Seminar 1:

Measuring light and managing colour

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CAMBRIDGE RESEARCH SYSTEMS

Overview

When studying vision we deal with the sensitivity to light.

To do this carefully, it is important to know:

- What light is
- How to measure it
- How to control it (so that intended visual stimuli are reproduced correctly)

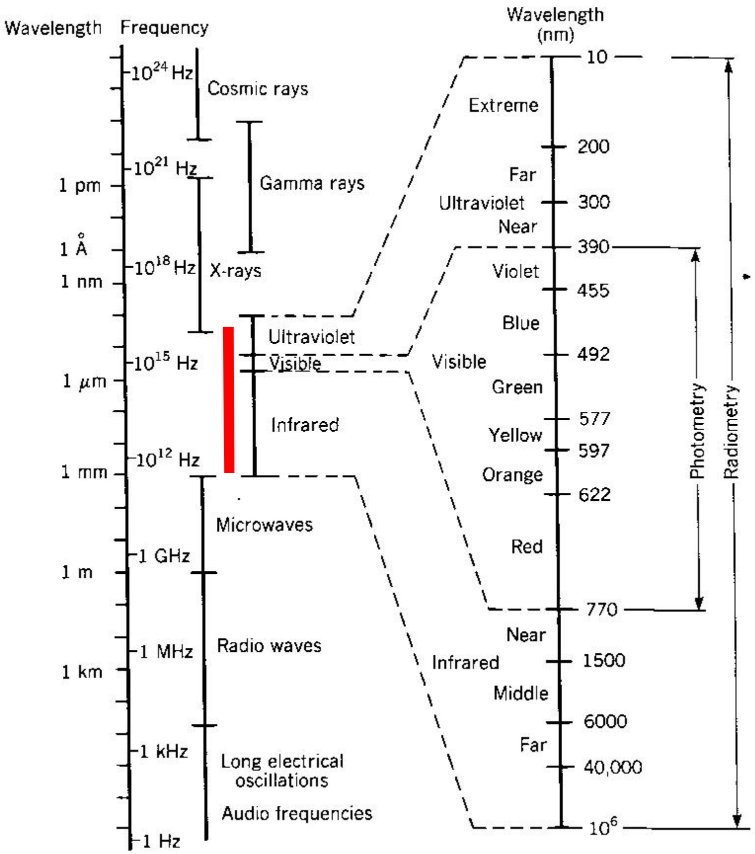
Overview (cont.)

During this seminar, we will talk about:

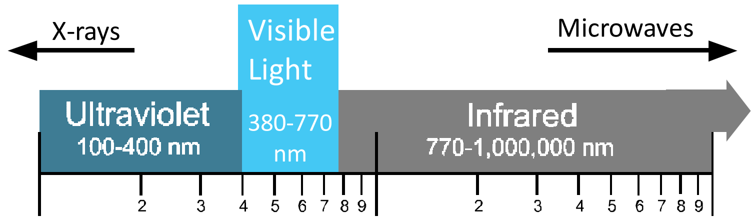
- Measuring instruments (for example: photometers, colorimeters and spectroradiometers)
- Colorimetric versus physiologically defined colour stimuli
- How to transform colour coordinates into RGB space so that coloured stimuli can be displayed on a characterised computer display
- Colour mixture and metameric lights
- Practical demonstrations on the above topics

What is light?

Light is electromagnetic radiation that occupies a small fraction of the electromagnetic spectrum.



It can be expressed in terms of frequency (Hz) or wavelength (nm). In vision science, it is more common to describe it in terms of wavelength.

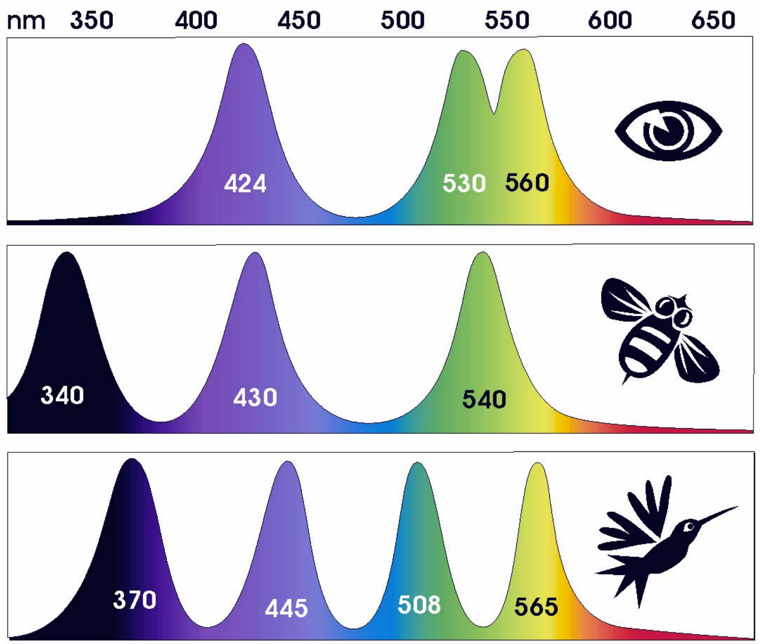


The optical portion of the electromagnetic spectrum

The optical radiation lies between radio waves and x-rays on the spectrum, exhibiting a unique mix of ray, wave, and quantum properties.

Adapted from: Light Measurement Handbook, International Light.

The optical radiation – Visible Light



Visible range

Image: http://coldcreek.ca/wp-content/uploads/2013/08/spectrum2.jpg

Visible light for man is conventionally considered to extend from 400-700nm (but the CIE tabulate 380-780nm).

Visible light for insects, birds, fish, and even some mammals may extend much further into the UV or the IR.

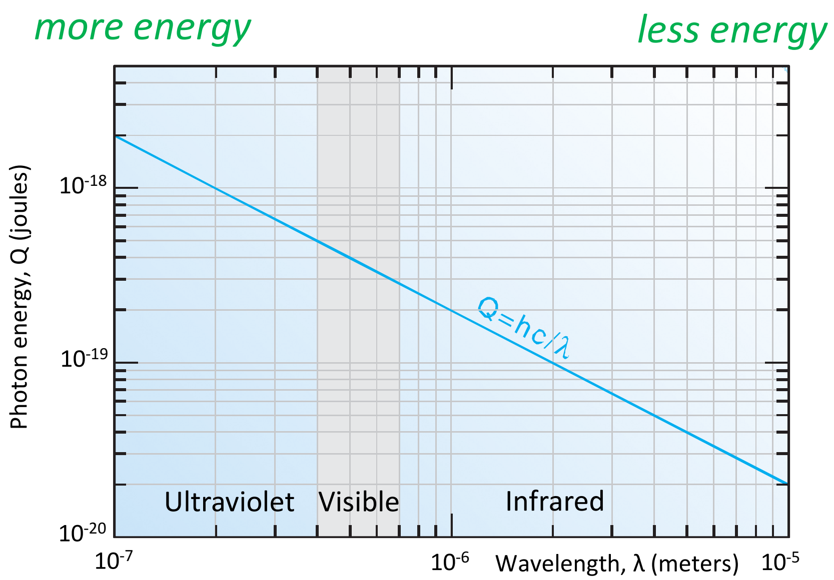
Animals can differ also regarding the number of sensors (i.e. photosensitive cells).

We will concentrate on human sensitivity.

The power of light - Radiometry

The fundamental unit of optical power is the watt (W), which is defined as a rate of energy of one joule (J) per second.

Optical power is a function of both the number of photons and the wavelength.



Planck's equation showing photon energy vs. wavelength

Each photon carries an energy that is described by the Planck's equation:

$$\mathbf{Q = hc/\lambda}$$

where:

Q is the photon energy (joules)

h is Planck's constant (6.623×10^{-34} J s)

c is the speed of light (2.998×10^{8} m s^{-1}),

λ is the wavelength of radiation (meters).

Adapted from: Light Measurement Handbook, International Light.

The power of light - Photometry

The lumen(lm), is the photometric equivalent of the watt, weighted to match the eye response of the "standard observer".

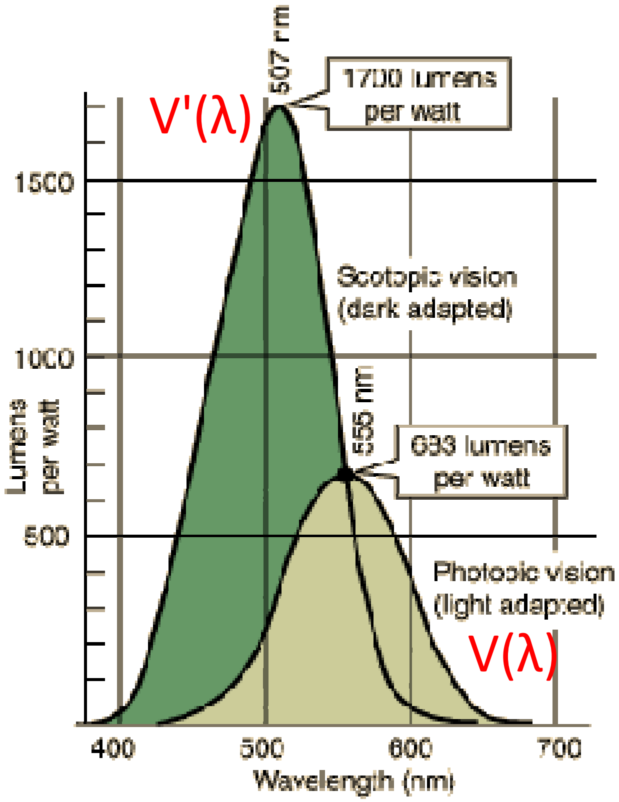


Image: http://hyperphysics.phyastr.gsu.edu/hbase/vision/imgvis/

1 watt at 555 nm = 683.0 lumens

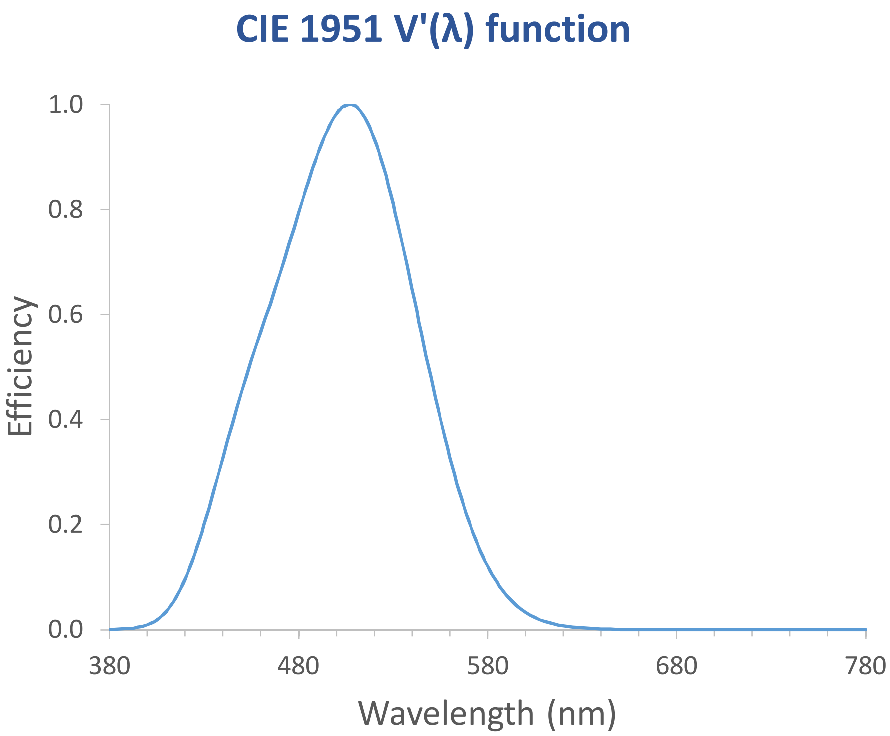
V(λ) and V'(λ) represent the sensitivity of the human eye at photopic and scotopic levels, respectively.

