Theory of colour measurement

Contemporary wool dyeing and finishing

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Colour measurement theory

Topics

1. How we see colour
2. Generation of colours
3. Measurement of colour

1. How we see colour

What is colour?

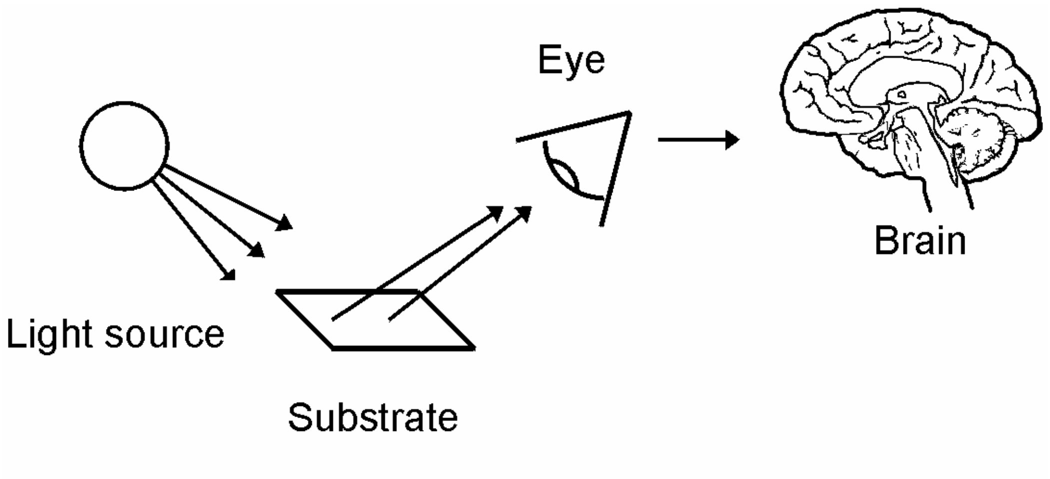
- According to the Committee on Colourimetry of the Optical Society of America, colour is defined as consisting of the **characteristics of light other than spatial and temporal inhomogeneities.**

- Light is described as the aspect of radiant energy which is apparent to a human observer through the visual sensations which arise from the stimulation of the cone and rods cells in the retina of the eye.

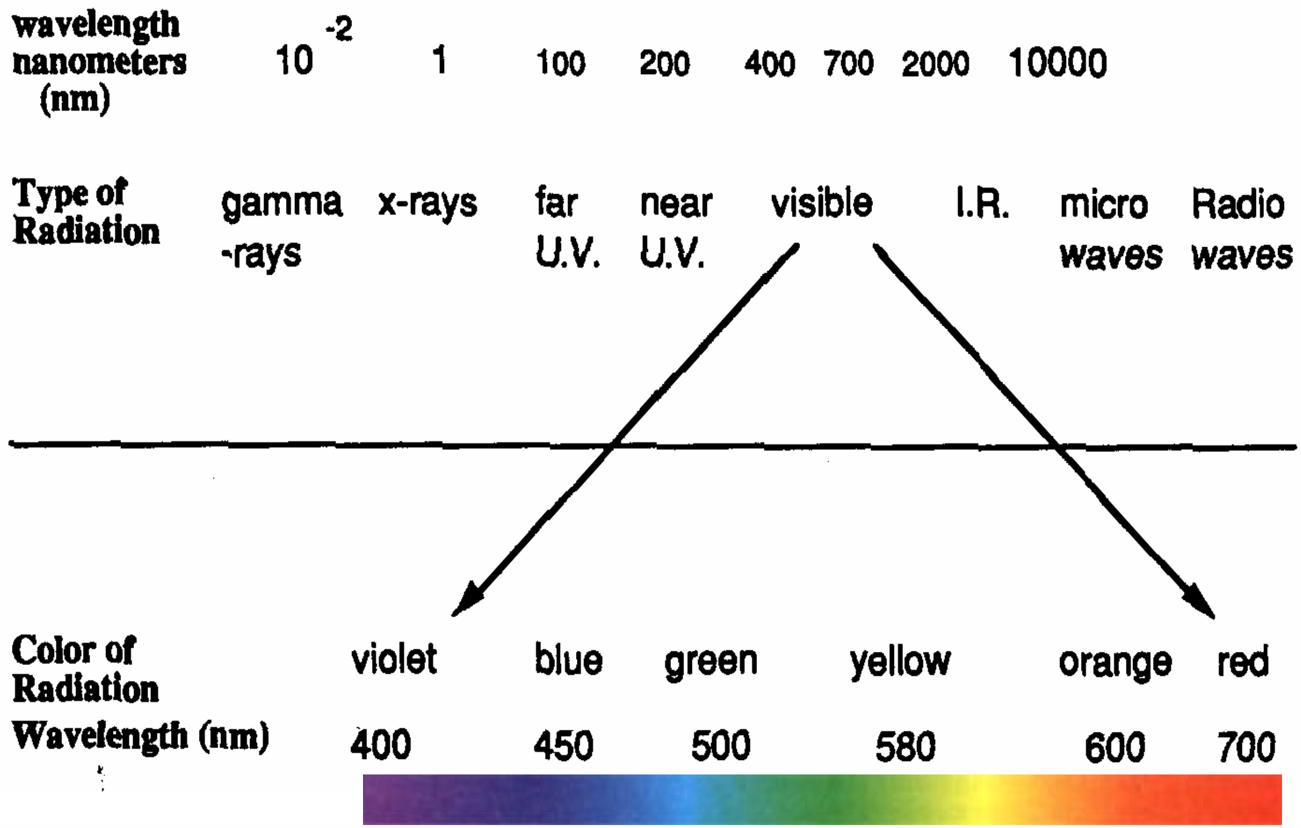
- Stimulation of the receptor cells initiates nerve impulses that are translated by the brain into a visual sensation of colour.

- Colour defined in this way is a psychological response to a physical stimulus produced by means of a physiological process.

The process of vision



The electromagnetic spectrum



The wavelengths of light absorbed and the colours perceived

Light Absorbed by the Object	*Wavelengths (nm) Absorbed (λmax)	Color Perceived
violet	400-435	yellow-green
blue	435-480	yellow
greenish-blue	480-490	orange
bluish-green	490-500	red
green	500-560	purple
yellow-green	560-580	violet
yellow	580-595	blue
orange	595-605	greenish-blue
red	605-700	bluish-green

* Range of maximum absorption

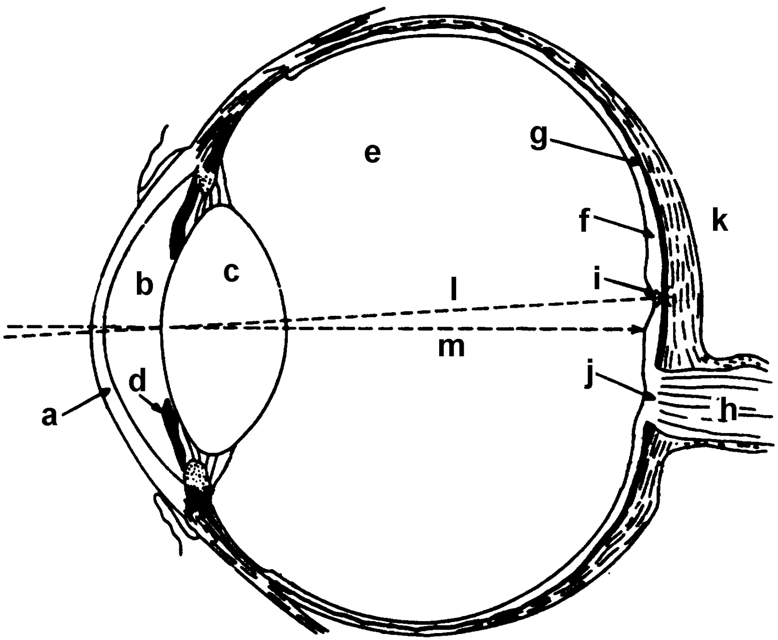
Colour seen and hue of light reflected from an object

