COLOUR PERCEPTION

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https://github.com/MalihaAshraf/LIM2022_workshop

Overview

Part 1: Physics of light and receptors: display spectra to receptor outputs (Exercise 1)

Part 2: Opponent processing; cone vs hue opponency (Exercise 2)

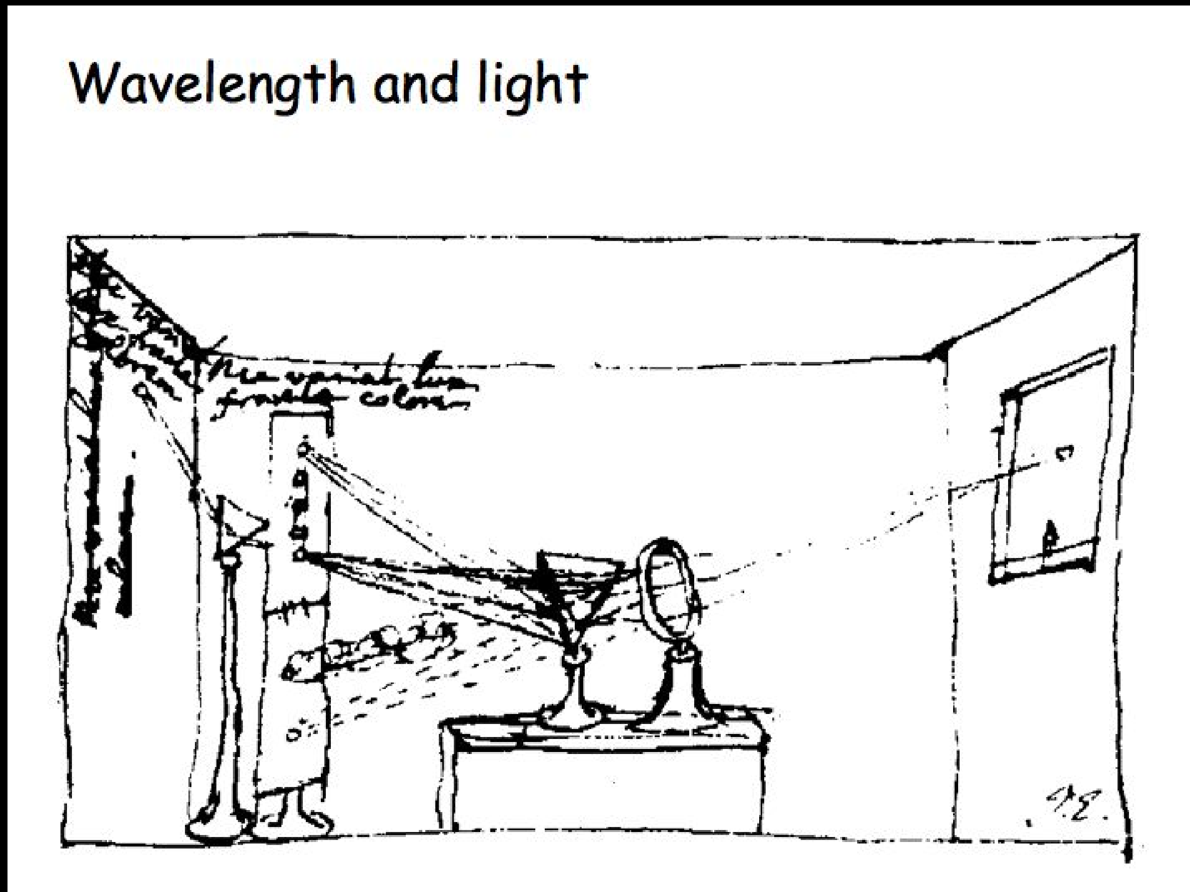
Part 3: Colour spaces: LMS, XYZ, CIELAB, CIELUV (Exercise 3)

Part 4: Achromatic and chromatic contrast sensitivity (Exercise 4)

Part 1
Physics of light and receptors

- Basics of human visual system: rods, cones, scotopic, mesopic, photopic vision
- Calculation of cone outputs and luminance (radiometric to photometric variables)

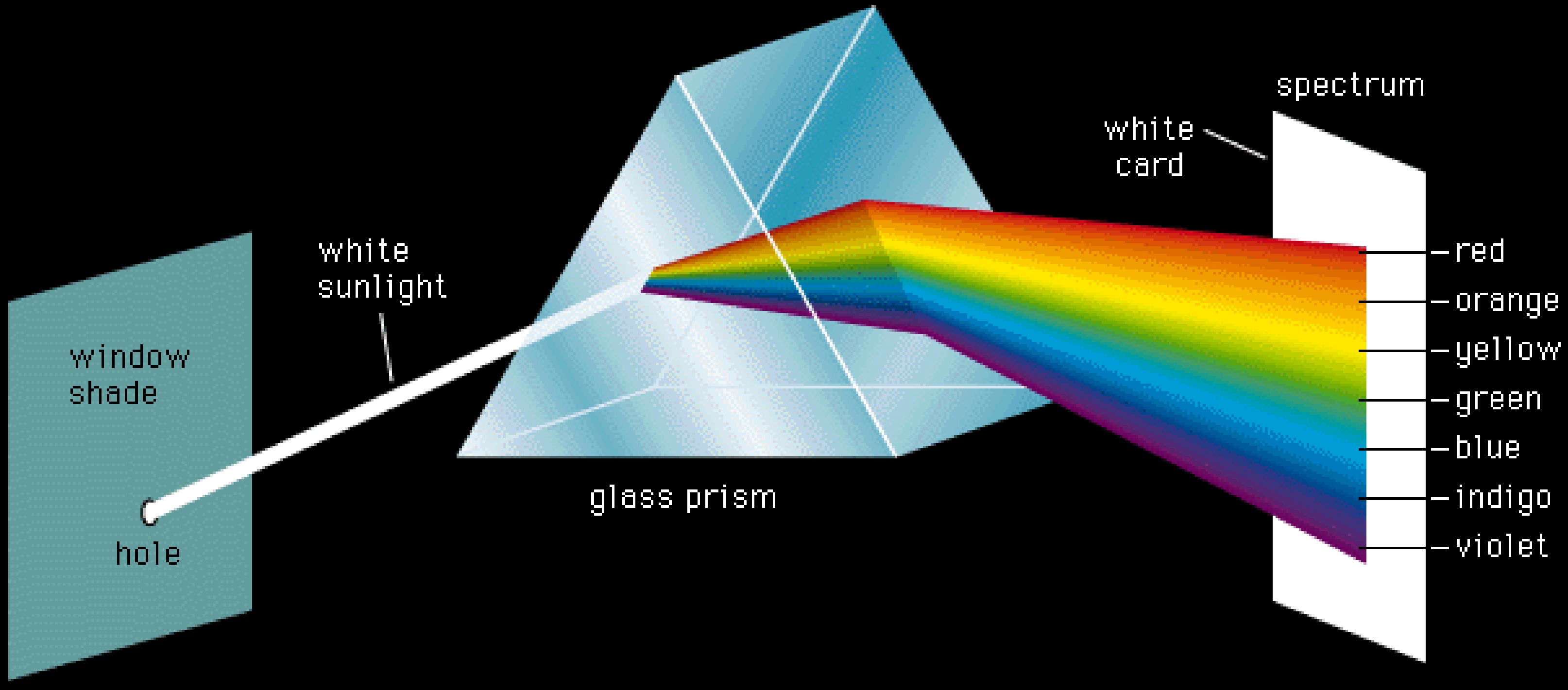
The physics of light



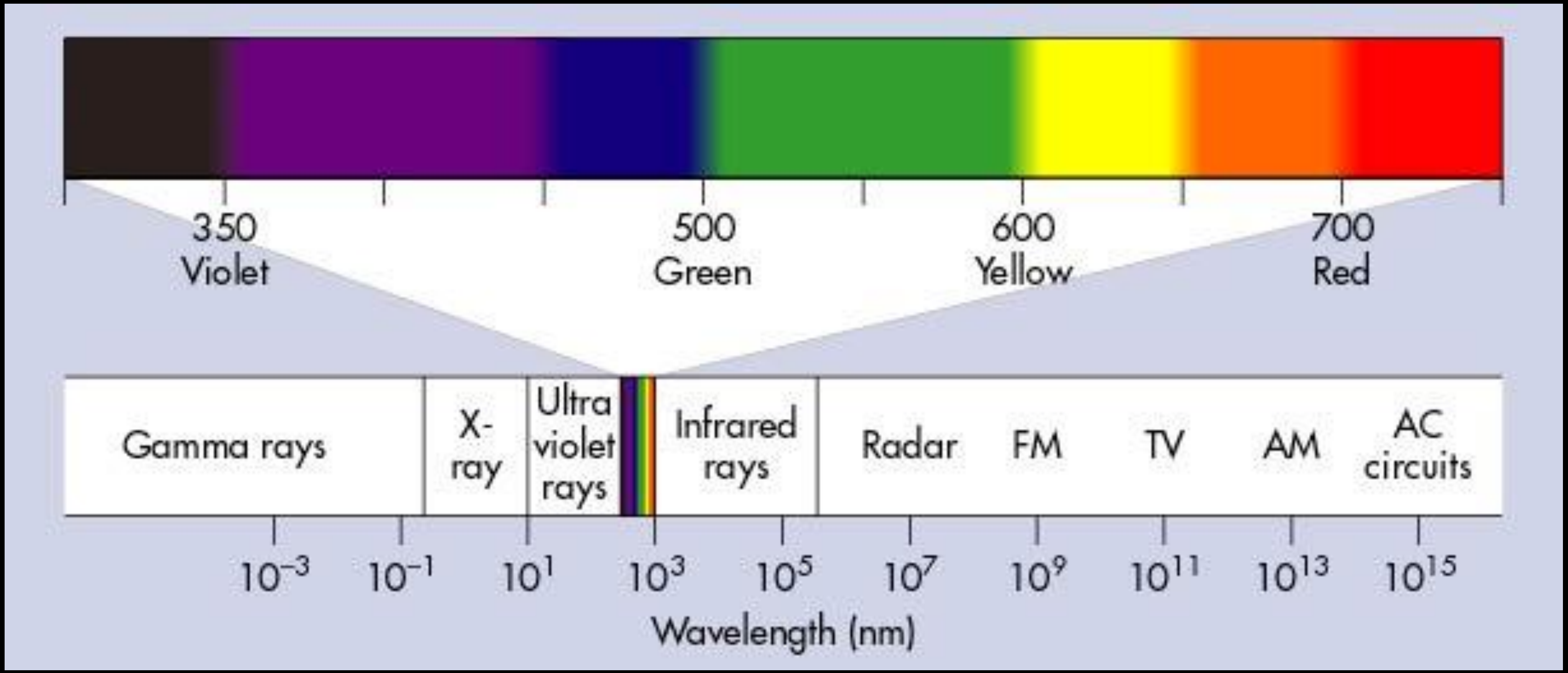
Isaac Newton (1666): decomposition of white light into separate wavelength components
https://www.youtube.com/watch?v=Aggi0g67uXM

Light

400 - 700 nm is important for vision



VISIBLE LIGHT



Visible light corresponds to a small range of the electromagetic spectrum roughly from 400 nm (which appears blue) to 700 nm (appears red) in wavelength.

How dependent are we on colour?

Split the image into...

ACHROMATIC COMPONENTS

CHROMATIC COMPONENTS

Courtesy of stockman@UCL

CHROMATIC COMPONENTS

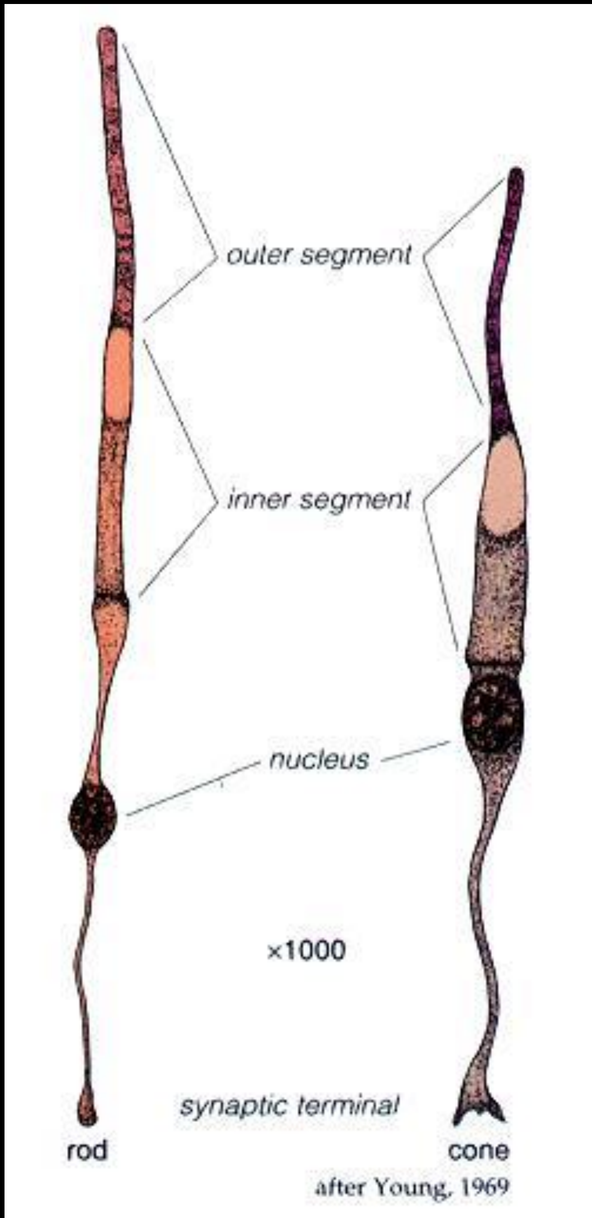
Chromatic information *by itself* provides relatively limited information…

Courtesy of stockman@UCL

ACHROMATIC COMPONENTS

Achromatic information is important for fine detail …

Courtesy of stockman@UCL



Human photoreceptors

- **Rods**
  - Achromatic night vision
  - 1 type
- **Cones**
  - Daytime, achromatic *and* chromatic vision
  - 3 types

Rod

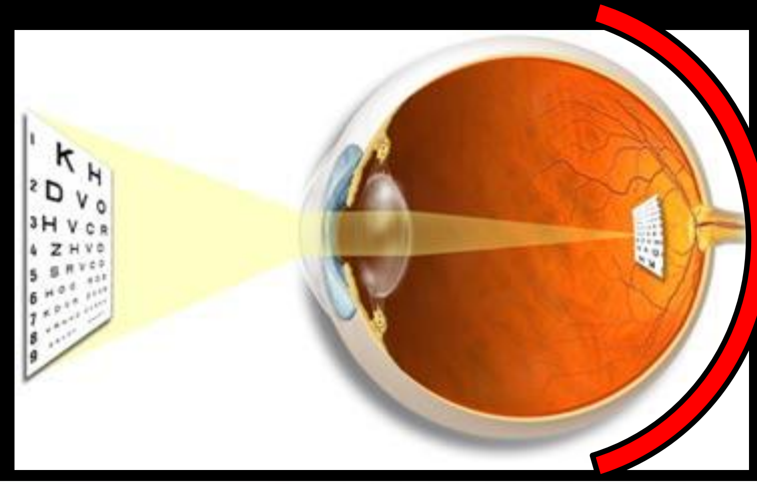
Long-wavelength-sensitive (L) or “red” cone

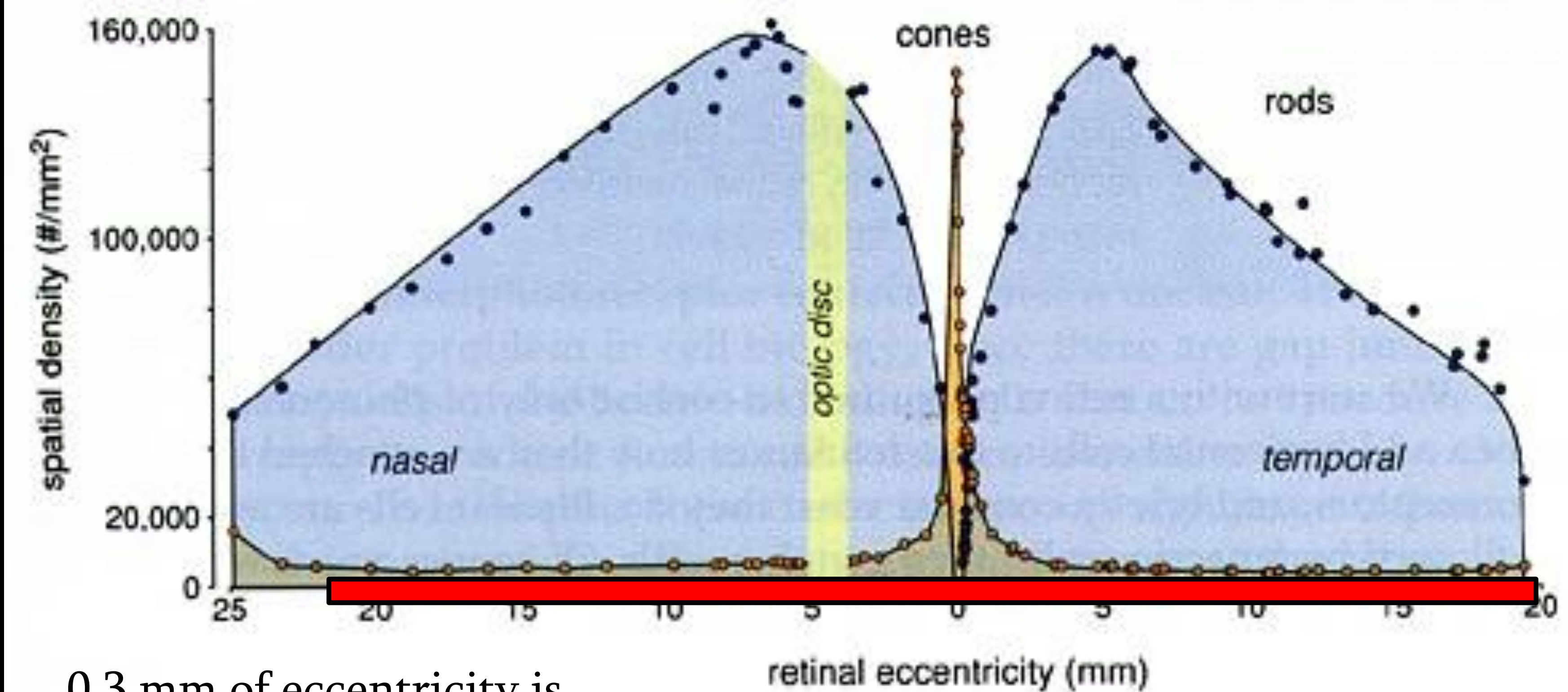
Middle-wavelength-sensitive (M) or “green” cone

