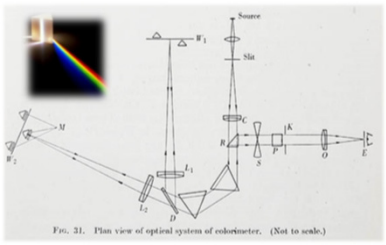
Sophie Wuerger, Professor of Psychology,
often described as **'A free spirit in life and science'**
who passed away on 3rd January 2024



WD Wright Colorimeter,
From Researches on Normal and Defective Colour Vision,
Newton Medallist 1963.
'The rays are not coloured'

THE COLOUR GROUP (GB)

....for those concerned with the measurement, reproduction and perception of colour.....

... and also for those involved in colour assessments in visually demanding occupations and in the clinic

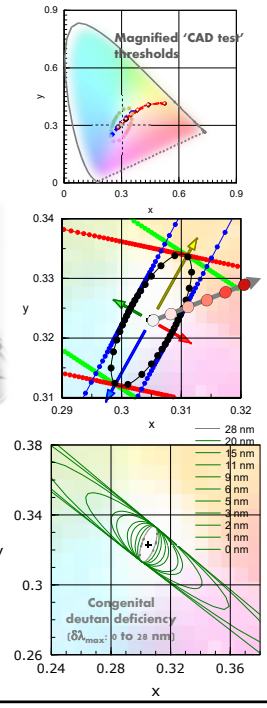
... to all Colour Group Committee Members, past and present, for all the work that enables us to enjoy the benefits of this multidisciplinary society

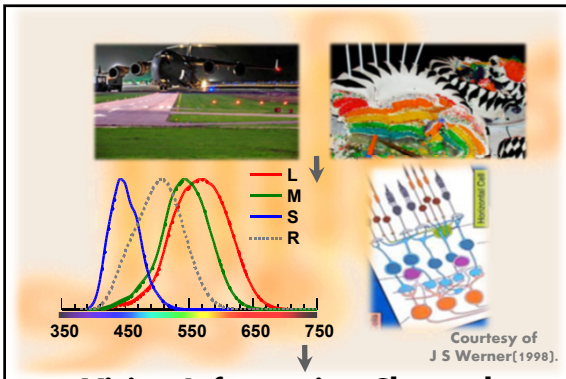
WDW' 90th Birthday Celebration

Newton Medallists

1963	**Prof W D Wright**	**The rays are not coloured**
1965	Dr W A H Rushton	The chemical basis of colour vision and colour blindness
1967	Dr W S Stiles	Mechanism concepts in colour theory
1970	G J Chamberlain	What use is colorimetry?
1972	Dr D B Judd	Colour in visual signalling
1975	Dr R W G Hunt	Sky-blue pink
1977	Dr C J Bartleson	Full circle: The study of chromatic adaptation
1979	Dr S T Henderson	The colour of daylight
1981	Prof R A Weale	Game-set-match
1983	Dr B H Crawford	Colour in signals
1985	D L MacAdam	Uniform colour scales (delivered in 1984)
1987	Miss M B Halstead	Lighting and colour rendition: quantity versus quality
1989	W N Sproson	Colour television
1991	J G Holmes	Suiting colour to the name (Lantern Tests and Railways
1993	Prof S M Zeki	Colour vision as a guide to brain organisation
1995	Dr R McDonald	The effect of colour physics on the textile industry
1997	Don Pavey	Aesthetics of colour and orientation
1999	Prof John D Mollon	The colour-sense: its origin and development
2001	John B Hutchings	Driving forces for colour usage in food, biological nature …
2003	James H Nobbs	Relating the Composition of Materials to their Colour
2006	Prof R L Gregory	Colours through a Bayesian Window
2008	Prof Roy S Berns	The Use of Color Science in Art Conservation
2010	Prof Janos Schanda	Do LEDs need a new colorimetry?
2012	Prof Françoise Vienot	The Novelty of Metameric LED White
2014	Prof Michael R Pointer	The Measurement of Appearance – Tortoise or Hare?
2016	Prof Andrew Stockman	Distorted Insights from Perceptual Anomalies to Colour ….
2018	Prof David Foster	The Randomness of Colours
2018	Prof M Ronnier Luo	Holy Grail of Colour Science – Version II
2022	**Prof Anya Hurlbert**	**From Light and Matter to the Concept of Colour**
2024	Prof John Barbur	Variability, colour thresholds and chromatic mechanisms

Variability, colour thresholds and chromatic mechanisms





Vision Information Channels

COLOUR CHANNELS

Red-Green

M L

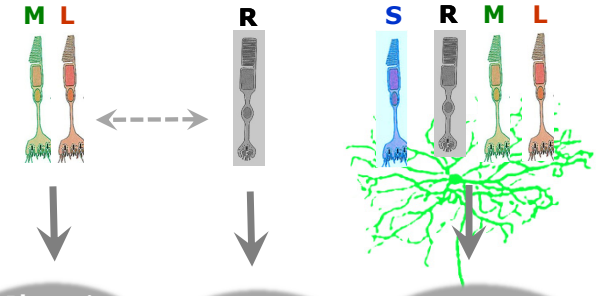
RG

Yellow-Blue

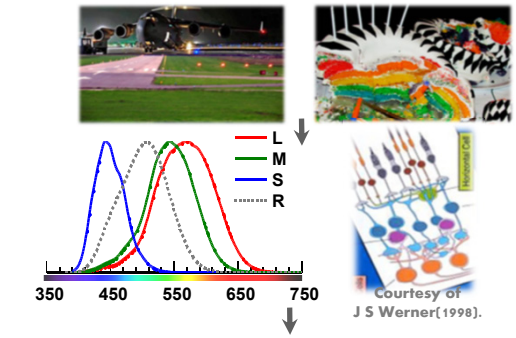
S M L

YB

LIGHT FLUX AND LUMINANCE CONTRAST CHANNELS



What happens to our vision when sensitivity in one of these channels is lost selectively?



Vision Information Channels

COLOUR CHANNELS

Red-Green

M L

RG

Yellow-Blue

S M L

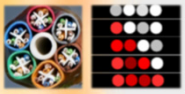
YB

How much use do we make of colour signals?

1. **Enhancement of object conspicuity**

2. **Pop-out and parallel processing of objects defined by colour signals**

3. **Coding of known information by means of colour**



4. **Segmentation of complex scenes into groups or areas of interest**

What is needed for complete colour assessment, in the clinic and in occupations?

- Full isolation of colour signals
- Selective stimulation of either RG or YB colour mechanisms, but not both
- Sensitive tests to assess the smallest changes in colour vision
- Ability to detect acquired loss in patients with congenital RG deficiency
- The ability to quantify severity of RG and YB loss

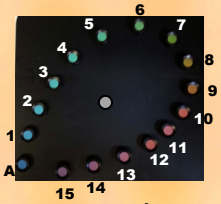
What are the challenges we have to overcome in order to achieve these objectives?

We need to understand better what is measured in many of the current tests and the cues one can use to pass these tests

We need to explain why the results are often variable within each test and also inconsistent amongst different tests

Establish how differences in functional vision relate to and can be attributed to specific changes in the properties of CV mechanisms

Examples of conventional colour assessment tests that have been employed for decades in visually-demanding occupations and also in the clinic?



