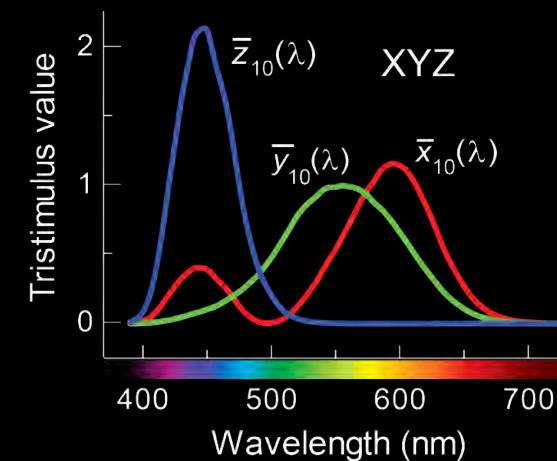
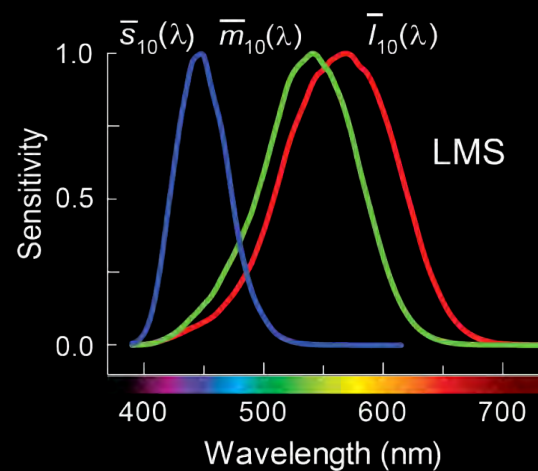


CIE LMS/XYZ developments

Andrew Stockman



CIE Technical Committee 1-104:

Verification of the physiologically-relevant CIE 2006 LMS cone fundamental CMFs and their linear transformation the 2015 XYZ CMFs

To verify the standard cone spectral sensitivities, colour matching functions and individual differences defined in CIE 170-1:2006, Fundamental chromaticity diagram with physiological axes – Part 1 [1], and in CIE 170-2:2015 Fundamental chromaticity diagram with physiological axes – Part 2 [2] referred to jointly as the CIELMS(06)XYZ(15) model.

To test and refine the standard cone spectral sensitivities, colour matching functions and individual differences defined in the CIELMS(06)XYZ(15).

CIE Technical Committee 1-104:

Verification of the physiologically-relevant CIE 2006 LMS cone fundamental CMFs and their linear transformation to the 2015 XYZ CMFs

Updates tomorrow

TC 1-104 meeting

11:00–12:00 [Building B, Room B210]

CIE Technical Committee 1-104:

Verification of the physiologically-relevant CIE 2006 LMS cone fundamental CMFs and their linear transformation the 2015 XYZ CMFs

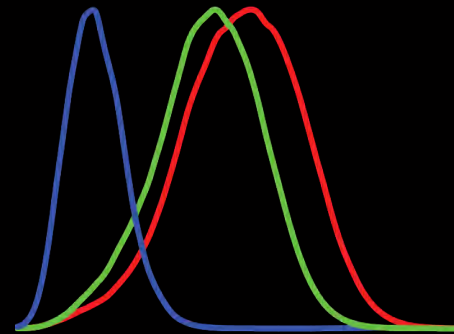
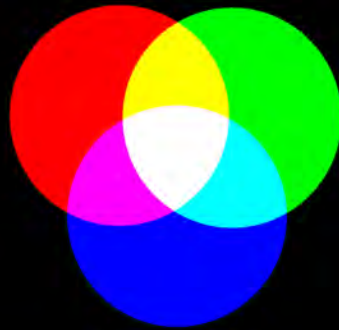
Yuta Asano	USA	Yoko Mizokami	Japan
Chris Bai	Taiwan	Michael Pointer	UK
Francisco Imai	USA	Andy Rider	UK
Jiaye Li	France	Andrew Stockman	UK
Ronnier Luo	China	Tommy Wei	China
Shining Ma	China	Kaida Xiao	UK
Manuel Melgosa	Spain	Yasuki Yamauchi	Japan

CIE Technical Committee 1-104:

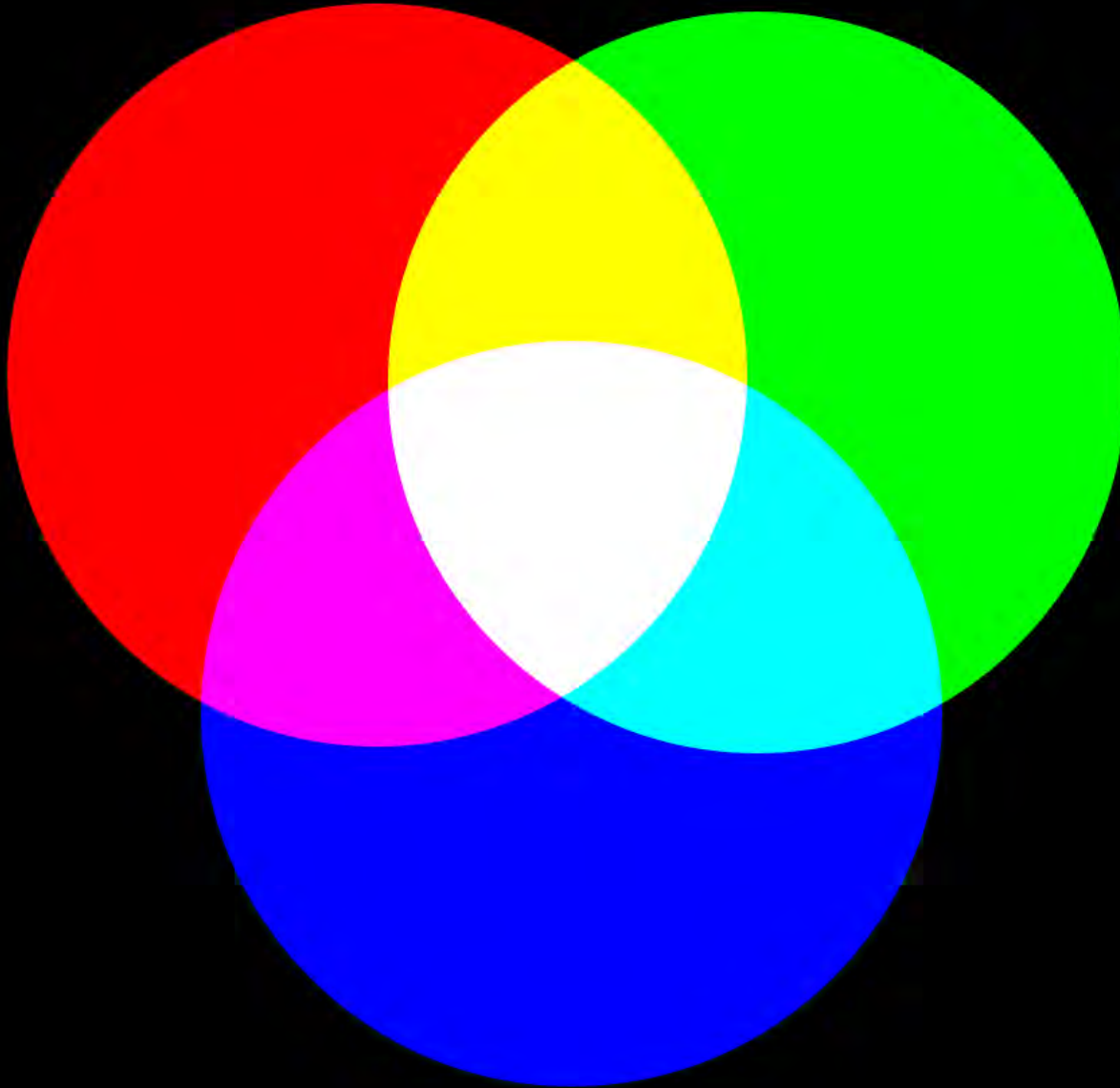
Verification of the physiologically-relevant CIE 2006 LMS cone fundamental CMFs and their linear transformation the 2015 XYZ CMFs

I'm going to talk about a new method we have developed to analyse Maxwell colour matching data.

1. TRICHROMACY, CONE SPECTRAL SENSITIVITIES AND COLOUR MATCHING



Trichromacy



Trichromacy means that colour vision at the input to the visual system is relatively simple.

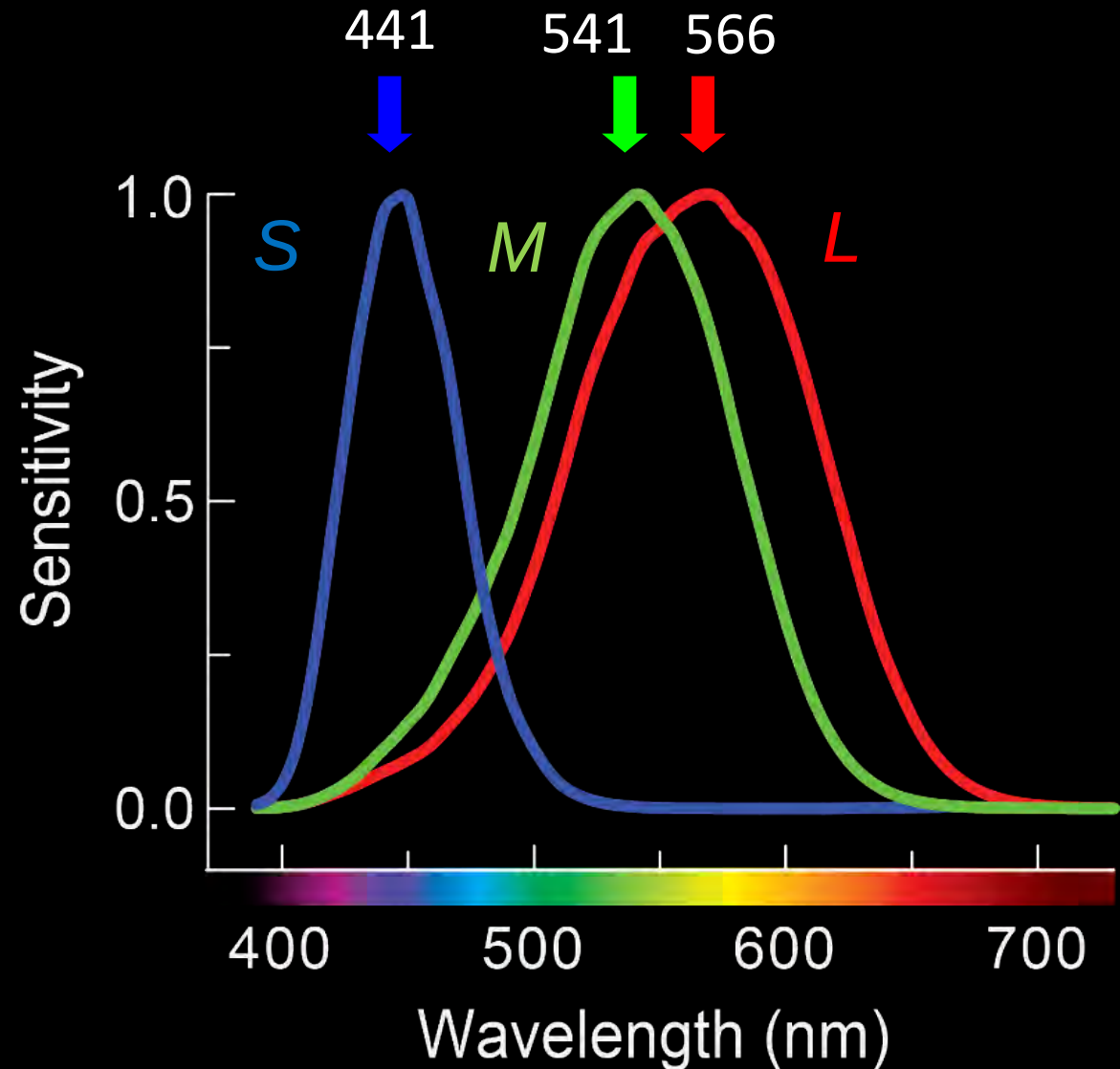
It is a 3-variable system...

Trichromacy

it arises because there are just three cone types (L, M & S) with different spectral sensitivities. Each responds only according to the *number* of photons it absorbs (independent of their wavelengths).

Trichromacy means that you can match colours in terms of just 3 real (e.g., RGB) or imaginary (e.g., XYZ) primary lights.

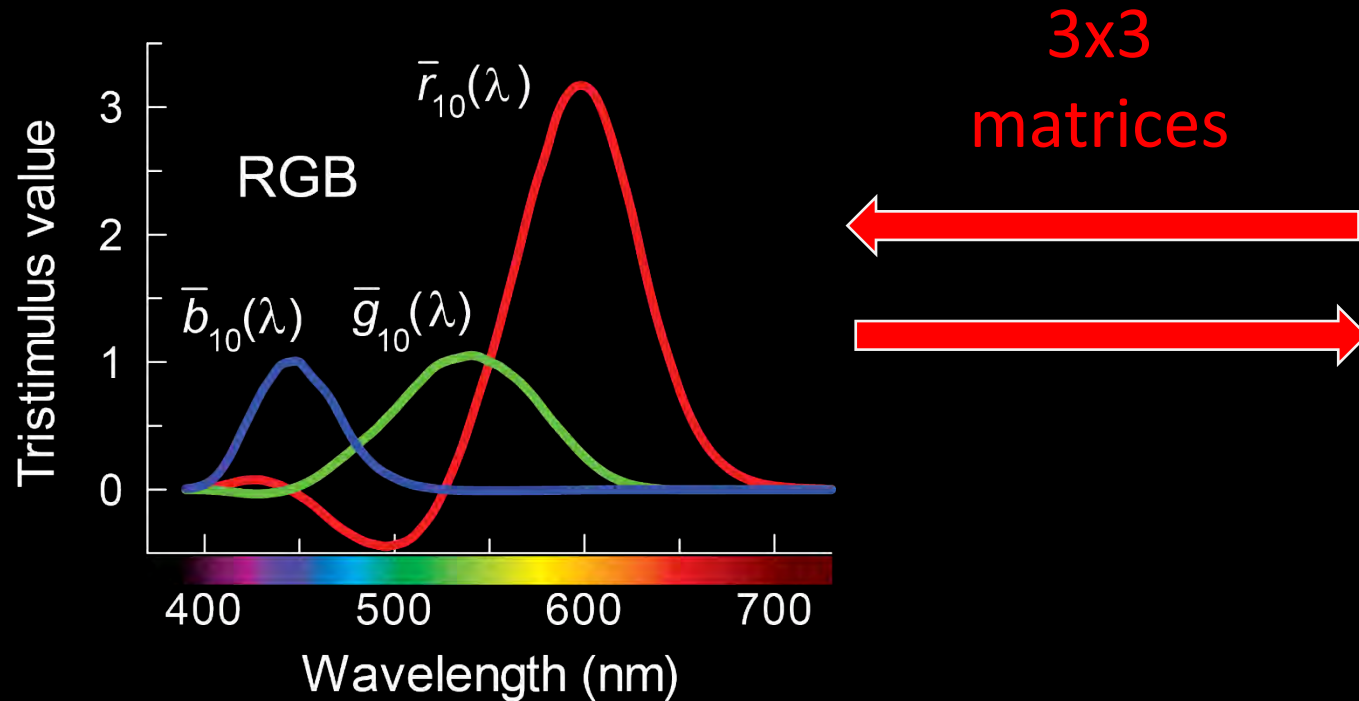
Human colour vision is trichromatic



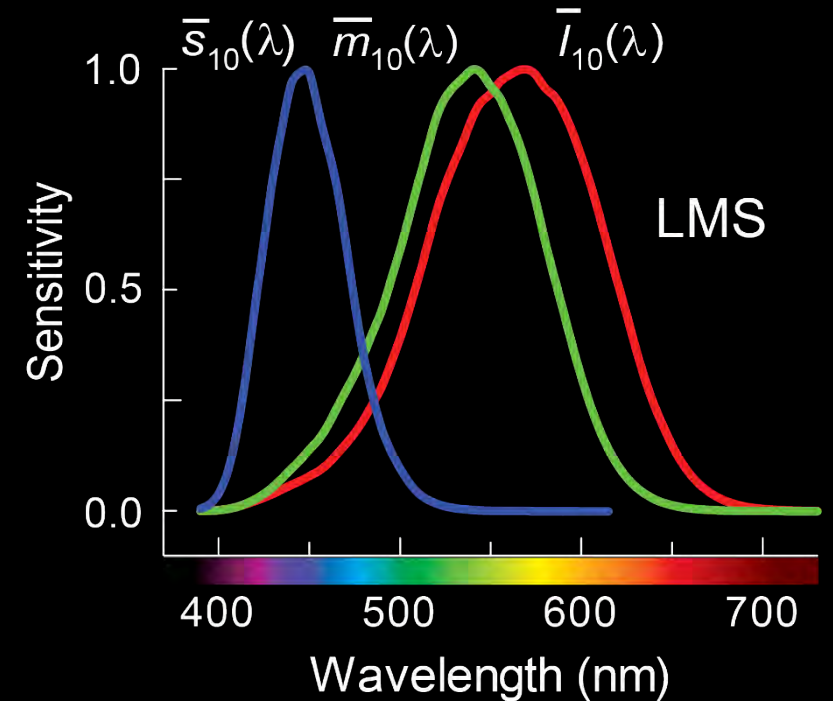
Colour matching

Given that colour matches are determined by the LMS cone spectral sensitivities there is a simple 3x3 linear transformation between LMS and RGB and back...

Classic Stiles & Burch (1959) “large-field” 10° colour matching functions

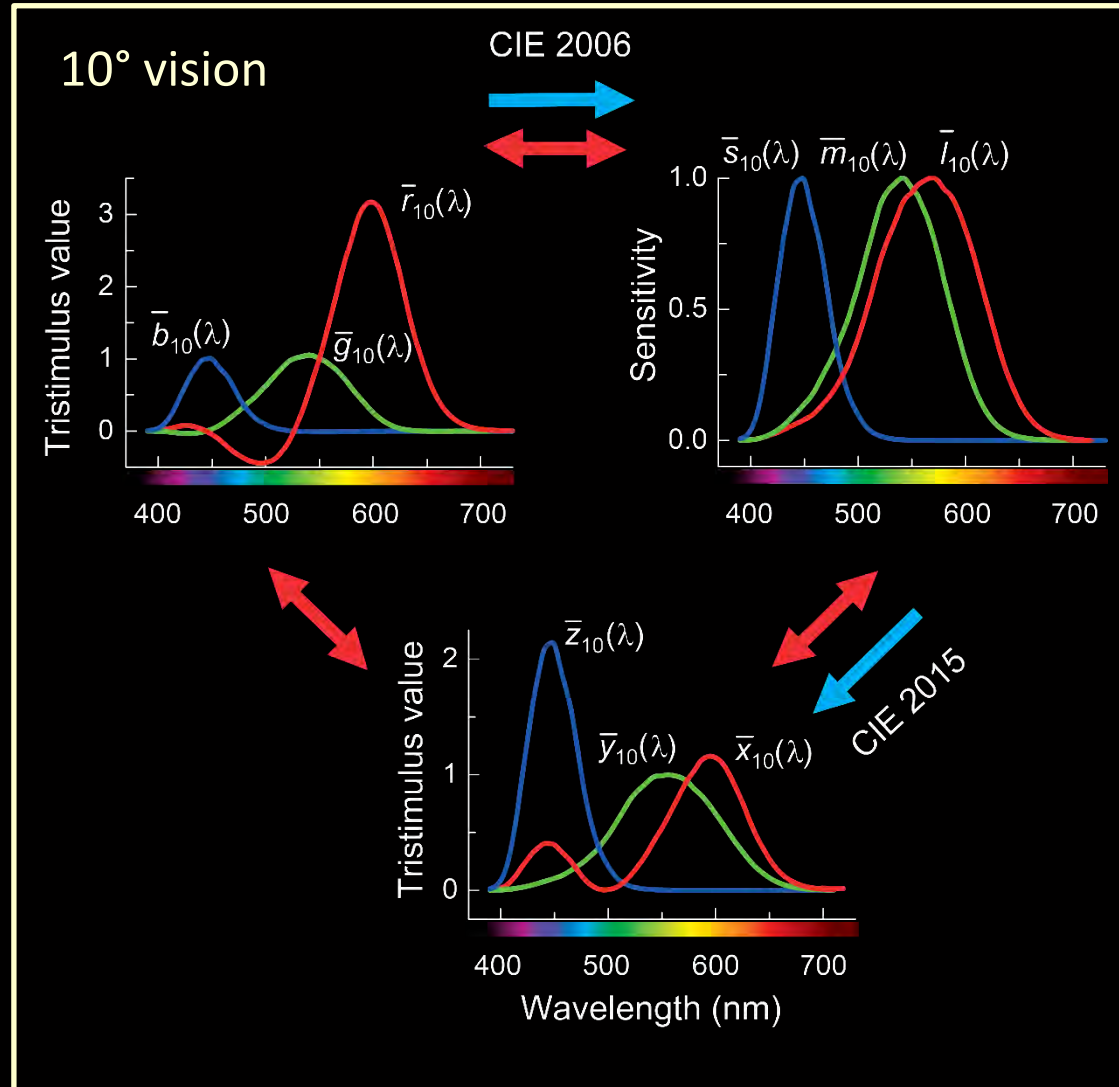


CIE (2006) 10° LMS cone fundamentals



CIE (2015) XYZ

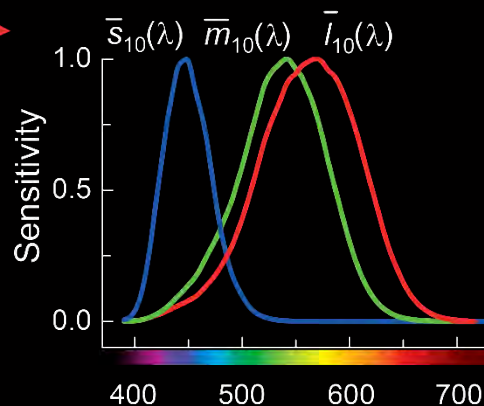
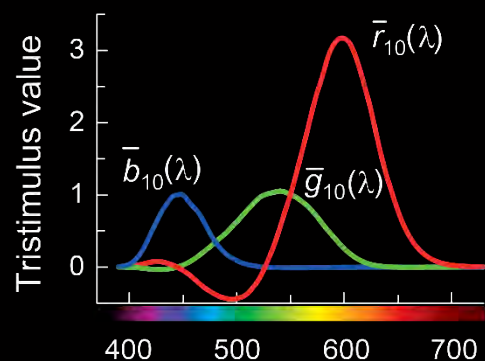
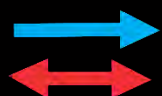
And between LMS or RGB and XYZ (and back).



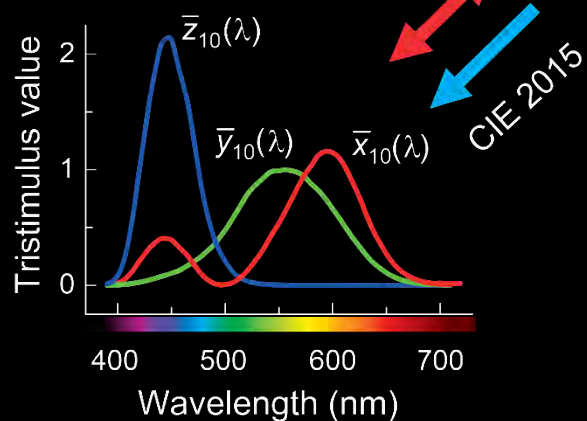
The CIE (2006) LMS and CIE (2015) XYZ CMFs are the recommended 2° and 10° functions for colorimetry and photometry.

10° vision

CIE 2006

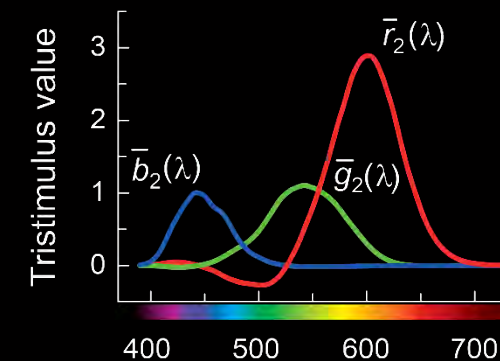
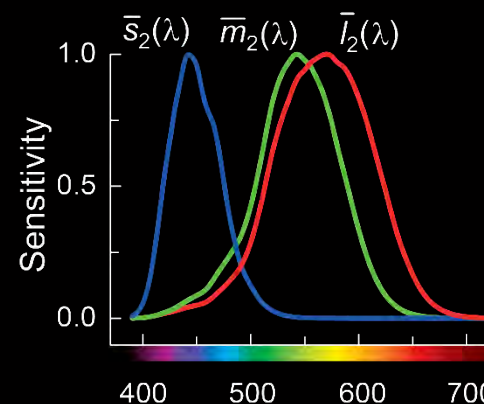


CIE 2006

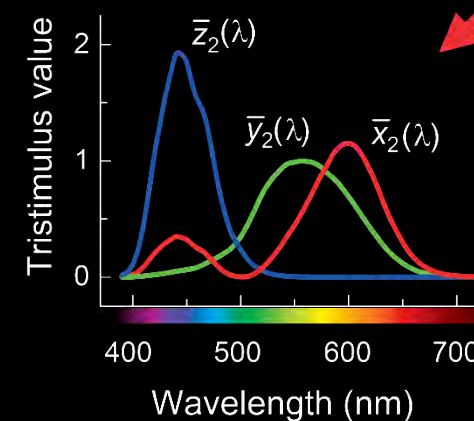


CIE 2015

2° vision



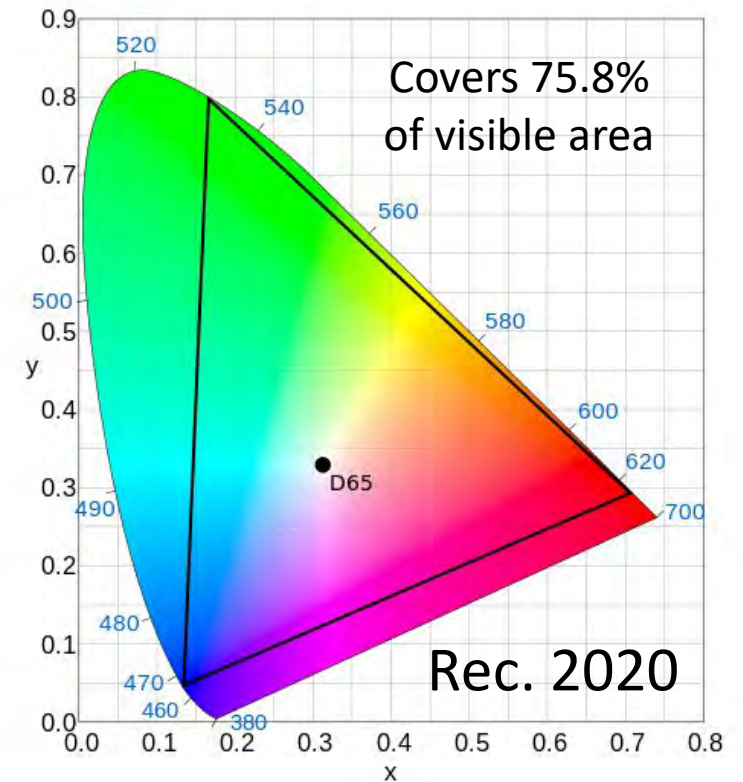
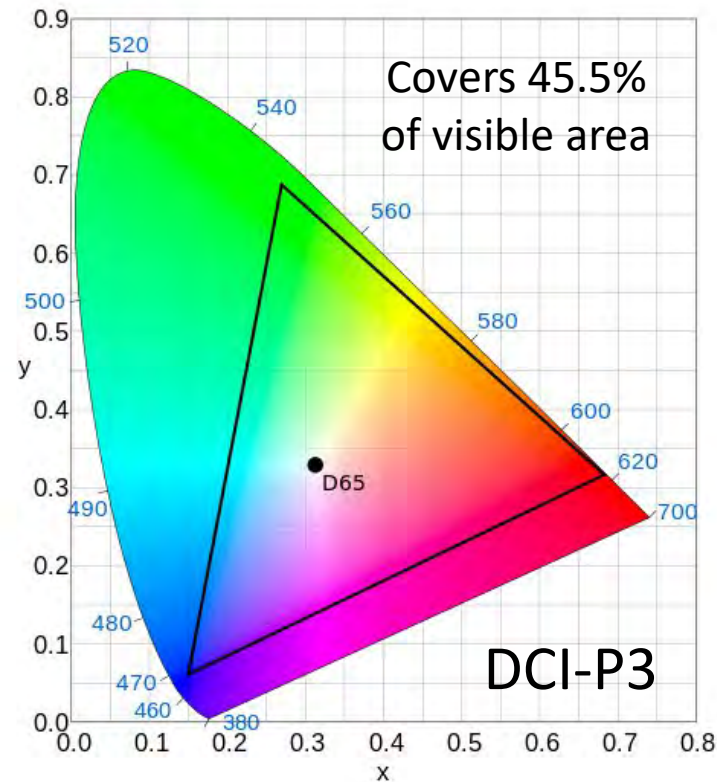
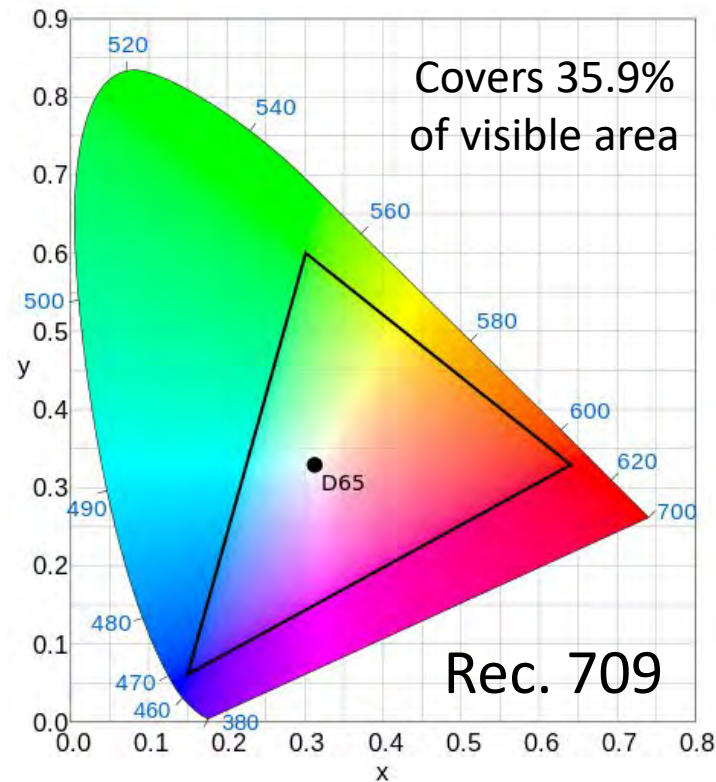
CIE 2015



Observer metamerism failures



If we know the chromaticities of a colour (in terms of LMS, XYZ or RGB), we *should* be able reproduce it on any display or other device, so for these three display types the colour should look the same for all observers...

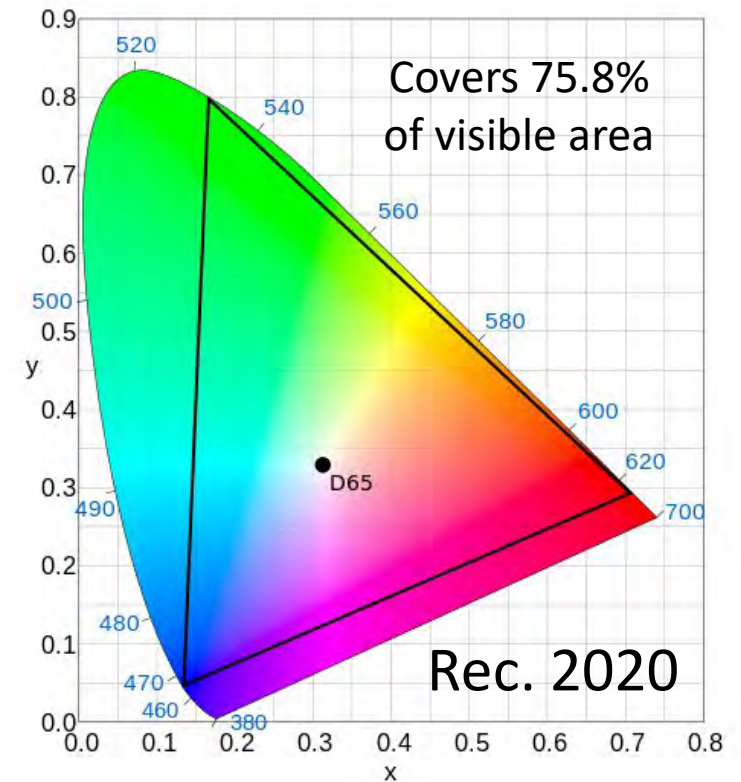
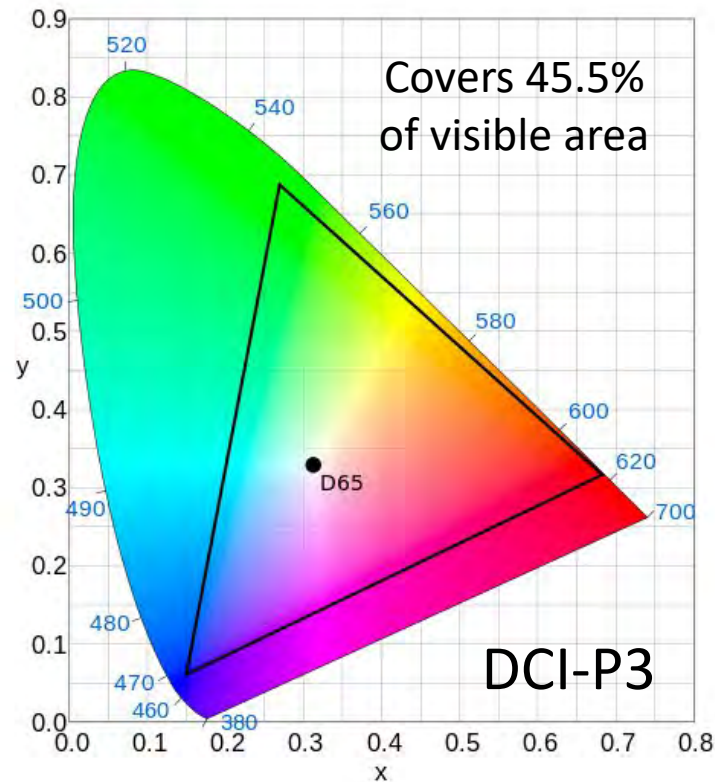
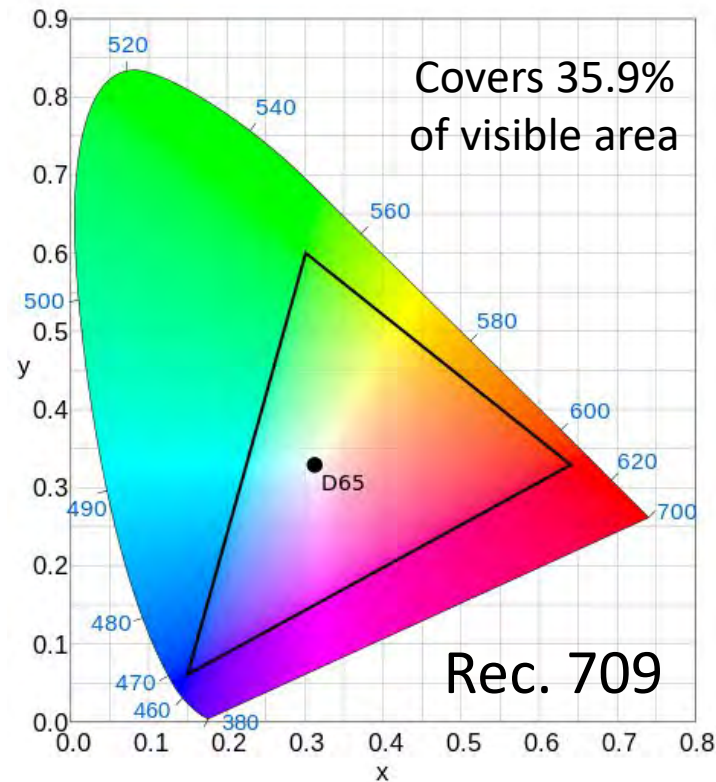


Observer metamerism failures



But frequently there is a mismatch—especially for displays with narrow-band primaries and wide colour gamuts.

These mismatches are caused in part by individual differences between observers.