Short-wavelength-sensitive (S) or “blue” cone

Courtesy of stockman@UCL

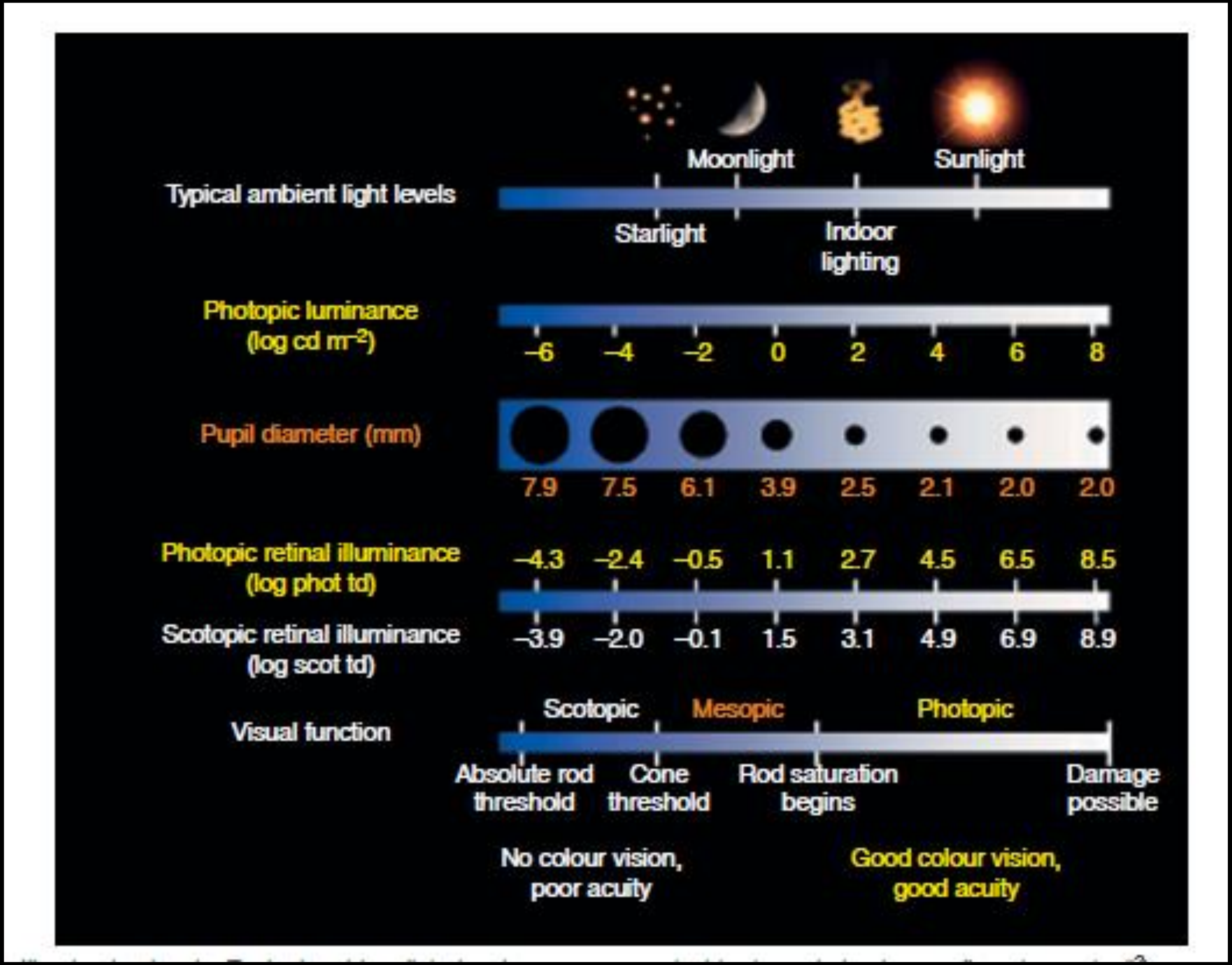
Rod and cone distribution





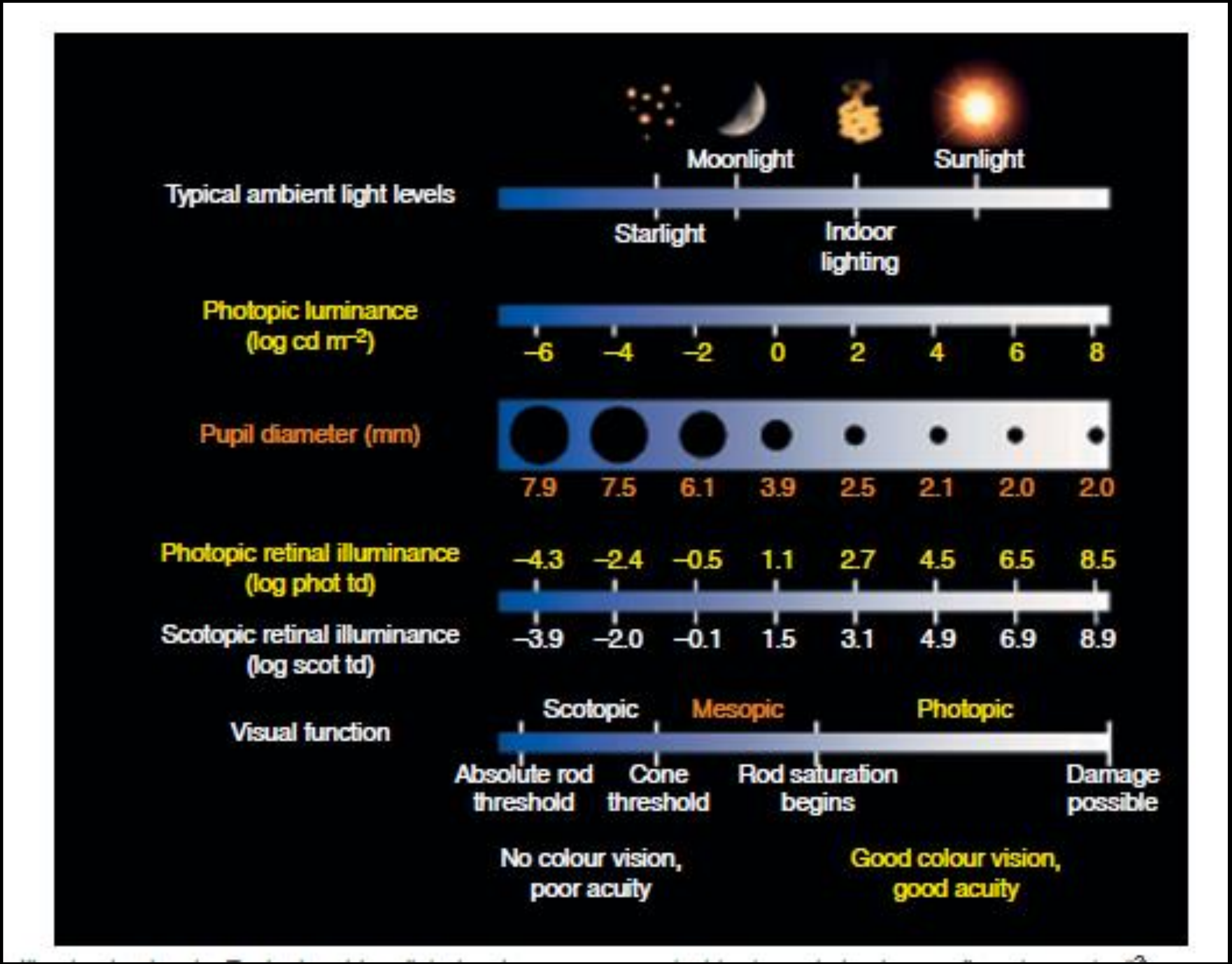
after Østerberg, 1935; as modified by Rodieck, 1988

0.3 mm of eccentricity is about 1 deg of visual angle



Under scotopic (< 0.01 cd/m2) light levels (Starlight, Moonlight) only rods function -> No colour vision; poor spatial acuity.

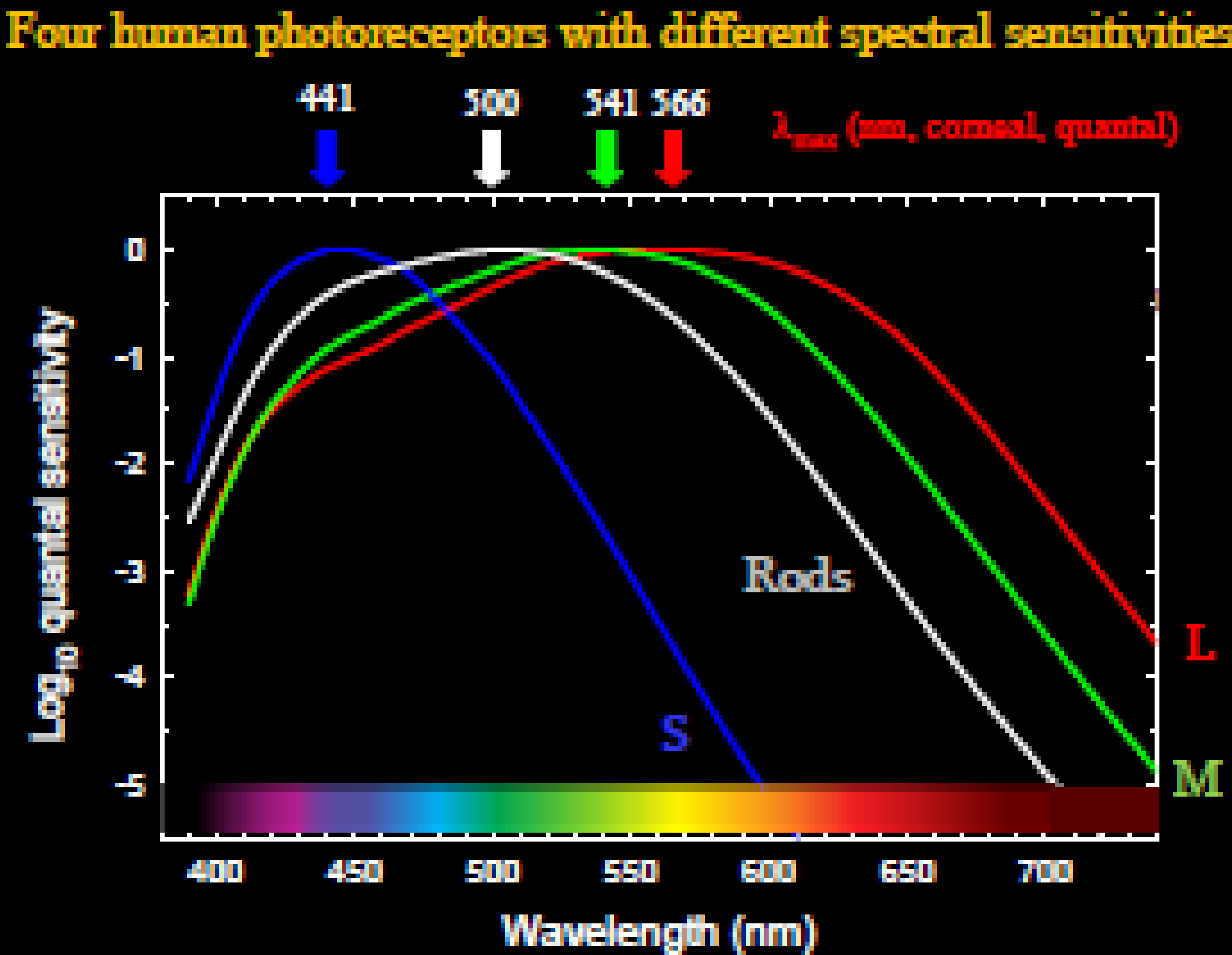
Stockman&Sharpe, 2006, OPO



Under photopic (> 3 cd/m2) light levels (indoor lighting, sunlight), the cone receptors operate which leads to good colour vision and good spatial acuity.

Stockman&Sharpe, 2006, OPO

Spectral sensitivity



Source: Andrew Stockman

From radiometric to photometric units:

Calculation of luminance and cone signals for stimuli presented on displays

Calculating Luminance

Radiometric vs photometric units

QUANTITY	RADIOMETRIC	PHOTOMETRIC
Power	W	Lumen (lm) = cd·sr
Power Per Unit Area	W/m^2	Lux (lx) = $cd \cdot sr/m^2 = lm/m^2$
Power Per Unit Solid Angle	W/sr	Candela (cd)
Power Per Unit Area Per Unit Solid Angle	$W/m^2 \cdot sr$	$cd/m^2 = lm/m^2 \cdot sr$ = nit

Radiance $\xrightarrow{\text{Visual system (eye)}}$ Luminance

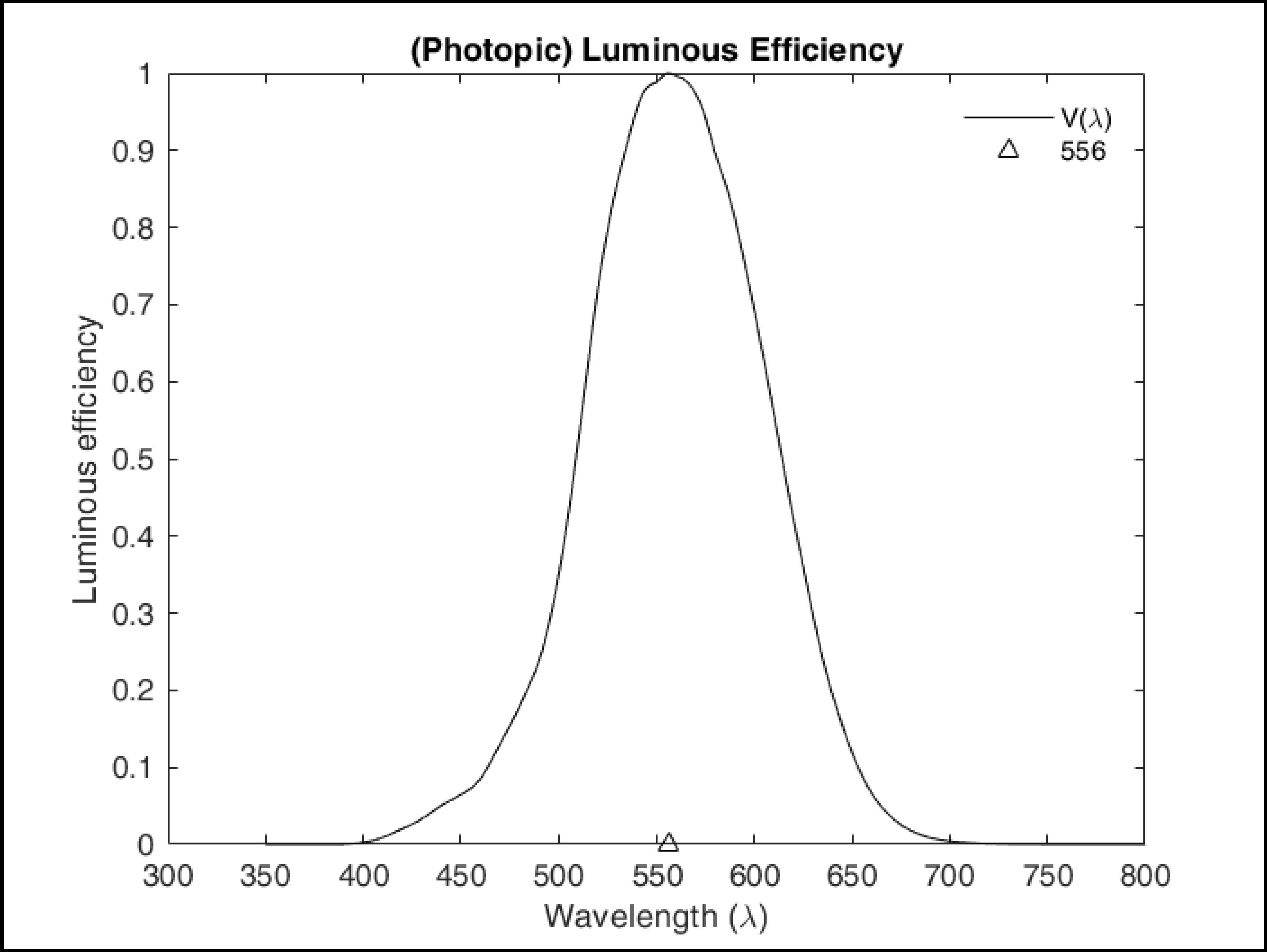
Spectral Power Distribution (SPD): in watt per square meter per steradian

Calculating Luminance

- Photometric variable
- Incorporates human standard observer
- Luminous efficiency curve

Luminous Efficiency

Visual sensitivity to light as a function of wavelength



[cvrl.org]

Calculating Luminance

$$\text{Luminance} = \int V(\lambda) * SPD(\lambda) d(\lambda) \; * k$$

Luminance is the integral over the product of the luminous efficiency and the spectral power distribution.

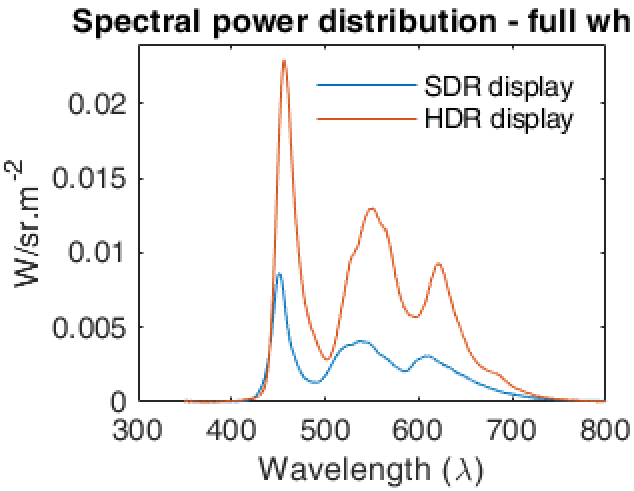
Luminance is expressed in candela/m^2

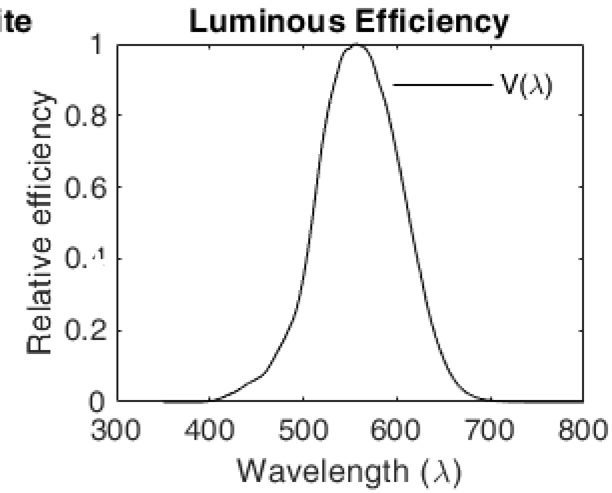
K=683: 1 watt at 555nm (=peak of V(lambda)) = 683 lumen*

[E2]

Calculating Luminance

$\int$





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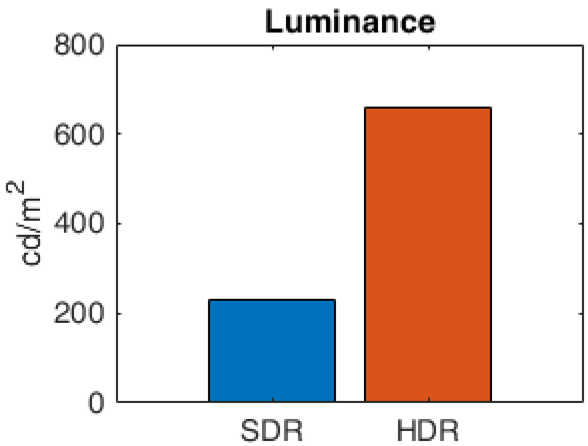


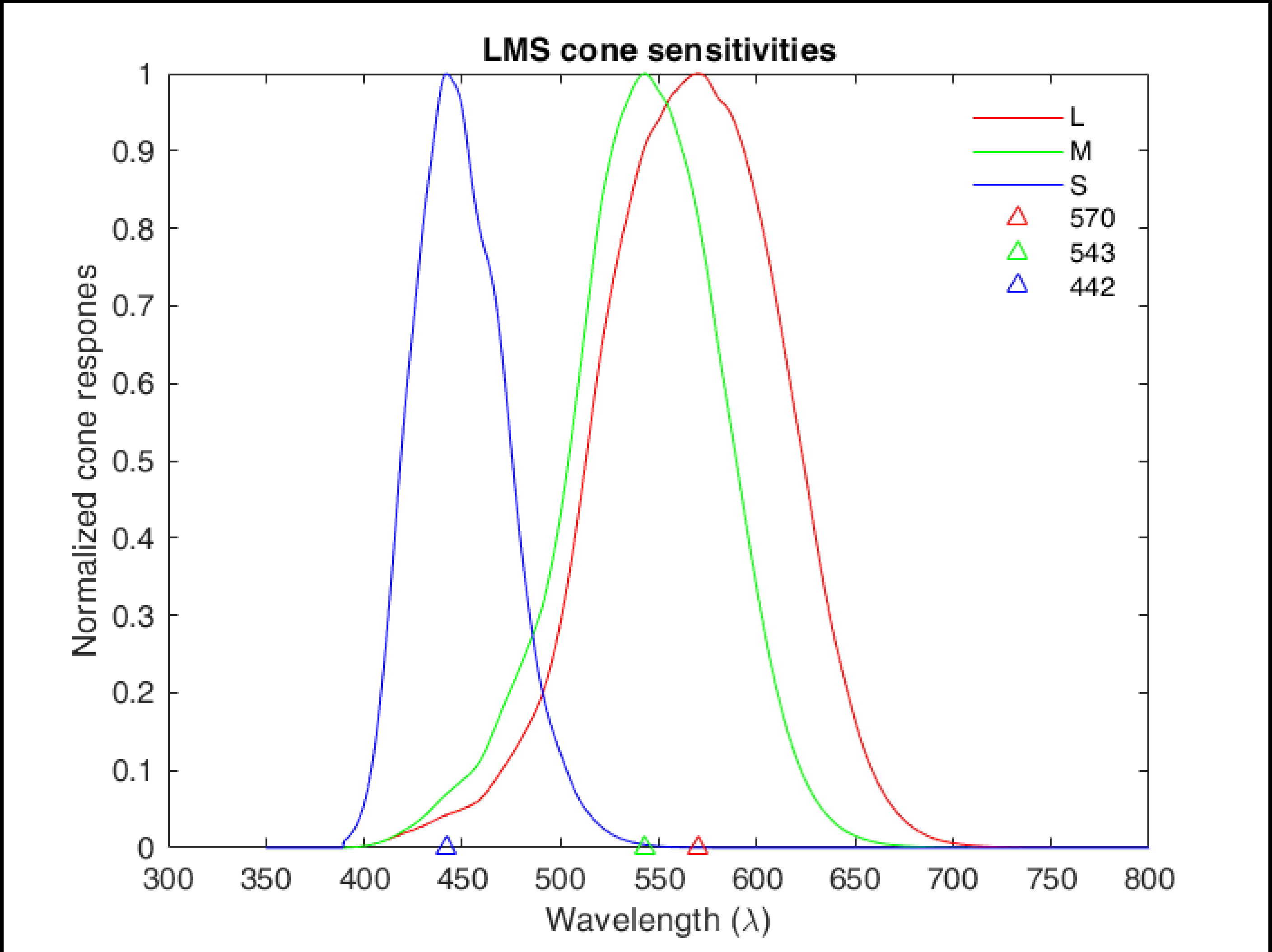
Luminance =

$$\int V(\lambda) * SPD(\lambda) d(\lambda) \quad * k$$

How do we compute the colour of stimuli (colorimeteric values) ?

