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Name of the Commentator/ Organization: ______________________________________

Part 2/ Section 1 General Principles		
Clause No. with Para No. or Table No. or Figure No. commented (as applicable)	**Comments / Modified Wordings**	**Justification of Proposed Change**
Part 2/Section 2 Vision		
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Part 2/ Section 3 Colour		
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BUREAU OF INDIAN STANDARDS

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Draft NATIONAL LIGHTING CODE OF INDIA

PART 2 PHYSICS OF LIGHT

Section 1 General Principles

[First Revision of SP 72 (Part 2/Section 1)]

Illumination Engineering and Luminaries Sectional Committee, ETD 49	**Last Date for Comments: 20-04-2024**

Section 1 General Principles

FOREWORD

The paradoxical nature of light makes it both elusive and indispensable. While light itself is not visible, it enables vision by illuminating the world around us. Its intangible nature—unable to be held like a physical object—doesn't diminish its significance in our lives.

Light indeed exhibits various fascinating behaviours. It can be bent or refracted when passing through different mediums, transmitted across vast distances, and even dispersed to reveal its diverse colours. Despite its intangibility, its impact is undeniable.

Describing light as an electromagnetic wave aligns with its fundamental nature. Light comprises electric and magnetic fields oscillating perpendicular to each other, propagating through space. Understanding light as energy is crucial; it carries energy and drives numerous processes vital for life and technology.

The study of light has seen diverse models and theories throughout the history of physics. From the particle-like behaviour proposed by Isaac Newton to the wave-like nature supported by Thomas Young's double-slit experiment, to the modern understanding of light as both particles (photons) and waves (electromagnetic radiation) in quantum physics—each model contributes to comprehending the complex nature of light.

Physics, often regarded as the foundational science, indeed holds a central position in unrevealing the mysteries of light and shaping lighting technology. Its diverse models and theories continue to pave the way for innovations in lighting, optics, telecommunications, and various other fields reliant on understanding and harnessing the properties of light.

The multifaceted nature of light—from its duality as waves and particles to its role as energy—continues to captivate scientists and engineers, driving advancements and innovations that profoundly impact our world.

1. SCOPE

This chapter delves into various lighting models and key characteristics of light, such as spectral power distribution, which hold significant importance for lighting professionals.

2. TERMINOLOGY

The terminology referred in this chapter already covered in the Chapter -lighting vocabulary

2.1 Propagation of light - Physical model

In the 1670's Christian Huygens proposed a mechanism for the propagation of light, known as Huygens' Principle. According to Huygens Principle, all points on a wavefront act as sources of new waves, and the envelope of these secondary waves constitutes the new wavefront as shown in Fig. 1.

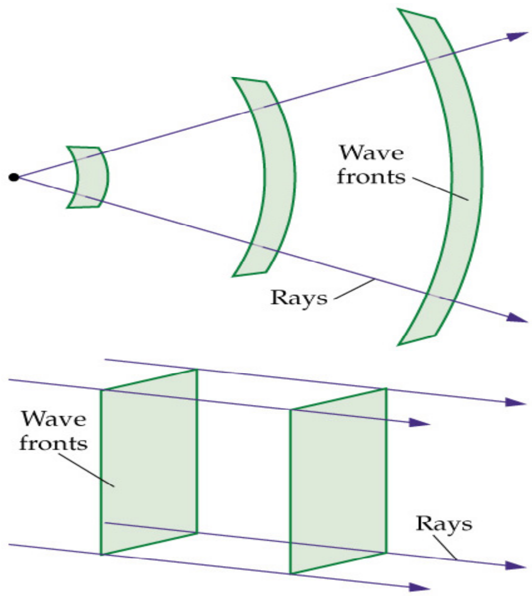

Fig. 1 Wave Fronts

In 1704 Isaac Newton published light theory discarding Greek thoughts that vision was the result of an `imago' dissociation from the object being viewed that enters the eye and the conviction that eye transmitted `visual rays', which scanned object being viewed. Newton regarded light consisting of endless stream of high-speed particles.

This theory could explain the following phenomenon:

a) Rectilinear propagation of light

b) Reflection of light
c) Refraction of light

However, this theory could not explain the phenomena of diffraction, interference, and polarization of light.

In 1873, Maxwell published his opinion that light is electromagnetic waves and that light waves are carried by an electromagnetic field. An electromagnetic wave is a transverse wave consisting of mutually perpendicular oscillating electric and magnetic fields (Fig 2). Electromagnetic waves are produced by an accelerating charge and are self-propagating waves that can travel through a vacuum or a material medium. Subsequently, Heinrich Hertz experimentally generated electromagnetic waves supporting Maxwell's theory.

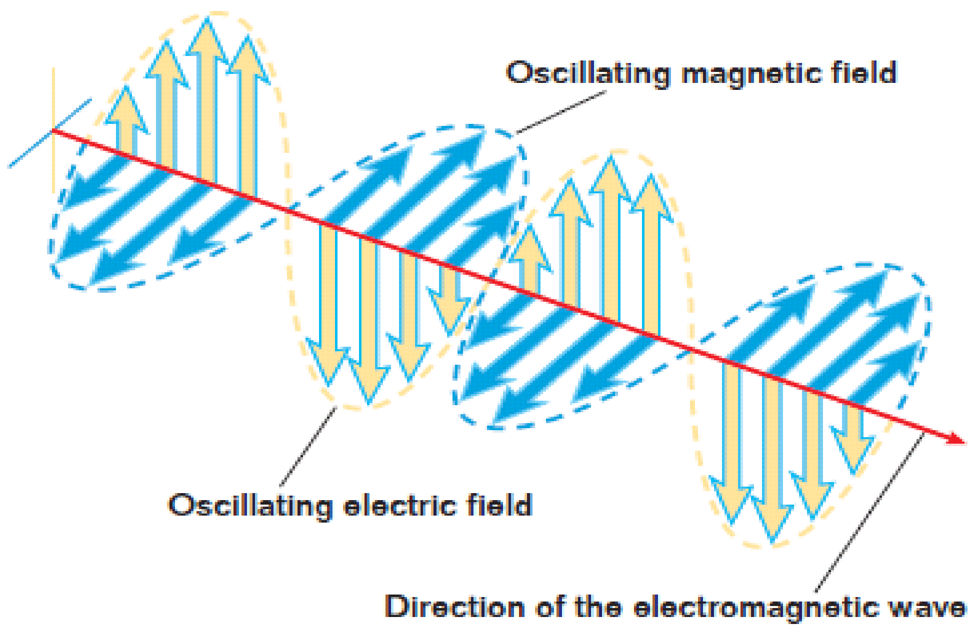

Fig. 2 An Electromagnetic Wave

All electromagnetic waves travel at the speed of light. Electromagnetic waves are distinguished from each other by their differences in wavelengths and frequencie. Wavelength is inversely related to frequency.

$$c = \nu \lambda$$

where c is the speed of light = 3.0 x 10 8 m/s in a vacuum
= 300,000 km/s

= 186,000 miles/s

This theory which deals with light as electromagnetic wave, namely, wave optics, successfully explains the optical phenomena of diffraction, interference, and polarization of light. However, is unable to explain phenomena involving the interaction of light and matter, such as the photoelectric effect.

In 1905, Einstein explained the photoelectric effect using the concept of photons. Einstein proposed that a beam of light is not a wave, but rather a collection of photons, each photon has a fixed amount of energy, which only depends on the frequency of light, thus, the quantum theory of light emerged. Quantum optics describes the wave–particle duality of light well.

2.2 Theories of Light: An Overview

Theories of light can currently be divided into three main branches: geometrical optics, wave optics, and quantum optics.

2.2.1 *Geometrical Optics*

Geometrical optics deals with light as rays that travel in straight lines in a homogeneous medium. In geometrical optics, the laws of reflection and refraction can provide very good explanations for many optical phenomena, such as specular reflection, the dispersion of light and many others. Furthermore, with the help of these two laws and the rectilinear propagation of light rays in homogeneous media, the path of a light ray can be traced throughout an optical system, revealing the main characteristics of that system. In addition, by introducing the diffraction phenomenon in terms of the laws of reflection and refraction, the diffraction of light by edges, corners, or vertices of boundary surfaces can be predicted using geometrical optics. Usually, geometrical optics can give reasonable explanations for most optical phenomena. However, because geometrical optics is determined from the approximation of wave optics as the wavelength of light approaches zero ($l \rightarrow 0$), the wave nature of light is neglected. Therefore, it is impossible to explain the physical reasons for the diffraction and interference of light using geometrical optics.

Ray optics model explain through the ray tracing principle for light distribution or redistribution of light which part and parcel for our luminaire optic design.

2.2.2 *Wave Optics*

Wave optics, which deals with light as waves, studies optical phenomena involved in the wave nature of light, such as diffraction, interference, and polarization. As light is a form of electromagnetic wave, all wave characteristics of light can be deduced from Maxwell's equations. It is highly convenient to describe the propagation of light in free space with the Rayleigh–Sommerfeld diffraction formula. In wave optics, the resolution of an optical imaging system is ultimately limited by the diffraction of light, which is different from the case of geometrical optics. Wave optics not only explains optical phenomena such as the diffraction and interference of light, but is also commonly used in optical system designs and optical metrology. However, as wave optics ignores the particle aspect of light, it cannot be used in scenarios involving in the interaction between light and matter, such as the photoelectric effect.

In illuminations technology, photometry and measurement still the age old lighting model is used.

2.2.3 *Quantum Optics*

Optical phenomena concerning the interaction between light and matter, such as characteristic emission, the photoelectric effect, etc., is in the realm of quantum optics. The concept of the photon, proposed by Einstein in 1905, is fundamental to quantum optics, and the interaction between light and matter can be considered as interactions between photons and atoms of matter. The invention of the laser is the most famous application of quantum optics. This new type of optical source provided an important experimental tool for the development of modern optics. Furthermore, commonly used photoelectric detectors, such as charge-coupled devices (CCDs), photodiodes, and photomultiplier tubes are all successful applications of quantum optics. Quantum optics describes the wave–particle duality of light well. So far, it is the most accurate theory of optics.

This optical model explains the light generation & light source spectral distribution for all kind of product be it incandescent to OLED .

2.3 Reflection of Light

Reflection of light when the waves encounter a surface or other boundary that does not absorb the energy of the radiation and bounces the waves away from the surface. The incoming light wave is referred to as an incident wave and the wave that is bounced away from the surface is called the reflected wave. The simplest example of visible light reflection is the glass-like surface of a smooth pool of water, where the light is reflected in an orderly manner to produce a clear image of the scenery surrounding the pool (Fig. 3).

Percentage of reflection factor of the materials and ray tracing is very important for luminaire optical design.

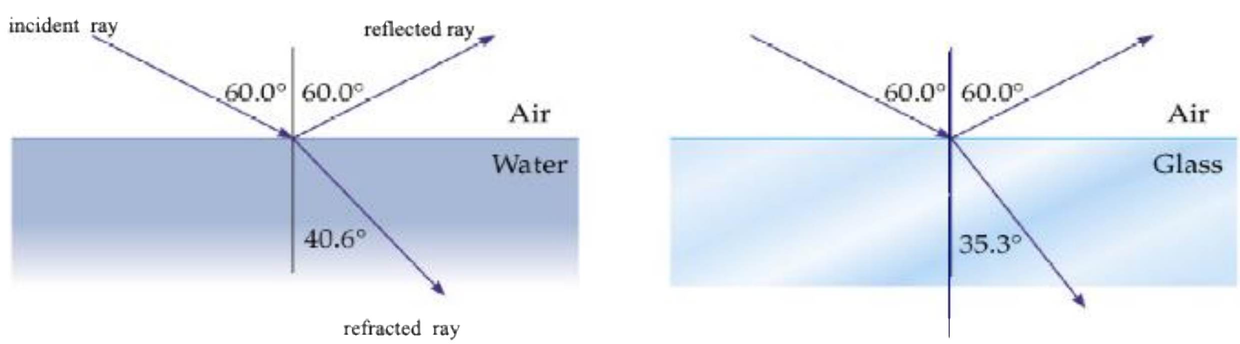

Fig. 3 Reflection of Light

If the surface of which the light is reflected is smooth, then the light undergoes specular reflection (parallel rays will all be reflected in the same directions). If, on the other hand, the surface is rough, then the light will undergo diffuse reflection (parallel rays will be reflected in a variety of directions)

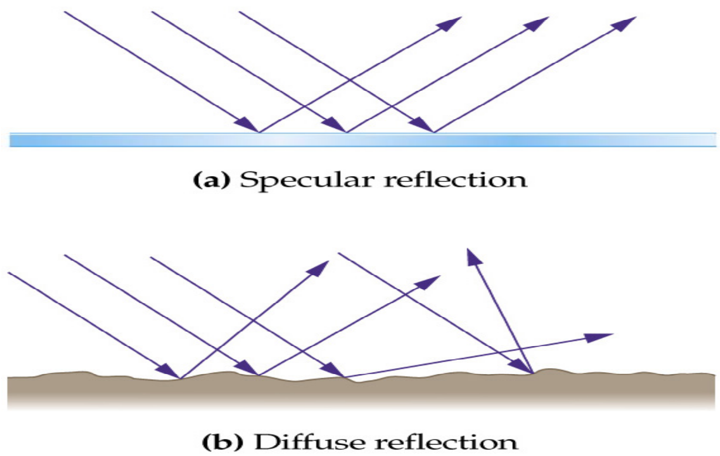

Fig. 4 (A) Specular Reflection, (B) Diffuse Reflection

2.4 Refraction of light

When light propagates in a transparent material medium, its speed is in general less than the speed in vacuum c. An interesting consequence of this is that a light ray will change direction when passing from one medium to another. Since the light ray appears to be "broken", the phenomenon is known as refraction.

The speed of light is different in different materials. The index of refraction, *n*, of a material is written as, the ratio of the speed of light in vacuum to the speed of light in the material

$$n = c/v$$

2.5 Snell's Law

In general, when light enters a new material its direction will change. The angle of refraction θ_2 is related to the angle of incidence θ_1 by Snell's Law. The angles θ_1 and θ_2 are measured relative to the line normal to the surface between the two materials as shown in Figure 5.

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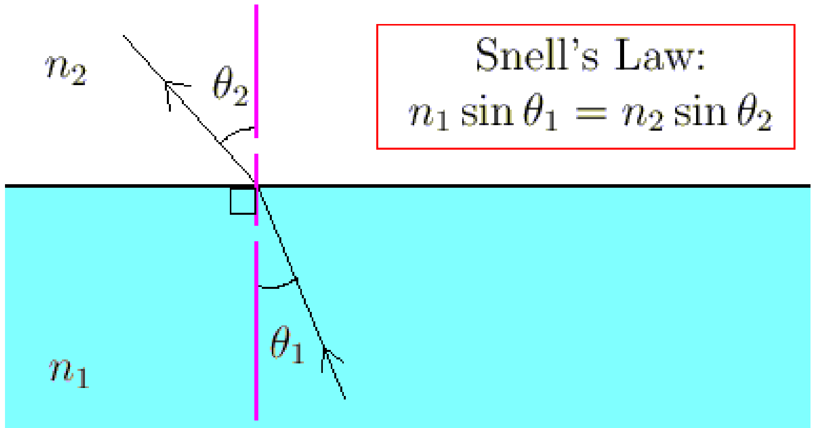


Fig. 5 Description of Snell's Law

2.6 Factors in Luminaire Optic Design & Its Efficacy

Transmission factor & reflection factor of the materials are very important in optical design as right material & its optic design decide the efficacy of the lighting system.

Over its life there may be deuteriation of these factors that need to be factored in for lighting design calculation.

As a guide line user / specifier should make a note of these factors like glass, plastic, aluminium etc used for optical design.

2.7 Total Internal Reflection

One important consequence of Snell's law of refraction is the phenomenon of total internal reflection. If light is propagating from a dense to a less dense medium, i.e. $n_1 > n_2$, there is an angle, called the critical angle θ_c, at which all the light is reflected and none is transmitted. This process is known as total internal reflection. The critical angle occurs when θ_2= 90 degrees and is given as

$$\sin \theta_c = \frac{n_2}{n_1}$$

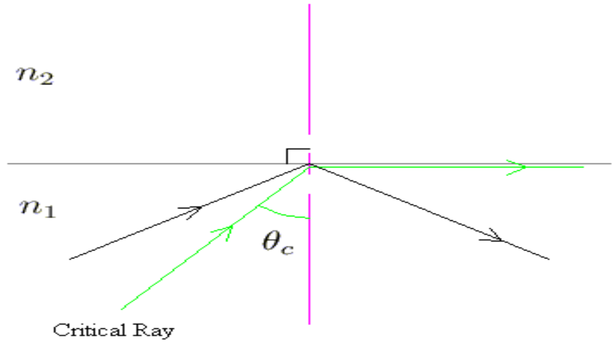


Fig. 6 Total Internal Reflection

For larger angles of incidence, the incident ray does not cross the interface, but is reflected back instead.

2.8 Dispersion

When a polychromatic light, passes through a transparent medium like a glass prism it splits into its component colours, this phenomenon is called dispersion of light, as given in Fig 7. When a wave is refracted into a dielectric medium whose refractive index varies with wavelength then the angle of refraction also varies with wavelength. If the incident wave is not monochromatic, but is, instead, composed of a mixture of waves of different wavelengths, then each component wave is refracted through a different angle.

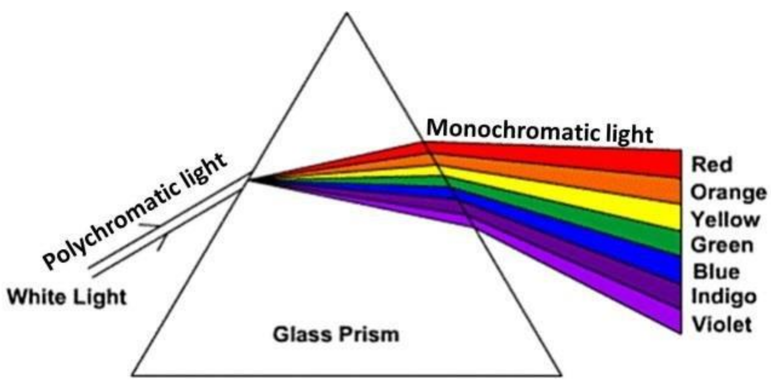


Fig. 7 Dispersion of Light by the Glass Prism

2.9 Polarization of Light

Light is a transverse electromagnetic wave and is generally unpolarized. The polarization of light can be described by specifying the orientation of the electric field at a point in the space. Light in the form of a plane wave in space is said to be linearly polarized. If light is composed of two plane waves of equal amplitude and 90° phase difference, then the light is said to be circularly polarized.

