Lighting Theory

Light. You need light to see the world around you. To see the beauty of a sunset or the moon rising depends on you and this thing, this energy called light. It is easy to take for granted electric lighting that we use when there is not enough natural light. Imagine for a moment a world without any electric lighting, it would be a dark and hazardous place. Many of the activities that people do just could not happen. The quality and intensity of light that you have around you totally affects your visual appreciation of your surroundings. This module on Lighting Theory covers the fundamentals of light and lighting, the relationship between light, colour, what we see and how we see it, including concepts, units and how light flows.

1 The Spectrum

What is light? It is a form of energy called **electromagnetic radiation**. Electromagnetic radiation occurs in many forms and the whole range or **spectrum** can be measured in **wavelengths**. The radio waves at the top have wavelengths of many kilometres, while the gamma rays at the other end have wavelengths smaller than the size of atoms. Light represents only a small section of this whole spectrum and is the only radiation visible to your eye. Light and all other electromagnetic radiation travels through a vacuum in a straight line at the same velocity that is about 300000 km/s. In other mediums such as air or glass the velocity is less than in a vacuum.

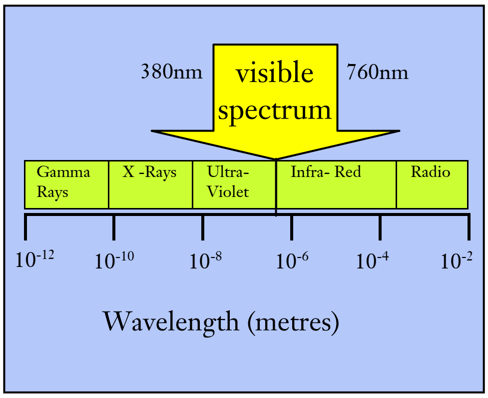


Fig 1 Electromagnetic Spectrum

The region of visible light extends from 380 to 760 nanometres - nanometre (nm) being one millionth of a millimetre - and the different wavelengths directly relate to the colour of the light rays. The shorter the wavelength, the more blue they appear. The longer the wavelength, the more red they appear.

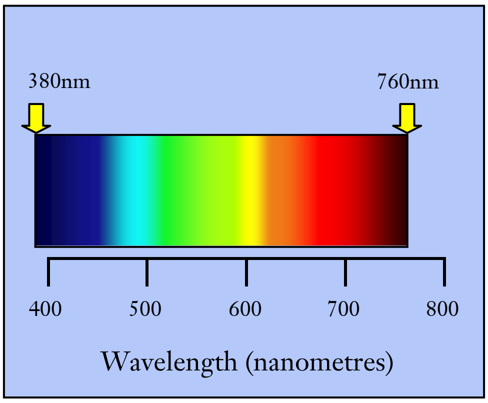


Fig 2 Visible Spectrum

To illustrate these different colours that make up white light a ray of white light can be directed through a prism that split the light into colours to form a visible spectrum. (Fig.3) The three distinct colours - red, green and blue - with a narrow yellow region between the red and green are there in the spectrum, plus many more colours, blended together.

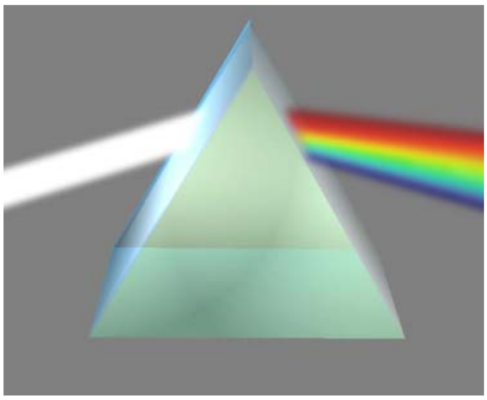


Fig 3 Light passing through prism

2 The Eye and Vision

The eye

The eye can distinguish minute variations of shape, colour, brightness and distance. The actual process of seeing is performed by the brain rather than the eye. The function of the eye is to translate the light into patterns of nerve impulses that are transmitted to the brain. The rays of light enter the eye through the **cornea** which is the transparent membrane that bulges out at the front of the eye.

They then pass through the **pupil**, which is a round opening in the coloured **iris**. The eye reduces the size of this opening to limit the rays of light to the central and optically best part of the **lens**, except when the full aperture is needed for maximum sensitivity. The pupil also closes for near vision to increase the clarity of near objects. It can change the area of the opening only over a ratio of about 16:1 although the eye works efficiently over a range of brightness of about 1,000,000:1.

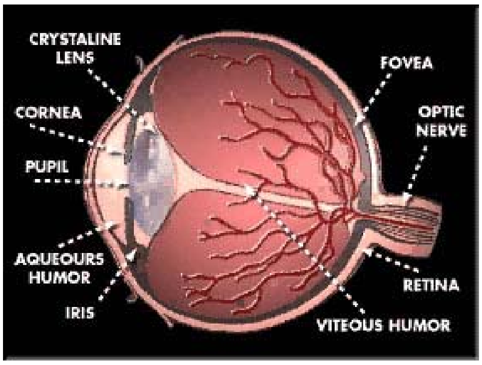


Fig 4 The human eye

The whole eye is filled with a jelly-like substance and the rays pass through this onto the lens, which focuses the image. Muscles around the lens make it fatter or thinner so the eye can focus sharply on distant or close objects. This ability is called **accommodation** and ensures that a sharp, clear image is focussed onto the light sensitive cells of the **retina**. We don't "see" with the retina - it is only when the information it collects has been transferred along the **optic nerve** to the brain that a conscious visual image is formed and we "see".

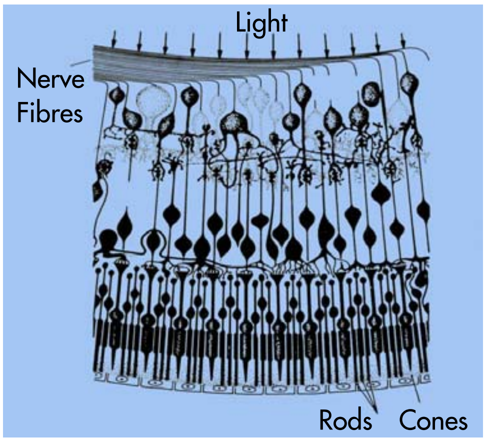


Fig 5 Rods and Cones in the Retina

The retina has two basic types of **receptors** – **rods** and **cones** - for collecting this information. By a chemical process in the retina the eye is able to work over the enormous range of brightness we see (mentioned above). Cones can differentiate between the different wavelengths of light and therefore enable us to see in colour; the rays of light are not actually coloured. Whereas the more sensitive rods, only give us black and white vision.

Vision

The cones operate during the day and normal daylight conditions and enable us to see in detailed colour. This is known as **photopic** or daytime adaption. As the light level drops, say to that of a well-lit street, the cones become less effective and are assisted by the more sensitive rods. Therefore, the eye is using a mixture of cones and rods to see. However, as the rods can only "see" a black and white image, the overall impression is much less brightly coloured. This is called **mesopic** vision. At even lower levels, much lower than average street lighting or moonlight, the cones cease to function. The eye loses all its facility to see in colour and the rods take over giving completely black and white vision, called **scotopic** or night-time adaption. Next time you are in really dark surroundings observe to what extent you can see colour. These different adaptions are important because not only does the eye discriminate between different wavelengths of light with the sensation of colour, but it is also more sensitive to some wavelengths than others - and this sensitivity alters between photopic and scotopic vision. For photopic vision, the eye has peak sensitivity at 555 nanometres, which is a yellow-green colour. However, for scotopic vision, peak sensitivity moves to 505 nanometres, which is blue-green light, although the

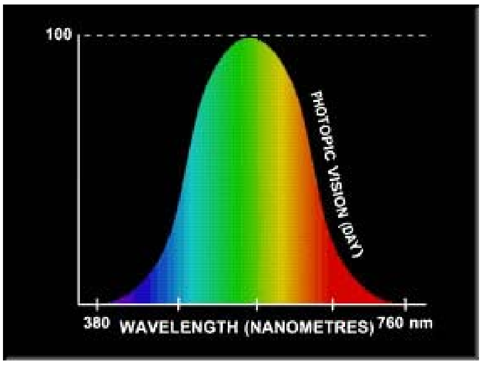


Fig 6 Photopic Vision Sensitivity

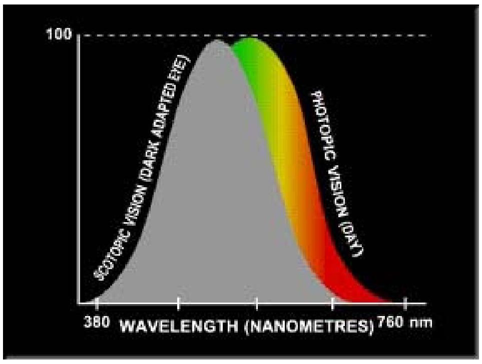


Fig 7 Scotopic Vision Sensitivity

vision is in terms of black and white. The mesopic vision peak will be somewhere between the two.

