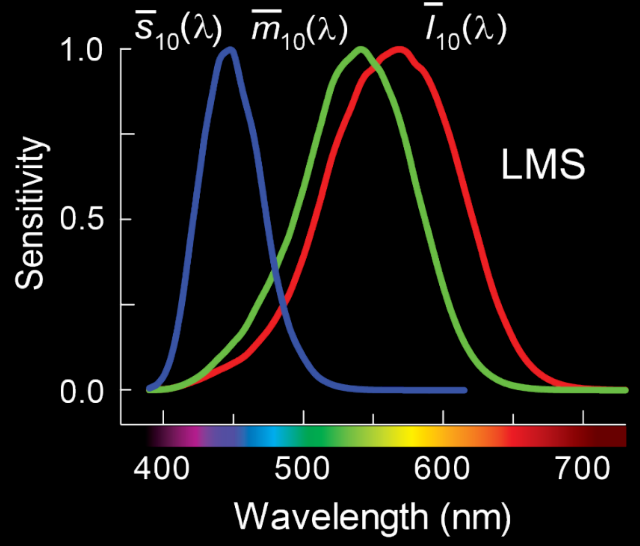
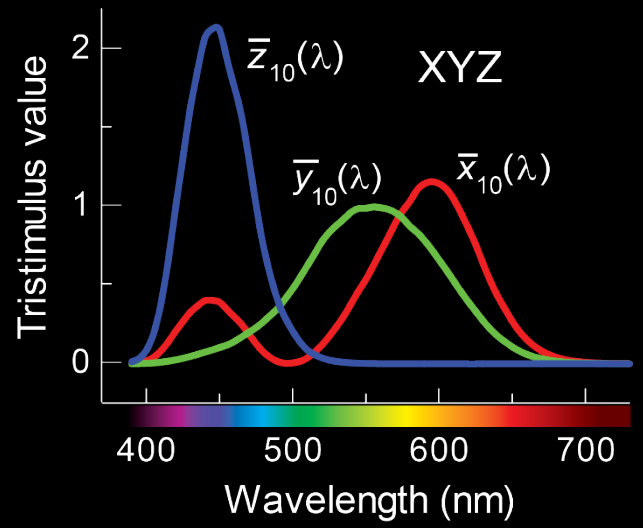
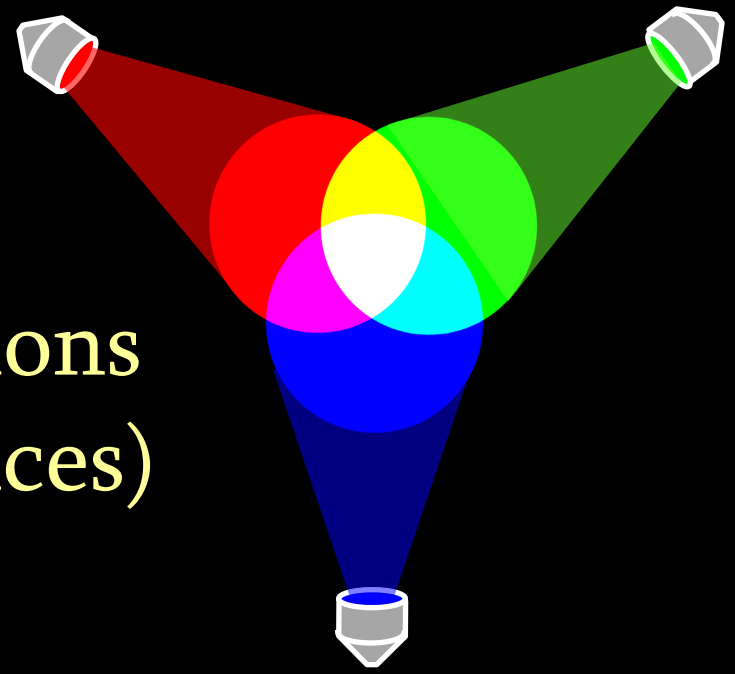


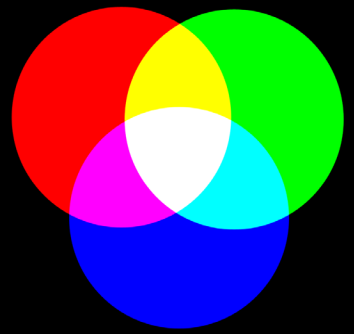


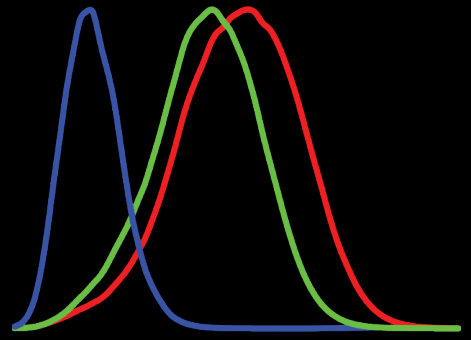
Colour matching functions (and individual differences)

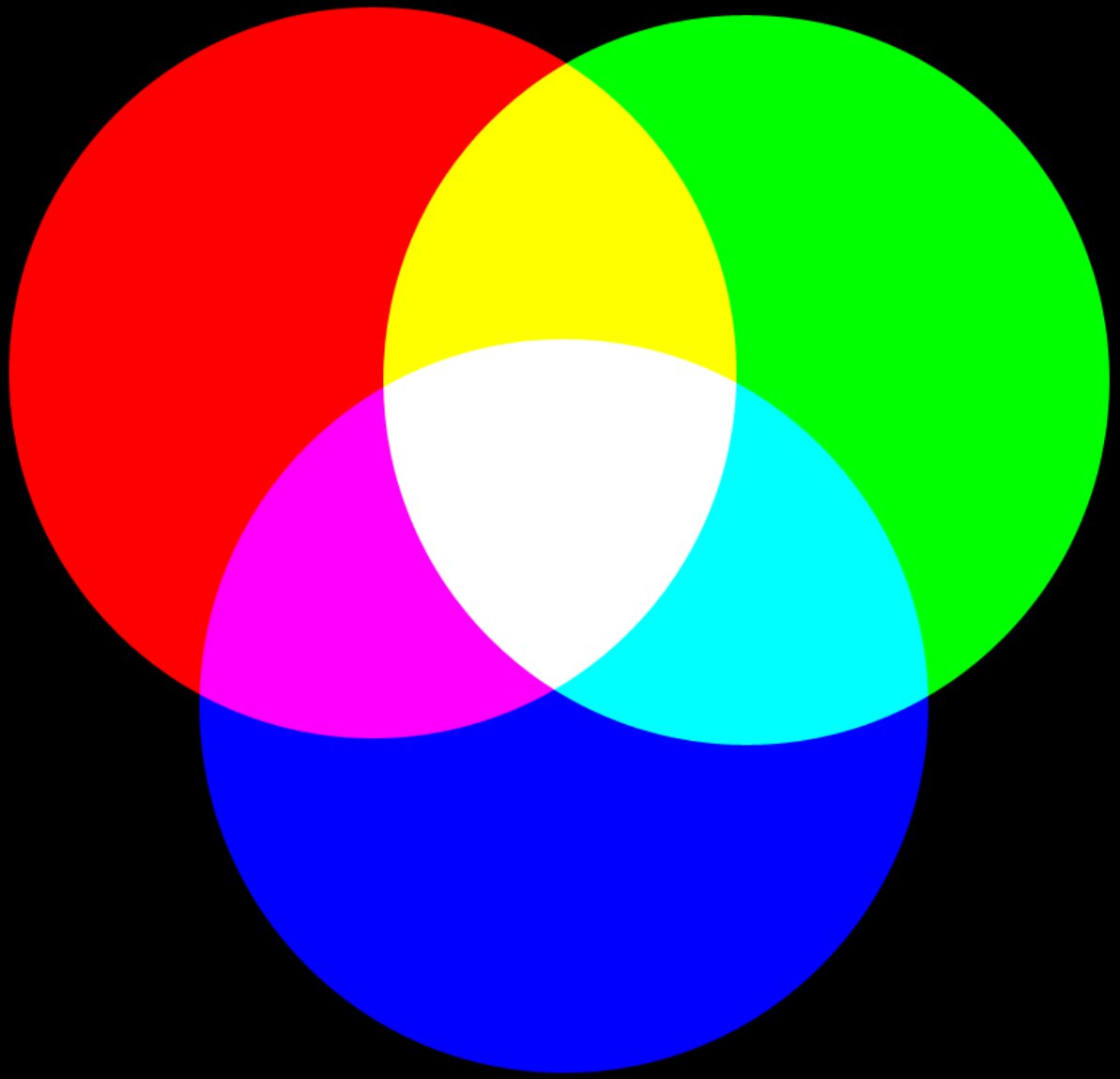
Andrew Stockman



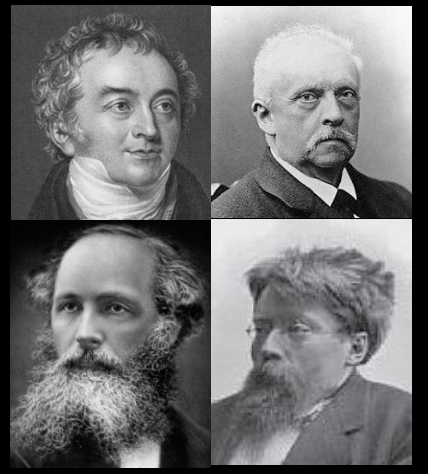
1. TRICHROMACY AND THE CONE SPECTRAL SENSITIVITIES







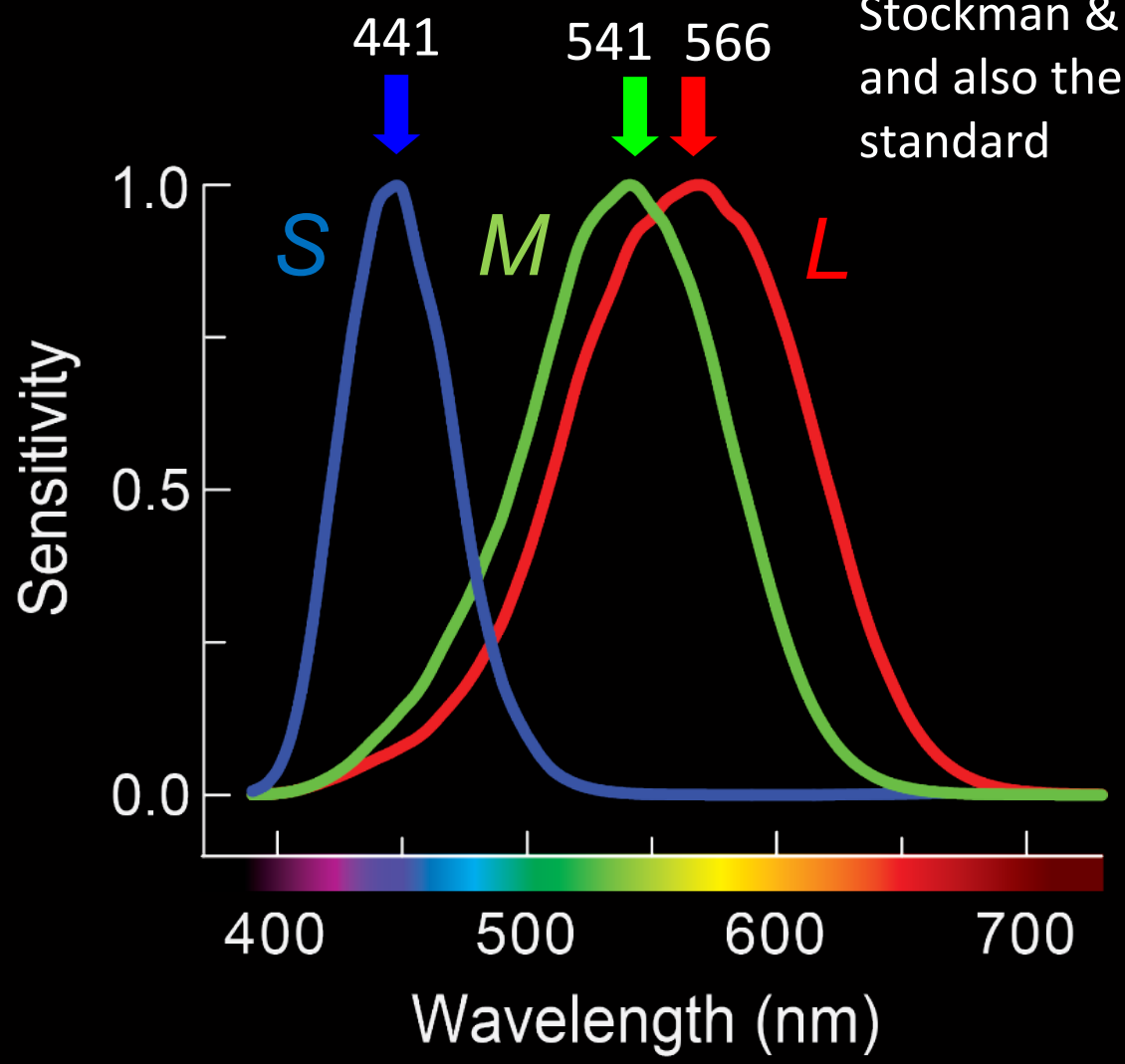
Trichromacy



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

It is a 3-variable system…

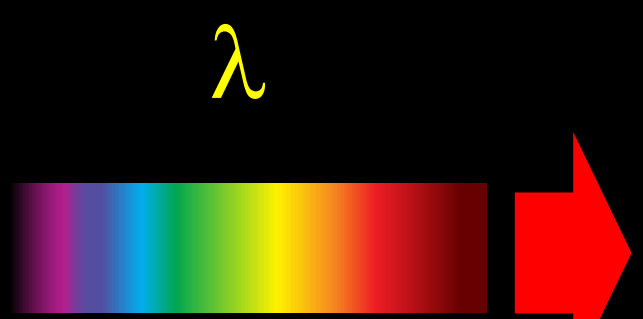
Trichromacy arises because there are just three cone types each of which is “univariant” (*i.e.*, responds only according to the number of photons it absorbs independent of their wavelengths) and each of which has a different spectral sensitivity.

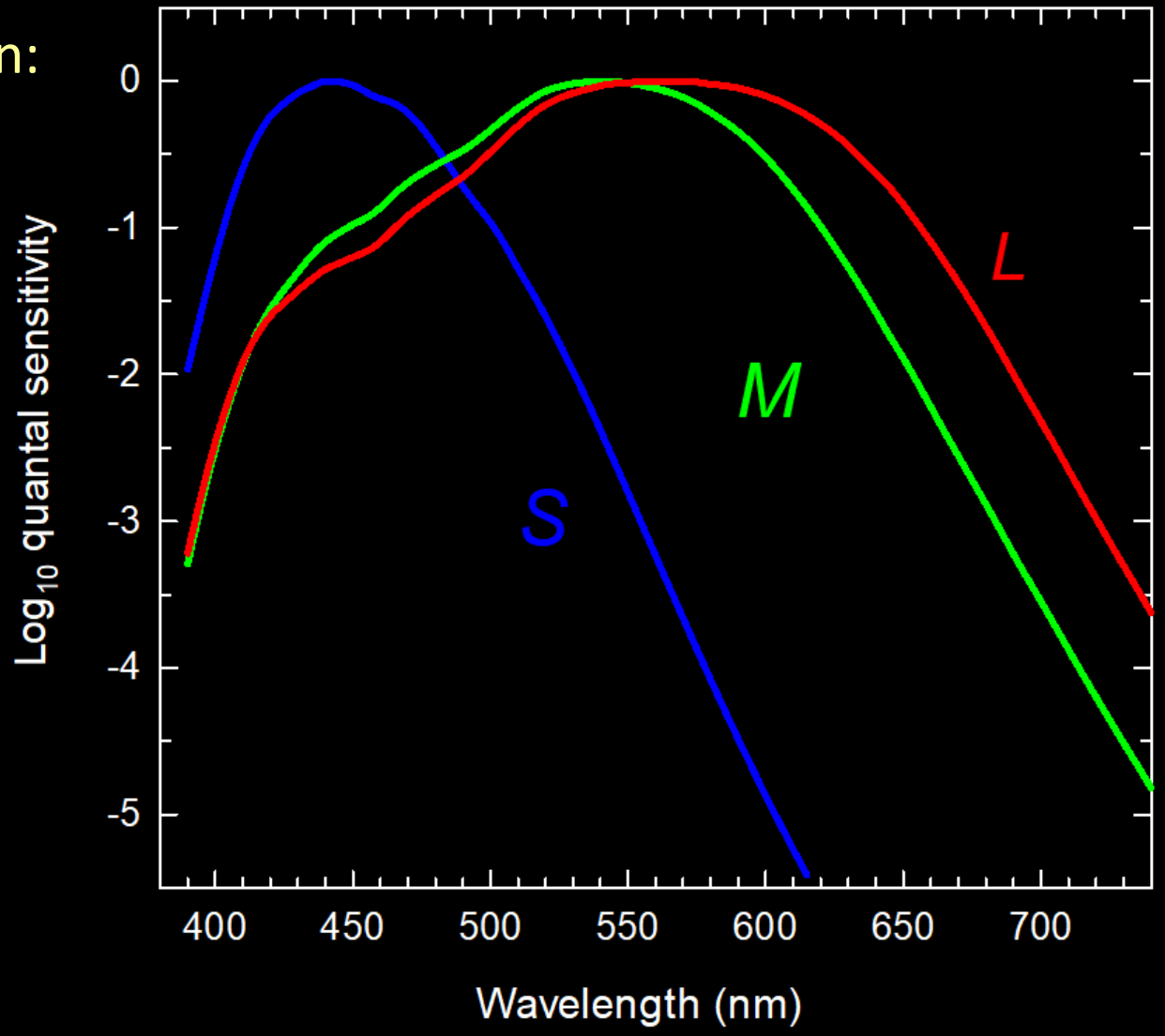


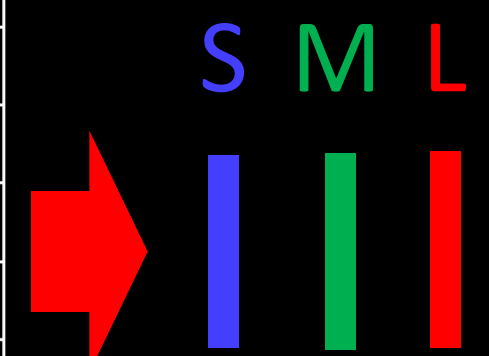
If we know the three spectral sensitivities, and thus the effects that a light has on the three cones, we can completely specify that light.

Information loss

At the first stage of vision:



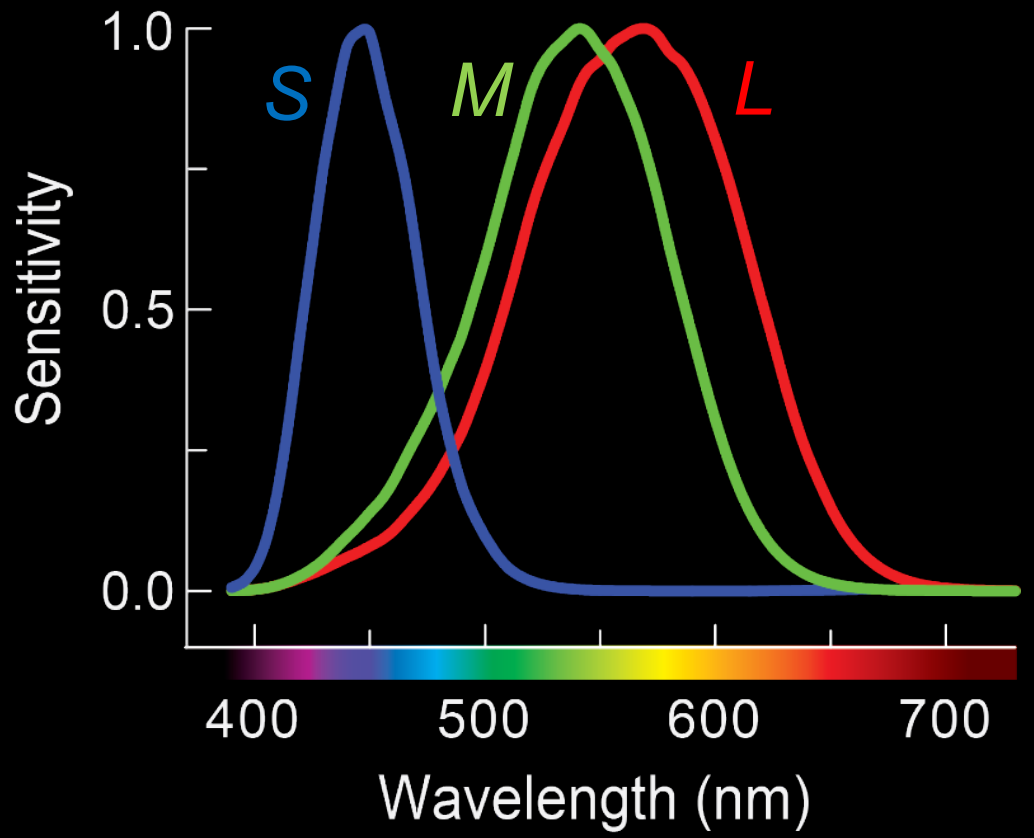




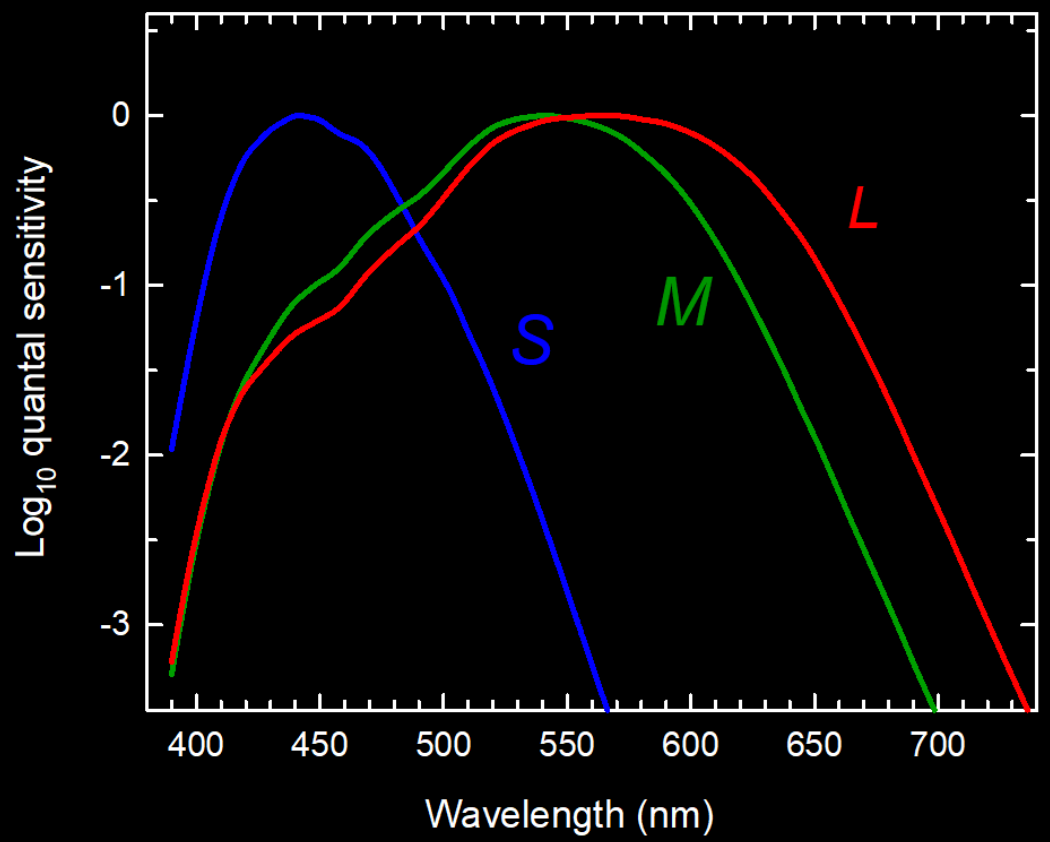
there is a massive loss
of spectral information!

I'll be showing linear and logarithmic versions of the cone spectral sensitivities:

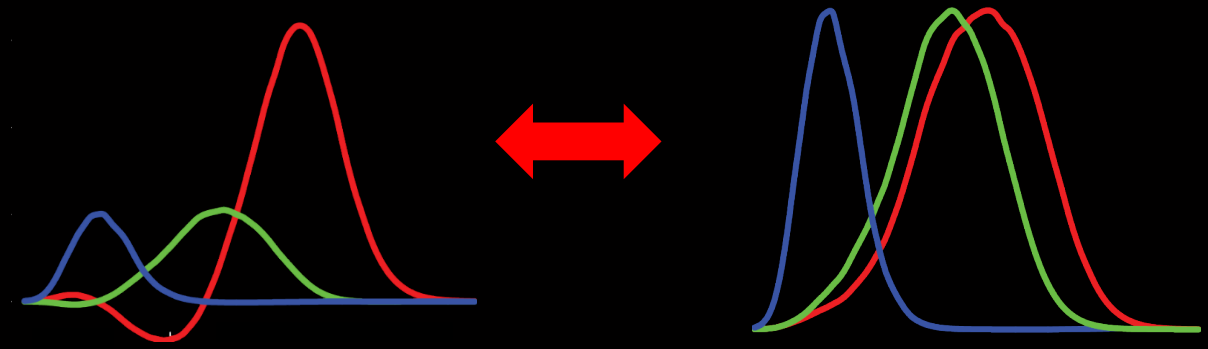
Linear



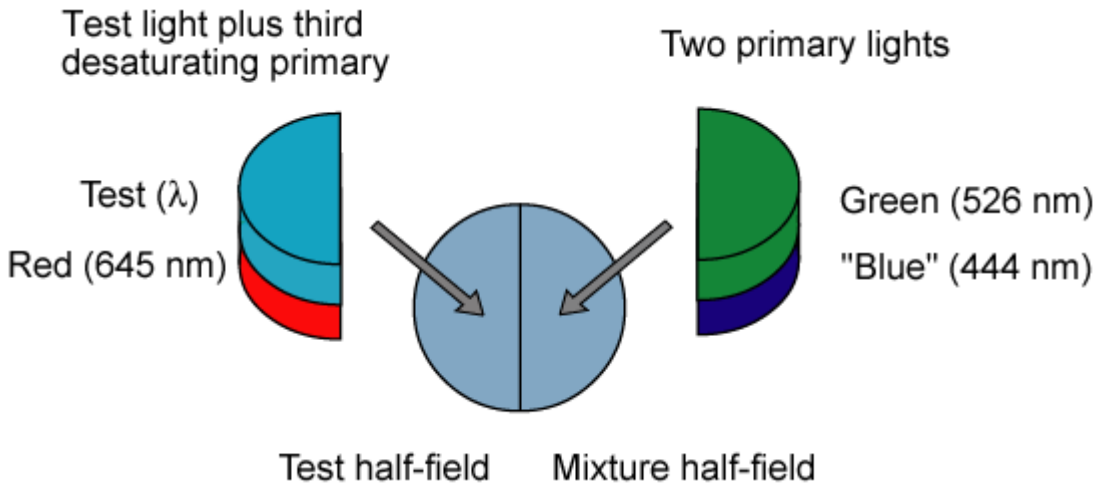
Logarithmic

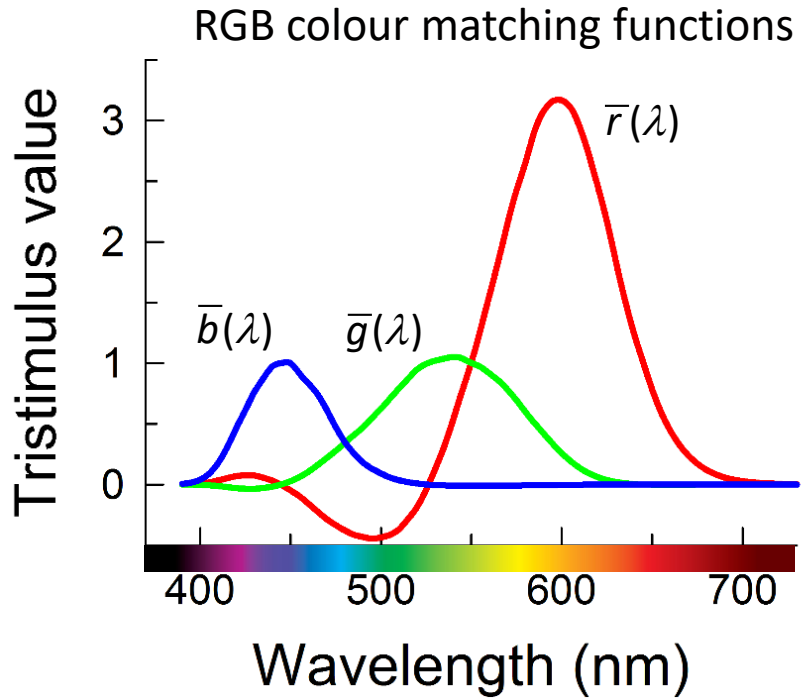


2. CONE SPECTRAL SENSITIVITIES AND COLOUR MATCHING FUNCTIONS



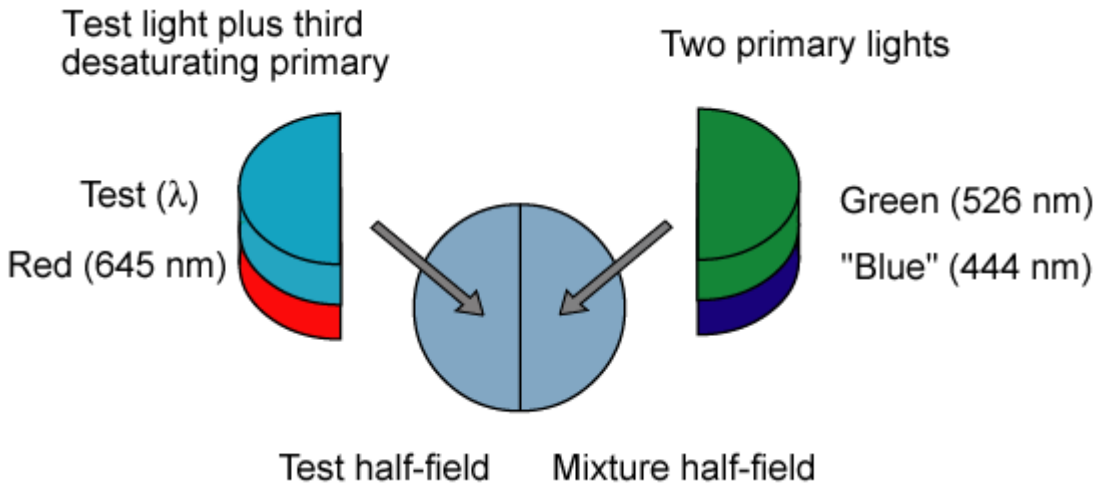
Another way of specifying colours that does not depend on knowing the cone spectral sensitivities is by making colour matches in a colour matching experiment:

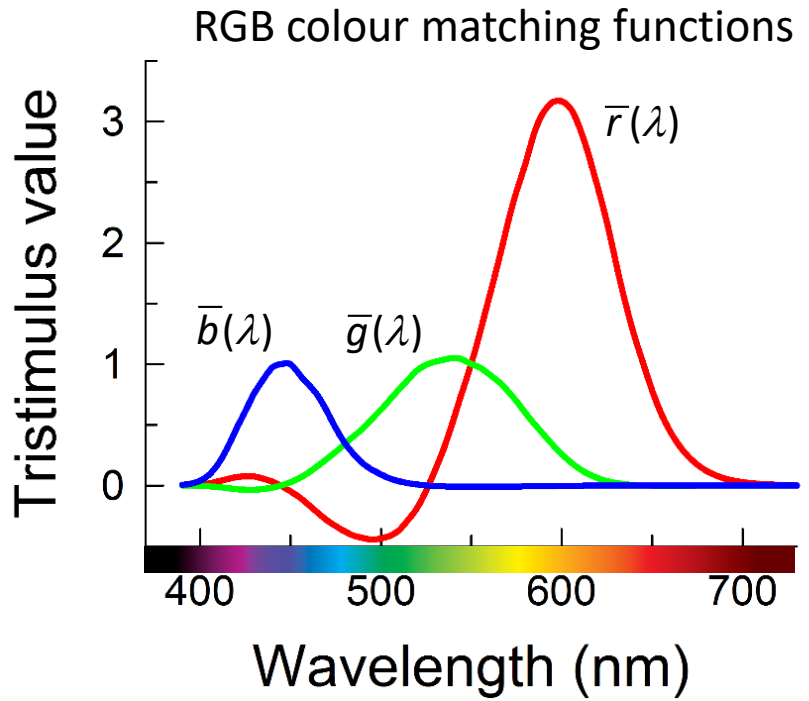




Another way of specifying colours that does not depend on knowing the cone spectral sensitivities is by making colour matches in a colour matching experiment:

But what has this got to do with cone spectral sensitivities?





