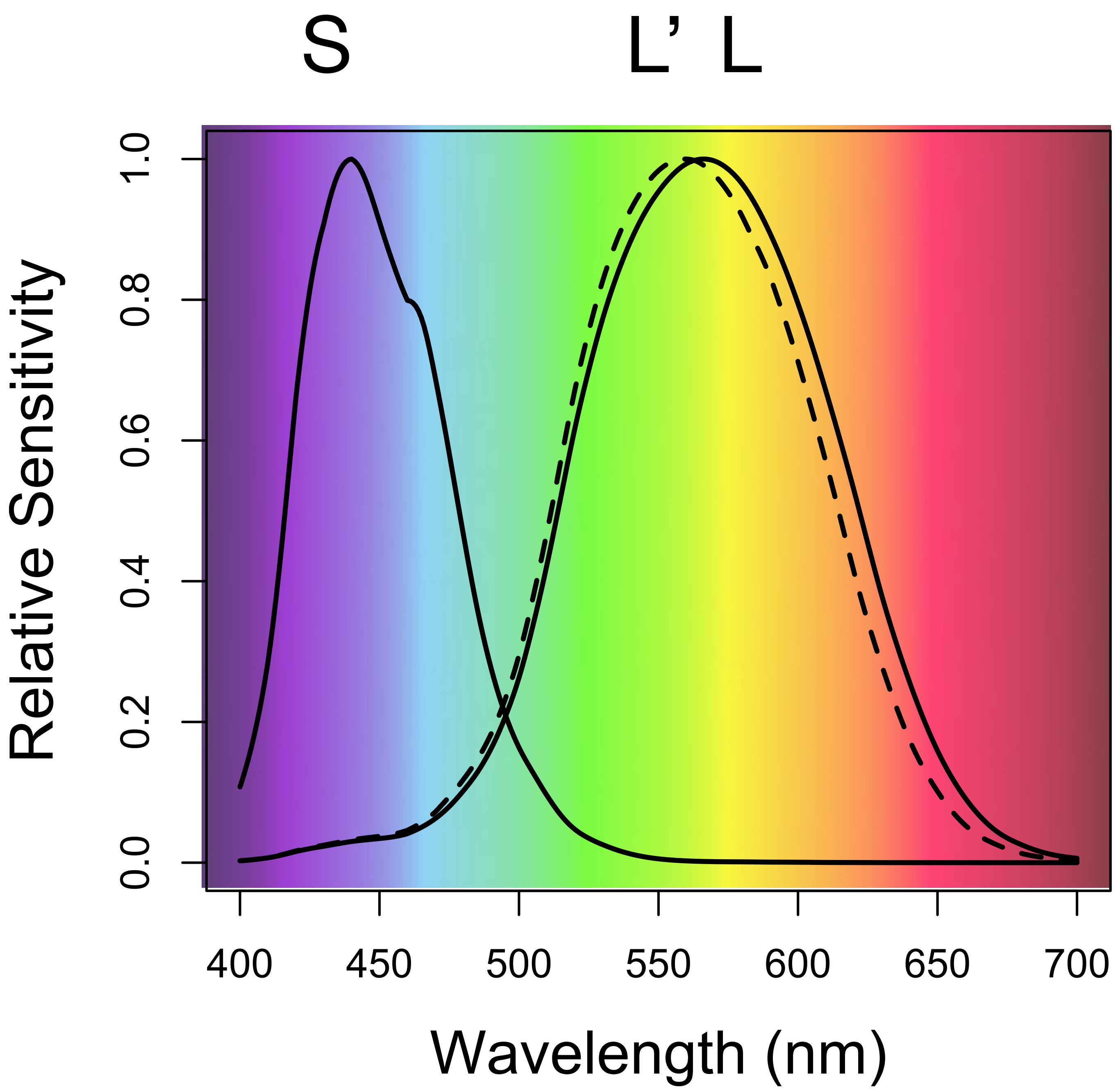
Normal



Protanomalous



Deuteranomalous



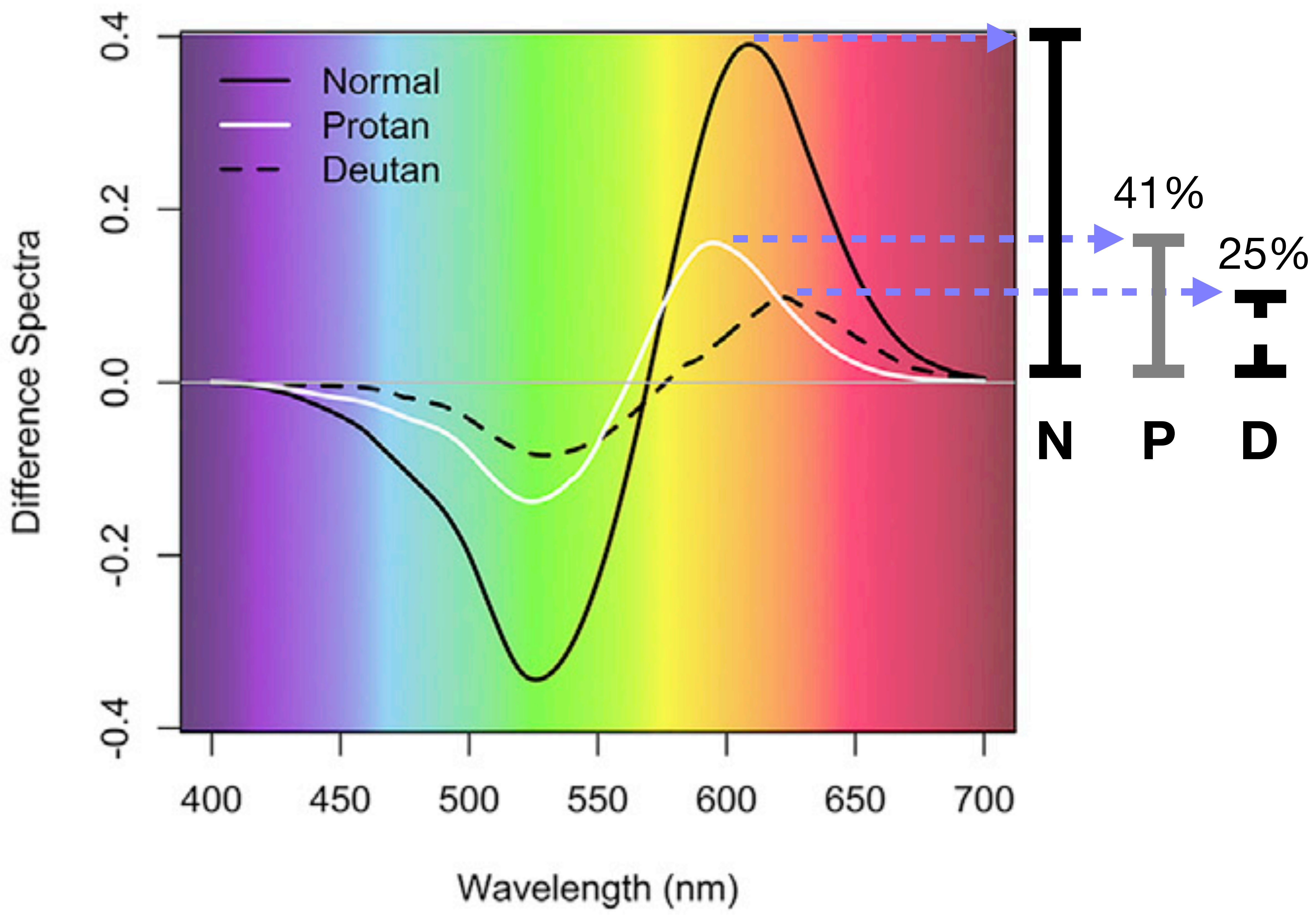
Peak Separation: 23 nm | 10 nm | 6 nm

Shift requires more red in match

Shift requires more green in match

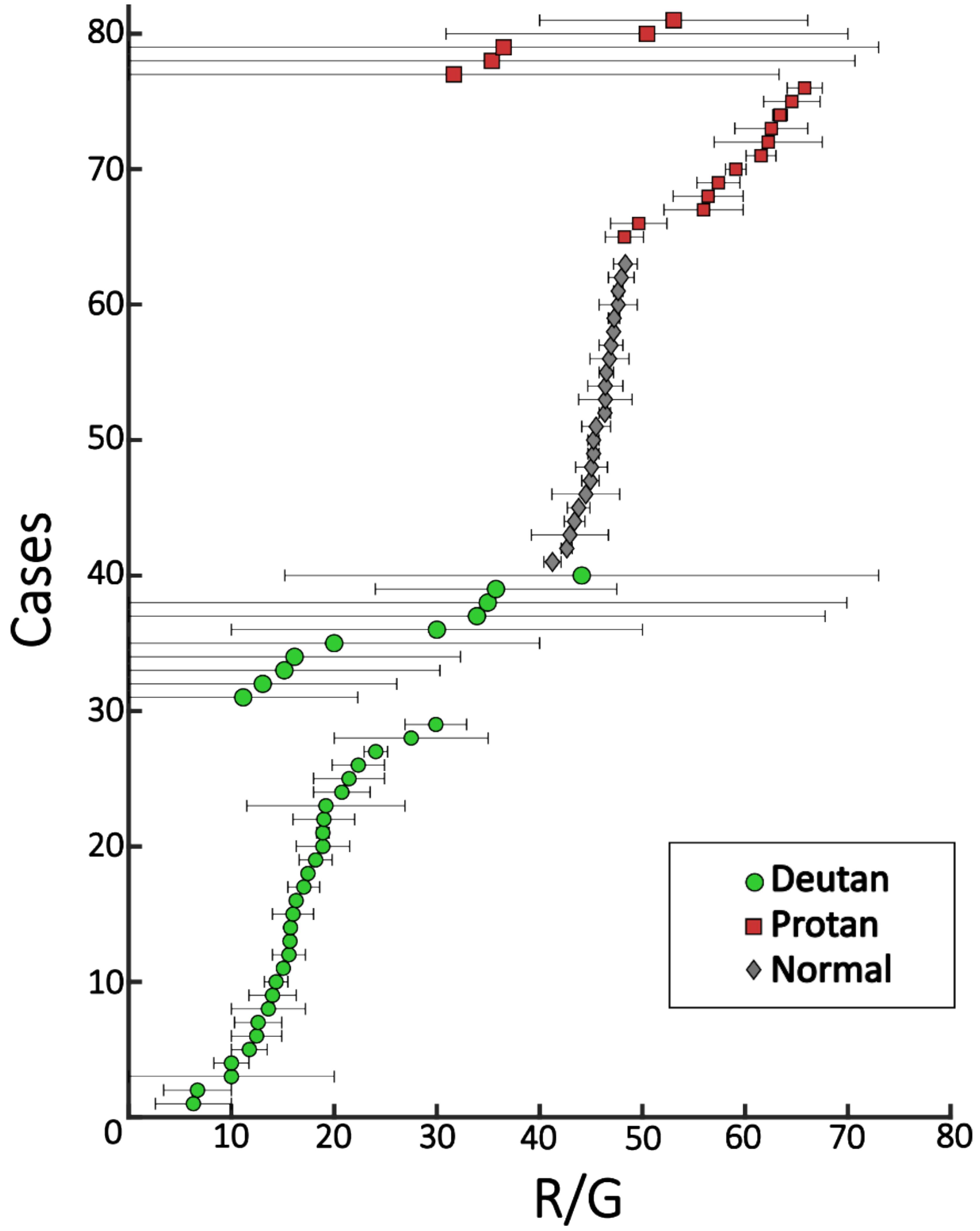
DeMarco, Pokorny & Smith (1992) *J Opt Soc Am A*

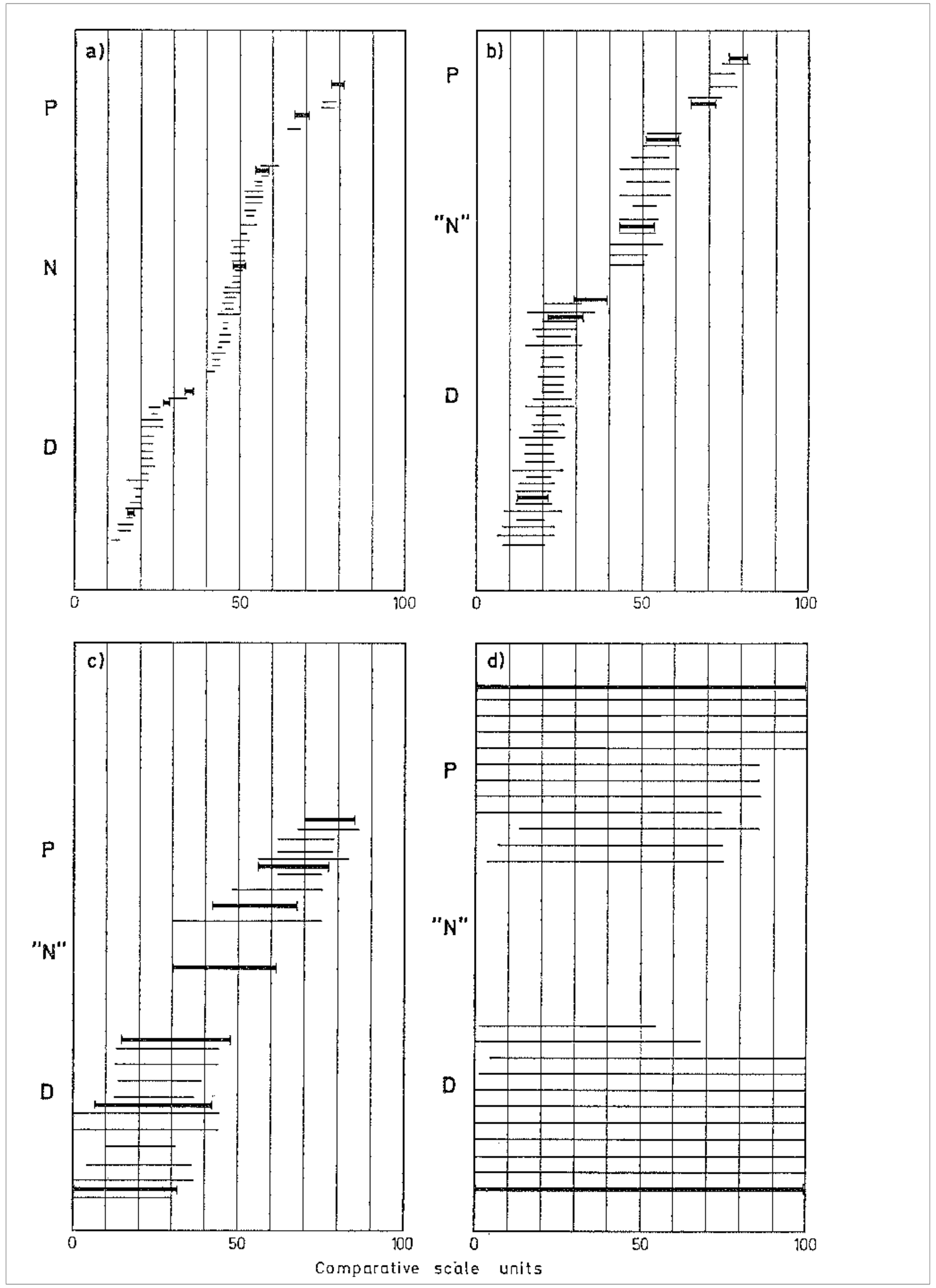
Predicted loss in chromatic strength from increased spectral sensitivity overlap



Increased spectral overlap predicts increased shift in R/G in Rayleigh match and decreased sensitivity to chromatic differences.

Lack of correlation between anomaloscope midpoint match and range of acceptance

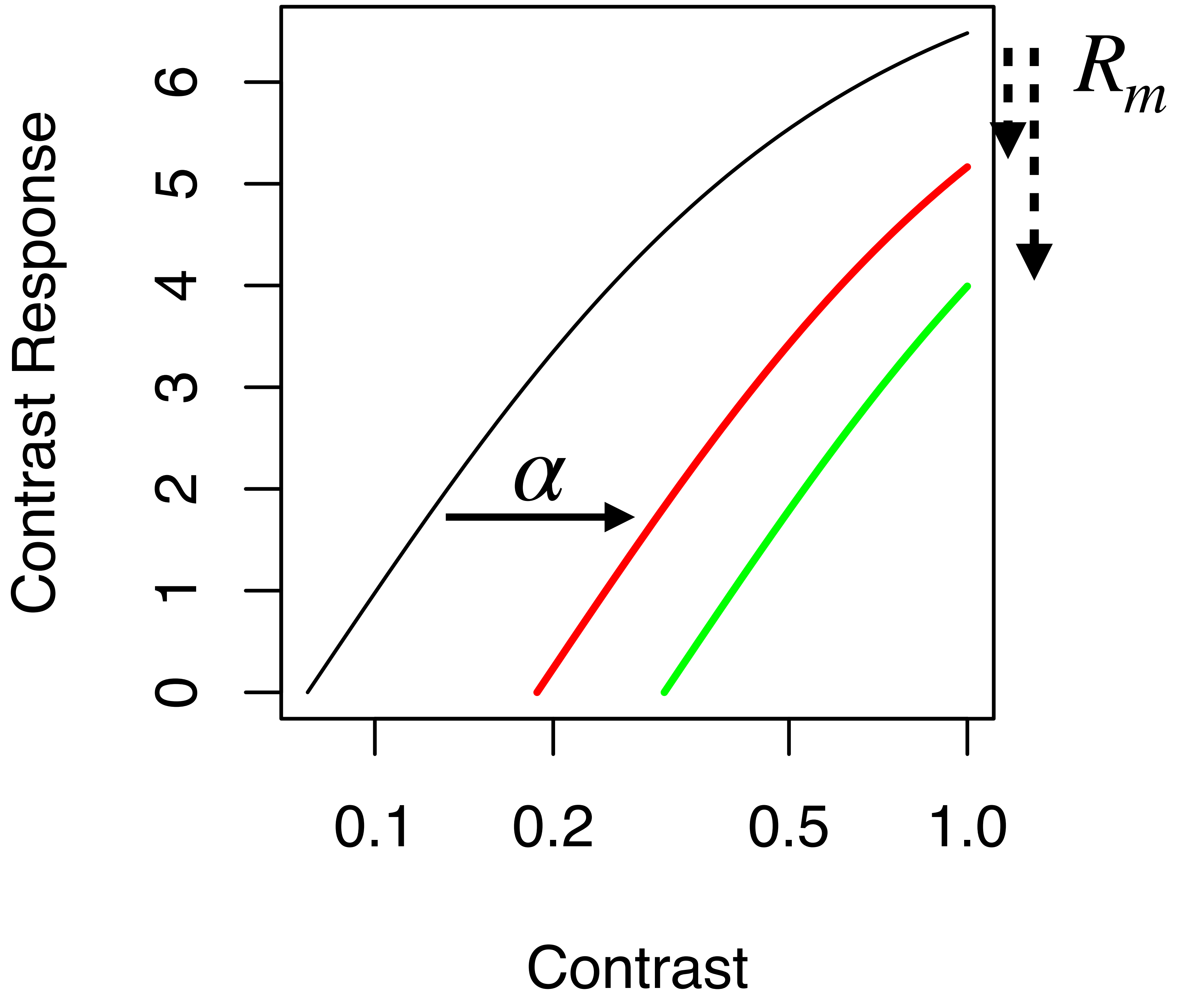




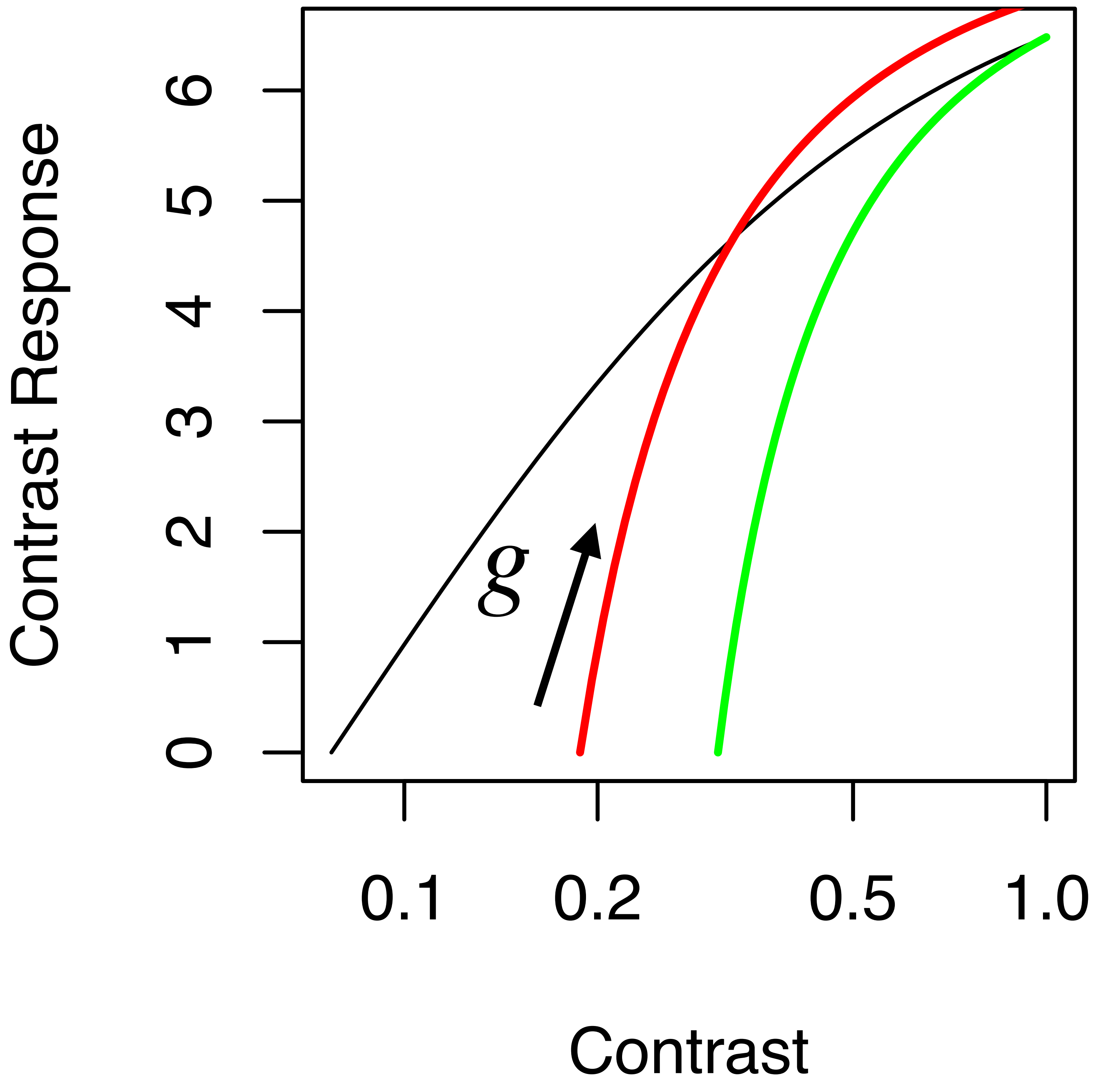
C. Pattie, S. Aston & G. Jordan (2022) *Optics Express*

Hurvich, 1972

Reduced spectral overlap, translates
the contrast response function (on log axis)
so that the range of outputs is reduced.