In lighting design photopic vision is the most important. As is to be expected not every individual has exactly the same sensitivity. So the CIE, an international lighting body, has adopted an internationally agreed standard response called the **CIE standard observer**. It is also known as the **V(λ) curve** (V-lambda) and is a standard sensitivity for the eye across the spectrum of wavelengths from 380 to 760 nanometres. At 555 nanometres the sensitivity is at its highest, whereas at 400 nanometres, the sensitivity is only about one thousandth of the highest level. This means that one watt of radiation in the yellow-green part of the spectrum is 1000 times more effective than one watt of radiation in the deep blue part.

Questions 1

1. What is the range approximately in nanometres of visible light within the electromagnetic spectrum?
2. What colour is associated with wavelengths near 760nm?
3. What radiation occurs just below 380nm?
4. What type of vision does cone receptors give?
5. What type of vision does rod receptors give?
6. What change in brightness can the iris of the eye adjust to?
7. What changes in brightness can the eye adjust to?
8. When do the cone receptors operate?
9. Under what conditions do the rod receptors mainly operate?

3 Lighting Concepts and Units

Luminous Flux

It is impractical to use the watt as a measure of light because of the variation in sensitivity of the eye with wavelength. Instead the **lumen** is used; a measurement of the rate of flow of the luminous energy, or the **luminous flux** as it is more often called. One lumen of luminous flux at 555 nanometres corresponds to a radiated power of 1/680th of a watt, but at 400 nanometres; 3.5 watts of radiated power are equal to one lumen. This relationship between the watt and the lumen is important as it is possible to calculate the luminous flux a particular lamp will produce by considering the radiated power at each wavelength and the corresponding eye sensitivity (as defined by the CIE) at that wavelength. This can be done mathematically or by means of specially corrected photocells with a response identical to that of the CIE standard observer. For example, a low pressure sodium lamp emits practically all its light at wavelengths 589 and 589.6 nanometres. As this is very close to the peak photopic sensitivity of the eye, it is very efficient in terms of the number of lumens produced for each watt of power.

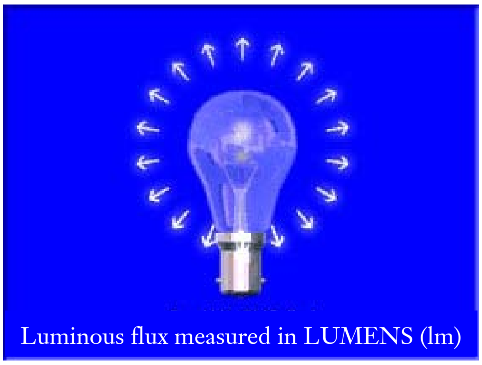


Fig 8 Unit of luminous flux

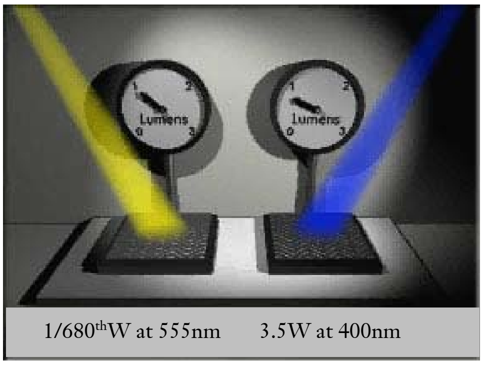


Fig 9 Light Units

Illumination

When a ray of light hits a solid surface, the process is known as **illumination** and in the same way as there are lumens to measure luminous flux, we need a measurement for the quantity of illumination or **illuminance**.

The illuminance E at a point on a surface is defined as the luminous flux F incident upon a small element of the surface, divided by the area of the element.

$$E = \frac{F}{A}$$

The basic unit of illuminance is the lumen per square metre or **lux**. For example, if an area of 0.1 square metres in size receives a luminous flux of 20 lumens, the illuminance which is usually given the symbol E, will equal 20 divided by 0.1, that is 200 lux.

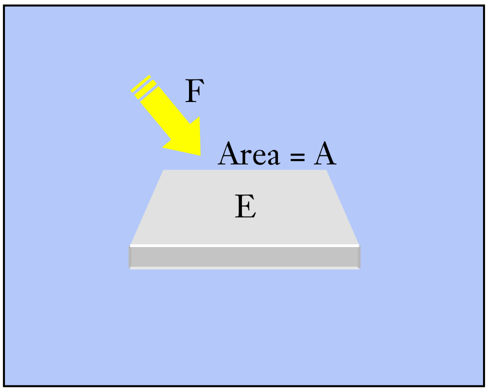


Fig 10 Illumination and Illuminance

Inverse Square Law

Importance is placed on the illuminance required for different purposes; therefore it is essential to have a method for calculating this quantity. The **Inverse Square Law** enables the calculation of illuminance. To understand this law, consider a cone-shaped beam of light coming from a small point source and hitting a surface some distance away. Suppose that the luminous flux within the cone is one lumen, and that it strikes a surface 1 metre away, producing an illuminated area of 1 square metre. By dividing the luminous flux by the area we can find the illuminance, which will be 1 lux.

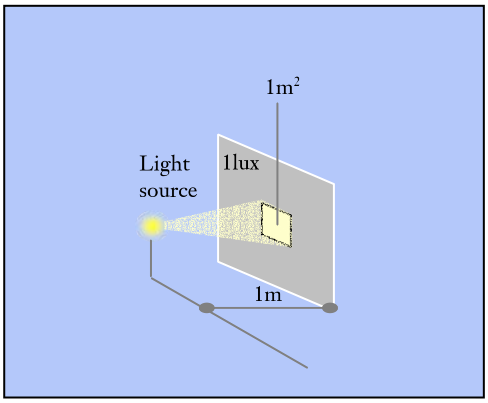


Fig 11 Inverse Square Law

If the surface is moved further away to a distance of 2 metres, then the luminous flux within the cone will stay the same, but the illuminated area will increase in size to 4 square metres. This will result in an illuminance of $\frac{1}{4}$ lux. By doing this the area has increased in proportion to the square of the distance from the light source, and the illuminance has changed inversely with the square of the distance. If the surface is moved still further away to a distance of 3 metres, the inverse square law operates again. The area has increased in proportion to the distance squared and is now 9 square metres and the illuminance falls inversely to $\frac{1}{9}$th lux. All of this is encompassed by the inverse square law which states that the illuminance E equals I, the intensity of the light source, divided by the distance squared.

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

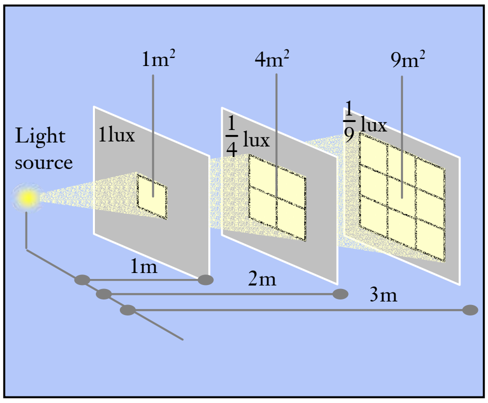


Fig 12 Inverse Square Law

The **luminous intensity** I is a measure of how much flux is emitted within a small conical angle in the direction of the surface and its unit is the **Candela,** abbreviated to cd. A lighthouse emits light in a small angle (Fig 13). If a source emits the same luminous flux in all directions, then the luminous intensity is the same in all direction. However for most sources the flux emitted in each direction is not the same, for example the luminous intensity of a spotlight varies with angle. It may have a maximum value of 1000 candelas at the centre of the beam. If this spotlight is aimed directly

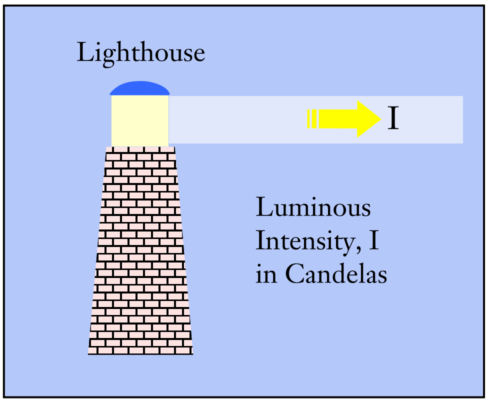


Fig 13 Luminous Intensity example

downwards onto the floor 2 metres below, the illuminance will be:

$$E = \frac{1000}{2^2} \text{ lux} \qquad E = 250 \text{ lux}$$

However, if the spotlight is angled so that the luminous intensity directed downwards is 100 candelas, the illuminance will now be:

$$E = \frac{100}{2^2} \text{ lux} \qquad E = 25 \text{ lux}$$

So far these calculations of illuminance have only covered situations where the rays of light hit the surface at right angles. Here the illuminance, which is the flux falling onto the surface divided by the area, can be found using the inverse square law.

Cosine Law

If the surface is turned so that the rays hit it at an angle, the illuminated area will increase in size and the illuminance will drop accordingly. The ratio of the original illuminated area to the new area is equal to the cosine of the angle through which the surface has been moved. Therefore the illuminance will fall by the factor of the cosine of the angle. This is known as the **Cosine Law** of illuminance. If a surface is illuminated to 100 lux is twisted through an angle of 60°, then the illuminance will fall to half or 50 lux because the cosine of 60° is $\frac{1}{2}$ or 0.5.

