SynthLight Handbook

Chapter 1: Fundamentals

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About

This is chapter 1 of 5 of the handbook for the SynthLight on-line course on lighting:

1. **Fundamentals**
2. Daylighting
3. Artificial Lighting
4. Integrating Artificial Light and Daylight
5. Case Studies

For more material and the other chapters, please visit the SynthLight web site at:
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This site also has an on-line test consisting of 15 questions each for each of the four main chapters. If you answer more than 80% of questions correctly, you will be sent a Certificate of Virtual Attendance.

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Disclaimer

Although much care has been taken in ensuring that all facts and conceptes laid out in this document are correct, the author can not be held liable for any mistakes that might have crept in. If you discover any inconsistencies, please notify <a.jacobs@londonmet.ac.uk>, so future revisions of this document can be corrected.

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1.1 Introduction

1.1.1 Light and Life

1.1.1.1 Sunlight

The Sun is the centre of our solar system around which all its planets, including the Earth, rotate. The distance between the Earth and sun is about 150 million km. Light travelling that distance will take about 8 mins. In other words, the Sun is 8 light minutes away from us, making it our closest star.

The diameter of the Sun is 1.4 million km or 109 times that of the Earth. The surface temperature is about 6000K, while the temperatures inside reach several million Kelvin. The process creating all this energy and heat is called solar fusion. Hydrogen ions are fused together creating helium and vast quantities of energy. This energy is the driving force for all life in out solar system.

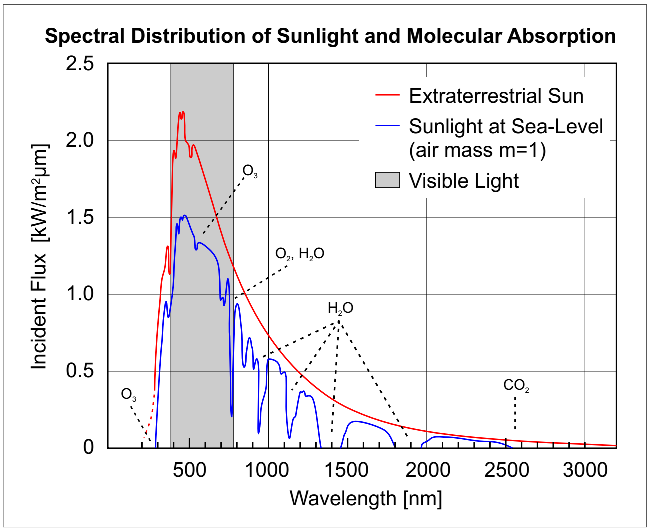


Figure 1: Extraterrestrial and terrestrial solar radiation

(Image based on [14, 21, 17])

Other than nuclear power, most other sources of energy available to man are directly or indirectly based on solar energy: Plants live on sunlight and CO_2, wind and waves are driven by the sun's energy, rain (the source of all rivers) is water vapourised by the Sun, and even fossile fuels such as oil and coal used to be energy consuming plants. [14, 28]

Wavelength [nm]	Radiation
100-280	UV-C
280-320	UV-B
320-380	UV-C
380-780	Light
780-5000	Near IR
5000-30000	Mid IR
30000-200000	Far IR

Table 1: Solar radiation

Life on Earth developed with the Sun as the main energy source. Terrestrial life forms (including man) are superbly adopted to those conditions. Put simply: Nothing beats natural light, in particular sun light. Although scientists and engineers have been trying for hundreds of years, they are still a long way away from producing sunlight-like light.

1.1.1.2 Effects of Light on Man

Man in his natural environment, i.e. outdoors and not living in buildings made of steel and concrete without any natural light, used to live a life that he is best adopted to. Over millions of years, all organs and functions of the human body (and that of other animals and of plants, too) have learned to perform optimally under the natural conditions. Although the climate varies across the populated regions of the Earth, all people have in common that they spend most of their live outdoors and only seek shelter at night or when the weather becomes too harsh.

With today's 'modern' lifestyle, this is no longer true. We live in houses that have small windows (at least when compared to a full 180x180° view of the sky we get outdoors) which block all the UV radiation with their glass. When we travel to work, this happens most likely in a car or bus, again without full-spectrum light. And if we are unlucky, we won't get to see any daylight work, sitting in an air-conditioned and artificially lit building. Most of us have to rely and our watches and the clock in the office rather than the natural variation of outdoor illuminance and the changing position of the sun on its path through the sky. We spend an average of 90% indoors. Even with good, 'bright' lighting, the light levels only reach about 1% of what is available outdoors. The light starvation leads to many modern day deseases, e.g. Sick Building Syndrom (SBS), Seasonaly Affective Disorder (SAD), depressions, or MA. Certain body function, such as the regulation of the sleep-wake cycle, require illuminances in excess of 4000lx [21].

While we all know that natural light has a positive effect on human being (or rather a 'normal' one, since this is what we are best adapted to), the exact mechanisms are still a long way from being understood. Generally, the effects are categorised into two categories–direct and indirect [28].

Direct effects

Direct effects are caused by chemical change in tissues due to the energy of the absorbed light. We are generally advised to stay out if direct sunlight because it causes skin cancer and all sorts other ill side-effects. However, this is only one side of the coin. High levels of sunlight only have a negative effect on use because we are not used to it. What most of try to achieve when on holidays is to catch up on the light we have been missing out on for the last 51 weeks of the year in a fortnight. This, however, will only lead to an overdosis of sunlight and UV, resulting in sun-burns and potentially skin cancer at a later date. It has been shown that workers who spend most of their time outdoors, e.g. gardeners, develop skin cancer less frequently than office workers.

Indirect effects

Indirect effects are a response of tissues to neural or hormonal signals. Wurtman [6] found that the production of the hormone melatonin was affected by the daily light patterns. Melatonin is secreted by the pineal gland. This organ, which is situated in the brain, affects sleep, the secretion of other hormones and the regulation of the body’s daily rhythm. It is sometimes referred to as the 'Third Eye', particularly in Eastern teachings. Melatonin is only produced by the pineal, and only in darkness. It has the effect of sending us to sleep. When we are exposed to bright light entering out eye, Melatonin production stops within half an hour. Sunshine is far more effective in waking us up than coffee or any other drug. Disturbances in the wake/sleep cycly caused by a lack of bright light above 1500lx are a feature of affective disorders, e.g. depression, anxiety and manic-depression.

The complex relationship between light and the bodily functions might not be completely understood yet, but one thing is clear: The overall aim of any artificial lighting system should be to model as good as possible the conditions and dynamics that occur outdoors. This is particularly true for offices, i.e. spaces that people spend large amount of their time in. Without proper light, we get sick, both physiologically and psychologically. The perfect light source which is a near-substitute to sunlight has not been created yet, but lighting engineers have a resonsibility to do whatever is possible to make the indoor space as human and as naturally lit as possible.

1.1.2 The Nature of Light

Since the 17th century, two rival theories about the nature of light have existed. Isaac Newton argued that light must be a stream of particles, while Christian Huygens thought that it must be propagating like a wave. Since waves require a medium to travel in, he postulated this to be the *aether*, something which is all around us but not visible or otherwise detectable by us.

Interestingly, both schools of thought deviced experiments to prove their point of view. It can actually be shown that both were right. Today, this is called the wave-particle-dualism of light. Essentially, there are properties of light that can be explained with the particle theory, while others follow the wave theory.

1.1.2.1 Light as Waves

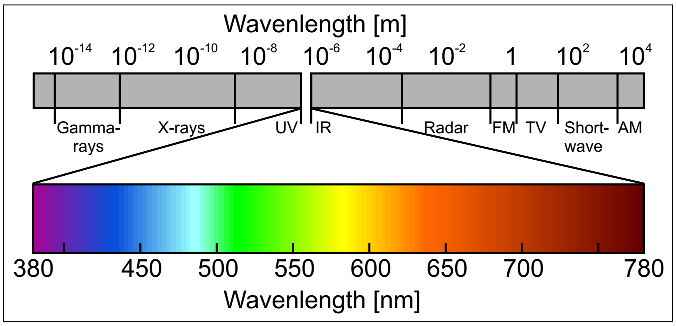


Figure 2: The electromagnetic spectrum

The electromagnetic spectrum covers an extremely broad range of radiation, ranging from radio waves with wavelengths of many metres, spanning several orders of magnitude, down to X-rays with wavelengths of less than a billionth of a metre.

Fig. 2 shows the range of the electromagnetic spectrum from 380 to 780 nm. This part is called *light*. Ultra-violet (UV) and infra-red (IR) radiation are sometimes referred to as *light*, although this is not strictly speaking correct, because we cannot detect those wavelengths with our eyes without the aid of instruments.

All waves can be described in terms of their frequency, their wavelength and their amplitude. Frequency and wavelength are related with the following formula:

$$c = \lambda f$$

with: λ .....Wavelength,
f ...... Frequency in Hz = s^{-1},
c ..... Speed of light, c = 300 000 km s^{-1}.

The speed of light given above is true for vacuum. Light travels slower in optically denser media such as water or glass. This causes *refraction*, i.e. a bend in the path of light on the passage from one medium to another.

Other optical phenomena can be explained with both, the wave and the particle theory. Those include *reflection* and *diffraction*.

Diffraction is the slight bending of light which occurs when it passes across an edge. It results in some of the light entering the umbra behind the obstruction. It is similar in nature to the way that sound can be heard behind an object, although the effect is much less noticable.

Reflection was elegantly explained by Newton as an elastic collision of the light particles, just like a billiard ball bouncing off the cushion of a billiard table.

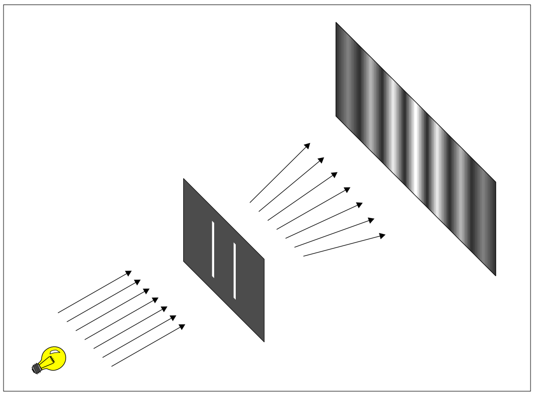


Figure 3: Young's double slit experiment shows the interference of light
(Based on [19])

One stumbling block for the early followers of the wave theory was finding an explanation for polarisation. Newton postulated that the particles are somewhat elongated, which, although proven to be wrong now, was sufficient to make a point against the wave theorists. Because they considered light to be longitudinal waves, they were unable to explain polarisation. Had they not ruled out that light could be a transversal wave, they could have easily explained polarisation, and more elegantly so than Newton with his particle theory.

Particle theory dominated physics for over 100 years until in the early 19^{th} century Thomas Young undertook a series of experiments which seriously underminded the particle theory. The most notable one was his double slit experiment. He quite rightly came to the conclusion that what he was observing was in fact interference of light to which there is only one possible explanation: Light must be a wave. He even went a step further and stated that light must consist of transverse waves.

