

# 11 LIGHT

## 11.1 Introduction

Care is needed when first learning about light because the names given to the various quantities of light do sound so similar. It also needs to be recognised that because light is a topic of interest to various disciplines there is a tendency to use different words to describe the same physical quantities. One example of this has already been brought to your attention because radiation from the sun was described both as the Intensity in  $W/m^2$  and Irradiance in  $W/m^2$ . The words 'irradiance' and 'intensity' refer to the same physical concept, the concentration of radiant power per unit area on a plane.

These slight difficulties can be overcome by making oneself familiar with the different units through tackling the problems given in the Question sheets. If this is done then misconceptions will be brought to light and you will build up confidence in the basic units used in lighting design.

## 11.2 Revision of units of radiation

Three units of radiation already have been introduced:

$\Phi_e$  Radiant Flux in W,

$M_e$  Radiant Exitance in  $W/m^2$ ,

$E_e$  Irradiance in  $W/m^2$ .

The subscript 'e' indicates that the quantities refer to electro-magnetic radiation.

The power in Watts  $\Phi_e$  radiated by a source may be either calculated for a theoretical Planckian radiator as shown in Figure 11.1 or established from measurement of the *spectroradiometric curve*.

The *spectroradiometric curve* shown in Figure 11.2 plots the spectral radiant exitance  $M_{e\lambda}$  in  $W/m^2\mu m$  at different wavelengths and the total radiant exitance  $M_e$  in  $W/m^2$  is found by summing the output over all wavelengths.

The radiant exitance  $M_e$  in  $W/m^2$  is the concentration of radiant flux exiting one square metre and is shown diagrammatically in Figure 11.3.

The Irradiance or Intensity  $E_e$  of radiation is the concentration of radiant flux incident upon a surface in  $W/m^2$  and is shown diagrammatically in Figure 4.

$$\Phi_e = A \times M_e^{th} = A\sigma T^4 \quad W$$

$\Phi_e$  Radiant power of source in Watts

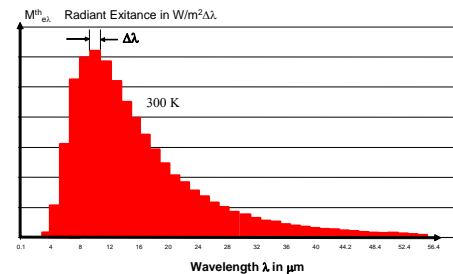
$M_e^{th}$  the Radiant Exitance in  $W/m^2$

$\sigma$  Stefan-Boltzmann constant  $5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$

$T$  Absolute temperature of the surface in Kelvin

Radiant Power,  $\Phi_e$  in W

Figure 11.1 Radiant Power in W



$$M_e^{th} = \sum_{\lambda=0}^{\lambda=\infty} M_{e\lambda}^{th} \Delta\lambda \quad \text{Watts/m}^2$$

Figure 11.2 Spectral Exitance

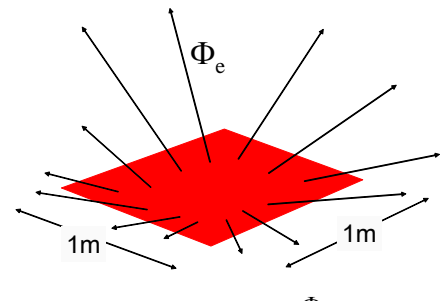
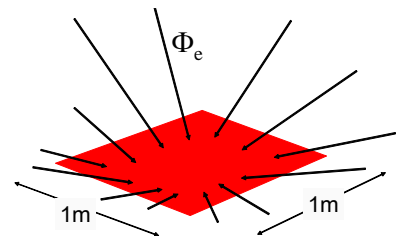


Figure 11.3 –Radiant Exitance  $W/m^2$



Irradiance, Radiant Intensity  $E_e = \frac{\Phi_e}{A_s} \text{ W/m}^2$

Figure 11.4 Irradiance in  $W/m^2$

### 11.3 Light

Physical System	Nuclear	Inner Electron	Outer Electron	Molecular
Wavelength in m.	$10^{-14}$	$10^{-10}$	$10^{-6}$	$10^{-2}$
Type of radiation	$\gamma$ -rays	X-rays	U.V <b>Light</b>	Infrared

Figure 5 Light

The feature of light that differentiates it from other electromagnetic radiations is that the human eye is sensitive to light. Figure 11.5 shows the band of light radiation in relation to some of the other types of electromagnetic radiations.

Radiations between the wavelengths of 380nm and 780nm stimulate the sense of sight but the extreme wavelengths are hardly noticeable and therefore I will simplify the visual range and take it to be from 400nm to 700nm. It is usual to describe the wavelengths of light in terms of nano metres, i.e.  $10^{-9}$  m.