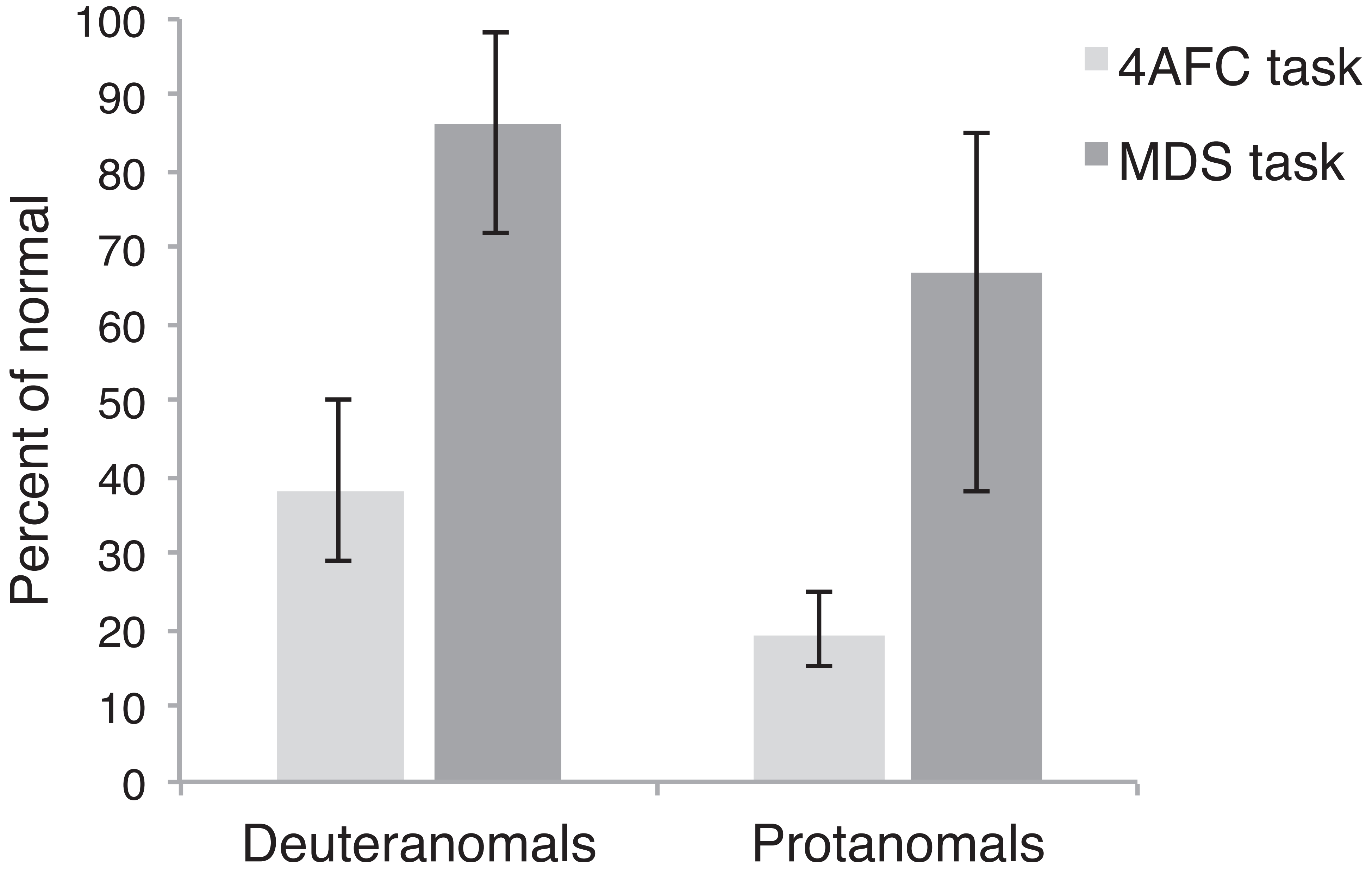
MacLeod (2003) proposed that
the visual system of anomalous observers
would compensate by increasing gain
so as to map inputs to the full range of outputs



Concept of ***allostasis*** (Sterling & Eyer, 1988, based on earlier ideas of Laughlin, 1981)
proposes that sensory systems would predictively modify gain in the presence
of reduced input range to map the output to the full neural response range.

Boehm, A. E., MacLeod, D. I. A., & Bosten, J. M. (2014). Compensation for red-green contrast loss in anomalous trichromats. *J Vis*, **14(13):19**, 1–17

Anomalous trichromats show reduced chromatic sensitivity at threshold, but this is not reflected in supra-threshold color appearance as estimated using multi-dimensional scaling. They suggested an adaptive adjustment of post-receptoral gain.



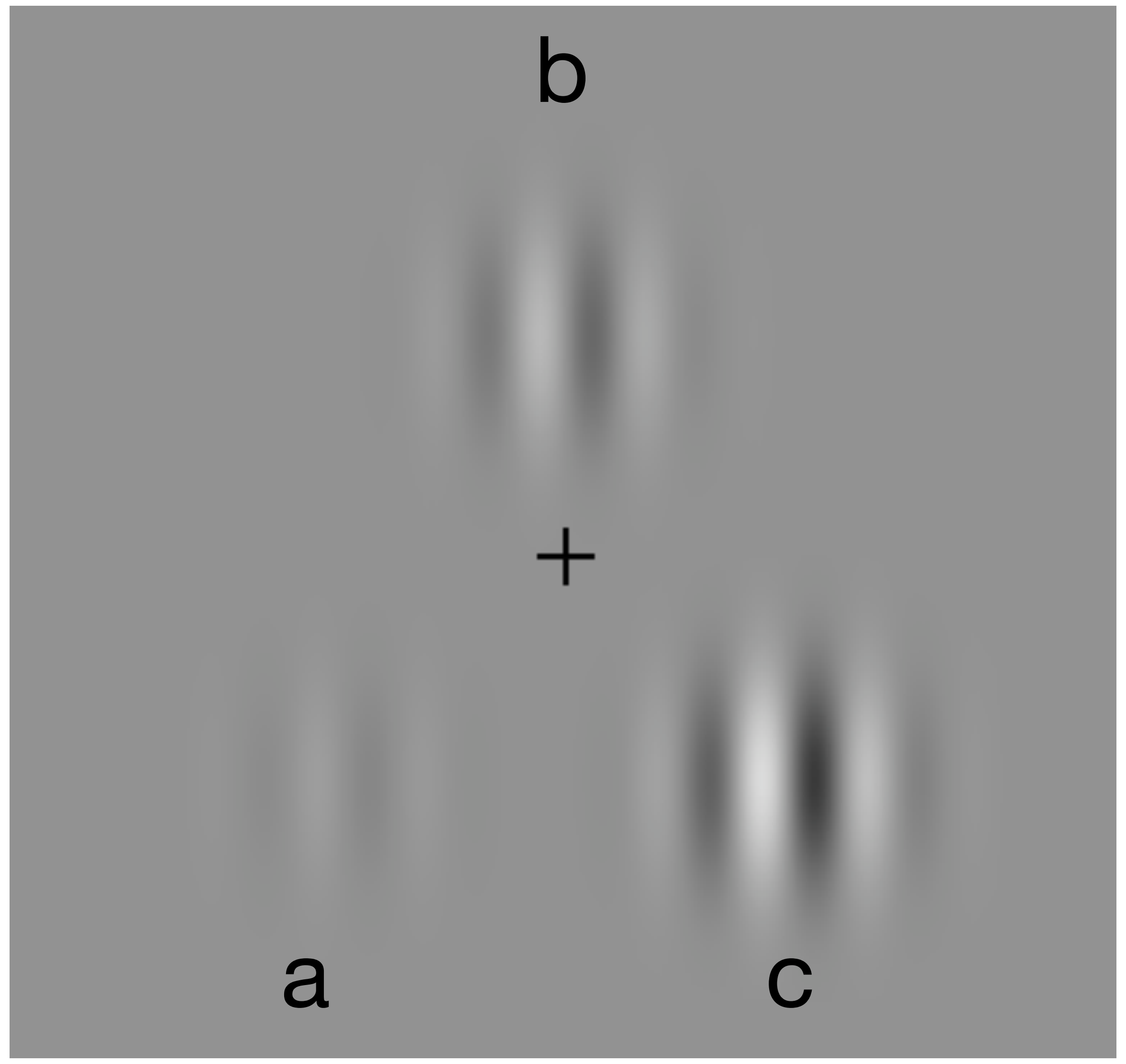
Empirical evidence for compensation in anomalous trichromats from several studies:
Regan & Mollon (1997), Boehm et al. (2014, 2021), Knoblauch et al. (2020), Lindsey et al. (2021), Vanston et al. (2021), Tregillus et al. (2021).

Maximum Likelihood Difference Scaling (MLDS)

(Maloney & Yang, 2003, *J Vis*)

Given a physical scale, $\{\phi_1, \cdots, \phi_n\}$, choose an ordered triad (a, b, c);
judge whether the *perceived difference* is least between (a, b) or (b, c).

Is the upper stimulus more similar
to the bottom one on the left or the right?

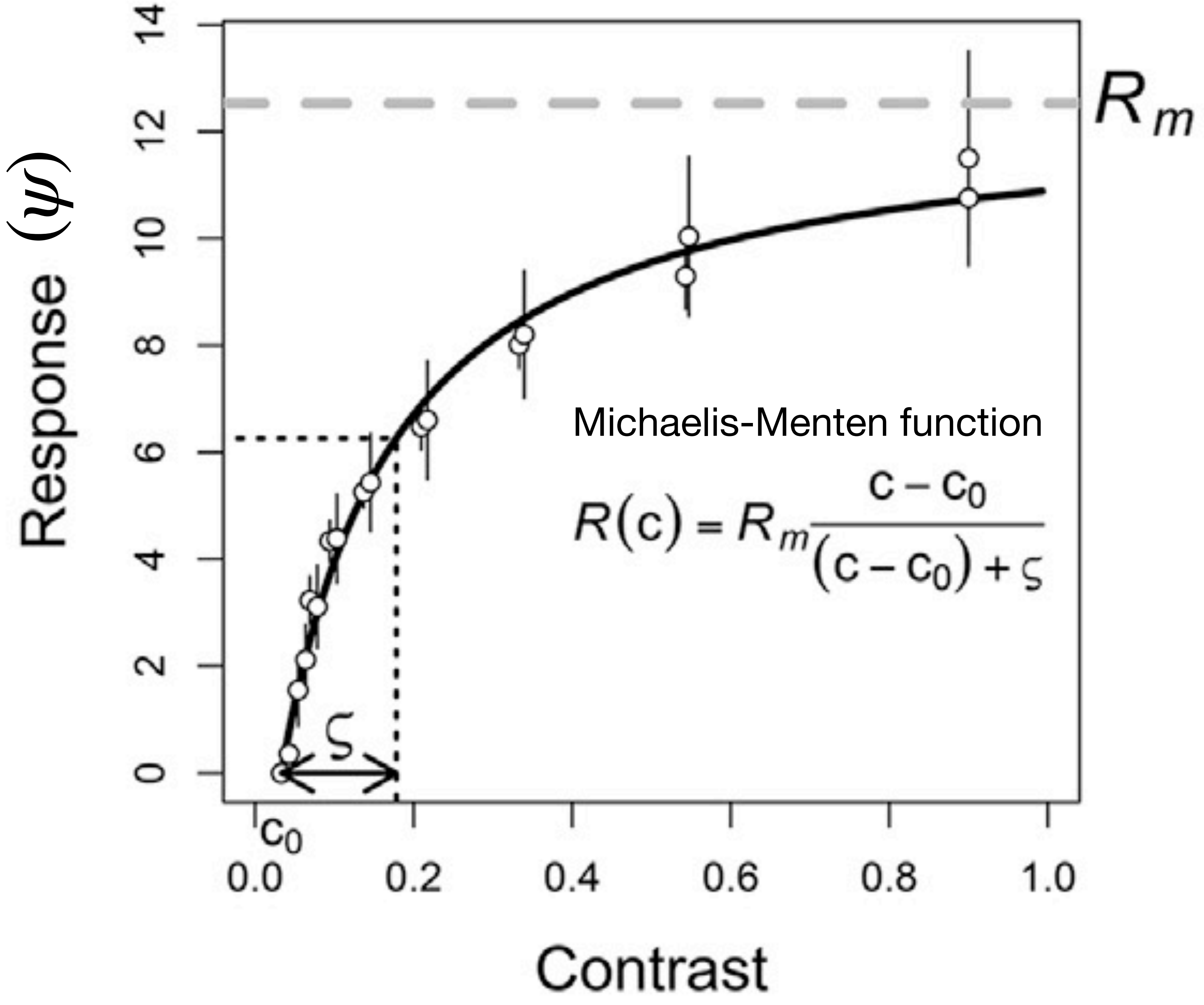


Decision rule:

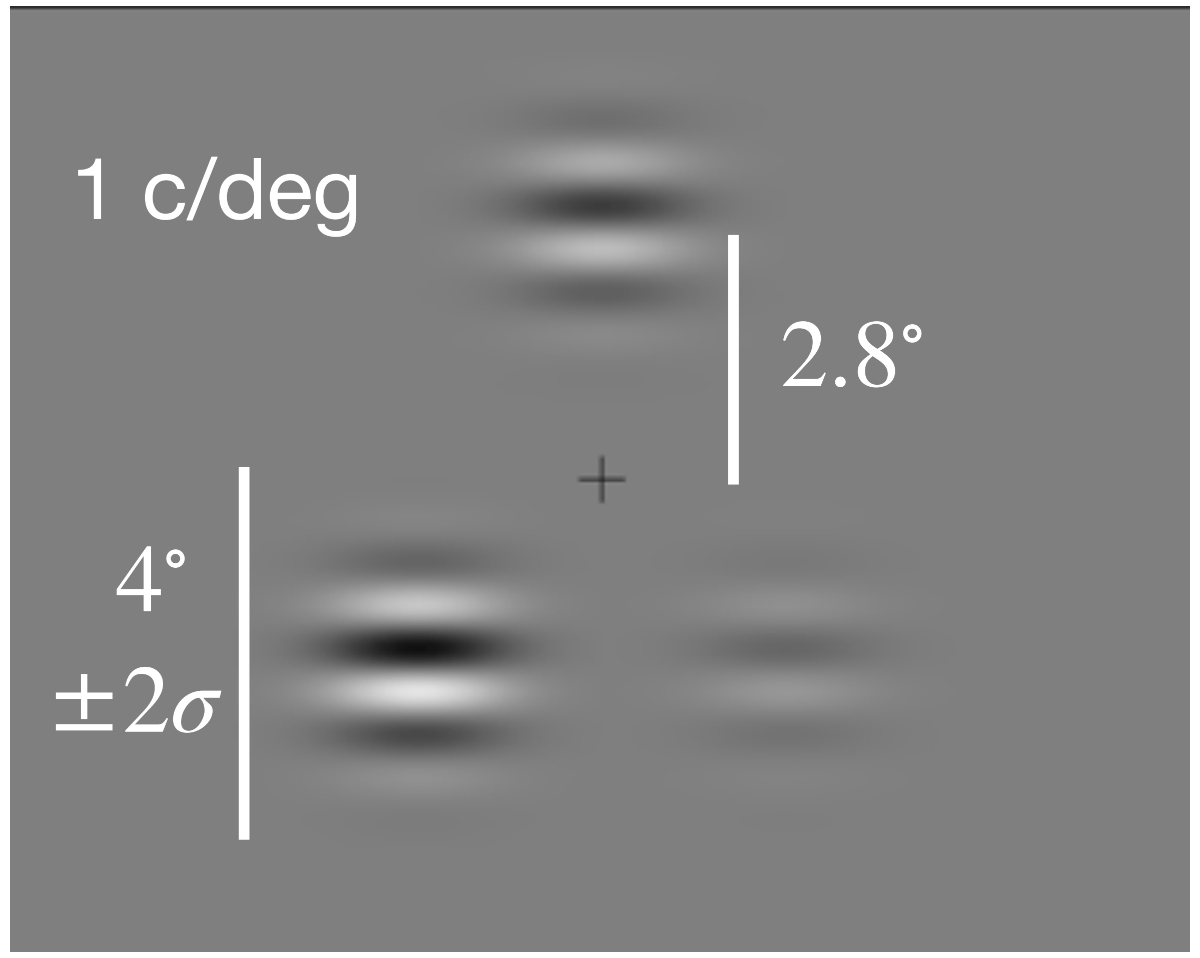
$$\Delta_{abc} = (\psi_b - \psi_a) - (\psi_c - \psi_b) + \epsilon$$
$$= 2\psi_b - \psi_a - \psi_c + \epsilon,$$
$$\epsilon \sim N(0, \sigma^2)$$