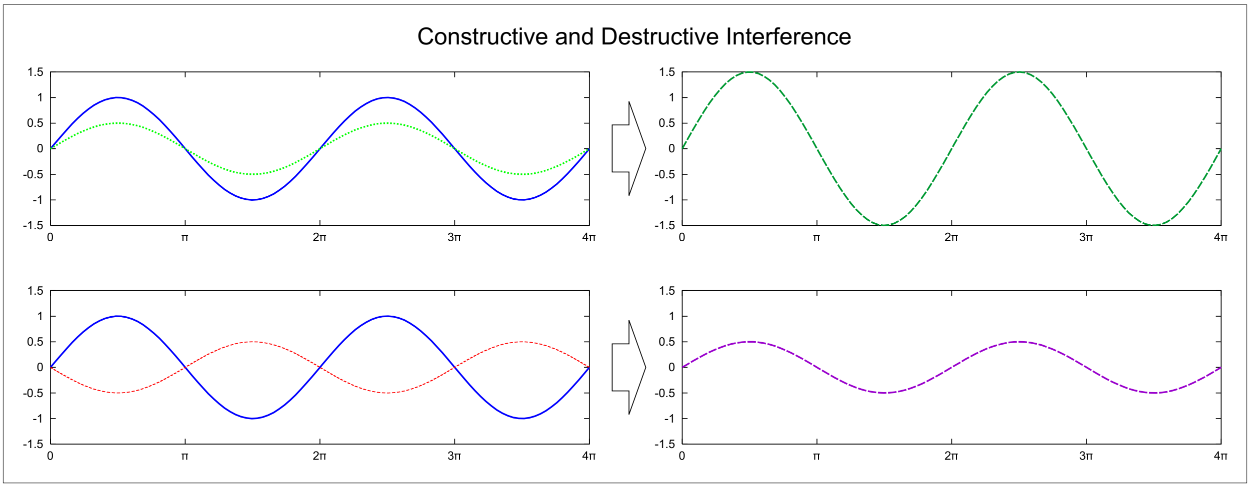


Figure 4: Interference of waves

Although this theory was at first heavily disputed by most fellow physicists, the mathematical framework later on developed by Augustine Jean Fresnel proved to be so successful that the wave theory had to be taken seriously. Albert Einstein proved in 1905 that although light is a wave, it does not need a medium unlike any other wave [19].

1.1.2.2 Light as Particles

It was Einstein, too, who proposed another fascinating idea. Light behaves like both, a wave motion *and* particles. This was then unheard of in physics; how can something be a wave and a stream of particles at the same time?

In 1900, a few years befor Einstein's ground-breaking suggestion, Mack Planck was able to show mathematically that electromagnetic radiation is produced by heated bodies not in a continuous manner but in discrete units instead. He was able to demonstrate that the energy of electromagnetic radiation is proportional to its frequency, with a constant h which is now known as Planck's constant forming the link between the two.

$$E = h\,f$$

with: E ..... Energy,
f ...... Frequency in Hz = s^{-1},
h ..... Planck's constant, $h = 6.626 \cdot 10^{-34}$ J s.

The discrete units of energy were named quantum, the particles of light photons. With them, Einstein was able to explain what had been described in 1902 by Philipp Lenard—the photoelectric effect. The quantum theory was to become so tremendously successful in describing all sorts of physical phenomena that it turned out to be the beginning to a new era in physics.

The blackbody radiation is defined by Planck's Law which states that the spectral radiation is proportional to the inverse of the wavelength to the power of five:

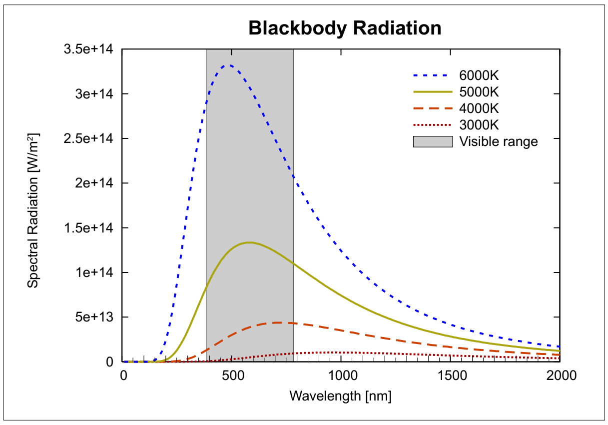


Figure 5: Blackbody radiation
(Graphs created with GNUplot)

$$S(\lambda)=\frac{2\pi c^2 h}{\lambda^5\left(e^{\frac{hc}{\lambda k T}}-1\right)}$$

with:
λ ..... Wavelength,
c ..... Speed of light, $c = 2.99 \cdot 10^8$ m s^{-1}
h ..... Planck's constant, $h = 6.626 \cdot 10^{-34}$ J s
k ..... Boltzmann's constant, $k = 1.38 \cdot 10^{-23}$ J K^{-1}
T ..... Temperature in K.

1.2 Photometry

All luminous measures have their counterpart in radiometry. While radiometry is concerned with the entire electromagnetic spectrum, lighting engineering only deals with the part that the human eye can see. For instance, the radiometric equivalent to illuminance is called irradiance.

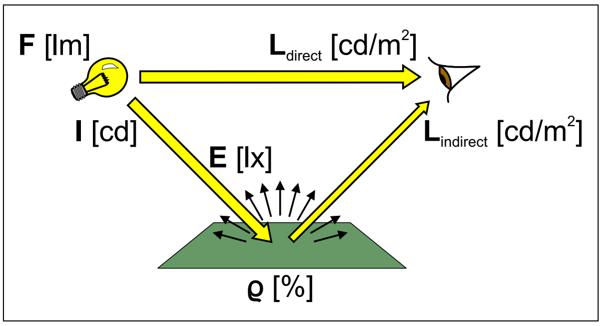


Figure 6: Schematic of the most important lighting terms

An overview of the most fundamental measures and their units used in lighting is shown in fig. 6. All terms will be explained further down in this chapter.

All lighting terms can be derived from the *luminous intensity*, which is an SI unit given in *candela*, by multiplying or dividing with the geometrical quantities *area* and *solid angle*.

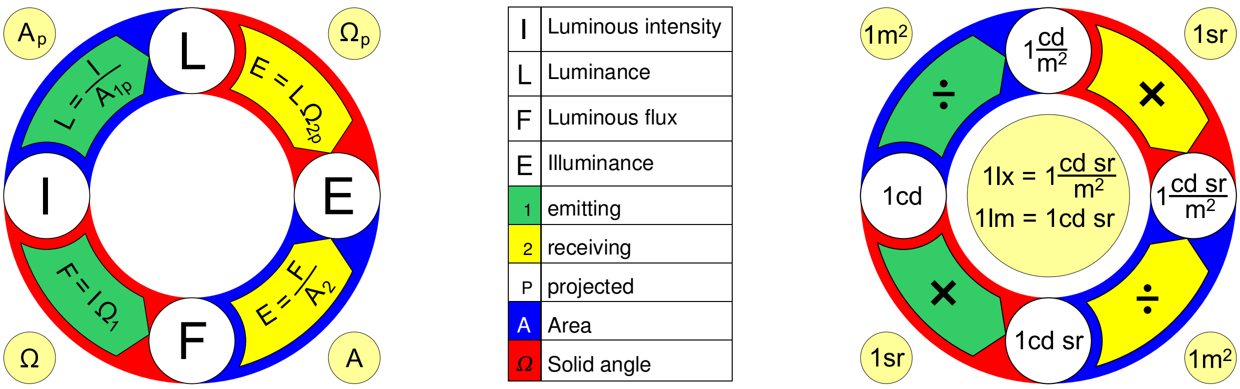


Figure 7: Measuring light – Luminous measures and their units

All measures of light can be derived from each other. They are linked by the geometrical terms:-

- Area A, given in m²
- Solid angle Ω, given in sr (steradian).

1.2.1 An Excursion into Geometry

1.2.1.1 Plane Angles

Area is a familiar concept. Solid angle, however, is not generally used other than in lighting and needs some explanation. For a better understanding, it might be helpful to recall the

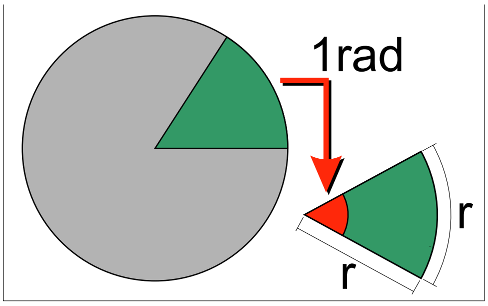


Figure 8: The plane angle

and needs some explanation. For a better understanding, it might be helpful to recall the concept of plane angle. Plane angles can be measured in radians. This is defined as the length of a circular arc *l* divided by its radius *r*.

$$\alpha=\frac{l}{r}$$

If the arc (i.e. the part of a circle´s periphery) that is subtended by the angle is exactly as long as the radius of the circle, the angle is by definition 1 radian. This is equivalent to about 57°. A full circle covers an angle of or 2π radians or 360°.

1.2.1.2 Solid Angles

The solid angle is very similar to the plane angle. The only difference is that it is three-dimensional rather than two-dimensional. Mathematically, it is a double integral over the longitude angle and the latitude angle.

In a simplified form which is only applicable for spherical surfaces viewed from the centre, it can be described as the ratio of the area of the surface of the cone *A* over the radius *r* of the sphere squared:

$$\Omega=\frac{A}{r^2}$$

The solid angle of objects which are too far away to estimate the area and the distance can be dealt with using the following formula which is based on the half-angle τ of the cone:

$$\Omega=2\pi(1-\cos\gamma)$$

Given a sphere of unit radius, a cone that subtends an area of unit m² on the surface of the sphere encloses a solid angle of 1 sr. A full sphere has a solid angle of 4π sr at the centre. Any surface, regular or irregular, of a sphere of unit radius, with an area of unit subtends an angle of 1 sr at the centre.

A round object that has an angular size of 57° subtends a solid angle of 1sr. In comparison, both, the sun and the moon cover a solid angle of only 0.000,06 sr which equates to a plane angle of 0.5°.

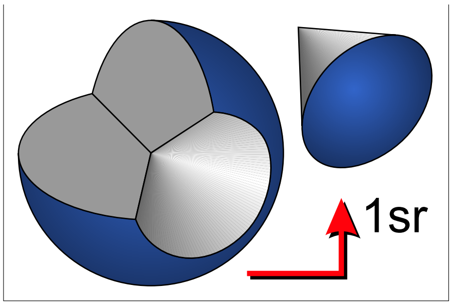


Figure 9: The solid angle

Sky	17" VDU	15° spotlight	Wristwatch	Moon	Sun
6.28 sr	0.25 sr	0.05 sr	8×10^{-3} sr	6×10^{-5} sr	6×10^{-5} sr

Table 2: Solid angles of some objects.

(Monitor at 60 cm, watch at 30 cm, beam-angle of spotlight)

1.2.2 Measuring Light

1.2.2.1 Luminous Intensity

symbol	**I**	unit	**candela**

Luminous intensity is a quantity which describes the power of a light source to emit light in a given direction. The difference between the luminous flux and the intensity is that the former is the total of all emitted light, whereas the latter is the fraction that is emitted into a certain direction or into a certain solid angle.

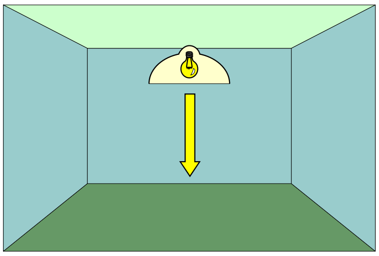


Figure 10: Luminous intensity

If a light source has no preferred direction of emission, it is said to be isotropic. In such a case, the luminous intensity in any direction multiplied by 4π (which is the full solid angle) is equal to the luminous flux.

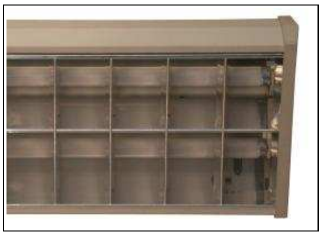
Candle	100W GLS	Sun
		
1 cd	110 cd	3×10^{27} cd

Table 3: Some typical luminous intensities

Very often, lighting designers and engineers need to know exactly how much light a fitting emits in a given direction. Unless a luminaire is perfectly diffusing, its luminous intensity will vary depending on the view point of an observer.

Figure 11: Goniophotometer
(Image courtesy of TechoTeam Ilmenau [C3])

To measure this distribution, the direction can be described in terms of angles of azimuth and elevation, similar to the virtual grid that covers our Earth, allowing us to pin-point the position of any place in terms of its geographical latitude and longitude.