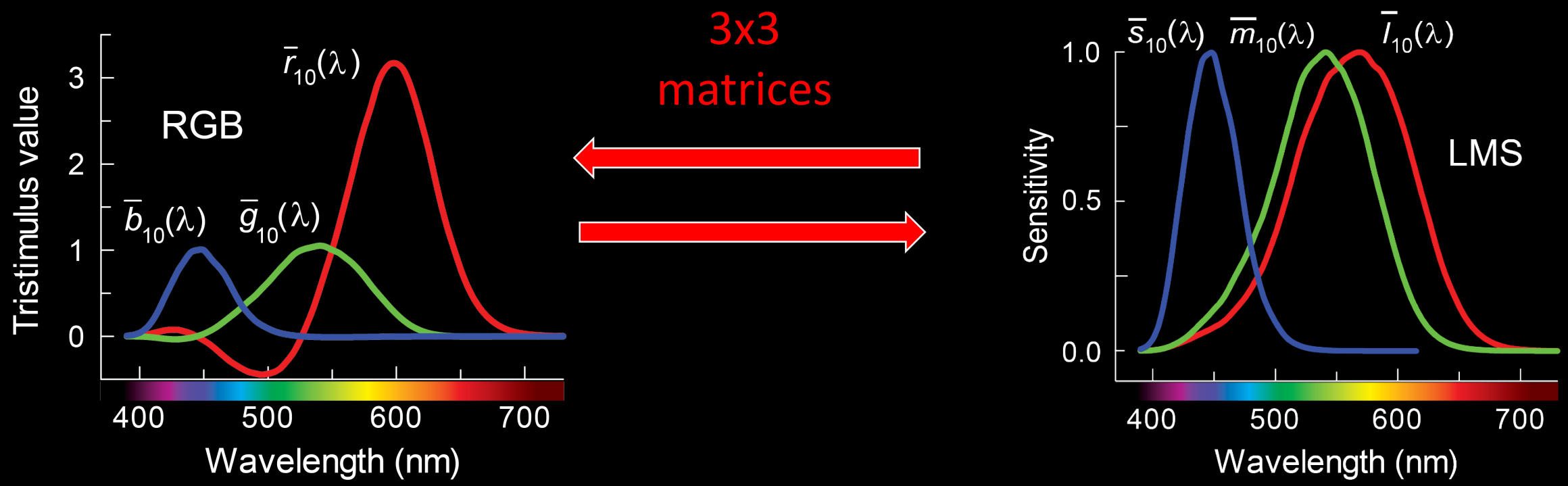
All colour matches are matches at the cone level and depend on the spectral sensitivities of the cones.

Consequently, the cone spectral sensitivities are the:

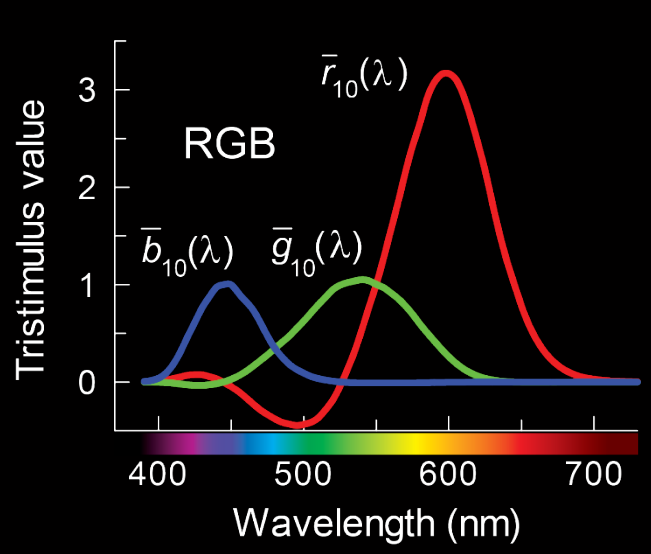
"Fundamental" colour matching functions

…upon which all other CMFs depend.

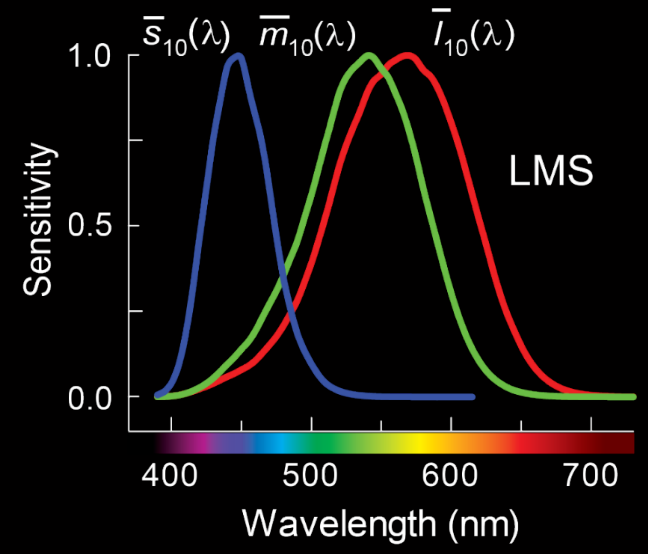
Accordingly, there exist simple linear transformations between RGB and LMS…

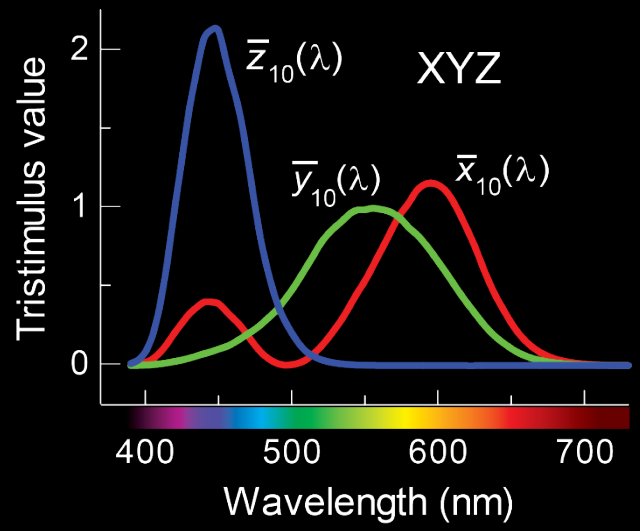


And also between RGB and LMS and XYZ.



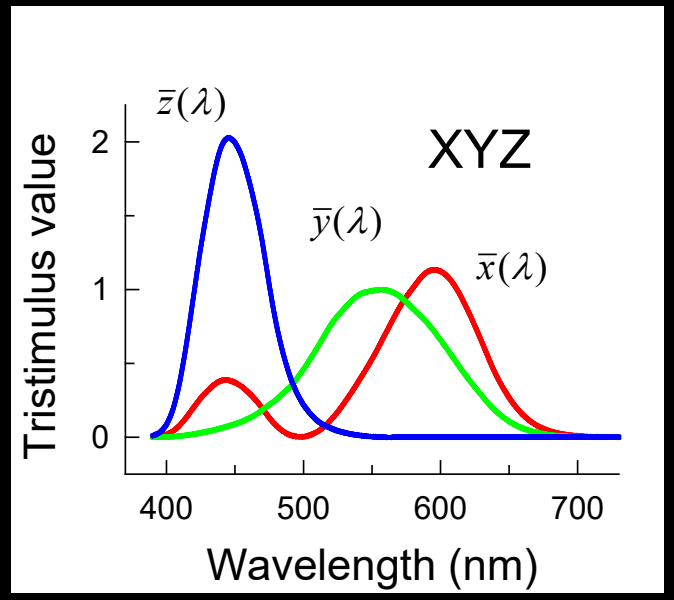
Linear transformations





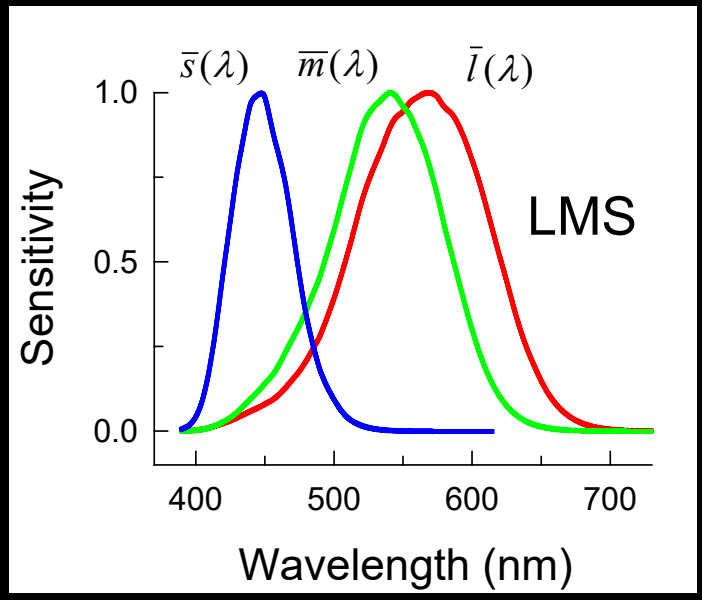
However, not all CMFs are physiologically correct…

CIE 1931 2-deg XYZ (or RGB) CMFs



Why?

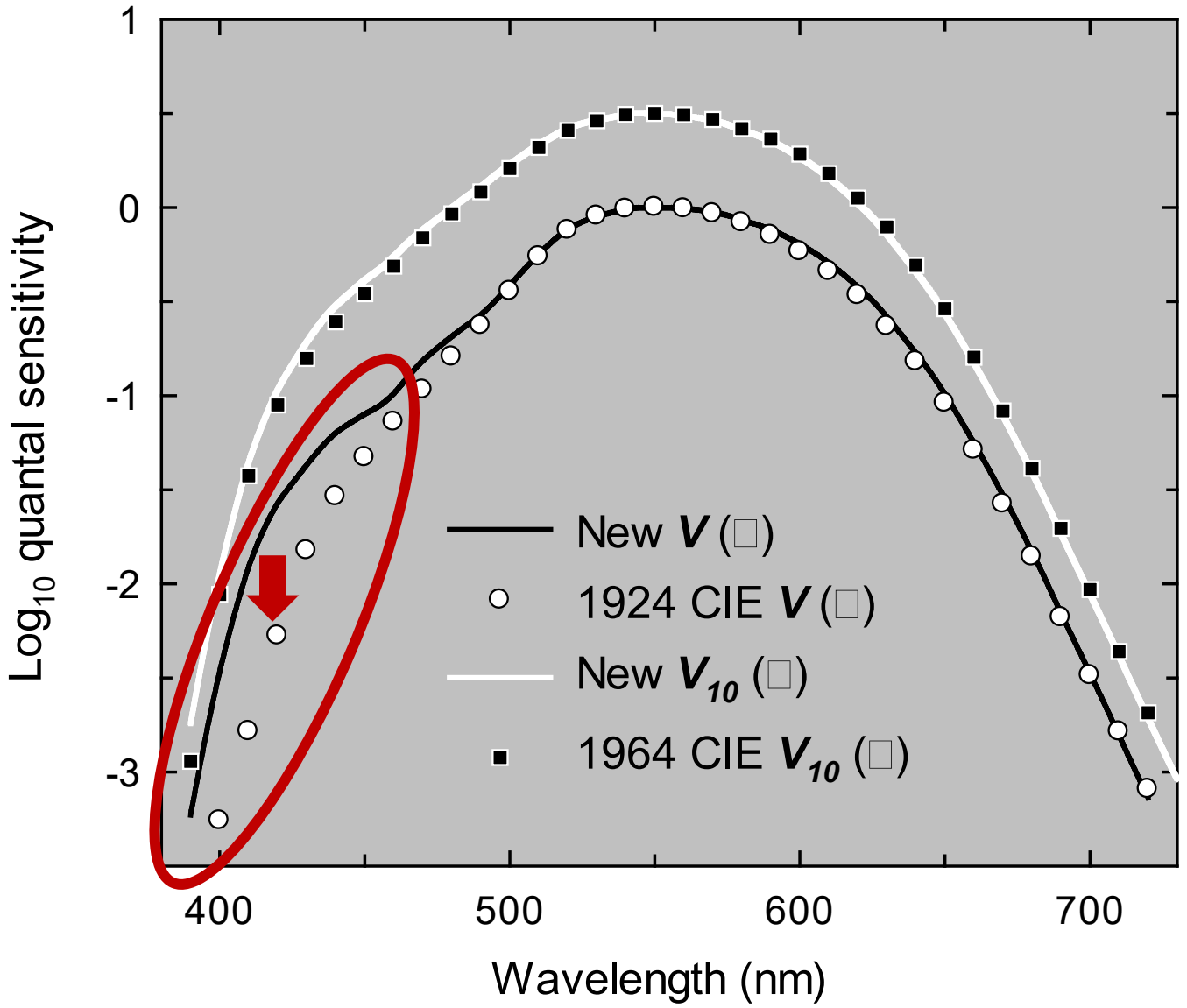
2-deg LMS cone fundamentals



Old and new V(λ) functions

There is a large error in CIE 1931 Y, which is also CIE 1924 V(λ)…

But, why??

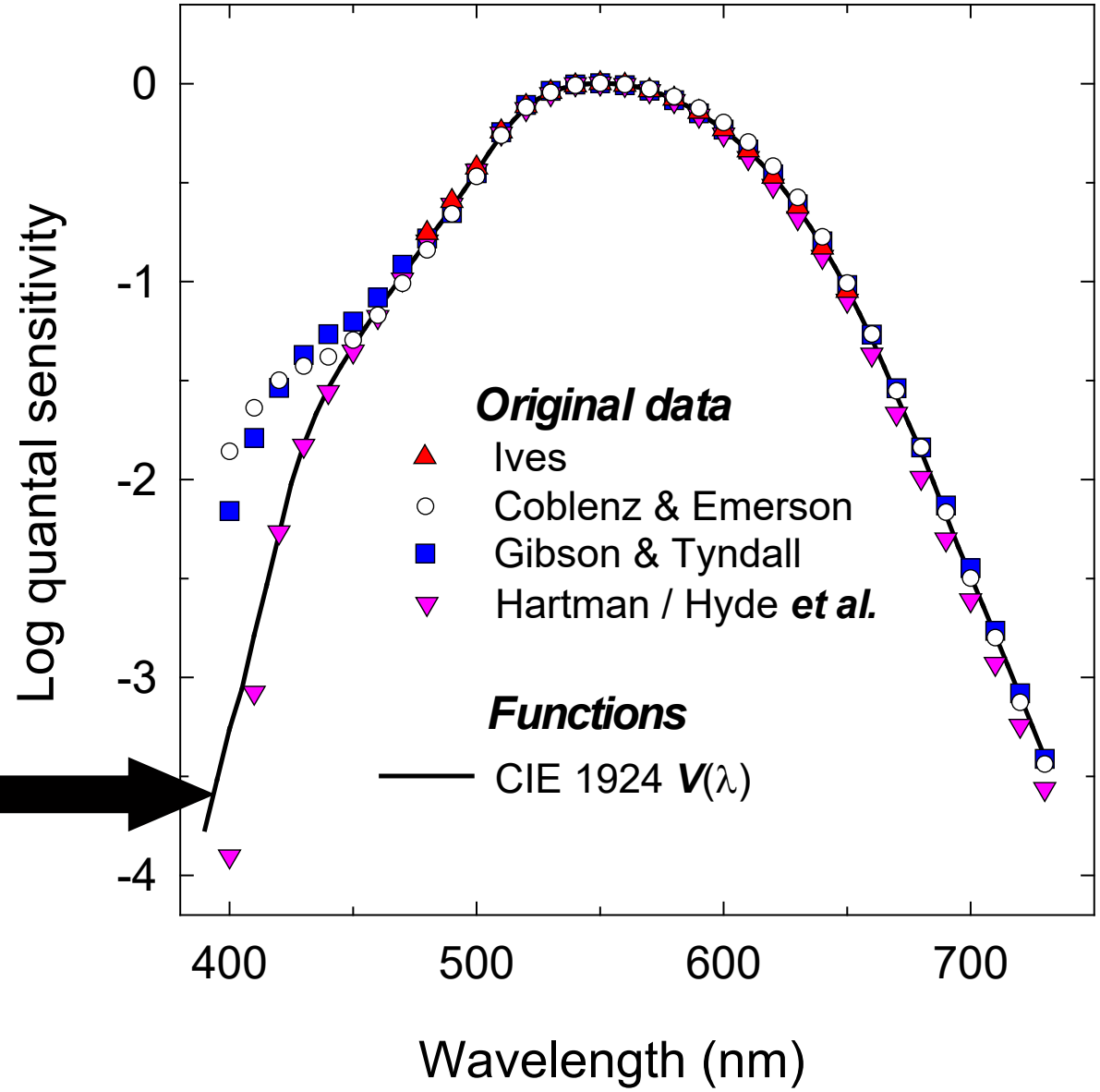


The mistake is related to the choice of V(λ) back in 1924…

Original data used to derive CIE V(λ) (which is also CIE Y)

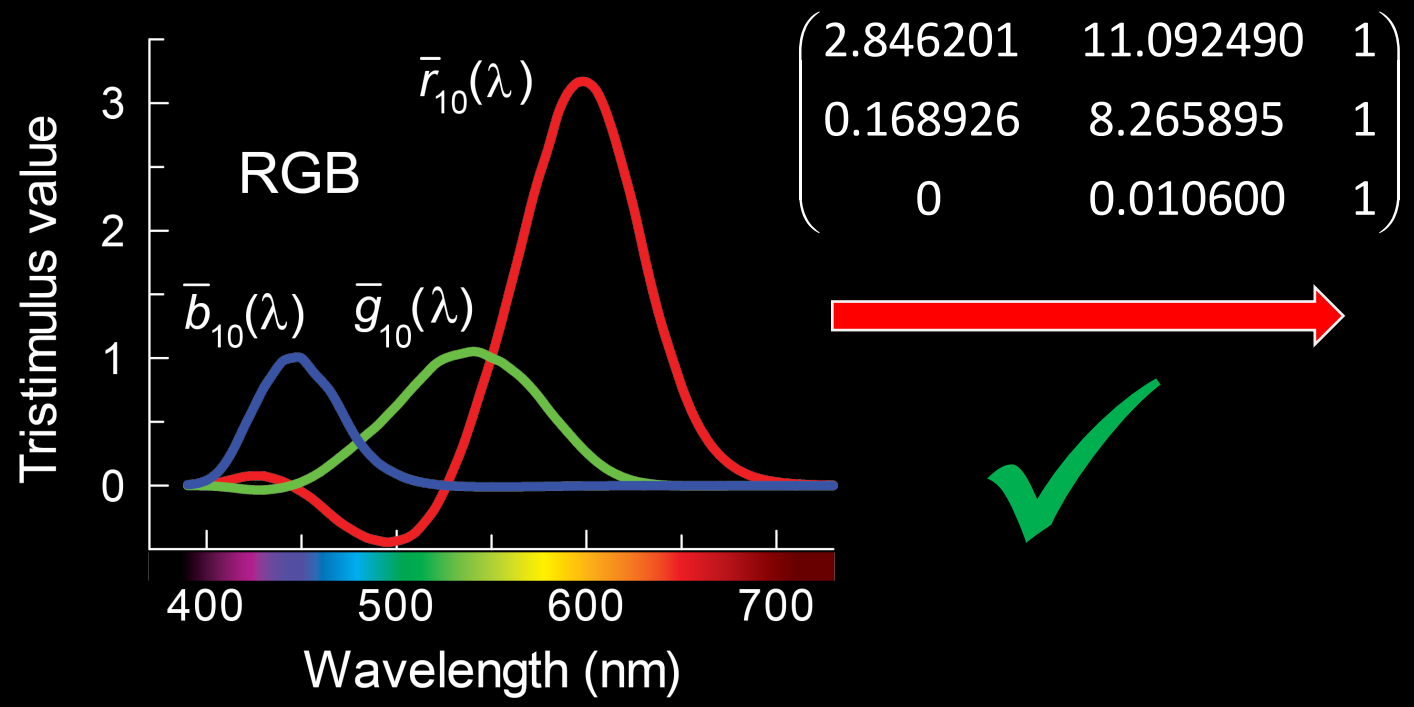
Here's what the CIE chose in 1924!!

This unfortunate choice continues to plague colorimetry and photometry 100 years later

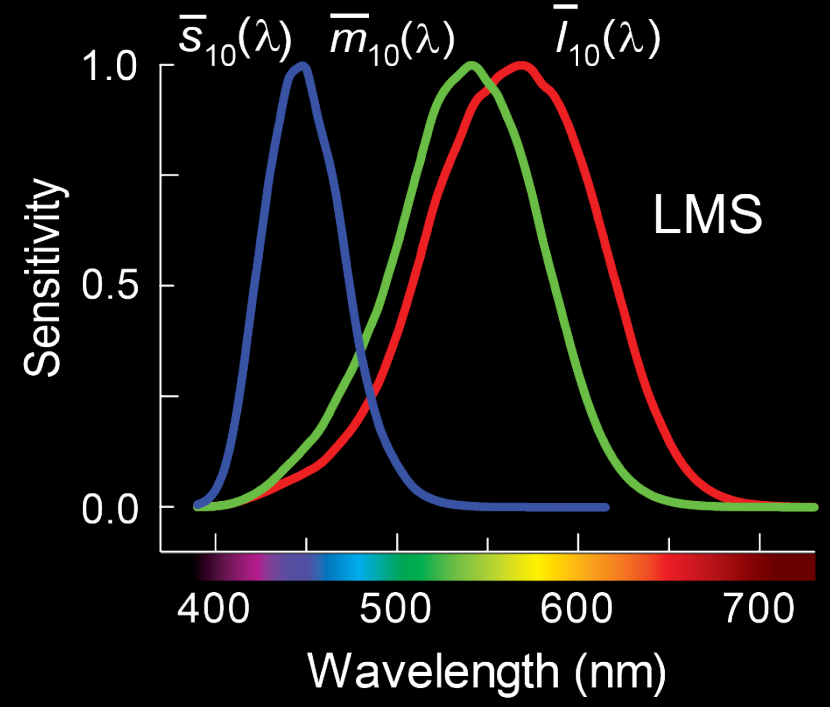


The CIE 2006 standard 10° LMS functions are defined as a linear transformation of Stiles & Burch (1959) 10° RGB CMFs:

These functions represent the average or “standard” spectral sensitivity or colour matching functions for normal observers.

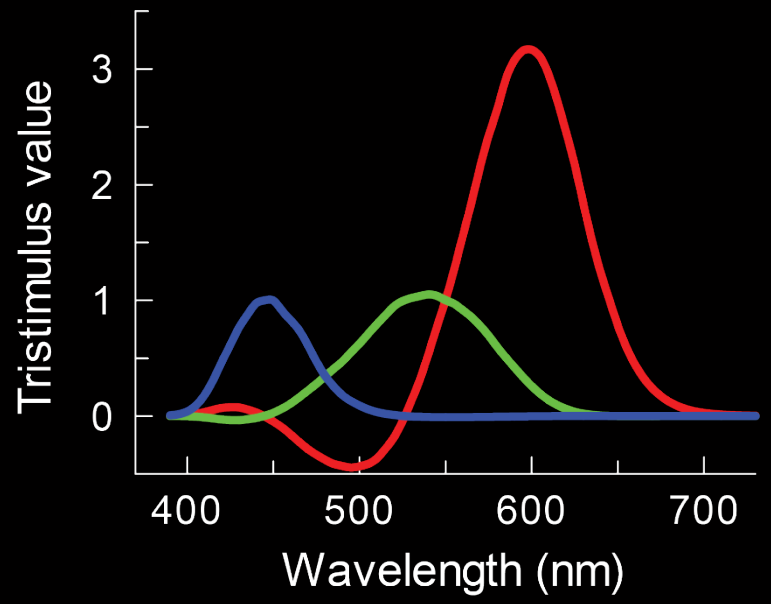


$$\begin{pmatrix} 2.846201 & 11.092490 & 1 \\ 0.168926 & 8.265895 & 1 \\ 0 & 0.010600 & 1 \end{pmatrix}$$

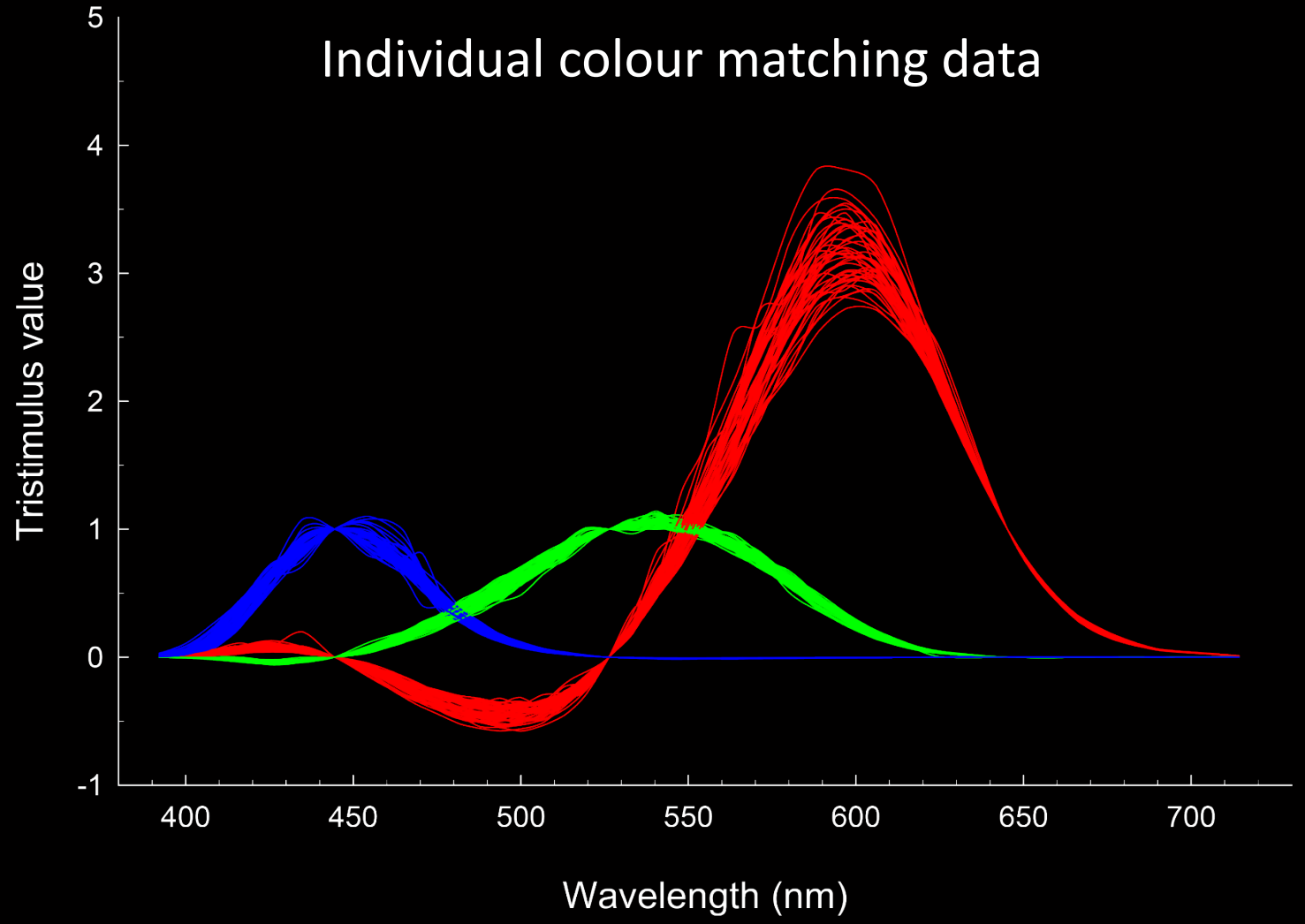


The standards, however, underplay the sizeable individual differences found in the original individual Stiles & Burch colour matching data.

Mean colour matching data

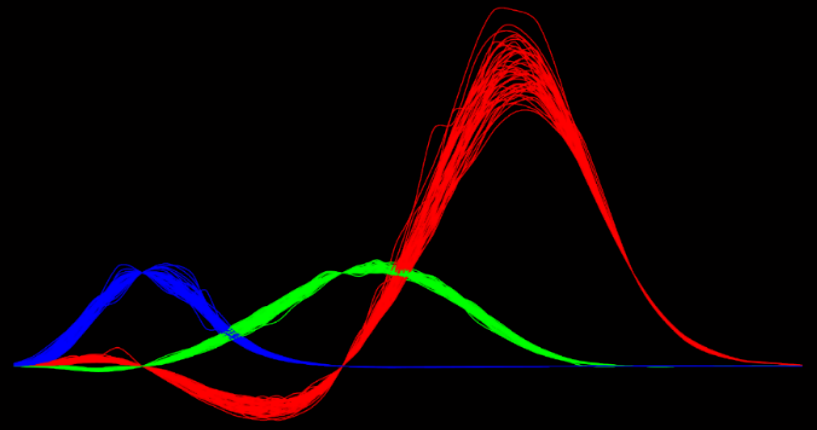


Individual colour matching data

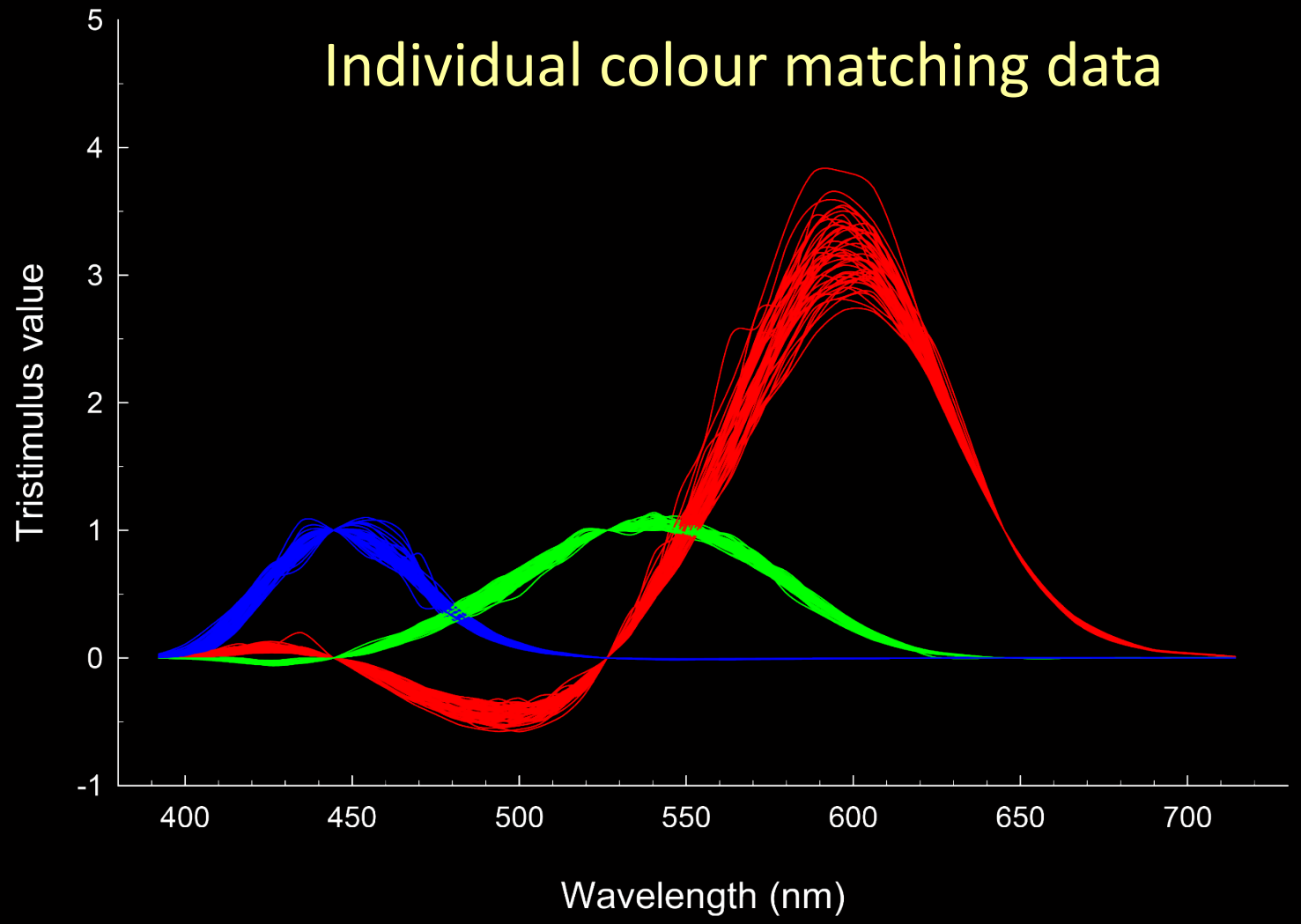


Stiles & Burch (1959) 10-deg CMFs

3. INDIVIDUAL DIFFERENCES



What causes these individual differences (and how can we model them)?