Elliptically polarized light consists of two perpendicular waves of unequal amplitude which differ in phase by 90° as shown in the Fig 8.

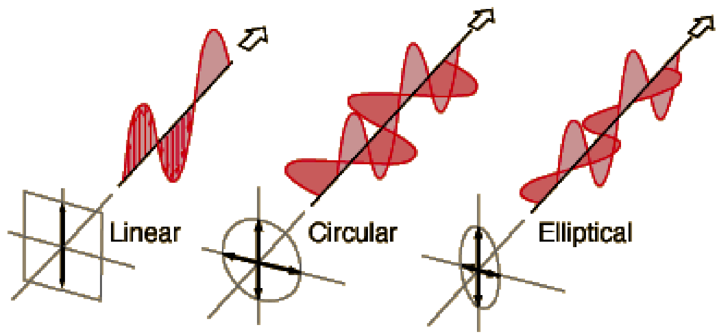


Fig. 8 Polarization of Light

The human eye does not have the ability to distinguish between randomly oriented and polarized light. The plane-polarized light can be detected through intensity and color effect.

2.10 Interference

The phenomenon of interference is of great importance. Interference occurs when two or more light beams are superimposed. If two waves are of the same frequency and phase, they vibrate at the same rate and are maximum at the same time, the wave amplitudes are added and produce constructive interference. Sametime, if the two waves are out of phase by half period, one is minimum when the other is maximum, the result is destructive interference, as given in Fig 9.

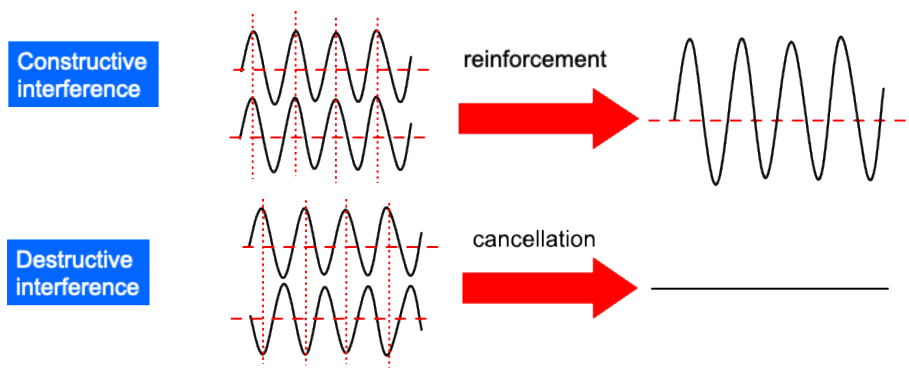


Fig. 9 Interference of Light

Most of us observe some type of optical interference almost every day. One of the best examples of interference is demonstrated by the light reflected from a film of oil floating on water.

2.11 Photoelectric Effect

In 1905, Einstein explained the photoelectric effect using the concept of photons. According to Einstein's theory, light is a collection of photons. Each photon has a fixed amount of energy, which only depends on the frequency of light. When photons fall on the surface of a metal, the energy of a photon is split into two parts. One part is used for releasing an electron from the metal, and the other part transforms into the kinetic energy of the released electron. According to the law of conservation of energy, the process of energy conversion in the photo electric effect can be expressed as

$$E = h\,n = 1/2\ m\ v^2 + w$$

where h is Planck's constant, n is the frequency of light, m is the mass of the electron, v is the speed of the photoelectron, and w is the work function of the metal, which represents the smallest energy needed for electrons to escape from the constraints of the metal. According to above equation, both the release of the photoelectron from the metal by light and the speed of the photoelectron are determined by the frequency of the incoming light, irrespective of the intensity of light incident on the metal.

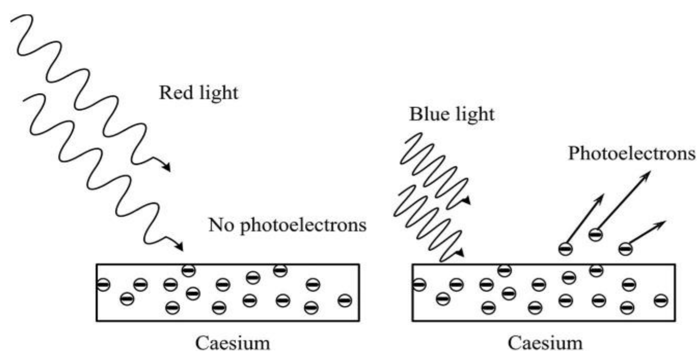


Fig. 10 Diagram of the Photoelectric Effect.

The concept of light as photons successfully explains the photoelectric effect and is confirmed by experimental results.

2.12 Light Sources

The generation of light from light sources can be roughly explained by the classical electromagnetic radiation theory and can be explained very precisely by the quantum theory of light.

2.13 Explanation by Classical Electromagnetic Wave Theory

Matter is made of atoms, and each atom is composed of a nucleus and some electrons around the nucleus. When an amount of energy is continuously infused into matter, the temperature of the matter will gradually increase, and electron movement around nuclei will be gradually accelerated. However, according to the law of conservation of energy, the temperature of matter cannot increase infinitely. Hence the accelerated electron will radiate energy in the form of electromagnetic waves. The sun, having a high temperature due to the thermonuclear reactions occurring in it, radiates electromagnetic waves across most of the electromagnetic spectrum, including gama rays, to radio waves as given in the Fig. 11.

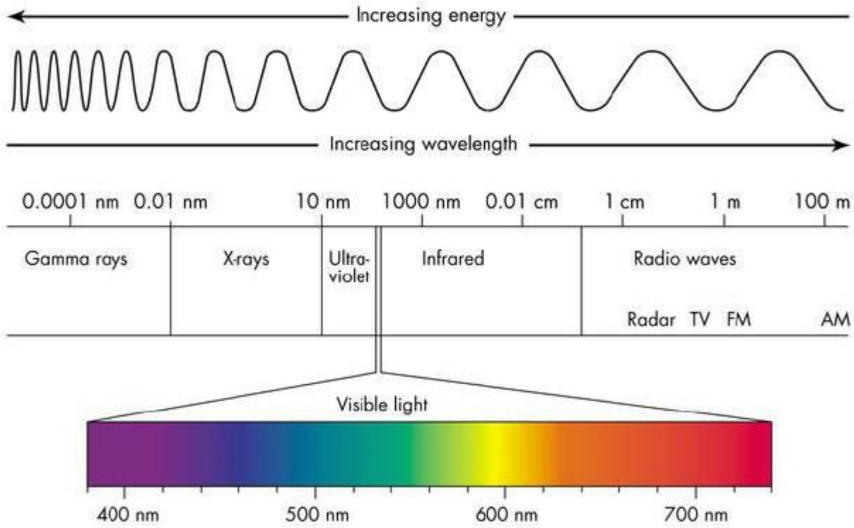


Fig. 11 Electro Magnetic Spectrum

2.14 Explanation by Quantum Theory

In quantum theory, all matter particles possess the wave–particle duality. In order to understand the formation of energy levels in matter, we will suppose that a particle, e.g., an electron, is trapped inside a potential well, shown as a one-dimensional (1D) well in Fig. 12.

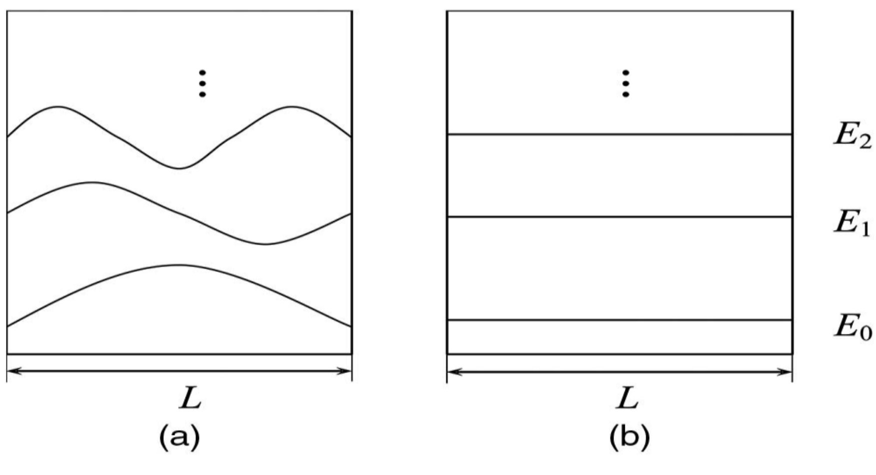


Fig. 12 Diagram of (a) Electron Waves in A 1D Potential Well And (b) The Corresponding Energy Levels

This description delves into the intriguing world of quantum mechanics, specifically focusing on electron waves confined within a potential well. When electron waves encounter two parallel barriers (forming a potential well) separated by a distance L, only standing waves can exist within this space.

Standing waves are formed when the round trip distance between the barriers is an integral multiple of the corresponding wavelengths of the waves. This condition creates a wavelength selector, allowing only specific discrete wavelengths to exist within the well, represented by 2L/m where m is an integer (1, 2, 3, and so forth). Consequently, this leads to the constraint of discrete frequencies and energies for electron waves in this confined region.

The lowest energy level, depicted as E_0 in the provided figure, signifies the ground state. Electrons in the ground state are at their most stable configuration within this potential well. Any energy levels above the ground state are referred to as excited states, where electrons exist temporarily and can transition back to the ground state or to other lower energy levels.

According to Boltzmann distribution, a majority of electrons in matter tend to reside in the state with the lowest energy, i.e., the ground state. However, when external energy is introduced—such as through heating or injecting energy into the system—electrons in the ground state can absorb some of this energy and transition to excited states.

In a two-level system transition, as depicted in Fig. 13(a), electrons in excited states possess higher energy levels but have limited lifetimes. They can rapidly transition back to the ground state or other lower energy levels. During this transition process, energy is emitted in the form of light. The energy (hv) of the radiated light corresponds to the energy gap between the two energy levels. Essentially, the larger the energy gap, the greater the energy of the emitted light, resulting in shorter wavelengths of light.

This phenomenon showcases how electrons in quantum systems can absorb and emit discrete amounts of energy, leading to the emission of light at specific wavelengths corresponding to energy level transitions within the system.

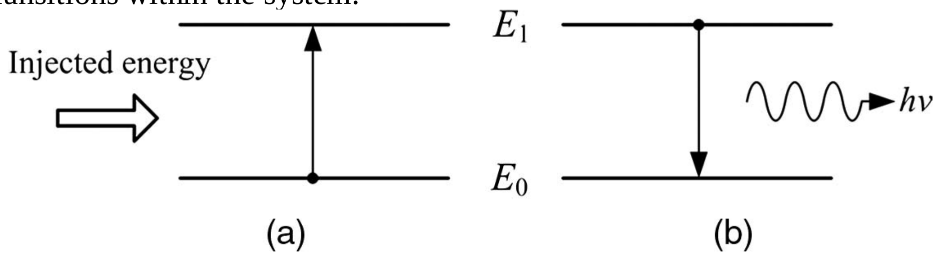


Fig. 13 Diagram of Transitions Between E_0 And E_1 And In A Two-Level System

Furthermore, energy levels and energy gaps between those energy levels for different types of matter are completely different due to the different configurations (or different constraints to electrons) of atoms. This is the reason that each type of matter has its own characteristic absorptions and emissions. For example, wavelengths of light emitted from any type of sodium lamp are all at 589.0 or 589.6 nm. Note that if transitions between states with many different energy gaps occur simultaneously, light in multiple wavelengths or even white light can be produced. In fact, the above just explained the generation of light from incoherent sources.

Incandescence lamp, heat produce light the object (filament for lamps) is heated to a high temperature the atoms within the material become excited by the many interactions between them and energy is radiated in a continuous spectrum as per theory of Max Plank known as black body radiator.

For generation of gas discharge lamps has been explained in earlier of this section.

2.15 Light Emitting Diode (LED)

Light Emitting Diodes, commonly referred to as LED, are one of the most energy efficient light sources available today. LEDs do not contain any filament, consume less power and have a longer life. It is interesting to note that in less than two decades when the first white LED was produced, the efficacy of white LEDs has hit the target of 200 lm/W (under laboratory test condition) surpassing the efficacy of both incandescent and fluorescent lamps.

LED & OLED – Semiconductor normally has very high resistivity but here in this case some doped materials introduced with high negatively charged and high positively charged combination. When charged these carriers of n-type and p type recombine which releases radiation plus some materials like phosphor convert electrical energy to light. So, here there is two process one recombination of n-p current carriers as well excitation of luminescent centres in phosphors.

The LED is a PN-junction diode which emits light when an electric current pass through it in forward direction. In LED, the recombination of charge carrier takes place. The recombination of the charge carrier occurs in the P-type material, and hence P-material is the surface of the LED. For the maximum emission of light, the anode is deposited at the edge of the P-type material. The cathode is made of gold film, and it is usually placed at the bottom of the N-region. This gold layer of cathode helps in reflecting the light to the surface. According to quantum theory, when the energy of electrons decreases from the higher level to lower level, it emits energy in the form of photons The energy of photons is equal to the gap between the valence and the conduction band.

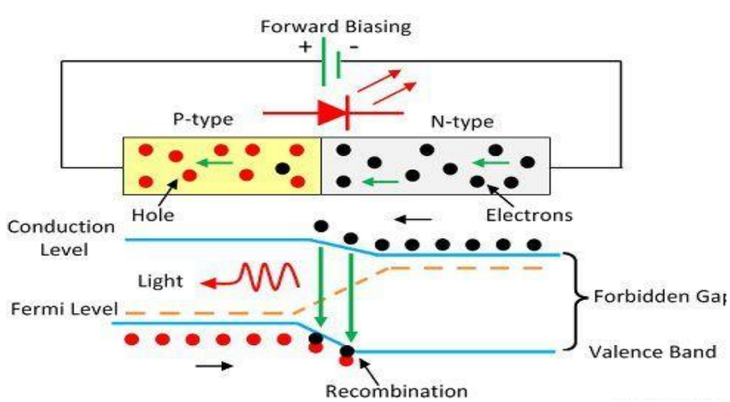


Fig. 14 Working Principle of Light Emitting Diode

2.16 Optical Systems

Optical systems encompass various configurations of optical elements to manipulate light and achieve specific functions. These elements include lenses, mirrors, gratings, detectors, and more. The primary objective of an optical system is to control the propagation of light within it, requiring meticulous design to achieve desired outcomes.

In the realm of light, there are two fundamental types:

a) Ordinary Light: This type of light is emitted naturally or artificially due to energy changes at the atomic or molecular level without external intervention. It includes the light we encounter daily, from sunlight to artificial lighting sources.
b) Laser Light: Laser light differs significantly from ordinary light. It arises when an atom or molecule holds onto its excess energy until it's stimulated to emit that energy in the form of light. Lasers are specifically designed to produce and amplify this stimulated emission of light, resulting in intense and highly focused beams. The term "laser" itself stands for "Light Amplification by the Stimulated Emission of Radiation."

The unique characteristics of laser light have made laser technology integral in various aspects of modern life:

a) Communications: Laser technology plays a crucial role in optical communication systems, enabling high-speed data transmission via fibre optics.

b) Entertainment: Lasers are extensively used in entertainment industries, such as laser light shows in concerts, laser displays in theaters, and more, due to their ability to create vivid and controlled light patterns.

c) Manufacturing: Laser cutting, welding, and engraving are key applications in manufacturing industries, leveraging the precision and intensity of laser beams for various processes.

d) Medicine: In medicine, lasers find application in surgical procedures, diagnostics, treatments like laser therapy, and even in medical imaging technologies.

The controlled and focused nature of laser light, along with its properties like coherence, monochromaticity, and directionality, makes it a versatile and indispensable tool across numerous fields, revolutionizing technology and enabling innovations that have become an integral part of our everyday lives.

2.17 Effect of Temperature - Energy Distribution Over the Wavelengths & BLACK BODY Radiator

The concept of temperature's effect on energy distribution over wavelengths, particularly concerning black body radiation, is fundamental in understanding how different temperatures influence the emitted light and the concept of perfect radiators.

When solid bodies are heated, they emit electromagnetic radiation, and this emission varies with their temperature. This relationship between temperature and emitted light is a fundamental principle. As the temperature of a body increases, the nature and color of the light emitted also change. For instance, a body heated to around 525 degrees Celsius would emit dull-red light. However, as the temperature increases, the emitted color changes sequentially from bright red to orange, yellow, white, and finally to a bluish-white hue.

Every material doesn't emit energy across the entire spectrum up to the theoretical maximum based on its temperature. Only when a body emits energy across the full spectrum according to its temperature, it's termed a perfect radiator and a perfect absorber of radiant energy that falls upon it. At lower temperatures where visible radiation emission doesn't occur, the body appears perfectly black. Hence, the concept of a black body radiator arises.

However, not a physical entity, a black body is an imaginary object whose spectral output is defined by mathematical relationships like Wien's displacement law and the Stefan-Boltzmann law. These laws describe how the spectrum of radiation emitted by a black body varies with temperature. Max Planck's quantum theory further explained this spectral energy distribution, describing it as discrete quanta of energy, which contributed significantly to understanding the black body concept.

In practice, certain objects like incandescent (filament) lamps and the sun closely resemble black body radiators. Even though they aren't perfect black bodies, they serve as essential reference light sources when analyzing the characteristics of other real light sources.

Understanding the black body concept is crucial in explaining color characteristics and spectral power distribution. It's often represented using X-Y coordinates to specify the appearance of light, particularly in color science.

Temperature scales like the Kelvin scale are used to measure these phenomena. Kelvin scale starts at absolute zero (-273°C), where theoretically molecular motion ceases. In lighting, temperatures are expressed in Kelvin (K), starting at absolute zero. For example, our body temperature of 37°C is approximately 310 K on the Kelvin scale.