Choose left stimulus if $\Delta_{abc} > 0$,
otherwise choose right stimulus

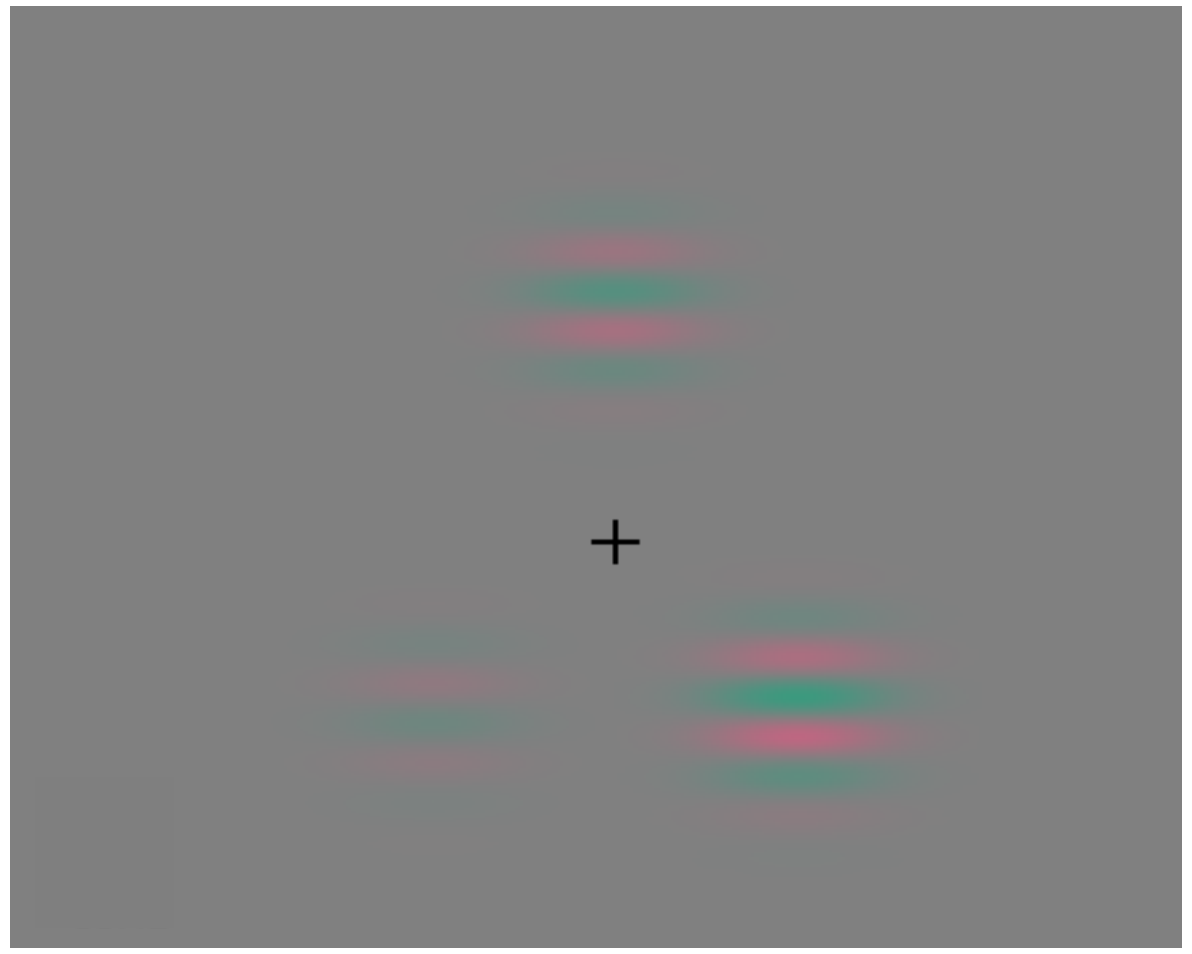
Perceptual Scale estimated
from a signal detection model
by maximum likelihood

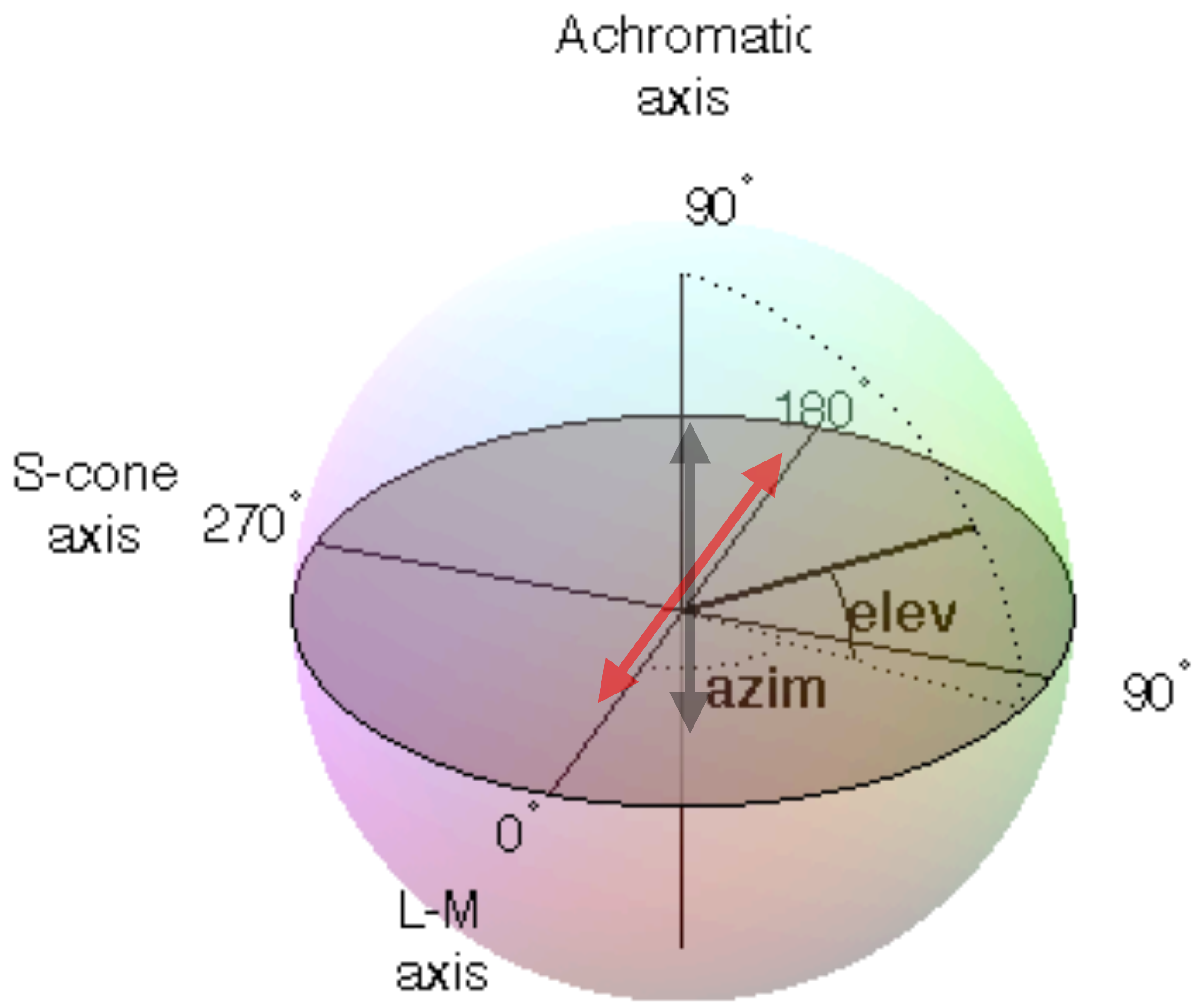


Luminance



L - M



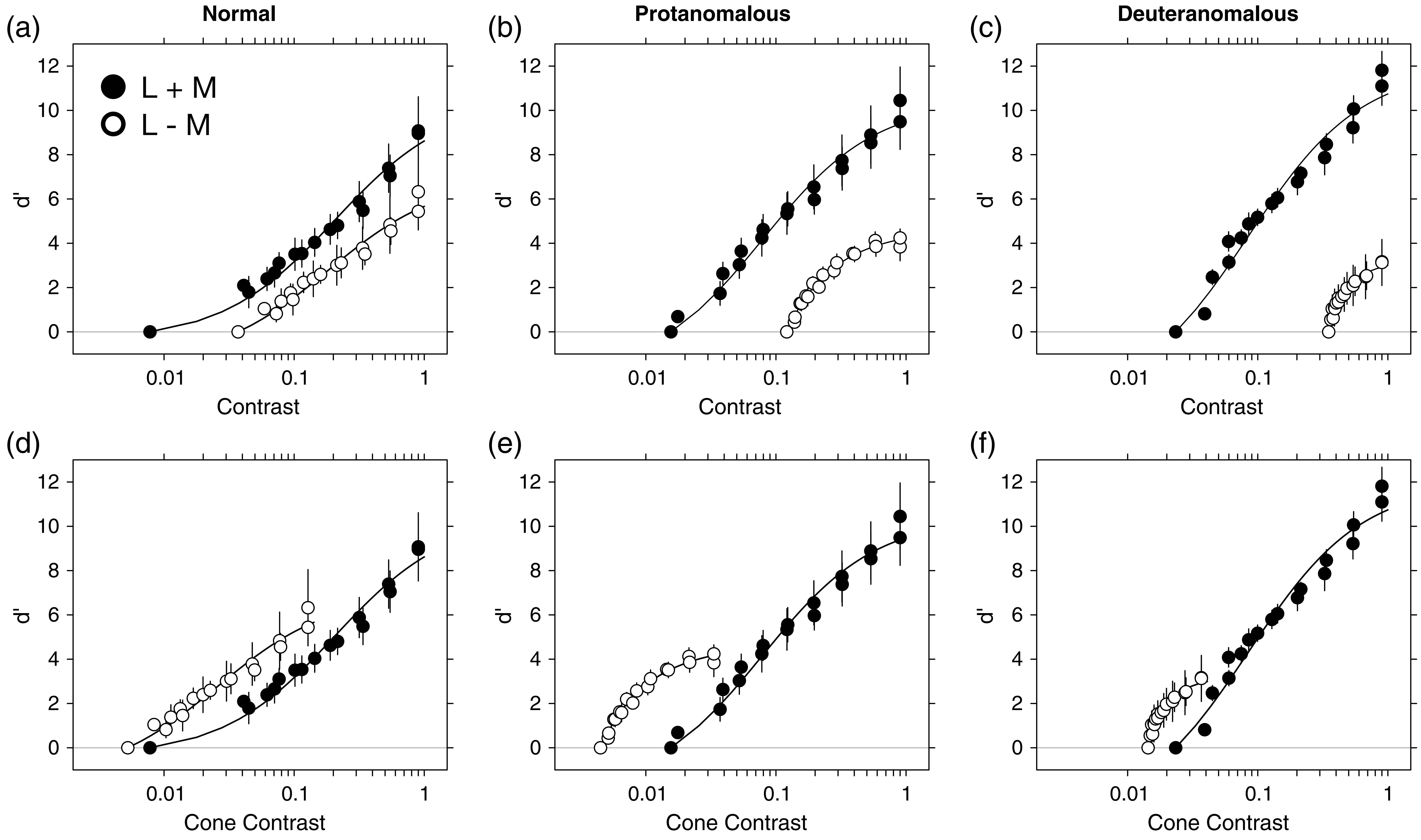


DKL color space

9 normal trichromats
9 protanomalous trichromats
9 deuteranomalous trichromats

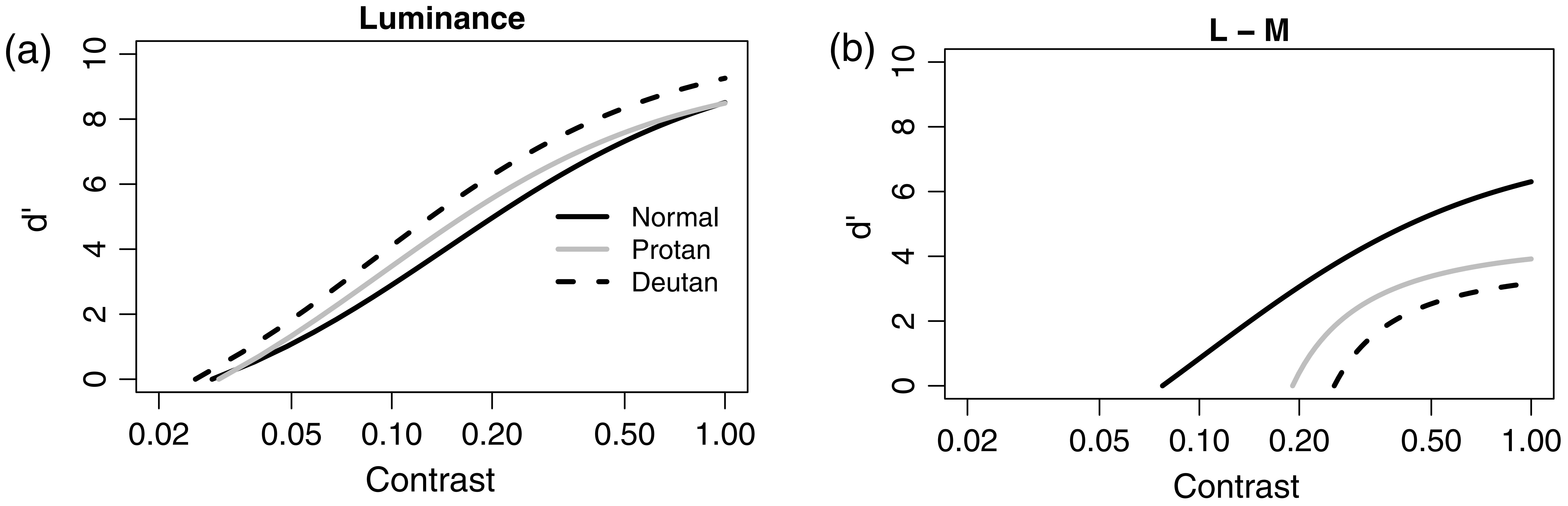
Pre-tests: anomaloscope, Cambridge tri-vector test,
HRR test, Farnsworth F2 plate, Panel D-15
Estimate of minimum perceptible contrast along both dimensions
Subjects tested 4 sessions with 6 runs/session,
9 contrasts which gives 84 triads/run, about 5 minutes.

Stimuli: Horizontal Gabor patches:
4 deg diameter (±2σ); spatial frequency: 1 c/deg; duration 0.5 sec.;
2.8 deg eccentricity from fixation cross.