#### A Measure of Light

The term *luminous flux* can be used in place of the term light, and this draws attention to some features of light which easily can be overlooked. Light is a flow of radiant energy, modified to take into account the propensity of the radiation to stimulate the sense of vision. Normally, it is the flow of light that determines what we see, but where the light source is of very low power, is very small or is of extremely short duration then other factors may need to be taken into account. However, we are going to be dealing with the levels of light normally found in interiors and out of doors and therefore we need only consider the flow of light, i.e. the visual power of the light.

At these levels of light, the overall effect of a light source can be found by summing the effects of each wavelength within the visual range.

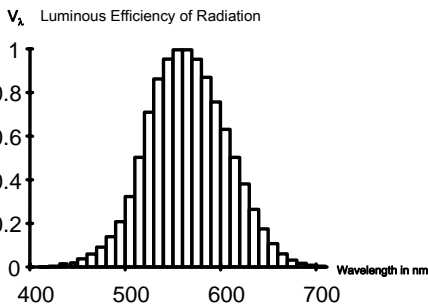


Figure 6  $V_{\lambda}$  Luminous Efficiency

#### 11.3.1 Luminous efficiency of radiation

Radiations of different wavelengths in the visual range do not all appear to be equally luminous. It has already been mentioned that at the extremes of the visual range, below 400nm and beyond 700nm the radiation evokes a very weak response from the visual receptors in the eye. In the middle of the visual range at a wavelength of 555nm radiation has its maximum effect and appears to be the most luminous.

The relative degree to which different wavelengths of radiation evoke the sense of light is known as the 'Luminous Efficiency' of radiation and is given the symbol  $V_{\lambda}$ . The  $V_{\lambda}$  curve is shown in Figure 11.6.

The *Luminous Efficiency of Radiation* may also be thought of as the relative sensitivity of the eye's receptors to radiation of different wavelengths. We are interested in the visual receptors called 'cones' because these are responsible for vision at higher levels of light. Vision mediated through cones is known as Photopic and a principal feature is that it allows colour discrimination.

Scotopic or 'night vision' is mediated by 'rods' and is achromatic. Figure 11.7 is a sketch of a section through the retina of the eye that shows the two types of vision receptors and some of the nerve cells.

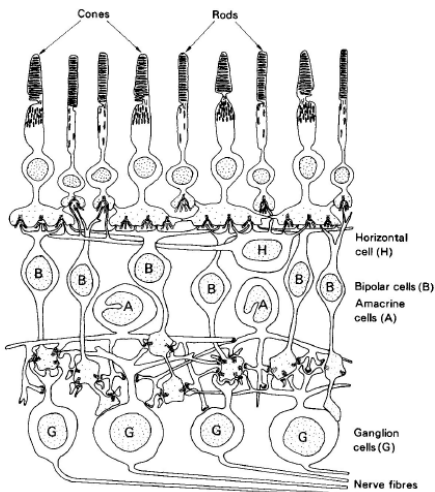


Figure 11.7 Retina of eye

**Relative Visual Stimulus**

Figure 11.8 shows the spectroradiometric curve of a source of radiation. The curve shows the power  $\Phi_\lambda$  emitted in 10nm bands of radiation between the wavelengths from 400nm to 700nm. The bandwidth over which measurements are made will vary depending upon the required degree of accuracy. In the question sheet, a bandwidth of 25nm is used in order to reduce the amount of arithmetic needed.

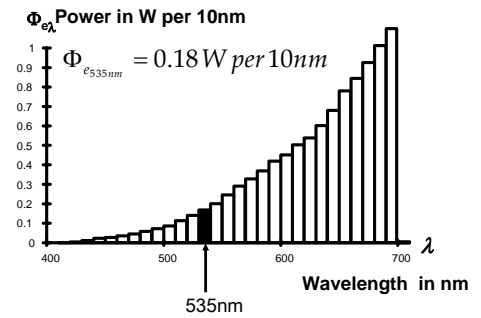


Figure 11.8 a Spectrum

The power of radiation emitted within the visible region will be given by,

$$\Phi_e = \sum_{\lambda=400nm}^{\lambda=700nm} \Phi_{e_\lambda} \Delta\lambda \quad W$$

A measure of visual stimulus i.e. the degree to which the sense of light is evoked, will need to take into account the luminous efficiency of the radiation shown in Figure 11.9. If first, the radiation at the wavelength 535nm is considered, then stimulus given by the band of radiation from 540nm to 550nm will be:

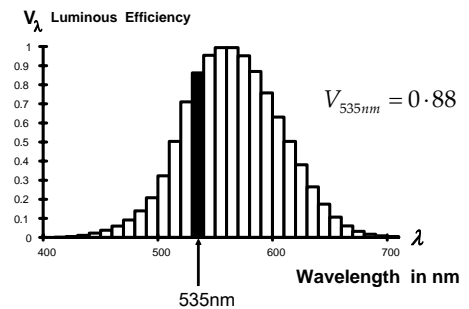


Figure 11.9  $V_\lambda$  Luminous efficiency

$$\begin{aligned} \text{Visual Stimulus} &\propto V_{535} \Phi_{e_{535}} \Delta\lambda \\ &\propto \frac{0.18}{10nm} \times 0.88 \times 10nm \\ &\propto 0.158 \quad \text{Lightwatts} \end{aligned}$$

Where:  $\Phi_{e_{535}}$  Power of the radiation at 535 nm,

$V_{535}$  Luminous efficiency of radiation at 535nm.