The color appearance of a black body at different temperatures is represented by the black body locus of the CIE Publication offering insights into how temperature affects the color perception of light emitted from such sources. This aspect is further detailed in the section dedicated to color science in lighting.

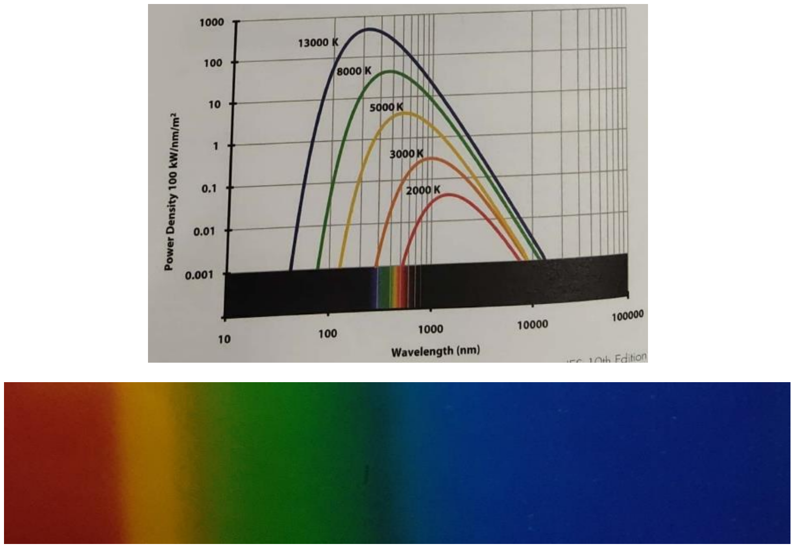


Fig. 15 Spectrum of Black Body Radiator the Continuous Spectrum for Thermal Radiator (Halogen Lamp 3000k)

2.18 Spectral Power Distribution, SPD

Spectral power distribution (SPD) is a fundamental concept in understanding light sources and their emissions across the electromagnetic spectrum. The core principle comes from the quantum theory, which explains how the energy emitted by a light source varies based on the material and its structure.

When discussing thermal radiation, the emitted energy spans a continuous spectrum, showcasing a broad range of wavelengths. However, in the case of luminescent sources like gas discharge or solid-state lighting, the emission isn't continuous but rather distributed across specific regions of the spectrum—such as infrared or ultraviolet, or even both—alongside the visible range.

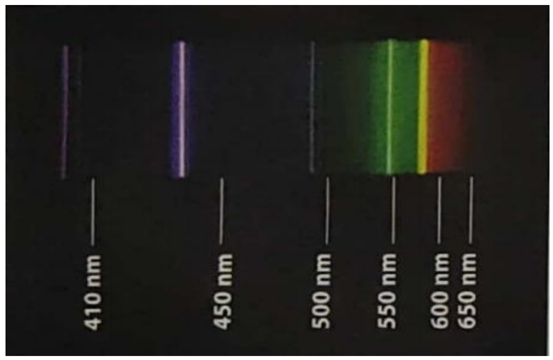
The discovery made by Kirchhoff and Bunsen in the mid-19th century demonstrated that each element emits its characteristic pattern of spectral lines. Niels Bohr and Rutherford's atomic model, later in 1913, provided explanations for the consistent spectral lines observed, marking a significant milestone in understanding atomic structure and spectral emissions.

SPD, as you rightly pointed out, represents the radiant power emitted by a light source across various wavelengths within the visible range (typically 360 to 770 nanometers). This distribution is crucial for lighting professionals, aiding them in various applications, including human-centric lighting design.

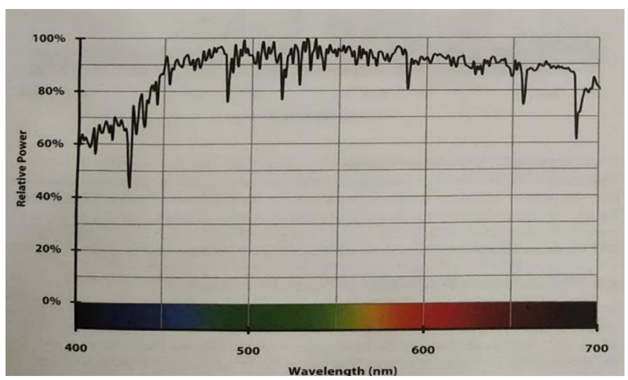
To measure SPD accurately, spectroradiometers are employed. These devices have become essential tools for lighting professionals and auditors, supplementing the traditional luxmeter in evaluating light sources.

Visualizing SPD can occur in two primary ways: one-dimensional chromatic representations and two-dimensional plots. One-dimensional representations involve scans across a wide range of wavelengths, with the relative power emitted at each wavelength depicted by the brightness or intensity of the colors at that specific point. However, this method can be limiting, as accurately representing high radiant power may necessitate brighter colors or wider lines, potentially causing blurring when displaying radiant power across closely-spaced wavelengths.

Understanding SPD aids in selecting appropriate lighting sources for specific applications, considering factors like color rendering, efficiency, and spectral characteristics, which directly impact human perception and well-being in illuminated environments.



One Dimensional Representation of SPD



Two-Dimensional Representation of SPD For Sun

Fig. 16

Two dimensional plots are histograms consisting of bars with hights proportional to radiant power at a wavelength. Colour is often added to bars to help indicate the position in the visible spectrum. for a continuous spectrum, the bar of the histogram merge. Here height of the conveys the information about the amount of radiant power at a wave length height of an individual bar not the brightness what the case of one-dimensional representation. Two dimensional plots are always liner with respect to wavelength, where as one dimensional are scans from spectrometers are presented either linearly or non-linearly with respect to wavelength. If spectrometer uses a prism for example, the spectrum will be represented non-linearly. If it uses grating (Spectroradiometer) , the spectrum will be represented linearly.

Colour is often used in the display of spectral power data. Histograms or continuous plots of radiant power distribution as a function of wavelength often show the prismatic spectrum below the line of the plot i.e optical radiant each wavelength in the visible spectrum is associated with monochromatic colour produced by that wavelengths.

SPD is a very useful & suggestive but one cannot inferred totally the total chromatic effect of the light source by those colours .Additionally, the media used to represent the spectral data in colour like colour printing, video , lcd projection and computer etc. cannot represent true chromatic colour plus colour appearance.
Few spectral power distributions for light sources are as shown in Fig. 17:

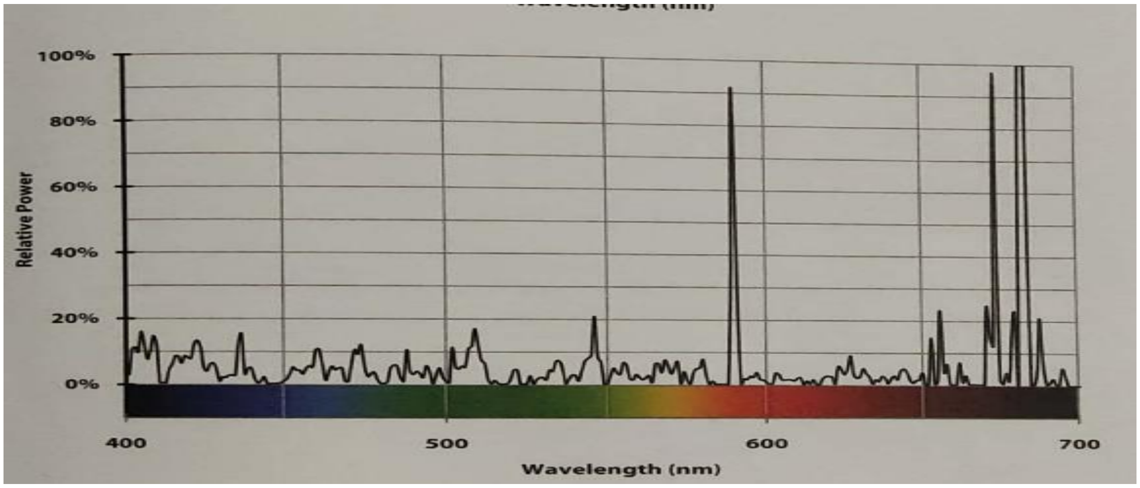


Fig.17 (a) Spectra of Metal Halide Lamps

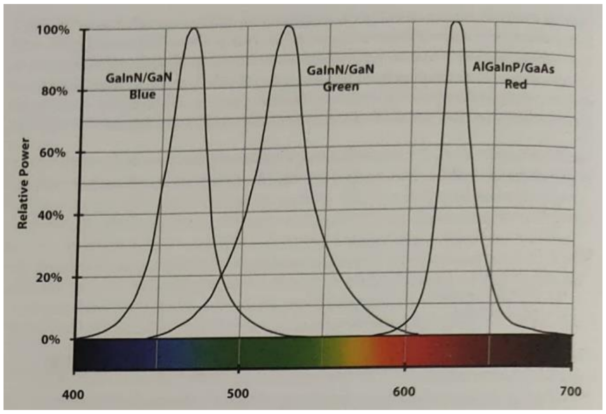


Fig. 17 (b) Spectra of LED

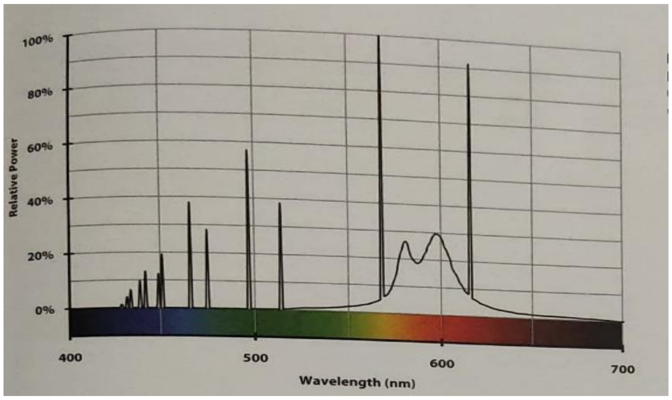


Fig. 17 (c) Spectra of High Pressure Sodium Vapour

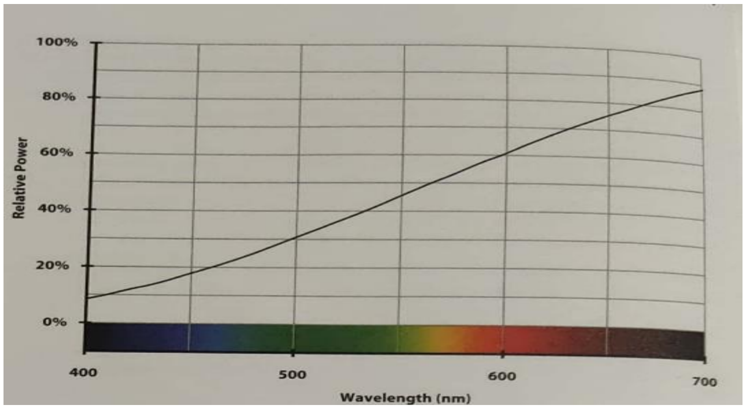


Fig. 17 (d) Spectra of Tungsten Halogen

Fig. 17 Spectral Power Distribution for Light Sources

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PART 2 PHYSICS OF LIGHT

Section 2 Vision

[First Revision of SP 72 (Part 2/Section 2)]

Illumination Engineering and Luminaries Sectional Committee, ETD 49	**Last Date for Comments: 20/04/2024**

FOREWORD

Light is invisible, yet essential for sight. While the human eye plays a vital role in sensation, visual perception is a complex interplay between the eye and the brain. Despite centuries of scientific inquiry, many aspects of vision remain unresolved, driving ongoing research. Understanding the eye's intricate functionality and its role in visual processes is crucial for lighting professionals. Visual mechanisms involve intricate interplays of photo-mechanical, photo-chemical, and photo-electrical processes.

Indeed, the subject matter is both multidisciplinary and specialized, drawing upon a wide range of disciplines including biology, chronobiology, medicine, and lighting design. A basic understanding of this subject is crucial in today's context, given the continuous stream of research findings being published almost daily. As such, professionals across various fields must grasp the fundamentals of visual mechanisms to stay informed and contribute effectively to their respective fields.

1 SCOPE

This section offers an in-depth exploration of the human eye, covering its structure, function, mechanisms, and its interconnectedness with the human body. Divided into distinct sections, each segment addresses various aspects pertaining to the eye.

Lighting has two types of effects: visual and non-visual biological effects. Visual effects influence how well we see and how comfortable we feel. Biological effects, on the other hand, affect our health and overall well-being. Human Centric Lighting (HCL) combines both effects to create lighting systems that prioritize human needs.

This section delves into the salient features and diverse components of the visual system, including its profound impact on visual performance, as well as factors such as visual satisfaction and comfort. It emphasizes the significance of recent advancements in nonvisual mechanisms, crucially related with human behavior. Moreover, it explores the implications of lighting on performance, sleep patterns, and age-related changes in visual insight. Understanding the effects of aging on the eye is pivotal for grasping its practical implications.

2 EYE STRUCTURE & VISUAL PROCESS

This section covers details of the structure of the Eye, its property & followed by the visual process.

The structure of the human eye is fundamentally similar to that of an optical system, such as a camera, regardless of its configuration.

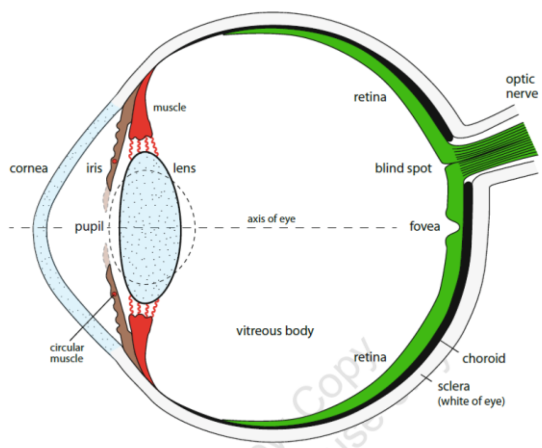


Fig. 1 Cross Section of the Eye Structure *

The cross section of the optical structure has following:

a) Sclera- white of the eye is a hard transparent tissue that gives the rigidity of the eye.

b) Cornea- the bulged out portion where from light enter to the eye & then reaches to a circular diaphragm formed by Iris.

c) Iris -It determine the colour of the human eye.

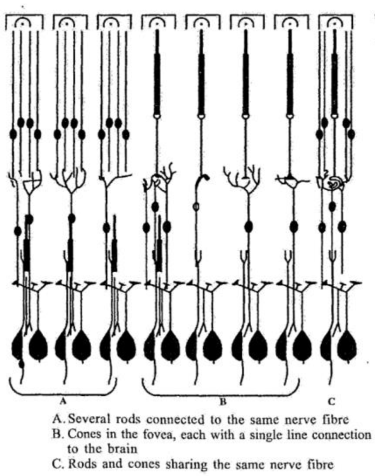
d) Pupil - The pupil, which is the opening of the iris, acts like the aperture of a camera. The muscles surrounding the pupil control its size, regulating the amount of light entering the eye based on the surrounding lighting conditions. This adjustment process is known as adaptation. Similarly to a camera's diaphragm, the eye alters the size of the pupil to focus on objects and ensure sharp vision. A smaller pupil size increases the depth of field, allowing objects at various distances to appear sharp. This critical feature will be further explored in upcoming clauses dedicated to this topic.

e) The eye lens creates an inverted image of an object located in front of the eye. This inverted image falls onto the inner part of the eye known as the retina. The shape of the lens adjusts depending on where the eye is focused. It takes on a spherical shape for nearby objects and becomes flatter for distant objects. This adjustment process of the lens, based on the distance of the viewed object, is called accommodation. The eye lens is made of transparent fibers containing protein, similar to the crystalline lens. The retina, located at the back of the eye, resembles the light-sensitive film of a traditional camera or the CCD cells in a digital camera. The projected images are ultimately processed by 100 to 300 million photoreceptor cells situated inside the retina.

f) The fovea is positioned along the axis of the line of sight. The shape of the lens changes due to the movement of its muscle membrane.

g) Eye lens is embedded in the transparent colour less jell called the vitreous body.

h) The layer behind the retina is called the Choroid. Its primary function is to prevent internal reflections of stray light within the eye, much like the dark interior of a camera. The Choroid is rich in blood vessels, which provide nourishment to the internal structures of the eye.



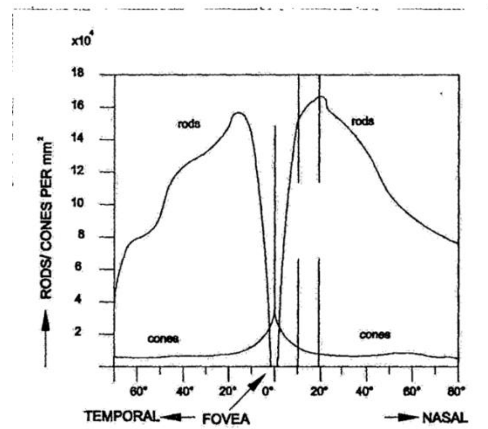


Fig. 2 Rods & Cones Structure Inside The Eye

Fig. 3 Distribution of Rods & Cones at Retina.

3 VISUAL PROCESS - NEURON CELLS & PHOTORECEPTOR CELLS

The process of seeing is fundamentally an electrochemical one. The eye possesses remarkable sensitivity, with a range of sensitivity spanning 1:10, combined with high resolving power. This allows for the discernment of up to 10,000 different shades of color. Additionally, the eye is capable of adapting to varying lighting levels, from as low as 0.1 lux under moonlight to as high as 100,000 lux in bright sunlight.

The retina is a thin tissue, typically between 0.1 and 0.3 mm thick, consisting of various layers. These layers comprise nerve or neuron cells, including ganglionic and collector cells, as well as photoreceptor cells such as rods and cones. In the process of vision, light initially passes through the different neuron cells before reaching the photoreceptor cells. The retina is nourished by numerous thin layers of blood vessels. The tips of the photoreceptor cells make contact with the pigment epithelium located at the back of the retina.