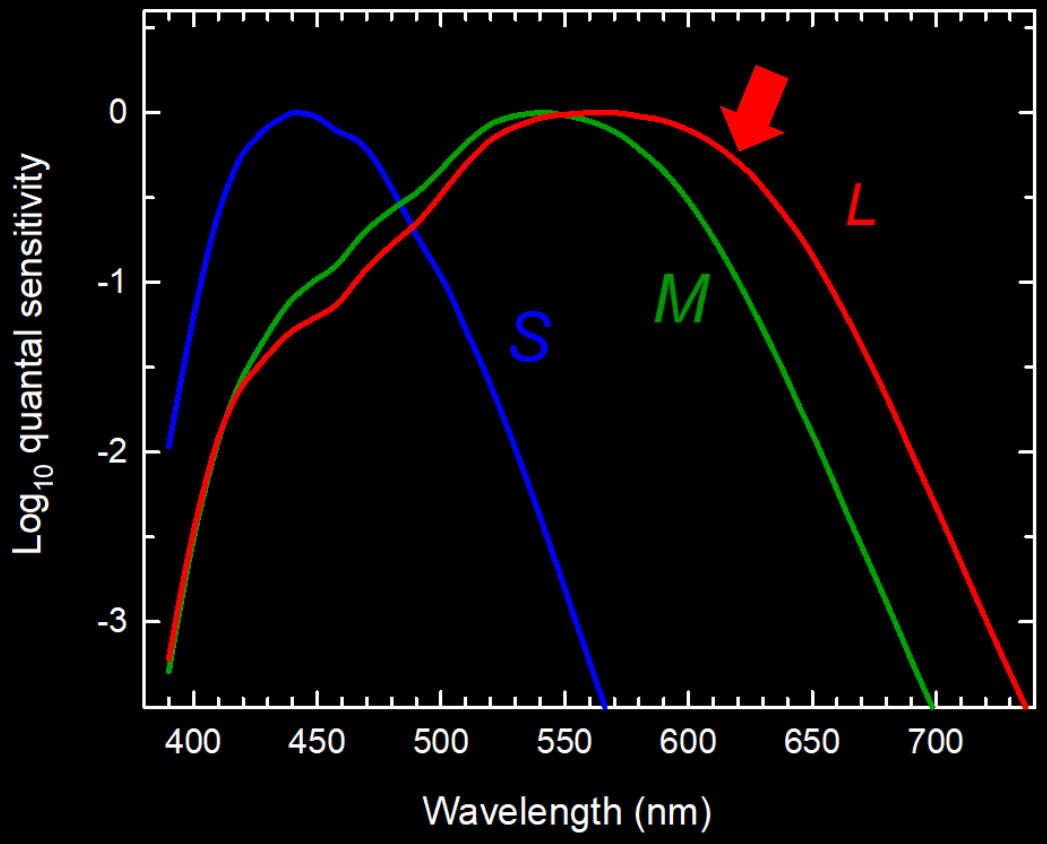


What causes individual differences?

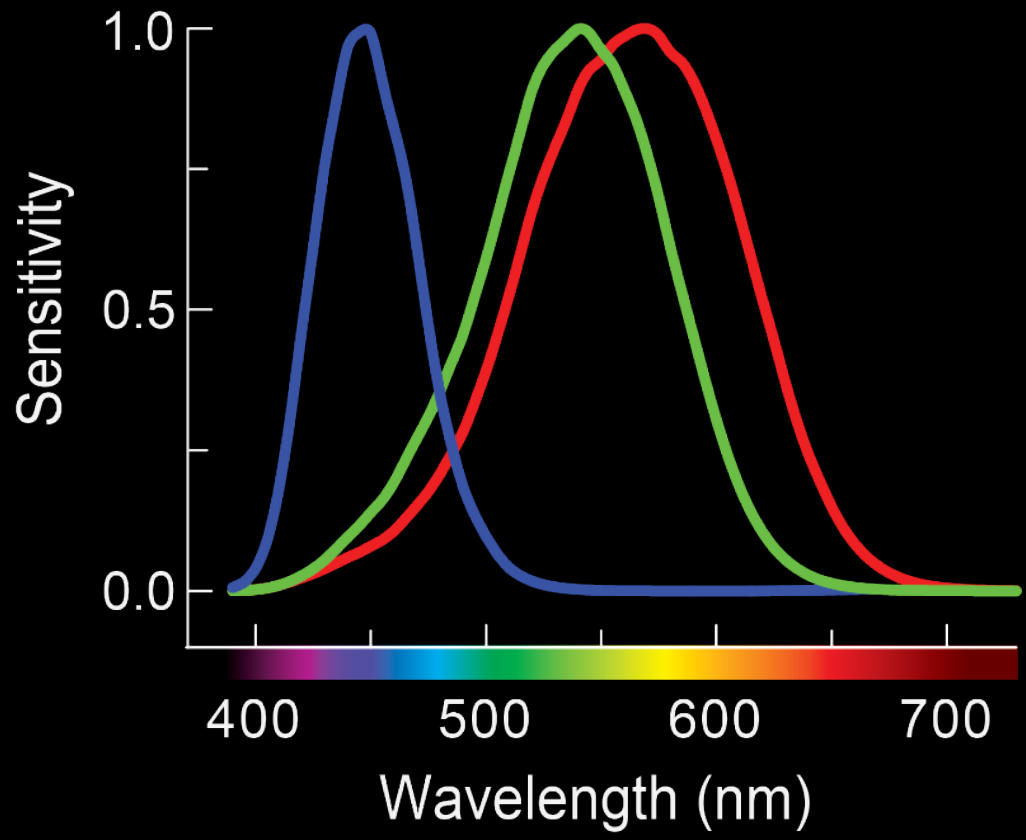
- Macular pigment optical density differences
- Lens pigment optical density differences
- Photopigment optical density differences
- Spectral shifts in photopigment sensitivity

Individual differences are most easily visualized and modelled as effects on the cone spectral sensitivities or the “fundamental” LMS colour matching functions (rather than on XYZ or RGB CMFs)...

Logarithmic



Linear

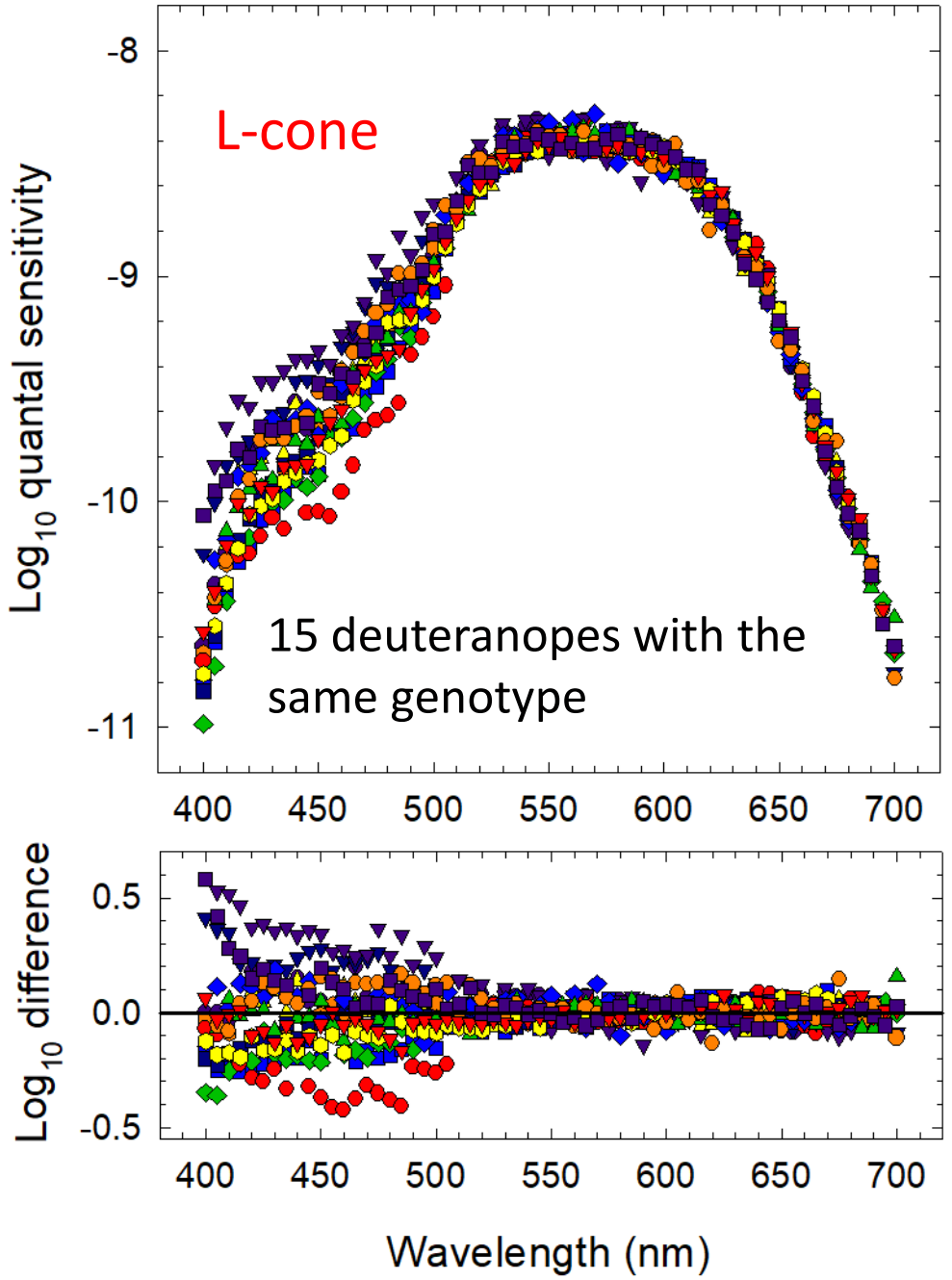


Individual data for deuteranopes with the same L-cone photopigment

L

L-cone data from fifteen deuteranopes with the same genotype (and therefore with the same photopigment)

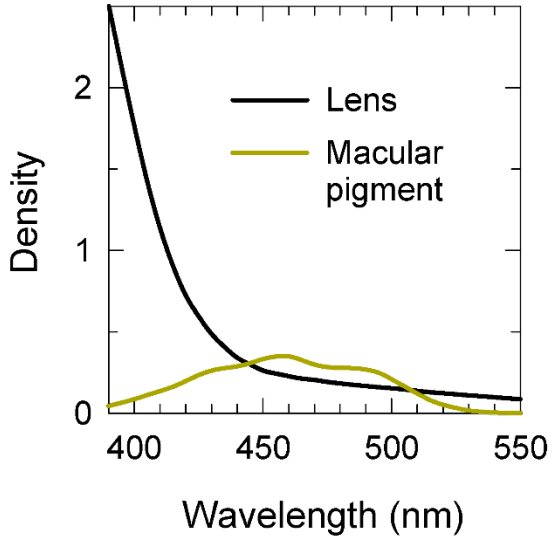
Why are the results so variable at short wavelengths?

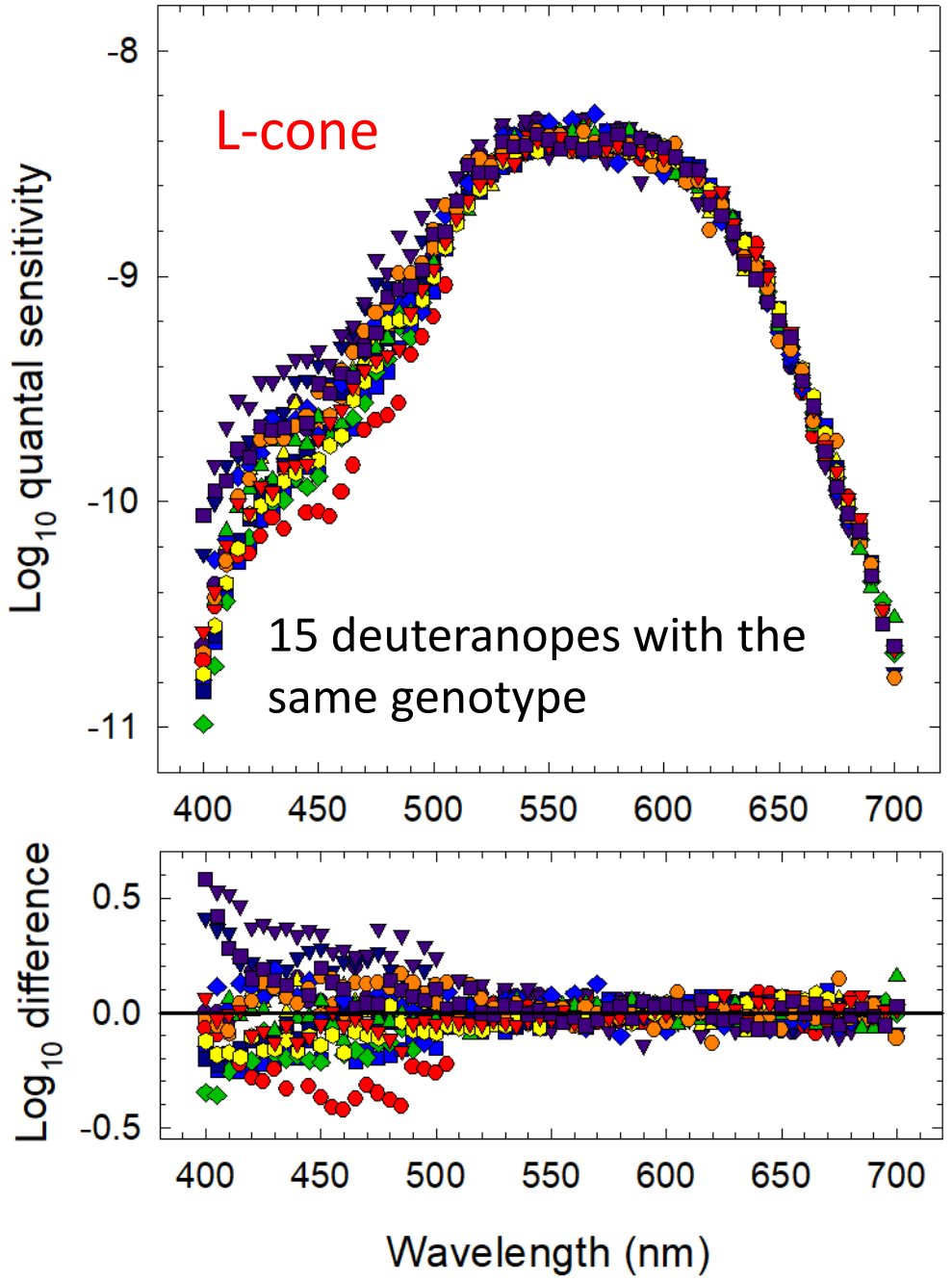


Individual data for deuteranopes with the same L-cone photopigment

L

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

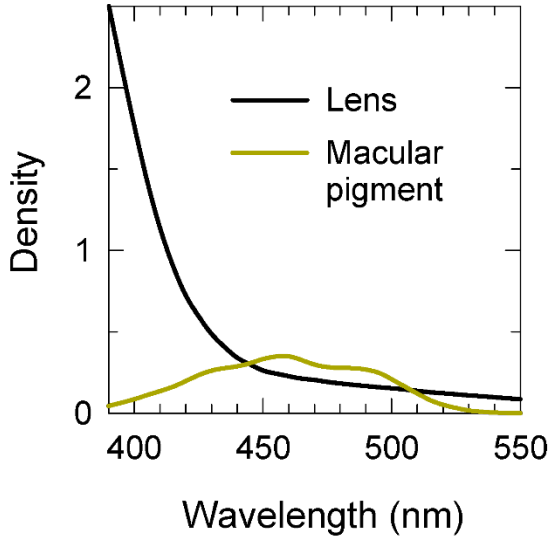


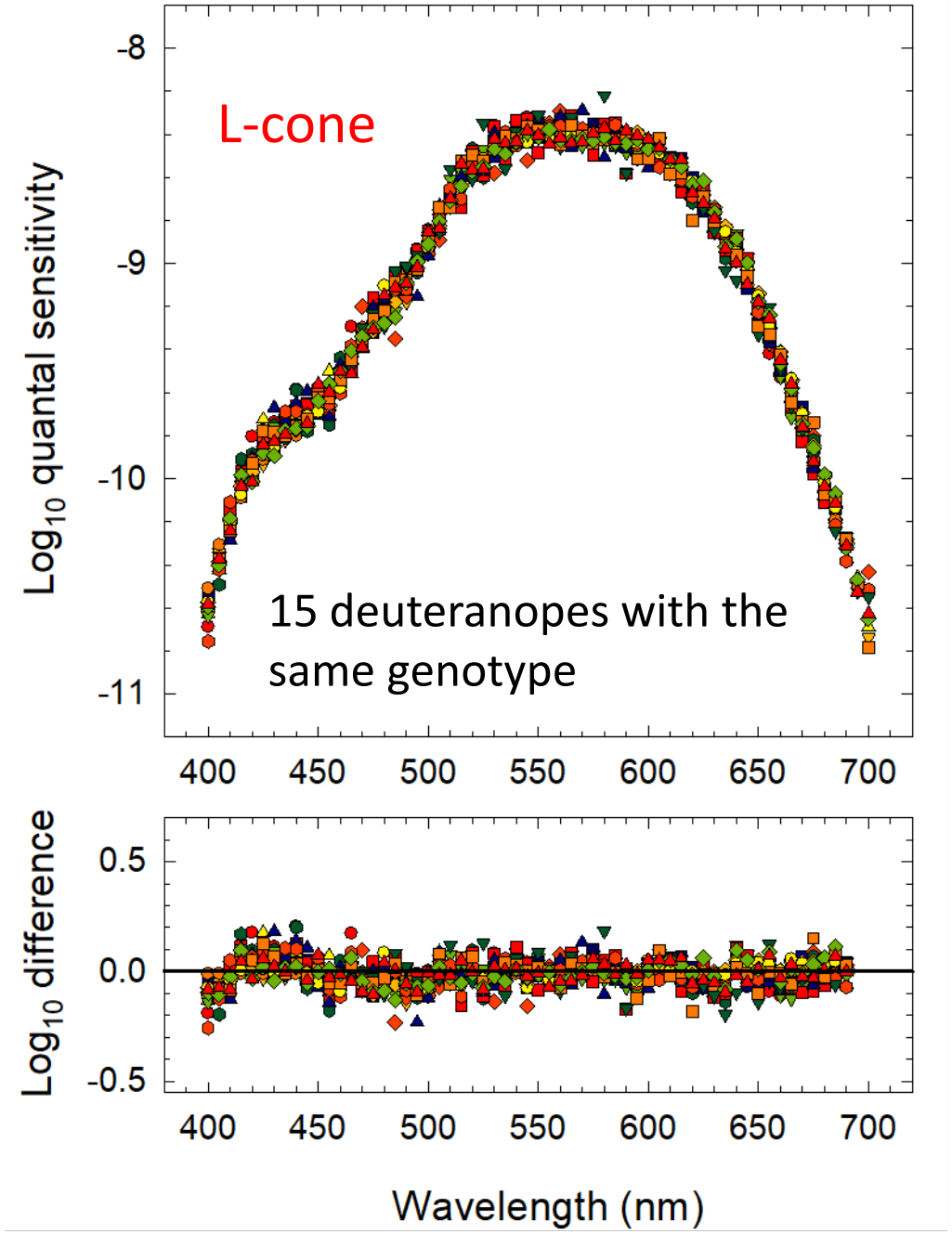


Individual data for deuteranopes with the same L-cone photopigment

L

L-cone data adjusted to the same mean macular and lens optical densities





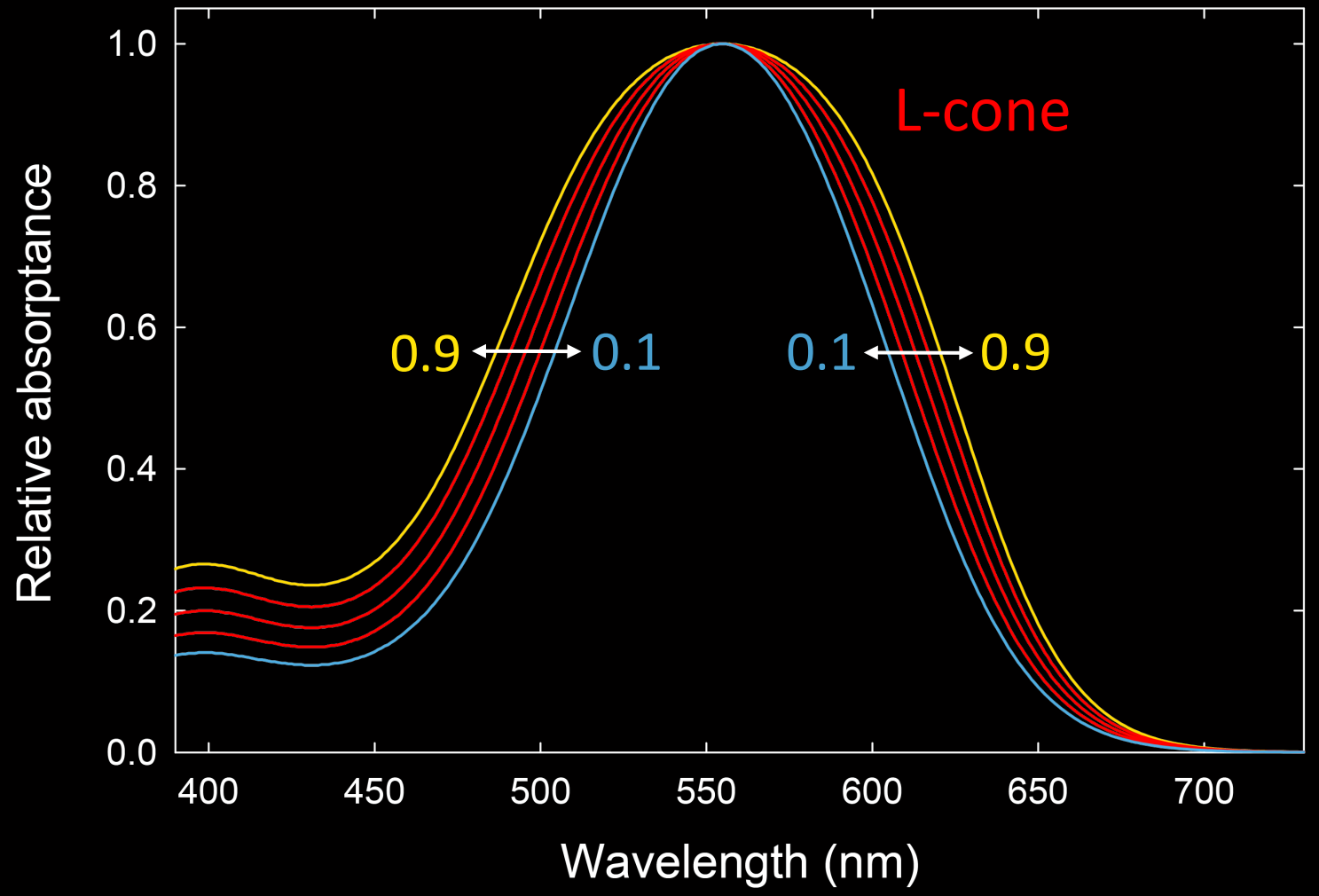
What causes individual differences?

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

Individual differences in photopigment optical density

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

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

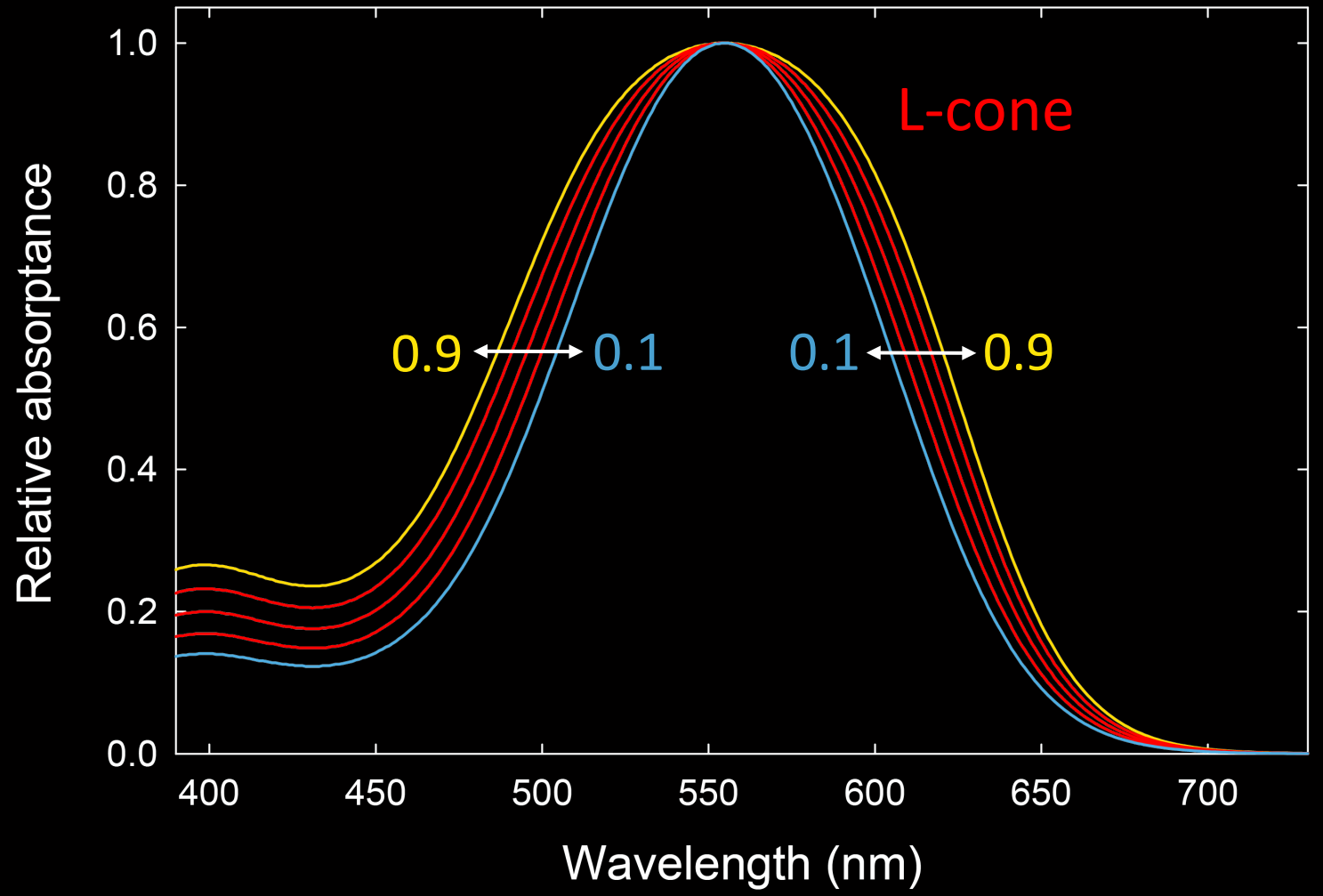


Individual differences in photopigment optical density

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 (also affected by bleaching).

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



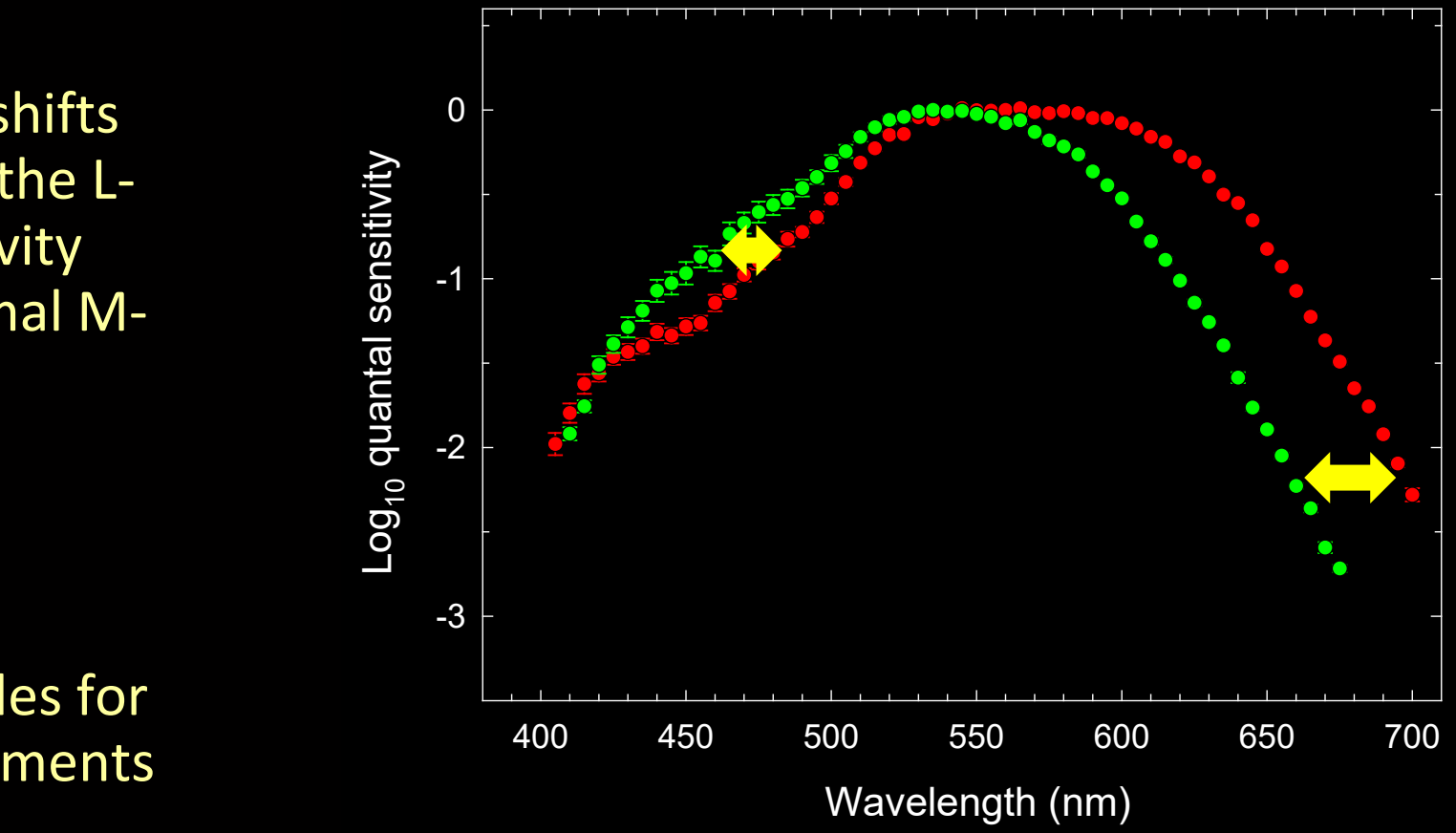
What causes individual differences?