It has already been mentioned that at the high levels of light that we are interested in, the total visual effect can be by summing the effects of different wavelengths. Therefore the total visual effect of the radiation described by Figure 11.8 can be found by applying the summation,

$$\text{Visual Stimulus} \propto \sum_{\lambda=400nm}^{\lambda=700nm} V_\lambda \Phi_{e_\lambda} \Delta\lambda \quad \text{light watts} \quad \dots 4$$

**Maximum Luminous Efficacy of radiation**

The recognised unit of light flux is the **Lumen**, and in order to convert lightwatts into Lumens it is necessary to take into account how efficacious is a lightwatt at evoking a visual stimulus measured in Lumens.

The currently agreed maximum luminous efficacy of radiation occurs at a wavelength of 555nm and has a value of 683 lm/watt. It is generally given the symbol  $K_m$ .

### Basic units of Light

$\Phi_v$ Light flux	in Lumen, lm
$E_v$ Illuminance	in Lux, lx, (lm/m <sup>2</sup> )
$M_v$ Luminous Exitance	in Apostilb, asb, lm/m <sup>2</sup>

The subscript 'v' indicates visual radiation, i.e. light

### 11.3.2 Light flux in LUMENS

The luminous flux in lumens is generally denoted by the symbol  $\Phi_v$  and is given by,

$$\Phi_v = K_m \int_{\lambda=400nm}^{\lambda=700nm} V_{\lambda} \Phi_{e_{\lambda}} \Delta\lambda \text{ lm}$$

and as  $K_m = 683 \text{ lm/w}$

$$\Phi_v = 683 \int_{\lambda=400nm}^{\lambda=700nm} V_{\lambda} \Phi_{e_{\lambda}} \Delta\lambda \text{ lm}$$

The subscript 'v' is used to denote that the flux being described is visual flux or light, and in these notes this subscript will be omitted as being understood. Where it is necessary to make clear the difference between visual flux and flux of electromagnetic radiation, then the suffix 'e' will be appended to the emr flux.

### 11.3.3 Illuminance

The higher or the lower the level of light on a plane surface, the more or less well we can see details on that surface. The level of light on the plane surface is described by the concentration of the incident light flux and is known by the term *illuminance*. It is measured in *lux* and is defined as,

$$E_p = \frac{\Phi}{A} \text{ lm}$$

### 11.3.4 Luminous Exitance

The concentration of light flux leaving a plane surface is known as the *luminous exitance* of the surface. It is measured in *apostilbs* and is defined as,

$$M = \frac{\Phi}{A} \text{ asb}$$

### Opaque reflective surfaces

The luminous exitance of an opaque surface is related to the illuminance by the surface reflectance,  $\rho$ ,

$$M = E\rho \text{ asb}$$

Figure 11.9 – Lighting Units

$$E = \frac{\Psi_v}{A} \text{ lx}$$

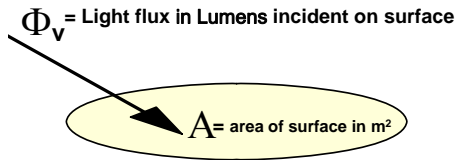


Figure 11.10 –Illuminance

$$M_v = \frac{\Phi_v}{A} \text{ asb}$$

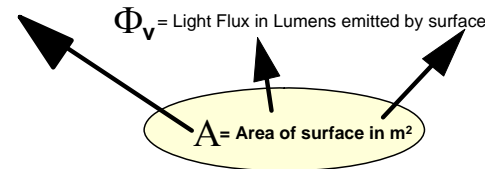
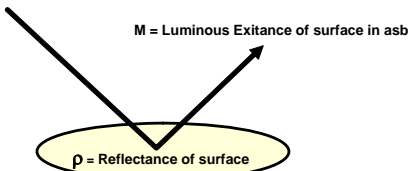


Figure 11.11 –Luminous Exitance

E = Illuminance on surface in lx

M = Luminous Exitance of surface in asb



$$M = E \cdot \rho \text{ Apostilbs, asb}$$

Figure 11.12 –Luminous Exitance

### 11.4 Average illuminance

The approximate average illuminance in a room can be calculated simply if it is assumed that the light flux from the light sources is evenly distributed over the surfaces of the room. Although this is an over simplification of what happens in most real lighting installations, it allows us to start to get a feeling for how the room characteristics affect the average illuminances in rooms. Also, for many circumstances it will provide an answer which is sufficiently close for the designer to check the feasibility of a design.