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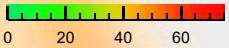
HW- Type A lantern

Yellow (589nm) field

R (671 nm) & G (546 nm)



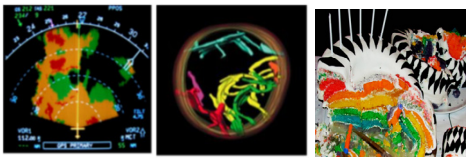
Nagel RG mixture

No current, conventional test fulfils the full range of requirements!

- Many of the current tests fail to isolate the use of only RG or only YB colour signals (Example - D15)
- No conventional, CV test has close to 100% sensitivity and specificity. Current protocols often employ two or more tests with only limited success (e.g., IH, lanterns, D15, City University Colour test, anomaloscope tests, etc)

The challenge:

How do we specify colour and how do we quantify the strength of colour signals?

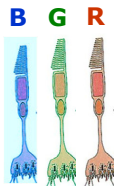


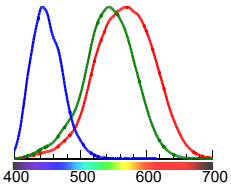
Solution:

The 1931 CIE XYZ system

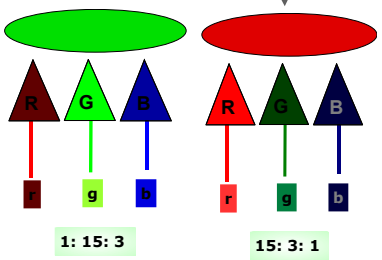
Measure tristimulus values and chromaticity coordinates.

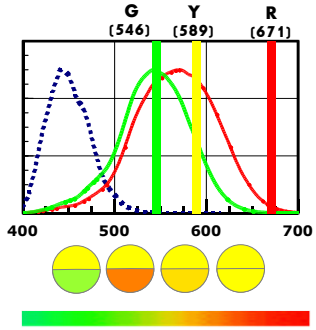
What are the X,Y,Z values?





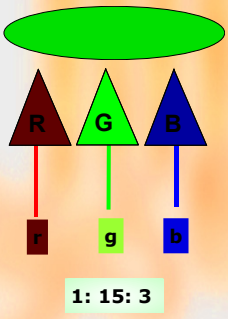
Many metamers





The CIE 1931 (X,Y,Z) system

3D space that plots three quantities derived from linear combination of cone signals. The quantity Y represents the sum of 2L +M cone signals and is therefore also proportional to luminance



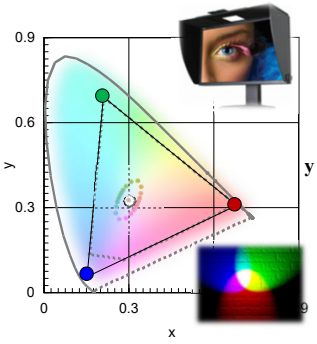
$$x = \frac{X}{X+Y+Z}$$

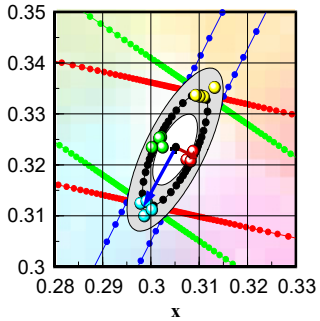
$$y = \frac{Y}{X+Y+Z}$$

$$z = \frac{Z}{X+Y+Z}$$

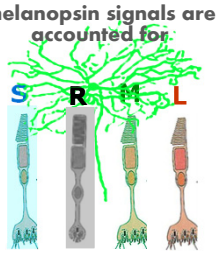
$$x + y + z = 1$$

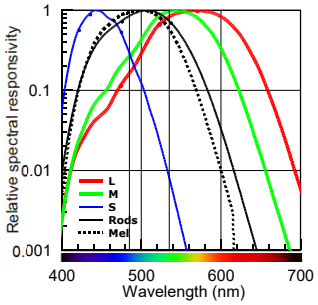
$$z = 1 - (x + y)$$





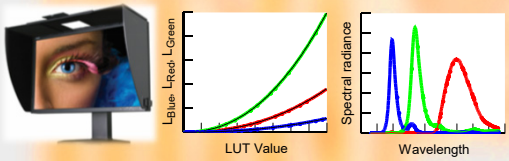
Neither rod nor melanopsin signals are accounted for





The assessment of colour vision:

Where are we now and how did we get here?



Colour Vision Screener (CVS)

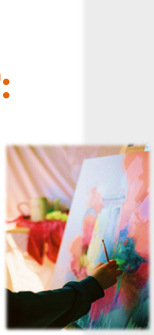
- Detection of deutan and protan deficiencies: 100%
- Specificity, i.e., % of normal trichromats classified as having normal RG colour vision: 99.45%

DOI: 10.1002/col.22599

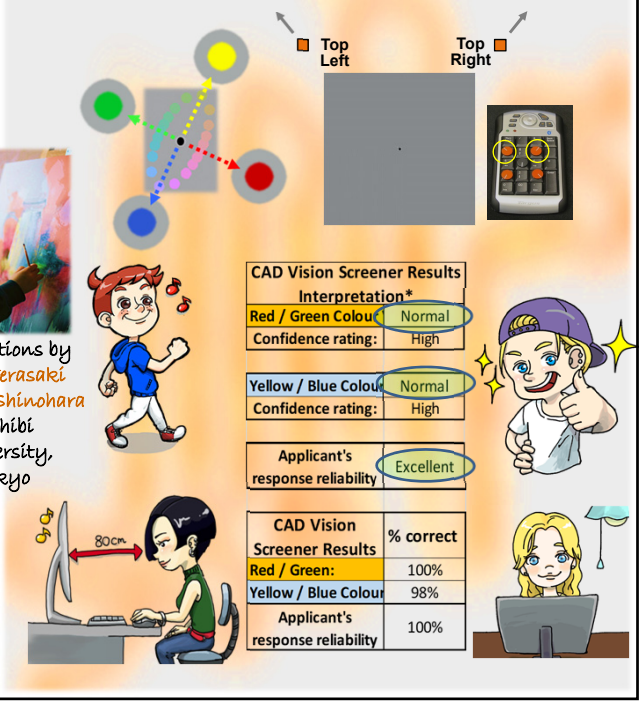
- Full isolation of colour signals
- One can stimulate selectively either RG or YB chromatic mechanisms
- One can measure reliably the smallest changes in colour vision that are needed to quantify the effects of healthy aging and to separate normal trichromats from those with colour deficiencies
- Ability to detect acquired loss in patients with congenital RG deficiency
- The ability to quantify severity of RG and YB loss

Advantages of the CVS (Screener) test:

- Simple and easy to use, suitable for young and older subjects
- The time needed to test for RG and YB colour vision in around 2.5 minutes
- The screener passes almost all normal trichromats, fails all protans and achieves close to 100% sensitivity in screening for deutan deficiency
- The CVS test detects both congenital and acquired loss of chromatic sensitivity

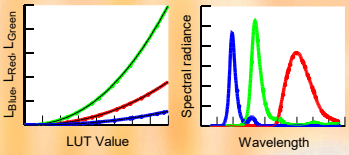


Illustrations by
Mari Terasaki
Miharu Shinohara
Joshibi University, Tokyo

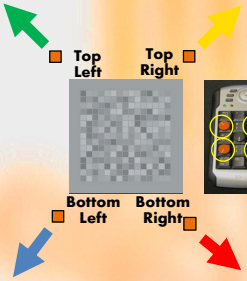


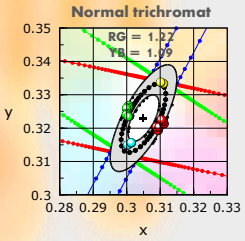
The assessment of colour vision:

- Where are we now and how did we get here?



