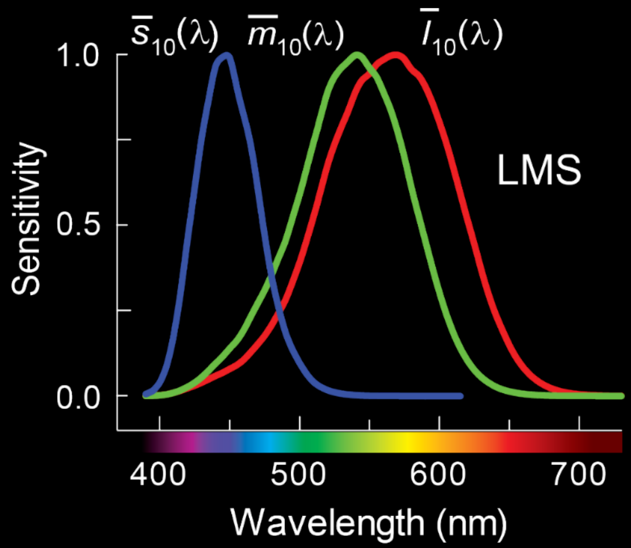
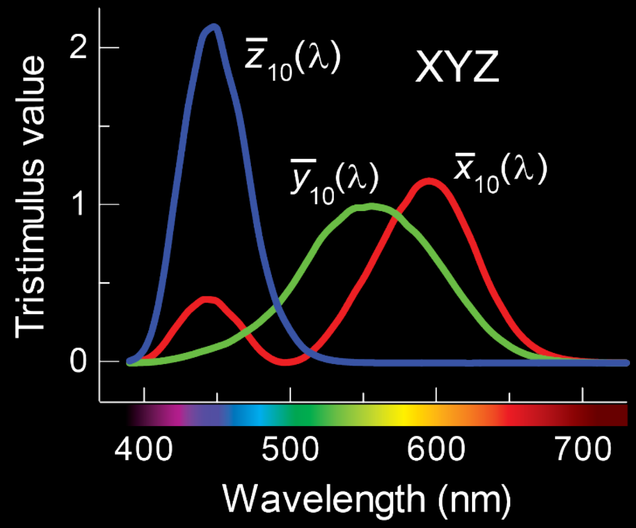
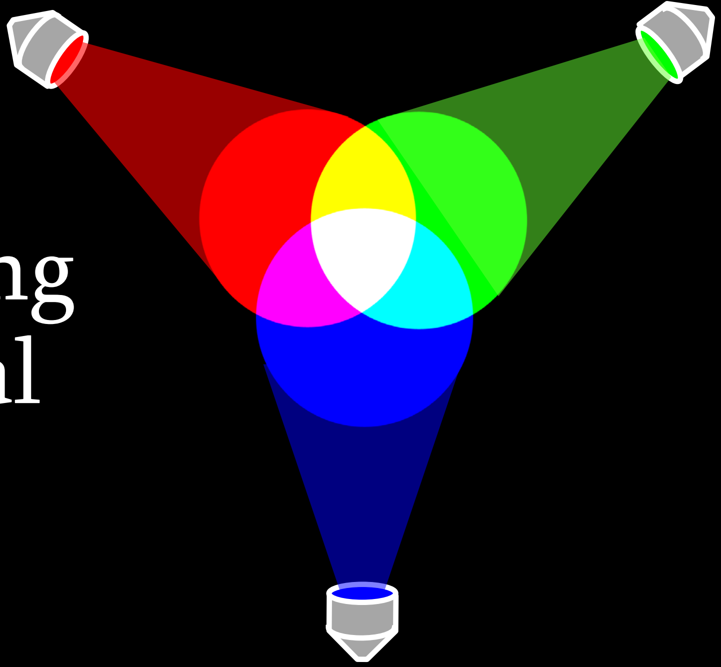




Modelling and estimating individual cone spectral sensitivities



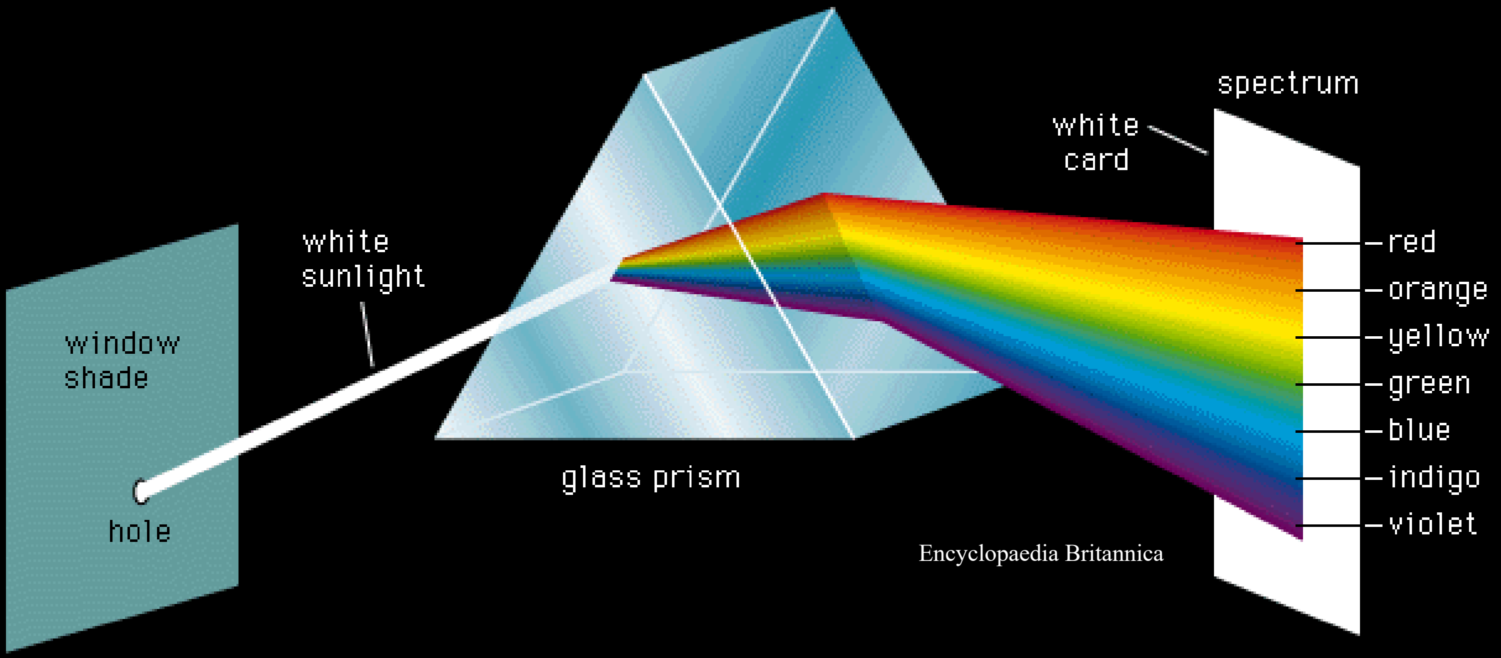
Andy Rider

Outline

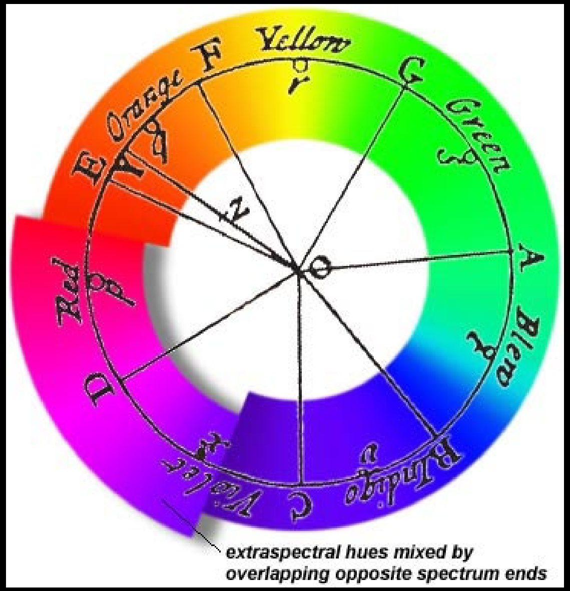
- Introduction to vision, cone spectral sensitivities, and colour matching functions (CMFs)
- Individual differences in cone fundamentals and CMFs
- Modelling cone fundamentals
- Estimating individual differences

Light

390 - 700 nm is important for vision

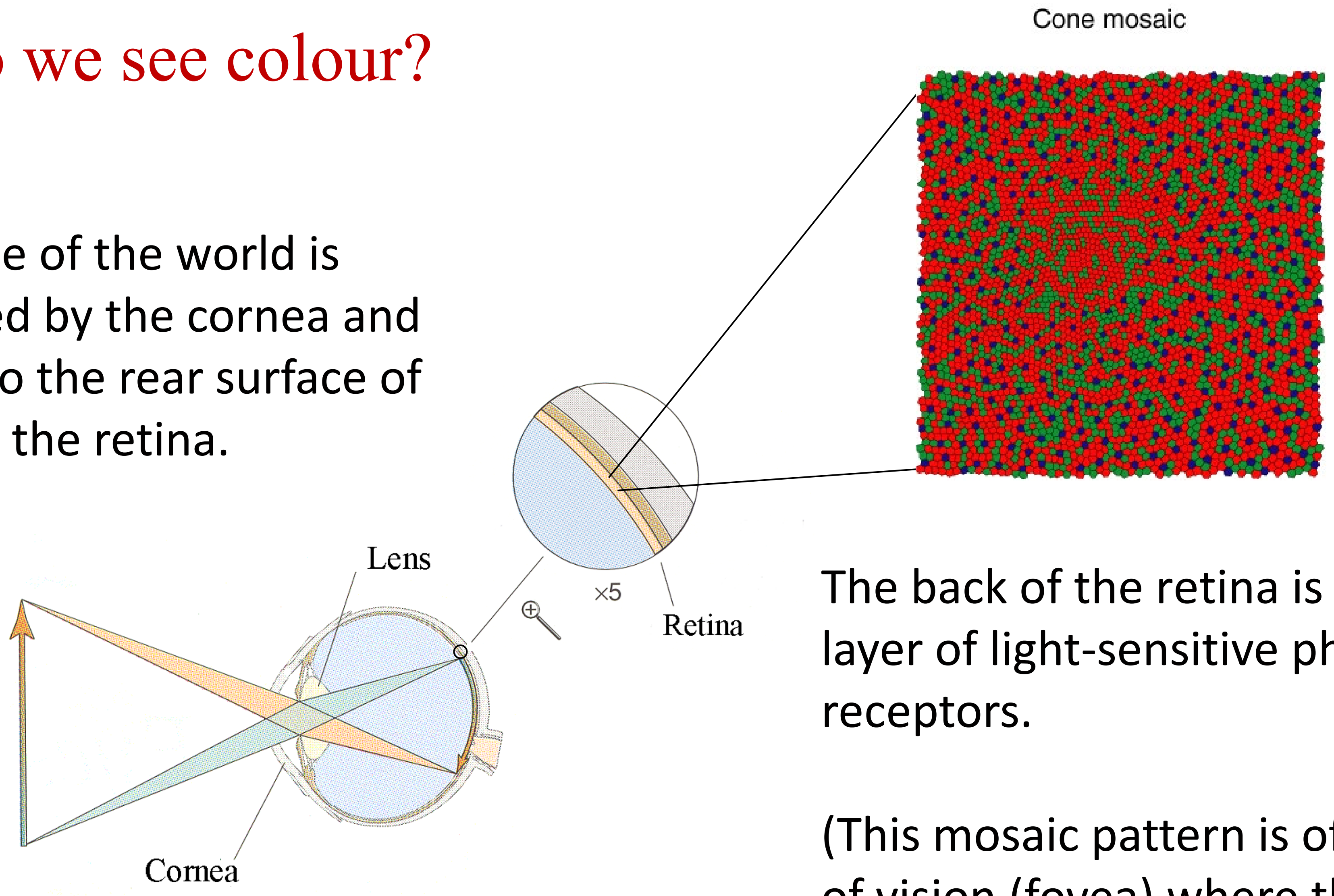


Encyclopaedia Britannica



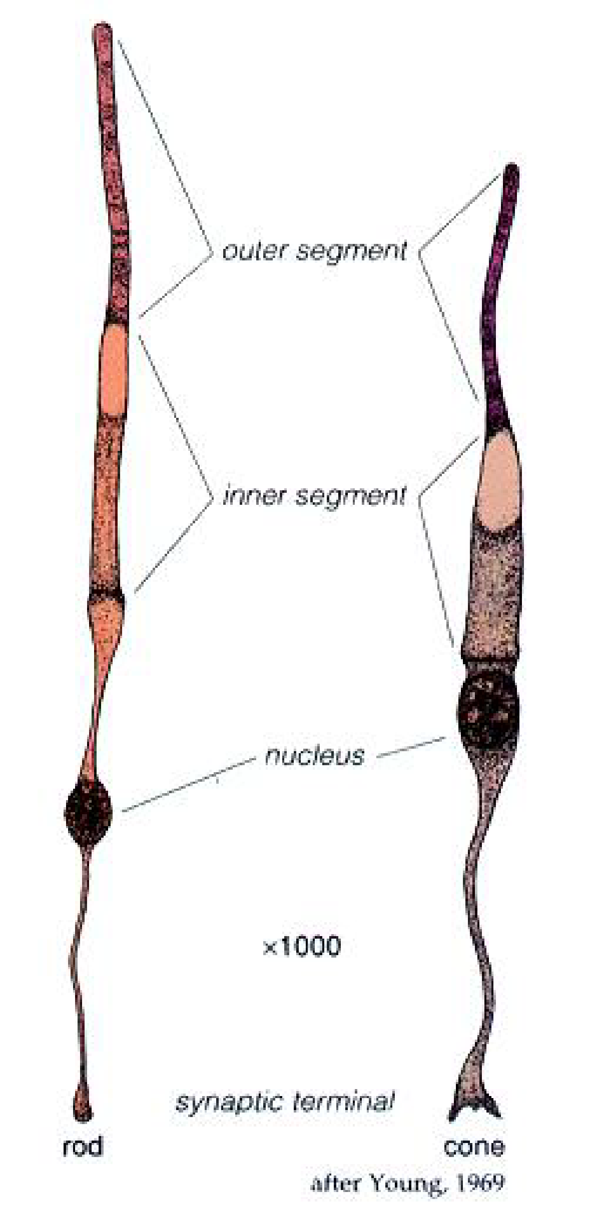
How do we see colour?

An image of the world is projected by the cornea and lens onto the rear surface of the eye: the retina.



The back of the retina is carpeted by a layer of light-sensitive photo-receptors.

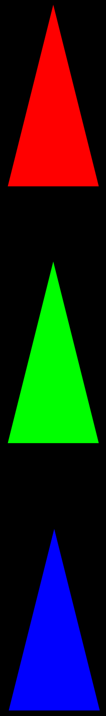
(This mosaic pattern is of the centre of vision (fovea) where there are only cone (daytime) photoreceptors.)



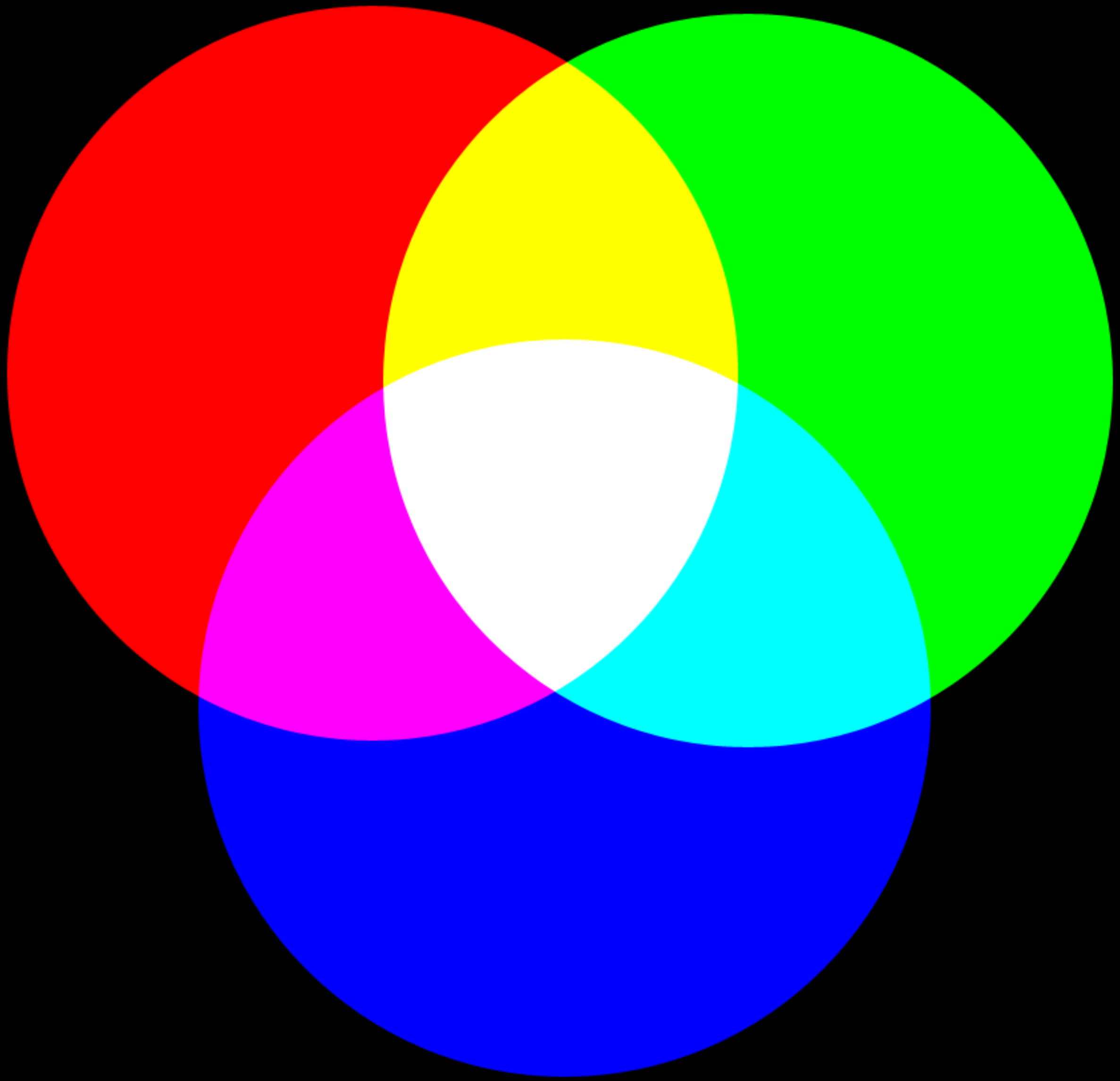
Human photoreceptors

- Rods
  - Achromatic night vision
  - 1 type

- Cones
  - Daytime, achromatic *and* chromatic vision
  - 3 types



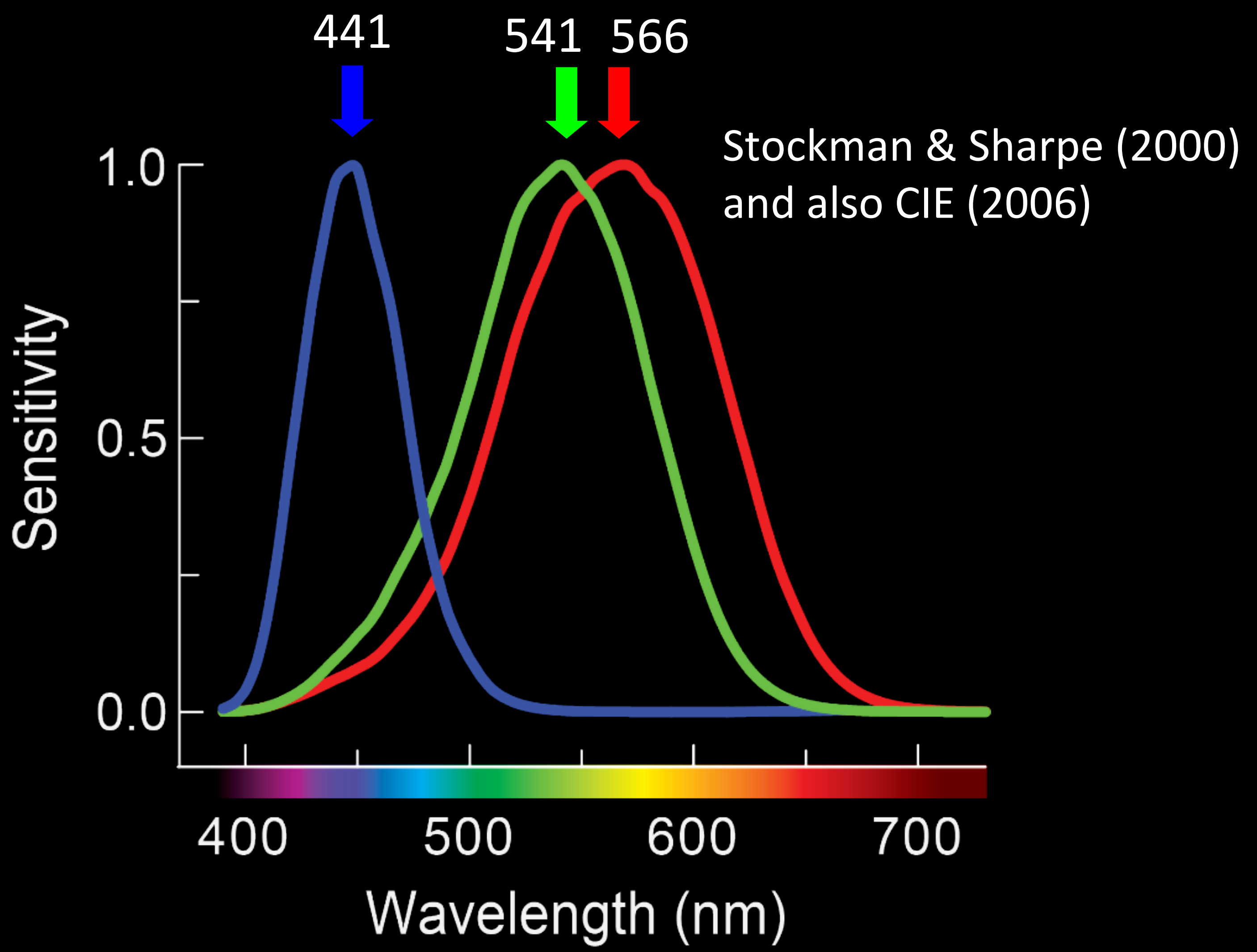
Trichromacy



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

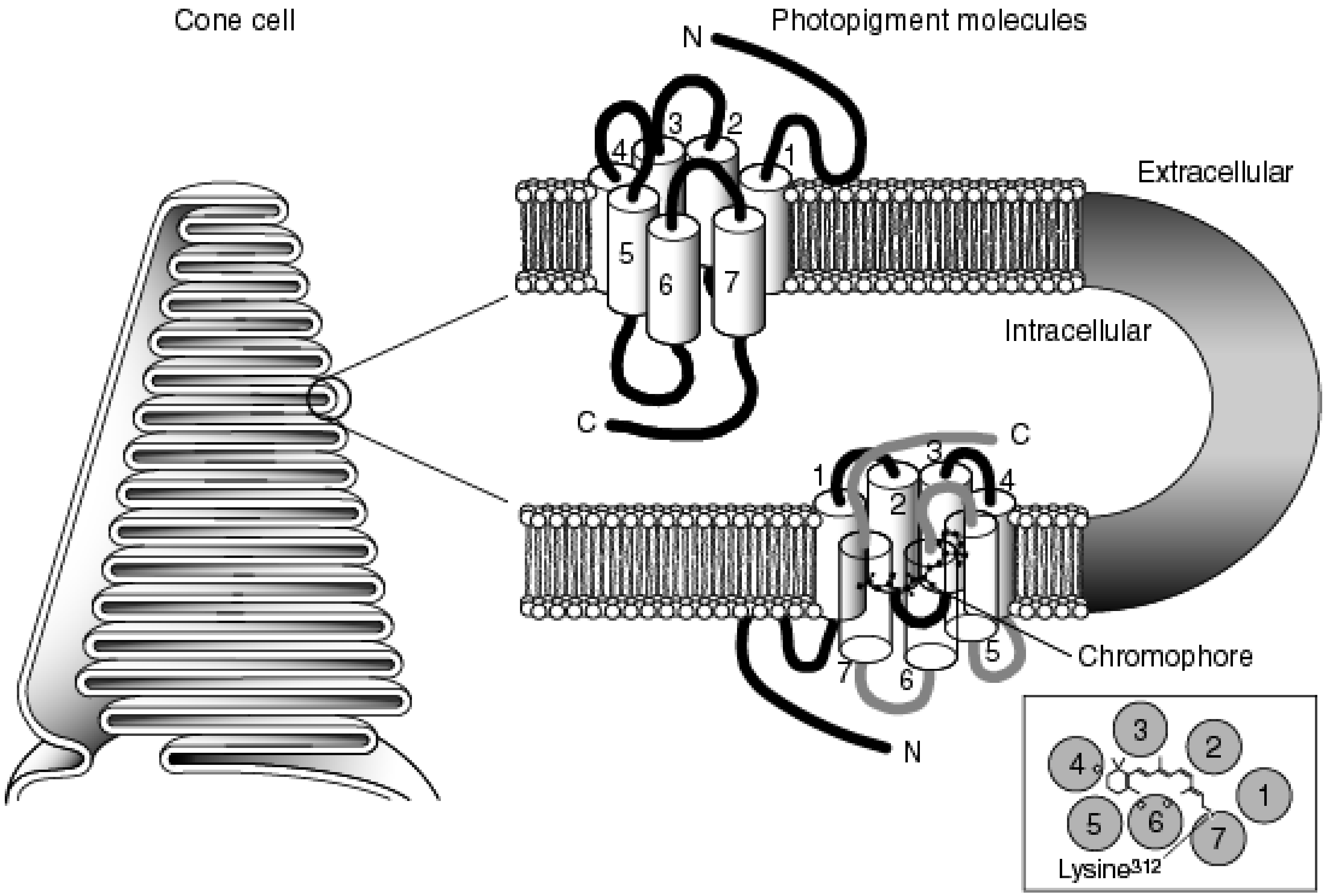
It is a 3-variable system

Trichromacy arises because there are just three cone types each of which is “univariant” and each cone type which has a different spectral sensitivity.



If we know the three cone spectral sensitivities, and thus the effects that lights have on the three cones, we can completely specify those lights.

Cone outer segment



The photopigment, **opsin**, has 7 transmembrane helices

The chromophore, **retinal** (the aldehyde of vitamin A), sits in the middle

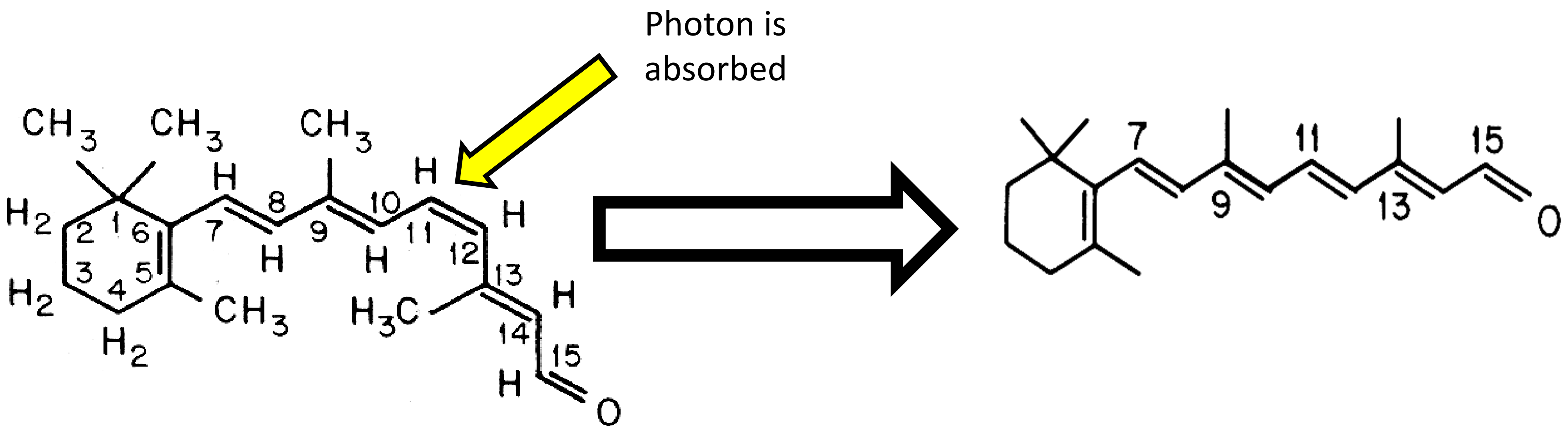
Retinal

Doesn't matter what wavelength!

The inactive form of the chromophore is **11-cis** retinal

There is a twist at the 11th carbon atom

Cones are "UNIVARIANT"



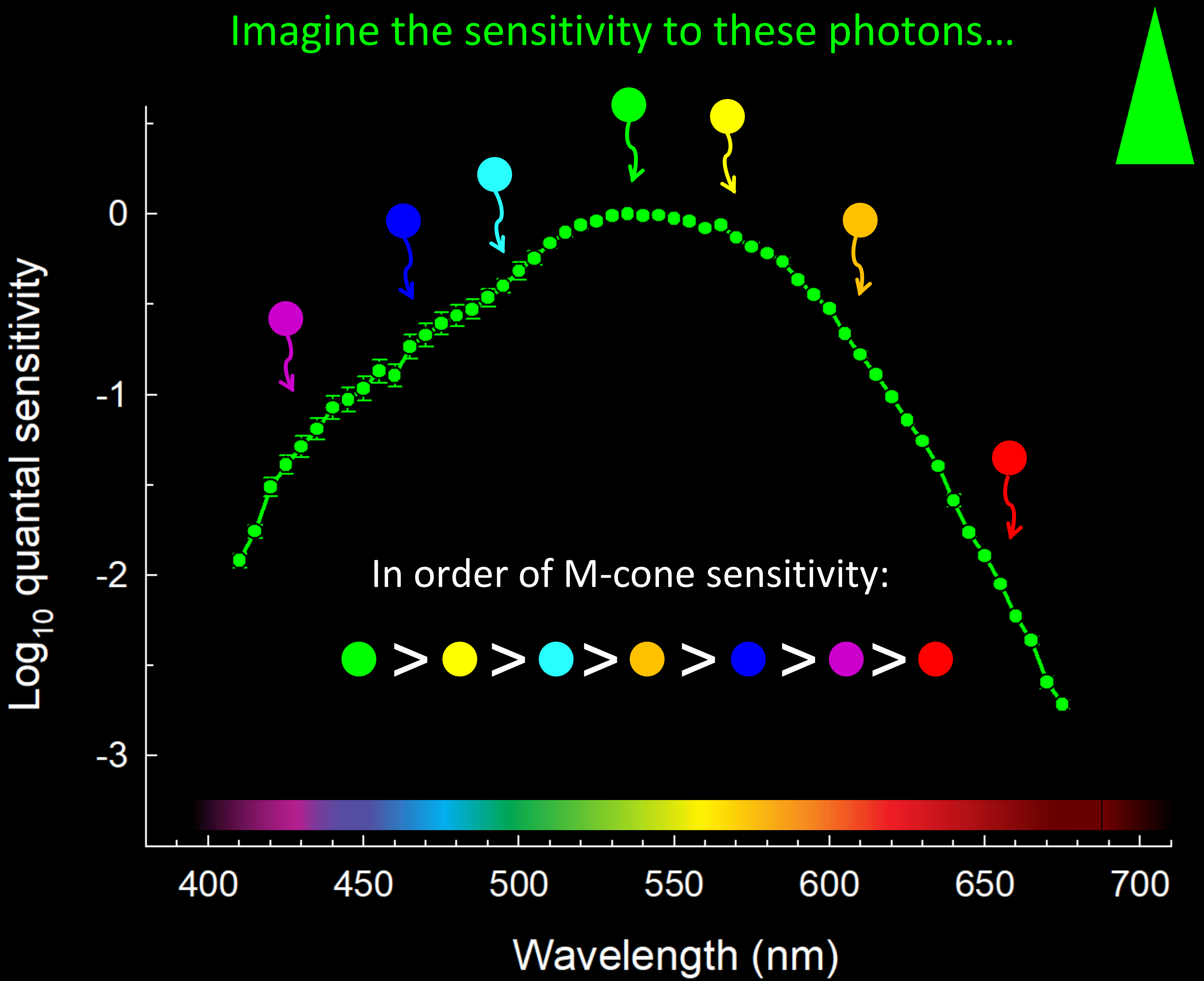
The chromophore becomes **all-trans** retinal

This triggers a series of reactions leading to the cone response

Univariance

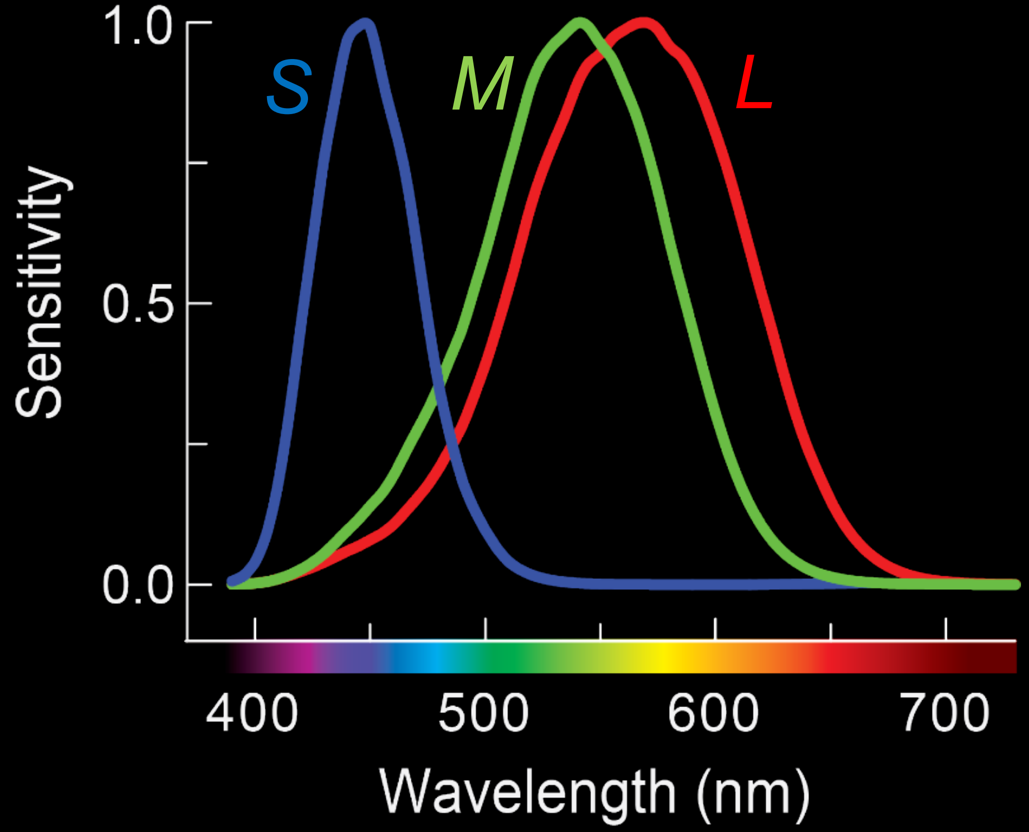
- Cones are "photon counters"
- Wavelength information is lost at the first step in vision, how do we get it back?
- Wavelength changes the ***probability*** of a photon being absorbed
- This dependency varies between cone types

Imagine the sensitivity to these photons...

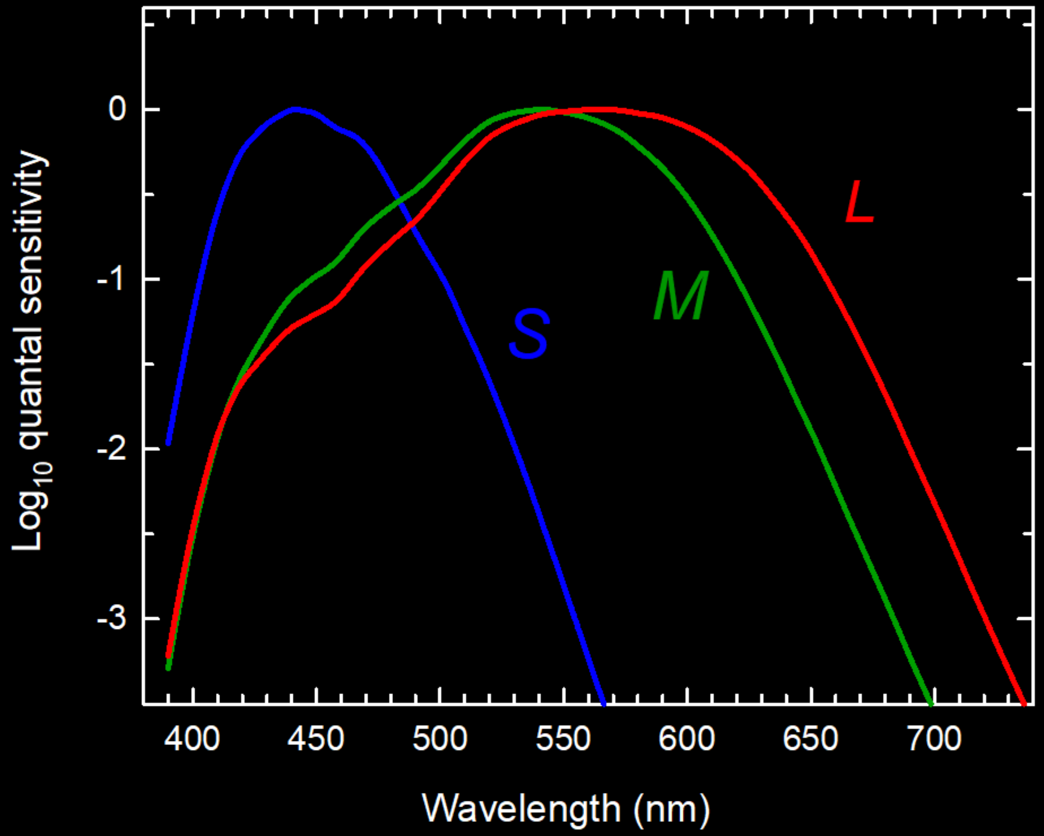


I’ll be showing linear and logarithmic versions of the cone spectral sensitivities:

Linear

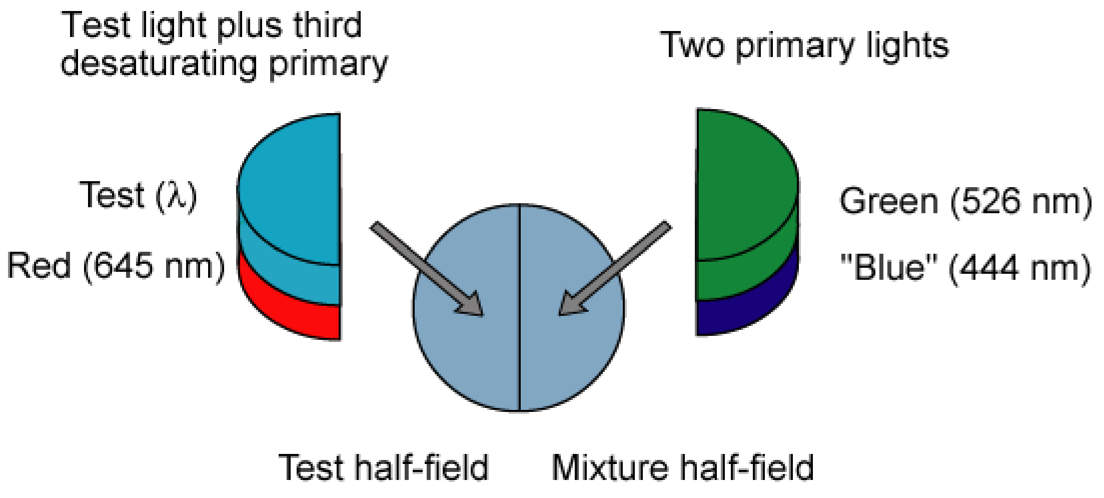


Logarithmic

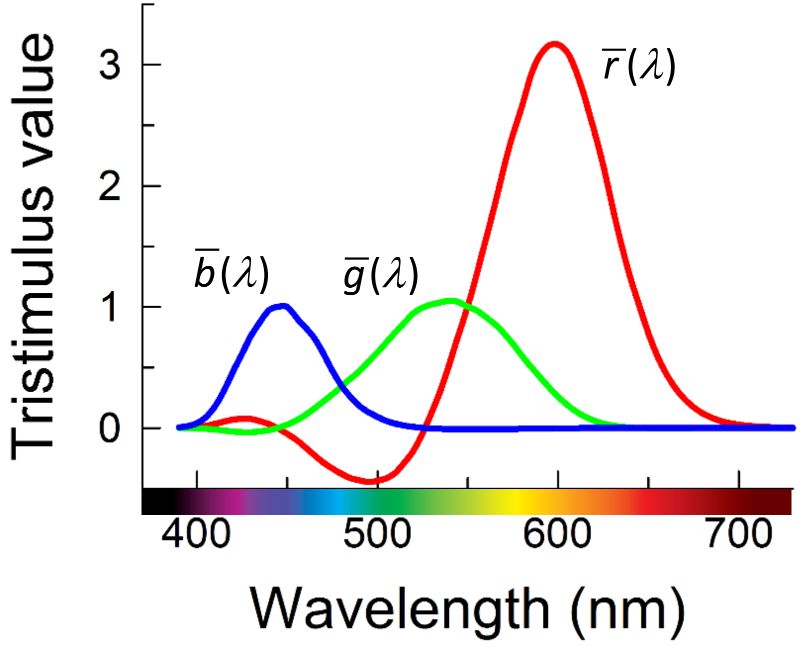


- Measuring cone sensitivities in isolation is difficult/impossible as they overlap throughout the visible region
- Monochromats are rare
  - S-cone monochromacy < 1 in 100,000
  - L or M cone monochromacy < 1 in 1,000,000
- Dichromatic vision is more prevalent and can provide useful corroboration, see Stockman and Sharpe, 2000
- Before molecular genetics, it wasn’t clear that monochromatic and dichromatic vision are due to a simple deletion – do they lack some cone type(s) with the remaining cones being exactly the same as in normal trichromats?
- Can we extract the same information another way?

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:



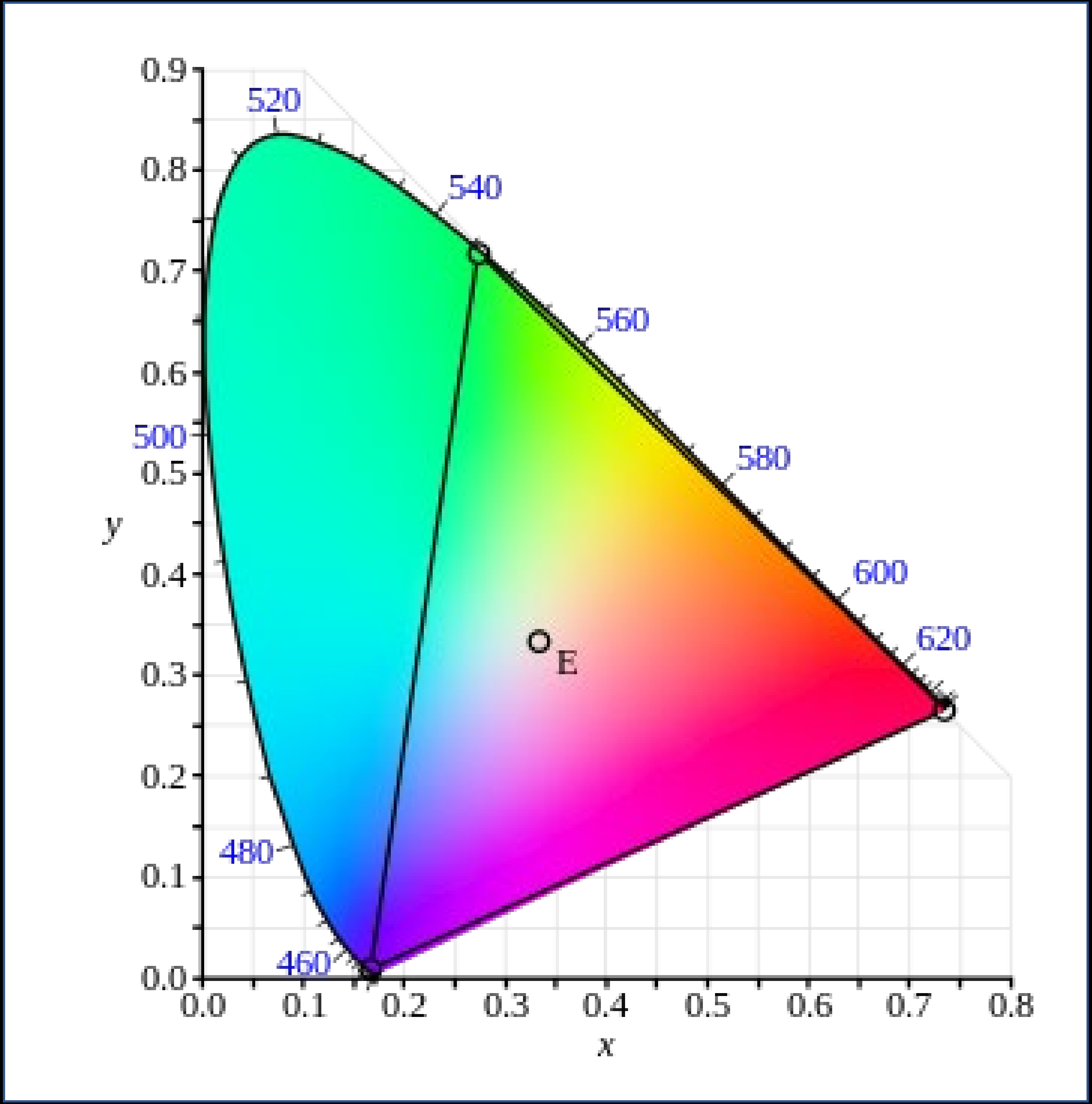
RGB colour matching functions



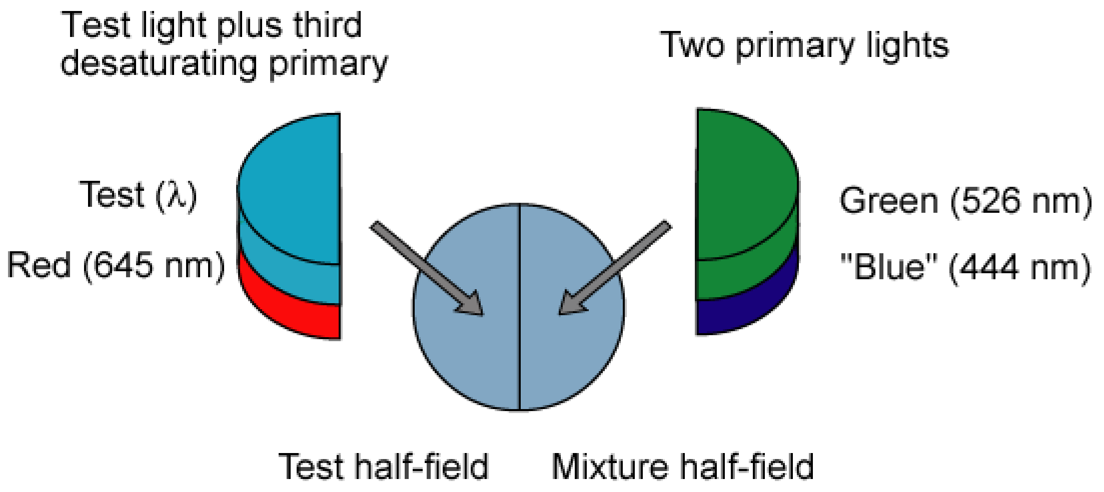
Why are RGB functions negative for some wavelengths?