This cosine law can be combined into one equation with the inverse square law.

$$E = \frac{I.\cos A}{d^2}$$

Returning to the angled spotlight mentioned earlier, if it is 3 metres above the floor, aiming at a point 3 metres away, then its intensity in this direction is 1000 candelas. The distance from the point of illumination to the spotlight is calculated using cos 45° as 4.24 metres. The light is striking the floor at an angle of 45 degrees so using the combined inverse square and cosine law equation, we can calculate the illuminance:

$$E = \frac{I.\cos A}{d^2}$$

$$E = \frac{1000.\cos 45°}{4.24^2} = 39 \text{ lux}$$

These calculations have only referred to one light source, but when there are several, the illuminance is calculated in the same way for each source in turn, and then these are added together for the total illuminance.

High pressure discharge light sources and spotlights normally conform to the inverse square law when calculating illuminance, but fluorescent fittings are larger and need to be dealt with separately. For most practical applications, the inverse square law can be used with reasonable precision if

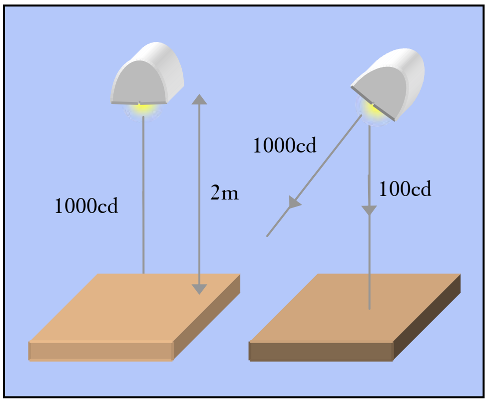


Fig 14 Inverse Square Law - Example

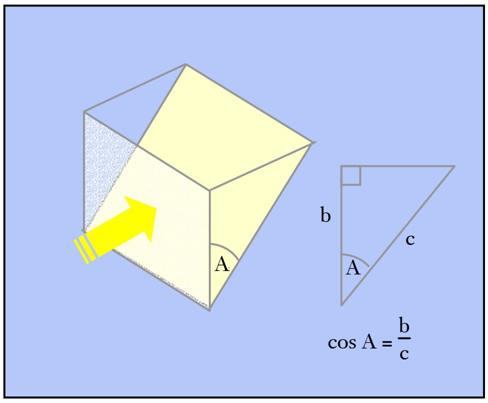


Fig 15 Effect of tilted surface

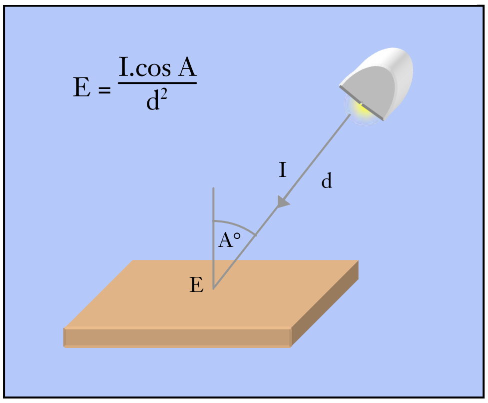


Fig 16 Inverse Square & Cosine Law

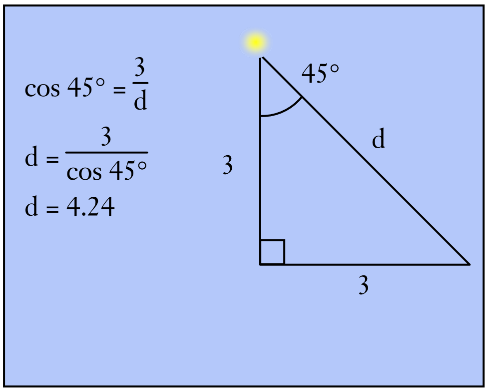


Fig 17 Inverse Square Law - Example

the point of illuminance is more than five times away in distance than the maximum dimension of the light source. In the case of a 600 millimetre fluorescent tube, the inverse square law is sufficiently accurate at distances of 3 metres or more.

The Inverse Square Law and Cosine Law can be expressed as a different formula to:

$$E = \frac{I.\cos A}{d^2}$$

In can be easier to find the illuminance in terms of the height that the luminaire is away from the surface on which the illuminance is required. When several calculations are being carried out where the height between luminaire and the surface is the same, the following formula is useful:

$$E = \frac{I.\cos^3 A}{h^2}$$

This is because h will be known and constant, whereas d will vary with each calculation.

$$E = \frac{I.\cos A}{d^2} \quad (1)$$

$$\frac{h}{d} = \cos A$$

$$\frac{1}{d} = \frac{\cos A}{h}$$

Squaring both sides

$$\frac{1}{d^2} = \frac{\cos^2 A}{h^2} \quad (2)$$

Substitute equation (2) into (1)

$$E = I.\cos A.\frac{\cos^2 A}{h^2}$$

$$E = \frac{I.\cos^3 A}{h^2}$$

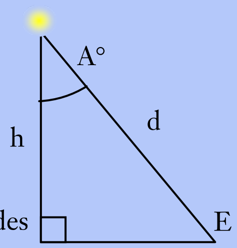


Fig 18 Inverse Square & Cosine Law

Questions 2

1 Why is the watt not used as a unit for quantities of light?
2 What unit is used for quantities of illuminance?
3 What unit is used for luminous intensity?
4 What formula can be used for calculating the illuminance from a small light source when the surface is at an angle to the direction the light is coming from?
5 What is the minimum distance that the inverse square law can be sufficiently accurate for a single tube 1200mm luminaire?
6 Calculate the direct illuminance directly below the centre of one twin 1800mm Popular Range Rack Reflector mounted at 9.0m. Using a luminous intensity of 133cd per 1000 lamp lumens and lamp lumens from a Polylux 1800mm 70W tube of 6550lm. First check that an Inverse Square Law calculation is suitable.
7 A Novaline luminaire with a 38W 2D lamp is mounted in a ceiling 2.0m above a surface. Calculate the illuminance directly below the luminaire on the surface and at a point on the surface 1.5m away from the first point. Use lamp lumens of 2850lm and the following partial data:

Angle	Intensity cd/1000lm
0	131
5	130
10	131
15	128
20	127
25	126
30	125
35	124
40	124
45	120
50	

8 The centre of a recessed downlight is mounted 600mm away from a vertical wall, in a ceiling that is 3.0m above the floor. Calculate the vertical illuminance on the wall half way down the wall. Take the luminous intensity to this point to be 300cd.

4 Visual Performance

The visual system is able to work across a very wide range of illuminance from bright sunlight which could be anything from 100,000 to 500,000 lux, to streetlighting with illuminance of about 5 lux, and even starlight which is only about 0.2 lux.

The visual system does not operate equally well at every level of illuminance. For instance, illuminance has a direct bearing on the eye's **visual acuity** – that is its ability to see small detail. In general, the more light there is, the better the eye sees, but more and more increases in illuminance results in less improvement in visual acuity.

Visual performance is measured in terms of the speed and or accuracy with which a given visual task is carried out. Visual performance improves with task size and contrast, and with illuminance. It is more sensitive to changes at low illuminance than at high illuminance, at lower sizes than larger sizes, and at low contrast than at high contrast. In the design of lighting, these relative performances have to be considered closely in order to produce the best level of illuminance for a specific function. For example, in an office corridor where we only have to see things of large size with comparatively high contrast, then we can make do with low illuminance. Whereas, in situations of fine detail, poor contrast or a combination of both – such as an operating theatre or micro-electronics assembly area – high illuminance is essential to ensure the best visual performance and minimise fatigue.

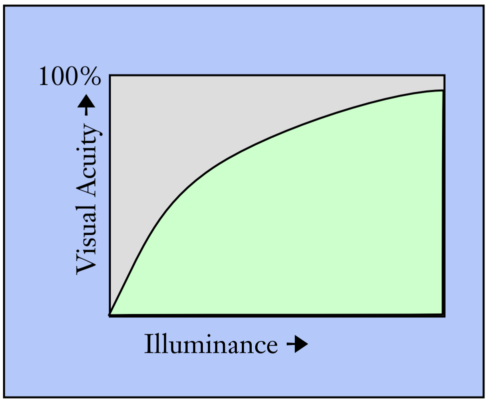


Fig 19 Visual Acuity

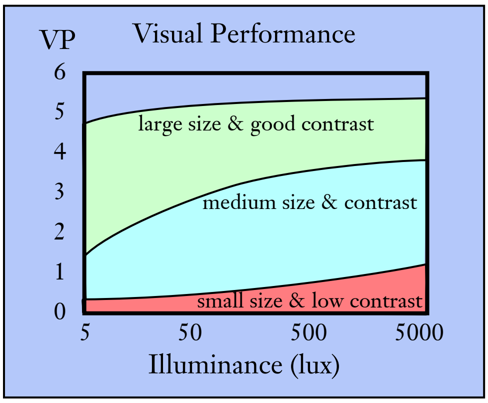


Fig 20 Visual performance

5 Reflection, Transmission, Refraction and Obstruction

Reflection

In lighting design it is also necessary to consider the reflective properties of the surface being illuminated. When light strikes an opaque surface - and by opaque it is meant a surface that will not transmit light - some of the light is absorbed and some is reflected. The ratio of the luminous flux reflected to the luminous flux received is known as the **reflectance**. If a small element of a surface receives 1000 lumens and reflects 700 lumens, then the reflectance is 0.7 - or it can be expressed as a percentage as 70%. The remaining 0.3 or 30% is absorbed.