The CAD test





- The CAD test provides full colour assessment (both RG and YB) and grades the severity of congenital and acquired loss.
- The CAD test matches the results of the Nagel anomaloscope in detecting and separating deutan and protan deficiencies.

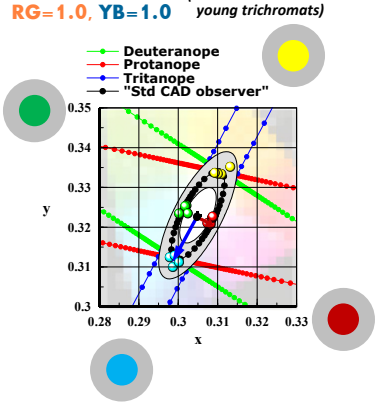
DOI: 10.1002/col.22599

(Only ~ 6% of all applicants require the CAD test)

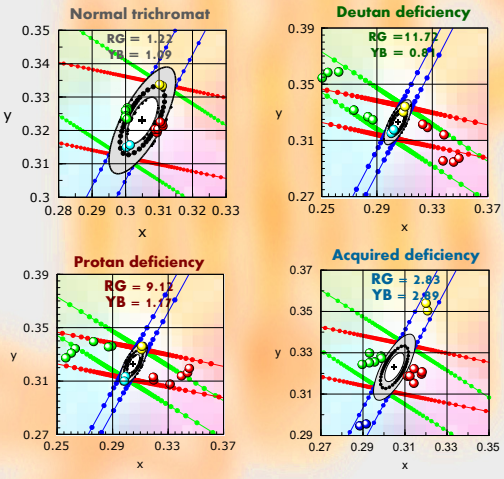
Examples of Colour Assessment results using the CAD test

The Standard Normal (SN) CAD Observer

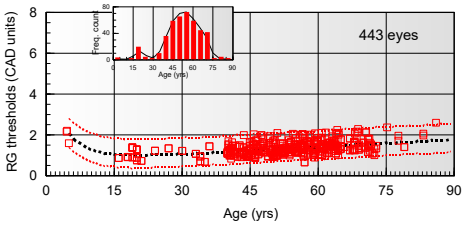
SN CAD units: RG=1.0, YB=1.0 *(Based on 330 normal young trichromats)*

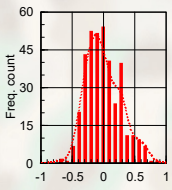


Examples of CAD results



CHANGES IN RG AND YB COLOUR VISION THAT CAN BE RELIABLY ATTRIBUTED TO NORMAL AGING

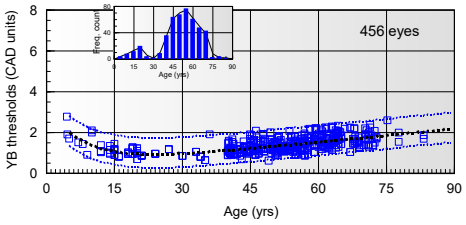


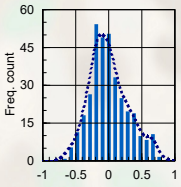


Statistical distribution of the deviations of measured RG thresholds from the best-fit prediction of mean thresholds

Binocular ±2.5 σ Normal Age Limits

Dotted red / blue lines represent the 2.5σ limits computed from the RG and YB histograms

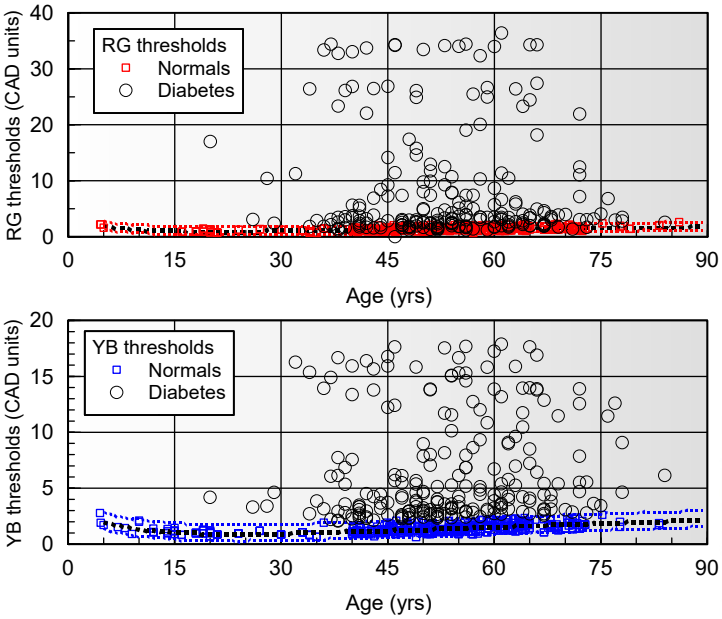


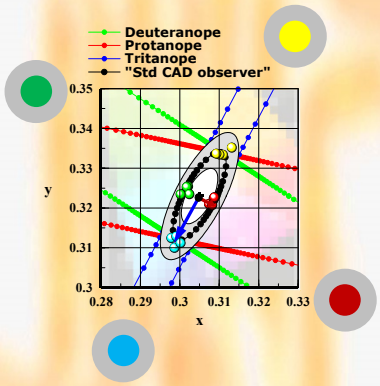


Deviations of measured YB thresholds from the best-fit prediction of mean thresholds.

COLOUR VISION LOSS IN DIABETES (All subjects)

(219 subjects; I Ansari & C Canning, Moorfield's Eye Hospital Dubai)



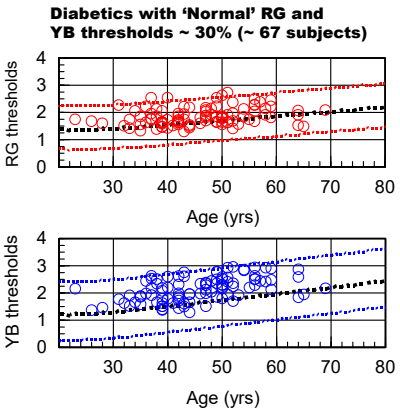


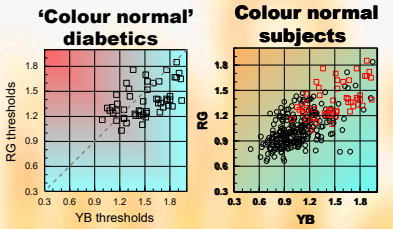
Similar findings obtained by:
Ahmed Abdel-Hay and Shoba Sivaprasad
(Moorfields / Kings College Hospitals, London)
https://doi.org/10.1371/journal.pone.0199693