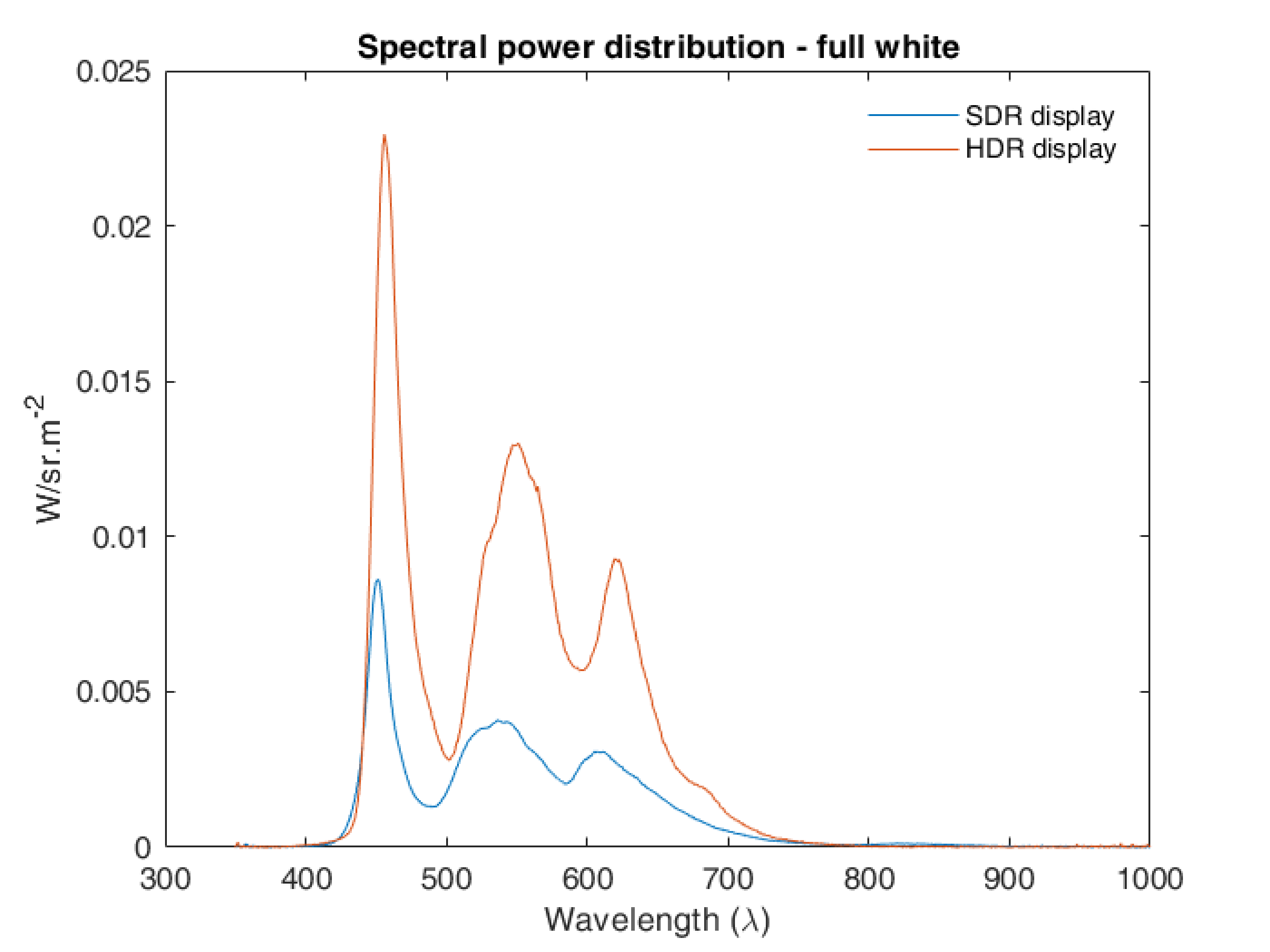
Calculation of cone signals for stimuli presented on displays

Calculating cone outputs



[Stockman & Sharpe 2deg cone fundamentals: www.cvrl.org]

Calculating cone outputs



Spectral Power Distribution (SPD) in watt per square meter per steradian

Calculating cone outputs

$$L\ cone\ output = \int L(\lambda) * SPD(\lambda) d(\lambda) \ \ *k$$

$$M\ cone\ output = \int M(\lambda) * SPD(\lambda) d(\lambda) \ \ *k$$

$$S\ cone\ output = \int S(\lambda) * SPD(\lambda) d(\lambda) \ \ *k$$

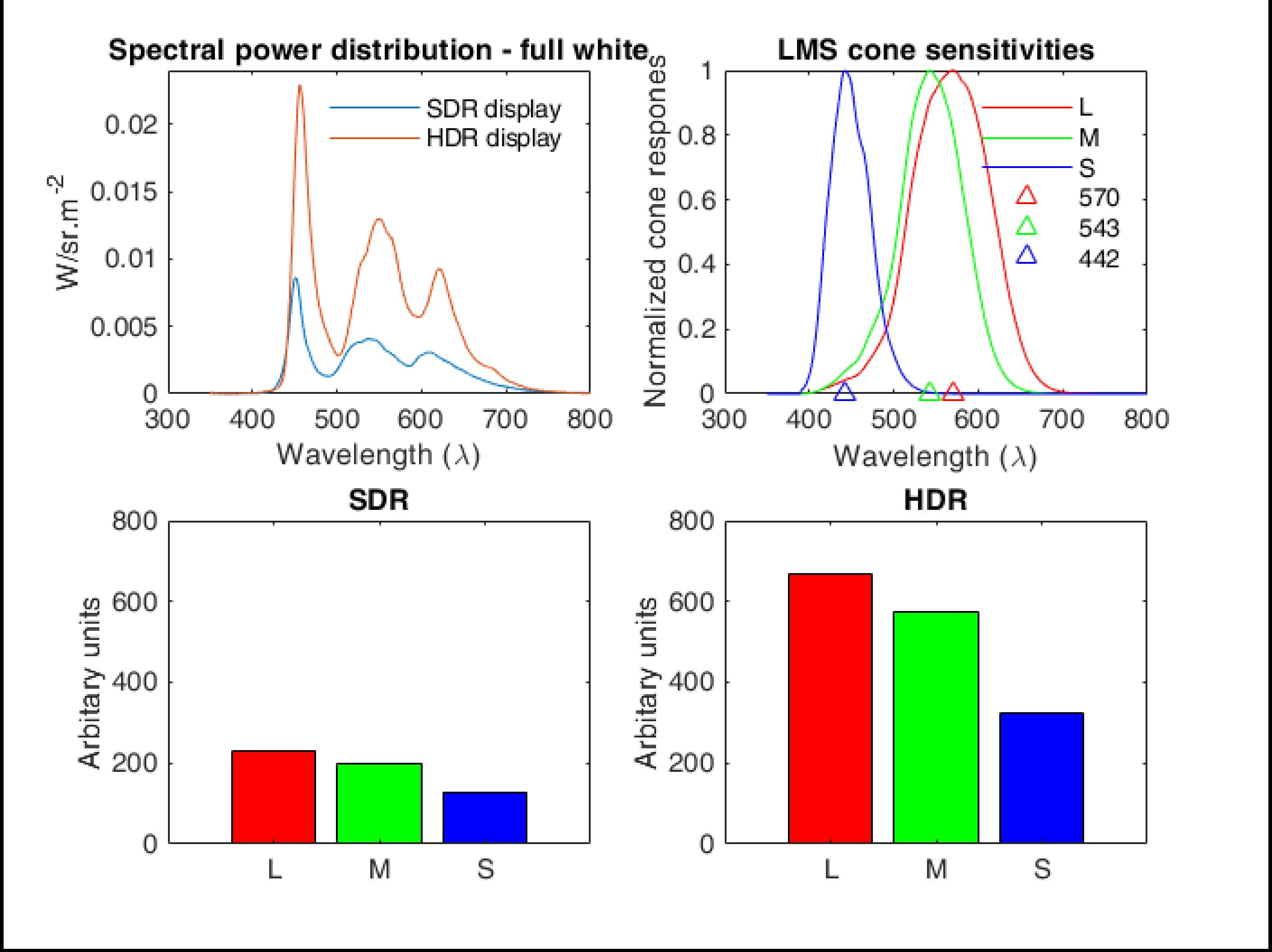
The non-normalised L,M,S cone outputs are the integral over the product of the cone sensitivities and the spectral power distribution.

K=683: 1 watt at 555nm (=peak of V(lambda)) = 683 lumen*

Calculating cone outputs

$\int$

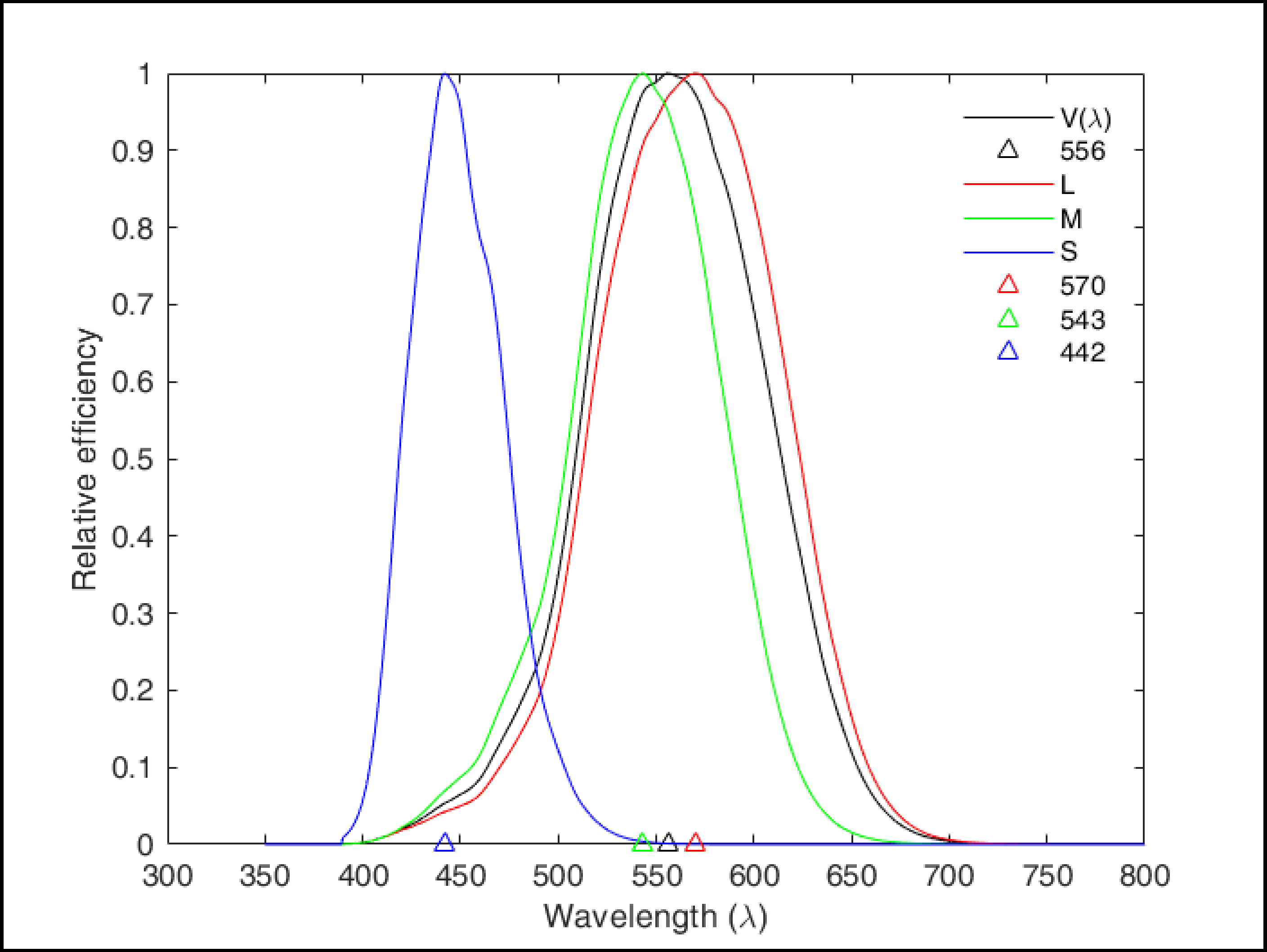
=



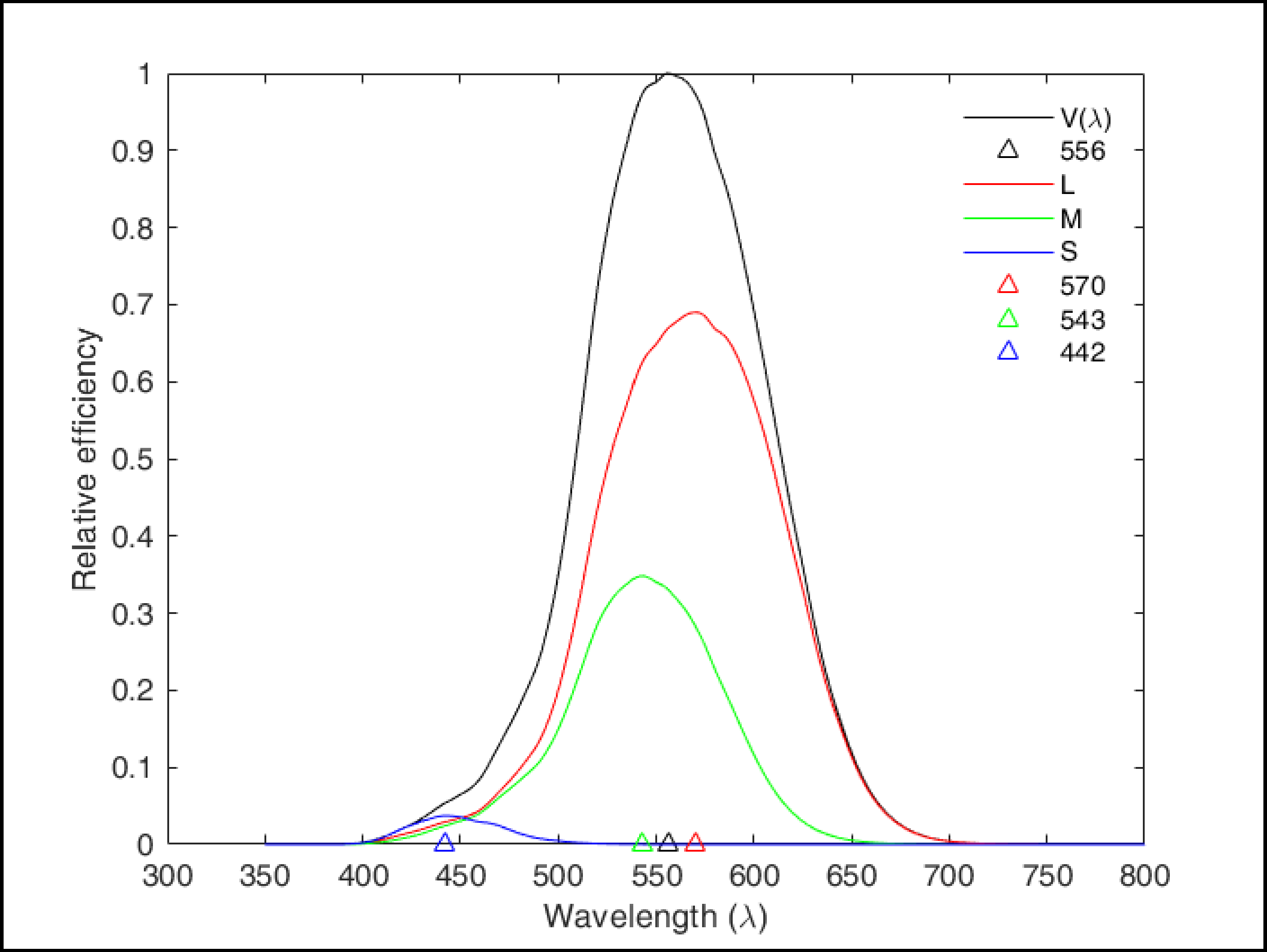
We also know that the luminance mechanism is primarily driven the L and M cones. Therefore we normalise the L and M cone sensitivities such that their sum yields luminance