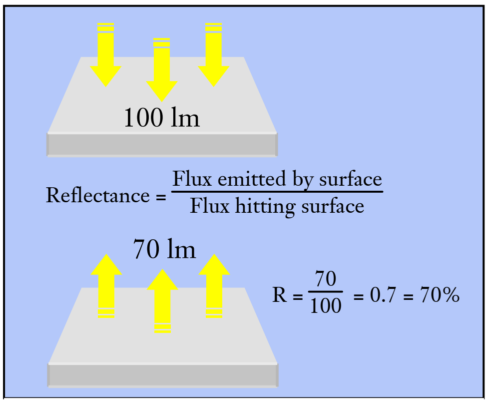


Fig 21 Reflectance of a surface

Diffuse reflection

Different surfaces also reflect light in different ways. Diffuse reflection occurs in matt surfaces and scatters light uniformly in all directions. For example, surfaces such as paper, emulsion paint, carpets and so on, exhibit what we call

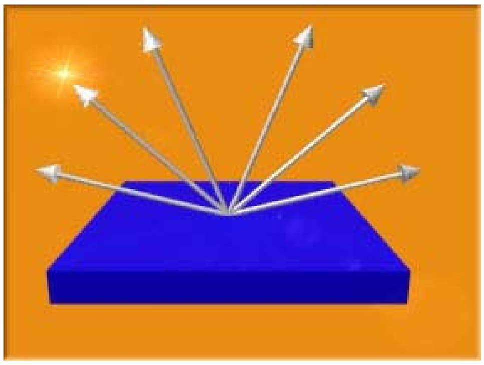


Fig 22 Diffuse reflection

matt or **diffuse reflection** - that is, the light reflected from the surface is scattered equally in all directions. Truly matt surfaces therefore appear equally bright from any direction of view and, in fact, this is the definition of a **uniform diffuser**. A diffusing reflecting surface will scatter light without producing a clear image of the source.

Specular reflection

At the other extreme is mirror or **specular reflection** exhibited by shiny metal surfaces such as chrome, silver or pure aluminium. It is most important to realise that although specular reflections produce a clear image in the surface of the material, the actual amount of light reflected may be deceptively low. A matt white painted surface for instance has a reflectance of 75% to 80% compared with only 60% specular reflectance from a polished stainless steel surface. Many surfaces such as gloss paint, wood, plastic and so on, exhibit a combination of these two types of reflection. Gloss paint, for example, scatters most of the light that it reflects but also produces a specular reflection in the surface of the paint. In lighting design it is important to measure and assess the reflectances of the main surfaces of a room because they will reflect any light that falls onto them and increase the illuminances within the space. Colour charts exist which have reflectances marked on them and matching these with the surfaces of the room will give a guide. The reflective properties of surfaces are made use of in the control of light from light sources, and luminaires. (The international name **luminaire** is often used instead of light fitting or fixture). Specular reflection occurs in smooth polished surfaces, such as mirror glass or polished aluminium. For any ray of light that strikes the specular surface of a reflector the angle of incidence is equal to the angle at which the ray is reflected. This principle still applies to each part of a specular reflector regardless of its shape. Practical specular reflectors are often curved or a series of flat facets. The degree of optical control will depend upon the size of the source relative to the reflector, how much light from the lamp the reflector collects, and the degree to which the reflective material will scatter light (i.e. non mirror reflection). For example, compact low voltage tungsten halogen display lamps with integral mirrors, such as Lightstream, use facetted reflectors. The overall shape of the reflector is approximately parabolic to give a near parallel beam. Because the lamps have a compact filament precise beam control can be achieved with a small reflector.

Mixed reflection

Some surfaces show a mixture of a diffuse and specular reflection. The bodywork of a car would look shabby if it did not provide both types of reflection. A specular image of the sky will be produced in the paint surface, yet most of the

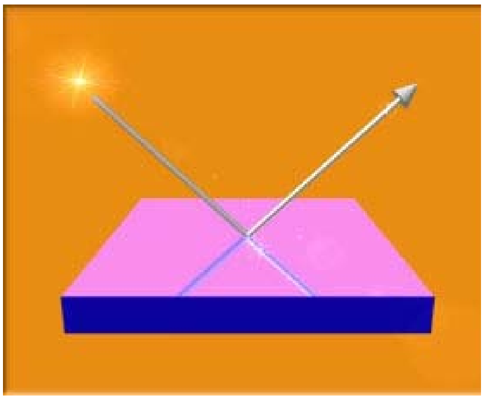


Fig 23 Specular reflection

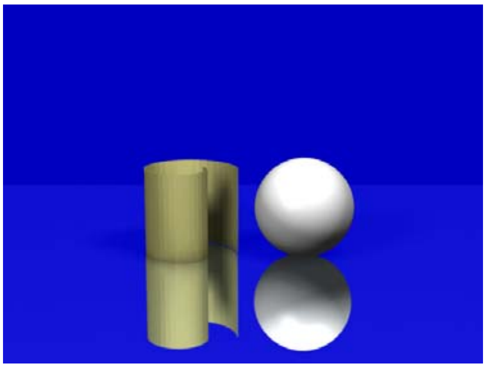


Fig 24 Example of specular reflection

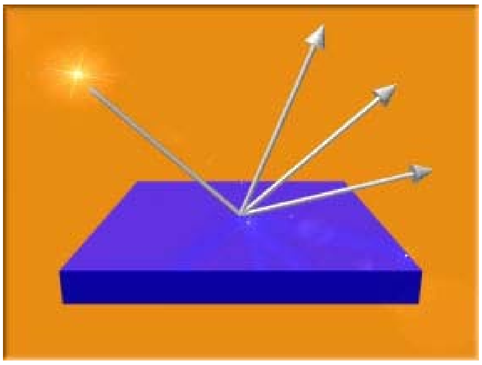


Fig 25 Mixed reflection

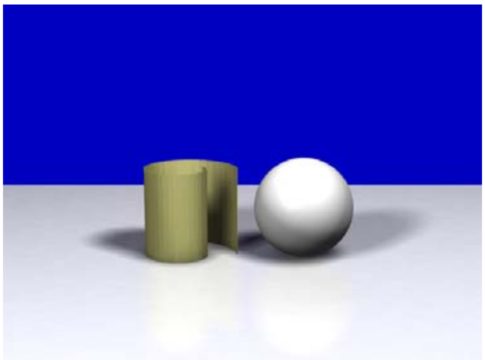


Fig 26 Example of mixed reflection

light will be reflected in a different manner by the pigment to produce the car's colour.

Transmission

Certain materials have the ability to transmit and diffuse light this principle is known as diffuse transmission and occurs with opal glass and opal plastic diffuser luminaires. When a ray of light falls on translucent (light transmitting) opal material some light is reflected specularly and some light passes through the material. This light is scattered or diffused, thus spreading the brightness of the bare lamp over a larger area. The area of illuminated brightness is therefore enlarged and for a given number of lumens coming from the luminaire, the lumens per unit area or candelas per unit area are reduced which in turn reduces the brightness i.e. glare from the luminaire is reduced. The amount of light that is emitted from a material, after passing through it, as a fraction or percentage of the light falling on the material is called the **transmittance.**

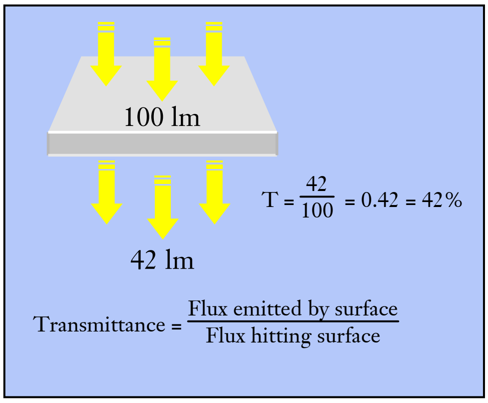


Fig 27 Tranmittance

Refraction

When light passes from one transparent medium to another of different density, it bends this is known as **refraction**, e.g. air to glass, the light bends towards the perpendicular or normal to the surface. When light passes from a dense to a rarer medium, e.g. glass to air, the reverse occurs. If light is passed through a triangular glass prism, it is deflected from its original path. Prisms, in glass or plastic can be designed to control light. Plastics are used extensively in prismatic controllers (fig 29) for both interior luminaires and street lighting lanterns.