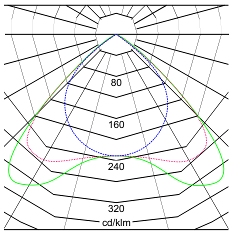


Figure 12: Luminous intensity distribution (right) of a fitting (left)

Intensity tables are available in electronic form for most recent luminaires. They are mainly used as input for computer-based lighting and visualisation programs. To make the tables more meaningful for the lighting designer, they can be visualised in polar curve, isocandela or isolux diagrams.

1.2.2.2 Luminance

symbol	**L**	unit	**candela/m²**

Luminance is defined as the luminous intensity of a surface in a specific direction, divided by the projected area as viewed from that direction. Unless the object is perfectly diffusing, the luminance will vary with the angle from which it is viewed. A perfectly diffusing surface is called a *Lambertian emitter.*

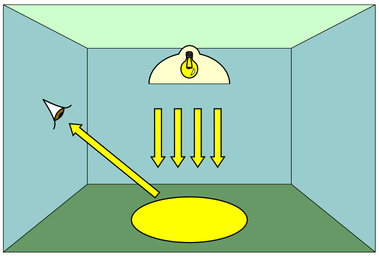


Figure 13: Defining the luminance

This definition implies that the object emits light. It does not, however, need to be a lamp. Every object can be an emitter just by reflecting light or by transmitting it, in which case it can be described as a secondary light source.

The luminance normalises the intensity to the area. To put it an other way, the luminous intensity is the product of luminance and projected area of the light source.

The luminance of an object is not the same as the perceived brightness which is dealt with later on in this document, but gives rise to the perception of brightness in the brain.

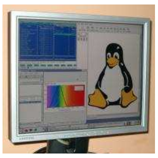
VDU	Moon	Candle	Fluorescent	Sun
				
100	2500	8000	10000	$1.6x10^9$

Table 4: Luminance of some light sources (in cd/m²)

Modern luminance meters incorporate an optical system trough which an object of interest is looked at. A small display in the viewfinder gives an immediate reading of the luminance by the push of a button. Such luminance meters are straightforward to use. However, they tend to be quite expensive.

Figure 14: Modern luminance meter

(Image courtesy of Minolta [C2])

A simpler way of measuring the luminance is to use a photocell with a special shading rod. The shading device defines a solid angle of incidence. By knowing the area of the sensor and the solid angle, the luminance can be derived.

1.2.2.3 Luminous Flux

symbol	**F**	unit	**lumen**

Luminous flux *F* a measure of the power of visible light. Photopic flux, expressed in *lumen* (abbreviated as *lm*), is weighted to match the responsivity of human eye, which is most sensitive to yellow-green light. The unit is defined so that 1 lm is 1.464 mW of optical radiation at a wavelength of 555 nm.

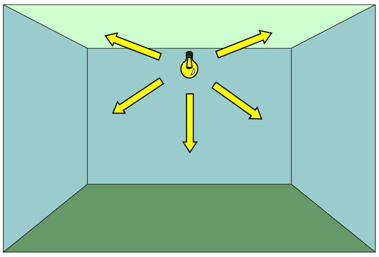


Figure 15: Luminous flux from a lamp

1 lm is the same as 1 cd sr, i.e. 1 lm is produced by 1 cd radiation through 1 sr solid angle.

GLS, 100W	Fluorescent, 58W	SOX, 70W
		
1200 lm	4800 lm	98000 lm

Table 5: Luminous flux of some typical light sources

The flux of a lamp or luminaire can only be measured in specially equipped lighting labs. Since the flux is the total of the lamp's or luminaire's output, an integrating sphere is used that catches all of the emitted light. Its inner surface is painted with a highly reflective, diffuse white paint based on Barium Sulphate, $BaSO_4$ or polytetrafluoroethylene, PTFE. Both materials offer a reflectance of >97% over a broad spectral range with near perfect diffusion. [W17]

The illuminance which the light source produces on the inner surface of the sphere is uniform over the whole sphere due to the special characteristics of the paint. The lux level is measures with the luminance meter. The flux output of the lamp or fitting can then be derived by calculation.

The luminous flux of a lamp will have to be compared to a standard source in order to get an accurate and absolute result. For luminaires, on the other hand, the *light output ratio*, LOR is usually of interest. For this, the measurements are taken in two-steps: First, the fitting is put in the sphere and the output measured. The result is then compared to the lamp without the fitting.

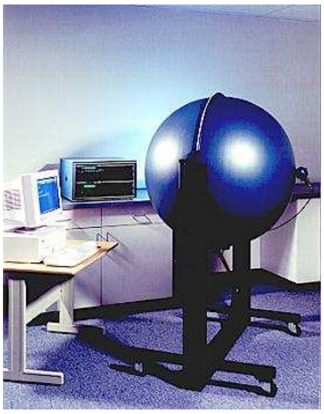


Figure 16: An integrating sphere for measuring luminous flux
(Img. courtesy of Labsphere [C5])

1.2.2.4 Illuminance

symbol	**E**	unit	**lux**

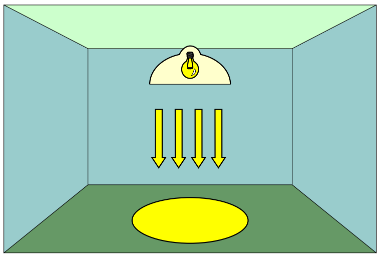


Figure 17: Defining the illuminance

Illuminance is defined as the luminous flux that is received per unit area of a surface. In other words, it can be described as the flux density on the receiving surface. The unit is *lux* or *lm/m²*. When stating the illuminance for a surface, its orientation will always have to be given, too. For instance, the illuminance on a desk is measured as the horizontal illuminance, the illuminance on a façade or on a wall as vertical illuminance.

Sunlight	Overcast	Office	Corridor	Dusk	Street	Moon	Stars
							
100,000lx	10,000 lx	500 lx	100 lx	50 lx	10 lx	0.5 lx	0.2 lx

Table 6: Some typical illuminances
(Images courtesy of Marlin Lighting [C4])

Illuminance is a quantity that can be measured very easily. Illuminance meters, sometimes referred to as lux meters are affordable, as long as the demands on accuracy are not too high.

Figure 18: Illuminance meter
(Image courtesy of Megatron [C1])

All illuminance meters need to be v(λ) corrected to match the response characteristics of the human eye. This is also known as colour correction. An additional requirement is for them to be cosine corrected. The response of the meter should depend on the angle of incidence. This means that light hitting the sensor perpendicularly (or along its axis) results in a higher reading than light which is incident under a steeper angle.

Because illuminance is easy to measure and calculate, most recommendations on the lighting in offices and other working environments are based around it. This is in contradiction to the way the eye actually works, because it responds to the luminance of objects rather than their illuminance. In other words, the eye responds to the light reflected from an object rather than the light falling onto it. For the UK, recommended illuminance levels for selected work places are defined in the CIBSE Code for Interior Lighting [13].

1.2.2.5 Reflectance, Transmittance and Absorption

symbols	ρ , τ, α	units	%

Reflectance, transmittance and absorption which have the Greek letters ρ (rho), τ (tau) and α (alpha) as their symbols, characterise properties of materials. Reflectance is an indicator for how much light hitting a surface will be reflected back, while transmittance indicates how much light will go through an object. The absorption is a measure for how much light is neither transmitted nor reflected, but instead absorpt by the body. All are given as percentages, but are sometimes normalised to unit. The sum of reflectance, transmittance and absorption for any material is always 100%:

$$\rho + \tau + \alpha = 1$$

A reflectance of 100% means that all the light received is reflected back. Such an object appears as bright white. A body with 0% reflectance will not reflect any light and appear completely black. In praxis, reflectances above 90% and below 1% are very difficult to achieve.

Traffic blue	Teak wood	Traffic yellow	Light grey	Pure white
7	18	54	67	85

Table 7: Reflectance values of paints and materials (in %)

Similar, the transmittance of an object indicates how much light it will let pass through. 100% transmittance means that all of the light received on one side will travel through a

100% transmittance means that all of the light received on one side will travel through a body, so there is no reflectance and no internal losses. This is just a theoretical maximum, since not even the clearest glass can achieve this.

Solar control glass (6mm)	Climalit solar control (6-12-6)	Bronze body tinted glass (4mm)	Double glazing (6mm-6mm)	Single glazing (3mm)
18	49	61	78	90

Table 8: Transmission values of glazing materials (in %)

The reflectance of a material can be measured with an illuminance meter and a luminance meter. The luminance meter is pointed at an area of the surface that is relatively evenly lit. The illuminance at that point is then determined. The reflectance of the material can be calculated using the formula below:

$$\rho=(L\pi/E)100\%$$

For quickly determining the transmittance of a glazing unit, two illuminance meters can be used to measure the inside and outside illuminance, i.e. in front and behind the pane. The transmittance is then

$$\tau=E_{internal}/E_{external}\times 100\%$$

1.2.3 Photometric Laws and Rules

1.2.3.1 The Law of Additivity

Because light is a form of energy, it obeys the principles of energy conservation. This means, for instance, that illuminance is additive, i.e. the illuminance received by an element of a surface from two or more light sources is equal to the sum of the illuminance received from each of the light sources independently. This Law of Additivity is also know as Abney's Law.

1.2.3.2 The Law of Transitivity and Distributivity

If an illuminance E_1 is equal to another one E_3 (which may be of a different colour), and if an illuminance E_2 is also equal to E_3 than

(1) $E_1=E_2$ (Law of Transitivity)

(2) $mE_1+nE_2=E_3$ (Law of Distributivity) (where $m+n=1$)

1.2.3.3 The Inverse Square Law

When the luminous intensity of a point source is known, the illuminance it produces at a certain distance can be derived using the Inverse Square Law.

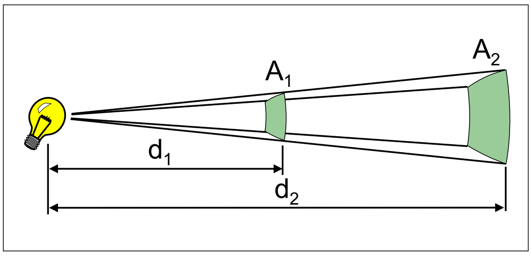


Figure 19: The Inverse Square Law

The surfaces A_1 and A_2 both cover the same solid angle from the light source. Because light travels in straight lines, they both intercept the same luminous flux. However, since their areas are different, the illuminance that this flux produces on the surfaces is not the same. The illuminance depends on the area onto which the light is falling; it is proportional to the inverse of the distance to the source squared:

$$E=\frac{I}{d^2}$$

An alternative way of writing this is:

$$I=d_1^2 E_1=d_2^2 E_2$$

This formula is only correct if the required illuminance is on a plane perpendicular to the light source and if the source is a point source. However, in practical applications, the formula produces figures with a 1% accuracy if the distance to the light source is at least five times the largest dimension of the source. If the surface is not perpendicular to the way the light travels, then the Inverse Square Law needs to be modified with a cosine correction. [W17]

1.2.3.4 The Cosine Law

If the light rays fall obliquely, then the same flux from the source will be spread over a larger area which is inversely proportional to the cosine of the angle between the surface normal and the rays. The Inverse Square Law may then be modified to the Cosine Law (Variables are explained in fig. 20):

$$E=\frac{I(\Phi)}{d^2}\cos\theta$$

The luminaires used for artificial lighting do not normally emit light equally in all directions, e.g. they are not Lambertian emitters. Reflectors, louvres and lenses modify the distribution, so that most the light is directed to where it is needed. The distribution characteristics of the fittings can be described in so called luminous intensity digrams which can be obtained from most manufacturere in electronic form. They are essentially pairs of (Φ, I(Φ)) values with Φ being the angle off the vertical and I(Φ) being the luminous intensity produced by the luminaire in that direction.