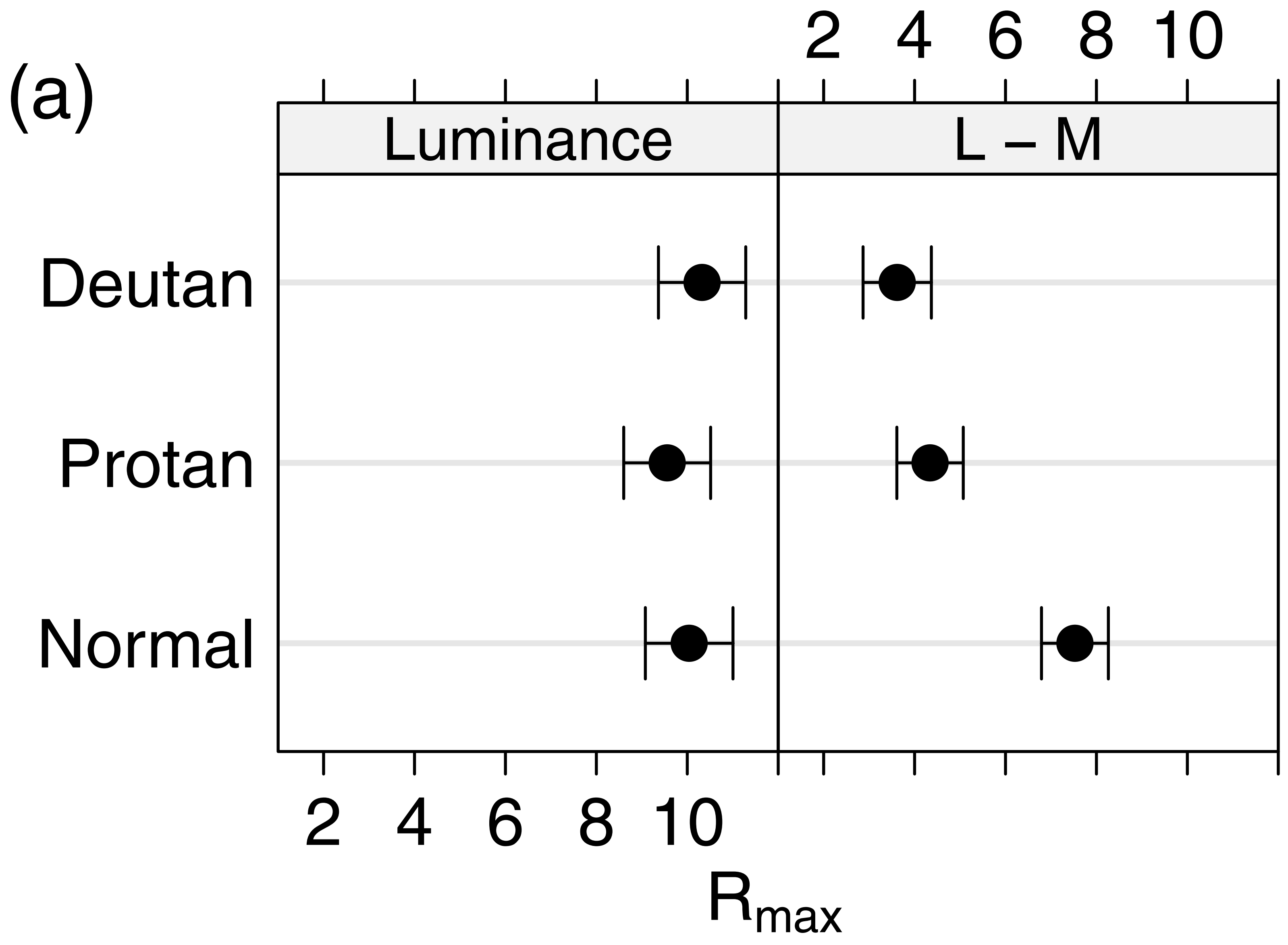


Knoblauch, Brennan-Marsh & Werner (2020) *J Opt Soc Am A*

MLDS contrast appearance curves based on average parameter estimates

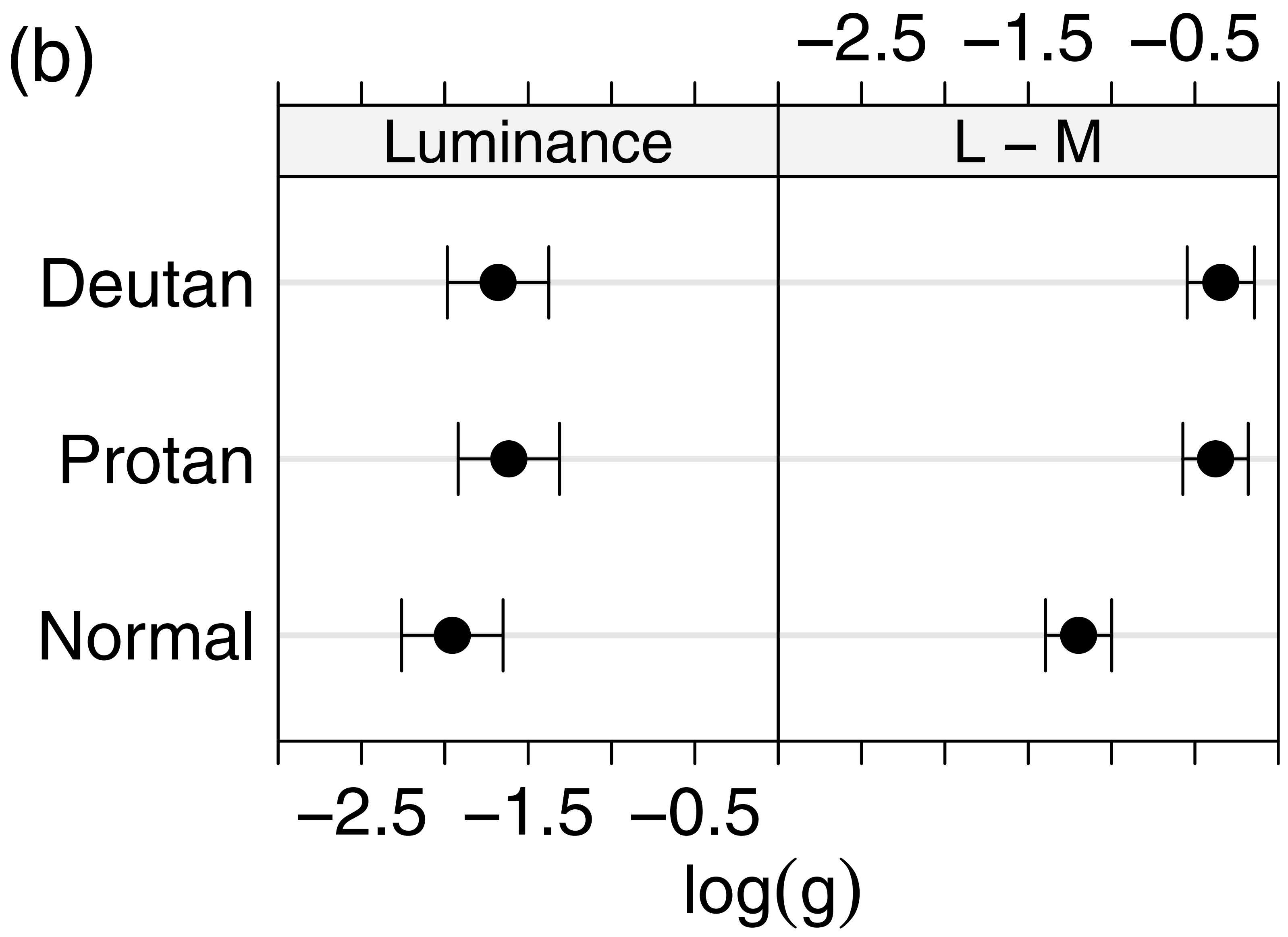


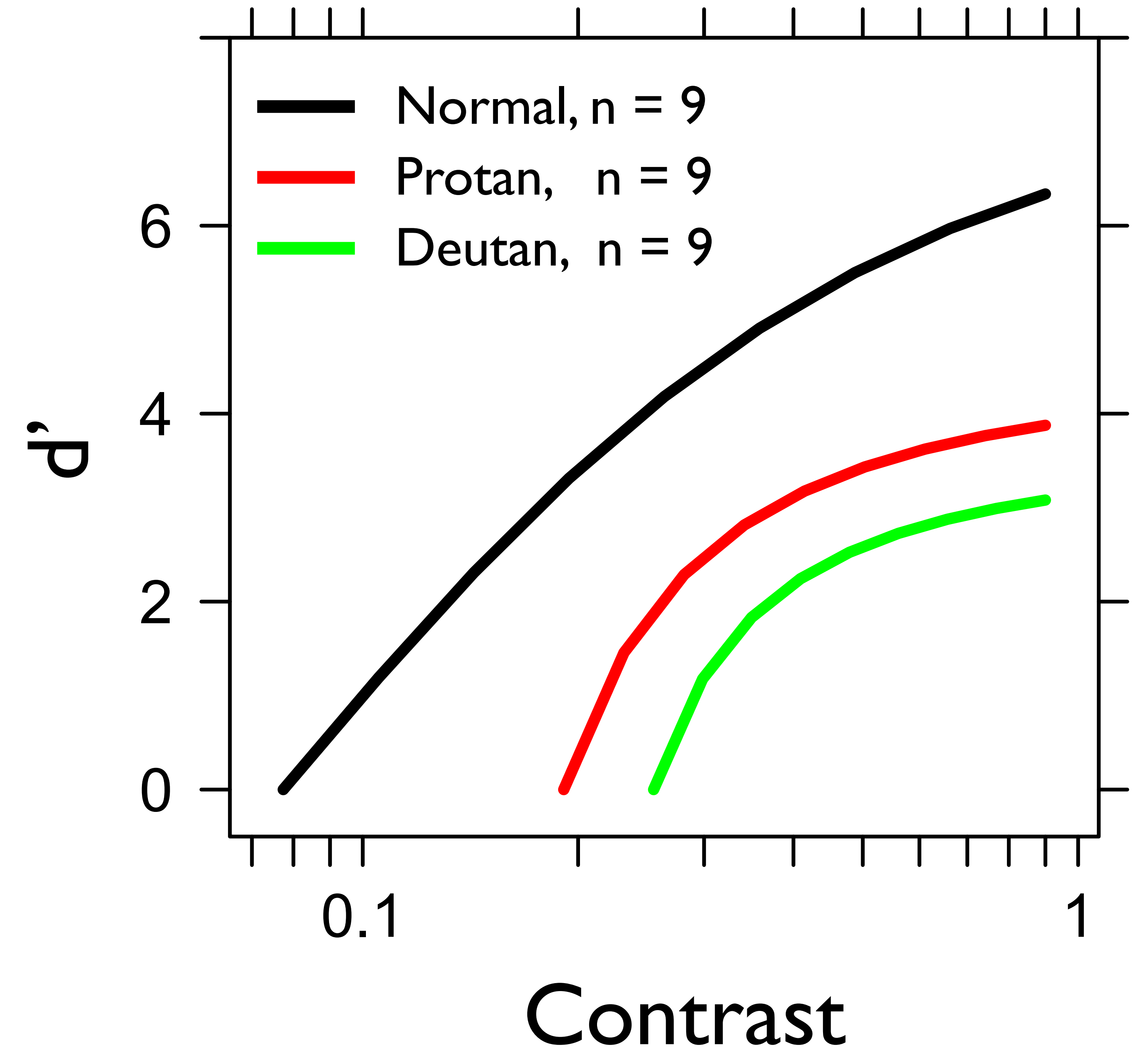
Knoblauch, Brennan-Marsh & Werner (2020) *J Opt Soc Am A*



$$R(c) = R_m \frac{g(c - c_0/\alpha)}{g(c - 2(c_0/\alpha)) + c_0/\alpha}$$

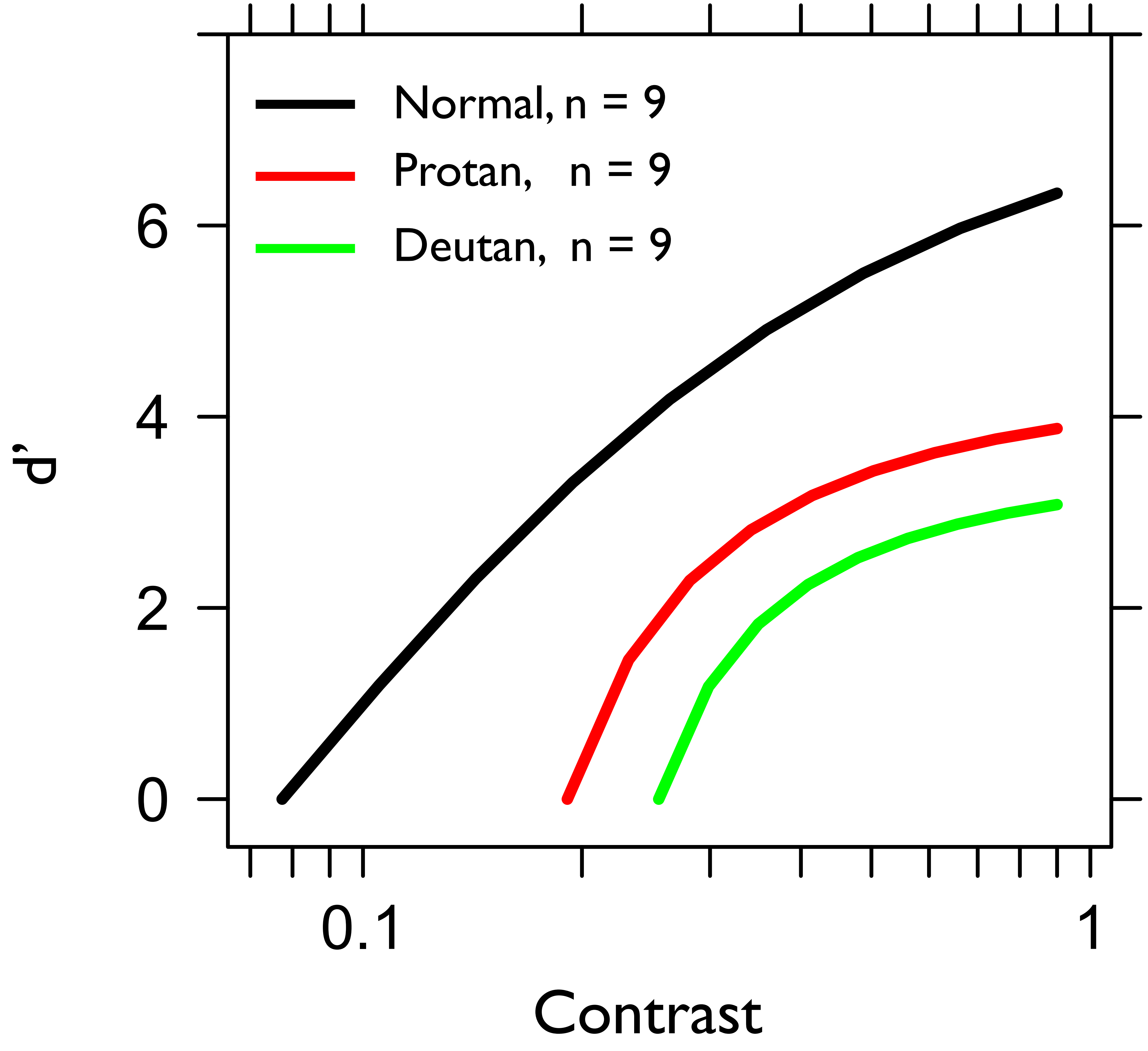
c - Contrast
R - Contrast response
R_m - Response maximum (response gain)
g - Contrast gain (c_0/c_{50})
c_0 - Minimum normal contrast
α - Relative attenuation due to spectral shift





Knoblauch, Brennan-Marsh & Werner (2020) *J Opt Soc Am A*

Interim Conclusions



Contrast gain is steeper in anomalous observers, but the response scales asymptote at lower values than the normal curve, thus, apparently not achieving the aim of mapping input to the full range of neural responses.

Perhaps, noise can account for the maximum response decrease.

Intuitively, the gain would amplify the noise as well as the contrast signal.

We considered including a noise at the level of contrast encoding.

Such noise can be introduced as either an additive or multiplicative term:

Additive Gaussian Noise

$$R(c) = R_m \frac{g(c + \epsilon - c_0/\alpha)}{g(c + \epsilon - 2(c_0/\alpha)) + c_0/\alpha}$$

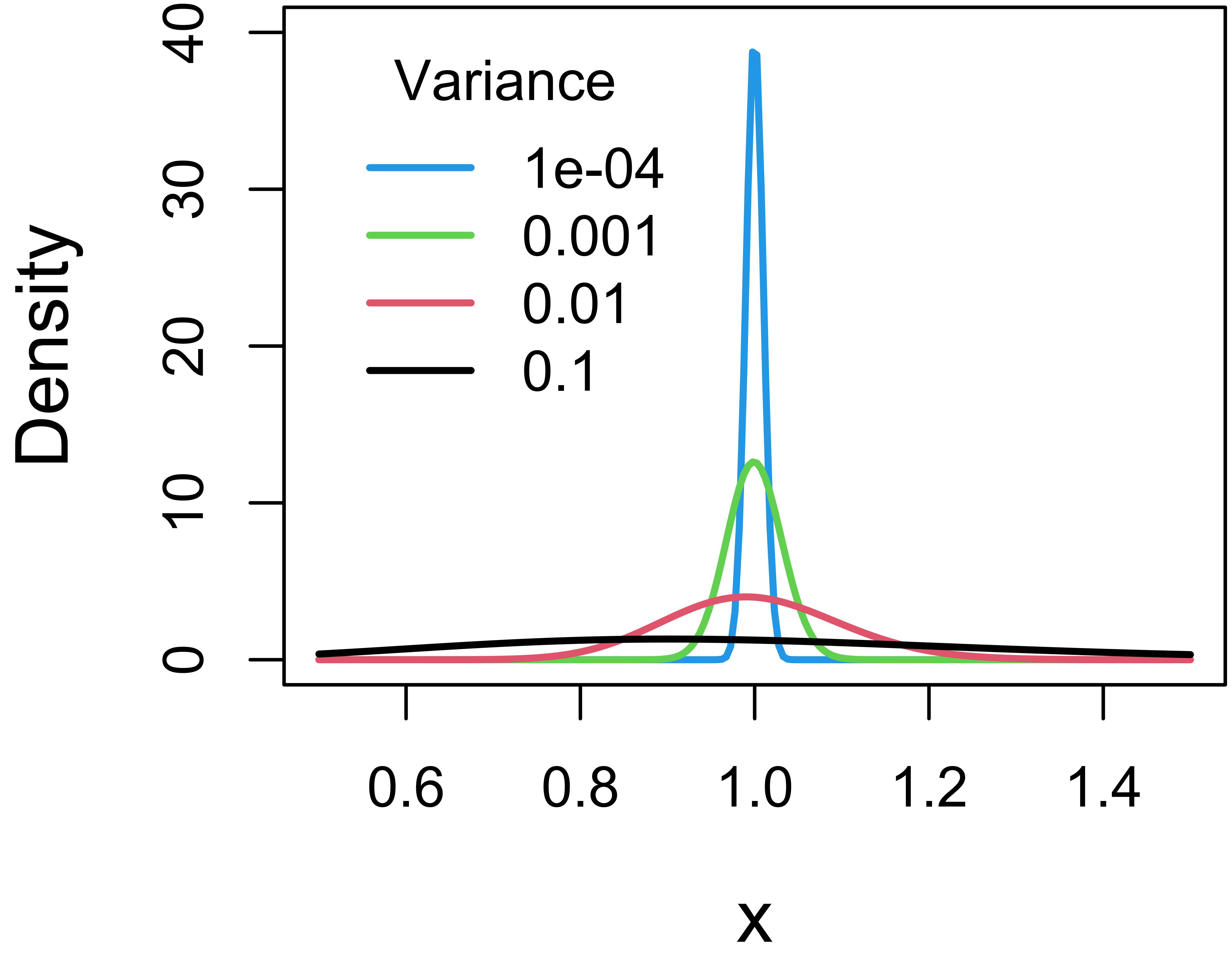
$$\epsilon \sim N(0, \sigma^2)$$

Multiplicative Gamma Noise

$$R(c) = R_m \frac{g(c\gamma - c_0/\alpha)}{g(c\gamma - 2(c_0/\alpha)) + c_0/\alpha}$$

$$\gamma \sim \text{Gamma}(s, s)$$

$\gamma \sim \text{Gamma}(s, s)$



Gamma density: $f(x; s, r) = \frac{r^s}{\Gamma(s)} x^{s-1} e^{-xr}$

The Gamma distribution has shape parameter, s, and rate parameter, r.

Mean: $\mu = s/r$; Variance: $\sigma^2 = s/r^2$.

By fixing $s = r$, we obtain a family of Gamma distributions with mean = 1 and variance = $1/r = 1/s$.

We used a randomly distributed value, γ, to multiply contrast, c, on each simulated trial.

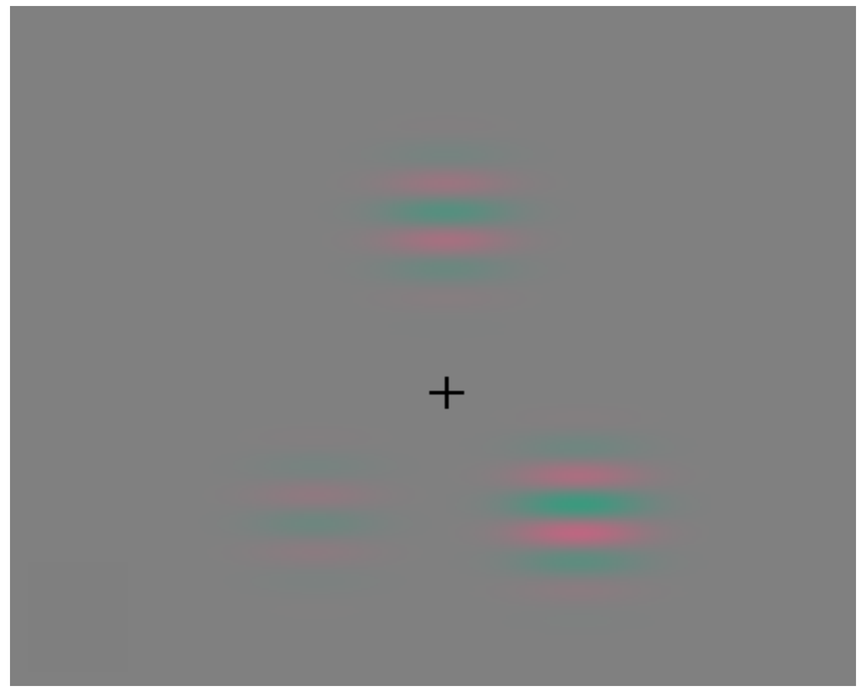
$$R(c) = R_m \frac{g(c\gamma - c_0/\alpha)}{g(c\gamma - 2(c_0/\alpha)) + c_0/\alpha}$$

$$\gamma \sim \text{Gamma}(s, s)$$

Simulation Procedure

1) Choose contrasts, (c_a, c_b, c_c) for trial and calculate noise-perturbed response for each.

C_a	C_b	C_c
	. . .	
0.358	0.194	0.142
0.142	0.194	0.487
0.662	0.194	0.142
0.142	0.194	0.900
0.358	0.263	0.142
	. . .	



$$R(c) = R_m \frac{g(c\gamma - c_0/\alpha)}{g(c\gamma - 2(c_0/\alpha)) + c_0/\alpha}$$

$$\gamma \sim \text{Gamma}(s, s)$$

2) Calculate decision variable using the 3 noise-perturbed responses:

$$\Delta_{abc} = 2\,R(c_b) - R(c_a) - R(c_c)$$

3) if $\Delta_{abc} > 0$, choose a, else choose c, coded as choices 0 and 1, respectively.

4) Repeat for next trial.

5) When all trials completed, estimate scale values with MLDS procedure.

Simulation:

9 contrasts (for each observer), 20 MLDS runs of 84 triads each, repeated 100 times

True response function:

$$R(c) = R_m \frac{g(c\gamma - c_0/\alpha)}{g(c\gamma - 2(c_0/\alpha)) + c_0/\alpha}$$

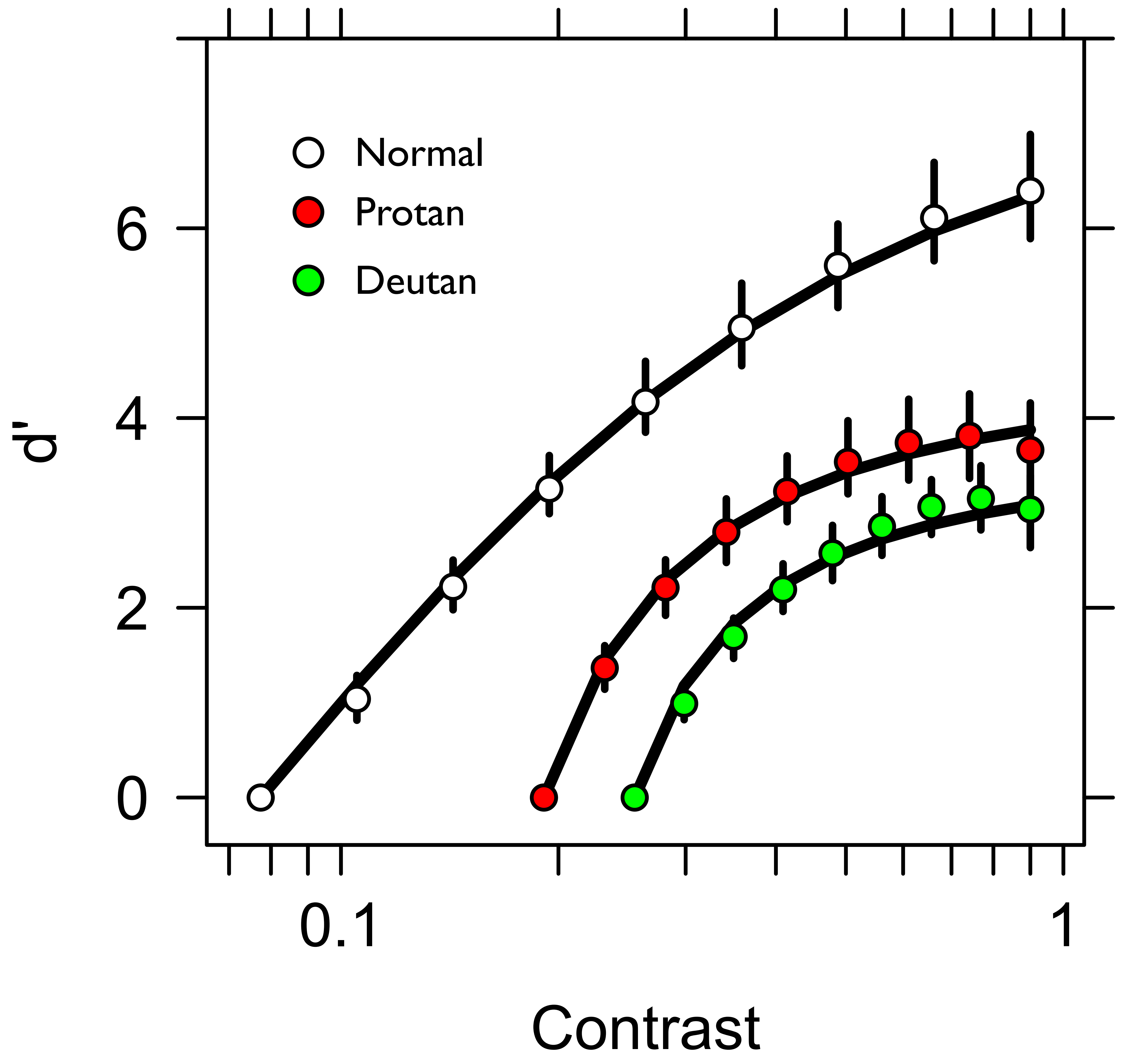
$$\gamma \sim \text{Gamma}(s, s)$$

R_m: 7.467 (all observers)

Noise variance $(1/s)$: 0.021 (all observers)