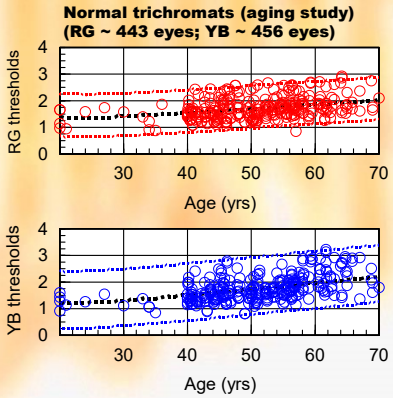
COLOUR VISION LOSS IN DIABETES
(Patients within the normal range)

219 diabetic patients (141 males, 78 females - 7 with congenital RG colour deficiency)

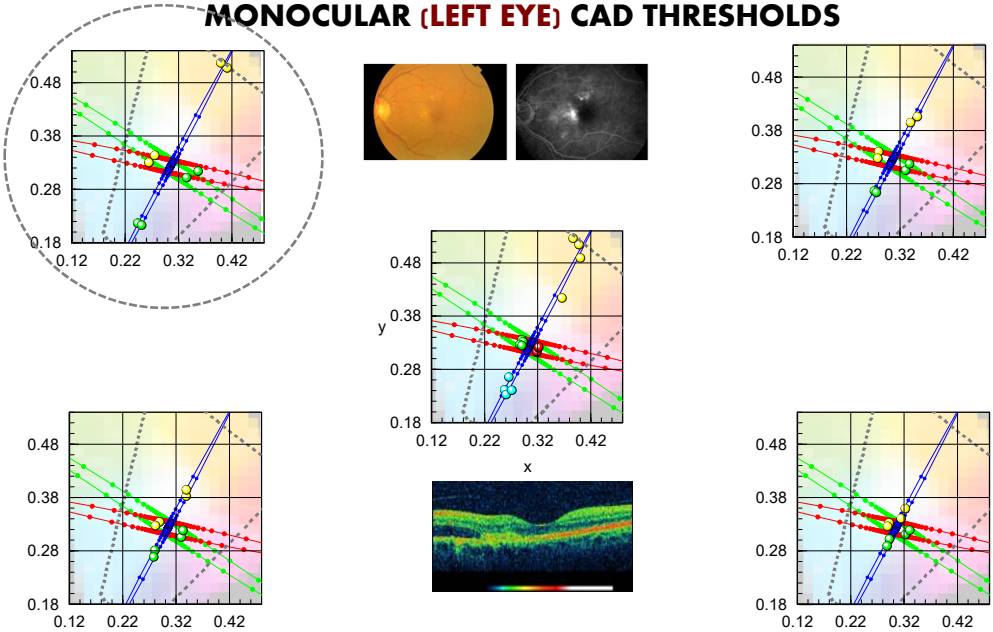
30% of the patients have RG and YB thresholds that fall within the age-corrected normal range



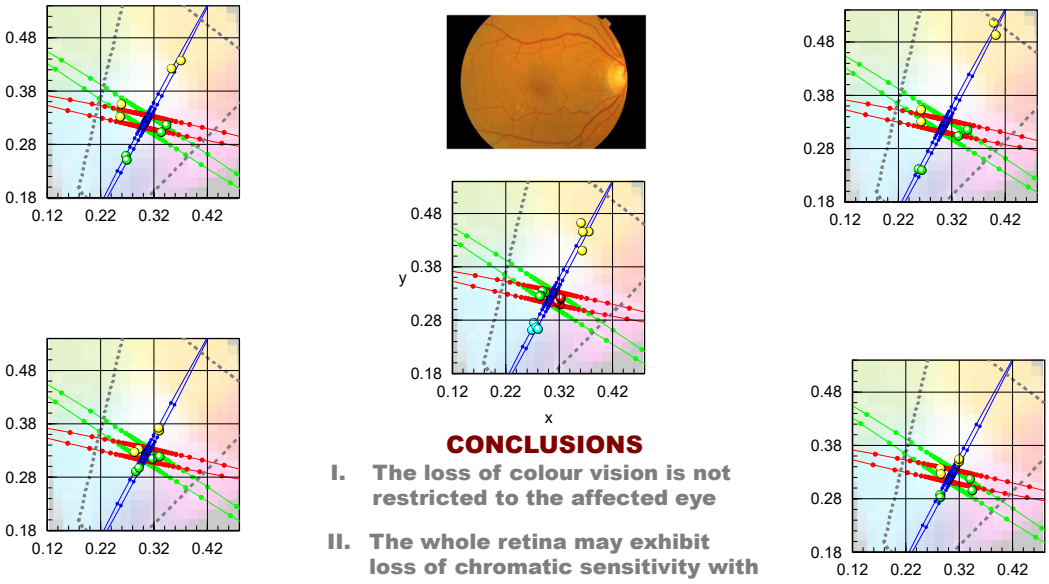




AMD PATIENT (WITH RETINOPATHY IN LEFT EYE)
MONOCULAR (LEFT EYE) CAD THRESHOLDS



AMD PATIENT (WITH RETINOPATHY IN LEFT EYE) MONOCULAR (RIGHT EYE) CAD THRESHOLDS

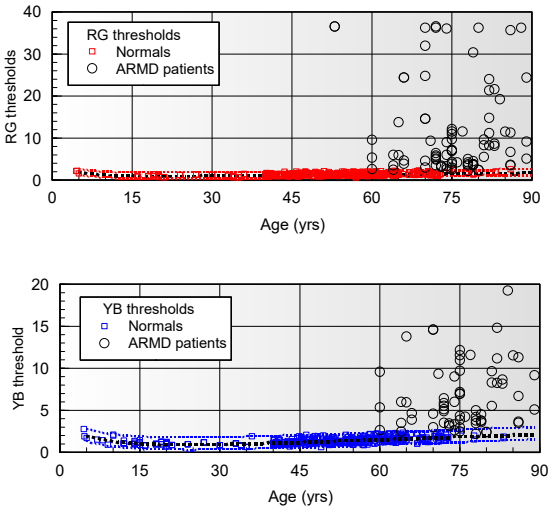


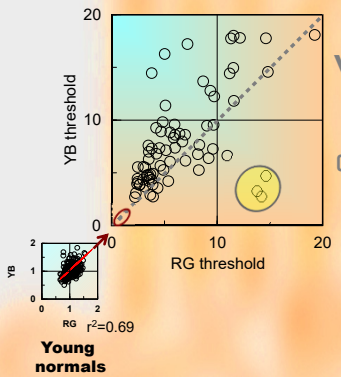
CONCLUSIONS

I. The loss of colour vision is not restricted to the affected eye

II. The whole retina may exhibit loss of chromatic sensitivity with YB being affected most

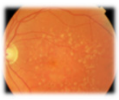
Colour vision loss in patients with age-related macular degeneration





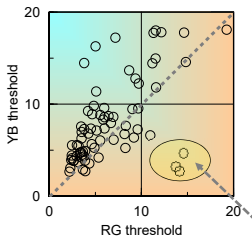
Study with Roopa Vemala and Shoba Sivaprasad

(Moorfields / Kings College Hospitals, London)



Detection of 'Acquired' loss in patients with 'Congenital' RG deficiency

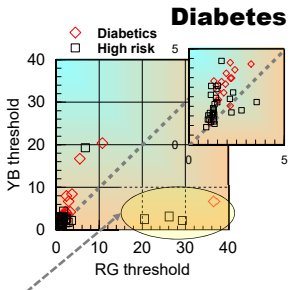
AMD



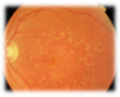
Roopa Vemala: doctoral thesis, City University 2017