They are also known as the spectral luminous efficiency functions.

V(λ) and V'(λ) were introduced by the CIE in 1924 and 1951, respectively.

Scotopic luminous efficiency function V'(λ)

The standard V'(λ) function was adopted by the CIE in 1951 (CIE, 1951) and it is based on measurements by Wald (1945) and Crawford (1949).



V'(λ) describes the sensitivity of the human visual system at scotopic levels.

It peaks at 507 nm.

It is relatively insensitive to very long wavelengths.

Data available at: www.cvrl.org

Photopic luminous efficiency function V(λ)

The standard V(λ) function (CIE 2-deg, 1924) is the average of several measurements obtained from different studies and using several methods.

CIE 1924 V(λ) function

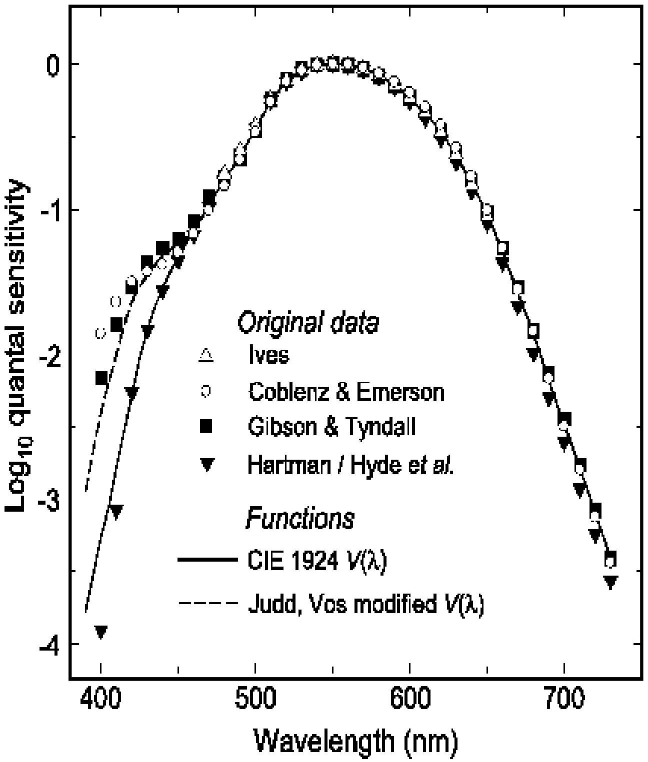


Image: Sharpe et al. (2005)

Note that the values from the different studies that were averaged to define it, diverge by as much as a factor of ten in the violet (CIE, 1926; Le Grand, 1968).

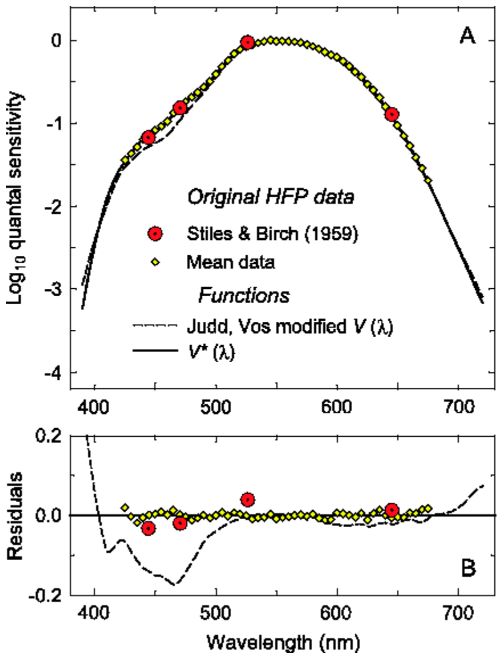
This means the function seriously underestimates sensitivity at short wavelengths.

[*From Wyszecki & Stiles (1982)*]

More attempts have followed to improve the estimates of the luminous efficiency function.

CIE "physiologically-relevant" luminous efficiency functions

Recently, a new set of luminous efficiency functions (2 and 10-deg) have been proposed by Stockman et al., and accepted by the CIE (CIE, 2006).



V*(λ) function (Sharpe *et al.*, 2005)

The new functions (2 and 10 deg) are based on the Stockman & Sharpe (2000) cone fundamentals and are known as V*(λ).

A) V*(λ) continuous line.

B) Differences between the V*(λ) and the other functions are shown in panel A.

Note: Few light-measuring devices have started to specify luminance in terms of V*(λ)

Image: Sharpe et al. (2005)

Data available at: www.cvrl.org

COMMISSION INTERNATIONALE DE L'ECLAIRAGE
INTERNATIONAL COMMISSION ON ILLUMINATION
INTERNATIONALE BELEUCHTUNGSKOMMISSION

“The International Commission on Illumination, also know as the CIE, is devoted to worldwide cooperation and exchange of information on all matters relating to the science and art of light and lighting, colour and vision, photobiology and image technology”

It was founded in 1913 initially to provide colorimetric standards.

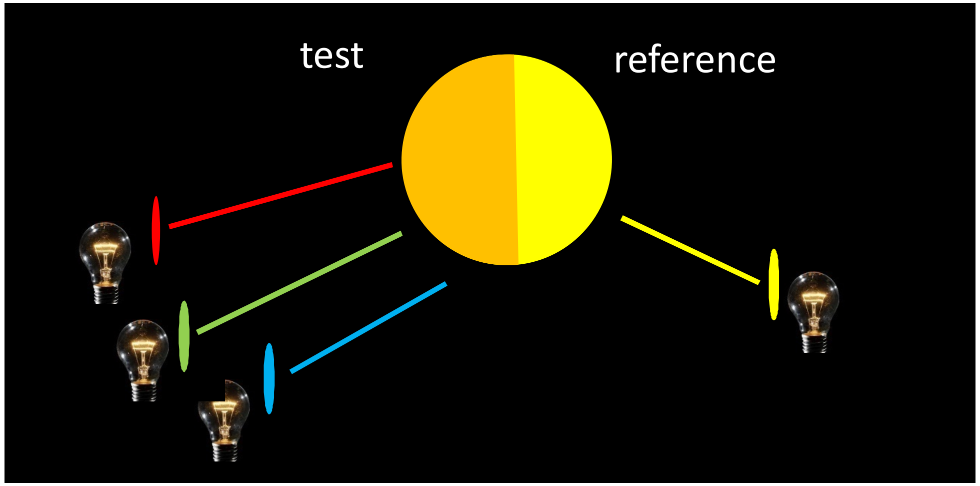
In 1931 it developed a system for the specification of colour stimuli.

Additive colour mixing

All colour stimuli can be matched by the additive mixture of three appropriately chosen primaries.

The amounts of the primaries used for any given stimulus are commonly known as the tristimulus values.

Split field



The observer adjusts the intensities of each of the three primaries until the additive mixture of the test stimulus is visually indistinguishable from the reference stimulus.

$$S \equiv R[R] + G[G] + B[B]$$

where:

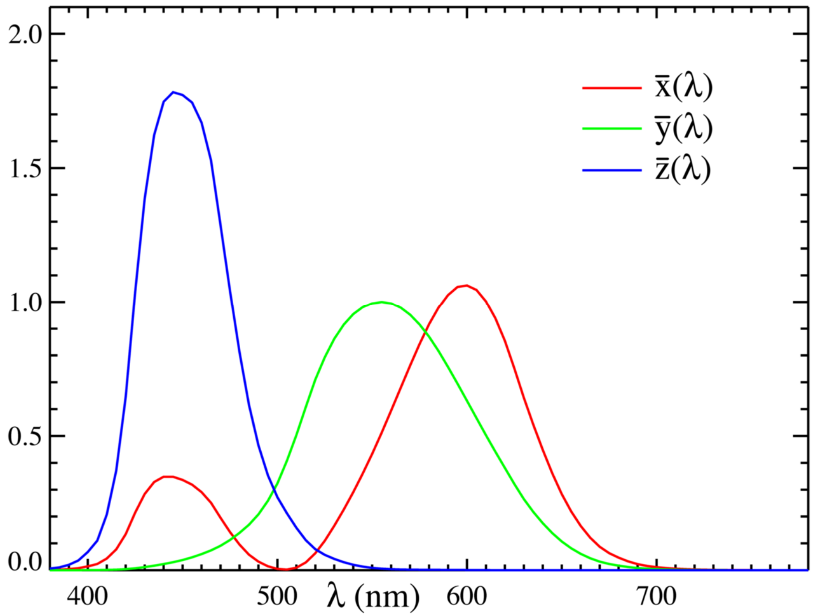
the symbol ≡ means 'matched by'.

[R], [G], and [B] are the red green and blue primaries and R, G, and B are the tristimulus values.

CIE 1931 Colour Matching Functions

In 1931, the CIE transformed the two sets of colour-matching functions obtained from experiments carried out by Wright (1928) and Guild (1931) into a single set of colour-matching functions for each wavelength of the visible spectrum.

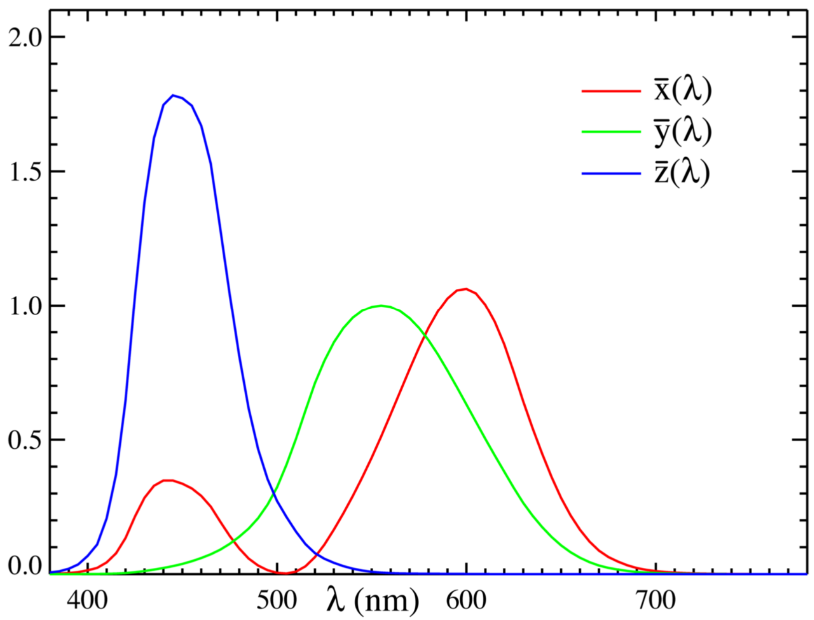
CIE 1931 colour matching functions



CIE 1931 Colour Matching Functions

The CIE system as we know it today is based upon a transformation of the original colour-matching functions averaged from Guild and Wright to a set of primaries known as *X*, *Y*, and *Z*. The colour-matching functions are known for each wavelength and are therefore represented by: $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$.

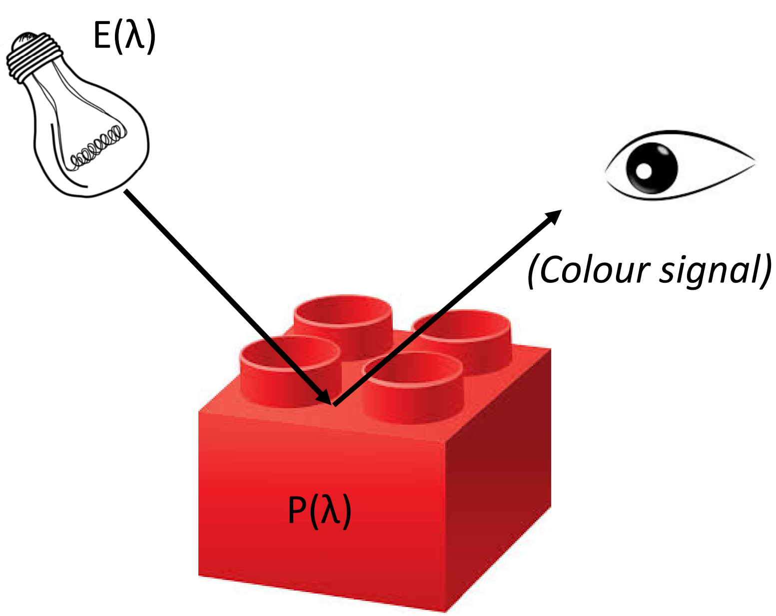
CIE 1931 colour matching functions



Although the colour matching functions are not the human cone sensitivities, they are approximately linear transformations of the cone sensitivities (Mollon, 2003).