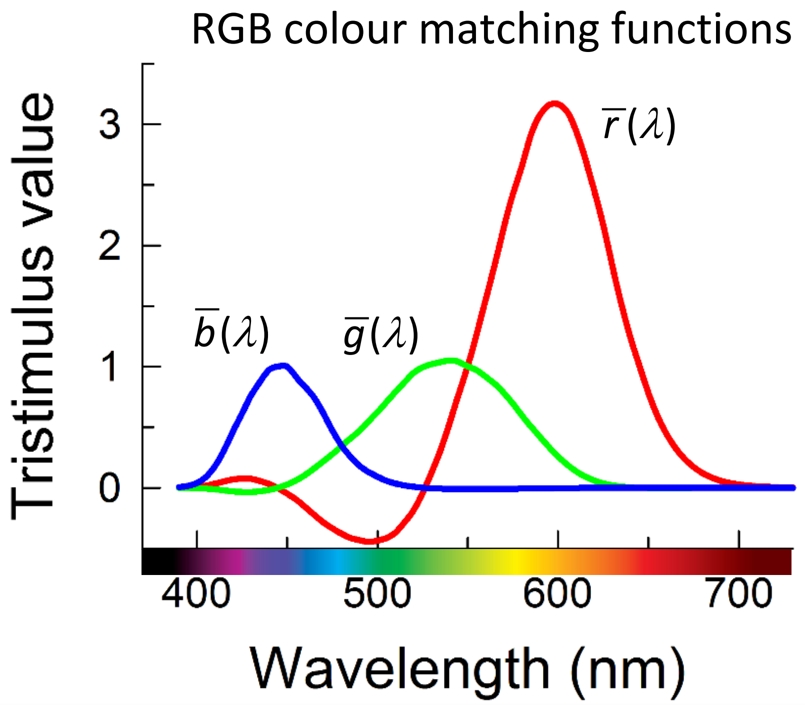
or

Why do we need to "desaturate" the test field?



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?

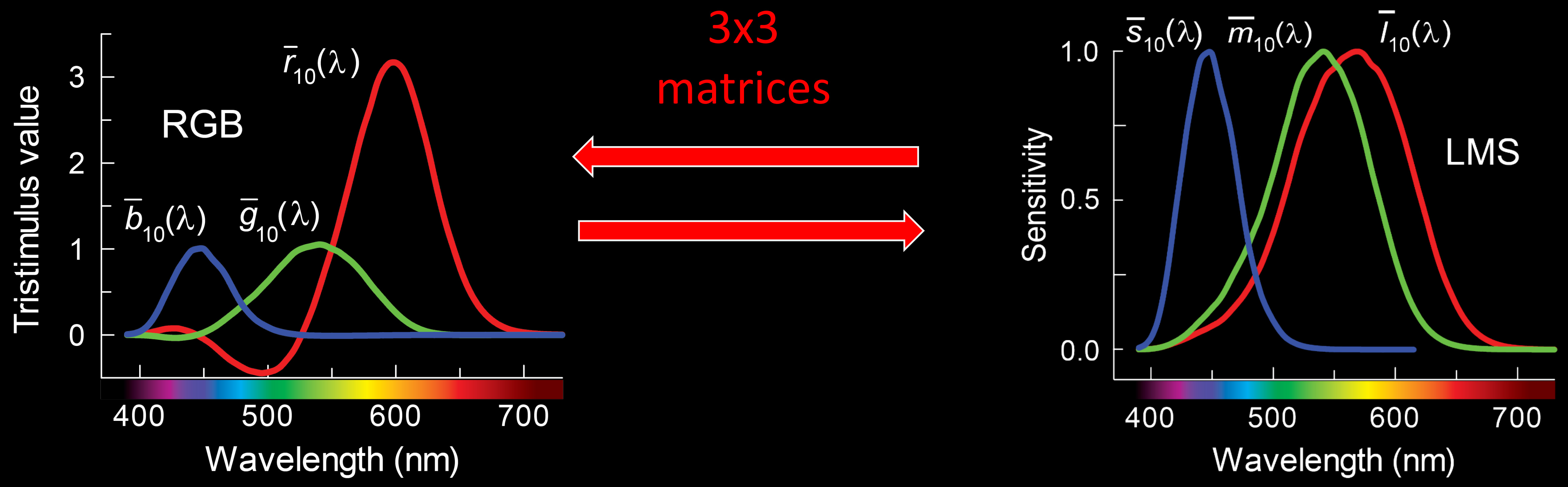
All colour matches are matches at the cone level and depend on the spectral sensitivities of the cones.

Consequently, the cone spectral sensitivities are the:

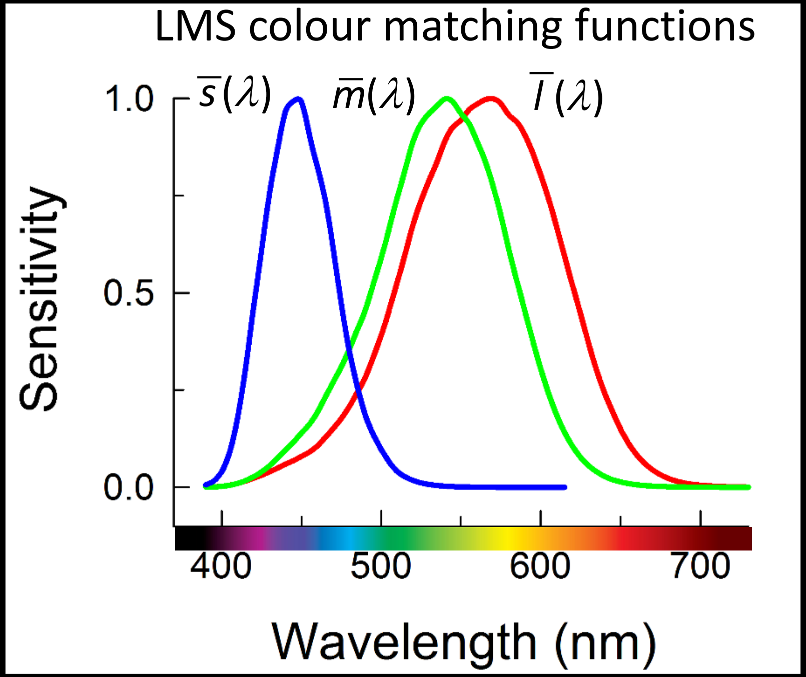
"Fundamental" colour matching functions

…upon which all other CMFs depend.

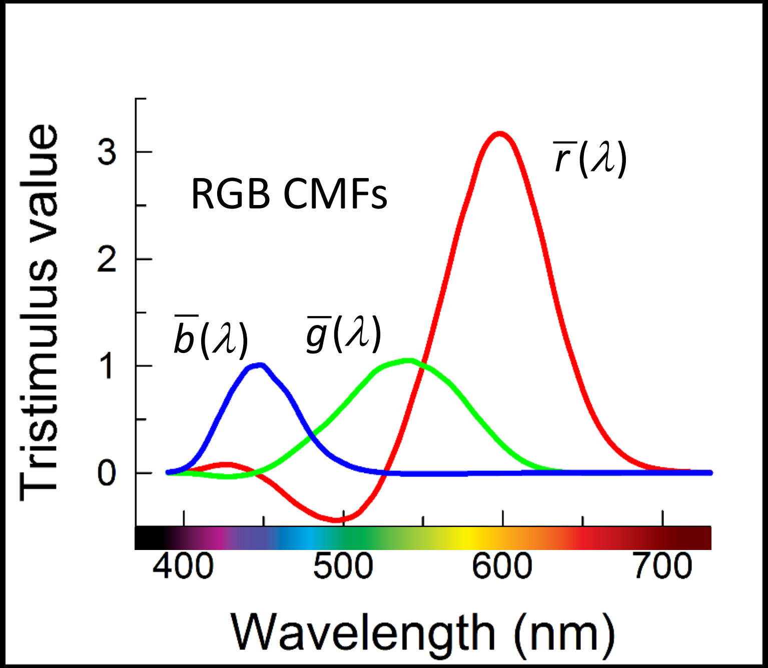
Accordingly, there exist simple linear transformations between RGB and LMS…



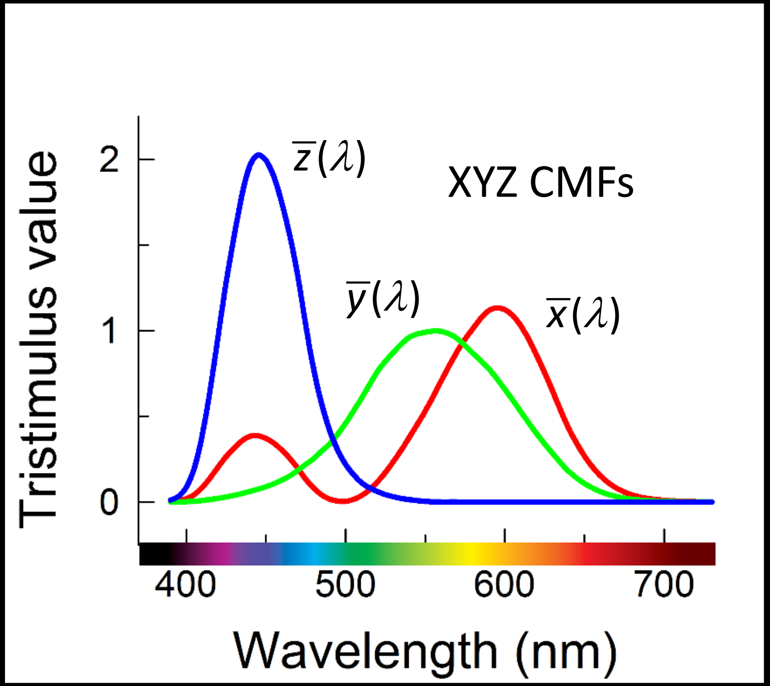
So, there *must* exist simple linear transformations between LMS and RGB *and* between LMS and XYZ.



3x3 matrix

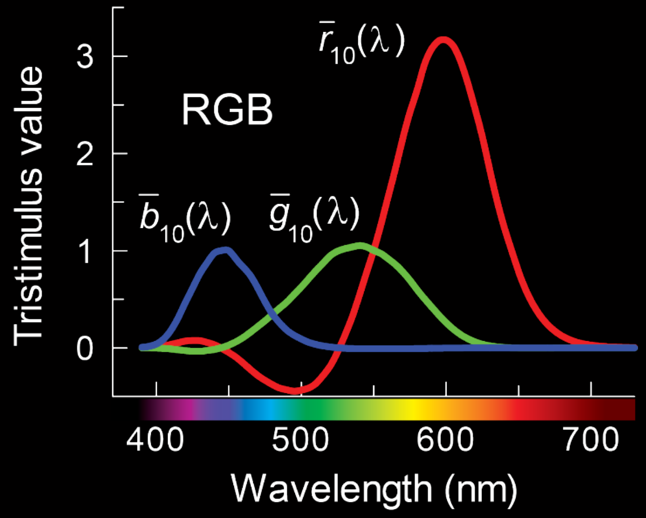


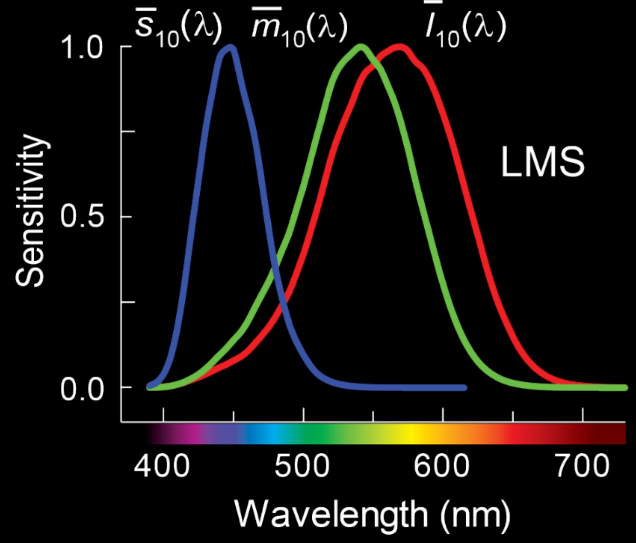
3x3 matrix



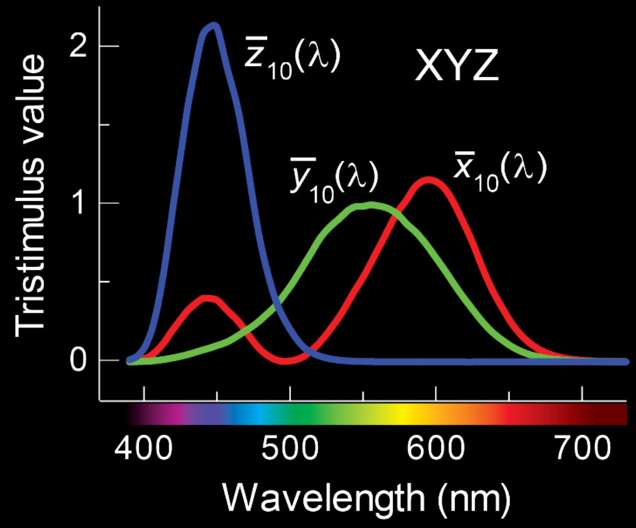
Based on Guild and Wright relative color matches with Y defined by the CIE 1924 luminosity function, V(λ)

And also between RGB and LMS and XYZ.

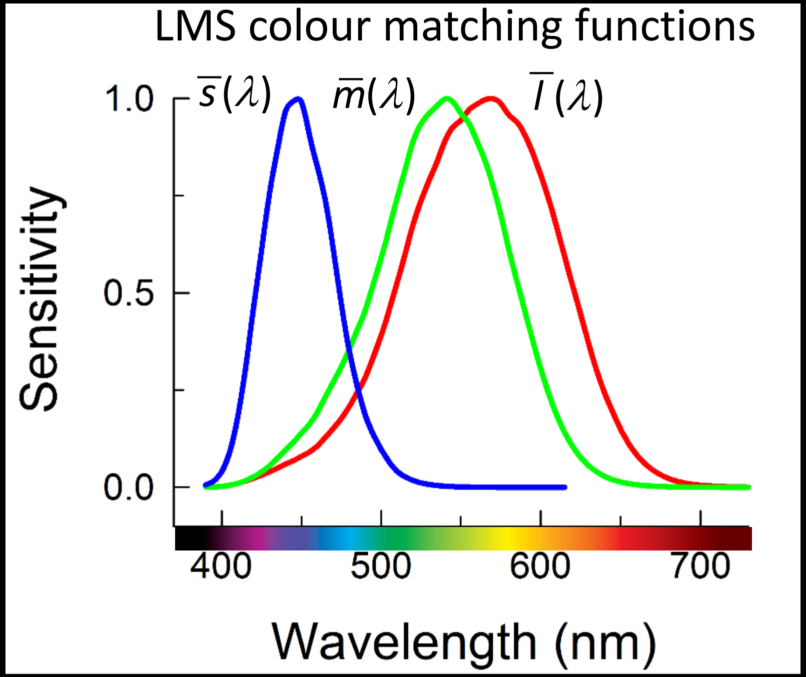




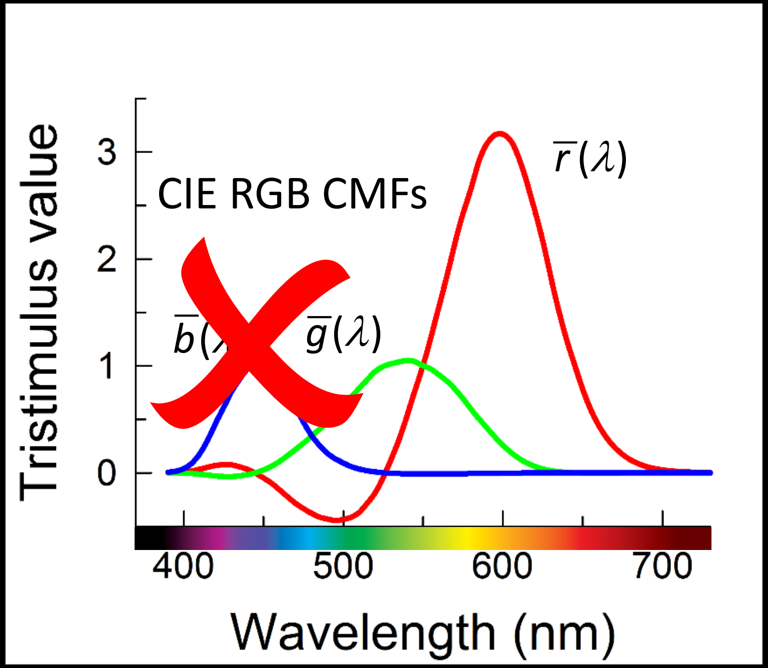
Linear transformations



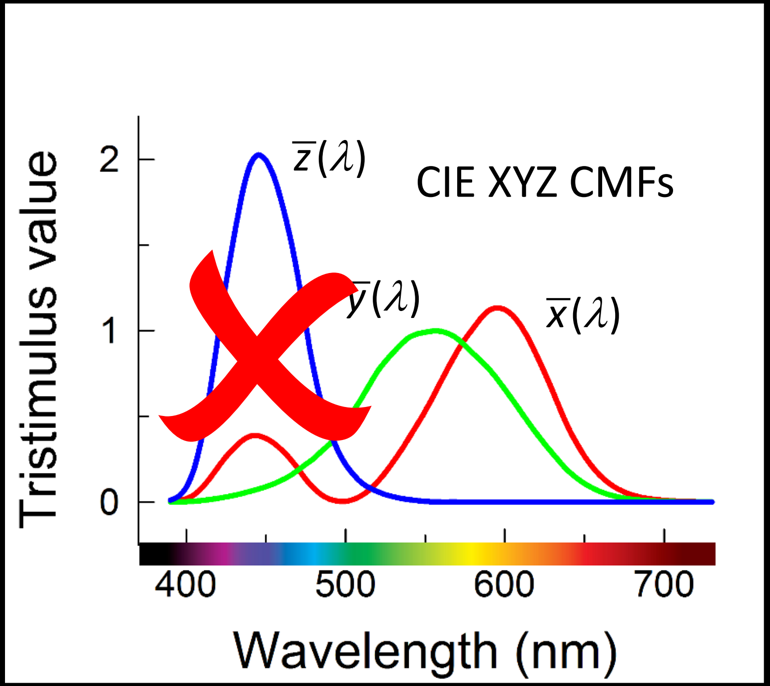
But for 1931 CIE RGB and XYZ CMFs there aren't…
because they are wrong especially at short wavelengths



3x3 matrix



3x3 matrix

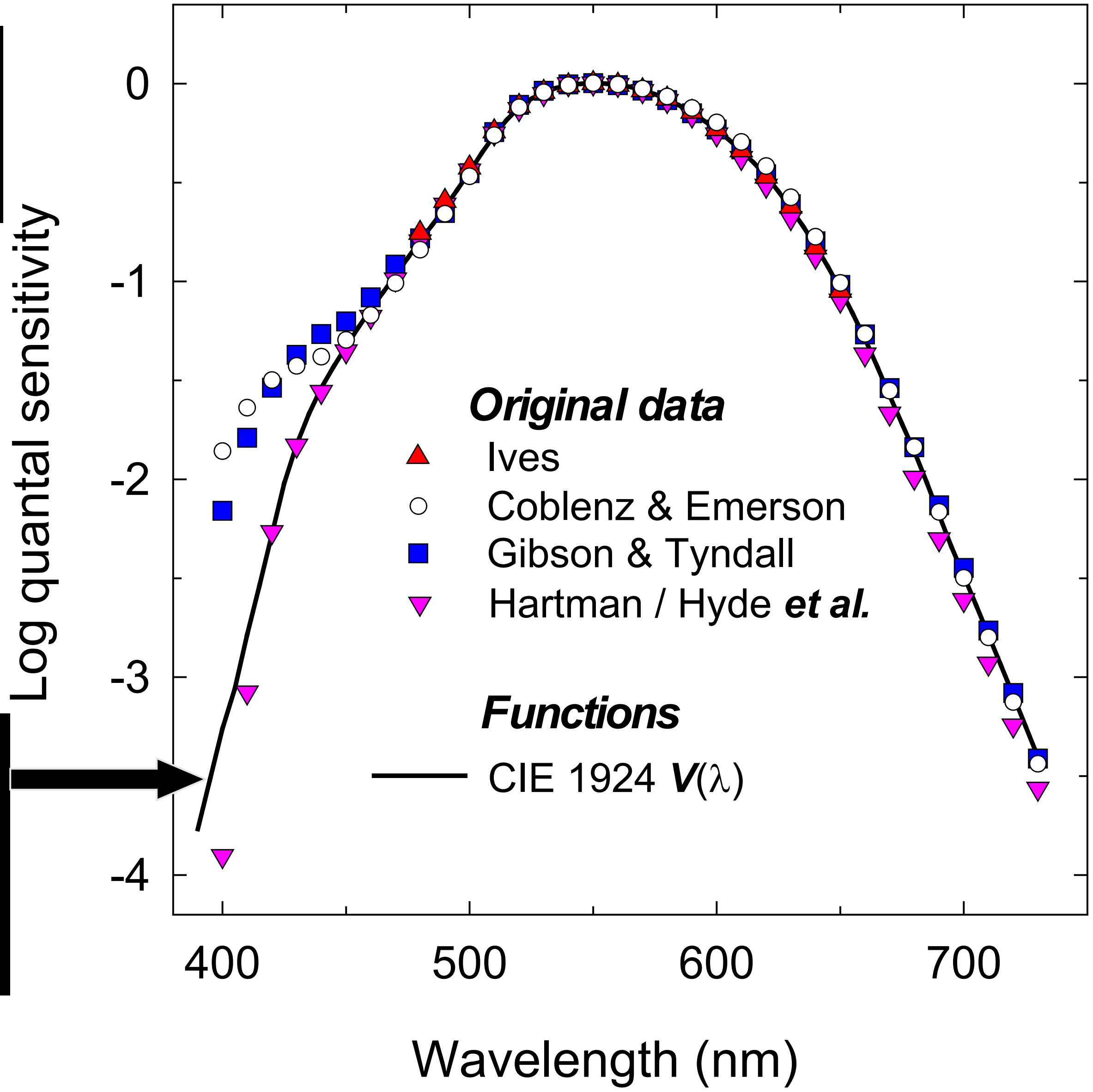


The reason is related to the choice of V(λ) back in 1924…

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

Here's what the CIE chose in 1924

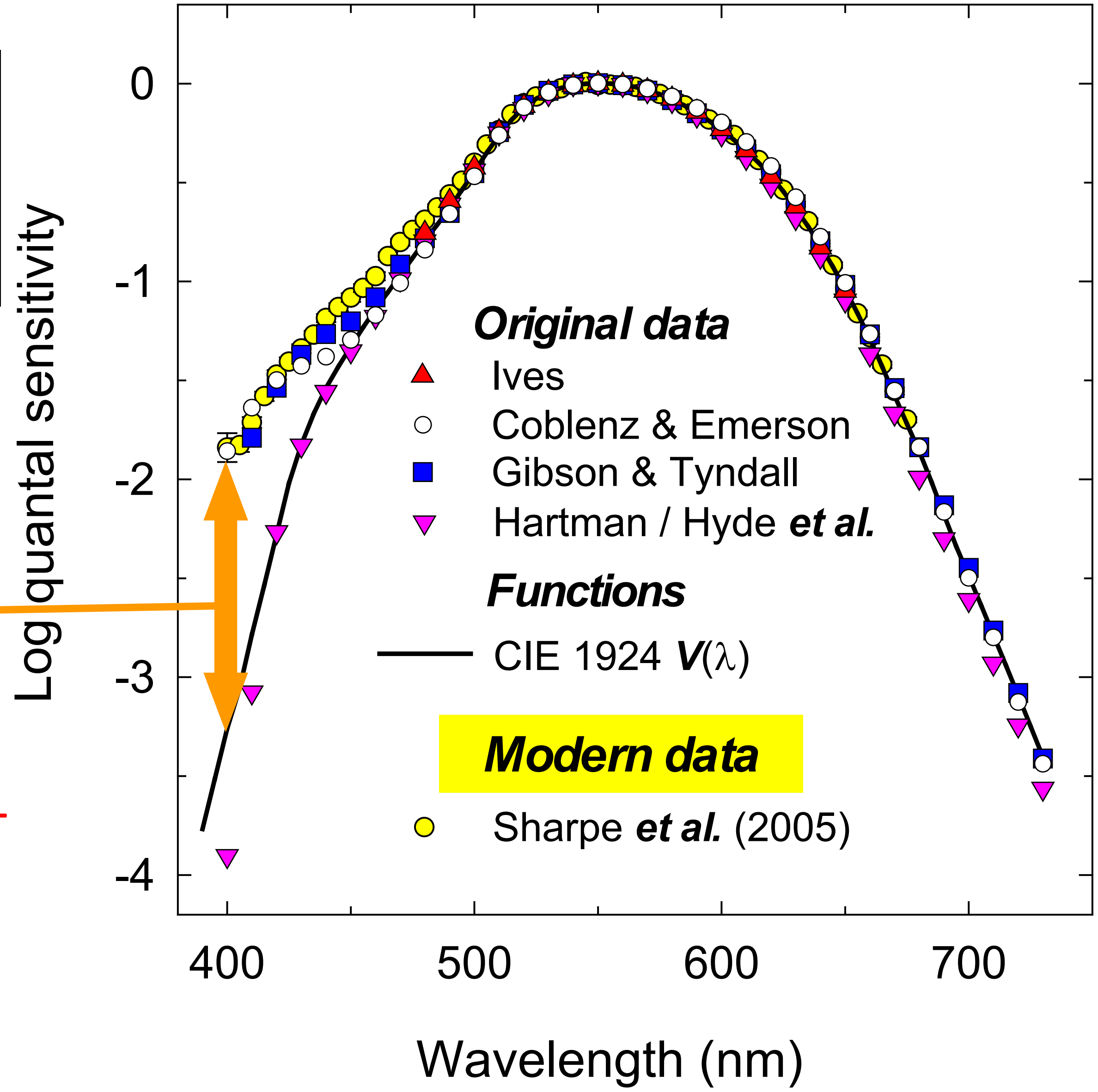
This unfortunate choice continues to plague colorimetry and photo-metry 100 years later



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

Modern data supports the original data overlooked by the CIE at short wavelengths

>10x error



Using (alas ubiquitous) CIE 1931 XYZ standards will produce large errors, particularly for short wavelength lights

In 1991, CIE technical committee TC1-36 was established that led to:

NEW DEFINITION OF LMS:

CIE Technical Report 170-1: 2006

Fundamental Chromaticity Diagram with Physiological Axes – Part 1

NEW DEFINITION OF XYZ:

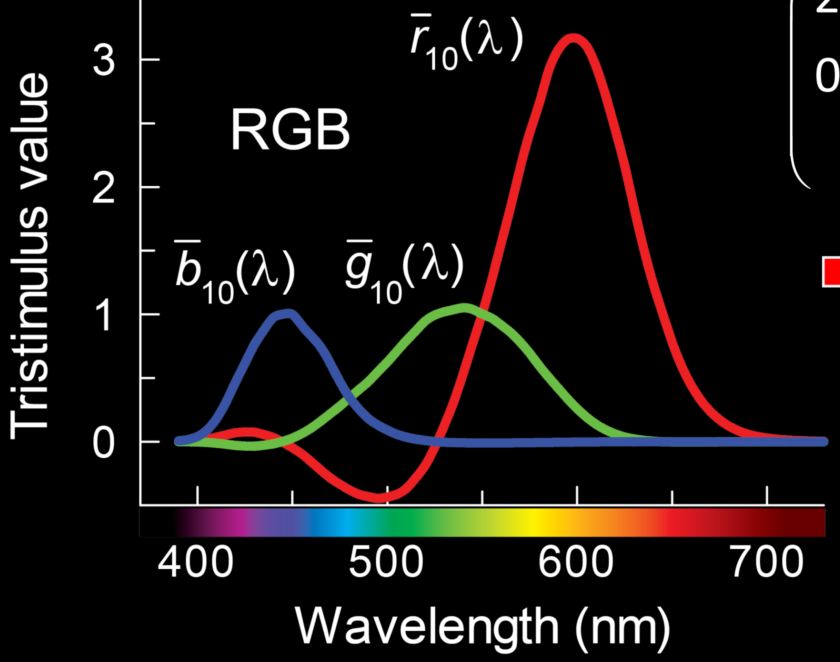
CIE Technical Report 170-2: 2015

Fundamental Chromaticity Diagram with Physiological Axes – Part 2: Spectral Luminous Efficiency Functions and Chromaticity Diagrams

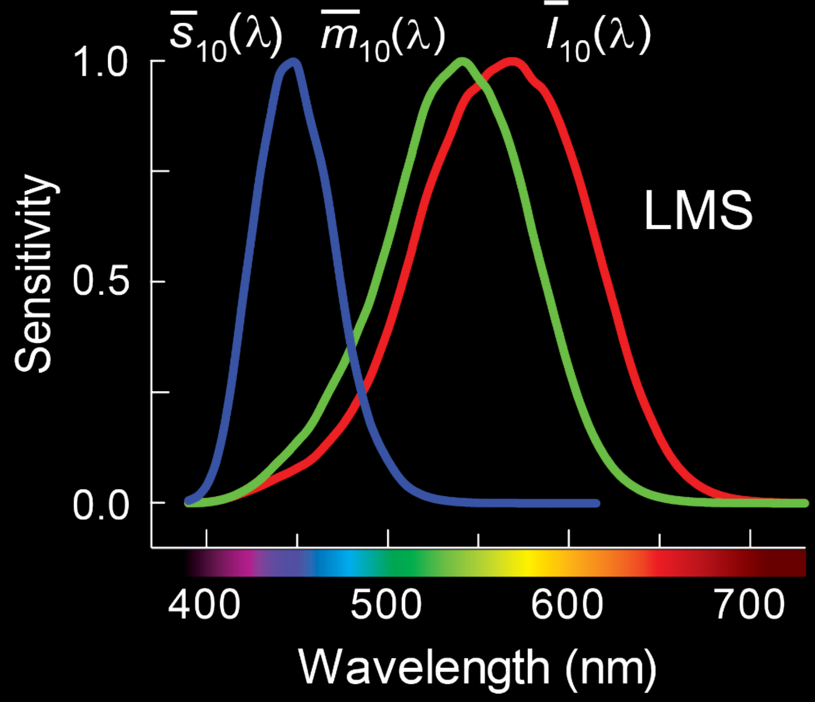
Together these represent a consistent set of "physiologically-relevant" LMS, RGB and XYZ CMFs for 2-deg and 10-deg vision

CIE 2006 LMS functions are defined as a linear transformation of Stiles & Burch (1959) RGB CMFs

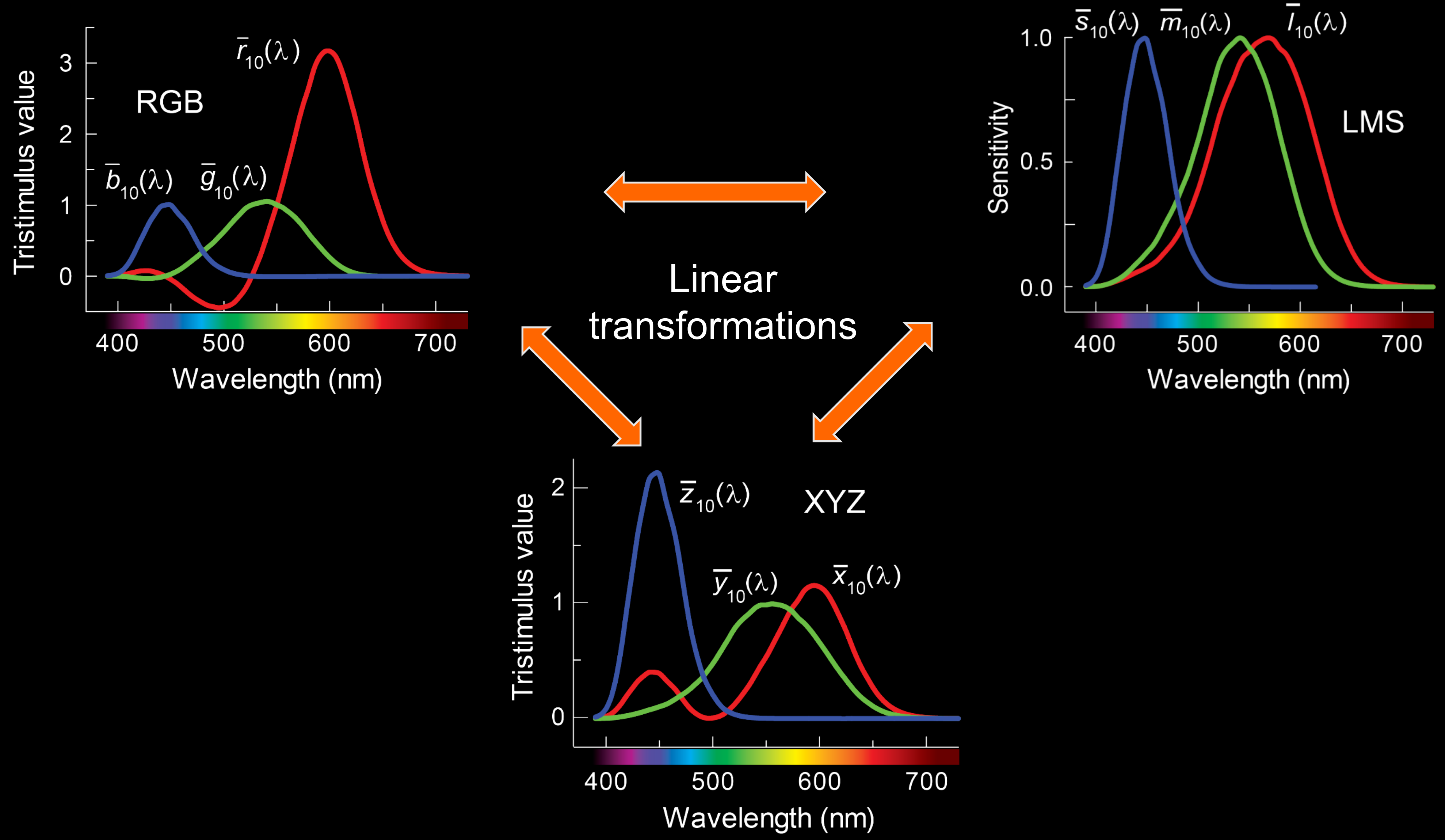
The Stockman & Sharpe (2000) cone fundamentals and other flicker photometry measurements have been used to generate new CIE XYZ CMFs…



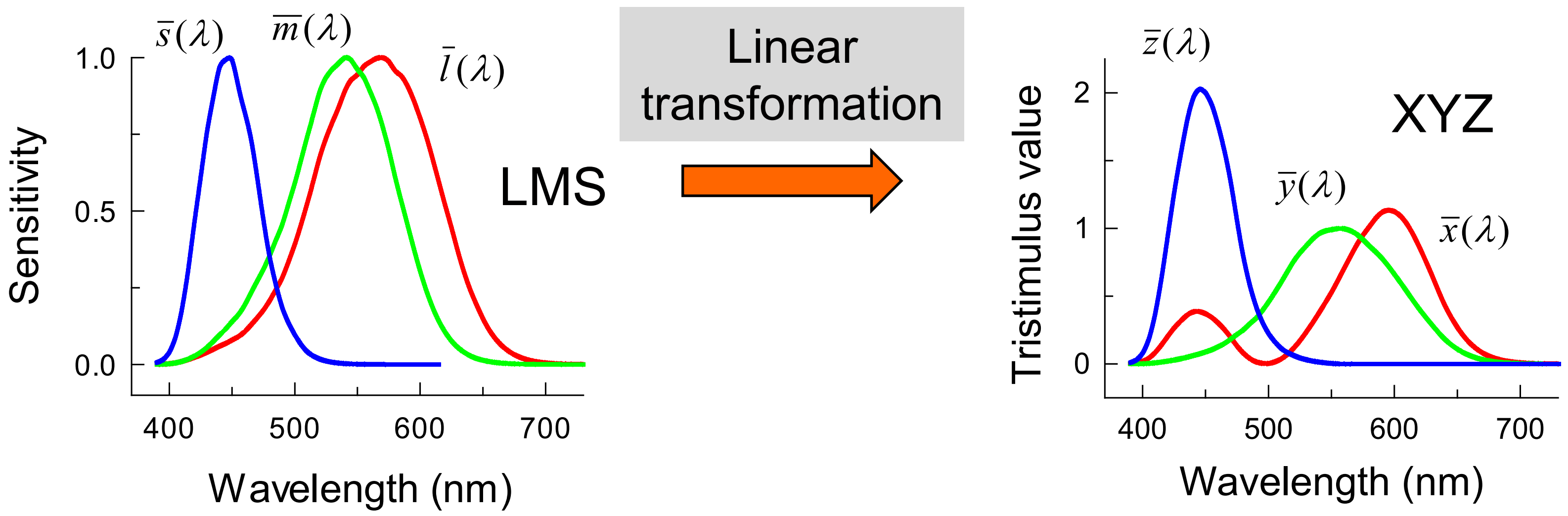
$$\begin{pmatrix} 2.846201 & 11.092490 & 1 \\ 0.168926 & 8.265895 & 1 \\ 0 & 0.010600 & 1 \end{pmatrix}$$



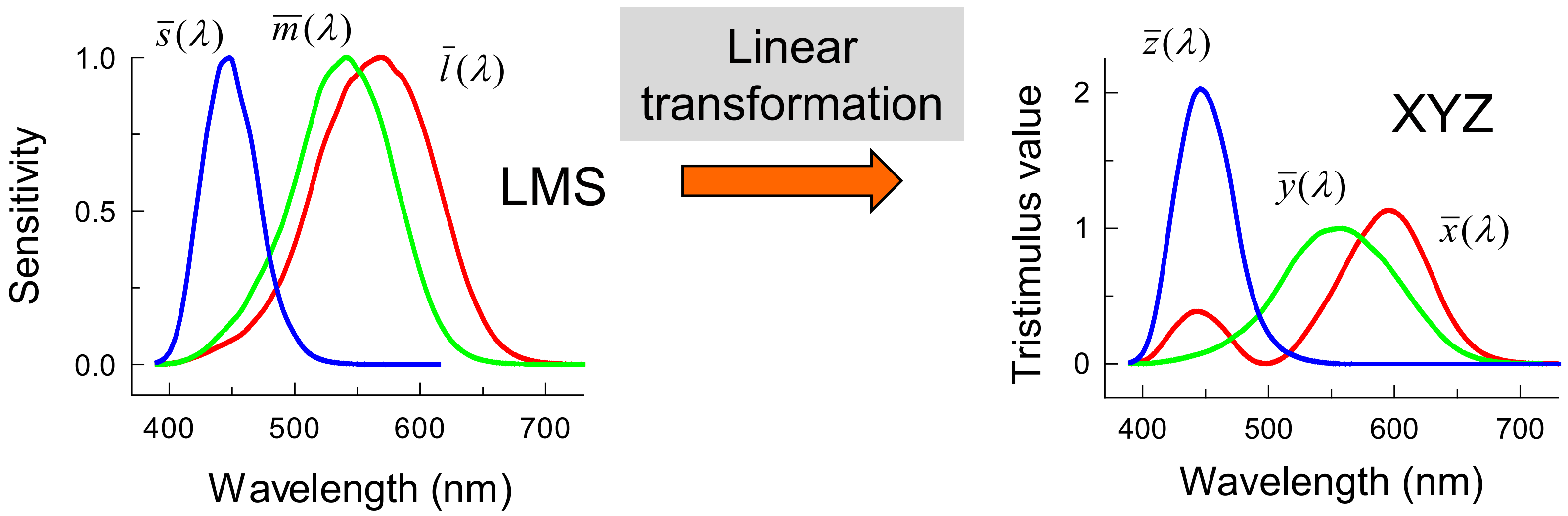
Linear transformations between RGB and LMS and XYZ (CIE 2015).



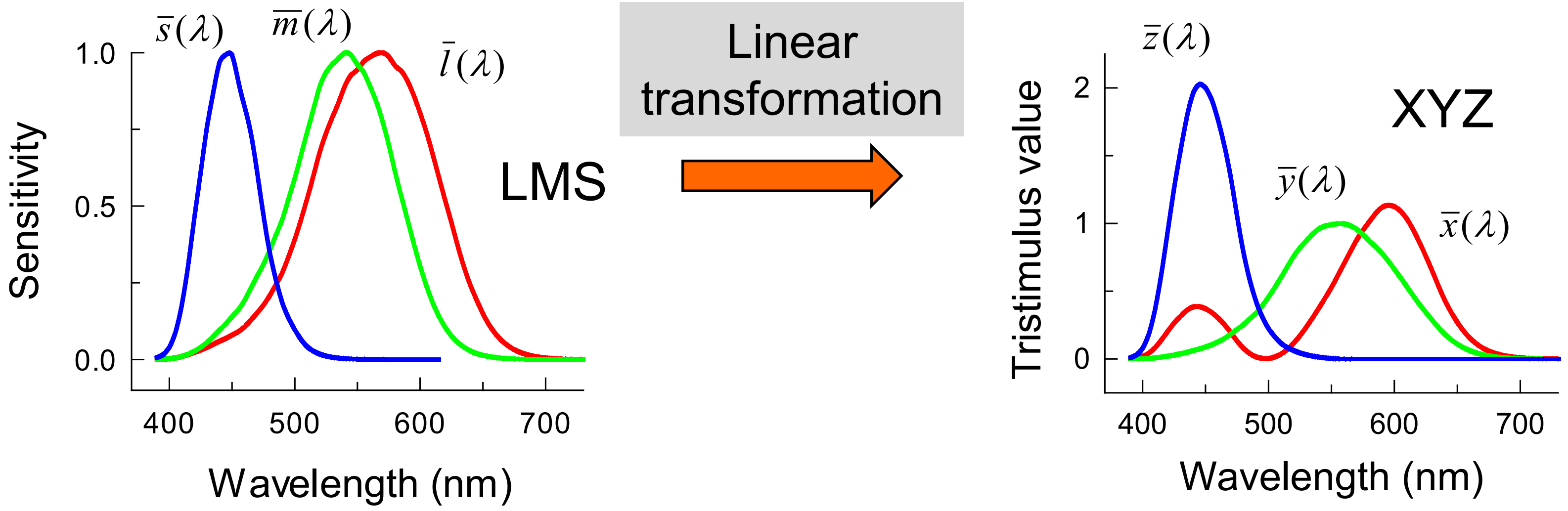
Linear transformation from the CIE (2006) LMS CMFs to the new XYZ CMFs



Requires a series of simple assumptions…

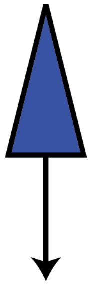


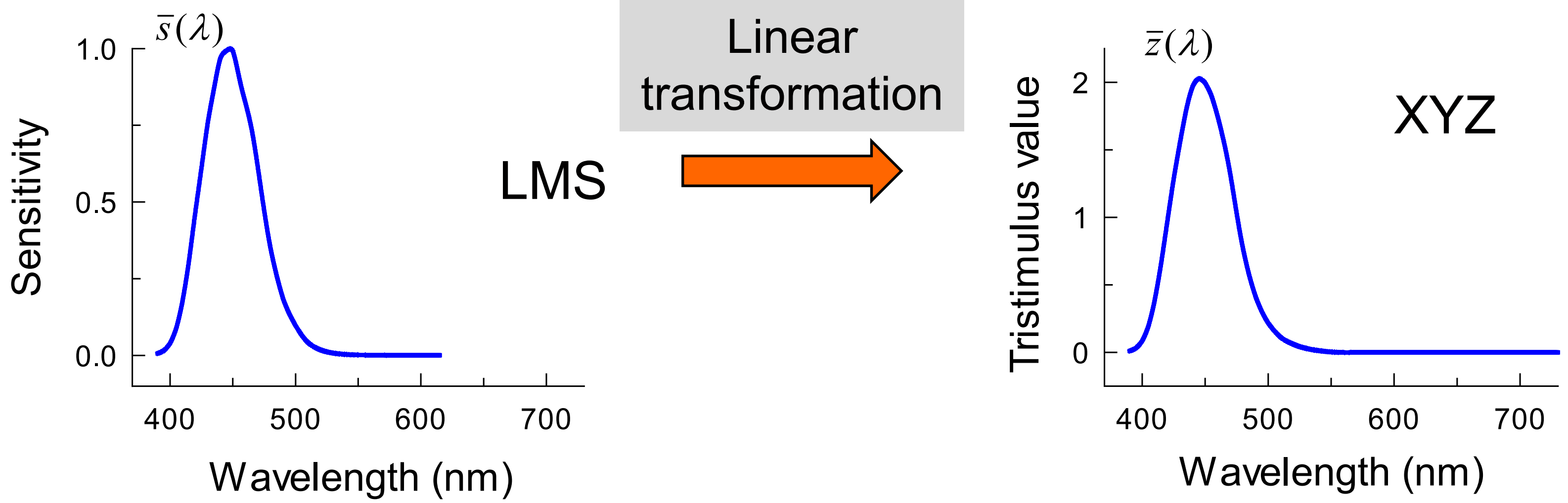
ASSUMPTION 1:



ASSUMPTION 1:

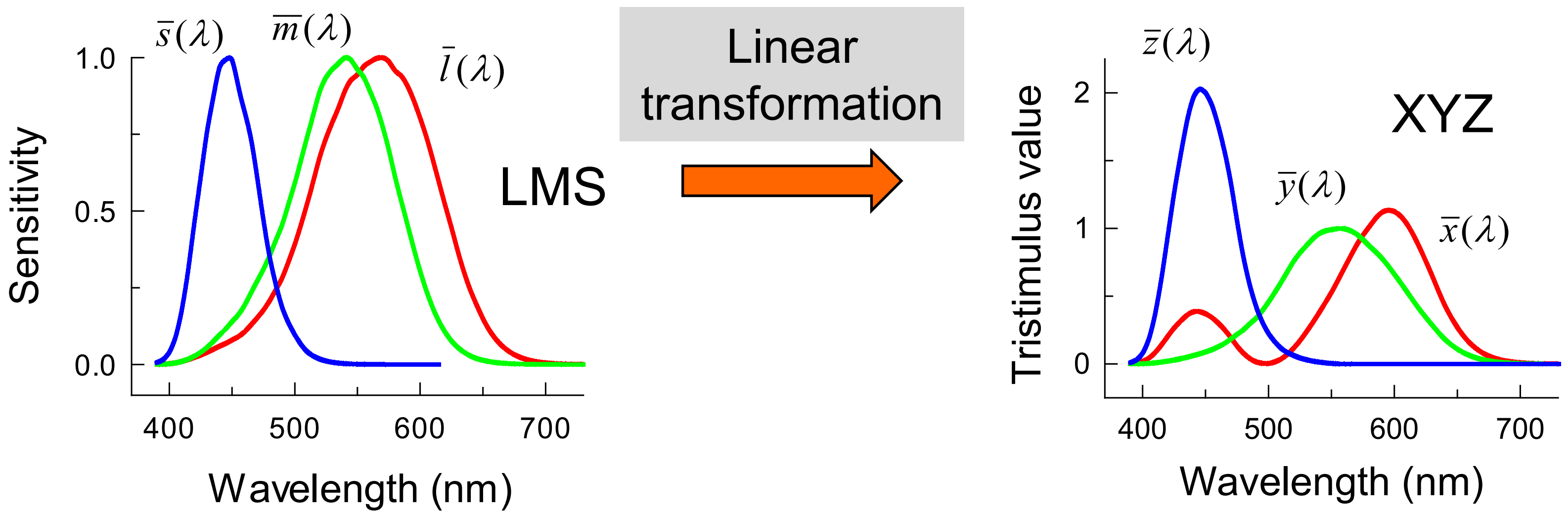
$$\bar{z}(\lambda) = k\bar{s}(\lambda)$$





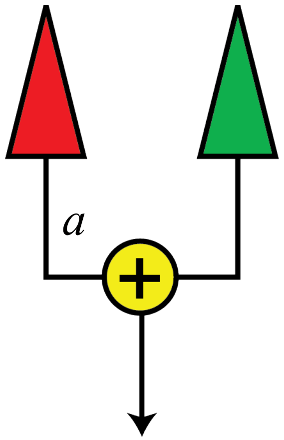
The $\bar{s}(\lambda)$ and $\bar{z}(\lambda)$ CMFs are the same (except for a scaling factor).