Human photoreceptor cells for vision come in two types: rods and cones, named for their distinctive shapes. The eye contains approximately 5-6 million cones and 100-120 million rods. The outer part of both rods and cones contains hundreds of thin membrane plates that house photopigment molecules called opsins. Rods and cones each have different types of opsins; rods contain rhodopsin, while cones contain photopsin. The epithelium layer provides vitamin A to the opsin molecules of the photoreceptors, making them photosensitive.

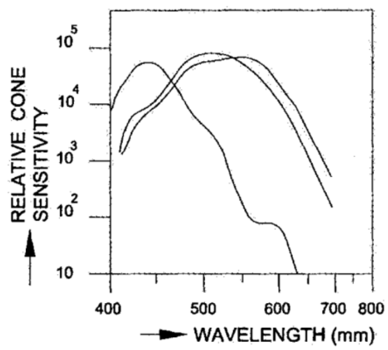


Fig 4. Spectral Sensitivity Curves of the Three Colour Receptors in Cones

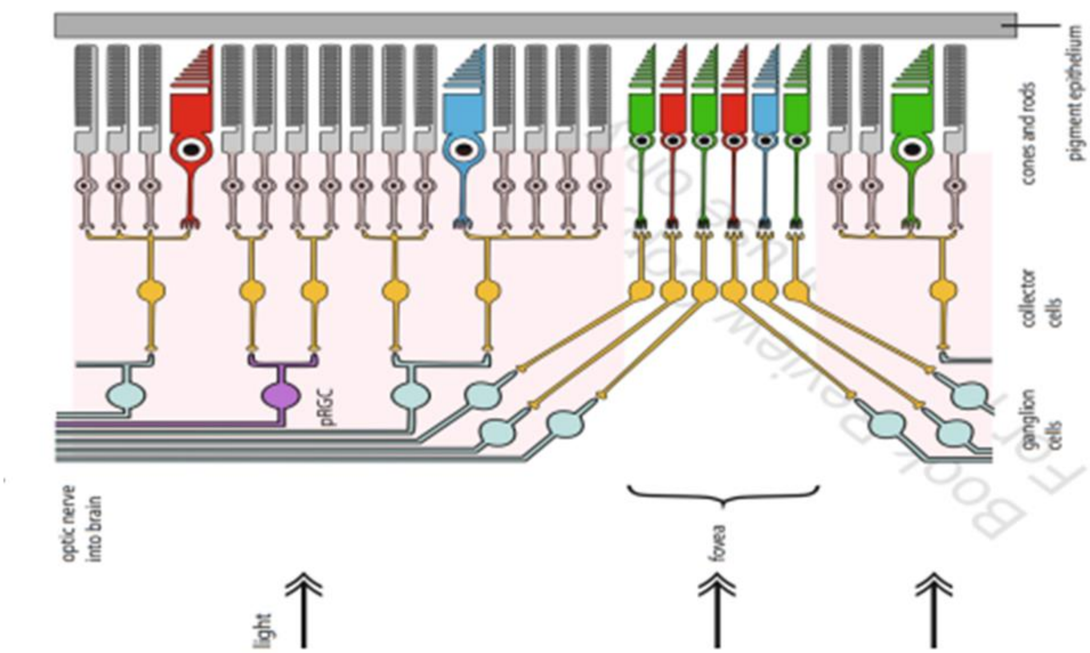


Fig 5 Eye & Brain Mechanism -Visual Path Way

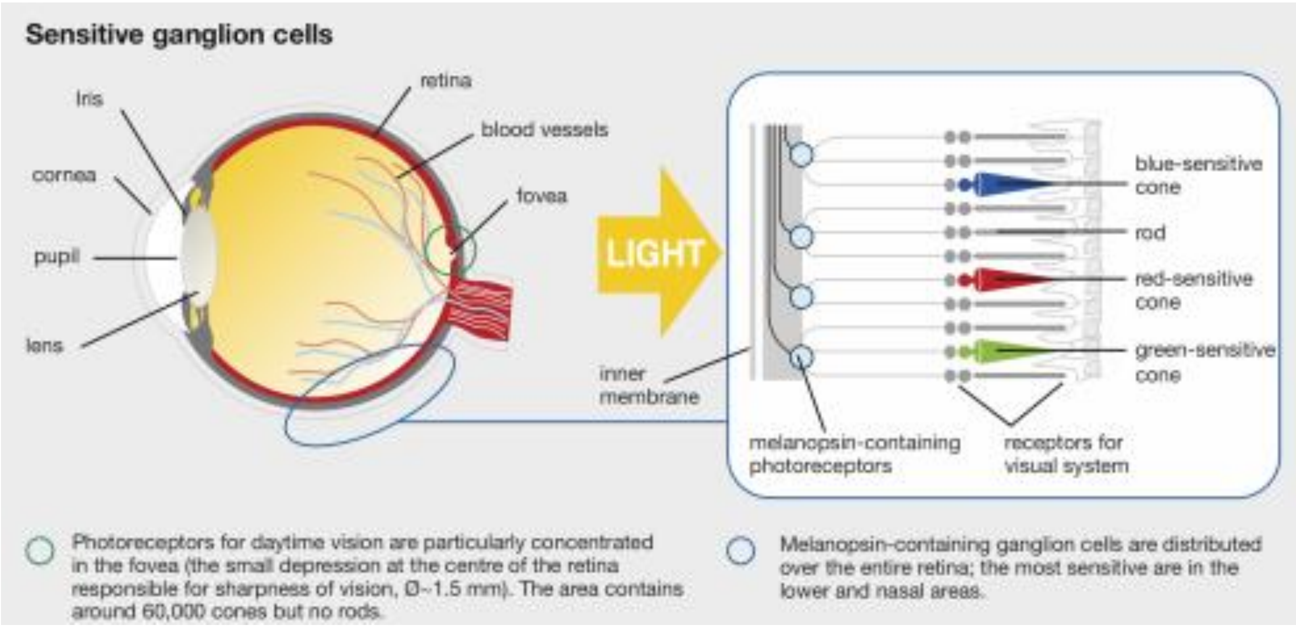


Fig 6 Eye & Brain Mechanism - Eye Photoreceptors

According to Weston (1949), Tovee (1996), and Kolb (2013), the visual process is termed phototransduction. When light enters the eye, opsin molecules absorb photons, initiating a series of chemical reactions. These reactions generate a minute electrical current, which is then carried by nerve fibers to the brain, specifically to an area known as the cortex.

However, the visual process is not as straightforward as one might assume. Initially, both eyes are connected to the visual cortex in the brain's two halves. However, the optic nerves from both eyes merge immediately after entering the cranial cavity, forming what is known as the optic chiasm. From there, they divide again into two branches, known as the optic tracts, which lead to the two halves of the visual cortex.

The optic chiasm serves as a crossover point, where the optic nerve fibers from each eye split into two strands. Each optic tract contains nerve fibers originating from both eyes. This arrangement ensures that information from both eyes is transmitted to both hemispheres of the brain for processing. Ref Fig. 5.

Indeed, the arrangement is such that the left half of the visual cortex processes information from the right side of each retina, and vice versa. Therefore, if someone has one of their optic tracts severed, they will experience half-blindness in both eyes.

Each nerve fiber creates an unbroken connection between its endpoint in the retina and a specific area of the visual cortex. This allows for the mapping of the retinal area onto the cortex. Interestingly, although not illogical, the foveal area occupies a significantly larger region of the visual cortex compared to the peripheral areas of the retina. This emphasizes the importance and intricacy of central vision in the visual processing system. *See* Fig. 7.

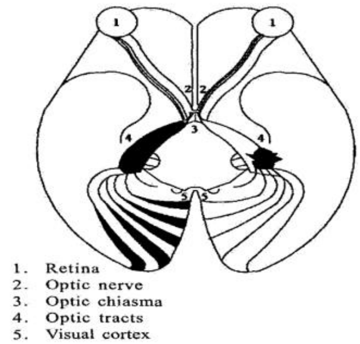


Fig. 7 Schematic Diagram of the Visual Pathway, Showing How the Retina of Both Eyes Are Connected To the Two Halves of the Visual Cortex

4 SPECTRAL SENSITIVITY OF VISION

4.1 Rods & Cones

It is clear that vision functional processes are attributed to the rods and cones. The rods are highly light sensitive and principally responsible for detection of shape and movement, but cannot distinguish colours. Cones, on the other hand, are less sensitive to light, but can distinguish colours. They also enable us to see finer details.

In the case of rods, approximately one hundred of them are connected to a single nerve fiber. This clustering results in high sensitivity to light, as the stimulation of multiple rods is combined. However, this also leads to poor definition because the brain cannot distinguish between individual rods within a cluster. Consequently, when relying solely on rods for vision, the resulting image is often blurred.

Rods are unable to discern colors, but their sensitivity to light varies across different spectral colors. At high lighting levels, the photopigments in rods, such as rhodopsin or rod-opsin, become bleached or exhausted, with their probability approaching zero at lighting levels exceeding 5 cd/m2. Therefore, rods are more sensitive to light than cones. As lighting levels increase, rods become inactive, and cones take over vision.

Adaptation from high light to low light or darkness takes only a few minutes because rods become less active and cones become more functional. However, adaptation from darkness or low light to bright light takes more than 30 minutes for full adjustment.

Rods exhibit maximum sensitivity at a wavelength of 507 nm, which is in the green-blue range, and sensitivity sharply declines toward both ends of the spectrum. Rod vision is characterized by low acuity and monochrome perception.

Sparsely distributed, cones occur over the entire retina, but in the fovea they are densely packed (*see* Fig. 2 & Fig. 5). Unlike with rods, which are very less in the foveal area, each cone is individually connected directly to the brain, resulting in a very high resolving power, colour perception. On the other hand, sensitivity to light for cones is far less than for rods. Therefore, at luminance levels of 3.5 cd/m² and less, cones gradually cease to function. The overall spectral sensitivity curve for cones is different from that for rods. The point of maximum sensitivity lies at 555 nm (bright yellow), and the fall off toward the red side of the spectrum is less pronounced. The result is that at very low lighting levels, when the cones no longer function and the rods take over, blue colour seem to become brighter with respect to red colours [Fig. 8 (a)].

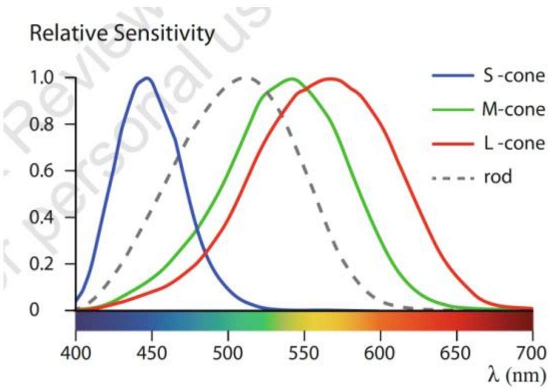


Fig. 8 (A) Relative Spectral Sensitivity Curve For Different Opsin Of Cones & Rod.

The cones enable us to distinguish colours. Until a few decades ago the underlying processes were hardly understood, it was then known as Photopsin photoreceptor but now it is experimentally proved that of three types of cones as per absorption of wavelength (sensitivity) S-CONE opsin pigment (Blue light short wavelength), M CONE opsin pigment (Green Middle wavelength), L CONES opsin pigment Red Long wavelength) which was earlier known as Photopsin (Fig. 7). Cones are not evenly distributed in the retina. The blue S cone located more at the outside boarder of the fovea. The number of 3 cones are different. S cones are only 5 to 7 % of total cones.

So, cones pigments sensitive to the red, green and blue parts of the spectrum, respectively. Persons who miss one type of cone present in the eye are fully COLOUR BLIND. Also to be noted that those eye having only rods such people have many other visual deficiencies as well.

The division in rods and cones explains much of the characteristics properties of the human eye. At normal visual conditions (sufficient light available), the image of the object we are studying is brought to focus on the foveal region, which is so small that it is just covered by the image of the full moon. Larger scenes are scanned by continually revolving movements of the eyes. This can be clearly seen when somebody is reading a book. The spot of focal attention is sharply pictured in full colour by the cones of the fovea. The periphery of vision, covering a horizontal angle of more than 200º when seeing with both eyes without moving one's head, produces no detailed image, but permits of general perception. Toward the edge of the scene, colour perception falls off through lack of cones.

4.2 Photopic Vision, Scotopic Vision, Mesopic Vision

The state of vision, which always occurs if sufficient lighting level larger than 5cd/sqm where rods cease to work & cones function taken over, the vision is called "P**hotopic Vision**". Higher lighting level vision applicable most all indoor lighting applications.

At very low luminance levels (less than 0.005 cd/m²), the cones do not function. Vision is then by rods only, resulting in a general picture of low definition and no colours. Therefore, 'in the dark all cats are grey literally makes sense. Although it will be impossible to focus on an object, movements are comparatively easily detected. Because of the Purkinje-shift, blue objects remain visible longer than do red ones with decreasing luminance. This situation is called `**Scotopic Vision**, 'very low to dim lighting vision at night without any artificial light. [Fig. 8 (b)]

Between photopic and scotopic vision range 5 to 0.005cd/m² where both rods & cones are functional. Vision under this condition is called '**Mesopic vision**'. Most road, area and environmental lighting comes in this segment.

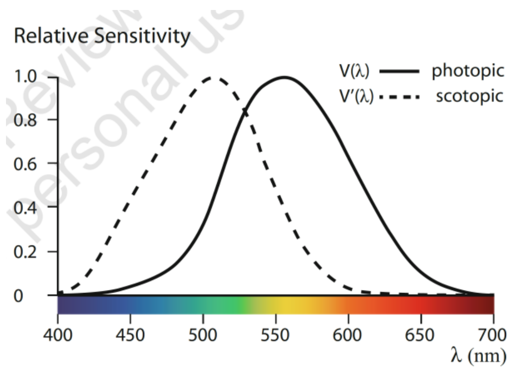


Fig. 8 (B) Peak Of Photophic at 550nm, Peak of Scotopic At 507nm.

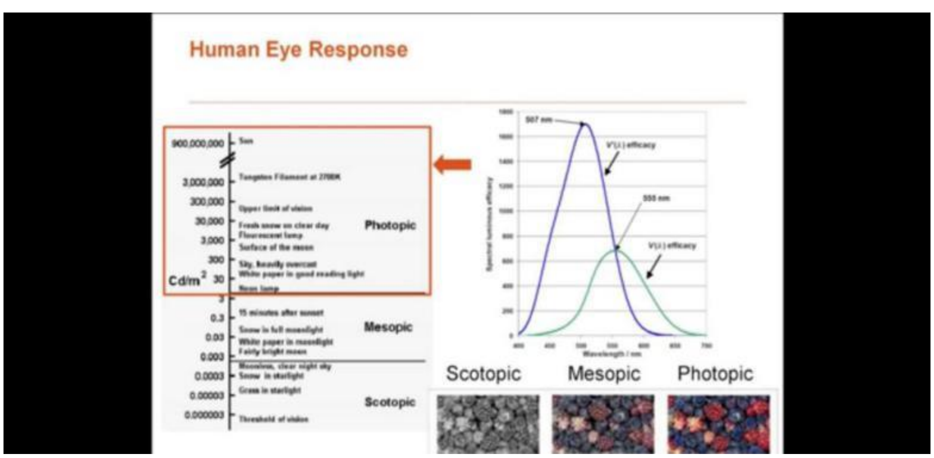


Fig. 9 Human Eye Response

With the understanding of Mesopic vision a new area has been opened up in understanding and measurement lighting parameter. This is because so far photometric unit are derived long back with Photopic lighting condition means photopic spectral sensitivity is used as a weighing function to convert radiometric unit (radiant power expressed in watt) into photometric unit like luminous flux expressed in lumen. Therefore in mesopic measurement the use of photopic measurement technique will not give proper result as efficacy of light sources changes as well lux level changes in mesopic. Fig. 10.

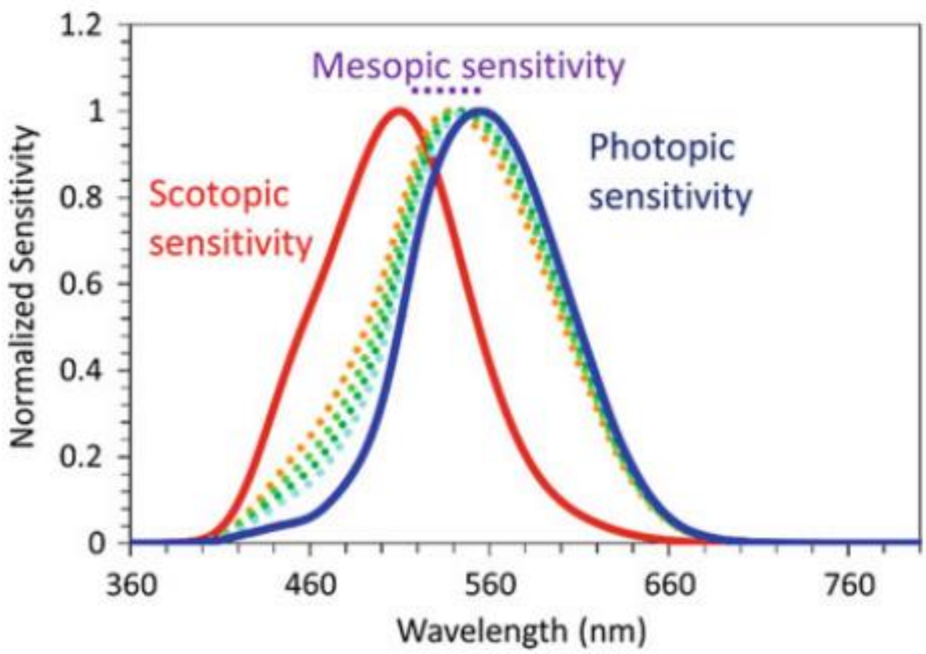


Fig. 10 Mesopic Vision

In 2010, the International Commission on Illumination (CIE) has recommended a mesopic photometry system based on peripheral visual performance of tasks, which provides the mesopic table to obtain mesopic luminance (Lumen) corresponding to some selected photopic luminance (within the range of 0.005 cd/m2 to 5 cd/m2) for all relevant S/P ratio (i.e. Scotopic/Photopic ratio) of lamps.