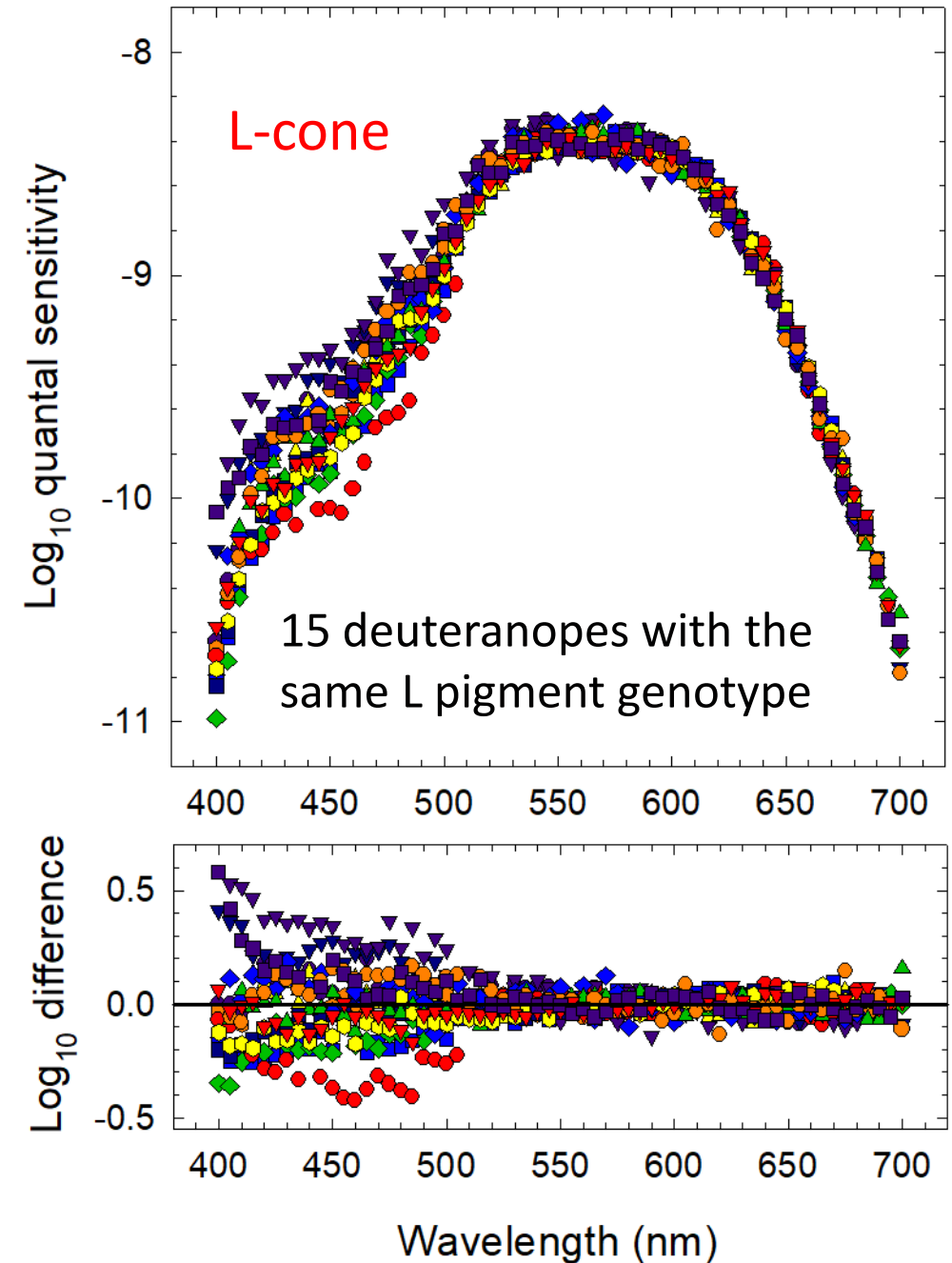
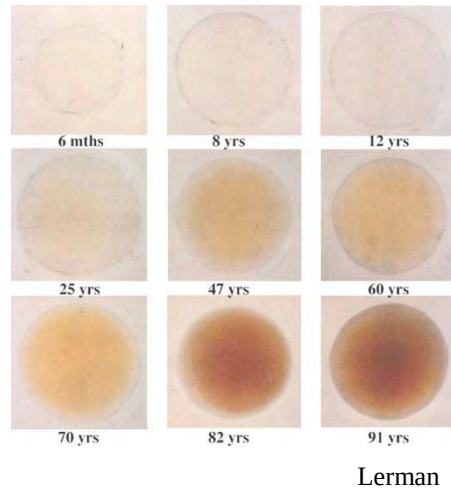
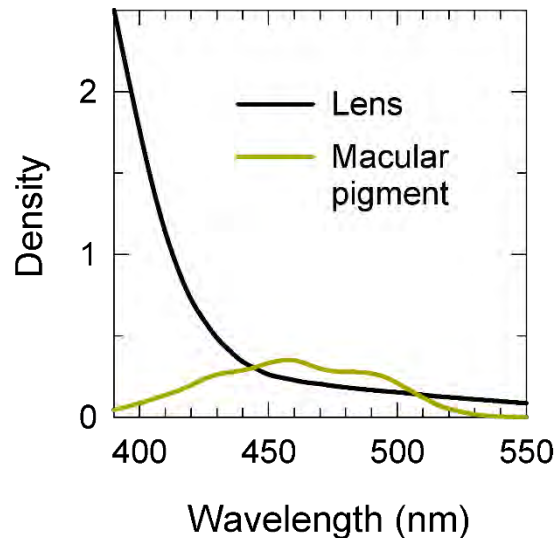
What causes individual differences?

- ▶ Macular pigment optical density differences
- ▶ Lens pigment optical density differences
- ▶ Photopigment optical density differences
- ▶ Spectral shifts in photopigment sensitivity

Macular and lens density differences

Individual data for deuteranopes with the same L-cone photopigment

The variability is due to individual differences in macular and lens pigment optical densities.



What causes individual differences?

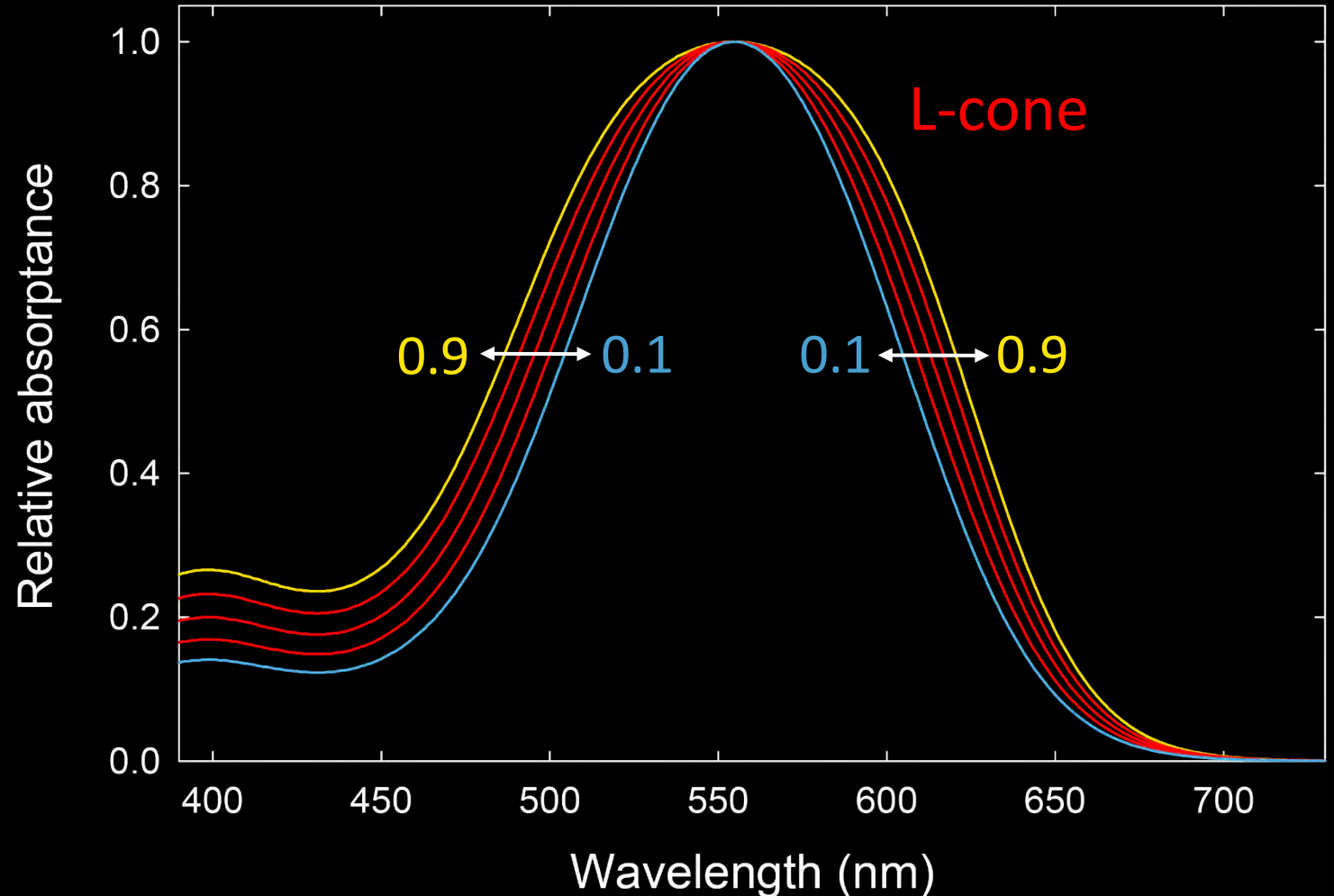
- ▶ Macular pigment optical density differences
- ▶ Lens pigment optical density differences
- ▶ **Photopigment optical density differences**
- ▶ Spectral shifts in photopigment sensitivity

Photopigment optical density differences

Increasing photopigment optical density broadens the spectral sensitivity around the λ_{max}

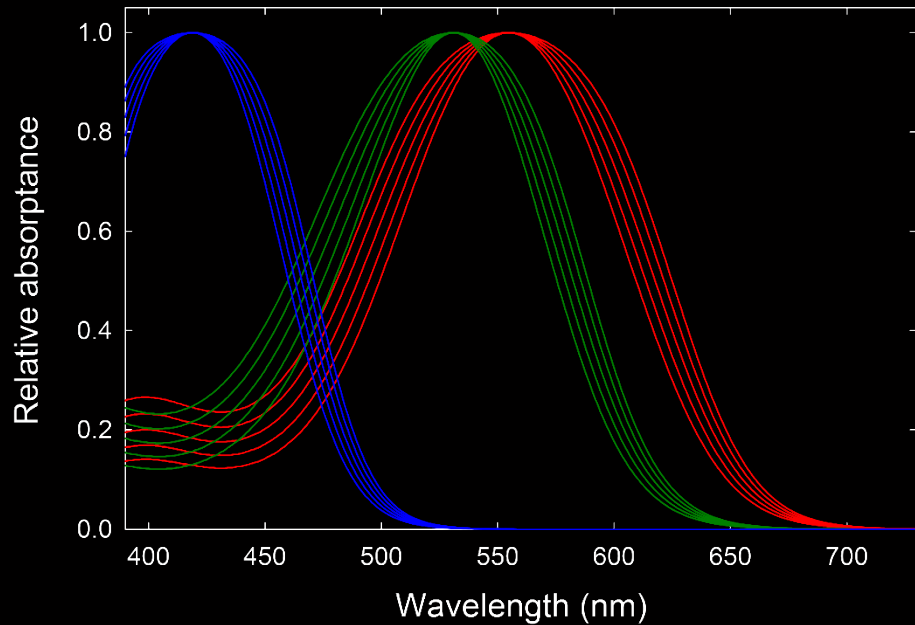
Photopigment optical density also varies with eccentricity because the cones in the fovea are longer and thus have a higher photopigment optical density than cones outside the fovea.

Cone photopigments varying in optical density from 0.1 (narrow) to 0.9 (broad) in 0.2 steps

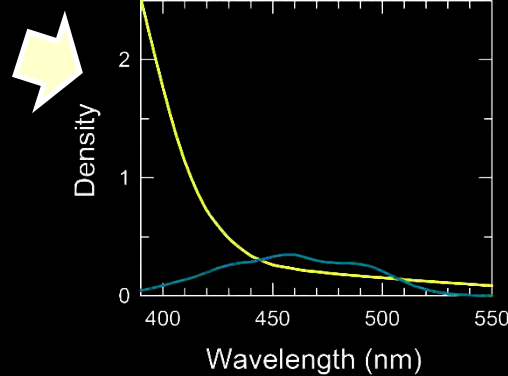


Photopigment optical density differences

Photopigments

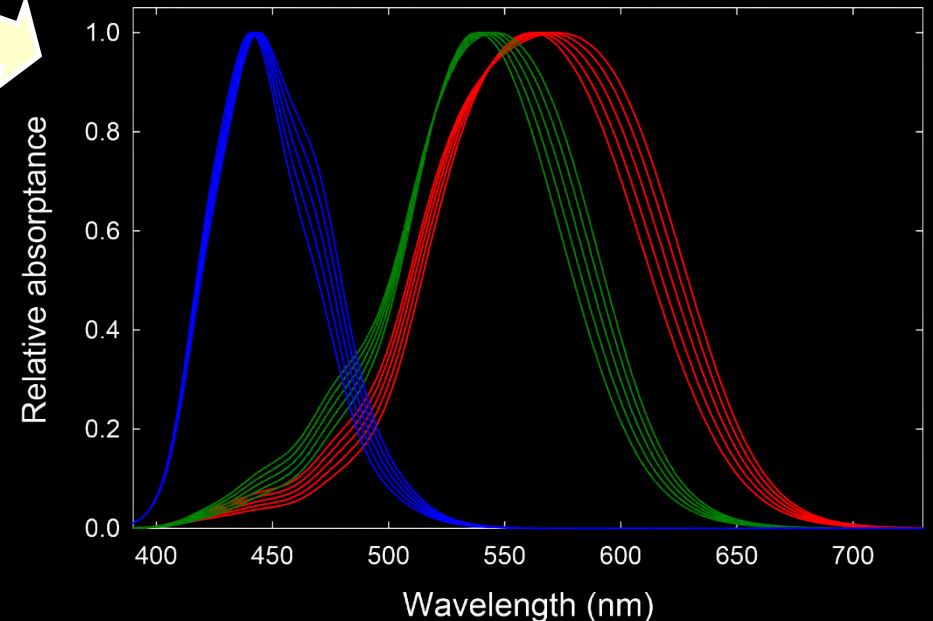


Add mean lens and macular filtering to produce the corneal spectral sensitivities.



Note here that you can only model these changes if you start with the LMS cone spectral sensitivities, NOT the XYZ or RGB CMFs!

Cone spectral sensitivities at the cornea



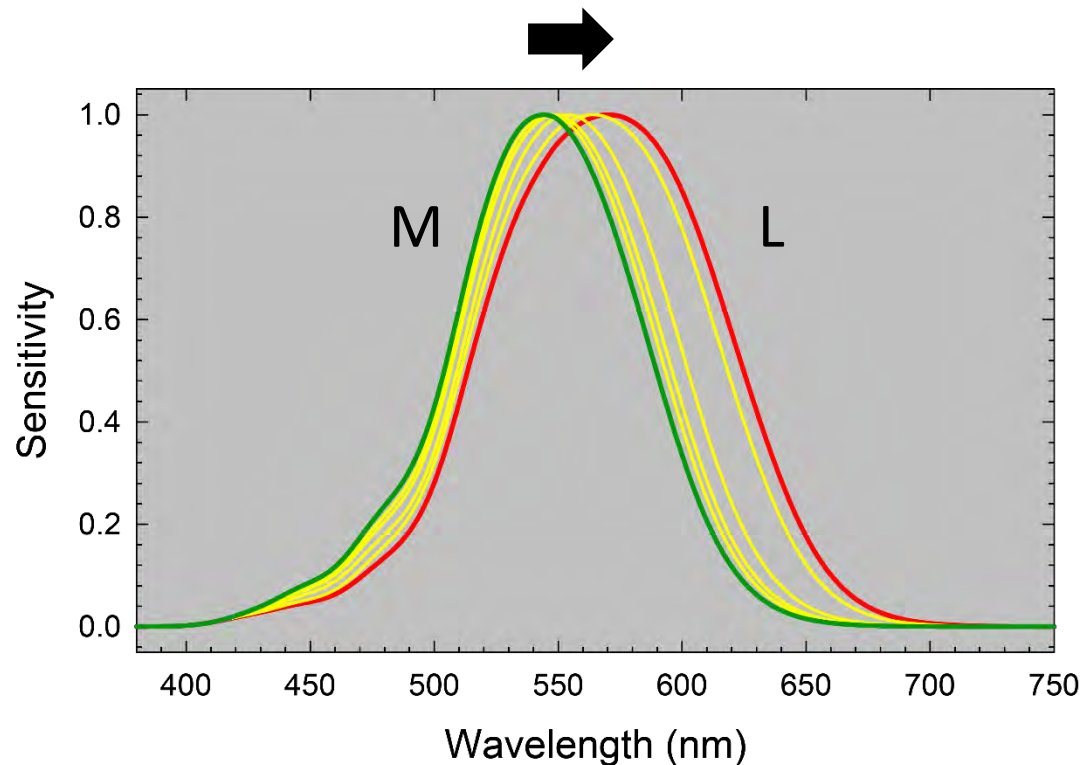
What causes individual differences?

- ▶ Macular pigment optical density differences
- ▶ Lens pigment optical density differences
- ▶ Photopigment optical density differences
- ▶ Spectral shifts in photopigment sensitivity

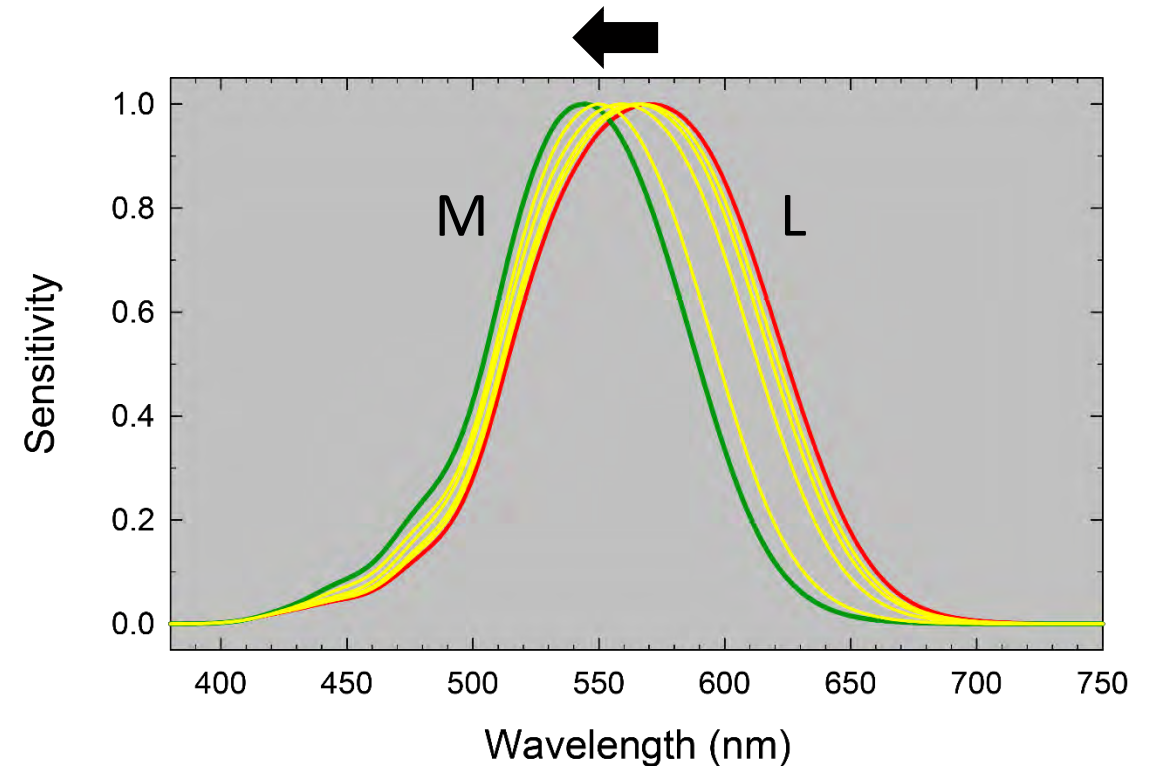
Why are there spectral shifts?

Spectral shifts in the positions of the M- and L-cone spectral sensitivity functions are caused by changes (substitutions) in the genes that encode the M- and L-cone photopigment opsins.

M-cone functions can shift towards L.

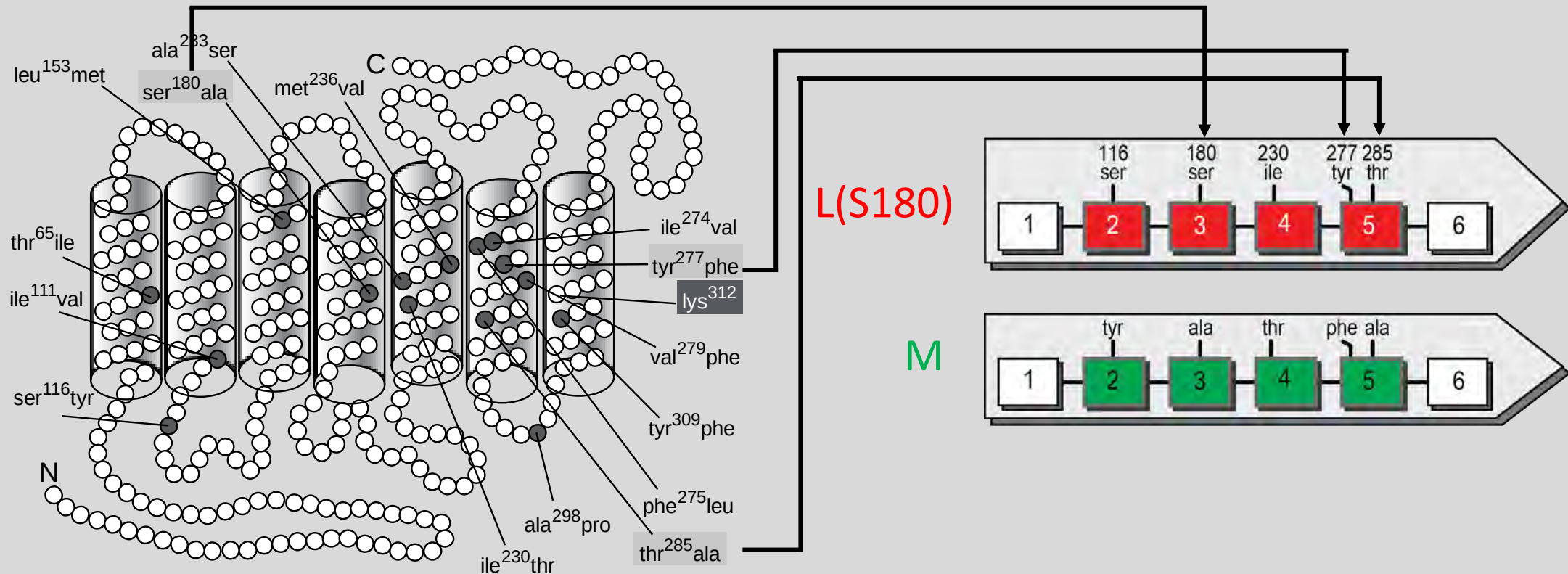


L-cone functions can shift towards M.



Amino acid differences between the L- and M-cone opsins

There are only **fifteen** amino acid differences between the L- and M-cone photopigment opsins. Only about **five** of those cause wavelength shifts between their spectral sensitivities.



Spectral shifts

The spectral shifts are caused by genetic substitutions that cause one or more of five important amino acids to change from the L-cone to M-cone versions or *vice versa*.

SPECTRAL
SHIFT (nm)
L to M



0

14

7

4

3-4

2-3

0



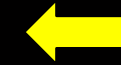
L gene

285
277

230

180

116



SPECTRAL
SHIFT (nm)
M to L

0

14

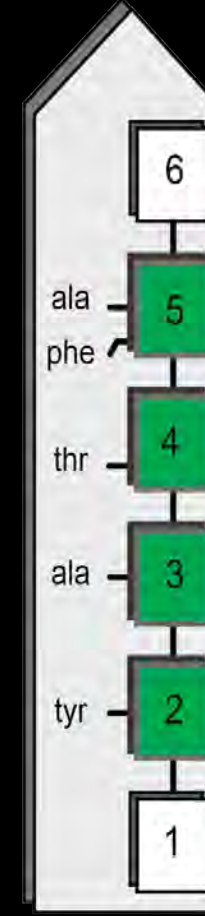
7

3

3

0

0



M gene

Spectral shifts

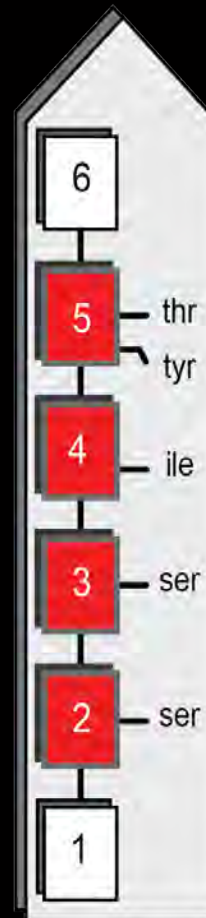
Larger shifts result in anomalous trichromacy.

Smaller ones might be considered as colour normal and the observer might be passed as normal in colour vision tests.

SPECTRAL
SHIFT (nm)
L to M



0
14
7
4
3-4
2-3
0



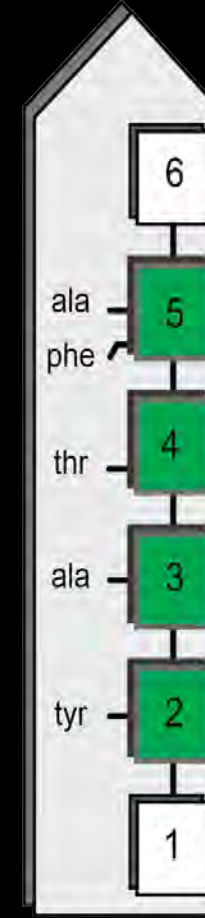
L gene

285
277
230
180
116

SPECTRAL
SHIFT (nm)
M to L



0
14
7
3
3
0
0



M gene

CVD prevalence

Main types of colour vision defects with approximate proportions of occurrence in the population.

8.5% of males will see colours on displays differently from colour normals because of anomalies in their cone opsins.

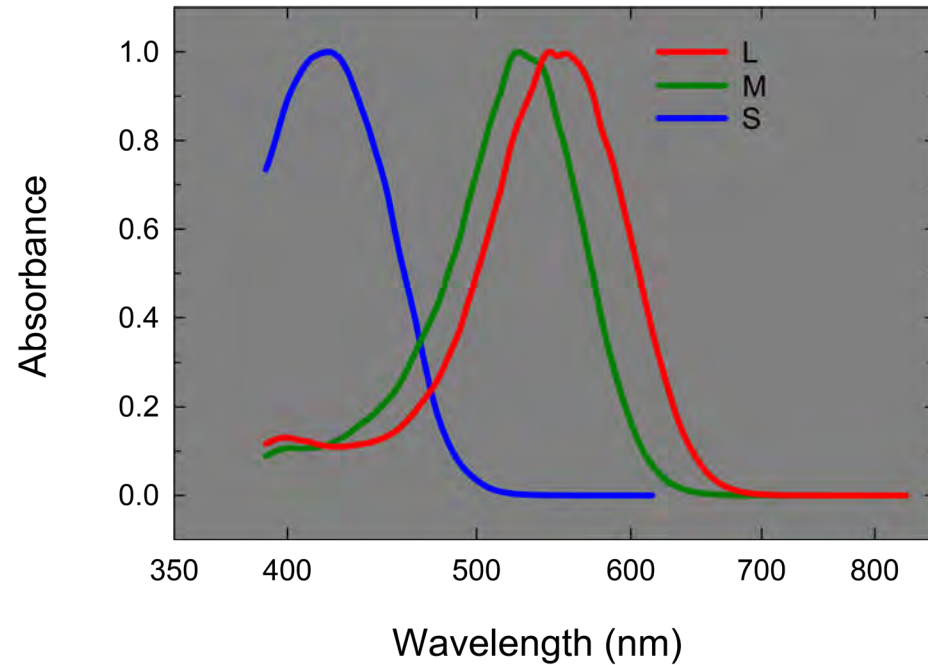
		percent in UK	
Condition		Male	Female
Protanopia	no L cone	1.0	0.02
Protanomaly	milder form	1.0	0.03
Deuteranopia	no M cone	1.5	0.01
Deuteranomaly	milder form	5.0	0.4
Tritanopia	no SWS cone	0.008	0.008
TOTALS		8.50%	0.46%

2. MODELLING INDIVIDUAL DIFFERENCES

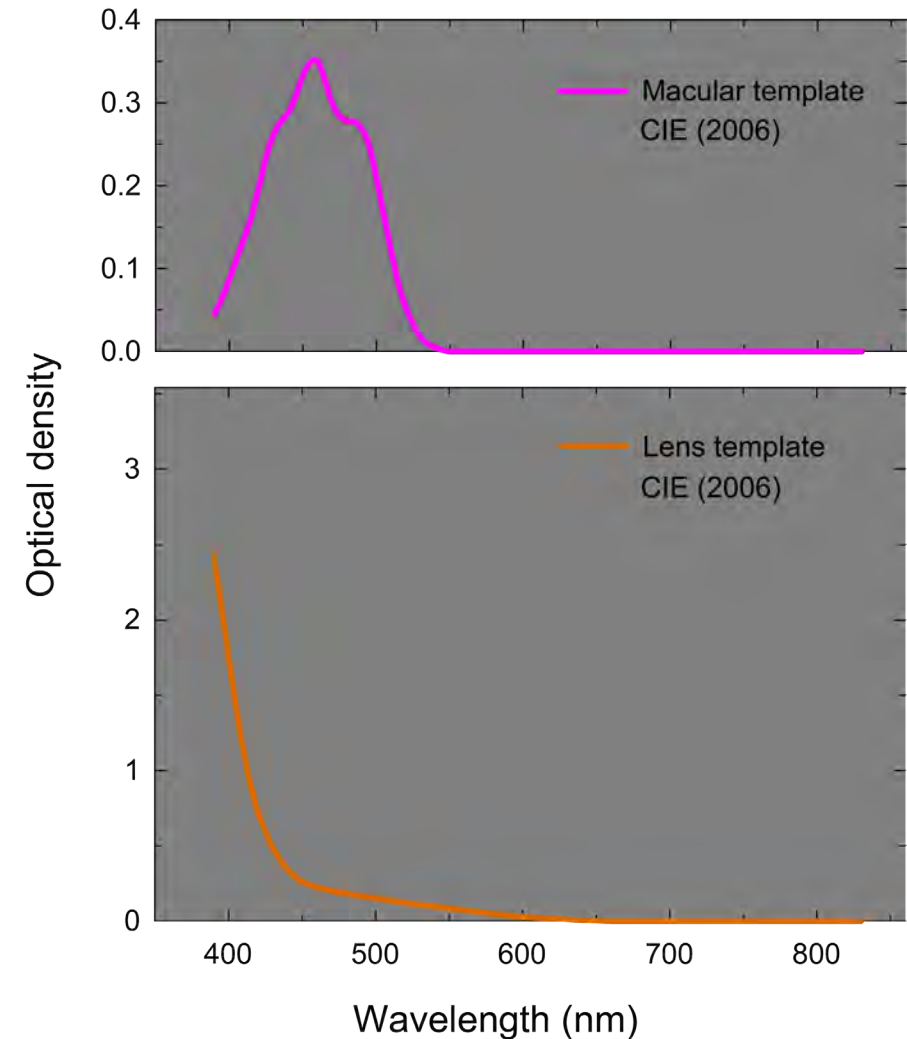
Colour matching analysis

We used the CIE 2006 models to analyse the matching data, but these are pointwise (discrete) functions.

Cone photopigment spectra

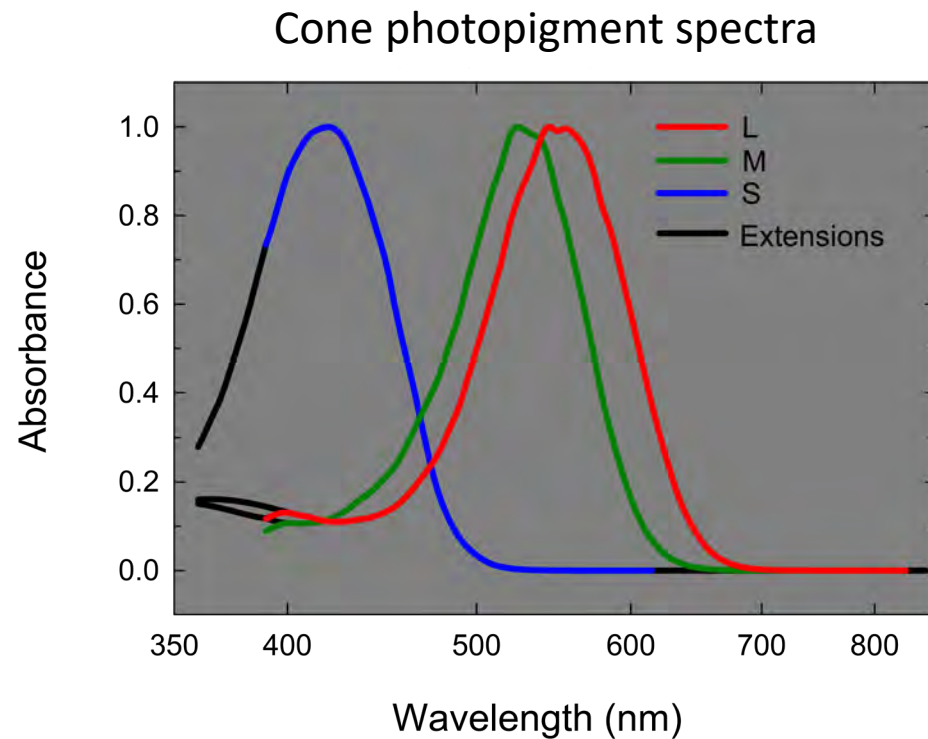


Macular and lens optical density spectra



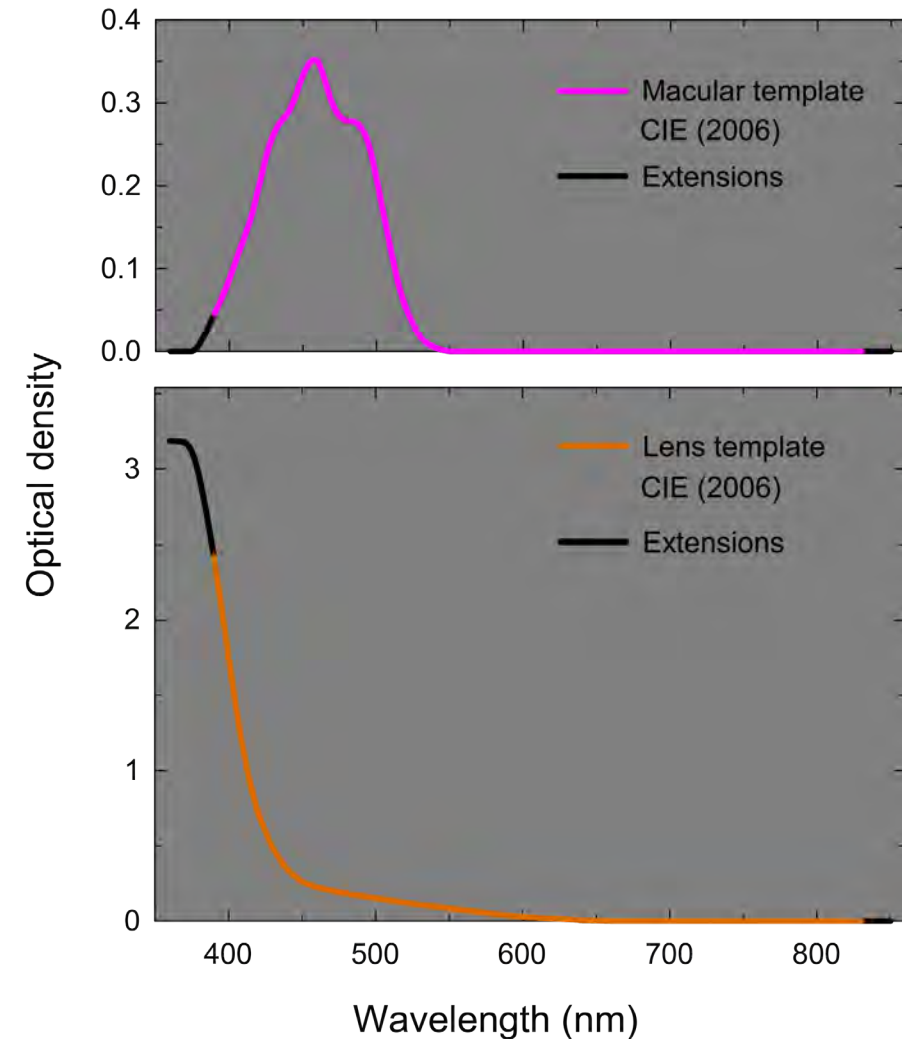
Colour matching analysis

First, we spectrally extended the functions partially to allow for spectral shifts of the cone spectra.



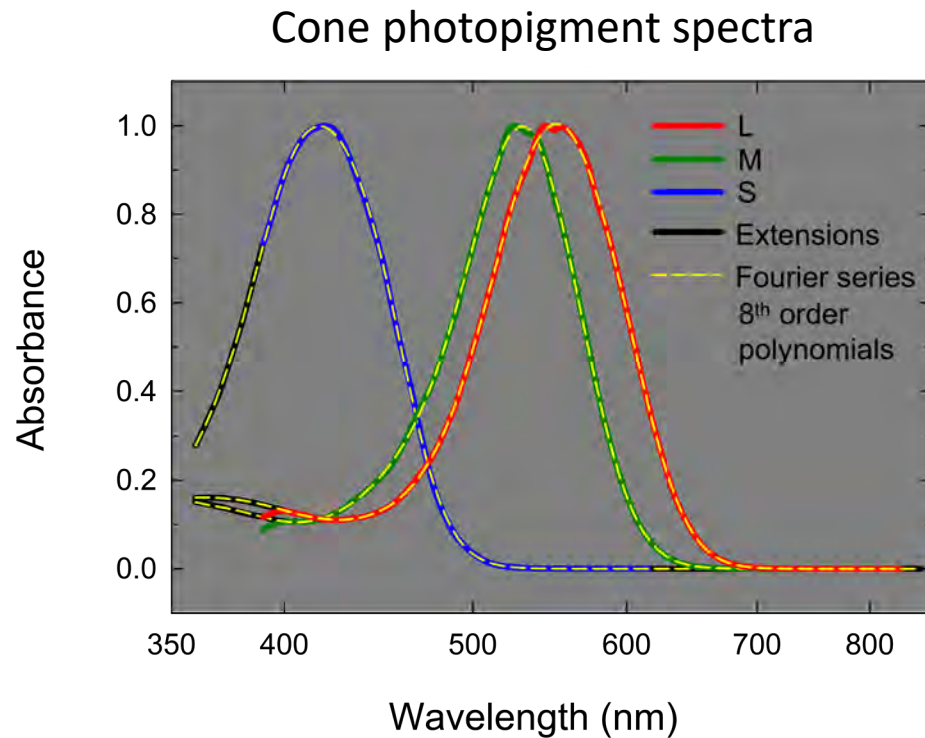
Stockman & Rider, "Formulae for generating standard and individual human cone spectral sensitivities," Color Research & Application 48, 818-840 (2023).