ACQUIRED loss in patients with RG **CONGENITAL** deficiency

Diabetes

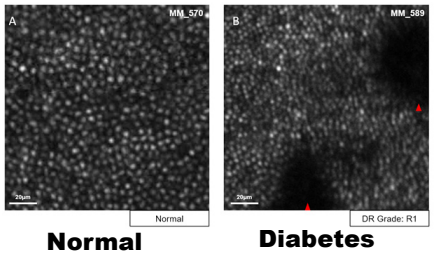


Study with Marisa Rodriguez-Carmona and Qais Bastaki, City University 2018

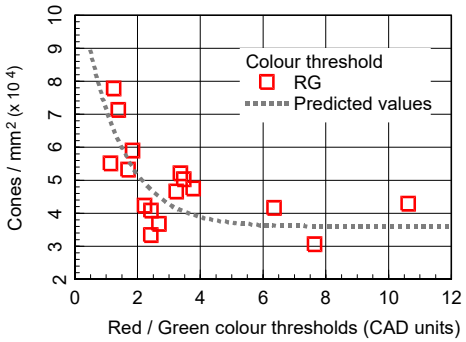


What factors cause early functional changes in diabetes?

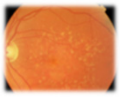
Colour vision and the integrity of cone photoreceptors in patients with diabetes*



Normal **Diabetes**



M Vaughan, E Patterson, M Michaelides et al. Moorfields Eye Hospital, Institute of Ophthalmology, City University, (*IOVS, to be submitted)



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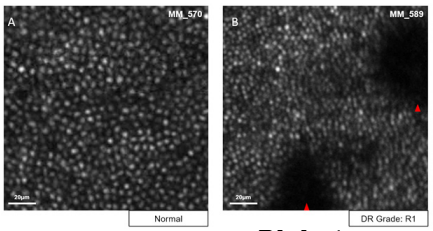
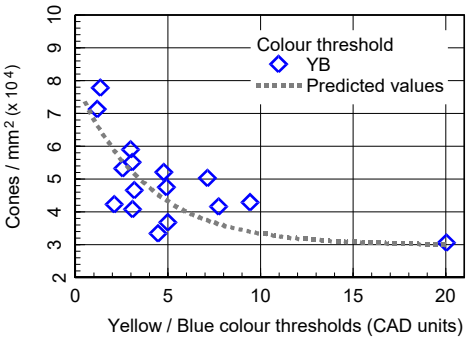


Normal **Diabetes**



M Vaughan, E Patterson, M Michaelides et al.
Moorfields Eye Hospital, Institute of Ophthalmology
(IOVS, to be submitted)

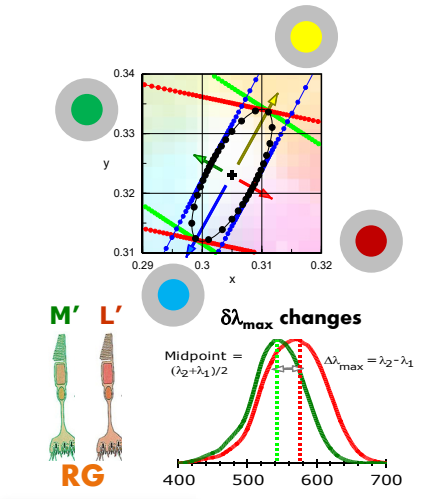
Modelling of Colour Ellipses

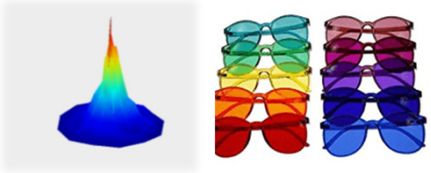
1) Can one predict the colour ellipses and the effects of chromatic adaptation from what we know about chromatic mechanisms in the eye?

2) How well can one predict the loss of RG chromatic sensitivity in congenital RG deficiency from a knowledge of $\delta\lambda_{max}$?

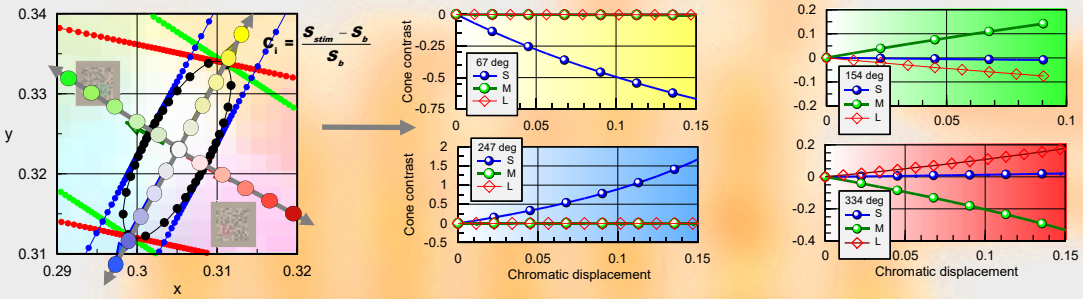
3) How does the colour of isoluminant stimuli change the effective photopic and scotopic luminance contrast as seen by deutans and protans with known severity of loss?

4. How are the colour signals and the luminance contrast of coloured stimuli affected by coloured lenses and/or pre-receptor filters in the eye?

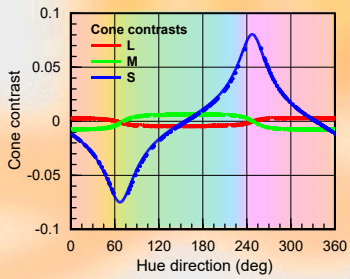




CE MODEL BASED ON CONE CONTRASTS AT THRESHOLD

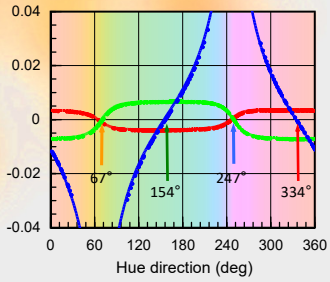


THRESHOLD CONE CONTRAST SIGNALS FOR NORMAL TRICHROMATS



Cone contrasts at threshold:

L = 0.4%
M = 0.8%
S = 7%



Colour Ellipse (CE) Model

Stimulus specification:

$L_s, (x_s, y_s)$, *or* X_s, Y_s, Z_s

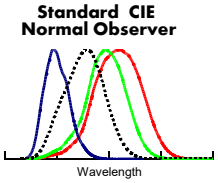
$R_{Test}(\lambda)$: $L_{Blue} + L_{Green} + L_{Red}$

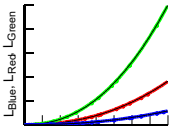
Background specification:

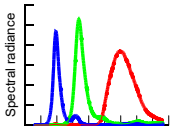
$L_b, (x_b, y_b)$, *or*, X_b, Y_b, Z_b

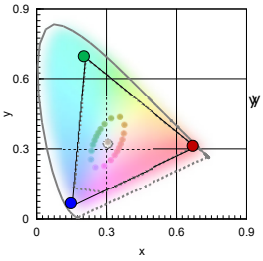
$R_{Bkg}(\lambda)$: $L_{Blue} + L_{Green} + L_{Red}$

Standard CIE Normal Observer

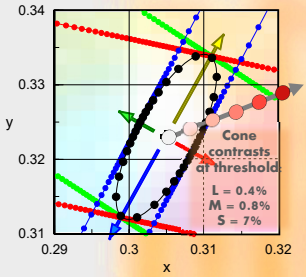








How do we implement the CE Model?