The mesopic photometry system also defines mesopic luminous efficiency function Vmes (λ) as a linear combination of photopic luminous efficiency function V(λ) and scotopic luminous efficiency function V'(λ), the spectral efficiency of which depends on the luminance called as adaptation luminance to which the eyes are adapted.

Table 1 has been given for real value effective calculations.

IESNA TM12 TEST guide lines how to evaluate the different S/P ratio for a given photopic region measurement.

Table 1 What Over Watts

Sl. No 1)	Source 2)	Photopic lm/W 3)	Scotopic lm/W 4)
1.	Incandescent	12	12
2.	CFL 2700K	55	43
3.	T8 Fluor 3000 K	100	79
4.	T8 Fluor 4100 K	100	114
5.	T8 Fluor 6500 K	90	139
6.	T12 Fluor 7500 K	55	91
7.	Metal halide	95	114
8.	White LED	62	108

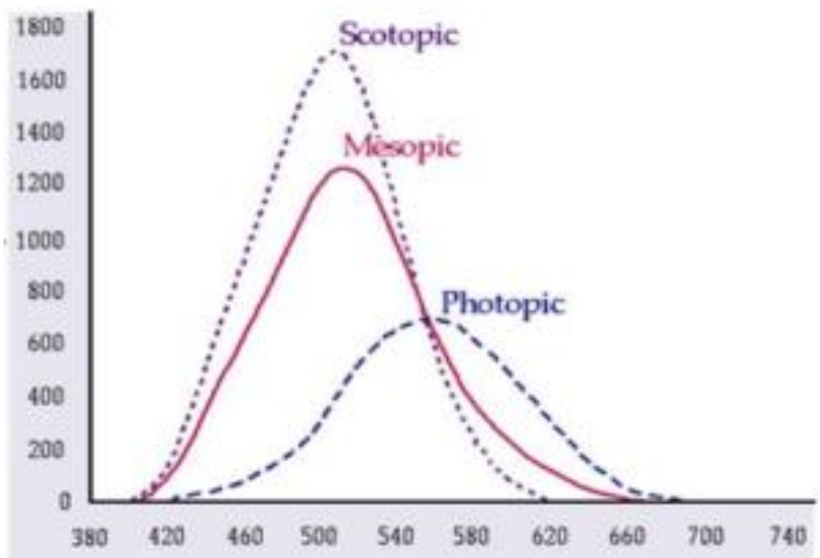


Fig. 11 Luminous Efficacy versus wavelength

5. THREE DIMENTIONAL VISION, EYE & AGE FACTOR

Three-dimensional vision is possible with the help of both eyes. Good three-dimensional vision depends on coordination between two eyes and binocular vision. It is found that a difference in distance over a range of more than one kilometre is possible to judge by three-dimensional vision.

Eye-sight deteriorates first slowly, but then at a rapidly increasing rate with age. From about 45 years of age, nearby seeing, (reading for example) becomes increasingly more difficult, whereas distant objects give no problems, a condition that is known as `presbyopia'. From about 50 years of age human being will suffer from overall eye sensitivity, visual acuity, contrast sensitivity and colour sensitivity. Old people need as much as 15 times more light for a specific task than do the young. (*see* Fig.12)

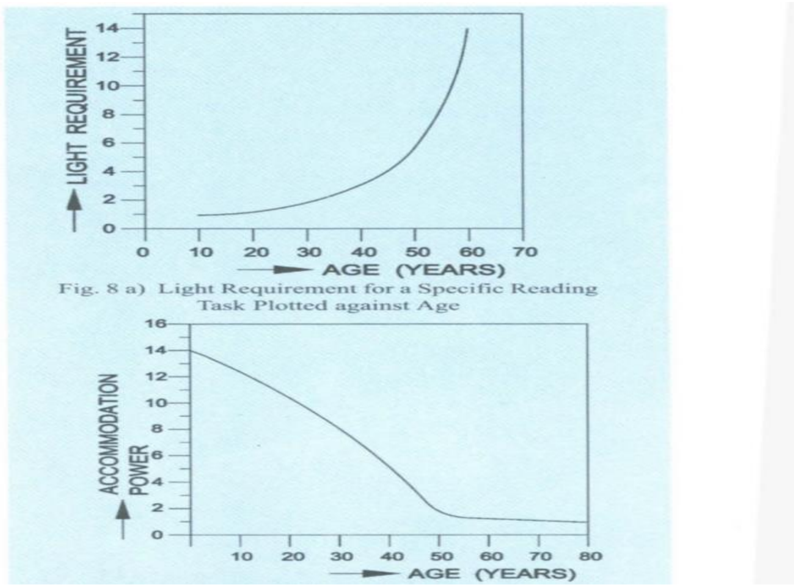


Fig. 12 Eye Visibility Factors With Age

Lighting specification or lighting designer or even owner or users of the premises need to consider the age factor of the occupants while recommending the lighting level. Yellowing of lens start at age 25. The relative transmittance becoming less plus blue light absorbed. The relative transmission power of the eye with different age 100% upto 25yrs age at fixed colour 2700k fixed luminance 10Cd/sqm. 84% for 50 years old,75% for 65 years old.

The following cause & effects can be summarized:

a) loss of lens elasticity leads to loss of accommodation.

b) Permanent damage of photosensitive & ganglion cells, reduced path way. smaller pupil size.

c) Lens yellowing and finally reduced retinal illuminance.

d) Loss of blue light.

e) Change of perceived colour and effect , lowering the circadian rhythm as well as reduced visual performance.

f) Disturbed rod pigment regeneration, slower dark adaptation, also reduction of the visual comfort and visual performance.

g) With age the structure of the cornea, lens, retina and blind spot changes. These changes increase the scattering effect inside the eye, hence increasing more disability glare. With aid of lighting lot of defects can be taken care but all cannot be eliminated .

h) The blue enriched white light has various effects e.g., boosting alertness., helping brain function and memory, elevation of mood and regulation of body's natural biological clock for both young and older persons. For older people, at lighting level of 1000 lux, this effect starts reducing and becomes completely off at 3500 lux. Again blue light has more scattering effect inside the eye for older people. So blue light has both positive & negative effects on older people. At the same time green monochromatic light has also the same circadian effect for young & older people.

Eye is very complex mechanism and has critical phenomena with body and nerve which are not yet solved and regular new findings are coming which need updating every 2 years thoroughly.

6 VISUAL PERFORMANCE & VISUAL SATISFACTION

Visual performance is heavily influenced by various factors, including the size of the object being observed, the background against which it is viewed, the level of contrast, the lighting level of the background, and the overall surroundings. There exists a threshold limit for visual performance, beyond which tasks become challenging to observe or carry out effectively.

Different models, such as the Relative Visual Performance (RVP) curve, are available for calculating and understanding visual performance quantitatively. However, for the purpose of this discussion, we'll adopt a practical approach that doesn't delve into the intricacies of mathematical formulas and graphs. Instead, we'll focus on a basic understanding of how these factors impact our day-to-day experiences with lighting applications.

In the past, traditional lighting applications engineers or planners primarily focused on visual performance, prioritizing task-oriented lighting levels without always considering the clarity of visual objects or their surrounding conditions, nor did they always consider the well-being of individuals.. However, over time, the concept of visual comfort and satisfaction became integral to their design considerations. This includes factors such as glare, uniformity of lighting, color rendering, flicker, and overall ambiance. Incorporating these elements into lighting design ensures not only adequate illumination for tasks but also creates environments that are visually pleasing, comfortable, and conducive to well-being.

This section deals with the criteria for visual performance & visual comfort.

6.1 Visual Task & Contrast

What we perceive visually is essentially the reflected light from objects, referred to as luminance. Contrast plays a significant role in our visual experience, especially when viewing screens like those on mobile phones, laptops, desktops, or tablets. We often adjust the contrast settings to enhance clarity and comfort.Consider reading a book versus reading a poorly reproduced, faint copy. The difference in quality impacts our visual comfort and clarity. We may find ourselves adjusting our eyes to accommodate for the differences in contrast or adjusting the background or surrounding environment to improve our viewing experience.

Contrast can be of two types either on colour contrast and luminance contrast. Both the contrast can happen together most of the time. Contrast is defined by the difference between the luminance of the target itself and luminance of its back ground. contrast is positive if the object is brighter than the back ground and contrast is negative when object is darker than the back ground example of reading a book white paper back ground black letter. Contrast in luminance can be expressed as contrast value or contrast ratio. Contrast value has more importance under conditions of artificial lighting. The mathematical expressions are as given below:

$C = (L_o - L_b)/L_b$ = Contrast value

$C = L_h / L_i$ = Contrast ratio

Where,

C — Contrast Value/Contrast Ratio

L_o — Object Luminance

L_b — Background Luminance

L_h — Higher Luminance

L_i — Lower Luminance

Contrast in colour can be distinguished better, under an overall luminance level sufficient to permit full adaptation for cone vision, without excessive brightness contrasts in the field of view and under a light source having spectral energy distribution curve approximately similar to spectral eye sensitivity curve for photopic vision. The eye will not appraise luminance values the same way under all circumstances. A white surface placed against metamerism is perceived matching of colours with different non matching spectral power distributions. Colours that match ways are called metamers & takes place when two colour shades are observed under sources having line spectrum, separately.

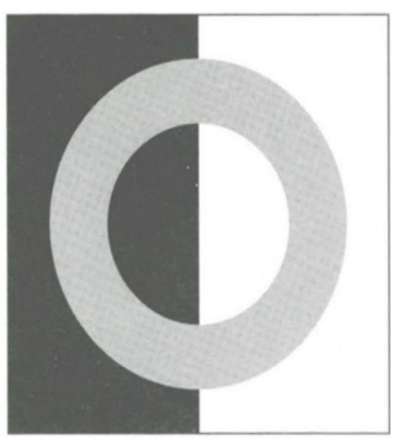


Fig. 13 (A) Contract Effect A Black Background Will Make The White Seem `Whiter'. Dark Object against a Very Bright Background Will Appear Darker

Successive and simultaneous contrast Fig. 13 takes place when looking away from a surface of strongly saturated colour and when looking at adjacent coloured surfaces respectively.

The performance also depend upon the viewing angel like children can see the object sharp from a shorter distance and can see also see far object better than older one. This is due to the visual angel subtended by the object at the eye of the observer.

6.2 Visual Ability

Visual ability provides different visual information like ability to differentiate between closely spaced visual stimuli, luminous variations in the field of view and three dimensional visions.

6.3 Visual Acuity & Threshold Visibility

Visibility measurement of objects are the threshold of contrast and threshold of acuity. Qualitatively, visual acuity helps in distinguishing fine detail and quantitatively it provides details on angular separation of two neighbouring objects that the eye can just perceive as being separated. Visual acuity depends on the quality of the visual organ and varies with background luminance and observation time. It is measured by bringing the size of the object to its threshold of vision and also depend upon contrast. Threshold contrast is the

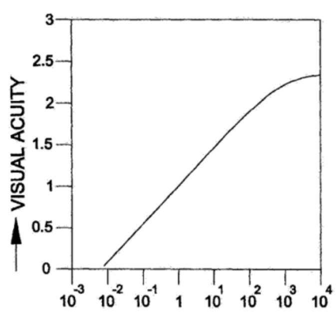


Fig. 13 (B) Relative Visual Acuity Plotted Against Adaptation Luminance Age Below 50 Years Under The Same Optimum Contrast.

Least detectable contrast of an object. For indoor lighting applications safe comfortable working condition visibility should be clearly above threshold visibility.

What is generally assessed as `visual' in the consulting room of the ophthalmologist is not so much the pure visual acuity of the eye, but the recognition acuity. For scientific research, the study of resolution acuity is essential. Age has a marked negative effect on visual acuity. Visual acuity is expressed as reciprocal of the minimum visual angle (in minutes of arc), being detected. Visual acuity depends on the average luminance level in the field of view to which the eye is momentarily adapted (adaptation luminance). (Fig. 13)

For an example in a more demanding task means where object is smaller and less contrast, there increasing lighting level say from 200 lux to upto 500 lux) improve the performance but after certain lux level (here 500 lux) it saturates means even increasing lighting level does not give any visual performance benefit. The piratical example is while reading the eye testing chart.

CIE 2002 has developed a mathematical model with WSTON'S VISUAL performance values where back ground luminance, contrast, visual angel and age are plotted with RVP (Relative Visual Performance) values.

6.4 Visual Satisfaction & Glare

6.4.1 *Visual Satisfaction*

Visual satisfaction related to the space means how the appearance of the whole space in which the activity is conducting & making the visual task satisfactory for that person. This is the experience of feeling for the person while performing the task. This has a direct link to the motivational lighting environment of feeling the well-being.

Visual comforts relate to different aspects like spaciousness, attractiveness, relaxedness, intimacy & workers stimulation.

The main components that determine visual satisfaction include the spatial distribution within a space, the distribution of spectral wavelengths, room appearance (such as surface illuminance and luminance), overall brightness, light directionality, and modelling (including factors like the vector and scalar ratio of light, light flow, and degree of discomfort glare). Additionally, factors such as color background, tint, and color composition play crucial roles in shaping visual satisfaction.

LED lighting systems, which inherently emit directional light, therefore, designers face no challenges in applying the concept of scalar and vector ratios. This concept, often referred to as the "Three-Dimensional Effect" by lighting designers, can be effectively utilized due to the directional nature of LED lighting.

In the absence of directional light, the ratio is zero. When a single parallel light beam fully illuminates a completely black interior, the ratio reaches its maximum value of 4. These concepts hold significant importance in various applications such as shop lighting, museum lighting, sports lighting, and architectural lighting.

The impact of room surfaces on visual satisfaction has been thoroughly researched and documented by Loe et al. (1994) and Veitch et al. (2011).

In well-lit rooms, an interesting mood is created, while dimly lit spaces often result in a less engaging visual experience. Glaring conditions can lead to unpleasant sensations, such as discomfort, tension, or dislike, while glare-free environments offer a pleasant, dramatic, and relaxing experience. It's important to note that these responses are subjective and can vary widely among individuals, serving as general guidelines rather than strict rules.

6.4.2 *Glare*

Glare is a crucial aspect of visual perception, closely tied to vision problems and overall visual satisfaction. It refers to the vision impairment caused by excessive light. Glare occurs when an excessive amount of light enters the eye, surpassing its threshold for comfortable vision. This phenomenon can be directly or indirectly related to various factors, including the characteristics of light sources, the lighting system itself, reflections, and the contrast between objects or between the lighting system and objects.

Glare can occur due to internal reflections within the eye (known as the veiling effect) or when light travels through and scatters off media with different optical refractive indices. It's a common occurrence in our daily lives. Beyond being unpleasant, glare can also pose significant dangers at times.

There are 4 types of glares:

a) Distracting glare
b) Indirect glare /Blinding glare
c) Disability glare
d) Discomfort glare

Among these types of glare, discomfort glare holds particular significance for lighting professionals, especially lighting designers. They constantly endeavor to determine and recommend the most suitable Glare Index Ratio for each specific task, aiming to minimize discomfort and optimize visual comfort for users.

6.4.2.1 *Distracting glare* - We observe this effect when our spectacles scratched or smoked. These creates different layers in our lens and light scattered, refracted, reflected from the different layers cause this glare. This type of glare can also be experienced at night forming “halos” around headlights or street lights. Distracting glare can represent an annoyance or distraction to the viewer and leads to eye fatigue. Different type of coating in the glass reduces this type of glare UV coating, AR coating, transition lens etc.

6.4.2.2 *Indirect glare or Blinding glare* - The reflected light becomes polarized from the glossy, shiny and semi matt finish materials like surfaces may be snow, water , screen of the laptop or mobile. Blinding glare block the vision to the extent that the wearer becomes visually compromised. This can be removed by using the diffuse light wherever possible. The glossy surface of the lap top or mobile or tablet is self-luminous means negative contrast that is dark back ground bright symbol creates the indirect glare. So creating the positive contrast means bright back ground and dark symbols make the visibility better. Very easy solution is tilting the positing so that offended zone of reflected light is avoided. Vantage lens with variable polarization are good solution.

6.4.2.3 *Disability glare or Veiling glare* - Simple means that it disables the visual task. This form glare is responsible for a negative influence of glare on visual performance means reduction of visibility. In that sense both the above glare can be called disability glare. We have defined separately for better understanding as those term are used in many occasions. This type of glare interferes with visibility & make such an high impact that our eye immediately shifts from that vision away. This is an instinct reaction of the eye. This type of glare comes from excessive intense light that can occur when one face directly into it for example when you see directly at halogen or metal halide lamp and sun. This is calling veiling glare as light scattered inside the eye when light enters into the eye that reduces the sharpness of the vision and raises the differential light threshold. As explained earlier that disability glare trend to become more problematic with older age personnel as the decreasing transparency of the crystalline lens that comes with age leads to developing contract formation.

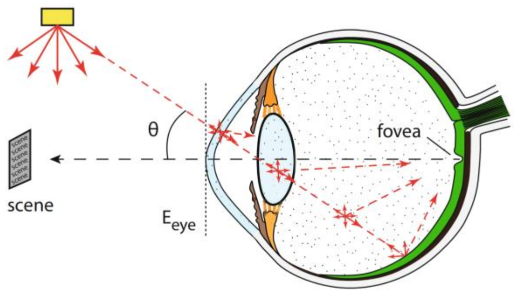


Fig 14 Internal Reflection Veiling Glare.

The light at direct line of sight and partly scattered in the cornea, eye lens, eye ball. Part of light scattered light redirected towards the fovea, where it acts as a bright veil drawn across the field of vision.
The physiological and psychological mechanism still not understood for the disability glare. But at the same time, In the case of interior artificial lighting condition, it is evident after huge research that the disability glare has a neglectable effect on our visual performance and comfort.

6.4.2.4 *Discomfort glare* **-** This type of glare creates the discomfort feeling in performing our visual task. This is very important and critical for interior lighting & sports lighting. This cause irritation and fatigue painful feeling & cause head ache. Unlike disability glare, the discomfort glare is better understood and established. Magnetic resonance imaging (MRI) scan showed that physiological properties respective fields and their on -off cantered surround the ganglion cells for discomfort glare. Possible cause of discomfort because of repetitive change of retinal image or pain control mechanism in the brain protecting the retina from bright light.
For LED luminaire the discomfort glare plays an important role as LED luminaire are matrix format means combination of number of individual light source i.e LED chips. These individual chip creates more edges and overlap in the ganglion cells means more information is sent through optic nerve in the brain. These effects engaged the brain to stress and therefore in the case of LED luminaires the disability glare is very important features to deal with.