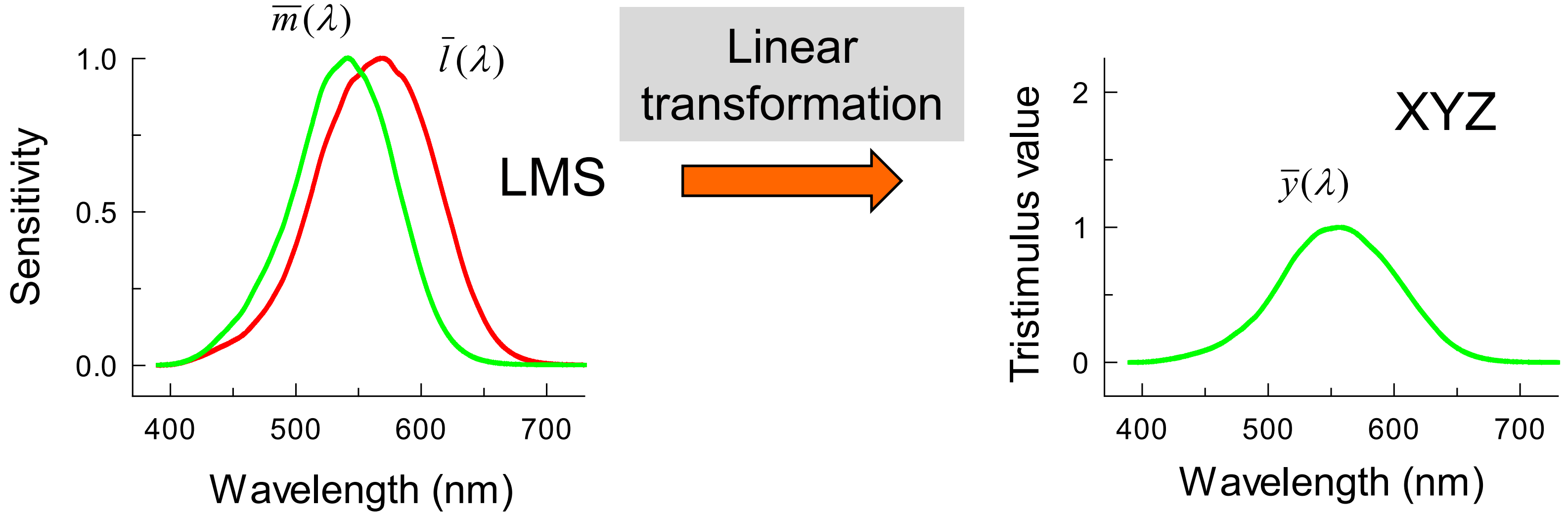
ASSUMPTION 2:



ASSUMPTION 2:

$$\bar{y}(\lambda) = a\bar{l}(\lambda) + \bar{m}(\lambda)$$

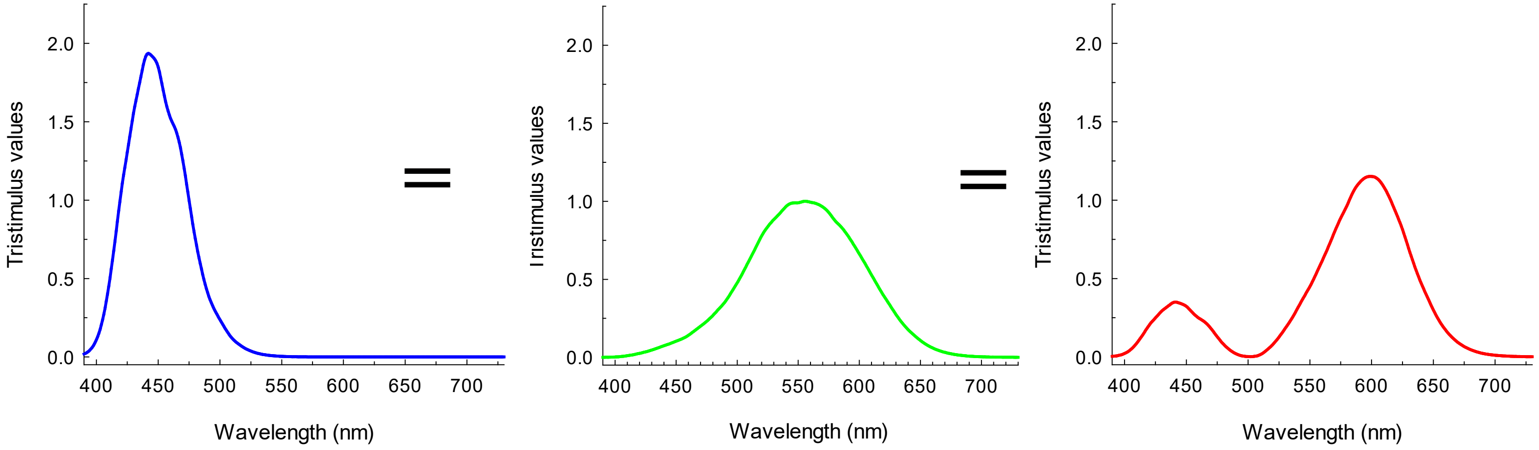




The $\bar{y}(\lambda)$ CMF (or V(λ), the luminous efficiency function) is a linear combination of the $\bar{l}(\lambda)$ and $\bar{m}(\lambda)$ CMFs.

ASSUMPTION 3:

$$\int \bar{x}(\lambda)d\lambda = \int \bar{y}(\lambda)d\lambda = \int \bar{z}(\lambda)d\lambda$$

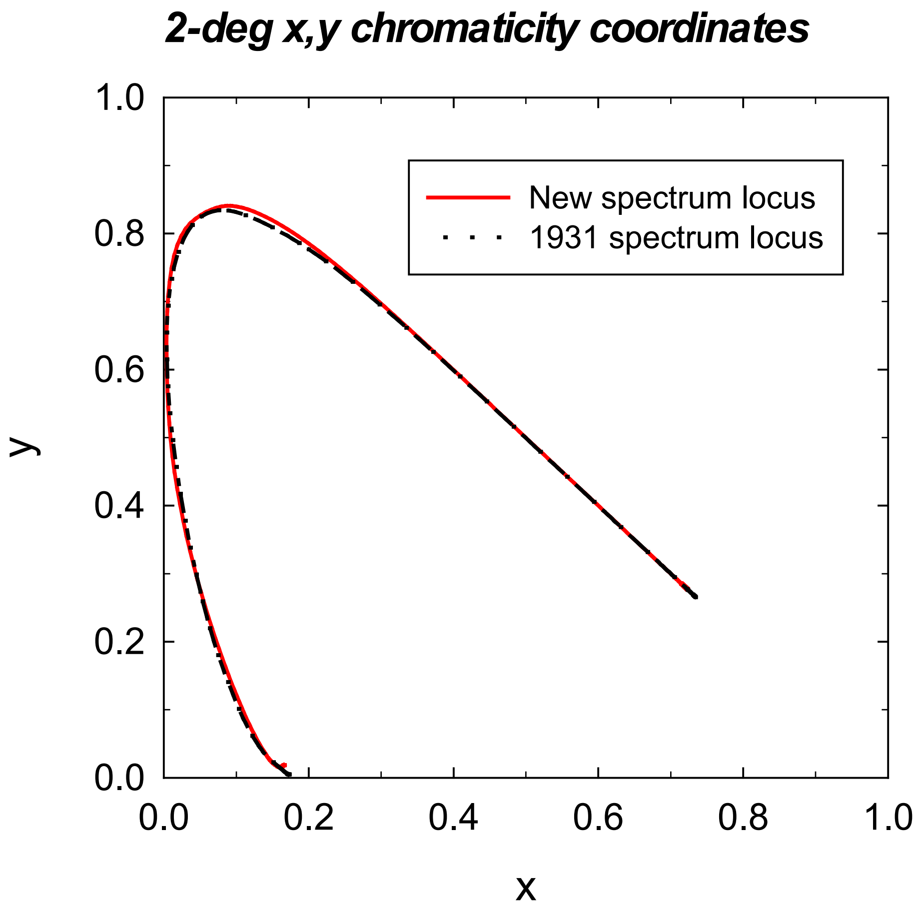


Equal areas for an equal energy spectrum

ASSUMPTION 4:

Choice of $a\bar{l}(\lambda)+b\bar{m}(\lambda)+c\bar{s}(\lambda)=\bar{x}(\lambda)$

Should minimize the Euclidian differences between the new chromaticity coordinates and the old ones (1931 or 1964).

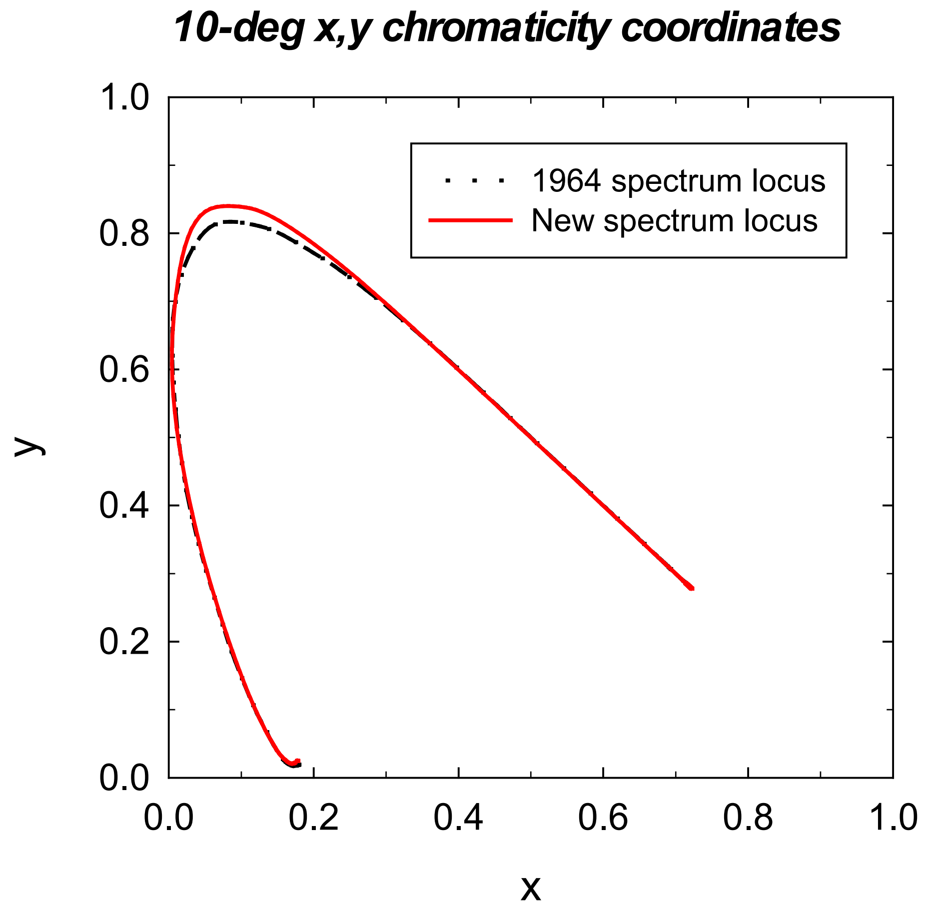


Fits by Jan Henrik Wold

ASSUMPTION 4:

Choice of $a\bar{l}_{10}(\lambda) + b\bar{m}_{10}(\lambda) + c\bar{s}_{10}(\lambda) = \bar{x}_{10}(\lambda)$

Should minimize the Euclidian differences between the new chromaticity coordinates and the old ones.



Fits by Jan Henrik Wold

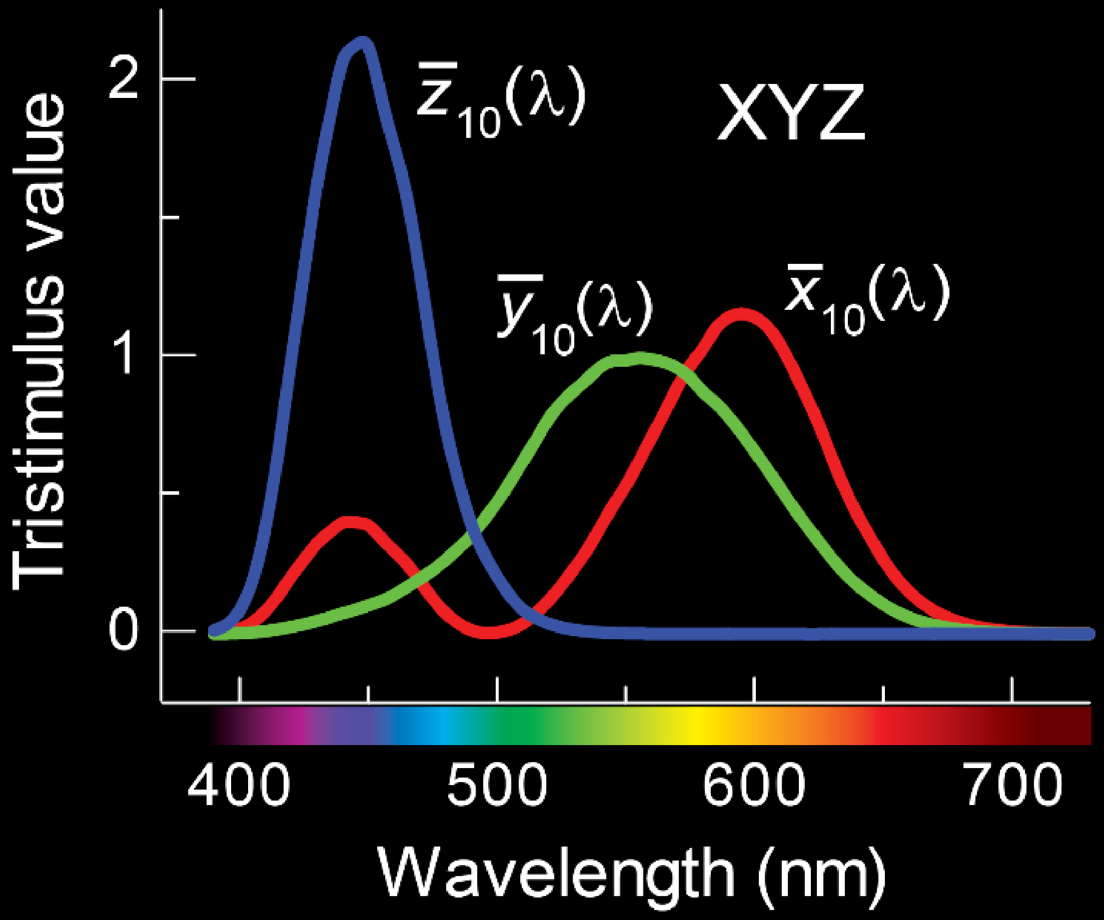
What are the XYZ CMFs recommended by the CIE?

They are a linear combination of the CIE 2006 LMS cone fundamentals.

Z is S.

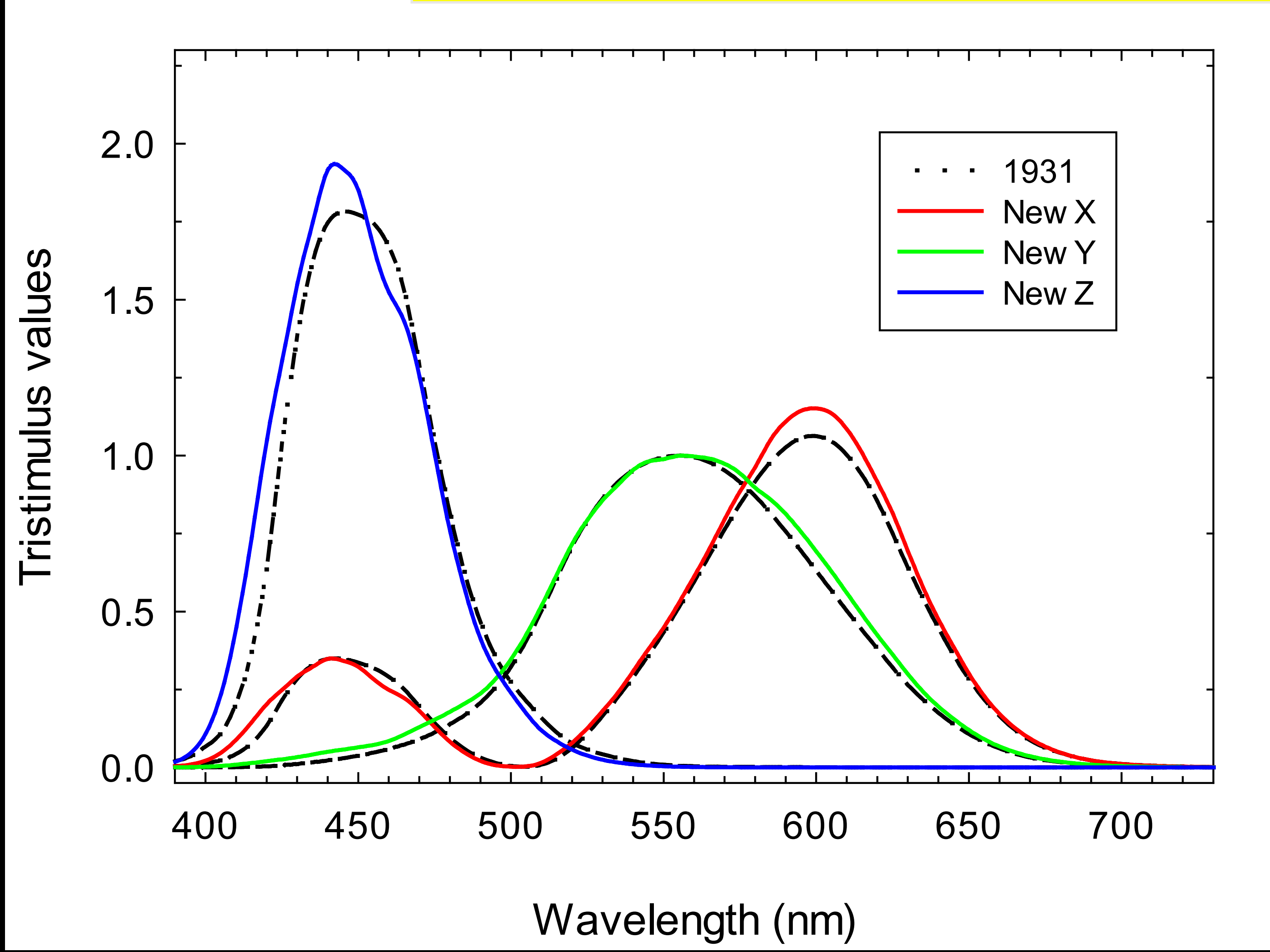
The derivation of Y is based on the work of:
Sharpe, Stockman, Jagla & Jägle (2005).
Journal of Vision, 5, 948-968.
Sharpe, Stockman, Jagla & Jägle (2011).
Color Research & Application, 36, 42-46.

X was chosen by Jan Henrik Wold.



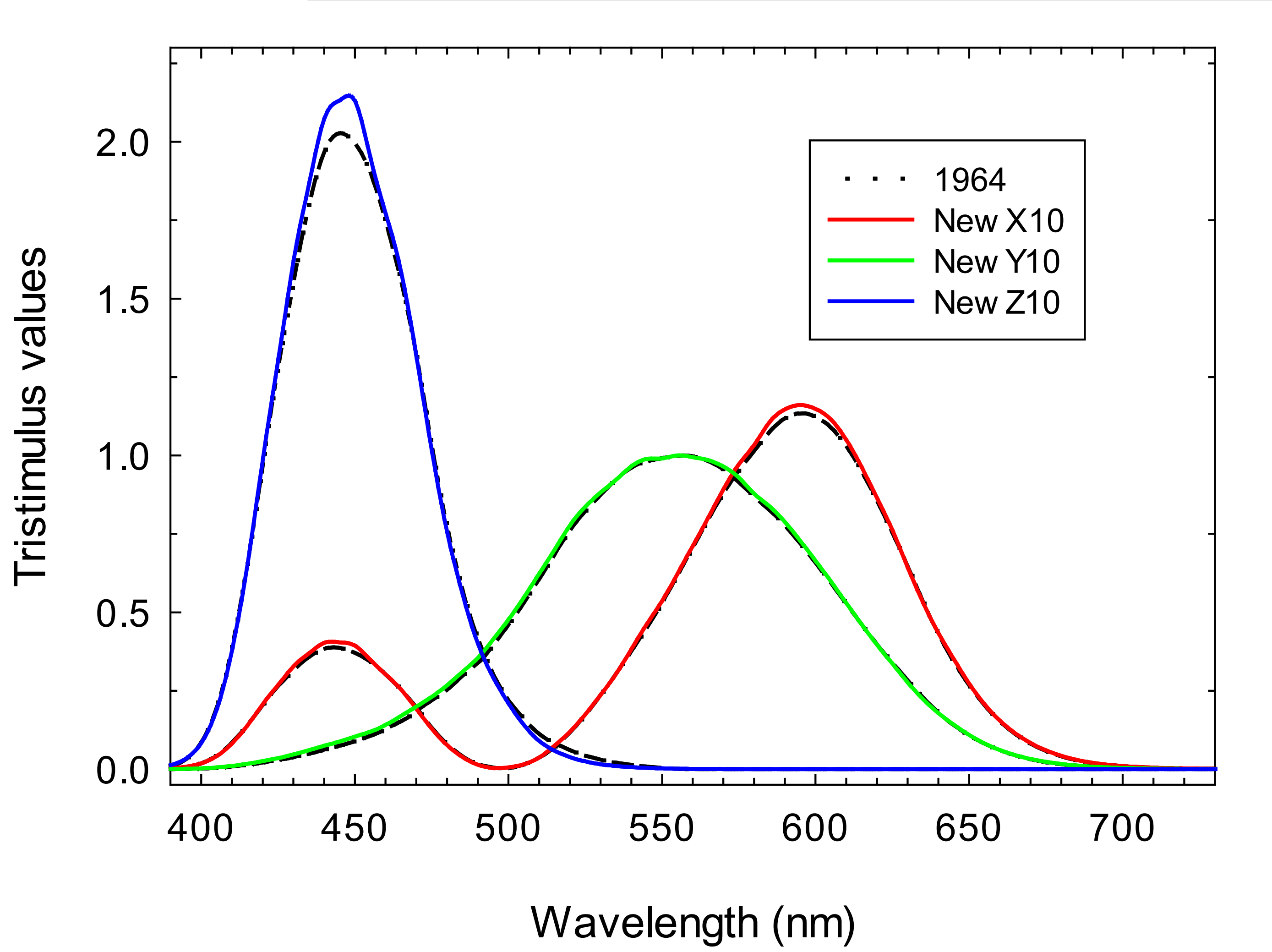
2-deg LMS →XYZ transforms

$$\begin{pmatrix} 1.94735469 & -1.41445123 & 0.36476327 \\ 0.68990272 & 0.34832189 & 0 \\ 0 & 0 & 1.93485343 \end{pmatrix} \begin{pmatrix} \bar{l}(\lambda) \\ \bar{m}(\lambda) \\ \bar{s}(\lambda) \end{pmatrix} = \begin{pmatrix} \bar{x}(\lambda) \\ \bar{y}(\lambda) \\ \bar{z}(\lambda) \end{pmatrix}$$



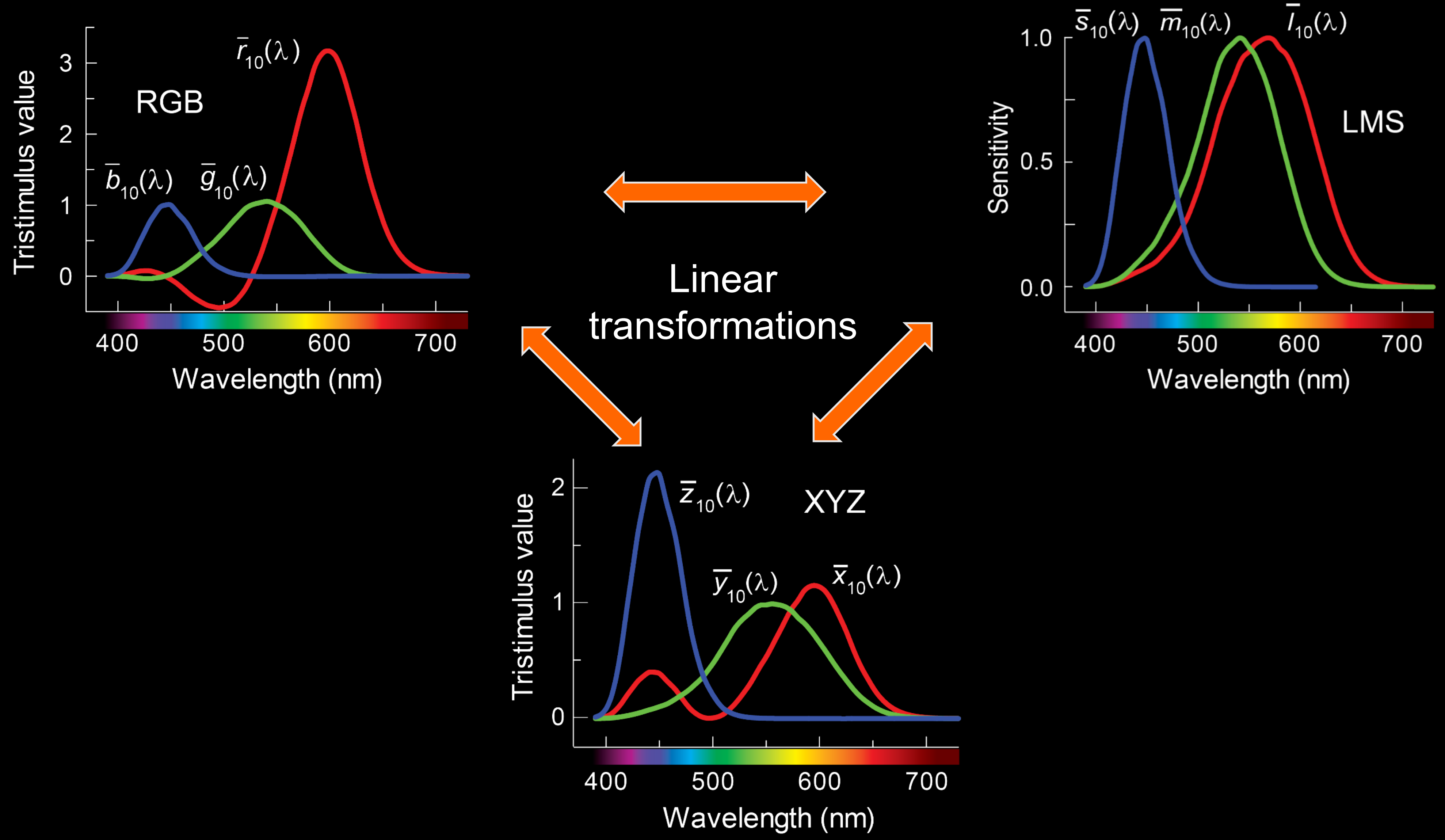
10-deg LMS →XYZ transforms

$$\begin{pmatrix} 1.93986443 & -1.34664359 & 0.43044935 \\ 0.69283932 & 0.34967567 & 0 \\ 0 & 0 & 2.14687945 \end{pmatrix} \begin{pmatrix} \bar{l}_{10}(\lambda) \\ \bar{m}_{10}(\lambda) \\ \bar{s}_{10}(\lambda) \end{pmatrix} = \begin{pmatrix} \bar{x}_{10}(\lambda) \\ \bar{y}_{10}(\lambda) \\ \bar{z}_{10}(\lambda) \end{pmatrix}$$

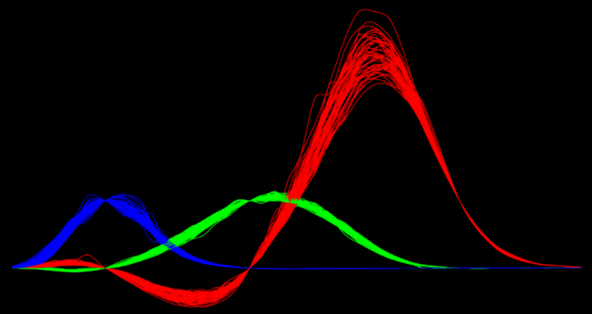


Less deviation with the CIE (1964) 10-deg functions

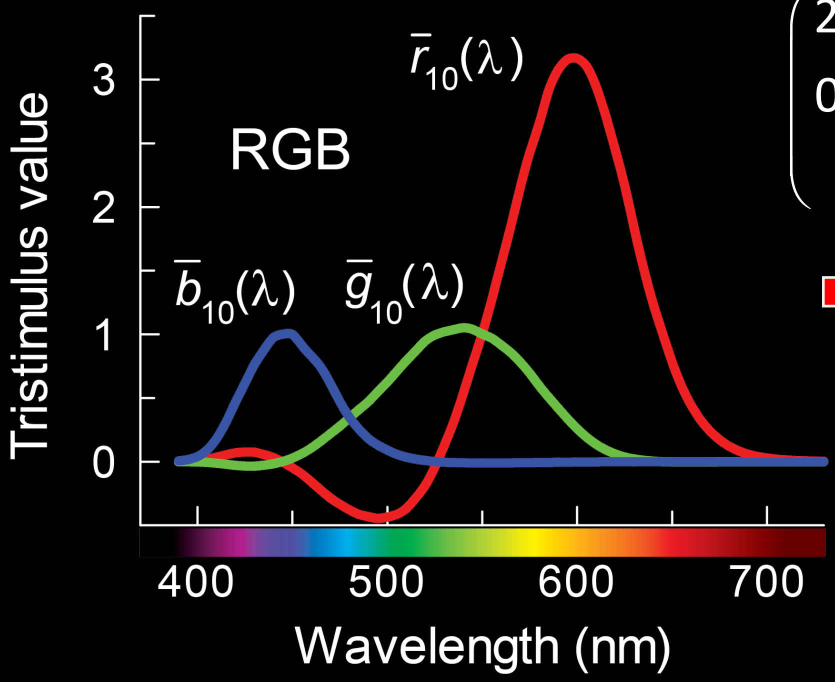
Linear transformations between RGB and LMS and XYZ (CIE 2015).



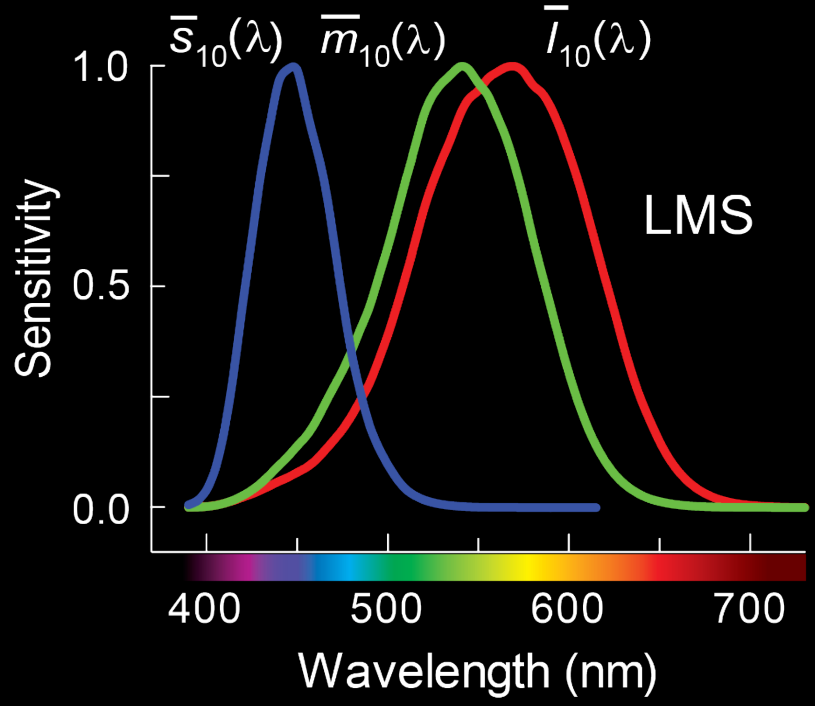
INDIVIDUAL DIFFERENCES



As just discussed, the CIE (2006) LMS standards represent the average normal spectral sensitivity or colour matching functions and are defined as a linear transformation of the average Stiles & Burch (1959) CMFs.

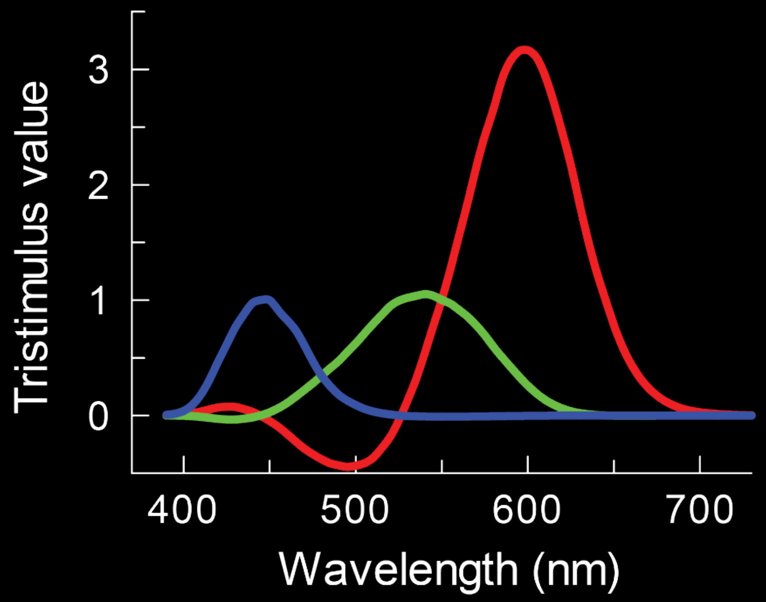


$$\begin{pmatrix} 2.846201 & 11.092490 & 1 \\ 0.168926 & 8.265895 & 1 \\ 0 & 0.010600 & 1 \end{pmatrix}$$

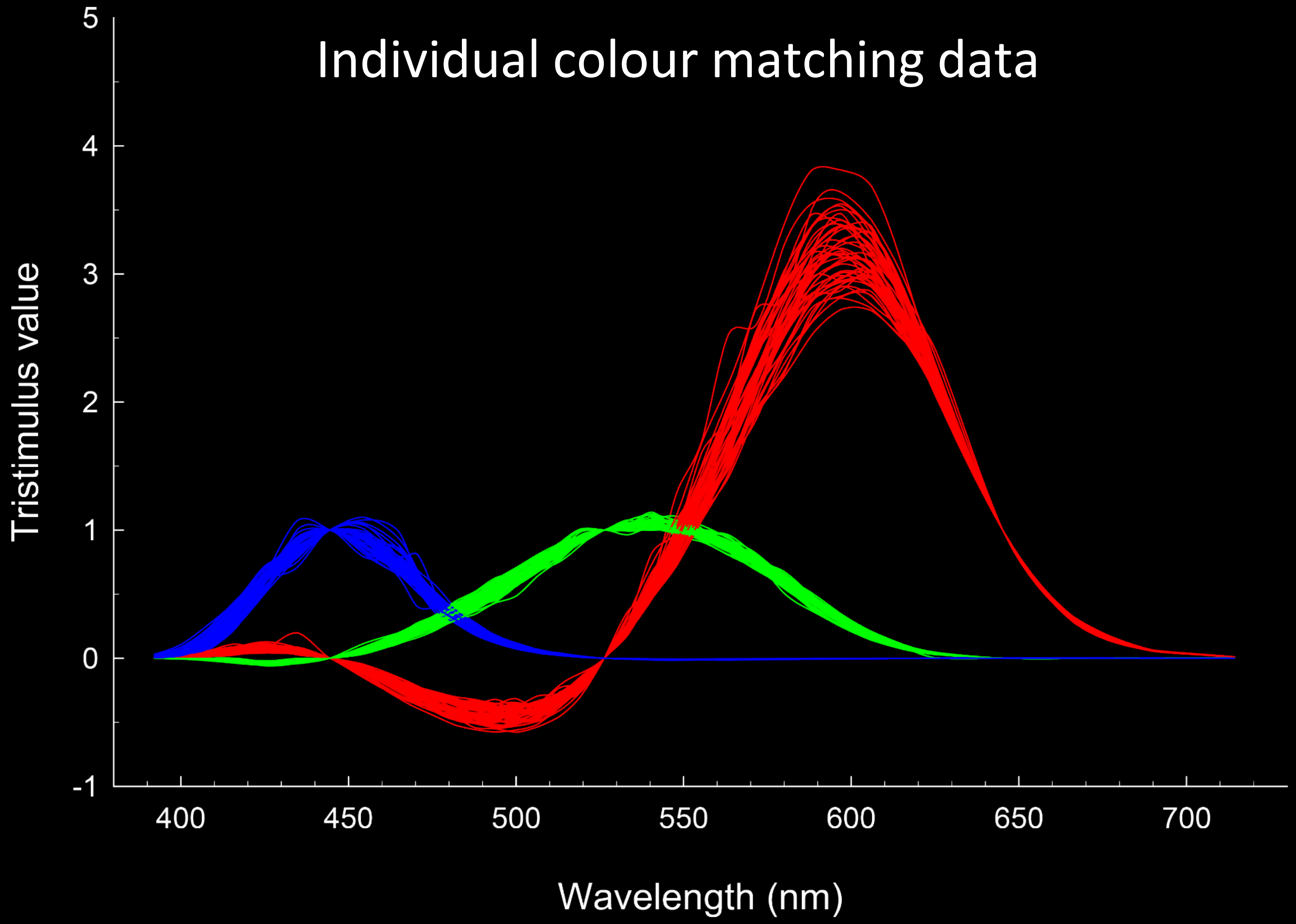


However, this underplays the sizeable individual differences between the colour matches made by colour-normal observers that can be seen in the original individual Stiles & Burch colour matching data.

Mean colour matching data



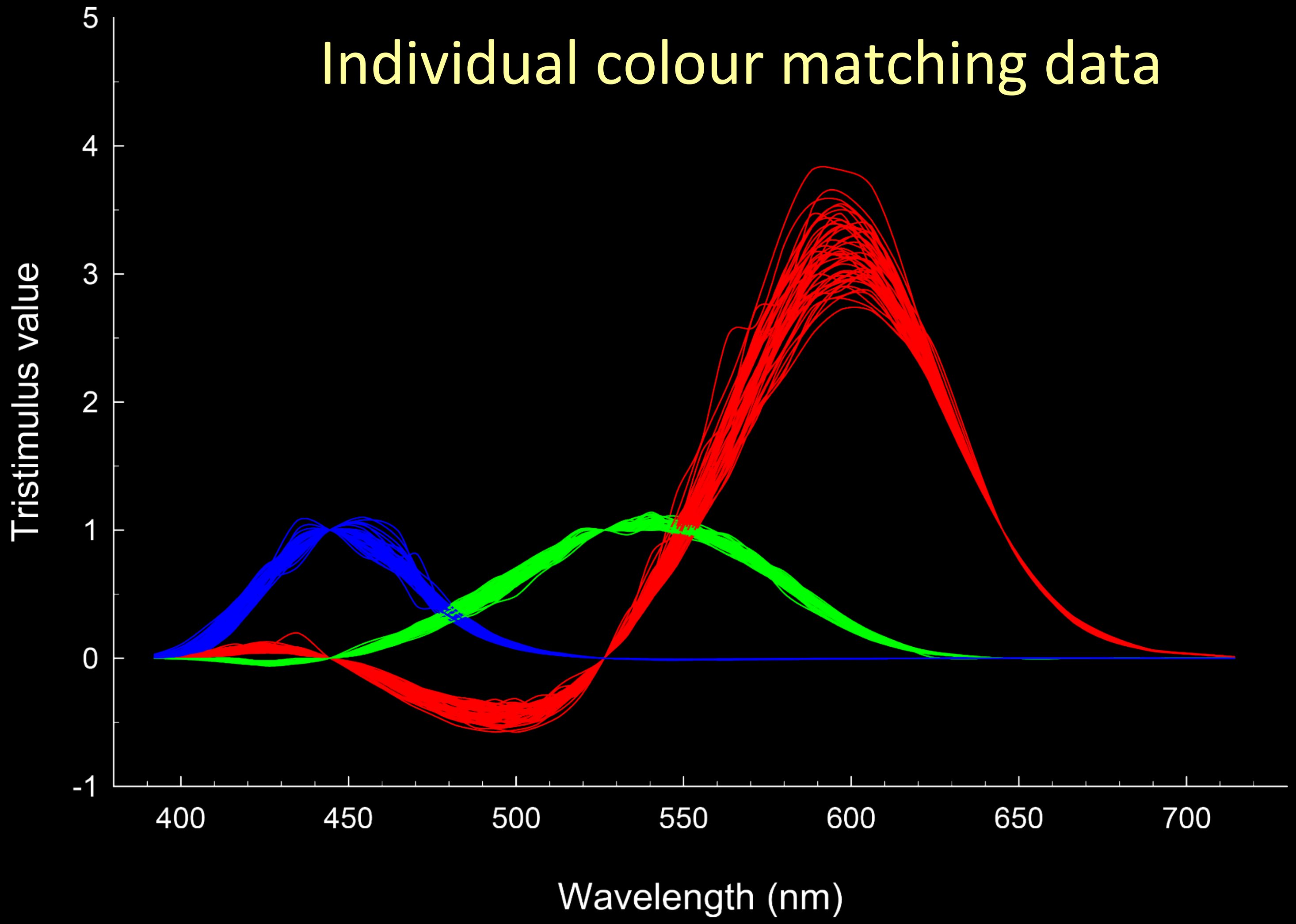
Individual colour matching data



Stiles & Burch (1959) 10-deg CMFs

What causes these individual differences?

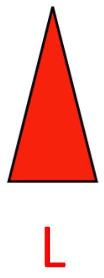
How can we model them?



What causes individual differences?