CIE 1931 Tristimulus values

From the colour matching functions, it is possible to derive a set of values (XYZ) that describe the visual sensation of the standard observer when viewing a stimulus with surface reflectance P(λ) and illuminated by an illuminant E(λ):



$$X = k\sum E(\lambda)P(\lambda)\bar{x}(\lambda)d\lambda$$
$$Y = k\sum E(\lambda)P(\lambda)\bar{y}(\lambda)d\lambda$$
$$Z = k\sum E(\lambda)P(\lambda)\bar{z}(\lambda)d\lambda$$

where:

$$k = 100/(\sum \bar{y}(\lambda)E(\lambda)d\lambda)$$

Adapted from Westland, Ripamonti, and Cheung (2012).

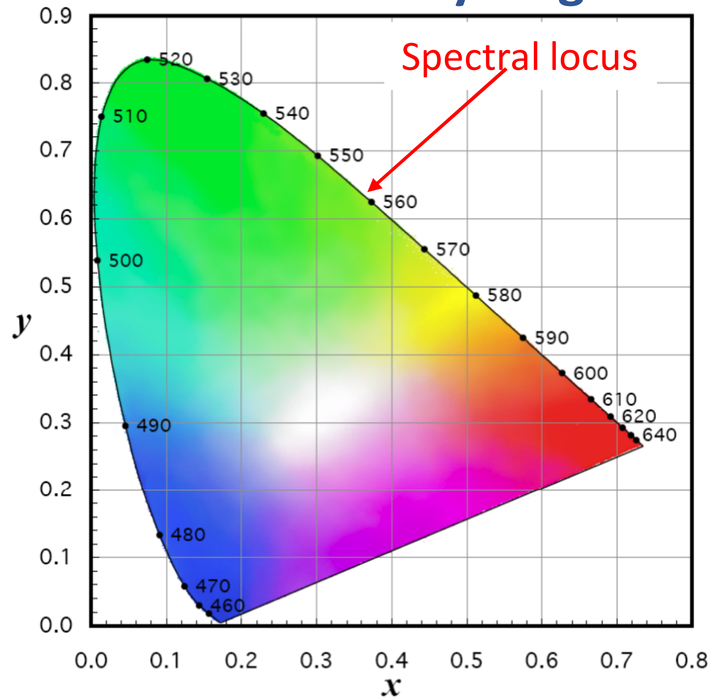
CIE 1931 (*x*,*y*) chromaticity coordinates

The CIE *XYZ* tristimulus values specify a colour stimulus in terms of the visual system. It is often useful, however, to reduce this specification in terms of chromaticity coordinates.

These coordinates can be obtained from the tristimulus values as follows:

$$x = X/(X+Y+Z)$$
$$y = Y/(X+Y+Z)$$

CIE chromaticity diagram



Adapted from Westland, Ripamonti, and Cheung (2012).

CIE 1931 (*x*,*y*) chromaticity coordinates

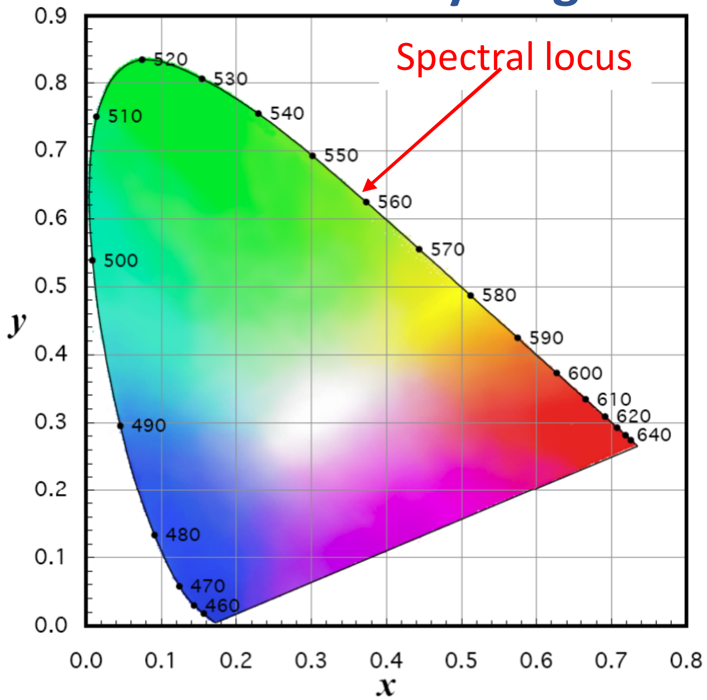
The 3rd dimension is luminance, which corresponds to Y.

$$x = X/(X+Y+Z)$$
$$y = Y/(X+Y+Z)$$
$$Luminance = Y$$

Note that stimuli of identical chromaticity but different luminance are collapsed onto the same point in the 2-D plane of the chromaticity diagram.

The gamut of all colours is contained by the convex shape of the spectral locus and a straight line that can be considered to be drawn between the two ends of the locus.

CIE chromaticity diagram



Adapted from Westland, Ripamonti, and Cheung (2012).

CIE system and colorimetry

The CIE system of colorimetry was developed for colour specifications rather than for colour appearance. At that time the spectral sensitivities of the human photoreceptors (as measured psychophysically) were not available.

Image: x-rite.com

Image: http://www.colorsolutionsinternational.com/my_uploads/image/SUBSTRATES.jpg

CIE system and colorimetry

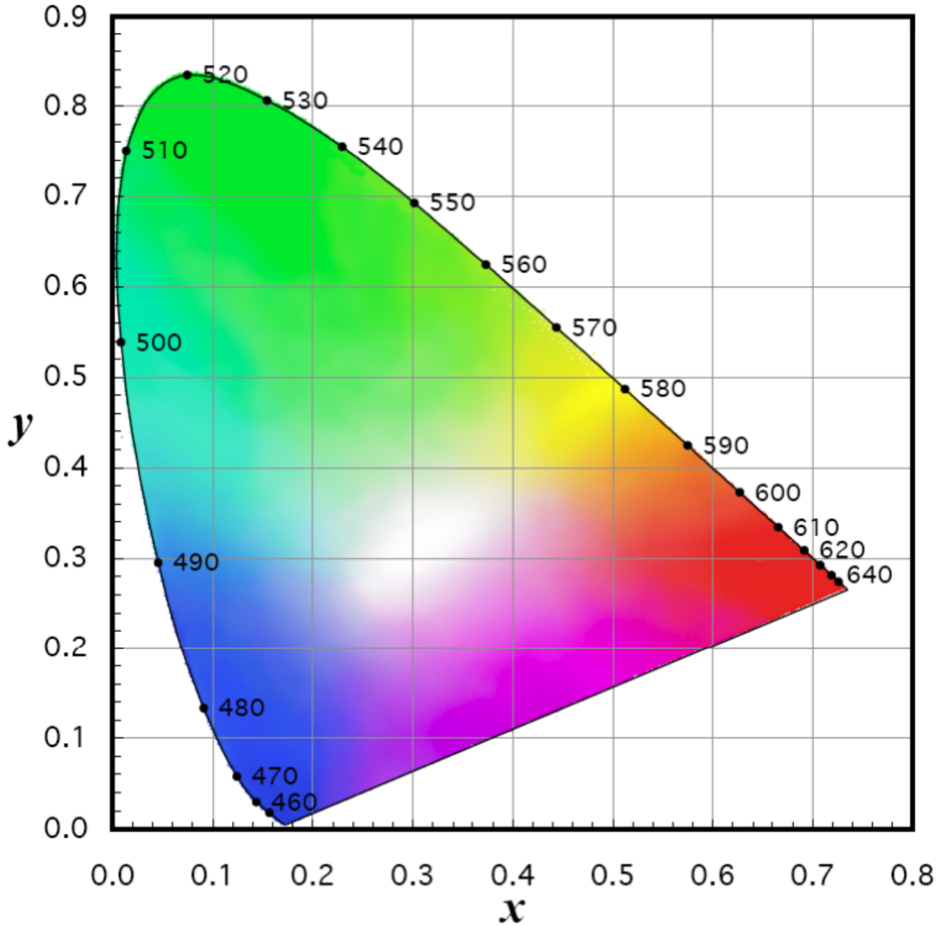
Advantages:

- Widely used
- Communicate precise colour
- Reliable

Limitations:

- It is based on human sensitivity
- It represents a standard observer
- It is non uniform

CIE chromaticity diagram



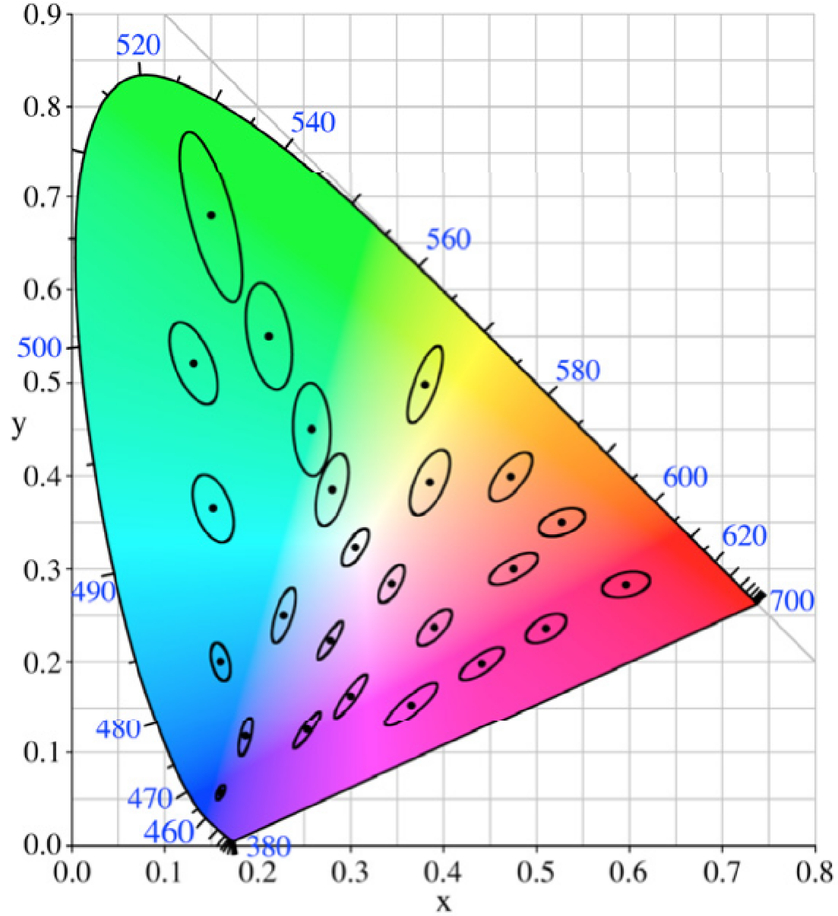
Non uniformity of the CIE (*x*,*y*) chromaticity diagram

The ellipses are magnified by 10.

The colours included in each ellipse cannot be distinguished.

If the diagram was uniform, the ellipses would be circles of the same size.