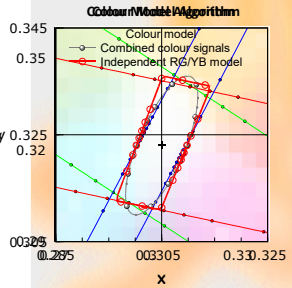
1. Calculate photoreceptor contrasts needed to compute the RG and YB colour signals
2. We also calculate the stimulus photopic and scotopic luminances and corresponding luminance contrasts

Case 1. Independent Model: i.e., the threshold is set by either the RG or the YB colour signal, whichever gets to threshold first!

Calculate:

$YB'_T(\theta) = F(S'_{cone}, M'_{cone}, L'_{cone})$

$RG'_T(\theta) = F(M'_{cone}, L'_{cone})$

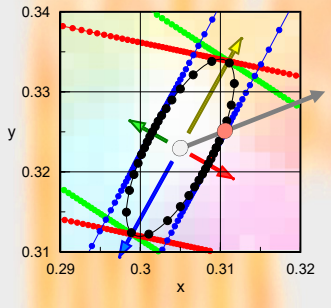


Case 2. The Combined Colour Signal Model: i.e., the threshold is set by only ONE colour signal that remains invariant with position in the chromaticity chart.

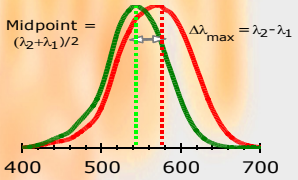
Calculate:

$CT(\theta) = F(YB'_T(\theta), RG'_T(\theta))$

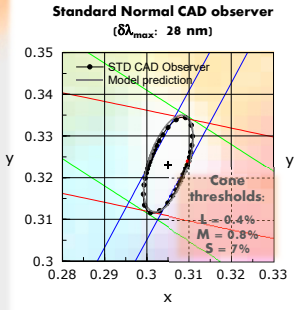
CE Model Predictions in congenital RG deficiency



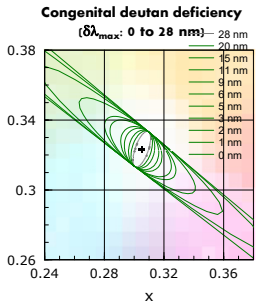
$\delta\lambda_{max}$ changes



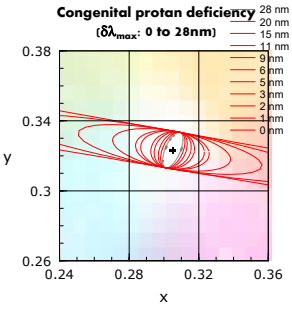
1. **Prediction of thresholds for STD normal CAD observer**



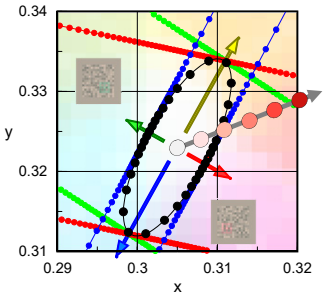
2. **Examine effects of systematic M > L shifts on colour thresholds**



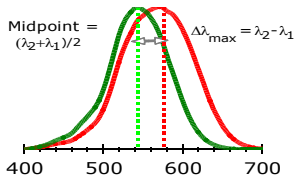
3. **Effect of systematic L > M shits on colour thresholds**



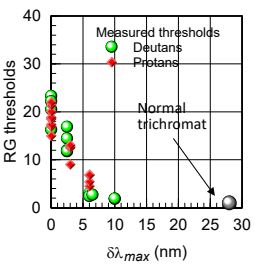
CE Model Predictions: Thresholds versus $\delta\lambda_{max}$



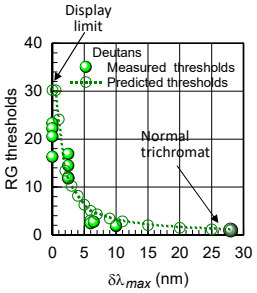
$\delta\lambda_{max}$ changes



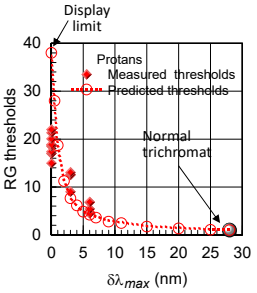
1. **Measured RG thresholds plotted against $\delta\lambda_{max}$. The latter variable is based on genetic analysis cone pigment genes.**



2. **EC model predictions of RG thresholds for deutan-like deficiency (M > L shifts)**

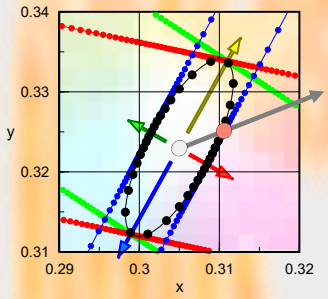


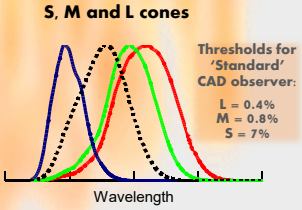
3. **EC model predictions of RG thresholds for protan-like deficiency (systematic L > M shits)**

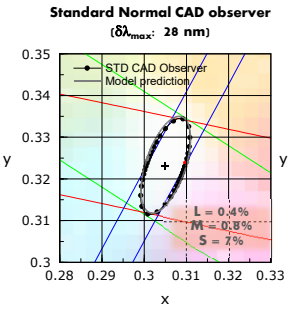


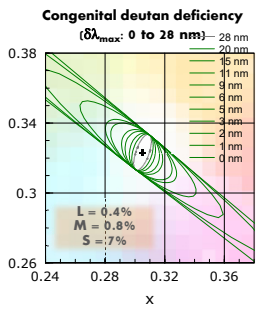
Visual Neuroscience
DOI: https://doi.org/10.1017/S0952523808080619

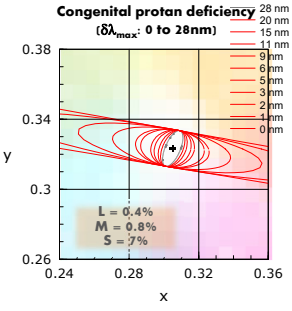
CE Model Predictions in acquired YB deficiency

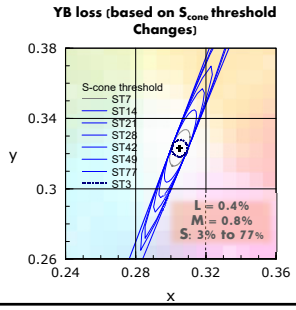






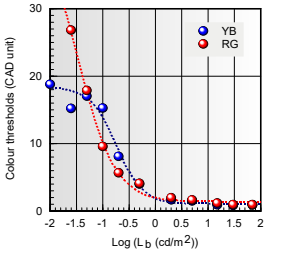






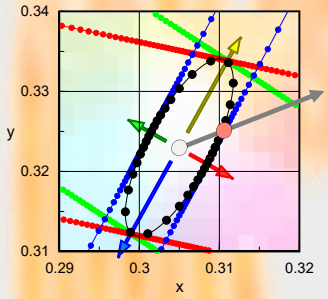
Factors affecting S-cone contrast thresholds