$$Lum = a*L + b*M$$

Cones and luminous efficiency



Scaled cone responses

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lms_weights = [0.689903 0.348322 0.0371597];
```

Calculating cone outputs

∫

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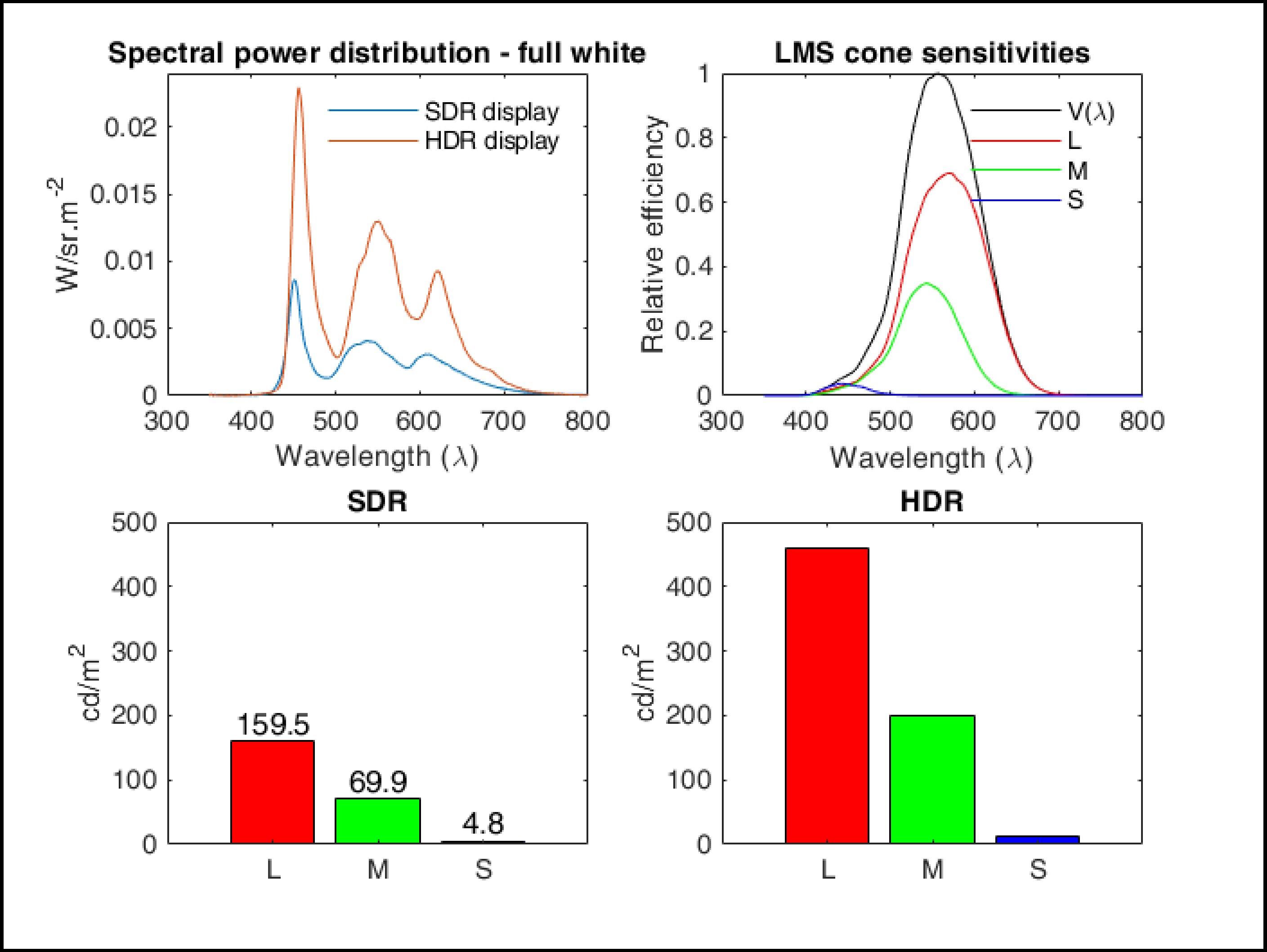
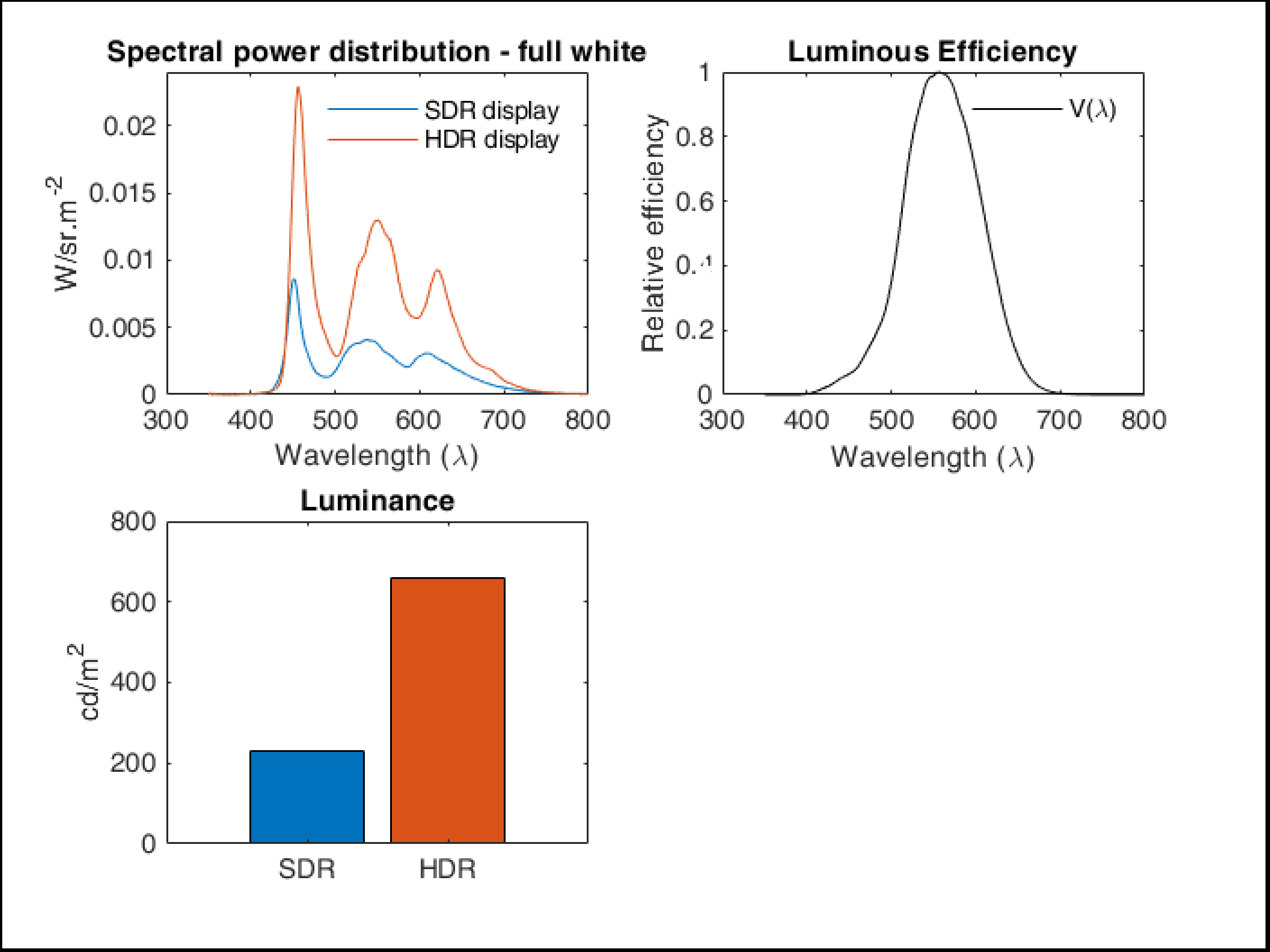


Calculating Luminance

$\int$



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Calculating Luminance

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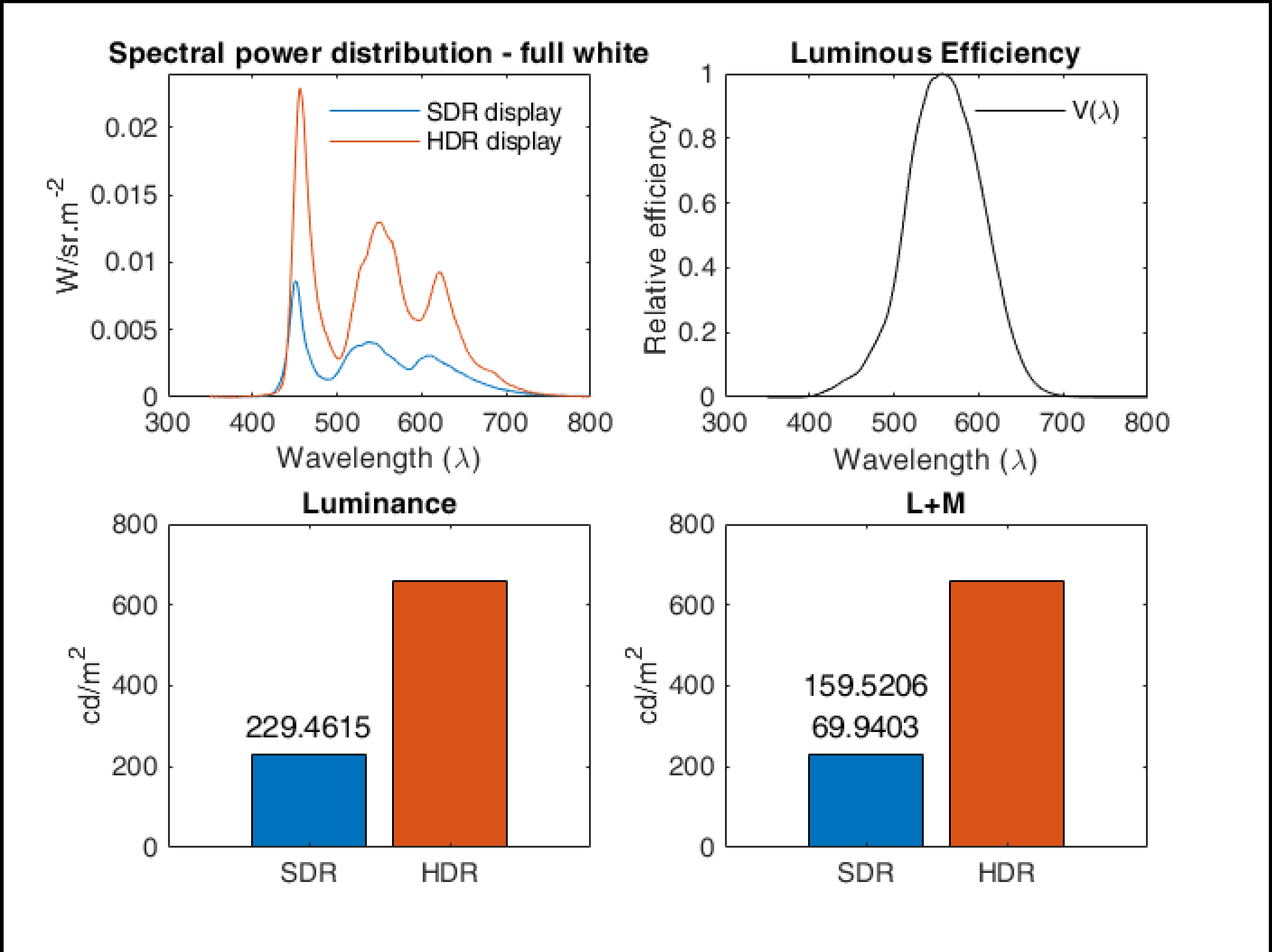


Calculating cone outputs

For a given display (fixed RGB SPD) we can derive a matrix that converts the RGB values to LMS outputs.

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} L_R & L_G & L_B \\ M_R & M_G & M_B \\ S_R & S_G & S_B \end{bmatrix} * \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

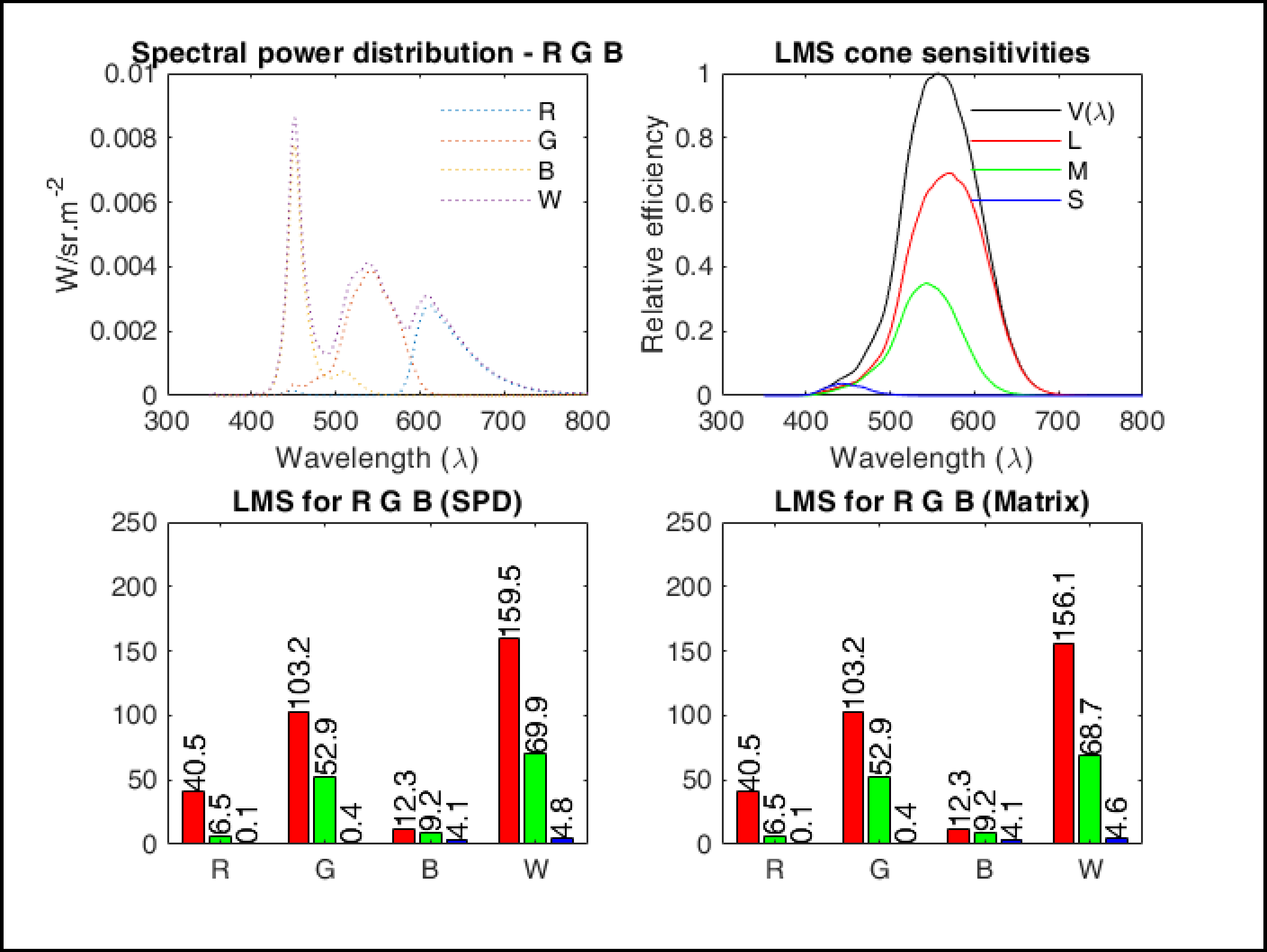
where

$L_R = \int L(\lambda) * SPD\_R(\lambda) d(\lambda) \; * k \; * \; w$

K=683; $W = 0.689903$

(same for the other matrix coefficients; use lms_weights)

Calculating cone outputs



Summary of Part 1

Cones and rods operate under different light levels (scotopic/mesopic/photopic)

To convert from radiometric (radiance etc) to photometric or colorimetric units (e.g. luminance, cone signals) requires a standard human observer.

Depending on whether the spectra are fixed, the LMS cone signals may be computed by integrating the product of the cone sensitivities and the SPD, or, alternatively, use the RGB2LMS matrix.

Exercise 1

1.1. Compute LMS outputs for the Red channel only; same for G and B using the SPDs for RGB

1.2. Compute LMS outputs for R, G, and B channels using the matrix RGB2LMS

1.3. Compute Luminance for R,G,B separately using first the SPD and the luminous efficiency function, then the matrix RGB2LMS.

1.4. Generate stimuli that isolate the S cones, when presented on a grey (RGB=[0.5 0.5 0.5]) background. Compute the RGB values of such lights.

Overview

Part 1: Physics of light and receptors: display spectra to receptor outputs (Exercise 1)

Part 2: Opponent processing: cone vs hue opponency (Exercise 2)

Part 3: Colour spaces: LMS, XYZ, CIELAB, CIELUV (Exercise 3)

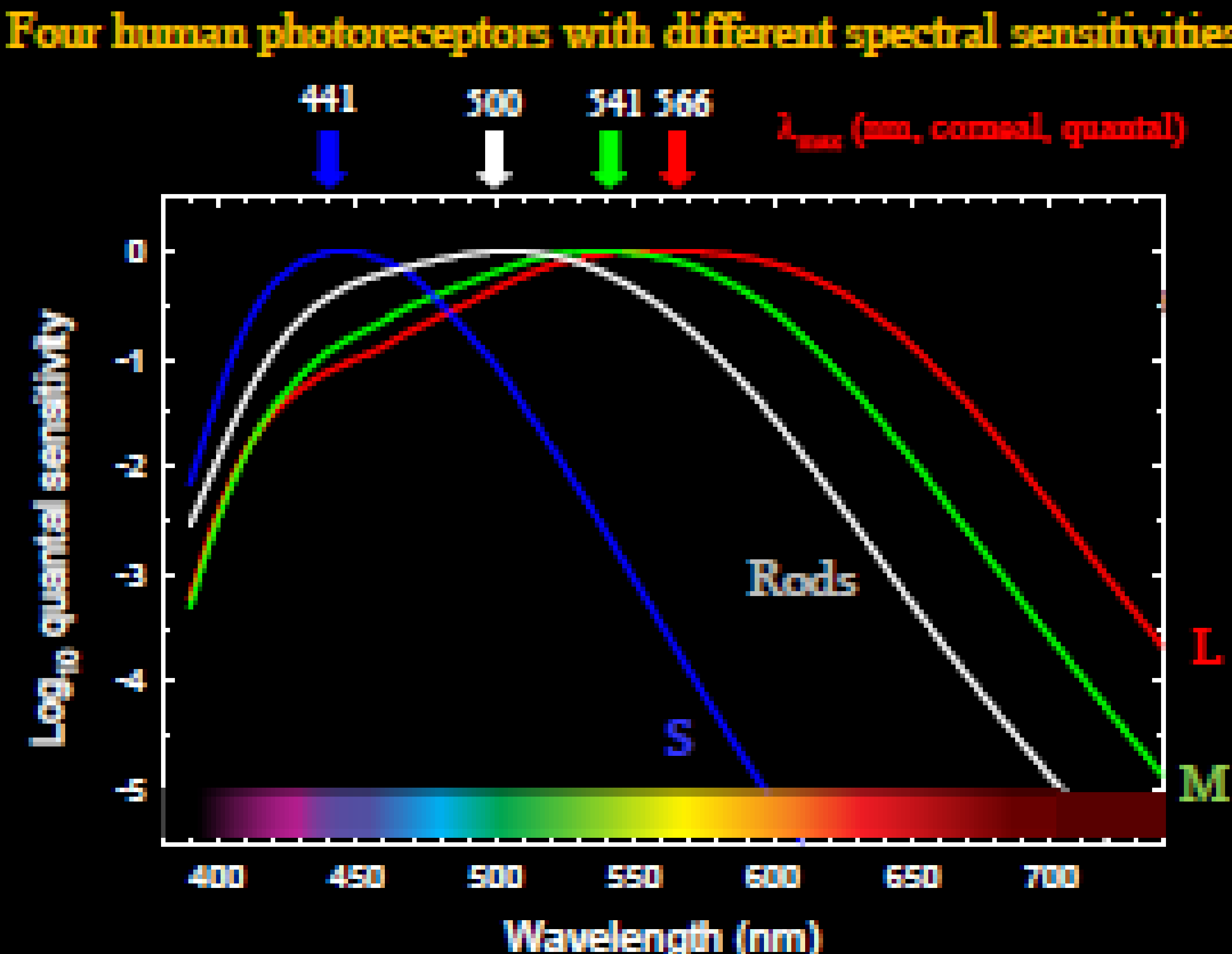
Part 4: Achromatic and chromatic contrast sensitivity (Exercise 4)

Part 2
Beyond the cones: opponent processing

- Cone vs hue opponent processing

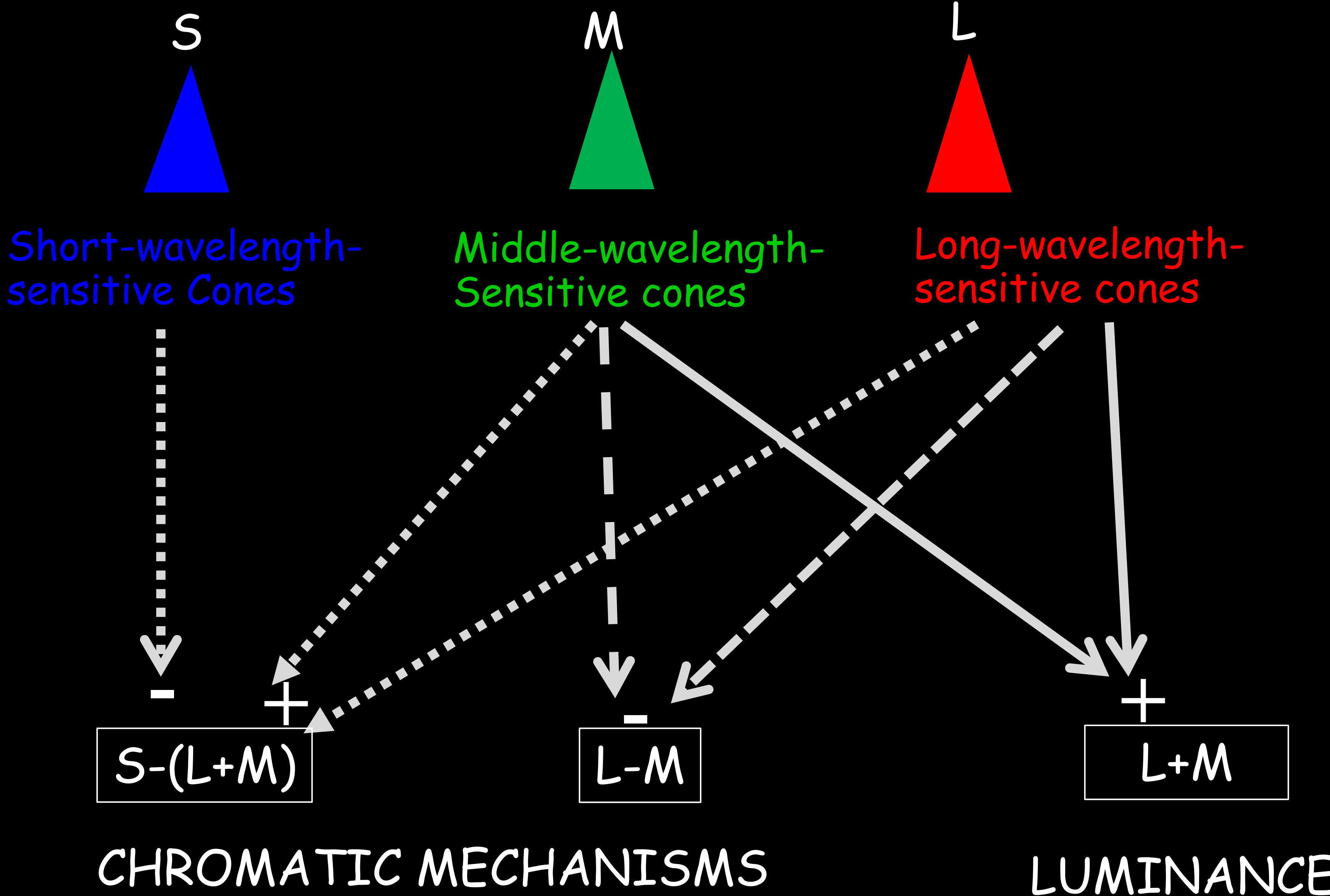
- Mapping from LMS cone space into cone-opponent and colour-opponent spaces

Spectral sensitivity

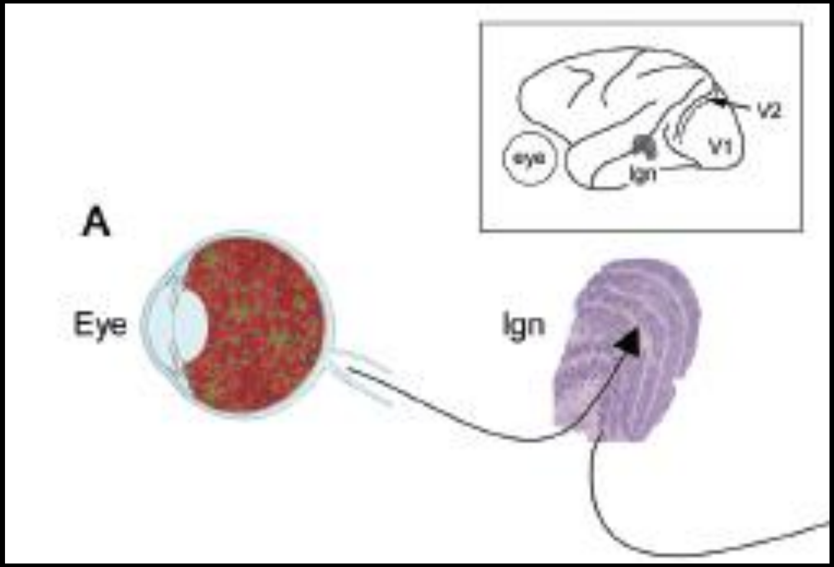


Source: Andrew Stockman

2nd stage of colour processing

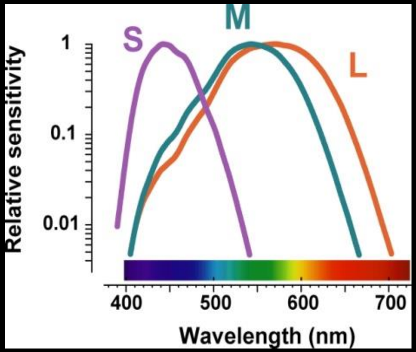


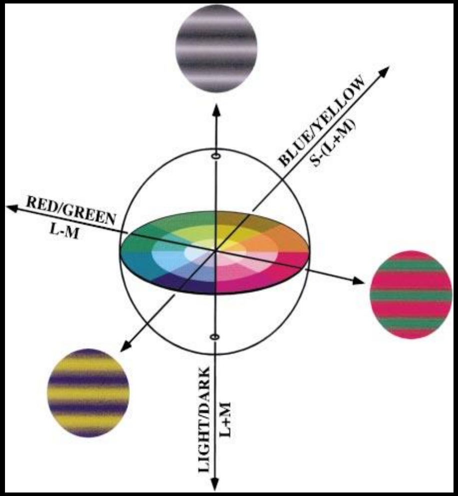
2nd stage colour processing



Adapted from Conway, Current Biology, 2003

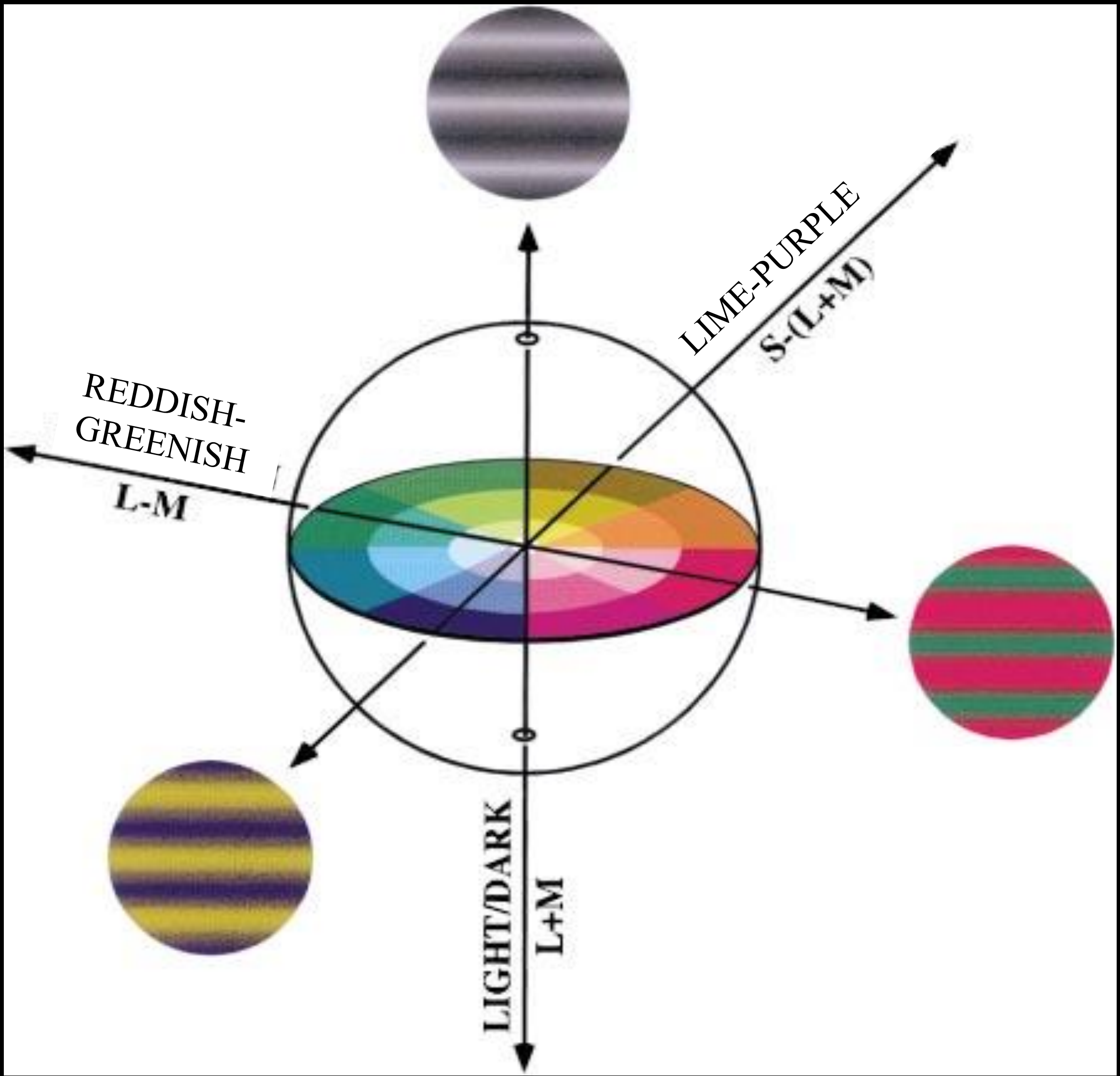
- DKL space
- 3-dimensional space inspired by physiology
- 3 mechanisms:
  luminance (L+M)
  L-M chromatic
  S-(L+M) chromatic





Derrington et al., 1982

2nd stage colour processing



Derrington-Krauskopf-Lennie, 1982

DKL space

Stimulus Appearance:
- Achromatic
- Reddish-Greenish
- Lime-purple

Defined in relation to a particular background colour

From cones to DKL space

For a given background (BG), we can derive the matrix that converts incremental LMS values to DKL coordinates.

$$\begin{bmatrix} \Delta\, LUM/kLUM \\ \Delta\,(L-M)/k_{LM} \\ \Delta\,(S-LUM)/k_{SLUM} \end{bmatrix} = \begin{bmatrix} & 1 & 0 \\ 1 & -LBG/MBG & 0 \\ -1 & -1 & (LBG+M_{BG})/SB1_{G} \end{bmatrix} * \begin{bmatrix} \Delta L \\ \Delta M \\ \Delta S \end{bmatrix}$$

where

$L_{BG}, MBG\ , S_{BG}$ *are the cone coordinates of the background.*

The coefficients k are chosen such that for a unit input vector in DKL space the DKL mechanism output equals 1 in cone contrast space.

From cones to DKL space