MacAdam (1942) ellipses

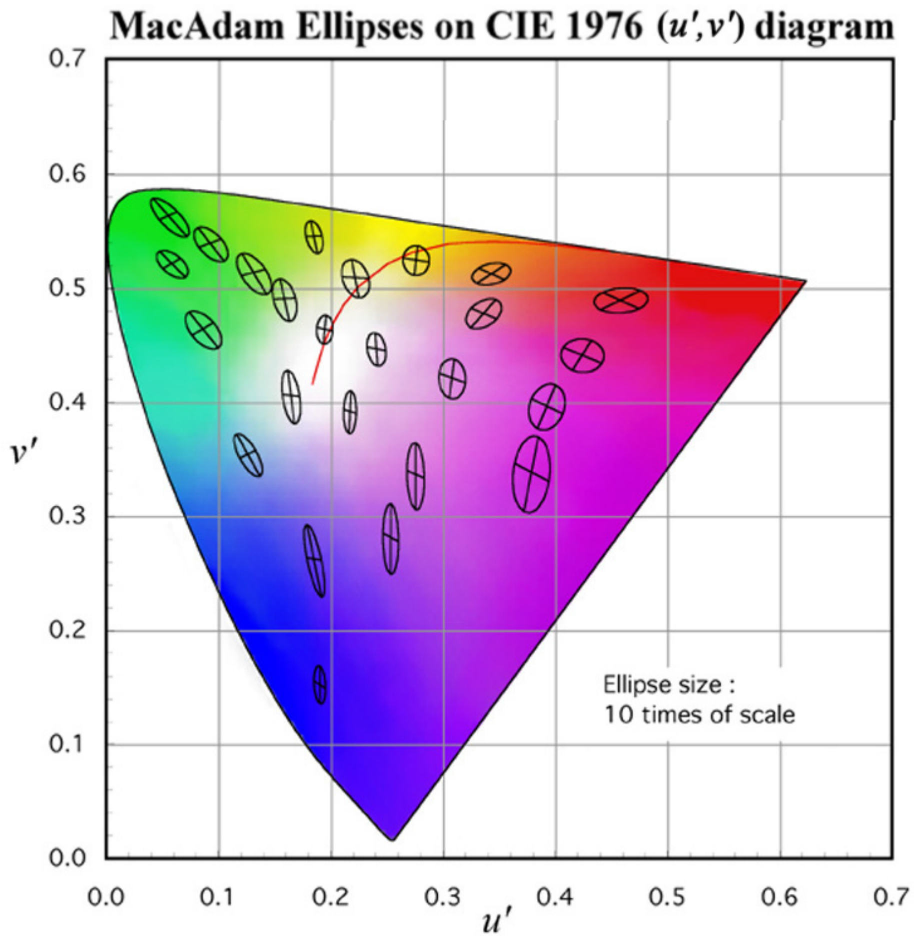


CIE 1976 (u',v') chromaticity diagram

In 1976, CIE adopted additional transformations to the original CIE chromaticity diagram, to make the space more uniform:

$$u' = 4X/(X + 15Y + 3Z)$$
$$v' = 9Y/(X + 15Y + 3Z)$$

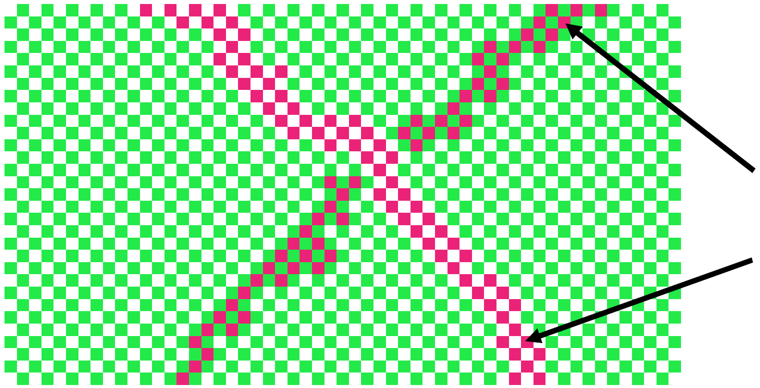
In the new CIE 1976 (u',v') diagram the area of the transformed ellipses is much more similar (though still not identical!) than the area of the ellipses in the (x,y) diagram.



Colour specifications and colour appearance

The CIE colour systems provide colour specifications for standard conditions.

Colour appearance and colour discrimination may depend on context (i.e. background/surround).



The red squares along the diagonals have identical (*x,y*) chromaticy coordinates.

Image: illusionspoint.com

The CIE has never stopped working on this problem and has already developed several alternative colour systems (e.g., CIELAB, CIECAM, etc.).

CIE systems and vision science

If you know the CIE chromaticity coordinates of a stimulus, you can reproduce it quite accurately.

Although the CIE chromaticity coordinates are based on the human colour matching functions they don't say anything about the colour appearance of the stimulus.
This is because the stimulus coordinates are not a direct representation of the physiological mechanisms that allow us to see that colour.

To a certain extent, the chromaticity coordinates provide a number which has no physiological meaning.

Limitations:

- It is based on human sensitivity
- It represents a standard observer
- It is non uniform

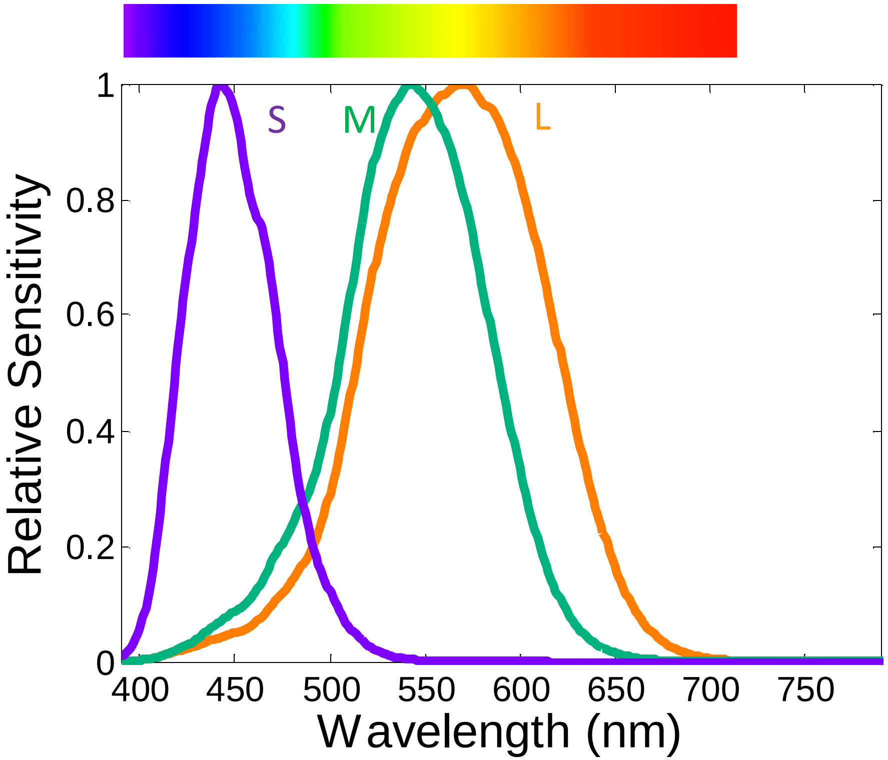
Cone sensitivities (absorptions, fundamentals)

Often, in vision experiments it would be more appropriate to use colour representations that make more explicit the contribution of the physiological mechanisms underlying the ideal observer's response.

For example, we can describe a stimulus directly in terms of the excitations produced by the cones in response to that stimulus.

The most recent and precise cone fundamentals are the Stockman & Sharpe (2000), upon which the CIE (2006) physiologically-relevant LMS fundamental colour matching functions are based.

Cone fundamentals



The curves show the cones sensitivity profiles derived by Stockman & Sharpe (2000).

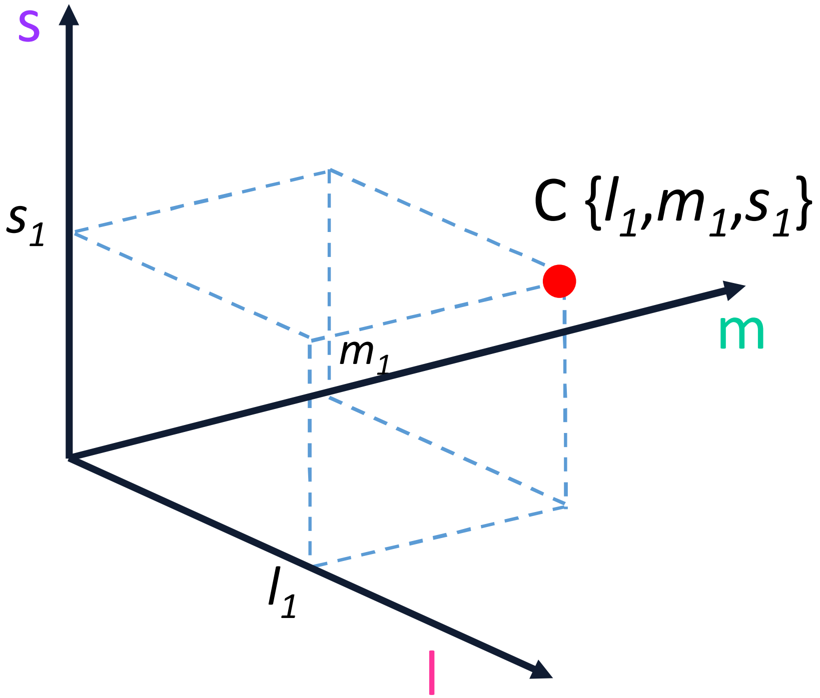
The relative sensitivities of the Short- (S), Middle- (M), and Long- (L) wavelength-sensitive cones are normalized to unity.

The M- and L-cones' sensitivities overlap to a large extent and include almost the entire visible spectrum.

Cone excitation space or LMS space

Cone excitations represent the responses of the cones to a light stimulus.

Cone excitation space



Therefore, any colour stimulus can be specified by three numbers, corresponding to the responses of the L-, M-, and S-cones.

These responses can be represented in a three-dimensional colour space, the LMS space.

How to calculate cone excitations

In vision science, a light stimulus is often described in terms of quantum catches absorbed by each individual cone class.

For a given visual stimulus, the corresponding quantum catches will be equal to:

$$l = \sum_{\lambda=390}^{\lambda=780} L(\lambda)C(\lambda)$$

$$m = \sum_{\lambda=390}^{\lambda=780} M(\lambda)C(\lambda)$$

$$s = \sum_{\lambda=390}^{\lambda=780} S(\lambda)C(\lambda)$$

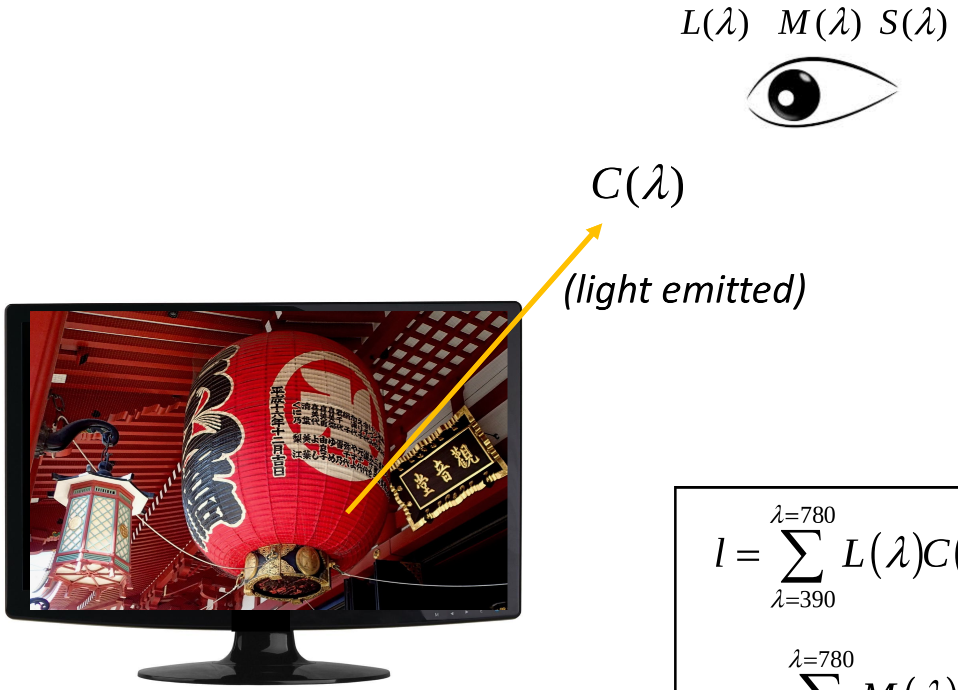
where *l*, *m*, and *s* represent the quantum catches or cone excitations of the long-, medium-, and short-wavelength-sensitive cones, whose sensitivities are indicated by $L(\lambda)$, $M(\lambda)$, and $S(\lambda)$, respectively.