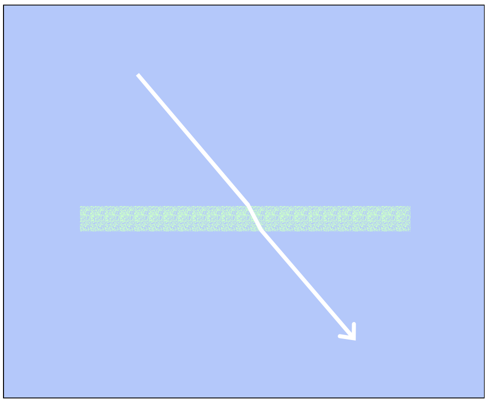


Fig 28 Refraction through glass

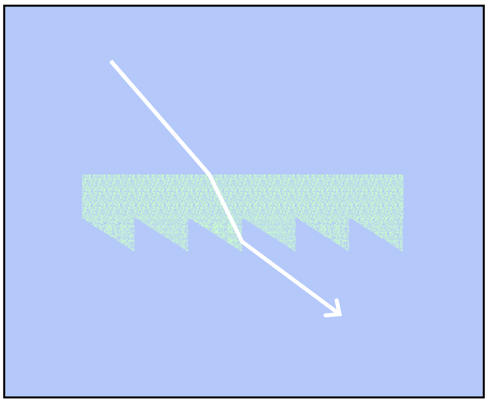


Fig 29 Prismatic controller (section)

Obstruction

Light can be controlled in many different ways. One approach is to limit the flow of light by obstructing its path. Obstruction can have two purposes to limit the flow of light and to obscure the view of the luminaire from normal viewing angles. For example, louvres, spill rings or barn doors fitted to the front of floodlights to limit the amount of spill light or to shape the beam pattern. When obstruction is being used in a practical manner the finish is often matt black but if a device causing obstruction is there to shield viewing angles and for looks then it could be any colour, even white.

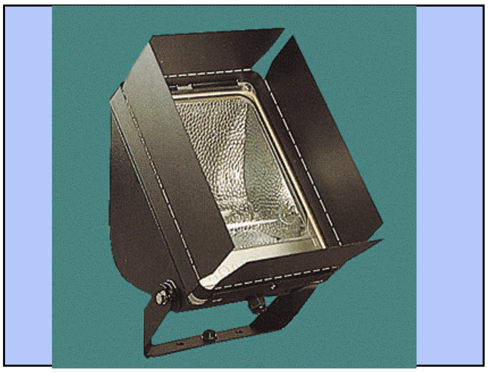


Fig 30 Barn doors on floodlight

Questions 3

1 What illuminance approximately does starlight give?
2 Why is a higher illuminance required in a situation of fine detail and low contrast?
3 Why does usually doubling the illuminance on a task not double the visual performance?
4 Name three characteristic types of reflection?
5 What is a uniform diffuser?

6 If 12% of the incident lumens on an opaque surface are absorbed, what is the percentage reflectance?

7 A tinted glass window reflects 4% of light falling normally onto it at both surfaces and absorbs 12%. What is the transmittance of the glass window?

6 Glare

Glare is the result of excessive contrasts of luminance in the field of view. The effect may vary from mild discomfort to an actual impairment of the ability to see. This is usually caused by viewing a bright source against a dark background. When the ability to see is impaired this is called **disability glare**. At night where there is no surrounding lighting, when a car comes towards you with main beam headlights on what you experience is disability glare. Outdoors direct glare from lighting equipment can be restricted in several ways. The techniques commonly used include careful positioning and aiming of floodlights and other sources of high luminous intensity. The use of hoods, spill rings and louvres for screening lamps from sight at normal viewing angles are often used but these will reduce the lighting performance.

Fig 31 Discomfort glare

Fig 32 Luminance meter

Discomfort glare is associated more with interiors, it refers to the discomfort or distraction caused by bright windows or luminaires. While disability glare will always impair visual performance, discomfort glare has little or no measurable effect on vision. Discomfort glare depends on the brightness and arrangement of light sources in relation to their background. It is currently measured by the Glare Index System in the UK, which is likely to be replaced by the CIE Unified Glare Rating. (CIE is an international lighting organisation.)

Veiling reflections can impair visibility, this is sometimes referred to as **reflected glare**. Bright light sources are reflected in the visual task, such as glossy paper or a computer screen. In the case of paper, people tend to automatically adjust the angle the paper is held to improve visibility. In any case, this can be avoided by eliminating or controlling the luminance of any bright source that cause reflected glare. Luminance is measured by means of a luminance meter, a typical example is shown in Fig 32.

7 Visual Amenity

In interiors it is not sufficient to provide good task lighting without considering the overall lit appearance of the space – the lighting aesthetics. People prefer an interior to be visually attractive and lighting can play a big part in this. An attractively lit interior will give people a greater sense of well-being and they are likely to perform better through greater satisfaction and stimulation. This approach could also contribute to a healthier environment, which could mean less absenteeism. Research has shown that people prefer a space to appear 'visually interesting' and 'visually light' particularly in the **normal field of view** which is defined as a horizontal band approximately 40° high and centred at normal eye height. (Fig 33)

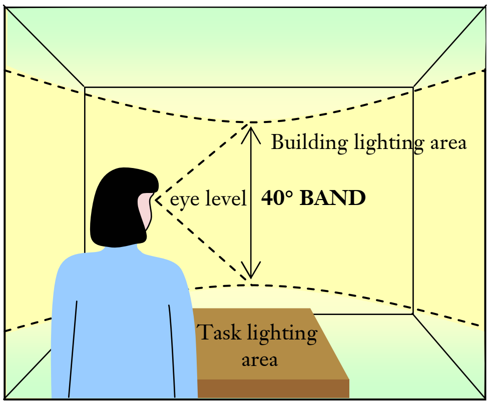


Fig 33 Normal field of view

Visual Interest

To create 'visual interest' it is necessary for the light pattern to have some illuminance variation. This is to create areas of 'light' and 'shade' which people find attractive and stimulating. A very uniform light pattern, like the light from an overcast sky, is seen as dull and unappealing. Too much illuminance diversity can be equally unacceptable even uncomfortable, particularly if the change in illuminance is rapid. Hard shadows should also be avoided particularly in the work area.

Visual Lightness

To create a feeling of 'visual lightness' it will be necessary to project light directly on to some room surfaces and particularly on those surfaces, which are prominent in the normal field of view. Often these will be the walls, but the ceiling may also be included, especially in large rooms. Where work-stations are employed using vertical partitions, some light on the partitions will be beneficial. Without this the room can appear gloomy and under-lit.

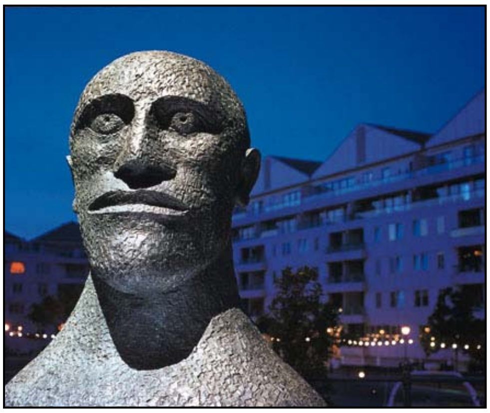


Fig 34 Strong directional modelling

8 Modelling

Revealing form

The revelation of the form of an object or structure is determined by the relationship of the light falling on the surface and the nature of the surface. Light reveals surfaces by three basic methods: **emission**, **silhouette**, and **reflection**. A glass vase with light directed into the base will refract and emit light from the surface of the glass. Objects come into silhouette when there is solely or dominantly light directed to light the object from behind and there is little appreciation of three-dimensional form. When an object is lit from side or front positions the three-dimensional form becomes apparent. The intensity, direction, colour of the light and the reflective properties of the surfaces, all contributes to how the object is revealed. This is a fascinating subject to experiment with a few objects and lights. Fig 37 shows an egg lit in different ways to understand the connection between the technique and the appearance of the object.

Fig 35 Revealing texture in wall

Revealing texture

The showing of the texture of a material can have both aesthetic and functional value. Fig 35 shows an example of lighting that reveals the texture of the stone wall giving character to this small space. By close off-set lighting the light falls on the wall at a shallow angle revealing the texture. The deliberate use of non-uniform luminance provides greater visual impact and sets off the picture hanging from the wall. The other example (Fig 36) shows texture in the surface of metal plates by lighting that is oblique to the surface. Rugged textures are shown on the left side and finer surfaces are on the right side.