Macular and lens optical density spectra



Colour matching analysis

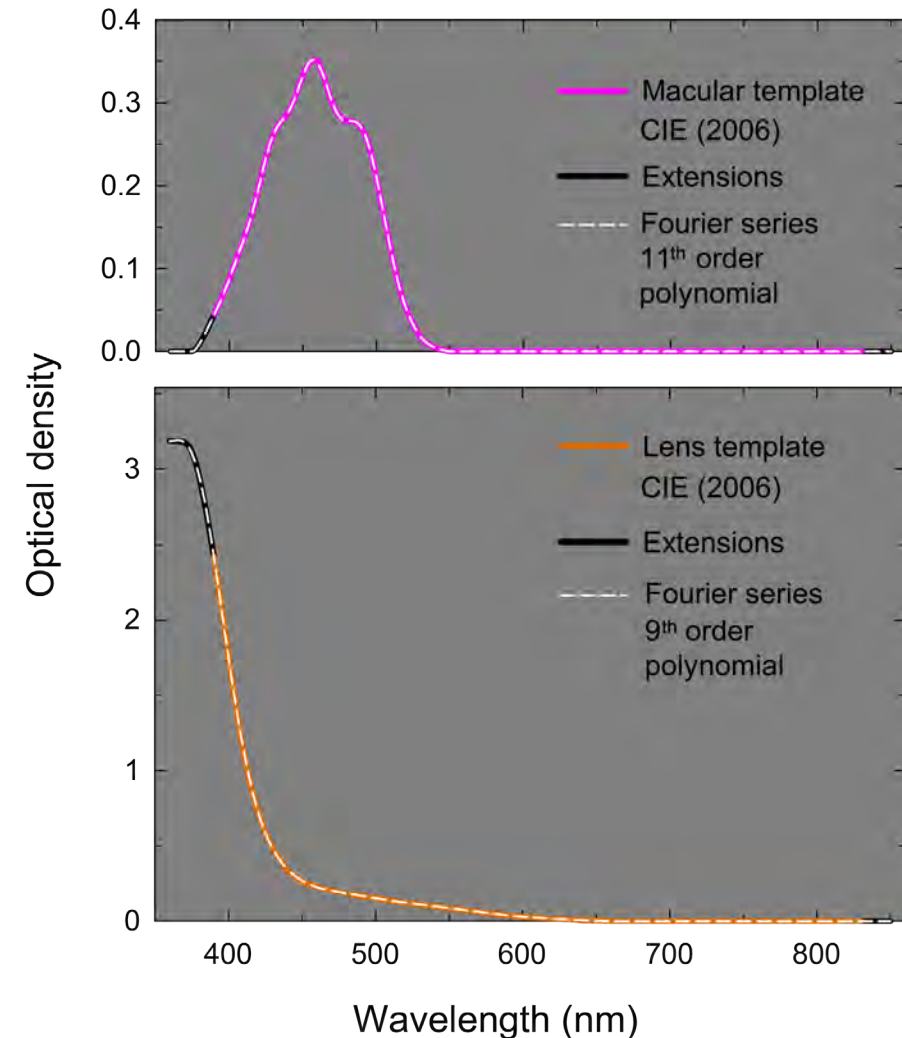
Then we generated continuous functions by fitting Fourier polynomials shown by the dashed lines.



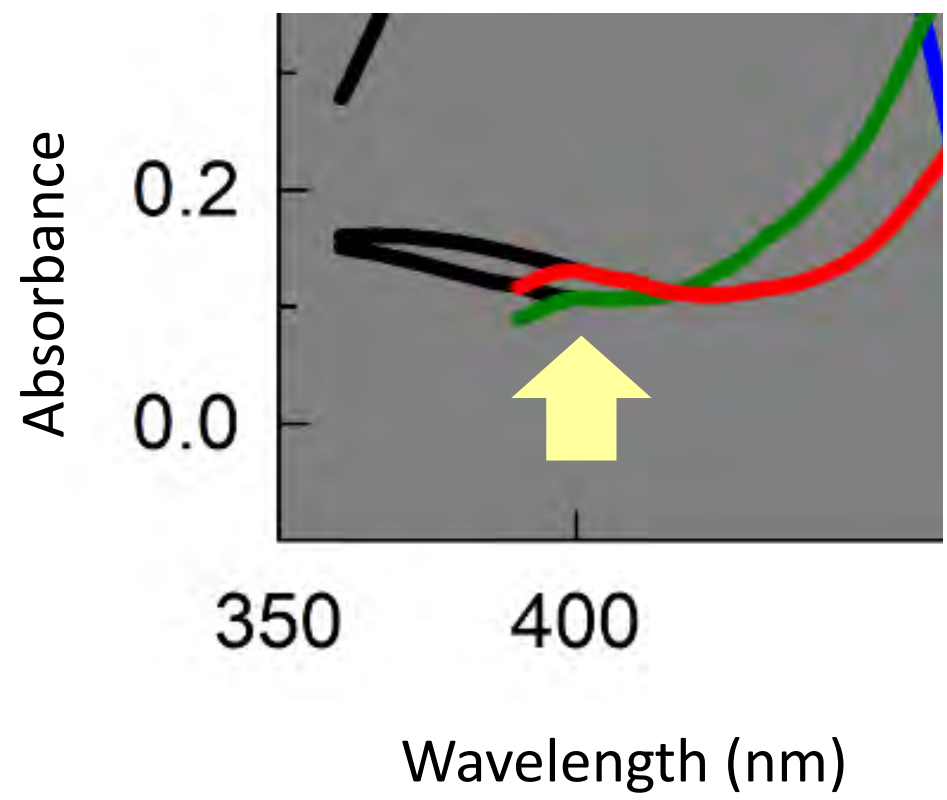
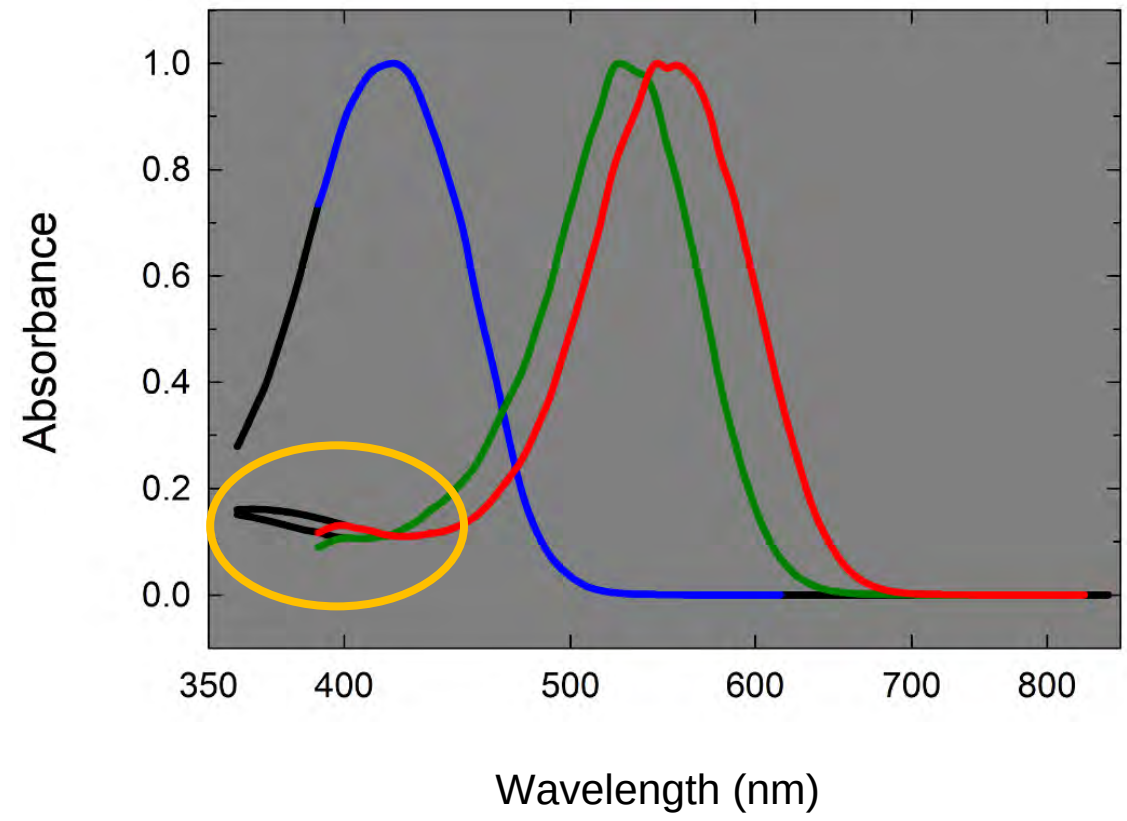
Stockman & Rider, "Formulae for generating standard and individual human cone spectral sensitivities," Color Research & Application 48, 818-840 (2023).

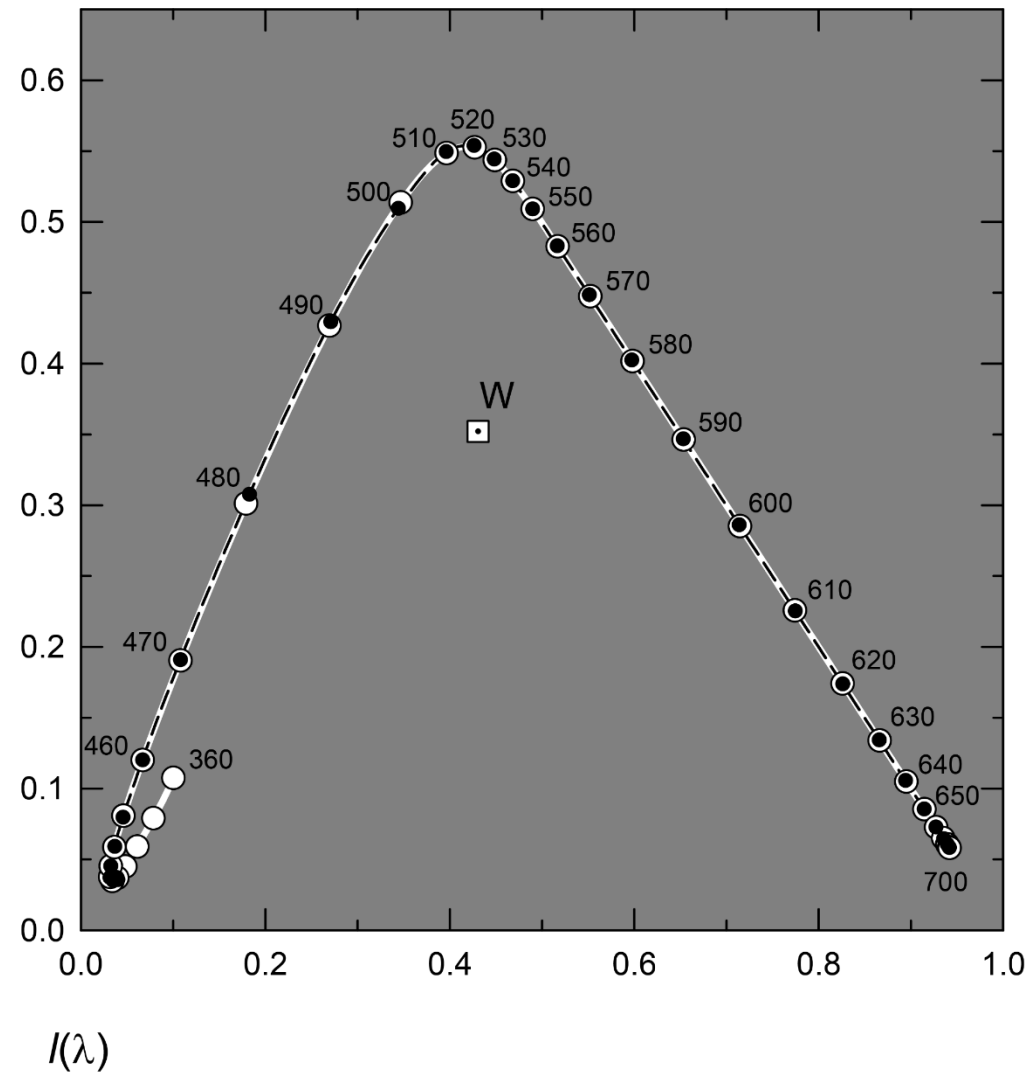
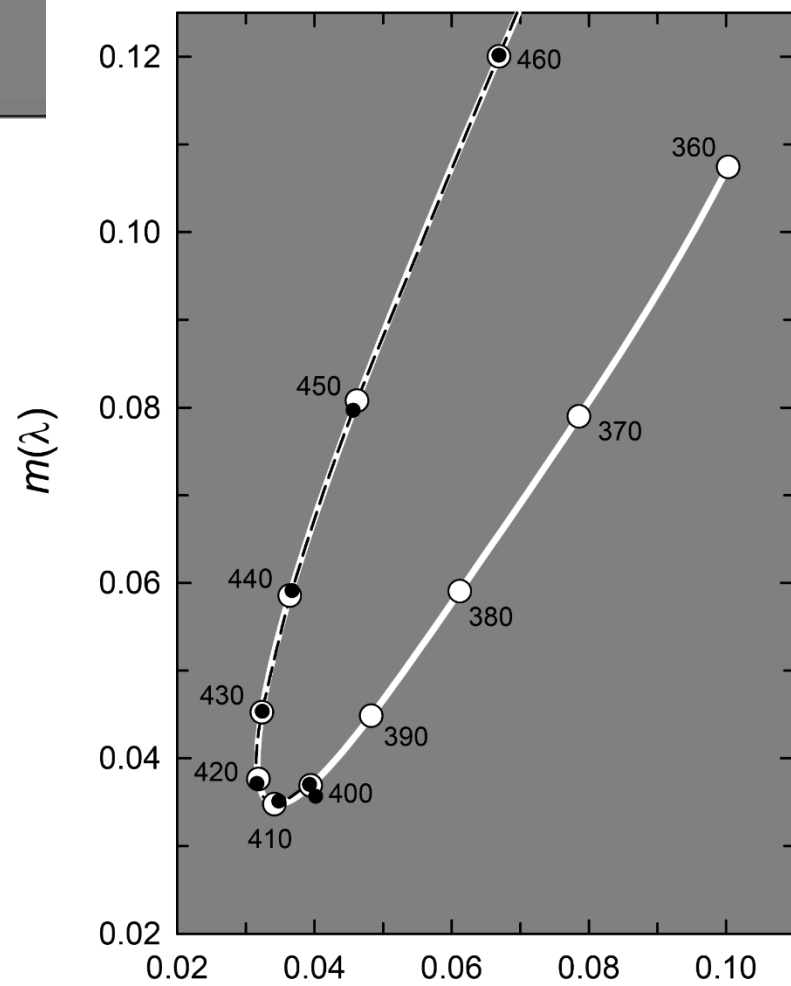
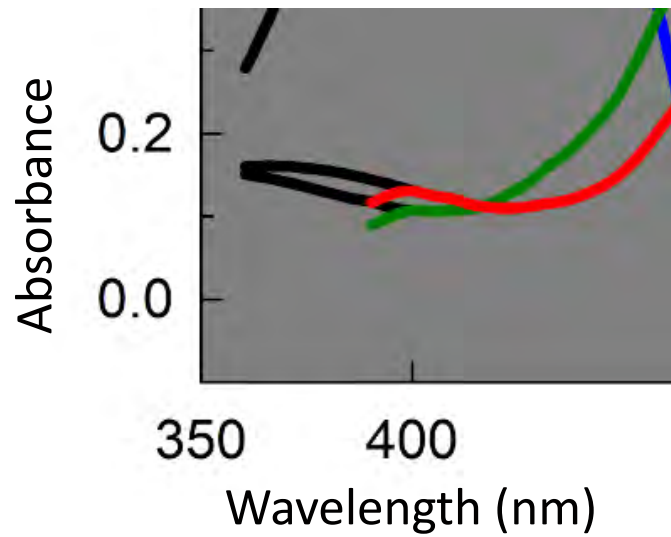
$$\text{Fourier polynomials: } F(\theta) = a_0 + \sum_{k=1}^n [a_k \cos(k\theta) + b_k \sin(k\theta)]$$

Macular and lens optical density spectra



One important correction of the CIE 2006/2015 functions:





MainWindow



Fundamental CMFs (LMS cone spectral sensitivities)

Longer L (or M) cone parameters

λ_c max shift from L
-40 to +10 nm only

Optical density

Use codons to calculate L and M shifts

Shorter M (or L) cone parameters

λ_c max shift from M
+30 to -20 nm only

Optical density

S-cone parameters

Optical density

Standard 2-deg densities (default)

Standard 10-deg densities

Common parameters

Lens pigment density (at 400 nm)

Macular pigment density (at 460 nm)

Plot CMFs

Reset to defaults

INDIVIDUAL LMS TEMPLATES

Step-size
☐ 0.1 nm ☒ 1 nm ☐ 5 nm

Data output choices (Excel file)

Fundamental CMFs
(Corneal cone spectral sensitivities)

Quantal units ☐ linear ☐ log

Energy units ☐ linear ☐ log

Retinal cone spectral sensitivities

Quantal units ☐ linear ☐ log

Absorbance ☐ linear ☐ log

RGB CMFs ☐

Primary wavelengths (Stiles & Burch default)

R G B

Output Written to local 'CMFs_out' directory

CMFs directory CMFs filename

☐ Overwrite file?

Generate Excel file

Generate unshifted mean L (ser/ala180) M and S Excel file

Python program that incorporates these polynomials is available on Github at:

<https://github.com/CVRL-IoO/Individual-CMFs.git>

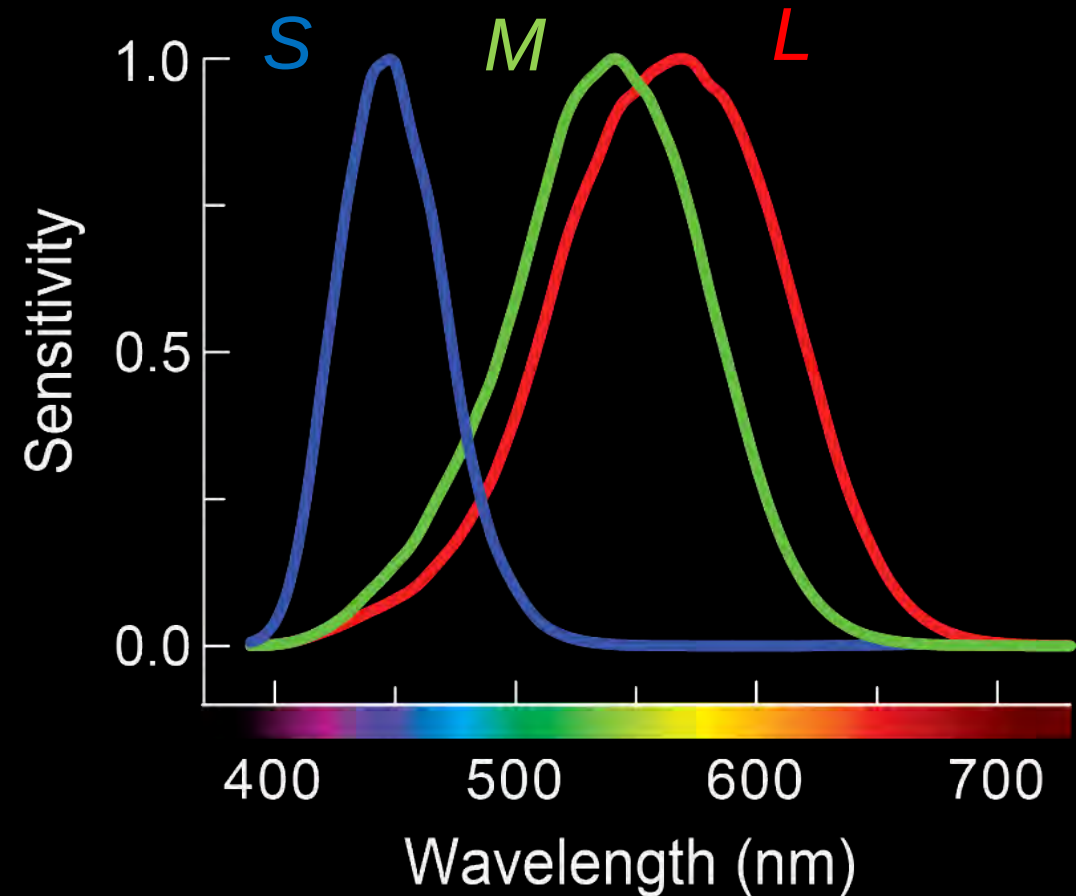
3. MEASURING INDIVIDUAL DIFFERENCES

Individual cone spectral sensitivities (CMFs)

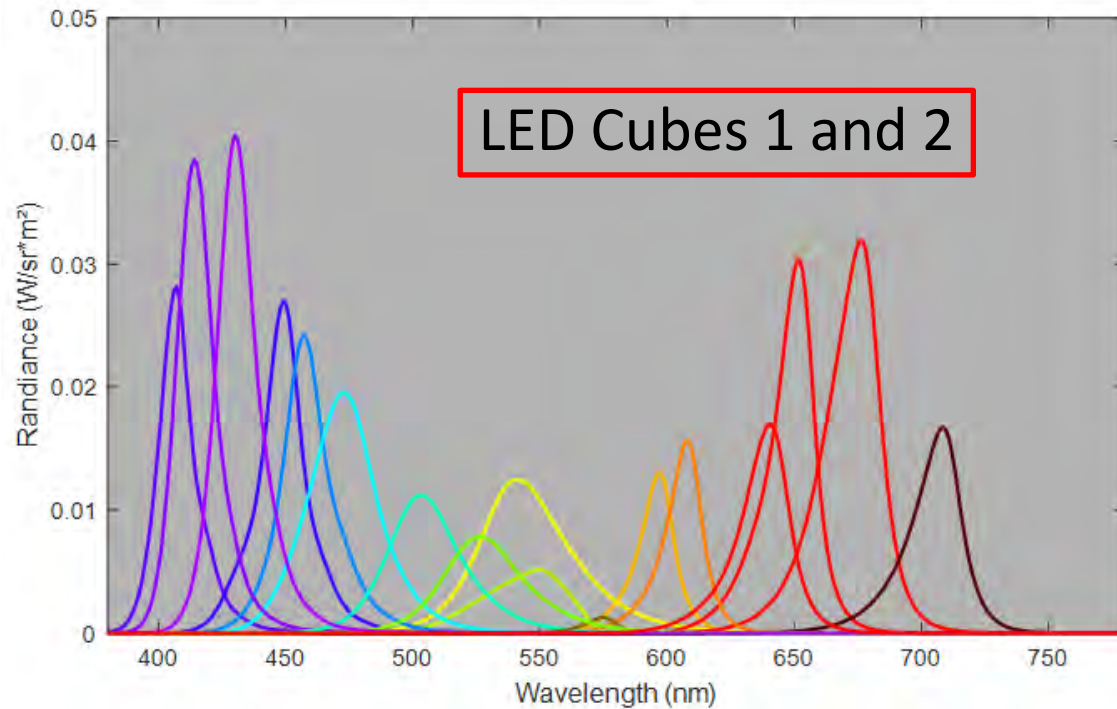
We can overcome the problems of individual differences by measuring an individual's own cone spectral sensitivities.

To measure them, we use a...

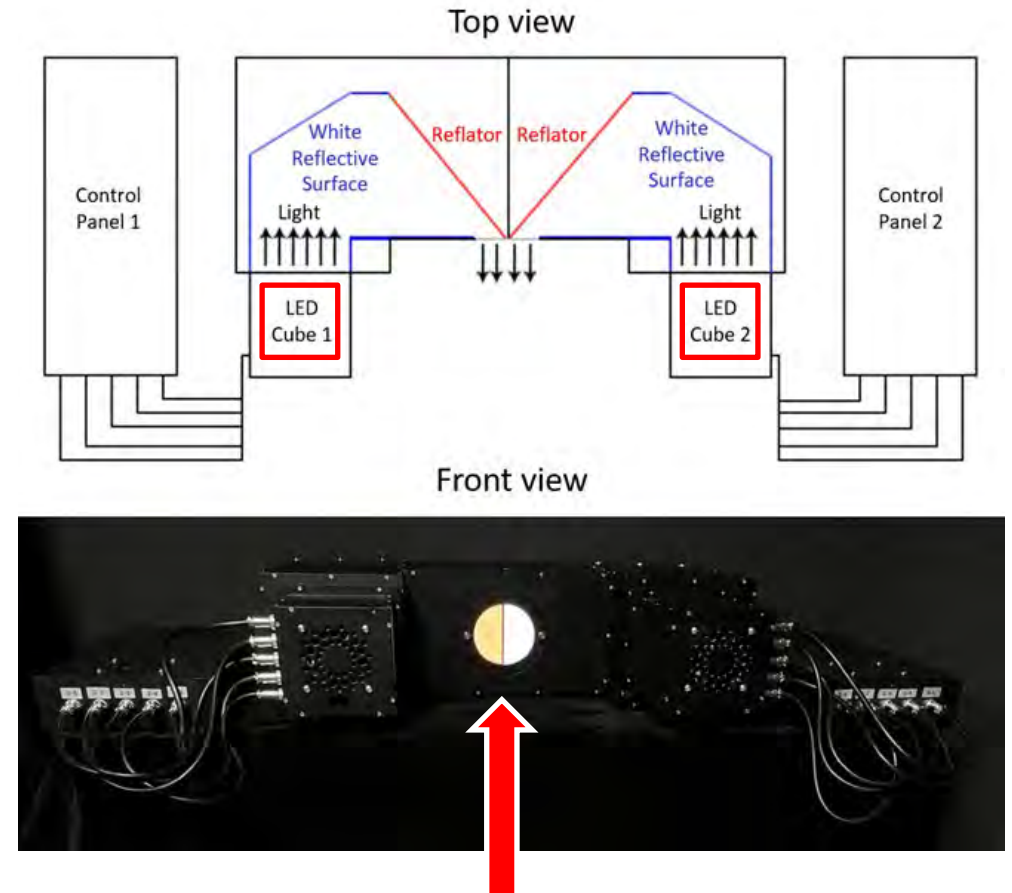
Individually measured functions



Trichromator (LEDMax) (developed in collaboration with Thouslite)



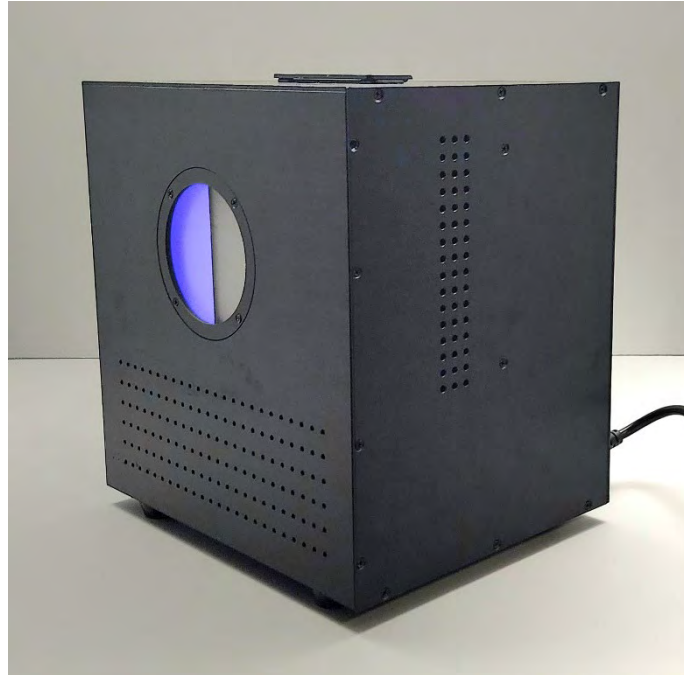
Collaborative work with Ronnier Luo's lab
with Lucas Shi and Alan Song and Andy Rider



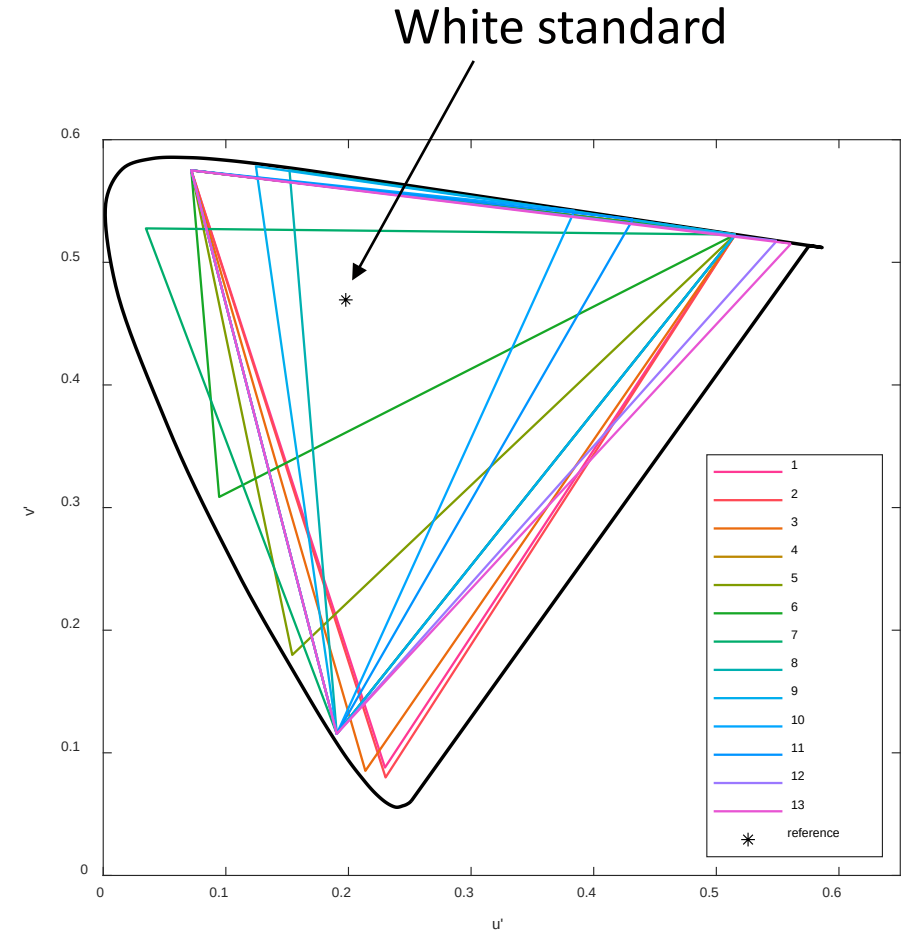
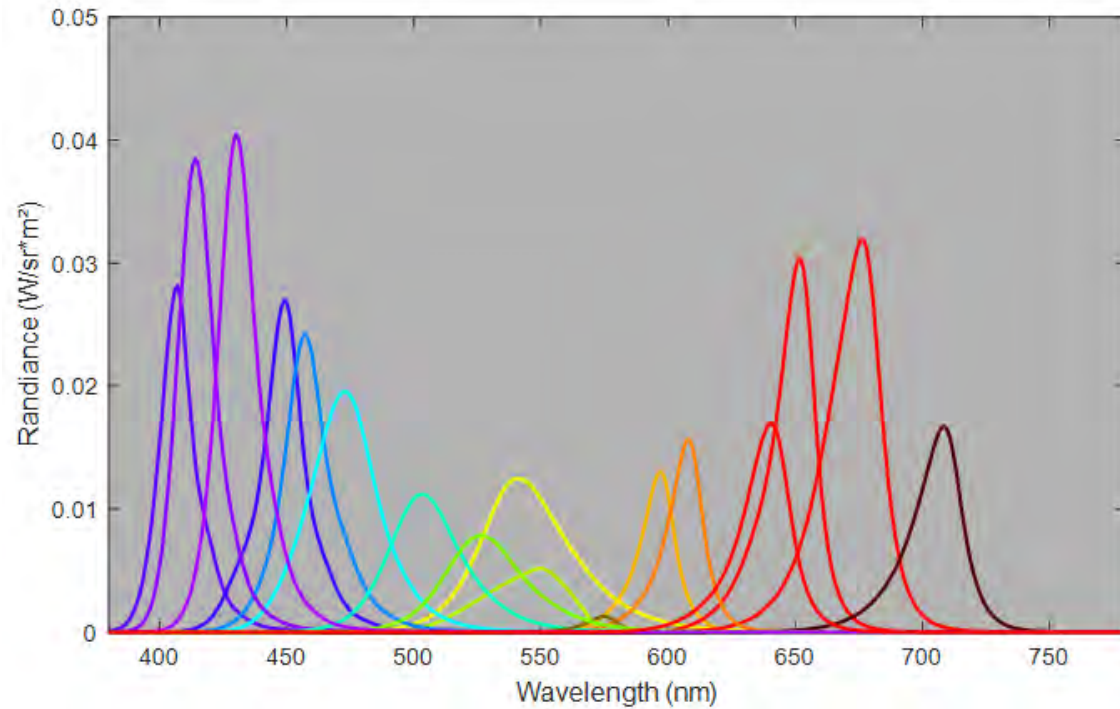
Subject view

Trichromator (LEDMax) updated version

A compact version has been developed, which is on the Thouslite stand outside...