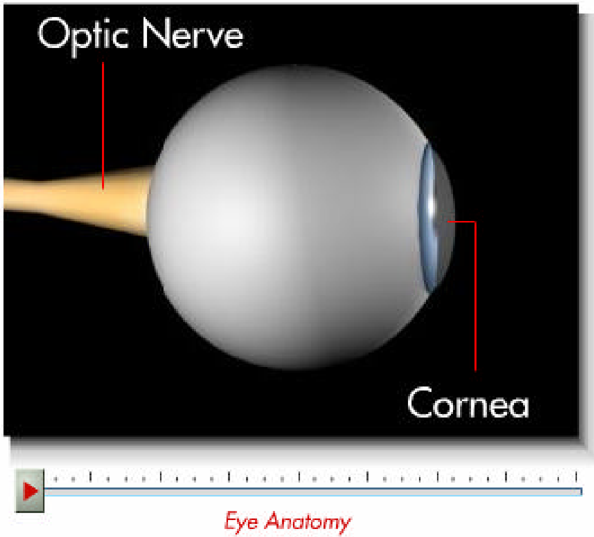
Color of Object (Color Seen)	Light Reflected or Radiated from Object		
White	Blue	Green	Red
Black	---	---	---
Blue	Blue	---	---
Green	---	Green	---
Red	---	---	Red
Cyan	Blue	Green	---
Yellow	---	Green	Red
Magenta	Blue	---	Red

Subtractive mixing of coloured dyes and pigments

Pigments Mixed	Color Seen
Cyan + Yellow	Green
Cyan + Magenta	Blue
Yellow + Magenta	Red
Cyan + Magenta + Yellow (all to the same amount)	Gray Black
Cyan + Magenta + small amount of Yellow	Navy-blue
Yellow + Cyan + small amount of Magenta	Olive
Yellow + small amounts of Cyan and Magenta	Brown

The human eye



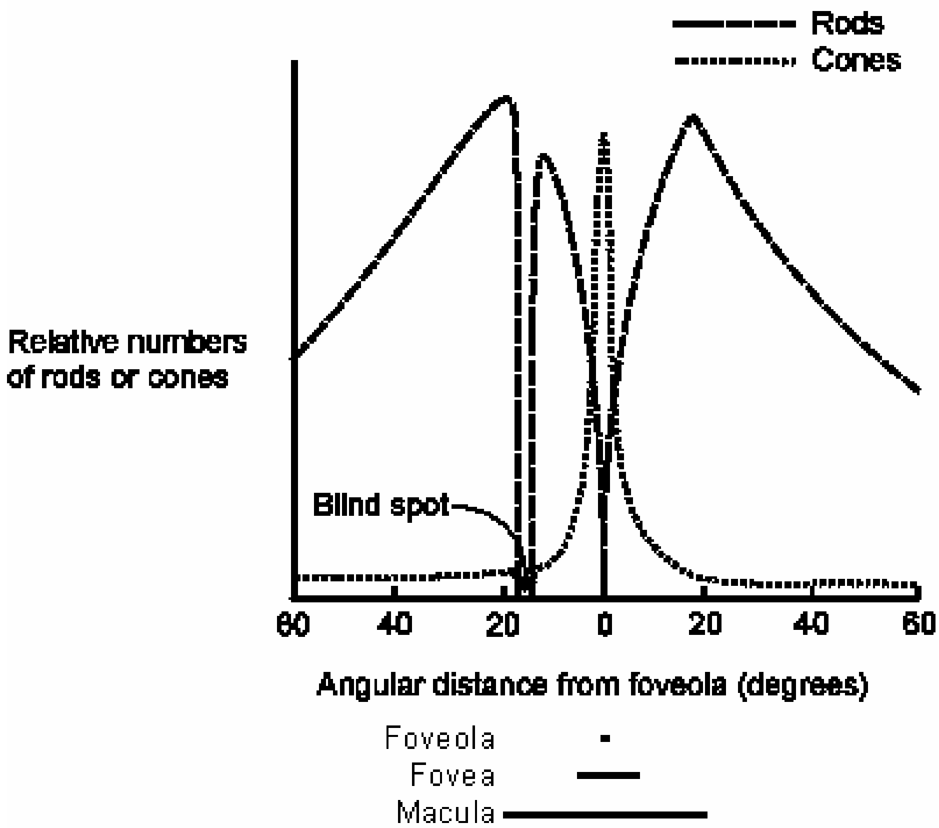


(a) cornea (b) aqueous humor (c) lens (d) iris (e) vitreous humor (f) retina (g) choroid (pigmented membrane) (h) optic nerve (i) fovea (j) optic disc (blind spot) (k) sclera (l) visual axis (m) optical axis.