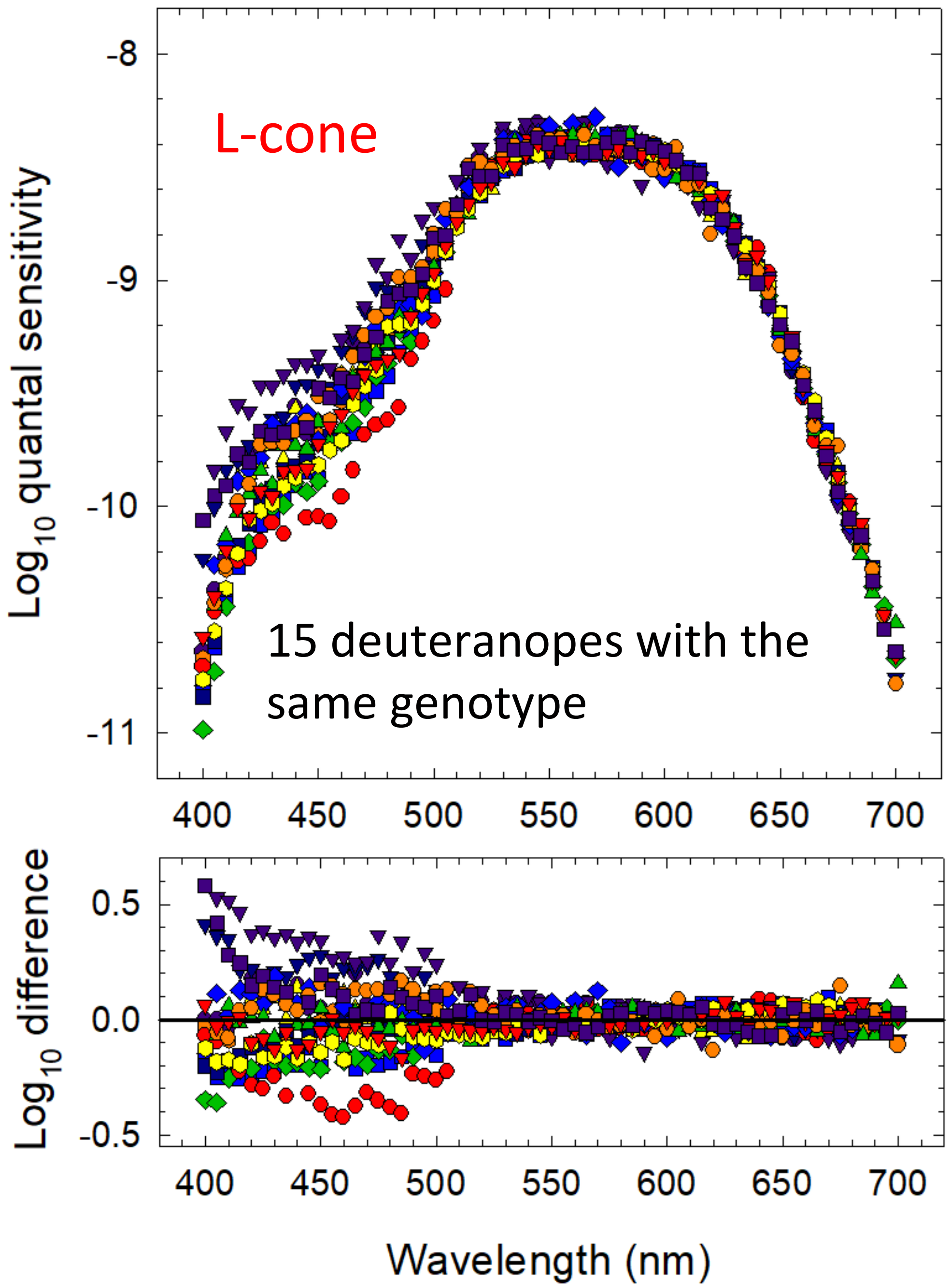
- Macular pigment optical density differences
- Lens pigment optical density differences
- Photopigment optical density differences
- Spectral shifts in photopigment sensitivity

Individual data for deuteranopes with the same L-cone photopigment



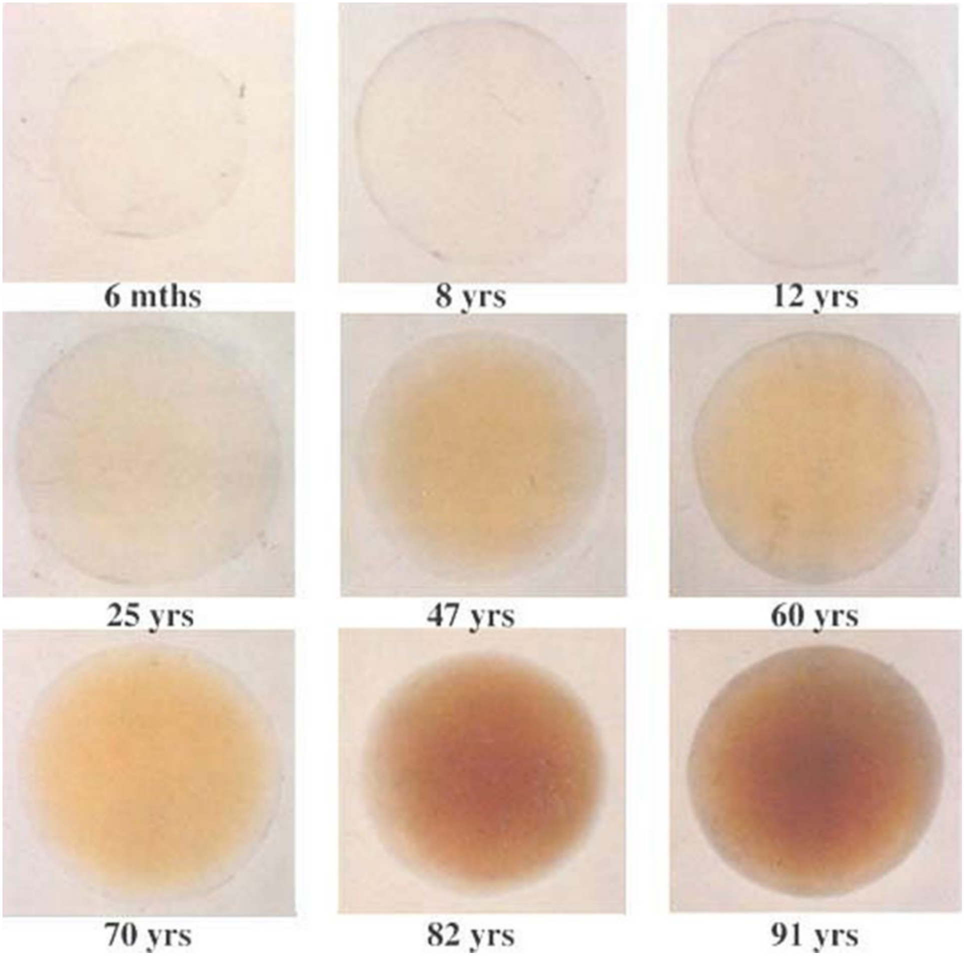
L-cone data from fifteen deuteranopes with the same genotype (and therefore with the same photopigment) *(Stockman and Sharpe, 1999)*

Why are the results so variable at short wavelengths?



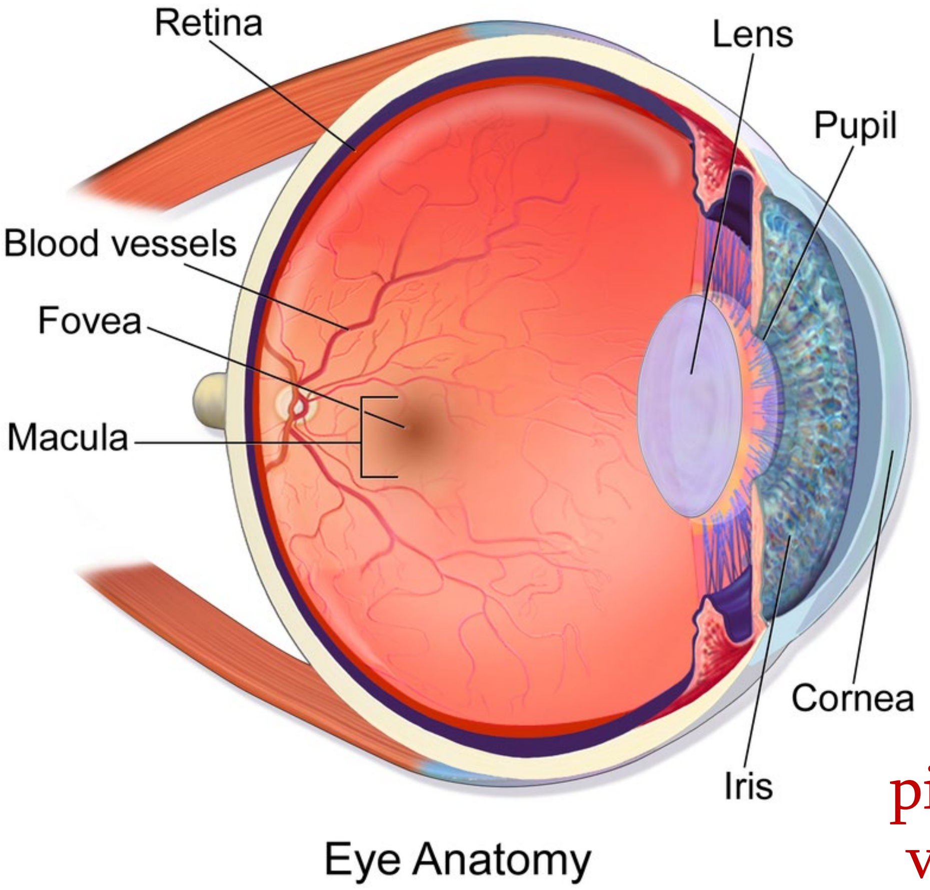
Lens pigment

Lens pigment density varies between observers and across the lifespan



Lerman's "Radiant Energy and the Eye"

Macular pigment

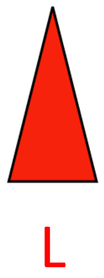


Blausen.com staff (2014). "Medical gallery of Blausen Medical 2014"

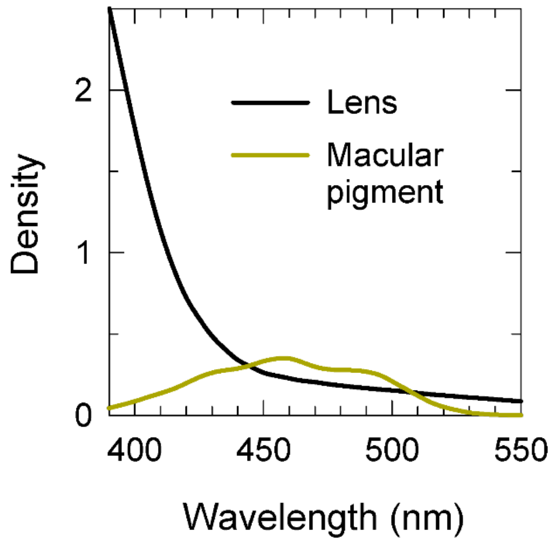
Macular pigment density varies between observers and across the retina

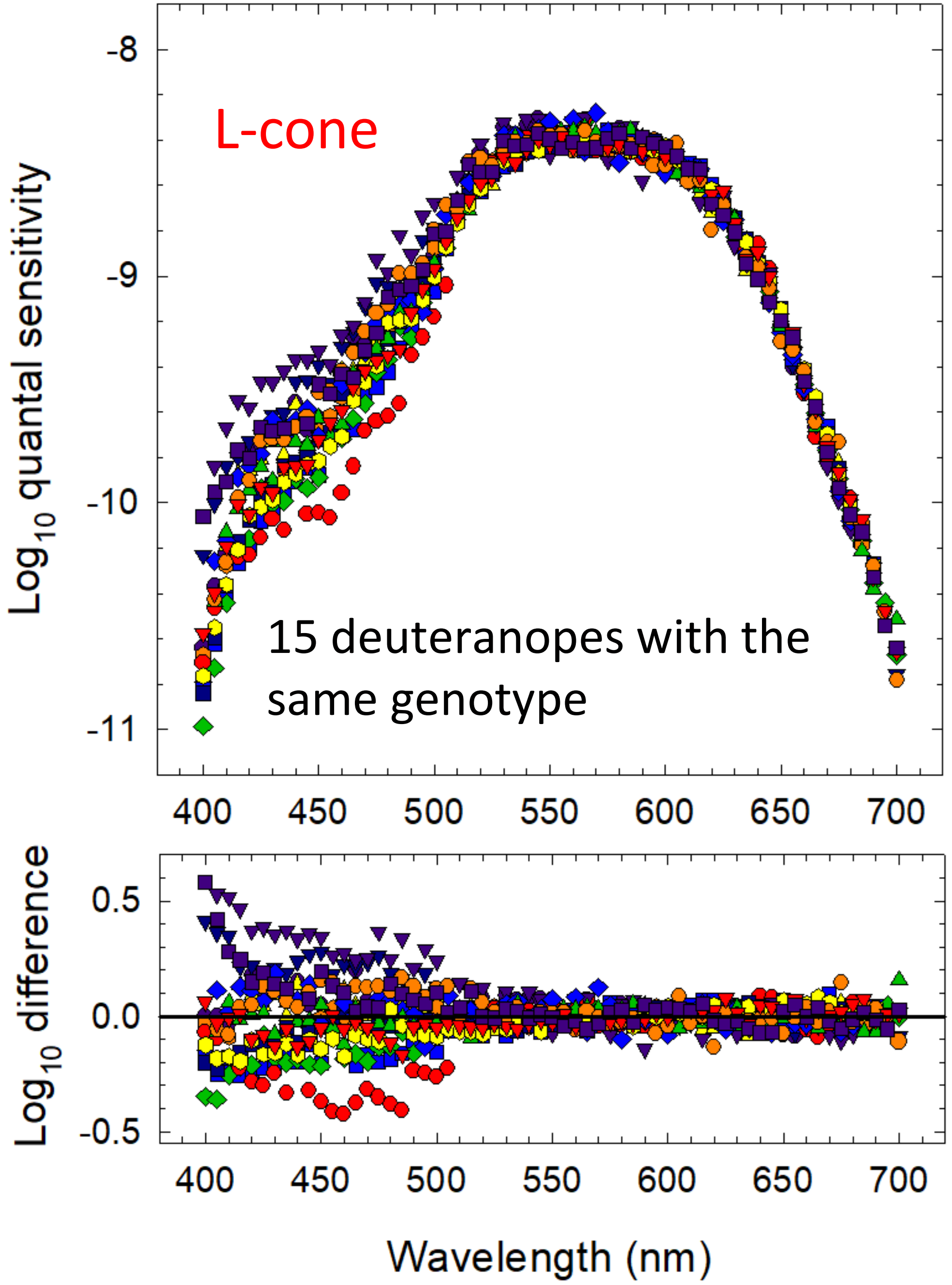
Häggström, M. (2014). "Medical gallery of Mikael Häggström 2014"

Individual data for deuteranopes with the same L-cone photopigment

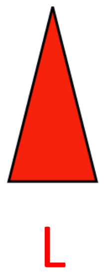


The variability is due to individual differences in macular and lens pigment optical densities.

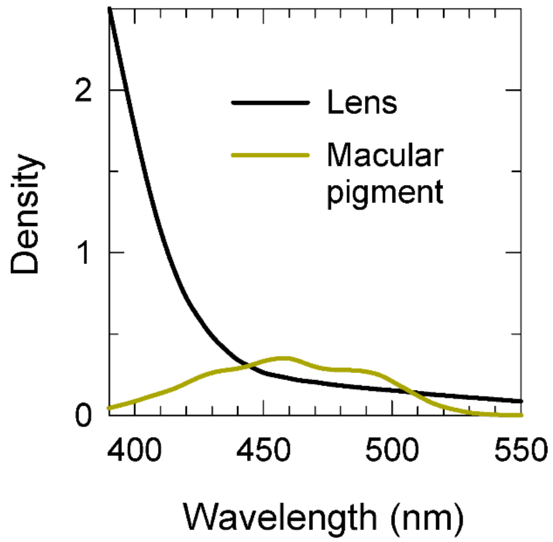


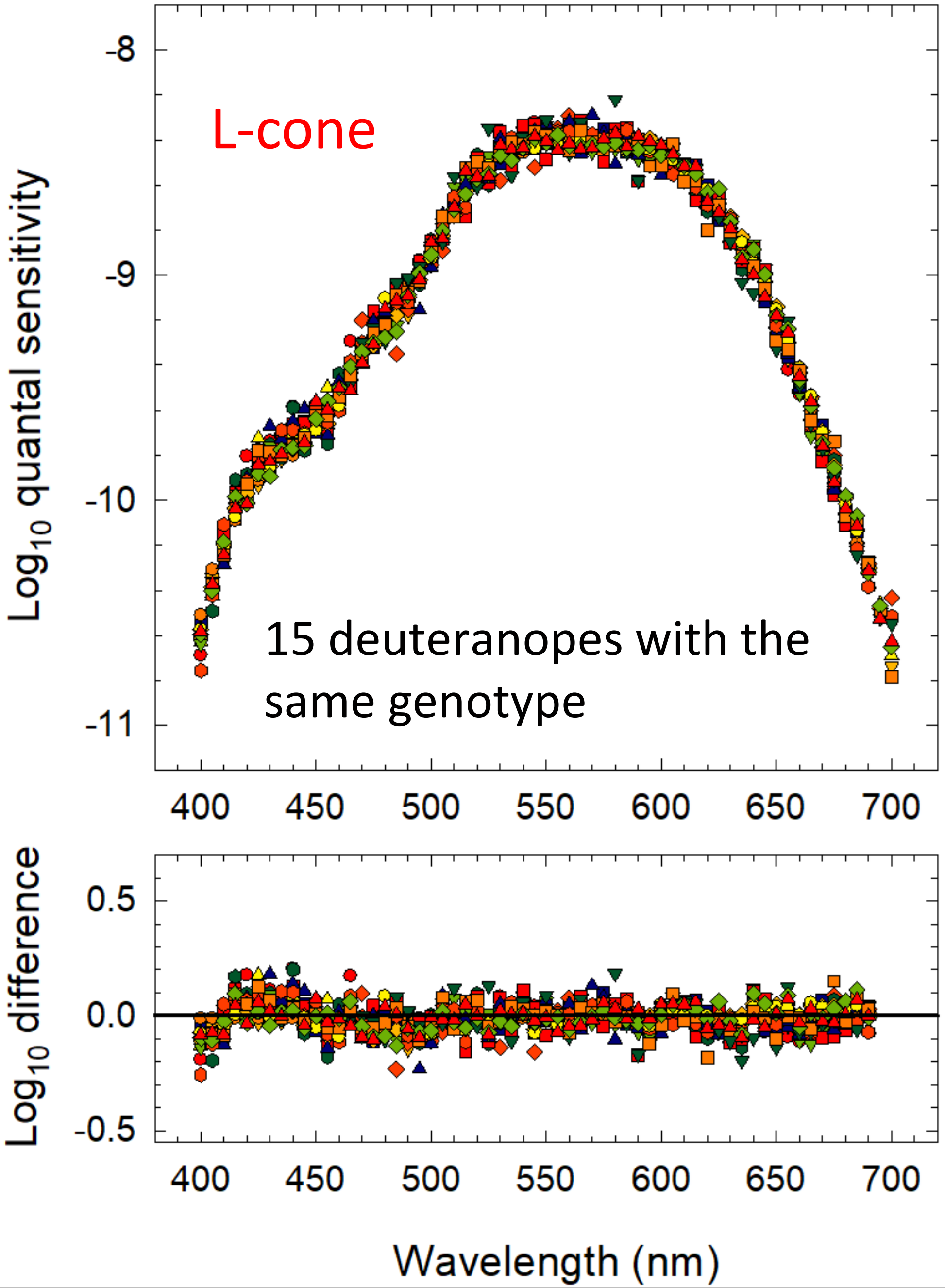


Individual data for deuteranopes with the same L-cone photopigment



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

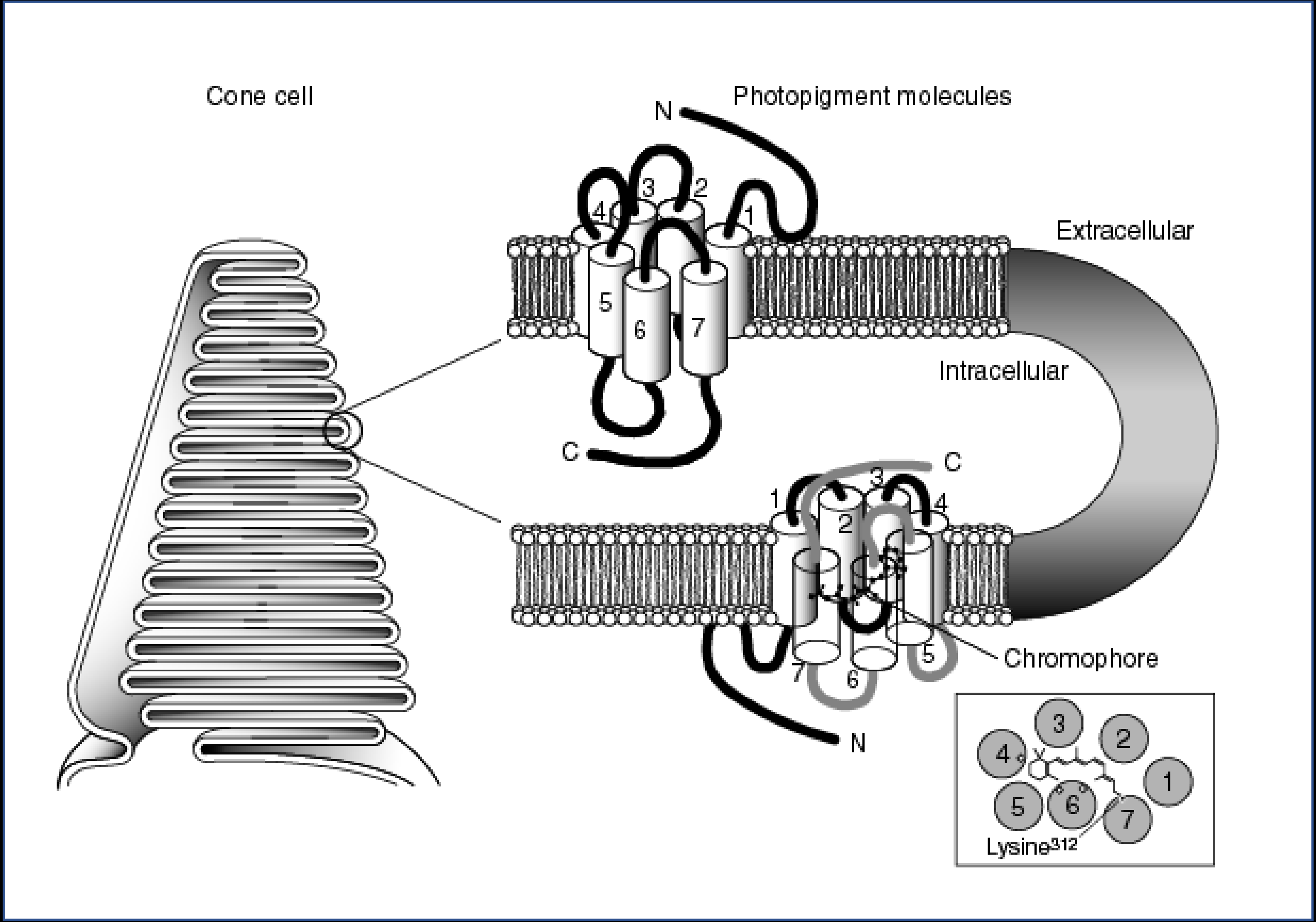




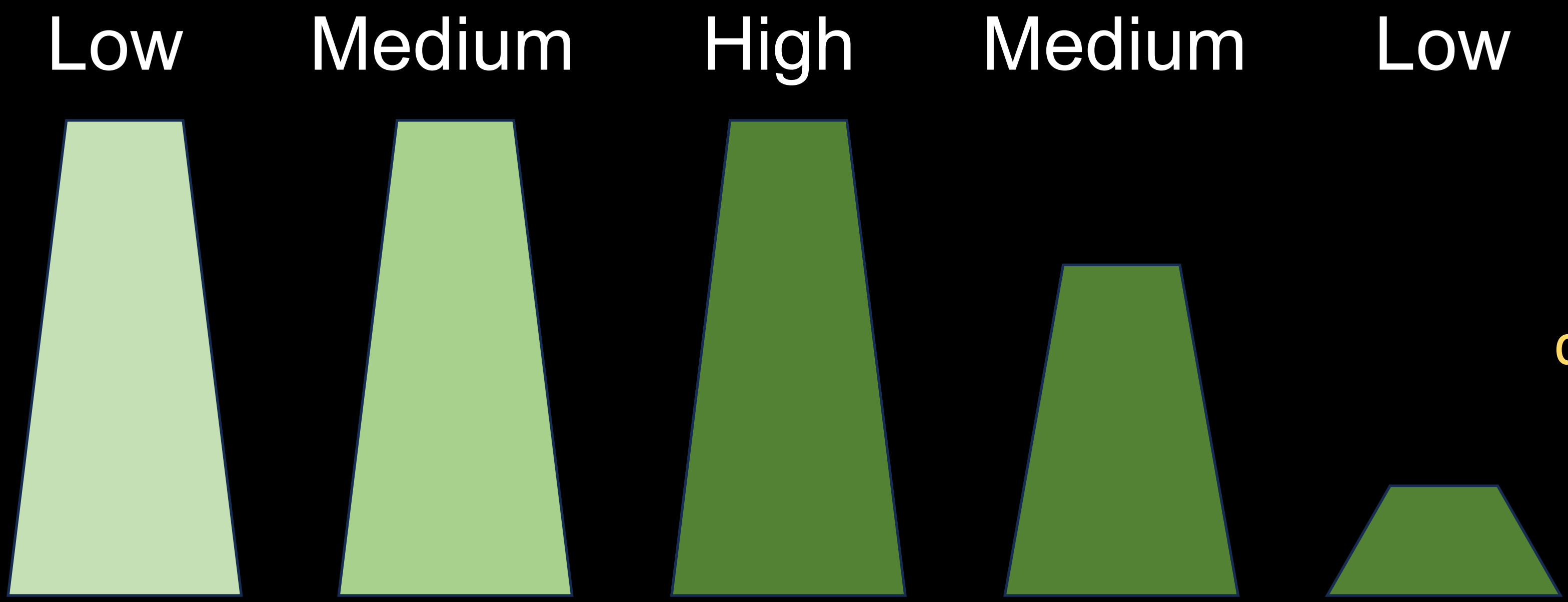
What causes individual differences?

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

Photopigments in the cones



Photopigment optical density

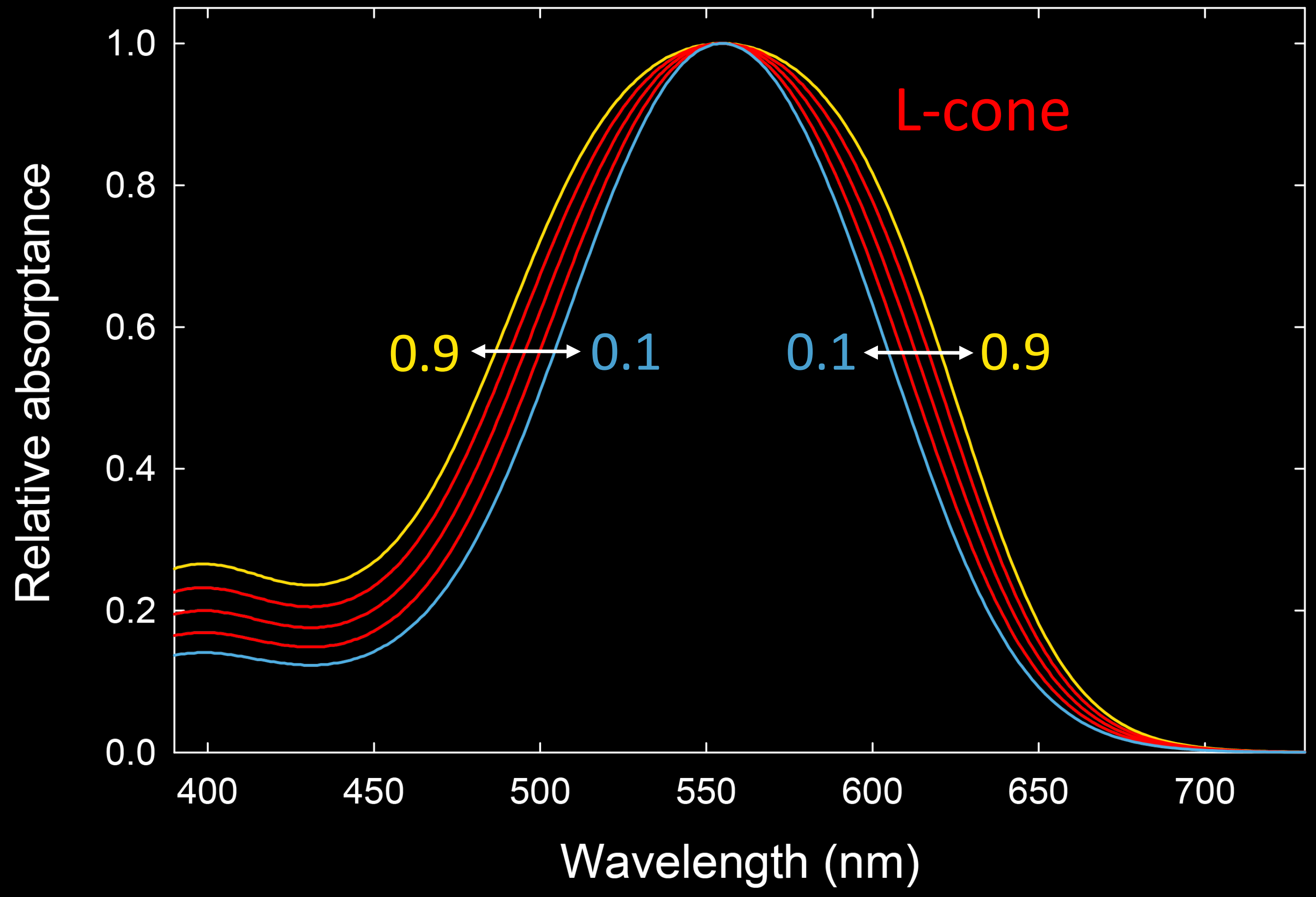


Optical density ≈ density × axial length

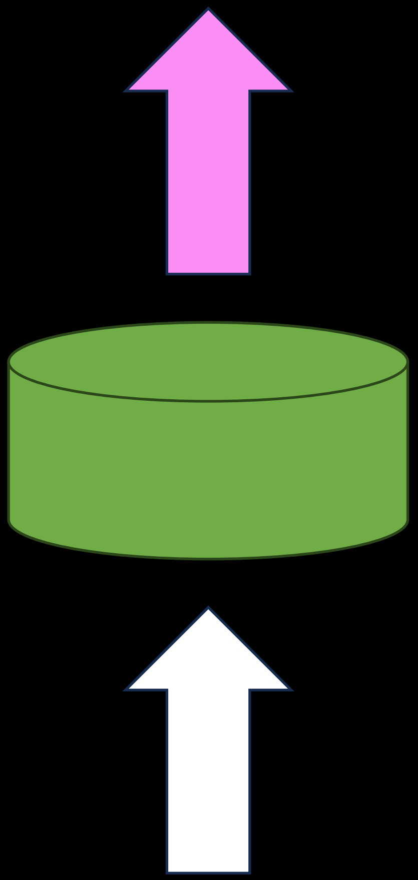
Individual differences in photopigment optical density

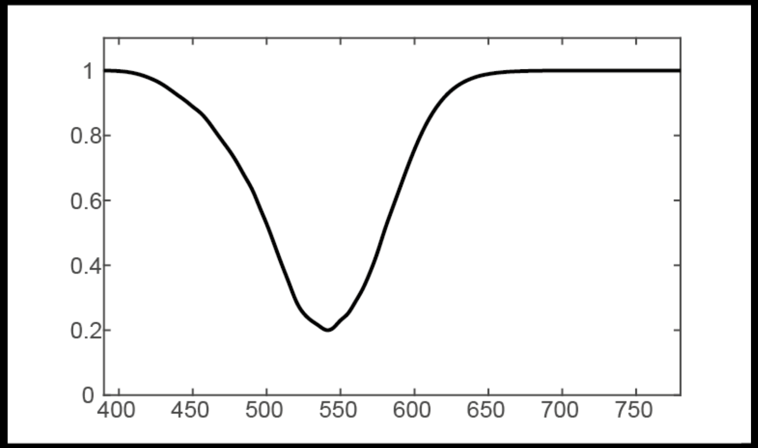
Increasing photopigment optical density broadens the spectral sensitivity around the λ_{max}

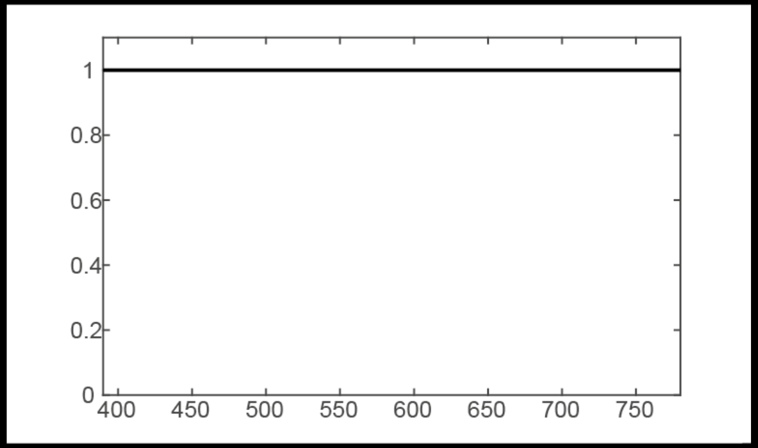
Cone photopigments varying in optical density from 0.1 (narrow) to 0.9 (broad) in 0.2 steps



Self-screening

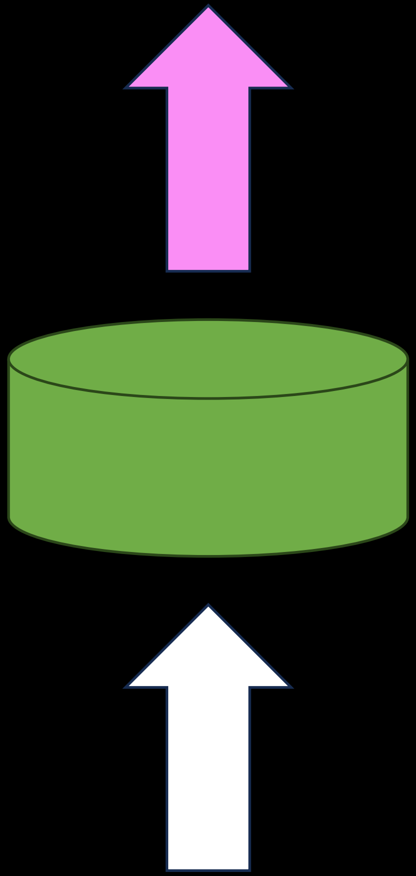




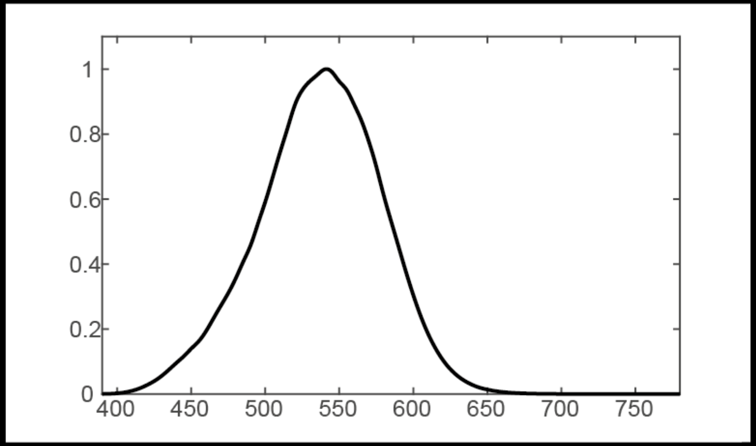


Self-screening

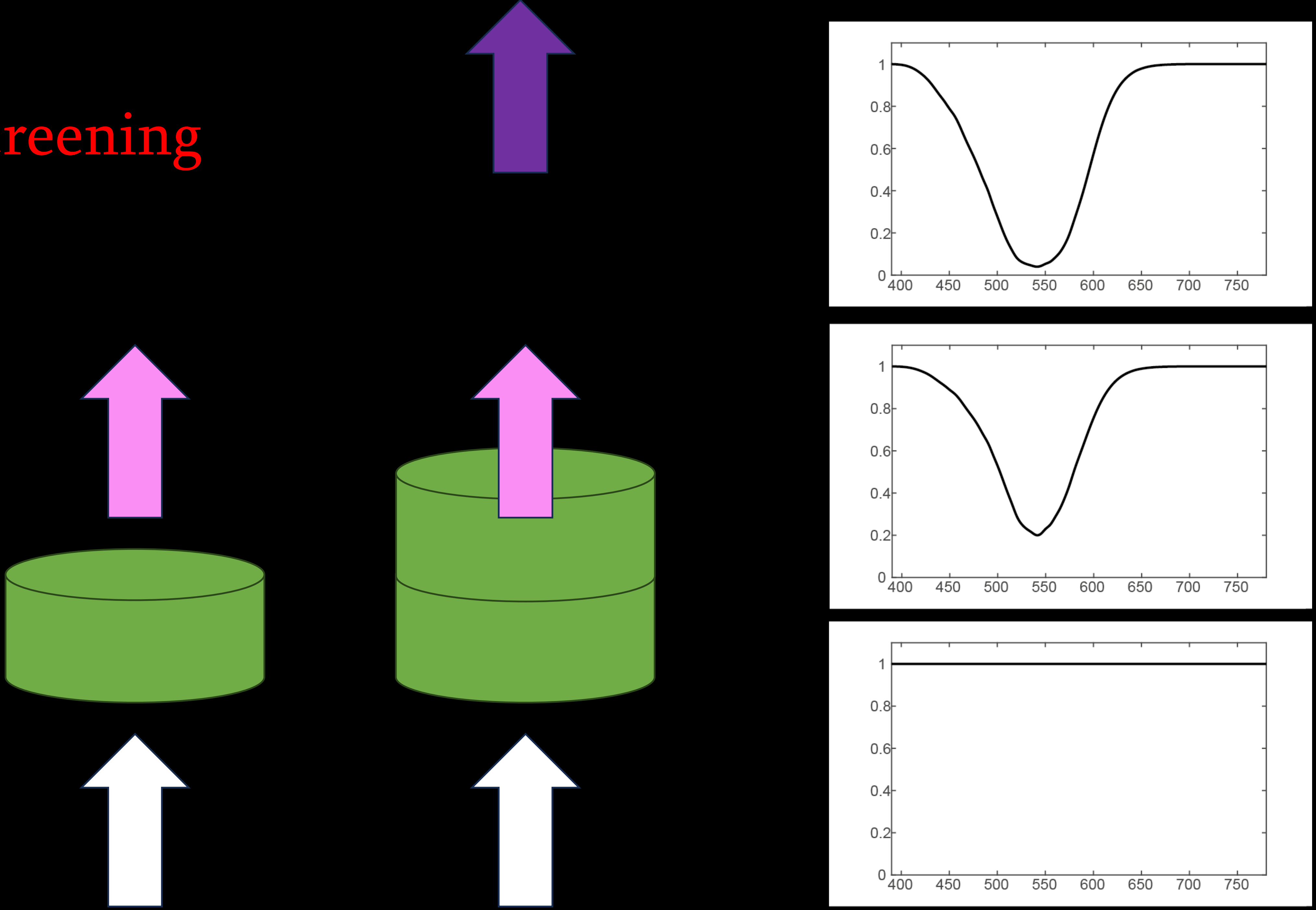
Difference between light entering and light exiting gives the light absorbed



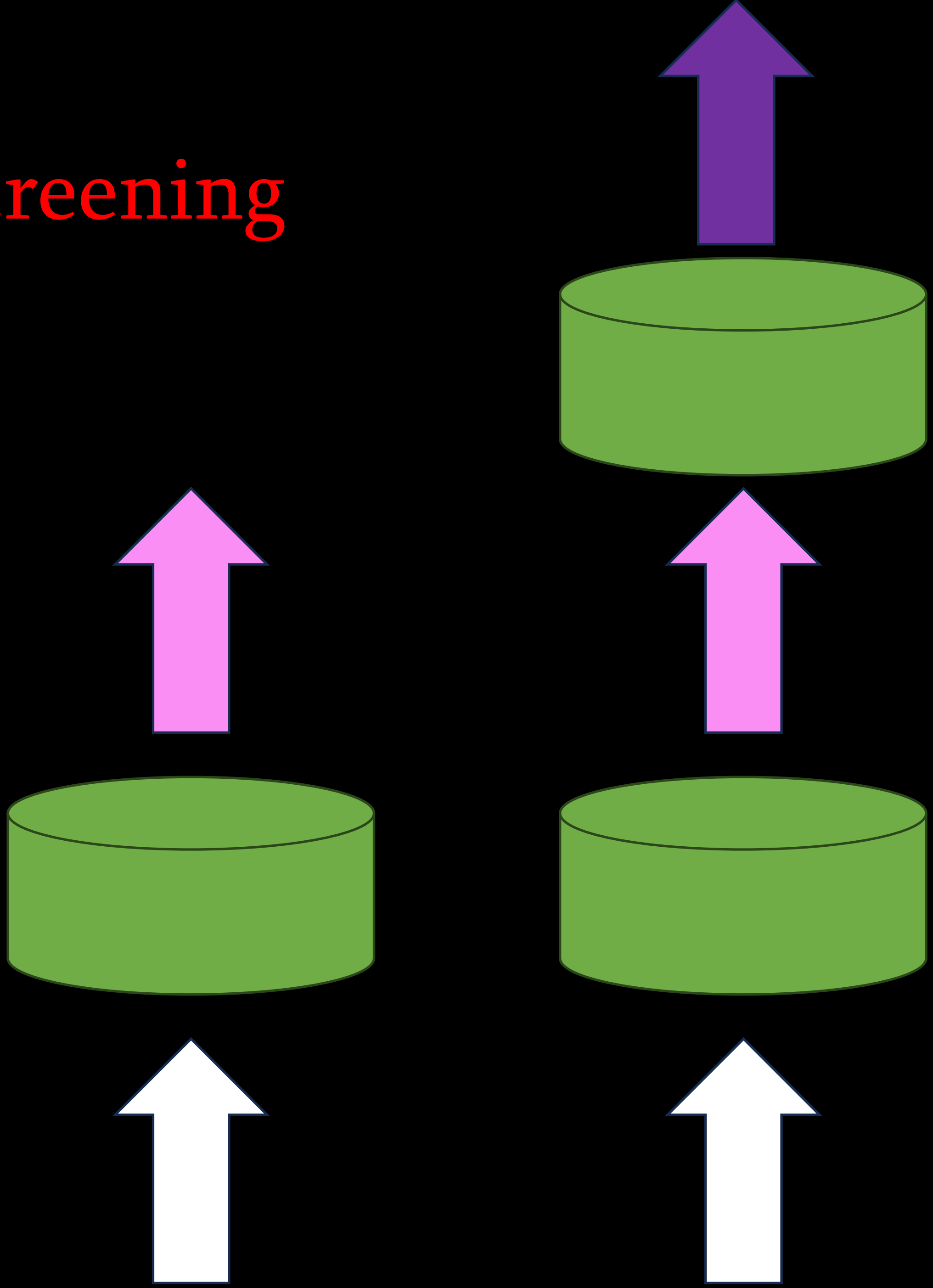
Absorbance spectrum

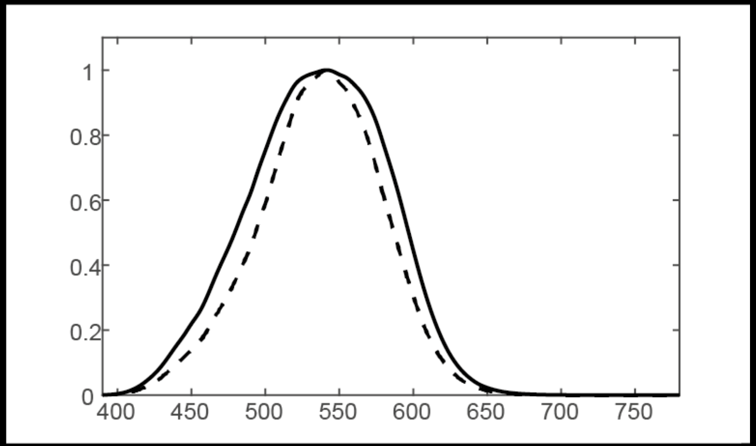


Self-screening



Self-screening



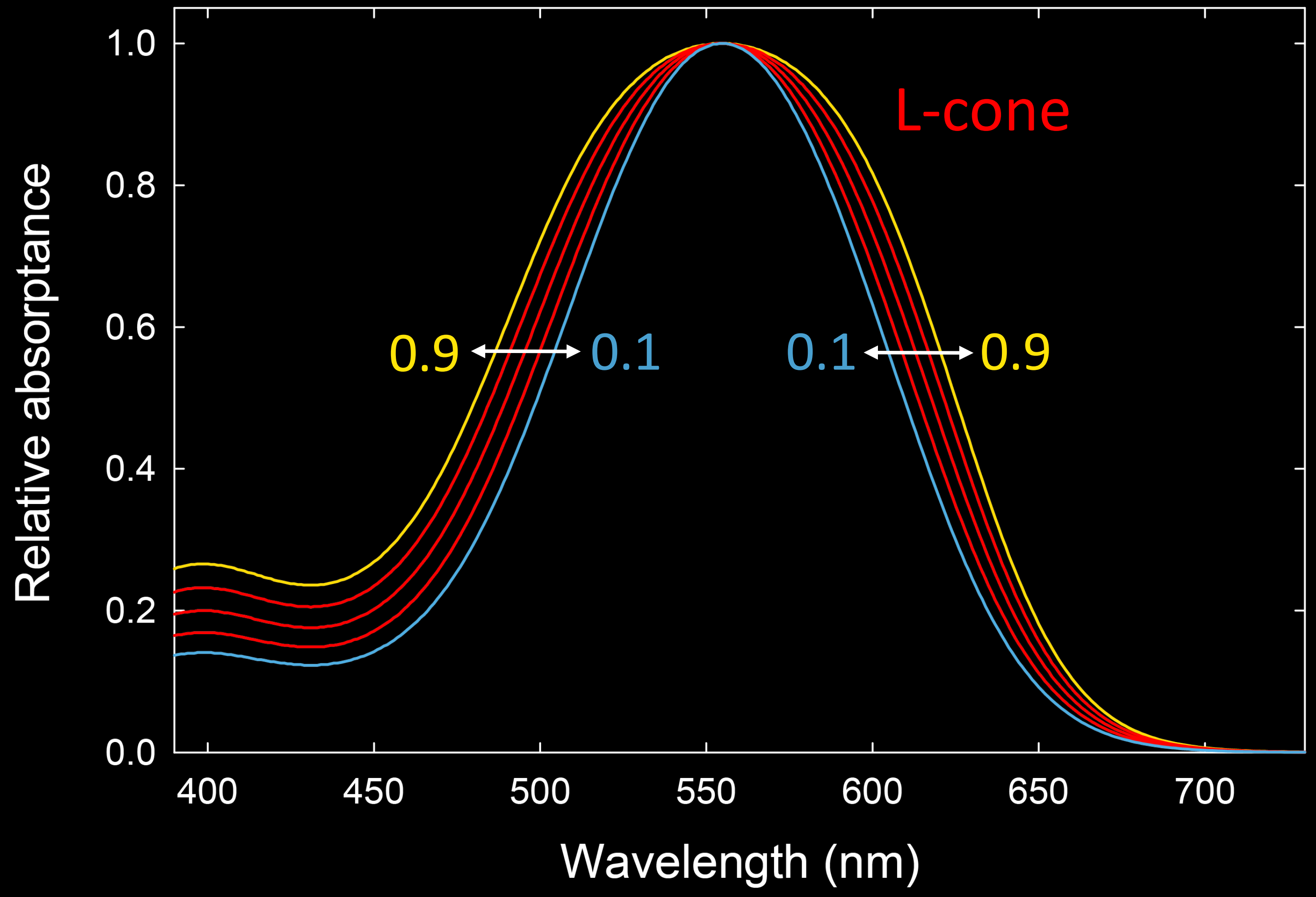


Individual differences in photopigment optical density

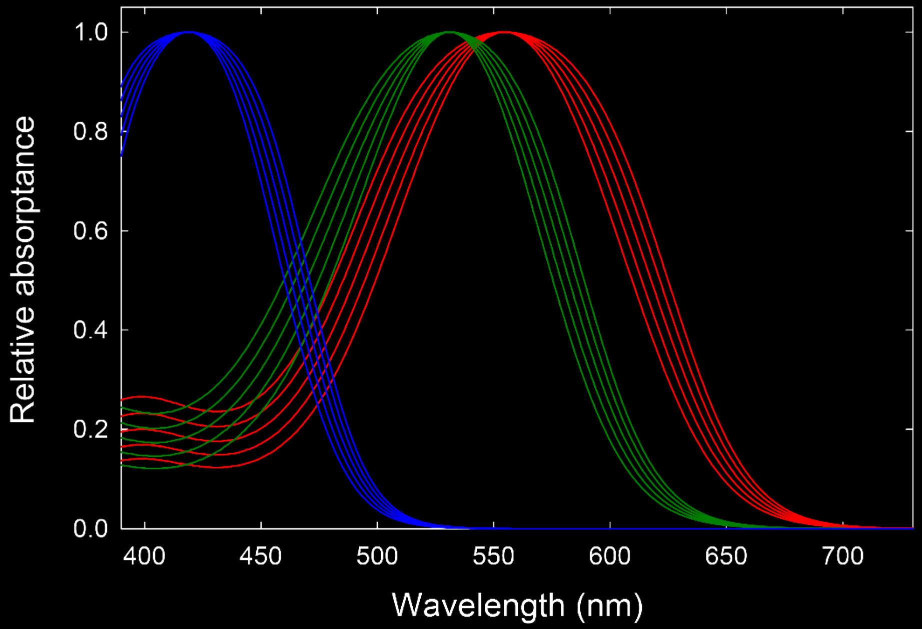
Increasing photopigment optical density broadens the spectral sensitivity around the λ_{max}