Consider the situation shown diagrammatically in Figure 11.13. A light source evenly illuminates the surfaces of the room and the average illuminance on the surfaces of the room is given by,

$$E_{average} = \frac{\Phi_{source}}{A_T (1 - \rho_{av})} \text{ lx}$$

where:

- $A_T$  = total surface area of room in  $m^2$ ,
- $E_{average}$  = average illuminance in lux over the surfaces of the room,
- $\Phi_{sources}$  = light flux in lumens introduced into room from lights
- $\rho_{av}$  = average reflectance of room surfaces.

#### Average reflectance

The average reflectance of the surfaces in the room used in the above formula is the area weighted average reflectance,

$$\rho_{av} = \frac{\rho_1 A_1 + \rho_2 A_2 + \rho_3 A_3 + \rho_4 A_4}{A_1 + A_2 + A_3 + A_4}$$

where:

- $\rho_{av}$  = average reflectance of room surfaces,
- $\rho_n$  = reflectance of surface n,
- $A_n$  = area of surface n.

#### Derivation of formula for $E_{AV}$

The equation for the average illuminance is found by summing the direct and the reflected light

Total Light flux on surfaces = Direct light from source + Reflected light

$$E_{AV} A_T = \Phi_S + E_{AV} A_T \rho_{AV}$$

re-arranging,

$$E_{AV} (1 - \rho_{AV}) = \frac{\Phi_S}{A_T}, \text{ which gives } E_{AV} = \frac{\Phi_S}{A_T (1 - \rho_{AV})} \text{ lx}$$

- Where:  $E_{AV}$  Average illuminance over all room surfaces,
- $A_T$  Total surface area of room,

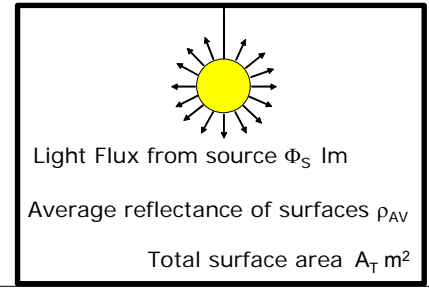


Figure 11.13 – Light in a room

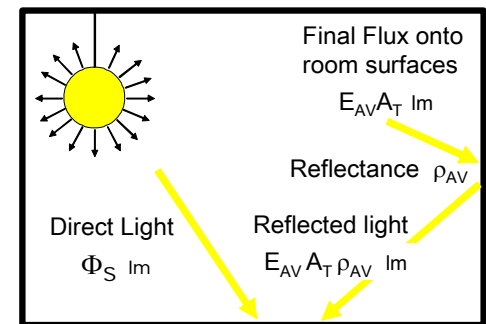


Figure 11.13A – Light in a room

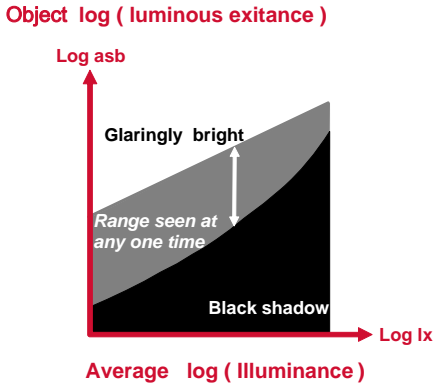


Figure 11.14 – Range of vision

## 11.5 luminous exitance as stimulus of vision

Luminous flux is a measure of the radiant power of a light source corrected to take into account the sensitivity of the receptors in the eye to different wavelengths of radiation.

Illuminance is a measure of the concentration of luminous flux per square metre incident upon a surface and the luminous exitance of a surface is the concentration of light flux leaving a surface. Our eyes intercept the light leaving a surface and therefore the luminous exitance of a surface may be considered to be the stimulus of vision. The higher the luminous exitance of a surface the more luminous it will appear to be.

However, it has been stated earlier that the subjective effect of an impingement is not linearly linked with the level of stimulus and that in general, the subjective effect depended upon the logarithm of a stimulus. When we consider vision, the subjective effect is the brightness of a surface and the stimulus will be the luminous exitance of the surface.

Therefore,

$$\log (\text{Brightness}) = k \times \log (M) - (\text{Luminous Exitance}).$$

Here k is an arbitrary constant that will change depending on the conditions under which the illuminated surface is viewed.

The exact relationship between brightness and stimulus is very complex, but the above generalised relationship indicates that if we wish to relate a subjective effect to light level, then it is better shown on a logarithmic scale than a linear scale.

Thus in Figure 11.14 which shows the visual range between black and glaringly bright at different ambient levels of light, then the adoption of a logarithmic is sensible.

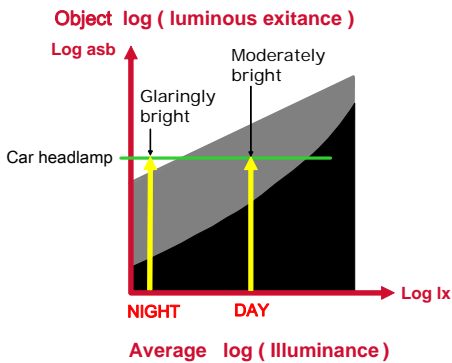


Figure 11.15– car headlamp

An application of Figure 11.14 is shown in Figure 11.15. The green line indicates the luminous exitance of a car headlamp which is constant over time. At night the ambient light level is very low and because of this the eye is adapted to low levels of light and the headlamp appears glaringly bright. However, during the day the eye is adapted to much higher levels of light and therefore the car headlamp appears to be only moderately bright.