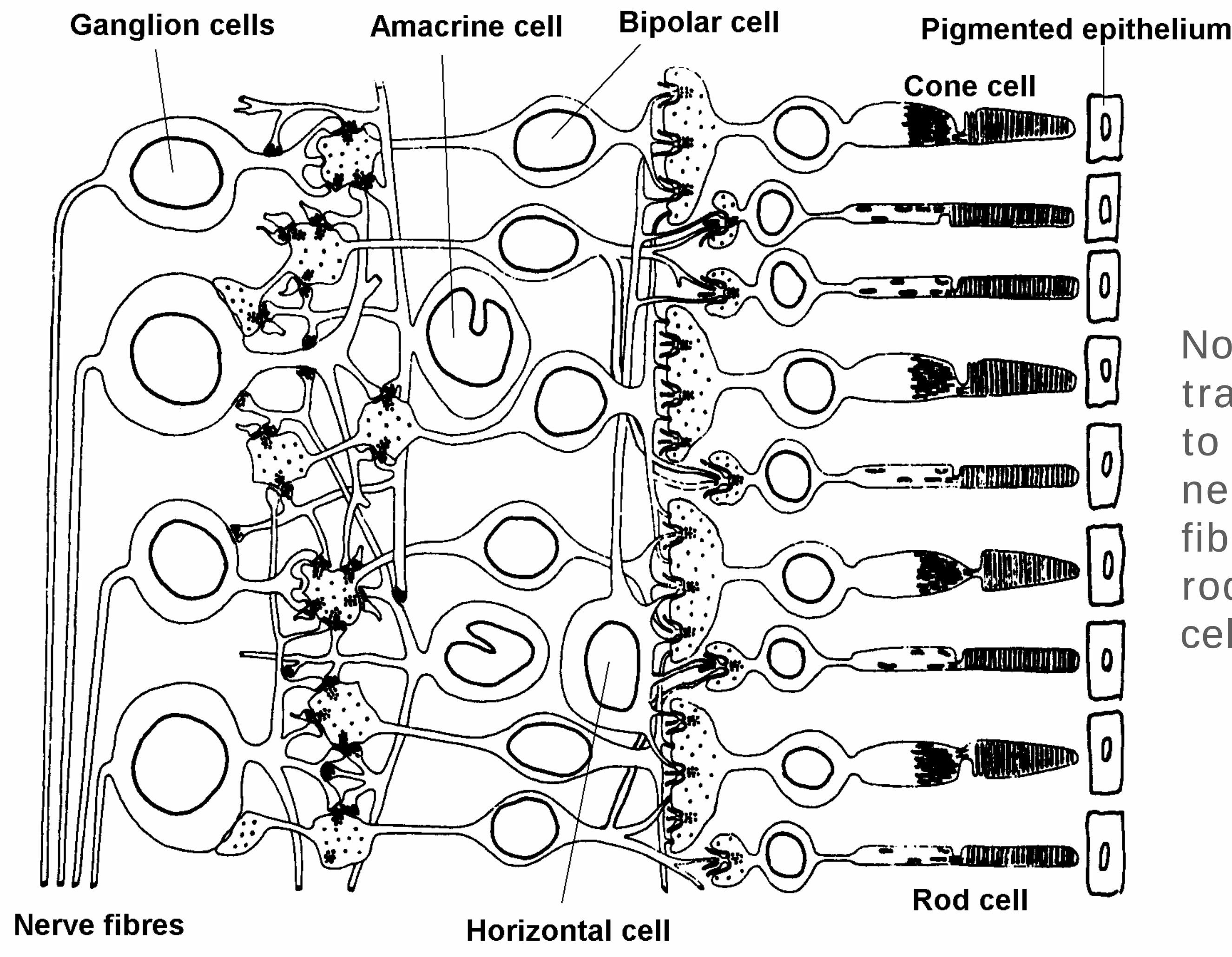
Function of the rod and cone cells

- Rods are almost 1000 times more sensitive than cones and are responsible for vision at low levels of illumination (e.g. starlight which corresponds to less than one lux). Rods only register levels of lightness and darkness, so we are unable to see colours. This is called scotopic vision.
- Cones provide us with colour vision and the ability to see fine detail. They predominate vision at higher light levels, This is called photopic vision.

How the rod and cone cells are distributed in the retina

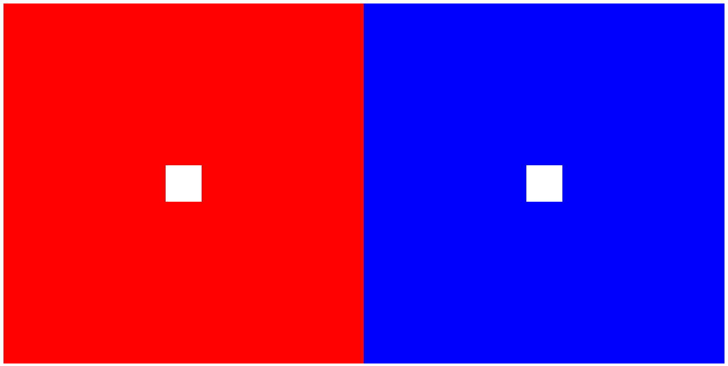


A simplified section through the retina.

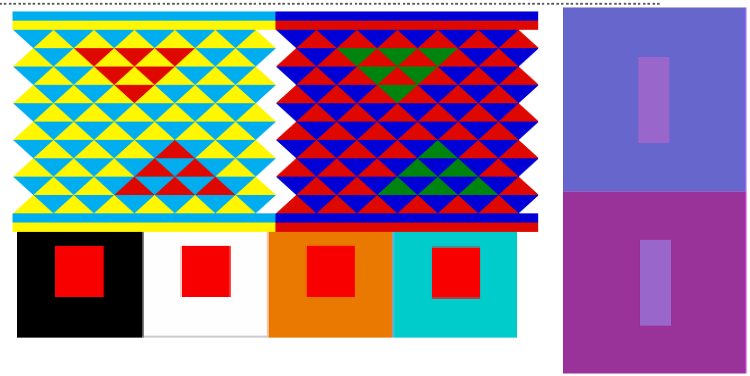


Note that light travels from left to right, i.e. the nerve cells and fibres overlay the rod and cone cells.

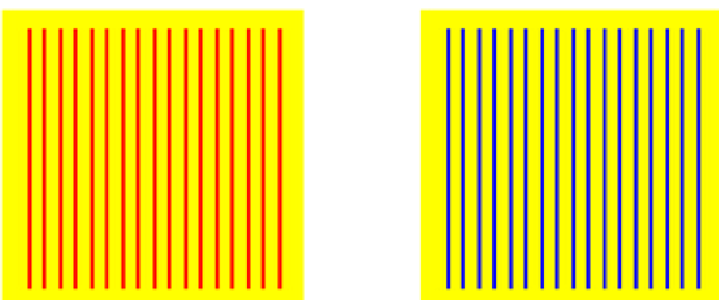
Colour illusions



The hues of the white squares shift hue in the direction of the surrounding colour.

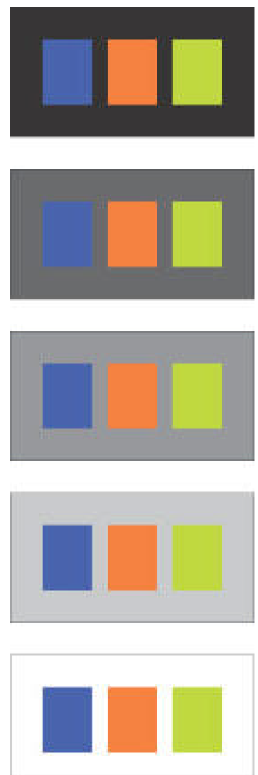


The colour of the surrounding background alters the perception of identical hues.



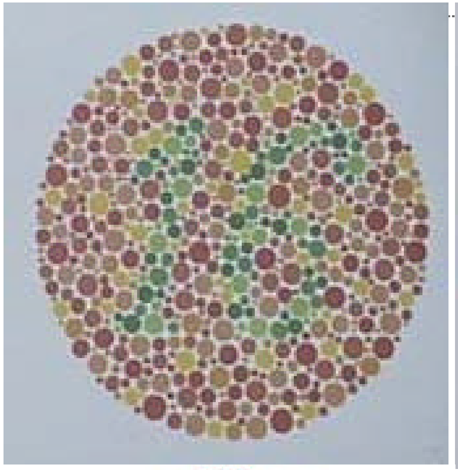
The yellow squares are the same hue but the red stripes make the hue appear warmer than the blue stripes.

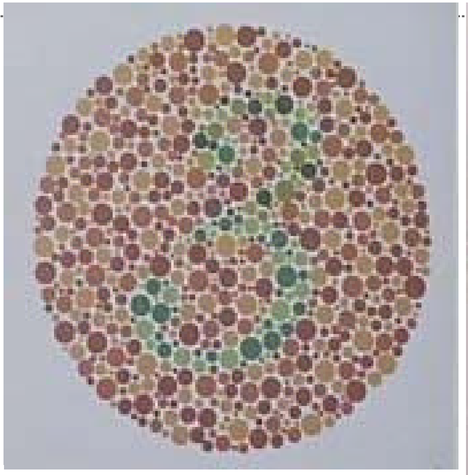
- The brain produces these illusions because its ability to perceive colours is not absolutely perfect.
- The viewing conditions can alter our colour perception.

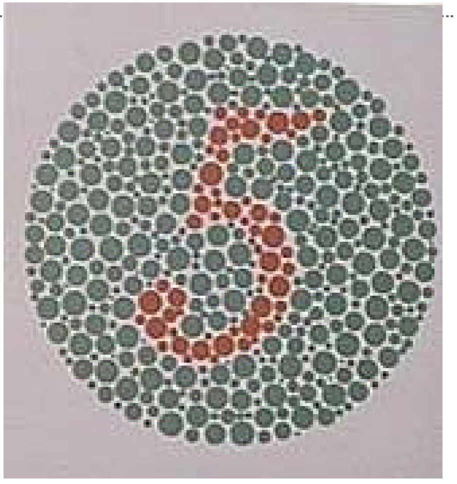


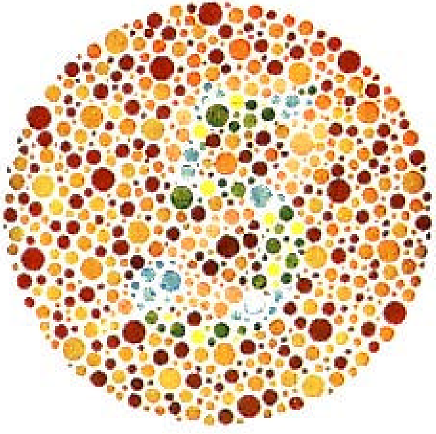
Colour blindness

Ishihara tests.