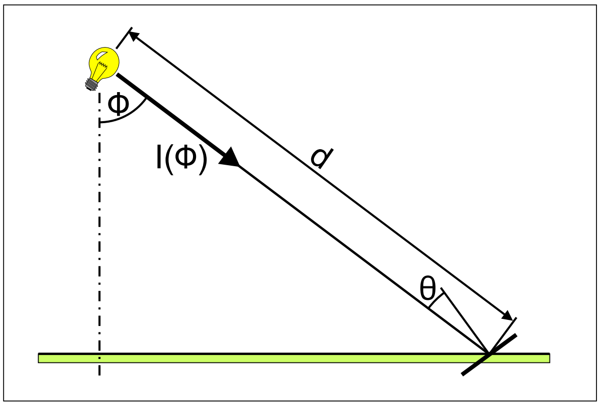


Figure 20: The Cosine Law of illuminance

1.2.3.5 The Cosine-cubed Rule

The horizontal illuminance on the working plane which is produced by one luminaire can be calculated with the Cosine-cubed Rule:

$$E_{horiz} = \frac{I(\Phi)\cos^3(\Phi)}{h^2}$$

The Cosine-cubed Rules is essentially the Cosine Law with one assumption: The plane receiving the light is horizontal, so that $\theta = \Phi$. The distance d is substituted with h / cos Φ, following simple trigonometrics.

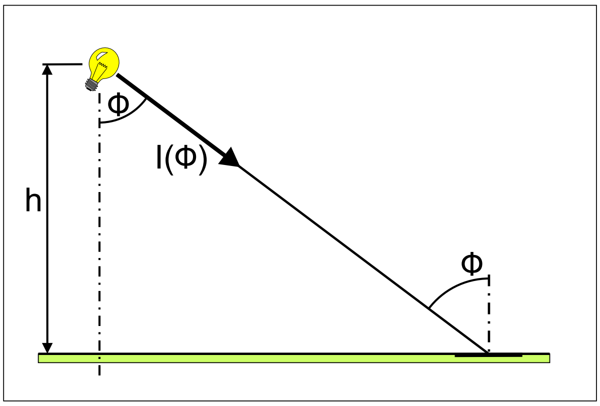


Figure 21: The Cosine-cubed Law describes the horizontal illuminanceproduced by a small source.

This rule was devised for quick calculations in a room with many similar luminaires. It does not use the distance *d* between the light source and the object, but uses the mounting height *h* above the reference plane. In offices, the reference plane is usually taken to be 0.85 m above the floor. The mounting height is usually known or can be determined easily. The position angle, Φ, can be taken out of architectural drawings, and the luminous intensity distribution is provided by the luminaire manufacturer in the form of polar diagrams.

1.3 Colour

Colour is a phenomenon of perception not an objective component or characteristic of a substance. Colour is an aspect of vision; it is a psychophysical response consisting of the physical reaction of the eye and the automatic interpretive response of the brain to wavelength characteristics of light above a certain brightness level (at lower levels the eye senses brightness differences but is unable to make colour discriminations).

That light is the source of colour was first demonstrated in 1666 by Isaac Newton, who passed a beam of sunlight through a glass prism, producing the rainbow of hues of the visible spectrum. This phenomenon had often been observed before, but it had always been related to latent colour that was said to exist in the glass of the prism. Newton, however, took this simple experiment a step further. He passed his miniature rainbow through a second prism that reconstituted the original white beam of light, His conclusion was revolutionary: Colour is in the light, not in the glass, and the light people see as white is a mixture of all the colours of the visible spectrum.

1.3.1 Correlated Colour Temperature

The correlated colour temperature, CCT (in Kelvin, K), is a measure for describing the colour of light sources. It indicates the equivalent temperature that a black body radiator would need to have in order to produce light of the same colour.

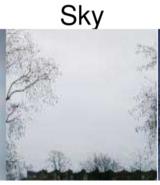
Candle	Incan-descent	Fluorescent (neutral)	Fluorescent (cool white)	Sun	Overcast Sky	Sky without sun
						
1850K	2700K	3500K	4100K	5800K	6000K	30000K

Table 9: Correlated colour temperature of different light sources

Confusingly, the concept of a colour temperature is somewhat contrary to what we would describe as 'warm' or 'cold' colours. The reddish light produced by an incandescent lamp, for instance, has a low colour temperature, whereas daylight has a very high one. This is because when a body is heated up, its light goes through red, orange, yellow, white and finally blue as it becomes hotter and hotter.

CCT	CCT class
Below 3300 K	warm
3300...5300 K	intermediate
Above 5300 K	cold

Table 10: Classes of correlated colour temperature

The way we feel when put into an environment with a dominant CCT class depends on the brightness of the room. The higher the illuminance, the more comfortable we feel with cool colour temperatures. Colour itself not only contributes to the appearance of the surface of the interior of the buildings but its also affects human mood. Helms and Belcher [5] found that colour actually influence human beings in terms of the subjective impression of ambient temperature. People feel the orange colour the hottest and blue the coldest.

Illuminance (lux)	Colour of light sources		
	warm	neutral	cold
	Emotional response		
below 500	***pleasant***	neutral	cold
500...1000			
1000...2000	stimulating	***pleasant***	neutral
2000...3000			
above 3000	un-natural	stimulating	***pleasant***

Table 11: The emotional response depends on the ambient illuminance level

Birren [4] stated that warm illumination gave occupants a sense of friendliness but cool light made people feel ghastly and eerie. The colour of light perceived by the occupants is not necessarily the colour of the finishes. A white wall or ceiling will reflect coloured light from the luminaires and lamps hence the importance of choosing the right colour temperature for a particular environment.

1.3.2 Colour Rendering

The colour rendering of a light source is an indicator of its ability of realistically reproduce the colour of an object.

Following the CIE (*Comission Internationale de l'Eclairage*, International Lighting Commission), colour rendering may be expressed as an index between 0 and 100, where lower values indicate poor colour rendering and higher ones good colour rendering. The colour rendering of a light source is compared to daylight if its CCT is above 5000 K and to a black body, i.e. a source that produces a continuous spectrum otherwise.

Figure 22: Left: A colour comparison box with test strips under different light; Right: Test swatches and their appearance under different CRI

To make a comparison of the colour rendering qualities of light sources easier, colour rendering groups have been introduced:

Group	R_a	Importance	Typical application
1A	90...100	accurate colour matching	Galleries, medical examinations, colour mixing, graphics and clothing industries
1B	80...90	accurate colour judgment	Home, hotels, offices, schools
2	60...80	moderate colour rendering	Industry, offices, schools
3	40...60	accurate colour rendering of little importance	Industry, sports halls
4	20...40	accurate colour rendering of no importance	Traffic lighting

Table 12: The CIE colour rendering groups

Some tasks such as colour matching in the printing industry have high demands in accurate colour rendering and require special attention from the lighting designer. For normal offices, however, the colour rendering group will be 1B or 2, which is easily achieved with normal fluorescent lamps.

Incan-descent	Metal halide	Fluorescent	SON	SOX
1A	1A...2	1A...3	1B...4	4

Table 13: Colour rendering index for different light sources

The reason for lamps with a poor colour rendering such as high and low pressure sodium being used at all is their high efficacy. They tend to produce more lumen per Watts of electrical power than lamps that provide a good colour rendering. The luminous efficacy is given as the ratio of lamp lumens/lamp watts. It is generally true that lamps with high wattages are more efficient than their low-wattage counterparts.

1.3.3 Colour Systems

The colour of surfaces is a combination of the spectral reflecting properties of the surface and the spectral composition of the light source. Many different classification systems are in use today. There is no universal colour system which is always physically and subjectively correct. Depending on the particular application, a particular one might be more useful or accurate. The science of measuring and describing colours is called colourimetry.

Colour can be descibed as the human interpretation of the neural impulses transmitted to the brain from the eye when it is stimulated by visible radiant energy. This definition encompasses all three sciences involved in understanding colour: Physics, physiology, and psychology. To put it in other words: Colour is a concept resulting from the interaction of light source, object, eye, and brain [W12].

1.3.3.1 The RGB Colour System

The RGB colour system is probably the most well-known notation, since it is used very widely in computer graphics and television where the image is made up of tiny red, green and blue emitters. One such triplet is called a pixel. It is also most closely related to the way we perceive colour.

Additive colours are created by mixing two or more spectral colours. When two of the additive primaries are mixed with the exclusion of the third, the secondary colours cyan, magenta and yellow are created. Those form the primaries for subtractive colour mixing. CMY can be considered a subset of RGB. Mixing the three primary colour at equal intensities results in white.

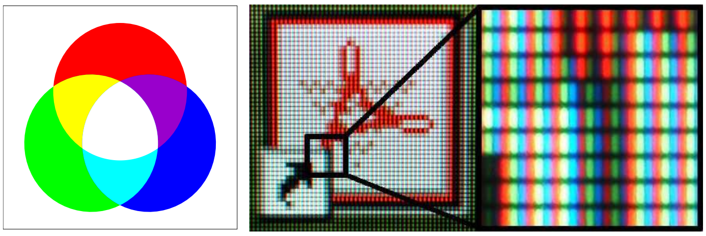


Figure 23: Red, green and blue are the primary additive colours in the RGB system. On the right is a close-up of a modern flat-panel computer screen. The image shows clearly how White is a result of mixing the three primaries. Each triplet or pixel is about 0.26 millimetres square.

The three subtractive primaries are cyan, magenta and yellow. When all three are combined, the result is black. Subtractive colour mixing is not only used in printing. The colour of any object, be it man-made or natural, is the result of subtractive mixing.

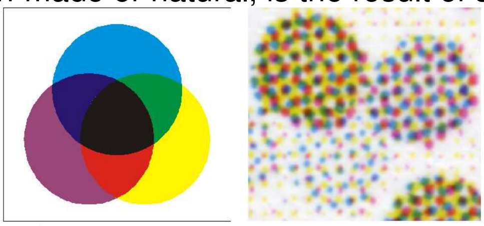


Figure 24: Cyan, magenta and yellow are the primary subtractive colours, used in printing (left). The image on the right is a 2400dpi scan of a printed colour image in [25]. The individual dots can be distinguished clearly.

Any two hues that combine additively to give white or subtractively to produce a natural grey are called complementary colours.

1.3.3.2 The CIE Colour Systems

The CIE was founded in 1913 in order to set international standards for anything related to lighting. Its first colour model came out in 1931 and was designed to be completely independent of any device or other means of reproducing colours.

The specifications included the definition of standard light sources and a standard observer with a 2º field of view. The three standard light sources were:

Source	Corresponding to	CCT	X	Y
A	tungsten-filament lamp	2854K	0.448	0.407
B	noon sunlight	4800K	0.348	0.352
C	daylight	6500K	0.310	0.316

Table 14: The 1931 standard CIE light sources

(XY coordinates from [25])

CIE XYZ (1931)

Because some colours can not described with the RGB system without resorting to negative values, the CIE derived a new set of tristimulus values, XYZ. The Y curve is identical to the response of the human eye to the total spectral power of a light source and is called the luminance factor. It is normalised to be 100.

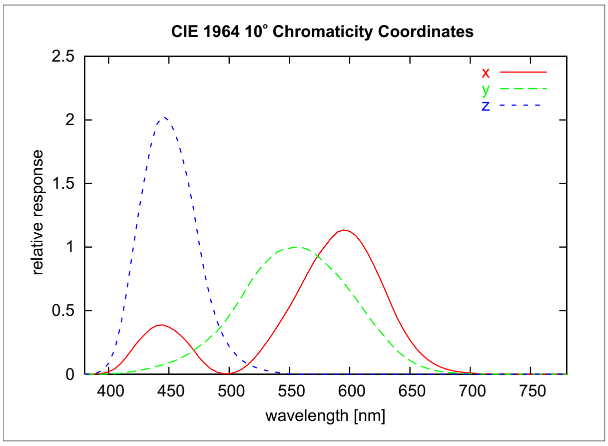


Figure 25: CIE XYZ tristimulus values
(Graphs plotted with gnuplot, data obtained from [W16])

To be able to draw a two-dimensional chart of the colour system, the XYZ tristimulus values are transformed into the xyz colour co-ordinates with x + y + z = 1. One of the three values is redundant and can be derived from the other two.