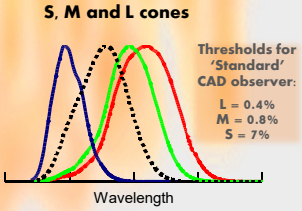
- Aging
- Exposure to neurotoxins
- Presence of retinal / systemic diseases
- Decreased short-wavelength retinal illuminance

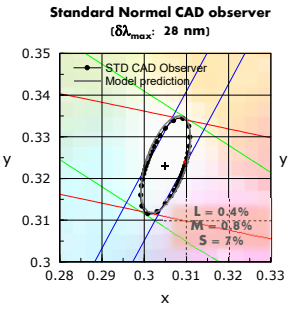


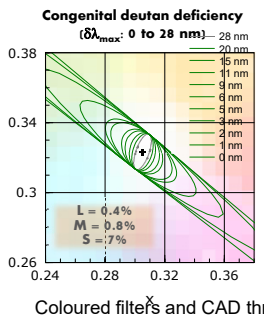
(Study with Emsal Llapashtica 2023)

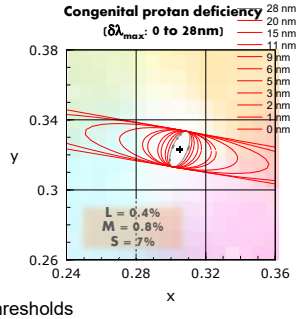
CE Model Predictions in acquired YB deficiency





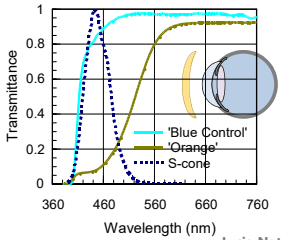


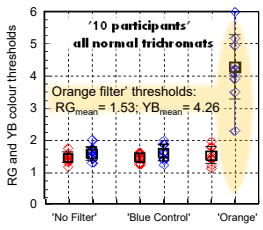


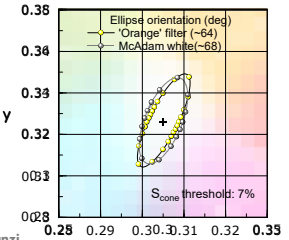


Coloured filters and CAD thresholds

Effects of 'BlueControl' and 'Orange' filters on YB colour thresholds

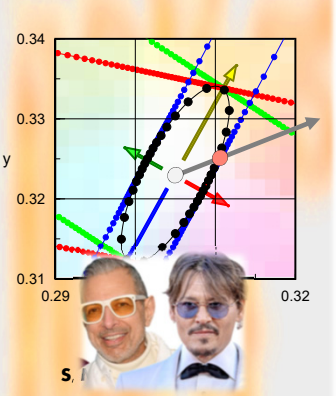


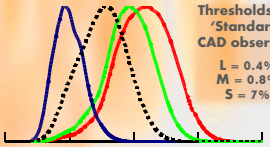




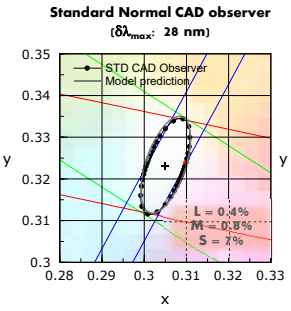
Lucia Natali, Alessandro Farini and Elisabetta Baldanzi,
(Istit. Nazionale di Ottica-CNR)

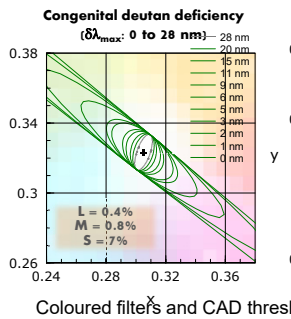
CE Model Predictions in acquired YB deficiency

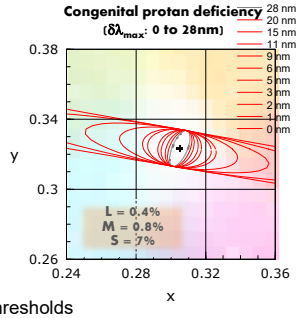




Thresholds for 'Standard' CAD observer:
L = 0.4%
M = 0.8%
S = 7%

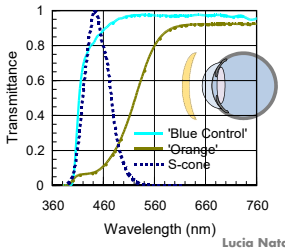


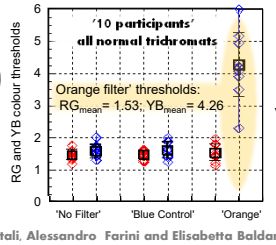


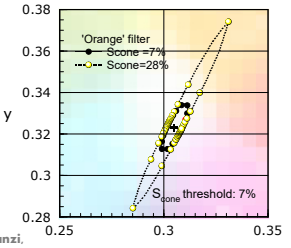


Coloured filters and CAD thresholds

Effects of 'BlueControl' and 'Orange' filters on YB colour thresholds







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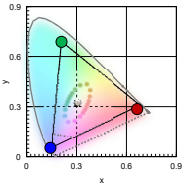
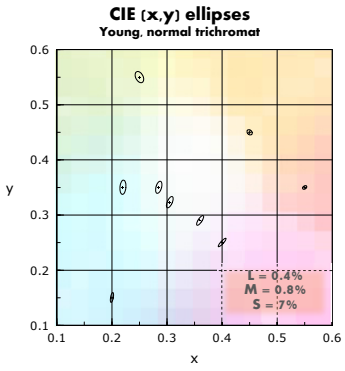
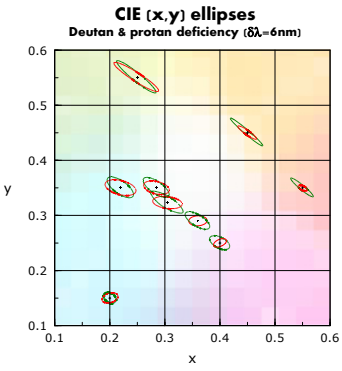
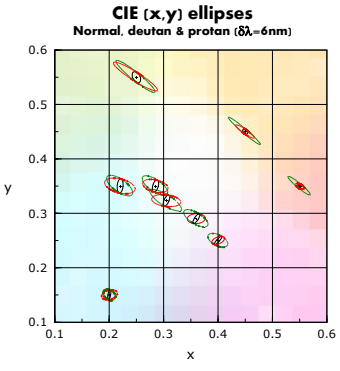
The effects of chromatic adaptation on colour discrimination







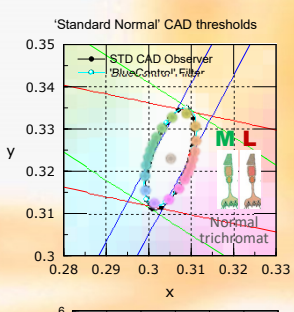


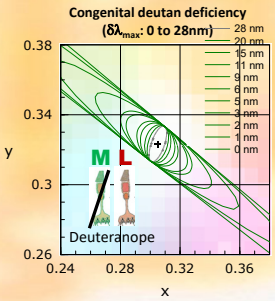
Ellipse model predictions for the standard CAD observer for different states of chromatic adaptation

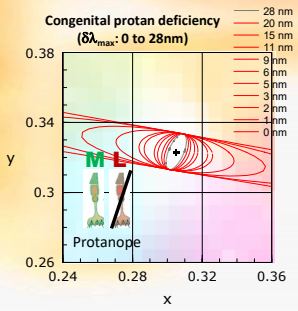
Threshold contours computed for the same states of chromatic adaptation for deutan and protan subjects for a $\delta\lambda_{max}$ (L to M spectral separation) of 6 nm.