If you can not see numbers in the top three pictures and see The number 2 in the picture on the left you suffer from red-green colour blindness.

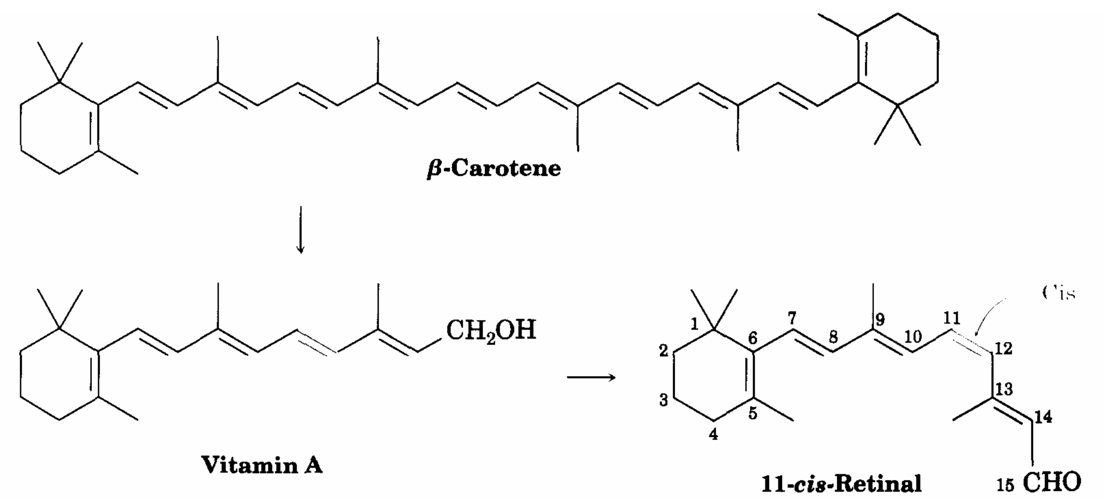
About 10 of people have some form of colour blindness.

The photosensitive pigments

- The visual pigment found in the rods and known as rhodopsin. It absorbs light in the yellow part of the spectrum at a wavelength of about 496 nm
- The peak sensitivities of the cones lie in the blue (approx. 425 nm), green (approx. 530 nm) and yellow-green (approx. 560 nm) parts of the spectrum. The visual pigments are all closely related to rhodopsin. The three different types of cone cells do not occur with equal frequency throughout the retina. There are approximately 40 red and 20 green to every blue sensitive cell, and in the foveola area, the blue cones are almost entirely absent. The probability of absorbance of a quantum of light therefore varies not only according to wavelength but also on the relative distribution of cone types.

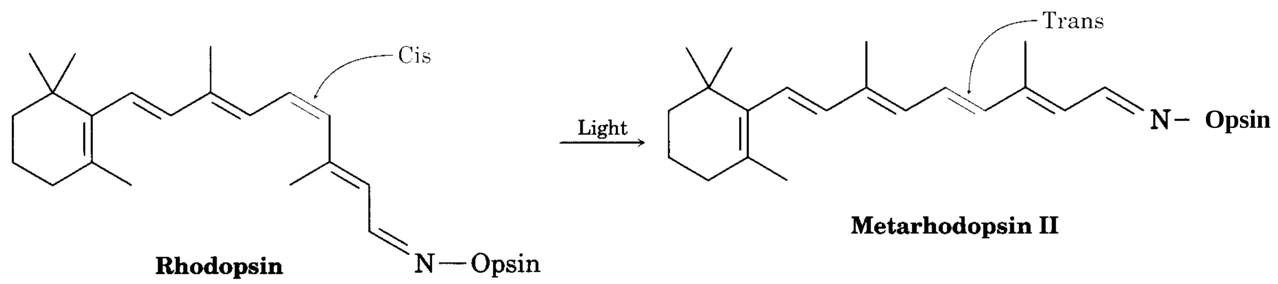
Carrots, alkenes, and the chemistry of vision

- Folk medicine has long held that eating carrots is good for your eyes. There's no question that the chemistry of carrots and the chemistry of vision are related.
- **Carrots are rich in b-carotene**, a purple-orange alkene that is an excellent dietary source of vitamin A.
    - **b-Carotene is converted to vitamin A by enzymes in the liver**,
    - oxidised to an aldehyde called all-trans-retinal, and then
    - isomerised, by a change in geometry of the C11-C12 double bond, to produce **11-*cis*-retinal, the light-sensitive pigment on which the visual systems of all living things are based**.



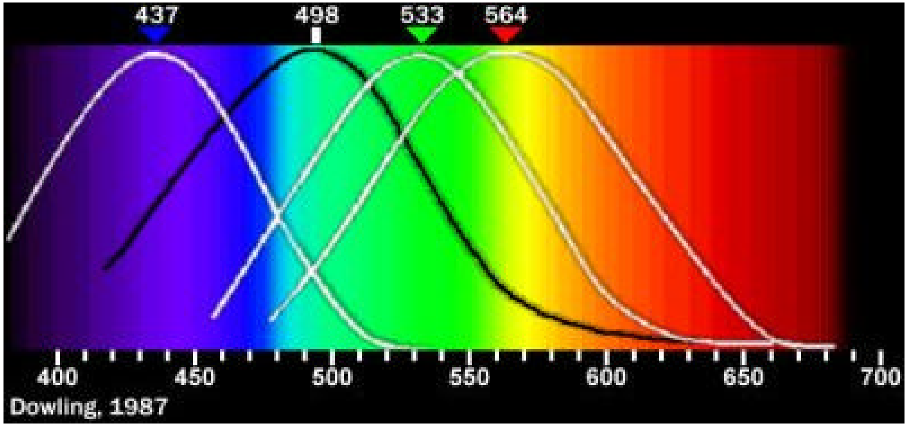
Chemistry of colour vision

- The two types of light-sensitive **receptor** cells in the retina of the human eye are **rod cells and cone cells**.
- The **three million rod cells** are primarily responsible for **seeing in dim light**, whereas the **hundred million cone cells** are responsible for **seeing in bright light** and for the perception of bright colours.
- In the rod cells of the eye, 11-*cis*-retmal is converted into rhodopsin, a light-sensitive substance formed from the protein opsin and 11-*cis*-retinal.
- When light strikes the rod cells, isomerisation of the C11-C12 double bond occurs and *trans*-rhodopsin, also called *meta*-rhodopsin II, is produced. This cis-trans isomerisation of rhodopsin is a change in molecular geometry, which in turn causes a nerve impulse to be sent to the brain where it is perceived as vision. (In the absence of light, the cis-trans isomerisation takes approximately 1100 years; in the presence of light, it occurs within 2 x 10-11 seconds!)
- *Meta*-rhodopsin II is then recycled back into rhodopsin by a multi-step sequence involving cleavage to 11-*trans*-retinal and cis-trans isomerisation back to 11-*cis*-retinal.



Eye sensitivity

- The three white curves to the right indicate the sensitivity level for the three types of cones.
- The black curve indicates the sensitivity of the rods The peak response moves from 550 nm to 500 nm at night.