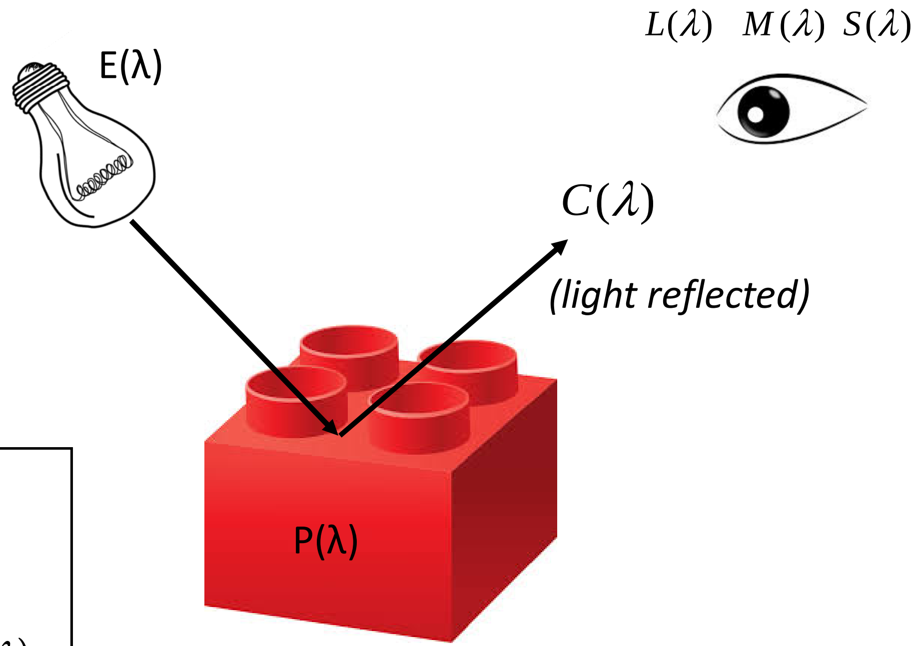
$C(\lambda)$ is the spectral power distribution of the light reaching the eye.

For example, $C(\lambda)$ can be the light emitted by a stimulus displayed on a computer screen, or the light reflected by an object when illuminated by a light source.

Adapted from Westland, Ripamonti, and Cheung (2012).

How to calculate cone excitations





$$l = \sum_{\lambda=390}^{\lambda=780} L(\lambda)C(\lambda)$$

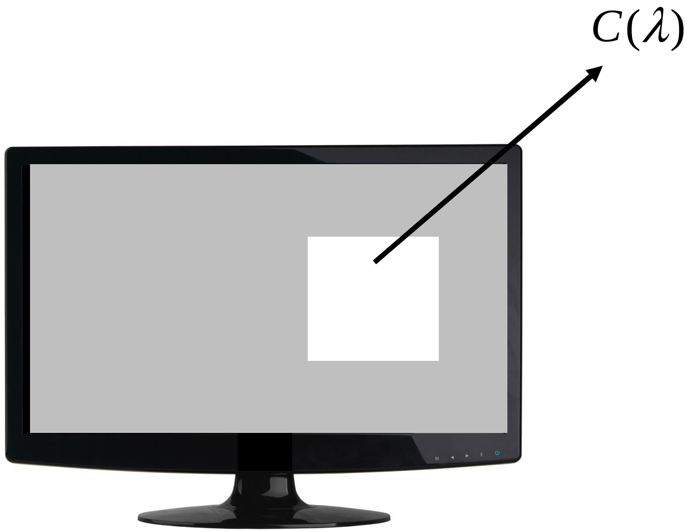
$$m = \sum_{\lambda=390}^{\lambda=780} M(\lambda)C(\lambda)$$

$$s = \sum_{\lambda=390}^{\lambda=780} S(\lambda)C(\lambda)$$

Measuring light

In order to proceed with the calculations, we need to be able to measure $C(\lambda)$.

$$C(\lambda) = rR(\lambda) + gG(\lambda) + bB(\lambda)$$



where $R(\lambda)$,$G(\lambda)$, and $B(\lambda)$ represent the spectral power distributions of the red, green and blue primaries respectively, and the constants *r*, *g,* and *b* represent the proportion of light emitted by each primary to generate the stimulus.

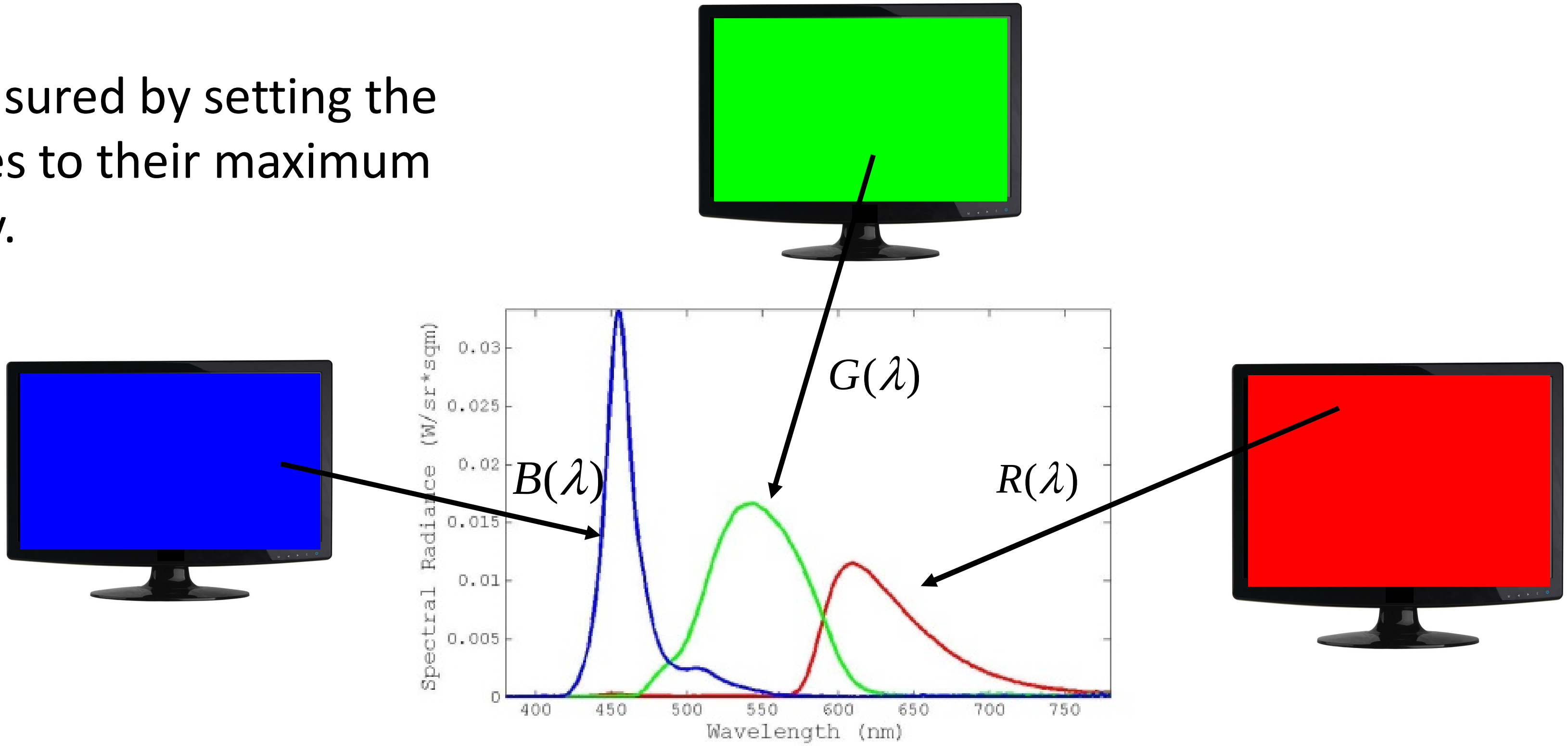
For example, to display a white stimulus the corresponding *r*, *g* and *b* values would all be equal to 1, and to display a mid-grey stimulus the corresponding values would all be equal to 0.5.

Adapted from Westland, Ripamonti, and Cheung (2012).

Measuring light - SPD

The spectral power distribution (SPD) describes the light energy across the visible range.

It is measured by setting the primaries to their maximum intensity.



Light meters- Spectroradiometer

The instrument that measures the SPD is the spectroradiometer.

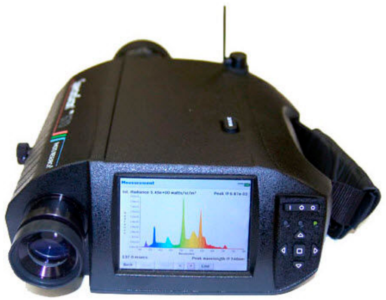
A spectroradiometer provides measurements in radiometric units.

Its accuracy depends on the bandwidth, sensitivity, and resolution of the device.

Spectroradiometers

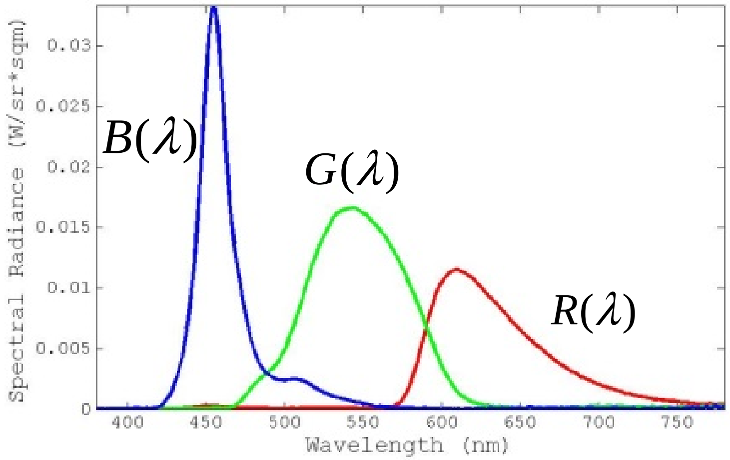
Konica-Minolta CS200

PR-670 SpectraScan



CRS SpectroCAL

RGB Spectral Power Distributions

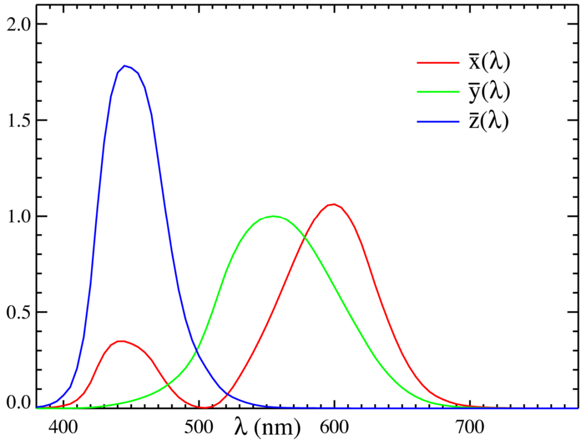


Light meters- Colorimeter

Measures emitted light by using three or more separate sensors.