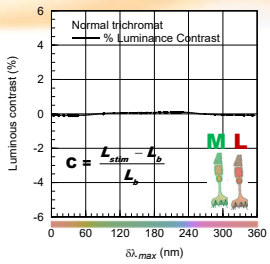
Model Predictions:

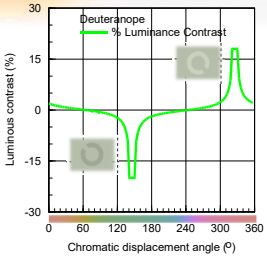
Photopic luminance contrast of coloured stimuli at threshold

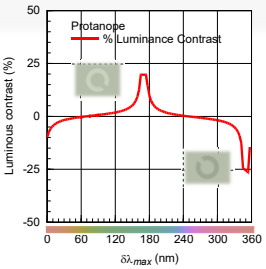






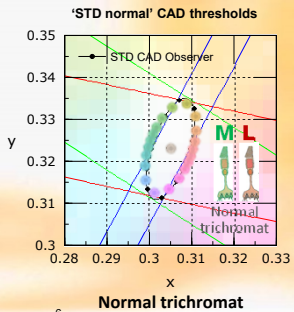


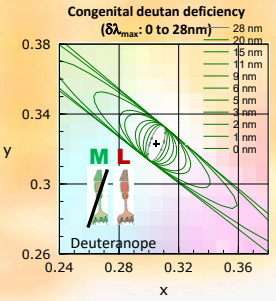


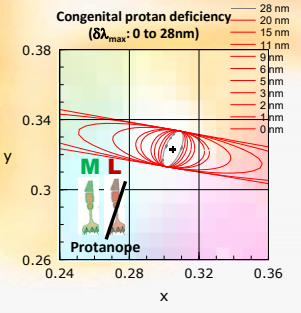


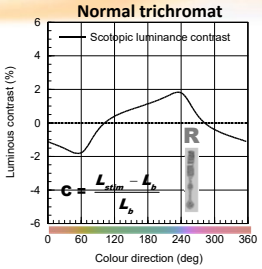
Model Predictions:

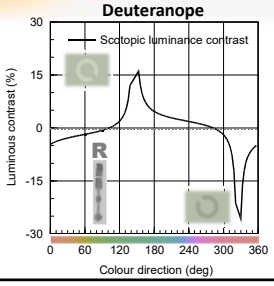
Scotopic luminance contrast of coloured stimuli at threshold

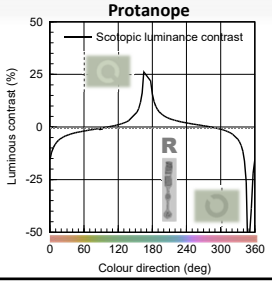




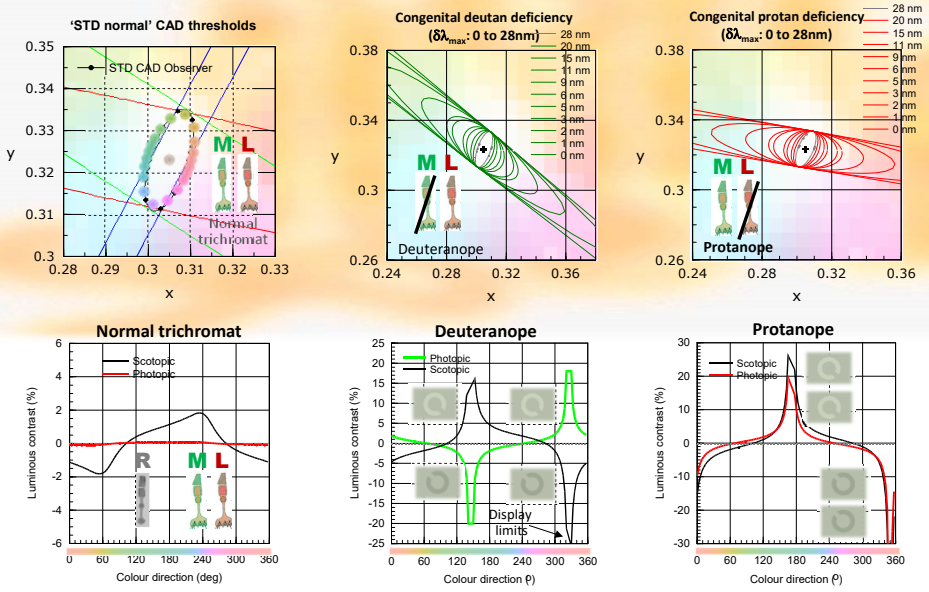








Comparison of photopic and scotopic luminance contrast for coloured stimuli at threshold



OBSERVATIONS

1. The coloured stimuli are truly, photopically 'isoluminant' for the 'Standard' normal CIE observer
2. The same 'Standard' normal CIE observer shows greater scotopic luminance contrast
3. The 'effective' luminance contrast of 'coloured' stimuli can be very large in subjects with congenital colour deficiency (for saturated colours that fall along colour confusion bands)
4. Significant differences emerge when comparing contrasts in deuteranopes and protanopes.

Protans benefit from a more effective combination of , combined photopic and scotopic luminance contrast

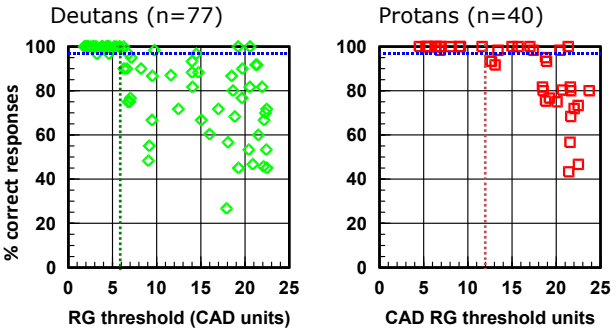
CONCLUSIONS

As we learn more about the use of colour and luminance signals in RG colour deficients, we begin to unravel more differences between **'deutan'** and **'protan'** like subjects that can affect real life performance in safety critical tasks.

There are other interesting, remaining applications of this model, particularly in relation to coloured and and narrow band illuminants, so more interesting work remains to be done!

PAPI system

- Too high
- Slightly high
- On slope
- Slightly low
- Too low



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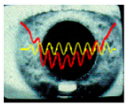

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