6.4.3.1 *Unified glare index or ratio*

UGR is a method of calculating glare from luminaires, light through windows, and bright sources. Glare is a very common problem in work place and India so far this subject matter is still not explored and practice in lighting installation. UGR rating to determine how likely a luminaire is a to cause discomfort to those around it. See, like discomfort that a led panel will cause the workforce within an office. This classification range from 5 to 50, low number indicating low glare. UGR concepts are being used in UK long back 40 years and thereafter various concept, formula and research work done. Still few things are not that clear and have some assumptions. But at the same time a good understanding & practical working are platform are made available by various standard/guiding organizations. UGR is a system for the evaluation of discomfort glare. Primarily, It has two methods of calculations which is discussed here and finally UGR for led luminaire explained today's context. First one is the calculations based on a formula and other one finding the index from the tables based on the photometric data as supplied by the luminaire manufacturer. Formula based bit complicated and ue of software required. Other one very rationally practical but based on some assumption.

UGR measurement are very subjective assessment method. A. Larger the source of the luminance in the observer direction higher the discomfort glare. B. Larger the solid angel subtended by the glare source at the eye of the observer i.e. larger the part of the visual field created by the source, higher will be the discomfort glare. C. Larger the background luminance discomfort glare is less. Means Darker the wall and ceiling higher the discomfort glare. D. of the glare source from line of sight less will be the discomfort glare.

The formula has been put forward by CIE IN 1995 and approved by technical committee on agreement basis called "CONSENSUS METHOD"

"CIE Unified Glare Rating (UGR)":

$$\mathrm{UGR} = 8 * \log\left\{\frac{0.25}{L_b} * \sum \frac{L_s^2 * \omega}{p^2}\right\}$$

with

p: position index, dependent on the displacement of the glare source away from the line of sight, obtained from Luckiesh and Guth (1949)

log: the logarithm to the base 10

L_s: the light source luminance

L_b: the background luminance, the value that can be calculated from the vertical indirect illuminance at the observer's eye with $L_b = E_{ind}/\pi$

This calculations for a specific location & viewing direction. This can be adopted to multiple glare sources.

Another method of UGR calculations CIE 1995, 2010 by using the UGR tables. This is also reasonably ok and easy to get a very good idea of the UGR index. But this based on few assumptions:

a) The luminaires are at a spacing to height ration of 1.
b) Luminaires are positioned at 2m above the eye level.
c) The total lumen output more than 1000lumen
d) Observer is located at the mid -point of a wall, with a horizontal line of sight towards the centre of the opposite wall
e) The eye level is 1.2 m above floor.

6.4.3.2 *UGR Preferred Method for LED Luminiare*

In 2019, CIE technical committee concluded the preferred method of UGR calculations of non - uniform light like LED luminaires. Use of ELE (Effective Light Emitting) area (not total area) and use standard UGR formula.

The effective light emitting area is determined from a high resolution luminance image of the luminaire by using ILMD (Imaging Luminance Measuring Device). Luminaire manufacturers need to determine, declare and provide the effective light emitting area for their luminaires. Luminaire manufacturers must supply these data along with the photometric data. Wat manufacturers can easily do at their lab by luminance map of the luminaire. UGR then be calculated by using the existing familiar formula & unchanged software packages available with them.

6.4.4 *LED Panel & Glare*

For restricting the glare, for more efficient mirror optics fittings for FL lamps, the CAT2 mirror optics cum aluminium louver was very popular in era of 1990 to 2005 but gone are those days as now in all office/commercial applications LED PANELS are used which are fully covered with diffuser.

Fig 15 LED Panel Installation

Is UGR still relevant? Absolutely. With the widespread use of LED panels, which often have high lumen outputs, there's a crucial need to consider Unified Glare Rating (UGR). LED panels can emit a significant amount of light directly onto surfaces, creating a brighter fixture against a darker background, leading to glare. UGR addresses how bright luminaires appear in interior lighting situations. While LED panels may not cause disability glare like reflections from VDU screens, they can cause discomfort glare, resulting in headaches, migraines, vision issues, and discomfort, potentially leading to errors or absenteeism.

6.5 UGR Recommendations

The UGR index is a numerical parameter that quantifies the level of psychological glare from a lighting installation. UGR values are categorized in steps within a scale ranging from 10 to 30, with the possibility of a zero UGR rating. It's important to note that according to DIN EN 1464-1:20111-08, UGR19 represents a level at which approximately 65% of observers do not experience glare. Specific UGR recommendations vary depending on the application, with detailed guidelines provided in the relevant chapters of this NLC code. Here, we offer general recommendations for quick reference.

Table 2 Broad Guideline of UGR Index

S.No	UGR VALUE (Less than)	APPLICATIONS
1.	16	Board room , Meeting room, Technical drawing room
2.	19	Office & Commercial area ,hospital general patient rooms
3.	22	Industrial work (general assembly work)
4.	25	Industrial work high
5.	28	Circulation Area & Corridor
6.	More than 28	Cllaed harsh lighting not acceptable
7.	22	Reception Area

Users and specifiers must understand that there are no luminaires explicitly labeled as "UGR COMPLIANT." Instead, they may be referred to as "UGR 19 SUPPORT luminaires." Compliance can only be confirmed once the ergonomic metrics, detailing how luminaires interact with occupancy in real spaces, are established.

It is imperative for lighting designers and specifiers to specify their UGR requirements clearly in tender documents. Ultimately, the designer, in collaboration with the luminaire company, must determine the UGR value at the site based on factors such as the shape and size of the space, surface lightness of walls, ceilings, and floors, and the direction of view for the intended work environment.

7 NON VISUAL BIOLOGICAL EFFECT- THE THIRD EYE

Light is life. Life created on earth by sun & water. Homo sapiens called MAN, being exposed 200,000 years on sunlight before artificial light came to human life which is only 160 years back. No wander, sunlight over the years created the genetically conditioned rhythm in human body by additionally inhabiting the hormone production. This is called 24 hours cycle means circadian rhythm or in a way this is our own BIOLOGICAL CLOCK or mater clock or internal clock.

The coordinated effect of the eyes, light, and brain on the human body has long been a mystery, only unravelled in recent decades, thanks to the study of non-visual effects by biological and medical researchers.

The study of visual effects has a rich history spanning over 500 years. However, it wasn't until 2002, with the work of Berson et al., that a new type of photoreceptor cell was discovered, known as Photosensitive Retinal Ganglion Cells (PRGCs). Unlike traditional rods and cones, these cells do not directly contribute to vision. Instead, they play essential roles in various aspects of human behavior.

The designation of these photoreceptor cells as the "third eye" is validated by their mechanism of action. PRGCs are sensitive to light, but their functions extend beyond traditional vision. They contribute to regulating circadian rhythms, influencing mood and alertness, and even affecting hormone secretion. Their ability to detect light levels without forming visual images aligns with the concept of an additional sensory organ, akin to an internal "eye," guiding non-visual responses to light stimuli.

PRGC cells are just like ganglion cell just like rod & cone located at the periphery of

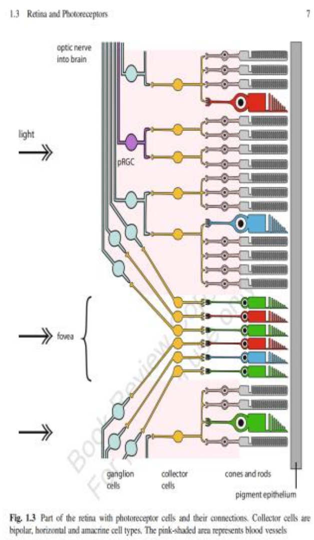


Fig.16 PRGC Cells In Eye

the retina outside the fovea.1 to 3% of the ganglion cells are of PRGC. The PRGC cells. has no direct contact with the pigment epithelium layers of the retina thus not directly responsible for seeing like rod & cone. PRGC cells have their own opsin photopigment type called MELANOOPSIN which is different spectral sensitivity peaks in the blue part of the wavelength. PRGC cells first relayed to SCN nucleolus of hypothalamus, an area of the brain well known to coordinate biological signal. (SCN is more preciously hypothalamus , the control centre i.e. acts like a pacemaker of the heart).

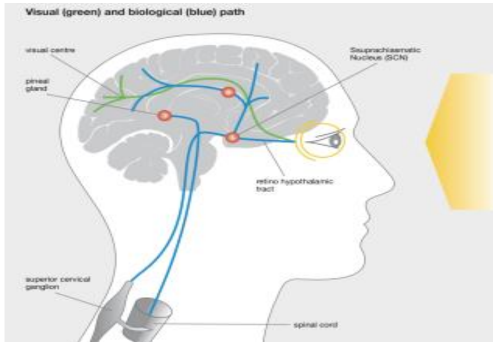


Fig .17 Non-Visual Track For Biological Rhythm

PRGC cells sends unconscious nonvisual photopic information through retina hypothalamic track to suprachiasmatic nucleus SCN, a structure within the brain that
act as a master biological clock with external environmental clock. The SCN in turn has connected by different path ways to the various part of the human body. The pathway which connected the retina's photoreceptor cell PRGC to SCN called retina hypothalamic tract and it goes to the spinal cord then ascends again to connect with pineal gland. The pineal gland produces & secretes hormone MELATONIN and SEROTONIN according to a pronounced circadian rhythm. This is the complete & proper connection is established between the eye & PRGC, time obtained from the SCN and hormone produced by the pineal gland. There are another path (tract) comes out from SCN goes towards adrenal cortex, the outer part of the adrenal glands sitting on the top of the kidneys. The adrenal cortex produces and secrets the hormone CORISOL
MELATONIN, SEROTONIN, CORISTOL are the three hormone responsible to make the respond of the human body with clear circadian pattern.

Besides there are few more path ways connected to various part of the body. Now it already proved that PRGC cells are connected with the brain area called OPN which controls the PUPIL reflex size means accommodation. Therefore, accommodation related to pupil size is a combined effect of rods & cones & PRGC cells.

Melatonin hormone feels us drowsy, slower our bodily function and lower our activity facilitate good night sleep. In this phase body secretes growth hormone that repair cells at night. Serotonin is precursor to the melatonin, this is a neurotransmitter that itself is derived from amino acid tryptophan within the pineal gland, serotonin then is acetylated and then methylated to form melatonin. Synthesis & secretion (a natural chemical production) of melatonin is dramatically affected by exposure to the eyes. Serum concentration of the melatonin are low during daytime and slowly increase to peak during dark. It is just before the melatonin works, the serotonin works for mood creation like evening and afternoon when the Cortisol in the blood fades means just before the internal clock switch to night mode. Cortisol is a stress hormone started producing in adrenal glands from around 3 A.M in morning. It stimulates metabolism again and program the body to work for day time operation. The first light of the day stimulates the PRGC cells and with control of SCN suppress the production of melatonin.

Thus light synchronize human internal clock of sleep, wake rhythm of the 24hrs cycle. The ability to adjust to the time of the day is achieved in our genetic make up hence rhythm is genetically synchronized. In 2017, Nobal prize winner American researchers Hall, Rosbach & young proved in their work of 1980s about the gens play a role in the biological clock.

Effective light exposure for PRGC medicated biological effect depend on intensity, direction, spectrum & timing relative to the phase of the light. PRGC needs more light than rod & cone to respond. The correlated colour temperature can be used only as rough indication for the characterisation of the lamp for non-visual biological use.

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PART 2 PHYSICS OF LIGHT

Section 3 Colour

[First Revision of SP 72 (Part 2/Section 3)]

Illumination Engineering and Luminaries Sectional Committee, ETD 49	**Last Date for Comments: 20/04/2024**

FOREWORD

Indeed, color is a fascinating and important aspect of our visual perception. It is true that color is a subjective experience that is perceived and interpreted by the human eye and brain working together. Our visual system responds to electromagnetic waves generated by light sources, and the brain processes this information to create the experience of color.

The association of color with the objects and things around us is a result of our learned experiences and cultural influences. Different individuals may perceive and interpret colours slightly differently due to variations in their visual systems and personal factors. This subjectivity has led to the development of various methods of color assessment and standardization to ensure consistency and accuracy in color representation.

The foundation of the concept of color can be traced back to Sir Isaac Newton, who first explained the nature of color in 1651. His work laid the groundwork for color science, also known as colorimetry. Newton's insights into the behaviour of light and his experiments with prisms led to the understanding that white light is composed of a spectrum of colours. His color wheel and theories on color mixing are still valid and form the basis of color theory today.

However, despite Newton's contributions, the study of color, its specification, and its characteristics remain an ongoing subject of research and development. Color is a complex phenomenon influenced by factors such as light source properties, surface reflectance, and human perception. As a result, organizations and researchers continue to explore and refine our understanding of color to improve its measurement, reproduction, and control.

Color also plays a vital role in lighting. Lighting designers use color to create visually appealing scenes and enhance the overall experience. With the advancements in solid-state lighting (SSL) and intelligent lighting electronics, a comprehensive knowledge of color and its properties has become crucial for lighting professionals. Understanding color temperature, color rendering, chromaticity, and other color-related concepts helps them design lighting solutions that meet specific aesthetic and functional requirements.

In summary, color is a psychological experience perceived by the human eye and interpreted by the brain. Sir Isaac Newton's foundational work in color science still holds true today, but ongoing research and standardization efforts continue to deepen our understanding of color and its complex characteristics. In the realm of lighting, color is a powerful tool used by designers to create visually appealing and impactful environments.

1 SCOPE

This chapter specifies the importance of colour in lighting, its concept, basic phenomenon, general information about colour theories.

2 REFERENCES

a) CIE 1931 Color Sapce ;
b) CIE 224: 2017 Colour Rendition Metrics ;
c) IES TM30 -15 Method for Measuring Color Rendition ; and
d) IES TM 30-18 Color Rendition Guidelines & Reports.

3 TERMINOLOGY

The definition given in the Part 1 of this code shall apply.

4 COLOUR FUNDAMENTAL

The existence of color requires three components: a viewer (such as a human eye), an object that reflects or emits light, and the presence of light itself. When these three elements come together, we perceive color.

Sir Isaac Newton's experiments with white sunlight passing through a glass prism are indeed significant in the understanding of color. By observing the dispersion of light, Newton discovered that white light is actually composed of a continuous spectrum of colours. He identified and named seven colours in the spectrum: violet, indigo, blue, green, yellow, orange, and red.

However, it's important to note that Newton's classification of these seven colours as primary colours was specific to his work and not the same as the primary colours used in modern color systems. In modern color theory, the primary colours are typically considered to be red, blue, and green, which are used in additive color mixing systems (such as those used in displays and electronics) to create a wide range of colours. This is different from the subtractive color mixing system (used in physical pigments and dyes) where the primary colours are cyan, magenta, and yellow.

Nevertheless, Newton's experiments and his identification of the spectral colours laid the foundation for our understanding of light and color. His work was instrumental in advancing the field of color science and color theory. Wave length of seven colours has shown in the Table 1.

Table 1 WAVELENGTH OF SEVEN COLOURS

Sl. No.	**Colour**	**Wave Length Range (nm)**
(1)	(2)	(3)
1.	Violet	380-420
2.	Indigo	420-440
3.	Blue	440-490
4.	Green	490-560
5.	Yellow	560-590
6.	Orange	590-630
7.	Red	630-780

Colour is perceived through the interaction of light, objects, and the human visual system. When white light is emitted or transmitted, it contains all the colours in the visible spectrum. However, light emitted or transmitted by specific sources or mediums may only contain certain colours or be close to monochrome.

When white light strikes an object, the object absorbs some colours and reflects others. The reflected light is what we perceive as the color of the object. The colours we see are a result of the mixture of different wavelengths entering our eyes.

The colour appearance of surfaces can be affected by the choice of light source. For example, a white paper appears white under white light because it reflects all the colours of the light spectrum to our eyes. However, if the same white paper is observed under red light, it will appear red because there are no other wavelengths present except for red to be reflected to our eyes.

It is important to note that not all spectral colours occur in all light sources, and even if they do, they may be present in varying proportions. Different light sources emit different combinations of colours, and this can impact the perceived colour of objects illuminated by those sources.

The color matching principle established by James Clerk Maxwell. This principle involves matching colours of different wavelengths using the primary colours of red, green, and blue lights (often abbreviated as RGB). By mixing these primary colours in different proportions, a wide range of colours can be achieved.

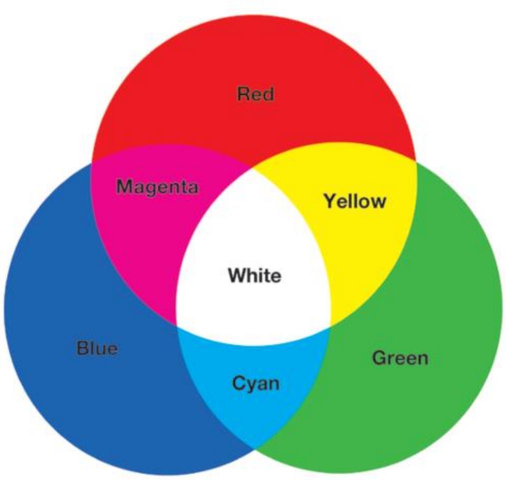
Overall, the relationship between light, objects, and colour perception, as well as the influence of light sources on the appearance of colours.

5 COLOUR ADDITIVE MIXING

There are two fundamentally different methods of color mixing: additive color mixing and subtractive color mixing. Additive color mixing occurs when colored lights are mixed together, resulting in a brighter color than the individual components. When the right colours are mixed in the right intensities, the ultimate result is white light. This process involves three primary colours: red, green, and blue.

In additive color mixing, the human brain functions similarly to a computer or a TV monitor. It combines the primary colours of red, green, and blue light to create virtually any color in the visible spectrum. This process is known as RGB (Red, Green, Blue) additive color mixing because it involves adding light to a dark background to produce different colours.

In summary, additive color mixing involves mixing colored lights to create brighter colours, and the combination of red, green, and blue light can generate a wide range of colours through the RGB process.