Lighting condition	Illuminance in lx
Bright sunlight	100,000
Bright cloudy day in Summer	30,000
Cloudy day in Winter	5,000
Stop play in cricket match	1,000
Moderately lit desk	300
Full moon	2
Starlight	0.1
Threshold of Vision	0.01

Figure 11.16 Natural illuminances

## 11.6 Illuminances of Natural light

The actual range of illuminances over which the eye is capable of seeing is really vast and is shown in Figure 11.16. The eye is not capable of seeing over the whole range at once, but will adapt to different ambient levels of light and see exitances that range from glaringly bright to pitch black as indicated in Figure 11.14.

## 11.7 Choosing Indoor Illuminances

### 11.7.1 Illuminances to perform tasks

Figure 11.16 shows that the eye is used to illuminances outdoors that are well above 10,000 lx. However, because our eyes adapt to the ambient level of light we do not need anything like this illuminance indoors.

When choosing an illuminance that is appropriate indoors, then the first factor that needs to be considered is how well we can perform the visual tasks expected of us. Some tasks are visually simple and do not require a lot of light for them to be done easily. Other more difficult tasks may require a considerable illuminance for them to be performed satisfactorily. Table 1 below gives the illuminances that are suggested by CIBSE for different types of task.

<b>Casual seeing with no need to see detail</b>	<b>50 lx</b>
<b>Occasional use and correct perceptions</b>	<b>100 lx</b>
<b>Long occupation and some detail seen</b>	<b>200 lx</b>
<b>Long occupation and easy tasks</b>	<b>300 lx</b>
<b>Moderately difficult tasks</b>	<b>500 lx</b>
<b>Difficult visual tasks</b>	<b>750 lx</b>
<b>Very difficult visual tasks, colour clear</b>	<b>1000 lx</b>
<b>Extremely difficult visual tasks</b>	<b>&gt;1500 lx</b>

Table 1 - Schedule of illuminances for different difficulty tasks

Figure 11.17 shows how different circumstances might influence the choice of illuminance e.g. if the consequences of errors is significant then there is good reason to increase the illuminance for the task.

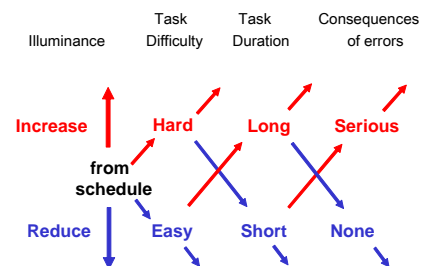


Figure 11.17– Modifying factors

### 11.7.2 Other influences on choice of illuminance

Other considerations that might affect the choice of illuminance in a room are shown in Figure 11.18.

If daylight and electric light are to be used together then it is necessary to ensure that there is a balance between the two sources of light. Excessive amounts of one will overwhelm the other and make it appear to be rather dull.

It may be that we deliberately introduce a sequence of illuminances in a series of spaces so that this either draws us on into ever brighter spaces or perhaps prepares us for a reduced light level in a later room, as might happen in a museum exhibition space. In a gallery we may deliberately reduce the light level so that paintings are exposed to only a limited amount of light and preserved for future generations.

We may deliberately increase the light level where people are unable to see out of a window or where plants require a minimum exposure to light in order to grow successfully.

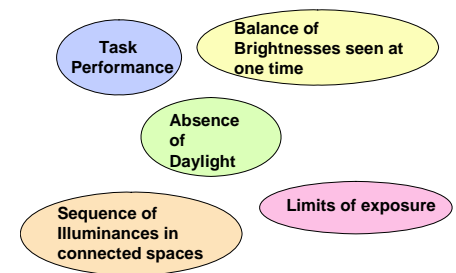


Figure 11.18– Additional factors

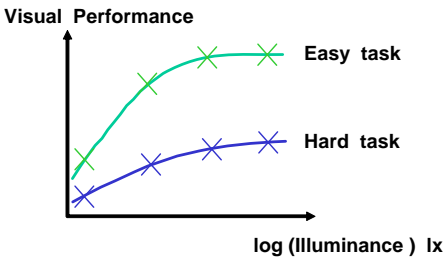


Figure 11.19 – Visual Performance

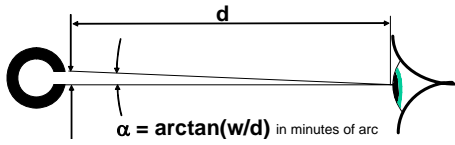
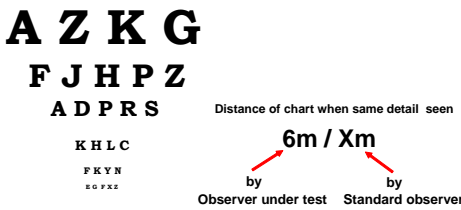