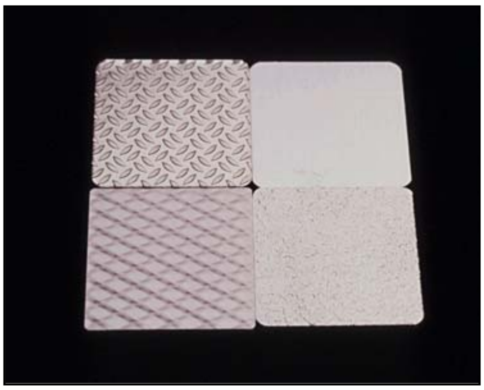


Fig 36 Texture of metal plates

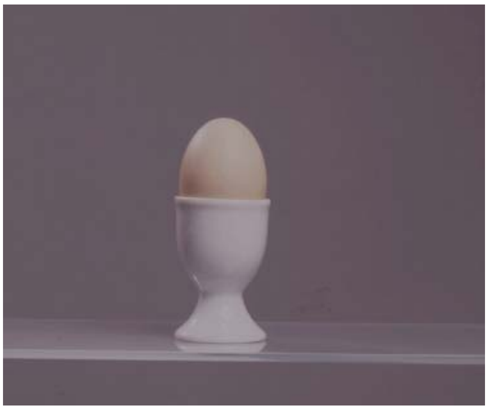
Modelling

Modelling is the use of light to bring out the form of three-dimensional objects, structures or spaces. The importance of modelling is obvious for retail display, exhibition work and the creation of mood. Any lighting installation that fails to create sufficient degrees of modelling will appear bland and monotonous. Virtually all environments can benefit from a lighting approach that considers light direction and the resulting revelation of architectural form, texture and facial modelling. Fig 37 shows some of the basic techniques for revealing form to best effect when viewed from one angle. The photographs show six basic approaches and the way they where achieved. In practise numerous combinations are of course possible.

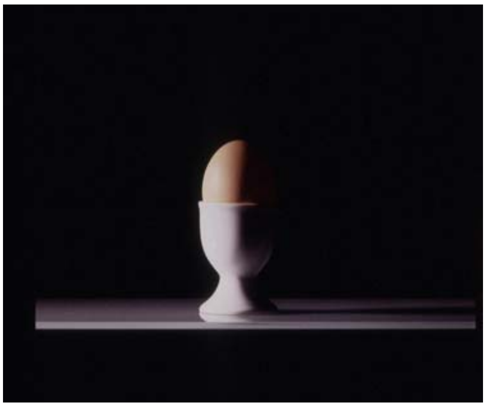
Fig 37 Egg in eggcup lit in different ways

Lighting from behind

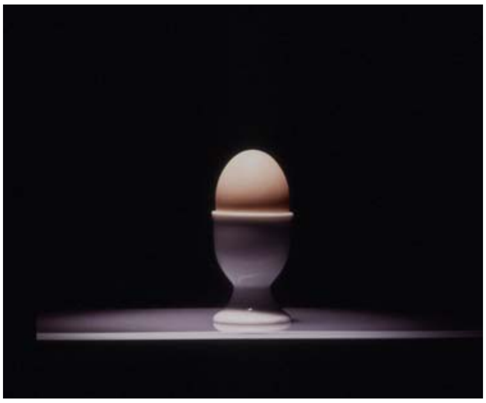
Lighting from below



Lighting from front



Lighting from left side



Lighting directly overhead

Key light from right & front fill light

Fig 38 Facial Modelling

1 Front lighting – diffuse light from the front at head level giving a flat effect
2 Back lighting – above and slightly to the right giving a halo to the head
3 Background lighting – no light on subject giving silhouette
4 1 + 2 Combined – giving improved modelling
5 1 + 2 + 3 Combined – giving improved modelling and separation from background

1

6

2

3

4

5

9 Colour

Colour mixing

The rods and cones in the retina of the eye enable us to see over a great range of illuminance, and it is the cones during the photopic or daytime adaptation of the eye, which give us full colour vision.

There are three basic types of cone receptors that enable the eye to do this. They respond to red, green and blue light respectively. It is the relative output of these three receptors that determine what particular colour we see. Thus if a mixture of two or more lights can stimulate the red, green and blue sensitive cones in the same proportion as a single light, then the two colours appear to be the same, even though one is a mixture. Mixing red, green and blue light in equal proportions gives white light since all three colour receptors are in balance (see Fig 39). Red and green light will give yellow; red and blue light, magenta; blue and green light, cyan. Red, green and blue are called the **lighting primaries**, the other three the secondaries. A mixture of the three primaries or the three **lighting secondaries** will give white light. For example, green and magenta in the correct proportions will give white light. This type of colour mixing using light is called **additive colour mixing** and should not be confused with the more familiar **subtractive colour mixing** when using paint for instance (see Fig 40).

Yellow paint is yellow because it absorbs blue light and reflects green and red. Cyan paint absorbs red light and reflects blue and green. If the two paints, yellow and cyan, are mixed, the result is that both blue and red light is absorbed, leaving only green. This principle is the subtractive mixing of colour, but in lighting we are usually concerned with additive colour mixing.

Surface Colours

Surface colour can be classified by use of a colour system. This allows colour to be specified precisely. In lighting design the reflectance of the surface colours is required, or in the absence of this information assumptions have to be made and stated. There are several colour systems, in the **Munsell system** for example, each colour is specified by three quantities: **hue**, **value** and **chroma**. **Hue** describes whether a colour is basically red, yellow, green, blue, purple, etc. **Value** describes the lightness of the colour and is related to its reflectance. Approximately the percentage reflectance is $V(V - 1)$ where V is the value. **Chroma** describes the strength of the colour. This system gives an easy way to discuss the effects of room surface colour on the appearance of spaces. A predominant hue for a space can create a 'cool' or 'warm', a 'restful or 'active' atmosphere.

The light reflected from a surface of strong chroma will be coloured and may influence the colour of other surfaces. For example, when a floor covering of strong chroma is lit by a lighting installation that does not light the ceiling directly, the ceiling will be mainly lit by light reflected from the floor. This will tend to colour the ceiling.

Object Colours

The colour of objects can have a marked effect on the appearance of a space. The combination of colours for both the surfaces and equipment within a space is preferable if the elements can be considered together. The actual choice of a combination of colours to produce a co-ordinated colour scheme is usually someone else's design task. There is a limitation to the choice of colours of some objects in an interior space because of colour coding on services to indicate potential hazards.

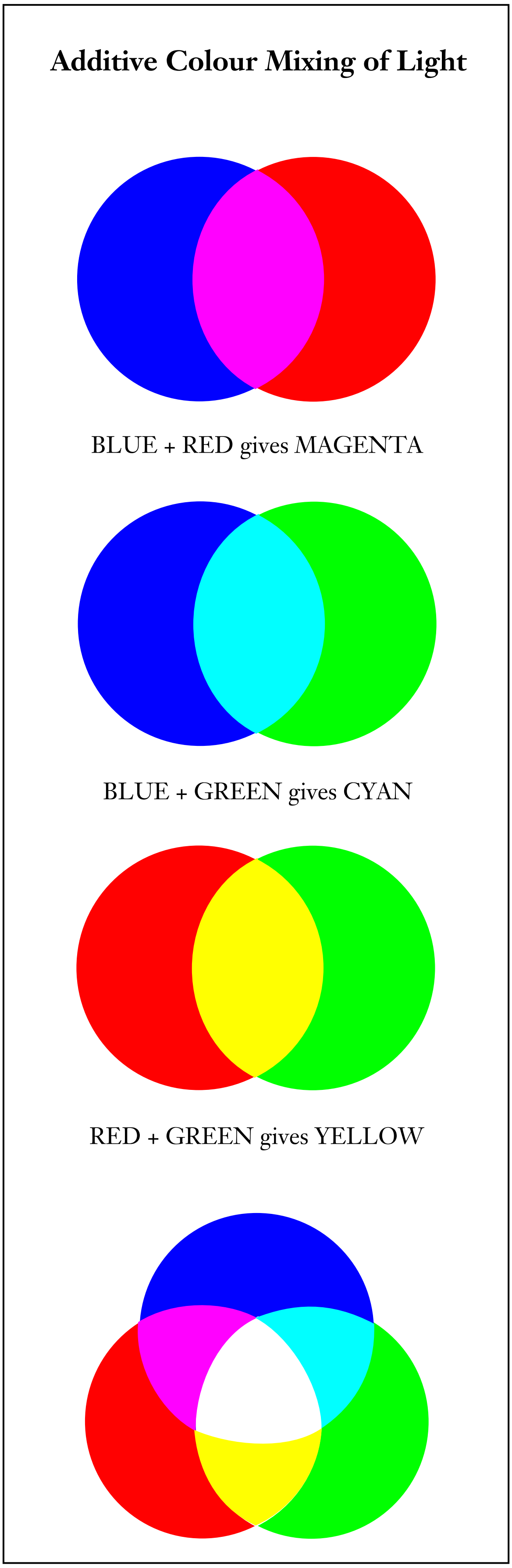


Fig 39 Additive Colour Mixing (Light)