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

Why does this variability occur?

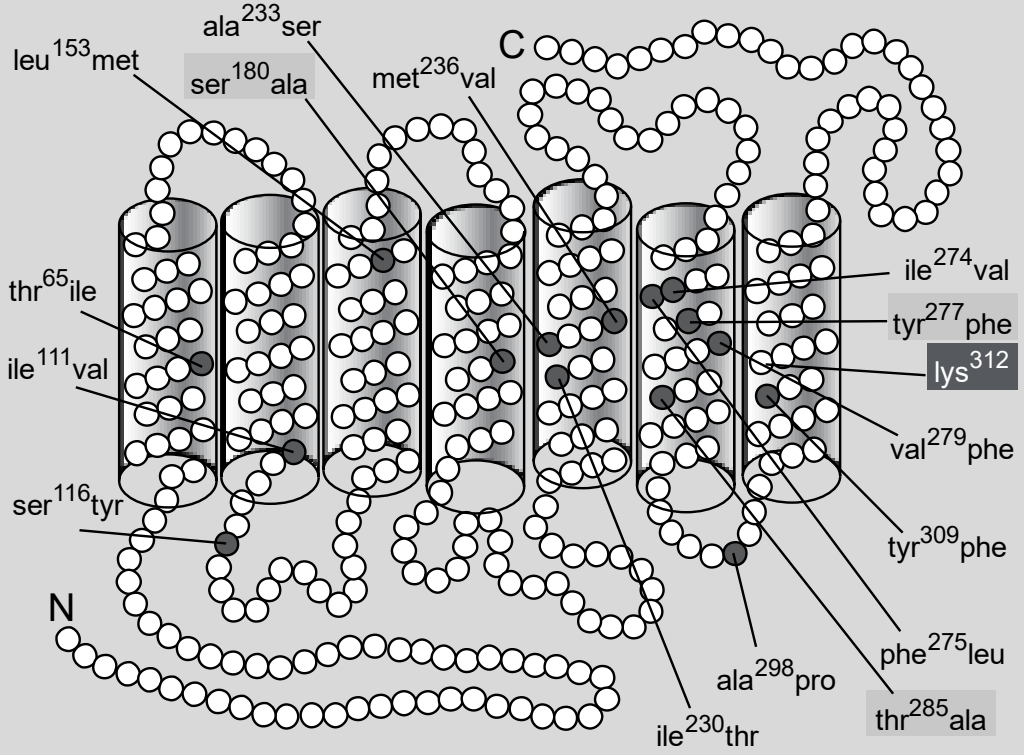
The variability is caused by shifts in the spectral positions of the L- and M-cone spectral sensitivity functions between the normal M- and L-cone functions.

The shifts are the result of variability in the genetic codes for the M- and L-cone photopigments

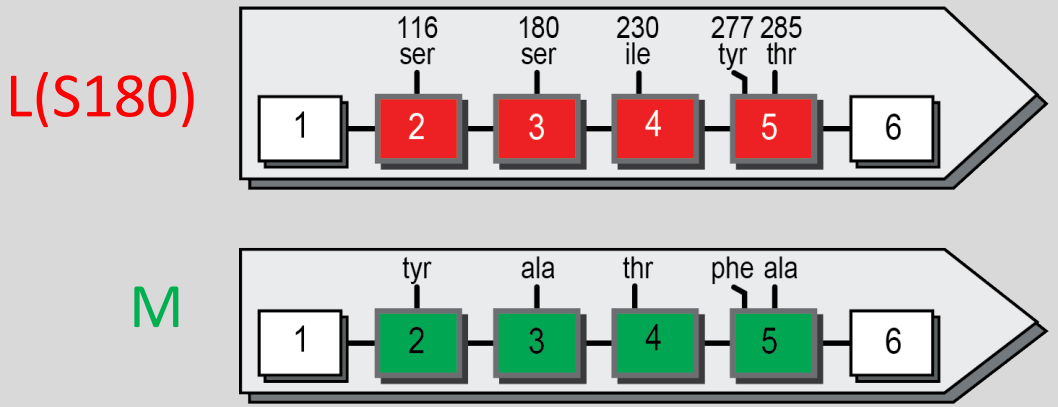


Amino acid differences between the L-and M-cone opsins

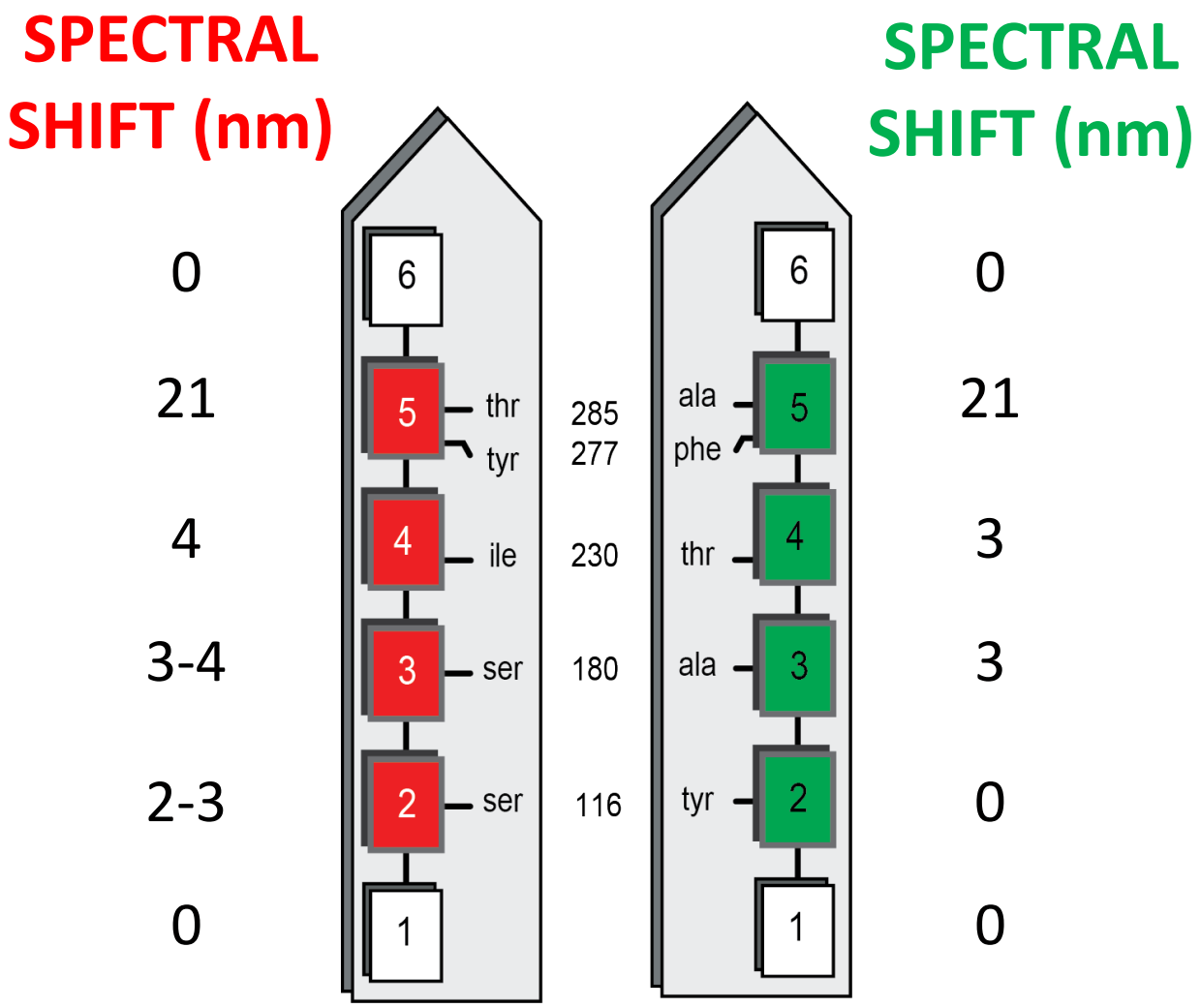
There are only fifteen amino acid differences between the L- and M-cone photopigment opsins. Only about five of those cause wavelength shifts between their spectral sensitivities.



Simple representation of gene (amino acid) sequence for L and M

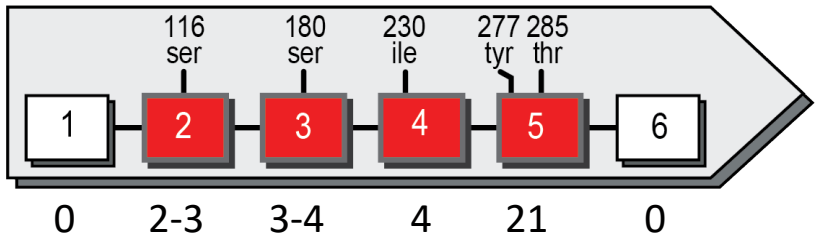


SUMMARY OF SPECTRAL SHIFTS PER EXON

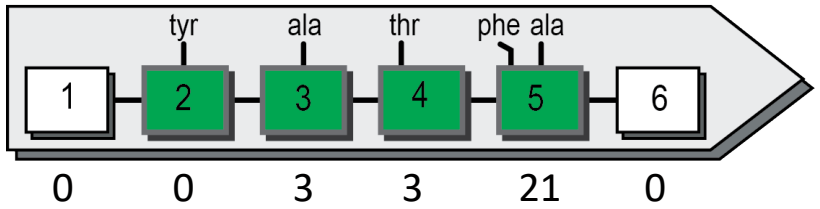


Values from Neitz and Neitz (2011)

L(S180)

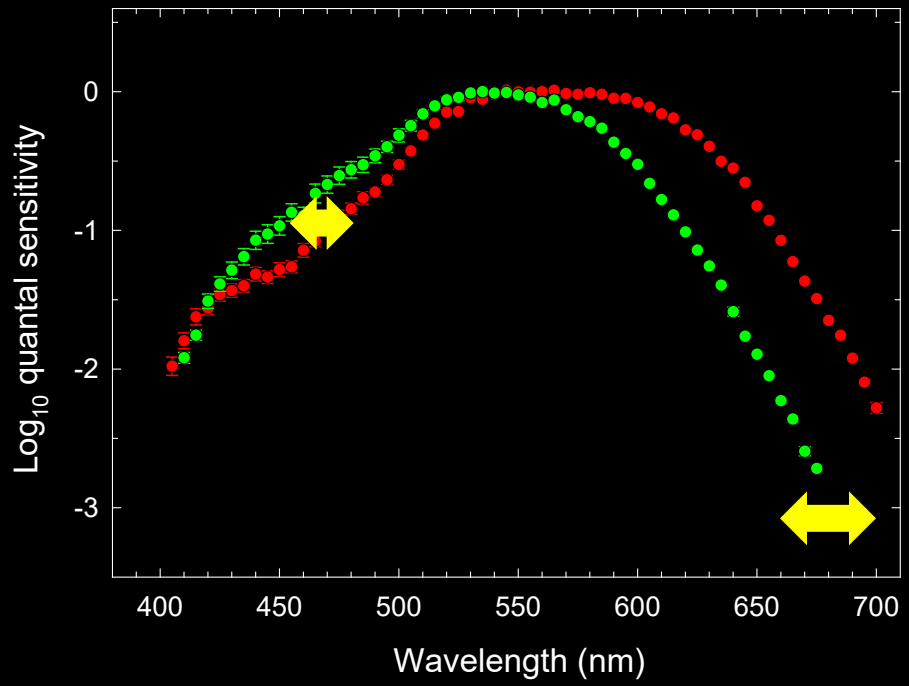


M



Changes (substitutions) at these sites are usually modelled as shifts in the λ_{max} of the photopigment absorbance spectrum, which is assumed to be of invariant shape when plotted against some function of wavelength. We use a $\log_{10}$ wavelength scale.

The spectral sensitivities of the "hybrid" photopigments vary between those of the M- and L-cones depending on where the crossover occurs.



XY inheritance

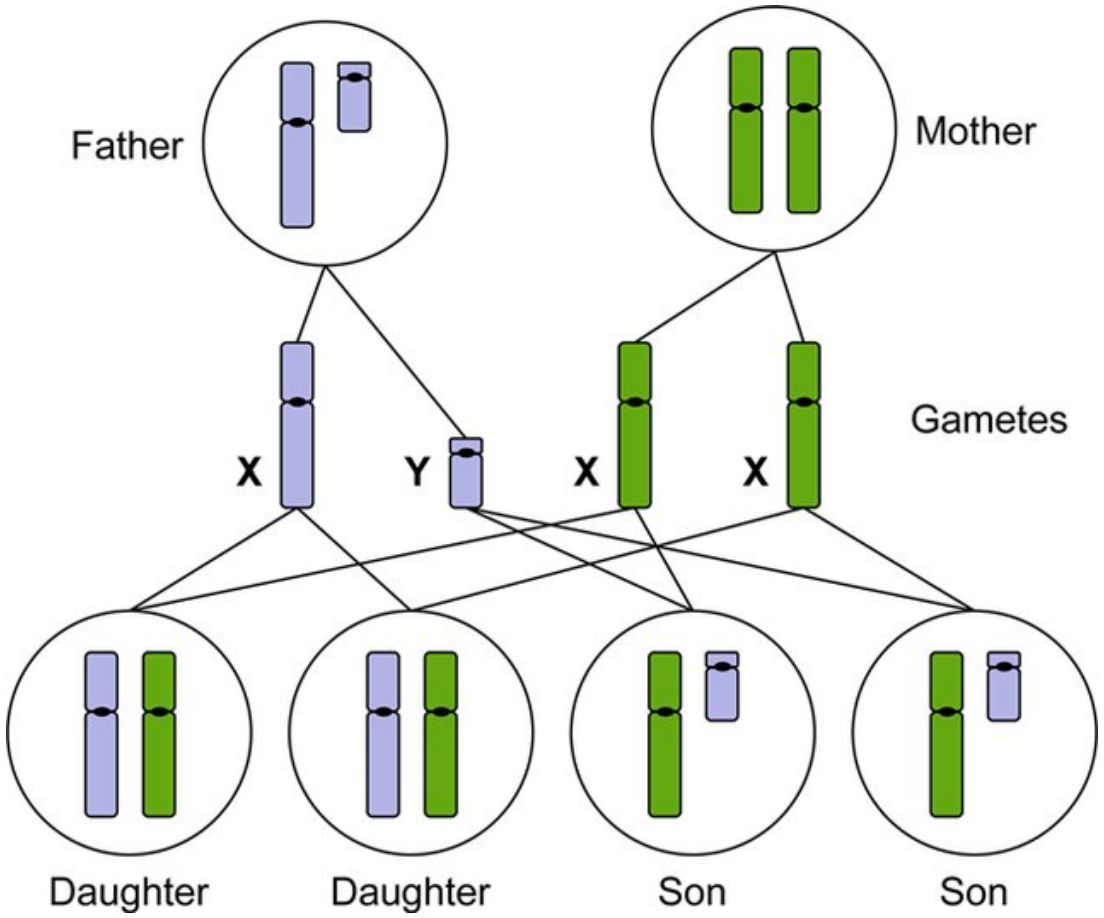


Figure 7 from Jackson, Marks, May & Wilson (2018) *Essays in Biochemistry 62*, 643-723

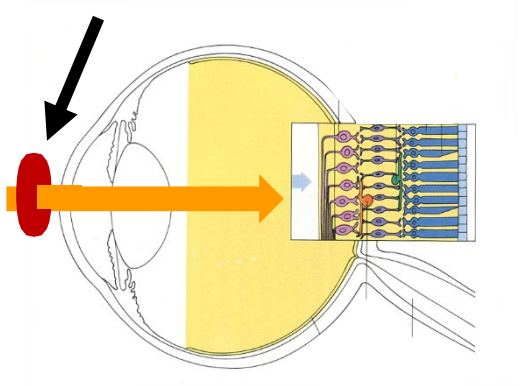
What causes individual differences?

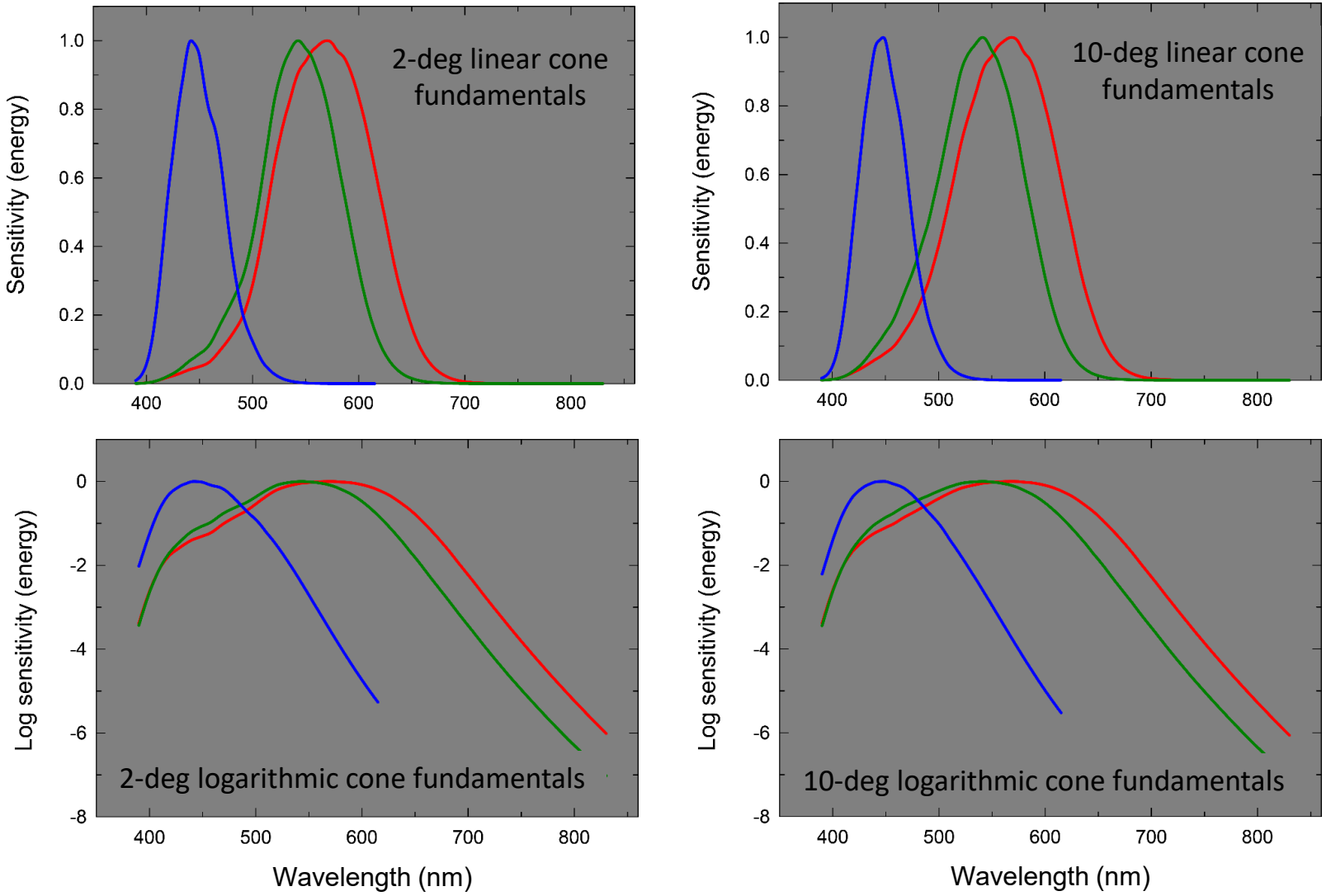
- Macular pigment optical density differences
- Lens pigment optical density differences
- Photopigment optical density differences
- Spectral shifts in photopigment sensitivity

4. MODELLING INDIVIDUAL DIFFERENCES

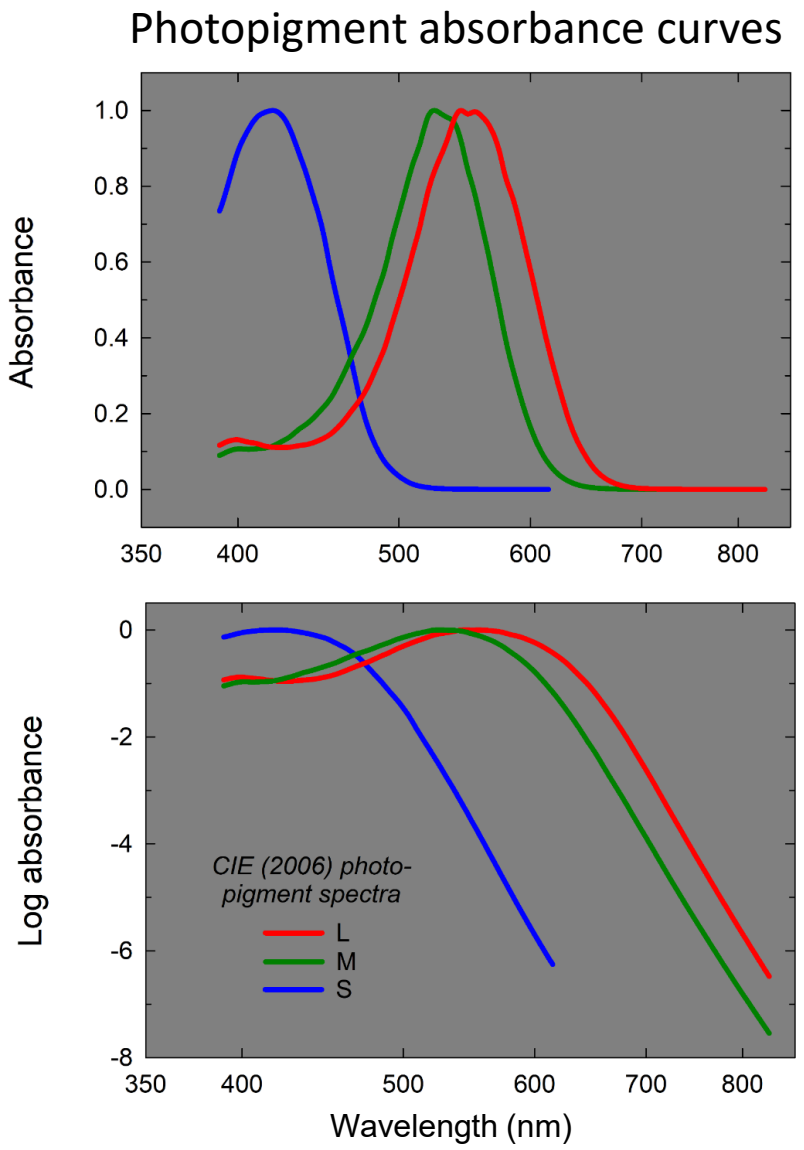
Stockman & Sharpe (2000) and CIE (2006) standard LMS observers for 2-deg and 10-deg vision.

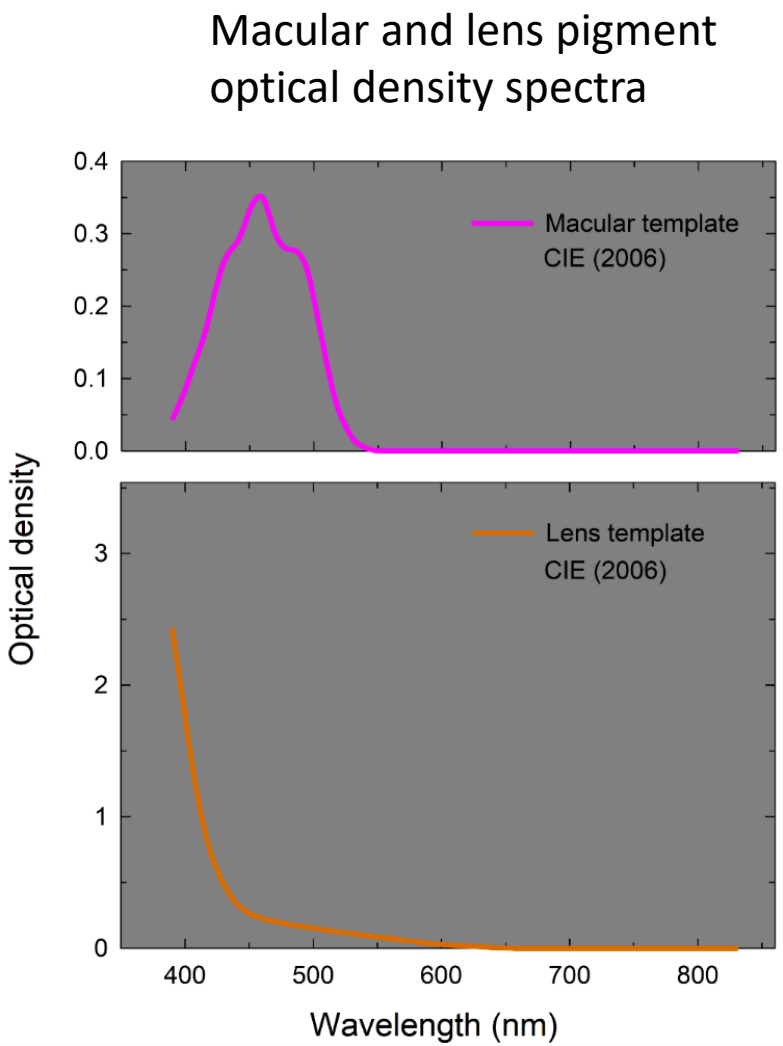
Measured with respect to light entering the cornea



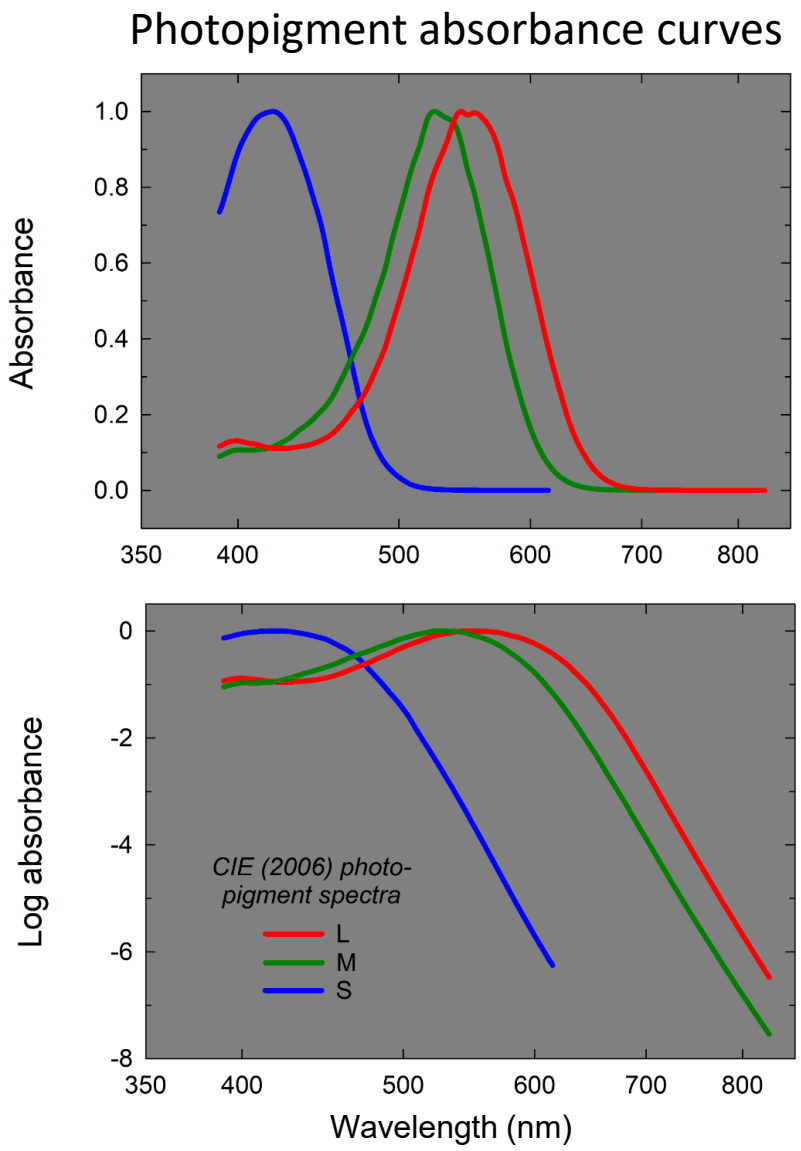


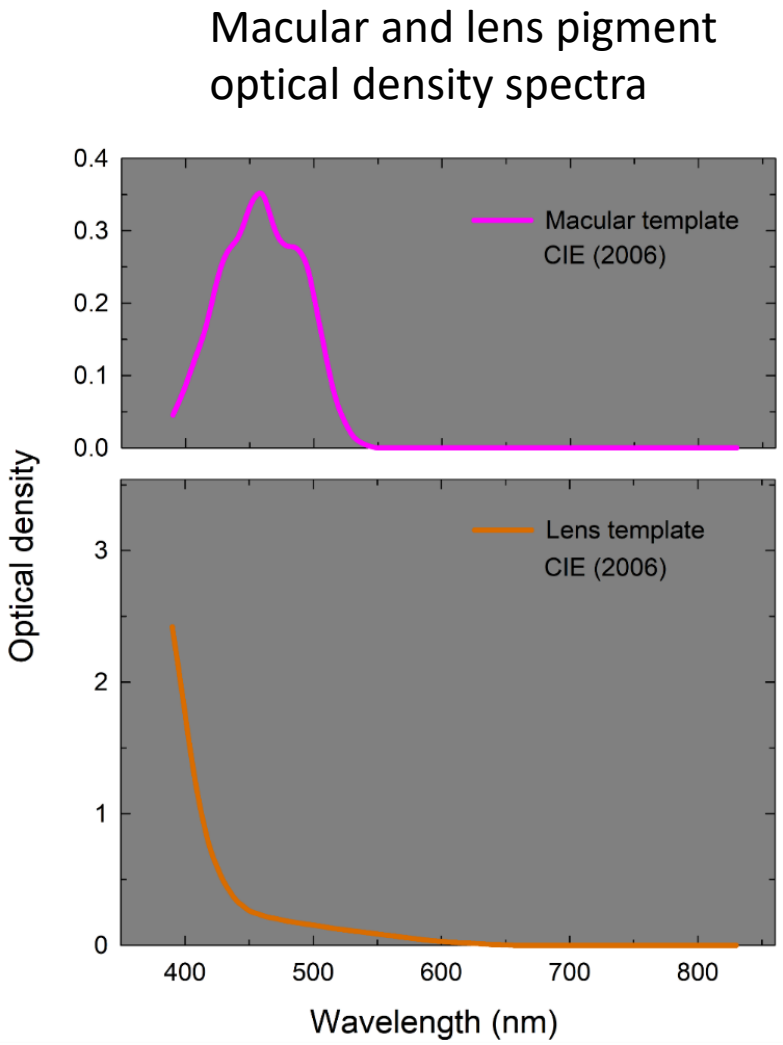
The new CIE standards also define the macular and lens pigment optical density spectra, the photopigment optical densities and the photopigment spectra.