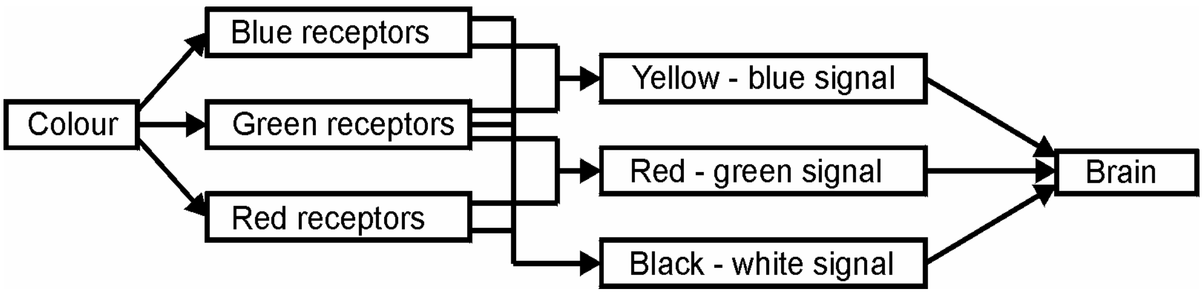
Implications of the structure of the retina for viewing colours

- The solid angle of the light entering the eye will have a considerable influence on colour vision and has to be taken into account when choosing conditions for viewing and measuring coloured samples.
- When viewing colours for comparison purposes, the lighting should be not too bright or dark. For photopic vision to be optimal, approximately 1500 lux is an appropriate lighting level.

Theories of colour vision

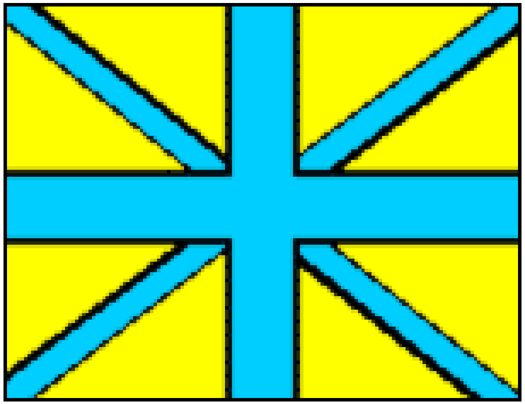
Young's theory of visual trivariance (1801) postulated three types of colour receptors (red, green and blue). This was extended by Helmholtz and is now known as the Young-Helmholtz theory of trichromatic vision.

- Hering (1878) postulated the opponent theory, or the theory of the three antagonistic or opposed pairs of receptors:
  - Six different receptors for the colours - red, green, yellow, blue, white and black.
  - All colours could be described in terms of their levels of stimulation of pairs of red - green, yellow - blue and white-black receptors
  - In 1930 Muller showed that both theories were compatible.



The Hering opponent theory of colour vision.

Afterimages



Look intently at the centre of the cross about 15 seconds and then look at the white area to the right.
Afterimages result from temporary saturation of photoreceptors in processing an image on the retina and consequent relative increased perception of the complementary colours against a neutral background. Normal perception resumes when the sensitivity of the saturated cones returns to normal.

The physical basis for colour

- Absorption of visible light by electrons when they are promoted from lower to higher energy states within molecules.
- As far as organic molecules such as dyes are concerned, suitable energy states for electronic transitions are generally only found in molecules with extended conjugated double bond systems.
- The electronic transitions in dyes usually involve promotion of electrons from non-bonding and π-bonding orbitals to antibonding π^* orbitals, as a result of absorption of a quantum of energy.
- The energy associated with a transition in quantum electronic states (ΔE) is related to the wavelength of the radiation as given by Planck's Law:

$$\Delta E = h v$$

where h is Planck's constant = 6.626176×10^{-34} J s, and v is the frequency of the radiation which is related to its wavelength (λ) by the relationship $c = v\lambda$, where c is the velocity of light = 2.997925 x 108 m s^{-1}.

2. Generation of colours

How colours can be generated

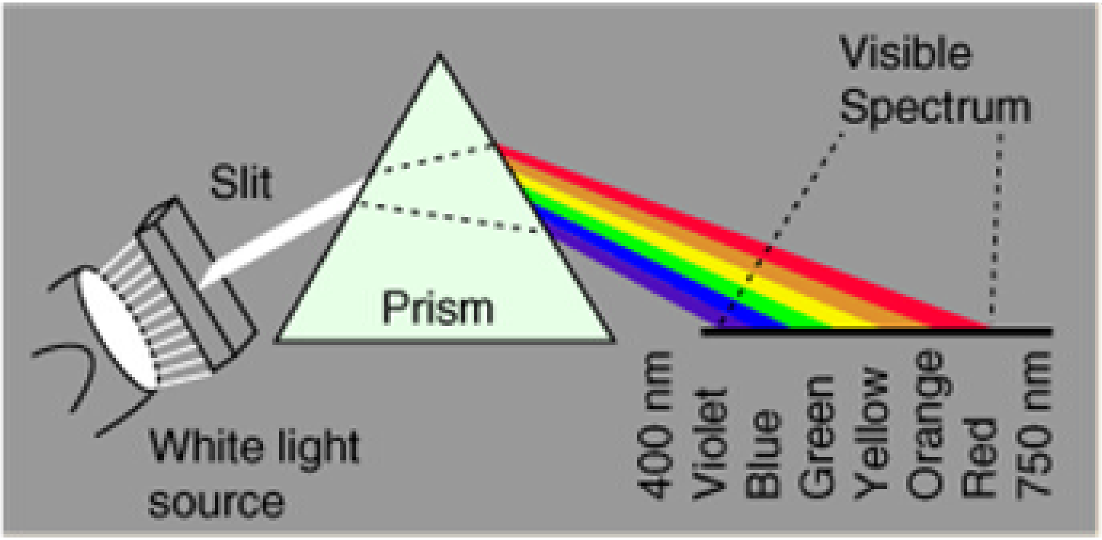
Colours can be generated:

- by visible electromagnetic radiation of a single wavelength
- by an additive process which involves mixing of coloured lights
- by a subtractive process in which coloured substances are mixed together.

Mixing of colours

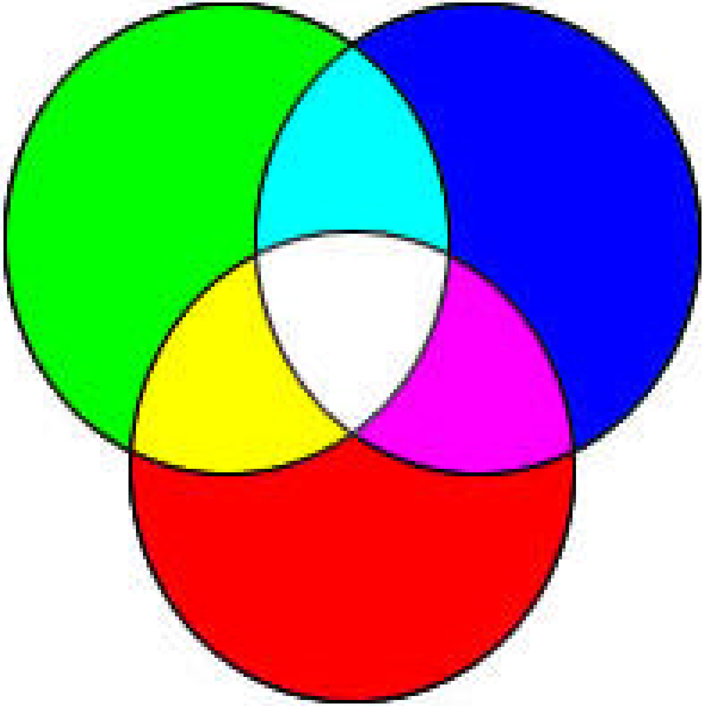
- Mixing colours by an **additive** process produces a resultant colour which **tends to white**.
- **Subtractive** mixing always darkens perceived colour and **tends towards black**.