Note that the 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

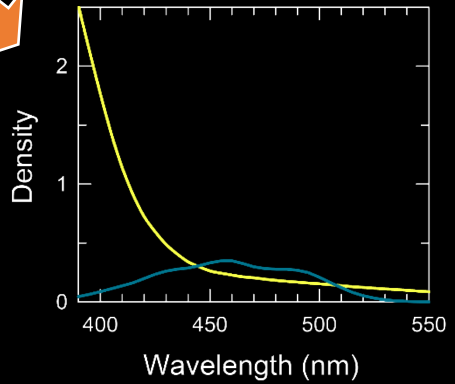
Cone photopigments varying in optical density from 0.1 (narrow) to 0.9 (broad) in 0.2 steps



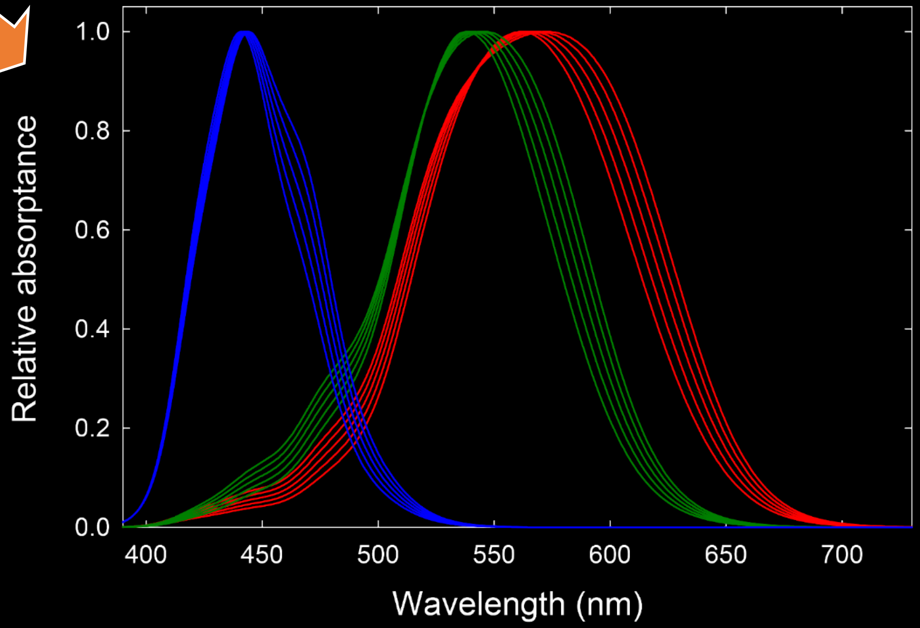
Photopigments



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



Cone spectral sensitivities at the cornea

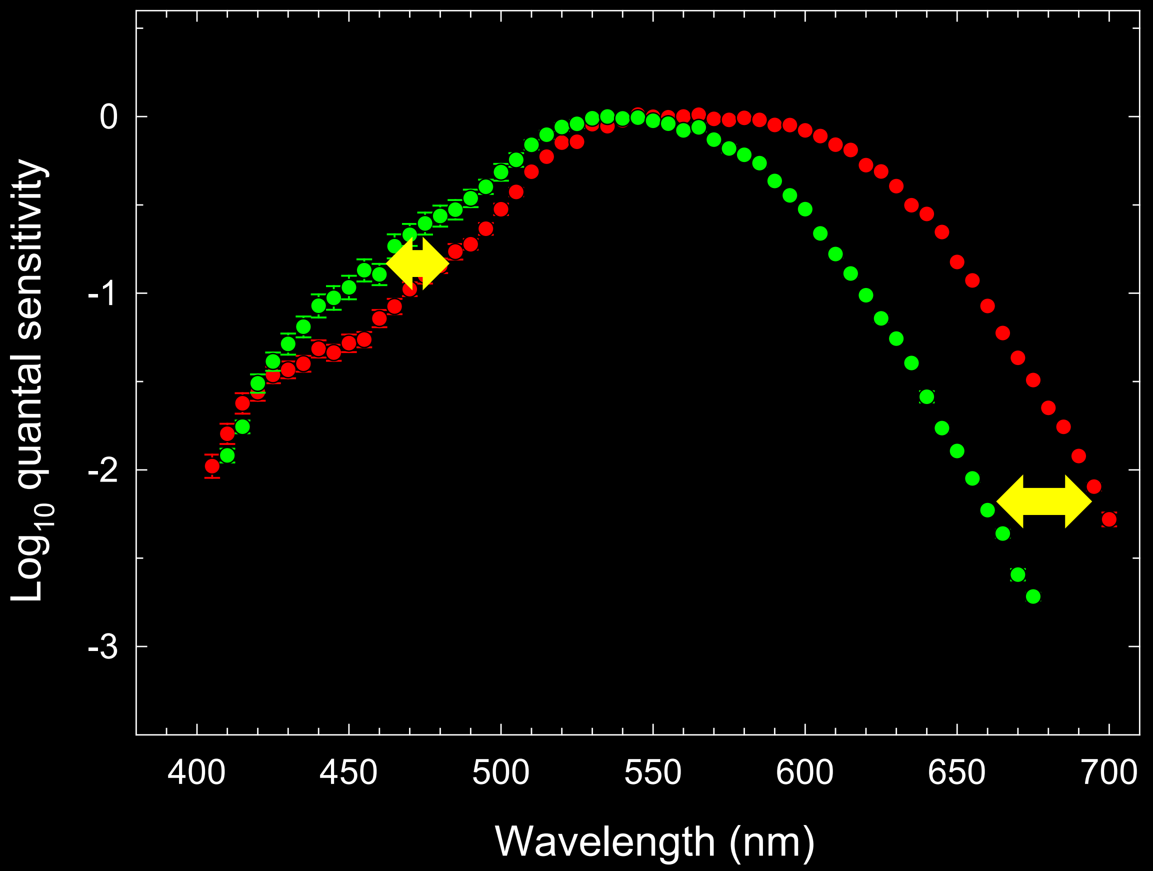


What causes individual differences?

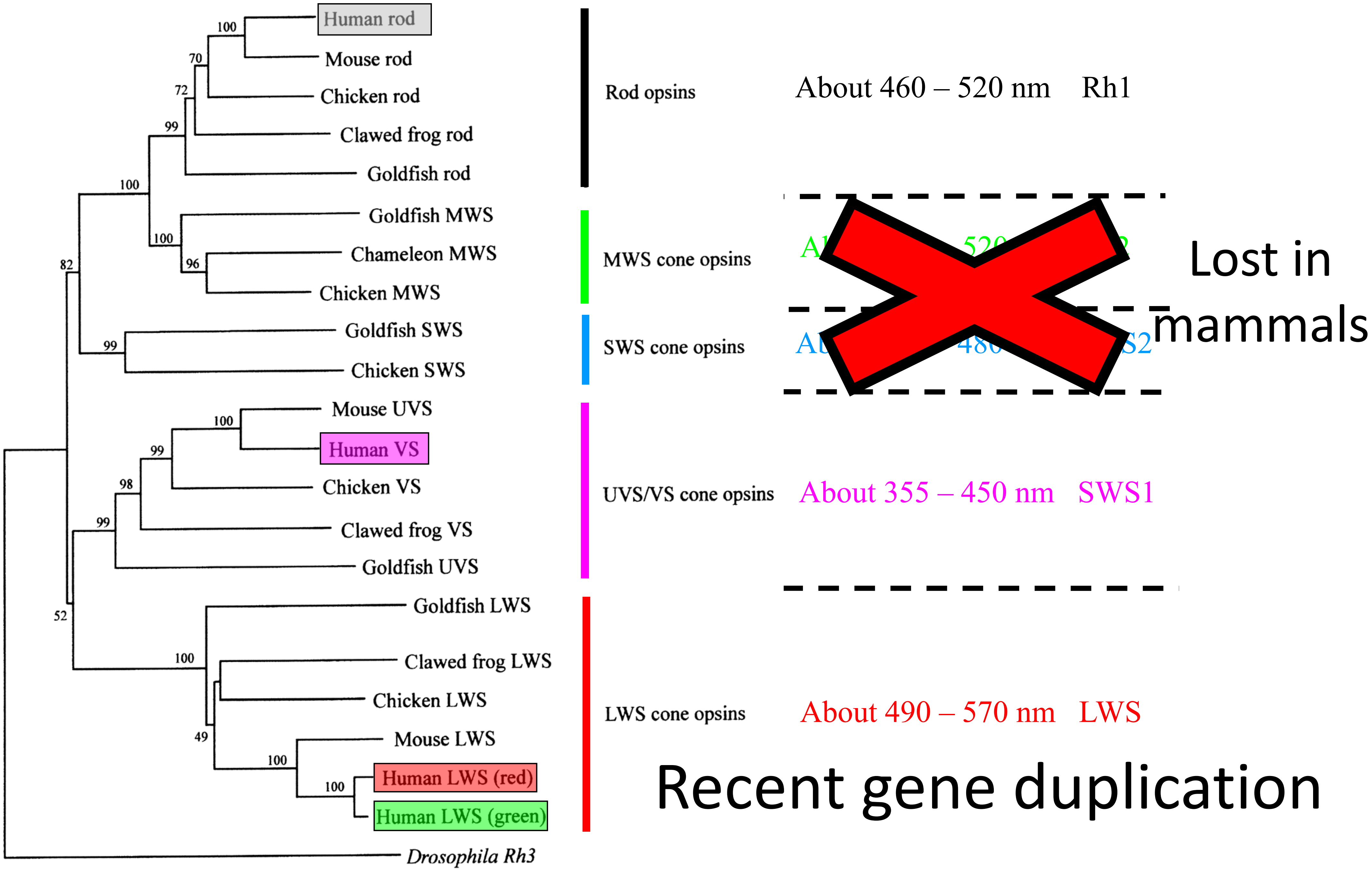
- Macular pigment optical density differences
- Lens pigment optical density differences
- Photopigment optical density differences
- Spectral shifts in photopigment sensitivity

Why does this variability occur?

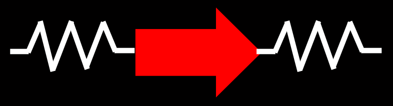
The shifts are the result of variability in the genetic codes for the M- and L-cone photopigments



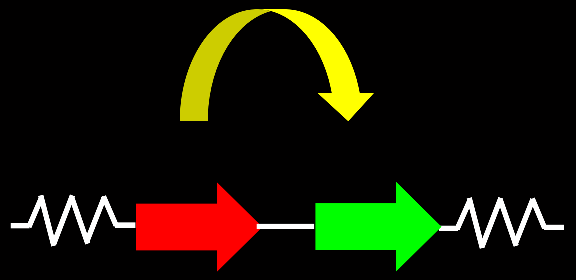
Phylogenetic tree of visual pigments / opsins



Gene duplication on the X-chromosome



Mammal

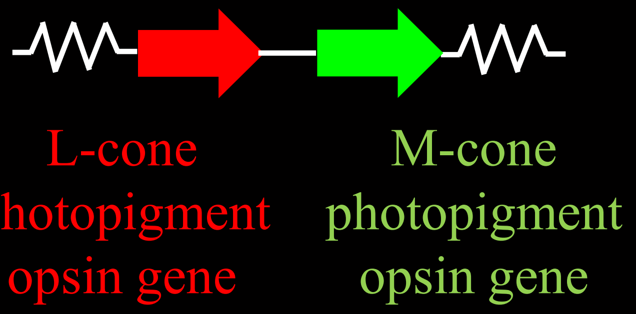


L-cone photopigment opsin gene

M-cone photopigment opsin gene

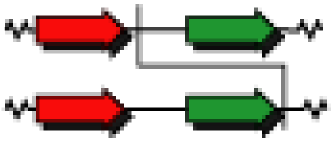
Human/ Old world primate

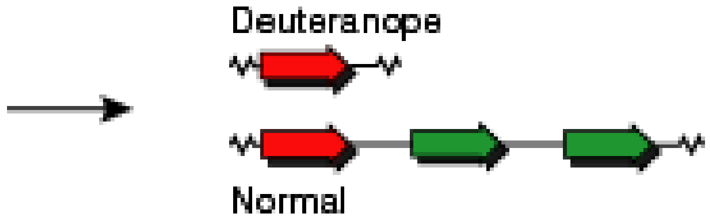
Because these two genes are in a tandem array, and are very similar…



Crossovers during meiosis are common:

Intergenic crossover

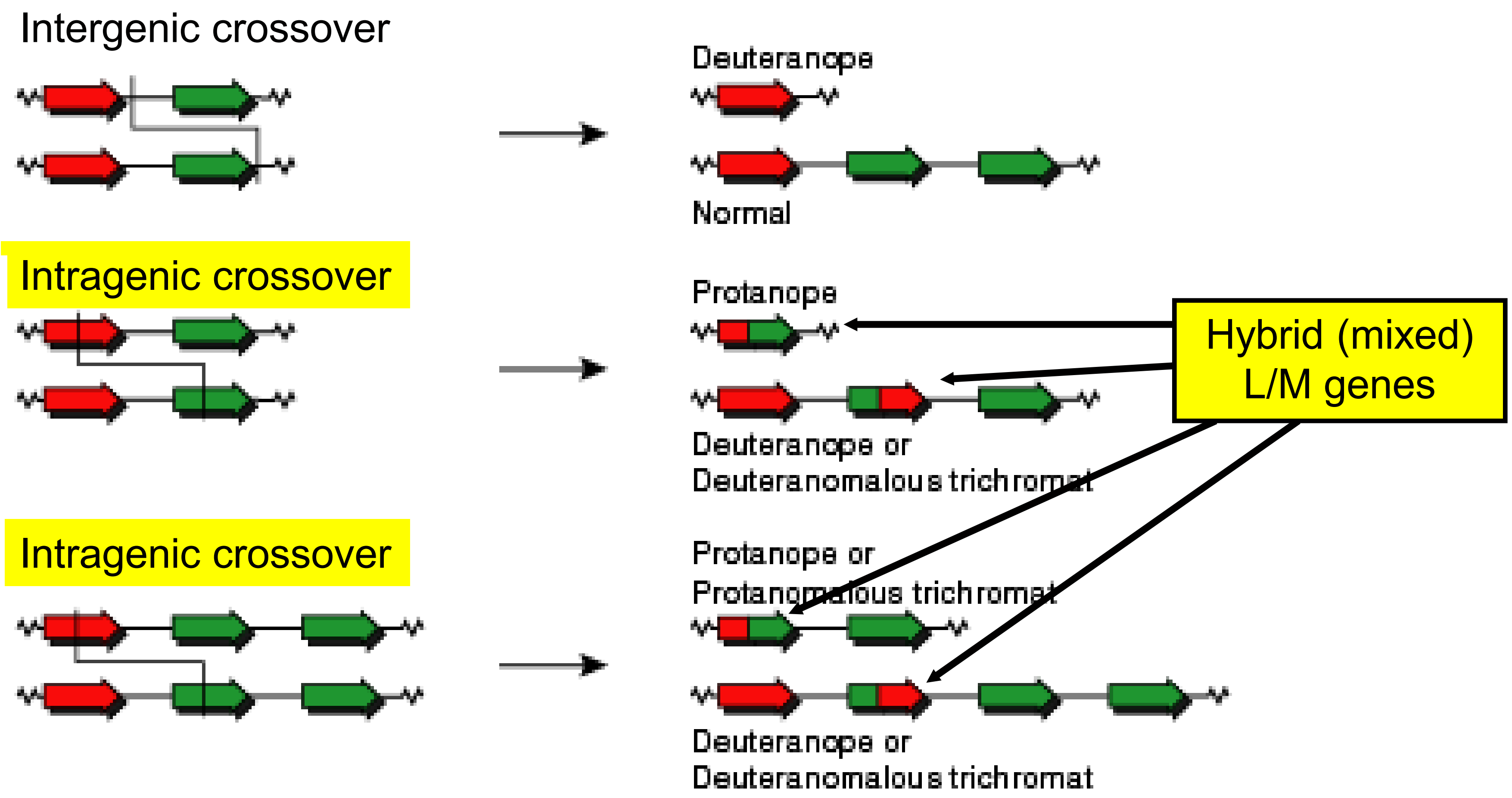




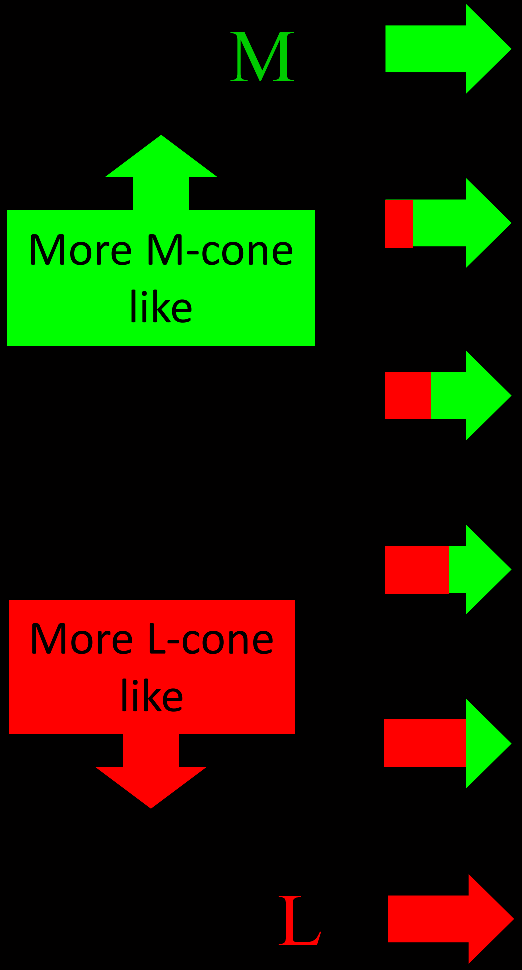
Intergenic crossovers produce more or fewer L and M-cone genes on each X chromosome

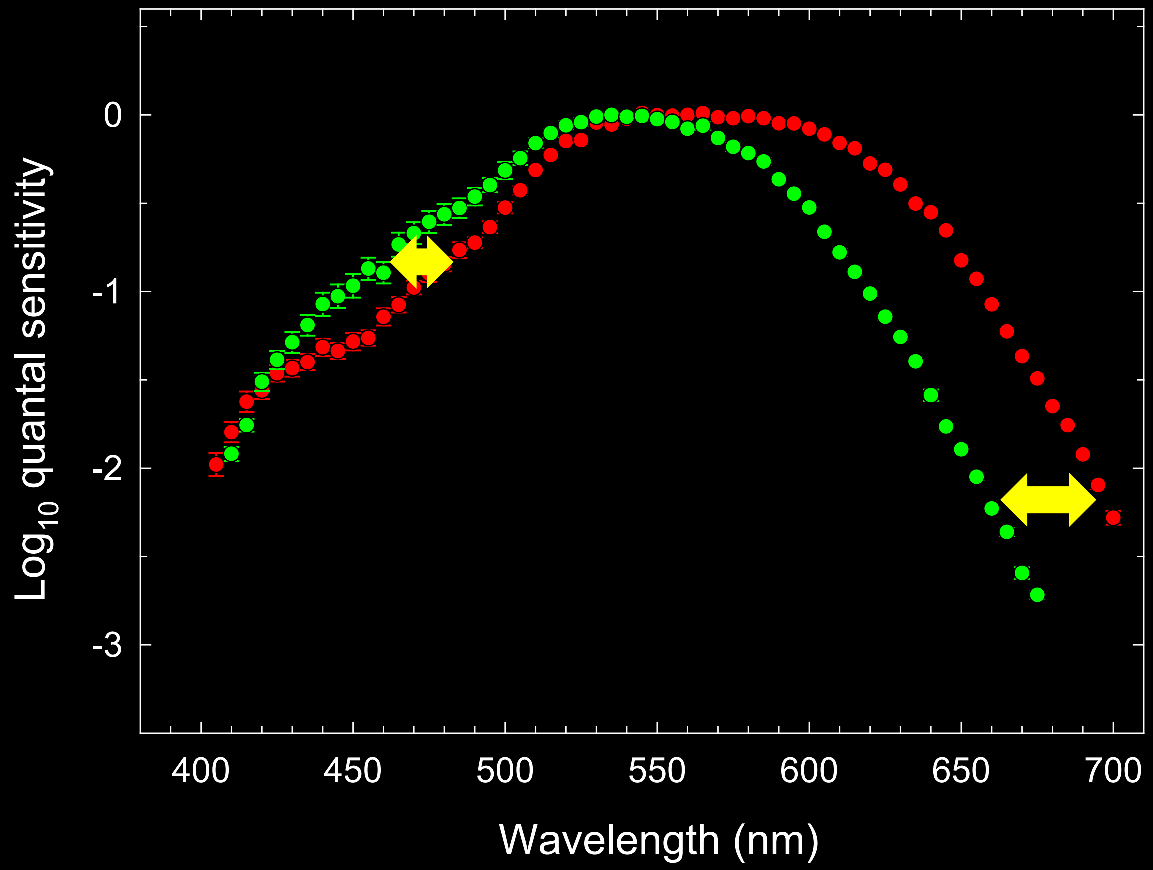
From Sharpe, Stockman, Jägle & Nathans, 1999

Intragenic crossovers produce hybrid or mixed L and M-cone genes



From Sharpe, Stockman, Jägle & Nathans, 1999

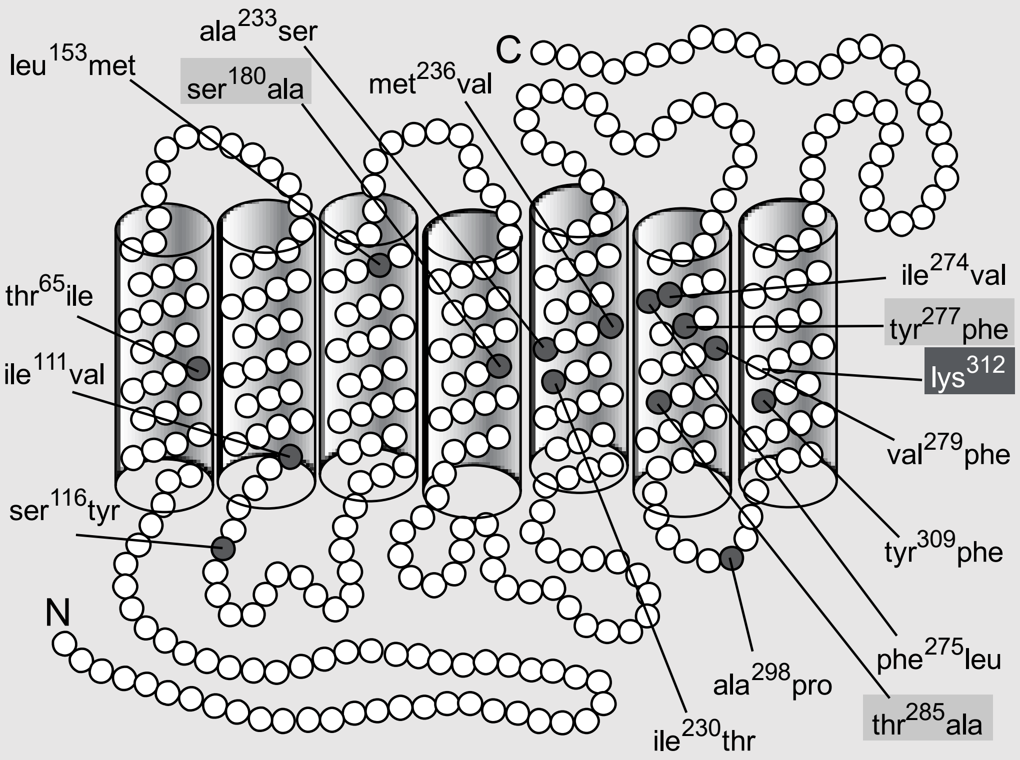


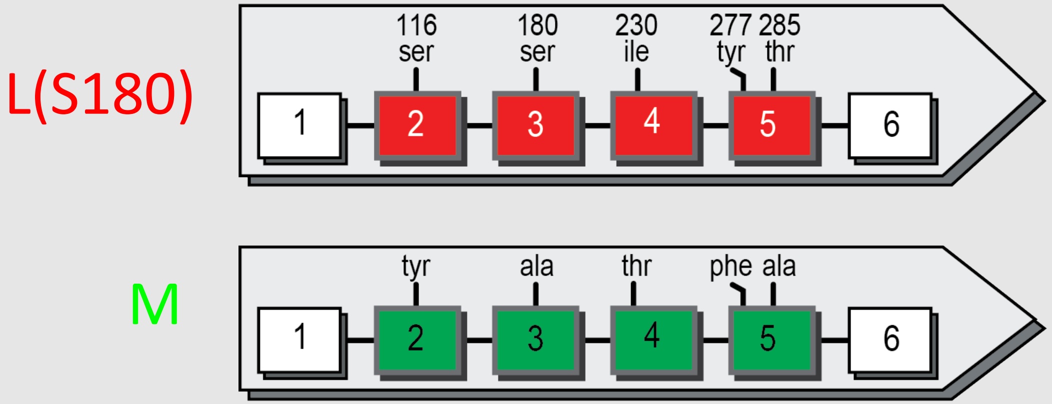


The spectral sensitivities of the hybrid photo-pigments vary between those of the M- and L-cones depending on where the crossover occurs.

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.

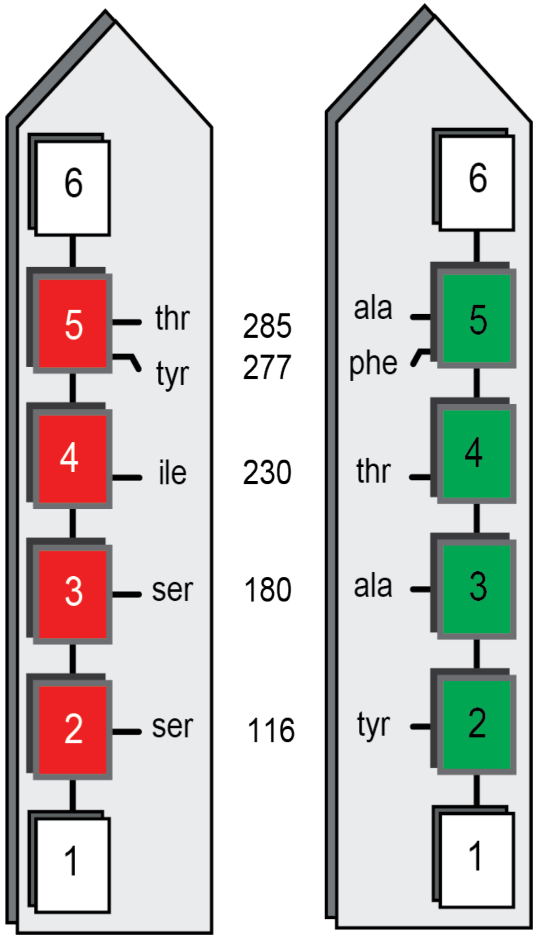




SUMMARY OF SPECTRAL SHIFTS PER EXON

Polymorphism (occurs in the normal population) →

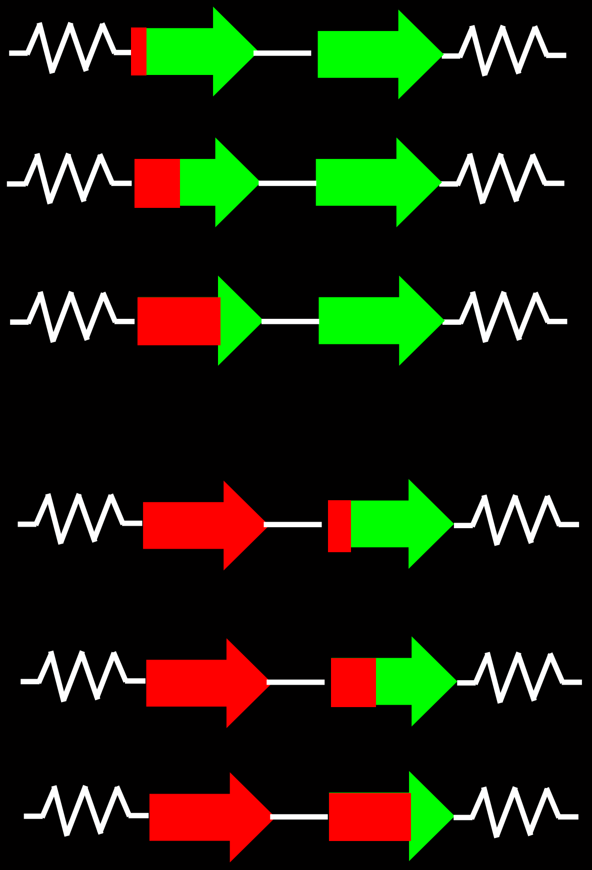
SPECTRAL SHIFT (nm)		SPECTRAL SHIFT (nm)
0		0
14		14
7		7
4		3
3-4		3
2-3		0
0		0



Values from Neitz and Neitz (2011)

Anomalous trichromats

Male observers with two different genes are “anomalous” trichromats



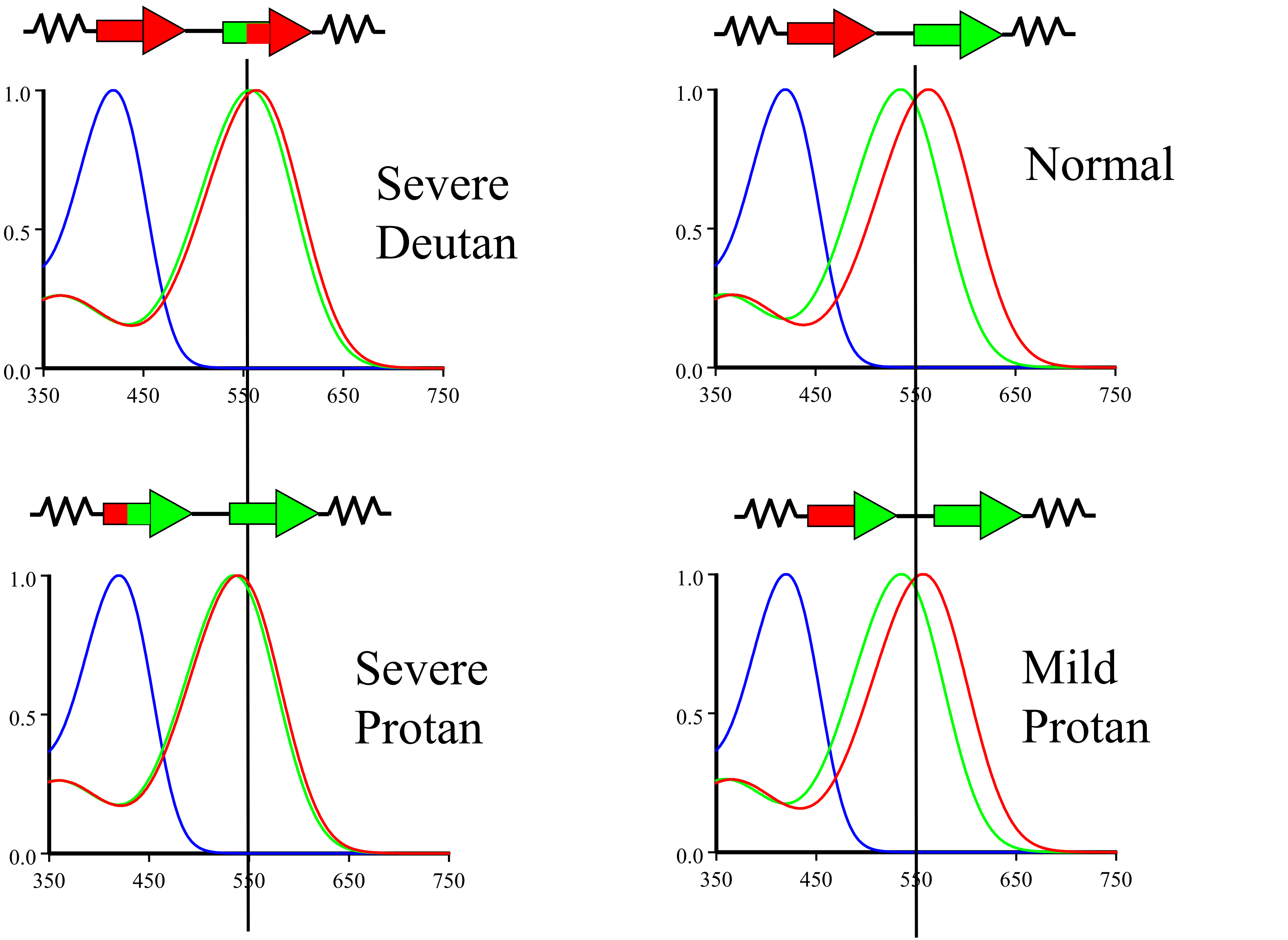
Severe

Protanomalous

Mild

Deuteranomalous

Severe



Severe
Deutan
Normal
Severe
Protan
Mild
Protan
1.0
0.5
0.0
350
450
550
650
750

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

Condition		percent in UK: Male	Female
Protanopia	no L cones	1.0	0.02
Protanomaly	milder form	1.0	0.03
Deuteranopia	no M cones	1.5	0.01
Deuteranomaly	milder form	5.0	0.4
Tritanopia	no S cones	0.008	0.008

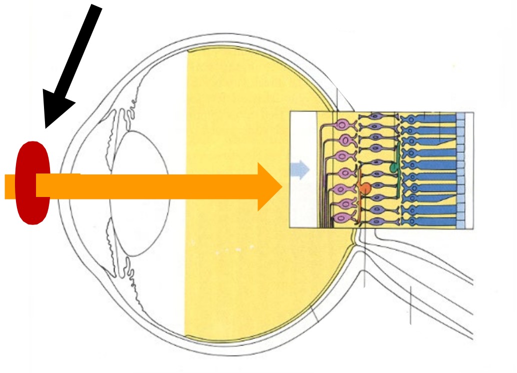
What causes individual differences?

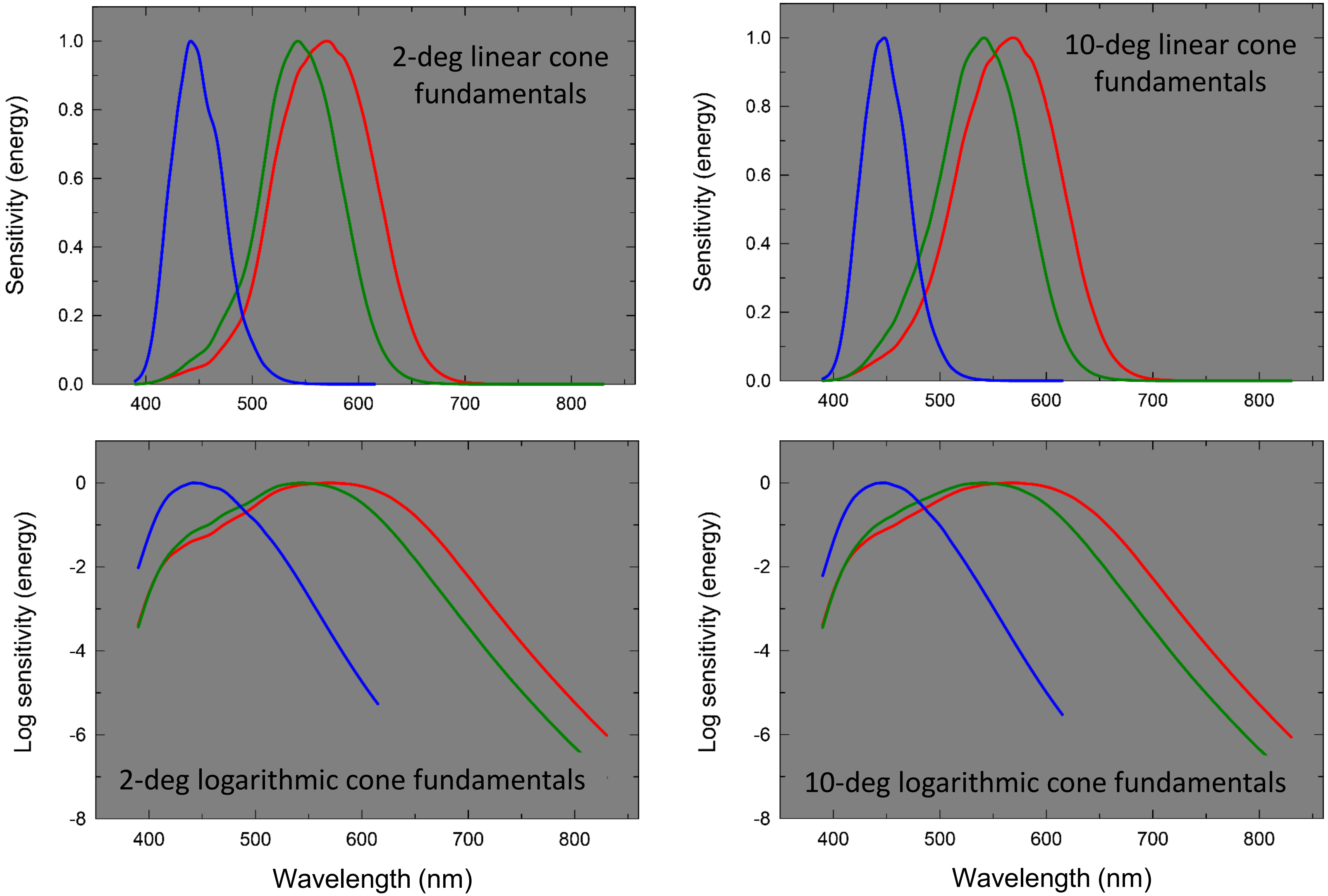
- Macular pigment optical density differences
- Lens pigment optical density differences
- Photopigment optical density differences
- Spectral shifts in photopigment sensitivity

MODELLING INDIVIDUAL DIFFERENCES

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

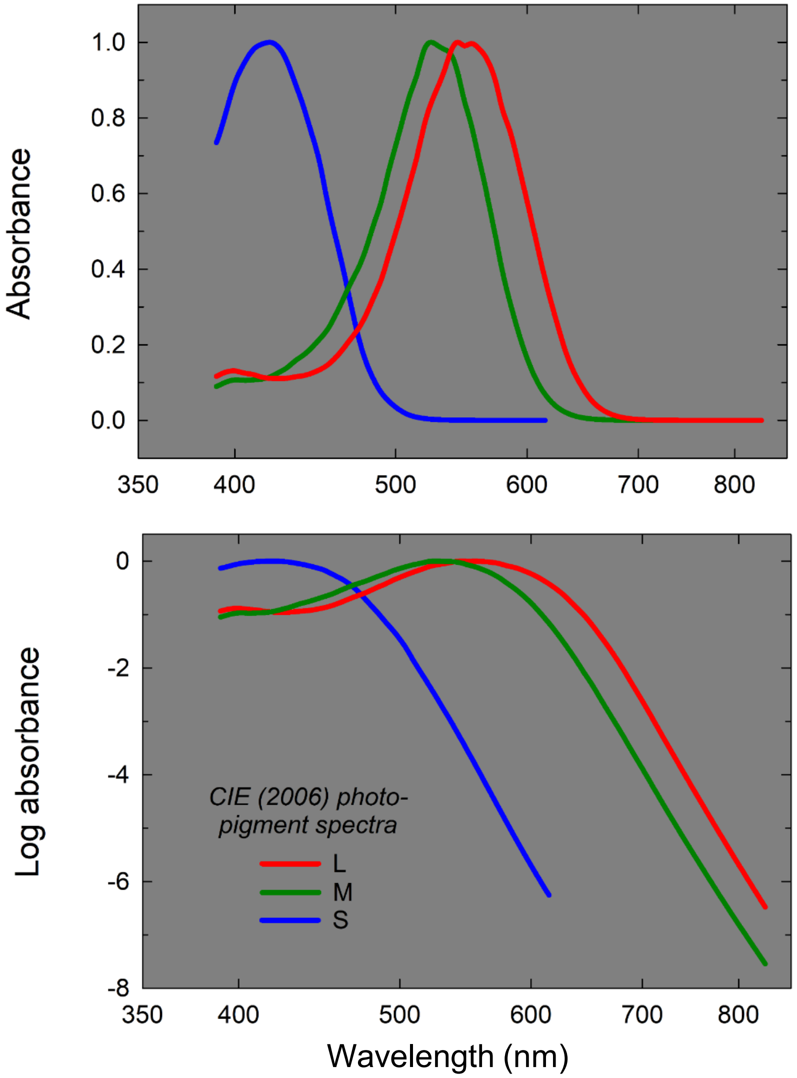
Measured with respect to light entering the cornea



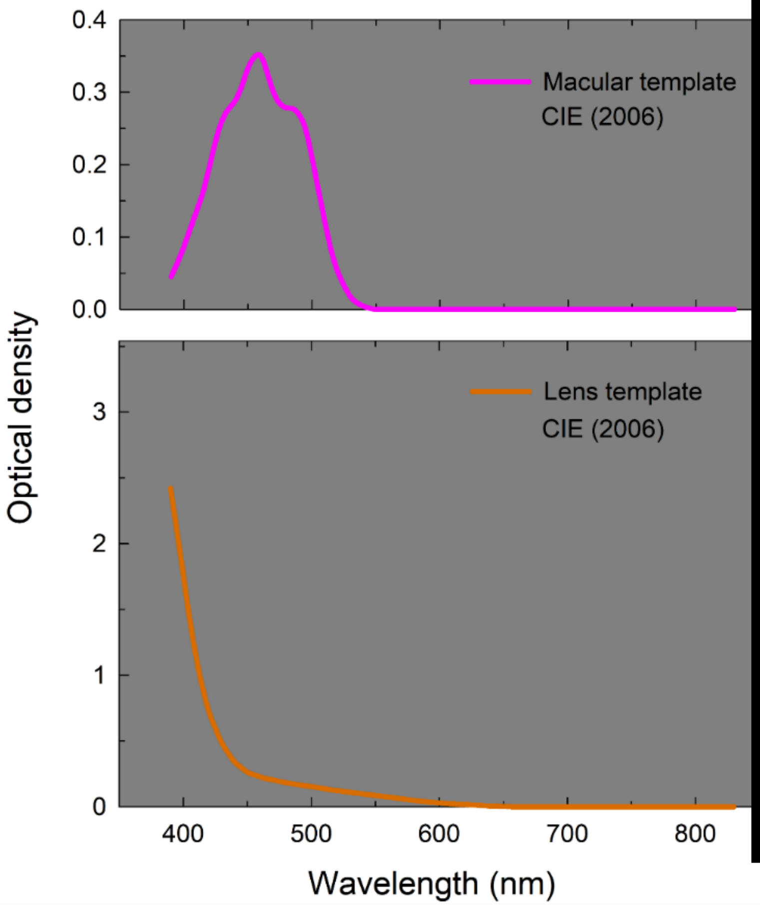


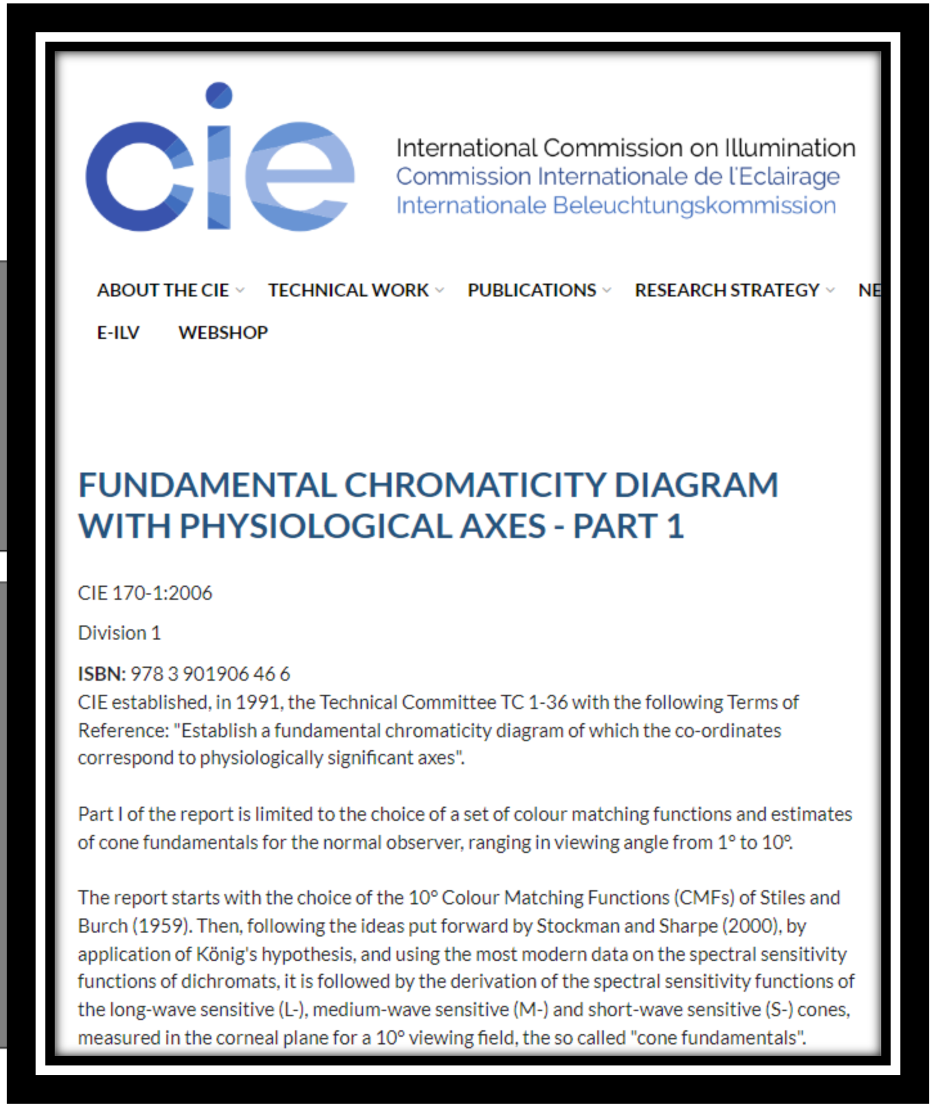
The new CIE standards also define the macular and lens pigment optical density spectra, the photopigment optical densities and the photopigment spectra.