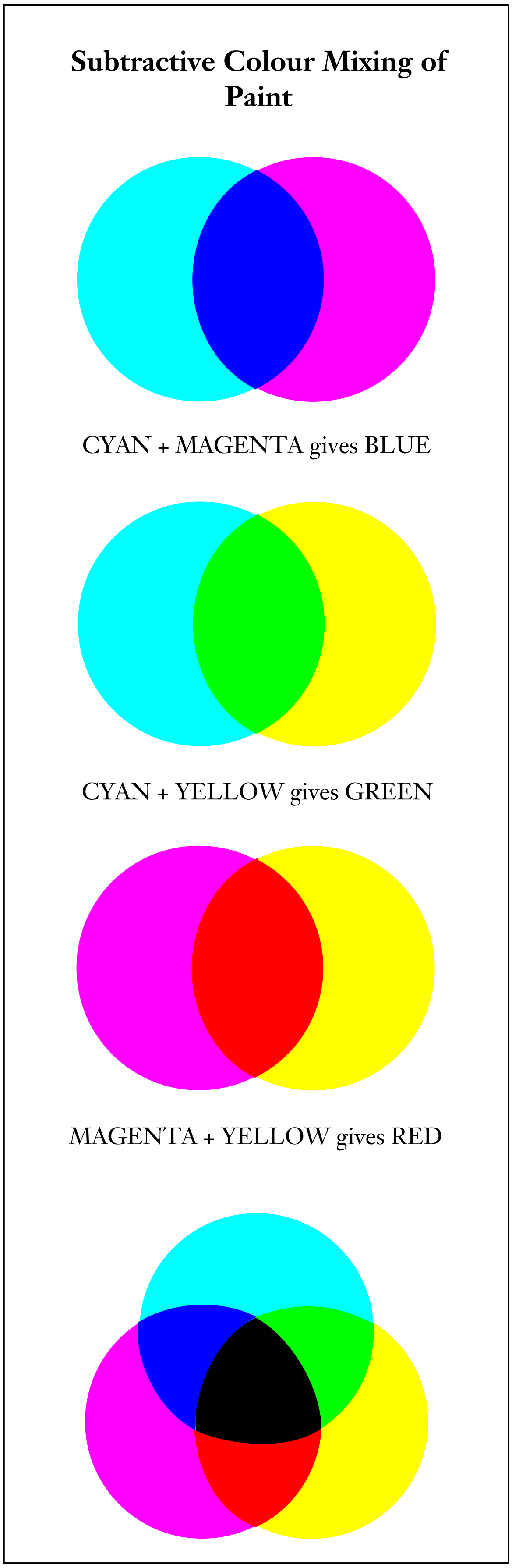


Fig 40 Subtractive Colour Mixing (Paint)

Colour Appearance

The colour emitted by a near-white light source can be indicated by its correlated colour temperature (CCT). Each lamp type has a specific **correlated colour temperature** measured in degrees Kelvin e.g. 3000K. (The Kelvin temperature scale is the same as degrees Centigrade with about 273°C added.) The correlated temperatures are described as **warm, intermediate, cool** and **cold** to give a broad appreciation of the 'feel' of a light source or the space it is lighting. (Fig 41) The higher the colour temperature the colder the light appears. An ordinary light bulb has a warm colour appearance and a CCT of about 2700K, which may engender a cosy and homely feel. A high CCT of 4000K from a metal halide lamp can suggest fresh air and physical activity.

In a cold, wet climate there is a preference for lamps that are warm. In hot climates or very hot weather our preferences reverse. We also prefer warm lamps at lower lighting levels, but dislike them at high levels. Items involving colour reproduction look better under cool lighting. Where it is desirable to blend with daylight, intermediate colour temperature light sources are preferable. It is also a good idea not to haphazardly mix light sources of different colour temperatures in the same space.

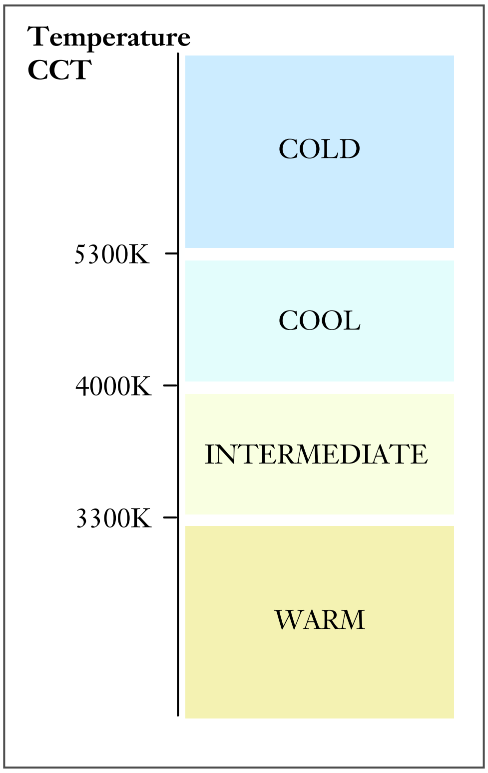


Fig 41 Colour Temperature

Colour Rendering

The ability of a light source to reveal the colours of an object is called **colour rendering.** It is determined by the **spectral power distribution** or spectrum of the light source. Only those colours that fall onto a surface can be reflected from it. Ordinary White fluorescent tubes, for example, are exceedingly poor. They distort yellows, greens, and blues, and make reds very subdued. Although it has some limitations, there is a simple measurement of colour rendering, called the **colour rendering index** (Ra). It is a number that indicates the colour quality of the lamp type. The higher the number the better, up to a maximum of 100. Lamps are grouped into colour rendering classes: 1A, 1B, 2, 3 and 4. For example, White fluorescent tubes are in Class 3, but triphosphor florescent tubes are Class 1B or higher. (Fig 43)

Better colour rendering improves **visual clarity**, the ability to see well. In a given situation people can distinguish more colours under good colour rendering light sources. When people compare areas lit with the older, less efficient lamps and the newer multi-phosphor, high colour rendering types, they prefer the appearance of the interior with the better lamps because it seems 'crisper' or 'clearer' and they feel more satisfied.

Metameric matches

The colour of a light source can be defined mathematical in terms of **chromaticity coordinates**, these may be calculated from the **spectral power distribution** – the amount of power emitted at each wavelength over the visible spectrum. Although a lamp's chromaticity is often referred to as its 'colour appearance', the chromaticity does not really describe

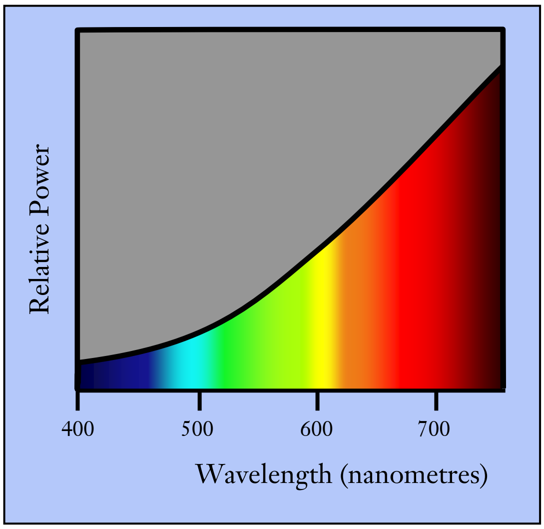


Fig 42 Spectral power distribution of tungsten filament lamp

Ra	Minimum Class Needed	Description
90 to 100	1A	Excellent colour quality. Where accurate colour matching is required (e.g. colour printing inspection)
80 to 89	1B	Very good colour quality. Where accurate colour judgement or good colour rendering is required for reasons of appearance (e.g. merchandising).
60 to 79	2	Good colour quality - Where moderate colour rendering is required, good enough for merchandising.
40 to 59	3	Poor colour quality - Where colour rendering is of little importance. Colours can be distorted but marked distortion is not acceptable.
20 to 39	4	Very poor colour quality - Colour rendering is of no importance and severe distortion of colours is acceptable.

Fig 43 Colour rendering indices and class

the perceived colour of the source, which is affected by visual adaption and viewing conditions. By definition the chromaticity is independent of the observer, so two lamps having the same chromaticity coordinates and luminance will look the same, though they may have different colour rendering properties.

Two lamps having the same chromaticity but different spectral power distributions are said to be **metameric**. They will have different colour rendering properties. Also two surfaces having the same luminance and chromaticity but different emission spectra are said to be **metameric.** They should look the same. However under a different light source a metameric match could breakdown, the colours just will not look the same. This principle can be important, clothes made of several fabrics are sometimes viewed by retailers before bulk purchases under different light sources to check on what the items look like to ensure that the colours are acceptable. If the clothes design is made under one light source it does not mean it is going to look the same under all light sources.

Questions 4

1 What does discomfort glare depend on?
2 How is discomfort glare assessed in the UK?
3 What is the normal field of view in an interior?
4 What creates visual interest in interiors?
5 What are the basic methods of revealing form?
6 How is texture revealed?
7 How is a silhouette of a three-dimensional form created?
8 What visual effect does strong overhead downward lighting have on facial features?
9 What colour is created when green light is mixed with red light on a white surface?
10 What parameters does the Munsell Colour System use?
11 Why can metameric matches be important?

10 Answers to Questions

Questions 1

1. Range of visible light within the electromagnetic spectrum is about 380 to 760nm.
2. Red is associated with wavelengths near 760nm.
3. Ultra-violet radiation occurs just below 380nm.
4. Cone receptors give photopic vision.
5. Rod receptors give scotopic vision.
6. The iris of the eye can adjust to brightness changes of 16:1.
7. The eye can adjust to brightness changes of 1,000,000:1.
8. Cone receptors operate when there is colour vision.
9. Rod receptors mainly operate at lighting levels below moonlight.