Single wavelength colours

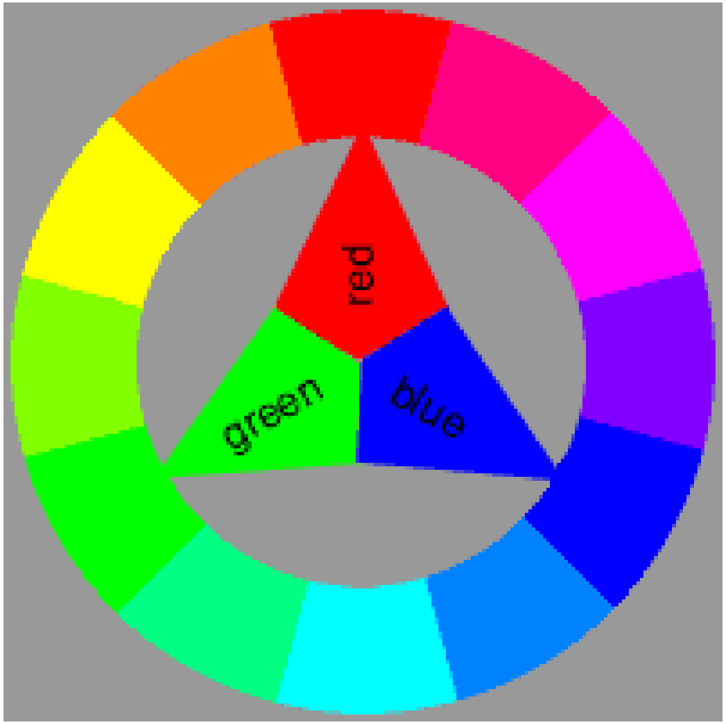


Each hue is associated with a particular wavelength of visible electromagnetic radiation.
The human eye can distinguish about 1000 different wavelengths in the range 380 nm to 740 nm.

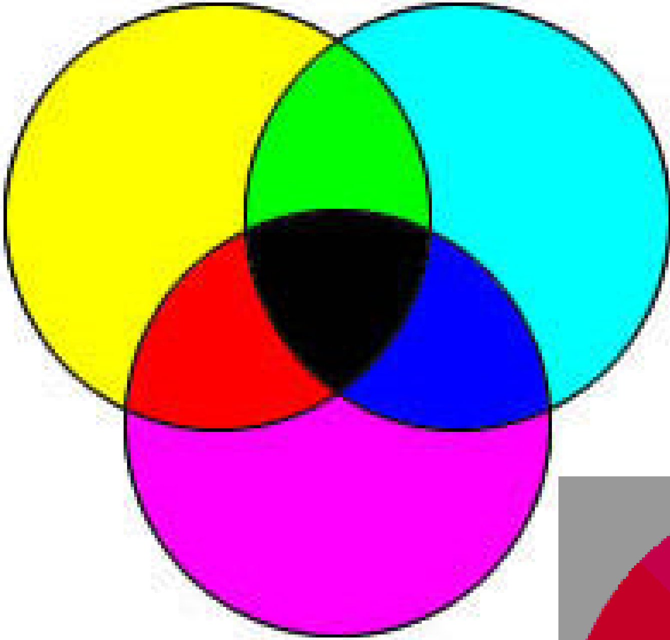
Additive primaries (lights) projected on a white screen



Mixtures become lighter and tend to white.

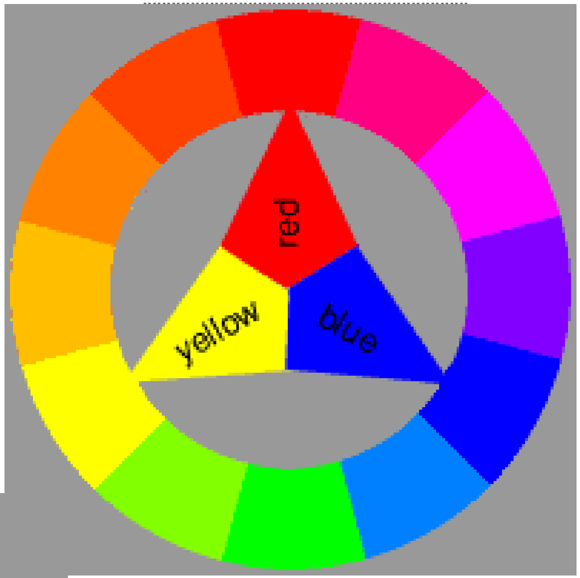


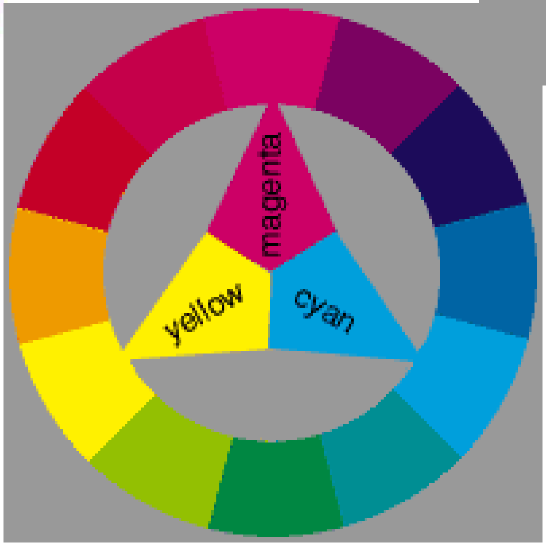
Subtractive colours



Mixtures become darker and tend to black.

Artist's palette





Printer's palette

3. Measurement of colour

The trinity of factors in colour perception

- From what we have now seen, it is evident that perceived colour of an object depends on the following factors:
  - the illuminating radiation
  - the reflectance of the object
  - the sensitivity of the eye.
- In addition, a minimum of three parameters are required to describe a visual colour.
- Three tristimulus values X, Y and Z, have been defined by The International Committee on Illumination (Commission Internationale de L'Eclairage or CIE) as the basis of colour perception.

CIE tristimulus values

- The CIE defined:
  - the energy distributions of a series of standard illuminants
  - the sensitivities of the three visual pigments in a ‘normal’ human eye.
- When combined with the measured reflectance of a sample, the three tristimulus values could be calculated for any of the standard illuminants.

Tristimulus values

The tristimulus values of a sample represent the amounts of red (X), green (Y) and blue (Z) primary colours which are necessary to produce the 'colour' of that sample.

$$X = k \int_{\text{Min } \lambda}^{\text{Max } \lambda} E_\lambda \, \bar{x}_\lambda \, R_\lambda \, d\lambda$$

$$Y = k \int_{\text{Min } \lambda}^{\text{Max } \lambda} E_\lambda \, \bar{y}_\lambda \, R_\lambda \, d\lambda$$

$$Z = k \int_{\text{Min } \lambda}^{\text{Max } \lambda} E_\lambda \, \bar{z}_\lambda \, R_\lambda \, d\lambda$$

where:

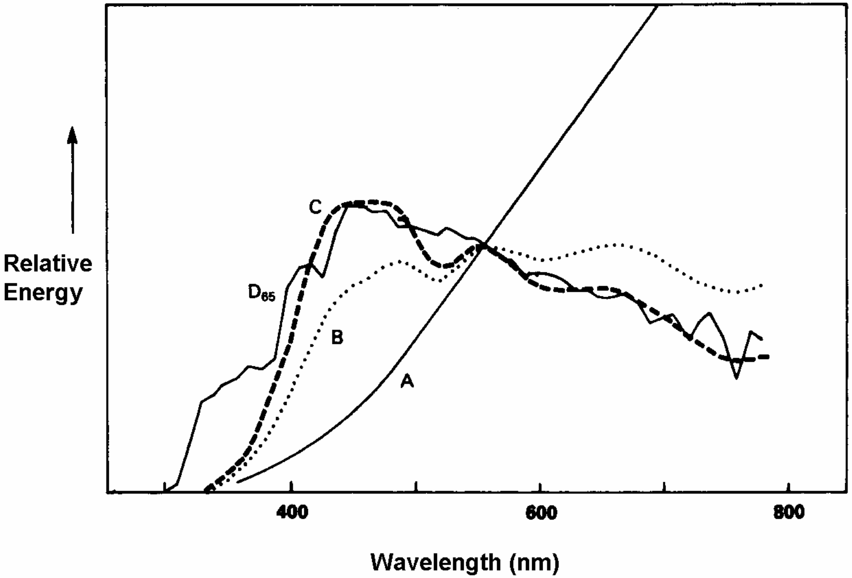
$$k = \frac{100}{\int_{\text{Min } \lambda}^{\text{Max } \lambda} E_\lambda \, \bar{y}_\lambda \, d\lambda}$$

where:

- λ is the wavelength of the radiation in nm (nanometers)
- E_λ is the spectral radiant flux incident on the object per unit area from a given source of light
- x_λ,y_λ and z_λ are the tristimulus eye sensitivity functions of the CIE standard observer
- R_λ is the reflectance from the sample
- k is a constant used to 'normalize' the results.