Photopigment absorbance curves



Macular and lens pigment optical density spectra




International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

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E-ILV · WEBSHOP

FUNDAMENTAL CHROMATICITY DIAGRAM WITH PHYSIOLOGICAL AXES - PART 1

CIE 170-1:2006

Division 1

ISBN: 978 3 901906 46 6

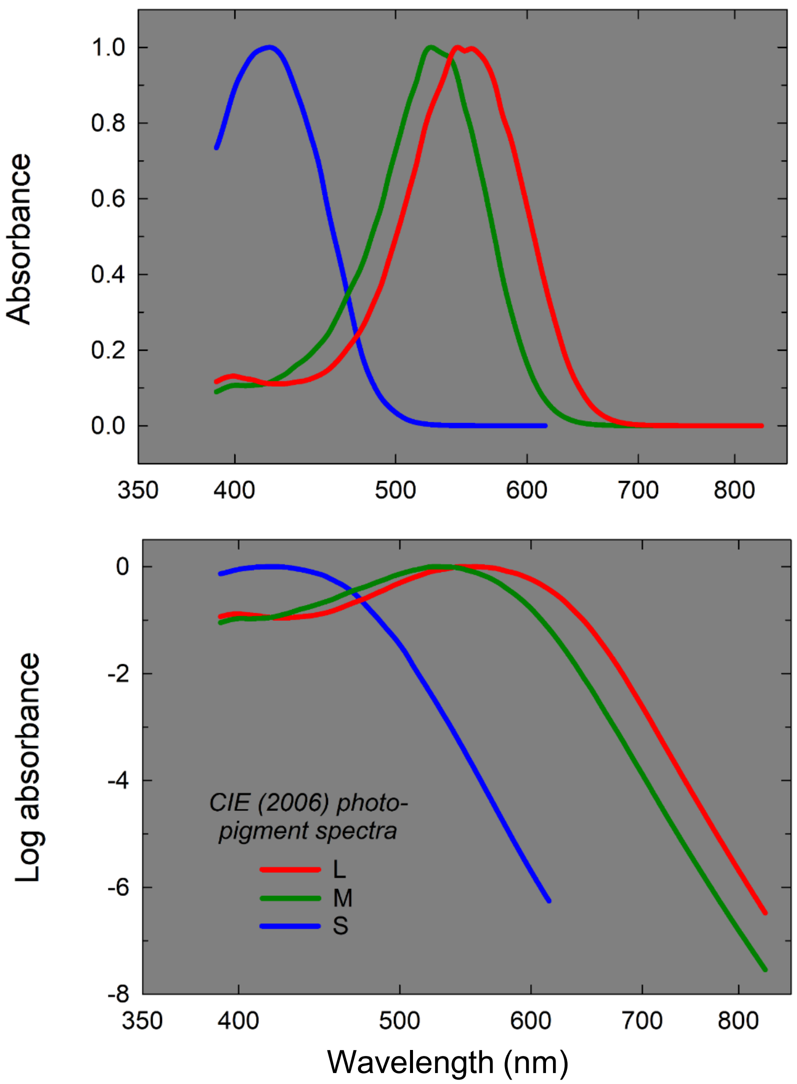
CIE established, in 1991, the Technical Committee TC 1-36 with the following Terms of Reference: "Establish a fundamental chromaticity diagram of which the co-ordinates correspond to physiologically significant axes".

Part I of the report is limited to the choice of a set of colour matching functions and estimates of cone fundamentals for the normal observer, ranging in viewing angle from 1° to 10°.

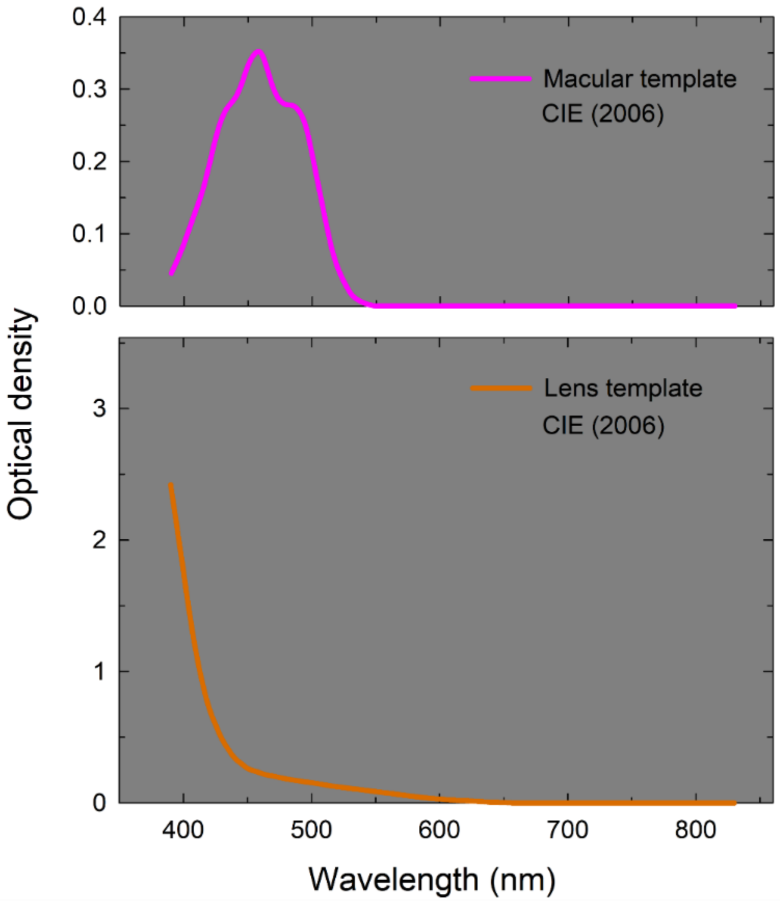
The report starts with the choice of the 10° Colour Matching Functions (CMFs) of Stiles and Burch (1959). Then, following the ideas put forward by Stockman and Sharpe (2000), by application of König's hypothesis, and using the most modern data on the spectral sensitivity functions of dichromats, it is followed by the derivation of the spectral sensitivity functions of the long-wave sensitive (L-), medium-wave sensitive (M-) and short-wave sensitive (S-) cones, measured in the corneal plane for a 10° viewing field, the so called "cone fundamentals".

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

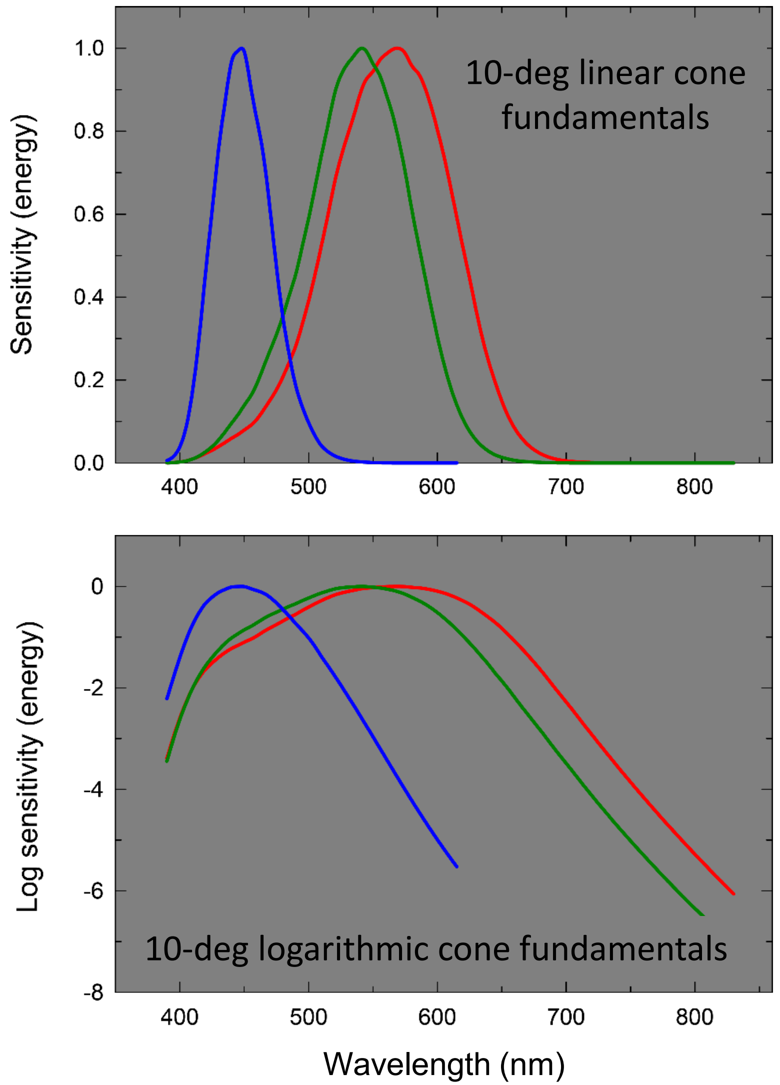
Photopigment absorbance curves



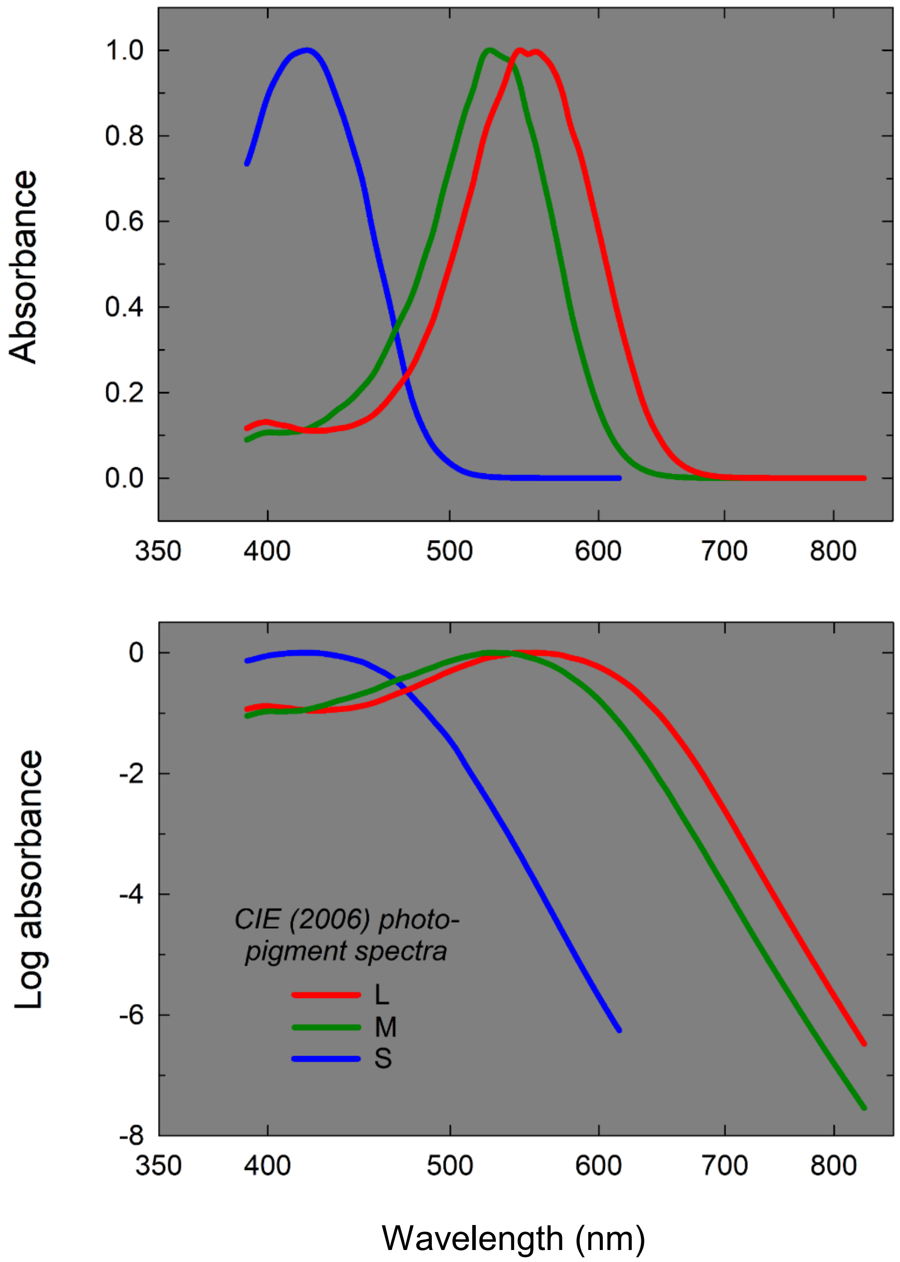
Macular and lens pigment optical density spectra

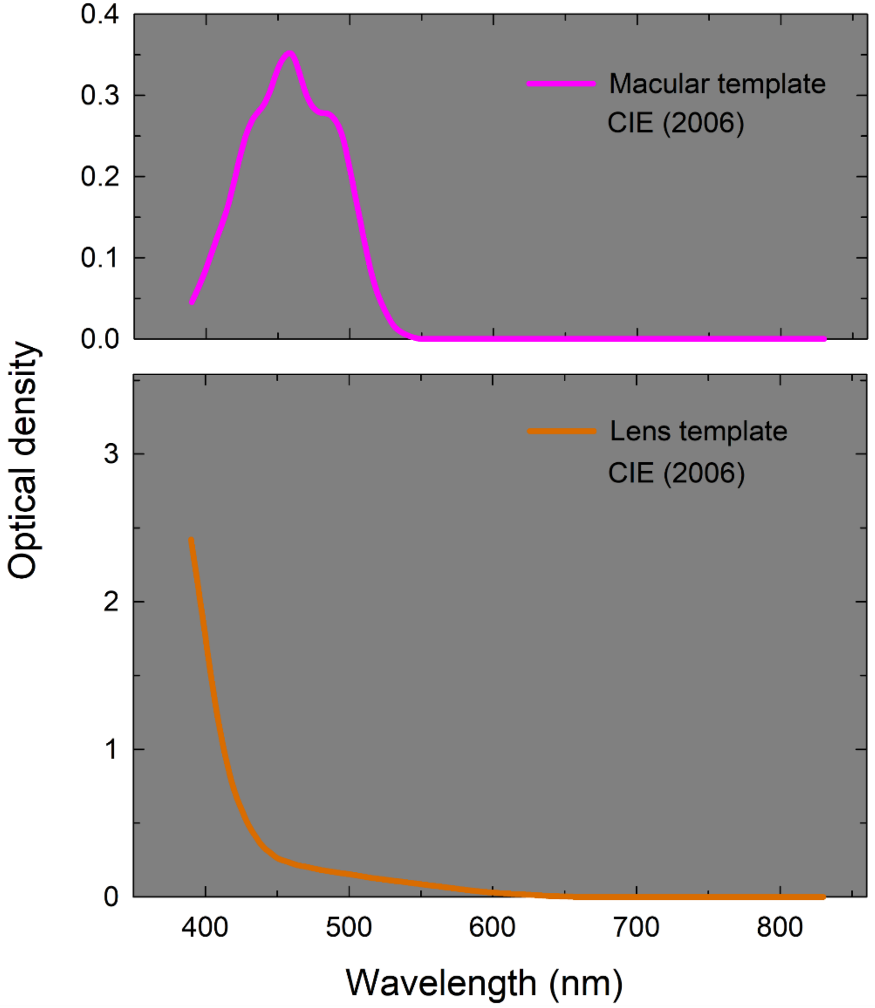


Corneal spectral sensitivities

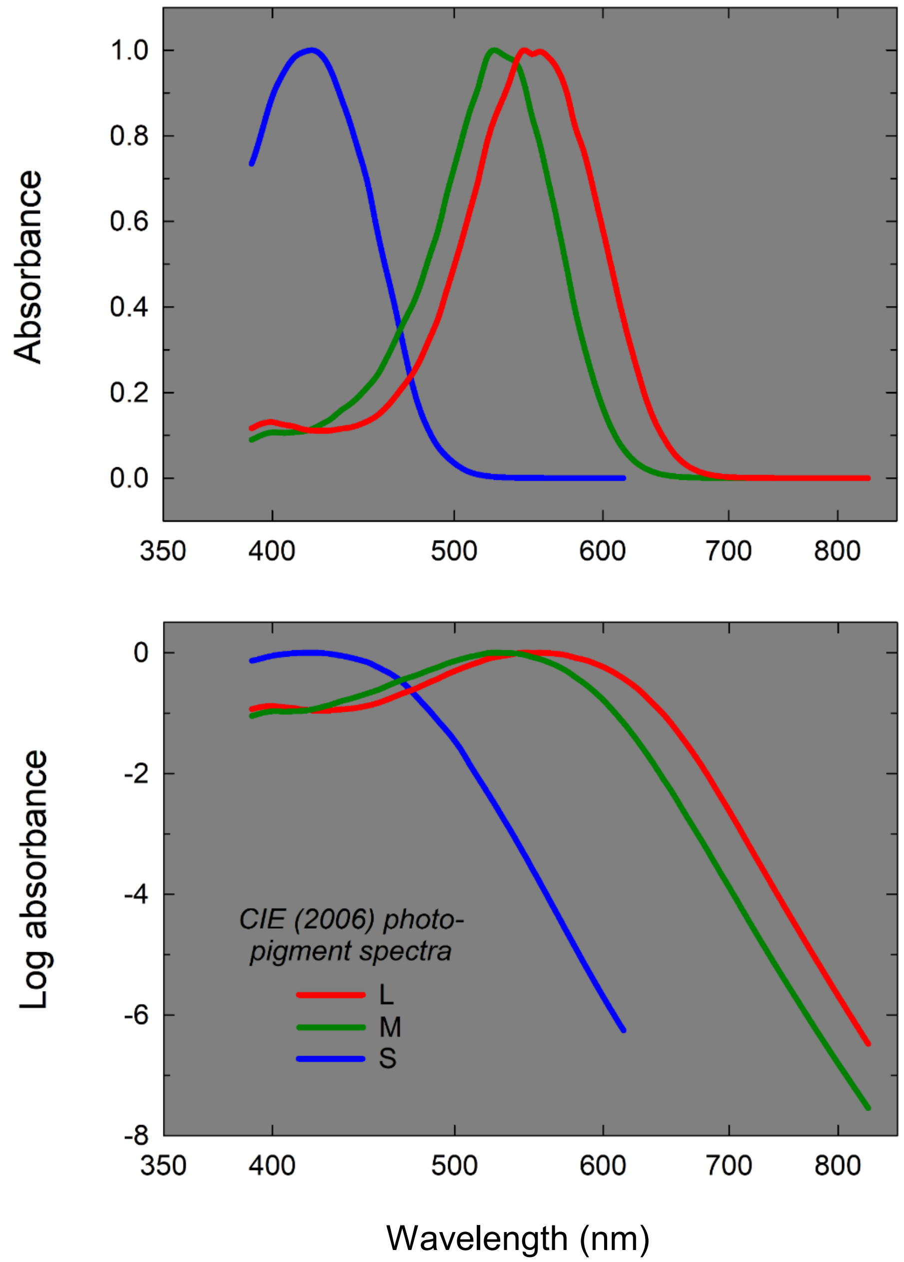


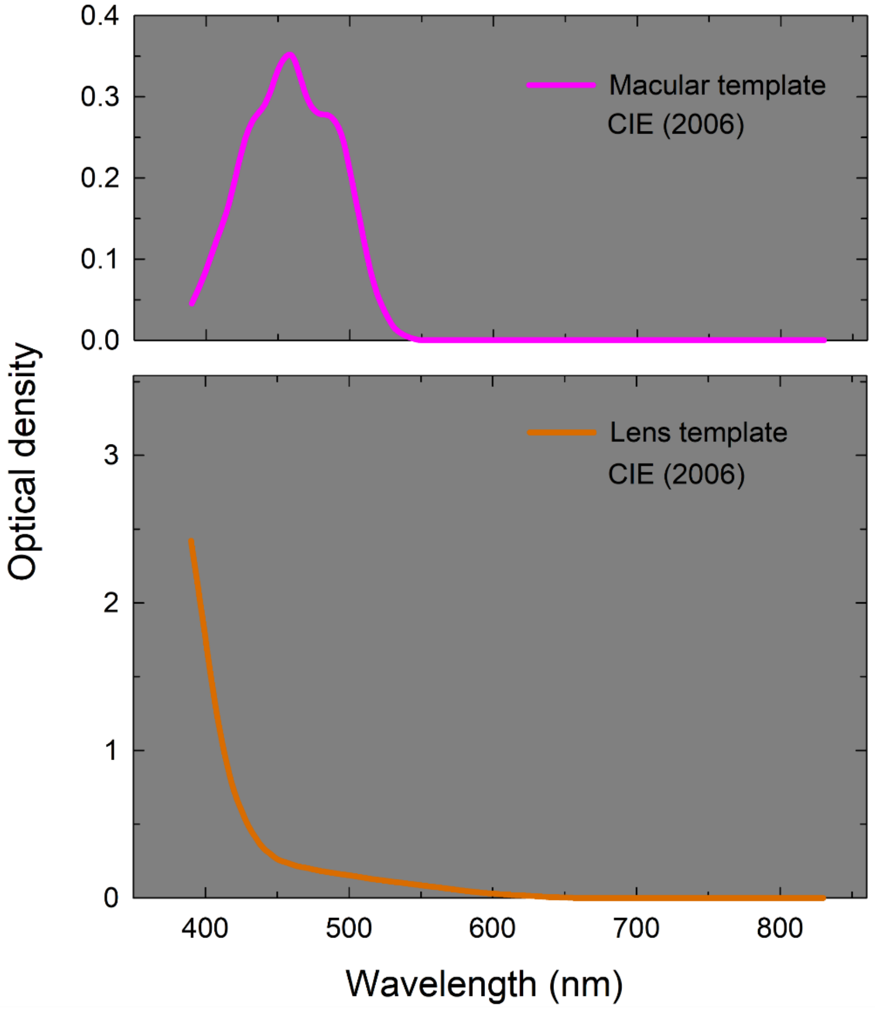
Unfortunately, the CIE (2006) LMS standards are defined as discrete values at 5 or 1 nm steps rather than as continuous functions of wavelength.



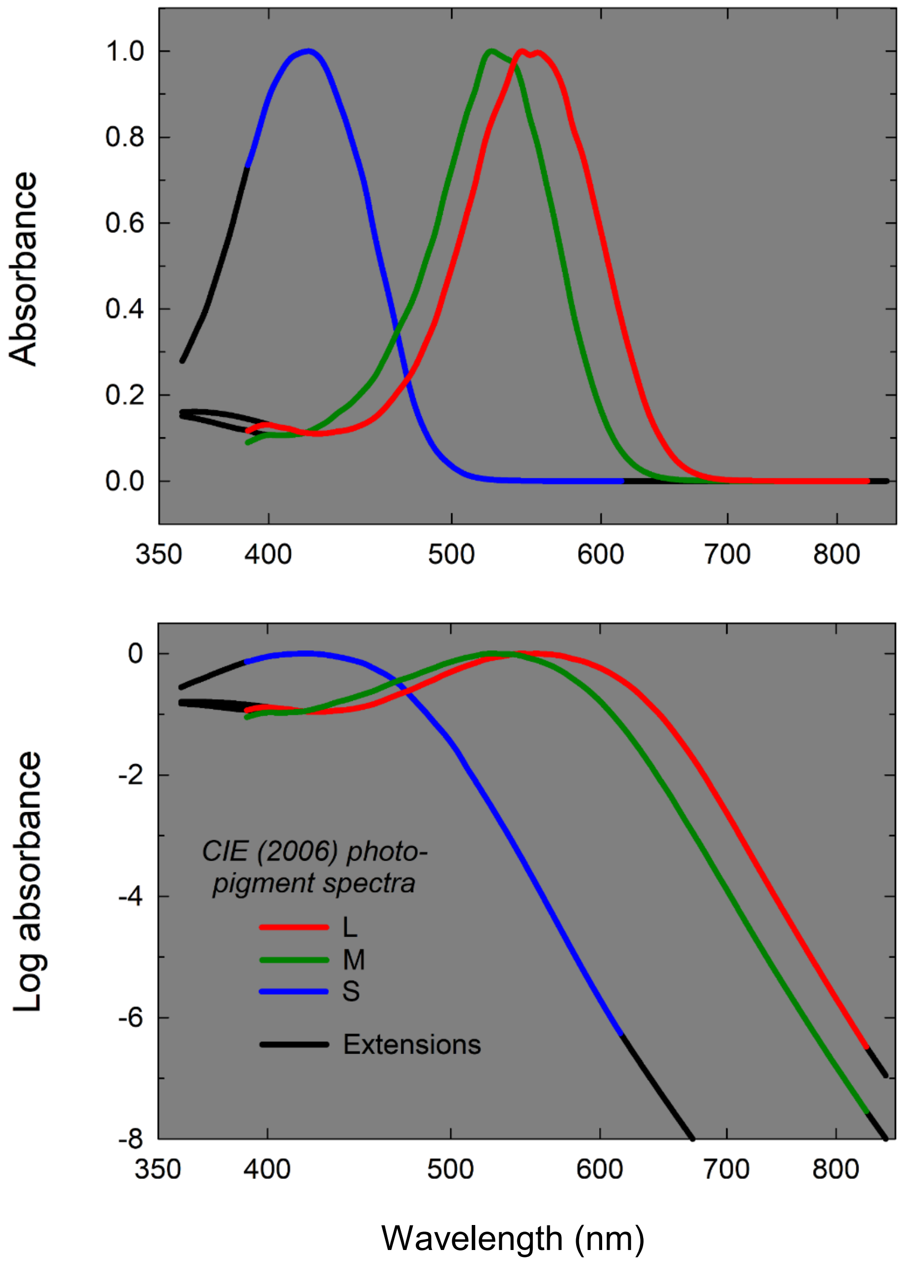


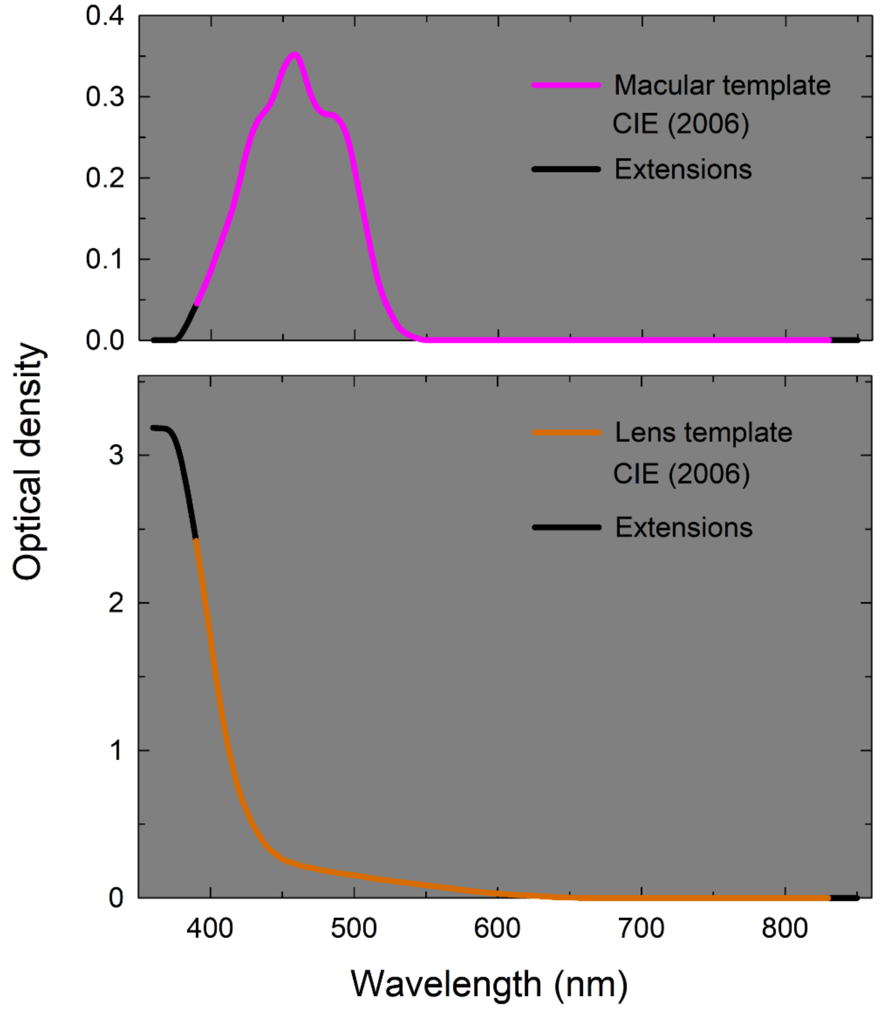
For computational convenience, we want to define these as continuous functions of wavelength…





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:

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

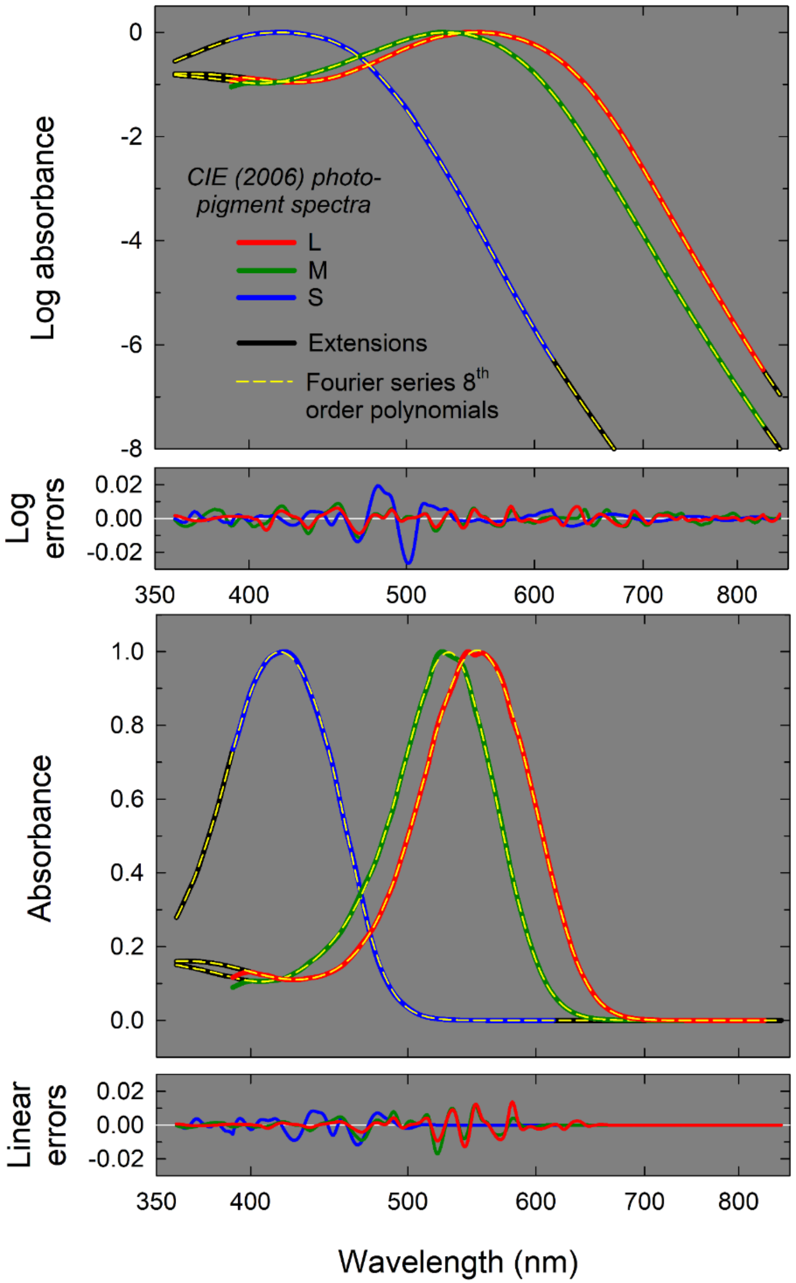
$$\theta = \pi \frac{\log_{10}(\lambda/360)}{\log_{10}(850/360)}$$

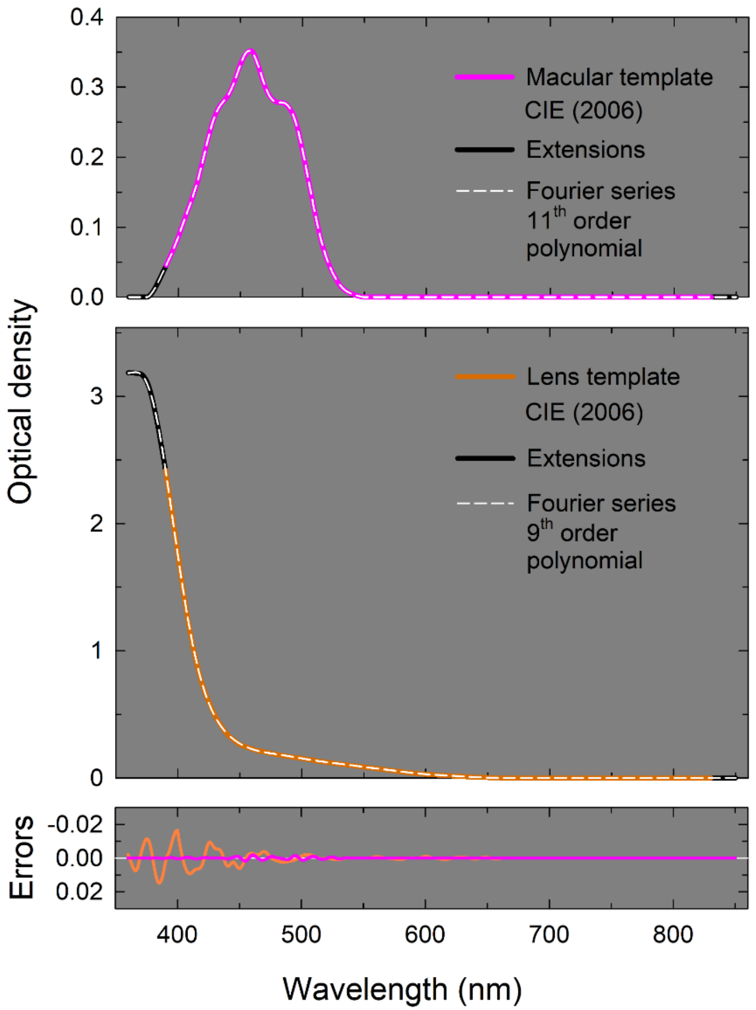
n is the number of harmonics.

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

No theoretical basis or significance to any individual parameter, just a template.

Important that they describe both log and linear absorbances





For (even) more details…

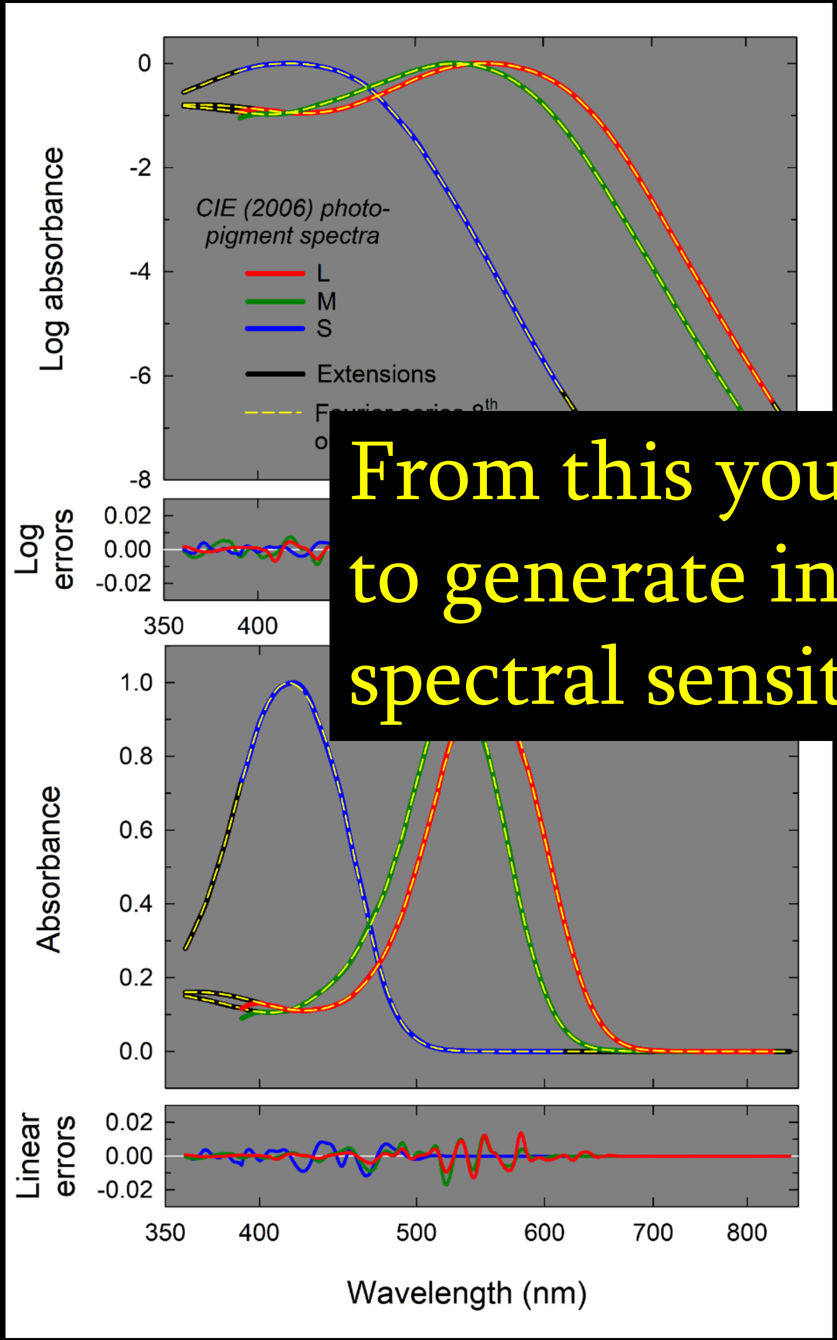
COLOR
RESEARCH AND APPLICATION

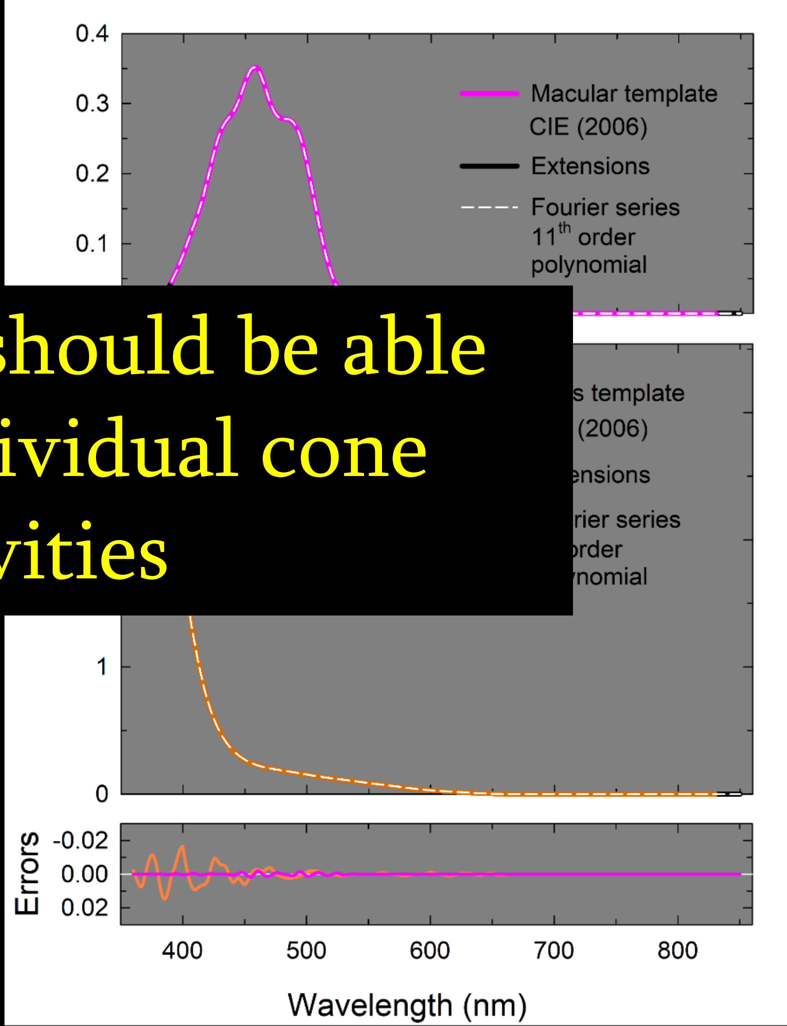
RESEARCH ARTICLE | Open Access

Formulae for generating standard and individual human cone spectral sensitivities

Andrew Stockman, Andrew T. Rider

First published: 19 July 2023 | https://doi.org/10.1002/col.22879



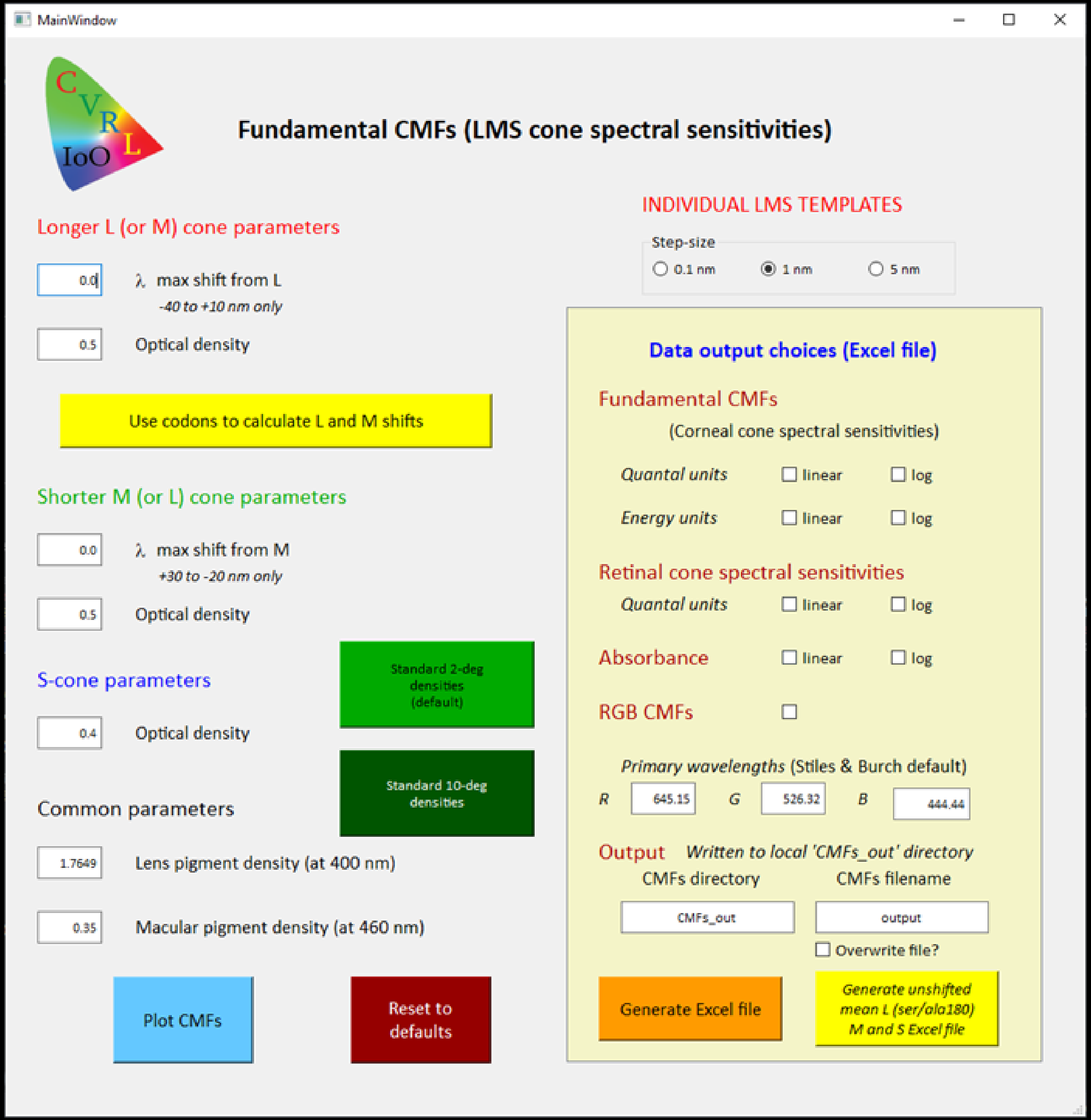


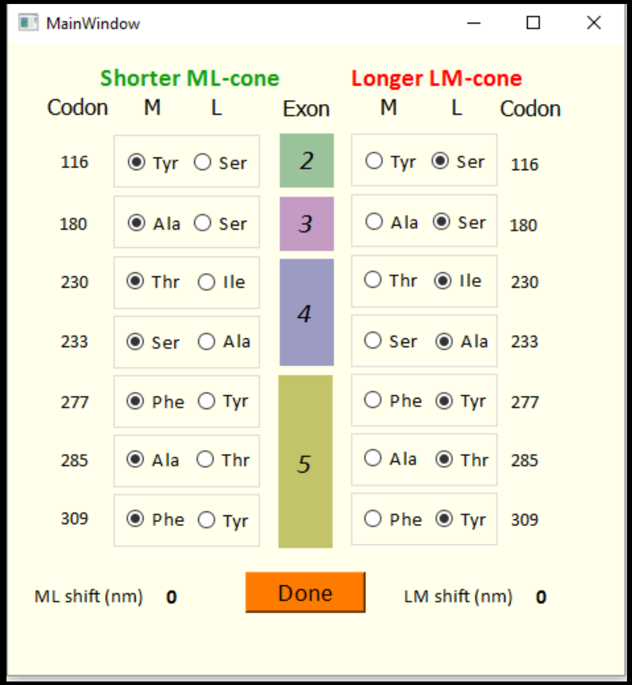
From this you should be able to generate individual cone spectral sensitivities

Stockman and Rider, 2023.
Color Research and Application

Individual difference parameters

1. Scalar for lens density
2. Scalar for macular density
3. L-cone optical density
4. M-cone optical density
5. S-cone optical density
6. L-cone spectral shift
7. M-cone spectral shift





Stockman & Rider (2023) *Color Research and Application*.