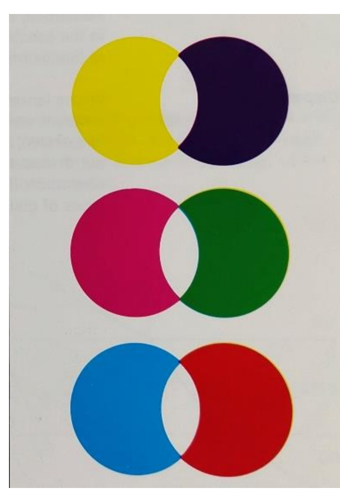


Fig. 1 Mixing of Colour

6 SUBTRACTIVE COLOUR MIXING

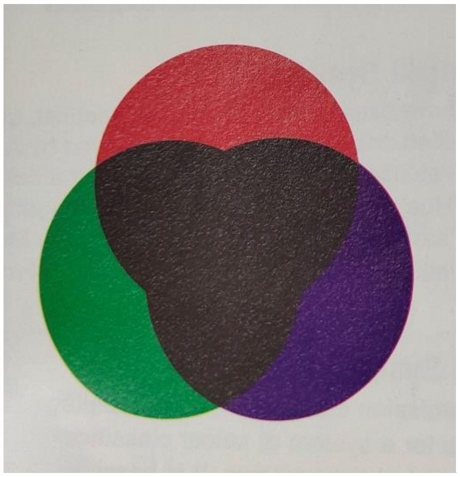
Subtractive mixing processes, such as mixing paints, operate differently from additive mixing and are more influenced by ambient light. In this case, the pigments in the paints transmit or absorb different wavelengths of light, leading to color perception.

When pigments are mixed, they subtract certain wavelengths of light and reflect or transmit the remaining wavelengths. The primary colours in subtractive mixing are typically cyan, magenta, and yellow. When these colours are mixed in varying proportions, they can produce a wide range of colours.

However, it's important to note that the pigments used in paints are less saturated than the colored light in additive mixing. As a result, when the primary colours in paint are mixed in equal amounts, the resulting color is not a pure, deep black but rather a brownish or blueish black. This is because the pigments used in paints are not completely saturated and cannot absorb all wavelengths of light effectively.

The perception of color in subtractive mixing is influenced by the ambient light that illuminates the painted surface. The interaction between the reflected light from the surface and the ambient light affects the overall appearance of the colours. Therefore, the colours produced in subtractive mixing can be more susceptible to variations in ambient lighting conditions compared to additive mixing, where the colours are created by adding light.

In summary, subtractive mixing processes, such as mixing paints, rely on the absorption and reflection of light by pigments. The resulting colours are influenced by the pigments' ability to absorb certain wavelengths, and the colours produced are less saturated than the colored light in additive mixing. Additionally, the colours observed in subtractive mixing can be influenced by ambient lighting conditions.



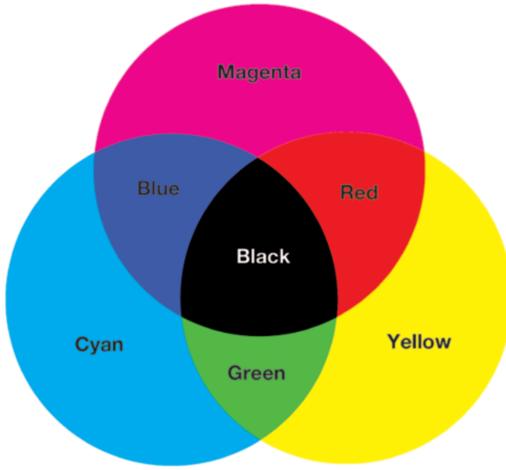


Fig. 2 Subtractive Colour Mixing

When colors in the form of paints are mixed, the result is always darker than the individual constituent colors. If the colors are mixed in the right proportions, the ultimate outcome is black. This process is known as subtractive color mixing, and it is commonly used in printing rather than with light sources.

In subtractive color mixing, different pigments or inks transmit or absorb various wavelengths of light. When these pigments are combined, they subtract specific wavelengths, resulting in different colors. For example, combining red and green paints will produce black, as will mixing red with violet-blue or green with violet-blue. By subtractively mixing complementary colors, the primary colors can be obtained again.

The subtractive color mixing process is particularly relevant in printing, where colors are created by adding and overlaying pigments on a white background. In multicolor halftone printing, the ink colors typically used are cyan, magenta, yellow, and black (CMYK). The addition of black ink is necessary because cyan, magenta, and yellow alone cannot produce a true black. The "K" in CMYK stands for "Key," which is a printing term for process black.

This understanding of subtractive color mixing also explains why digitally printed images, when backlit with LEDs of different color warmth, can produce significantly different effects in signage lighting. The combination of subtractive color mixing with the lighting conditions can lead to variations in color appearance.

In summary, subtractive color mixing in the form of paints or inks results in colors that are darker than the individual constituent colors. The ultimate effect of combining colors in the right proportions is black. This process is commonly used in printing, where pigments are added and overlaid to a white background. The inclusion of black ink in CMYK printing is necessary for achieving a true black. The interplay between subtractive color mixing and lighting conditions can create diverse visual effects, particularly in digitally printed images illuminated by different color LEDs.

7 COLOUR THEORIES

The foundation of color theory began with the tri-color colorimetry theory proposed by Young and Helmholtz. According to this theory, the human eye contains three types of receptors that selectively respond to different wavelengths of light in proportion to their intensity. This theory focuses on the stimulus aspect and assumes that color perception is based on the response of these receptors.

Another color theory, known as the opponent color theory, was introduced by Hering. It emphasizes the basic response of the eye rather than the stimulus. Hering's theory suggests that there are six basic colors: red, yellow, green, blue, black, and white. These colors are organized into three pairs of opposing processes. For example, there is a blue-yellow opponent pair, which means that a color cannot simultaneously appear both bluish and yellowish. Blue cancels out yellow, and vice versa. The same principle applies to the red-green opponent pair. In the black-white pair, a color can shift towards black or white from gray, but not towards both at the same time. White does not cancel out black; instead, they blend to produce shades of gray.

Both the tri-color colorimetry theory and the opponent color theory are needed to explain color perception comprehensively. Each theory provides a different perspective on color and its perception.

To understand the sensation of light and color in the eye, it is essential to consider the three cones present in the retina. These cones have different photopigments that capture incoming light and have distinct response curves, as explained in the previous chapter on the eye. Each cone type has a peak response at different parts of the visible spectrum: one at the short wavelength end, one in the middle, and one at the long wavelength end. The perception of color by the visual system depends on the strength of the signals obtained from each cone type, following the well-known V-λ curve.

In summary, color perception is a complex phenomenon that can be explained by both the tri-color colorimetry theory and the opponent color theory. The response of different receptors in the eye, along with the interaction between different colors and opposing processes, contributes to the experience of color.

8 COLORIMETRY & MATHEMATICAL FORMULATION

Colorimetry is a scientific discipline that involves the measurement and systematic design of color. One of the fundamental aspects of colorimetry is color mixing and color matching. The initial development of the "chromaticity characteristics of standard observer" was carried out by W.D. Wright, J. Guild, and D. Judd. They conducted experiments involving seventeen individuals with normal color vision. The participants were tasked with matching monochromatic visual stimuli using three primary colors.

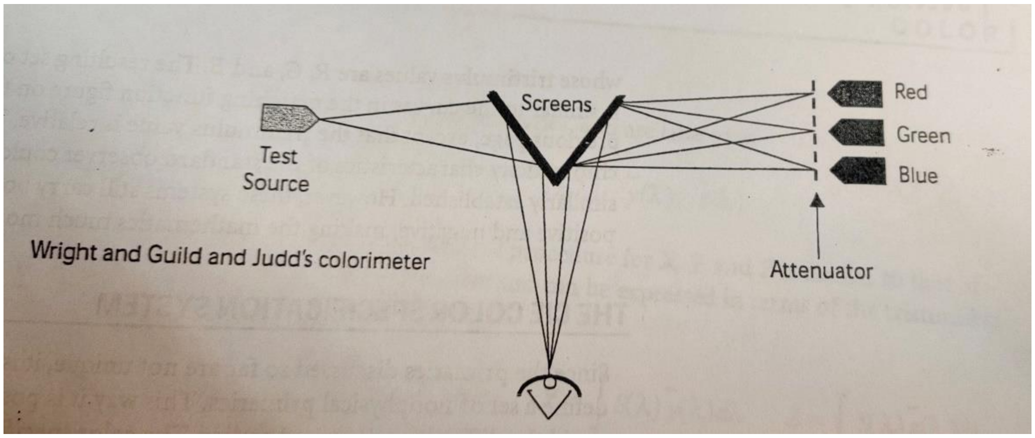


Fig. 3 Colour matching process -How much red, green, blue light needed to match the wavelength colour λ - very subject way by the individual observer.

However, the data obtained from the initial experiments lacked the necessary accuracy for precise color specification. These measurements were also influenced by individual observers, as well as the combined effects of luminance and color. While historically significant, they did not provide a strong foundation for color specification.

To address these limitations, two alternative approaches to color specification were developed. The first approach involves using tristimulus value curves, which are calibrated with respect to a reference white point. Through complex mathematical calculations and manipulations, tristimulus value curves were derived. However, this process was laborious and relative values introduced some drawbacks.

In the search for improved color specification, scientists explored and published alternative methods based on tristimulus values and color matching. These efforts aimed to overcome the limitations of the previous approaches and provide more accurate and reliable color specifications. Additive mixing of colour (Ref Fig. 1) can be being mathematically represent as

R +G = Yellow

G+B = Cyan

B+R = Magenta

R+G+B = White

Here, symbol "=" is used to represent matched equivalent. This trichromatic mixing however, follows algebraic law, i.e., any colour stimuli 'C' can be matched by adding R, G, and B and expressed as,

C(C) =R(R) +G (G) +B (B) …………… (1)

The symbols within brackets represent corresponding stimuli including the colour C to be matched. R, G, B and C are quantities or amounts of the stimuli. Now, as the stimuli is due to various quantities of reference lights only, we must have

C=R + G + B……………………………. (2)

Instead of using actual values of the quantities, a ratio of the matching stimuli can be used. Thus, dividing both sides of the equation (1) above by (R + G + B), we may write

$$1 = r + g + b \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where, r = R/(R + G + B); g = G/(R + G + B); b = B/ (R + G + B)

Thus, the equation (1) can be written as

$$1.0\ (C) = r\ (R) + g\ (G) + b\ (B) \ldots\ldots\ldots\ldots \quad (4)$$

The r, g and b are uniform. A white light is matched by equal amount of R (700 nm), G (546.1nm) and B (435.8nm).

It can be seen that it is possible to match all colours of the spectrum by means of additive mixture of three stimuli. This can be represented by curves as shown in Fig. 4 and are known as colour matching functions. It is to be noted that all three curves have negative portions but these are very small for blue and green.

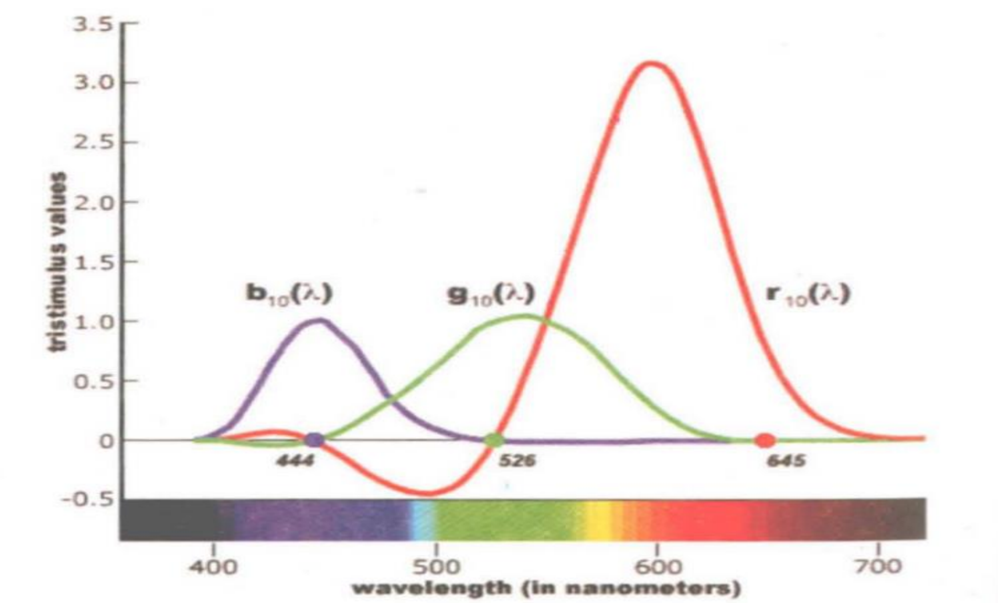


Fig. 4 Tristimulus value curves for r(λ), g(λ), b(λ)

In order to prevent the color matching functions from yielding negative values, a decision was made to transform the color axes. This transformation ensures that the functions remain non-negative at all times. To achieve this, the R, G, and B functions are converted into three imaginary primaries.

Additionally, one of the functions is aligned with the V (λ) standard observer curve, while another function is adjusted to be nearly equal to zero. This transformation helps ensure that the resulting values of the color matching functions are always positive or zero.

The International Commission on Illumination (CIE) has defined new stimuli denoted as X, Y, and Z. These values can be derived from the proportions of R, G, and B required for a color match using the transformation method. This approach allows for a more consistent and reliable representation of colors without the occurrence of negative values.

So, we have:

C(C) = X(X) + Y(Y) + Z (Z)……………………………….. (5)

Following the arguments given in 3.1, we can have,

1.0 (C) = x(X) + y(Y) + z (Z)……………………………….. (6)

where,

x = X/(X + Y + Z);

y =Y/(X + Y + Z);

z = Z/ (X + Y + Z) and

x + y + z = 1………………………………………………… (7)

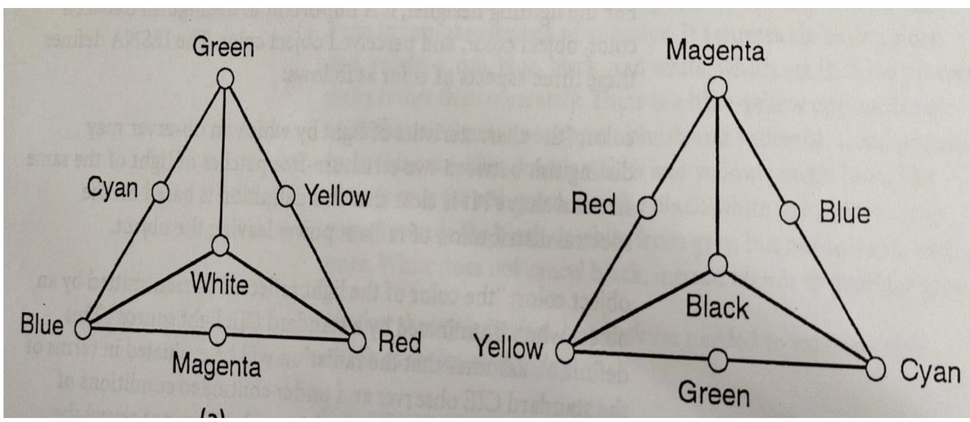


Fig. 5 Colour triangle placed at the corner and intermediate colours along the sides are the basic for understanding of the colour measurement.

9 PERCEIVED COLOUR

Understanding the distinctions between colors, object color, and perceived object color is crucial for lighting designers, especially in the context of sign lighting and the differentiation between reflected and emitted/transmitted light.

Colors in objects are essentially the result of their propensity to reflect certain types of light more prominently than others. To clarify these concepts, the Illuminating Engineering Society of North America (IESNA) provides the following definitions.

Color: "the characteristics of light that allow an observer to differentiate between two structure-free patches of light of the same size and shape." This is based on the spectral distribution of radiant energy emitted or transmitted by the object.

Object color: "the color of the light reflected or transmitted by an object when illuminated by a standard CIE light source." This definition assumes that the radiation is evaluated using the standard CIE observer under controlled viewing and adaptation conditions. Object color does not reveal the appearance of an object in a particular lighting environment, but rather categorizes its appearance when illuminated by specific light sources.

Perceived object color: "the color perceived as belonging to an object, resulting from the characteristics of the object, the incident light, the surround, the viewing direction, and observer adaptation." Perceived object color is influenced by the observer's past experiences, such as the surrounding environment, the colors last seen, and the observer's mood.

Therefore, lighting designers often focus on perceived color as it significantly influences how occupants feel about a lit space and perceive objects within it. While color can be quantified using the CIE system, it is important to note that a mathematical representation may not fully capture the overall effect a color has on a viewer. Two objects may appear to have the same color under one light source, such as an incandescent lamp, but differ in color under a different source like daylight or LED lighting.

The discussion on color mixing and matching, as well as the reference observer point, has already been covered in the earlier explanation of additive color mixing.

From the second theory, it becomes clear that color is a subjective perception resulting from a physical color stimulus. This stimulus is characterized by factors such as the spectrum and quantity of light, the size and shape of the stimulus, and the surrounding environment. The condition of the observer also plays a role, including their adaptation state.

Among the various systems developed for the practical quantitative classification of color, the A.H. Munsell model is widely used. This model defines perceived color using three attributes: HUE (the dominant spectral wavelength, encompassing monochromatic spectral colors like red, yellow, green, blue, and combinations of adjacent pairs of these colors, including purple and reddish shades of blue and red), VALUE (or lightness/brightness, representing the overall amount of light in the color stimulus), and CHROMA (or saturation, indicating the intensity or vividness of the hue). In the Munsell system, different hues are specified using hue surface colors, akin to the pages of a book (e.g., 5G for green, 5R for red, and 5YR for yellow-reddish). All colors converge at the axis of the Munsell book, where they are perceived as tints ranging from black to gray to white.