For a grey background with $L_{BG}, M_{BG}, S_{BG} = [78.03\ \ 34.34\ \ 2.31]$ the matrix is:

$$\begin{bmatrix} \Delta\, LUM \\ \Delta(L-M) \\ \Delta\,(S-LUM) \end{bmatrix} = \begin{bmatrix} 0.0154 & 0.0154 & 0 \\ 0.0097 & -0.0220 & 0 \\ -0.0088 & -0.0088 & 0.4319 \end{bmatrix} * \begin{bmatrix} \Delta L \\ \Delta M \\ \Delta S \end{bmatrix}$$

- The ‘LUM’ mechanism assigns equal weight to L and M cones and the S cone input is 0
- The L-M mechanism takes the weighted difference between the L and M cones
- The S-(LUM) mechanism takes the difference between the S cones and the sum of the equally weighted L and M cones

From DKL space to cone space

For a grey background with $\mathrm{L_{BG}, M_{BG}, S_{BG}} = [78.03 \;\; 34.34 \;\; 2.31]$ the inverse matrix is:

$$\begin{bmatrix} \Delta L \\ \Delta M \\ \Delta S \end{bmatrix} = \begin{bmatrix} 45.0520 & 31.4303 & 0 \\ 19.8256 & -31.4303 & 0 \\ 1.3369 & 0.0000 & 2.3155 \end{bmatrix} * \begin{bmatrix} \Delta\, LUM \\ \Delta(L-M) \\ \Delta\,(S-LUM) \end{bmatrix}$$

- A modulation along the LUM direction [1 0 0]' results in a modulation in all three cone classes, which keeps the colour achromatic.
- A modulation along the L-M direction [0 1 0]' results in a equal modulation of L and M cones but of opposite sign.
- A modulation along the S-LUM direction [0 0 1]' results only in a modulation of the S cones. That's why this direction is often referred to as S cone isolating.

From DKL space to RGB space

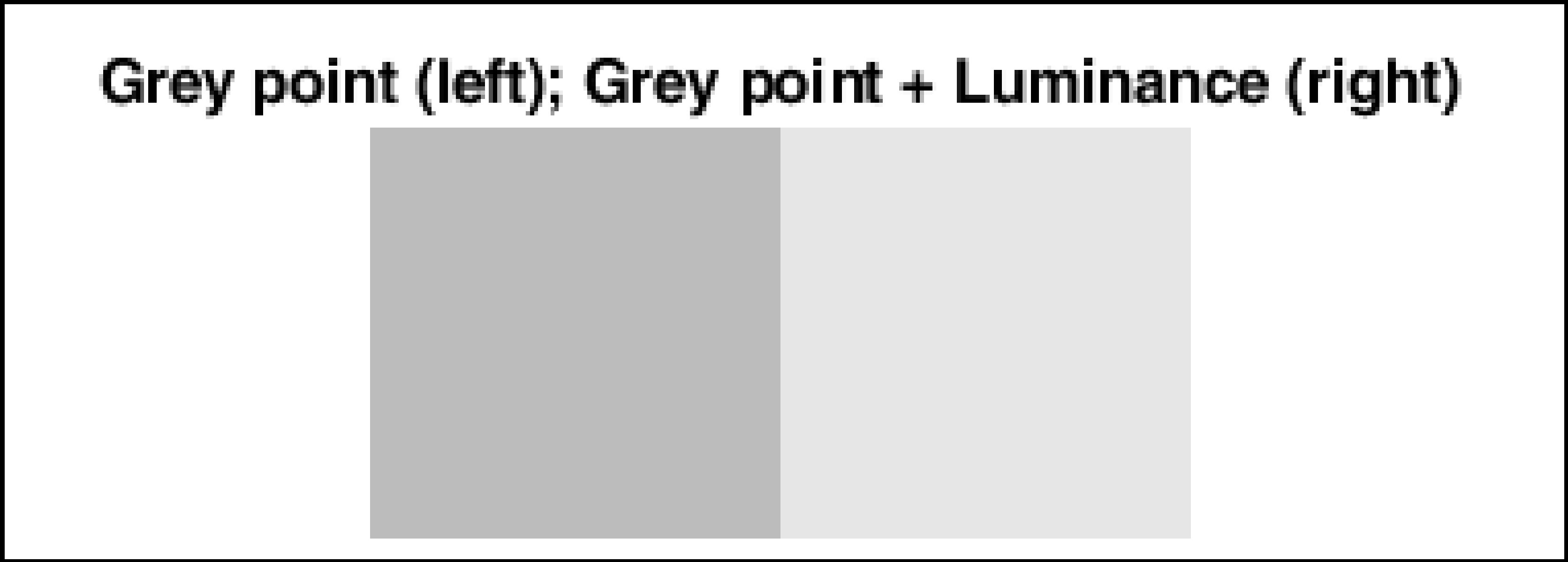
1. Set the background in RGB, i.e. mid grey (RGB=0.5 0.5 0.5)
2. Convert bg to LMS space using RGB2LMS (e.g. L_{BG}, M_{BG}, S_{BG} = [78.03 34.34 2.31])
3. Chose a vector in DKL space, e.g. a reddish stimulus [0 0.1 0]
4. Convert to LMS using matrix DKL2LMS
5. Add the LMS values to the LMS of the background
6. Convert to RGB using matrix LMS2RGB

(see exercises)

From DKL space to RGB space

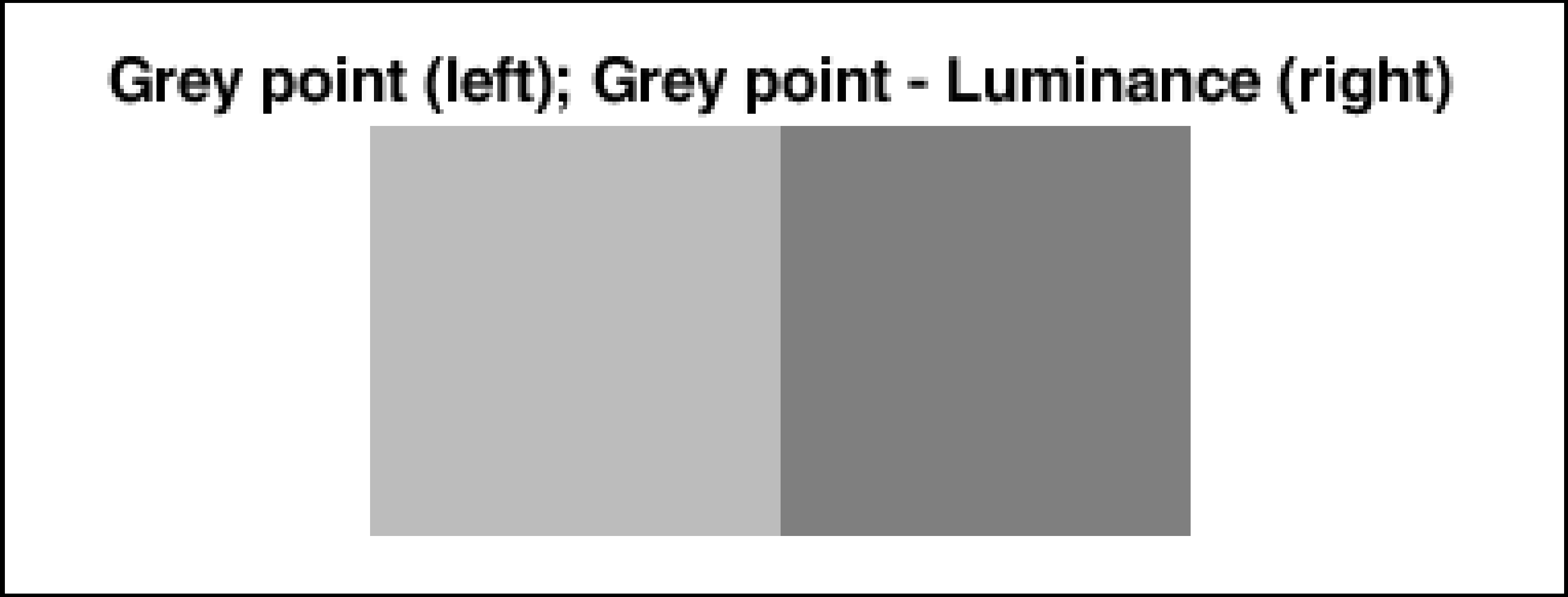
Set the background in RGB, i.e. mid grey (RGB=0.5 0.5 0.5)

Now we wish to isolate the lum mechanism by setting the dkl value to [1 0 0]'.



From DKL space to RGB space

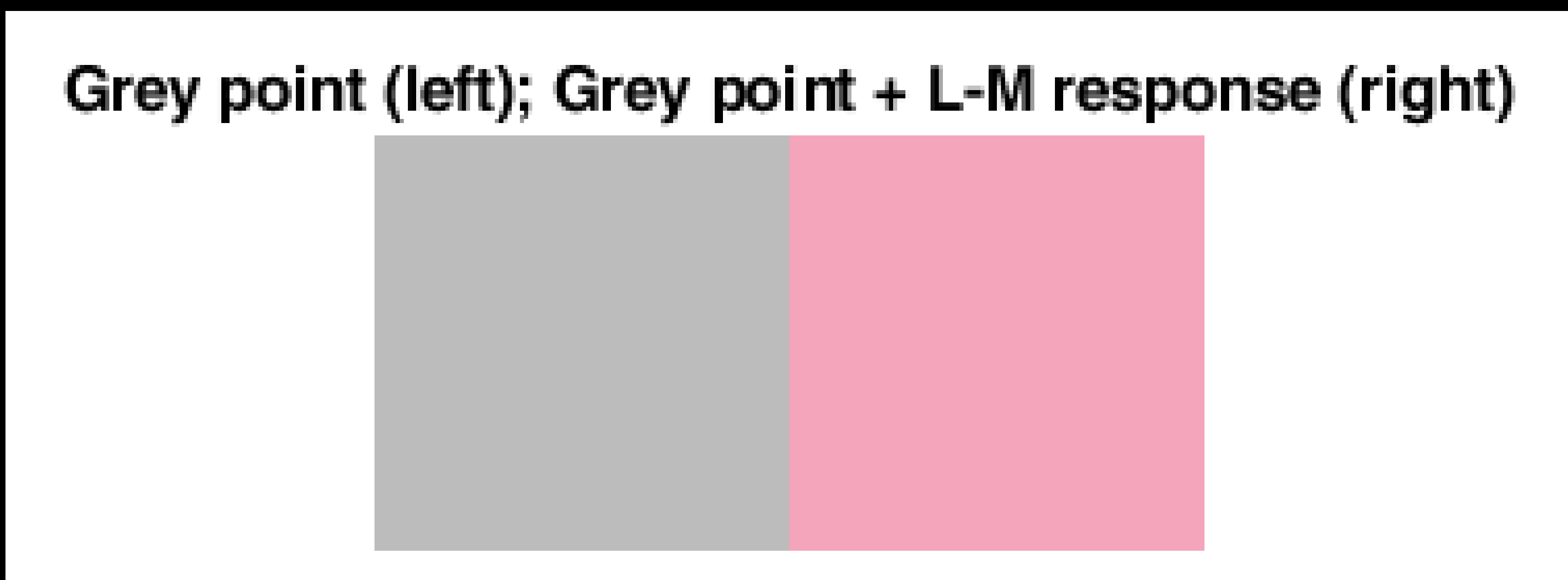
Set the background in RGB, i.e. mid grey (RGB=0.5 0.5 0.5)
Now we wish to isolate the lum mechanism by setting the dkl value to [-1 0 0]'.



From DKL space to RGB space

Set the background in RGB, i.e. mid grey (RGB=0.5 0.5 0.5)

Now we wish to isolate the rg mechanism by setting the dkl value to [0 0.12 0]'.



From DKL space to RGB space

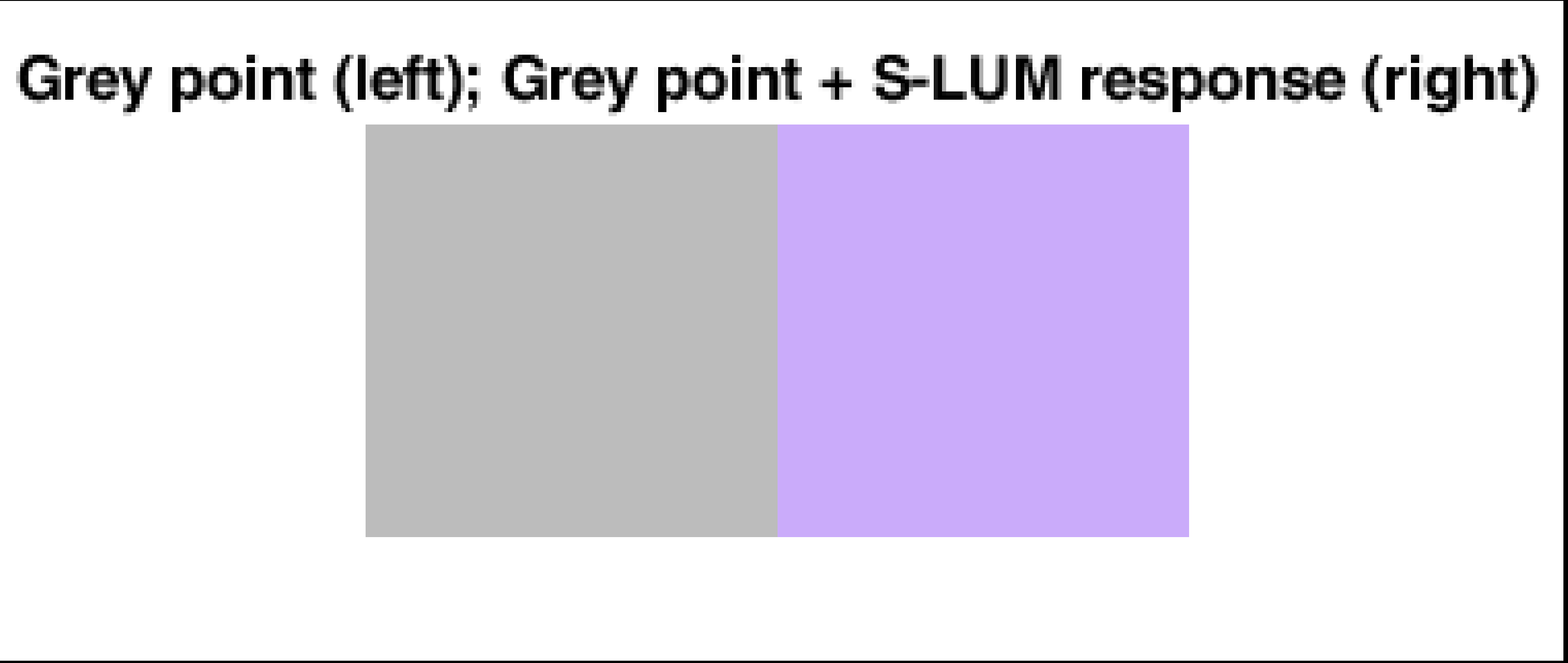
Set the background in RGB, i.e. mid grey (RGB=0.5 0.5 0.5)

Now we wish to isolate the rg mechanism by setting the dkl value to [0 -0.12 0]'.

From DKL space to RGB space

Set the background in RGB, i.e. mid grey (RGB=0.5 0.5 0.5)

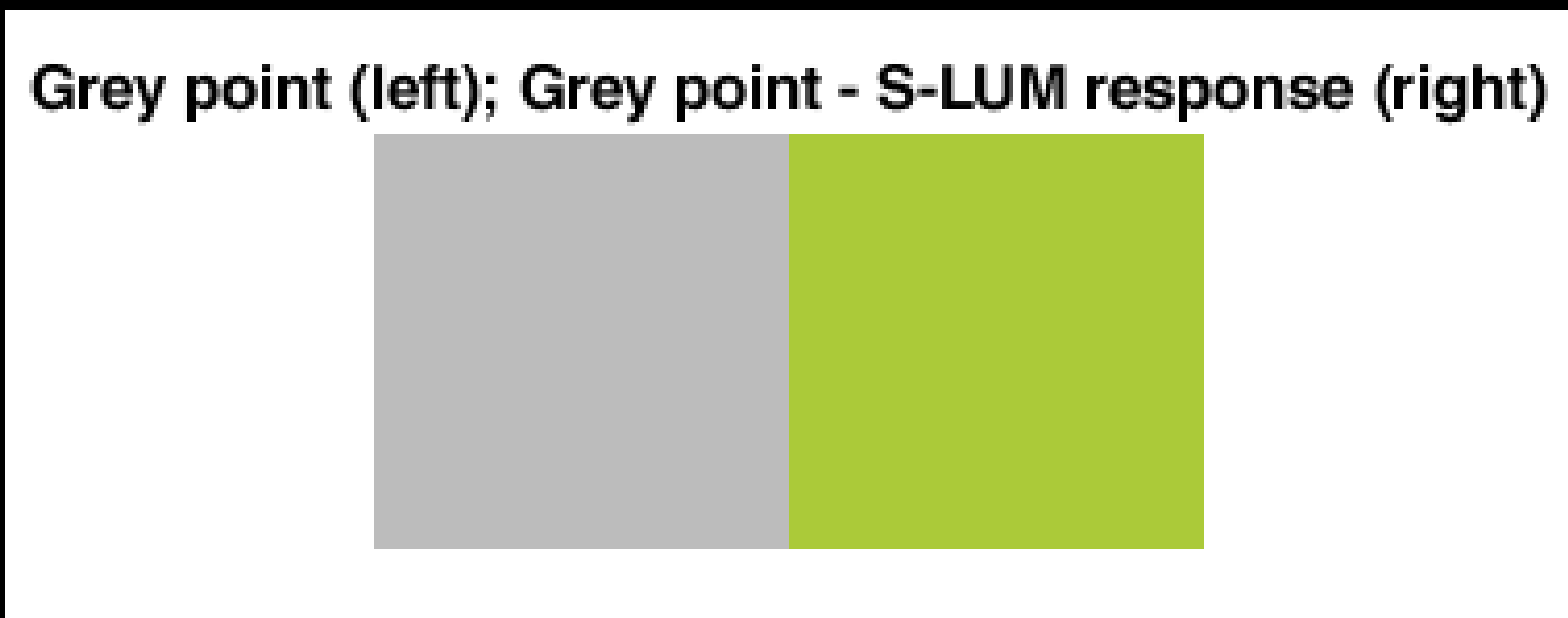
Now we wish to isolate the s cone mechanism by setting the dkl value to [0 0 0.8]'.



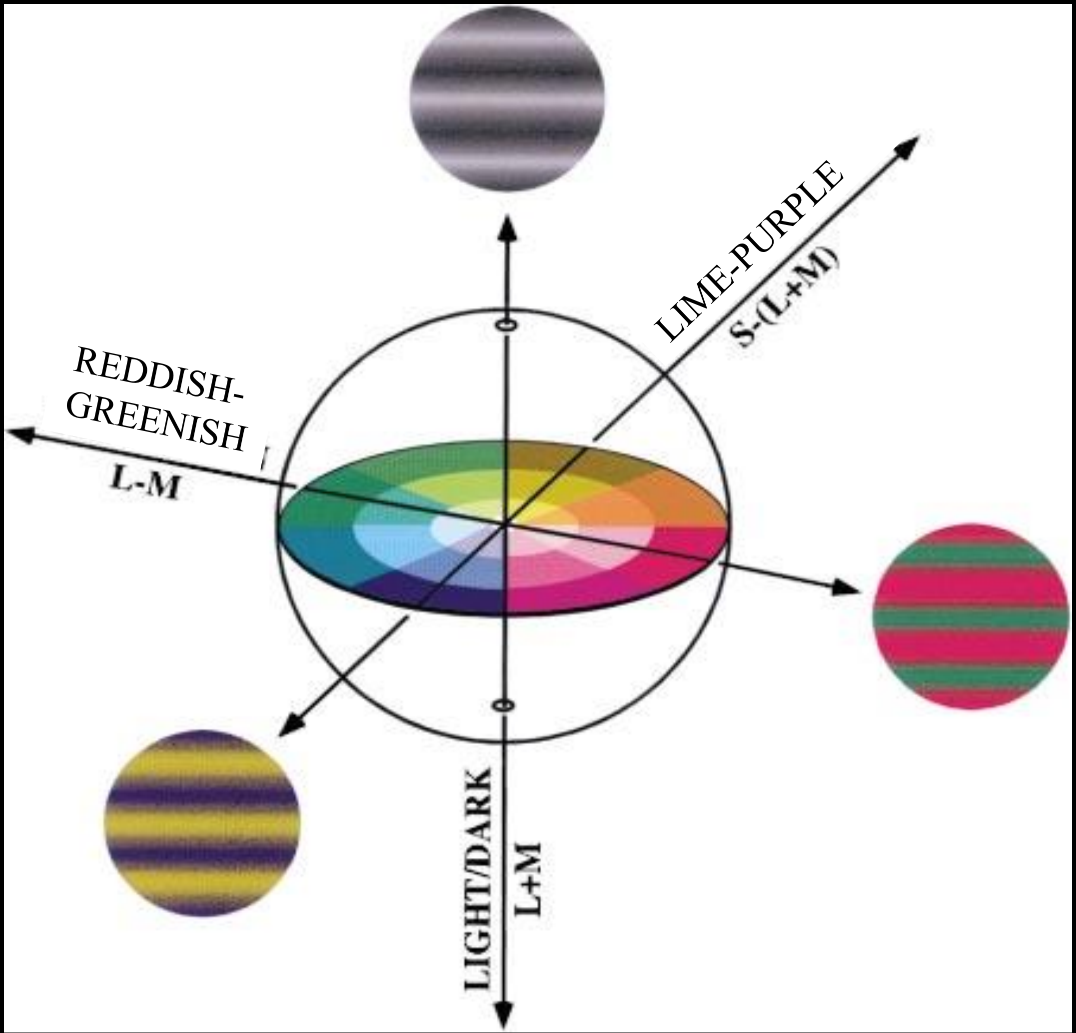
From DKL space to RGB space

Set the background in RGB, i.e. mid grey (RGB=0.5 0.5 0.5)

Now we wish to isolate the S cone mechanism by setting the dkl value to [0 0 -0.8]’.



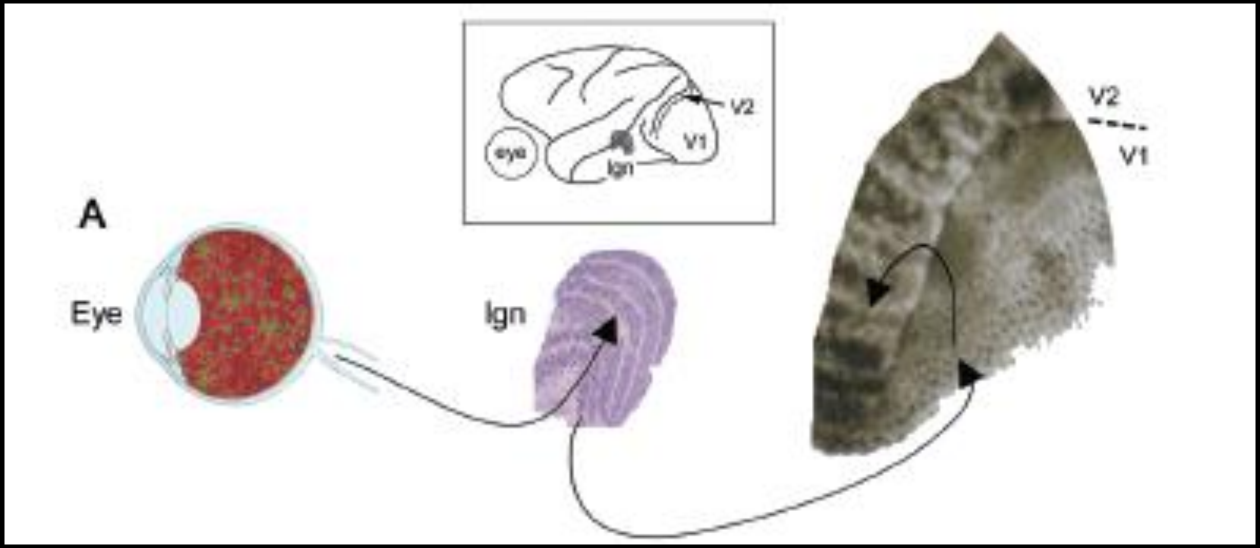
2nd stage of colour processing



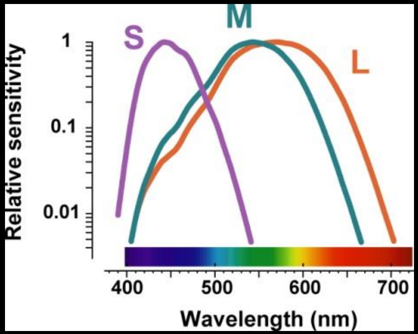
The endpoints of these physiologically inspired cone-opponent chromatic mechanisms do not reflect what colour normal observers consider 'Red', 'Green', 'Yellow' or 'Blue'.

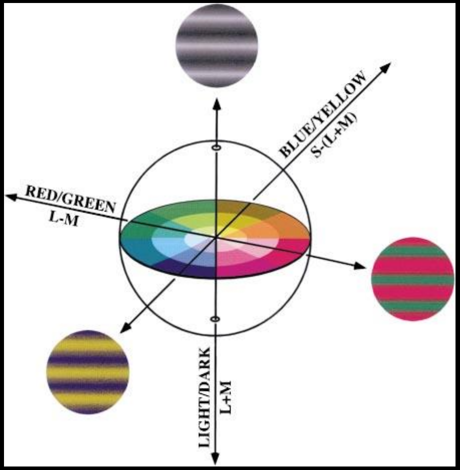
A third stage of colour processing must occur.

3rd stage of colour processing

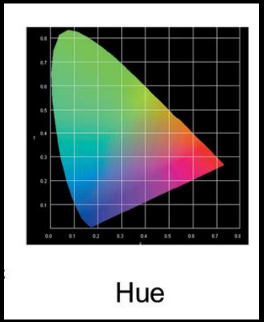


Adapted from Conway, Current Biology, 2003





Derrington et al., 1982

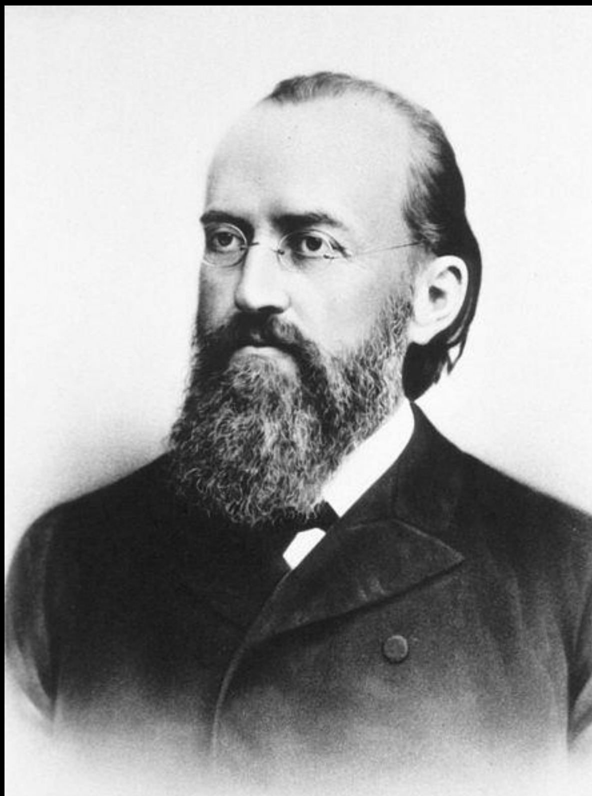


Color–opponent Theory

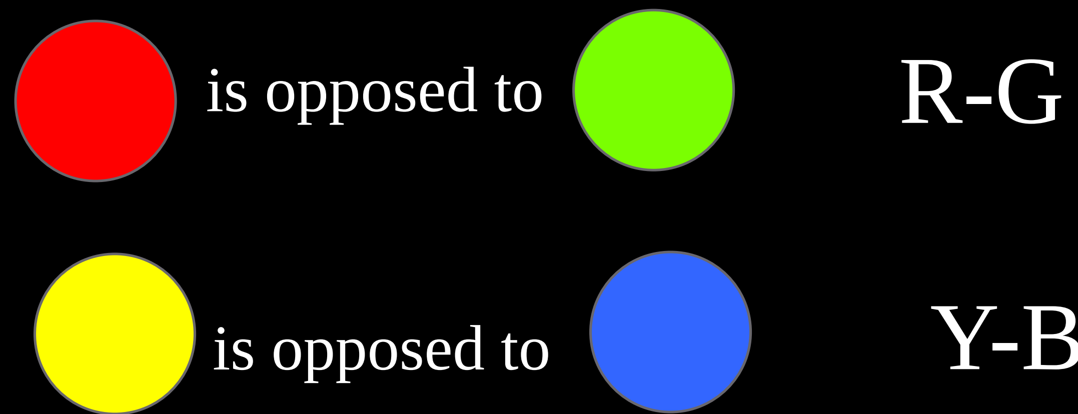
Karl Ewald Konstantin Hering
(August 5, 1834 – January 26, 1918)