Each of the sensors sits behind a filter that is tuned to a particular range of the spectrum.

CIE 1931 colour matching functions.

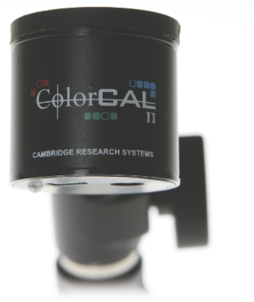


Colorimeters

Datacolor Spyder

X-Rite Eye One

CRS ColorCAL



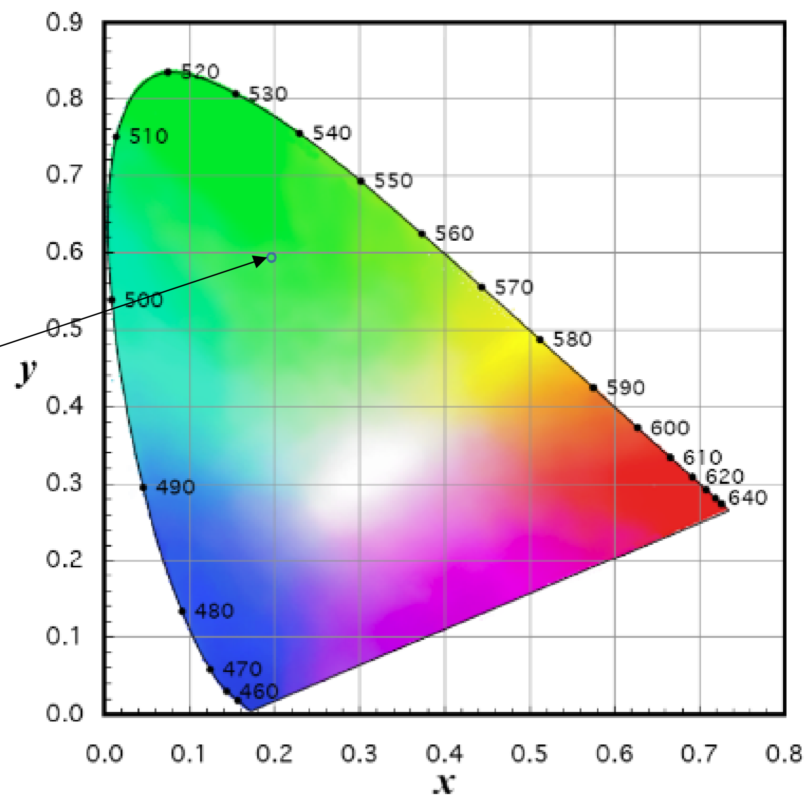
In an attempt to accurately model human colour vision, a three-filter colorimeter is designed to simulate the CIE 1931 Colour Matching Functions of the standard observer.

Light meters- Colorimeter

A colorimeter returns XYZ, which can be transformed into the CIE chromaticity coordinates and luminance.

CIE (x,y) chromaticity coordinates

x= 0.2; y=0.6; lum =30 cd/m²



Light meters- Colorimeter

The performance of a colorimeter depends on the manufacturer's ability to produce filters that match the Colour Matching Functions.

Hence, not all colorimeters have the same accuracy, as matching these complex curves and remaining affordable is always a trade-off.

Accuracy can also vary according to whether the light meter (not only colorimeters) has been calibrated at the factory against a known light source and whether the calibration is up-to-date.

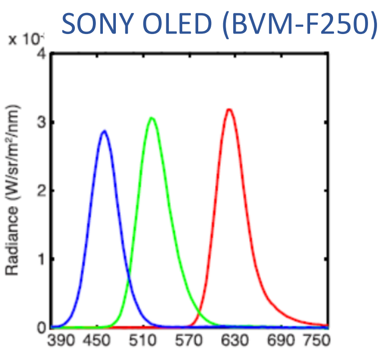
Some budget meters are not calibrated at the factory.

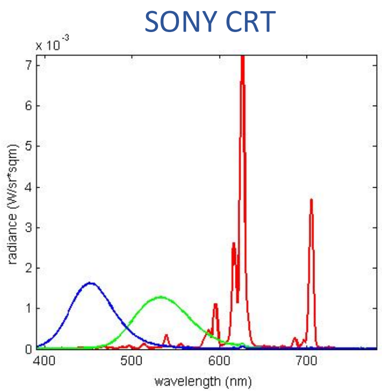
Light meters- Colorimeter

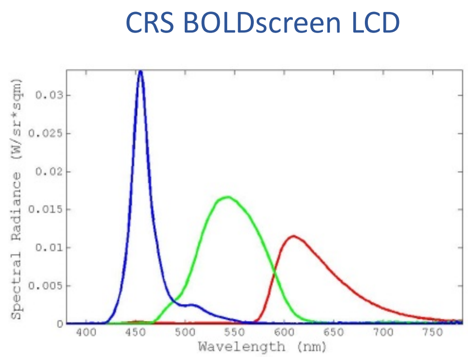
Light meters also vary in the time they take to make the measurements and how fast they degrade over time (routine calibration is recommended!), how sensitive they are at low as well as at high light levels (some saturate and burn) or temperature (if very sensitive, contact light meters might be inappropriate for some devices like OLED displays).

Colorimeters are generally calibrated to measure smooth signals. Hence, they need customized calibrations to measure spiky signals.

This means that they work generally well for measuring the SPD of OLED displays, while measuring the red phosphor of a CRT or the blue primary of an LCD is more challenging.







Light meters- Spectroradiometer

Spectroradiometers do not use filters, instead a holographic diffraction grating is combined with a diode array, made of many sensors.

Their accuracy depends on the number of sensors (resolution), their bandwidth and sensitivity.

The resolution is given by the number of sensors and the operating range.

The number of sensors varies across manufactures and is typically in the range 100:10,000.

Light meters- Comparison

Device	**N sensors**	**It returns:**		
		Spectral radiance	***XYZ Tristimulus values***	***Luminance***
Photometer	1	No	No	Yes
Colorimeter	3 or more	No	Yes	Yes
Spectroradiometer	Typically between 100 and 10,000	Yes	Yes*	Yes*

*Calculations required

Light meters- Spectroradiometer

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How to calculate cone excitations – Linear algebra

$L(\lambda)\ \ M(\lambda)\ \ S(\lambda)$

$C(\lambda)$

$$l = \sum_{\lambda=390}^{\lambda=780} L(\lambda)C(\lambda)$$

$$m = \sum_{\lambda=390}^{\lambda=780} M(\lambda)C(\lambda)$$

$$s = \sum_{\lambda=390}^{\lambda=780} S(\lambda)C(\lambda)$$

$\boxed{l\,m\,s}$ $\boxed{L(\lambda)\ M(\lambda)\ S(\lambda)}$ $\boxed{C(\lambda)}$

$$\mathbf{e} = \mathbf{FC}$$

$$\mathbf{C} = \mathbf{Pt}$$

$\boxed{R(\lambda)\ \ G(\lambda)\ \ B(\lambda)}$ $\boxed{r\,g\,b}$

Thus: $\mathbf{e} = \mathbf{FPt}$

Or, more simply: $\mathbf{e} = \mathbf{Mt}$

And its inverse: $\mathbf{t} = \mathbf{M}^{-1}\mathbf{e}$

Metamers

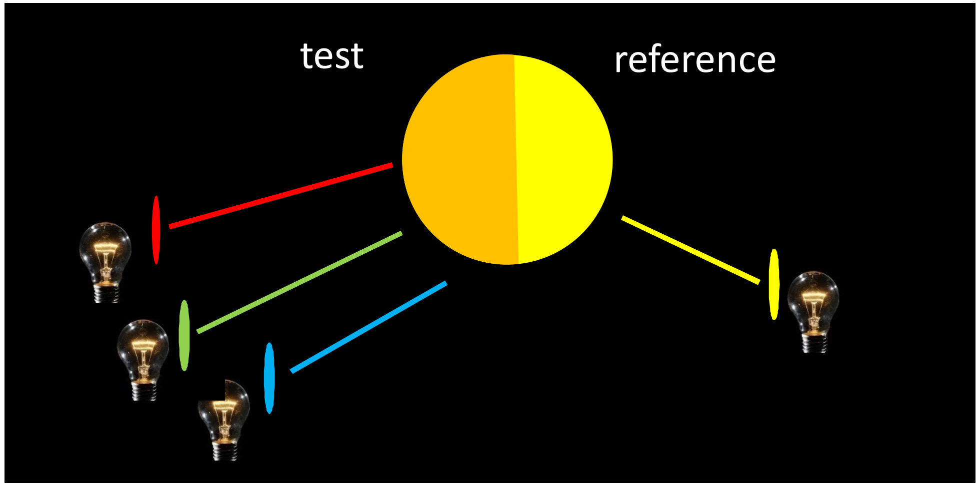
$$\mathbf{e} = \mathbf{M}\mathbf{t}$$

$$\mathbf{t} = \mathbf{M}^{-1}\mathbf{e}$$

Note that in both equations the information relative to the spectral power distribution of the stimulus is lost!

Display devices make use of the principle of additive colour mixing to display colorimetric metamers.

Colorimetric metamers are colour signals that generate the same cone excitations even though they are characterized by different SPDs.

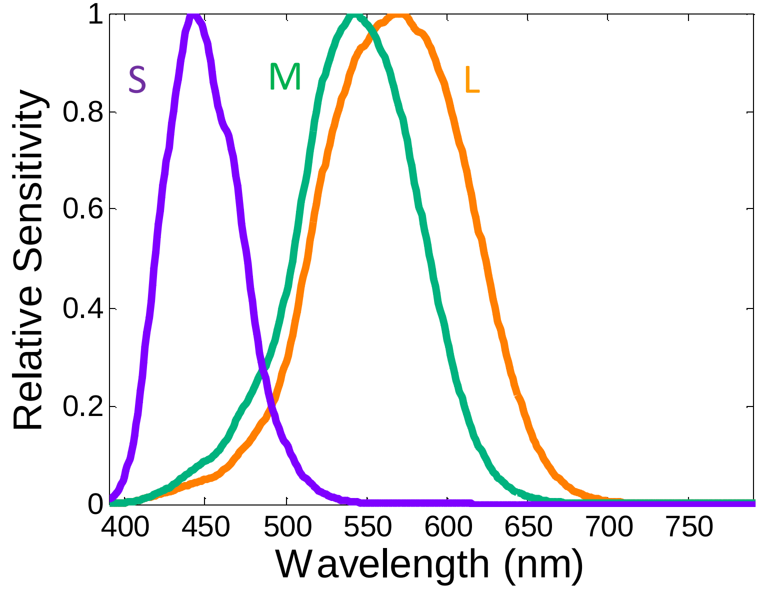


Isolating cone responses

In some colour vision experiments, we are interested in measuring the isolated responses of one cone class while the other two cone classes are silent.

One of the difficulties in isolating cone responses is due to the partial overlap of the cone sensitivities.

The second is due to the broad spectral responses of the device used to generate the stimuli.



Silent substitution

It is possible to achieve cone isolation by using silent substitution.

This technique was originally introduced by M. Ishihara at the beginning of the 20th century, although the method is known mostly through the work of W.A.H. Rushton et al. (1973). [See also Estevez and Spekreijse, 1974, 1982].