Spectral shift (c_0/α): Normal 0.077
Protan 0.191
Deutan 0.255

Gain (g): Normal 0.346
Protan 0.768
Deutan 0.764



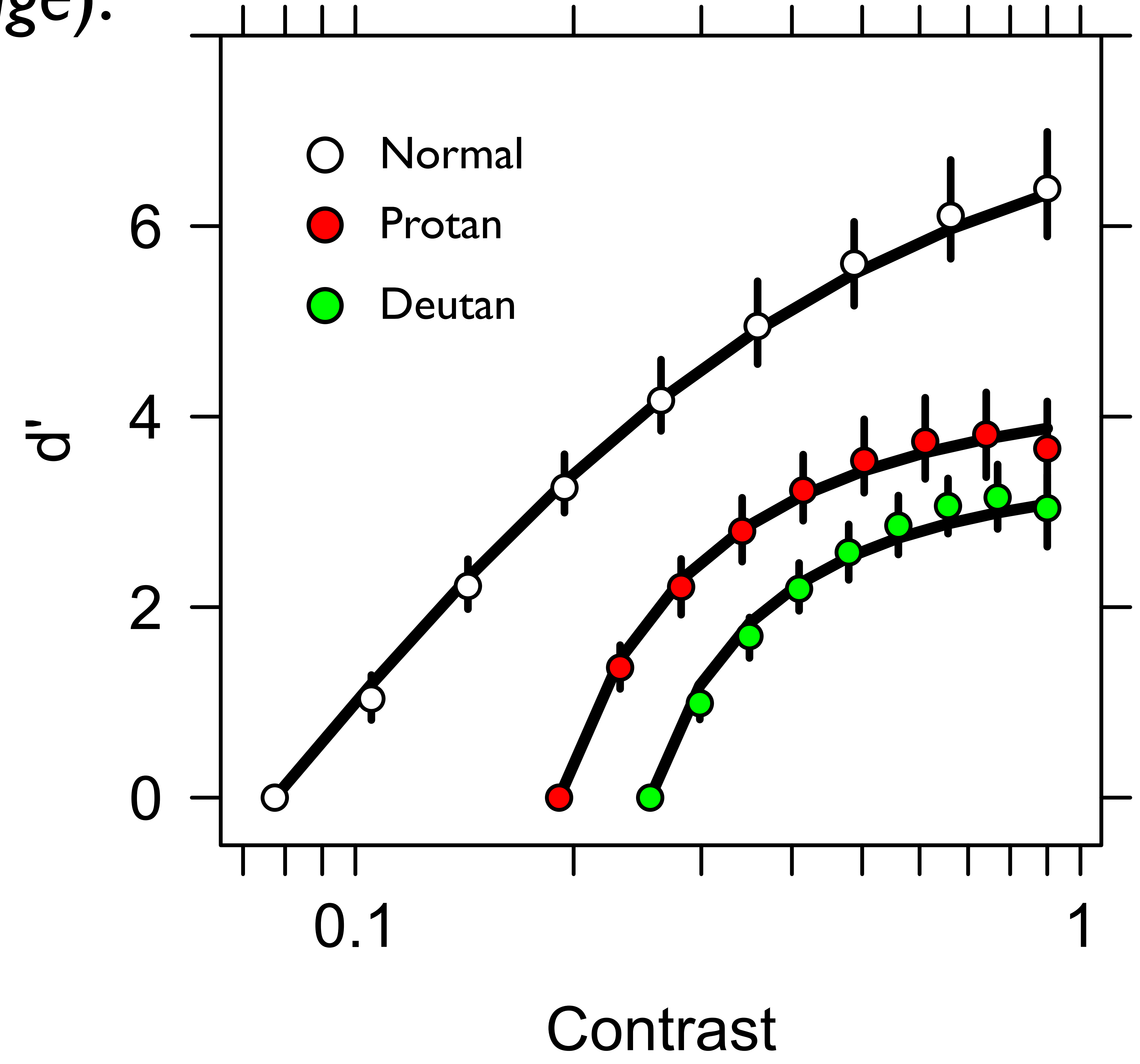
With a fixed multiplicative noise applied at the level of contrast encoding, and all other parameters equal, increasing the contrast gain, g, both:

i) increases steepness of the estimated perceptual response and

ii) reduces *apparent* maximum response level (*preventing use of full response range*).

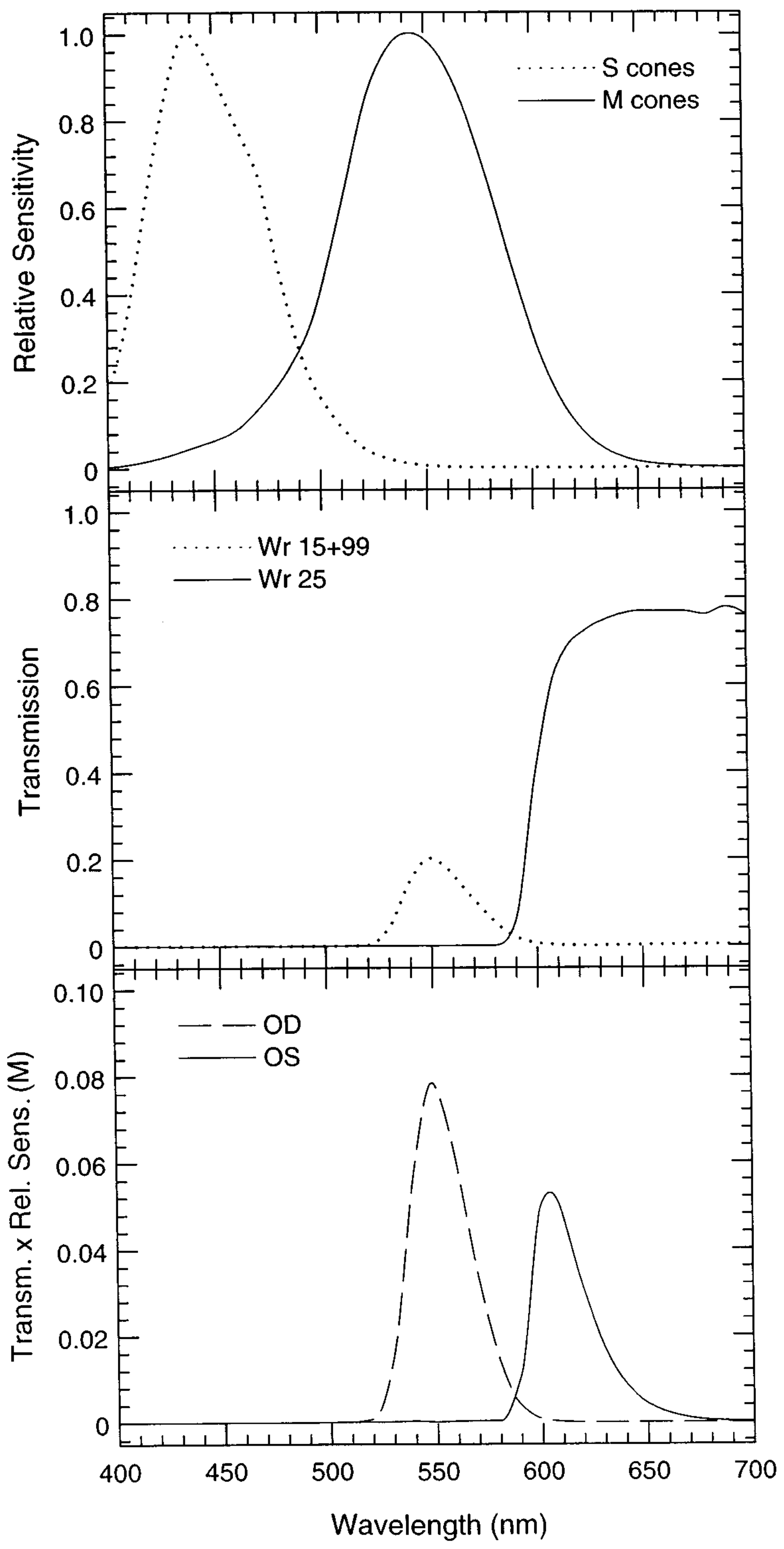
$$R(c) = R_m \frac{g(c\gamma - c_0/\alpha)}{g(c\gamma - 2(c_0/\alpha)) + c_0/\alpha}$$

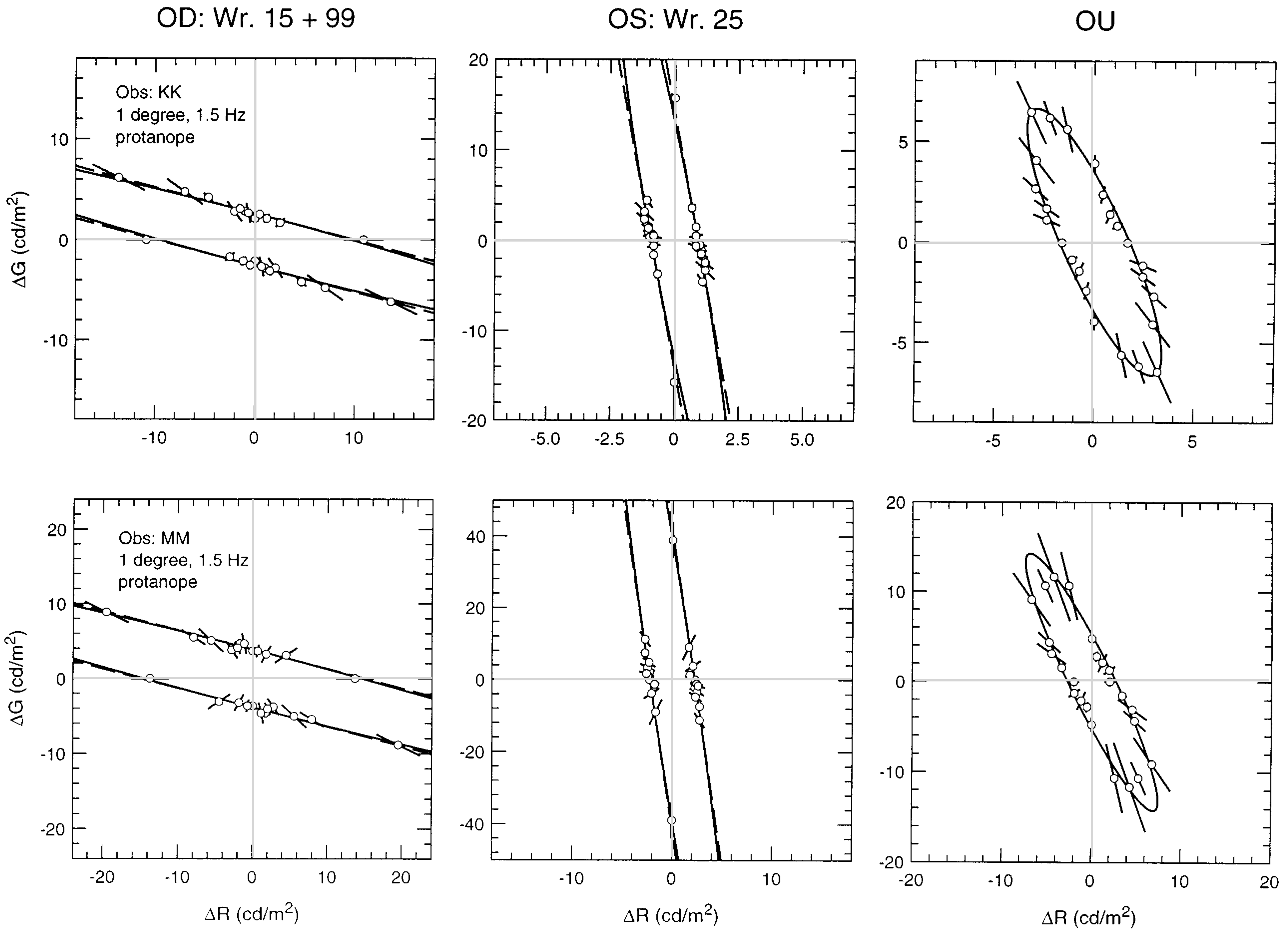
$$\gamma \sim \text{Gamma}(s, s)$$



Noise limits the extent to which natural mechanisms of compensation can enhance chromatic contrast response in anomalous trichromacy

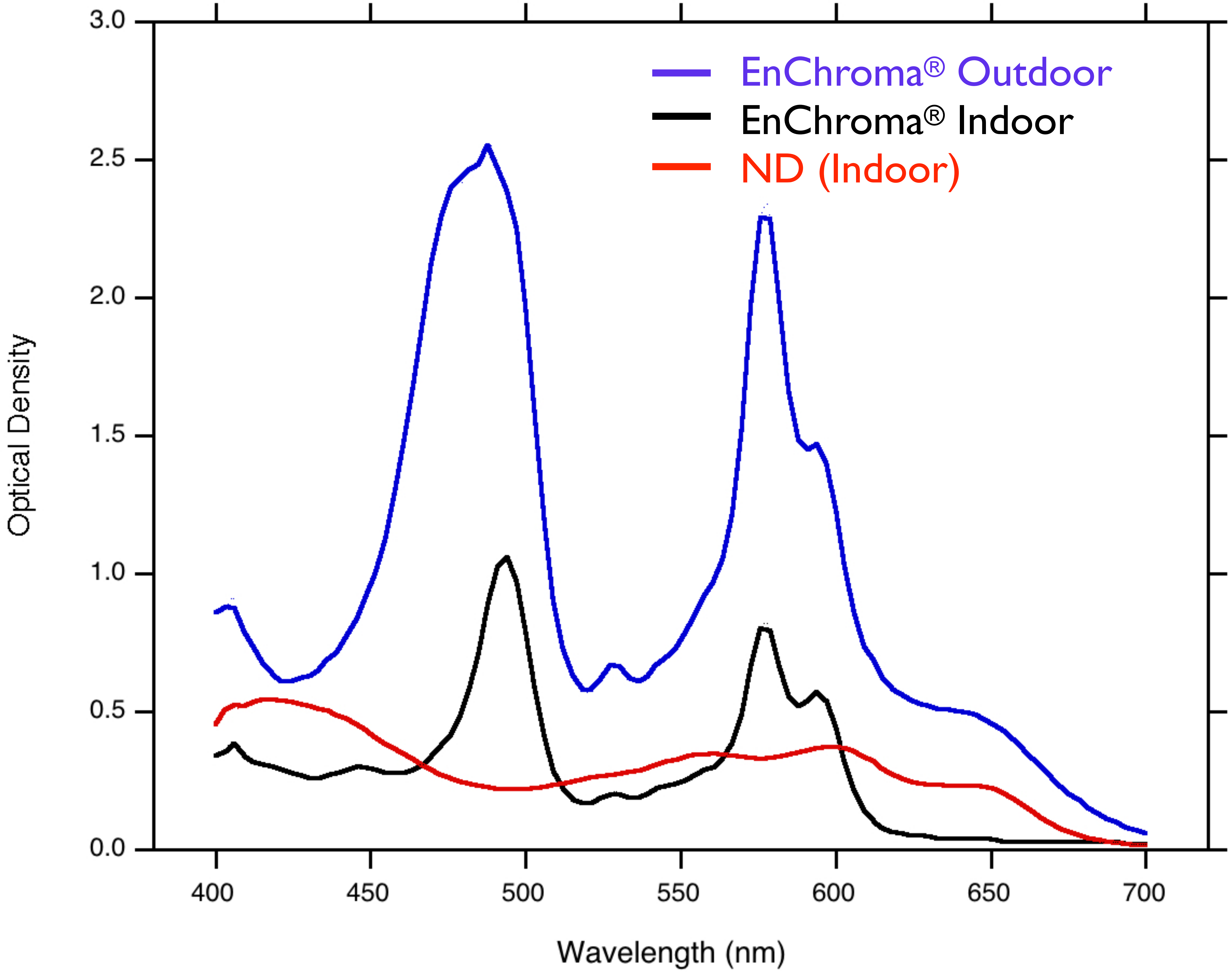
Filter-aided corrections for color deficiency





Knoblauch & McMahon (1995) *J. Opt. Soc Am A*

What are the long-term effects of wearing contrast-enhancing (notch) filters?



Specific Methods

8 Anomalous Trichromats and 2 Normal Trichromats

7 Anomalous Subjects Wore EnChroma® Glasses for ~ 12 days
  2 Protanamolous
  5 Deuteranaomalous

1 Protanomalous Observer Wore ND Glasses as a Control

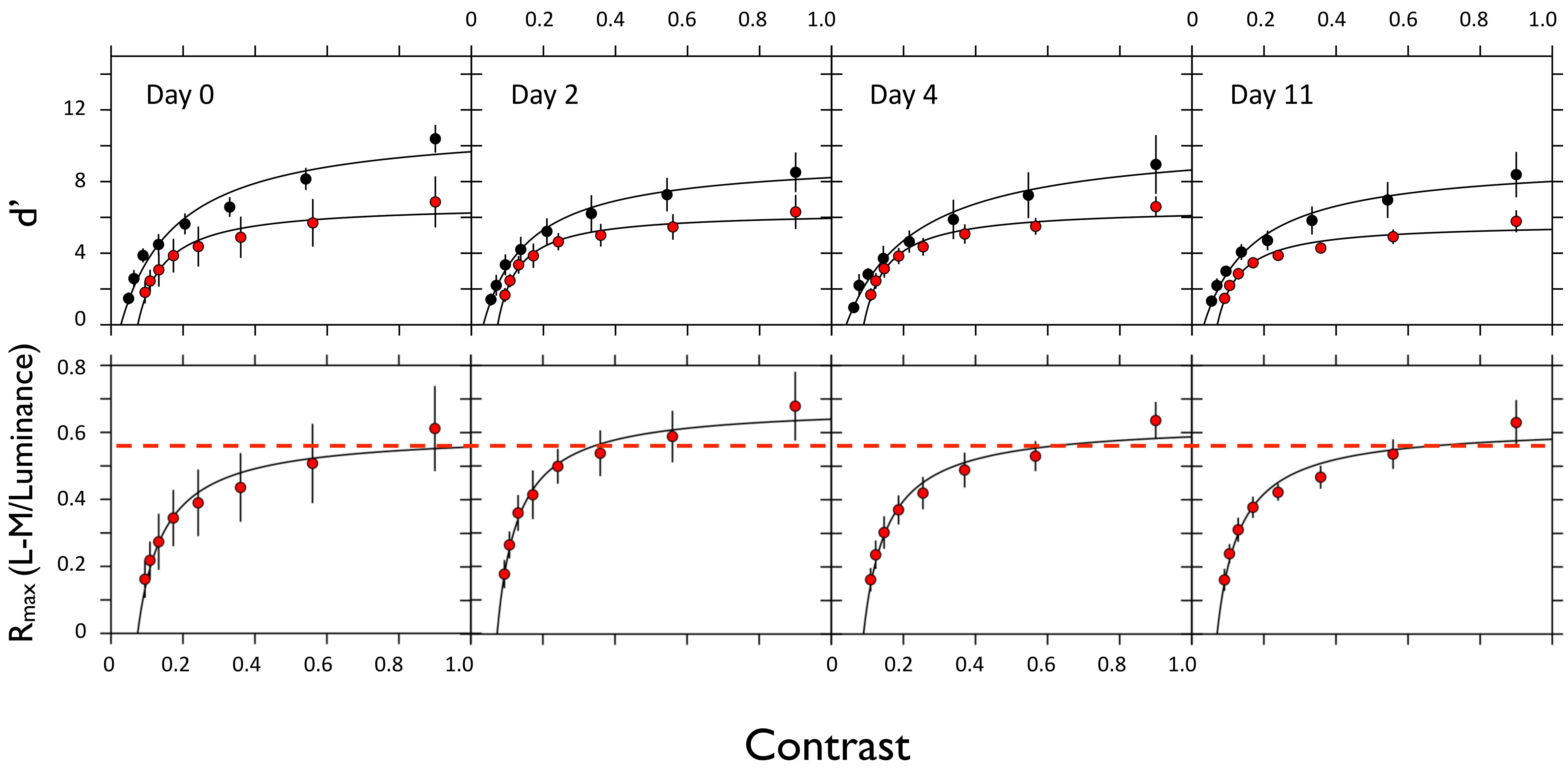
2 Normal Trichromats Wore EnChroma Glasses as a Control

Separate tests for Luminance and L - M Modulation; Days 0, 2, 4 and ~11-12.

Spontaneous comments were recorded.

All Testing was Performed Without the Glasses.