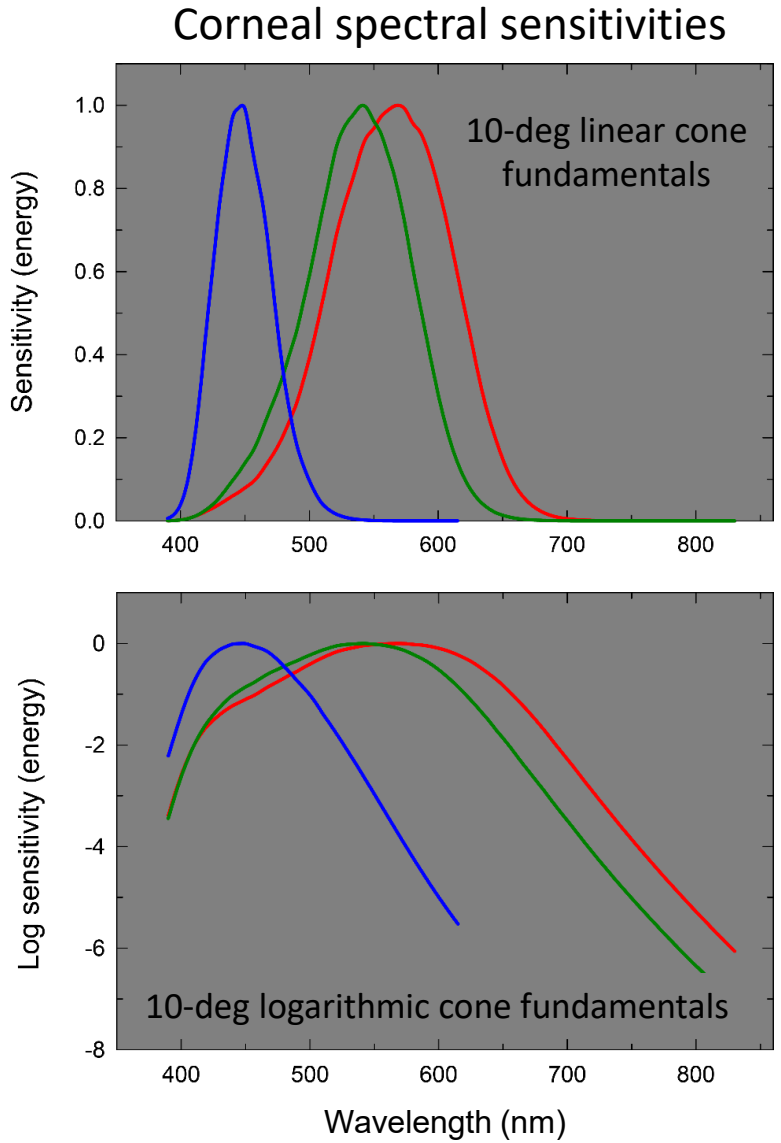




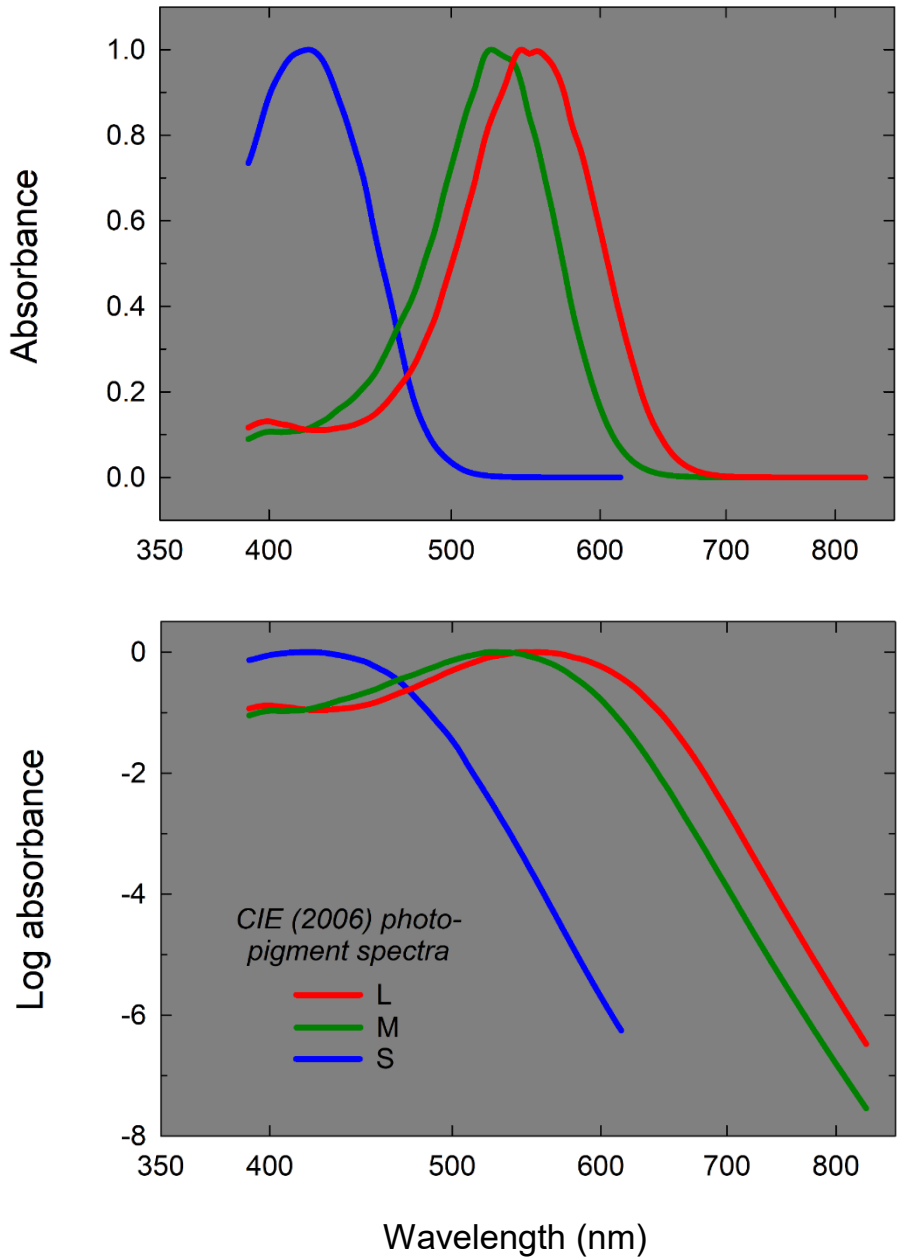
We model individual differences by adjusting the photopigment absorbance curves and varying the macular and lens optical densities

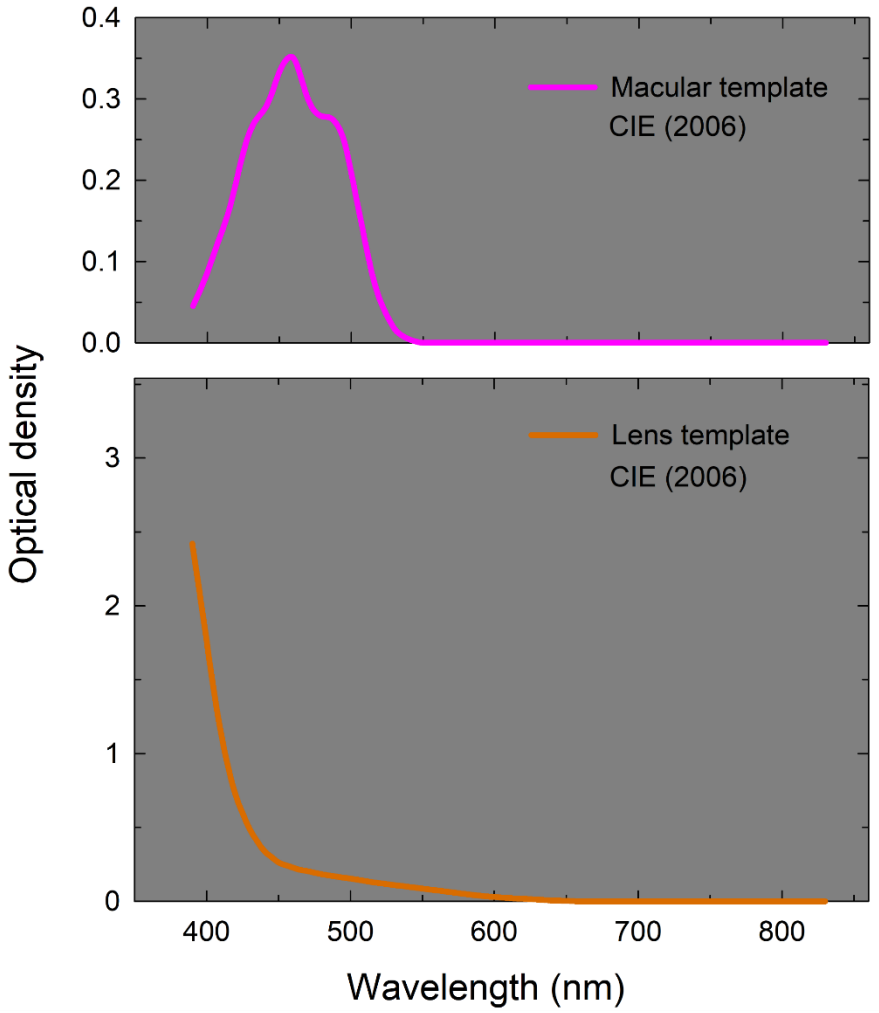


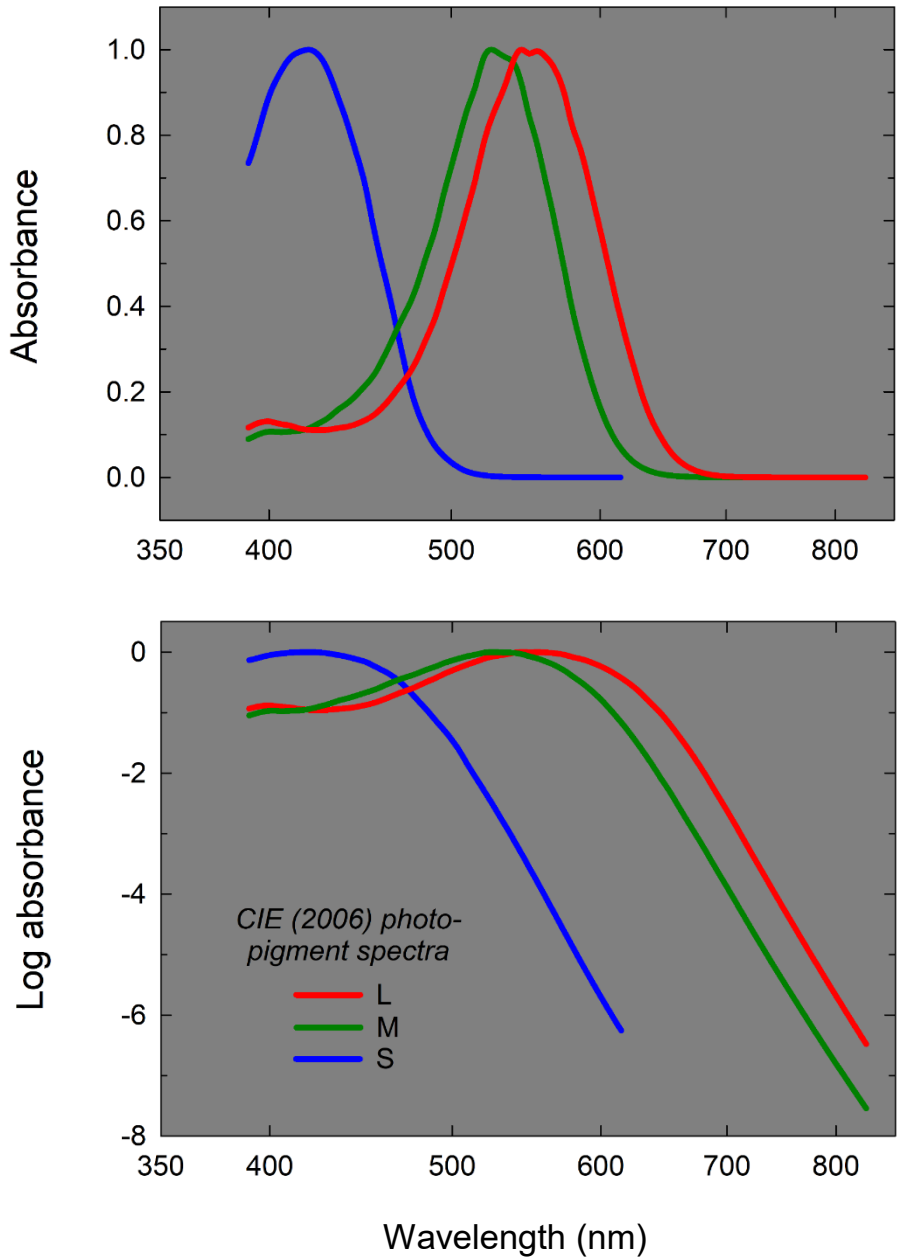




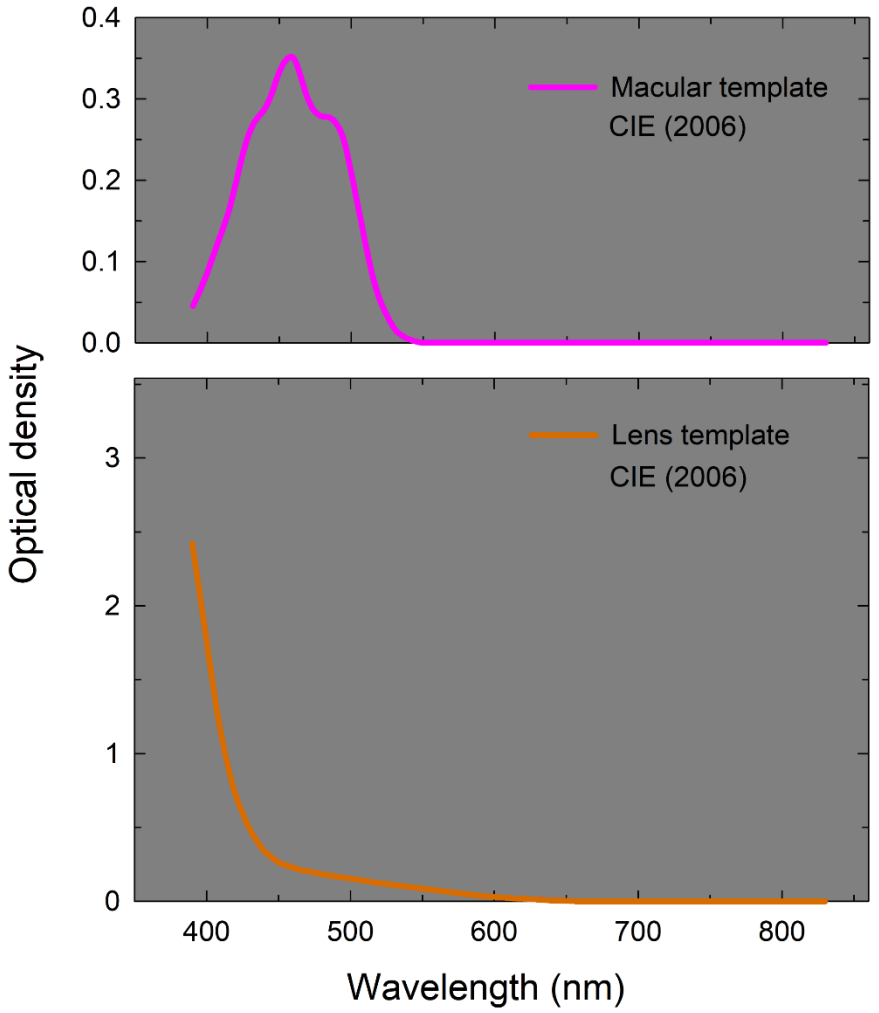
Unfortunately, the CIE (2006) LMS standards are defined as discrete values at 5 or 1 nm steps rather than as continuous functions of wavelength.



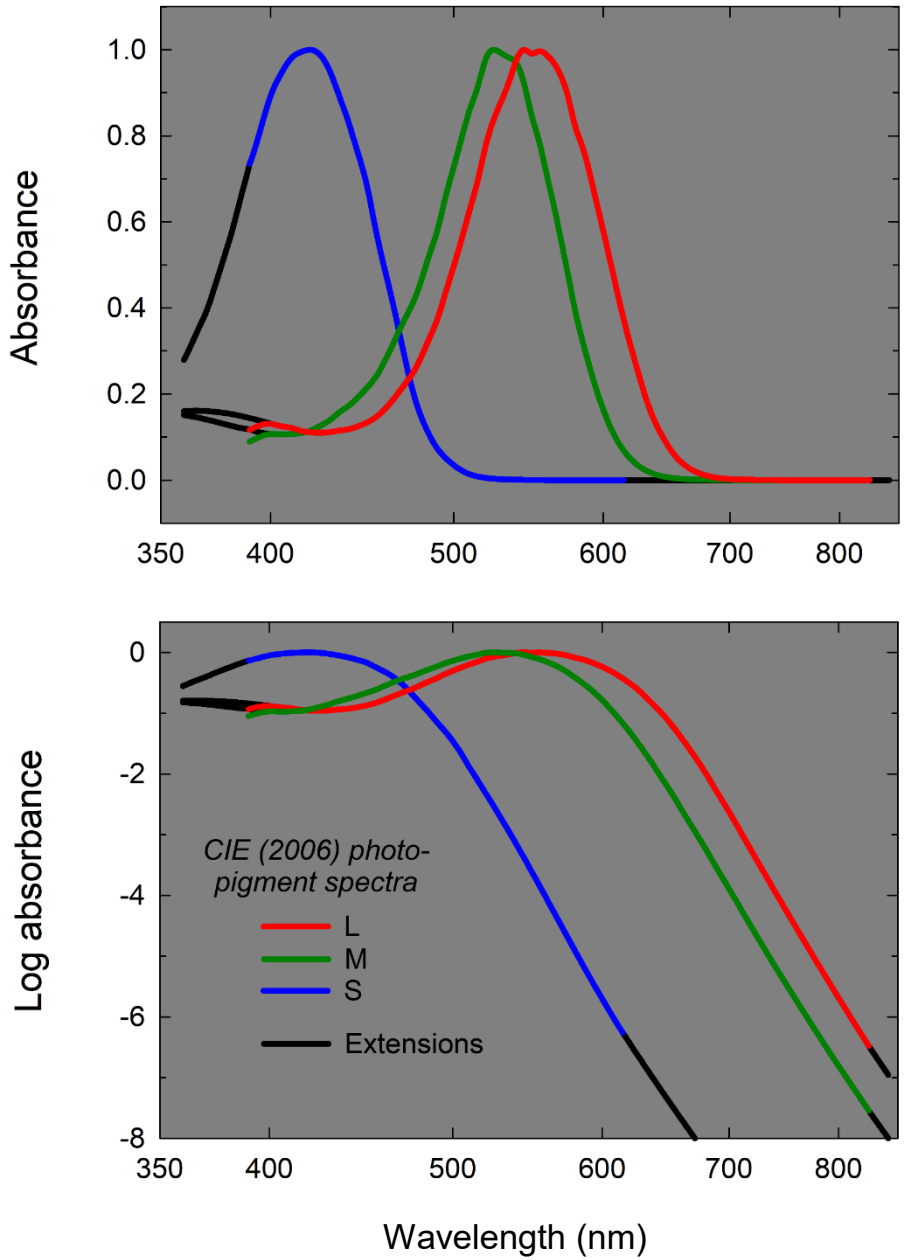


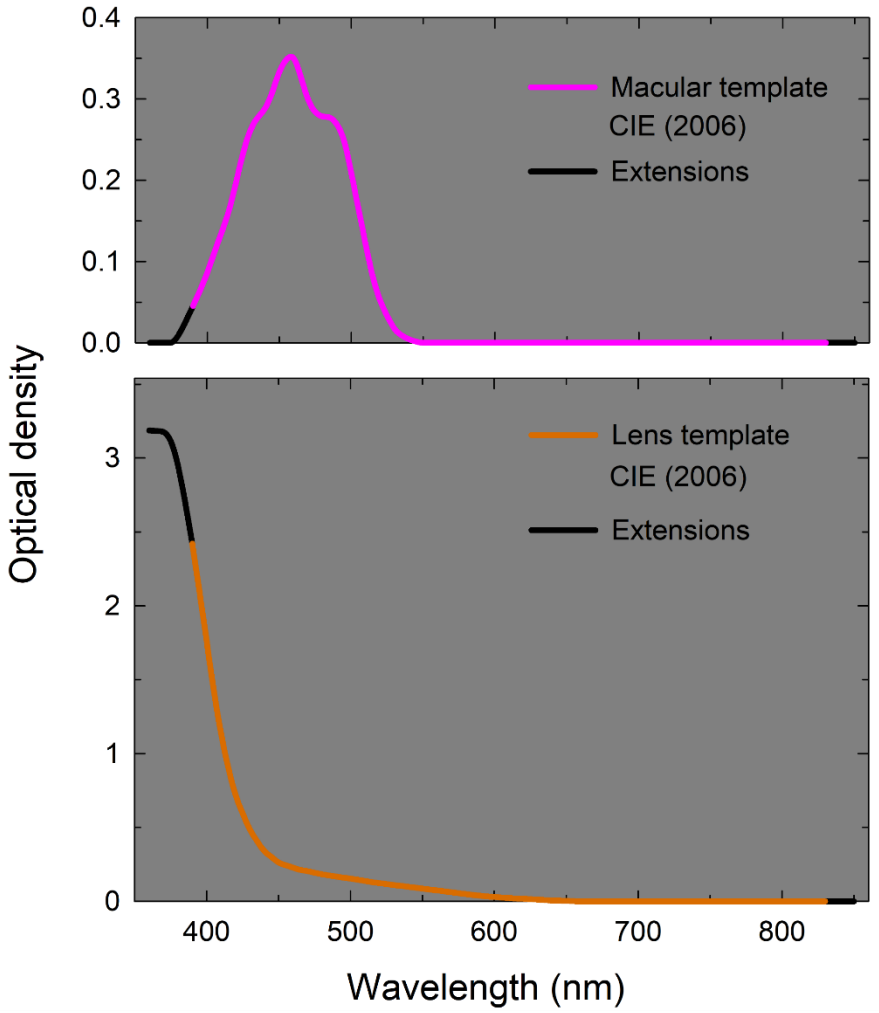


For computational convenience, we want to define these as continuous functions of wavelength…



First, we extended the discrete functions to 360 nm at short wavelengths and 850 nm at long.





Fourier polynomials were then fitted to the discrete functions and then used to define the template shapes

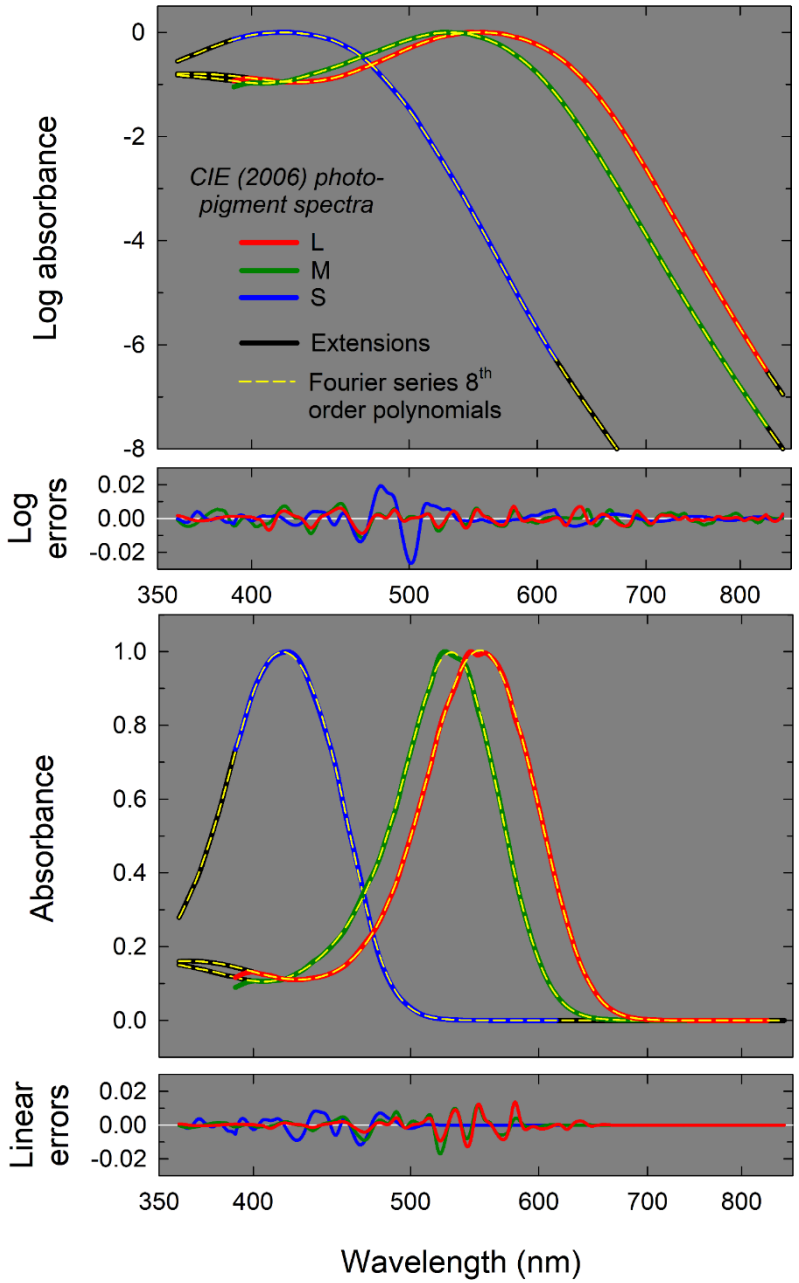
The templates are of the general form:

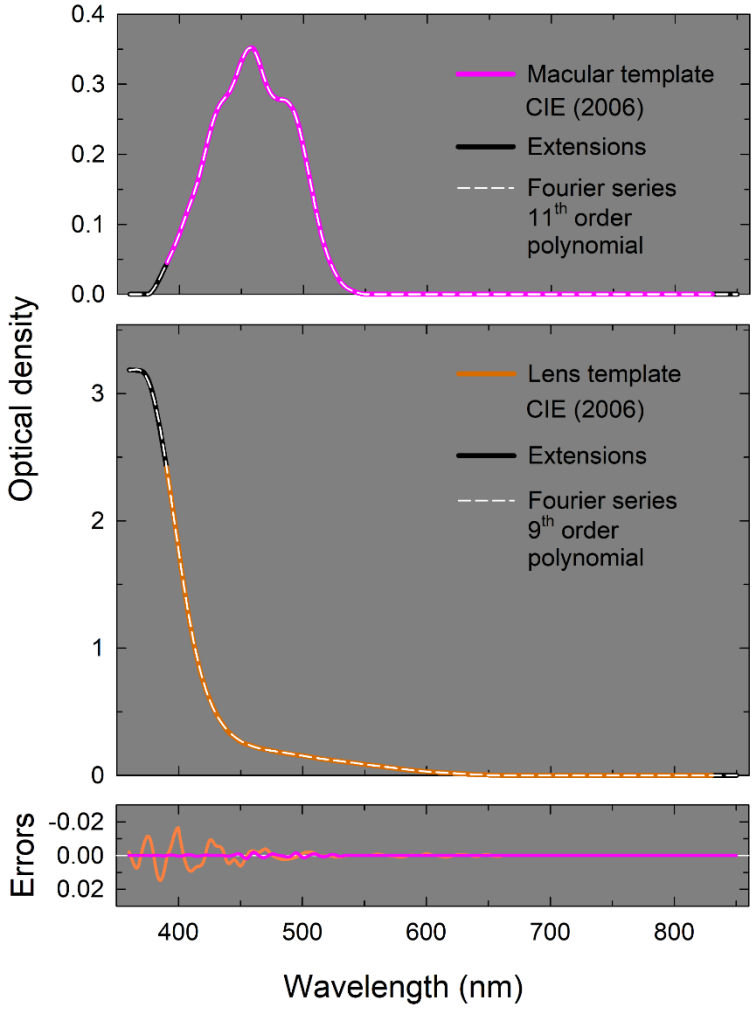
$$F(\theta) = a_0 + \sum_{k=1}^{n} \left[a_k \cos(k\theta) + b_k \sin(k\theta) \right]$$

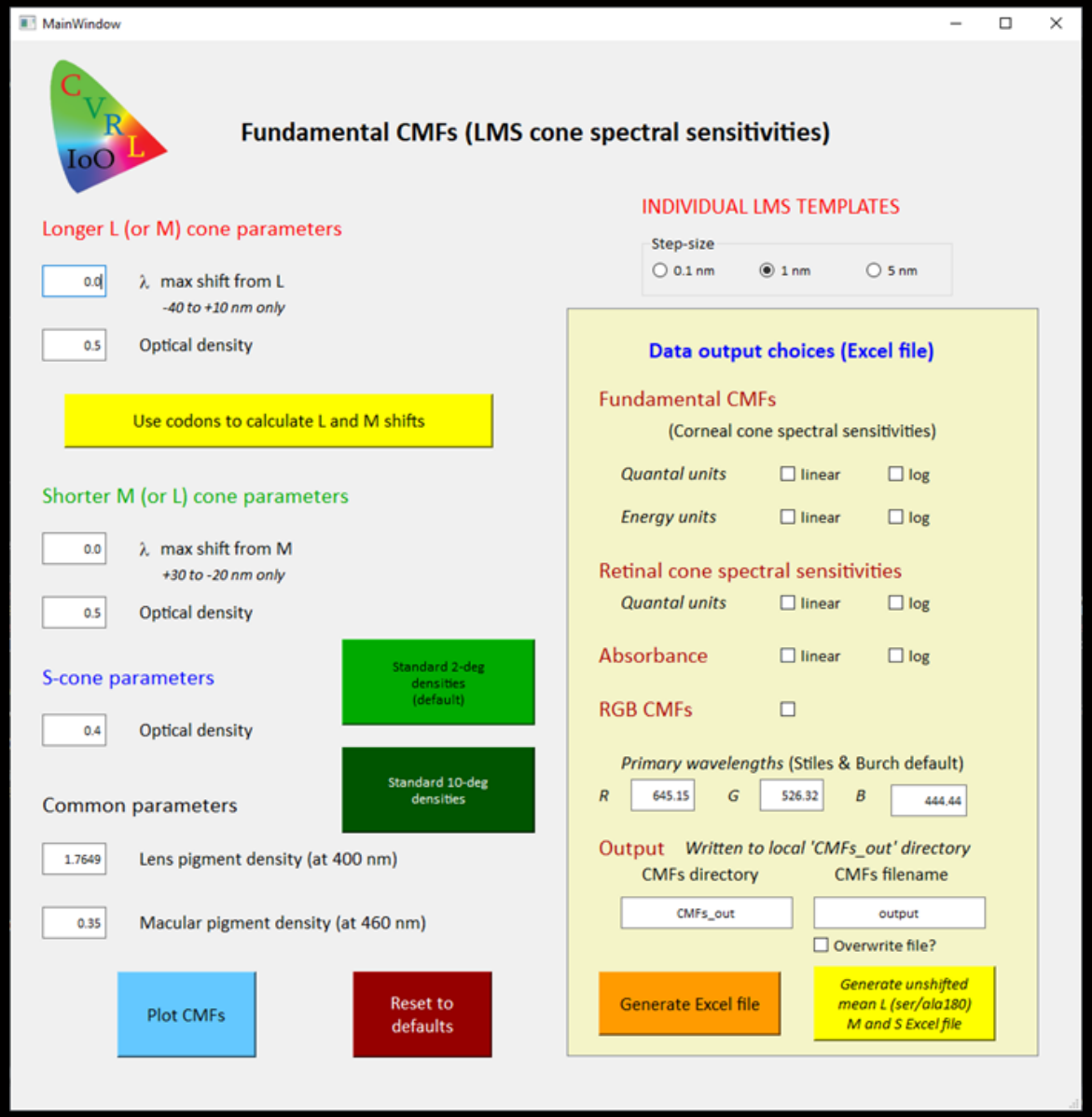
n is the number of harmonics.

Continuous functions of wavelength with little error when used to reconstruct fundamentals.

Important that they describe both log and linear absorbances!