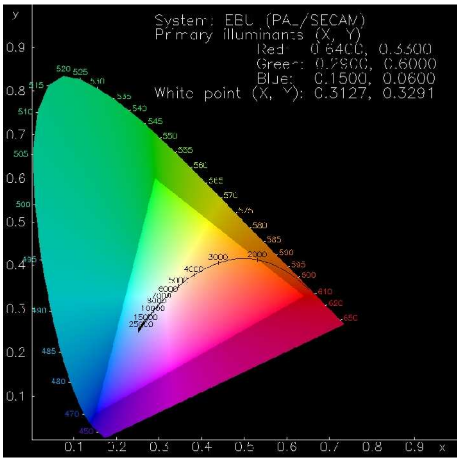


Figure 26: 1931 CIE xy chromaticity diagram with black body line. The hightlighted triangle in the middle is what can be displayed with the primaries used in European television broadcast.
(Image produced with ppmcie [W9])

The third dimension is indicated by the Y tristimulus value, thus making for the xyY colour system. At white spot is the colour of the standard illuminant C. The Y axis sits perpendicularly on this point. The higher the luminance Y, the smaller the gamut of colours (which is biggest in the xy plane at the white point).

The color gamut of a particular display device defines all the colours it can reproduce by with its primaries colours. Modern photo quality colour printer have up to 6 colour cartridges (plus black) to produce a wider range of colours making the printout look more realistic. In theoretical terms, any colour could be produced by introducing negative values, however, this is practically not possible.

One of the problems with the xyY diagram is that colours which have the same perceivable distance in colour are not always the same distance apart in the diagram. For instance, they are much farther apart in the green part than they are in the red or violet one. To remedy this situation, the CIE devised the 1976 Luv and Lab systems. [W4]

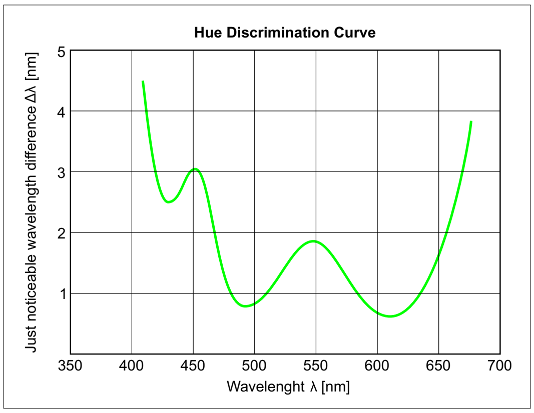


Figure 27: The noticable difference between two spectral colours depends on the wavelength
(Based on [20, 25])

CIE $L^*u'v'$

To overcome the problems of distortion of colour spacing in the 1931 xy diagram, the CIE introduced a new set of colour coordinates, uv, in 1960. These were derived from xy by means of a mathematical transformation. The result was still unsatisfactory, so in 1976 the u'v' diagram was created.

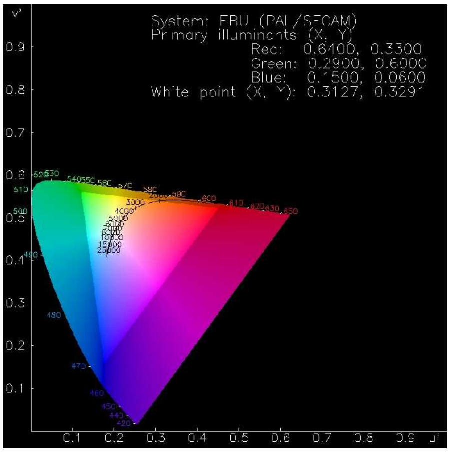


Figure 28: 1976 CIE u'v' chromaticity diagram with black body line. The highlighted triangle is the display gammut of the European television standards PAL and SECAM.
(Image produced with ppmcie [W9])

Another correction was the replacement of the Y lightness scale with L^*. In contrast to the Y scale, L^* is no longer equally scaled which makes for a better representation of the subjective human perception of colours. It is similar to the Munsell system's scale of lightness, except that L^* allows for values between 0 and 100, whereas Munsell's lightness value was in the range of 0 to 10.

Like the CIE XYZ system, the $L^*u'v'$ system is device independent which means it is not restricted by the colour gamut of any particular output device. But it still has significant drawbacks and is now almost entirely superseded by the CIE $L^*a^*b^*$ colour model. [W4]

CIE $L^*a^*b^*$

This CIE colour system is based on the Lab colour system proposed by Richard Hunter in

CIE $L^*a^*b^*$

This CIE colour system is based on the Lab colour system proposed by Richard Hunter in 1942. Discoveries made in the 1960s showed that somewhere between the retina and the brain, the RGB values detected by the cones in the retina are transformed into distinctions between light and dark, red and green, and blue and yellow. This was adopted in the CIE $L^*a^*b^*$ colour notation in the same year that the $L^*u'v'$ system was published.

The vertical lightness axis L^* is the same as in the CIE $L^*u'v'$ system. The colour axes are based on the fact that a colour can not be red and green or blue and yellow at the same time, since those are complementary colours which, when mixed at equal intensities, lead to grey. While one of the colour axes runs from green in the negative values to red in the positive, the other one covers blue on the negative end and yellow on the positive one.

One mayor advantage of the system is that it the illuminant can be specified in terms of the RGB output. The model therefore treats all colours as a combination of the object's surface colour and the colour of the illuminant. The colour space is also perceptually uniform. For example, a difference of 5 units in lightness has the same perceptual difference as a 5 unit difference in the chroma plane.

Because of its device independence, the $L^*a^*b^*$ colour system has gained importance in desk top publishing. It is the basic colour mode for the Adobe PostScript (levels 2 and 3) document language which is understood directly by many printers. Unlike other colour models, however, it is purely for colour measurement, no published atlas of the $L^*a^*b^*$ system exists. [W4]

1.3.3.3 The Munsell Colour System

The nearest to the universal method of colour specification is the Munsell system. This system of colour notation developed by the American Albert Henry Munsell in 1905 and revised in 1943 identifies colour in terms of three attributes: Hue, value and chroma.

Hue (H)
: The hue of a colour indicates its relation to a visually equally-spaced scale of 100 hues. There are five principal and five intermediate positioned hue steps within this scale. The hue notation in general use is based on the ten major hue names: Red (5R), Yellow-Red (5YR), Yellow (5Y), Green-Yellow (5GY), Green (5G), Blue-Green (5BG), Blue (5B), Purple-Blue (5PB), Purple (5P) and Red-Purple (5RP).

Value (V)
: The value indicates the lightness or darkness of a colour in relation to a neutral grey scale, which extends from absolute black (symbol 0) to absolute white (symbol 10). The symbol 5 is used for the middle gray and for all chromatic colours that appear half-way in value between absolute black and absolute white.

Chroma (C)
: The chroma indicates the degree of divergence of a given hue from a neutral gray of the same value. The scale of chroma extends from 0 for a neutral grey and depends on the strength (saturation) of the sample to be evaluated. The chroma scale is unlimited, however, chroma values above about 26 do not occur with real materials.

The complete Munsell notation for a colour is written symbolically: H V/C, e.g. 5G 6/8. The Munsell system is considered the simplest of all colour systems which is why it is the most

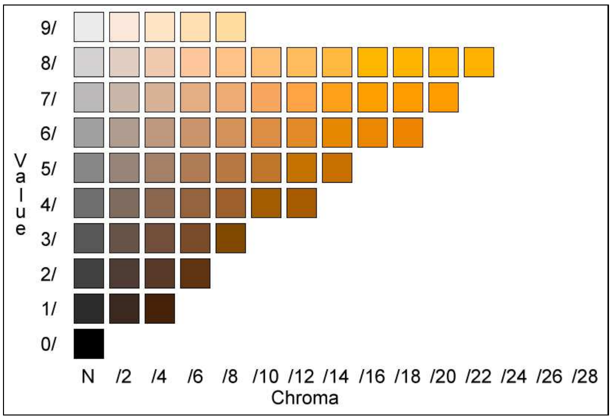


Figure 29: A page in the Munsell colour atlas. The Hue is 5YR.

widely used subjective colour system today. It is adopted by most paint manufacturers. The approximate reflectance factor can be determined quickly with the following formula:

$$\rho \approx V(V-1)$$

1.3.3.4 The Ostwald Colour System

This colour system was proposed by the German scientist Ostwald in 1914. It is based on four basic colours: yellow, ultramarine blue, red, and sea green and eight hues. These are then subdivided to produce a color wheel of 24 colors. Those colours are pure and contain no white or black. The system was originally published with those 24 colours with 28 variations of each in lightness or darkness.

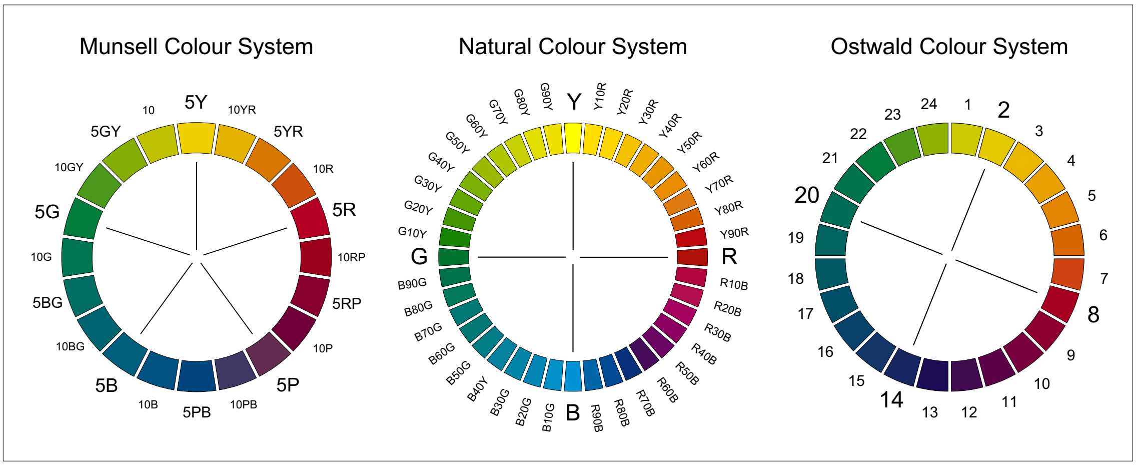


Figure 30: The hues in the Munsell, Ostwald and Natural colour systems

The full nomination is given as a triple reference composed the of dominant wavelength, purity and the luminance, e.g. 16,15,50. This example indicates a full colour of 16, a whiteness of 15, and a blackness of 50.

1.3.3.5 The Natural Colour System

The NCS system was first introduced in 1952 as a colour atlas with 600 colours. After its adoption as the Swedish standard in 1979 it had a major impact on colour communication in Europe. Owing to its birth place, this colour notation is sometimes referred to as the Scandinavian Colour System.

The NCS colour solid can be envisaged as two cones with their bases together. White (W) is at the top, black (S) at the bottom. Along the equator are the red and green and blue and yellow pairs whose members are situated opposite one another. Between each of the primaries yellow, green, blue and red lie 10% steps. For instance, Y50R is orange with equal parts of yellow and red, while Y20R on the colour circle is an orangy yellow.

To visualise the colours, vertical slices are taken like cutting a pie. The scales for chromaticity, whiteness and blackness are given in parts of 100, which can be taken as a percentage. An example for a complete NCS colour notation is 2030-Y60R. This is a colour with 20% blackness and 30% chromaticity. Its position on the colour circle is 60% between yellow and red, making it a reddish orange.

The colour is always defined in the following direction: Y -> R -> B -> G -> Y, and only between adjacing primaries. For instance, while Y70R is a valid notation for a reddish orange, R70Y is not. Equally, there is no B40Y or G50R.