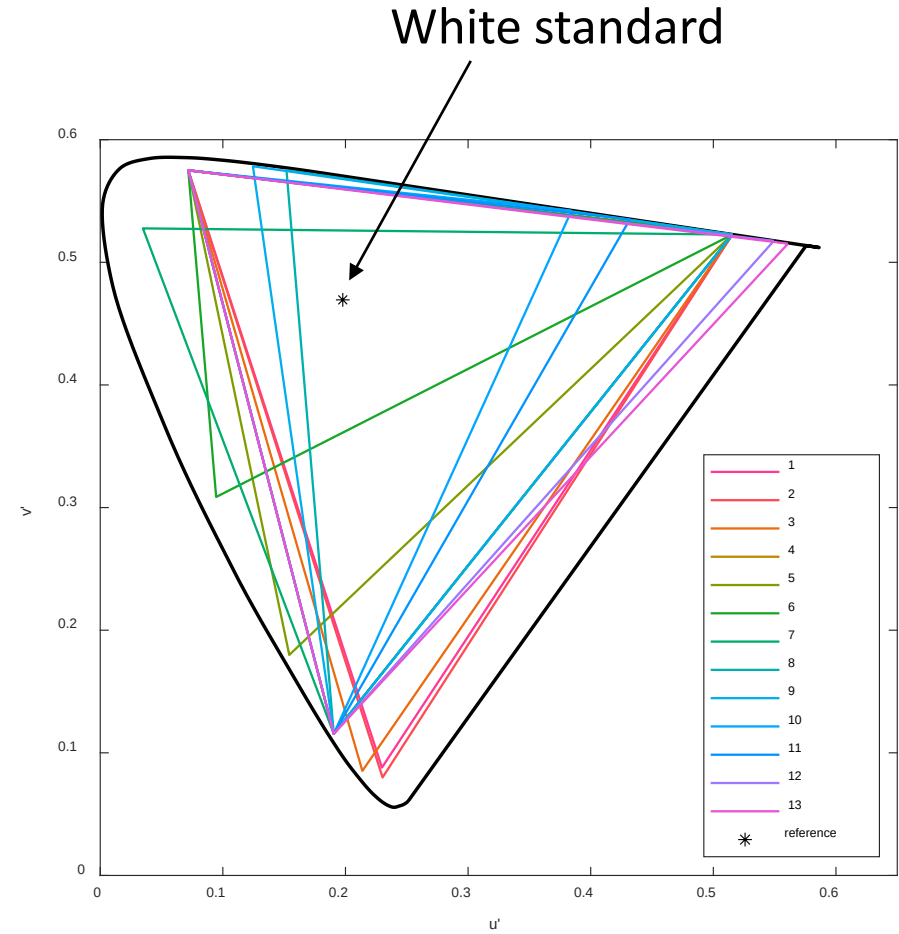
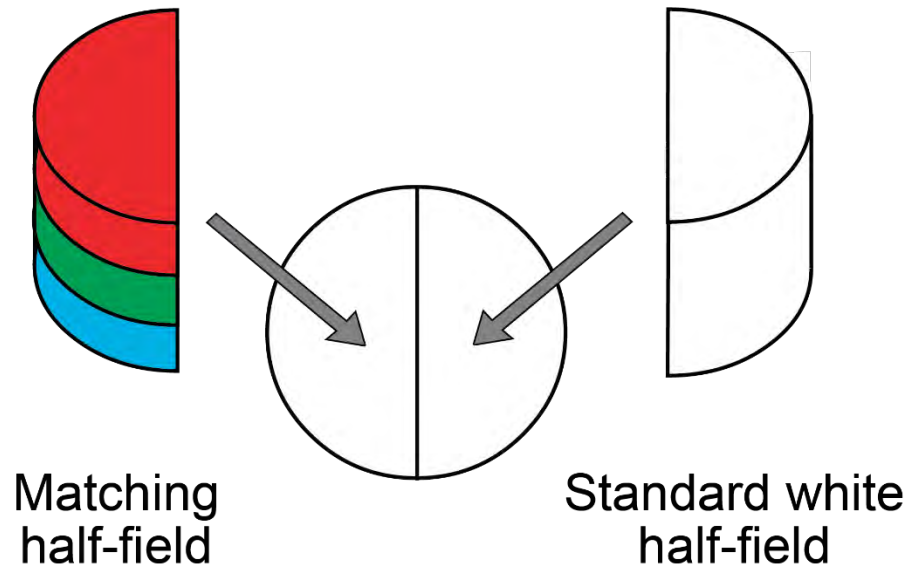


Colour matching measurements



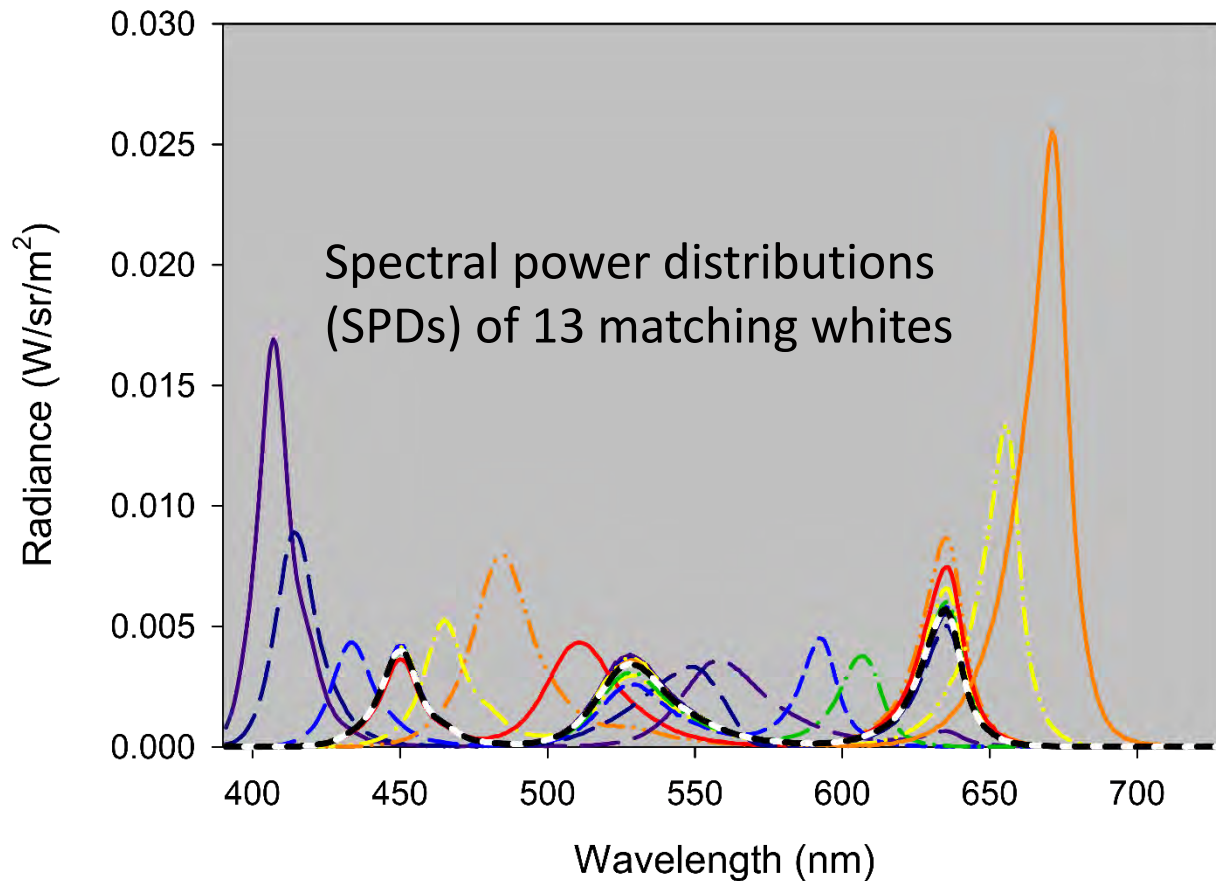
We chose 13 triplets of LEDs (primaries lights) that can be optically mixed to match a white standard (*).

Colour matching measurements

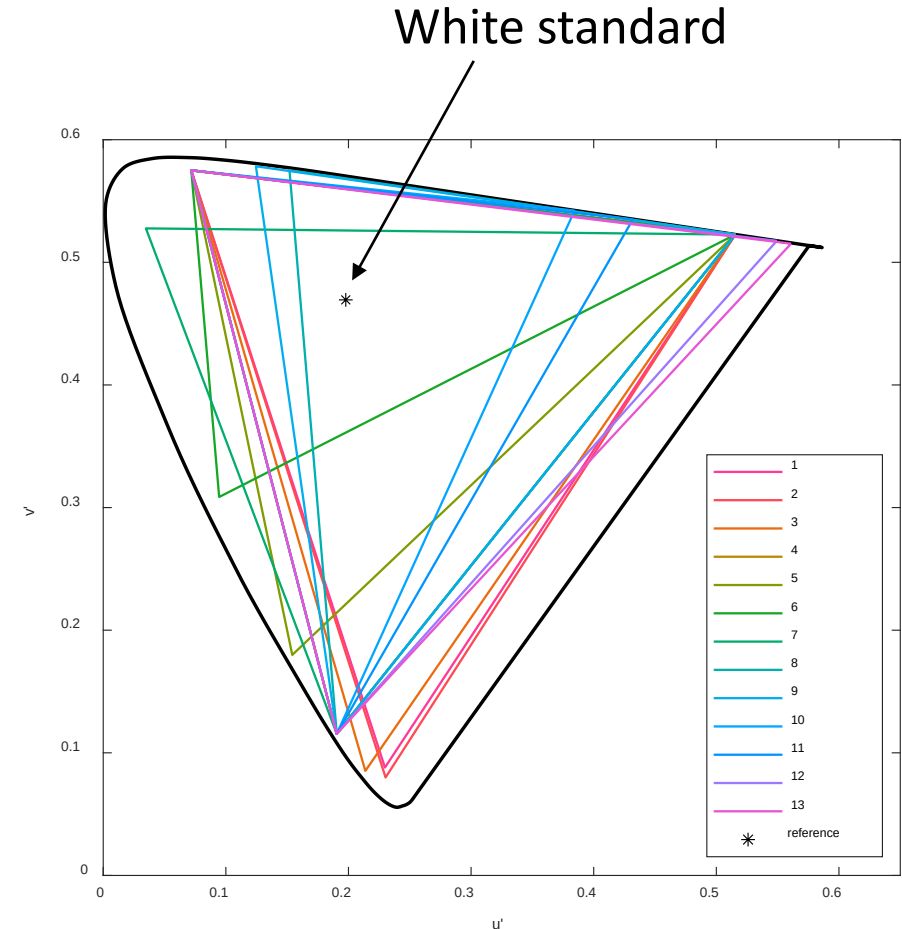


We then asked observers to adjust the intensities of each of the 13 triplets of primaries to match the white standard...

Colour matching measurements

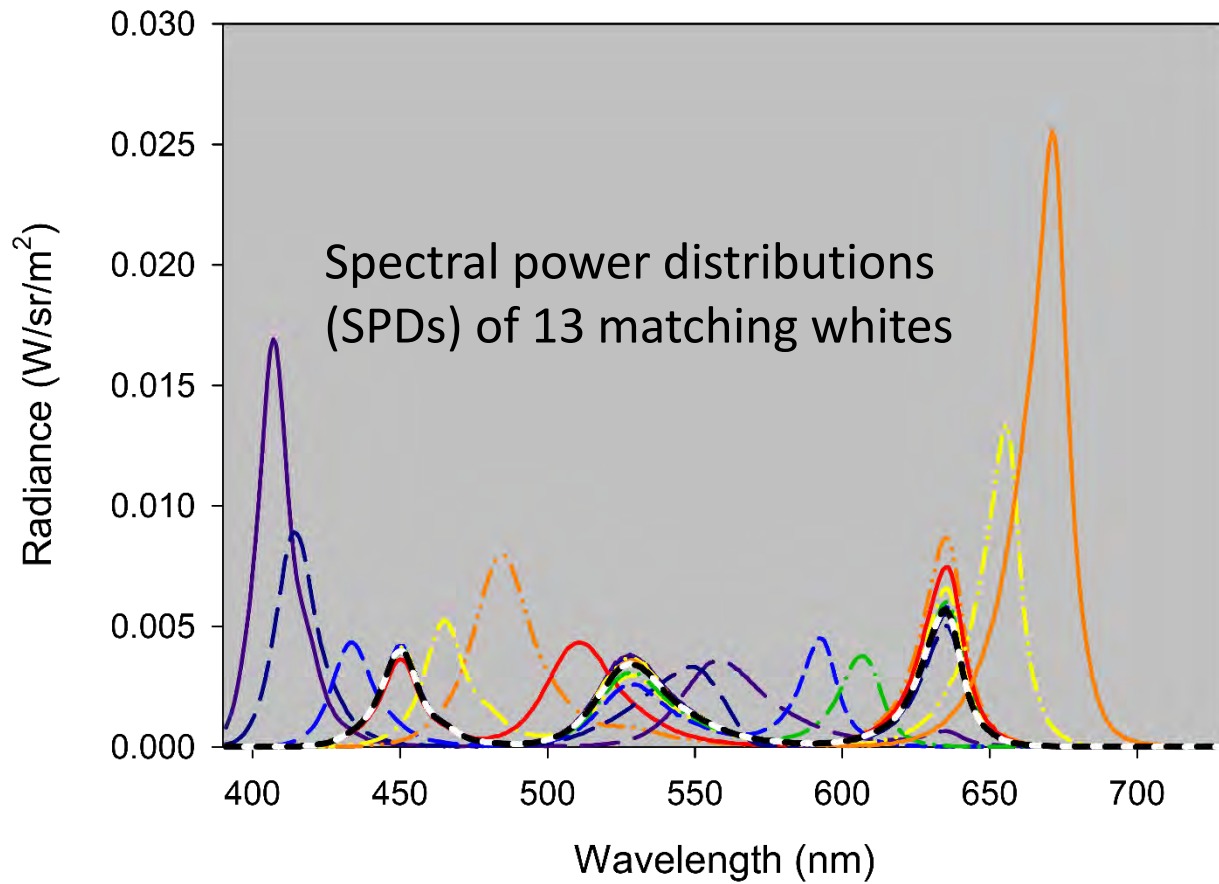


Here are the SPDs for the 13 matching whites (each SPD is made up of all three primaries) set by one of our subjects.



We then asked observers to adjust the intensities of each of the 13 triplets of primaries to match the white standard...

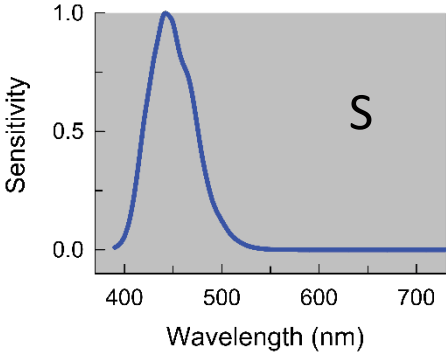
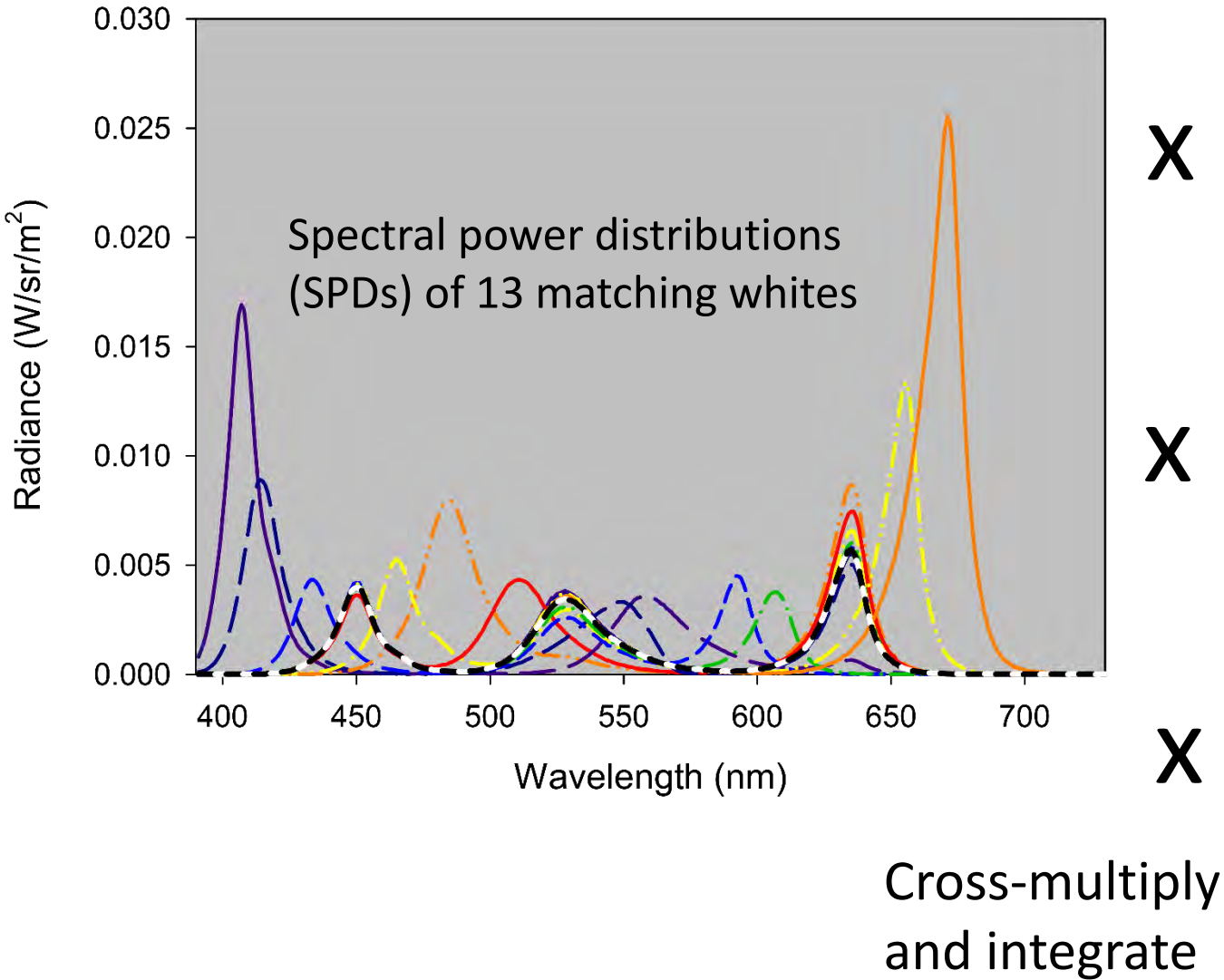
Colour matching analysis



These 13 matching whites should all produce identical L-, M- and S-cone excitations.

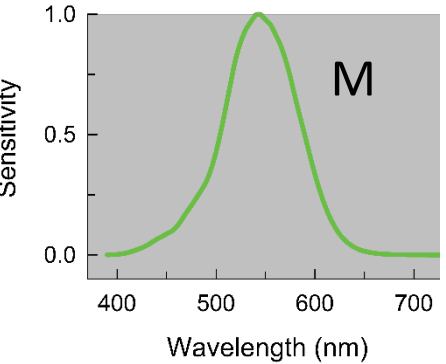
So...

Colour matching analysis



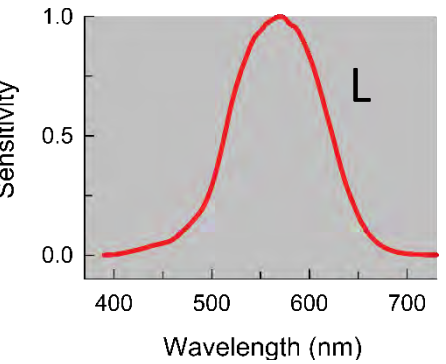
=

All 13 should produce the *same* S-cone excitation



=

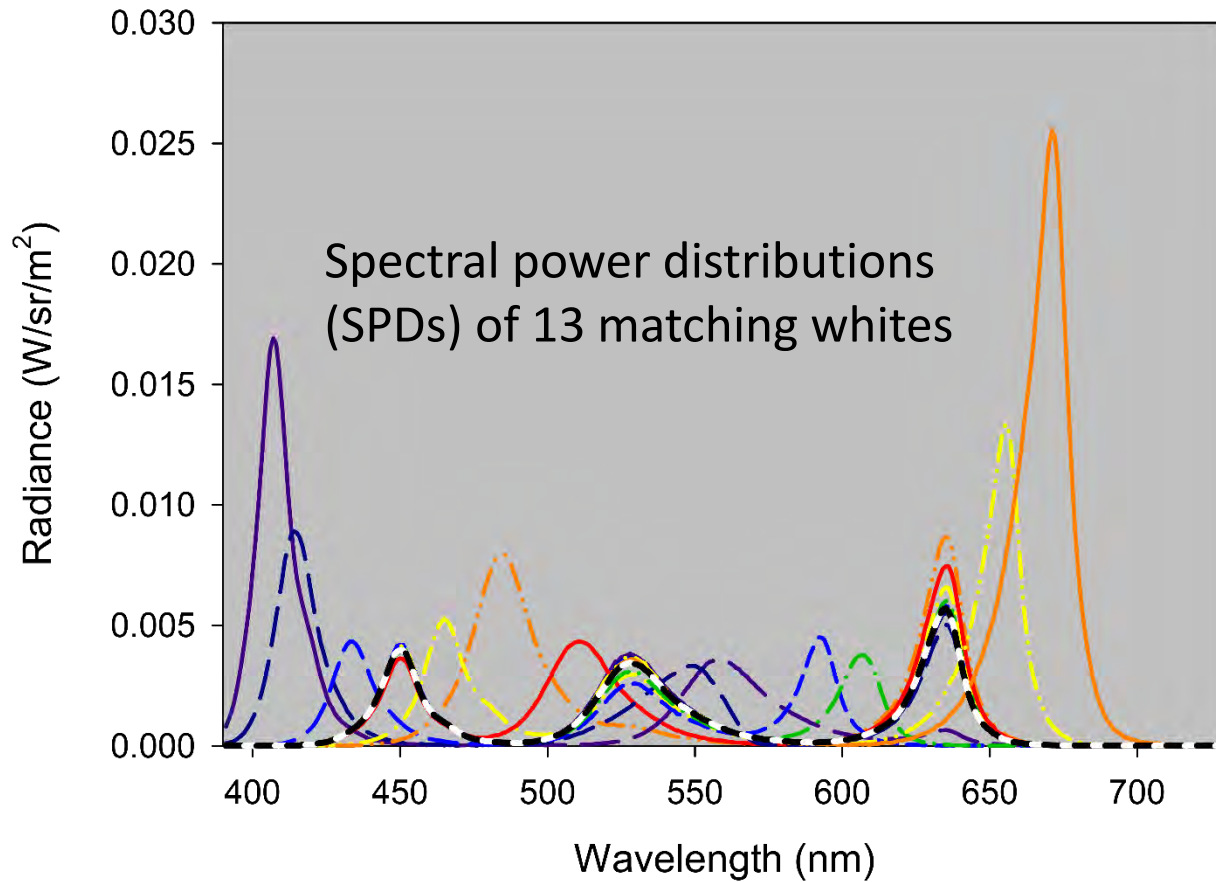
All 13 should produce the *same* M-cone excitation



=

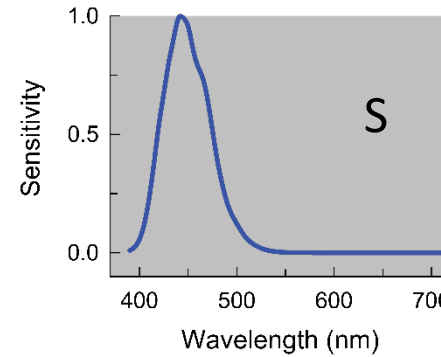
All 13 should produce the *same* L-cone excitation

Colour matching analysis



Goal is to find the versions of S, M and L that are closest to producing equal excitations...

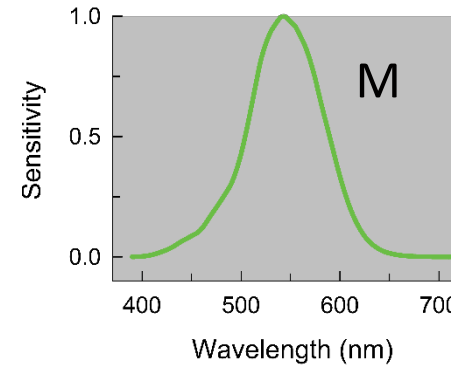
X



=

All 13 should produce the *same* S-cone excitation

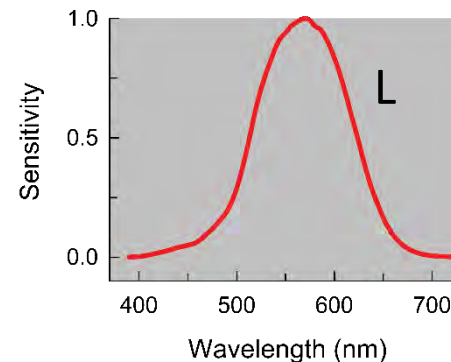
X



=

All 13 should produce the *same* M-cone excitation

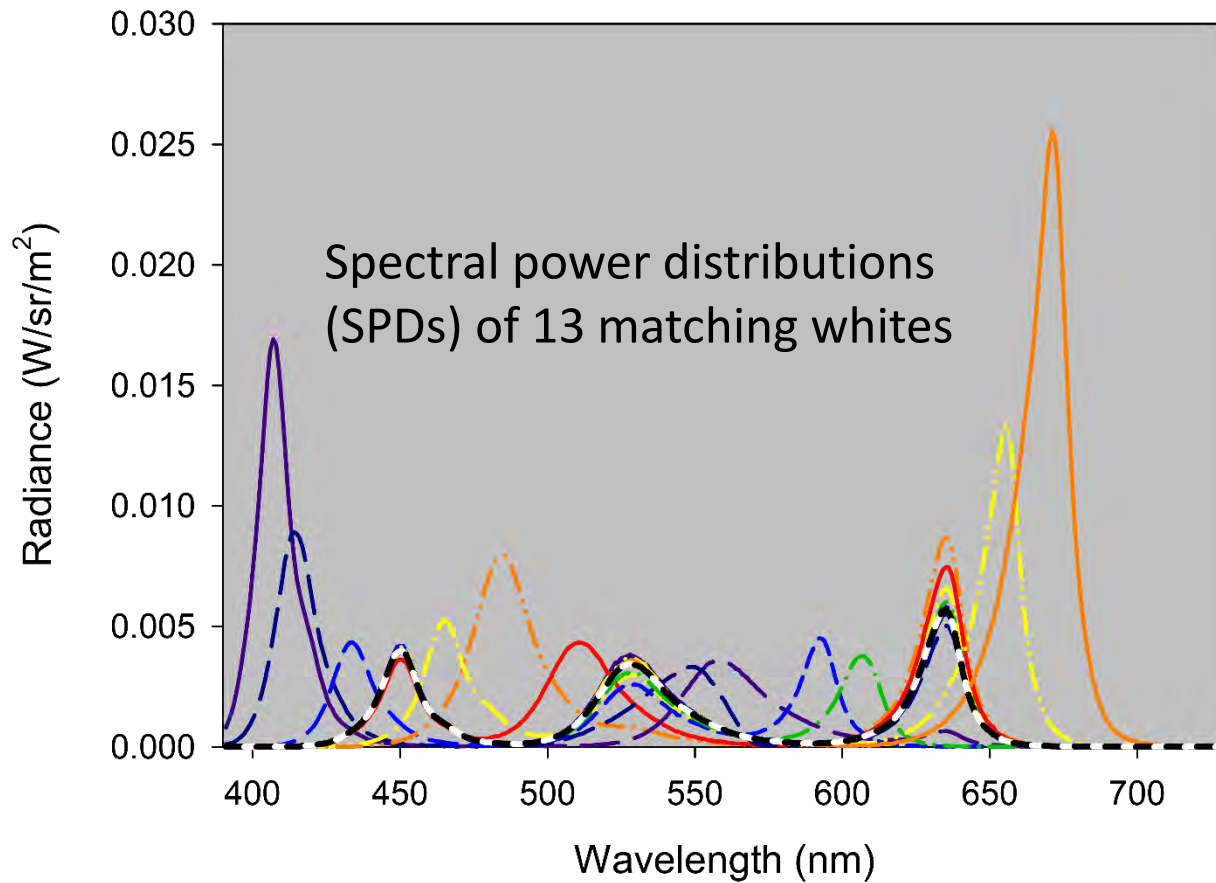
X



=

All 13 should produce the *same* L-cone excitation

Colour matching analysis

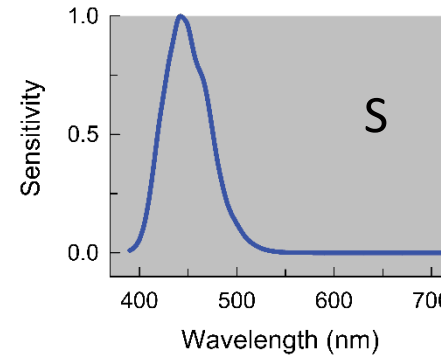


By varying the lens, macular, and photopigment optical densities and allowing spectral shifts in M and L.

X

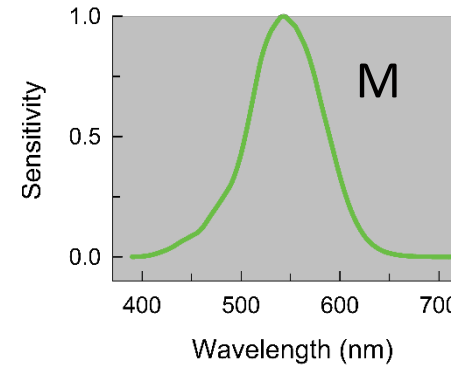
X

X



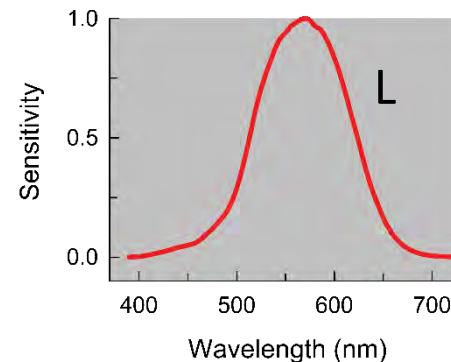
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All 13 should produce the *same* S-cone excitation



=

All 13 should produce the *same* M-cone excitation



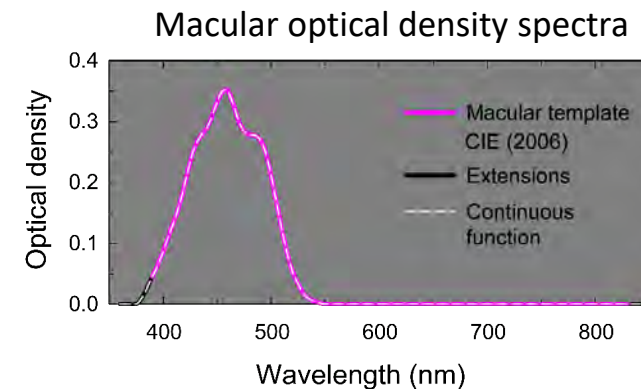
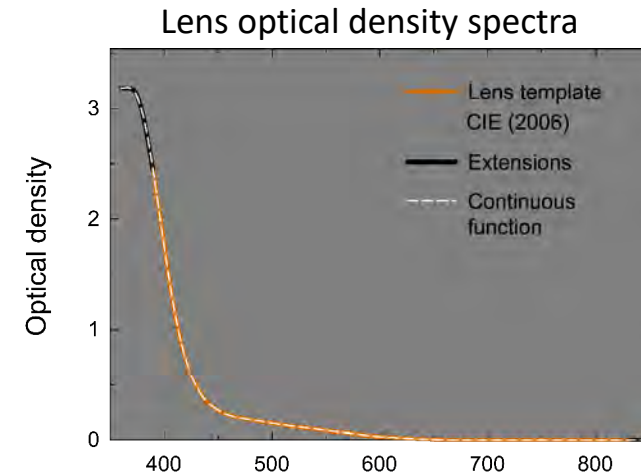
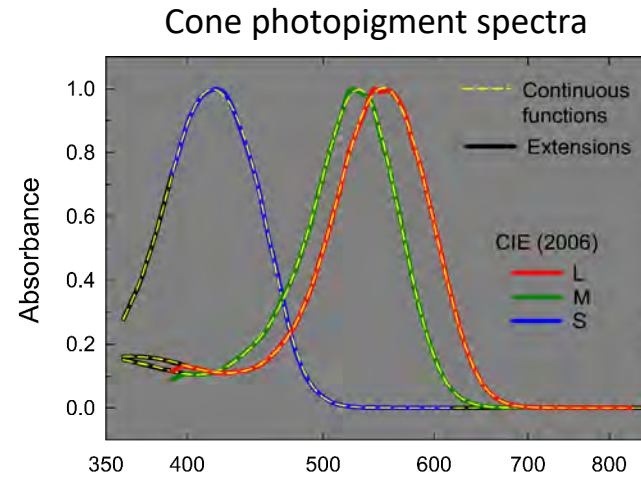
=

All 13 should produce the *same* L-cone excitation

Finding the best parameters

Each observer makes at least 26 matches: 13 at 2° and 13 at 10° fields of view.

From which there are eleven parameters to find:



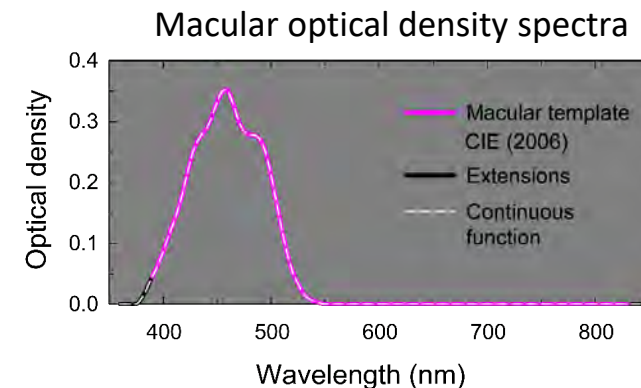
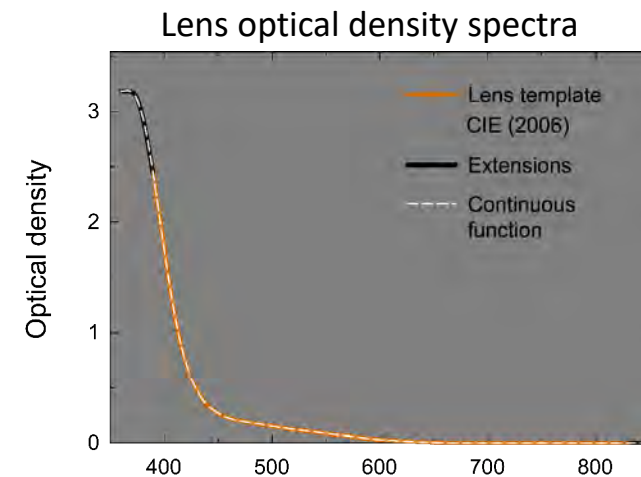
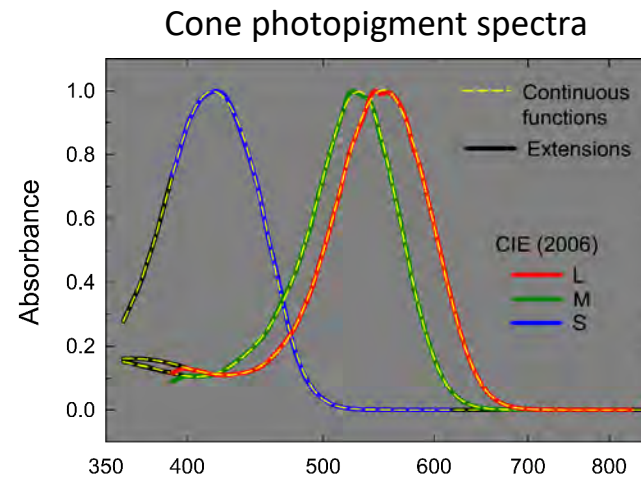
- 1) L-cone spectral shift
- 2) M-cone spectral shift
- 3) L-cone 2° photopigment optical density
- 4) L-cone 10° photopigment optical density
- 5) M-cone 2° photopigment optical density
- 6) M-cone 10° photopigment optical density
- 7) S-cone 2° photopigment optical density
- 8) S-cone 10° photopigment optical density

9) Lens pigment optical density

- 10) Macular 2° pigment optical density
- 11) Macular 10° pigment optical density

Finding the best parameters

Previously, we used simple curve-fitting procedures to find these parameters for each observer, but we have recently developed a more analytical approach that gives us more information and more confidence in the fits.



- 1) L-cone spectral shift
- 2) M-cone spectral shift
- 3) L-cone 2° photopigment optical density
- 4) L-cone 10° photopigment optical density
- 5) M-cone 2° photopigment optical density
- 6) M-cone 10° photopigment optical density
- 7) S-cone 2° photopigment optical density
- 8) S-cone 10° photopigment optical density
- 9) Lens pigment optical density
- 10) Macular 2° pigment optical density
- 11) Macular 10° pigment optical density

Finding the best parameters

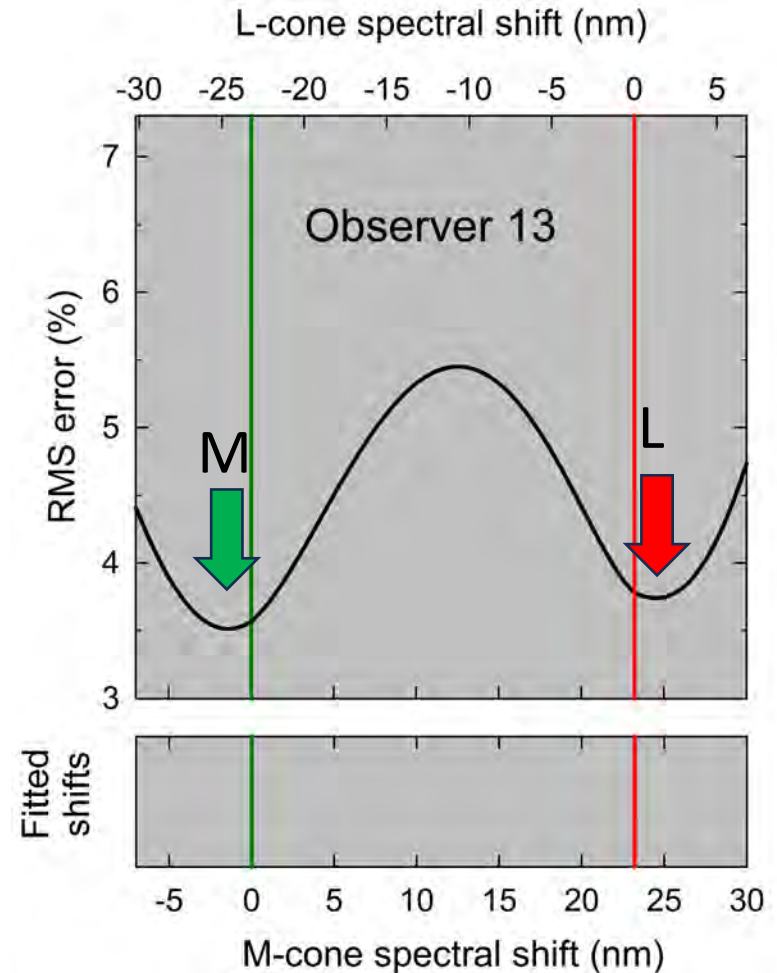
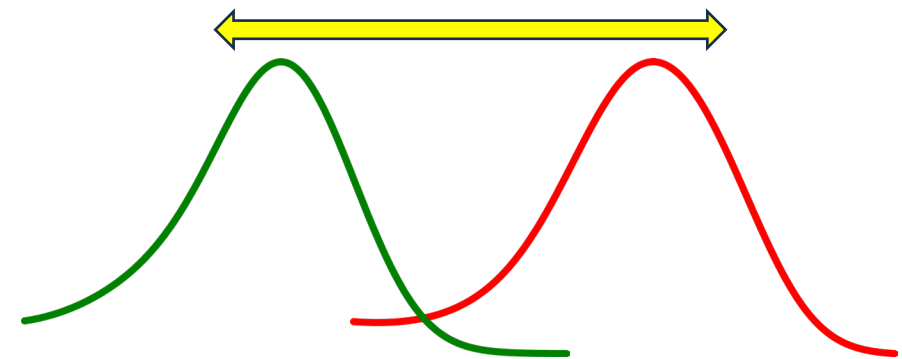
If we vary the $\lambda_{\max}$ (wavelength of peak sensitivity) of the photopigment templates and see how well they describe the matches. For colour normals, we should expect two minima in the RMS errors that correspond to the M-cone $\lambda_{\max}$ position and the L-cone $\lambda_{\max}$ position.

So, that's what we did...