Questions 2

1 Why is the watt not used as a unit for quantities of light?
2 Lux is used for quantities of illuminance.
3 The Candela (cd) is used for quantities of luminous intensity.
4 $E = \frac{I.\cos A}{d^2}$ can be used for calculating the illuminance from a small light source when the surface is at an angle to the direction the light is coming from.
5 6 m is the minimum distance.
6 Ratio of distance to luminaire maximum dimension is 5:1, so the Inverse Square Law is suitable.
Direct illuminance: 22lux
6 Illuminance directly below: 93lux
Illuminance at a point on the surface 1.5m away: 45lux
7 44lux

Questions 3

1 Starlight illuminance is approximately 0.2 lux.
2 Higher illuminance is required in a situation of fine detail and low contrast because of the characteristics of visual performance.
3 The relationship between illuminance on a task and visual performance is not constant.
4 Diffuse, specular and mixed reflection.
5 A uniform diffuser is a surface that appears equally bright from all viewing positions.
6 The average percentage reflectance is 88%.
7 The transmittance of the glass window is 80%.

Questions 4

1 Discomfort glare depends on the brightness and position of light sources in relation to their background brightness.
2 Discomfort glare is assessed by the Glare Index System in the UK.
3 The normal field of view in an interior is a horizontal band of about 40° centred at normal eye height.
4 Visual interest in interiors is created by a moderate amount of illuminance variation.
5 The basic methods of revealing form are by emission, silhouette and reflection.
6 Texture is revealed by light falling at shallow angles to the surface.
7 A silhouette of a three-dimensional form happens when there is solely or dominantly light directed from behind the object.
8 There is a distortion of facial features with eyes in shadow.
9 Green light mixed with red light on a white surface gives yellow.
10 The Munsell Colour System uses hue, value and chroma.
11 Colours that match under one light source may not match under a different light source when there is an expectation that they will look the same.

11 Summary

The Spectrum

Light is a form of energy called **electromagnetic radiation**. It occurs in many forms and the whole range or **spectrum** is measured in **wavelengths**. Light represents only a small section of this spectrum and is the only visible radiation. The region of visible light is from 380 to 760nm. The different wavelengths relate to the colour of the light. The three distinct colours - red, green and blue - with a narrow yellow region between the red and green are in the spectrum, plus many more colours, blended together.

The eye

The eye translates light into patterns of nerve impulses that are transmitted to the brain. 'Seeing' is performed by the brain. Light enter the eye through the **cornea** and passes through the **pupil,** which is a round opening in the coloured **iris**. Light is then focussed onto the **retina** by the **lens**. Muscles around the lens make it fatter or thinner so the eye can focus sharply on objects. It is the **optic nerve** that transfers information to the brain. The retina has **rods** and **cones receptors**. Cones can differentiate between the different wavelengths of light and give colour vision. The more sensitive rods give black and white vision.

Vision

The cones operate during the day and normal daylight conditions. This is known as **photopic** or daytime adaption. At very low light levels, lower than moonlight, the cones cease to function. The rods take over giving black and white vision, called **scotopic** or night-time adaption. For photopic vision, the eye has peak sensitivity at 555nm, which is a yellow-green colour. The peak sensitivity of scotopic vision moves to 505nm. The CIE, an international lighting body, has adopted an internationally agreed standard response called the **CIE standard observer**. It is a standard sensitivity for the eye across the spectrum of wavelengths from 380 to 760nm.

Lighting Concepts and Units

Luminous flux, the rate of flow of the luminous energy, is measured in **lumens.**
When a ray of light hits a solid surface, the process is known as **illumination.**
The **illuminance** E at a point on a surface is defined as the luminous flux F incident upon a small element of the surface, divided by the area of the element.

$$E = \frac{F}{A}$$

The basic unit of illuminance is the lumen per square metre or **lux**.
The **luminous intensity** I is a measure of how much flux is emitted within a small conical angle in the direction of the surface and its unit is the **Candela**. (**cd**)
The **Inverse Square and Cosine Law** enables the calculation of illuminance. .

$$E = \frac{I.\cos A}{d^2} \quad \text{or} \quad E = \frac{I.\cos^3 A}{h^2}$$

When there are several light sources, the illuminance is calculated for each source in turn, and then these are added together for the total illuminance.

Visual Performance

The visual system is able to work across a very wide range of illuminance from bright sunlight to starlight. The visual system does not operate equally well at every level of illuminance. In general, the more light there is, the better the eye sees, but more and more increases in illuminance results in less improvement in **visual acuity**. **Visual performance** improves with task size and contrast, and with illuminance.

Reflection

The ratio of the luminous flux reflected to the luminous flux received is known as the **reflectance**.
Diffuse reflection occurs in matt surfaces and scatters light uniformly in all directions. Truly matt surfaces appear equally bright from any direction of view without producing a clear image of the source.
Specular reflection is exhibited by mirrors and shiny metal surfaces. For any ray of light that strikes the specular surface of a reflector the angle of incidence is equal to the angle at which the ray is reflected.
Mixed reflection occurs when there is a mixture of diffuse and specular reflection.

Transmission

Certain materials transmit and diffuse light, this is known as diffuse transmission and occurs with opal glass and opal plastic diffuser materials. The amount of light that is emitted from a material, after passing through it, as a fraction or percentage of the light falling on the material is called the **transmittance.**

Refraction

When light passes from one transparent medium to another of different density, it bends, this is known as **refraction**, e.g. air to glass, the light bends towards the perpendicular or normal to the surface. When light passes from a dense to a rarer medium, e.g. glass to air, the reverse occurs.

Obstruction

Obstruction can have two purposes to limit the flow of light and to obscure the view of the luminaire from normal viewing angles.

Glare

Glare is the result of excessive contrasts of luminance in the field of view. The effect may vary from mild discomfort to an actual impairment of the ability to see. When the ability to see is impaired this is called **disability glare**. **Discomfort glare** is associated more with interiors, it refers to the discomfort or distraction caused by bright windows or luminaires. Discomfort glare is currently measured by the Glare Index System in the UK.
Veiling reflections can impair visibility, this is sometimes referred to as **reflected glare**. Bright light sources are reflected in the visual task. This can be avoided by eliminating or controlling the luminance of any bright source in the locations that cause reflected glare.

Visual Amenity

People prefer a space to appear 'visually interesting' and 'visually light' particularly in the **normal field of view,** which is defined as a horizontal band approximately 40° high and centred at normal eye height.
To create **'visual interest'** it is necessary for the light pattern to have some illuminance variation. This is to create areas of 'light' and 'shade' which people find attractive and stimulating. To create a feeling of **'visual lightness'** it will be necessary to project light directly on to some room surfaces and particularly on those surfaces, which are prominent in the **normal field of view**.

Revealing form

The revelation of the form of an object or structure is determined by the relationship of the light falling on the surface and the nature of the surface. Light reveals surfaces by three basic methods: **emission**, **silhouette**, and **reflection**.

Revealing texture

Lighting directed at shallow angles reveals surface texture.

Modelling

Modelling is the use of light to bring out the form of three-dimensional objects, structures or spaces. The importance of modelling is obvious for retail display, exhibition work and the creation of mood. Any lighting installation that fails to create sufficient degrees of modelling will appear bland and monotonous.

Colour mixing

Red, green and blue are called the **lighting primaries**. A mixture of the three primaries will give white light. This type of colour mixing using light is called **additive colour mixing** and should not be confused with the more familiar **subtractive colour mixing** when using paint.

Surface Colours

In the **Munsell system** each colour is specified by **hue**, **value** and **chroma**. **Hue** describes whether a colour is basically red, yellow, green, blue, purple, etc. **Value** describes the lightness of the colour and is related to its reflectance. **Chroma** describes the strength of the colour. A predominant hue for a space can create a 'cool' or 'warm', a 'restful or 'active' atmosphere.

Object Colours

The colour of objects can have a marked effect on the appearance of a space. The combination of colours for both the surfaces and equipment within a space is preferable if the elements can be considered together.

Colour Appearance

The colour emitted by a near-white light source can be indicated by its **correlated colour temperature** (CCT). Each lamp type has a specific **correlated colour temperature** measured in degrees Kelvin e.g. 3000K. The correlated temperatures are described as **warm, intermediate, cool** and **cold.** In a cold, wet climate there is a preference for lamps that are warm. In hot climates or very hot weather our preferences reverse.

Colour Rendering

The ability of a light source to reveal the colours of an object is called **colour rendering.** It is determined by the **spectral power distribution** or spectrum of the light source. There is a simple measurement of colour rendering, called the **colour rendering index** (Ra). It is a number, which indicates the colour quality of the lamp type. The higher the number the better, up to a maximum of 100. Lamps are grouped into colour rendering classes: 1A, 1B, 2, 3 and 4. Better colour rendering improves **visual clarity**.

Metameric matches

Two lamps having the same **chromaticity coordinates** but different spectral power distributions are said to be **metameric**. They will have different colour rendering properties. Also two surfaces having the same luminance and **chromaticity coordinates** but different spectra, are said to be **metameric.**