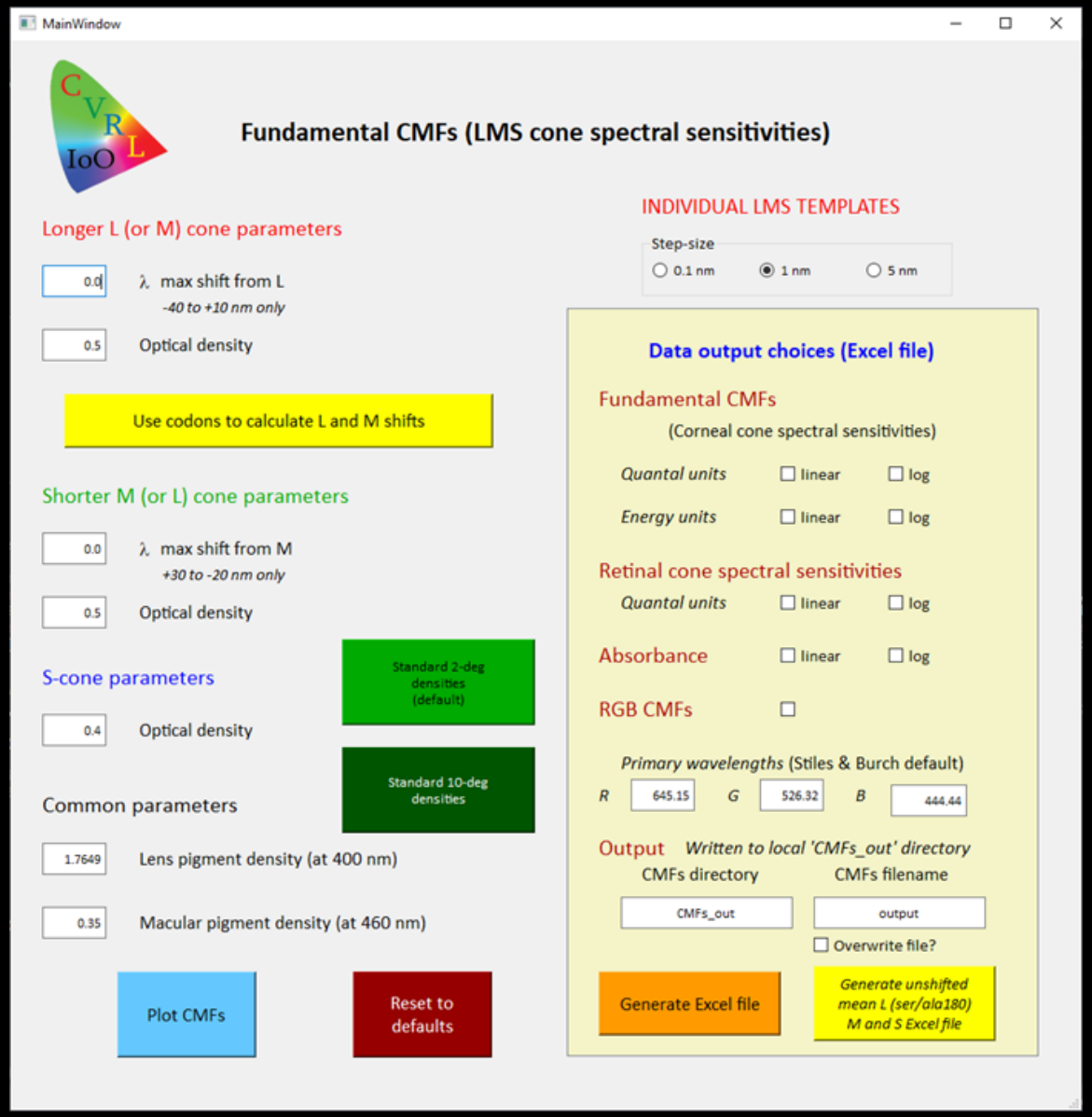






Stockman, A., & Rider, A. T. (2023). Formulae for generating standard and individual human cone spectral sensitivities. *Color Research & Application, 48(6), 818-840.*
doi: https://doi.org/10.1002/col.22879

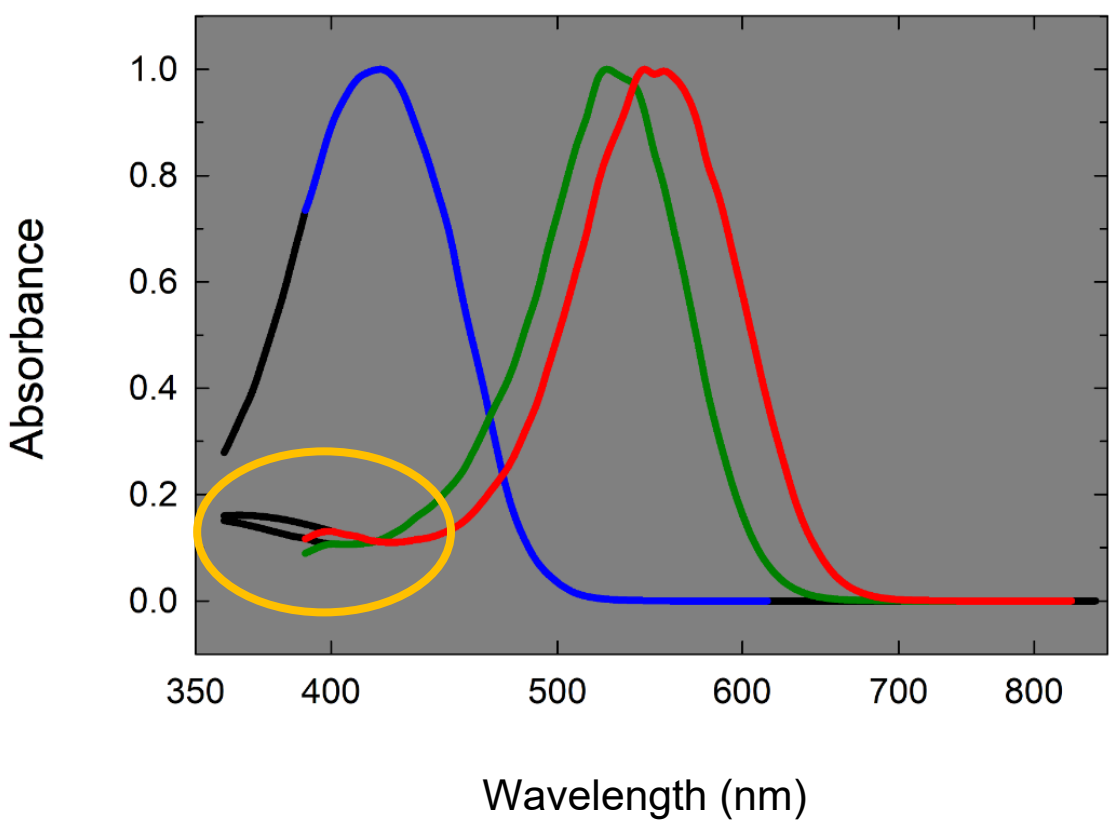
Python program is available on Github at: https://github.com/CVRL-IoO/Individual-CMFs.git

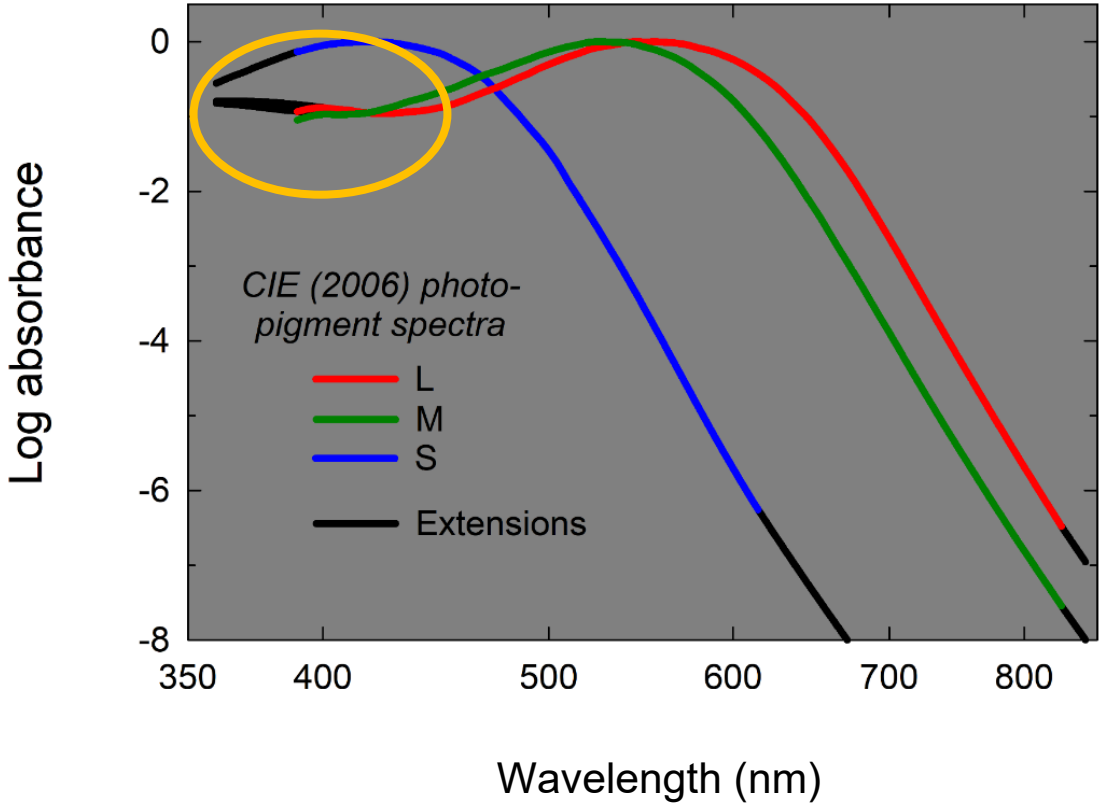


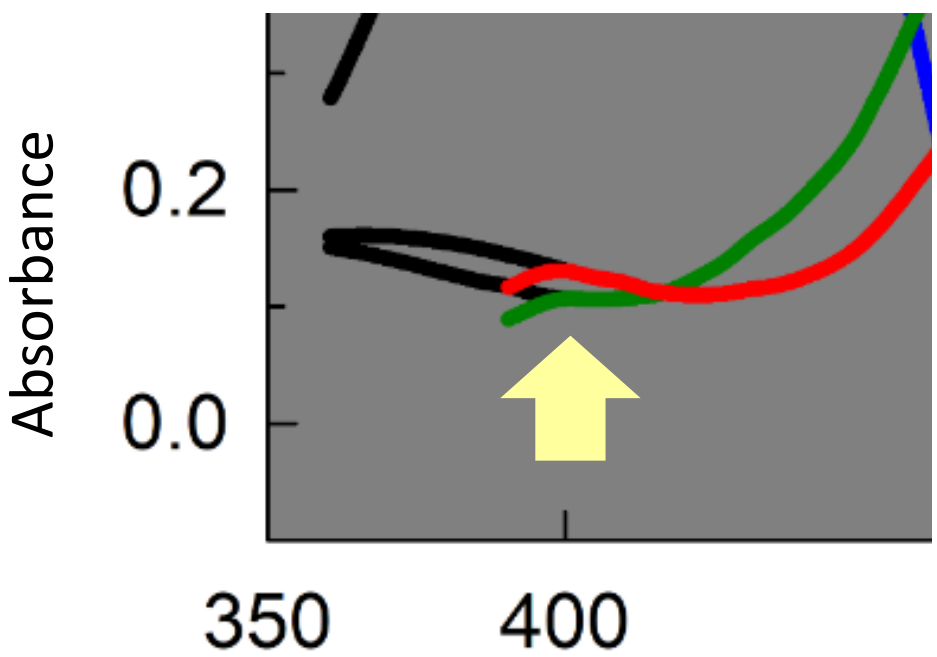
Given this software there is no need to use the anomalous cone spectral sensitivities of DeMarco, Pokorny & Smith, V. C. (1992) [with shifts of 13 nm for protanomalous L and 17 nm for deuteranomalous M].

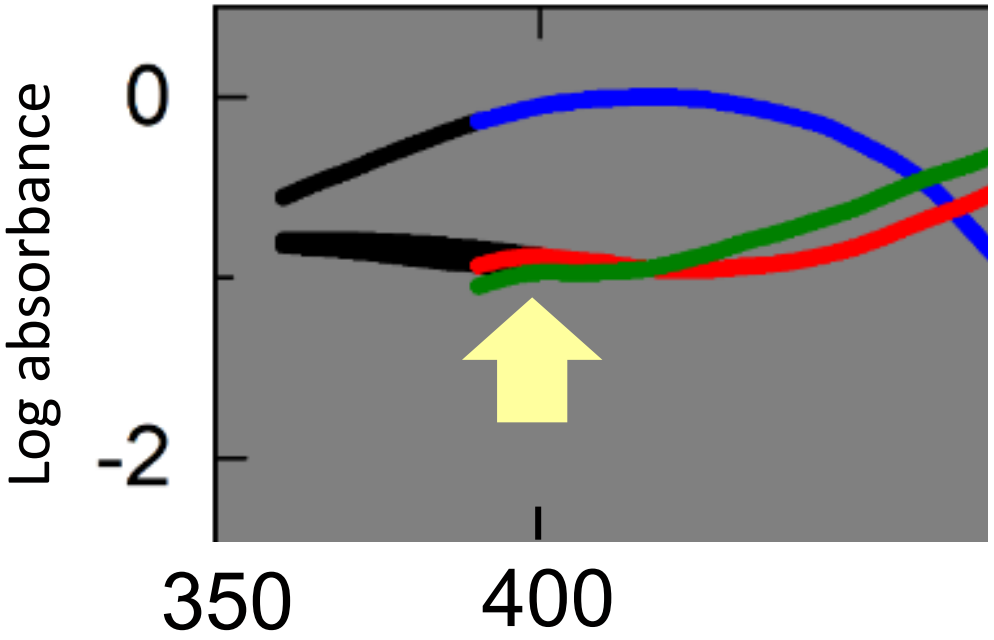
Python program is available on Github at: https://github.com/CVRL-IoO/Individual-CMFs.git

One correction of the CIE 2006 functions:

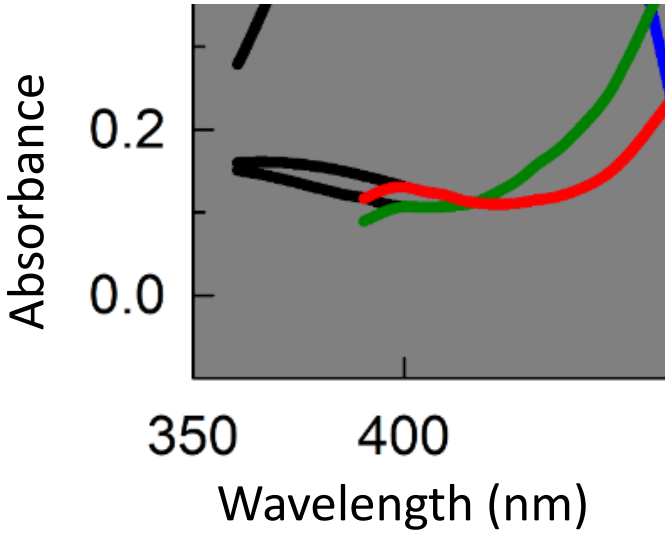


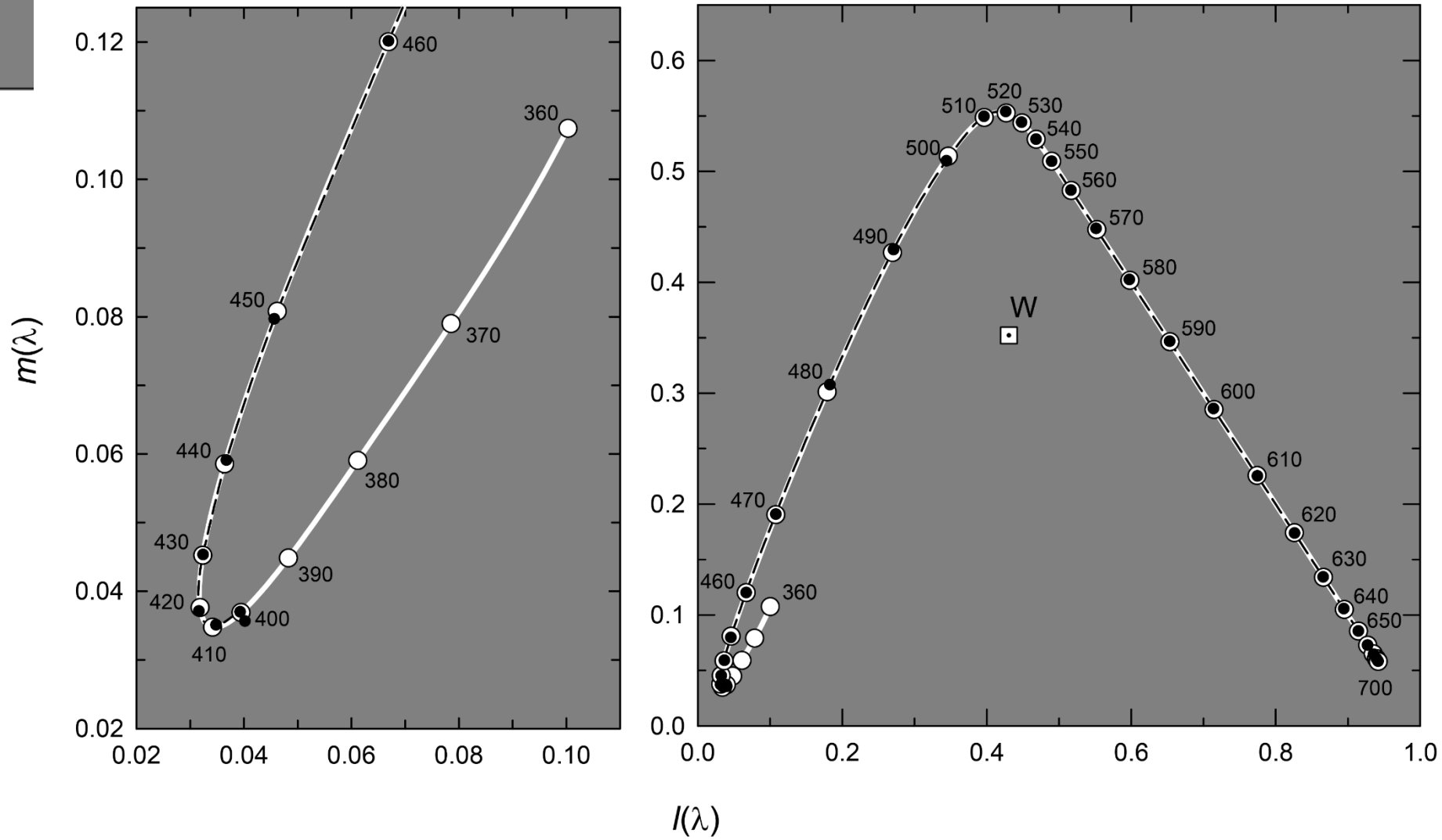






Wavelength (nm)


Absorbance
0.2
0.0
350
400
Wavelength (nm)


m(λ)
0.12
0.10
0.08
0.06
0.04
0.02
0.02
0.04
0.06
0.08
0.10
460
450
440
430
420
410
400
390
380
370
360
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0
0.2
0.4
0.6
0.8
1.0
l(λ)
W
520
510
530
500
540
550
560
570
490
580
590
480
600
610
470
620
630
460
360
640
650
700

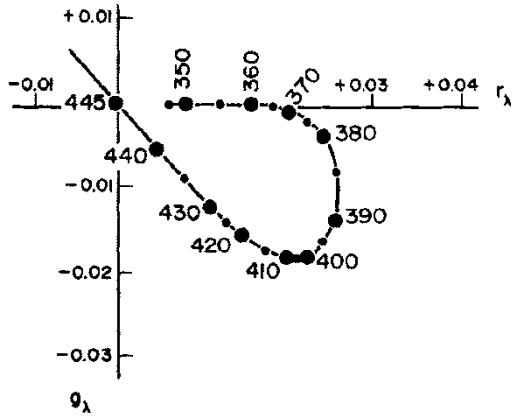


Figure 8. Chromaticity diagram averaged from two aphakic observers in the UV. Subjects matched a split field with primaries at 445 and 625 nm on the left and UV with 525 nm on the right. The color matching functions r_λ, g_λ and b_λ were equated by means of W. D. Wright's (1946) convention with normalizing 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).

Aphakics

Originally from
Tan (1971) thesis

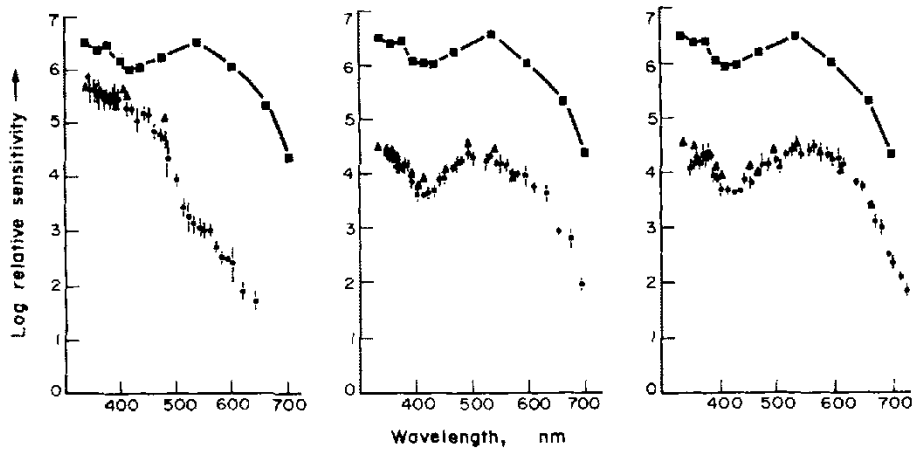
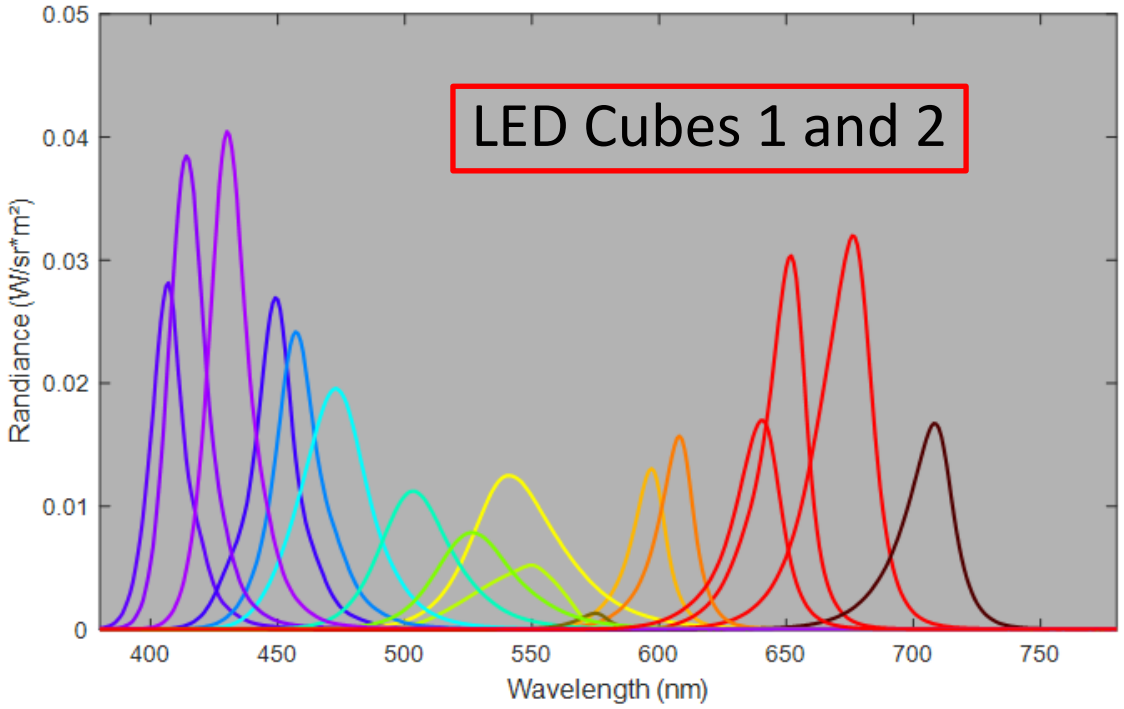
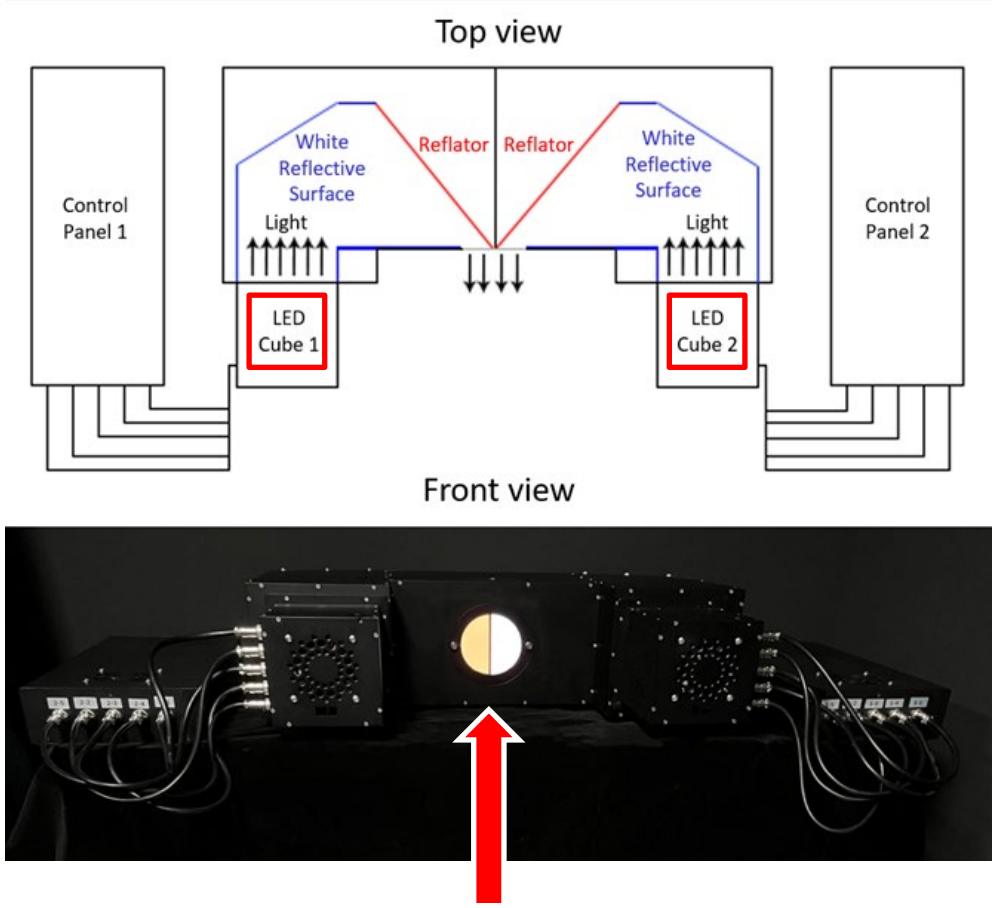


Figure 7. Photopic and cone spectral sensitivities of aphakic observers. (■), Foveal spectral sensitivity which is a composite spectrum of the 3 phototopic (cone) spectra. Left: blue cone spectra; (●), give the foveal spectrum obtained against a bright orange background (Wratten 23 A filter, 5.13 log Trolands) averaged for two subjects; (▲), show the spectral sensitivity of the $\pi 3$ 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 $\pi 4'$ 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 $\pi 5'$ mechanism determined for one subject. Redrawn from Tan (1971).

Trichromator (LEDMax) developed by Thouslite



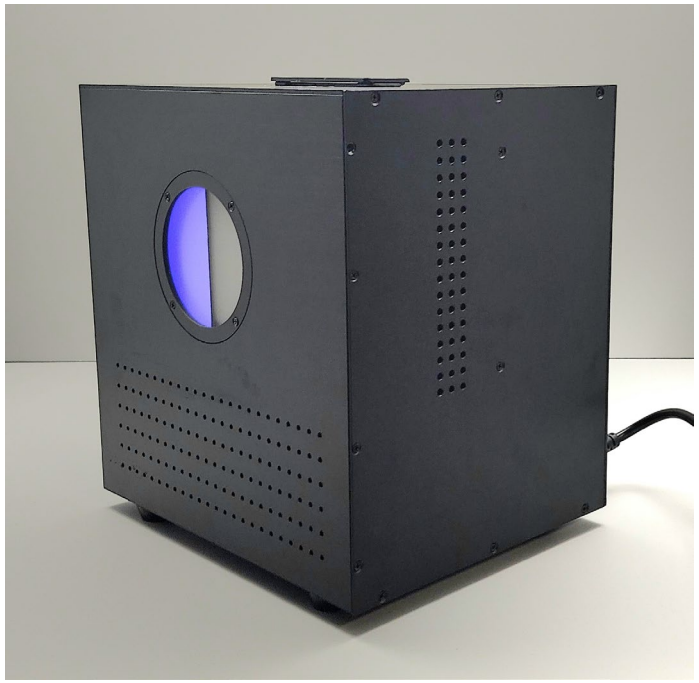


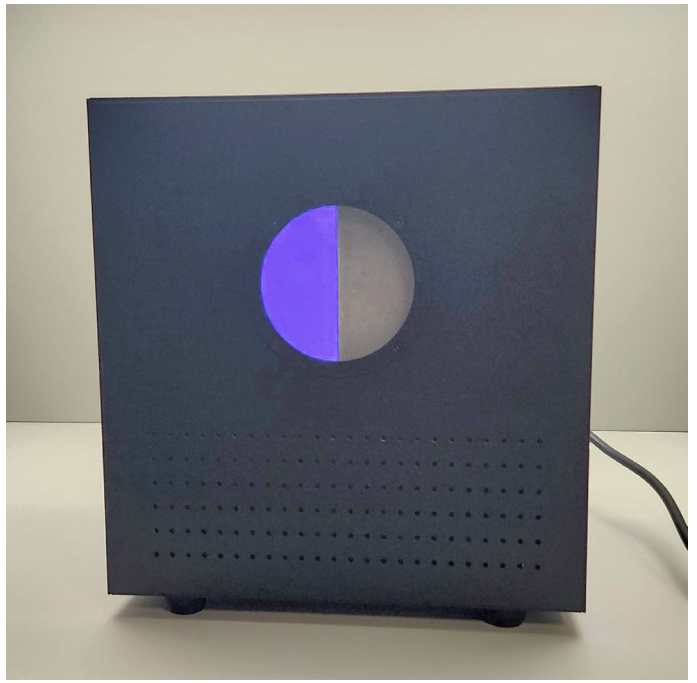
Collaborative work with Ronnier Luo's lab with Lucas Shi and Alan Song and Andy Rider