S
↓

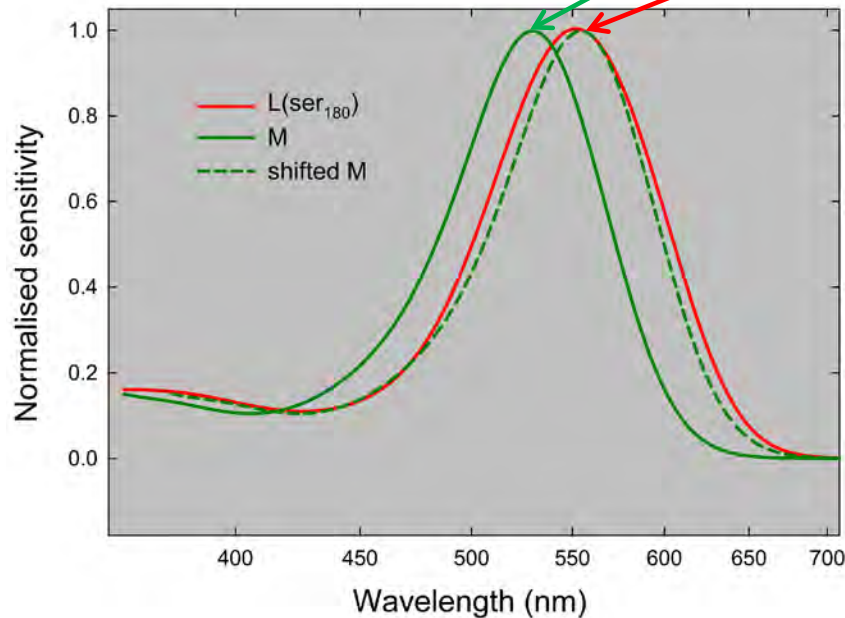


There will also be a minimum for S at much shorter wavelengths.

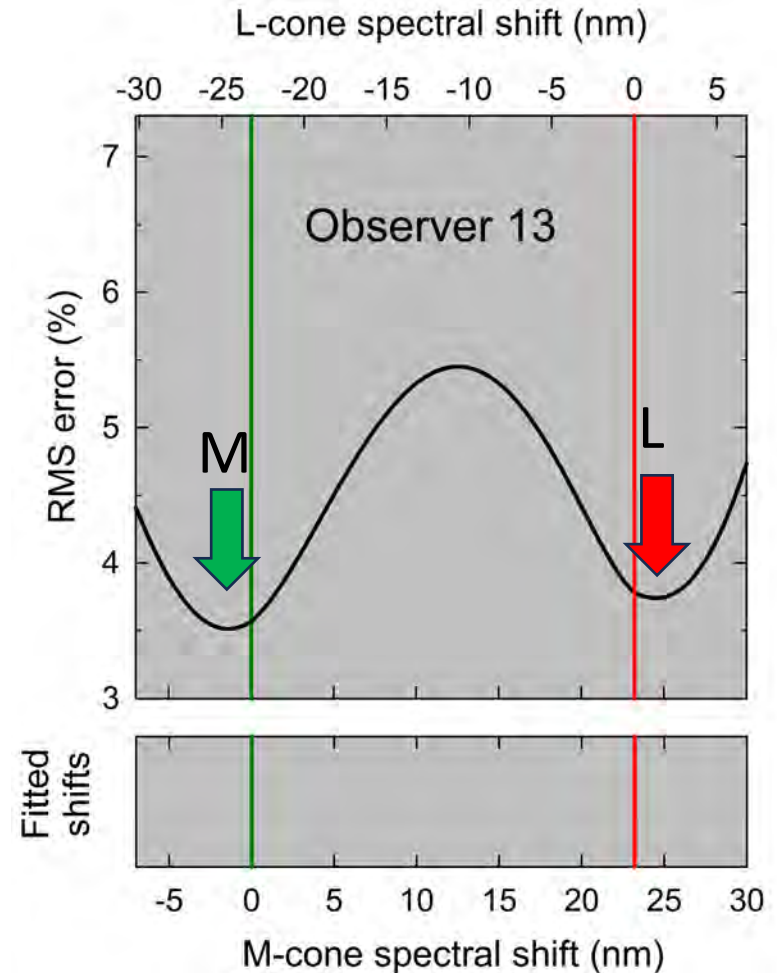


Finding the best parameters

One complication is that the photo-pigment templates for L and M derived from the Stiles & Burch 10° colour matching functions are slightly different in shape even when plotted on a log wavelength scale...

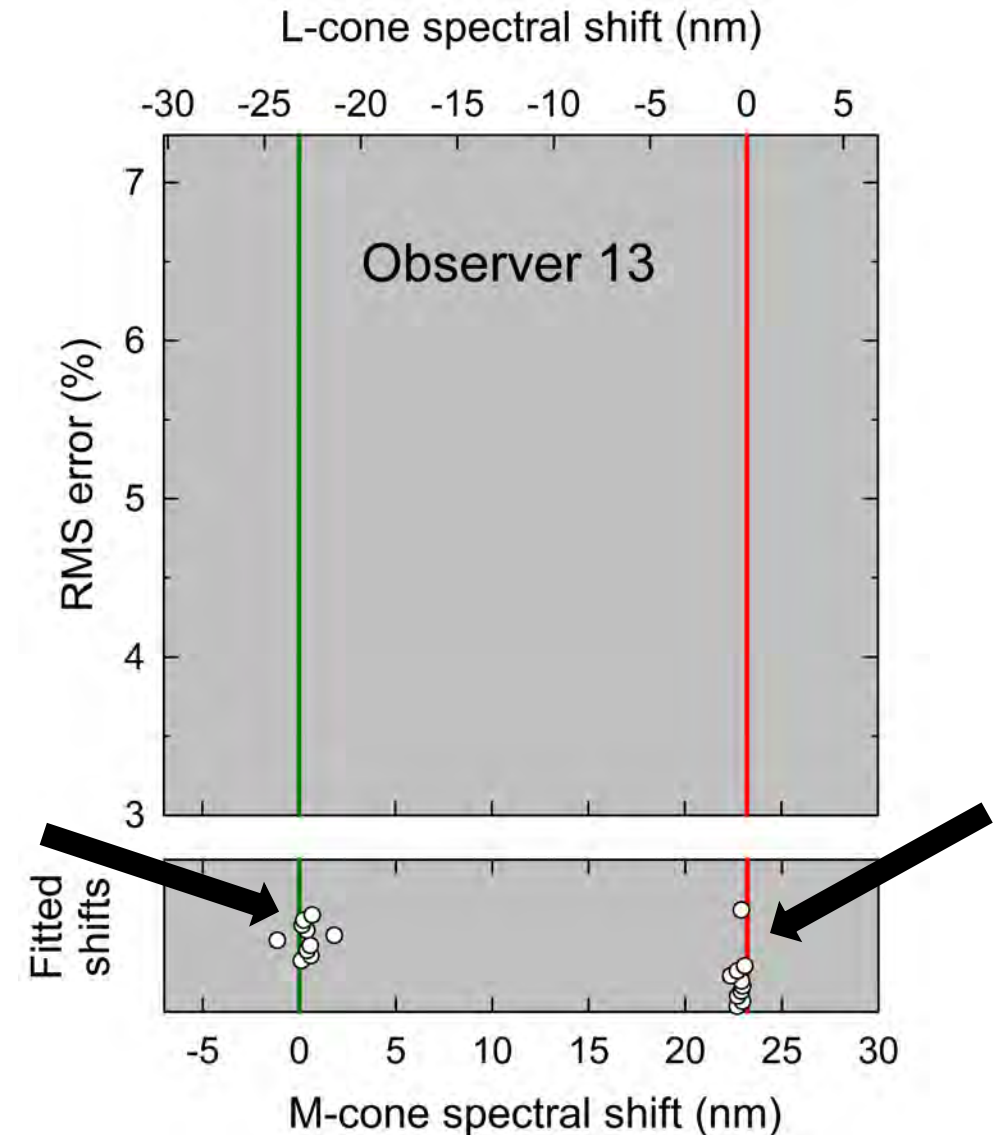


So, we gradually varied the template shape as we varied the λ_{max} wavelength from M to L or vice versa.



Finding the best parameters

First, we made 10 repeated fits* to find all seven parameters (including the spectral shifts).



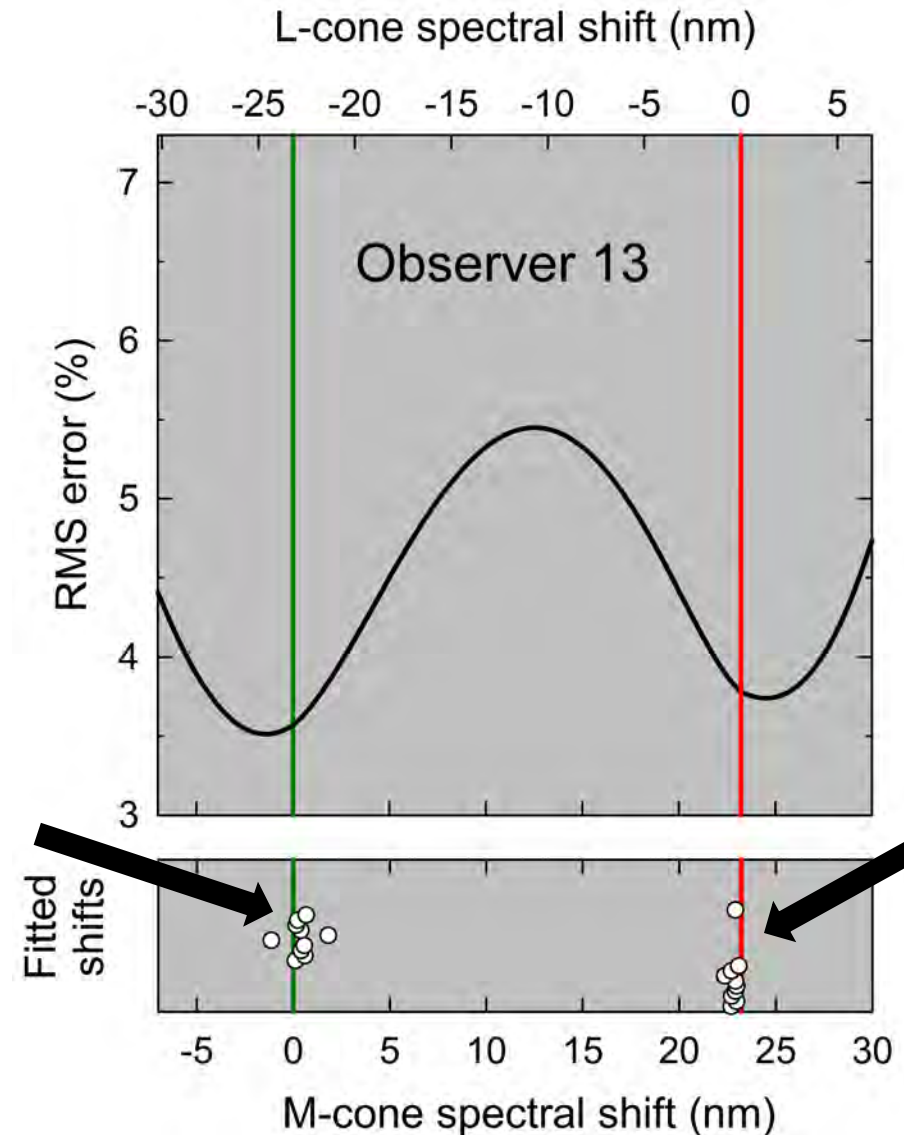
*Matlab's GlobalSearch algorithm using the fmincon

Finding the best parameters

First, we made 10 repeated fits* to find all seven parameters (including the spectral shifts).

Second, we fixed the five parameters (other than the M and L shifts) at the mean values for the 10 fits, and then...

scanned across wavelengths to calculate the RMS at each spectral shift and (hopefully) find the two minima in the fits.



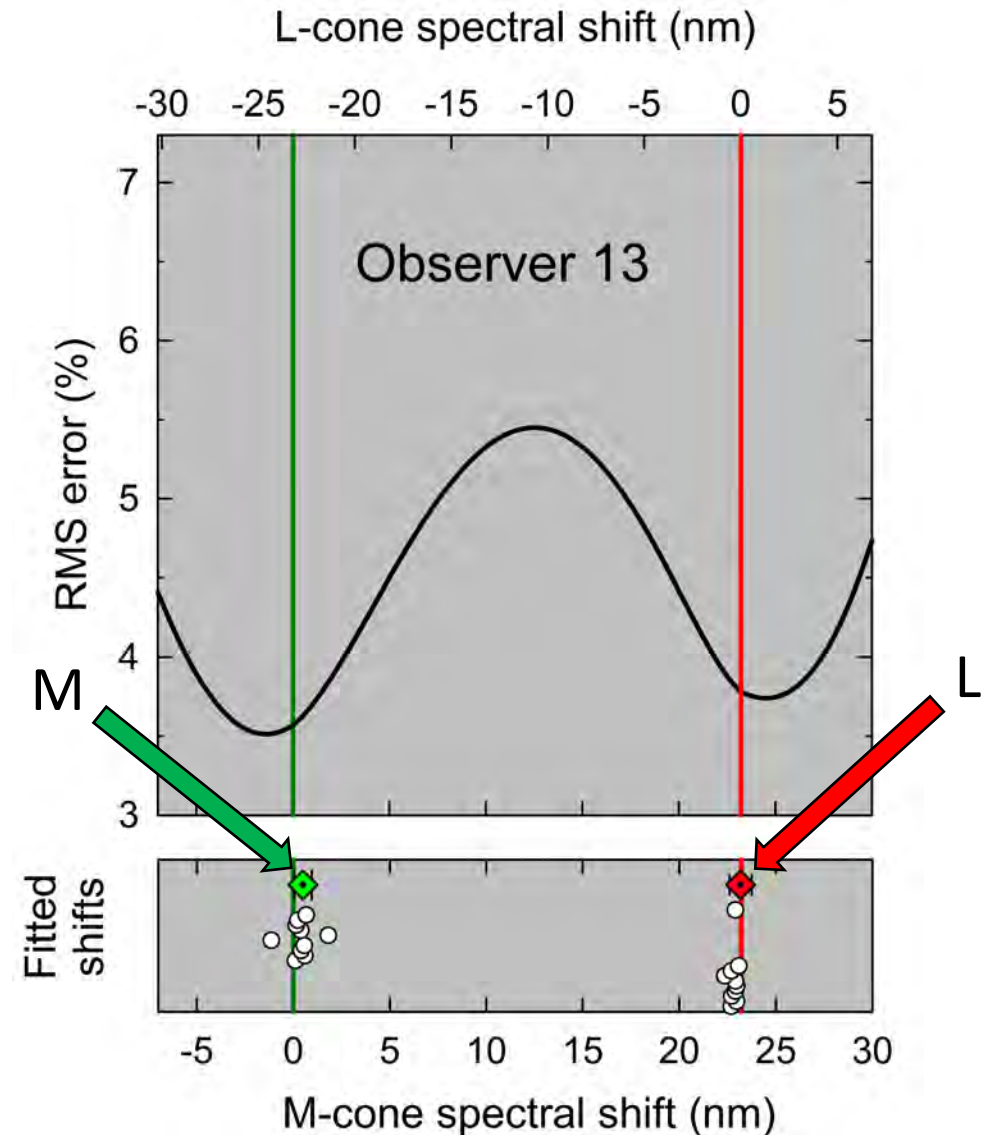
*Matlab's GlobalSearch algorithm using the fmincon

Finding the best parameters

Finally, we made 10 repeated fits allowing all seven parameters to vary but constraining the L and M shifts to be spectrally separated below and above the maximum separating the two minima.

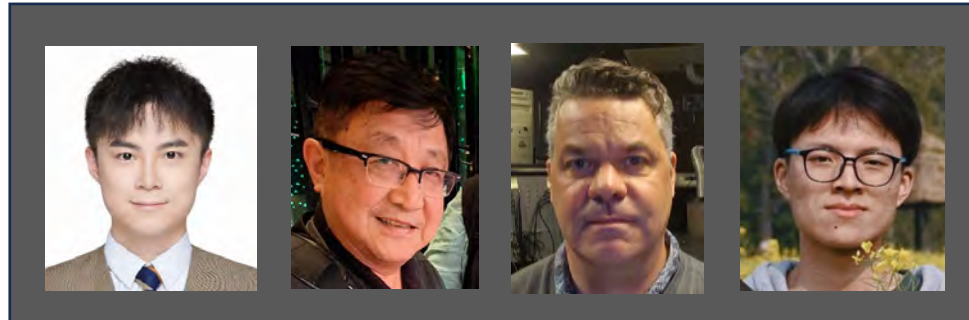
We performed this analysis on the colour matching data for 30 observers (numbered 11 to 40) aged between 20 and 30 from China. There were 15 male observers and 15 female observers.

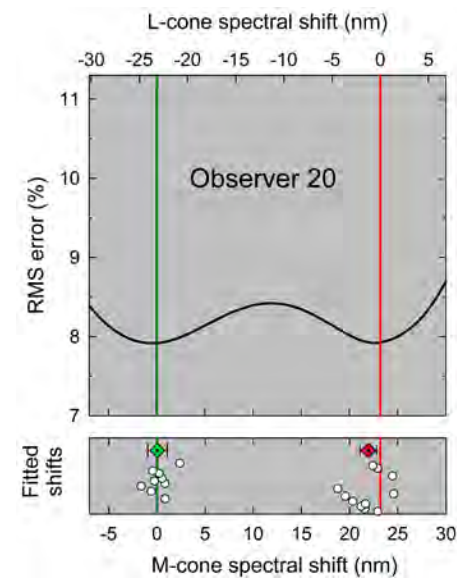
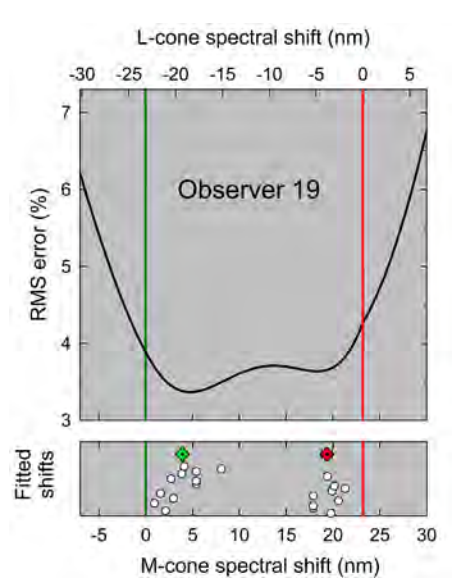
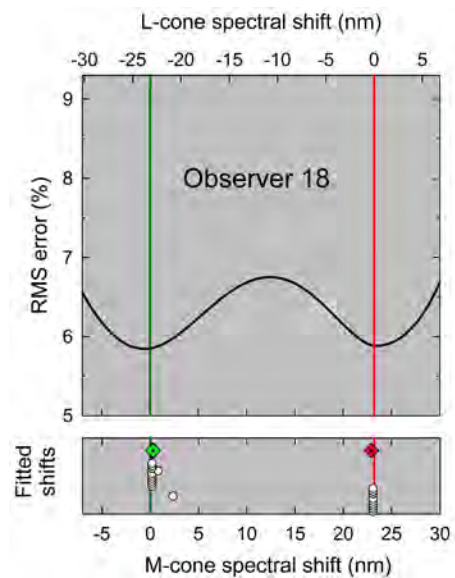
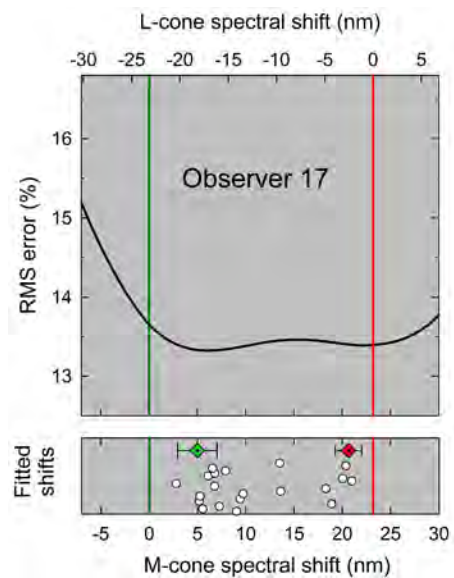
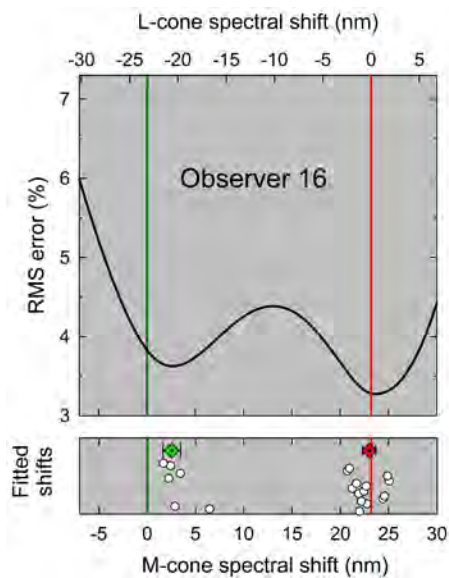
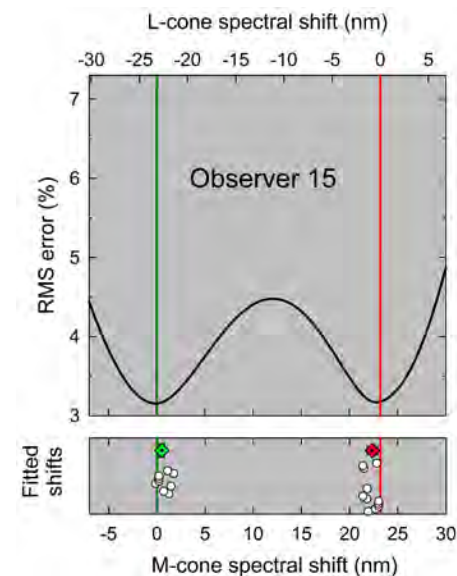
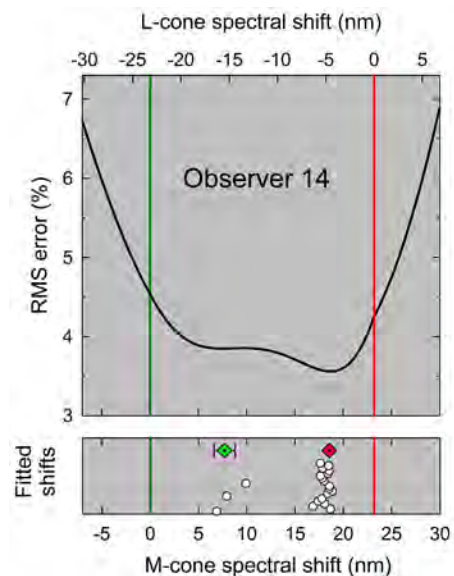
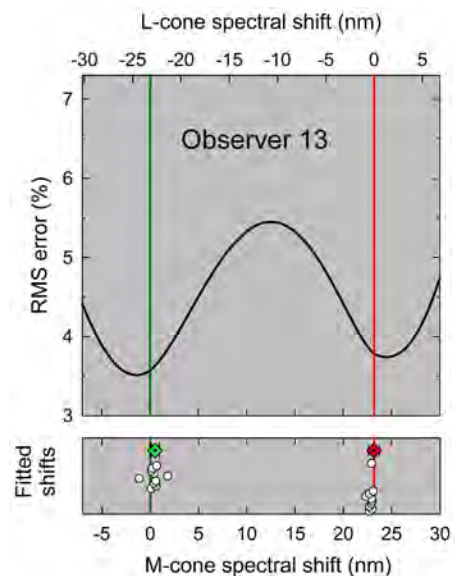
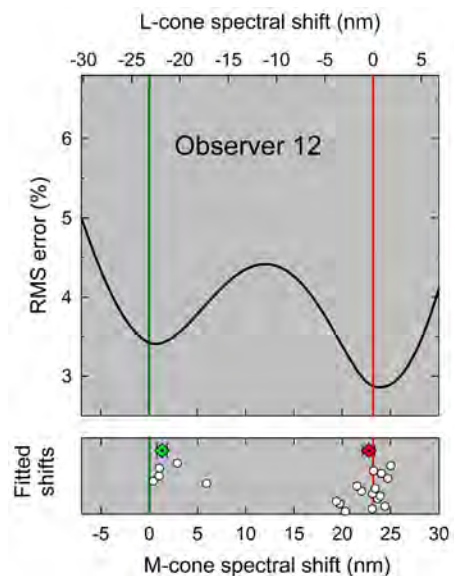
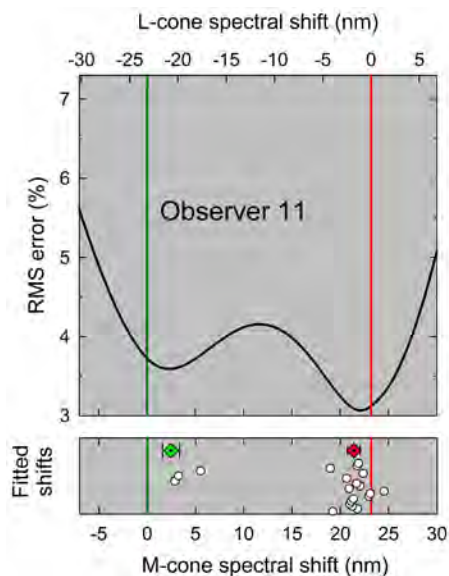
Here are the results...

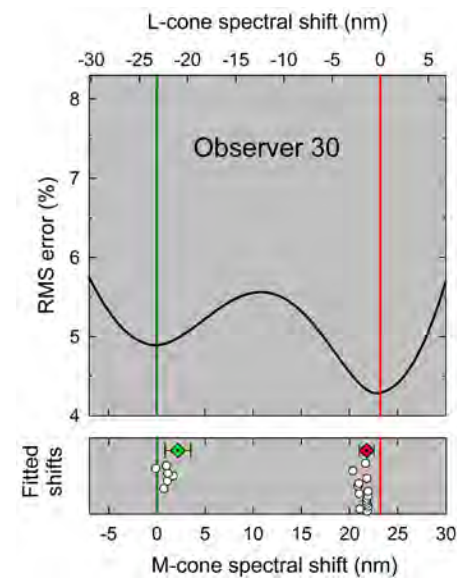
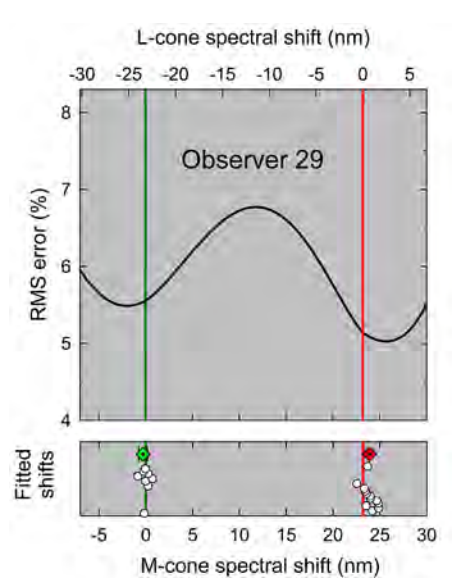
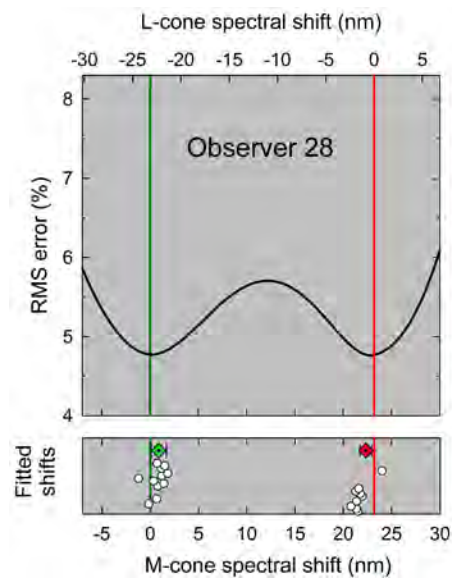
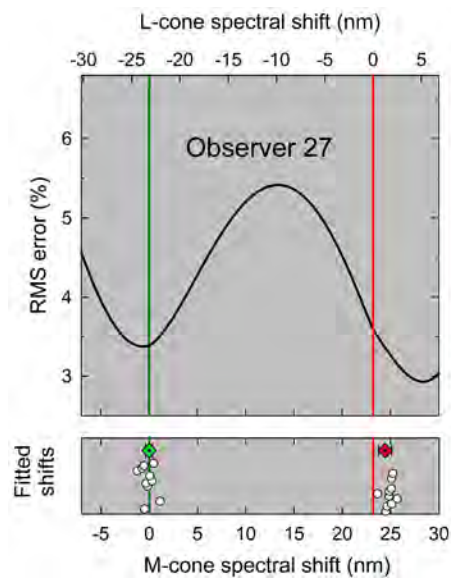
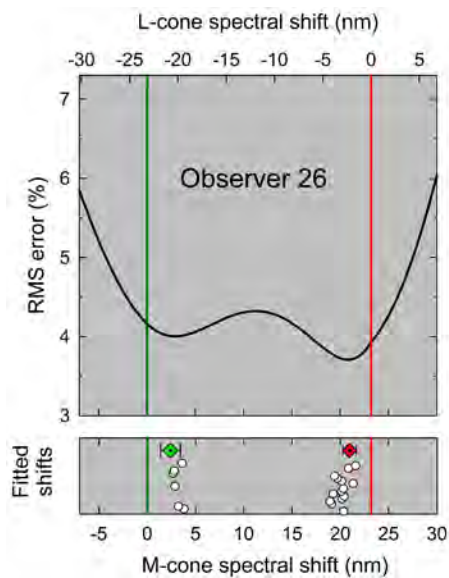
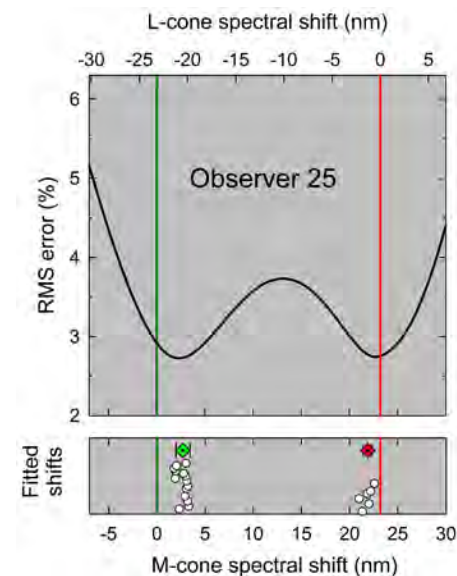
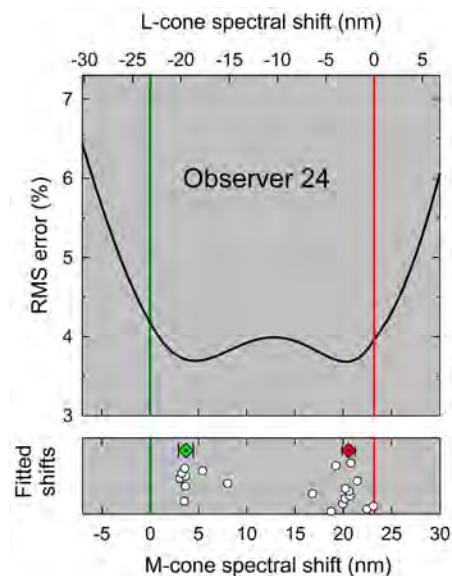
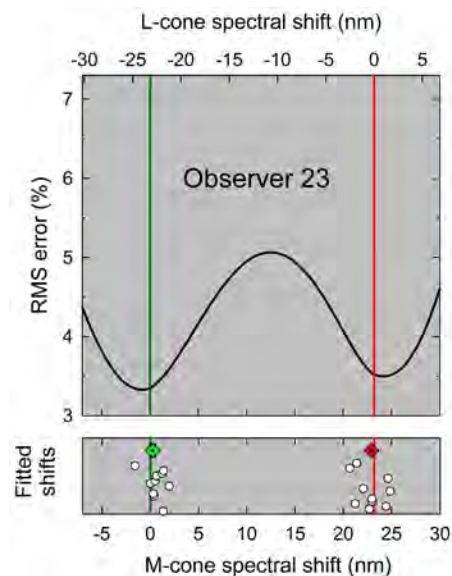
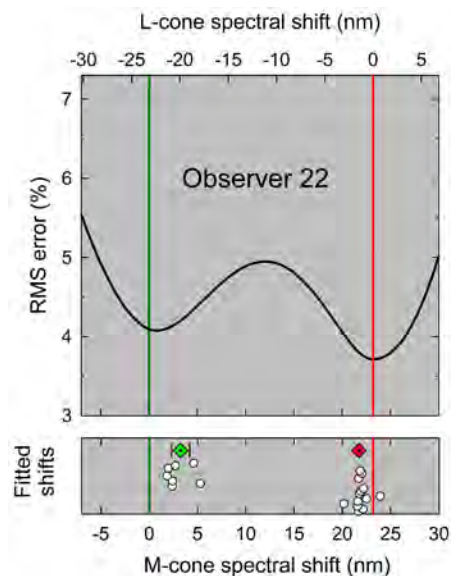
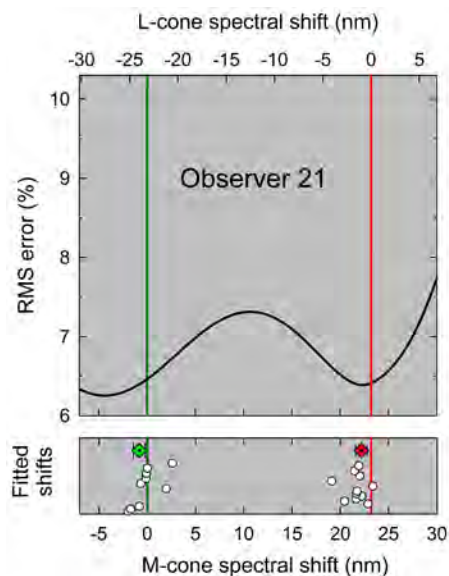


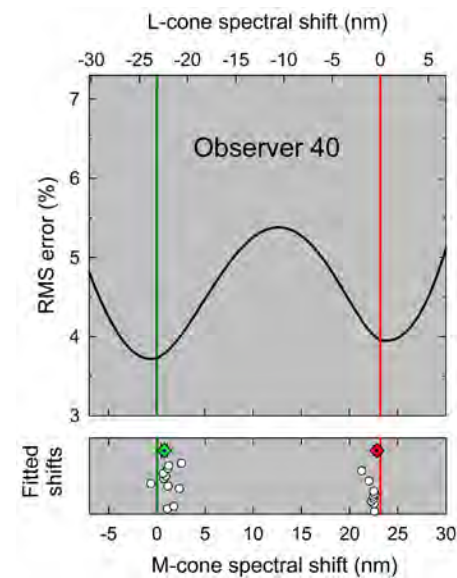
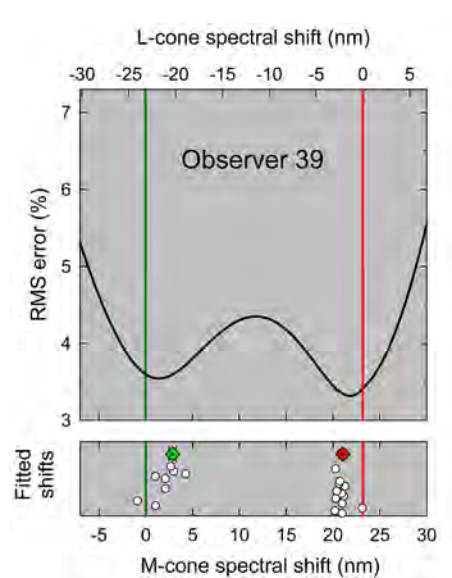
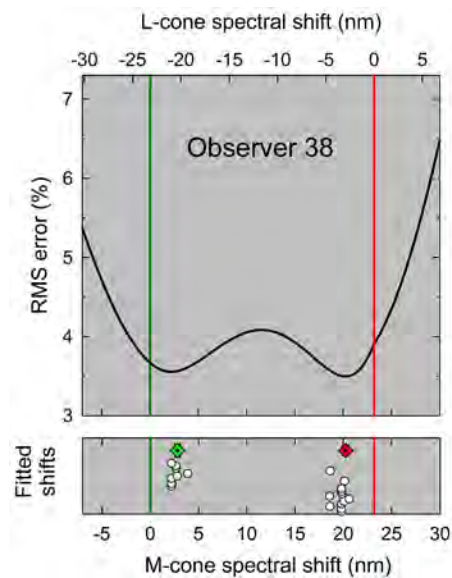
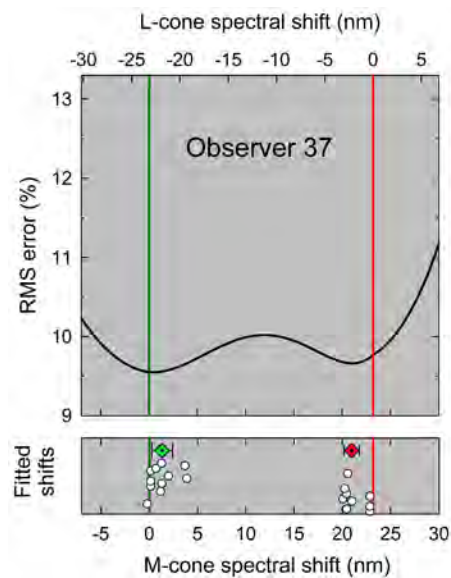
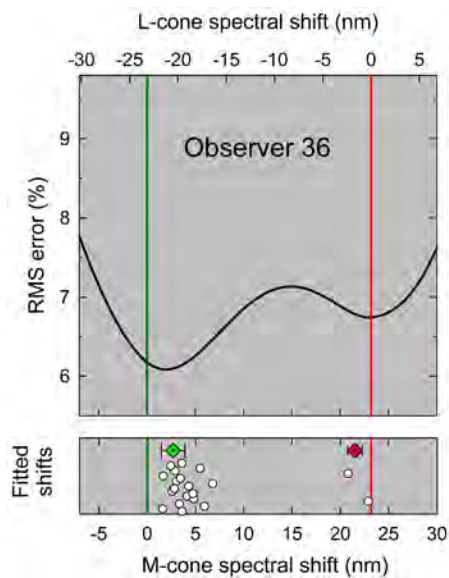
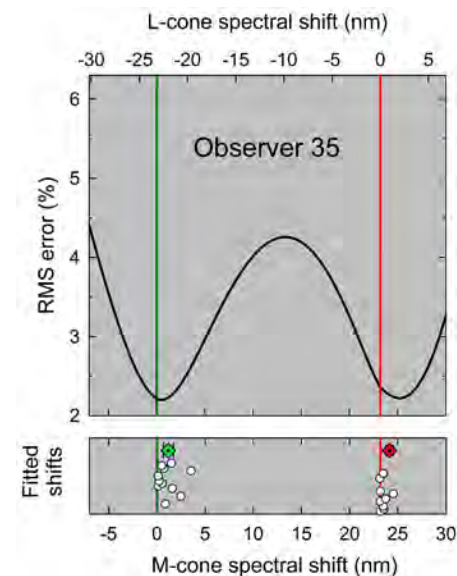
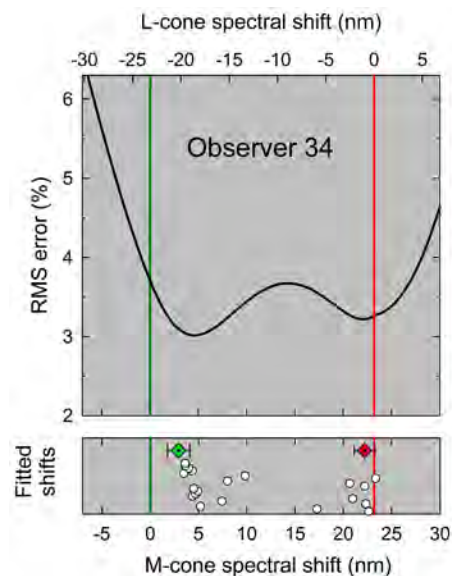
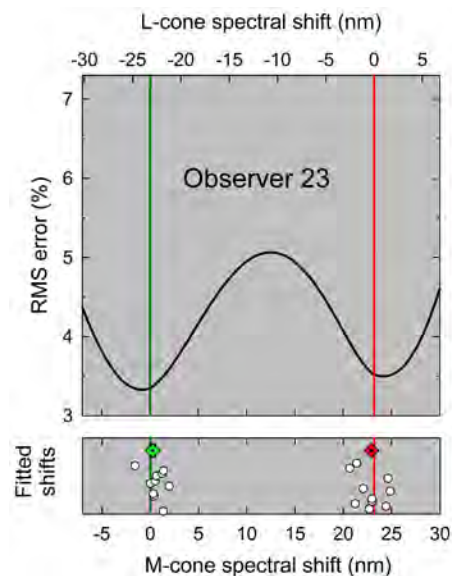
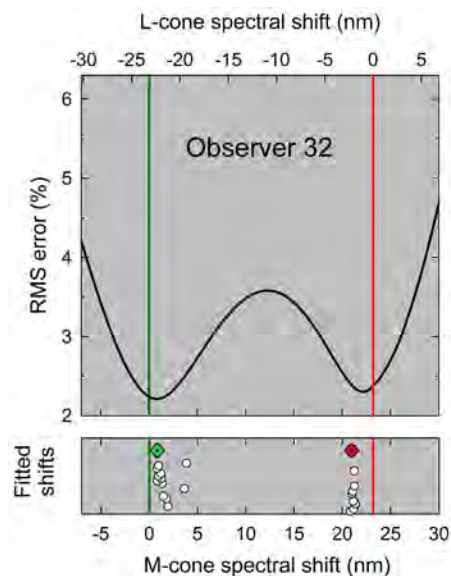
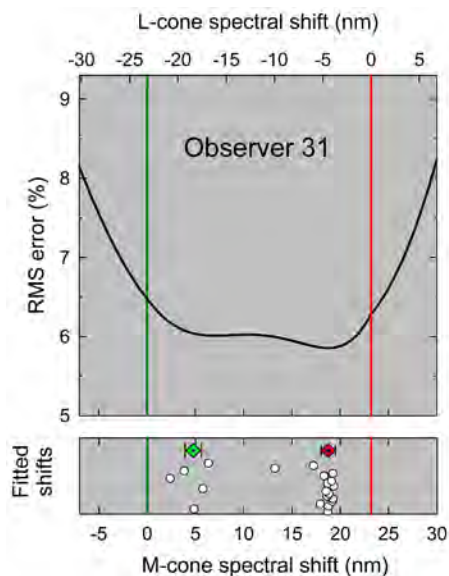
Reanalyzed data from:

Shi, Luo, Rider, Song, Huang & Stockman (2024). Individual differences in color matches and cone spectral sensitivities in 51 young adults. *Optics Express*, 32(13), 23597–23616



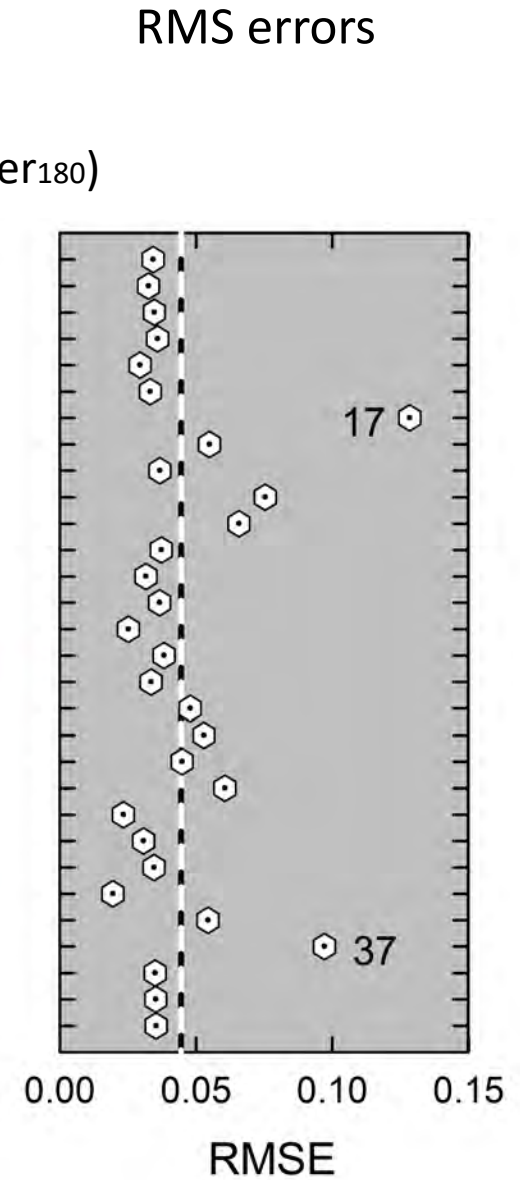
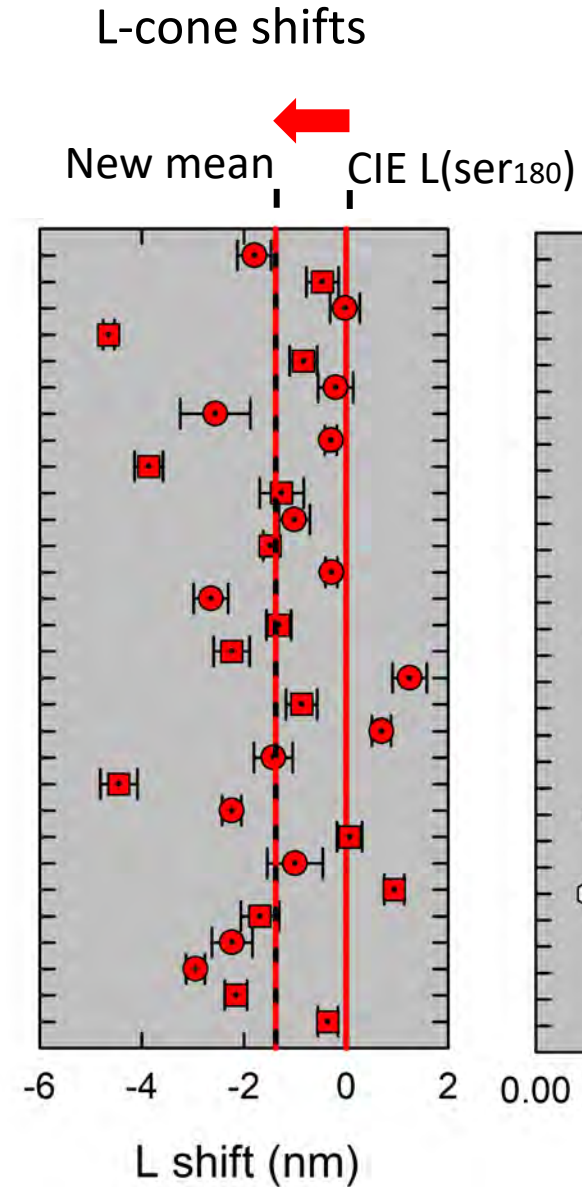
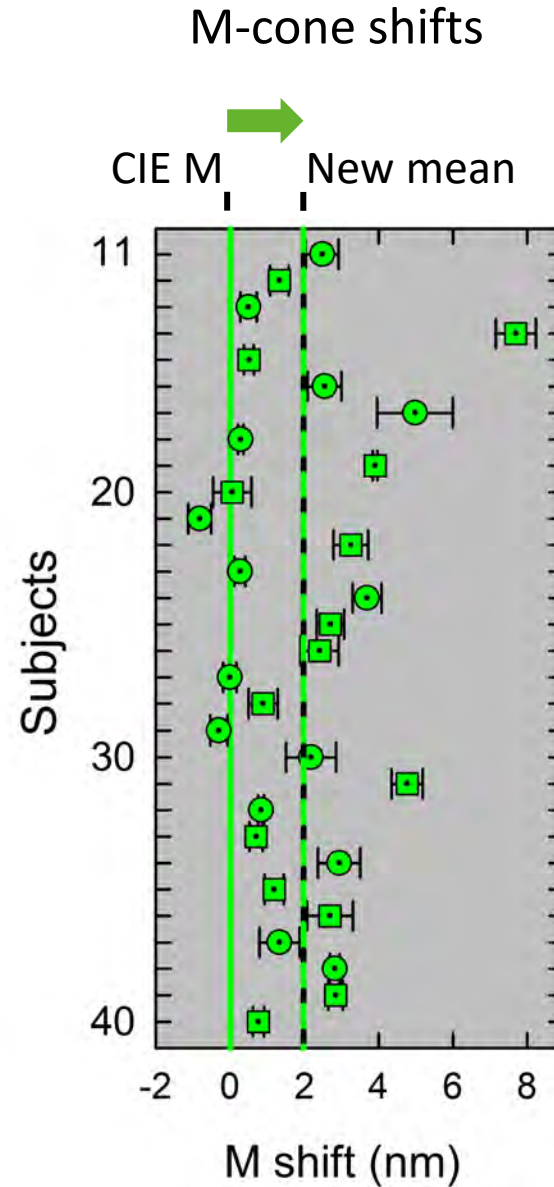
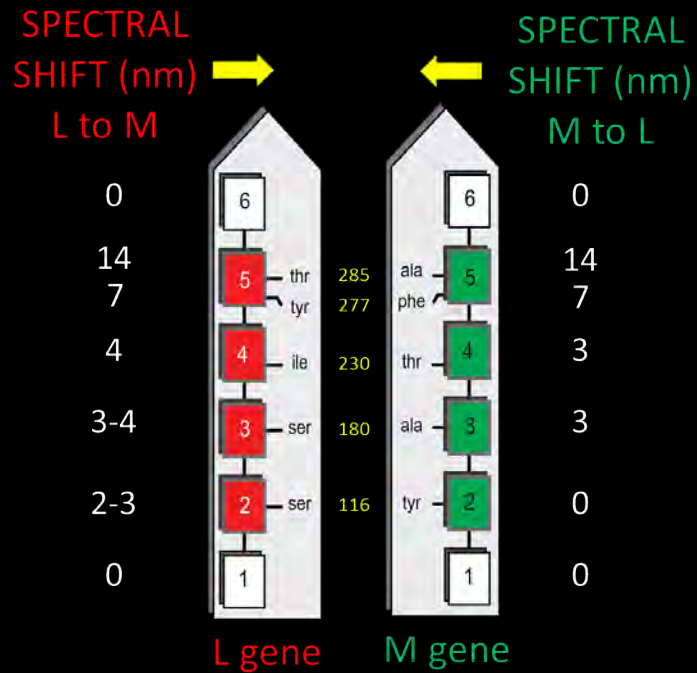


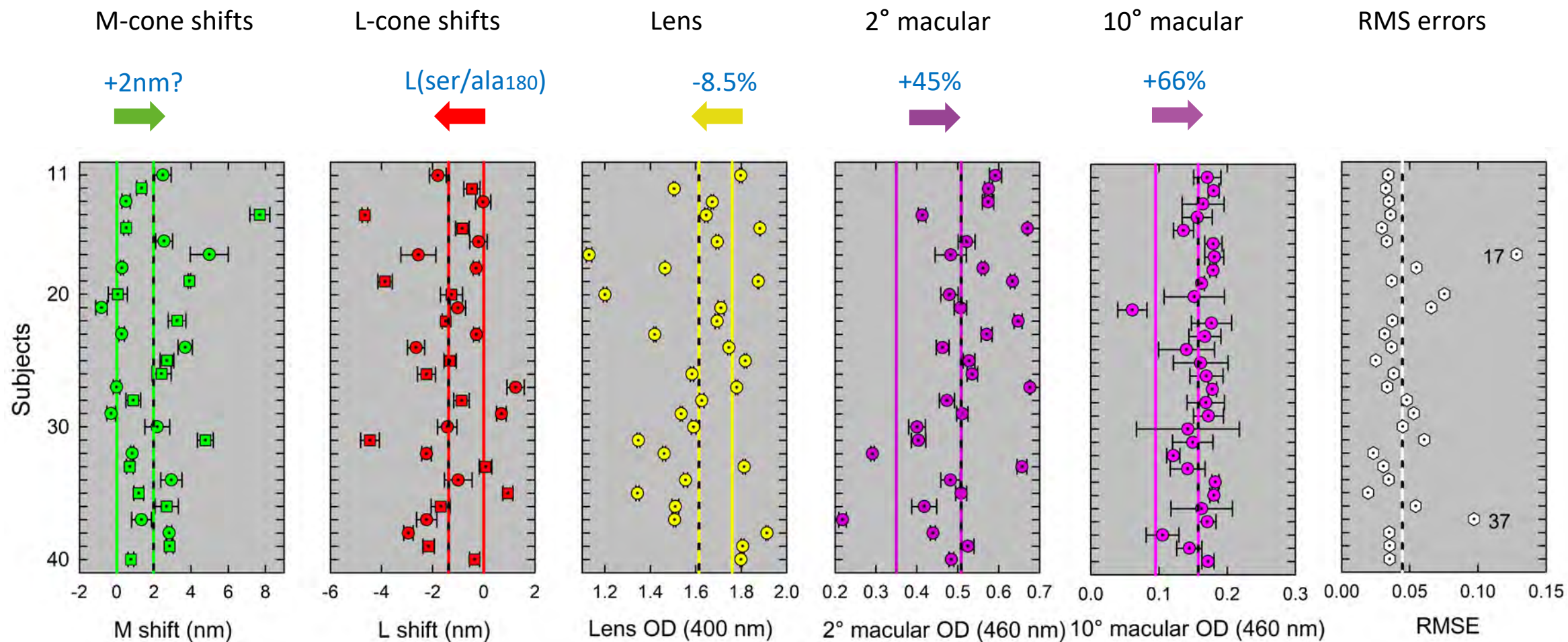




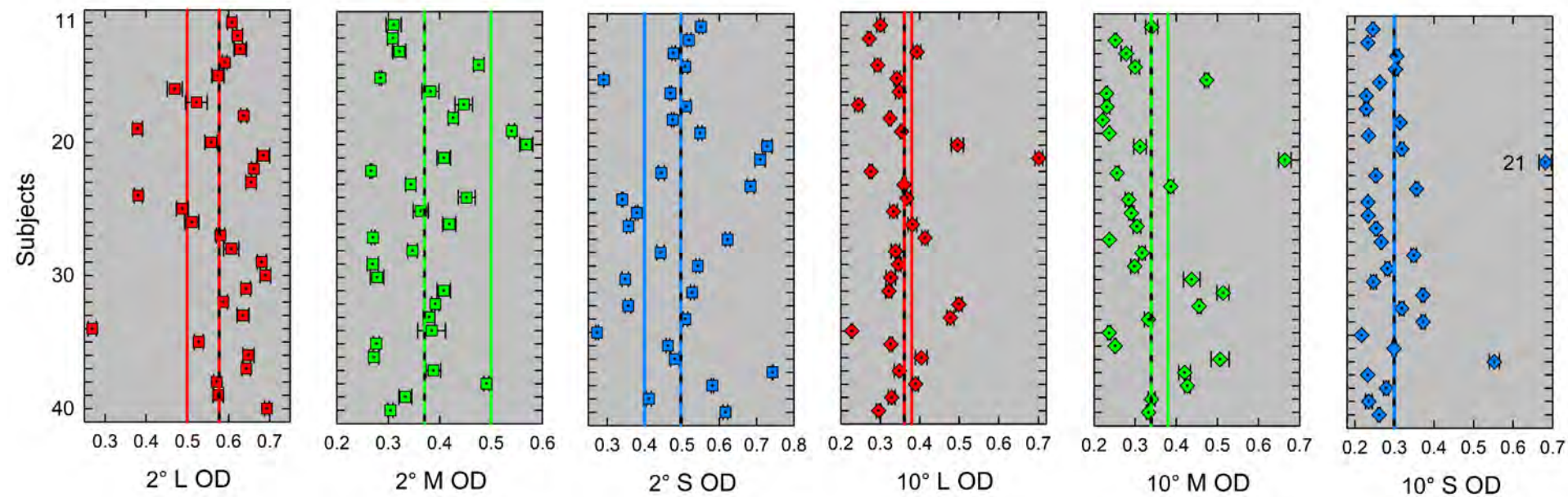
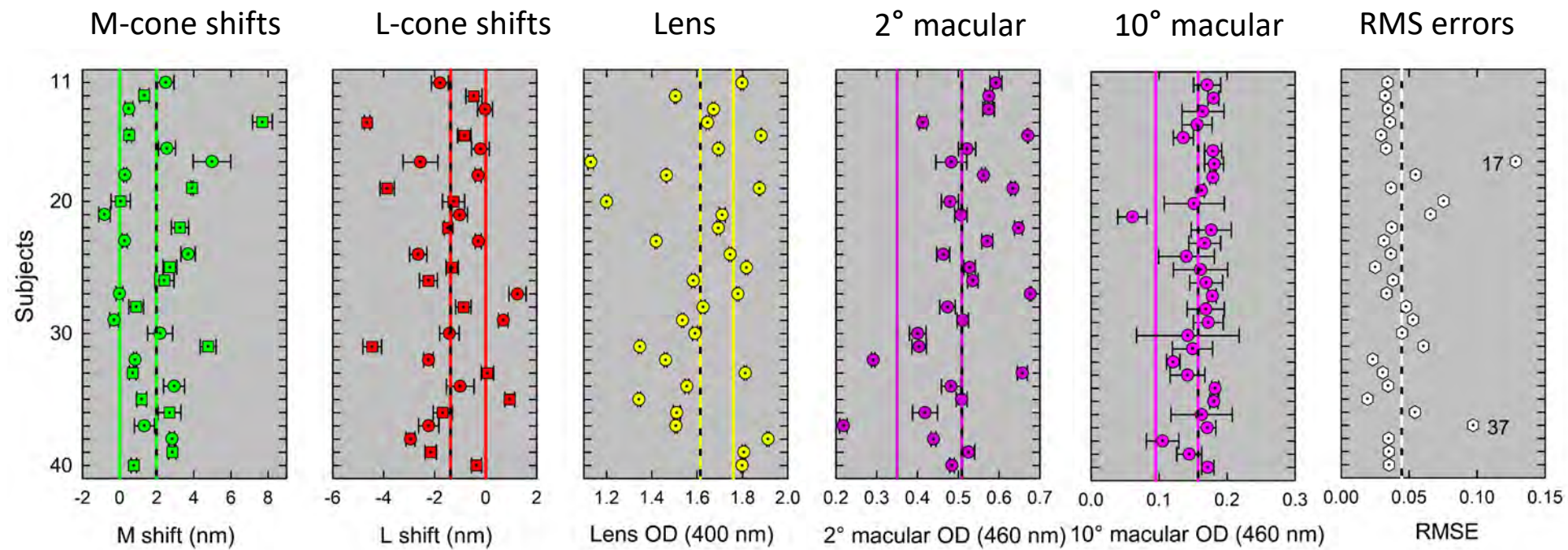
Let's look at the results...

◻ Male ◉ Female





Potential adjustments to CIE 2006/2015 LMS standards

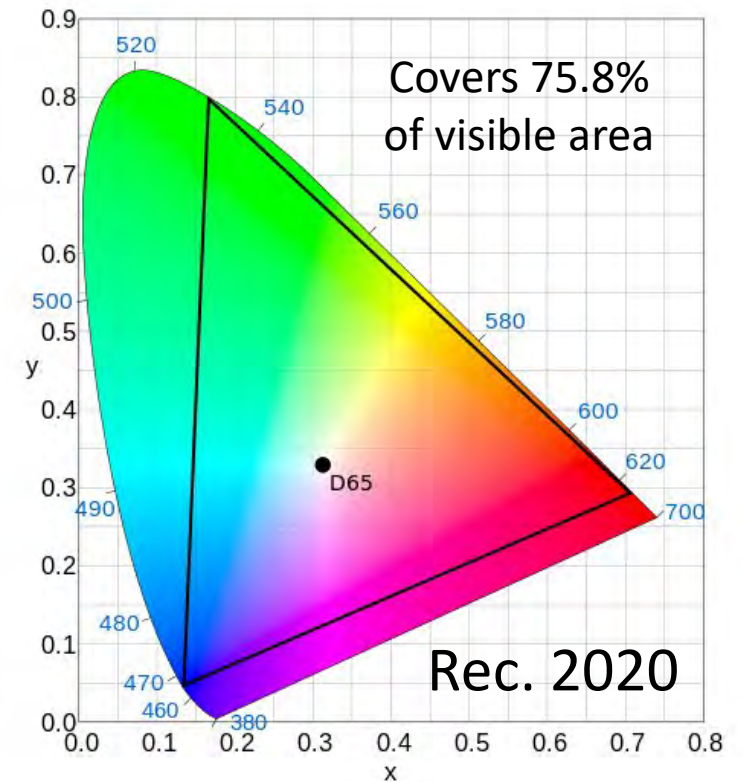
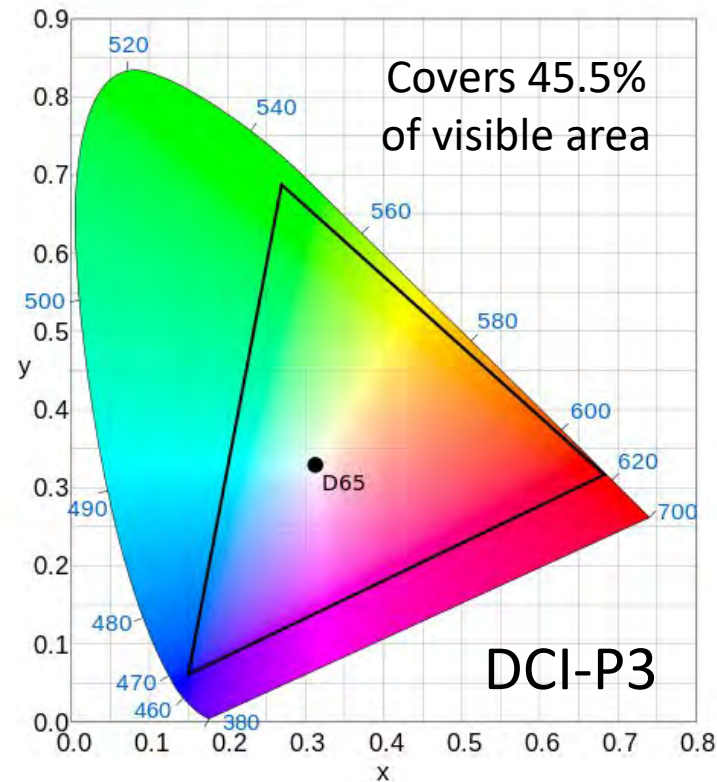
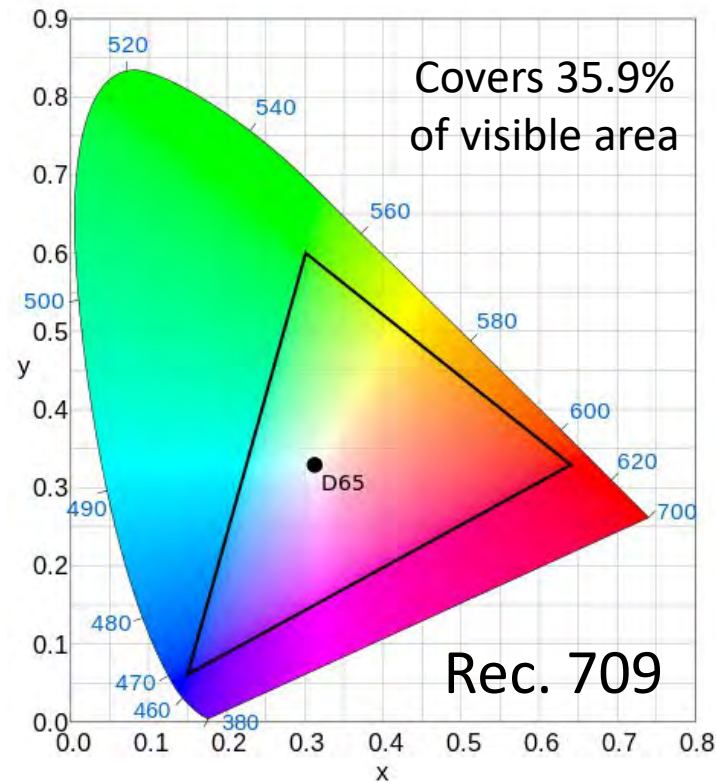


Metamerism failures

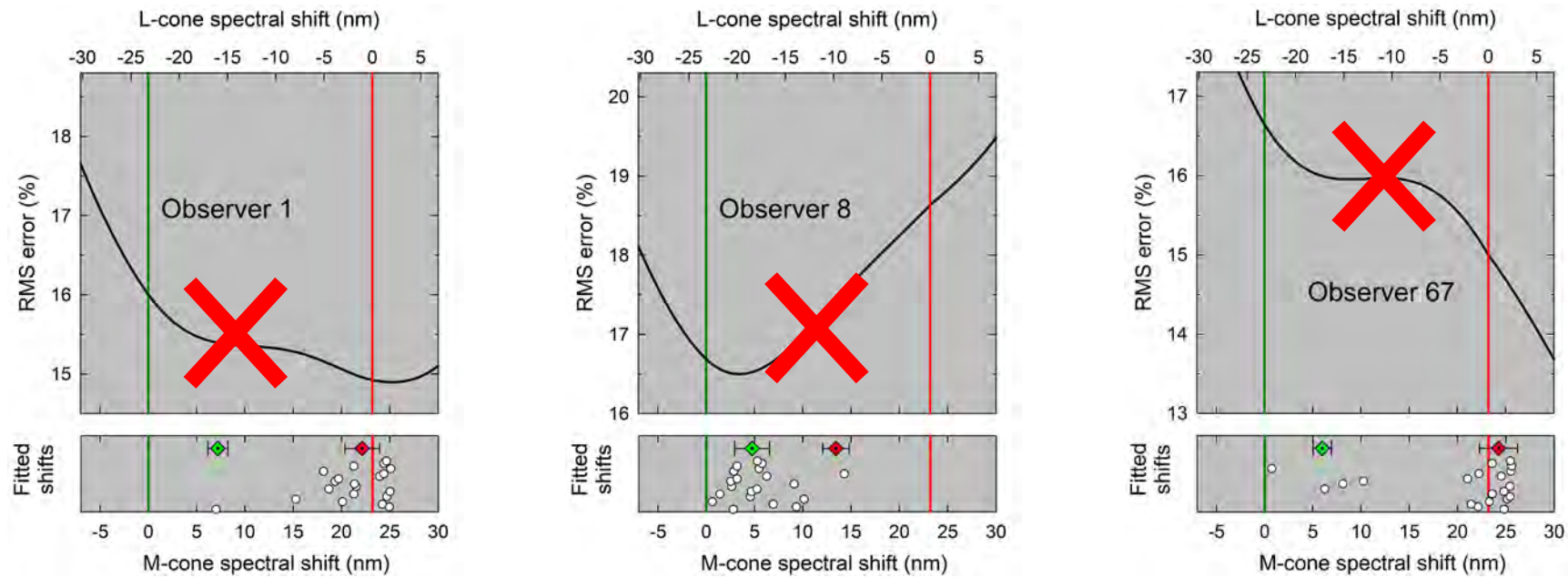


Using these methods, we can produce individualized colour matching functions and thus produce consistent colours with different displays and across other media.

We can also produce better representations of the mean or standard functions so that the displays look better to on average more people.



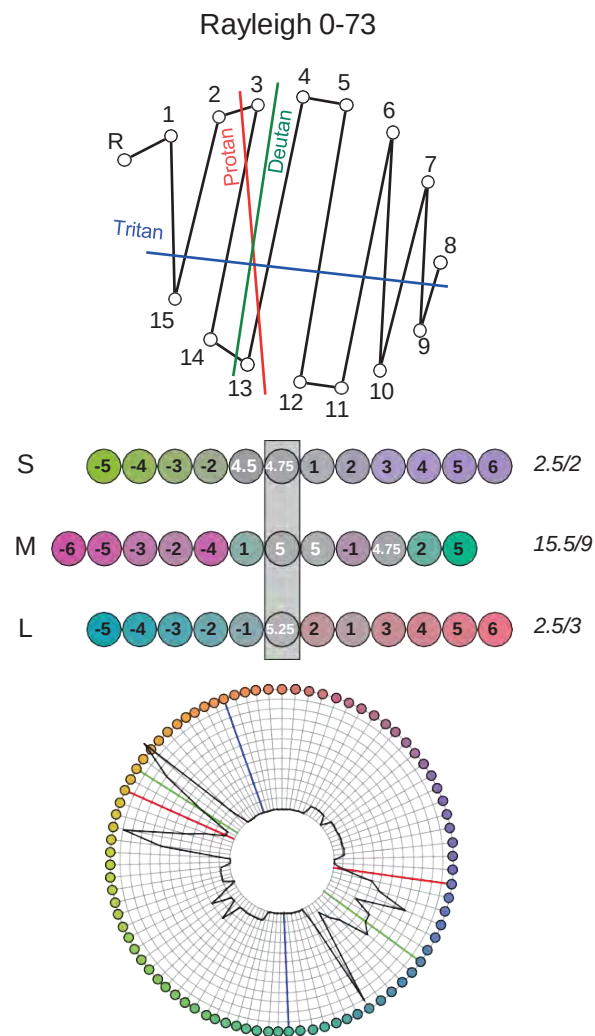
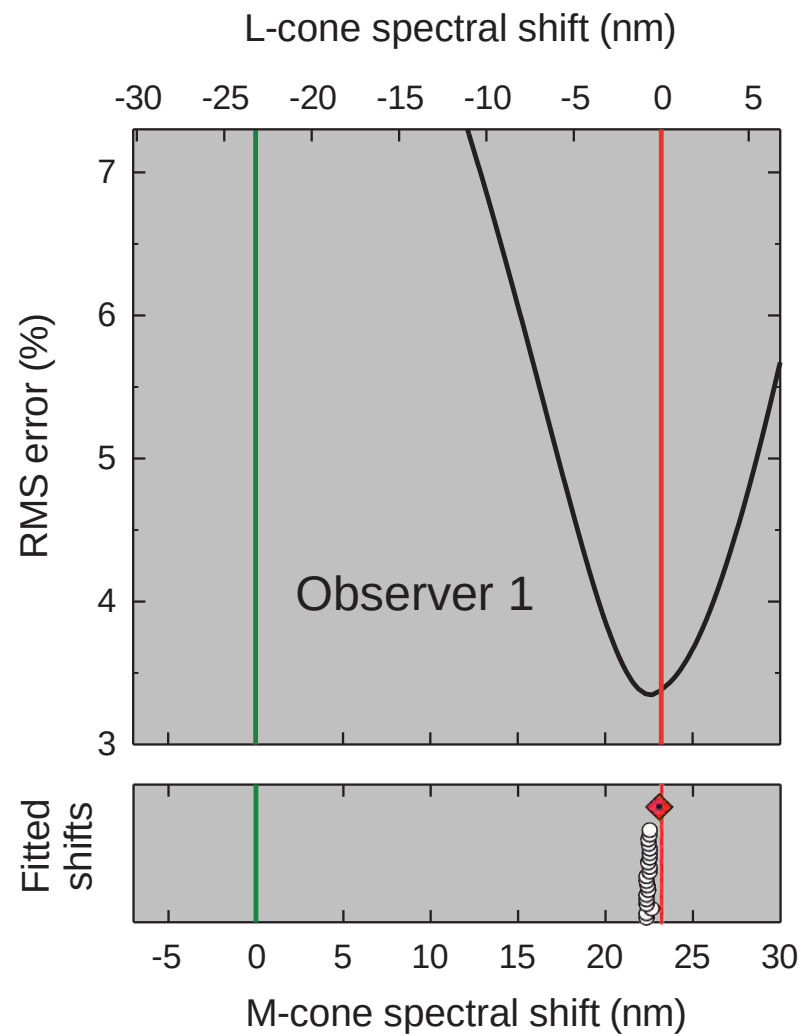
We can also use it to assess the quality of our own colour normal data....

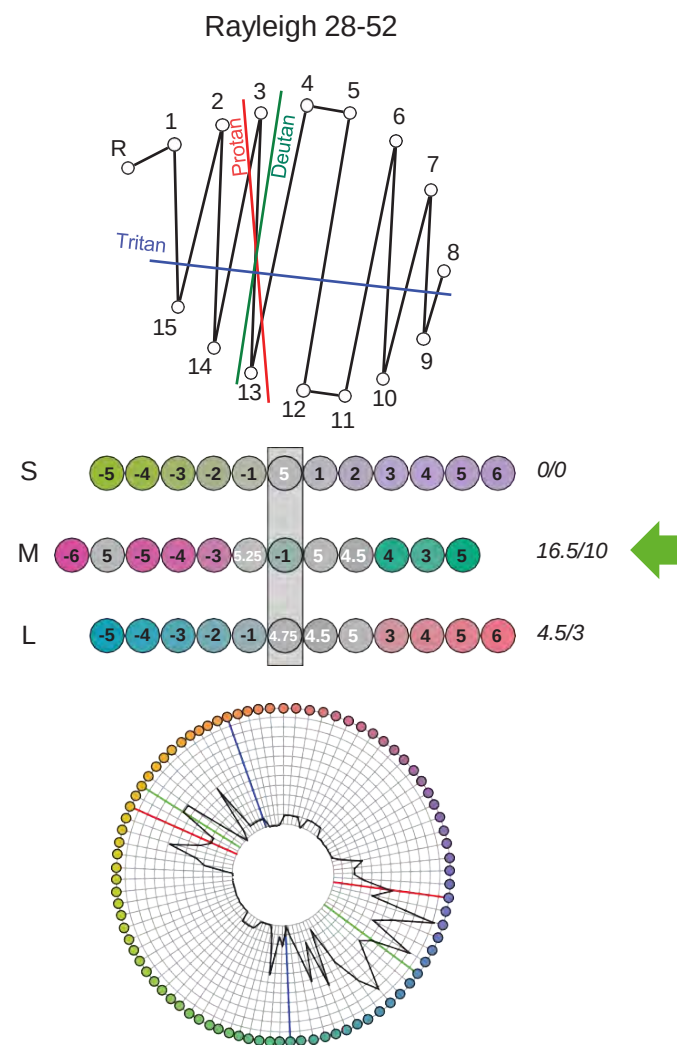
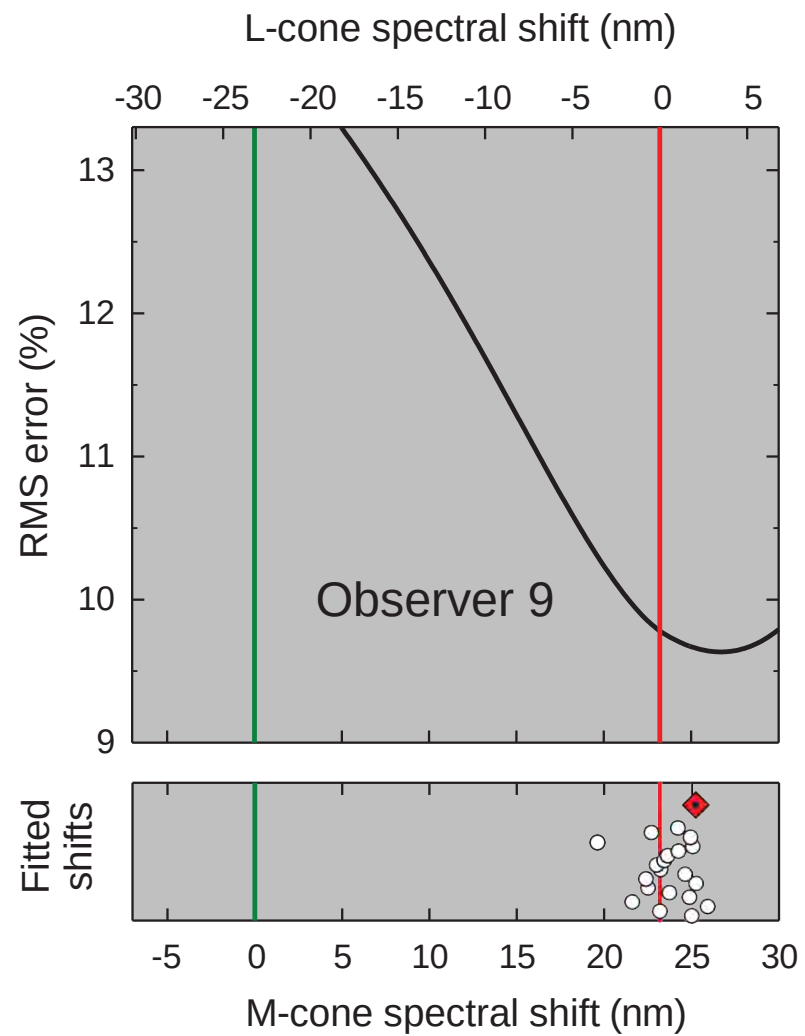


and analyse colour deficient data....