Figure 11.20 – Visual Acuity



**Snellen Chart**

Figure 11.21 – Clinical Visual Acuity

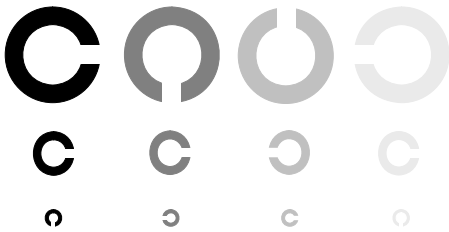


Figure 11.22 – Contrast of Landolt Rings

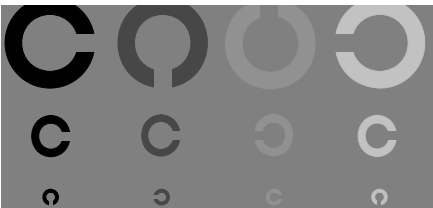
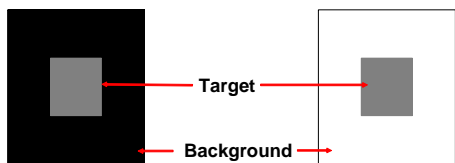


Figure 11.23 – Contrast of Rings



$$C = \frac{M_{Background} - M_{Target}}{M_{Background}}$$

Figure 11.24 – Defining Contrast

## 11.8 Visual Performance

The graph shown in Figure 11.19 shows how higher illuminances improve the performance of visual tasks. There are three important characteristics of performance that are shown by this Figure:

- For easy tasks, performance reaches a plateau and increasing illuminances further does not improve visual performance,
- For difficult tasks, people can improve their visual performance as the illuminance is increased and this continues up until very high illuminances,
- However, although people can improve their performance of difficult tasks up to very high illuminances, they are never able to perform them as well as simple tasks.

An important conclusion from these characteristics of performance, is that where there is a difficult task to perform, then it is best to first consider whether or not it is possible to make a task easier. For a child who has difficulty seeing a blackboard, it is simpler to move that child nearer the blackboard than to increase the illuminance. Similarly, when you try to remove a splinter from a finger, then it might be easier if you use a magnifying glass to see what you are doing.

### 11.8.1 Task difficulty

There are two primary factors that determine the difficulty of a task;

- The size of the critical detail,

The angle subtended at the eye by the critical detail will define its size as is shown in Figure 11.20. Clearly the greater the size of the detail the easier it is to see. The minimum size of discernable detail in minutes of arc is sometimes used as a measure of visual acuity.

Figure 11.21 shows the ‘Snellen Chart’ that you will be familiar with as the method opticians use to determine ‘Clinical Visual Acuity’

- The contrast between the detail and its background.

That we are able to see any detail at all depends upon there being contrast between a task and its background. Figure 11.22 and Figure 11.23 show a series of ‘Landolt Rings’ of different size and of different contrast. Contrast may be quantified as indicated in Figure 11.24,

$$Contrast = \frac{M_{Background} - M_{task}}{M_{Background}}$$

Thus a snowball lying in the snow is difficult to see because there is little difference between the reflectance of the snowball and the ground i.e. contrast = 0. Whereas black print on white paper has a contrast of 1 and is easy to see.

## 11.9 Lightness constancy

Perceptual constancies have already been introduced. They enable us to see the world about us in terms of unchanging physical characteristics. In the visual world one of the most important constancies is that of Lightness. At the light levels in which we are interested, the consequence of Lightness Constancy is that we see surfaces broadly in terms of;

- a) their reflectance,
- b) the illuminance lighting them.

Thus in the example shown in Figure 11.25, the coal appears black under moonlight and also black under sunlight and so its 'lightness' appears to be constant. However we are able to see that the coal under sunlight has a far higher luminous exitance than white paper lit by moonlight.

The two principal physiological processes that help us to see surfaces in this way are;

- a) Lateral inhibition

This is the process by which the sensitivity of the photoreceptors in the retina of the eye are affected by the degree to which adjacent receptors are stimulated.

The optical effects of this process can be seen in Figure 11.26 where the apparent lightness of the central spots can be observed to depend upon the lightness of the surrounding rectangle.

Additionally, the 'Mach band' effect can be seen in the way the apparent lightness of the edges of the rectangles change.

- b) Adaption

This is the process where the sensitivity of the receptors change with the ambient level of light. As the light level reduces so the sensitivity of the receptors in the eye increases. The sensitivity of the eye can be measured by finding the minimum luminous exitance that the eye can detect. This minimum level of luminous exitance is called the Threshold.