N6 with EnChroma glasses

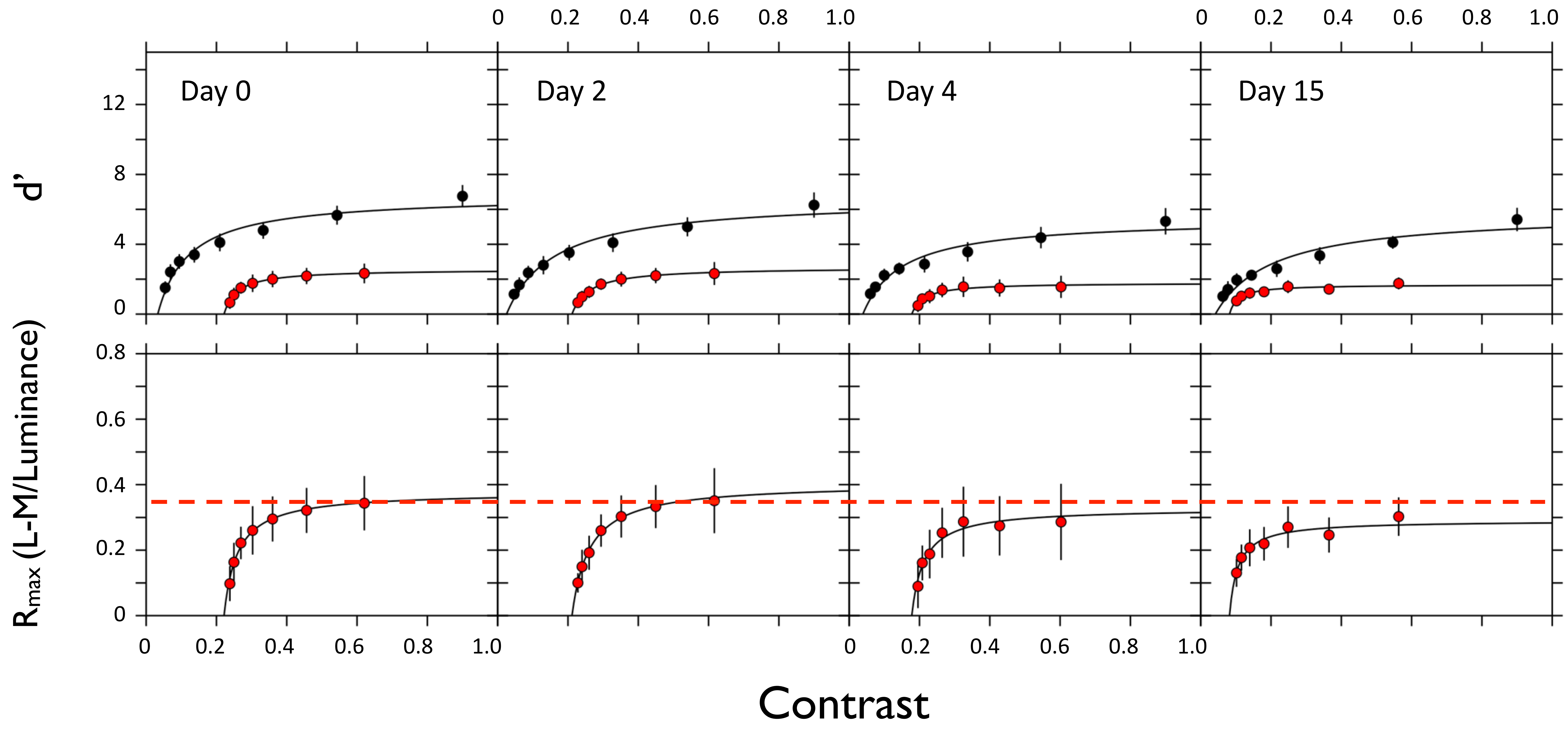


Day 4: "I don't notice any changes in vision, but will wear the glasses anyway."

Day 11: "I see no color differences in my surrroundings with the glasses."

Change in R_{max} (L-M/Luminance)
Day 0 - 11: 6.6%

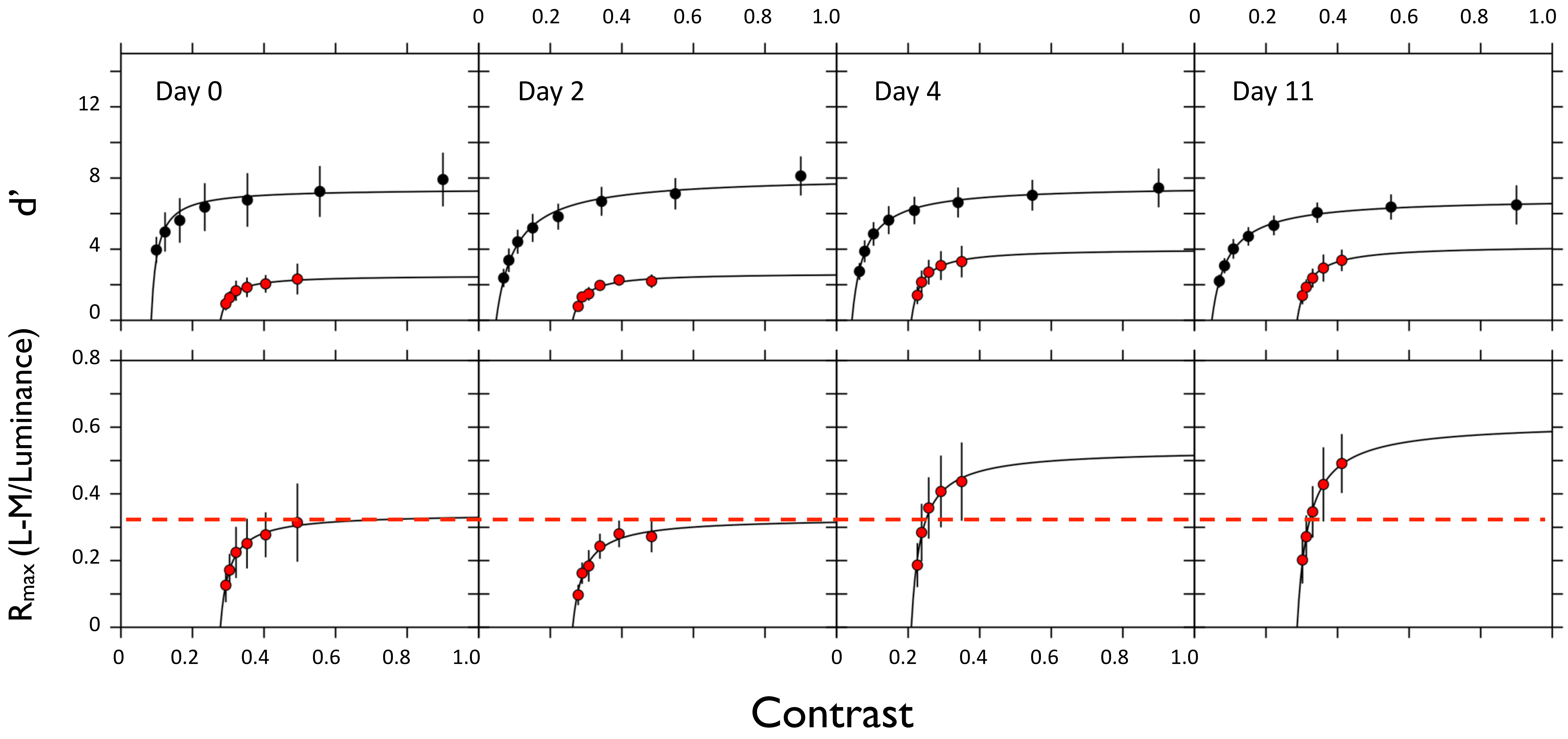
P2 with Neutral Density Glasses (Placebo)



Day 15: "Certain that there is no change in color vision, but maybe it's because of all the smoke."

Change in R_{max} (L-M/Luminance)
Day 0 -11: -19.6%

D4 with EnChroma glasses

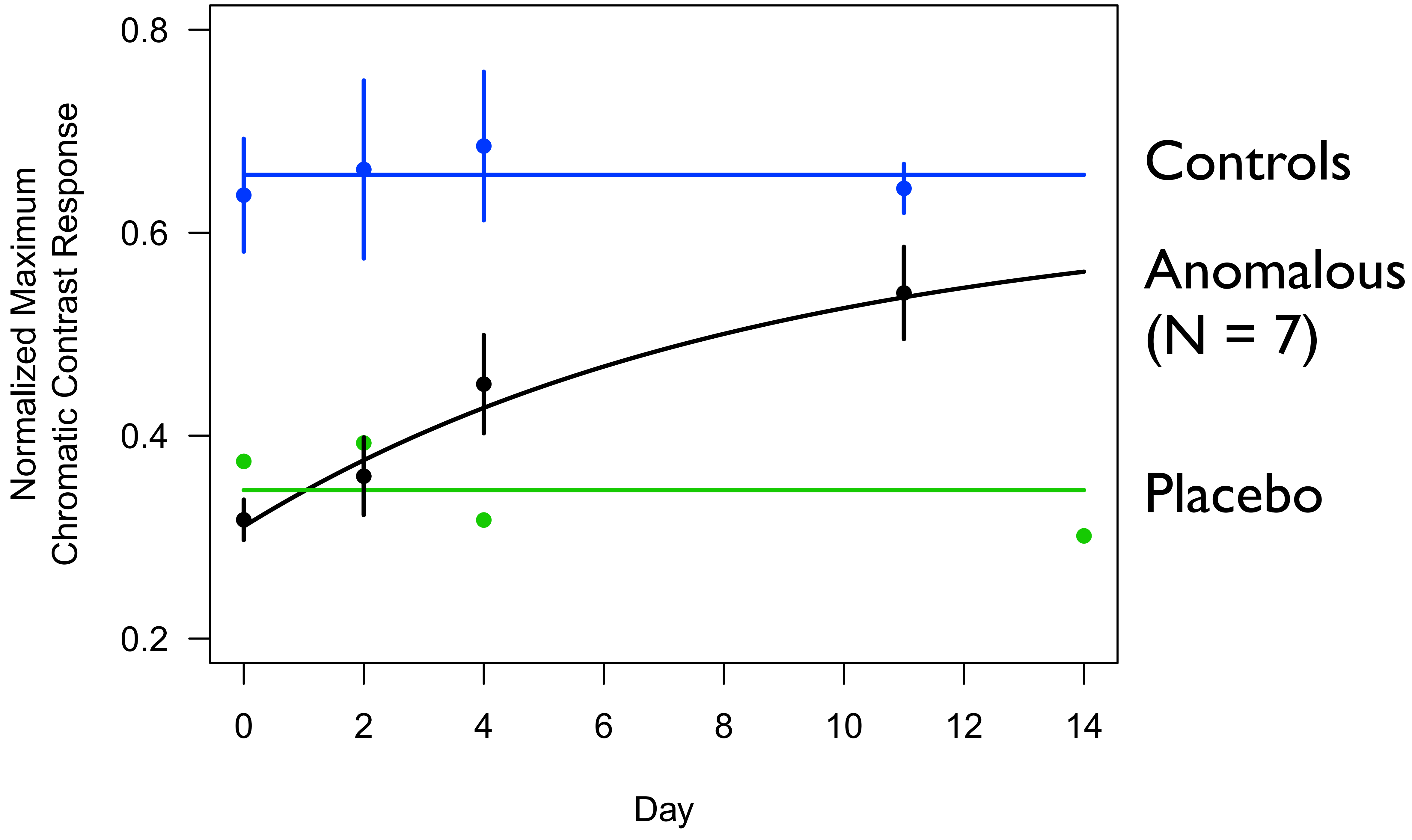


Day 2: "The fall leaves seem super vibrant…. I look at them while driving."

Day 11: "Not sure but believe I am seeing clothing colors (at work …) that I didn't see before."

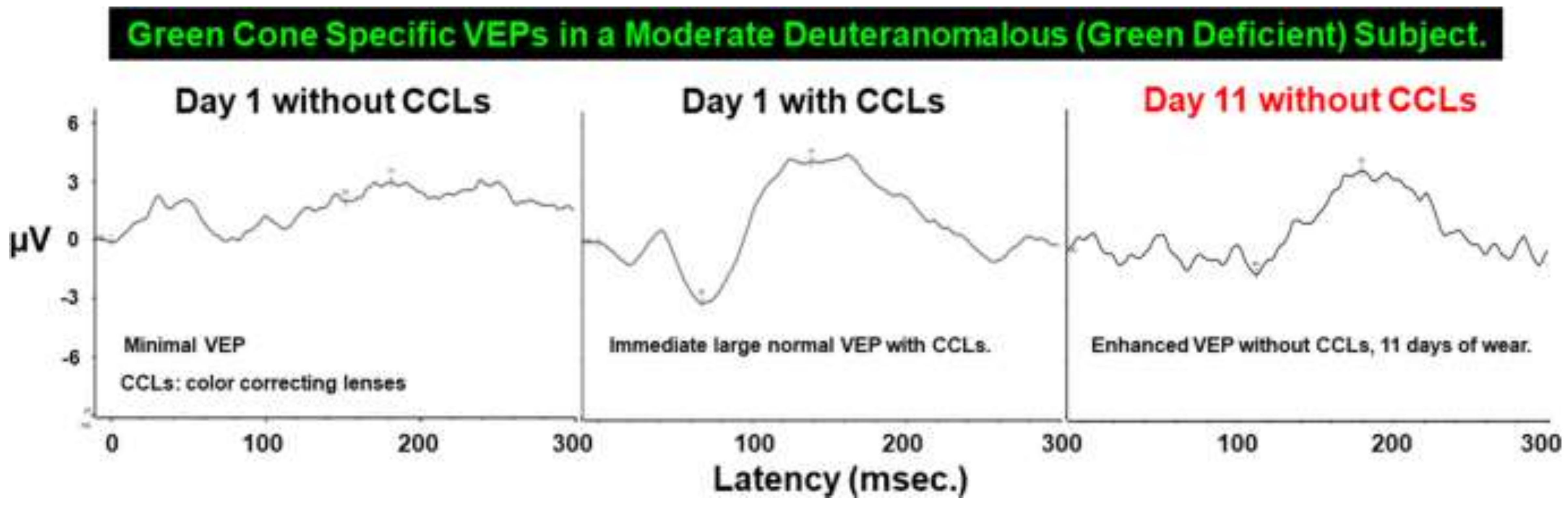
Change in R_{max} (L-M/Luminance)
Day 0 -11: 85%

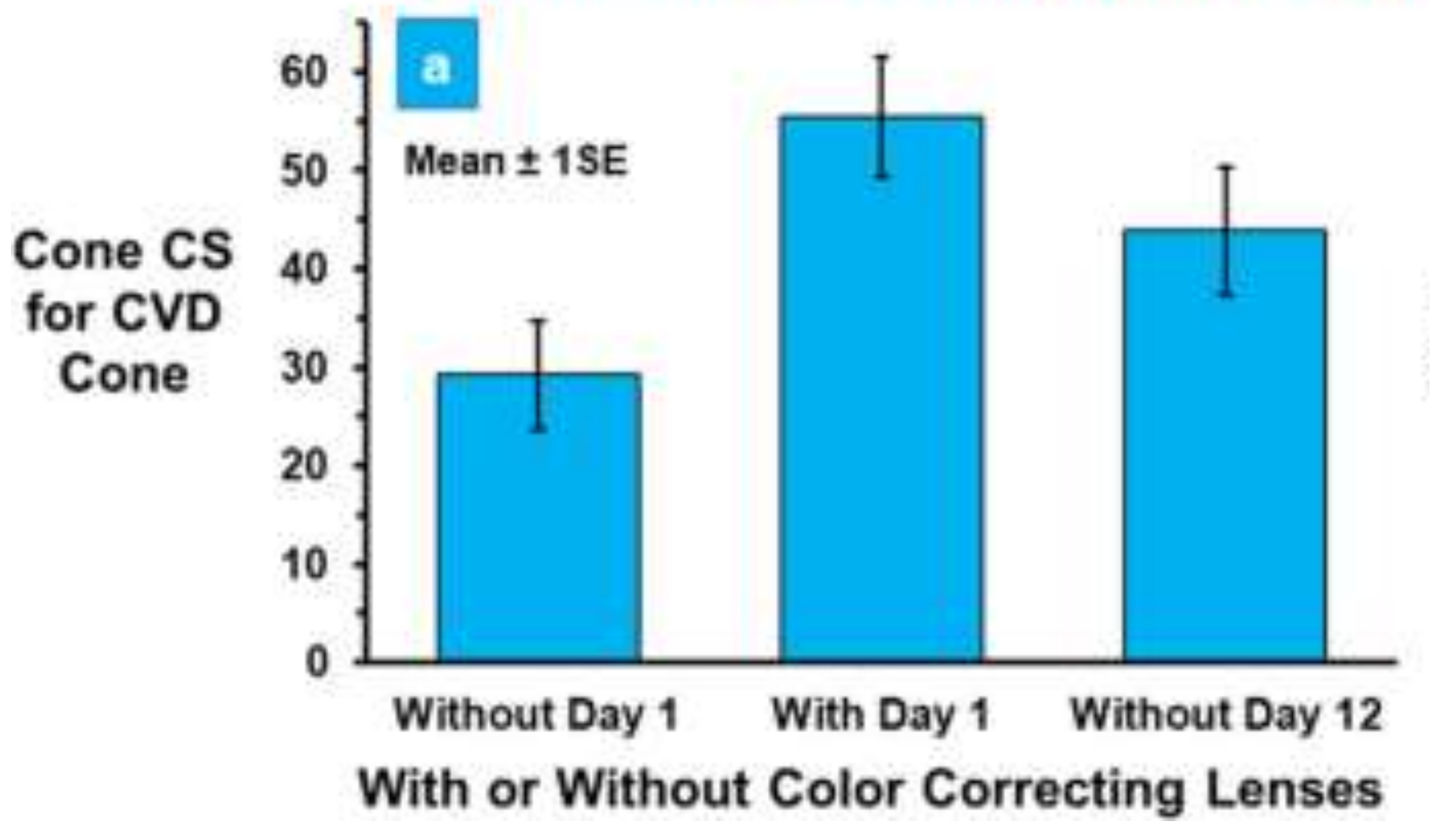
Anomalous observers display a relative increase (~71%) in R_m for L-M contrasts, subsequent to prolonged use of contrast-enhancing notch-filters (EnChroma®)



Werner, Marsh-Armstrong & Knoblauch (2020)
Current Biology **30**, 3011–3015.

Results from Rabin et al. (*Eye*, 2022) confirm this phenomenon, using VEPs and cone contrast sensitivities.





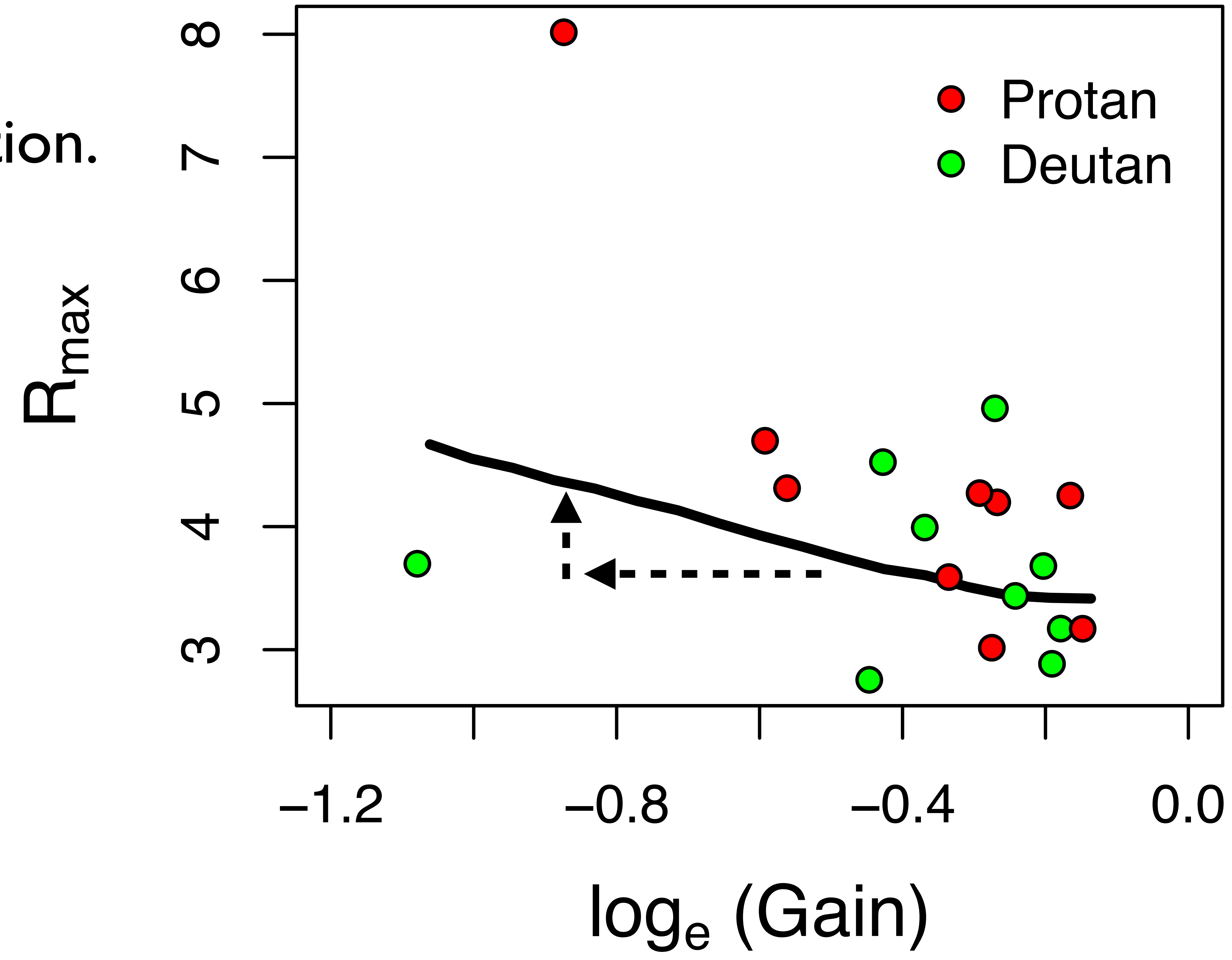
Rabin et al. (2022) *Eye*, 1-2;
https://doi.org/10.1038/s41433-021-01924-0

These findings might be considered paradoxical, since one might expect that exposure to enhanced chromatic contrasts would lead to an adaptive reduction of chromatic response (e.g., Ilic et al., 2022*). This led us initially to suggest that the phenomenon reflects a form of perceptual learning (Werner et al., 2020).