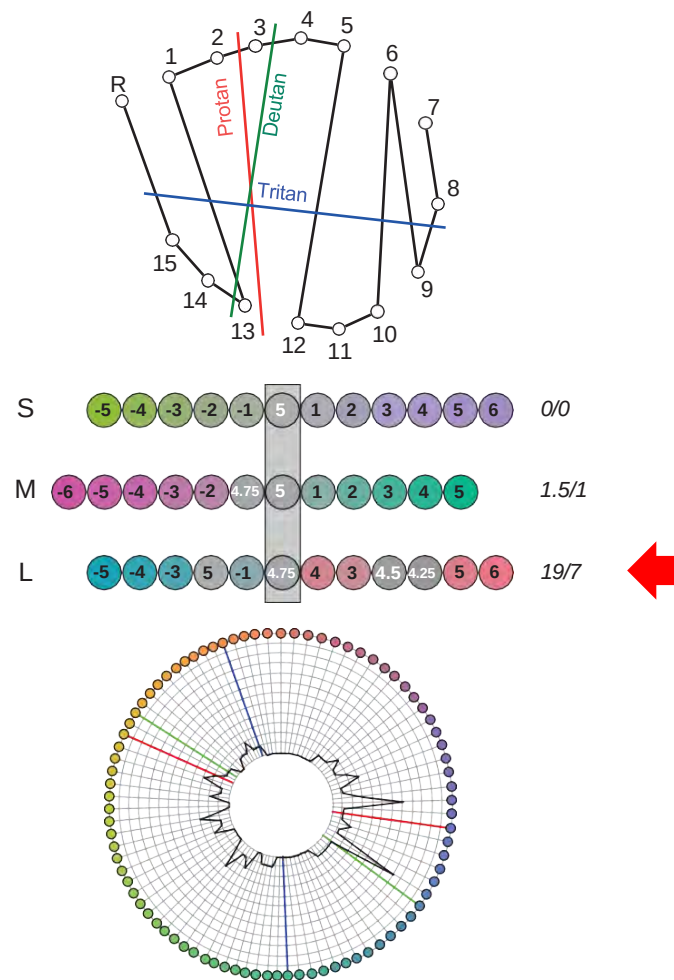
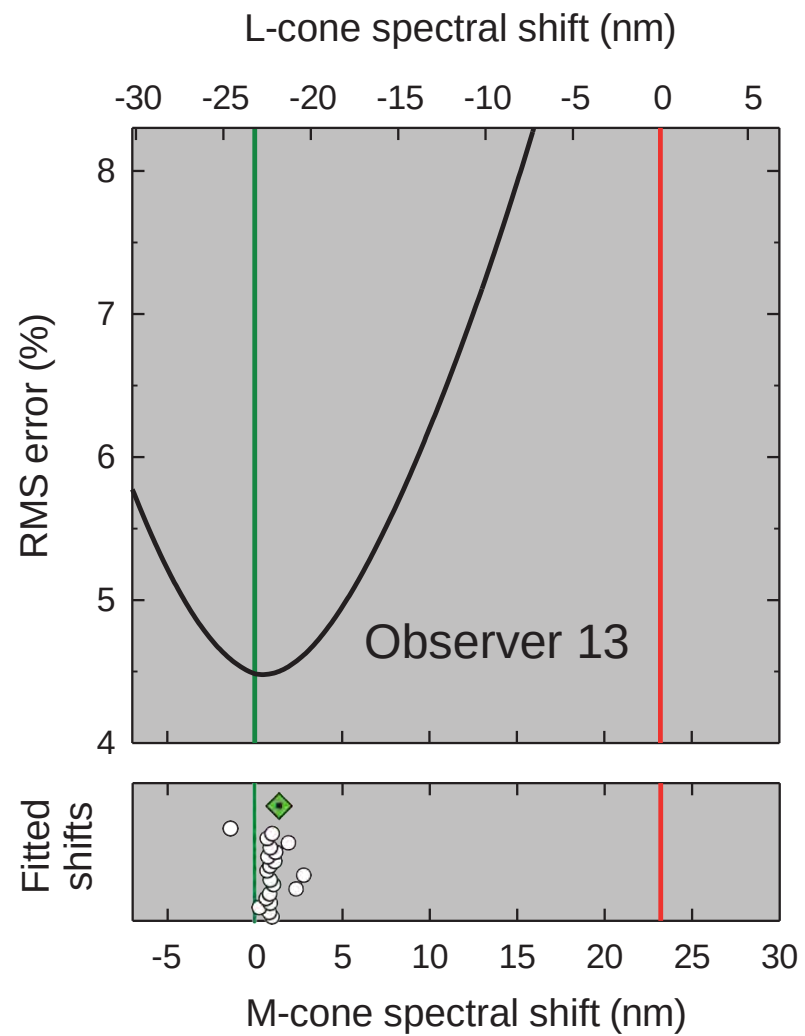
Deuteranopes

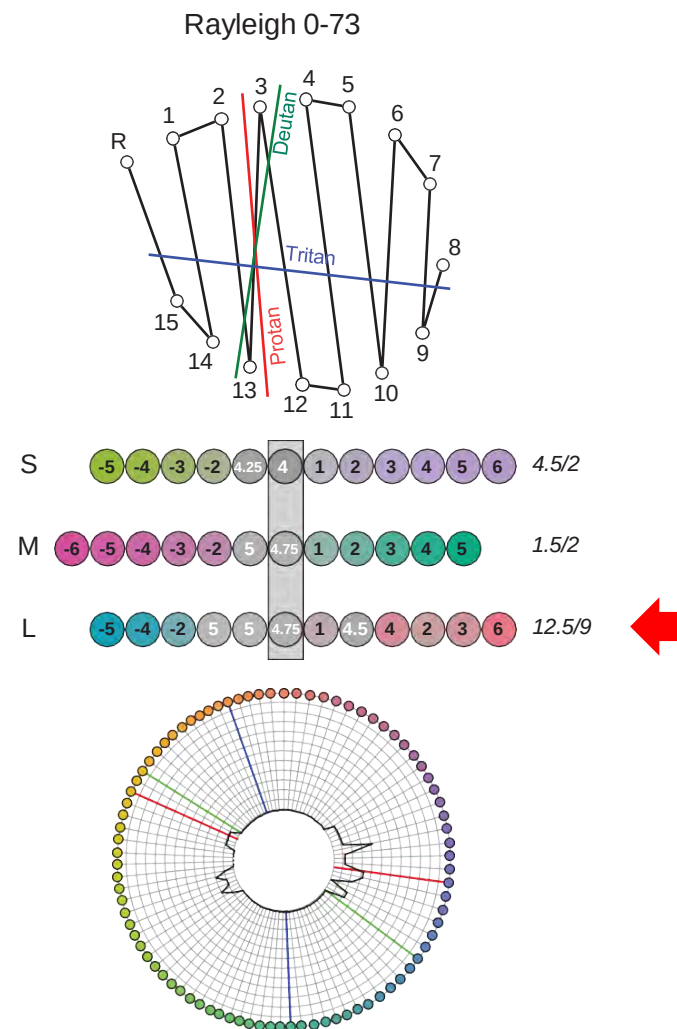
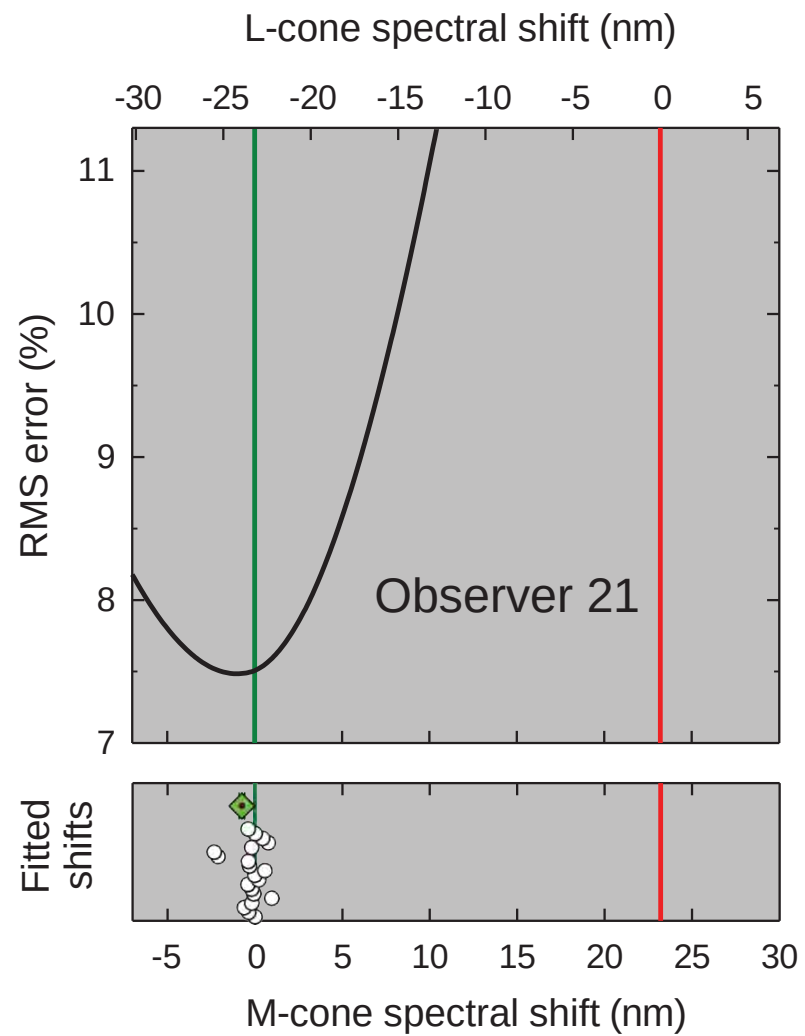
Unpublished work from Zhejiang University

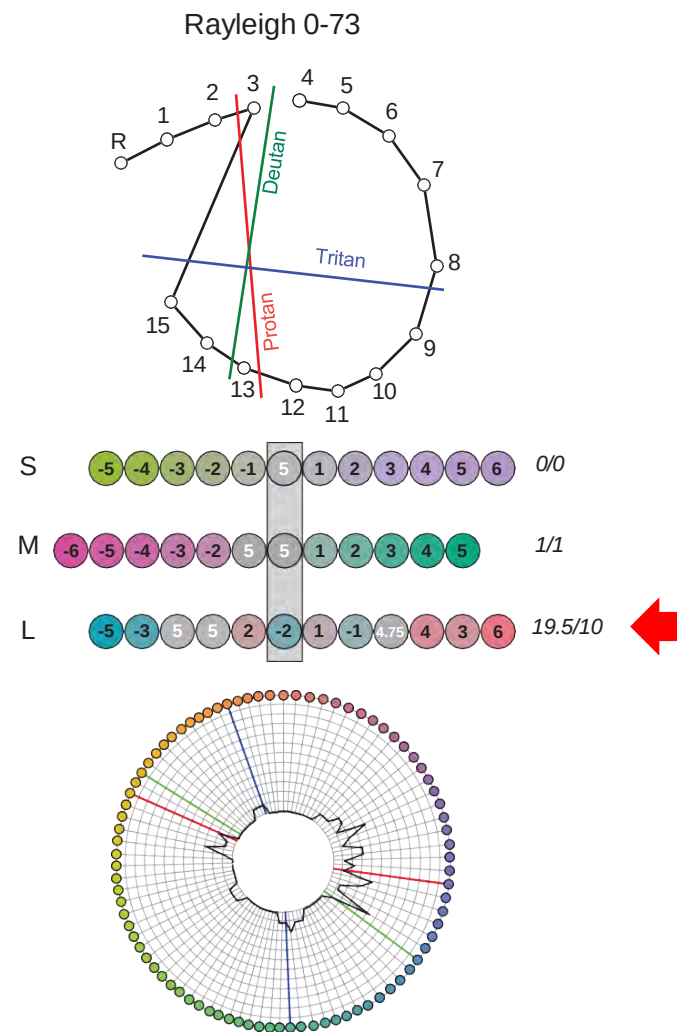
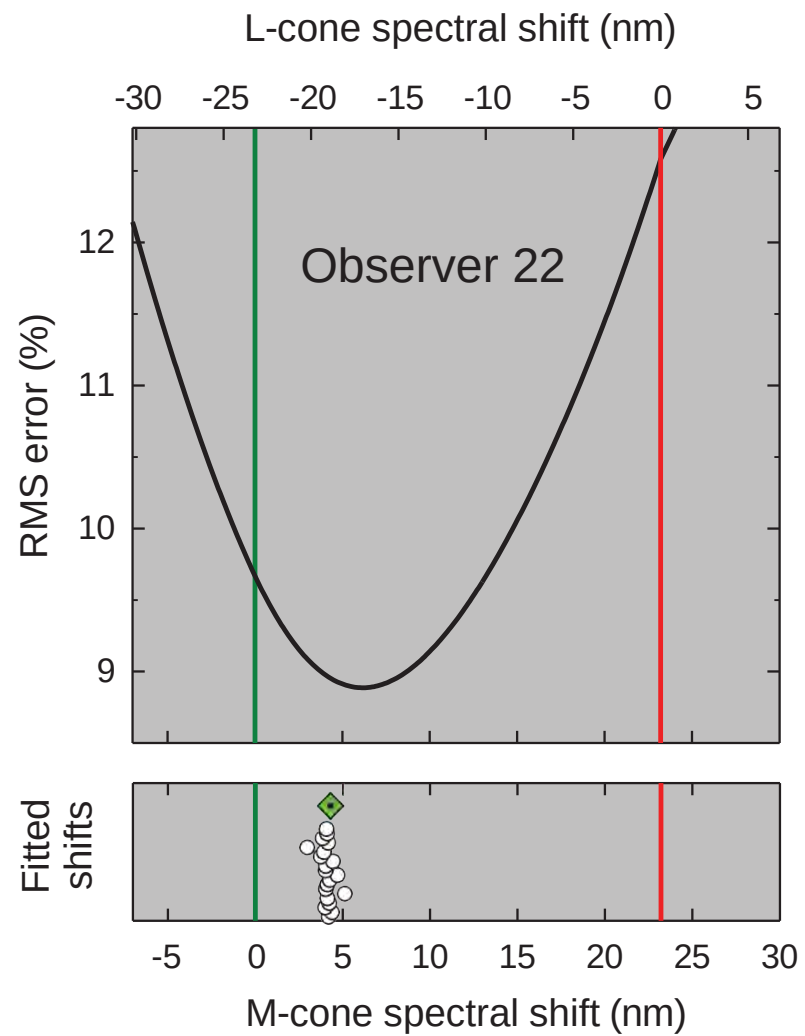


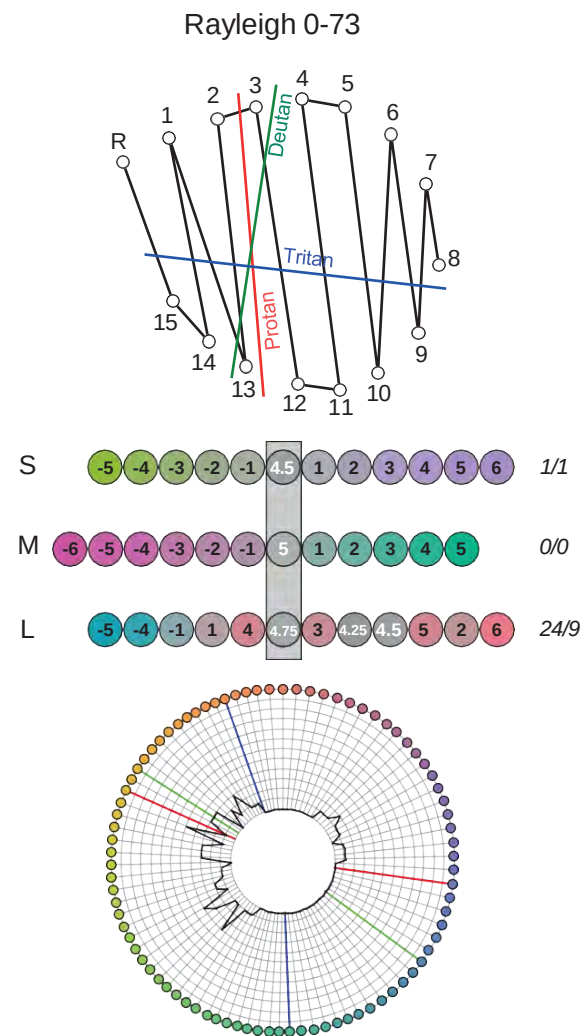
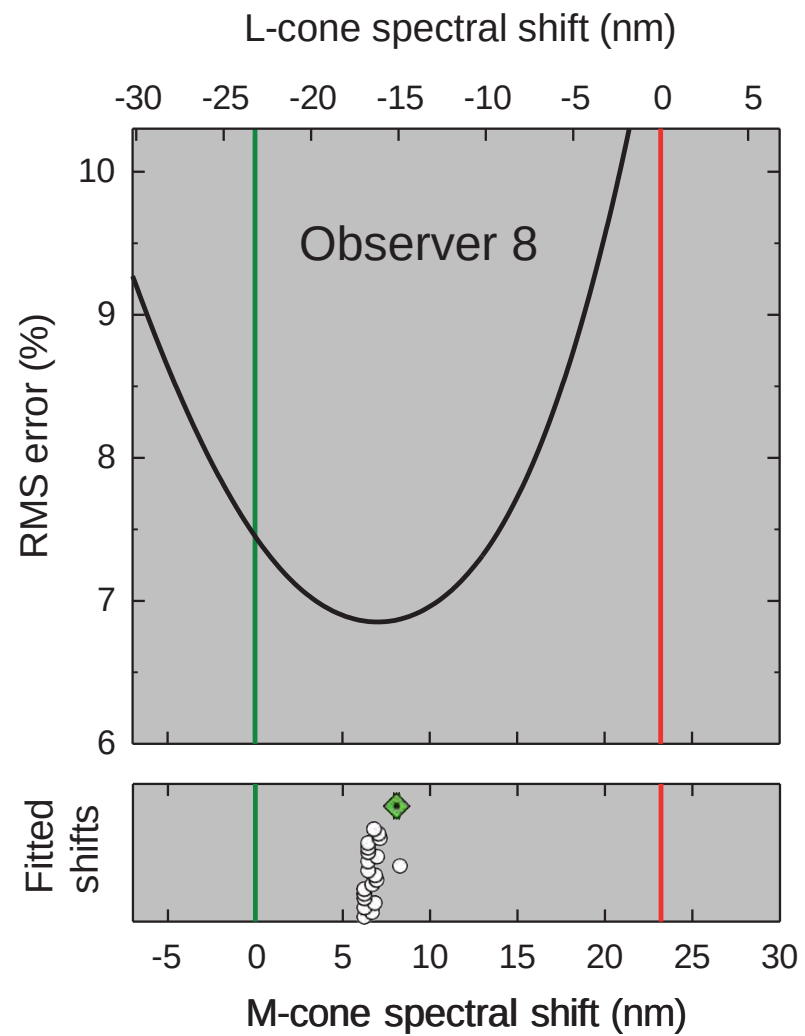


Protanopes

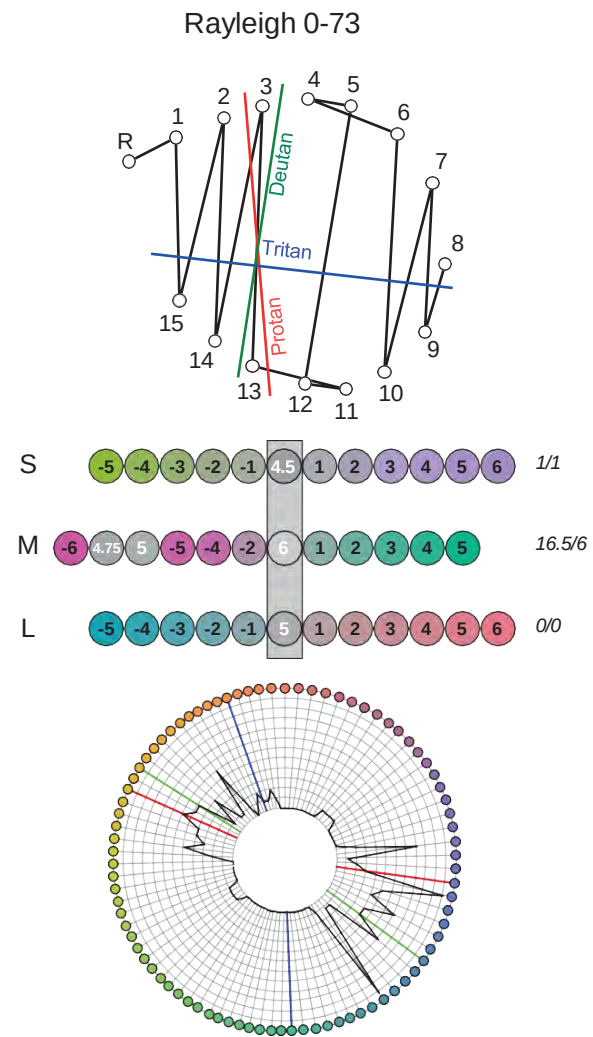
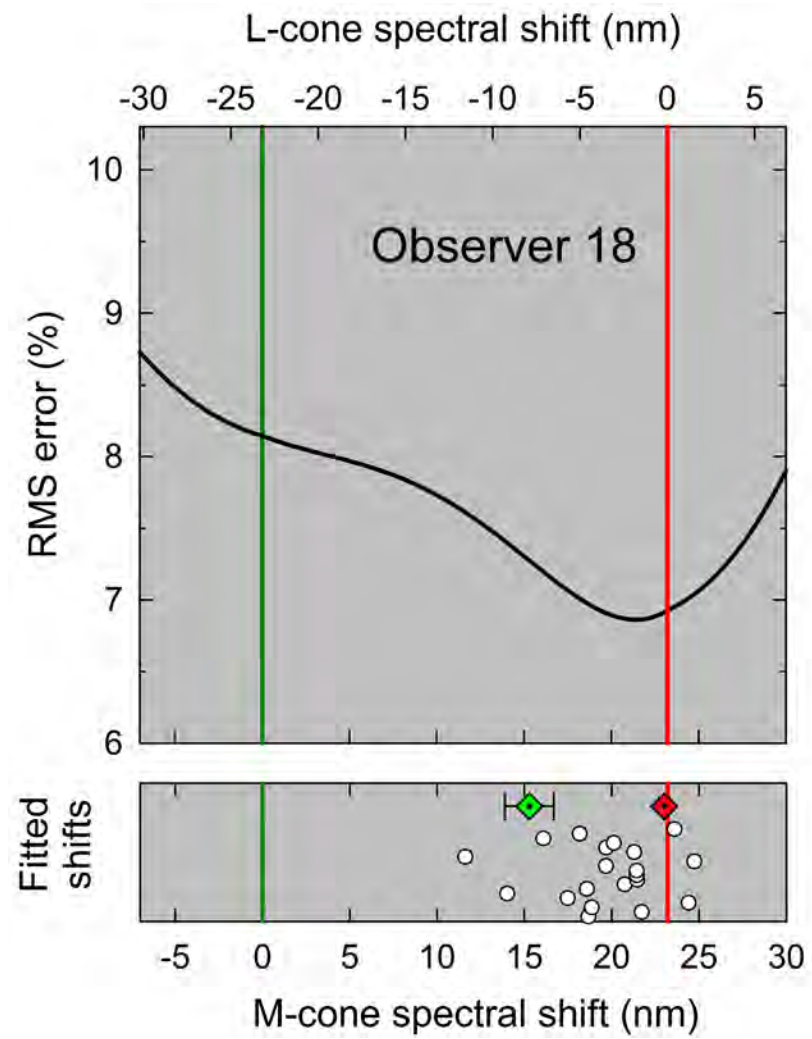


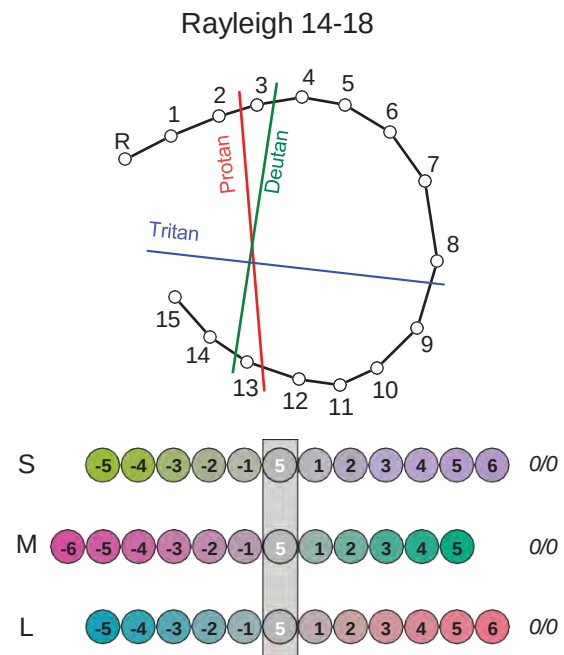
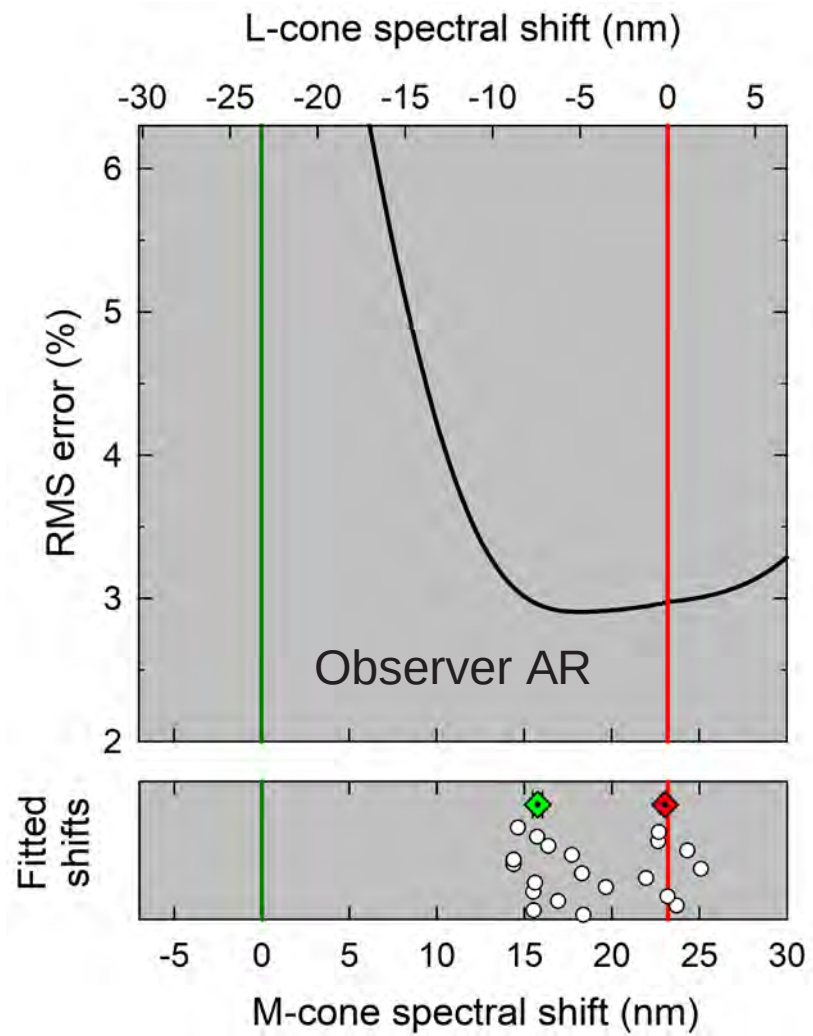


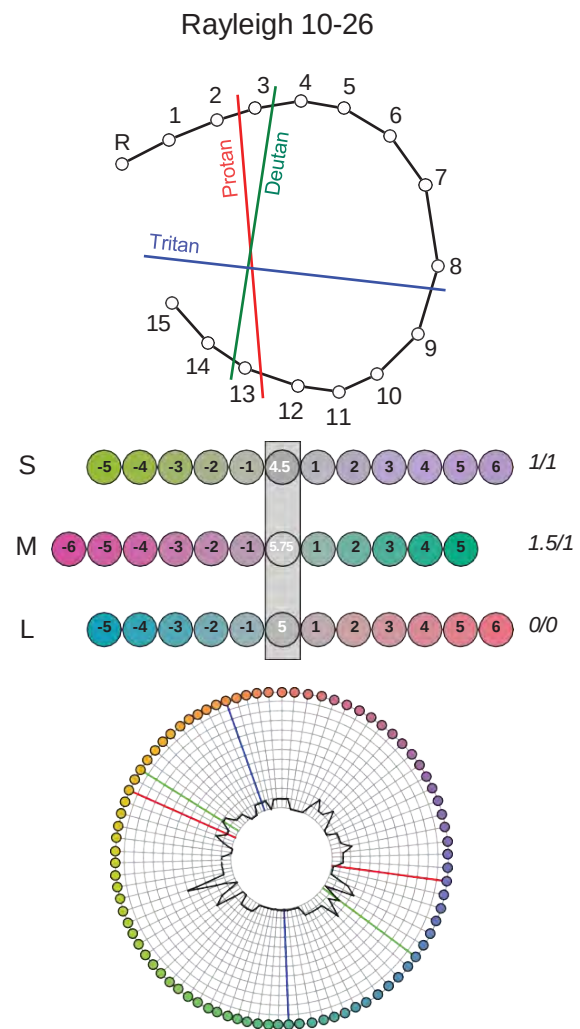
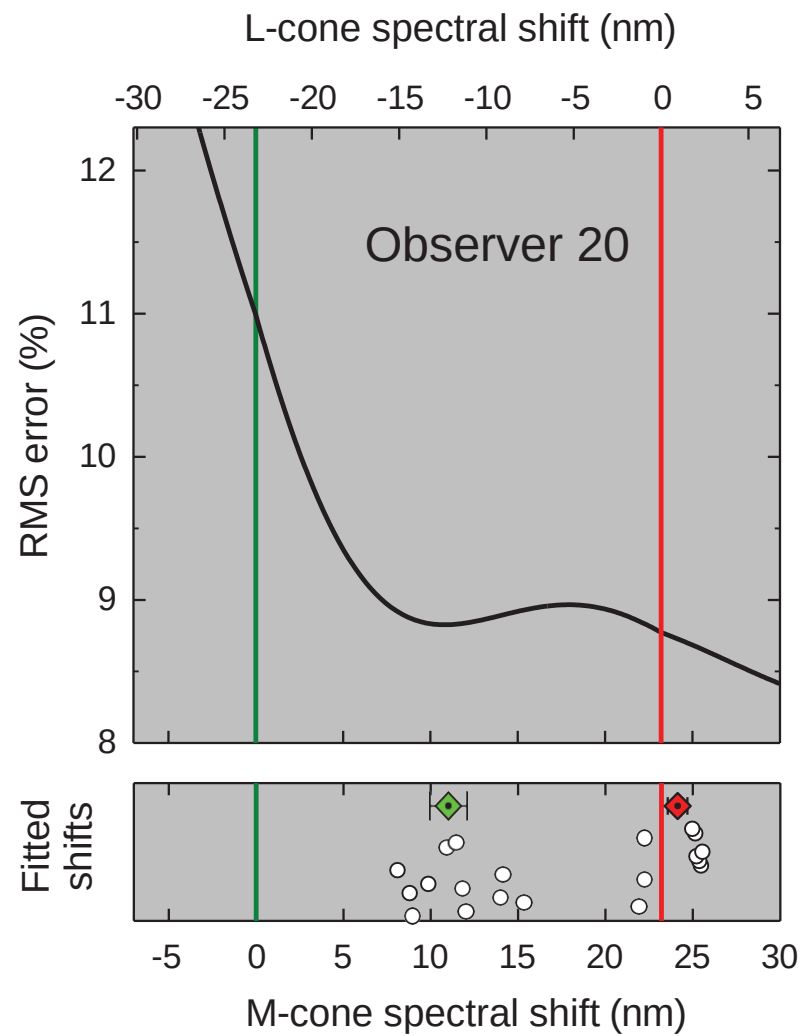


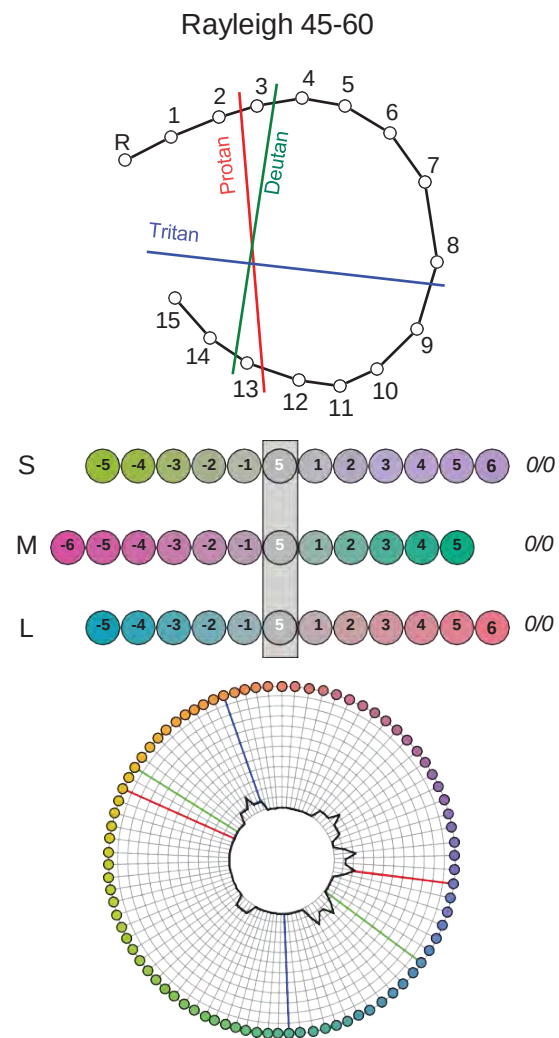
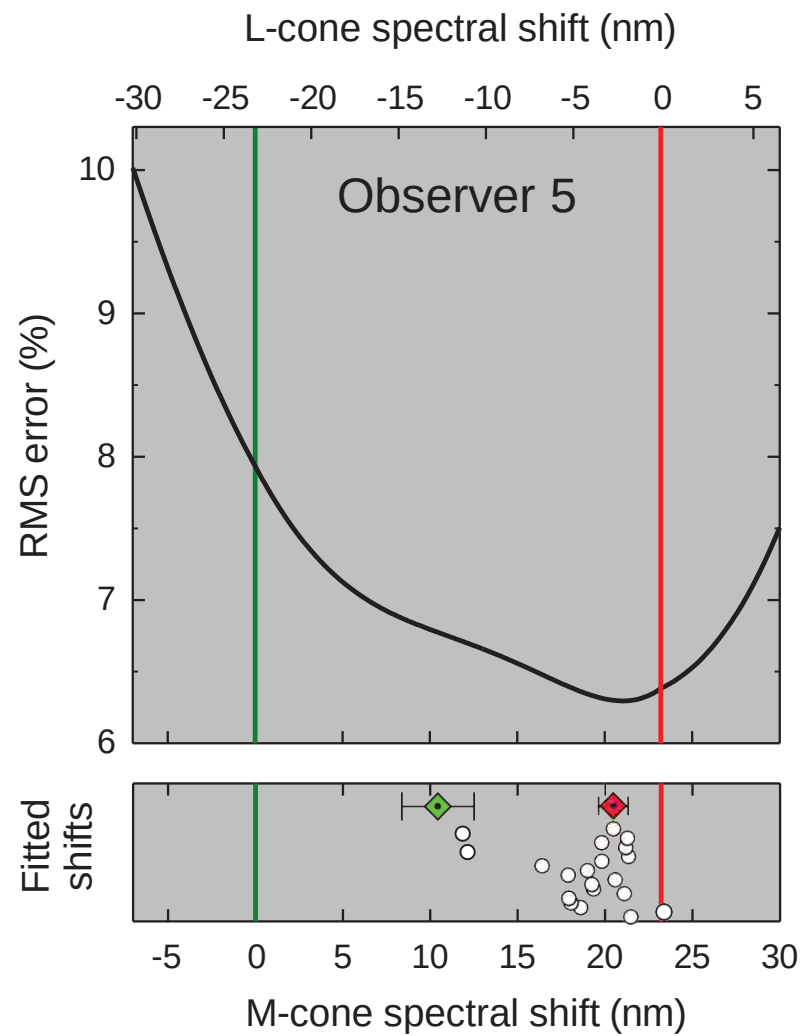