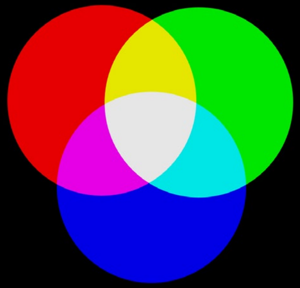
Python program is available on Github at:

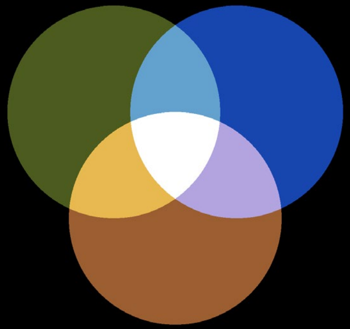
https://github.com/CVRL-IoO/Individual-CMFs.git

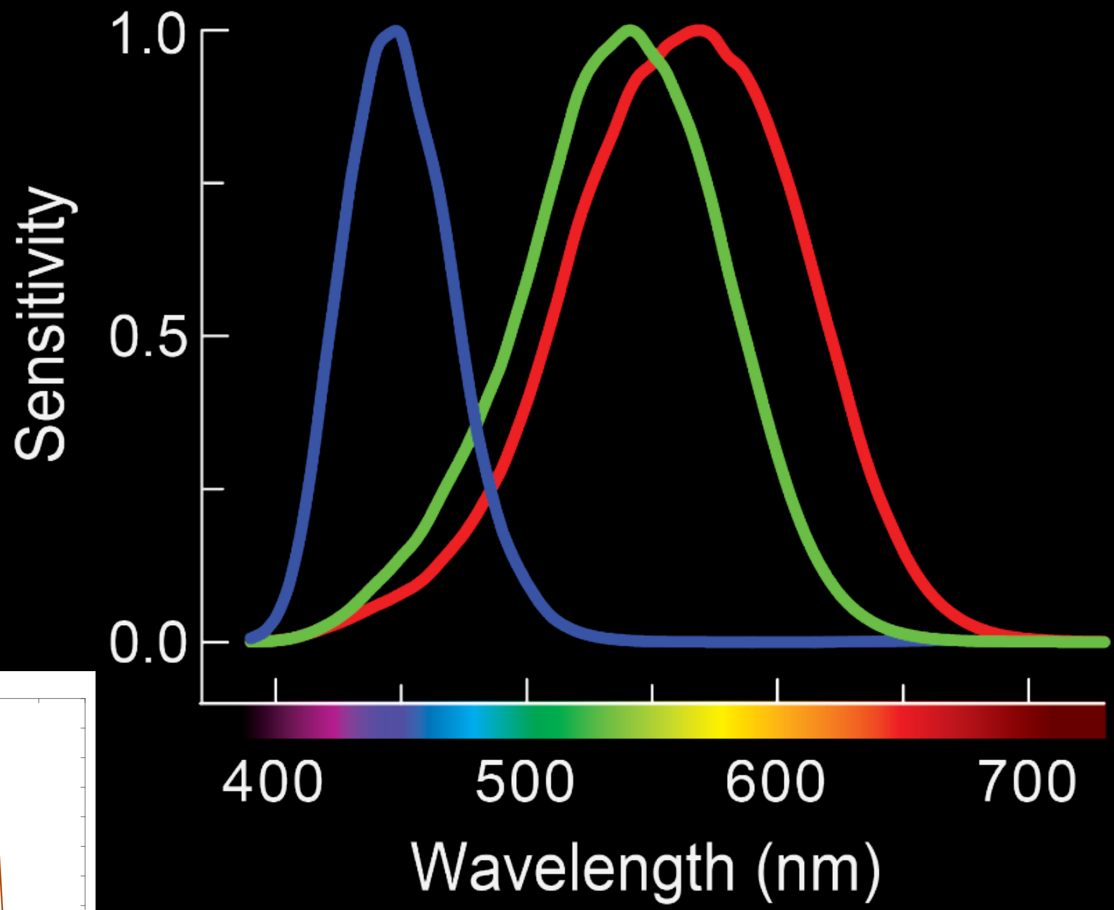
ESTIMATING INDIVIDUAL DIFFERENCES

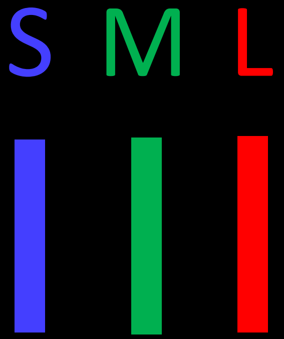
With individual cone fundamentals we can predict colour matches:

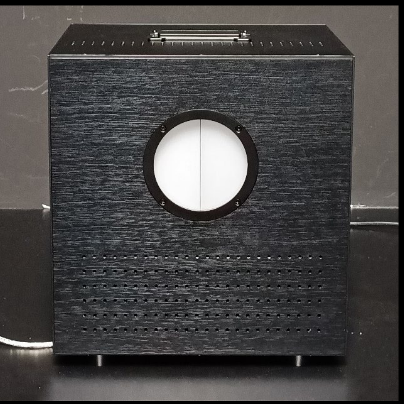
Or vice versa…

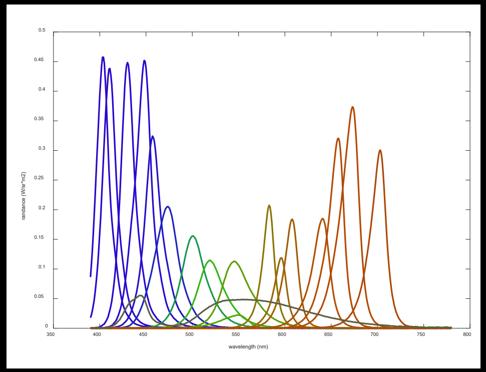




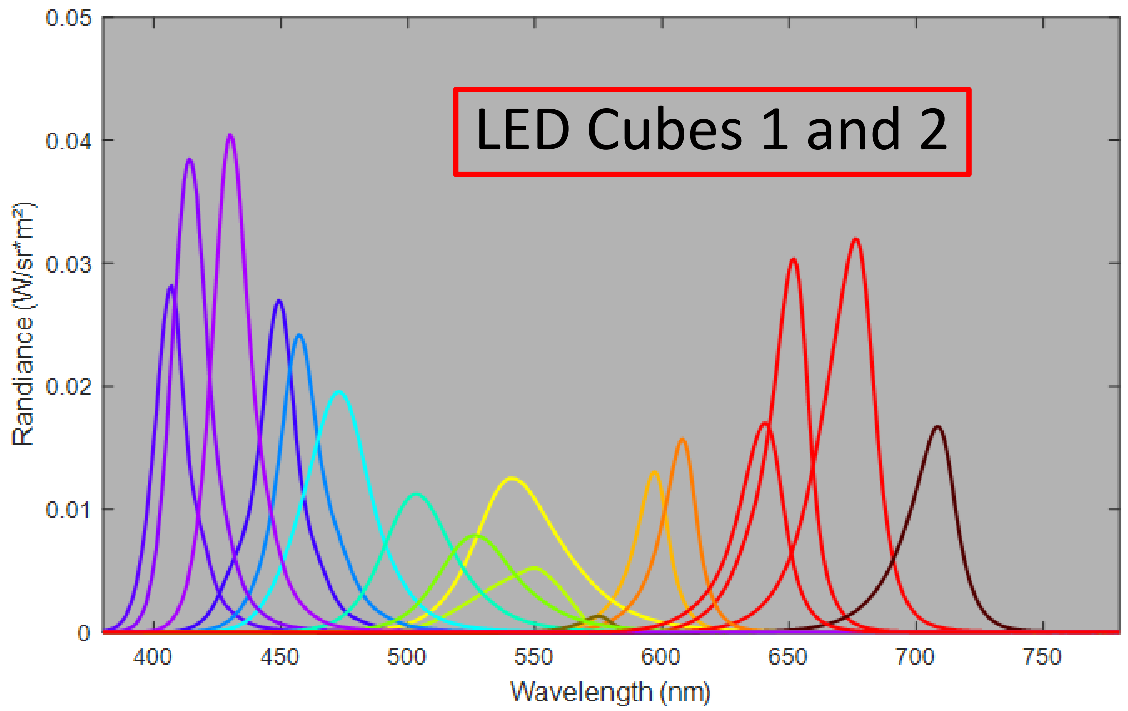


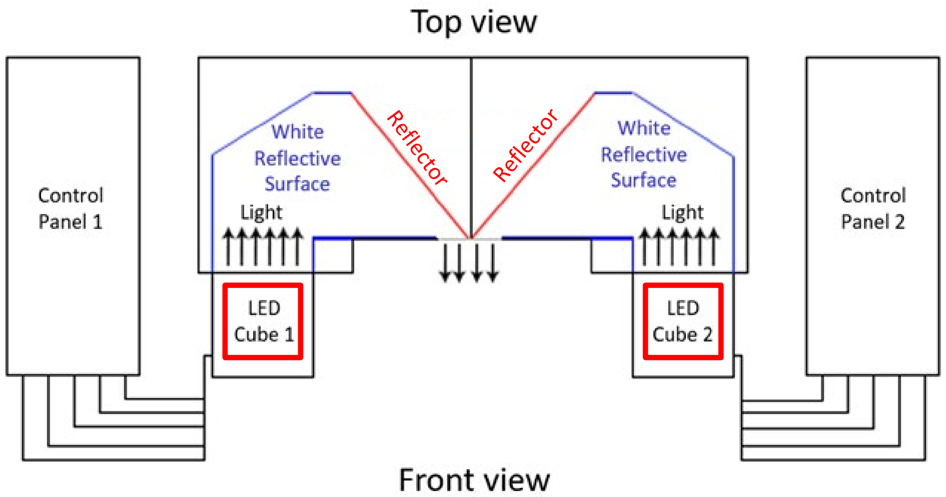


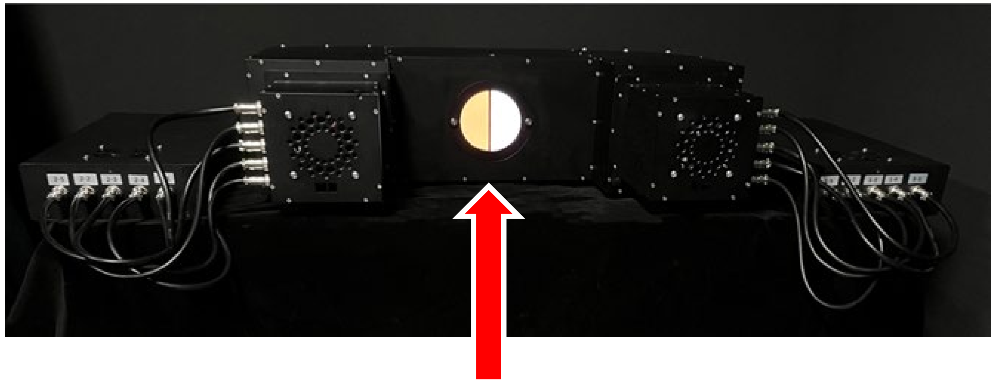




Trichromator (LEDMax) developed by Thouslite

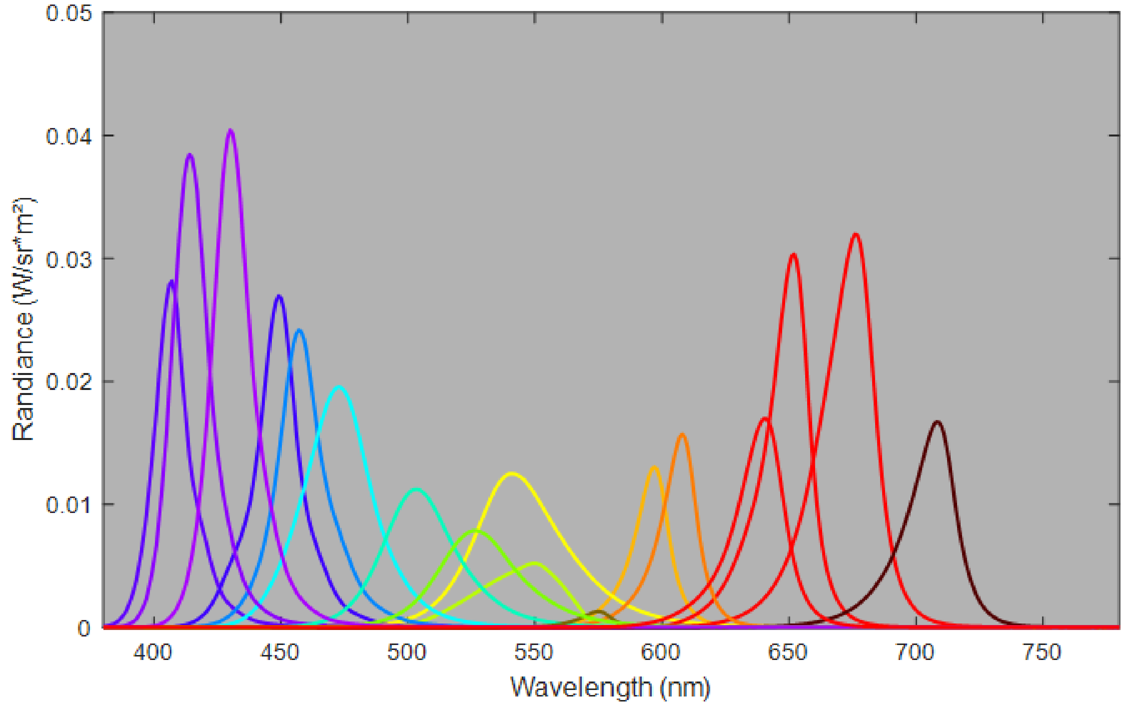


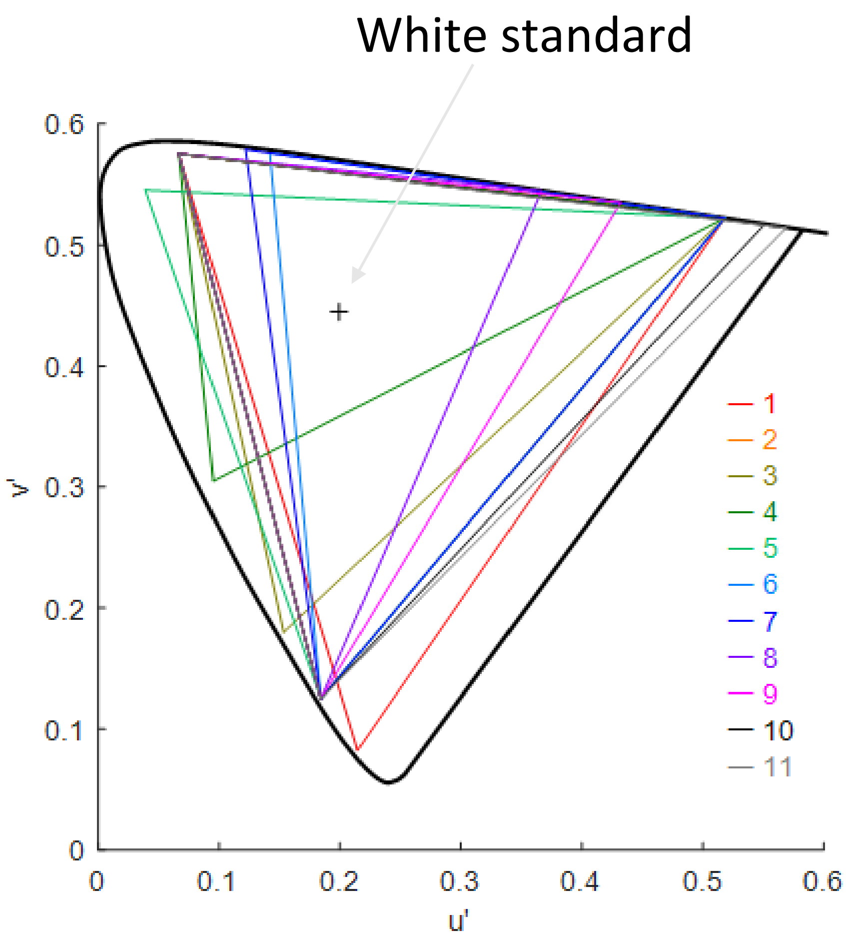




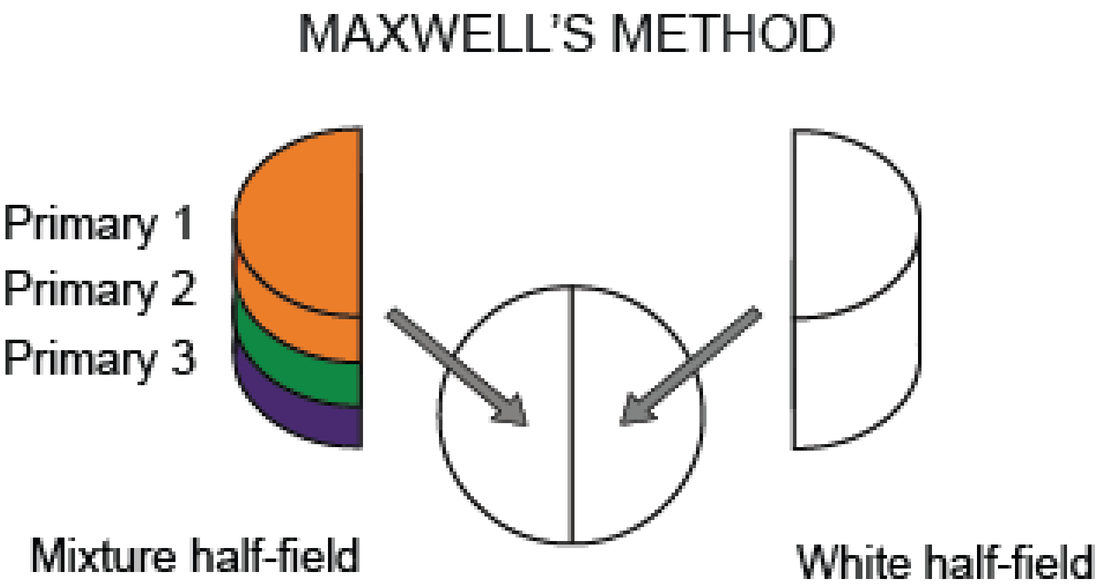
Subject view

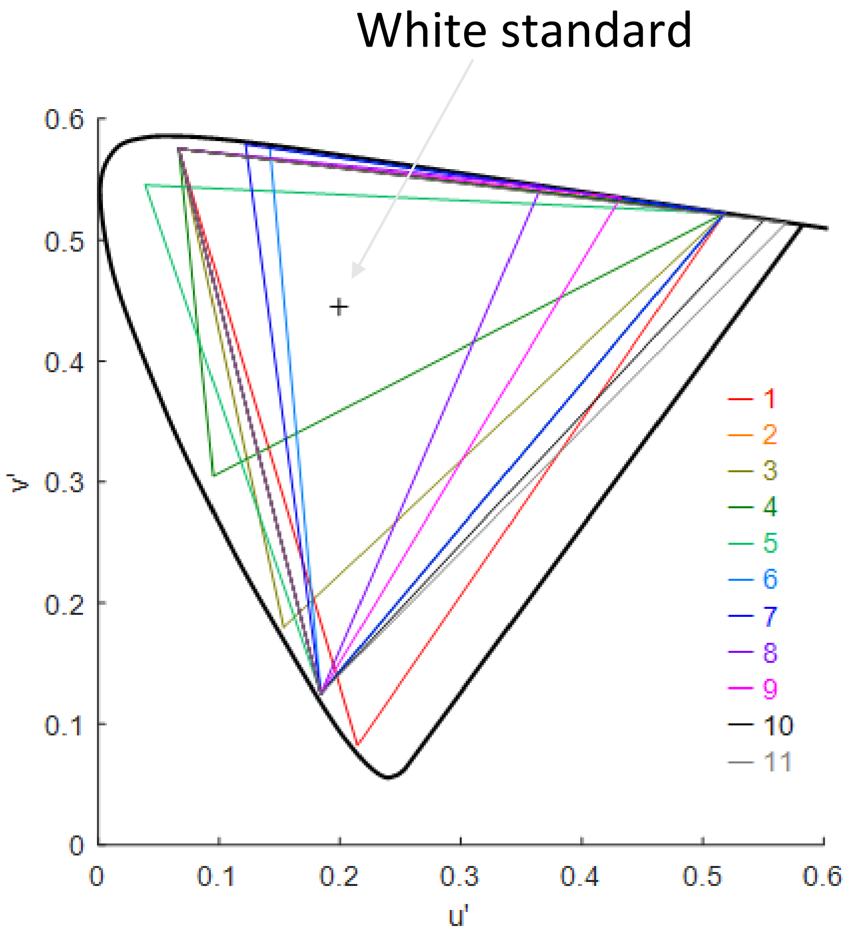
Collaborative work with Ronnier Luo's lab with Lucas Shi and Alan Song and Andrew Stockman





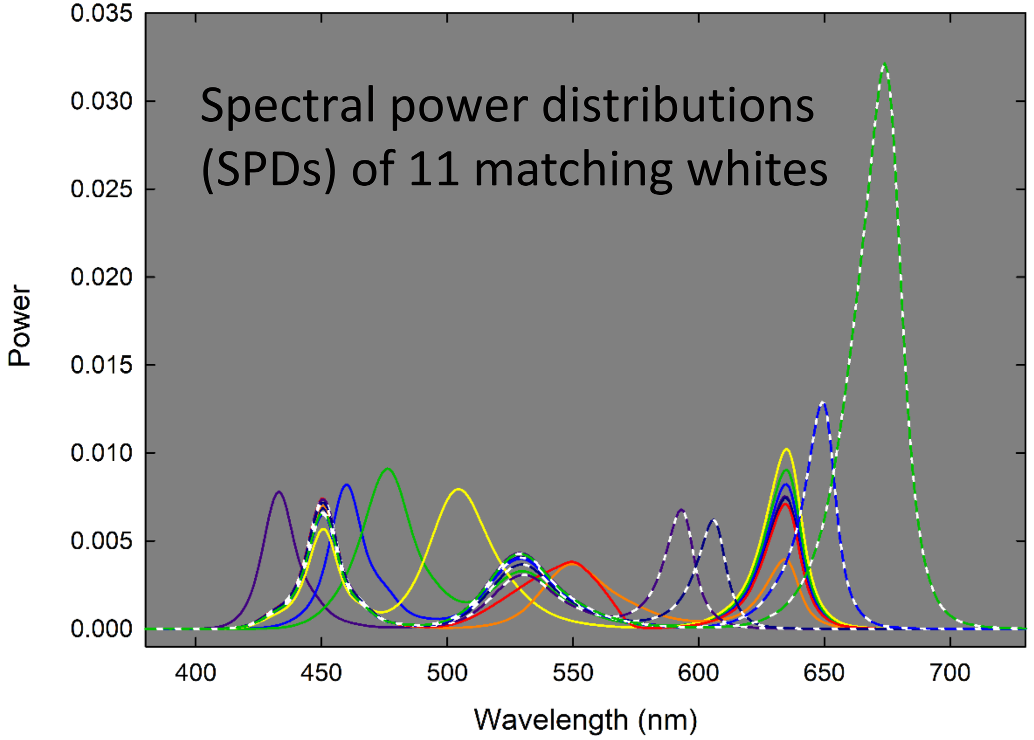
We chose 11 triplets of LEDs (primaries lights) that can be optically mixed to match a white standard (+)…

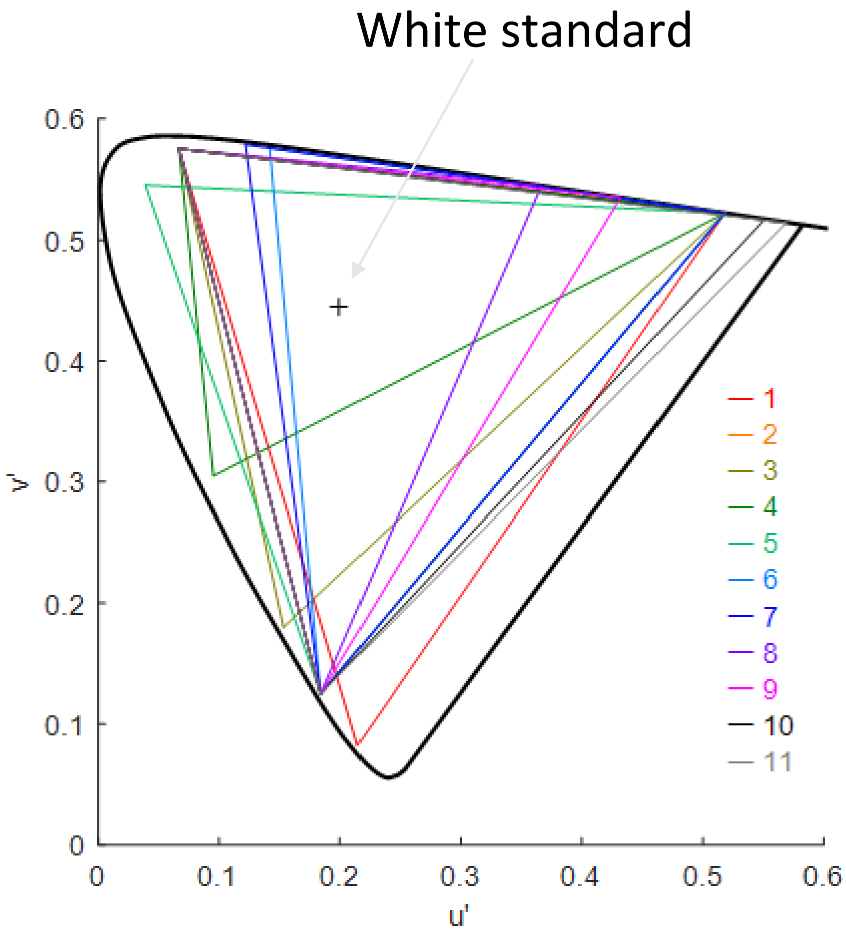




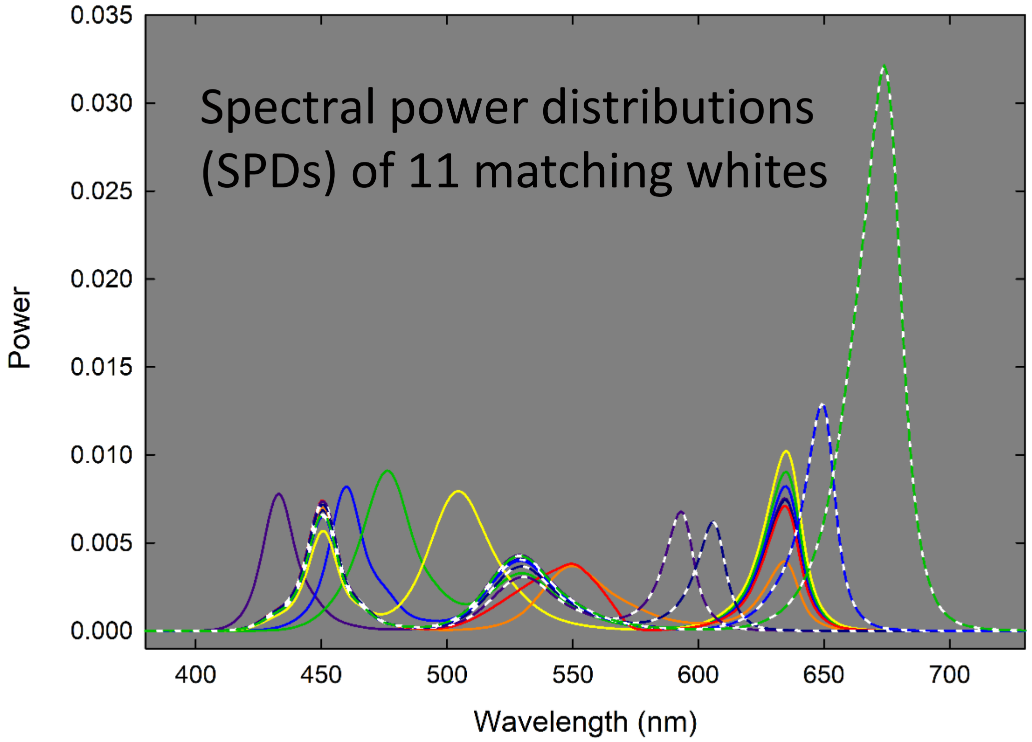
We then asked observers to adjust the intensities of each of the 11 triplets of primaries to match the white standard…

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





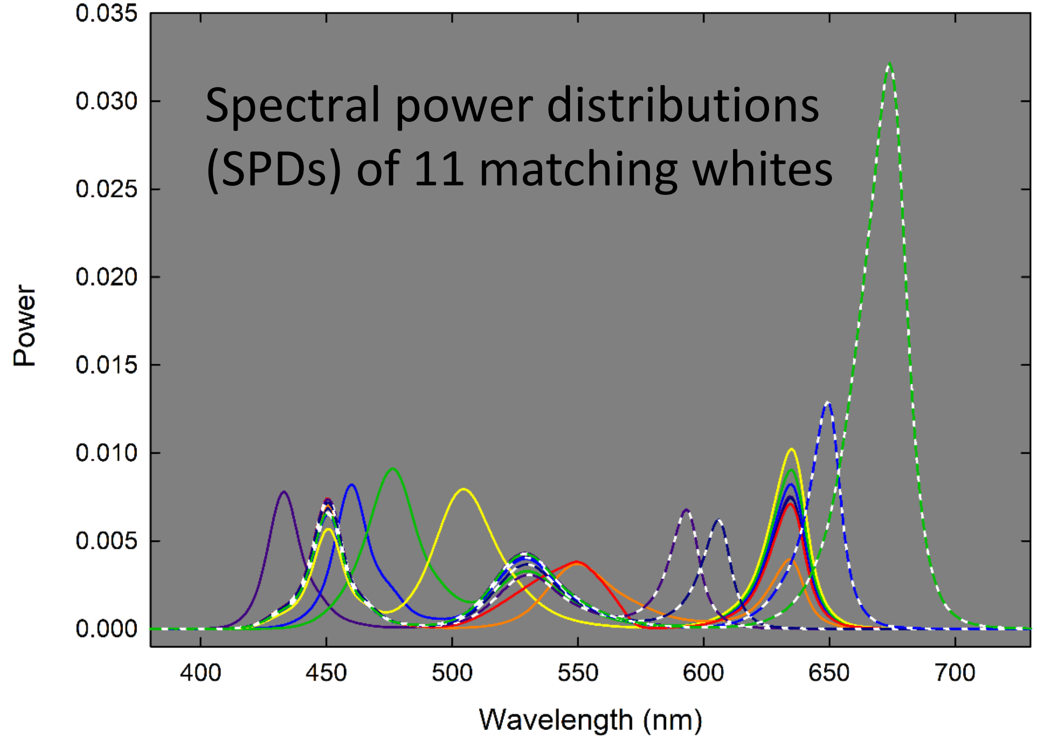
We then asked observers to adjust the intensities of each of the 11 triplets of primaries to match the white standard…



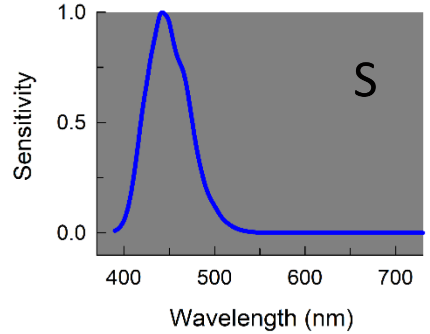
These 11 matching whites should all produce identical L-, M- and S-cone excitations.

So…

Cross-multiply and integrate



X



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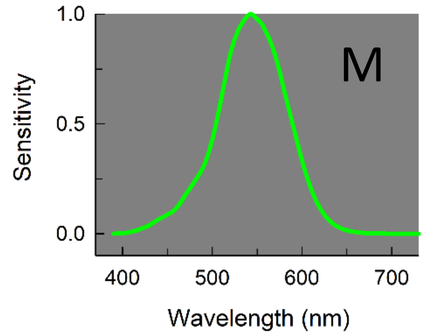
All 11 should produce the same S-cone excitation

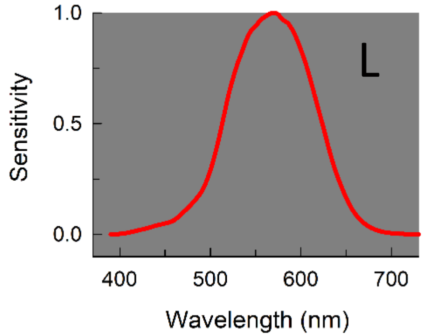
X



=

All 11 should produce the same M-cone excitation

X



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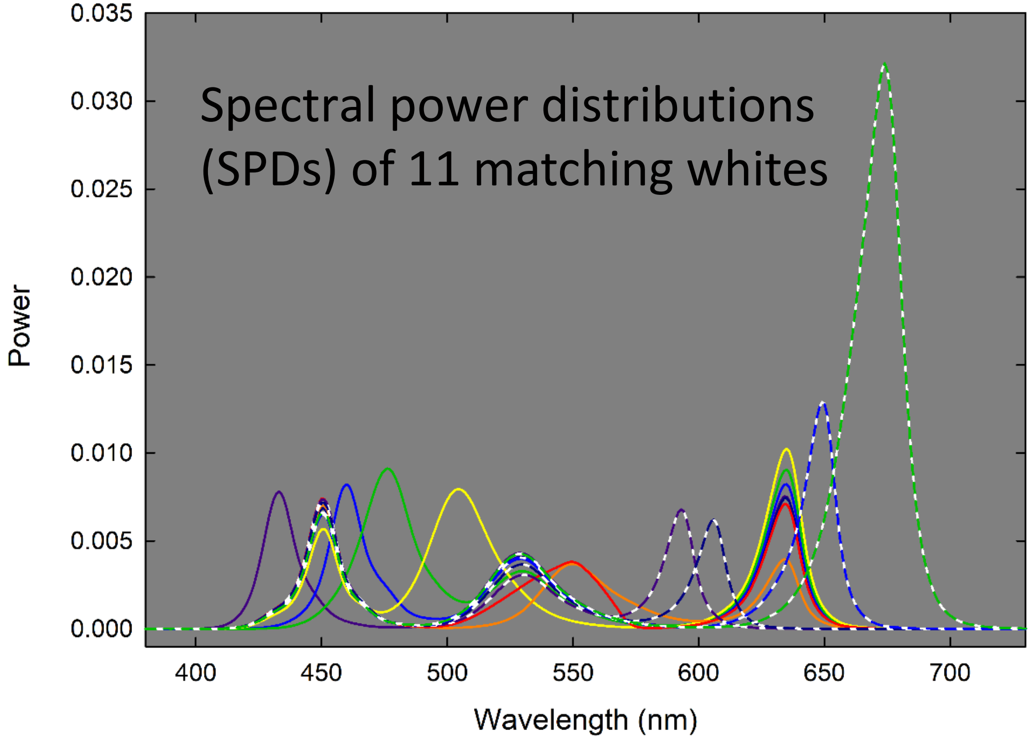
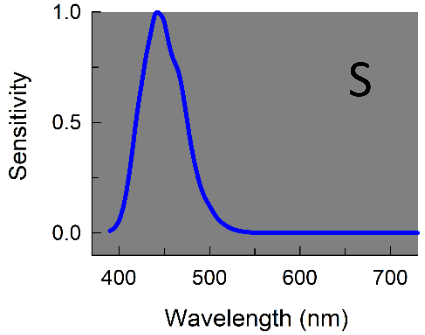
All 11 should produce the same L-cone excitation

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



X



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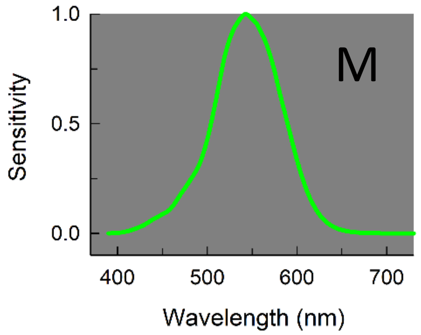
All 11 should produce the same S-cone excitation

X



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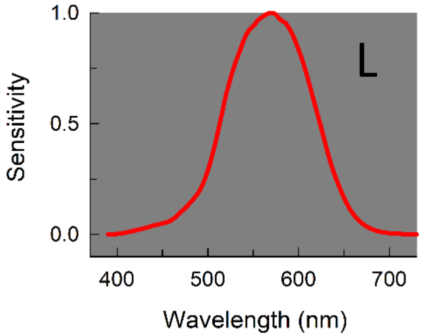
All 11 should produce the same M-cone excitation

X



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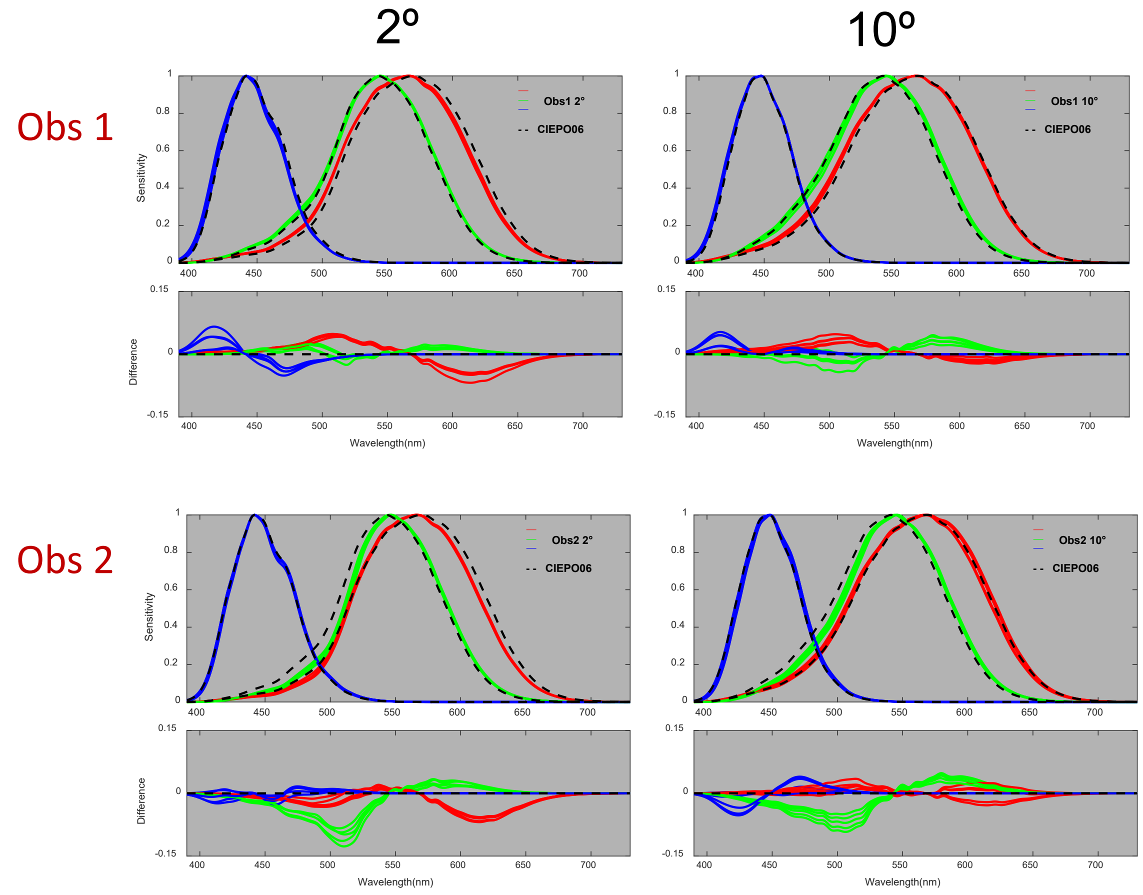
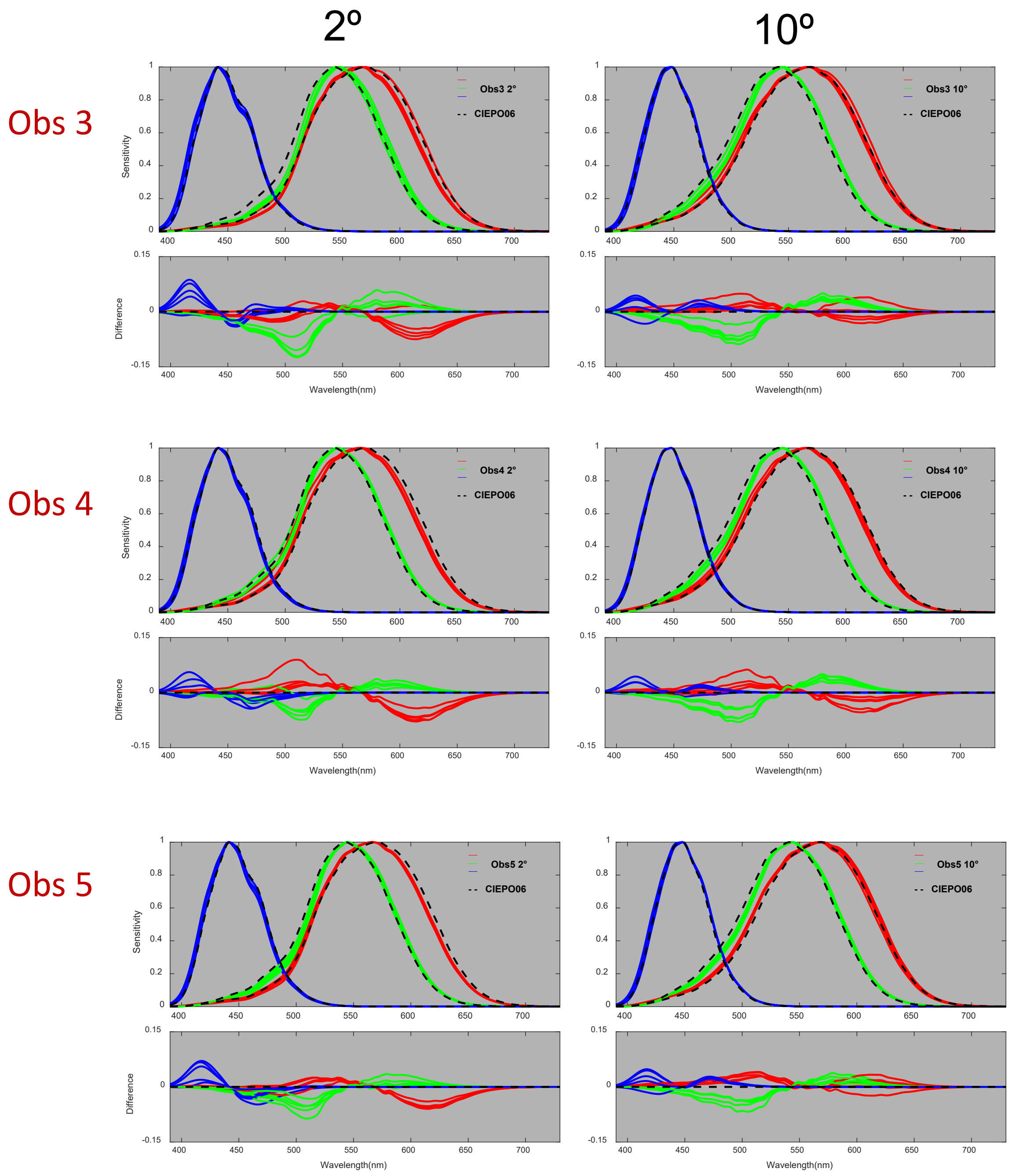
All 11 should produce the same L-cone excitation

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



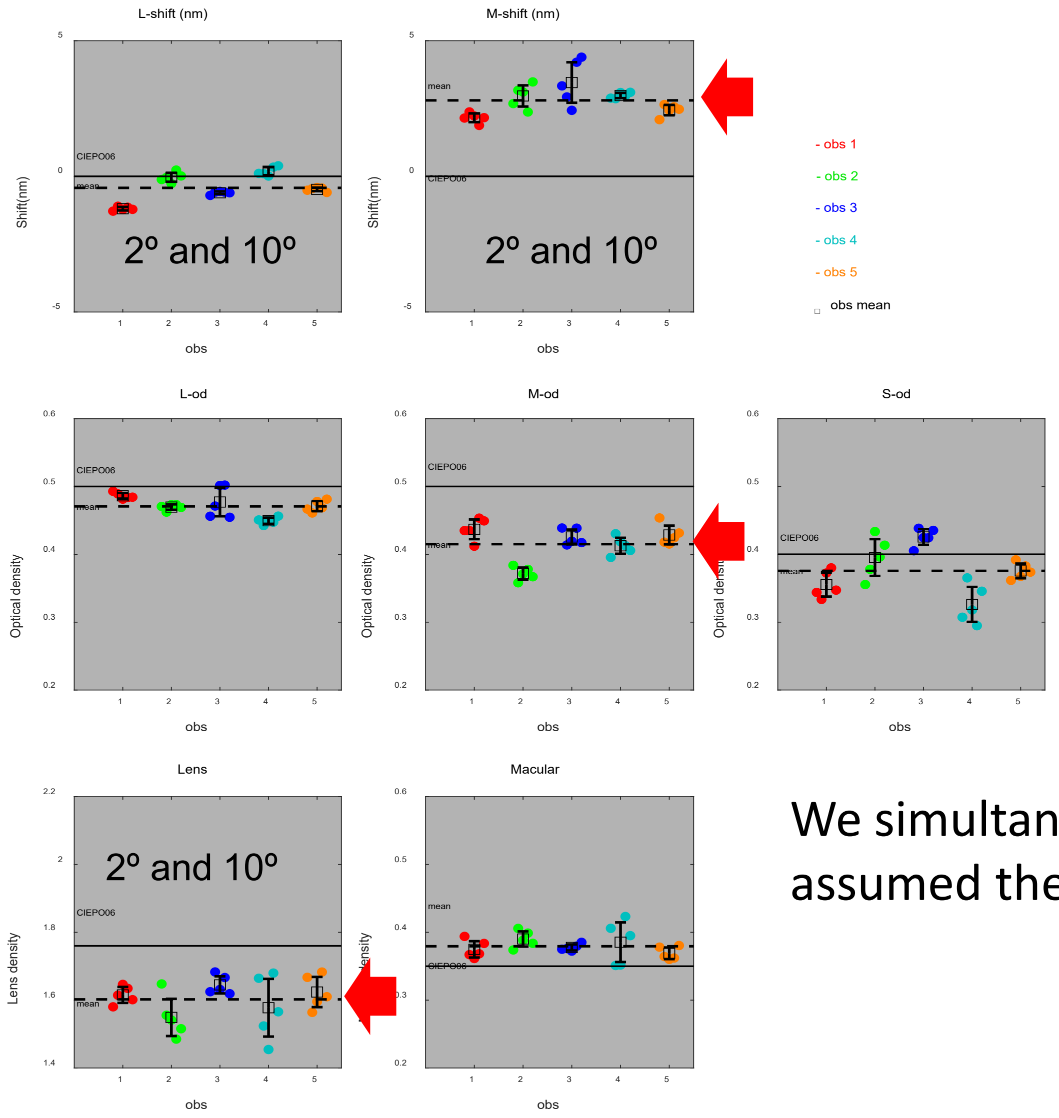


Here are the cone fundamentals that best predict the colour matches measured and estimated five times in five subjects.