Hering was the first to notice that some pairs of colours, namely red and green, and yellow and blue, cannot be perceived at the same time. He named these pairs of colours the opponent colours (red-green, yellow-blue) since they are mutually exclusive colours.

Color-opponent Theory



Karl Ewald Konstantin Hering (August 5, 1834 – January 26, 1918)

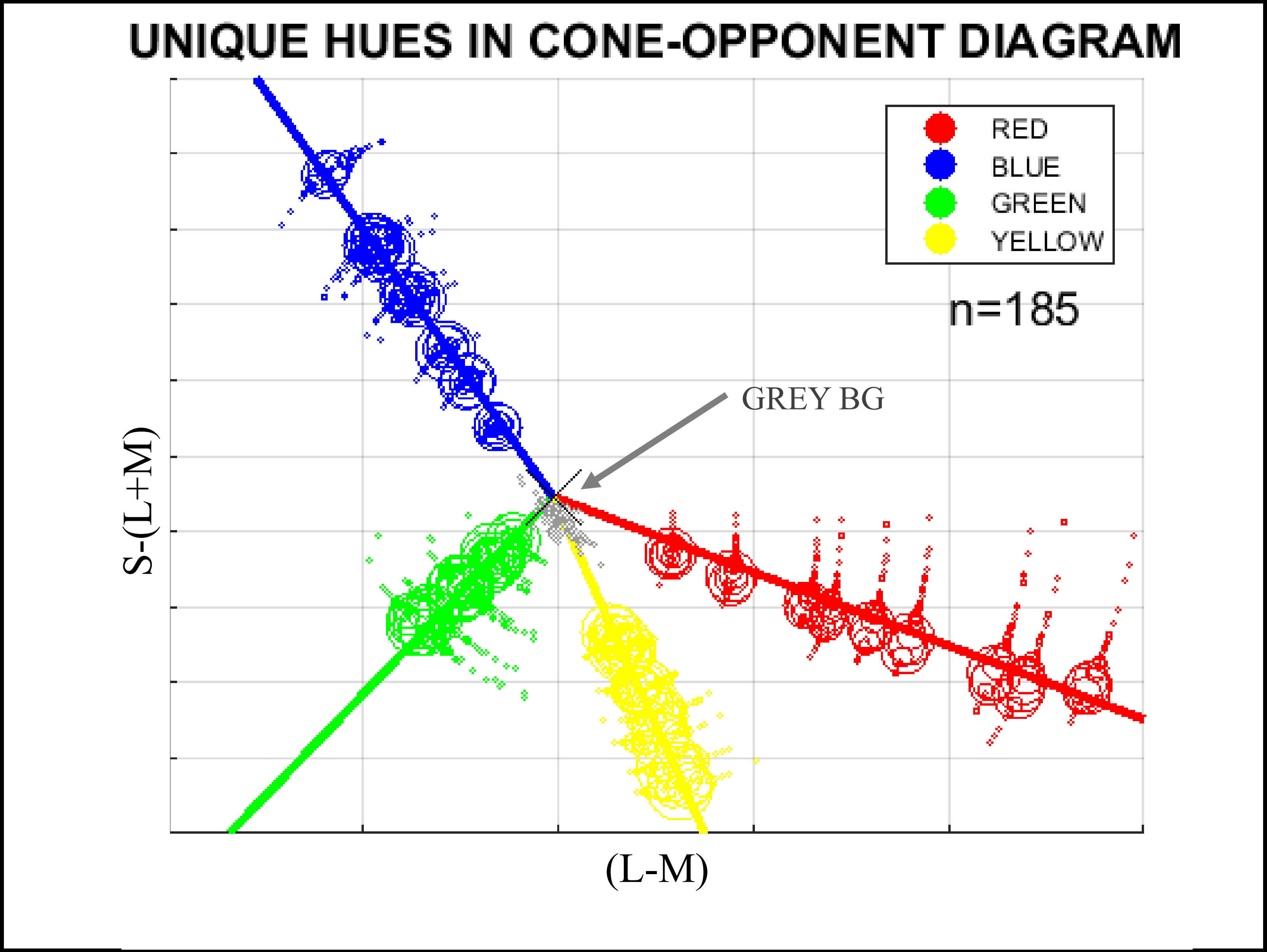


From these opponent processes, the 'unique hues' are derived.

Hues that are neither red nor green, are called unique yellow and blue.

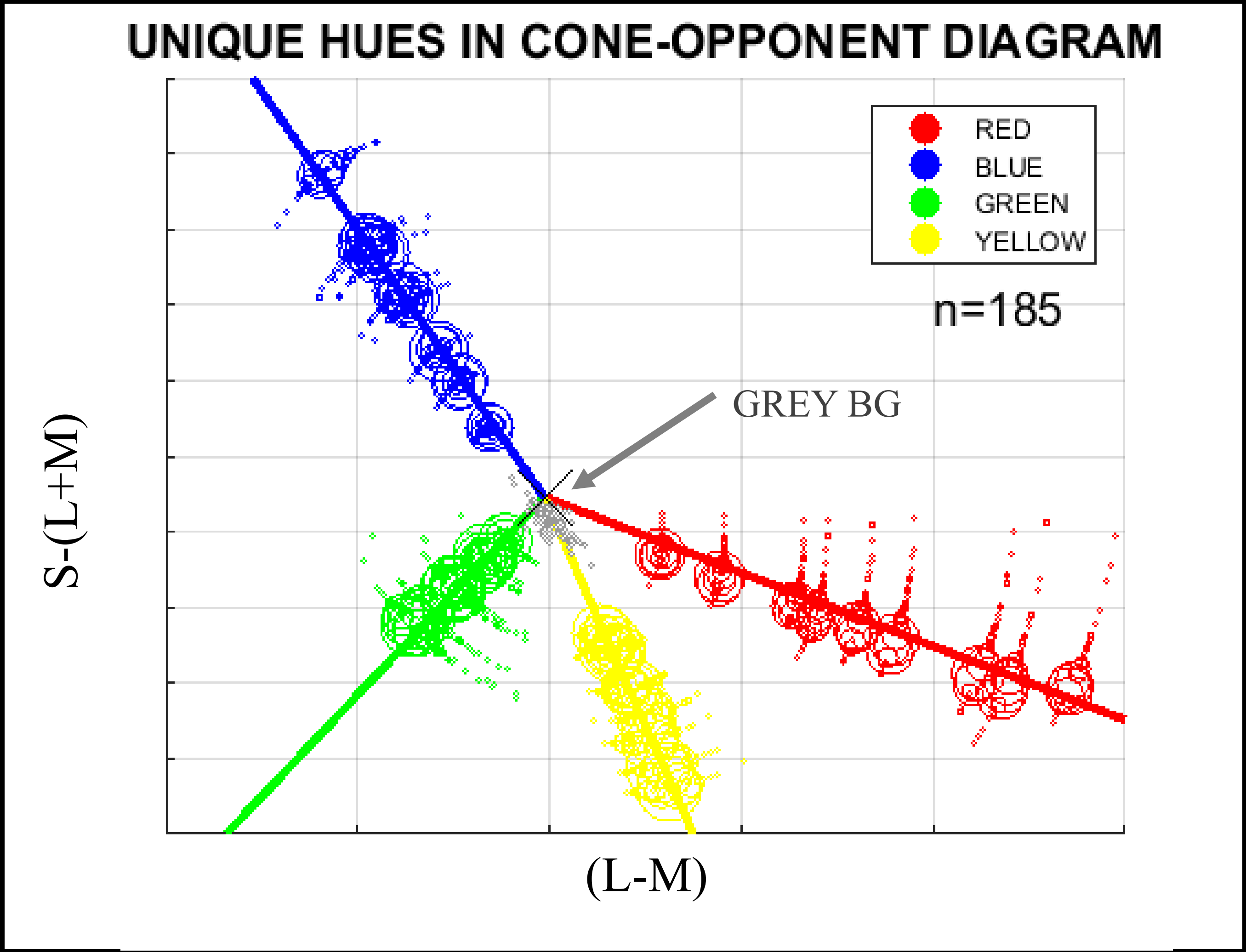
Hues that are neither yellow nor blue, are called unique red and unique green.

UNIQUE HUES



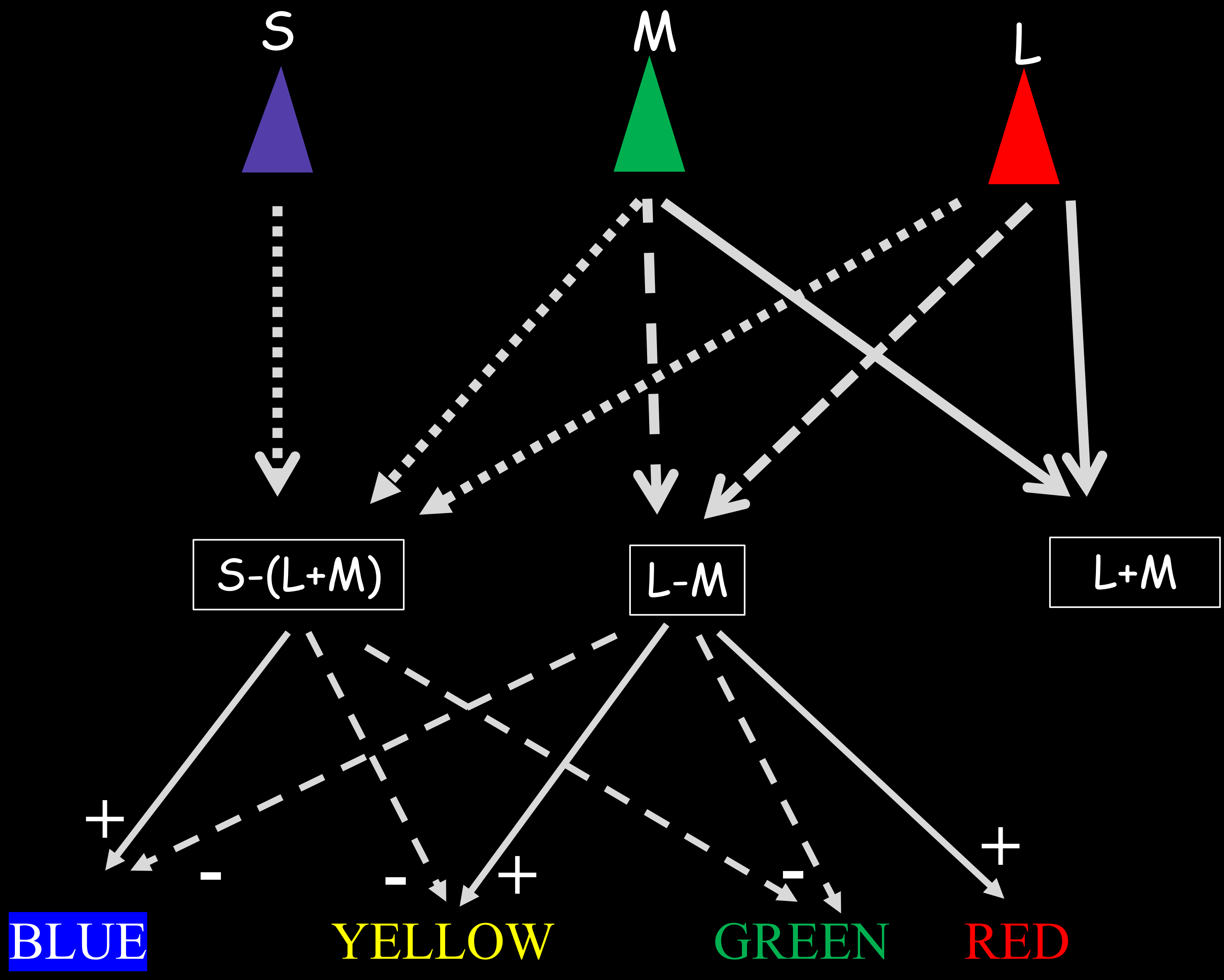
UNIQUE HUES IN CONE-OPPONENT DIAGRAM
RED
BLUE
GREEN
YELLOW
n=185
GREY BG
S-(L+M)
(L-M)

UNIQUE HUES



Unique hues are not aligned with the cone-opponent axes; further recombination of the cone-opponent outputs occurs

3rd stage of colour processing



3rd stage of colour processing

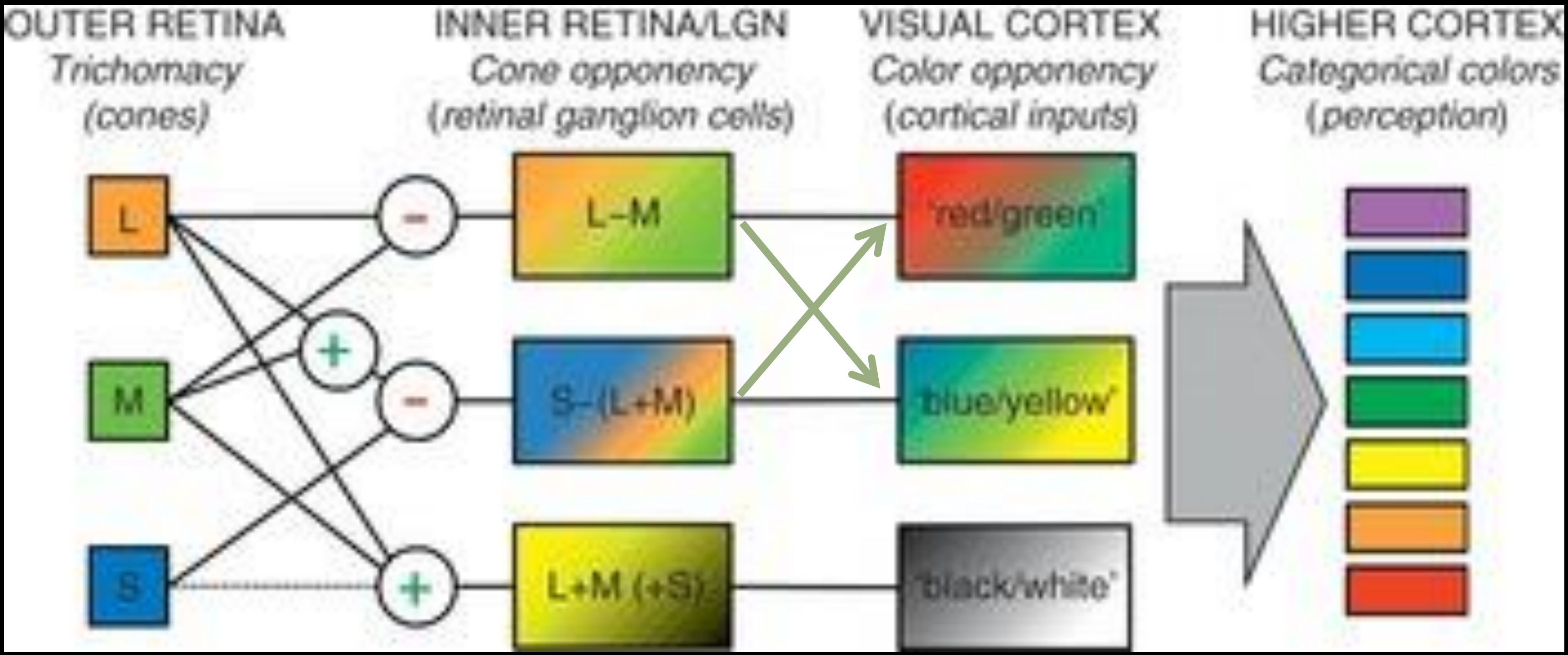


Figure from Parry, N: Color Vision Deficiencies; in Part III: Development of and differences in color vision, Ed: Elliot, Fairchild and Franklin (2016)

DeValois & DeValois, 1993,VR

Summary of Part 2

- The 2nd stage of colour processing consists of a cone-opponent stage where the cone signals are combined in three post-receptoral mechanisms: L+M, L-M, S-(L+M)
- The output of these cone-opponent mechanisms is further combined into colour-opponent (i.e. hue-opponent) mechanisms: red-green; yellow-blue; light-dark.
- The null points of these colour-opponent mechanisms are assumed to correspond to the unique hues.

Exercise 2

3.1. Compute the LMS cone outputs for an achromatic stimulus with a DKL coordinate of [0.5 0 0]. Compute the RGB values for this stimulus. Same for [1 0 0].

3.2. Compute the LMS cone outputs for an isoluminant red-green stimuli with a DKL coordinate of [0 0.5 0]. Convert to RGB. Is this stimulus within the gamut of the display?

3.3. Compute the LMS and RGB values for an isoluminant S-cone isolating stimulus with a DKL coordinate of [0 0 0.5]. Check whether it is within the gamut of this display.

3.4. Use the LMS of the background as the stimulus. Compute the DKL coordinate.

Overview

Part 1: Physics of light and receptors: display spectra to receptor outputs (Exercise 1)

Part 2: Opponent processing; cone vs hue opponency (Exercise 2)

Part 3: Colour spaces: LMS, XYZ, CIELAB, CIELUV (Exercise 3)

Part 4: Achromatic and chromatic contrast sensitivity (Exercise 4)

Colour spaces

Device-dependent

Spectra →

RGB space

Device-independent

LMS cone space

DKL

CIE XYZ

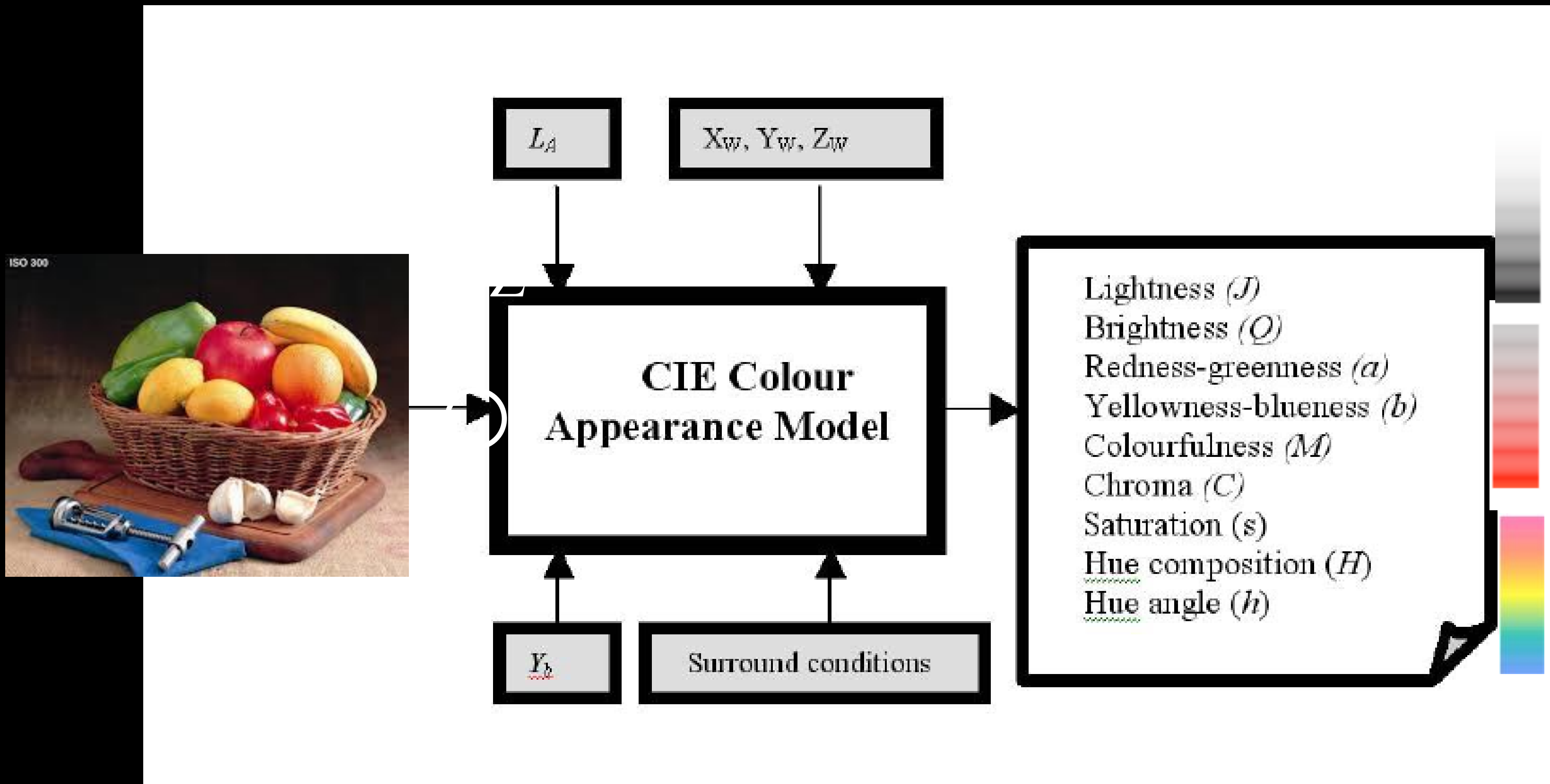
based on colour matching

no metric

Colour spaces

- **LMS, XYZ**: these colour spaces are based on colour matching - when two lights result in the same LMS cone outputs, these two lights will map into the same point in these colour spaces
- No distance measure that predicts the similarity of two colours (no metric)
- No direct link to colour appearance, such as redness, saturation, et.

COLOUR APPEARANCE MODELS



Luo & Li, 2017. Colorimetry: Understanding the CIE System, pp.261 – 294

Colour spaces

Device-dependent	*Device-independent*	
Spectra →	**LMS cone space** →	**CIE LAB**
RGB space	**DKL**	**CIE LUV**
	CIE XYZ	
	based on colour matching	*uniform appearance*
	no metric	

[6] Encyclopedia of Color Science and Technology (ECST) Ed. Luo/Shamey

CIE u′, v′ Uniform Chromaticity Scale Diagram and CIELUV Color Space

János Schanda
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Synonyms

CIE 1976 L*u*v* color space; UCS diagram; Uniform chromaticity scale diagram

Definitions

Uniform Chromaticity Scale Diagram (UCS Diagram)

The CIE 1976 uniform chromaticity scale diagram is a projective transformation of the CIE x,

János Schanda: deceased