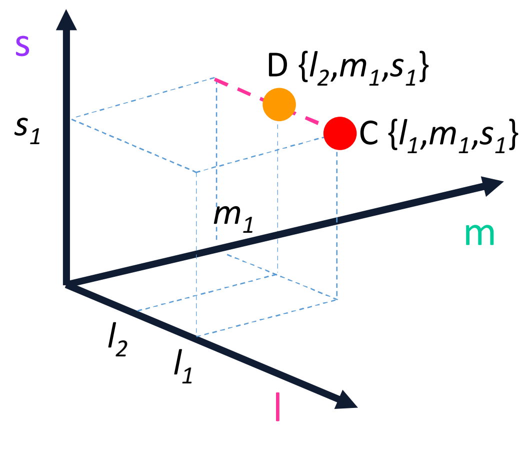
Example: Isolating L-cone responses

r g b   *l m s*

$$\mathbf{t} = \mathbf{M}^{-1}\mathbf{e}_L$$ *modulate*

$$\mathbf{t} = \mathbf{M}^{-1}\mathbf{e}_M$$ *keep constant*

$$\mathbf{t} = \mathbf{M}^{-1}\mathbf{e}_S$$ *keep constant*



MacLeod and Boynton chromaticity diagram

In 1979 MacLeod and Boynton introduced a chromaticity diagram which was based on the relative responses of the L-, M- and S-cone excitations (MacLeod and Boynton, 1979).

As the underlying concept was similar to that of Robert Luther, the authors called it the Luther diagram, although it has become known as the MacLeod and Boynton chromaticity diagram.

Advantages:

- It is based on physiologically-relevant responses
- It can be represented in only two dimensions

Drawback:

- It assumes that S-cones do not contribute to luminance

  (However, see Stockman et al. 1991; Ripamonti et al. 2009)

MacLeod and Boynton chromaticity diagram

Each cone excitation is scaled by luminance, which is defined as the sum of the L- and M- cone responses (no S-cones for luminance!).

Luminance

$$r_{MB} = \bar{l} \big/ \boxed{\left(\bar{l} + \bar{m}\right)}$$

$$g_{MB} = \bar{m} \big/ \left(\bar{l} + \bar{m}\right)$$

$$b_{MB} = \bar{s} \big/ \left(\bar{l} + \bar{m}\right)$$

MB chromaticity coordinates

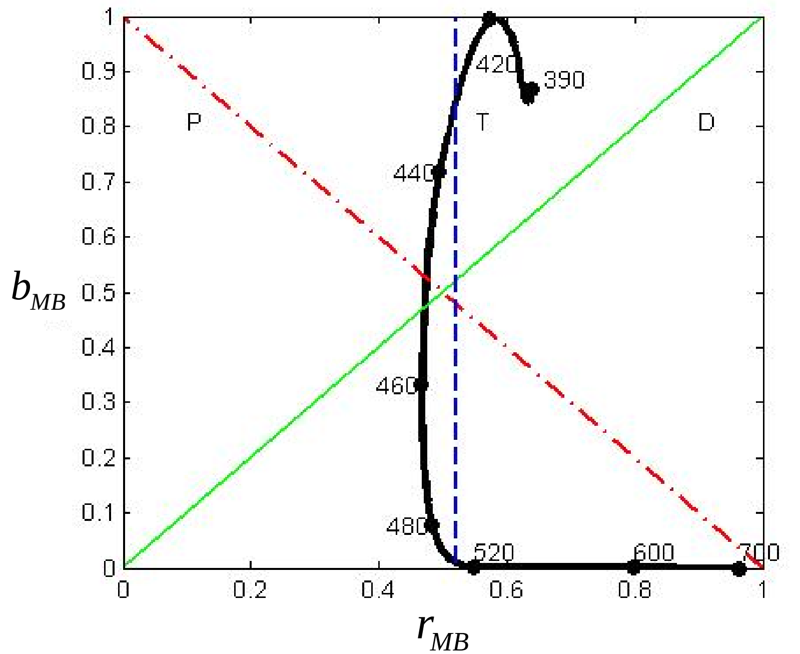
Stockman & Sharpe cone fundamentals

where:

$$\bar{l} = l / 0.689903$$

$$\bar{m} = m / 0.348322$$

$$\bar{s} = s / 0.0371597$$



The scaling factors depend on the cone fundamentals that are used.

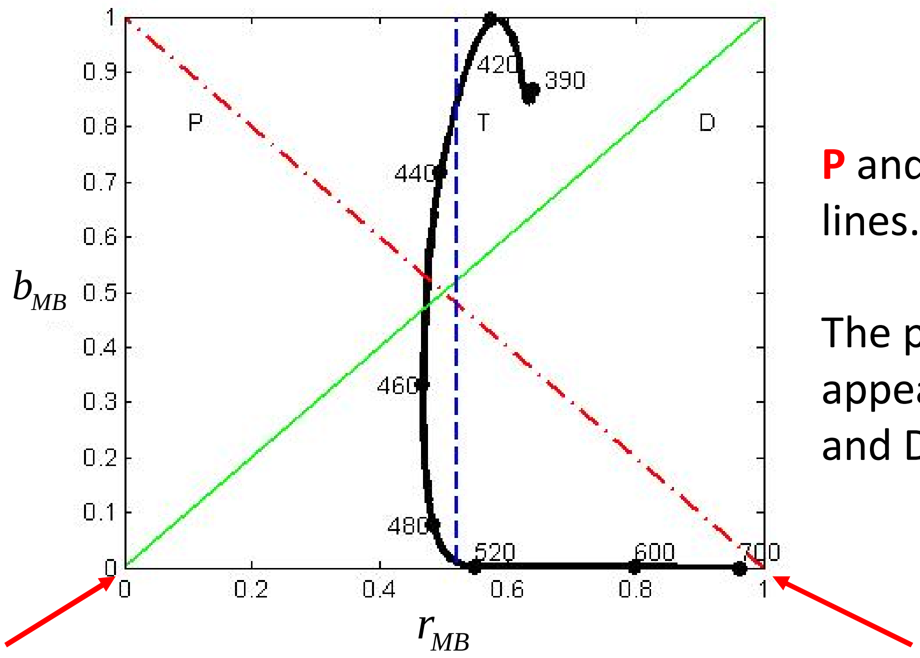
MacLeod and Boynton chromaticity diagram

Assuming that:

$$r_{MB} + g_{MB} = 1$$

Then:

$$g_{MB} = 1 - r_{MB}$$



P and **D** represent the confusion lines.

The points along the **P** and **D** lines appear indistinguishable to Protans and Deutans, respectively.

The origin represents the point where only M-cones are excited.

Only L-cones are excited.

DKL colour space

Proposed by Derrington, Krauskopf and Lennie (DKL, 1984) for distinguishing between responses originating from chromatically opponent cone outputs and responses originating from achromatic additive cone outputs.

The DKL colour space is partly based on ideas developed by MacLeod and Boynton (1979) and Krauskopf, Williams, and Heeley (1982).

The DKL colour space is recommended particularly when the test stimulus is seen against a background. The underlying idea is that the background provides the adaptation level according to which the relative excitations caused by the test stimulus can be calculated.

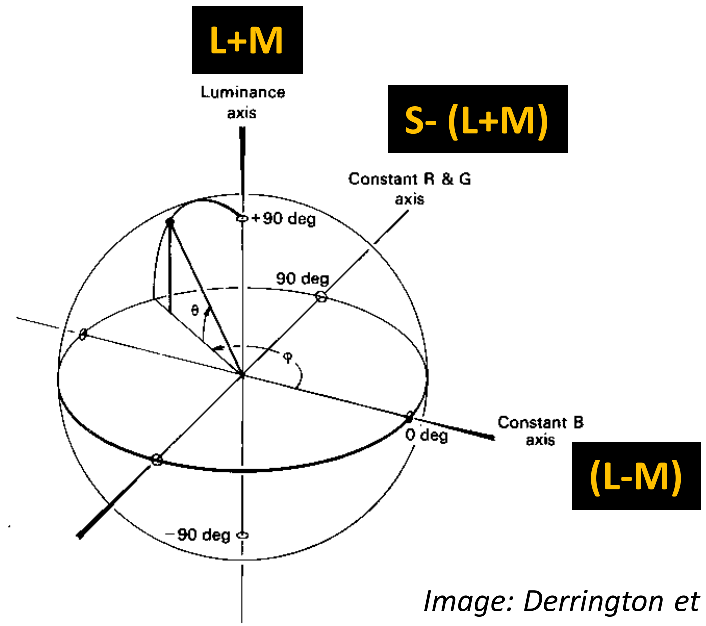


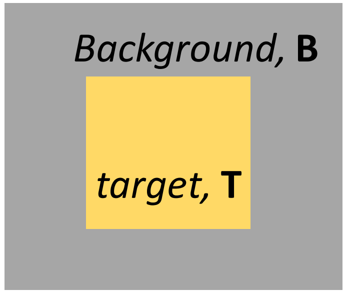
Image: Derrington et al. (1994)

Adapted from Westland, Ripamonti, and Cheung (2012).

DKL colour space

The test stimulus T is represented in terms of contrast C against the background B.

$$C = \frac{(T - B)}{B}$$



Implementations with descriptions:

Brainard (1996)
Capilla et al. (1998)
Westland, Ripamonti, and Cheung (2012)
CRS Colour Toolbox for MATLAB

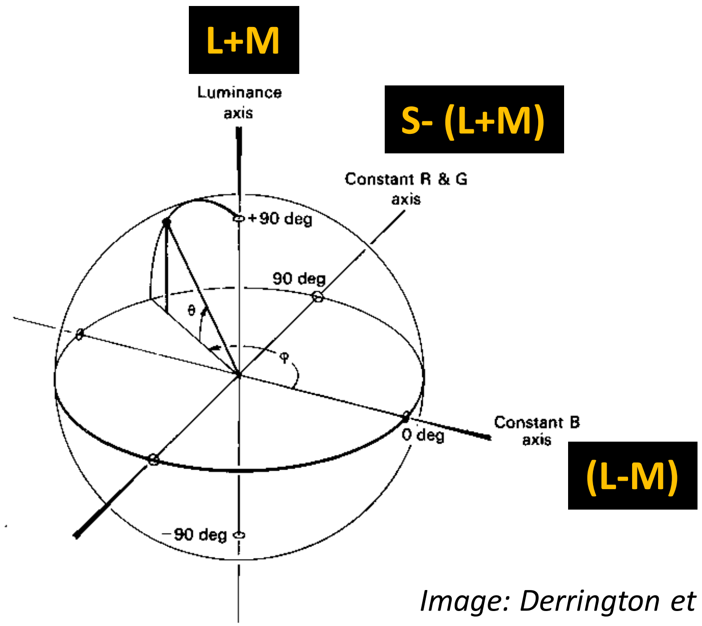


Image: Derrington et al. (1994)

Adapted from Westland, Ripamonti, and Cheung (2012).

Colour transformations

Sometimes we want to represent stimuli of known reflectance properties on a display device.

This can be the case of natural images collected by hyperspectral digital cameras, or reflectance spectra of Munsell chips.