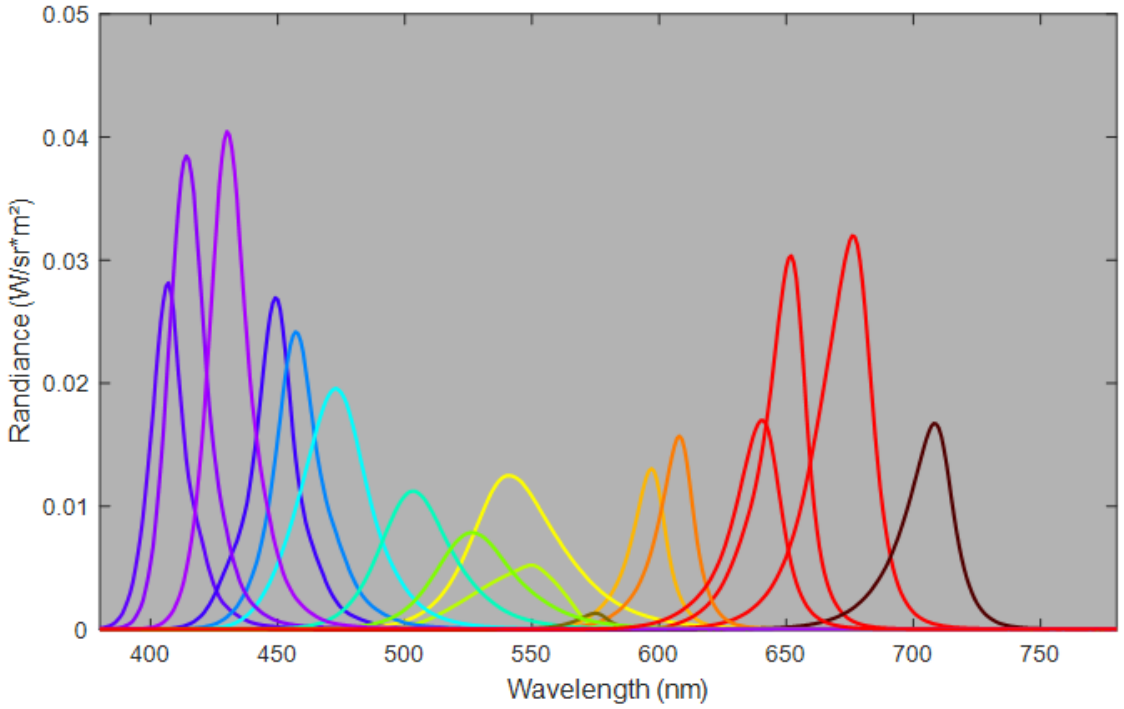
Subject view

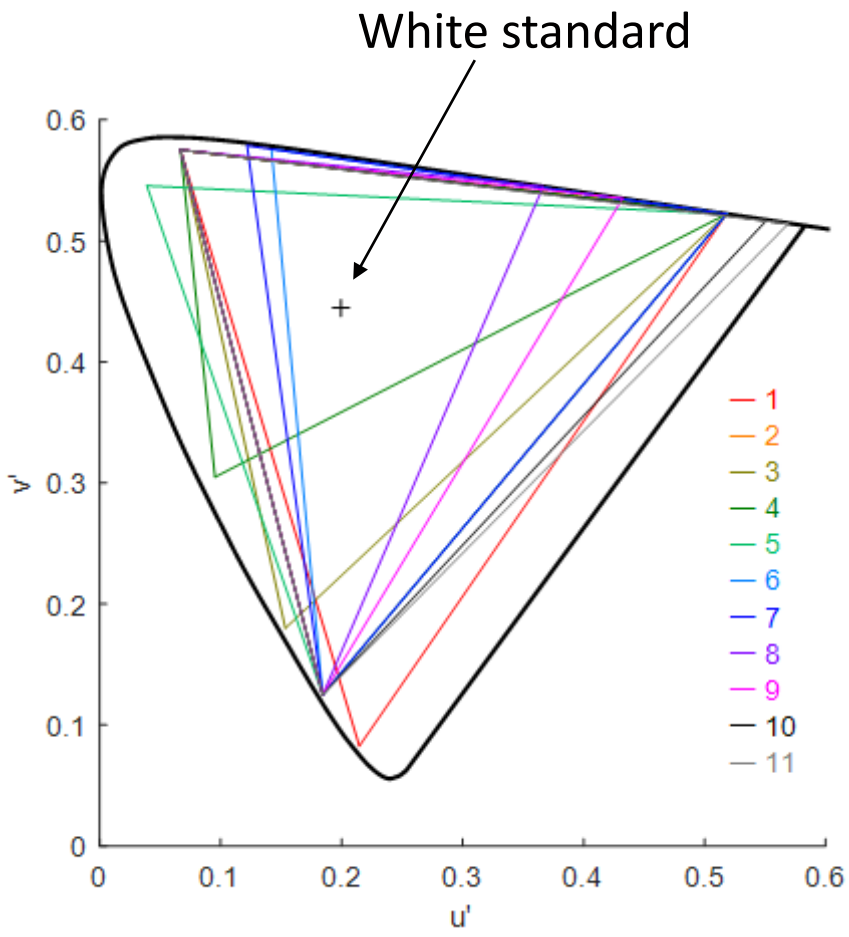
Trichromator (LEDMax) version 2

An newer compact version is on display outside…



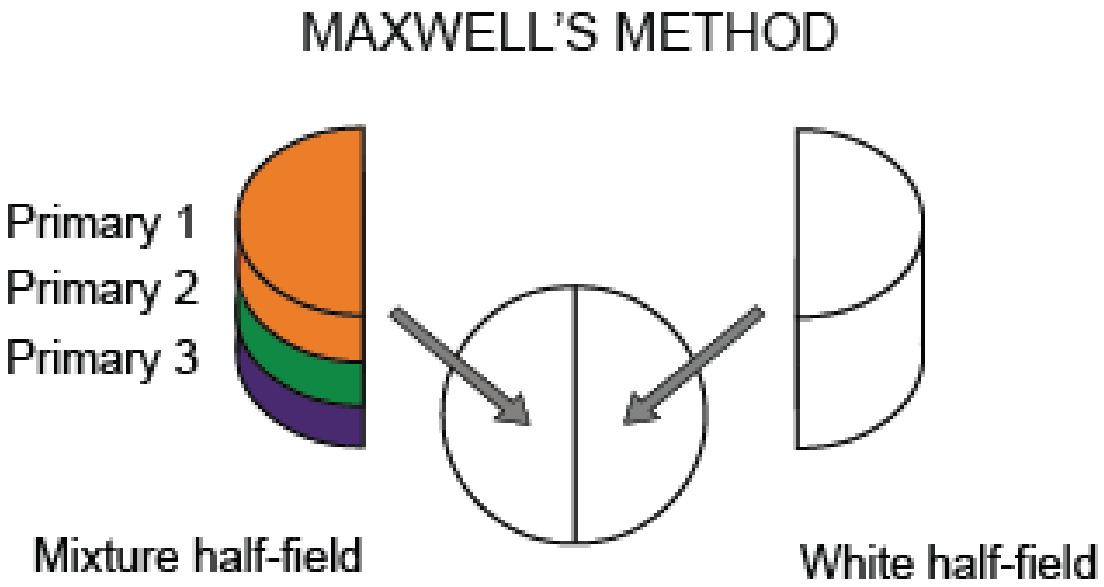


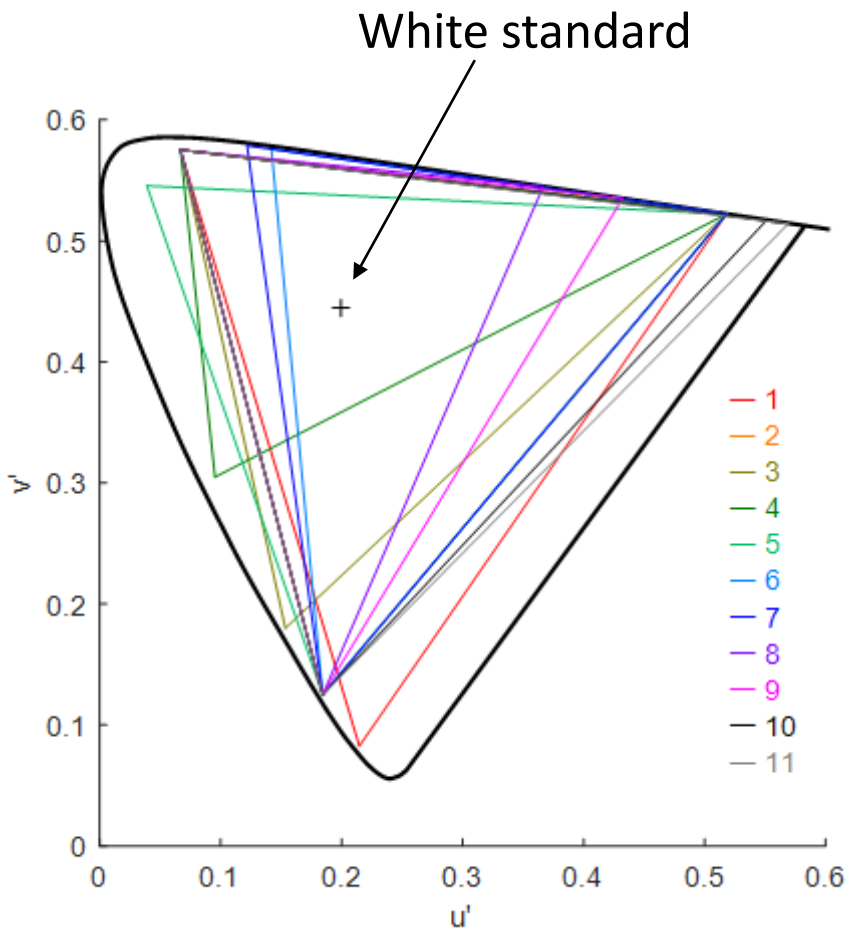




We chose 11 triplets of LEDs (primaries lights) that can be optically mixed to match a white standard (+)…

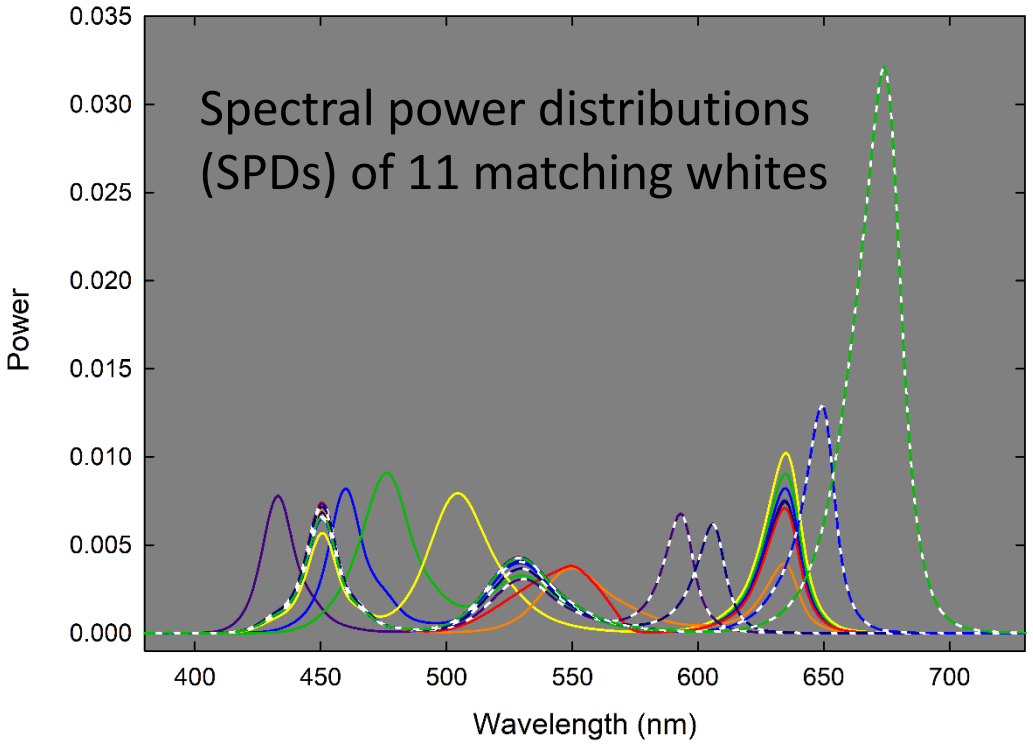
Collaborative work with Ronnier Luo's lab

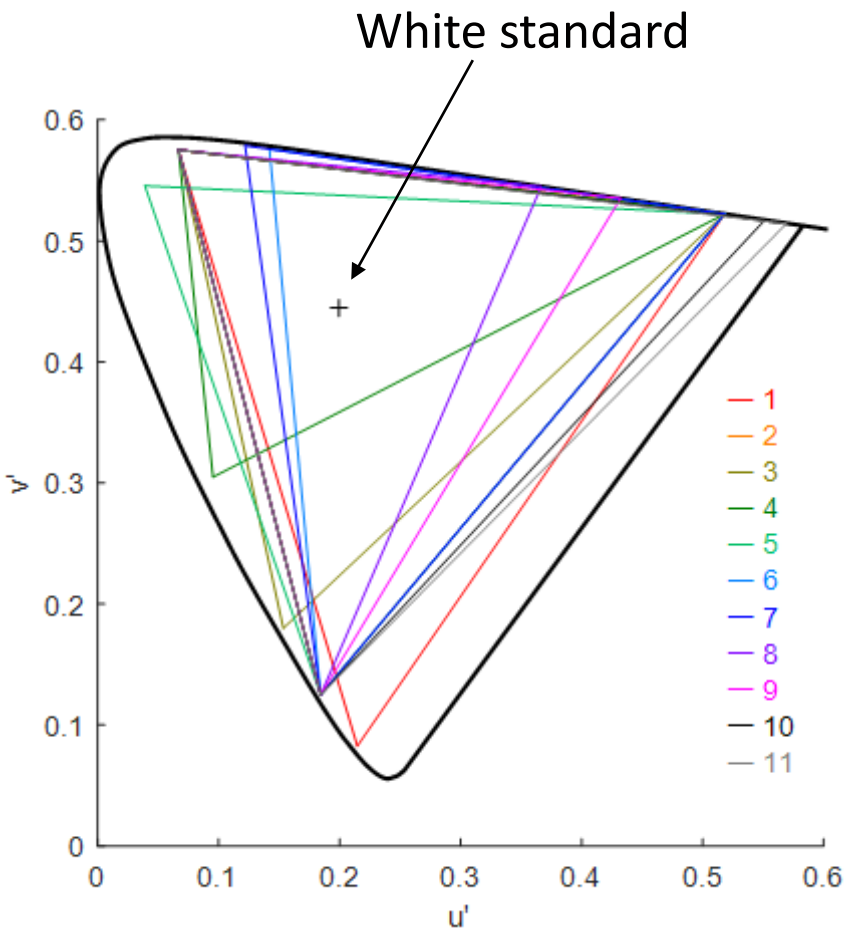




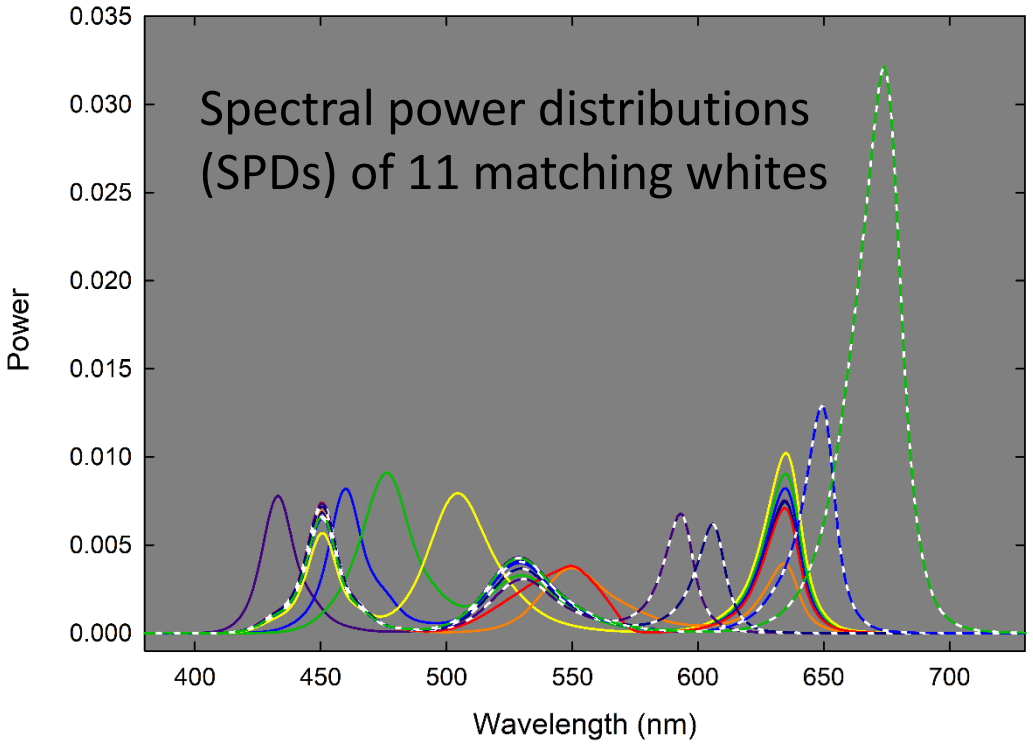
We then asked observers to adjust the intensities of each of the 11 triplets of primaries to match the white standard…

Here are the SPDs for the 11 matching whites (each SPD is made up of all three primaries) set by one of our subjects.





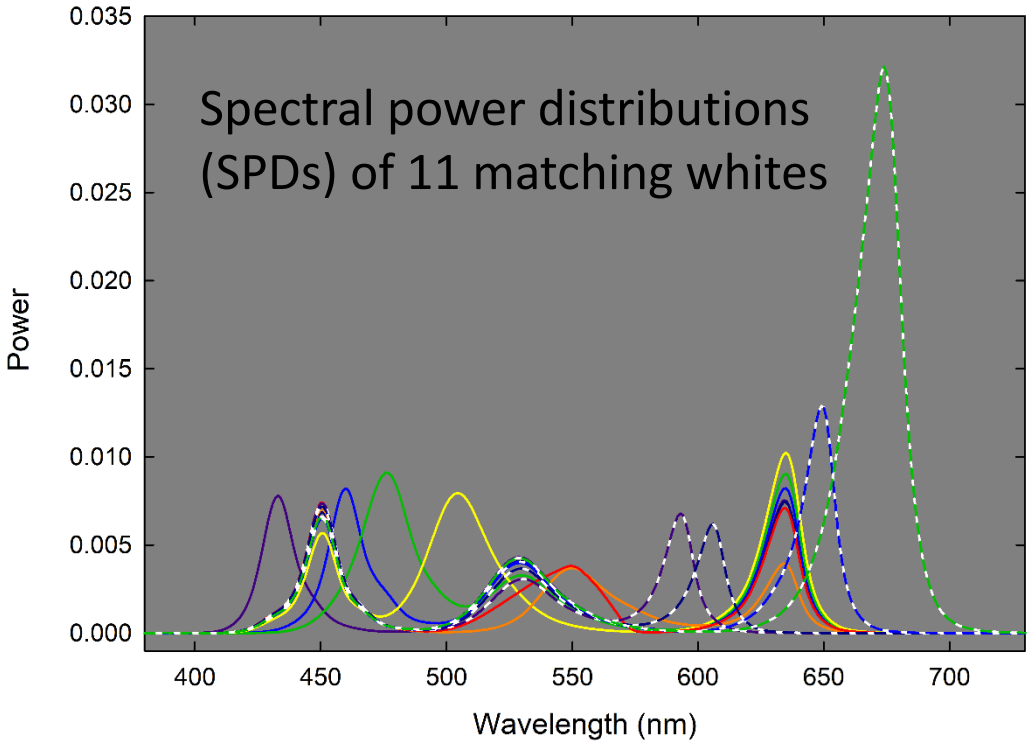
We then asked observers to adjust the intensities of each of the 11 triplets of primaries to match the white standard…



These 11 matching whites should all produce identical L-, M- and S-cone excitations.

So…

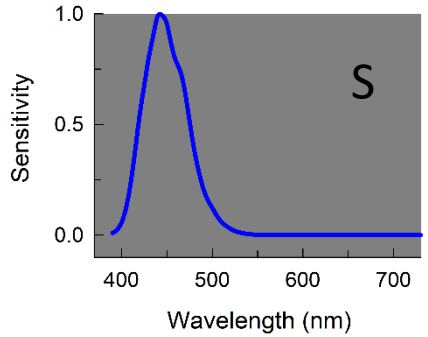
Cross-multiply and integrate



X

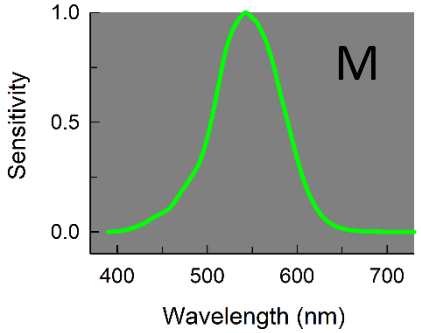
X

X



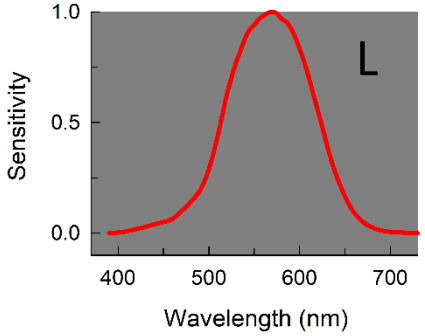
=

All 11 should produce the same S-cone excitation



=

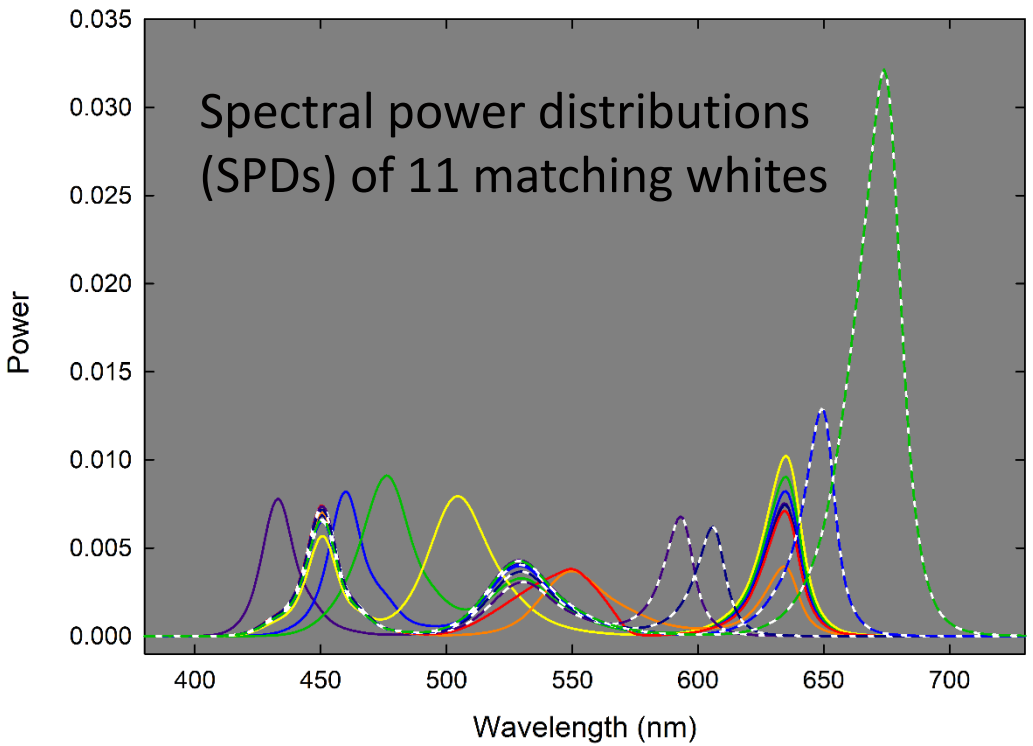
All 11 should produce the same M-cone excitation



=

All 11 should produce the same L-cone excitation

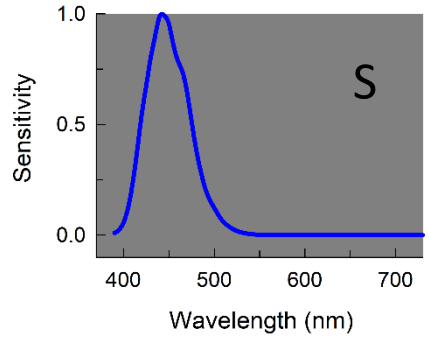
Goal is to find the versions of S, M and L that are closest to producing equal excitations.



X

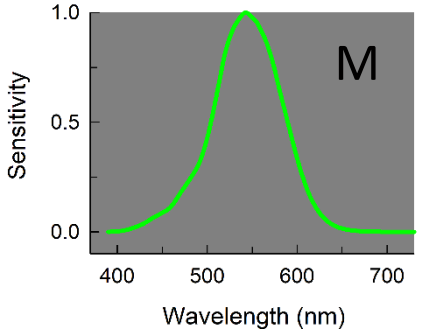
X

X



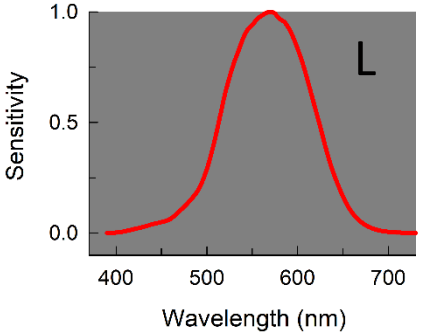
=

All 11 should produce the same S-cone excitation



=

All 11 should produce the same M-cone excitation

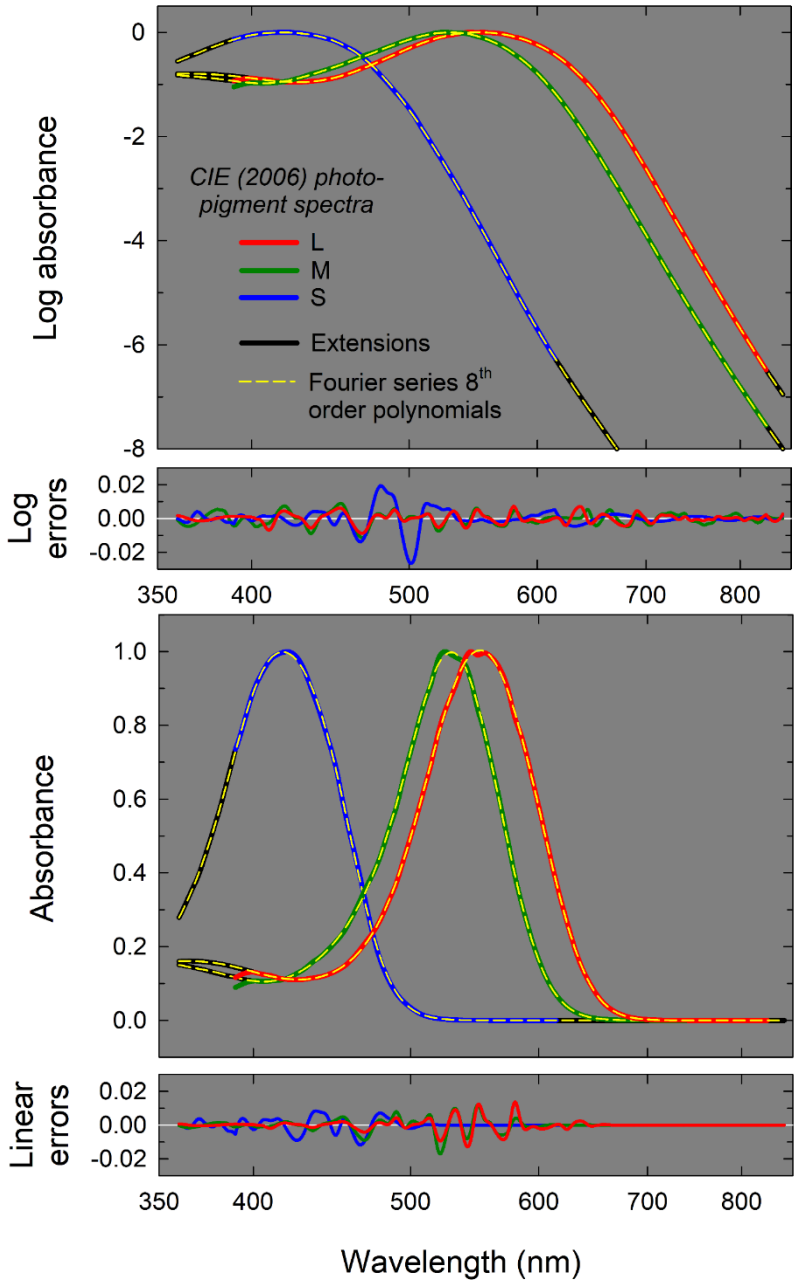


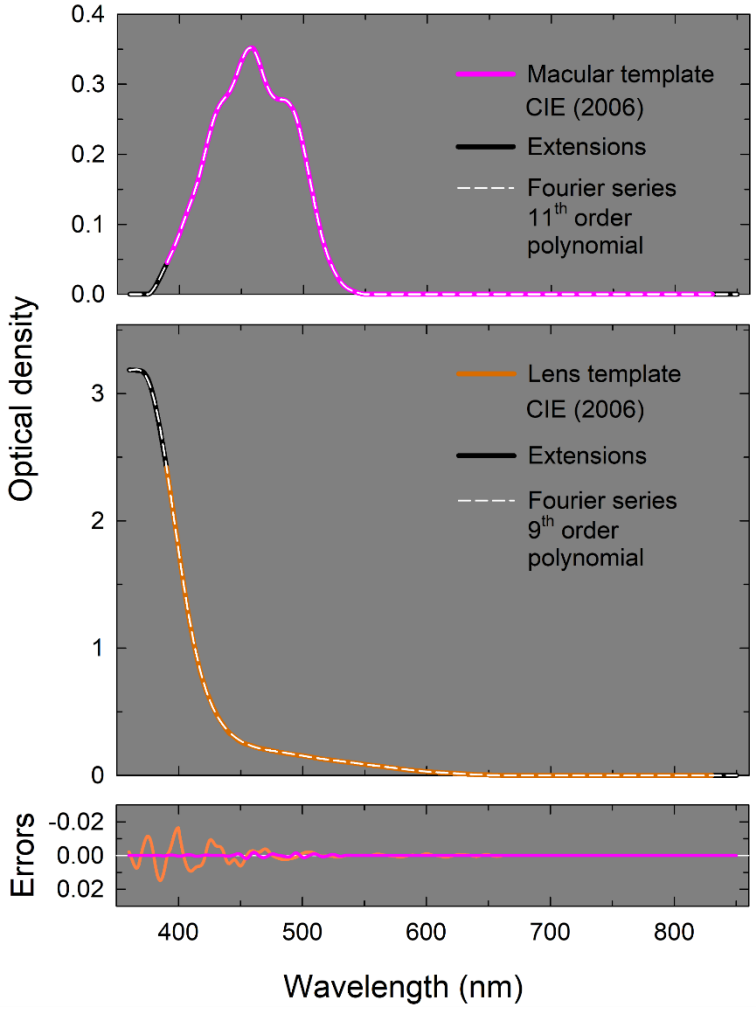
=

All 11 should produce the same L-cone excitation

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

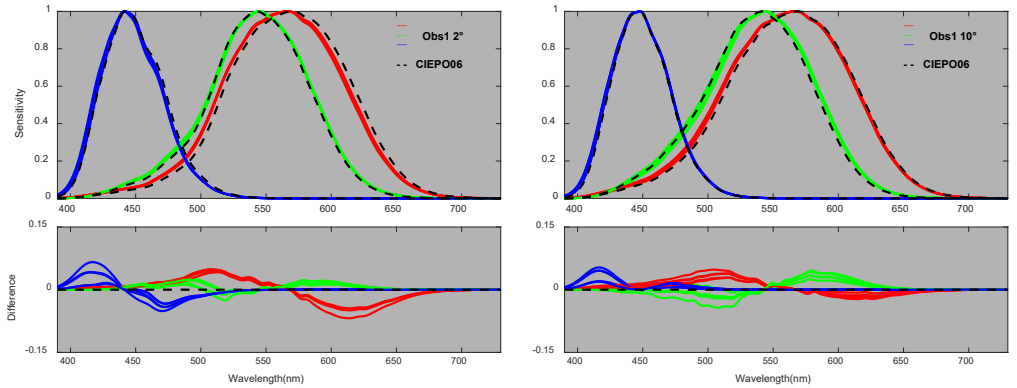
We use these continuous functions.