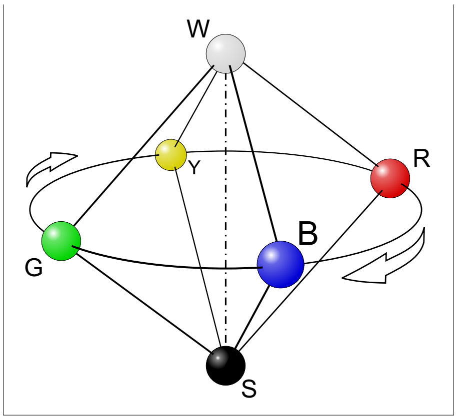


Figure 31: The double cone NCS colour solid

The NSC colour system is often found as the basis for the notation in trade catalogues from paint manufacturers.

1.4 The Visual System

1.4.1 The Eye

The human eye is a sophisticated visual system. It is capable of detecting light, colour and shapes which are transferred to the brain via electrical impulses.

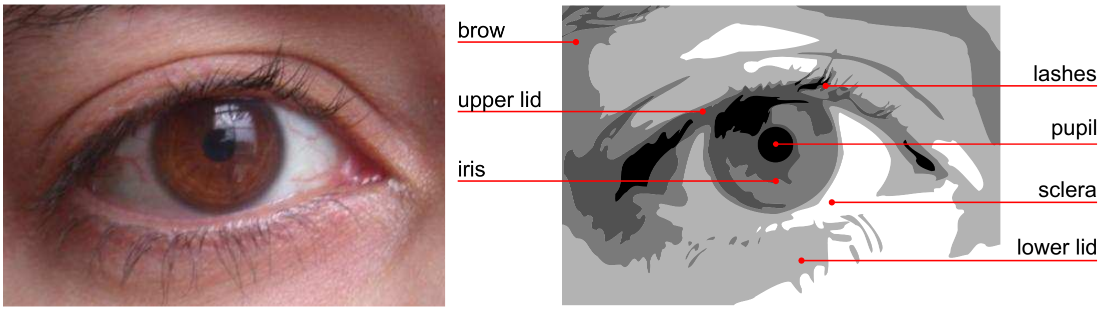


Figure 32: A human eye
(Thanks to Luisa Brotas)

The shape of the eyeball resembles a sphere, with the *cornea* forming a smaller segment in front. It is composed of three coats: the external tough layer, consisting of the white *sclera* over most of the eyeball and the *cornea* in the front; the middle *uvea*, consisting of the *choroid*, the *ciliary body*, and the *iris*; and the internal *tunic*, which consists primarily of the *retina*. The retina is about 0.2–0.4 mm thick and well supplied with blood, which is why the inside of the eyeball looks red. Interestingly, the light sensitive cells are actually behind the blood supplying layer, and another one containing the *ganglion cells*, which do some image pre-processing before the impulses generated by the detectors are passed down through the optic nerve to the brain. The light has to go through several layers before it can be detected. This leads to a 1:10 ratio of photons that are detected, compared to the total number of photons entering the eye.

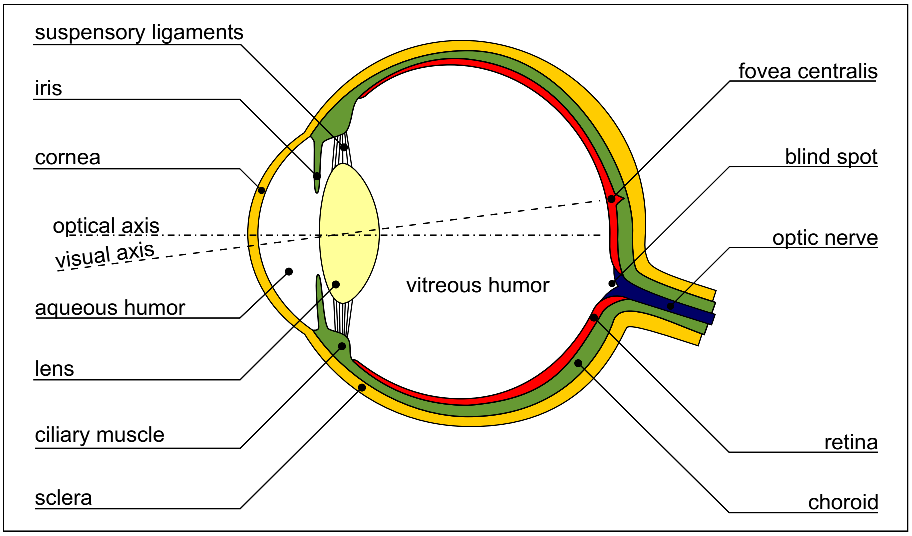


Figure 33: Sagittal section of a human eye

Within the three coats are the refracting media: the *aqueous humor*, the crystalline *lens*, and the *vitreous humor*. The lens is a double convex transparent body which sits between the vitreous and aqueous humor. It is about 10 mm in diameter and 3 mm thick. Its convexity is altered by the *ciliary muscle*. This process is called *accommodation* and results in a focussed image of the surrounding world on the retina. It was the astronomer Kepler who first realised the true function of the retina. This special part of the eye has been described as on outgrowth of the brain which has became sensitive to light.

In the back of the eye, the *optic nerve* which is about as thick as a pencil, leaves the eyeball. It transmits the electrical pulses generated by the cones to the visual centre of the brain. Where the optic nerve leaves, no light sensitive elements exist. This small area is therefore called the *blind spot*. There is another important spot within the retina called the *fovea centralis*. This small area has the highest density of cones and provides us therefore with the highest visual acuity. Whenever we need to look at an object which is difficult to see, be it that it is far away or very small, we automatically focus the image onto the fovea to make the most of the rest of our not quite perfect visual system. The areas immediately surrounding the fovea is called the *macula*. Sometimes, the two terms are used interchangeably.

There are two types of light-receptor cells: The *rods* and the *cones*. Each type has specific functions to perform.

The cones, which are distributed chiefly around the back and central area of the retina are very closely packed within the small indentation called the fovea - the focal point of the lens during normal conditions which sits on the eye's optical axis. The cones are responsible for colour vision under normal daylight conditions. The highest sensitivity of the cones occurs at an average wavelength of 555 nm. Their luminous efficacy is 683 lm/W. The table below shows that only 2% of all cones responds to blue light. However, their high sensitivity almost makes up for their small number, leaving us with only a slightly smaller sensitivity to blue light than to red and green. This is under daylight level and changes at low light levels when the rods become dominant.

Cone Type	Colour	Peak Wavelength	Percentage
L	red	570 nm	64.00%
M	green	535 nm	32.00%
S	blue	445 nm	2.00%

Table 15: The cones and their spectral characteristics and relative numbers.

There are between 6 and 7 million cones in the retina. About 10% are concentrated in the fovea centralis, which is an area of 1.5 mm in diameter with the highest visual acuity. This corresponds to about a 5º visual field. The rest are more or less evenly distributed across the rest of the retina.

The rods function under low light levels. They are only responsible for night vision, as well as the detection of motion. Rods are about 1000 times more sensitive to light than cones. Under optimal conditions, rods can be triggered by individual photons. 507 nm is the wavelength where the rods are most sensible.

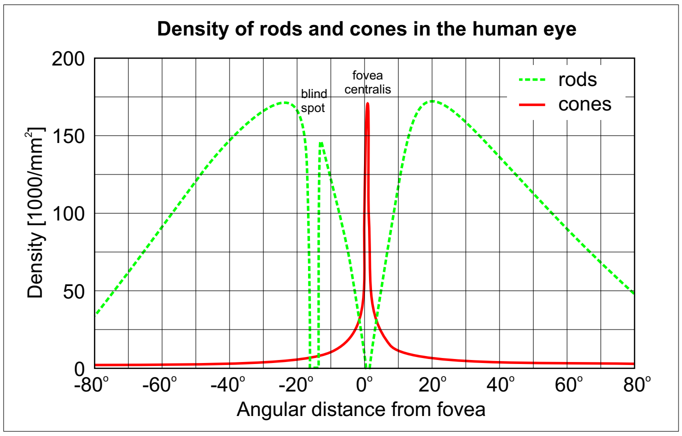


Figure 34: Density of rods and cones on the retina

(Image based on [23])

Of the 120 million rods we have in the retina, the highest concentration is about 20º away from the optical axis of the fovea. This explains why accurate night vision is best obtained by looking slightly to the left or right of the object being viewed so that foveal vision is not used. This technique is called averted vision. Towards the periphery of the retina, the rod density gradually decreases. [12, 19, W8]

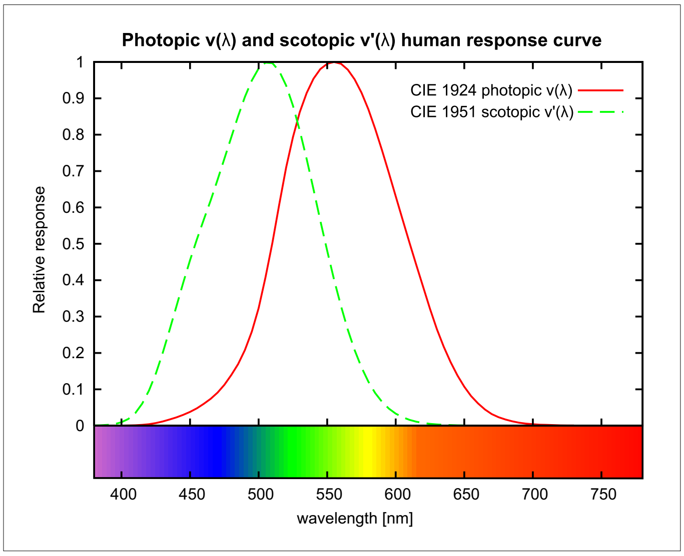


Figure 35: Visual acuity curves for photopic (grey line)and scotopic (black line) vision.

(Graph plotted with GNUplot, data obtained from [W16])

Daylight vision is referred to as *photopic*, while night vision is called *scotopic*. In the twilight, both, cones and rods are active to a certain degree. This intermediate state is termed *mesopic* vision. During scotopic vision, the peak visual response shifts from 555 nm to 505 nm. It takes approximately 1 hour for full scotopic vision to occur. Visual acuity curves for both photopic and scotopic vision are presented in the figure below. The photopic curve is referred to as v(λ), while the scotopic one is called v'(λ). Between photopic vision during the day and scotopic vision at night lies mesopic vision which happens in twilight conditions. During this period both, cones and rods, contribute to the image seen by the brain. This happens between a luminance of 15 and 0.005 cd/m² [12].

1.4.2 Field of Vision

The receptive angle of the human eye or its field of vision is determined by the fact that both eyes sit in front of the head facing the same direction. This might seem like a waste at first, since the argument might be made that an eye on either side of the head or one in front, one in the back might be more effective. We all know that pidgeons, for instance, have an almost 360º vision. This is true for most, if not all, animals that are preyed upon. Do we not sometimes wish that we could see what goes on behind us, too?

The fact that both our eyes lie in front of our face does, however, have enormous advantages without which we would not be where we are on the ladder of evolution. Because the eyes have roughly the same view but are spacially separated by about 60 mm, they enable us to see stereoscopically. The result is that we are able to judge the distance to an object relatively accurately, something that hunting animals can do, too.

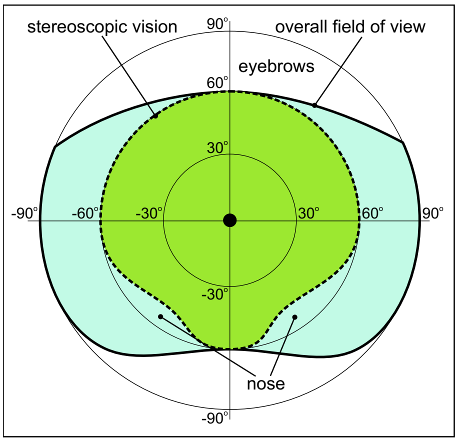


Figure 36: The human field of view
(Image based on [23])

Due to its design, the eye is able to produce an image of almost an entire hemisphere. The blue area in fig. 36 however, shows that this is not the case. The reason lies in our facial anatomy. The field of view is restricted above by the eye brows and below by the nose and cheeks. The eyebrows' purpose is to keep water, such as rain, out of the eyes, and to act as a sun shade. After all, vision is the most important of our senses. Without the eye brows, rain would seriously compromise our chances or survival. The water running down our forehead would impair our vision leaving us as an easy prey to our preditors.