Figure 11.27 shows how the threshold get lower as a person spends longer in the dark. There are two parts to the curve, and before microscopy had identified the two types of retinal receptors, this curve was the major evidence for there being two different types of receptor, one responsible for Photopic and the other for Scotopic vision. Figure 11.28 shows a section through the retina identifying the two types of receptor.

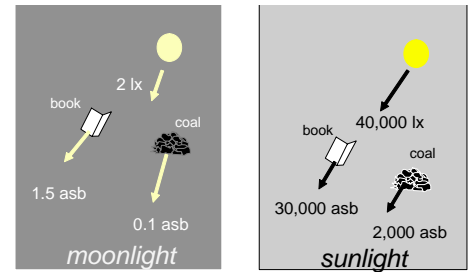


Figure 11.25 – Lightness Constancy

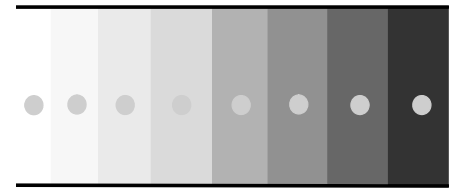


Figure 11.26 – Lateral Inhibition

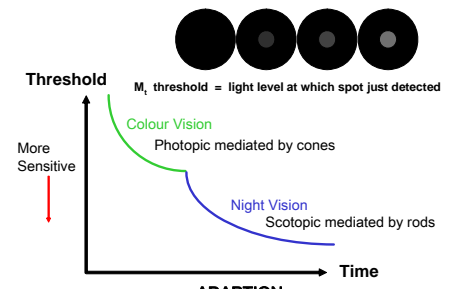


Figure 11.27 – Adaption

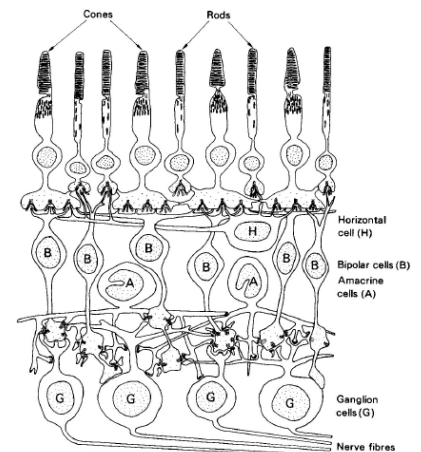
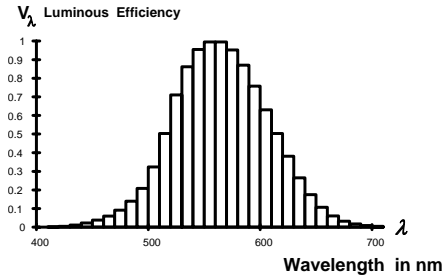


Figure 28 – Retina



## 11.10 Colour Vision

The sensitivity of the cones to different wavelengths of radiation is given by the  $V_\lambda$  curve, the Luminous efficiency of radiation which is shown again in Figure 11.29. Photopic vision allows us to discriminate colour and this is possible because there are three types of cone receptor. Figure 11.30 shows the sensitivity curves for each of these receptors, one sensitive to the short wavelengths, one sensitive to the middle range of wavelengths and the other sensitive to the long wavelengths.

It is the different degree to which each of these receptors is stimulated that gives rise to colour sensation. For instance, a light that stimulates principally the long wave receptor will be seen as red, Light that mostly stimulates the short wavelength receptor will be seen as blue.

This led Maxwell to construct his colour triangle shown in Figure 11.31 which allowed the specification of any colour by finding the proportion of red, green and blue light that was needed to match the colour.

Rather than use a colour triangle, we today specify colour by their 'Chromaticity co-ordinates'. This is similar to the colour triangle, except that a right angled triangle is used and instead of real colours, Red, Green and Blue, the chromaticity co-ordinates use Primary colours X, Y and Z. A chromaticity Chart is shown in Figure 11.32. On this chart are plotted the real colours Red, Green and Blue use in Maxwell's triangle, also the locus of the colours produced by a Planckian radiator and the locus of the spectral colours seen in the rainbow that result from individual wavelengths of light.

Figure 11.33 shows the colours associated with different parts of the Chromaticity diagram.

The advantage of the Chromaticity Diagram is that it can be used to accurately specify a colour, and also provide a methodology to automatically measure colour with an optical instrument without relying upon a human being to make a colour match.

The disadvantage of this method of colour specification is that it means very little to designers who work with colour.

Thus there is a need for other types of colour specification that better describe colour in terms that people can understand and visualise. There are a number of different colour systems based upon the experience of colour and each have their advantages and disadvantages:

- Ostwald,
- Swedish Colour system – based on Ostwald system,
- ICI colour dimensions based on Swedish Colour System,
- Munsell,
- British Standard – loosely based on Munsell system.