Our new results, showing that increasing *contrast gain* in the presence of an early multiplicative noise reduces the *estimated response gain,* suggests an alternative explanation.

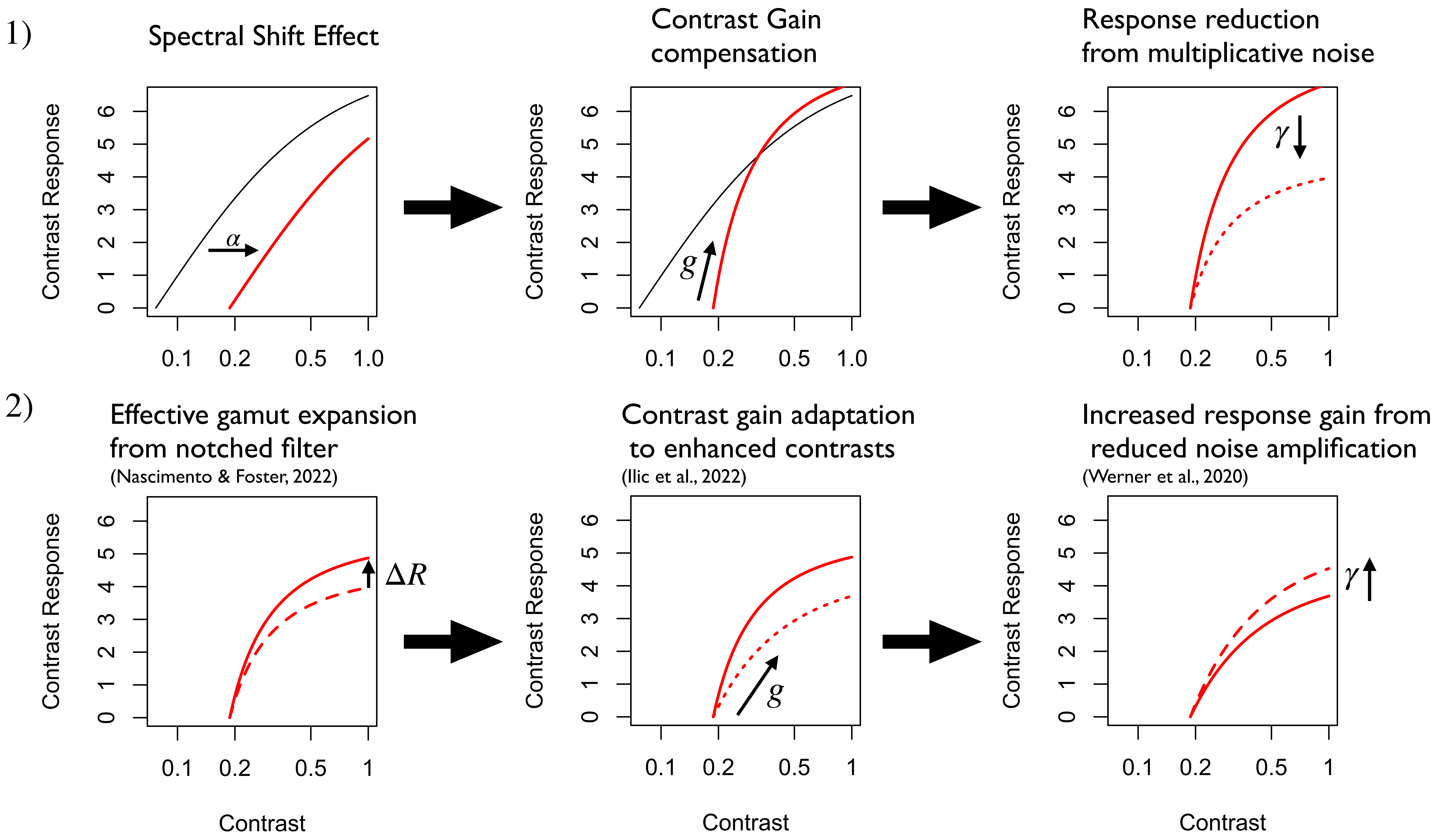
Hypothesis:

Exposure to the enhanced contrasts does result in an adaptive **reduction** of *contrast gain.* The reduced contrast gain then multiplies the noise less, leading to an **increase** in the *estimated* response gain, R_m.



data replotted from Knoblauch et al., 2020

*** Ivana Ilic, Kassandra R. Lee, Yoko Mizokami, Lorne Whitehead, and Michael A. Webster, "Adapting to an enhanced color gamut – implications for color vision and color deficiencies," Opt. Express 30, 20999-21015 (2022)**

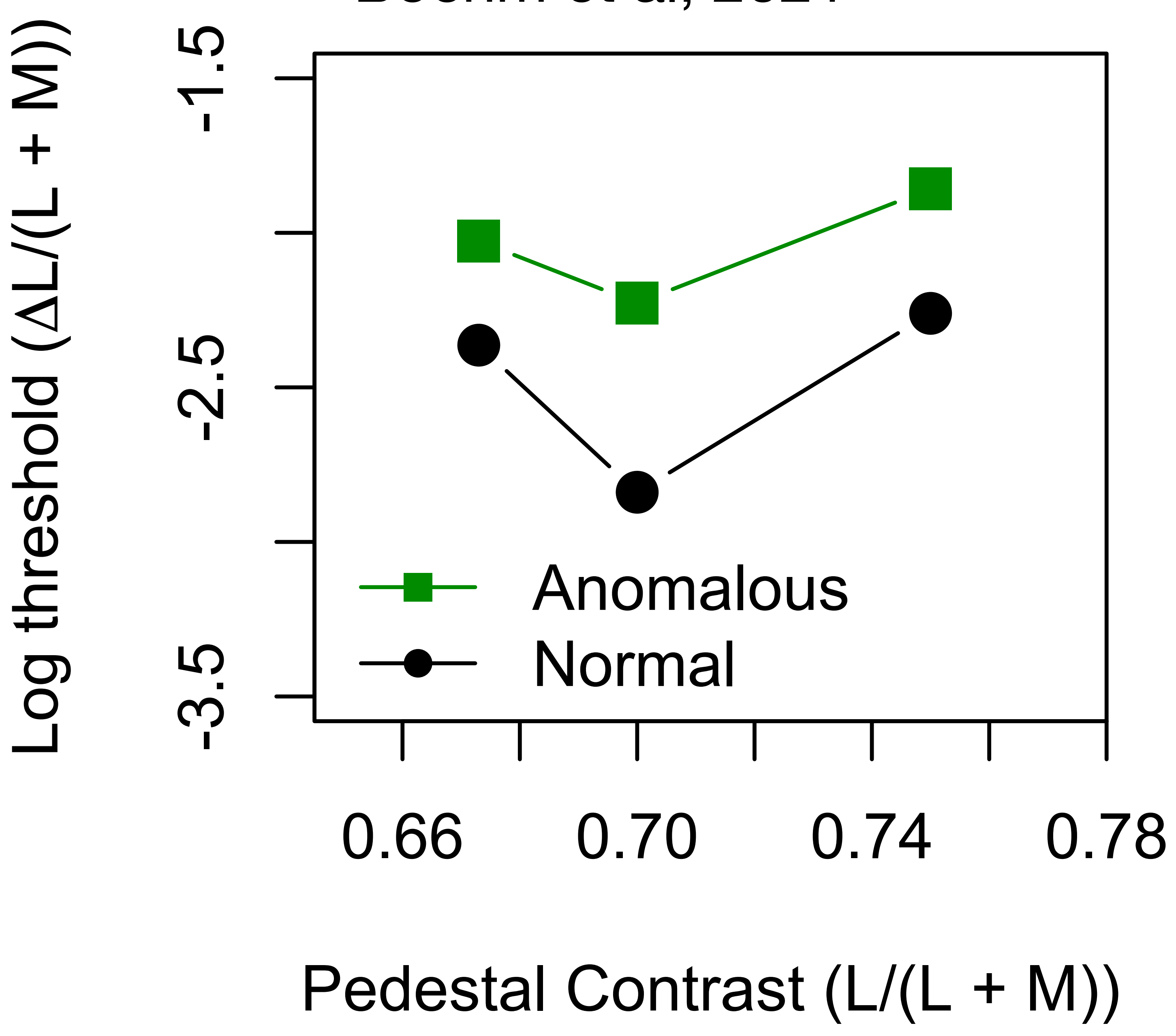

1)
Spectral Shift Effect
Contrast Gain compensation
Response reduction from multiplicative noise
Contrast Response
0 1 2 3 4 5 6
0.1 0.2 0.5 1.0
α
g
γ
0.1 0.2 0.5 1
2)
Effective gamut expansion from notched filter
(Nascimento & Foster, 2022)
Contrast gain adaptation to enhanced contrasts
(Ilic et al., 2022)
Increased response gain from reduced noise amplification
(Werner et al., 2020)
ΔR
Contrast

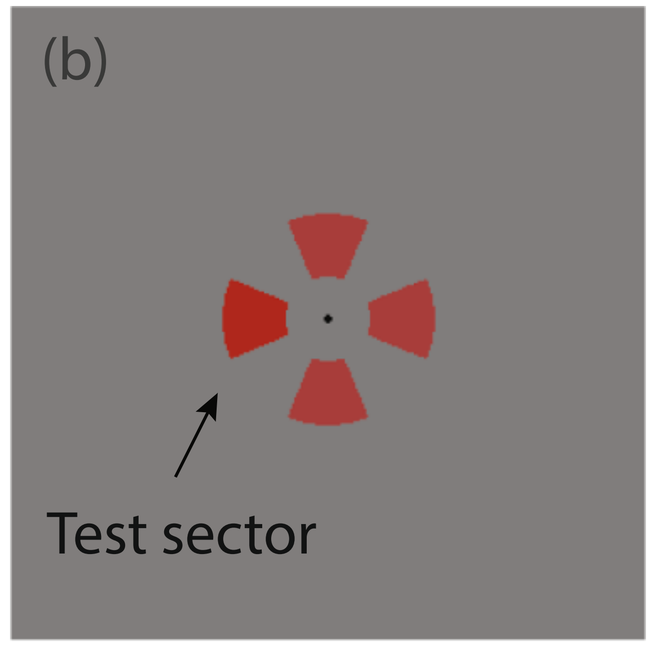
Noise limits the extent to which natural mechanisms of compensation can enhance chromatic contrast response in anomalous trichromacy

Artificially boosting the salience of chromatic contrasts will increase chromatic contrast gain *adaptation*, which may reduce discrimination, but will amplify noise less and lead to an enhanced range of perceived chromatic contrasts (at least, temporarily).

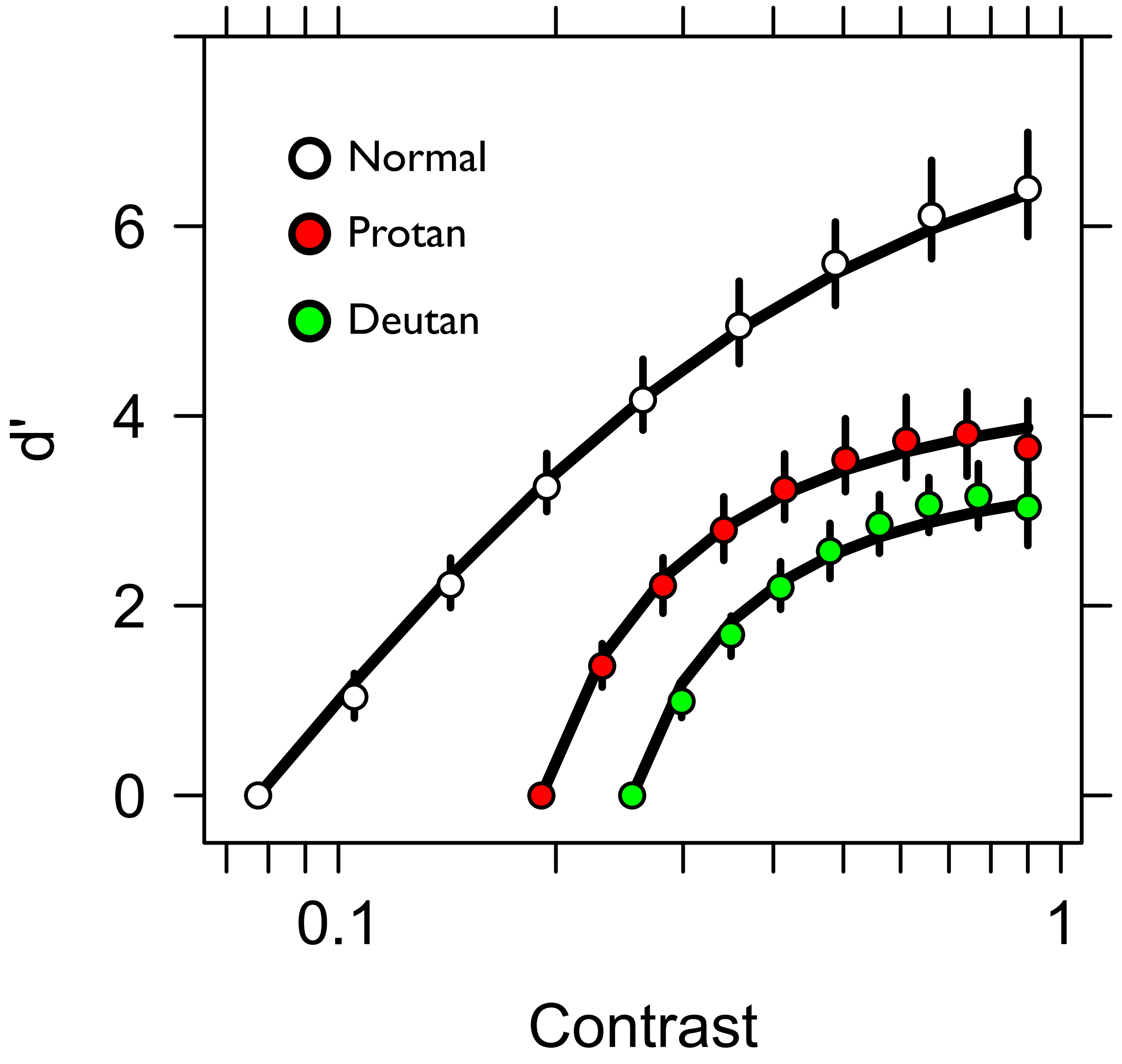
Qualitative comparison of MLDS scales and discrimination

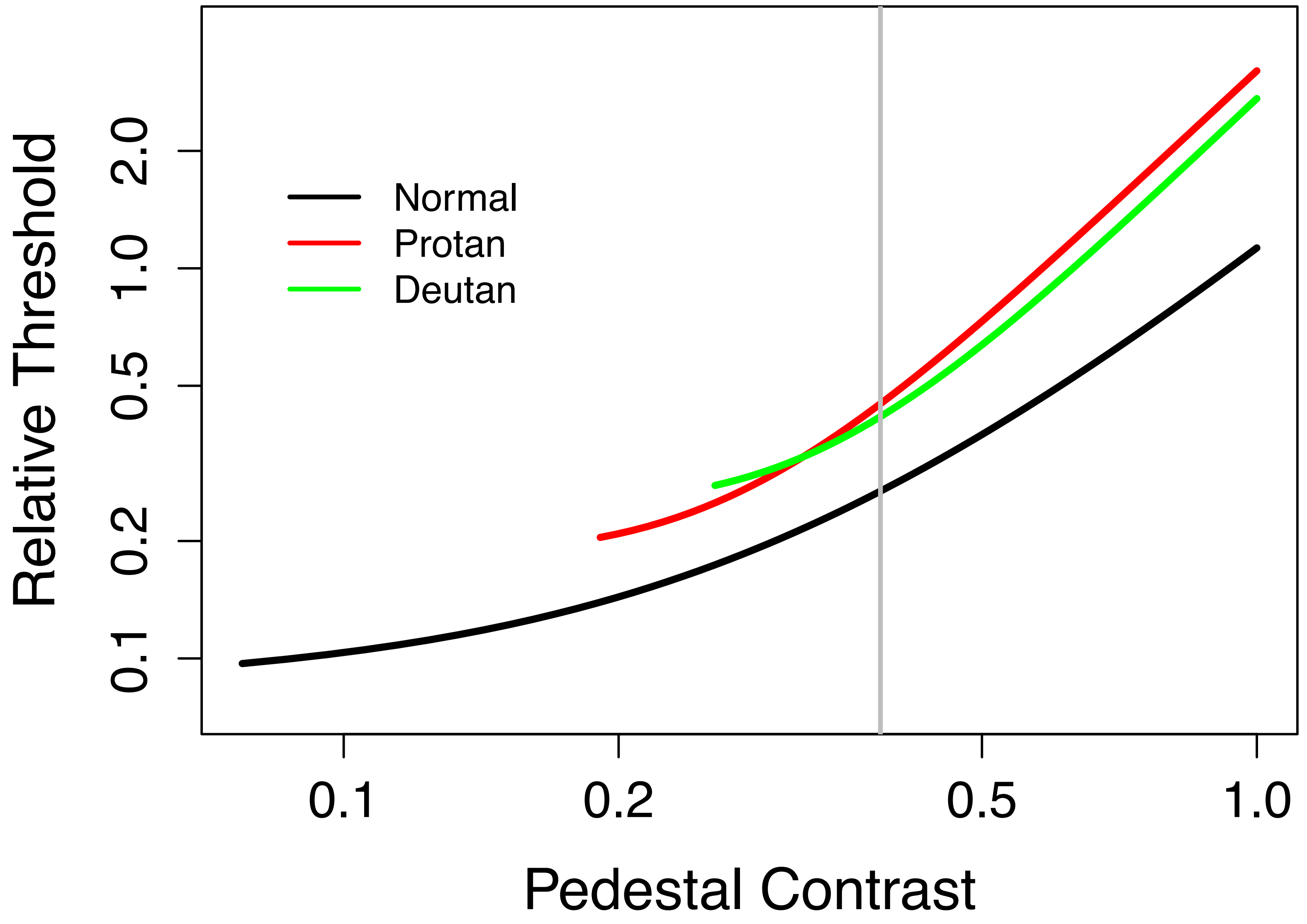
replotted from Fig 2d,
Boehm et al, 2021