Deuteranomalous

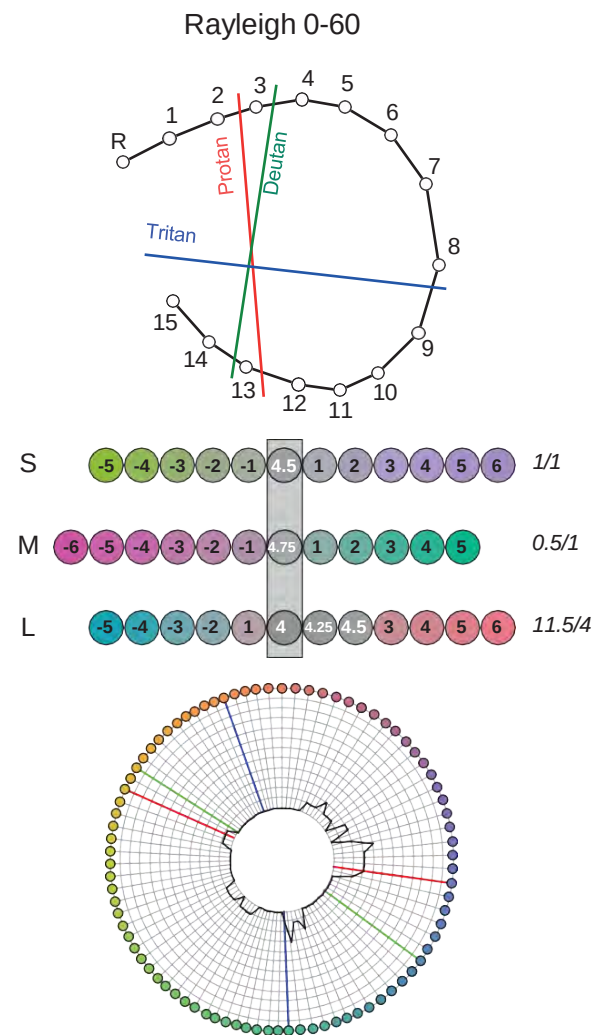
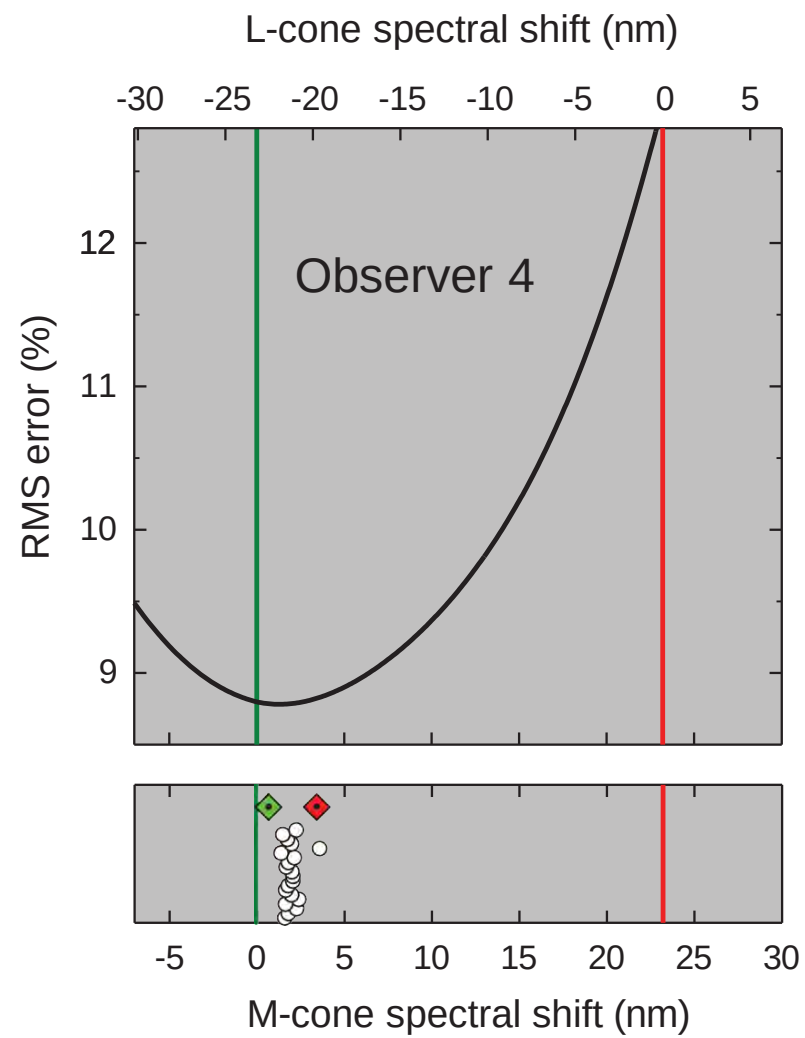


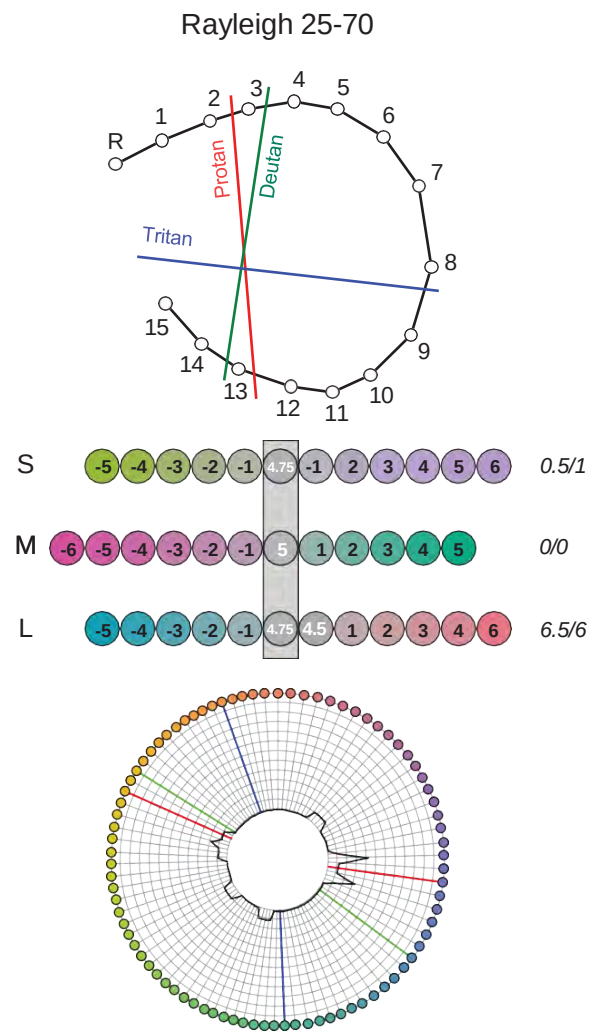
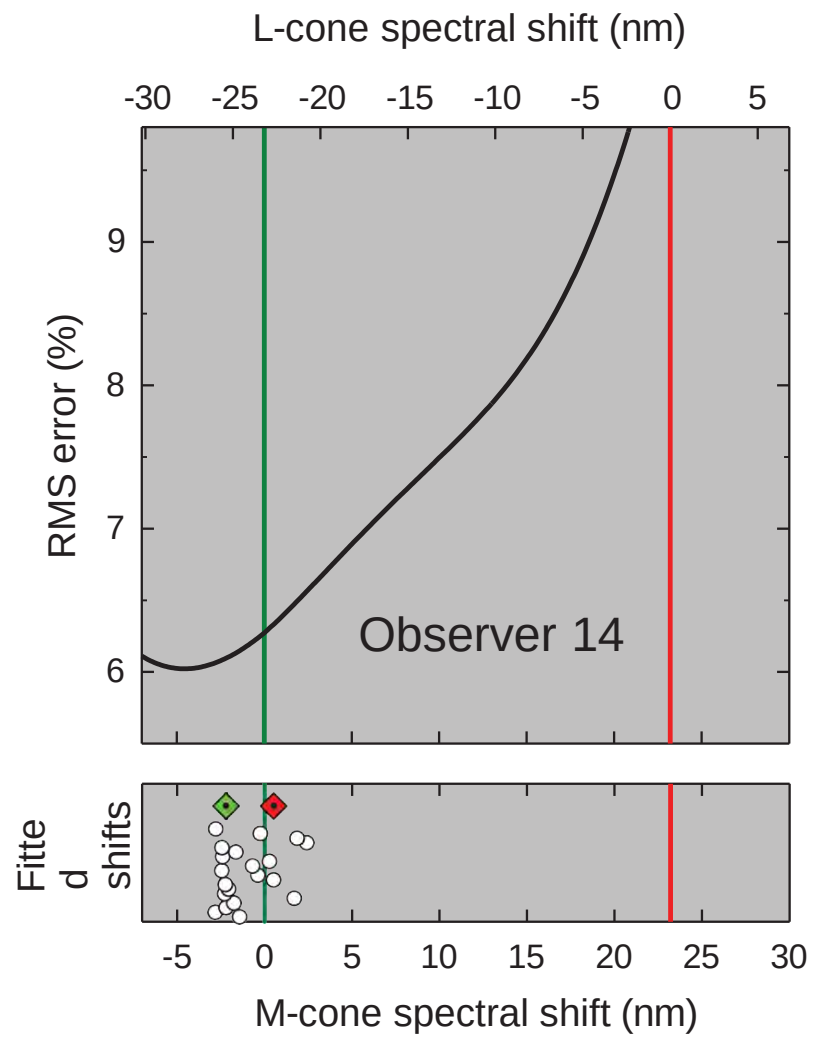


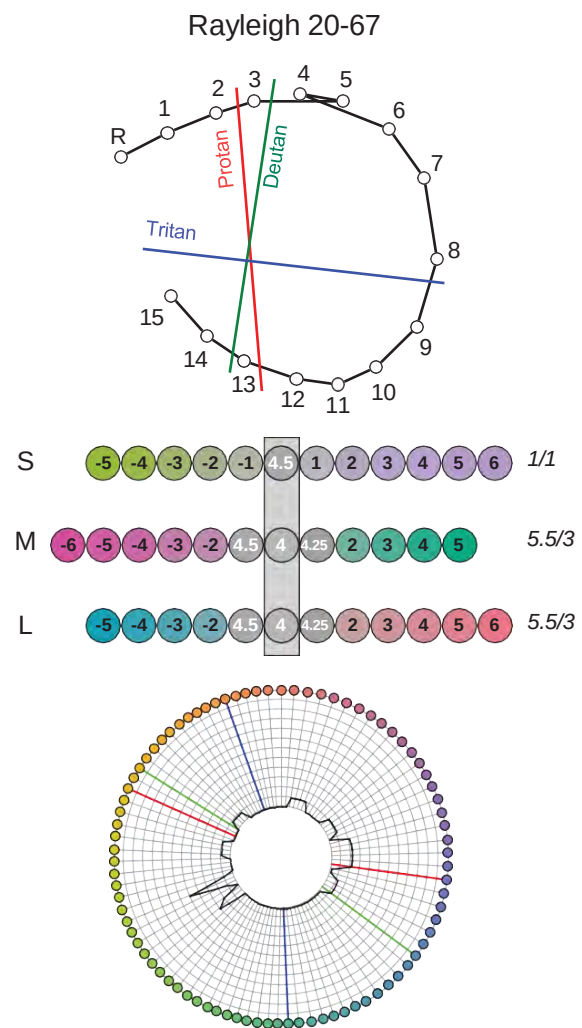
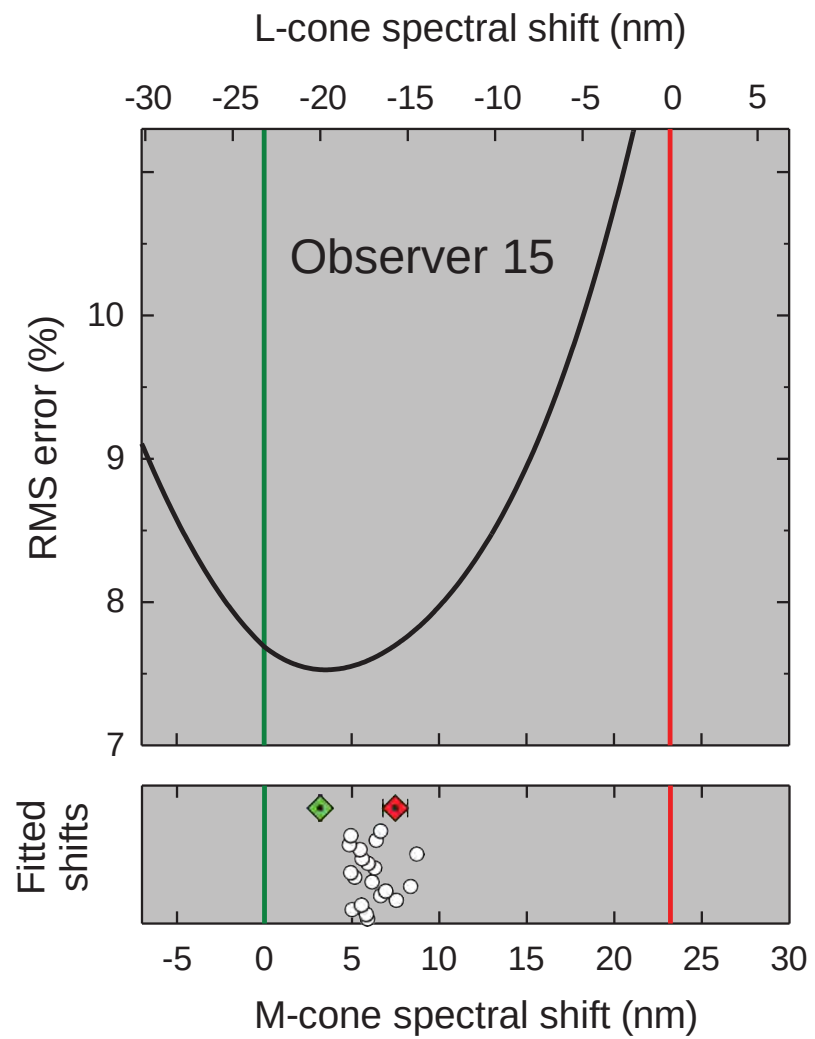




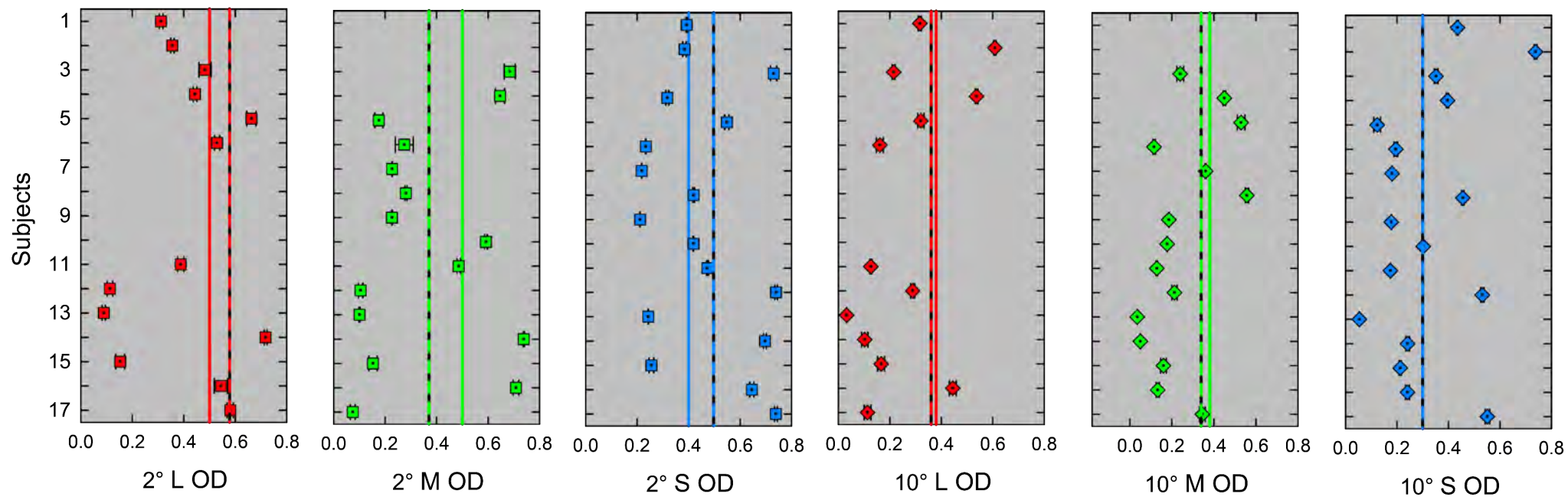
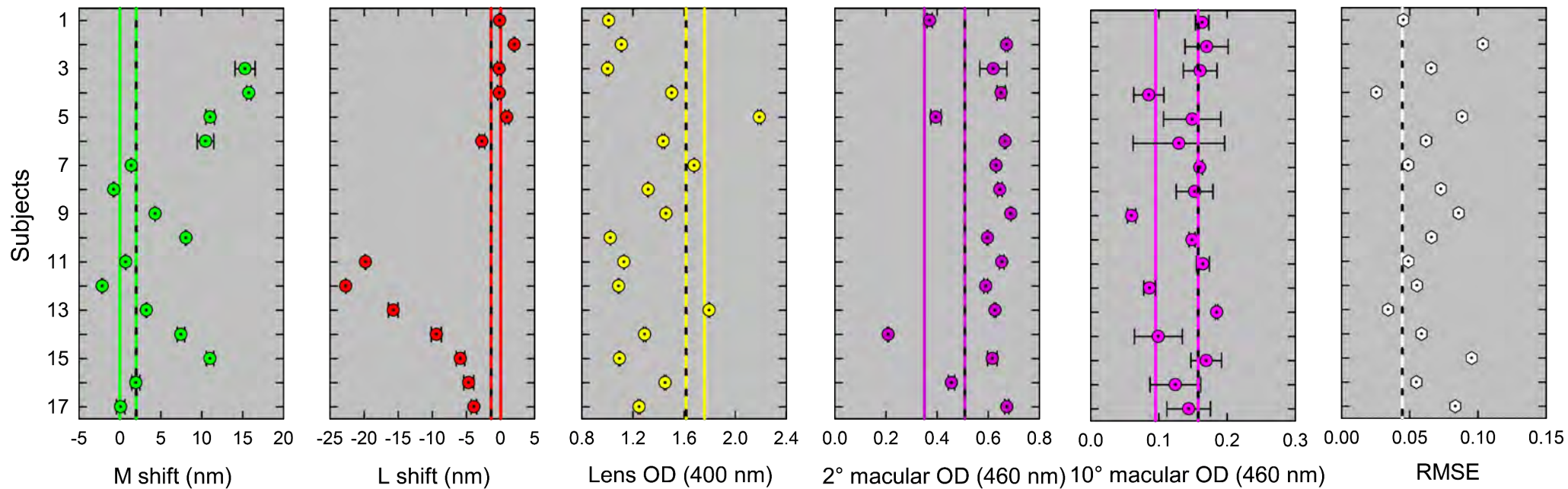
Protanomalous







Deuteranopes
Deuteranomalous
Protanopes
Protanomalous
Double anomalous
Trichromats



Most functions (ancient and modern) and the new
CIE standards can be downloaded from:



CVRL database

<http://www.cvrl.org>

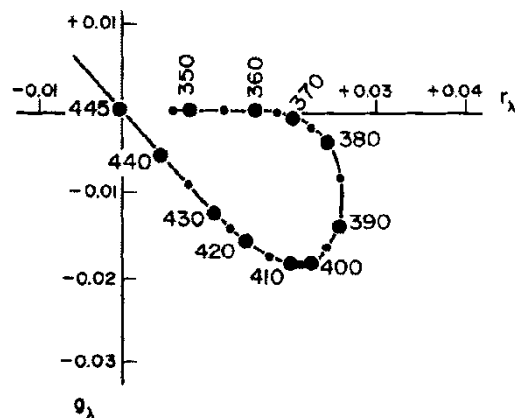


Figure 8. Chromaticity diagram averaged from two aphakic observers in the UV. Subjects matched a split field with primaries at 445 and 625 nm on the left and UV with 525 nm on the right. The color matching functions r_λ , g_λ and b_λ were equated by means of W. D. Wright's (1946) convention with normalizing wavelengths 494 and 582.5 nm. From these the (r_λ, g_λ) chromaticity diagram for UV stimuli, representing the lower left corner of the color triangle, is drawn here. Redrawn from Tan (1971).

Originally from
Tan (1971) thesis

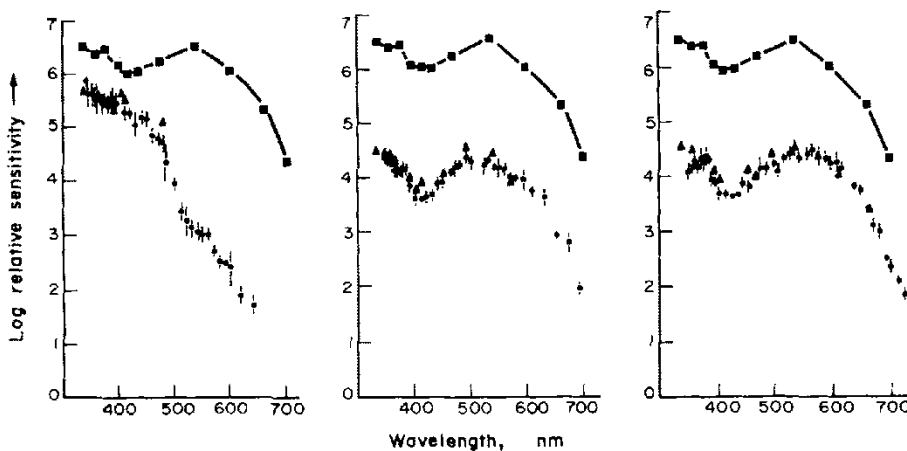
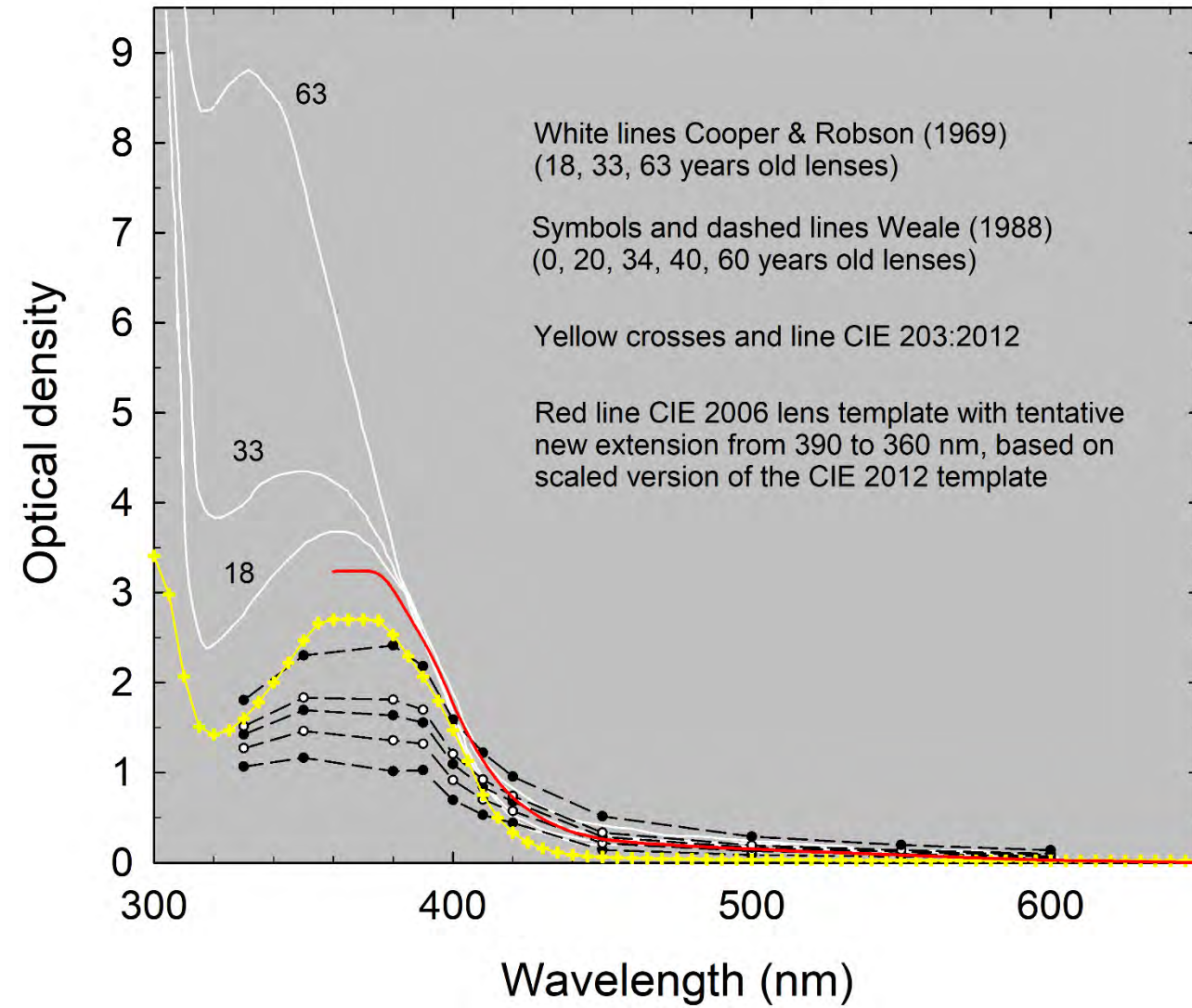


Figure 7. Photopic and cone spectral sensitivities of aphakic observers. (■), Foveal spectral sensitivity which is a composite spectrum of the 3 photopic (cone) spectra. Left: blue cone spectra; (●), give the foveal spectrum obtained against a bright orange background (Wratten 23 A filter, 5.13 log Trolands) averaged for two subjects; (▲), show the spectral sensitivity of the π_3 mechanism determined for one subject. Middle: green cone spectra; (●), foveal spectrum obtained against a bright purple background (Wratten 34 filter, 4.78 log Trolands) averaged for two subjects; (▲), spectral sensitivity of the π_4 mechanism determined for one subject. Right: yellow (red) cone spectra; (●), foveal spectrum obtained against a bright blue background (Wratten 47 filter, 5.22 log Trolands) averaged for two subjects; (▲), show the spectral sensitivity of the π_5 mechanism determined for one subject. Redrawn from Tan (1971).

Aphakics



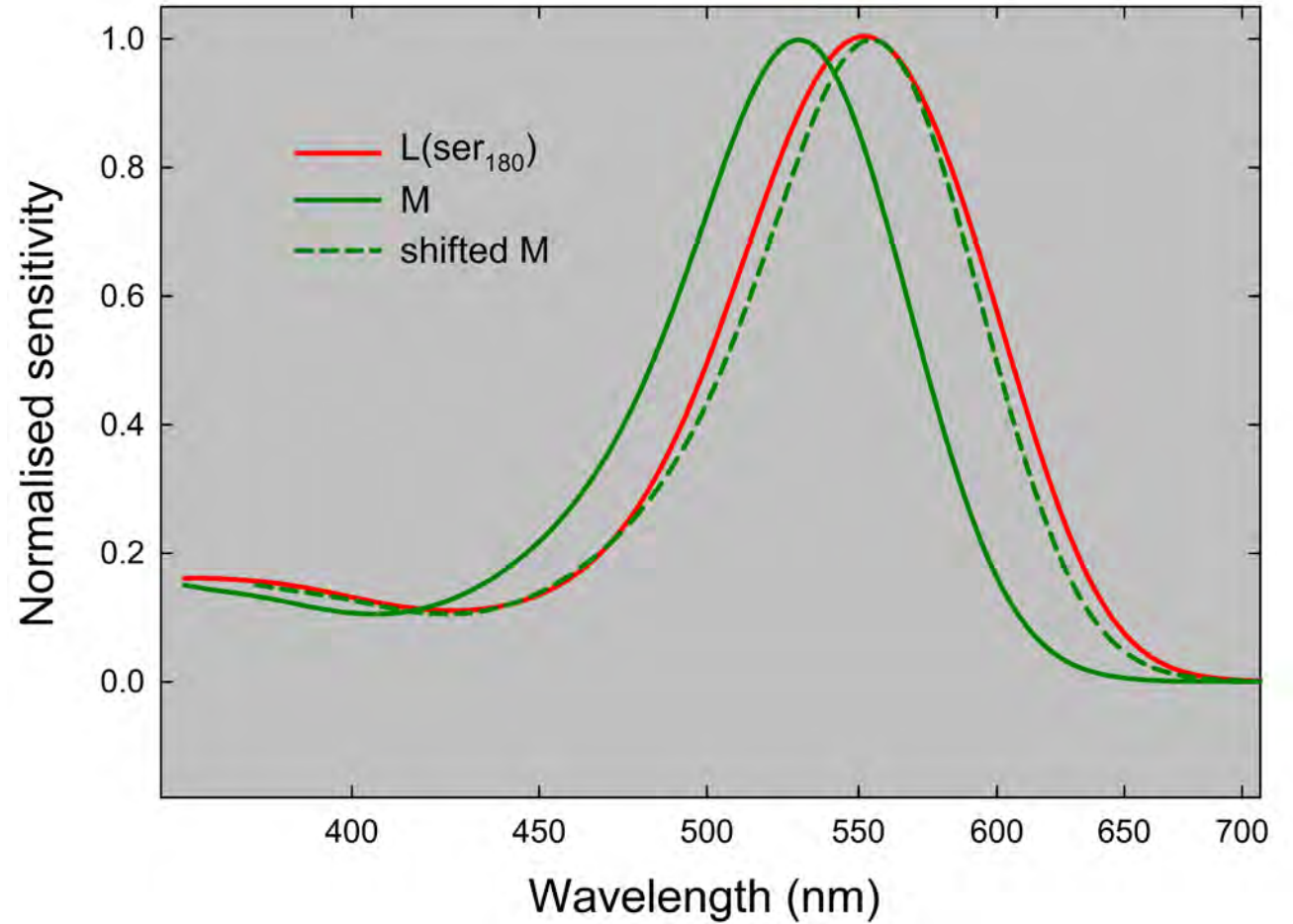
Finding the best parameters

If we vary the $\lambda_{\max}$ (wavelength of peak sensitivity) of the photopigment templates and see how well they describe the matches. For colour normals, we should find two minima in the RMS errors that correspond to the M-cone $\lambda_{\max}$ position and the L-cone $\lambda_{\max}$ position.

So, that's what we did...

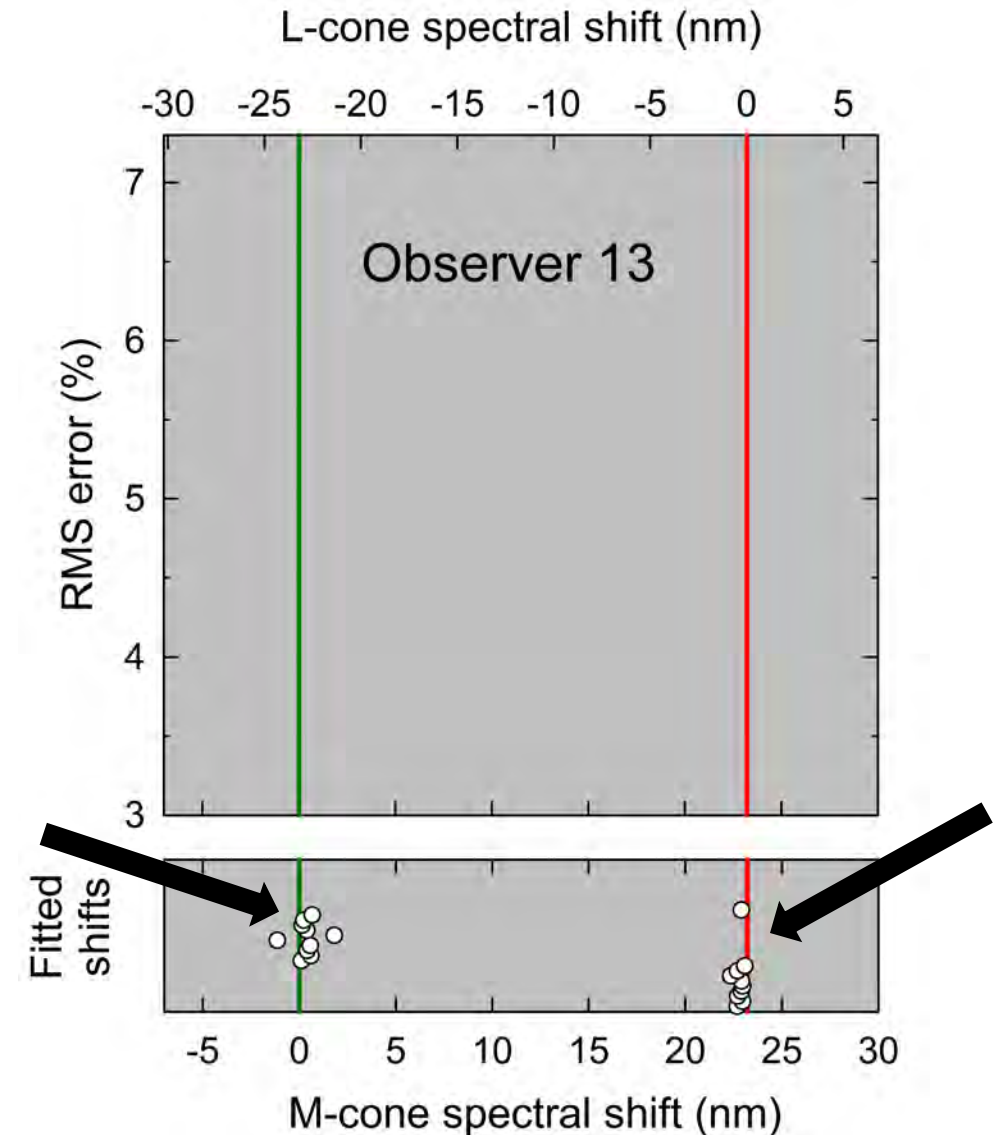
One complication is that the photopigment templates for L(ser_{180}) and M derived from the Stiles & Burch 10° colour matching functions are different in shape even when plotted on a log wavelength scale...

So, we gradually varied the template shape as we varied the $\lambda_{\max}$ wavelength from M to L or vice versa.



Finding the best parameters

First, we made 10 repeated fits* to find all seven parameters (including the spectral shifts). There were no constraints on the shifts except that the M shift had to > -5 and the L shift < 5 nm. (So, all 20 shifts could be for M or L!)



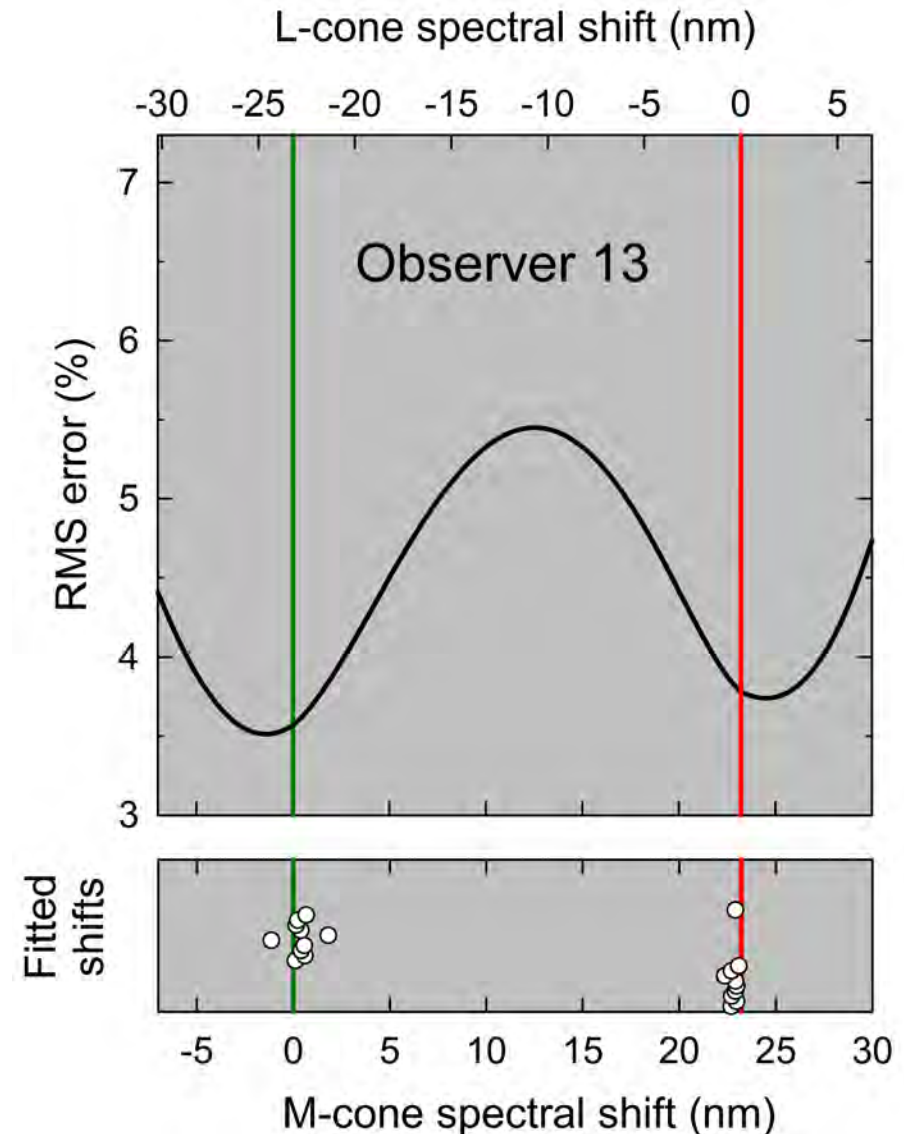
*Matlab's GlobalSearch algorithm using the fmincon

Finding the best parameters

First, we made 10 repeated fits* to find all seven parameters (including the spectral shifts). There were no constraints on the shifts except that the M shift had to > -5 and the L shift < 5 nm. (So, all 20 shifts could be for M or L!)

Second, we fixed the five parameters (other than the M and L shifts) at the mean values for the 10 fits, and then...

scanned across wavelengths to calculate the RMS at each spectral shift and (hopefully) find the two minima in the fits.



*Matlab's GlobalSearch algorithm using the fmincon

Finding the best parameters

Finally, we made 10 repeated fits allowing all seven parameters to vary but constraining the L and M shifts to be spectrally separated below and above the maximum separating the two minima.

We performed this analysis on the colour matching data for 30 observers (numbered 11 to 40) aged between 20 and 30 from China. There were 15 male observers and 15 female observers.

Here are the results...