Illuminants

- **Illuminant A** corresponds to a gas-filled incandescent lamp operated at a correlated colour temperature of 2854°K.
- **Illuminant B** (noon sunlight) corresponds to the same lamp as in Illuminant A in com-bination with a two-cell Davis-Gibson liquid filter giving a correlated colour temperature of 4870°K.
- **Illuminant C** (average daylight) corresponds to an incandescent source with a correlated colour temperature of 6770°K.
- **Illuminant D65** corresponds to an illuminant having a correlated colour temperature 6500°K. It is similar to Illuminant C but includes an ultraviolet component and is closer to natural daylight at low latitudes.

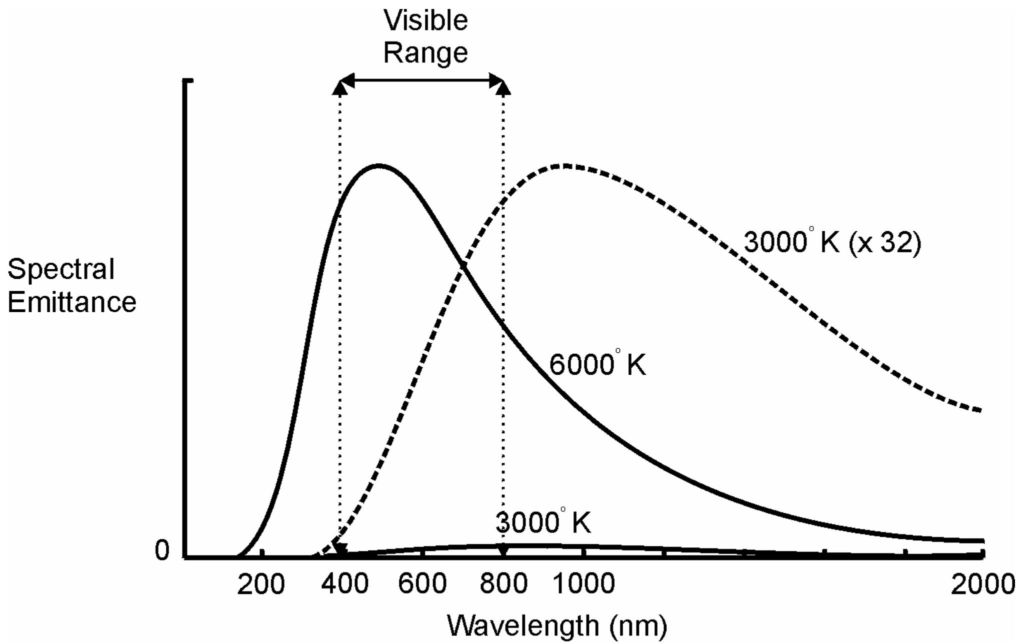


Black body radiators

The spectral emittance of a black body (M_λ) is given by :

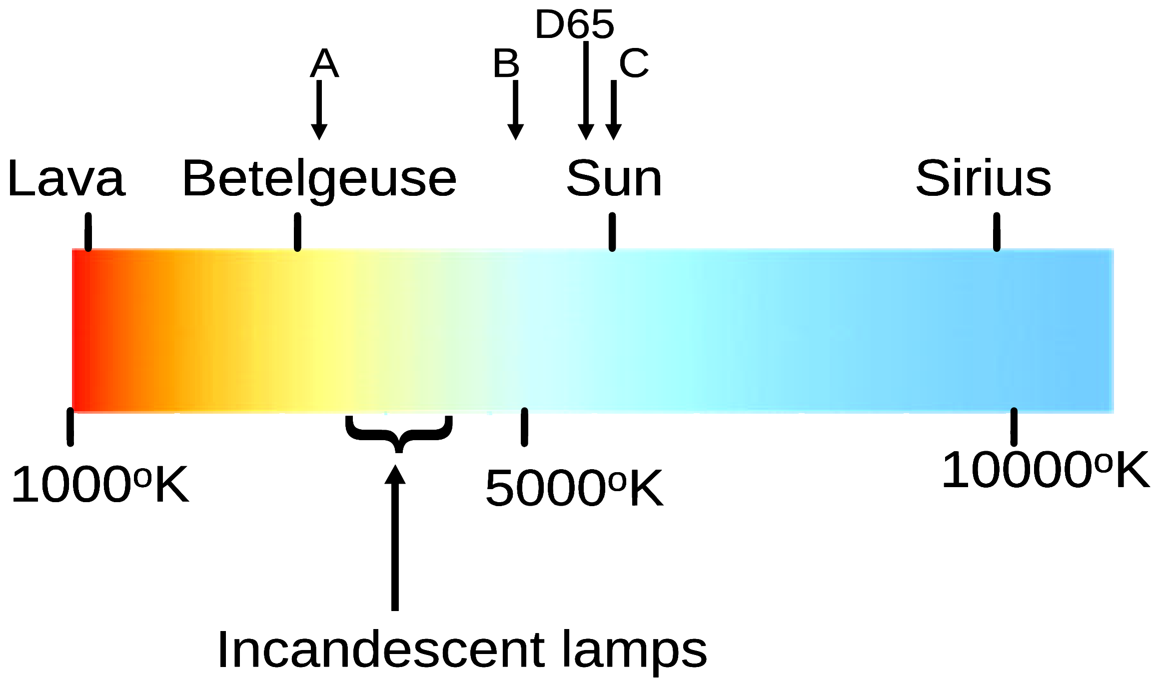
$$M_\lambda = \frac{2\pi hc^2 \times 10^{-9}}{\lambda^5\left[\exp(hc/\lambda kT) - 1\right]}$$

where: λ is the wavelength, h is Planck's constant, c is the velocity of light, K is Boltzmann's constant and T is the absolute temperature in ^oK.



Black body radiation

This shows the absolute temperatures and corresponding colours for some black body radiators and illuminants.