The green area in the diagram outlines the field of stereoscopic vision. The highest visual acuity is at an angle of +/- 2.5º away from the fovea centralis. This is where most of the cones are. For visually demanding tasks, we will unconciously turn the eyes in such a way that the image is produced on the fovea.

1.4.3 Accommodation

It is a common misconception that the light entering the eye is bent by the lens to form an image on the retina. Although this is correct for the eye of fish, it is somewhat more complex with the human anatomy because the parts of the eye have indices very similar to one another:

- Surrounding air: $n_{air} = 1.0$,
- Cornea: $n_{cornea} = 1.37$,
- Aqueous humor: $n_{aqueous} = 1.336$,
- Lens, inner layers: $n_{lens,inner} = 1.406$,
- Lens, outer layers: $n_{lens,outer} = 1.386$,
- Lens, average: $n_{lens,average} = 1.409$,
- Vitreous humor: $n_{vitreous} = 1.33$ [12].

Light changes its direction most strongly if the difference between the refractive indices of the two media is high. It is therefore clear that the air-cornea junction contributes most to the refraction of light rays which explains why laser eye surgery which changes the curvature of the cornea can be used so successfully for correcting defects of vision, particularly myopia (nearsightedness).

The lens, however, is important for altering the angle of refraction which is important for ensuring that the image of an object is in focus on the retina, no matter how far the object is away. This process of increasing the refractive power of the lens for near objects is called accommodation. The lens is suspended from the choroid by the suspensory ligaments. A relaxation of these muscles results in the lens springing into a more convex form which in terms increases its refractive power. This mechanism happens automatically and nearly instantaneously. Although we might squint when trying to focus on a very small or very distant object, the accommodation happening in our eye is beyond our control. [24, 19, 20].

1.4.4 Adaptation

1.4.4.1 Light and dark adaptation

Adaptation is the ability of the eye to cope with different orders of luminance. Adaptation is necessary because the range of luminance our eyes have to cope with is so huge. The eye is capable of adapting to luminances as high as 1,000,000 cd/m² and as low as 0.000,000,1 cd/m². Once adapted, the eye can cope with a luminance range of 1:1000, although this will decrease drastically with age and depends on the actual state of adaptiation.

It takes some time for the eye to fully adjust to the luminous environment. This can be easily experienced when moving from a well-lit to a dark room or when switching off the light. Dark adaptation, the adaptation from light to dark takes considerably longer than light adaptation.

There are a number of mechanisms that act together to bring about adaptation to the tremendous range of ambient luminances our eyes may be exposed to. The best-known one is the variation in size of the pupil (the opening in the iris allowing light to enter the eye). The diameter of the pupils varies from about 1.5 mm in bright light to about 6 mm in darkness. Because the area of a circle is proportional to its diameter squared, this allows for an adaptiation by a factor of 16. Clearly, this is nowhere near enough to explain how we can adapt to variations in luminance of several orders of magnitude.

As discussed already, there are two types of receptors in the retina-rods and cones. While the cones are responsible for colour vision under daylight, the rods can only detect shades of grey, but this at much lower light levels. They enable us to see at night, although not in total darkness.

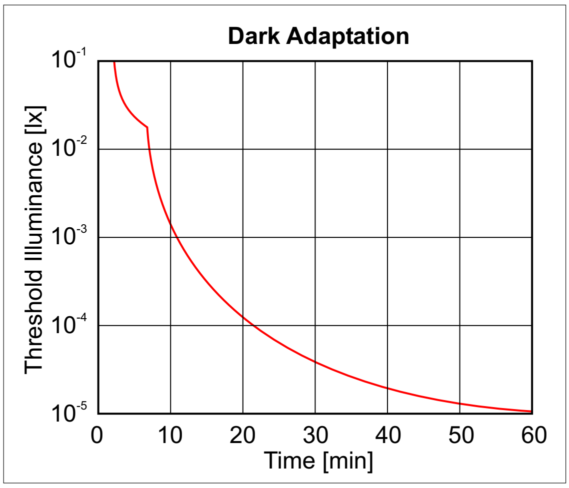


Figure 37: Several processes with different response times act together to bring about dark adaptation.
(Based on [12])

In addition to being equipped with two different types of sensors, the eye can also adjust the actual sensitivity of them. This happens within a few minutes and is a biochemical process. The photopigment in the retina is called rhodopsin. It is a colour pigment which is bleached under high levels of light. This results in a clever negative feedback loop: The higher the level of light hitting the retina, the more rhodopsin is bleached which results in a decreased sensitivity to light.

The adaptation of the cones takes about 3-9 minutes from the time the light is switched off. Above 10 minutes, adaptation processes in the rods start to take an effect. This is indicated by a bend in the graph in fig. 37.

1.4.4.2 Colour Adaptation

While light and dark adaptation are processes of coping with different light levels, colour adaptation enables us to get accustomed to different illuminants and their colour temperatures.

On entering a room lit with predominantly low colour temperature lamps after leaving from a sunny outdoor envirionment, all the objects will initially appear as if looked at through reddish or orangy glasses. Although the lamps might be incandescent filament lamps or warm white fluorescents. After a while, the visual system will adapt to the illuminants and set a new white balance. A white sheet of paper will again appear white, and we will be able again to judge colours correctly.

1.4.5 Colour Vision Theories

Isaac Newton was one of the first researchers to try to find an explanation for human colour vision. He started to be interested in optics in about 1663 when he began to construct telescopes. One of the experiments he carried out was to place a prism in the path of a beam of sun light. The prism split up the white light into the rainbow colours. To confirm his theory, he then combined the rainbow colours with a similar prism which again resulted in white light.

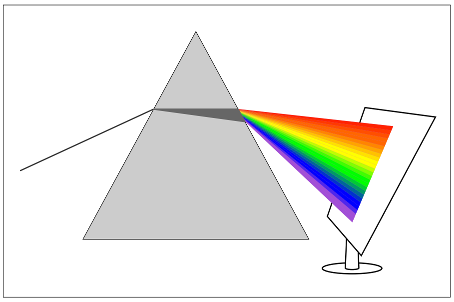


Figure 38: Newton was the first to explain the rainbow colours that are created when white light is broken apart with a prism.
(Image based on [19])

Newton was able to observe that the light formed a continuous succession of colours. Today we refer to the six colours of the rainbow, but Newton was also a practicing alchemist and the number seven is a magical number, he persuaded himself and his assistants that they were actually observing seven colours: Violet, indigo, blue, green, yellow, orange, and red.

Wavelength	Colour	Colour name
380-450 nm		violet
450-490 nm		blue
490-560 nm		green
560-590 nm		yellow
590-630 nm		orange
630-780 nm		red

Table 16: The six rainbow colours do not include indigo.
(table based on [25])

A much quoted passage in *Opticks* published in 1704 reads:

> ”For the rays to speak properly are not coloured. In them there is nothing else than a certain power and disposition to stir up a sensation of this or that colour.”

Newton suggested that the sensation of colour vision was produced from sympathetic vibrations set in motion “on the bottom of the eye” by the arriving light.

1.4.5.1 Trichromatic Theory

The ideas that Newton had about colour vision were revised and expanded by Thomas Young. Young qualified in medicine but was also a successful experimental scientist. He could not believe that the number of receptors in the retina could possibly be equal to the number of spectral colours and proposed that each point of the retina “could be put in motion more or less forcibly by three primary colours”. He anticipated the theory of colour mixing out of the three primary colours red, yellow, and blue. After hearing about experiments by William Wollaston, he changed those primary colours to red, green, and violet, discarding yellow because it could be mixed from red and green light.

Young's trichromatic theory was ignored for about 50 years untils it was taken up simulaneously by the Scottisch physicist James Clerk Maxwell and the German physiologist Herman von Helmholtz. Maxwell confirmed Young's theory by the use of a spinning disk. Helmholtz also experimented to investigated the trichromatic colour theory. He was successful to such an extent that trichromaticity later on became known as the Young-Helmholtz theory of colour vision.

Questions still remained about the trichromatic theory, and this lead to a search for other explanations of human colour vision. [25]

1.4.5.2 Opponent Colour Theory

Although yellow as a primary colour was so easily dismissed by Young, the German physiologist Edward Hering proposed an alternative colour vision theory in 1790 which brought yellow back on the agenda. His colour theory was based on the four primary colours red, green, yellow, and blue with a light/dark luminance mechanism also playing an important part. In his view, red was supposedly the opponent to green and yellow to blue. This is worth comparing to the CIE $L^*a^*b^*$ system of 1976 earlier in this document.

Through stressing the importance of yellow as one of the primary colours, after images and complementary colours could more easily be explained. [25]

1.4.5.3 Zone Theory

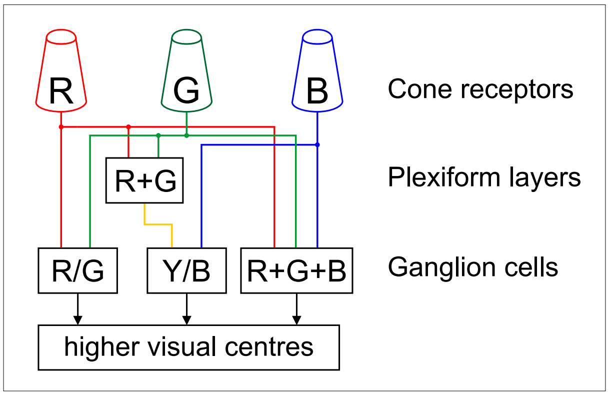


Figure 39: Schematic of the zone theory of colour vision
(Based on [19, 25])

Interestingly enough, both, the Young-Helmholtz and the Hering theory could both, be proven and disproven experimentally. Donders finally resolved the issue in 1881 by stating that colour vision was processed sequentially along the visual pathway. Trichromacy could occur at a particular level, opponency at another. This basically forms the basis of modern colour vision theories.In the retina at the receptor level, vision is trichromatic. Three different types of cone receptors are receptible to red, green, and blue stimuli (Young-Helmholtz). They produce electrical signals which are processed in the neural layers of the retina and in the ganglion cells into two opponent colour channels and a luminance channel (Hering). [25]

1.4.6 Colour Deficiency

Colour deficient people see fewer colours in the environment and confuse colours that look different to the rest of the population. The condition is usually inherited, but can also be acquired. Colour deficiency can be put into three different categories:

- Defective red-green vision,
- Defective blue-yellow vision,
- Complete colour blindness.

Defective red-green colour is inherited through the X-chromoson. It affects abouth 8% of men and 0.4 % of women. A defective blue vision is rare and affects men and women equally. Even rarer is complete colour blindness when only differences in brightness can be detected.

Colour defiency is caused by abnormal cone pigments and be just annoying to seriously disabling in everyday's life.

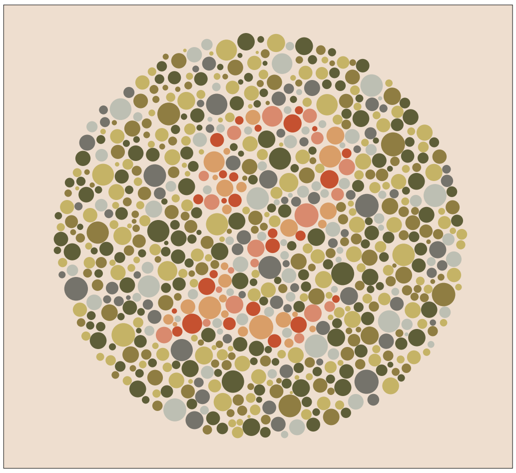


Figure 40: Plate 'vanishing design' from the Ishihara test for colour deficiency.
(Image from [25]; Colours are not reproduced accurately)

Quite often, people with a colour deficiency become fascinated by the subject of colour and colometry and manage to excel in the subject. A chemist called John Dalton lived in the 19th Century is one such example. Through a series of experiments on himself, he concluded that he could not see long-wavelength red light, a type of colour deficiency which is very common. He was delighted to find that his brother and four of his offspring showed the same symptoms. This lead him to assumed that red deficiency is rather common and that it can be inherited.