$$u' = \frac{4x}{-2x + 12y + 3} \tag{3}$$

$$v' = \frac{9y}{-2x + 12y + 3} \tag{4}$$

here

$$x = \frac{X}{X + Y + Z} \quad \textbf{and } y = \frac{Y}{X + Y + Z}\,. \tag{5}$$

Uniform Color Space

The CIE 1976 $L^*u^*v^*$ color space is a three-dimensional, approximately uniform color space produced by plotting in rectangular coordinates, L^*, u^*, v^*, quantities defined by the equations

$$L^* = 116\, f\left(\frac{Y}{Y_n}\right) - 116 \tag{6}$$

$$u^* = 13\, L^* \left(u' - u'_n\right) \tag{7}$$

$$v' = 13 L^* \left(v' - v'_n\right) \tag{8}$$

where

$$f\left(\frac{Y}{Y_n}\right) = \left(\frac{Y}{Y_n}\right)^{1/3} \quad \textbf{if} \quad \frac{Y}{Y_n} > \left(\frac{6}{29}\right)^3 \tag{9}$$

CIELUV

Correlates of Lightness, Saturation, Chroma, and Hue

Approximate correlates of the perceived attributes lightness, saturation, chroma, and hue are calculated as follows:

CIE 1976 lightness	L^* as defined by Eq. 6
CIE 1976 u,v saturation (CIELUV saturation)	$s_{uv} = 13\left[\left(u' - u'_n\right)^2 + \left(v' - v'_n\right)^2\right]^{1/2}$
CIE 1976 u,v chroma (CIELUV chroma)	$C^*_{uv} = \left[\left(u^*\right)^2 + \left(v^*\right)^2\right]^{1/2}$
CIE 1976 u,v hue angle (CIELUV hue angle)	$h_{uv} = \arctan\left({}^{v^*}/_{u^*}\right)$

Color Differences

The CIE 1976 $L^*u^*v^*$ color difference, ΔE^*_{uv}, between two color stimuli is calculated as the Euclidean distance between the points representing them in the space:

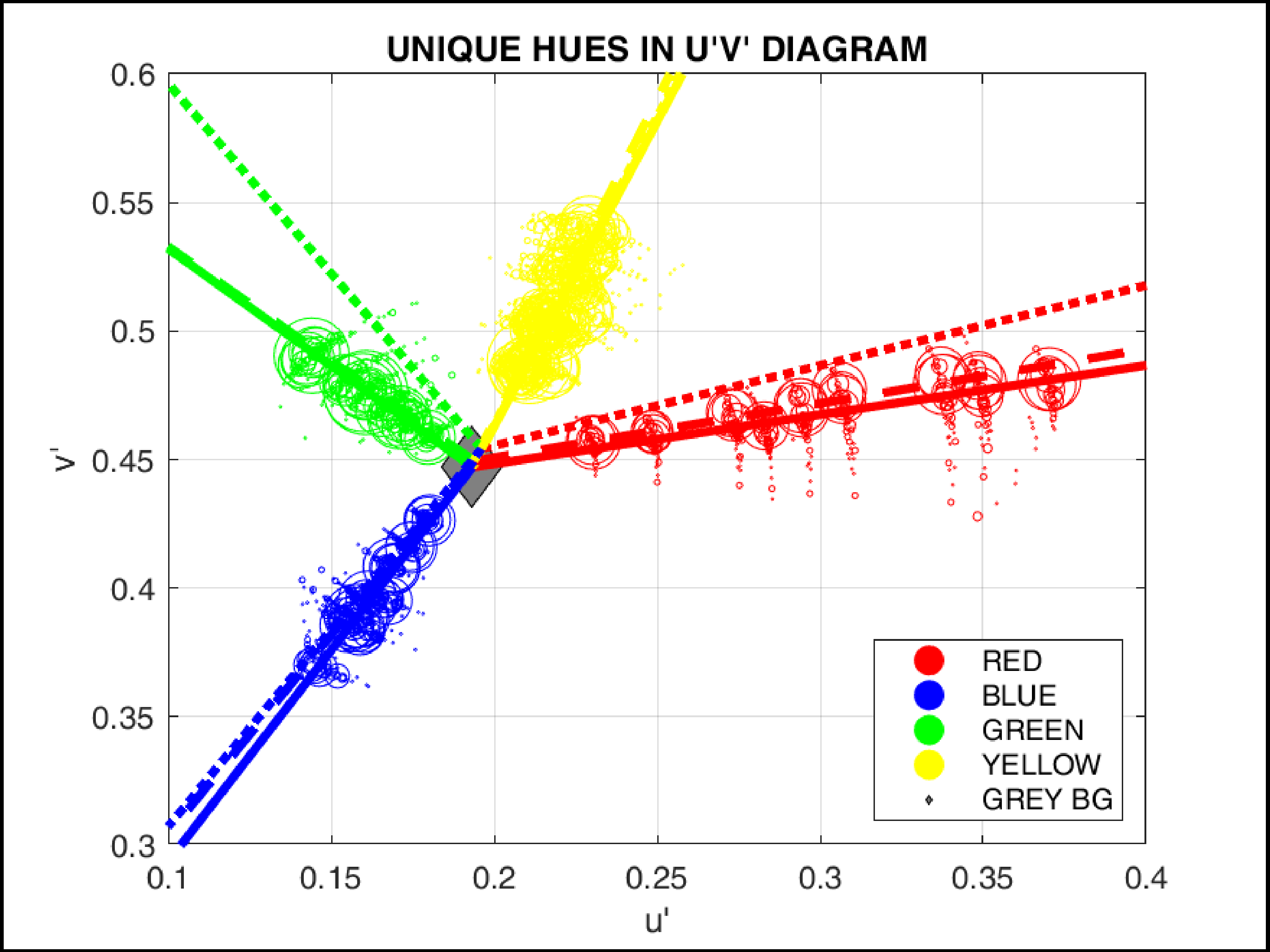
$$\Delta E^*_{uv} = \left[(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2\right]^{1/2}$$
$$\text{or } \Delta E^*_{uv} = \left[(\Delta L^*)^2 + \left(\Delta C^*_{uv}\right)^2 + \left(\Delta H^*_{uv}\right)^2\right]^{1/2} \tag{11}$$

where $\Delta H^*_{uv} = 2\left(C^*_{uv,1}\, C^*_{uv,2}\right)^{½} \sin\left(\Delta h_{uv}/2\right)$.

For further details and calculating differences of color coordinate components, see Eq. 1.

- Perceptual attributes
- Distance measure

CIELUV



u′,v′ are not aligned with unique hues

CIELAB

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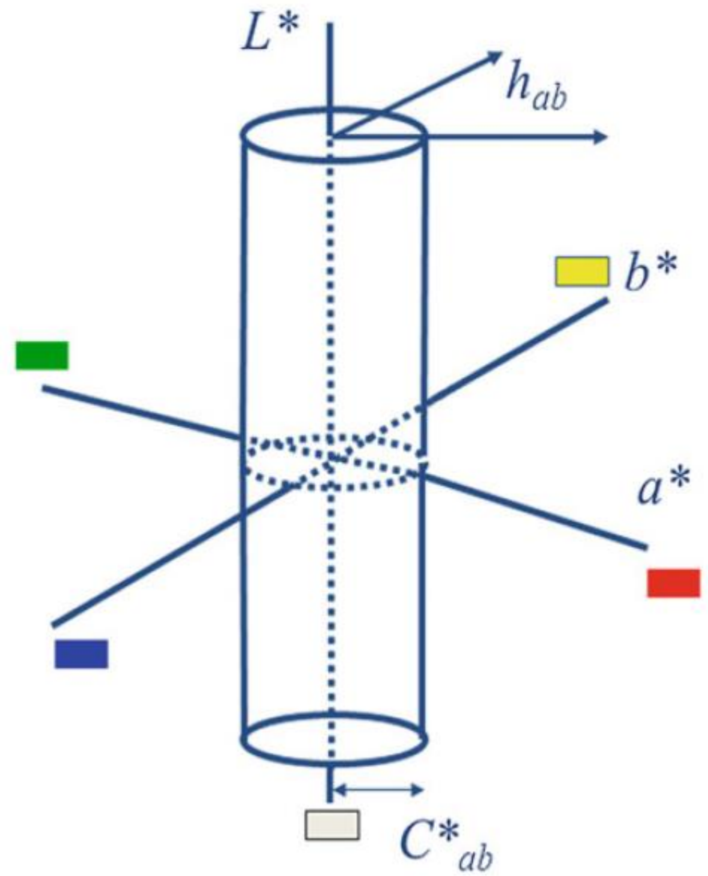
[6] Encyclopedia of Color Science and Technology (ECST) Ed. Luo/Shamey

$$
\begin{aligned}
L^* &= 116 f(Y/Y_n) - 16 \\
a^* &= 500[f(X/X_n) - f(Y/Y_n)] \qquad (2) \\
b^* &= 200[f(Y/Y_n) - f(Z/Z_n)]
\end{aligned}
$$

Figure 2 shows the CIELAB color space. It can be seen that the rectangular coordinates consist of L^*, a^*, and b^*. A positive and negative values of a^* represent reddish and greenish colors,



CIELAB, Fig. 2 Illustration of CIELAB color space

Exercise 3

Use colour toolbox to convert between colour spaces

- Compare luminance and lightness L*: luminance is linear as a function of linear RGB; Lightness L* is non-linear
- Change lightness level L* and check how the gamut is changing

Overview

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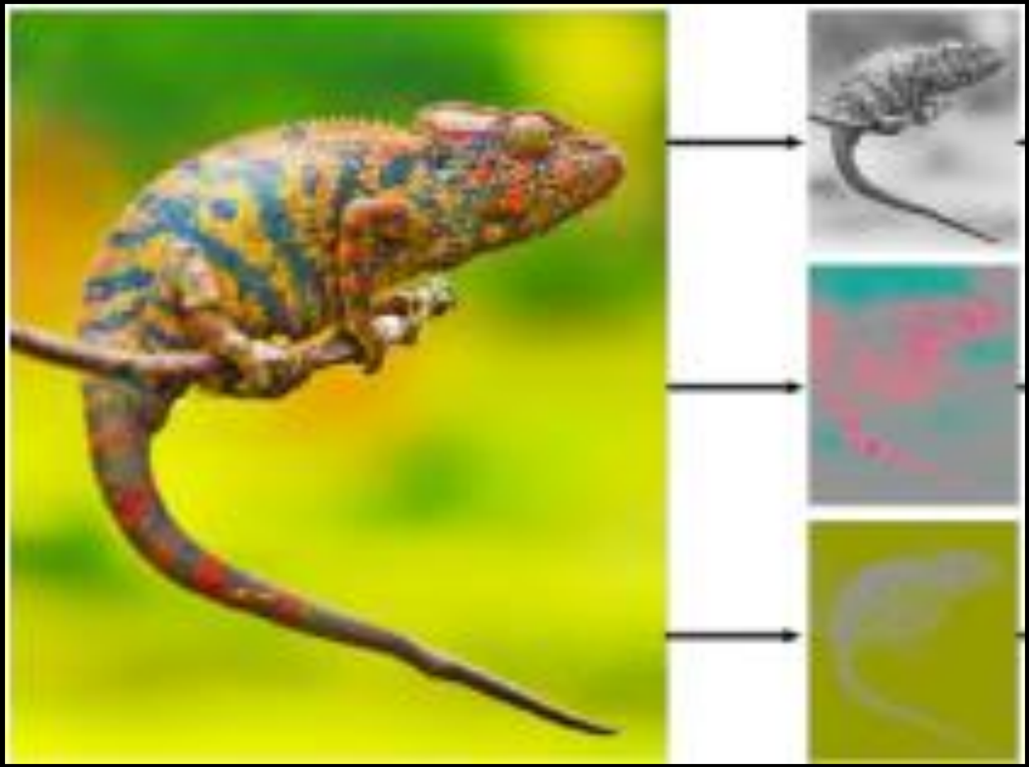
Part 4: Spatio-chromatic vision: achromatic and chromatic contrast sensitivity (Exercise 4)

SPATIO-CHROMATIC VISION

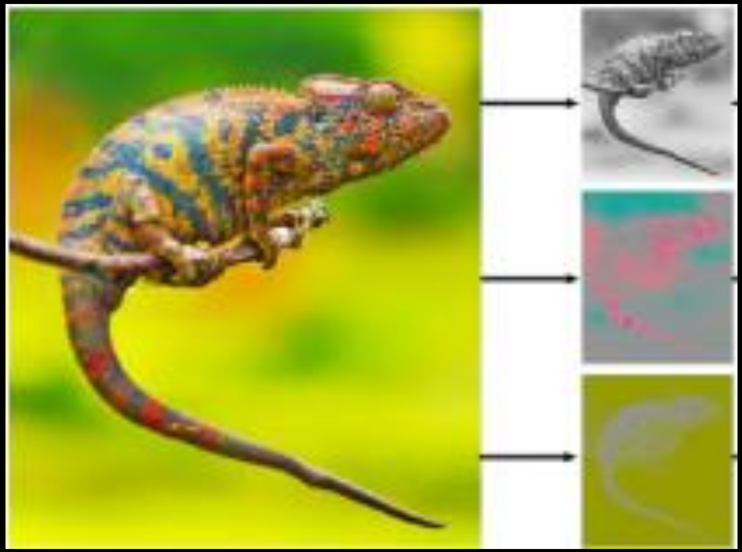


Colour Appearance depends not only on the colour signals, but also on the spatial content of an image; and vice versa, the human visual system is differentially sensitive to spatial detail in different colour planes (Lum, RG and YV)

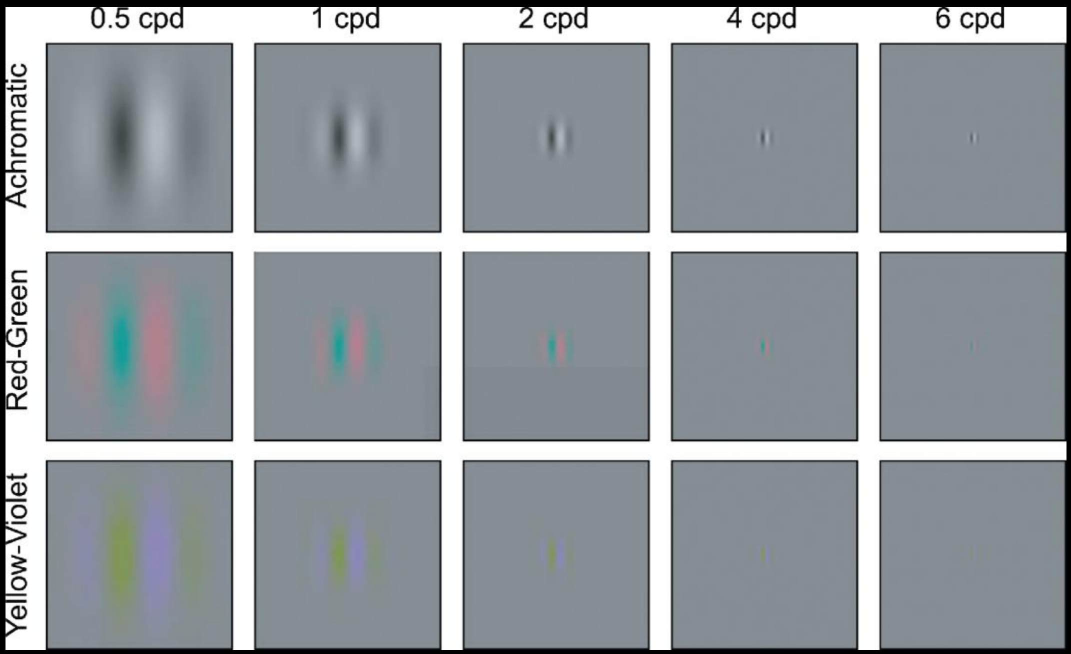
Courtesy of Rafal Mantiuk. Adapted from Wandell: Foundations of Vision

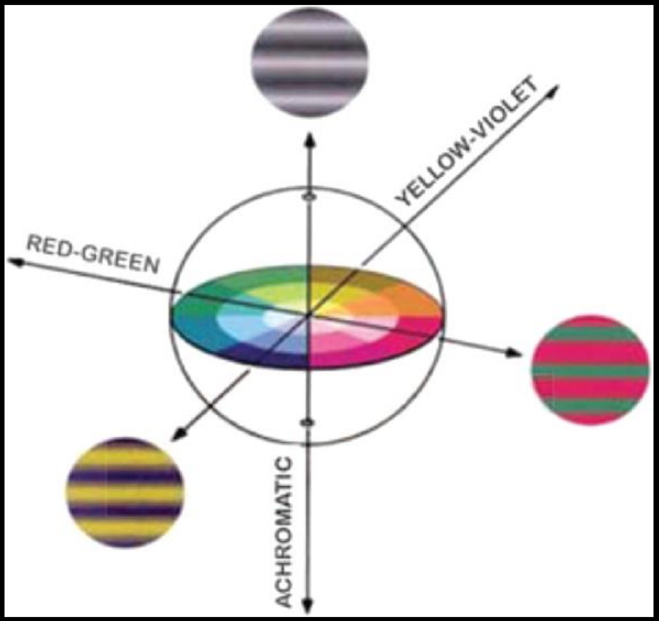
Purpose

- We measured spatial contrast sensitivity as a function of light level for the three post-receptoral colour directions
- One of the aims was to collect data necessary for retargeting images across different adapting light levels.
- To predict the visibility/appearance of complex images from threshold measurements for a set of simple spatial stimuli (Gabor patches) and a small set of colour directions