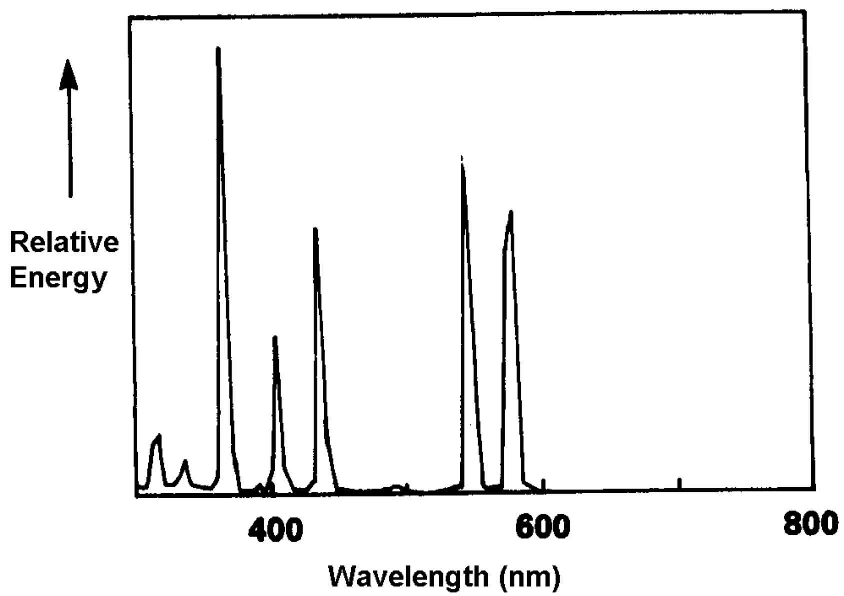


Summary on illuminants

- Incandescent lamps nearly behave as black body radiators and the temperatures of their filaments can be regulated to colour temperatures between 2800^oK and 3400^oK.
- The sun approximates a black body radiator of 6565^oK outside the earth's atmosphere but at the surface is vary variable depending on the time of day and atmospheric conditions.
- Illuminants B, C and D65 are intended to simulate sunlight under different conditions.
- Illuminant A represents artificial light from an incandescent source.

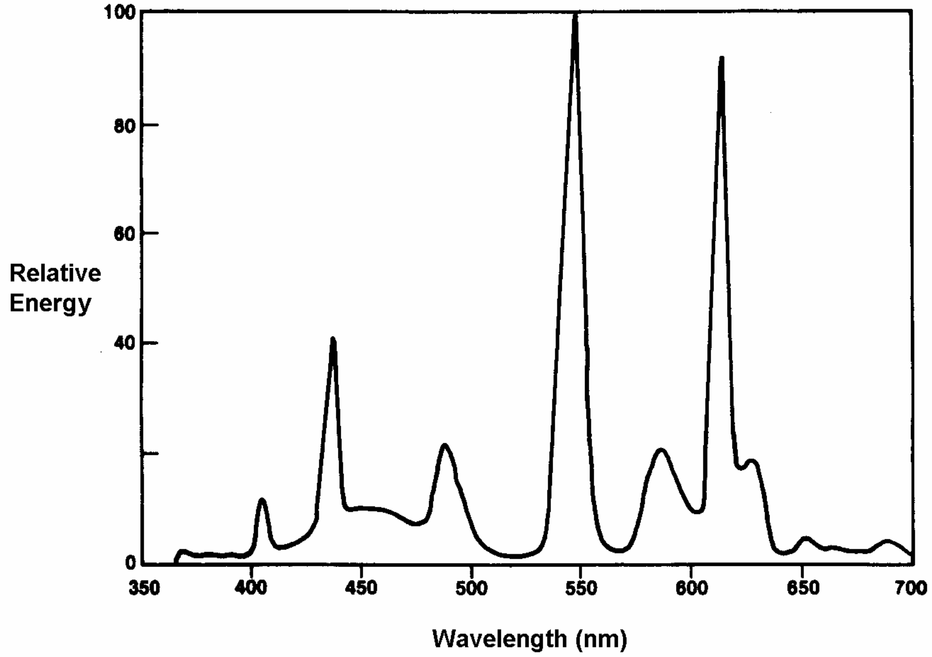
Arc sources as illuminants

Gas discharge tubes



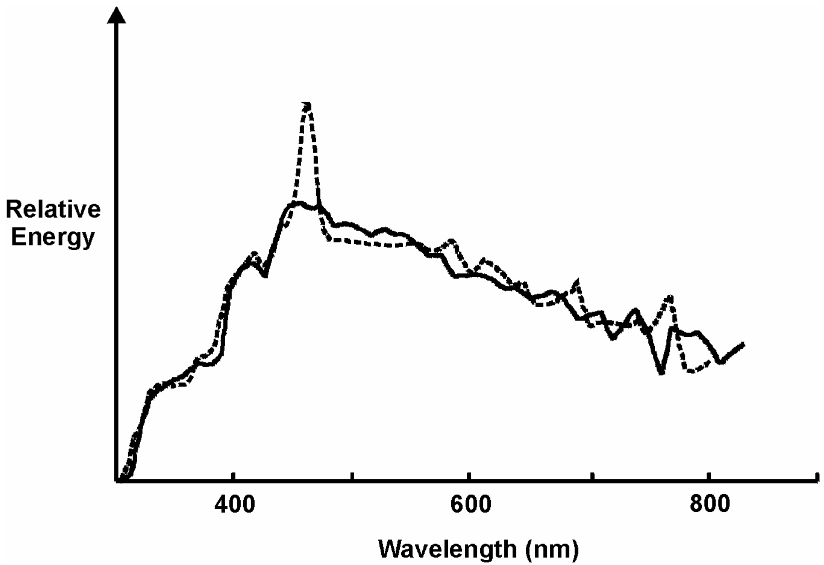
The spectral energy distribution of a high pressure mercury lamp.

Fluorescent lamps as illuminants



The spectral energy distribution of a fluorescent lamp (TL84).

High-pressure xenon arc lamp as illuminant

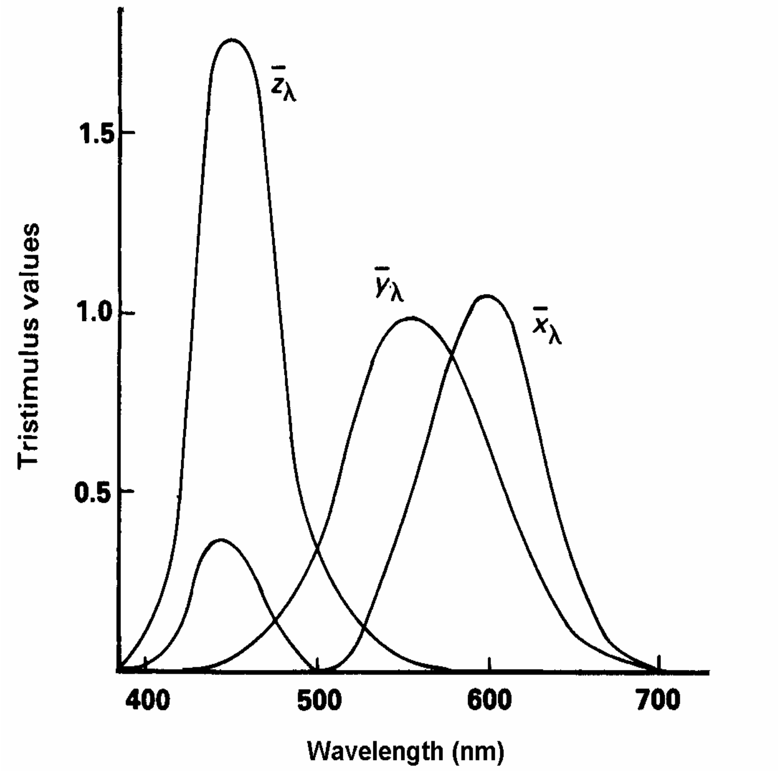


The spectral energy distribution of a filtered high-pressure xenon arc lamp (dotted curve) compared with Illuminant D65 (solid curve).

The CIE tristimulus eye sensitivity functions

- Slightly different sets of functions for two viewing conditions have been defined.
- These are referred to as the 2º and 10º observers.
- The angle relates to the area of the retina illuminated by the light from a sample.
- The larger area has a slightly greater contribution from the rods.

The CIE tristimulus eye sensitivity functions



Tristimulus eye sensitivity functions for the 10° observer.

Colour measurement in practice

In the next lecture we shall see how the reflectance of objects can be measured and combined with the standard illuminant and observer data to give quantitative measurements of colour.