1.4.7 Vision and Age

Like many other organs of the body, the eyes also begin to fail us when we get older. There are a number of different functions the eye of an older person can not perform as well as the one of a youngster. Lighting for older people should be designed more carefully than ordinary office lighting due to the special requirements in glare, visual acuity and the likes. Older people may need higher levels of illuminance to see as well as young people.

1.4.7.1 Macular degeneration

A condition called *macular degeneration* can occur in people aged 65 or above. Although it can also be triggered by certain drugs, it is usually age-related. In this case it is referred to as age-related macular degeneration, AMD. The condition is caused by a break-down of the *macula*, resulting in a gradual or sudden loss of central vision. Signs include: straight lines appearing wavy, fuzzy vision and shadowy areas in the central vision.

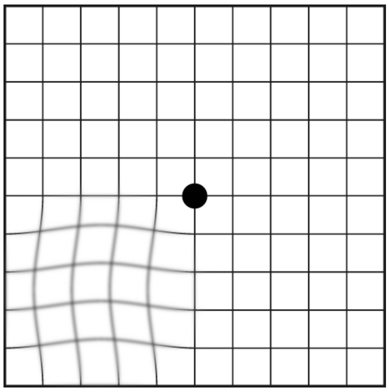


Figure 41: Amsler grid test as seen by a person with AMD
(Based on [W19])

Macular degeneration is the most common form of legal blindness among people over 60 years of age. About 90% of patients develp the *dry* form of AMD, the *wet* variety is not as common but more dangerous. [W18]

1.4.7.2 Glaucoma

Glaucoma is another common age-related eye problem. It has been shown to appear more often to people sufferring from diabetes (but that is not to say that not any over-60 year-old can develop the condition). It is characterised by an intraocular pressure (IOP) which is too high, caused either because too much aqueous humor is produced or because it is not drained properly. Glaucoma may also damage the optic nerve and result in a total loss of vision.

Glaucoma can be diagnosed before any vision loss occurs. It is important to have regular eye-examinations because the condition can cause total blindness. [W18]

1.4.7.3 Presbyopia

This most common form of age-related vision deficiencies will happen to almost anybody sooner or later. The lens gradually looses its elasticity. The result of this is that the ability of the eye to focus on near-by objects decreases. The near-point moves further and further away.

Typical indicators are the need to use reading glasses or holding the newspaper at arms length. Other symptoms of presbyopia are: Confusing similar letters and numbers such as 3 and 8, difficulties with reading price tags or the wrist watch. [W21]

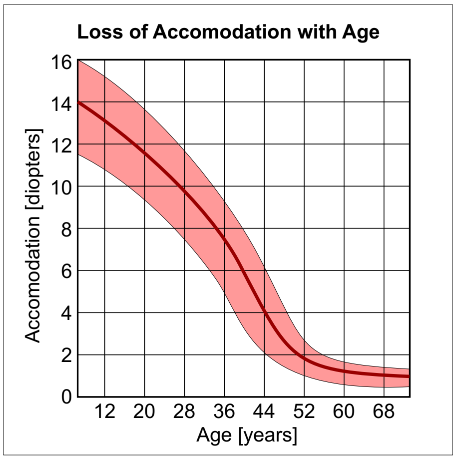


Figure 42: The accomodation ability of the eye decreases with age due to a hardening of the lens
(Image from [20])

1.4.7.4 Cataracts

A cataract is a clouding of the normally clear lens of the eye causing it to loose its transparency. Because it develops gradually, it might even go unnoticed until it seriously affects the patient's life style. Operations carried out at this point have a success rate of 95%. Other than a blurring of vision, simptoms include: glare, particularly at night, a frequent change of eyeglass prescription, a decrease in colour intensity and a yellowing of images. [W19]

1.4.8 Perception

Beyond the easily measurable or verifyable recommendations on good lighting practice, such as luminance ratios and illuminance levels, some guidance to the designer can be given by associating subjective impression with certain lighting conditions.

The retinal image of the environment is interpreted by the brain with a preference to simple comprehensive interpretations. This mechanism should be taken into account during the lighting design process. For example the luminance patterns on the side walls should always be in accordance with the architecture otherwise the whole situation can be very distracting.

The lighting distribution on an unstructured wall becomes a dominant feature, whereas the same lighting distribution on a structured wall is interpreted as background and not perceived.

1.4.9 Perceptual Constancy

Our perception functions by comparing the retinal image of an object with the visual database that we have accumulated in our memory. Although the image might not alway appear under ideal conditions, i.e. it might be scaled, distorted, partially incomplete or hidden, inverted or appear under a different angle to what we are used to, the funtions of perceptual constancy ensure that we are still able to interpret the image correctly. They include shape, size, lightness, and brightness constancy.

1.4.9.1 Shape Constancy

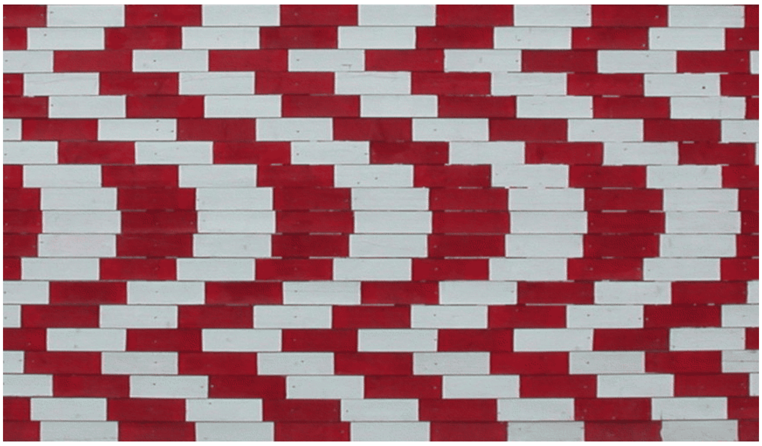


Figure 43: Tricking the brain's shape constancy. The horizontal lines are parallel.
(Image taken at the Yverdon site of the 2002 Swiss Expo)

Without the shape constancy inherrent in our brain, it would be difficult for us to recognise objects unless they appeared exactly as we remember them. Any variation in rotation, detail, scale, or deformation would result in us believing we were seeing a new object rather than one we have seen before under different conditions.

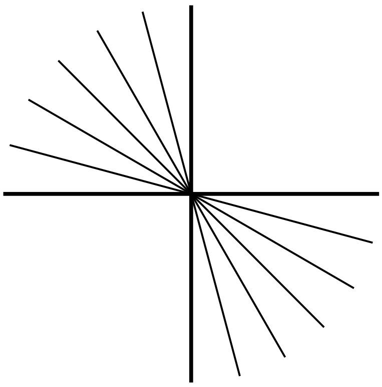


Figure 44: Shape constancy can produce visual illusions:The two thick lines are at right angles.

A plate on the dinner table, for instance, will be interpreted as round, although due to the perspective under which it appears, its actually oval. Experience and visual clues in the immediate surrounding of the object, however, teach us that it is indeed a round plate we are seeing.

So instead of paying too much attention to the actual object's properties, what we perceive is the universal, unchanging properties of objects irrespective of their momentary appearance. Shape constancy is an essential component to our perceiving objects in the visual world accurately. [12]

1.4.9.2 Size Constancy

In everyday life, we refer to the size of an object with comparisons taken from objects we are familiar with. An object can be 'the size of a penny', 'as thick as a pencil', 'as flat as a pancake', 'the size of a bus' or like 'the head of a pin'. Those associations with objects from everyday's life are true for small objects up to a distance of about 1.0 m and for large ones up to 50 m. Outside of this range it is diffucult to accurately estimate the true size of the object.

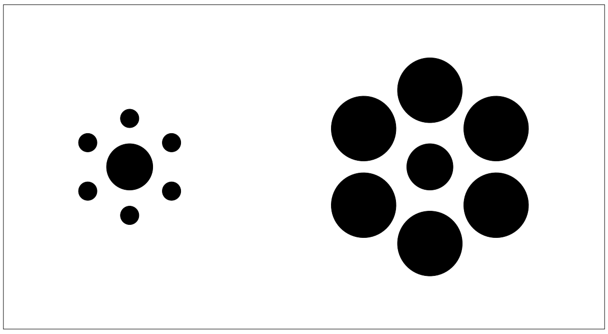


Figure 45: Playing with the brain's size constancy:The inner circles are of exactly the same size.

We are alway puzzled, for instance, about just how small cars and houses look when viewed from an airplane, because this is in contrast to what we usually experience.

1.4.9.3 Lightness constancy

It appears that our perception of lightness or brightness is based on the surface reflectance rather than the amount of light reflected off a given surface. In other words, it is independent of the level of illumination. This is probably based on the fact that what we actually see is contrasts, i.e. the relative brightness difference of two objects, and not the absolute difference.

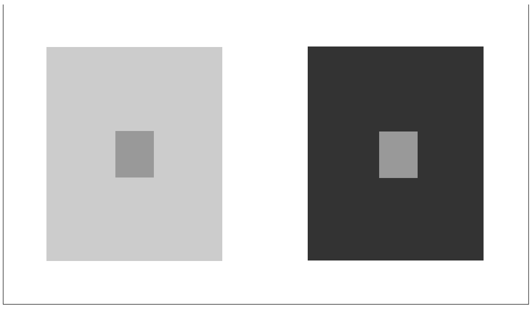


Figure 46: Lightness constancy is based on contrast: Although the small boxes are equally bright, the one on the left appears darker.

1.4.9.4 Colour Constancy

Colour constancy is similar in nature to brightness constancy, except, like the name suggests, colour plays an important part in it.

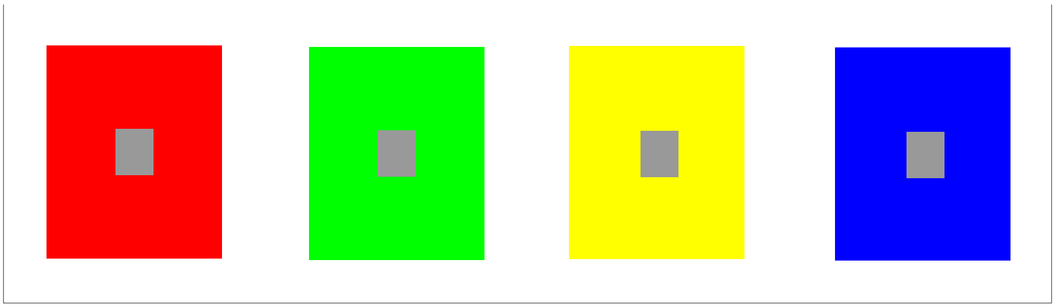


Figure 47: Colour constancy: The small boxes in the centre are all of the same grey colour,however, they appear to have a tint of the colour complementary to their surrounding.

1.4.10 Brightness

Unlike luminance which is a physical quantity (although it is corrected to the spectral response curve of the human eye), brightness is purely perceptual. It is the subjective counterpart of luminance.

The brightness response of the eye is roughly logarithmic. That means that the same difference of photometric luminance produces a much higher subjective difference for lower levels of object luminance than it does for higher. Because of this, the CIE $L^*a^*b^*$ colour system uses a logarithmic scale for the vertical lightness axis.

Rather frequently, the term brightness is misused to mean luminance. If the term is to be used in this context at all, which it shouldn't, it needs to be qualified as 'measured' brightness, to distinguish it from 'perceived', 'apparent', or 'subjective' brightness. [W13]

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[W4] Adobe Technical Guides: Color
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1.5.3 Contribution of Images

[C1] TechnoTeam Ilmenau, http://www.technoteam.de
[C2] Minolta, http://www.minoltaeurope.com
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[C4] Marlin Lighting, http://www.marlinlighting.com
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