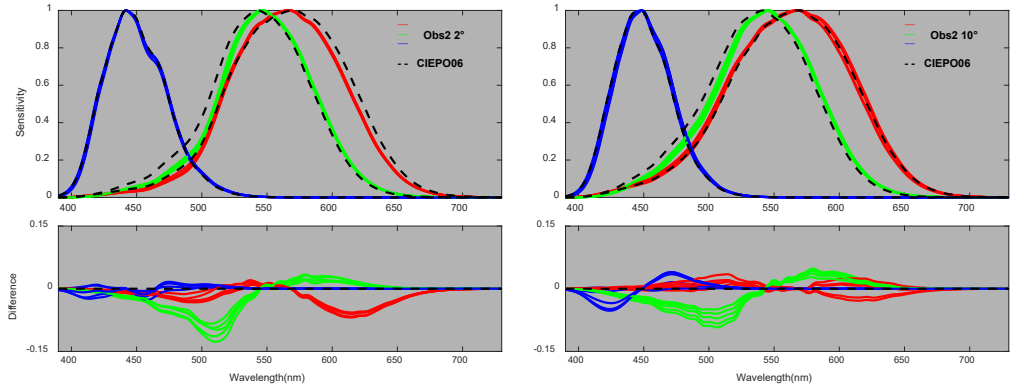


2º 10º

Obs 1

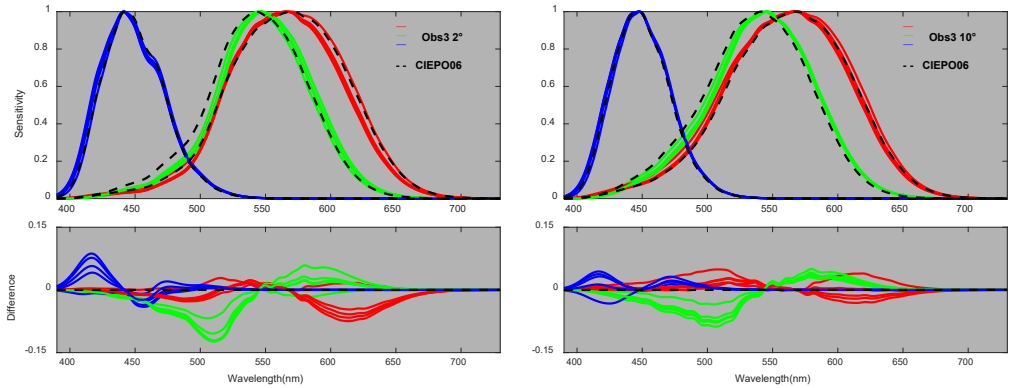


Obs 2

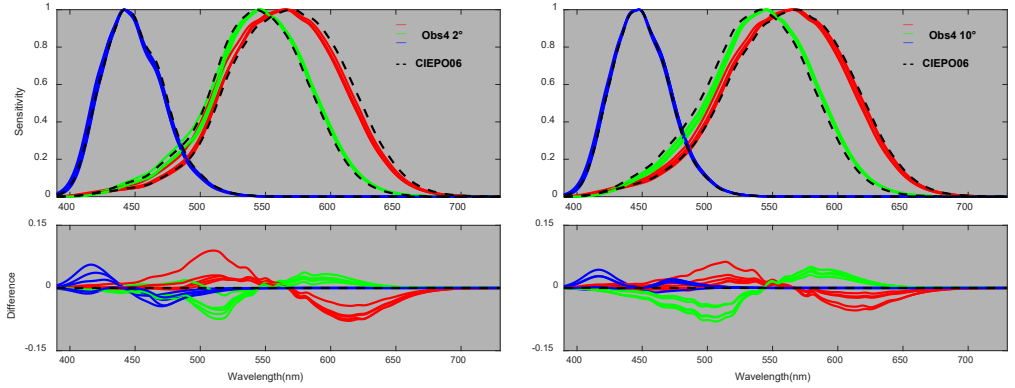


2º 10º

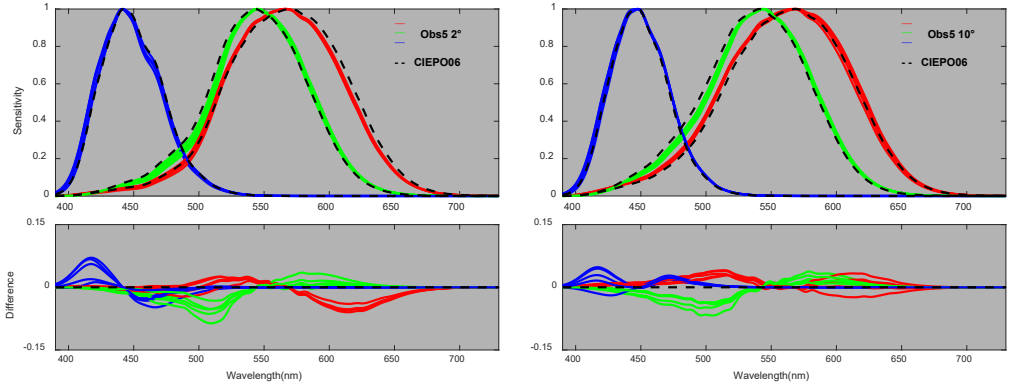
Obs 3



Obs 4



Obs 5



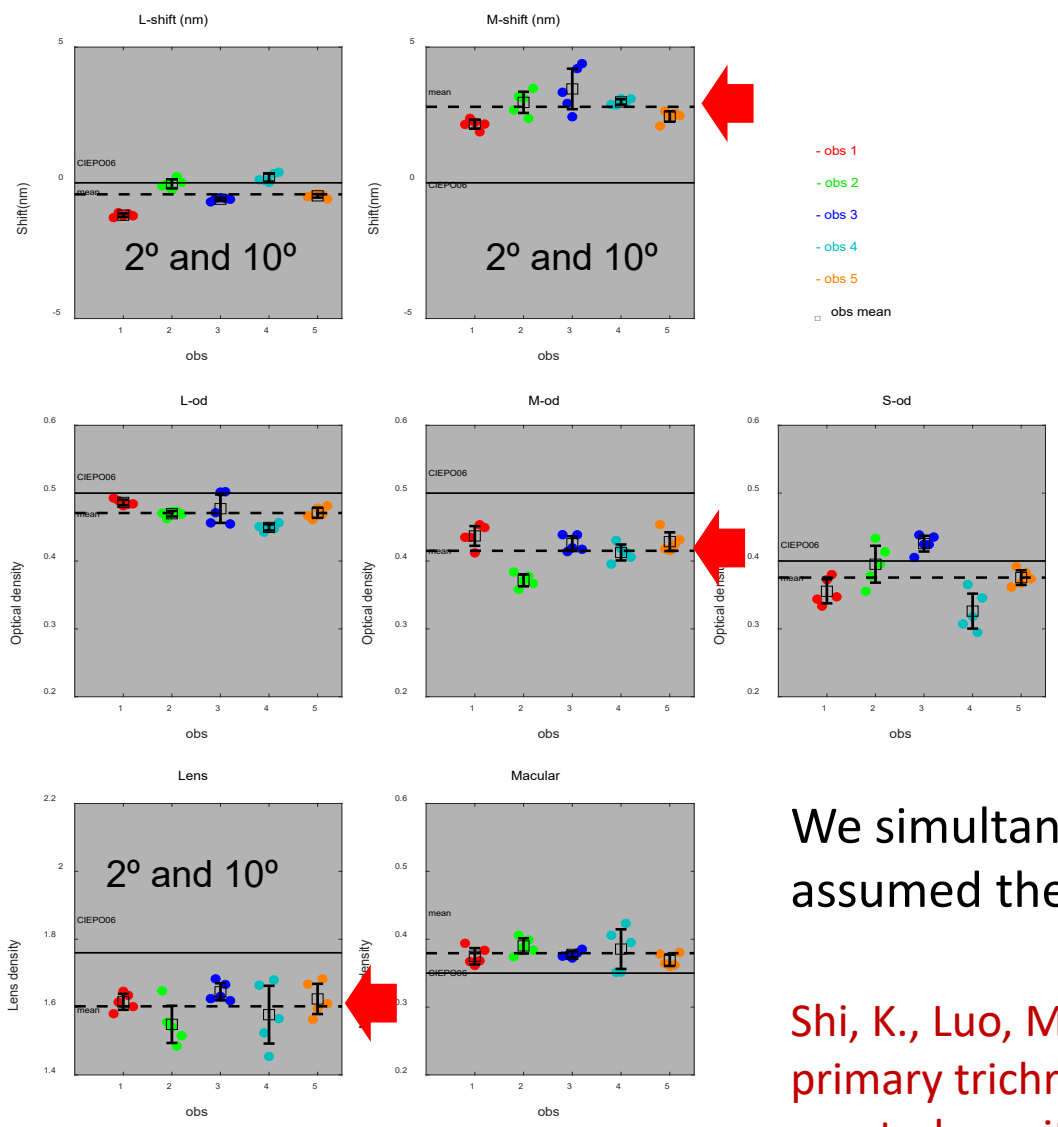
Here are the cone fundamentals that best predict the colour matches measured and estimated five times in five subjects.

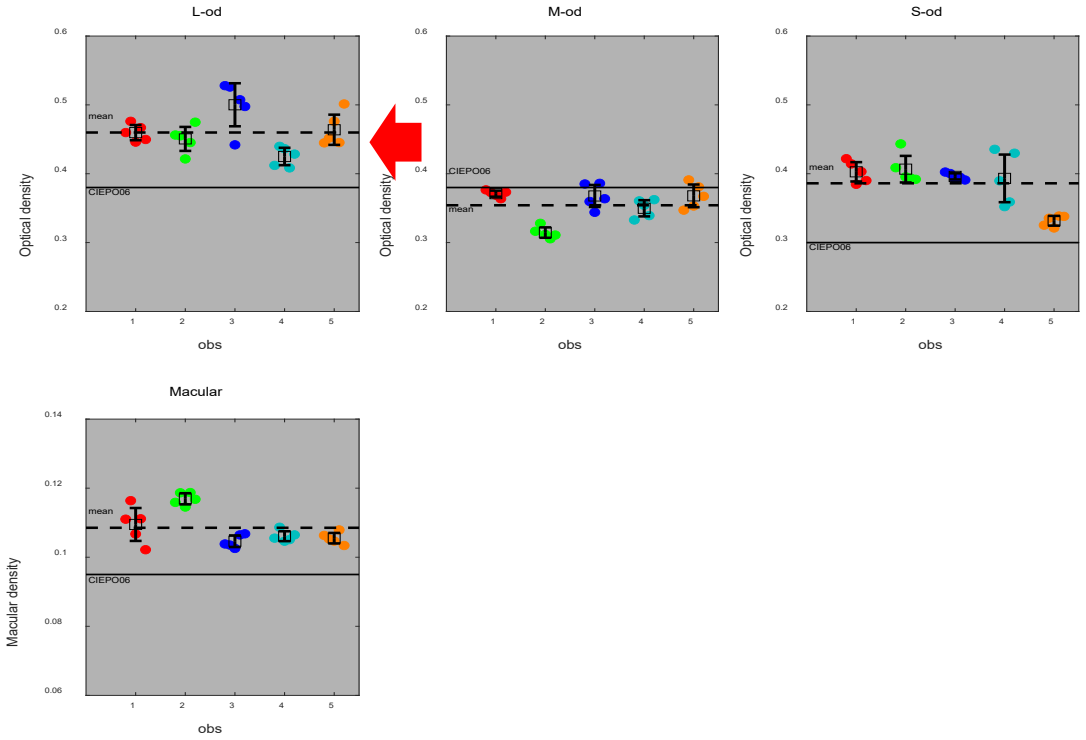
The CIEPO06 curves are the CIE standard LMS functions

Fitted parameters

2º

10º





We simultaneously fit 22 colour matches: 11 at 2° and 11 at 10° and assumed the same L- and M-shifts and lens densities for 2° and 10°.

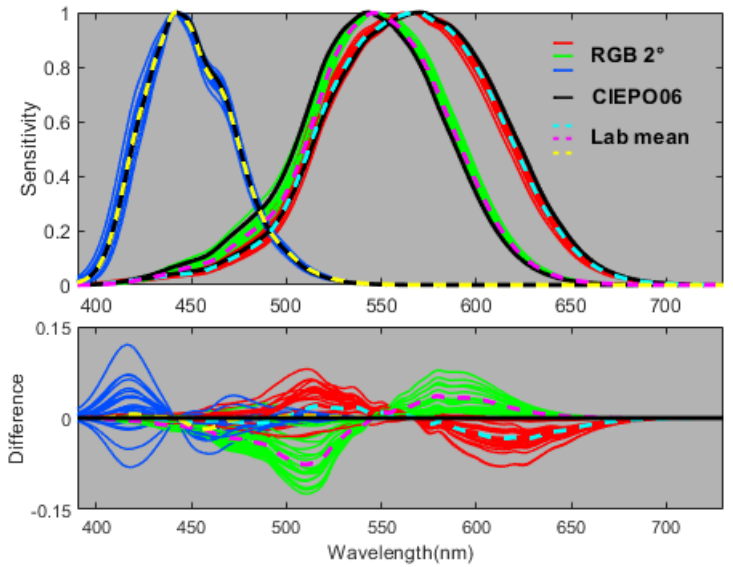
Shi, K., Luo, M. R., Rider, A. T., Huang, T., Xu, L., & Stockman, A. (2024). A multi-primary trichromator to derive individual color matching functions and cone spectral sensitivities. *Color Research & Application, 2024, 1-16*

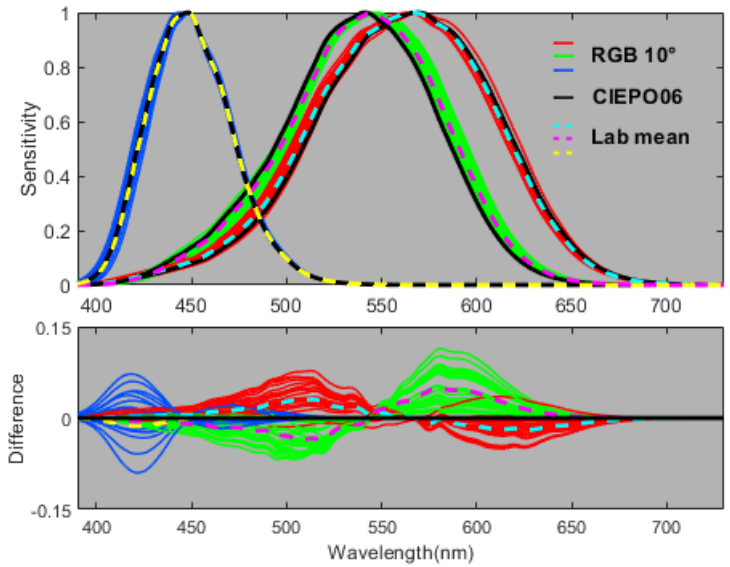
Now measured in a total of 51 young observers.

2º

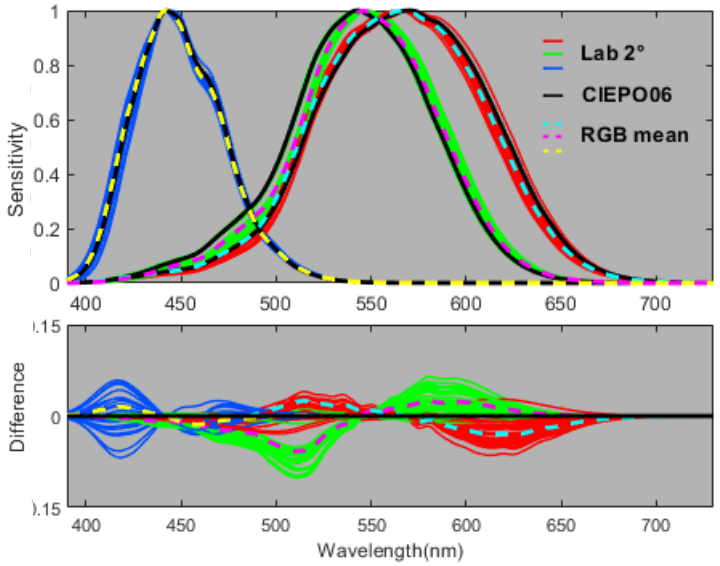
10º

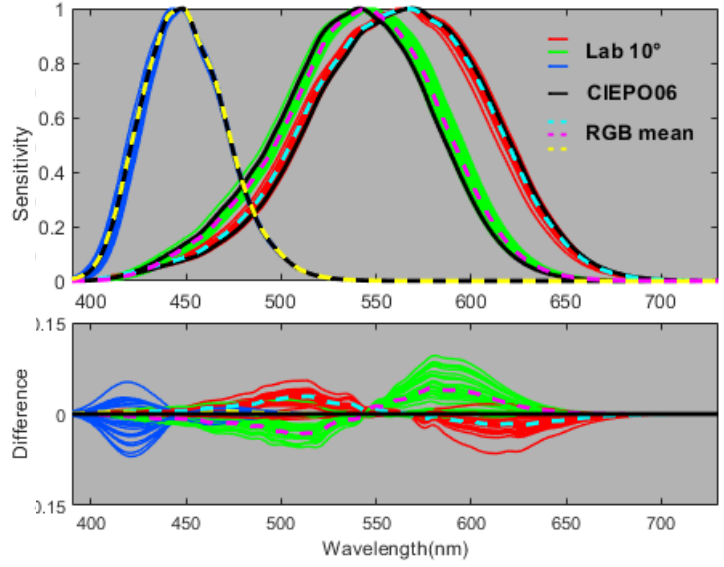
RGB method





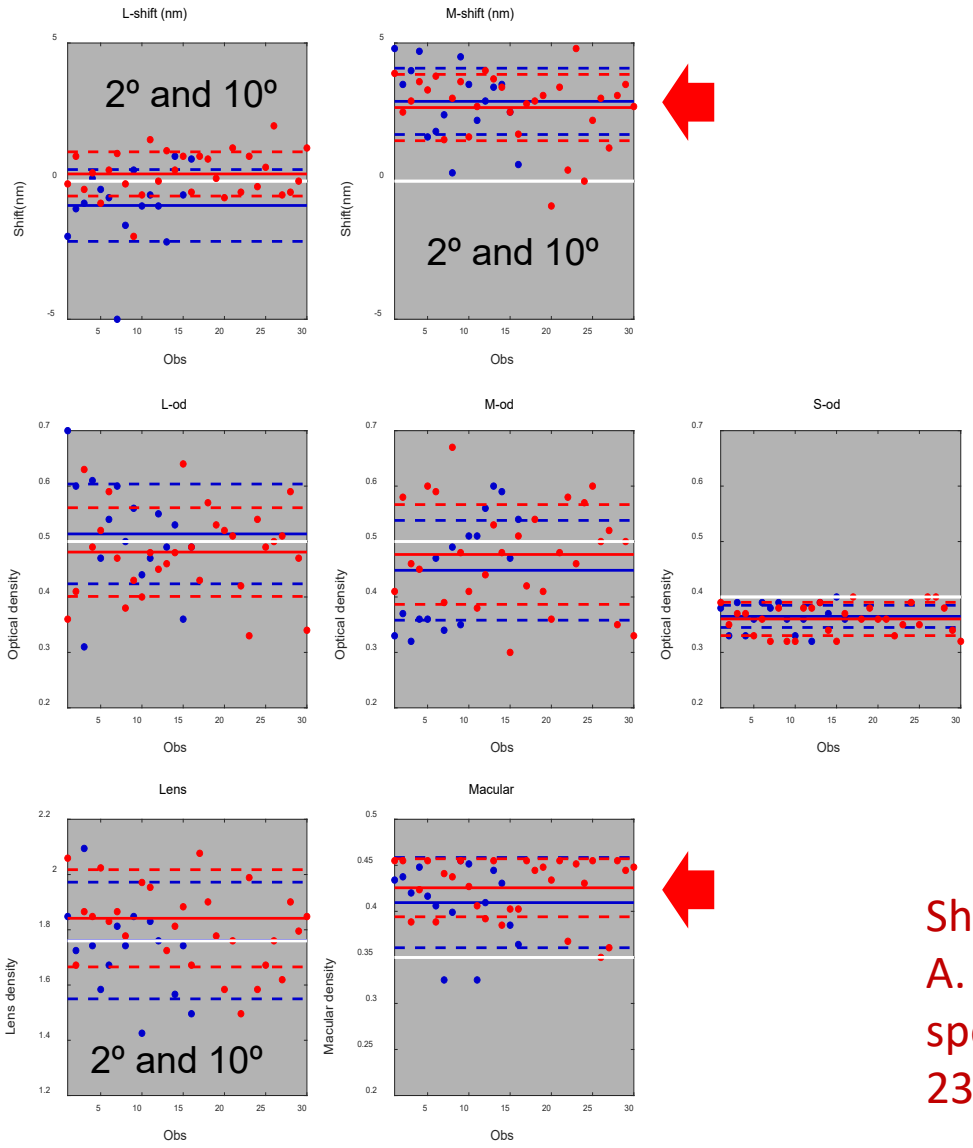
Lab method



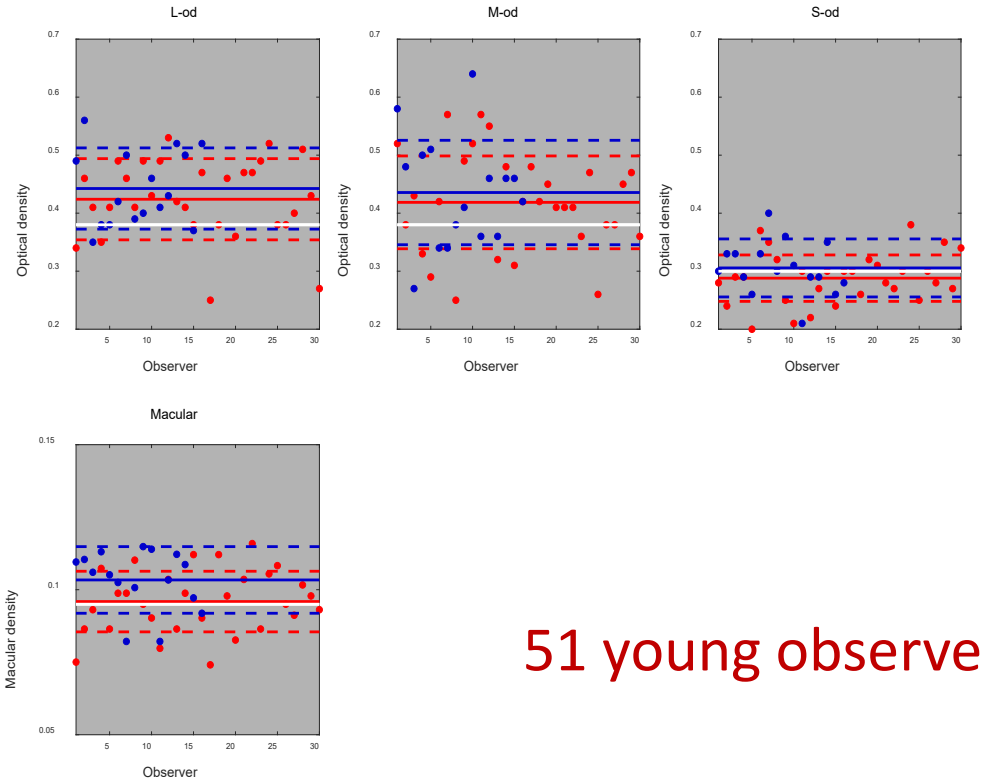


Fitted parameters

2º



10º



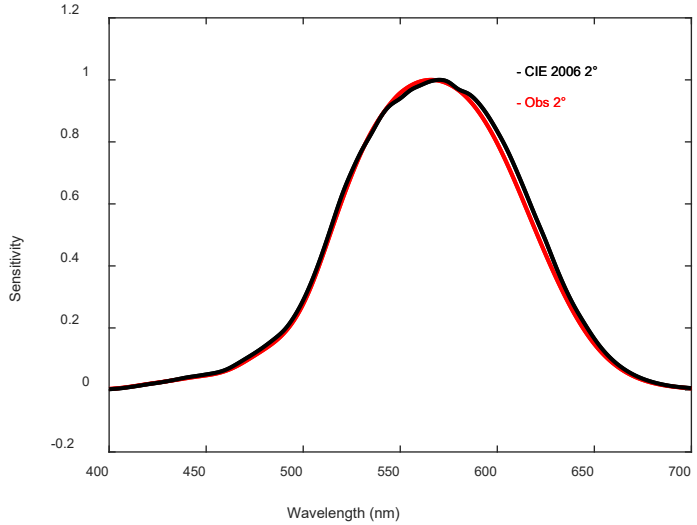
51 young observers.

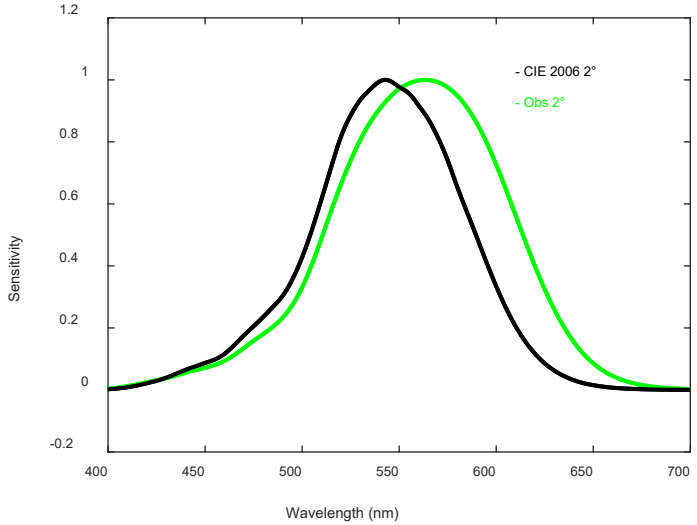
Shi, K., Luo, M. R., Rider, A. T., Song, S., Huang, T., & Stockman, A. (2024). Individual differences in color matches and cone spectral sensitivities in 51 young adults. Optics Express, 32(13), 23597-23616.

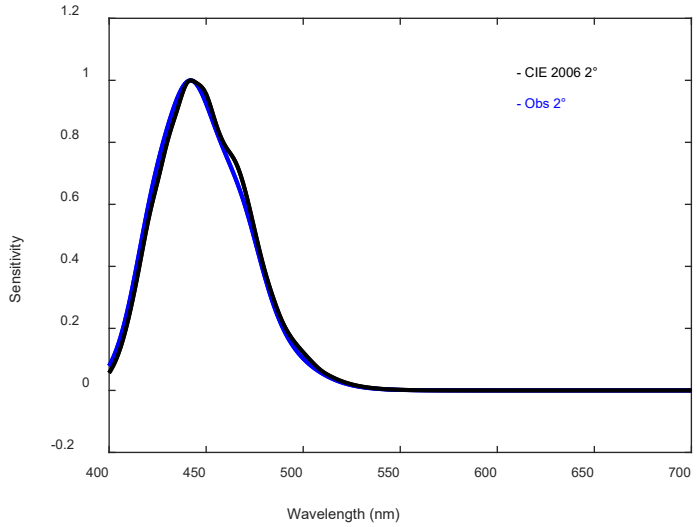
We are now working on different age groups and have measured 100 observers form young to old.

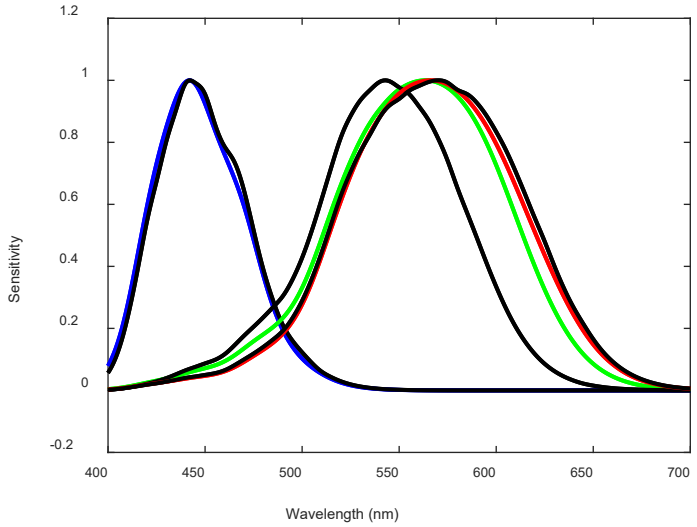
And also for, so far, 22 colour deficient observers, for whom, remarkably, the methods seem also to work. Here are two examples…

Typical severe deuteranomalous/ deuteranopic observer



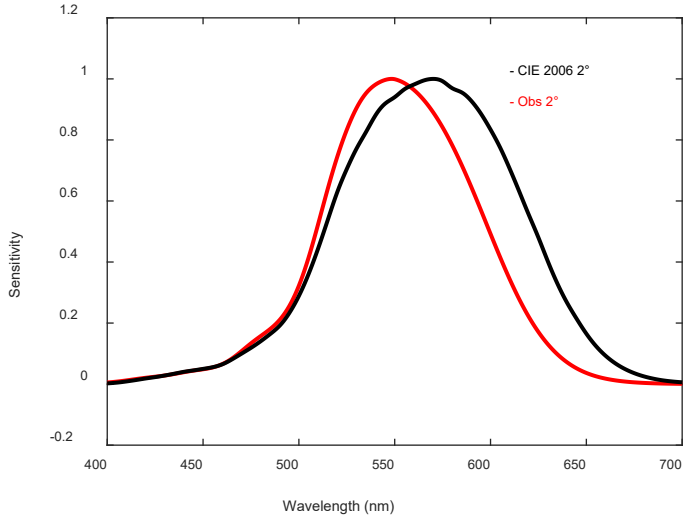


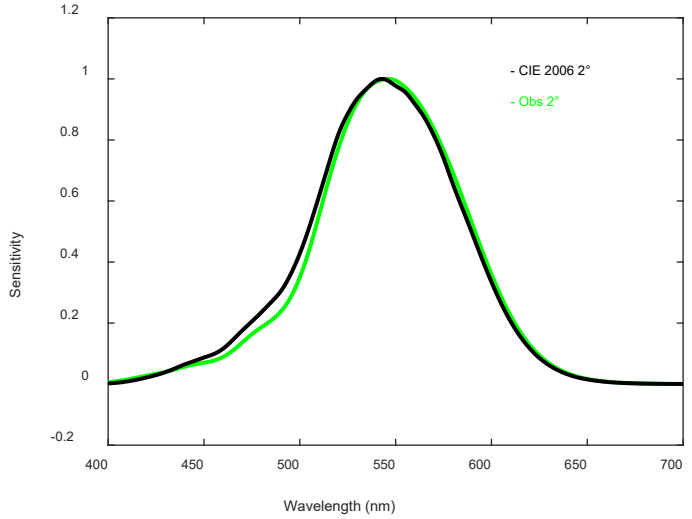


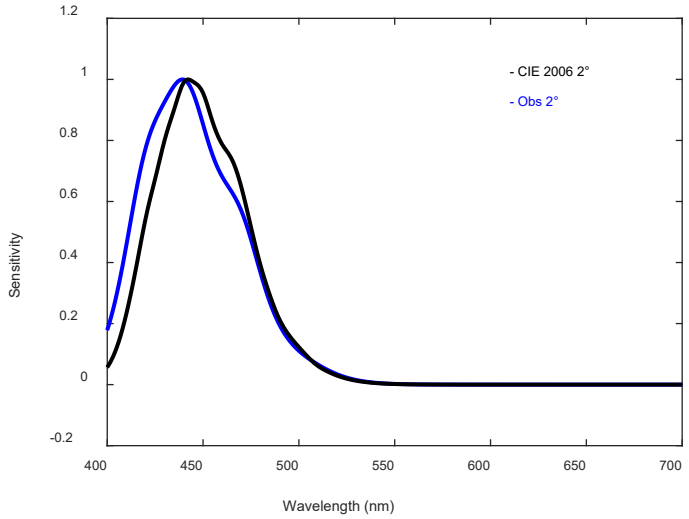


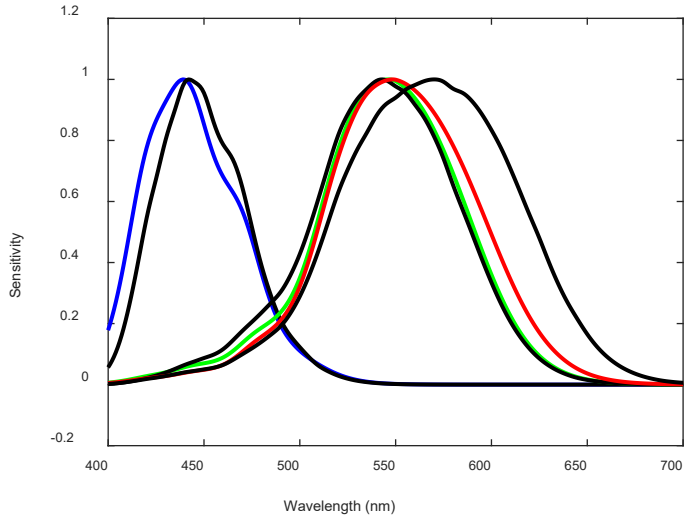
	Obs	CIE 2006 2°
L- shift	-0.1	0
M- shift	19.8	0
Density of L-	0.31	0.5
Density of M-	0.69	0.5
Density of S-	0.31	0.4
Lens density	1.57	1.76
Macular density	0.321	0.350

Typical severe protanomalous/ protanopic observer









	Obs	CIE 2006 2°
L- shift	-19.5	0
M- shift	0.3	0
Density of L-	0.34	0.5
Density of M-	0.64	0.5
Density of S-	0.35	0.4
Lens density	1.29	1.76
Macular density	0.536	0.350

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

CVRL database

http://www.cvrl.org