METHODS





Measure spatial contrast sensitivity for three cardinal directions for background luminances ranging from 0.02 to 7000 cd/m^2.

RESULTS

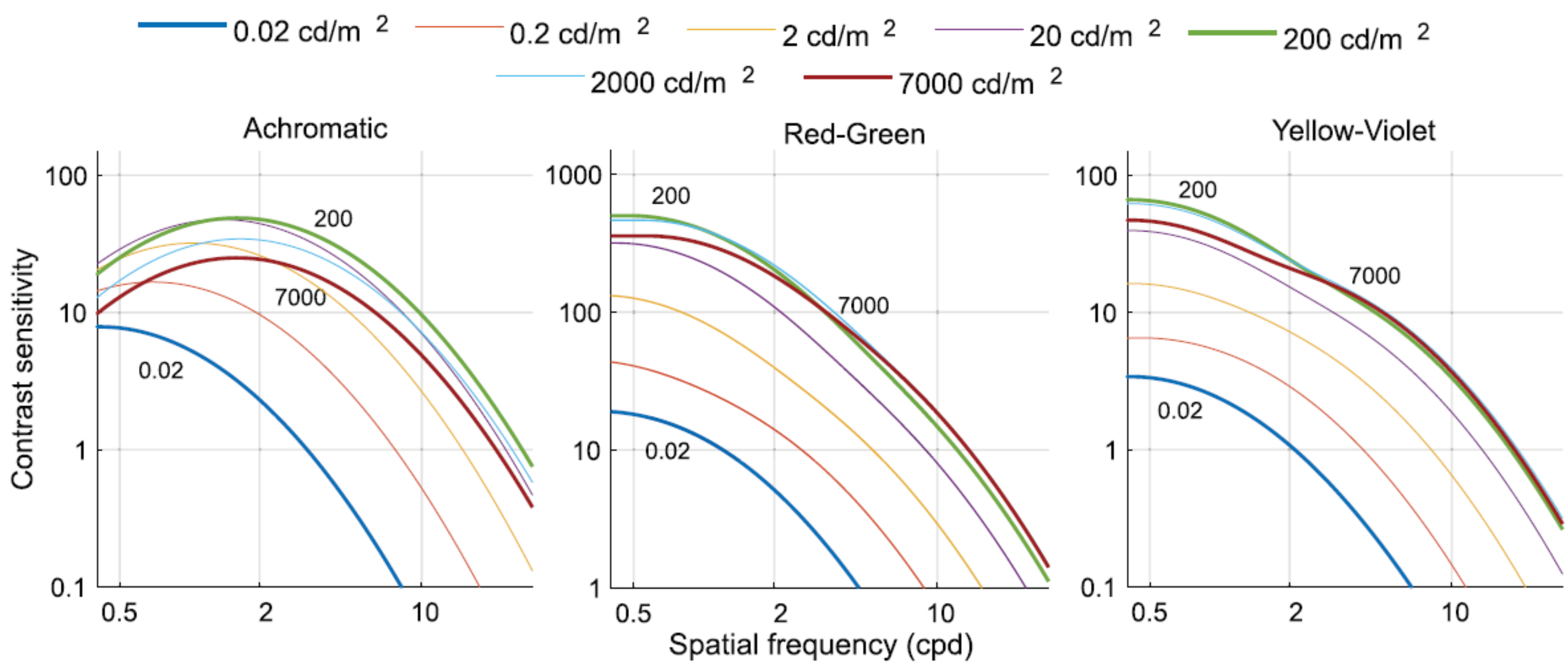
$$C_t = \frac{1}{\sqrt{3}}\sqrt{\left(\frac{\Delta L}{L_0}\right)^2 + \left(\frac{\Delta M}{M_0}\right)^2 + \left(\frac{\Delta S}{S_0}\right)^2}$$

C_t = Threshold cone contrast

$\Delta L, \Delta M, \Delta S$ = Incremental L,M,S-cone $\times$ absorptions

L_0, M_0, S_0 = L,M,S absorptions of the $\times$ display background (5)

Chromatic and achromatic contrast sensitivity as a function of light level



Contrast sensitivity as a function of light level

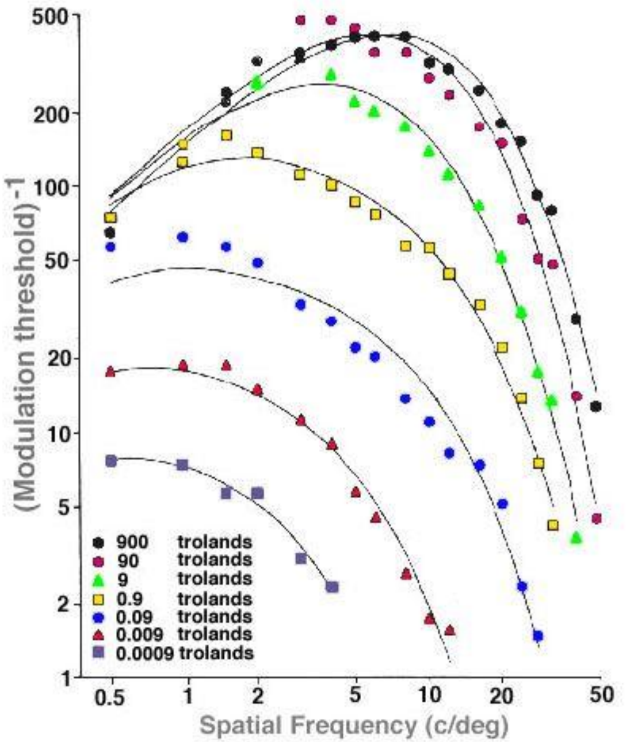


Figure 24. Contrast sensitivity function showing a change in shape from low pass at low luminances and bandpass at high luminances. van Ness' data from Lamming D., Contrast Sensitivity. Chapter 5. In: Cronly-Dillon, J., Vision and Visual Dysfunction, Vol 5. London: Macmillan Press, 1991.

- Contrast sensitivity for achromatic ('luminance') stimuli does not saturate at 200 cd/m^2 (Ness et al)
- Achromatic Sensitivity decreases at higher light levels

Contrast sensitivity as a function of light level

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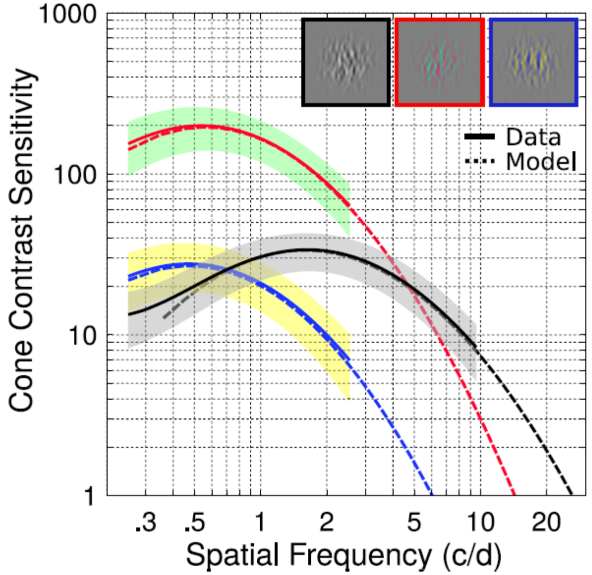

FIGURE 2. Measured CCS as a function of spatial frequency for the Ach (*solid black line*), RG (*solid red line*), and BY (*solid blue line*) conditions under monocular viewing. The average across the 51 subjects is shown. The *dotted lines* indicate the log-parabola model estimation, which is reconstructed with the average estimated values for each of the three parameters by the *qCSF*. The averaged model parameters are reported in the Table. The shaded regions represent ± SD.

- The chromatic contrast sensitivity functions are lowpass at all luminance levels (e.g. Mullen, 1985; Kim et al, 2017).
- Chromatic contrast sensitivity increases up to 200 cd/m^2; then saturates or slightly decreases at low spatial frequencies

- In summary, the spatial sensitivity of the visual system differs for achromatic and chromatic stimuli.
- For very high light levels, the achromatic sensitivity is decreasing, but fairly constant for chromatic stimuli.

- These data may be useful to predict colour appearance of images when the same content is presented at very low and very high light levels.

All the csf data can be downloaded via
https://github.com/MalihaAshraf/LIM2022_workshop

Thank you for your attention

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References and resources

[1] Brainard, D.H., & Stockman, A. (2010). Colorimetry. In M. Bass, C. DeCusatis, J. Enoch, V. Lakshminarayanan, G. Li, C. Macdonald, V. Mahajan & E. van Stryland (Eds.), *The Optical Society of America Handbook of Optics, 3rd edition, Volume III: Vision and Vision Optics*. New York: McGraw Hill.

[2] http://www.cvrl.org/ Andrew Stockman's lab website [cone fundamentals and luminosity functions can be downloaded from here]

[3] http://color.psych.upenn.edu/brainard/papers/Brainard32.pdf [how to implement DKL space]

[4] Computational Colour Science Using MATLAB: Edition 2. Stephen Westland · Caterina Ripamonti · Vien Cheung (also as ebook available)

[5] Wuerger & Self (2022). Color opponency, Unique Hues, Encyclopedia of Color Science and Technology (Ed: R Shamey).

[6] Luo M.R. (eds) Encyclopedia of Color Science and Technology. Springer, New York, NY. https://doi.org/10.1007/978-1-4419-8071-7_11. New Edition: R. Shamey (Ed)

[7] Sophie Wuerger, Maliha Ashraf, Minjung Kim, Jasna Martinovic, María Pérez-Ortiz, Rafał K. Mantiuk; Spatio-chromatic contrast sensitivity under mesopic and photopic light levels. *Journal of Vision* 2020;20(4):23. doi: https://doi.org/10.1167/jov.20.4.23.