Figure 11.29 – Luminous Efficiency

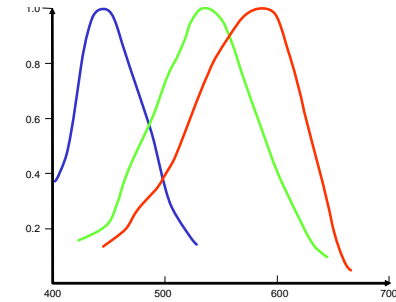


Figure 11.30 – Colour receptors

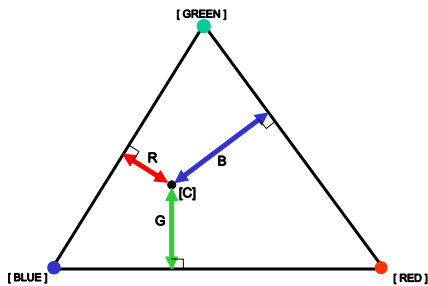


Figure 11.31 – Maxwell triangle

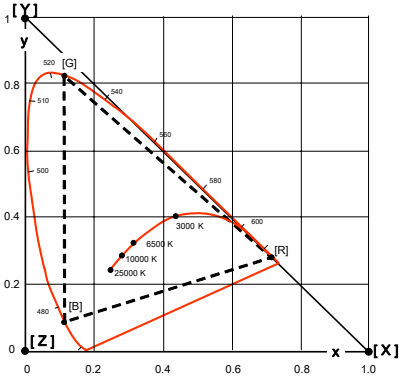


Figure 11.32 – Chromaticity

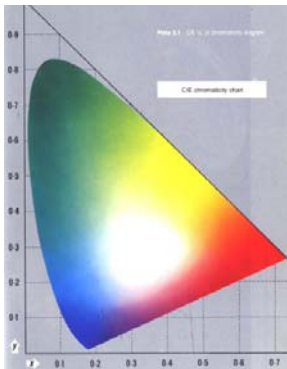


Figure 11.33 – Chromaticity

### 11.10.1 Munsell Colour System

The reason for considering the Munsell system in some detail is that it is the system that is most easily used by lighting designers.

This is because within the colour specification the Lightness of a colour is one of the colour attributes used. Because of this the reflectance of any colour can be derived if the Munsell specification is known. Also, in any system based on how we experience colour it is important that the intervals in the colour scale are equal subjective intervals.

There are three attributes of colour in the Munsell system, each of which can be seen in Figure 11.34;

#### Hue

This is specified by the position on the Hue circle. This starts with Red, R5 and moves step by step through orange 5RY, to Yellow, 5Y then to 5GY and on to Green, 5G and then on through a continuous change back to Red. Intermediate Hues are available.

#### Value

This is the position on the lightness scale. The scale goes from a minimum Value of 0 that represents black with a reflectance of 0% and maximum Value of 9.9 that represent 100% reflectance. The Value scale is made up of equal subjective steps, so that a grey with a Value of 5 appears to be a grey that is subjectively equidistant from black and white.

The reflectance  $\rho$  of a surface can be found approximately by applying the formula,

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

Where V is the Munsell Value.

#### Chroma

This specifies the strength of the Hue in the colour. An achromatic grey has zero Chroma, but as Hue is introduced into the colour then the Chroma is increased. This can be continued until the colour appears to be entirely composed of the pure Hue with no weakening of the Hue at all.

Figure 11.35 shows the way in which the Value and Chroma change for a single Hue, 5R.

Figure 11.36 shows the Munsell colour solid. From this a number of observations can be made. High Chroma Blues inevitably have a low Value and hence a low reflectance. Low Value yellows inevitably have a low Chroma, thus low reflectance deep yellows are not possible.

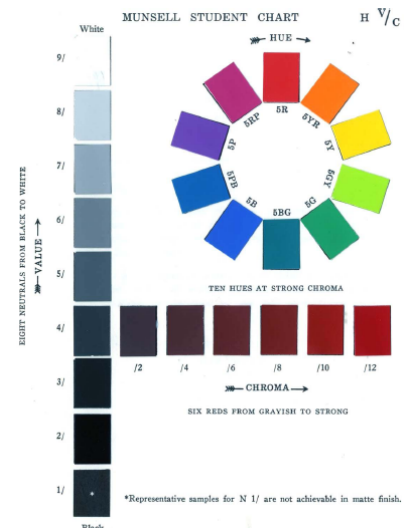


Figure 11.34 – Munsell Colour

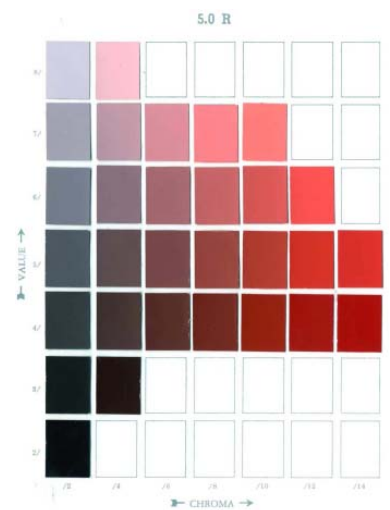


Figure 11.35 – Chroma vs Value



Figure 11.36 – Munsell Colour Solid