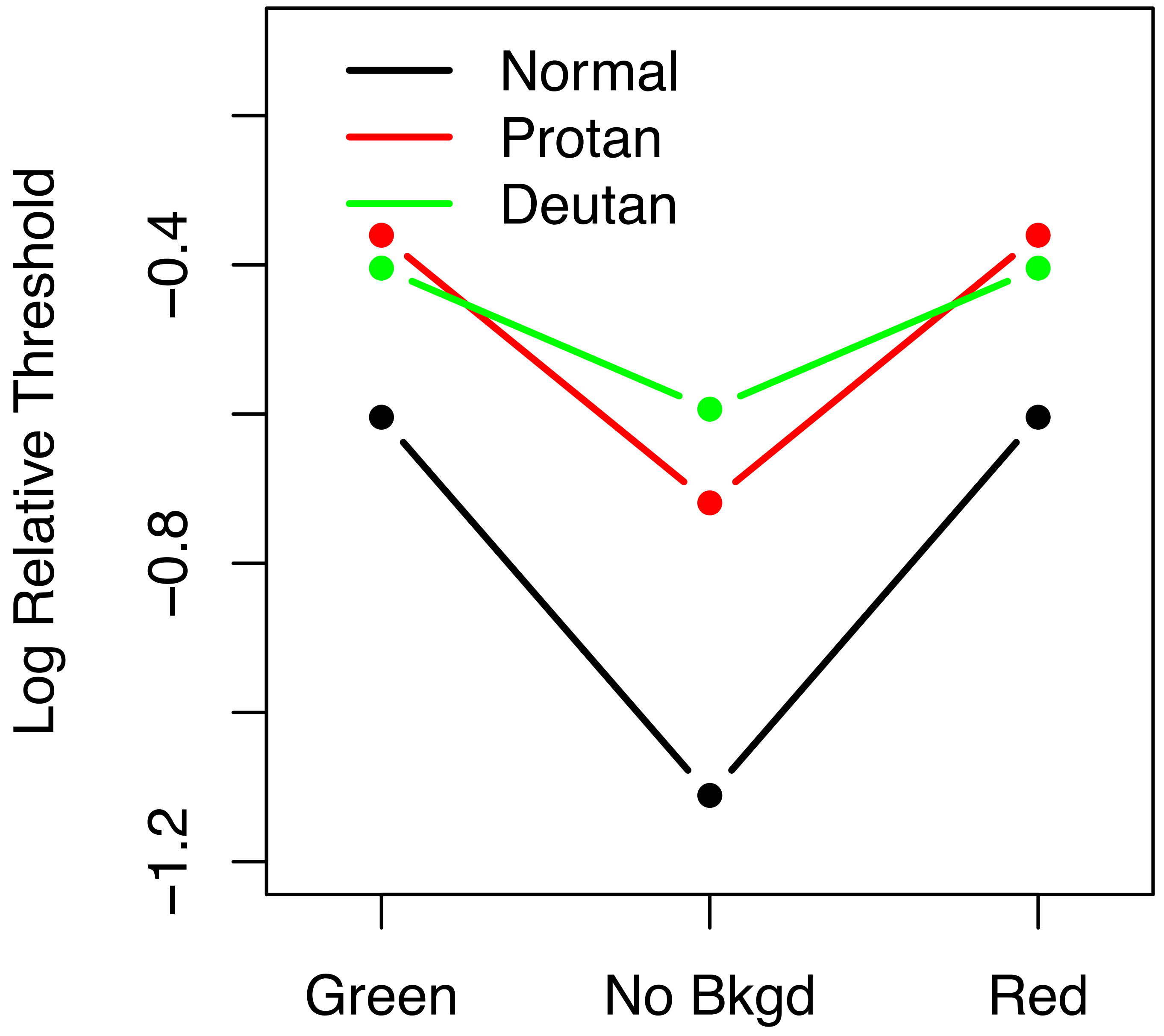




$$\Delta C = c_0 + \left(\frac{dR}{dC}\right)^{-1}$$

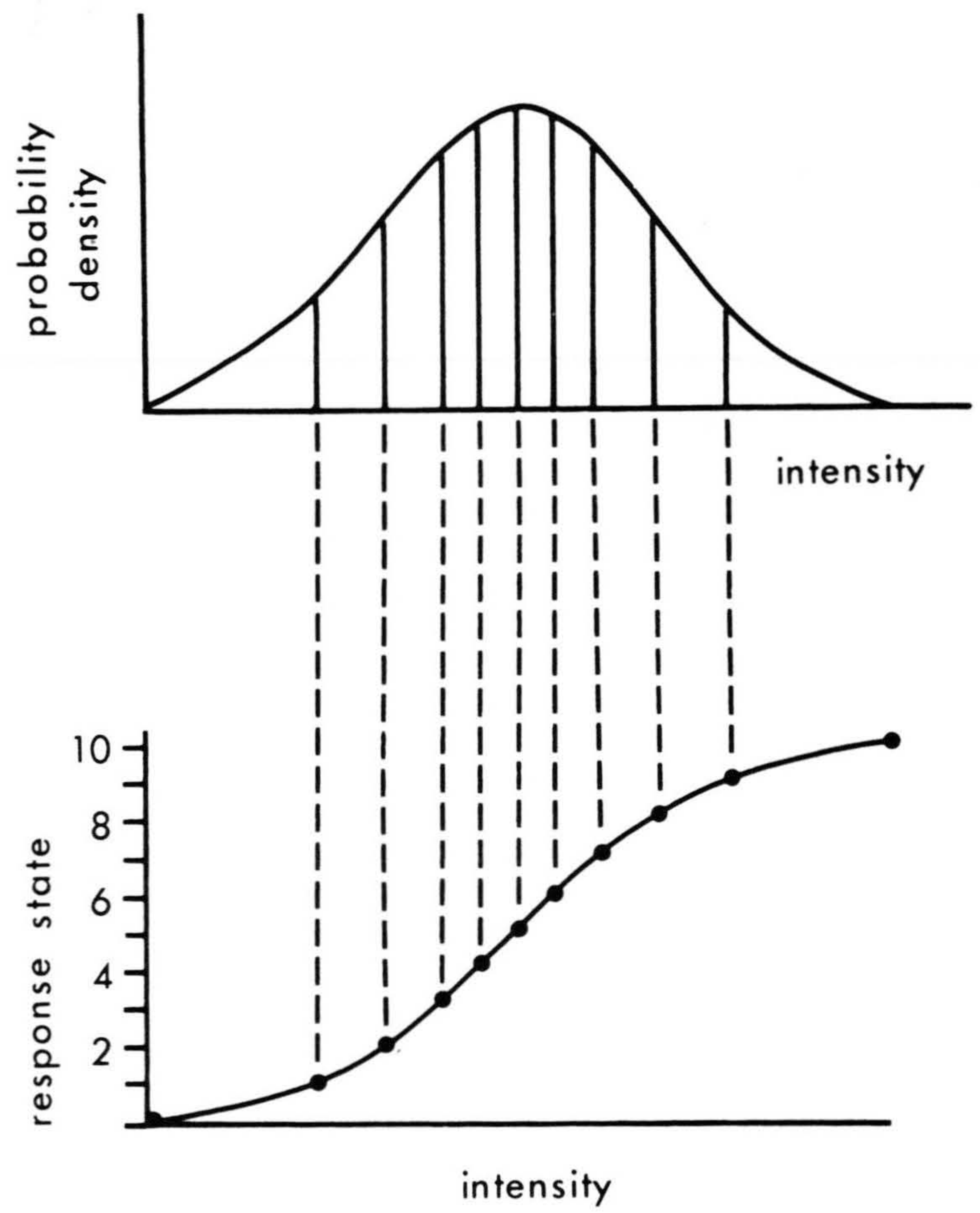






Boehm, Bosten & MacLeod (2021) *Vision Research*

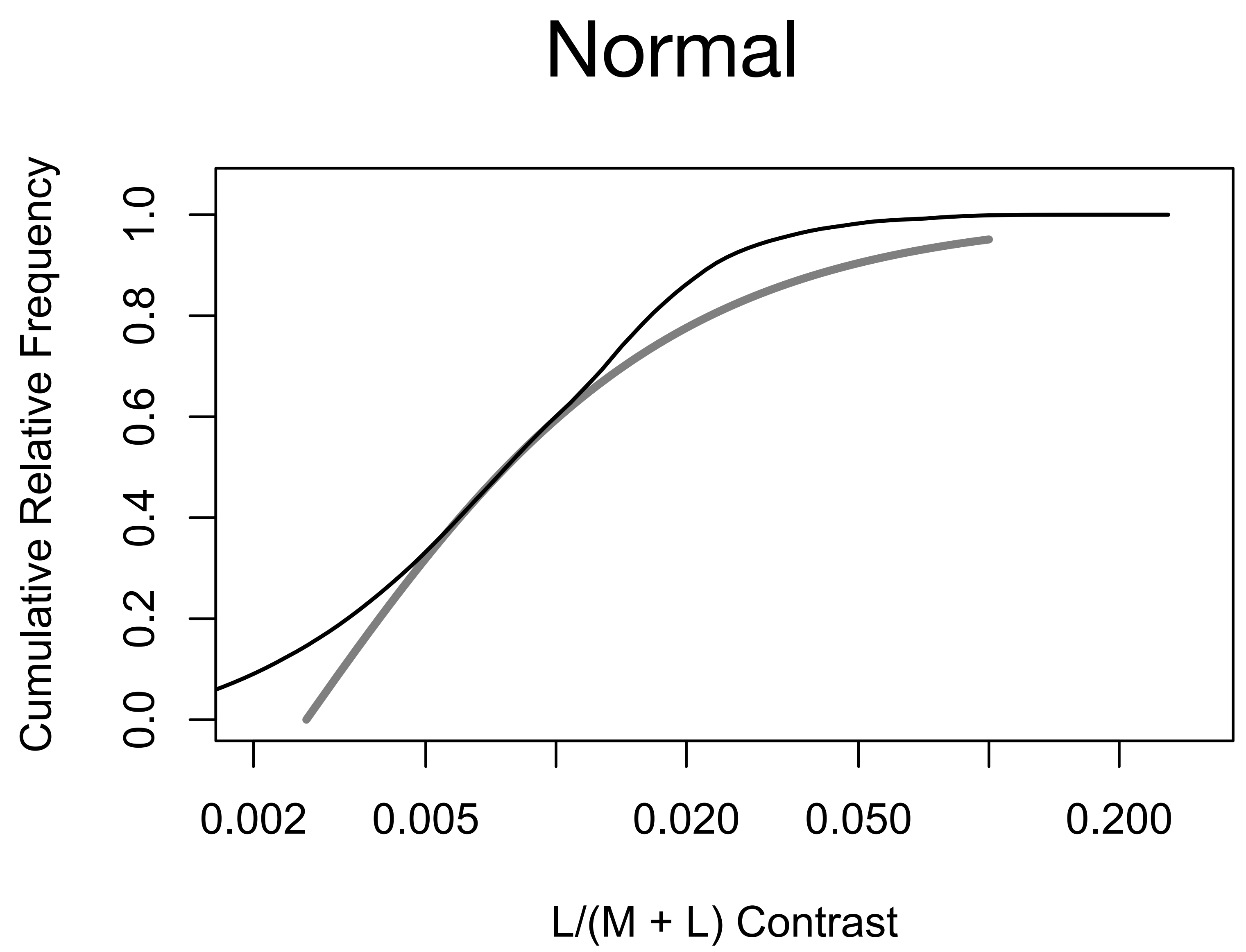
Coding Strategy for maximizing a neuron's information capacity

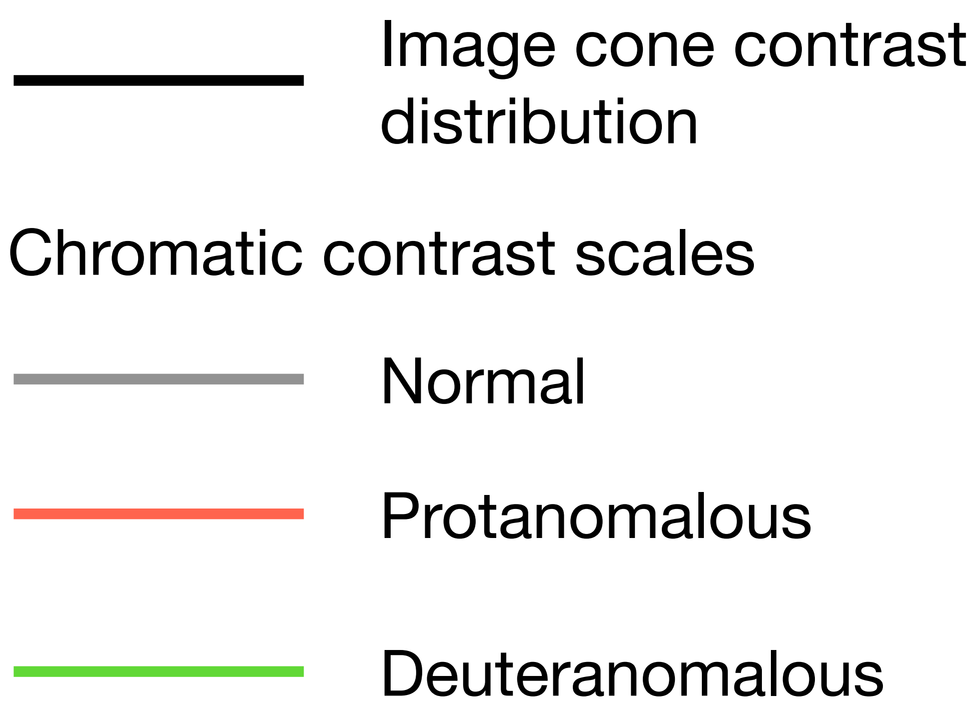


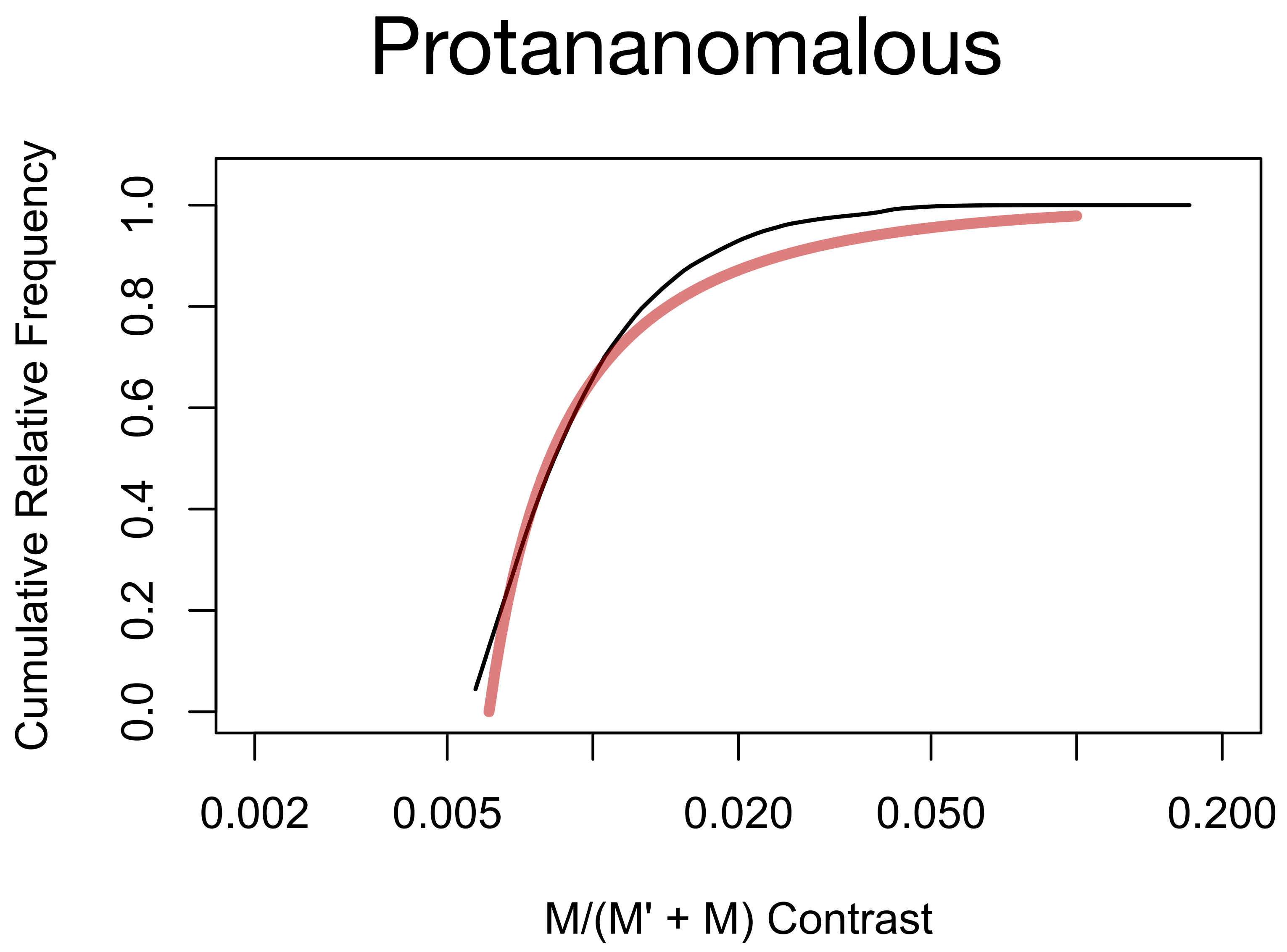
Laughlin (1981) *Zeitschrift für Naturforschung*

Comparison of cone contrast distributions with contrast response functions.

C.A. Párraga, G. Brelstaff, T. Troscianko, I.R. Moorhead (1998)
J. Opt. Soc. Am. A.
Nascimento, S. M., Ferreira, F. P., & Foster, D. H. (2002).
J. Opt. Soc. Am. A.
Foster, DH, Nascimento, SM, Amano, K (2004).
Vis Neurosci.
Chakrabarti, A. and Zickler, T. (2011)
Proc.~IEEE Conf.~on Computer Vision and Pattern Recognition







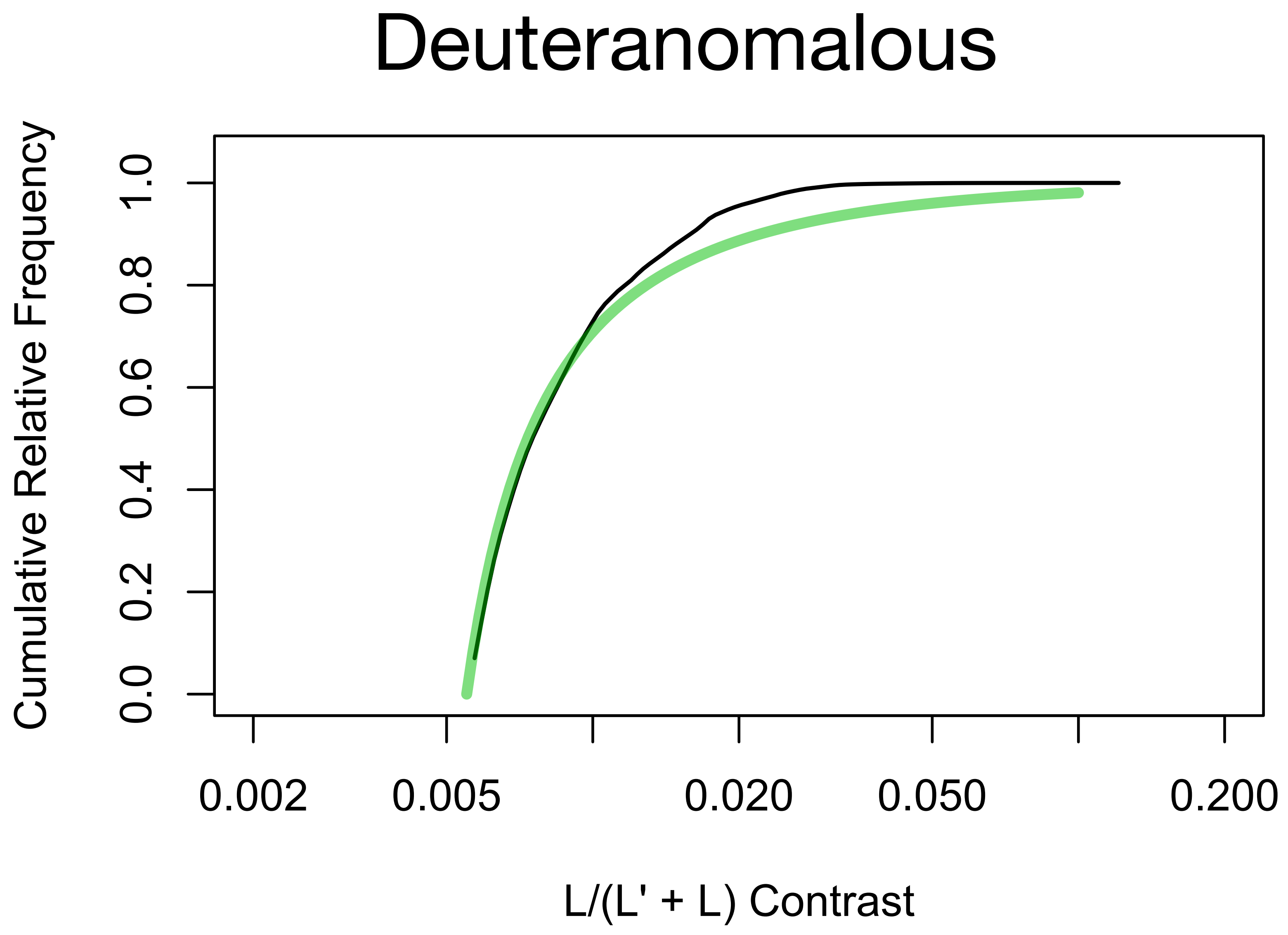


Image cone contrast data provided by Jenny Bosten

Noise limits the extent to which natural mechanisms of compensation can enhance chromatic contrast response in anomalous trichromacy

Artificially boosting the salience of chromatic contrasts will increase chromatic contrast gain *adaptation*, which may reduce discrimination, but will amplify noise less and lead to an enhanced range of perceived chromatic contrasts (at least, temporarily).

Qualitative evidence that the chromatic contrast response functions of normal and anomalous trichromats are optimized for their distributions of natural contrasts.

The results have implications for how to model the perception of anomalous color observers, i.e., taking into account both the differences in contrast and response gain as well as the reduced efficiency from spectral shift.

The results may have broader implications in understanding how environmental and cultural factors might lead to cross-cultural differences in color categorization.

Thank you

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