Image: www.rgbstock.com

Image: www.vision-systems.com

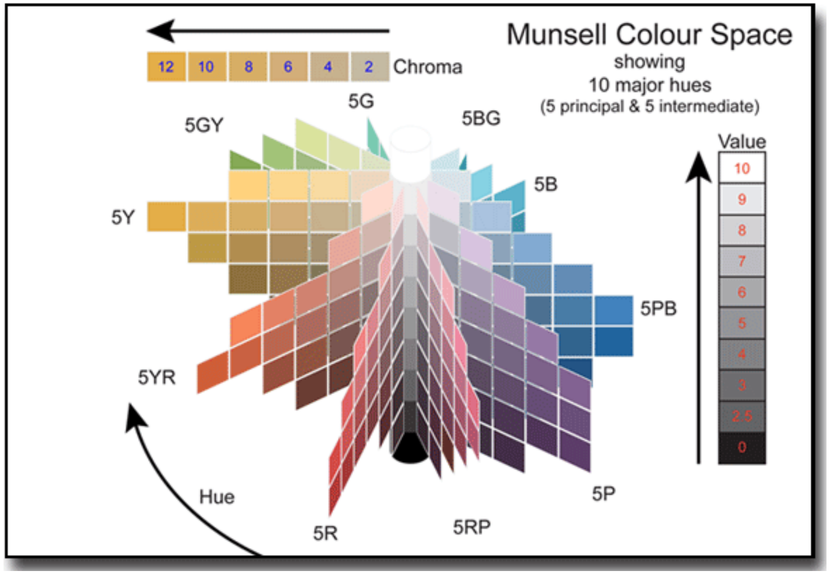
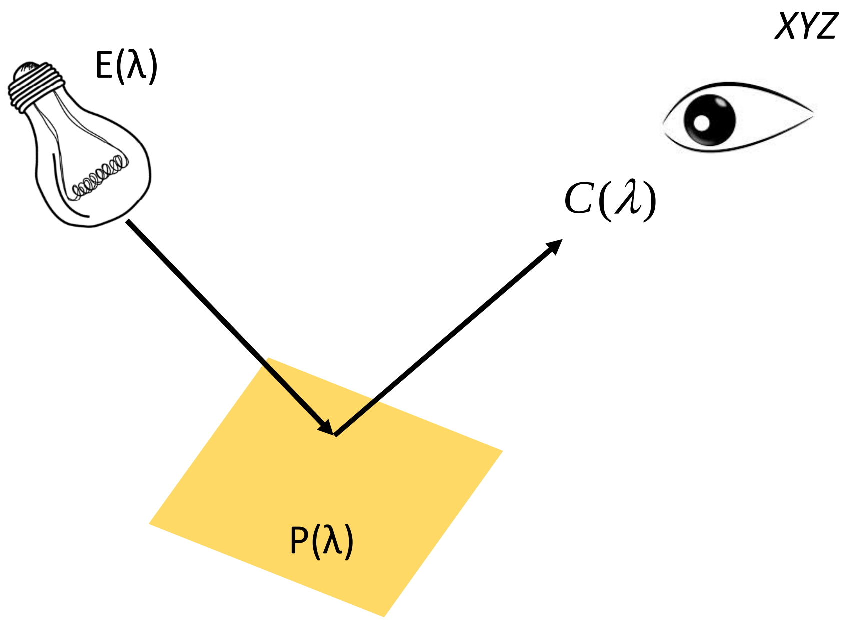
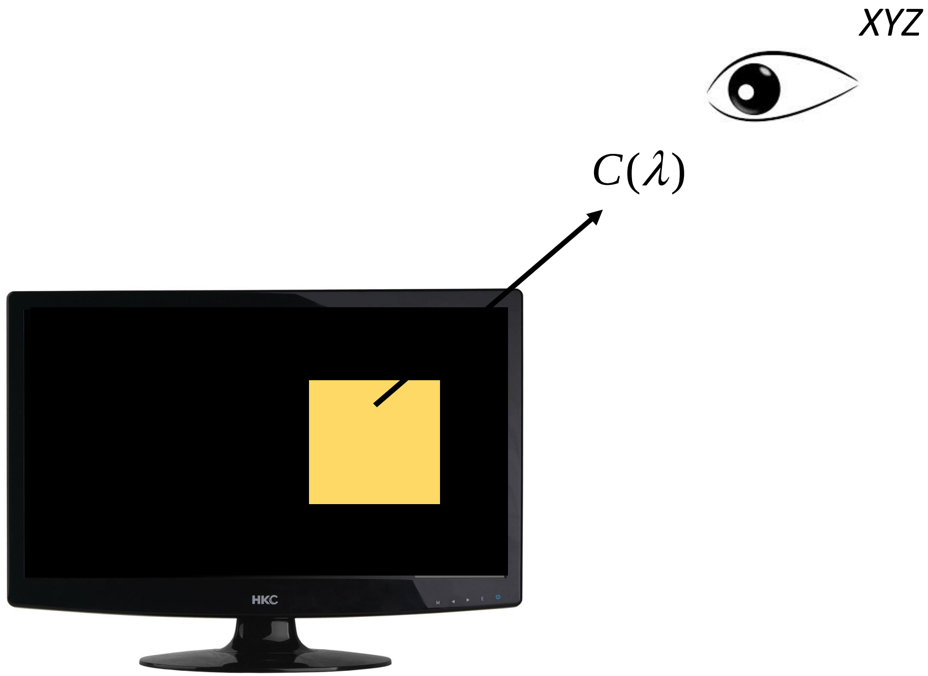


Image: www.blc.lsbu.ac.uk

From reflectance spectra to RGB

Example: How to transform a Munsell chip reflectance spectra into RGB so that it can be displayed on the screen.



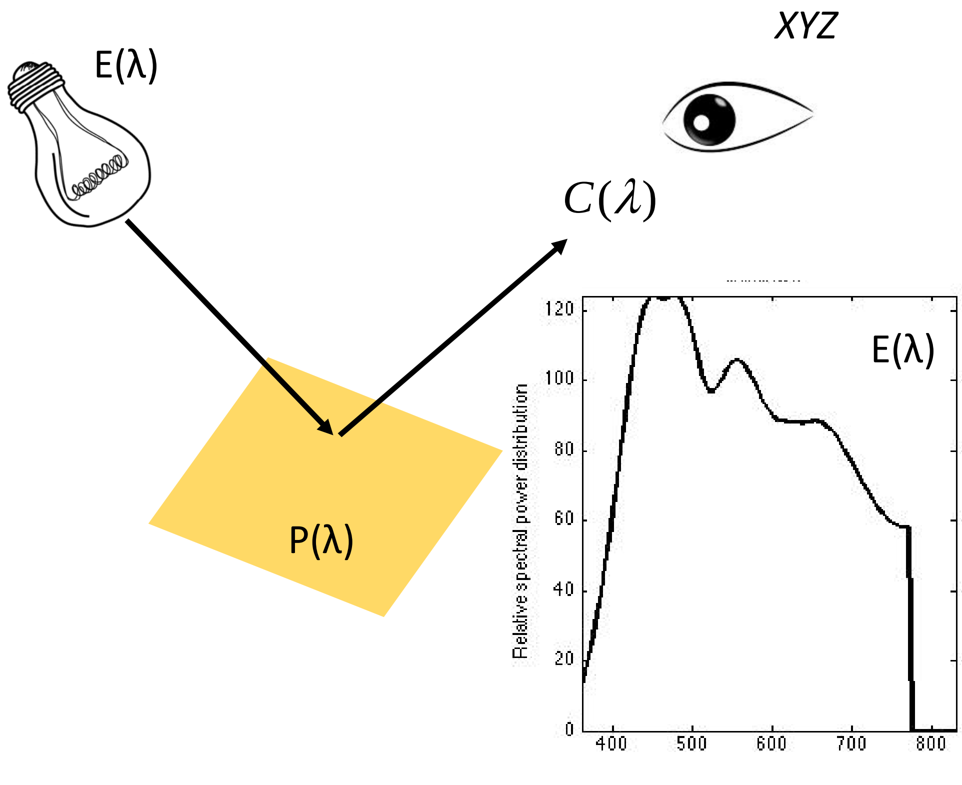


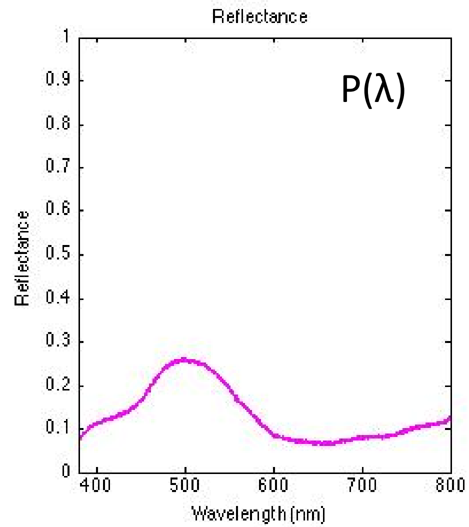
From reflectance spectra to RGB

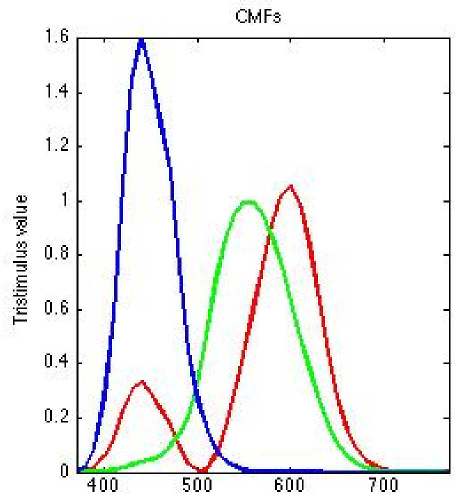
Example: How to transform a Munsell chip reflectance spectra into RGB so that it can be displayed on the screen.

CMF

$$X = k\sum E(\lambda)P(\lambda)\bar{x}(\lambda)d\lambda$$
$$Y = k\sum E(\lambda)P(\lambda)\bar{y}(\lambda)d\lambda$$
$$Z = k\sum E(\lambda)P(\lambda)\bar{z}(\lambda)d\lambda$$

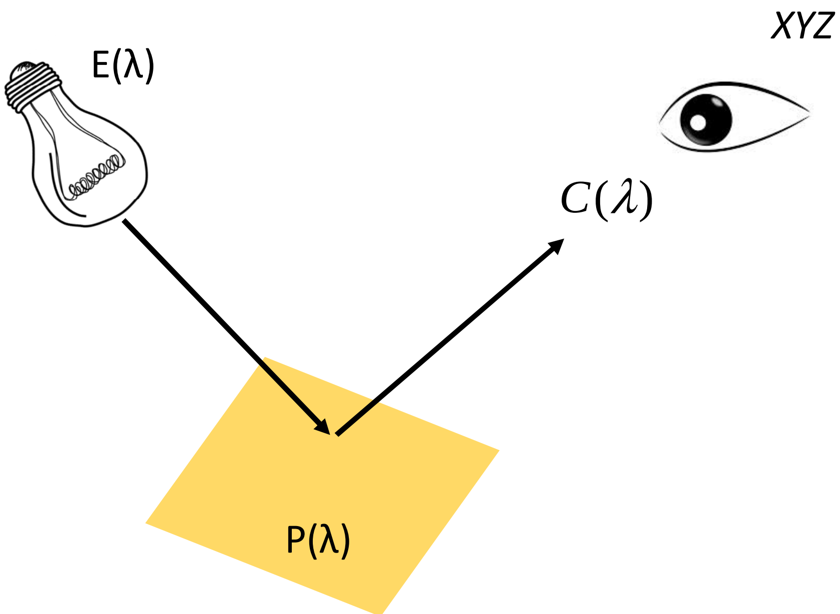






From reflectance spectra to RGB

Example: How to transform a Munsell chip reflectance spectra into RGB so that it can be displayed on the screen.



XYZ $\bar{x}(\lambda)\ \bar{y}(\lambda)\ \bar{z}(\lambda)$ $C(\lambda)$

$$\mathbf{e} = \mathbf{FC}$$

$$\mathbf{C} = \mathbf{Pt}$$

$R(\lambda)\ \ G(\lambda)\ \ B(\lambda)$ $r\,g\,b$

Thus: $\mathbf{e} = \mathbf{FPt}$

Or, more simply: $\mathbf{e} = \mathbf{Mt}$

And its inverse: $\mathbf{t} = \mathbf{M}^{-1}\mathbf{e}$

Summary

- Choose the ***right tool*** for the job (e.g., use the appropriate light meter).
- Consider the ***noise*** in the system (from the light meter and the display device), when setting the requirements of acceptable reproduction.
- Choose the right measurements for the task (be careful when generalizing measurements specified for the ***standard observer***).
  (For example, don't use V(λ) for setting isoluminance)
- Choose the ***colour space*** (CIE vs. physiologically-relevant) that is appropriate for what you are aiming to measure.

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The end ☺

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