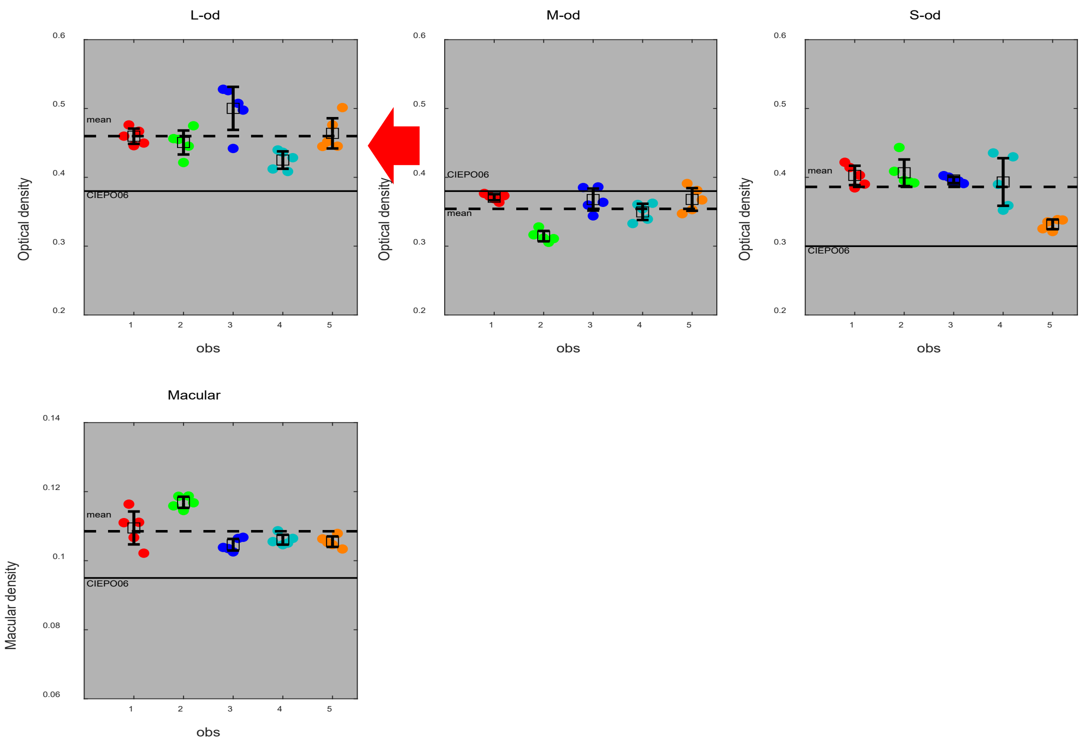
The CIEPO06 curves are the CIE standard LMS functions

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°.

For more details…

COLOR
RESEARCH AND APPLICATION

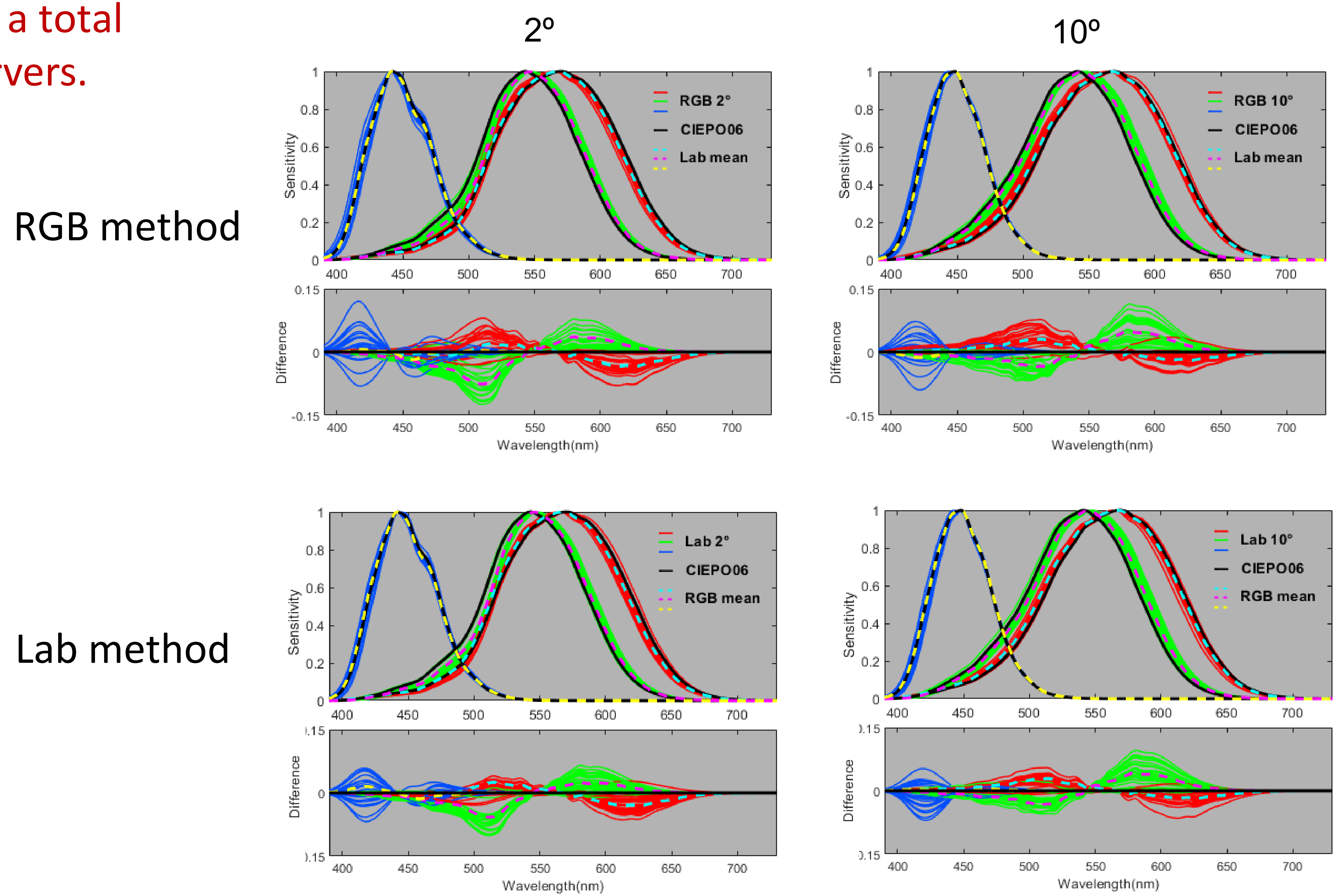
RESEARCH ARTICLE | Open Access

A multi-primary trichromator to derive individual color matching functions and cone spectral sensitivities

Keyu Shi, Ming Ronnier Luo, Andrew T. Rider, Tingwei Huang, Lihao Xu, Andrew Stockman

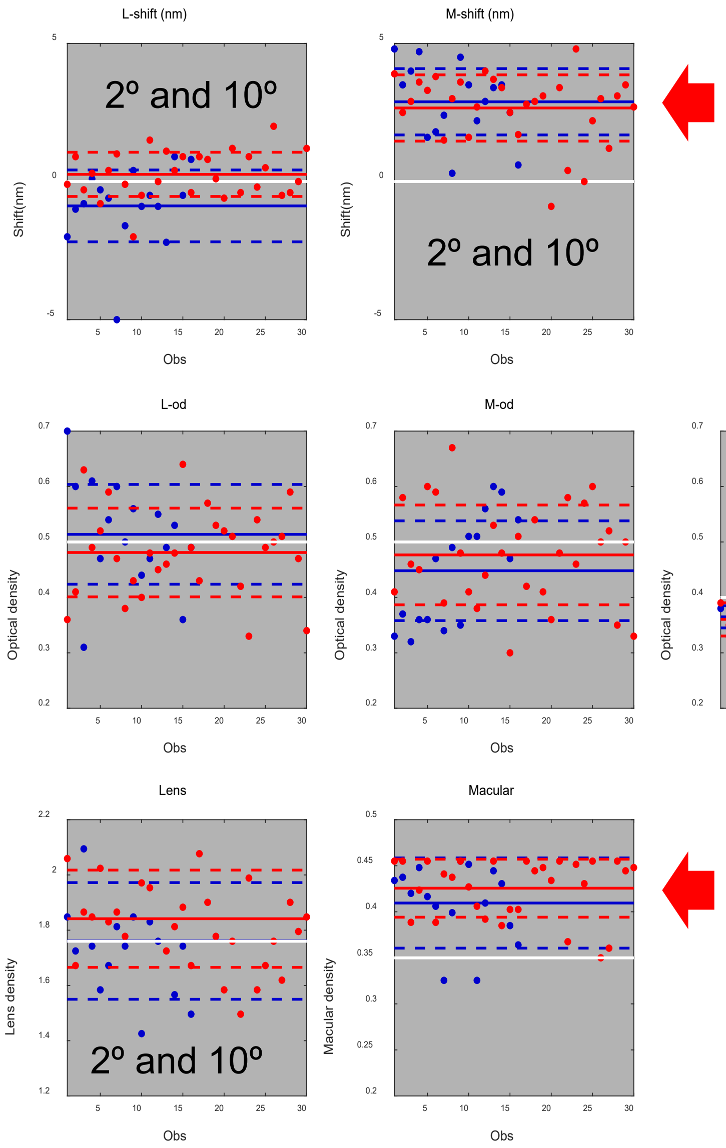
First published: 29 March 2024 | https://doi.org/10.1002/col.22928

Now measured in a total of 51 young observers.

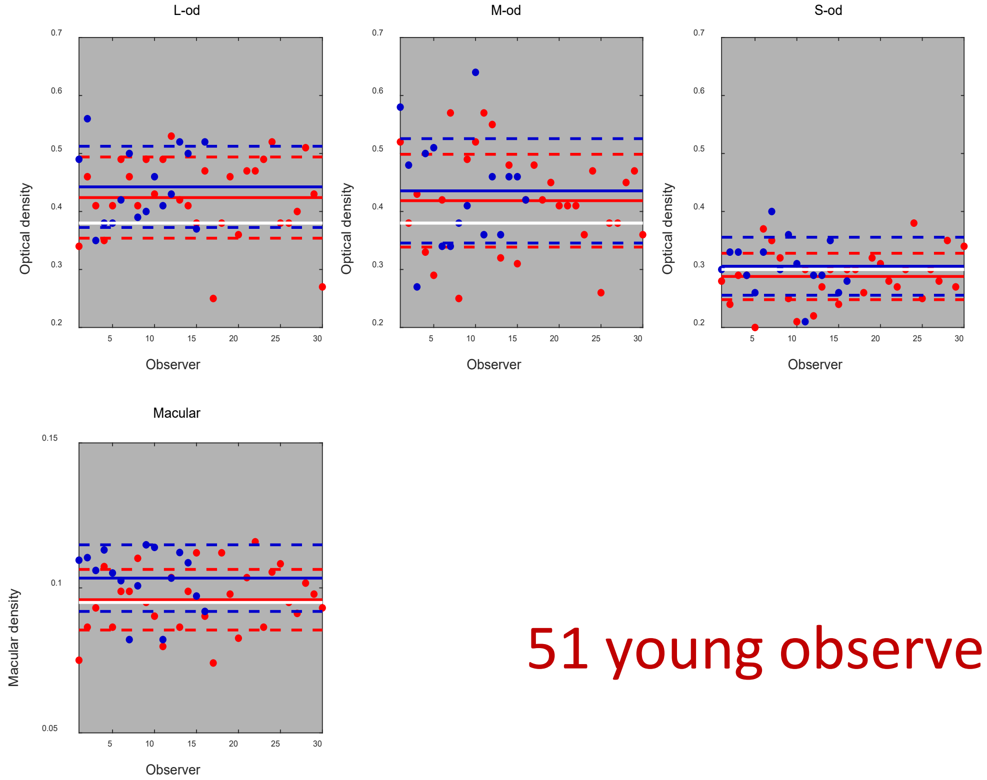


Fitted parameters

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.

For more details…

Research Article Vol. 32, No. 13 / 17 Jun 2024 / *Optics Express* 23597

Optics EXPRESS

Individual differences in color matches and cone spectral sensitivities in 51 young adults

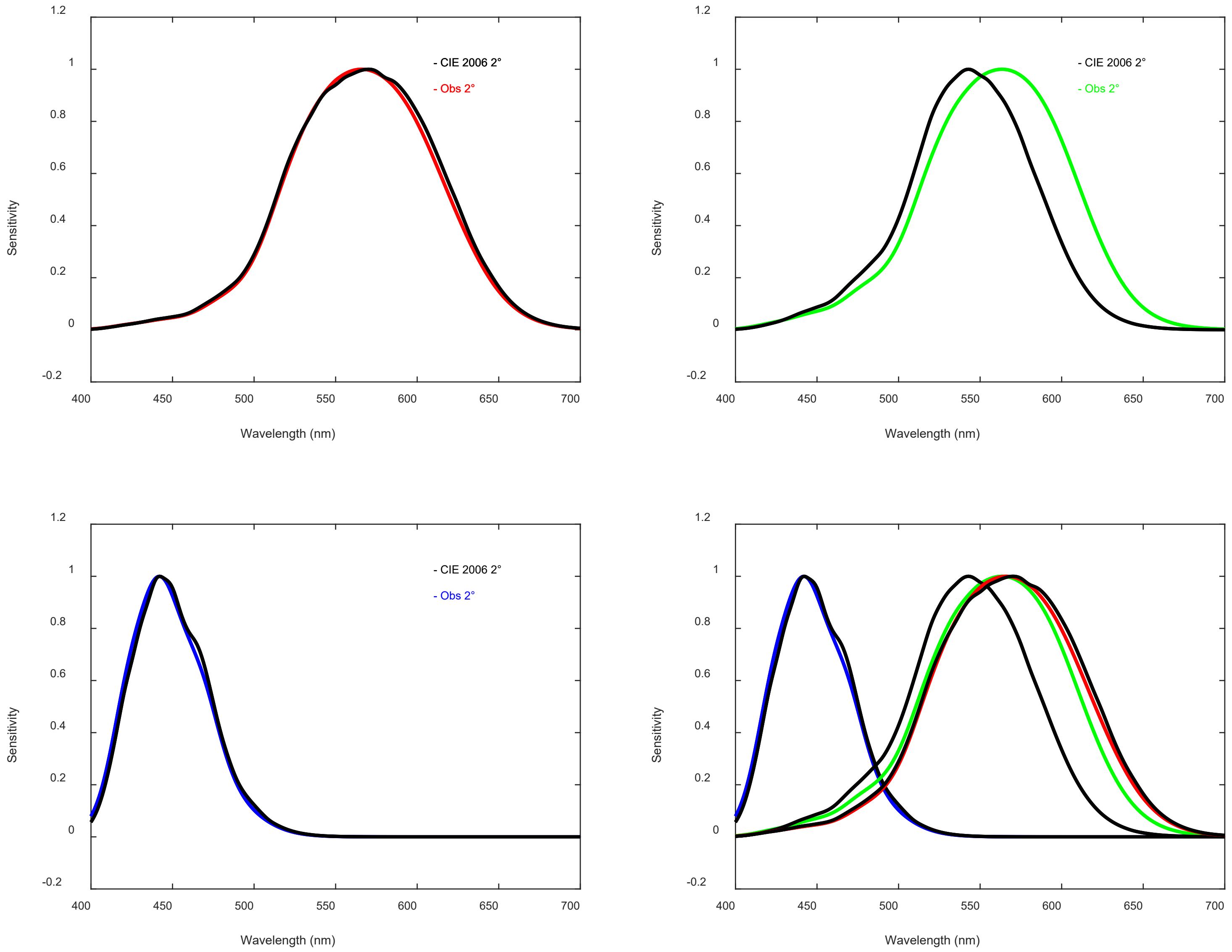
KEYU SHI,[1] MING RONNIER LUO,[1,*] ANDREW T. RIDER,[2] SIYUAN SONG,[1] TINGWEI HUANG,[3] AND ANDREW STOCKMAN[1,2]

[1] *State Key Laboratory of Extreme Photonics and Instrumentation, Zhejiang University, Hangzhou, China*
[2] *Institute of Ophthalmology, University College London, EC1 V 9EL London, United Kingdom*
[3] *Thousand Lights Lighting (Changzhou) Limited, Changzhou, China*
[*] *m.r.luo@zju.edu.cn*

We are now working on different age groups and have measured 100 observers from 8 to 80 years old.

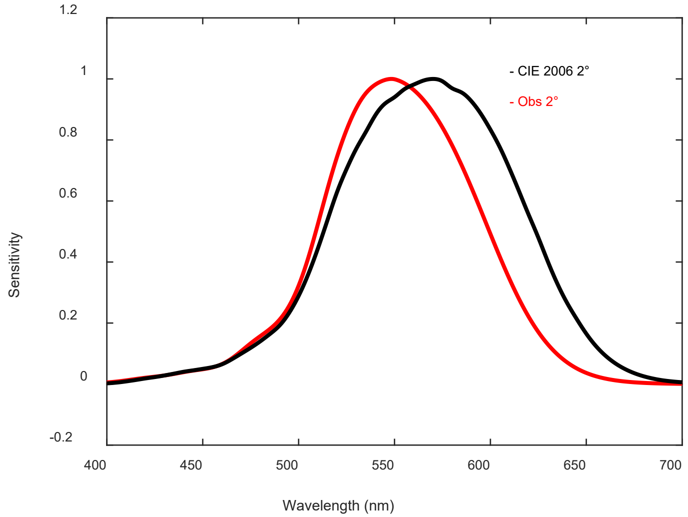
And also for, so far, 22 colour deficient observers, for whom, remarkably, the methods seem also to work. Here are two examples…

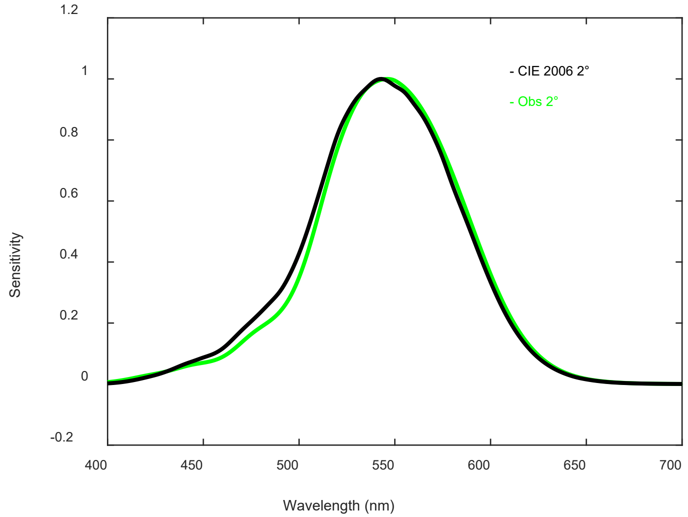
Typical severe deuteranomalous/ deuteranopic observer

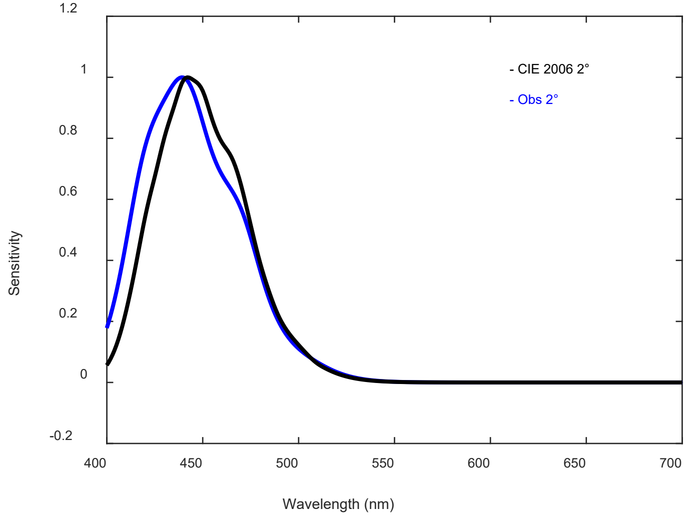


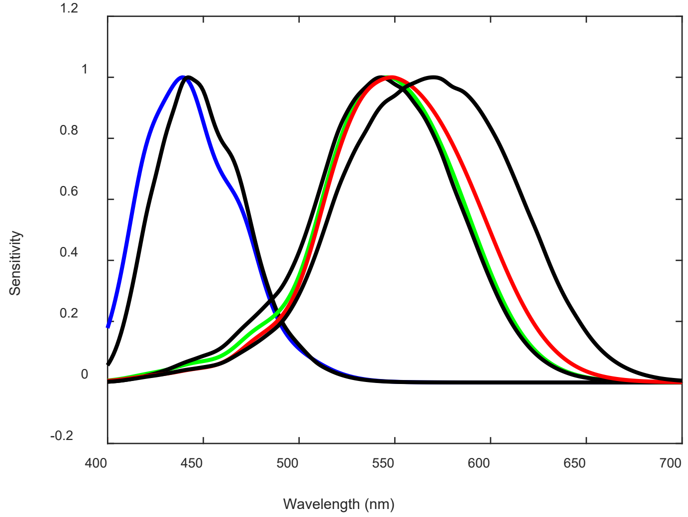
	Obs	CIE 2006 2°
L- shift	-0.1	0
M- shift	**19.8**	0
Density of L-	0.31	0.5
Density of M-	0.69	0.5
Density of S-	0.31	0.4
Lens density	1.57	1.76
Macular density	0.321	0.350

Typical severe protanomalous/ protanopic observer



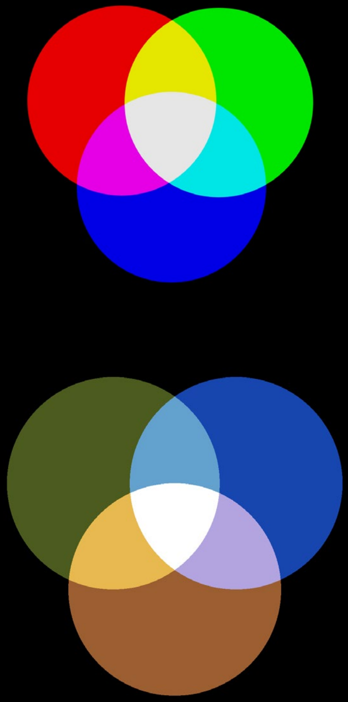


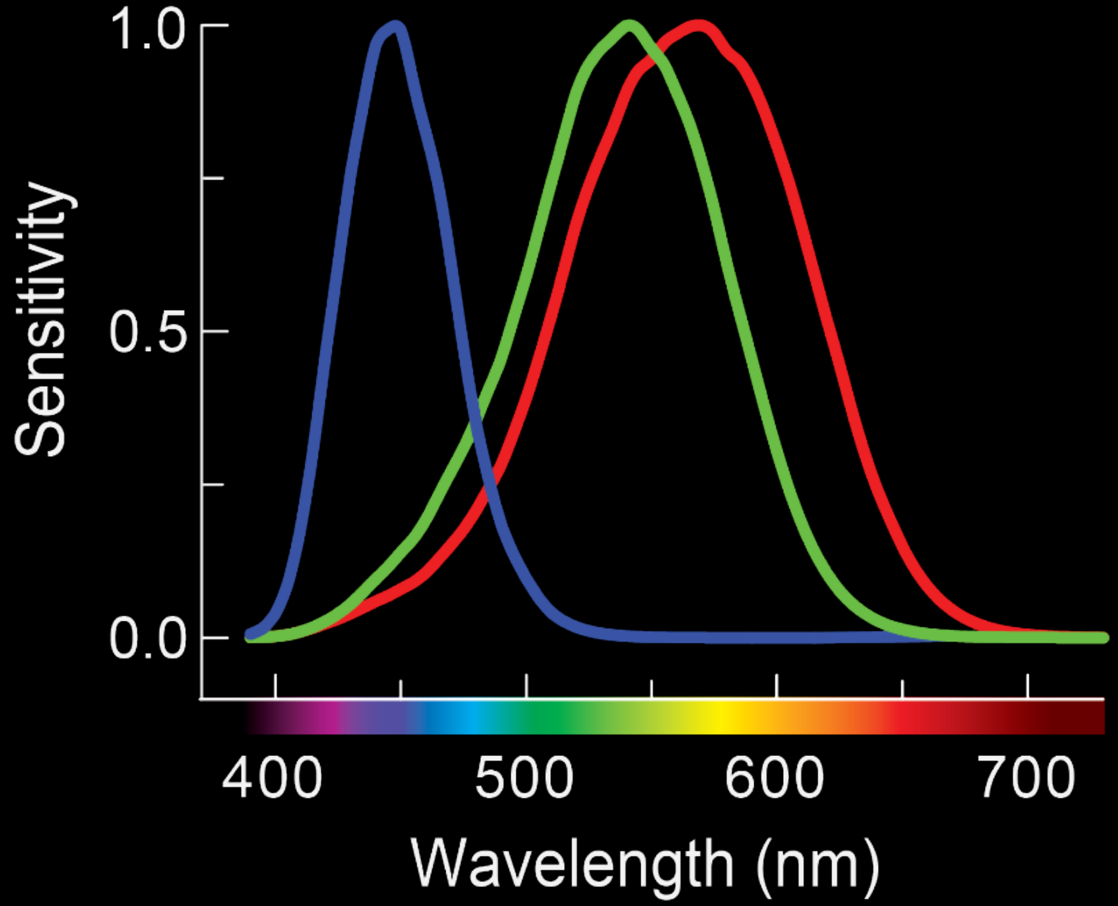


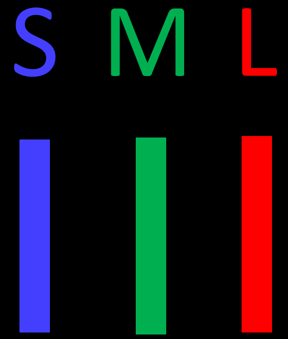


	Obs	CIE 2006 2°
L- shift	**-19.5**	0
M- shift	0.3	0
Density of L-	0.34	0.5
Density of M-	0.64	0.5
Density of S-	0.35	0.4
Lens density	1.29	1.76
Macular density	0.536	0.350

We have used a model of cone fundamentals and predicted individual cone fundamentals from a series of colour matches







Converting to other CMFs

- LMS to RGB is simple

$$\begin{pmatrix} \bar{l}_R & \bar{l}_G & \bar{l}_B \\ \bar{m}_R & \bar{m}_G & \bar{m}_B \\ \bar{s}_R & \bar{s}_G & \bar{s}_B \end{pmatrix} \begin{pmatrix} \bar{r}(\lambda) \\ \bar{g}(\lambda) \\ \bar{b}(\lambda) \end{pmatrix} = \begin{pmatrix} \bar{l}(\lambda) \\ \bar{m}(\lambda) \\ \bar{s}(\lambda) \end{pmatrix}$$

Cone activations from the R, G and B primaries

Estimated cone fundamentals

Converting to other CMFs

- LMS to RGB is simple

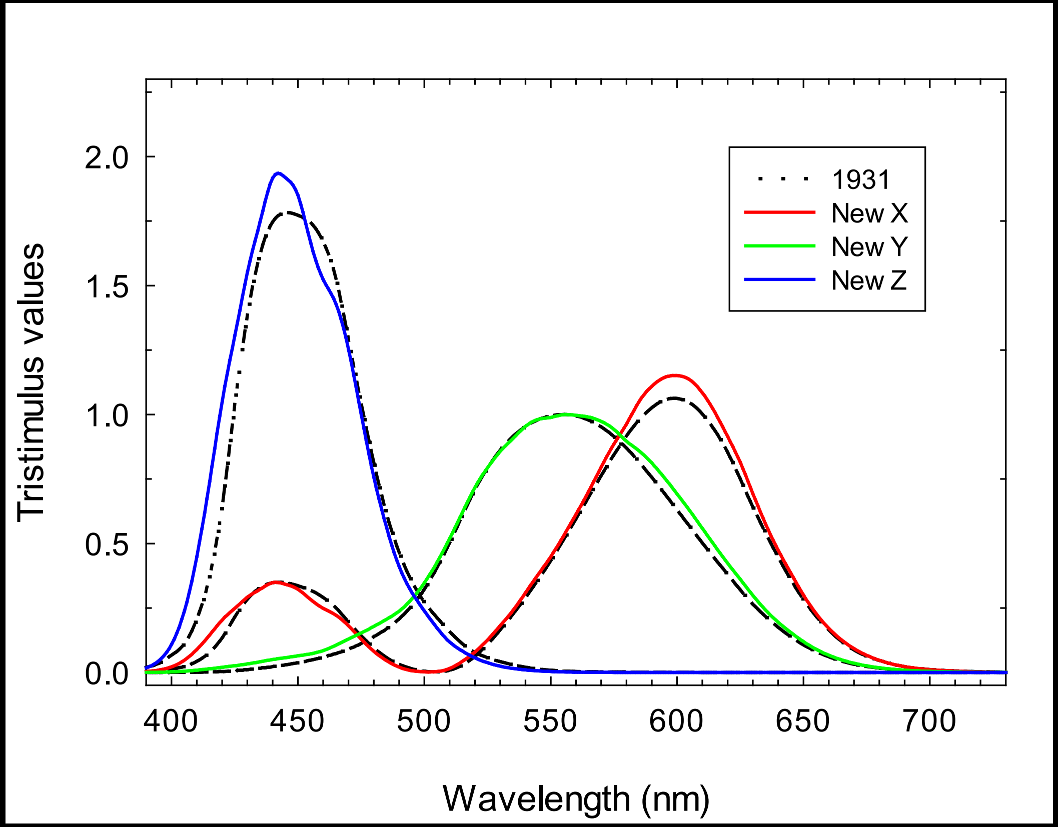
$$\begin{pmatrix} \bar{r}(\lambda) \\ \bar{g}(\lambda) \\ \bar{b}(\lambda) \end{pmatrix} = \begin{pmatrix} \bar{l}_R & \bar{l}_G & \bar{l}_B \\ \bar{m}_R & \bar{m}_G & \bar{m}_B \\ \bar{s}_R & \bar{s}_G & \bar{s}_B \end{pmatrix}^{-1} \begin{pmatrix} \bar{l}(\lambda) \\ \bar{m}(\lambda) \\ \bar{s}(\lambda) \end{pmatrix}$$

Cone activations from the R, G and B primaries

Estimated cone fundamentals

Converting to other CMFs

- LMS to XYZ is not so simple



2-deg LMS →XYZ transforms

$$\begin{pmatrix} 1.94735469 & -1.41445123 & 0.36476327 \\ 0.68990272 & 0.34832189 & 0 \\ 0 & 0 & 1.93485343 \end{pmatrix} \begin{pmatrix} \bar{l}(\lambda) \\ \bar{m}(\lambda) \\ \bar{s}(\lambda) \end{pmatrix} = \begin{pmatrix} \bar{x}(\lambda) \\ \bar{y}(\lambda) \\ \bar{z}(\lambda) \end{pmatrix}$$

- Z is a scaled version of S
- Y is a weighted sum of L and M {= V(λ)}
- X is not physiologically relevant

Summary

- Standard or ‘mean’ cone spectral sensitivities (fundamental CMFs) are helpful for describing colours for the average observer
- But the underlying functions can vary between observers for several physical, physiological and genetic factors
- We can parametrically model these variations to generate individualised cone fundamentals and colour matching functions
- We can perform colour matching experiments to estimate an individual’s cone fundamentals and examine variability due to:
  - Age
  - Ethnicity
  - Colour vision deficiency

Applications

- Display technologies
  - TVs, monitors, phones, laptops, tablets, projectors
- Colour reproduction and lighting
- Silent substitution
  - “Cone isolating” stimuli may not be, for different observers
  - Intrinsically photosensitive retinal ganglion cells (melanopsin containing)
  - Rods

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

CVRL database

http://www.cvrl.org

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

Thank you

Andrew Stockman, *UCL*

Ronnier Luo, *Zhejiang University*

Lucas Shi, *Zhejiang University*

Alan Song, *Zhejiang University*

Tingwei Huang, *Thouslite Ltd*

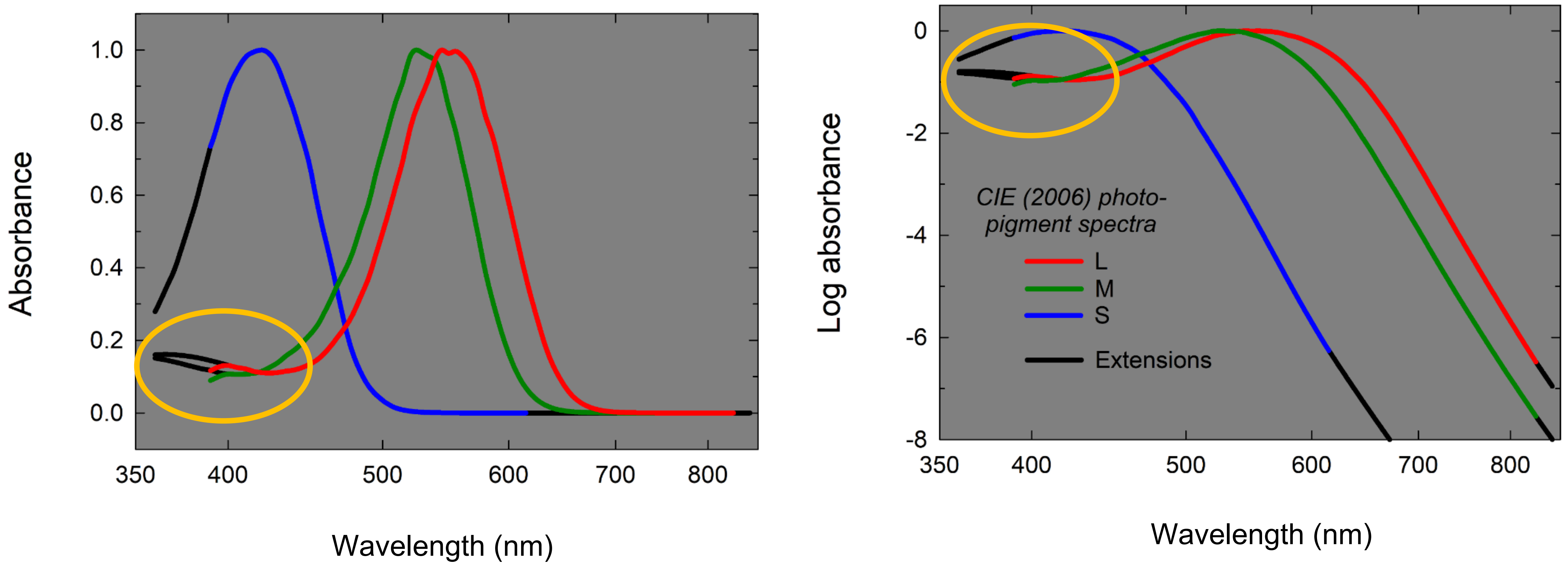
UKRI Biotechnology and Biological Sciences Research Council

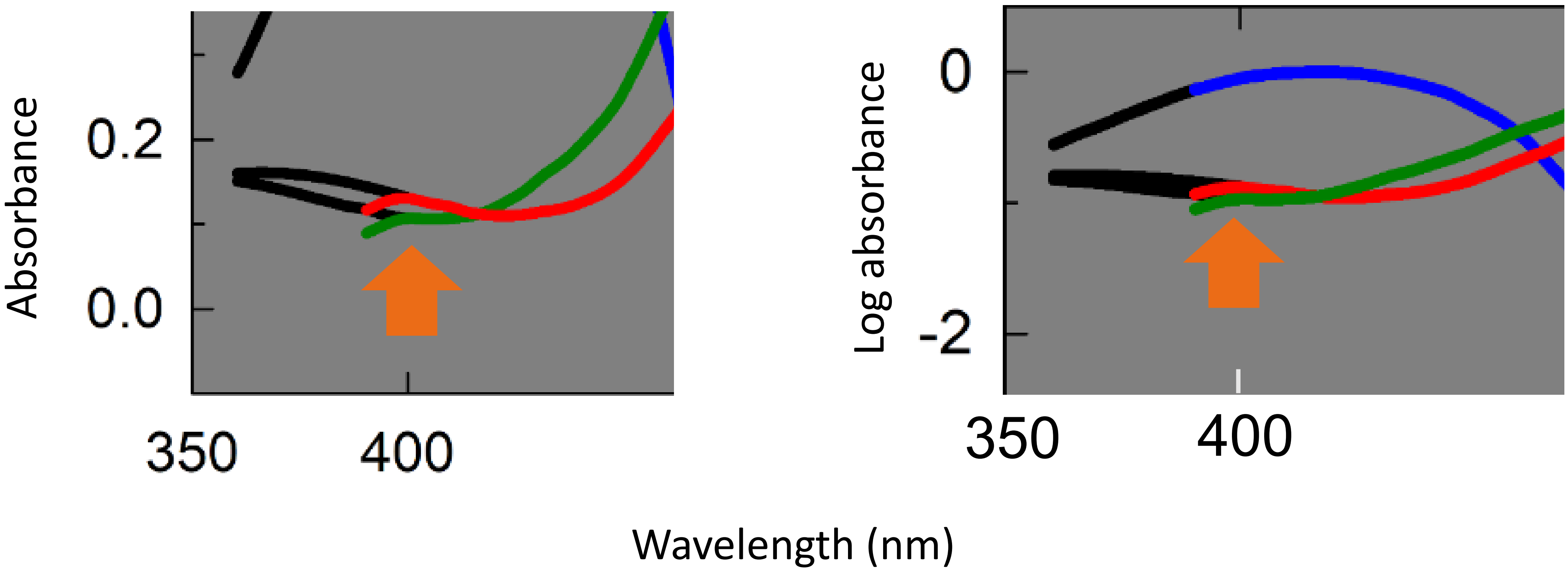
OPTICA | Formerly OSA

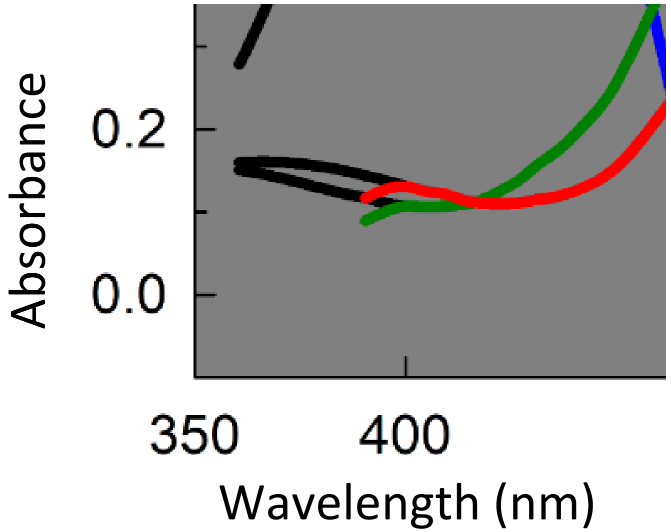
Uncertainty at very short wavelengths

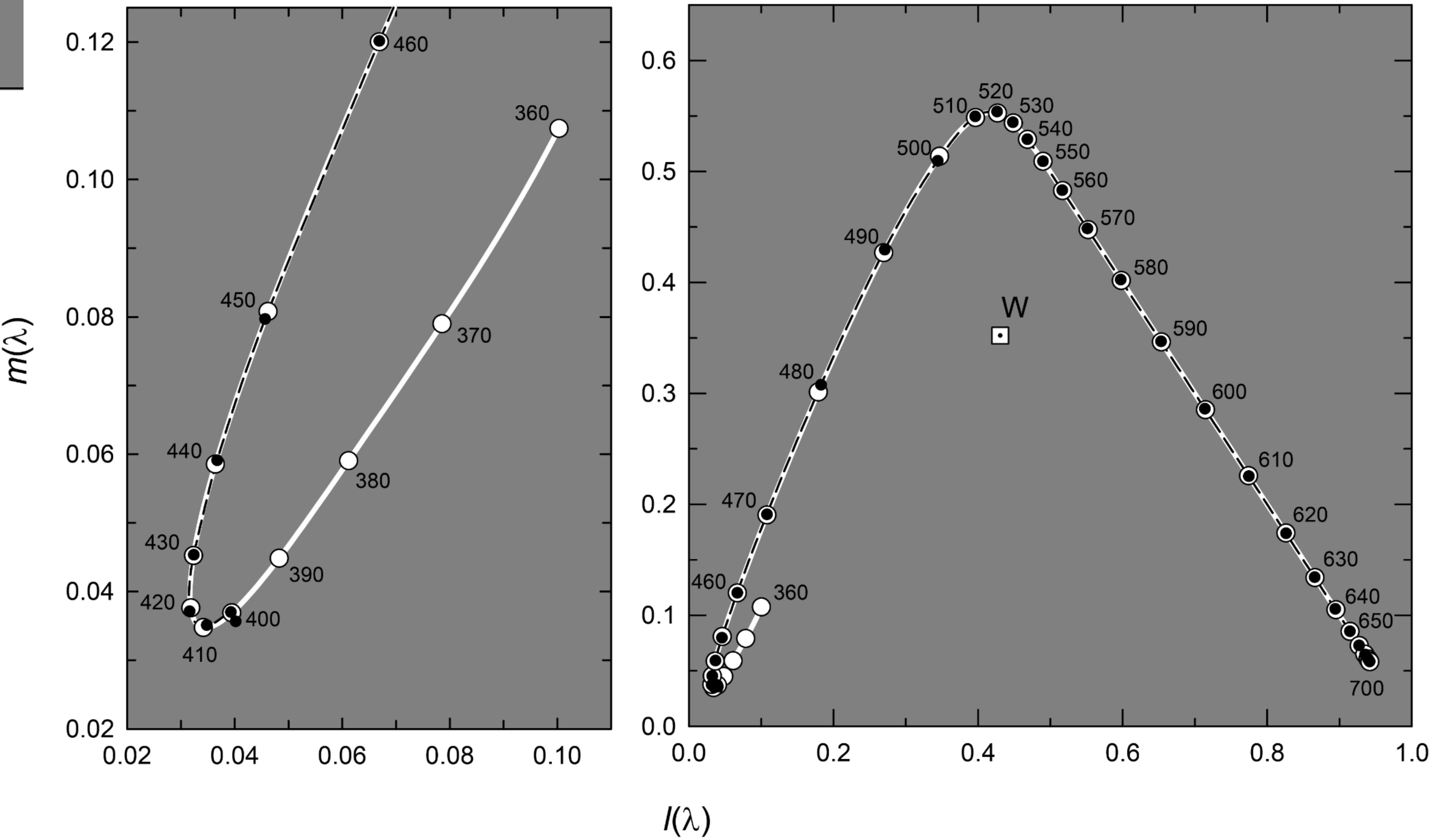
- General lack of colour matching data in this region
- Lens and macular pigment densities <390 nm are uncertain
- Fluorescence of the lens and cornea affect colour matches

One correction of the CIE 2006 functions:




Absorbance
0.2
0.0
350
400
Log absorbance
0
-2
350
400
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
360
370
380
390
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
510
520
530
540
550
500
560
570
490
580
W
590
480
600
610
470
620
630
460
360
640
650
700
l(λ)

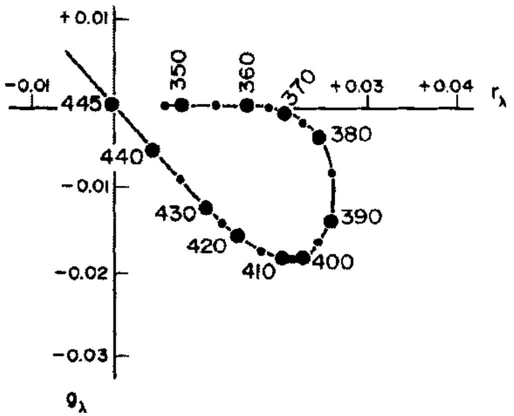


Figure 8. Chromaticity diagram averaged from two aphakic observers in the UV. Subjects matched a split field with primaries at 445 and 625 nm on the left and UV with 525 nm on the right. The color matching functions r_λ, g_λ and b_λ were equated by means of W. D. Wright's (1946) convention with normalizing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

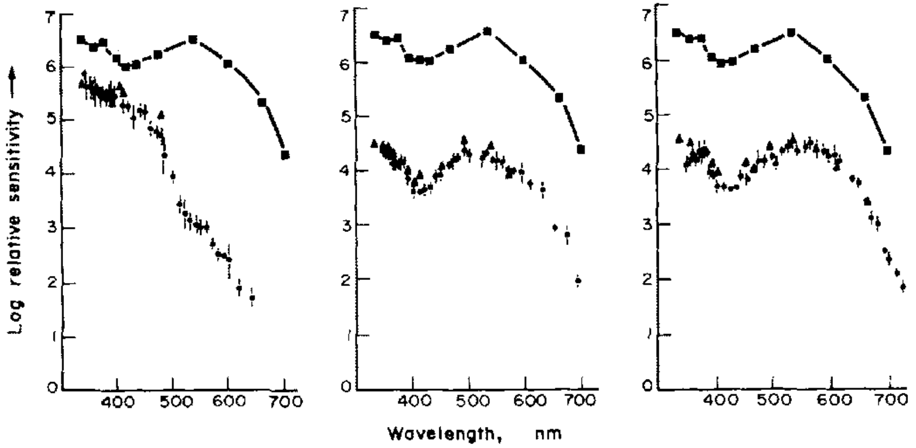


Figure 7. Photopic and cone spectral sensitivities of aphakic observers. (■), Foveal spectral sensitivity which is a composite spectrum of the 3 phototopic (cone) spectra. Left: blue cone spectra; (●), give the foveal spectrum obtained against a bright orange background (Wratten 23 A filter, 5.13 log 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).