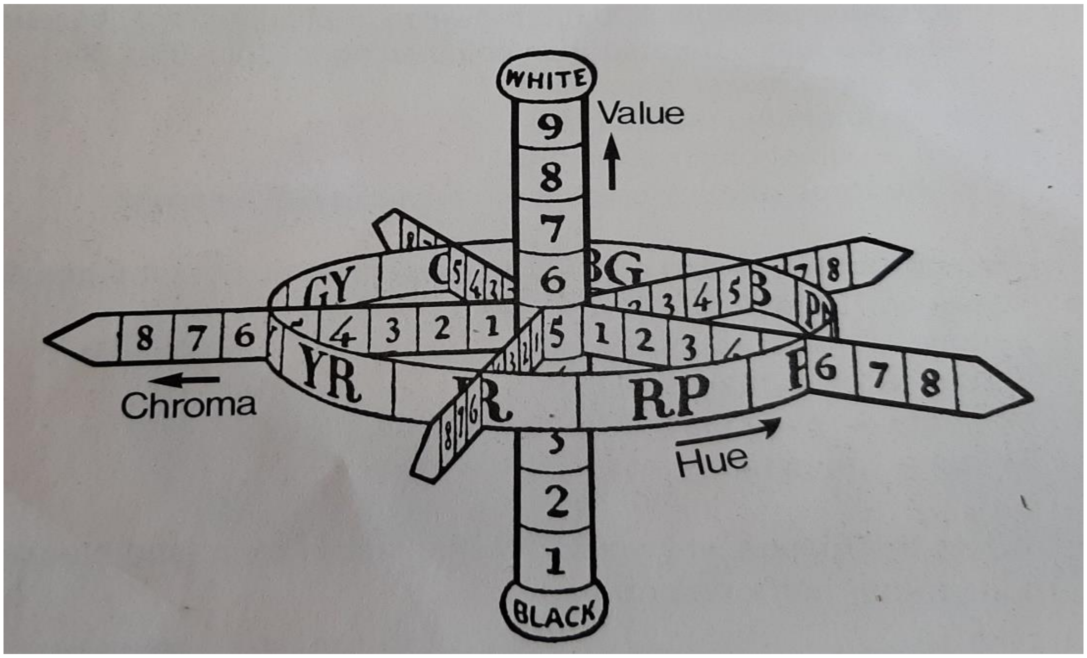


Fig 6. A.H. Munsell Model

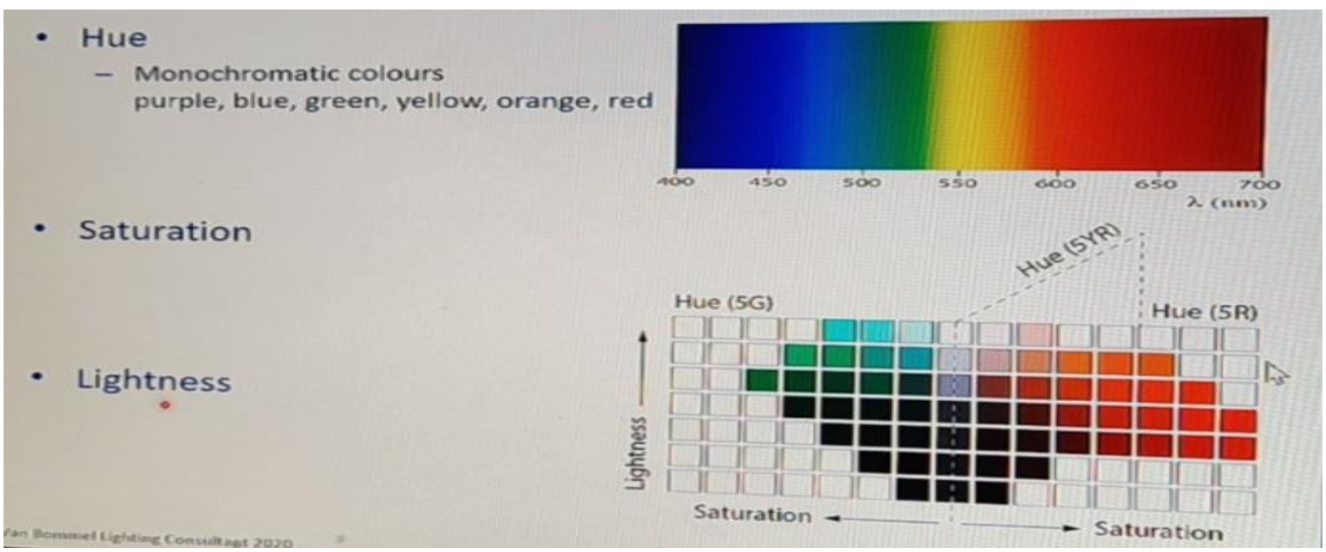


Fig. 7 Colour characteristics -Hue, Saturation, Lightness Courtesy Prof Vanbomel

10 THE CIE SYSTEM

All colours that can be produced by three primary colours can only be presented by in a three-dimensional space. However, by neglecting the effect of differences in brightness of the colour stimulus and concentrating on hue and saturation of the colour sensation only, a two-dimensional plane presentation is done here. In fact, one cross section of the three-dimensional space.

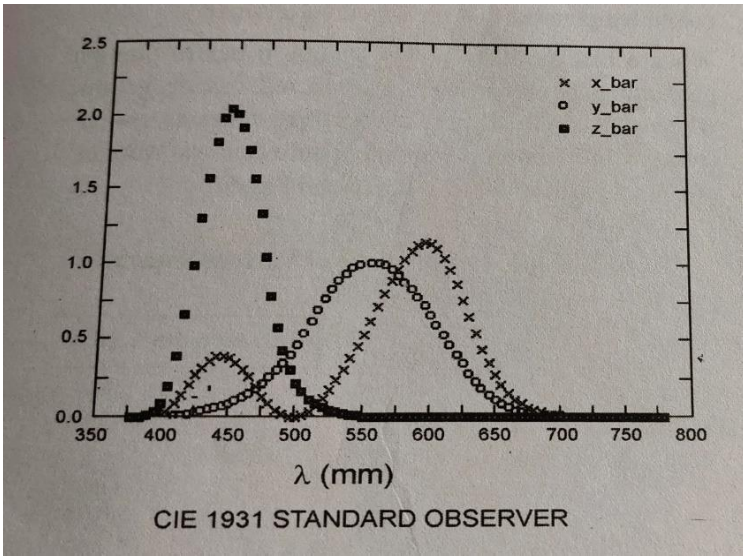


Fig. 8 CIE 1931 standard observer

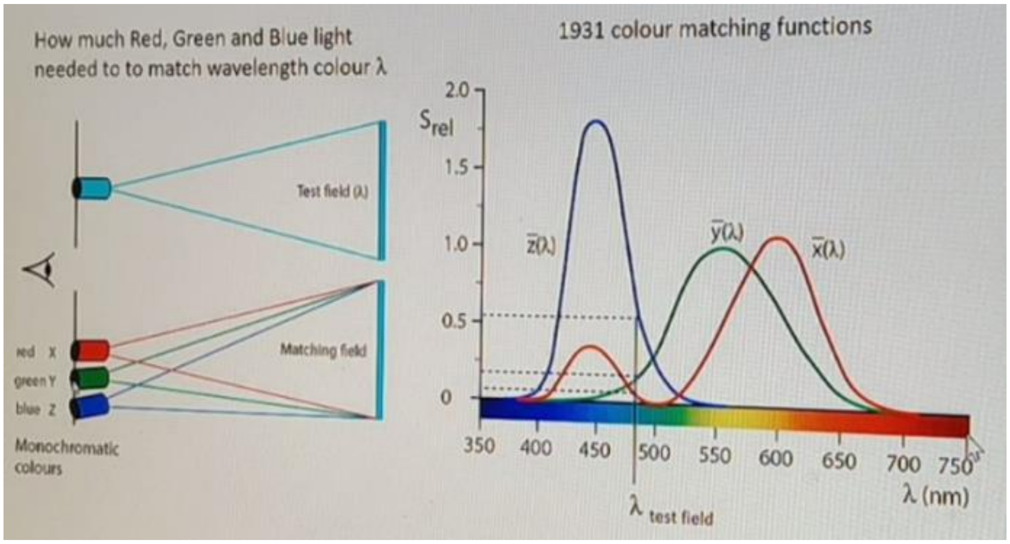


Fig. 9 CIE 1964 Colour matching & Tristimulus function*

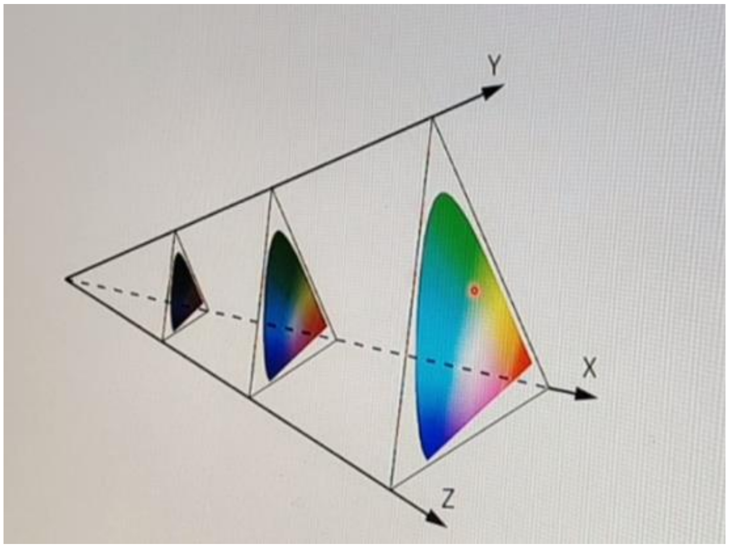


Fig. 10   X-Y-Z system to two-dimensional section X-Y*

*courtesy Prof Van Bomel

For defining colours in the two-dimensional plane, it needs to have its own coordinates that relate to the primary colours X, Y and Z of the three-dimensional space. These coordinates are defined by the relative amount of tristimulus values X, Y, and Z as shown in equation 6 in earlier of this section

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

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

these two coordinates used in a rectangular coordinating system.

International Commission on Illumination (CIE) developed three color matching functions that approximate the sensitivities of the three types of cones in the human eye: red, green, and blue. While based on additive color principles, this system also addresses its limitations. By multiplying the spectrum of a light source by these functions and applying mathematical transformations, a 3-coordinate system (X, Y, Z) and corresponding chromaticity coordinates (x, y, z) can be generated. The system was designed such that $x + y + z = 1$, allowing for color representation within the CIE 1931 color space using just the x and y values.

To make the system practical, two key changes were made. Firstly, the color triangle was "deformed" to provide more space for the representation of highly saturated spectral colors that are more distinguishable to the human eye. This primarily occurs in the green and blue regions of the spectrum, where subtle differences in color perception can be more easily observed. This led to the characteristic shape of the CIE color triangle, which is circumscribed by a curve known as the spectrum locus.

The second change involved plotting numerical color values along the axes of a right-angled triangle containing the color triangle. This allows each color to be defined by its x and y values, known as chromaticity coordinates. The CIE 1931 x, y coordinate diagram, shown in Figure 11, represents this system. The spectral colors are plotted along the sides of the triangle, while the primary colors (red, green, violet-blue) are placed at the corners. The base of the triangle represents the traditional color values between red and violet-blue, including various shades of purple that do not exist in the electromagnetic spectrum but can be obtained by mixing spectral red and violet-blue in different proportions. The x-coordinate runs along the bottom, the y-coordinate goes up the side, and the rounded triangle in the middle represents the various colors. The most saturated colors are found at the circumference of the color triangle, becoming lighter and less saturated as they move towards the center, where all colors meet to form white, in accordance with the principles of additive color mixing.

In comparison to the Munsell system, which defines colors using three characteristics (hue, value, and chroma), the CIE system determines hue based on the corresponding point on the spectrum locus, and chroma is determined by the distance to that point. Both hue and chroma are defined by the chromaticity coordinates of the color, known as the color point. In the CIE system, the value component is replaced by the reflectance of the colored surface for surface colors. Thus, in the CIE color system, a color is defined by its chromaticity coordinates (x and y) and, in the case of surface colors, by its reflectance value (ranging from 0 to 199). For example, x = 0.545, y = 0.389, and reflectance = 28.8 would represent a shade of orange.

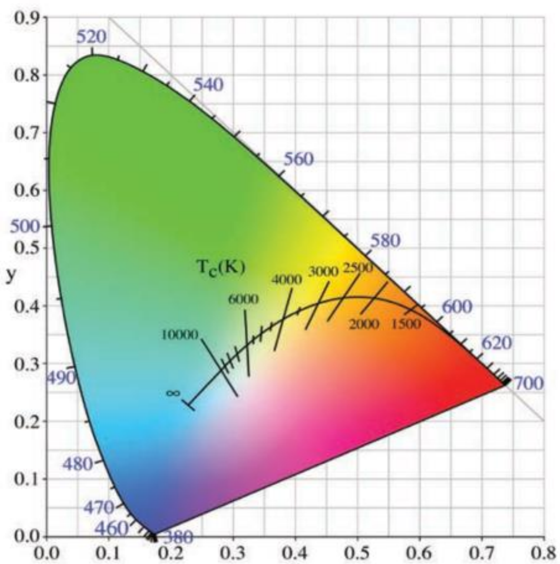


Fig. 11 CIE 1931 x, y co-ordinate diagram

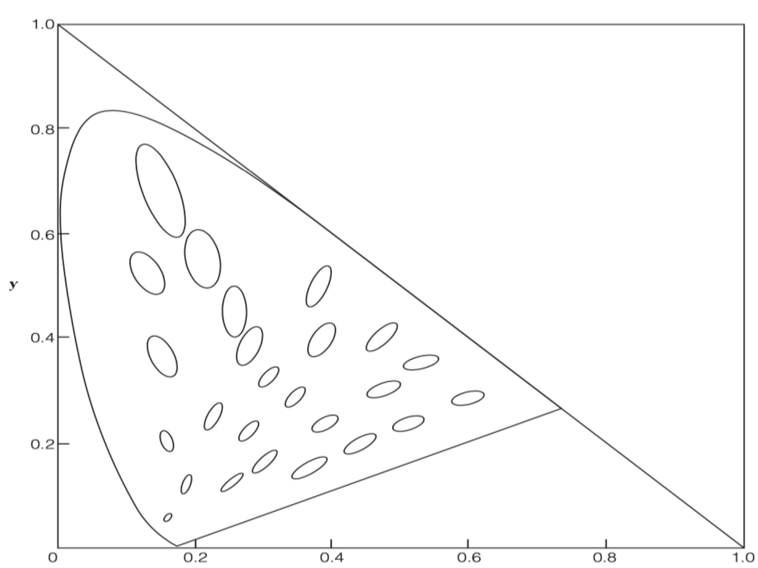
11 THE BLACK BODY LOCUS IN THE CIE COLOUR TRIANGLE, COLOUR APPEARANCE (CCT)

Color appearance refers to the perception of color resulting from the combination of different wavelengths entering our eyes. It is not an inherent characteristic of any surface. When determining how a color will appear under a specific light source, practical experience is often relied upon. In the Physics of Light chapter of this NLC review, the concept of a thermal radiator (black body radiator) has already been explained. When heated, such a body emits visible radiation with a color that is specific to its temperature. This color of light is referred to as "color temperature." A color temperature scale can be plotted within the CIE color triangle, forming a curve known as the "Black Body Locus" or the Planckian locus.

To compare the light characteristics of different light sources with those of thermal radiators in terms of color temperature, the concept of correlated color temperature (CCT) was introduced. It is important to note that these classifications are represented by lines perpendicular to the black body locus, rather than points. This means that two sources with the same CCT can actually have different colors. In the diagram below, the CCT lines for various temperatures such as 1500K, 2000K, 2500K, 3000K, 4000K, 6000K, and 10000K are labeled. The "K" stands for degrees on the Kelvin temperature scale, where 0 degrees Celsius is equivalent to 273 Kelvin.

12 MACADAM ELLIPSES & LED COLOUR AND BIN

Fig. 12, below is a representation of MacAdam ellipses drawn on the CIE 1931 Diagram. Note that the ellipses in the representation are magnified by a factor of 10. So, in reality they are actually very small. They are referred to as **Just Noticeable Differences,** or JNDs. Also note that, in practice, getting two fluorescent lamps, for example, within 3 JNDs is very difficult. For signs, differences of 5 or more JNDs might not be noticeable to the general public, depending on the circumstances. But more than 5 is not desirable at all in indoor lighting applications. Lower the colour MacAdam JND is required for very sensitive lighting applications like museum, shoplighting.



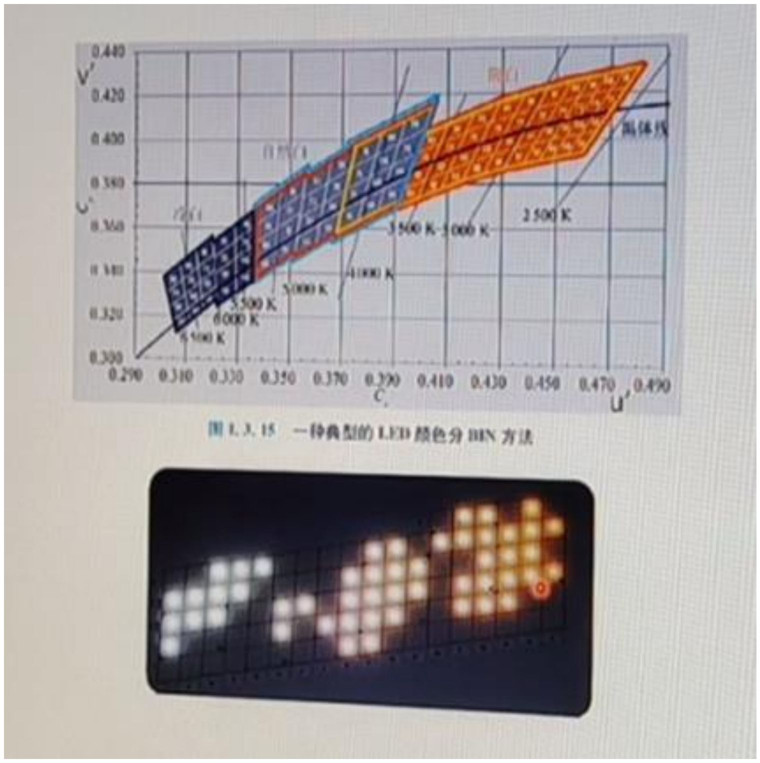


Fig. 12 Macadam Ellipse

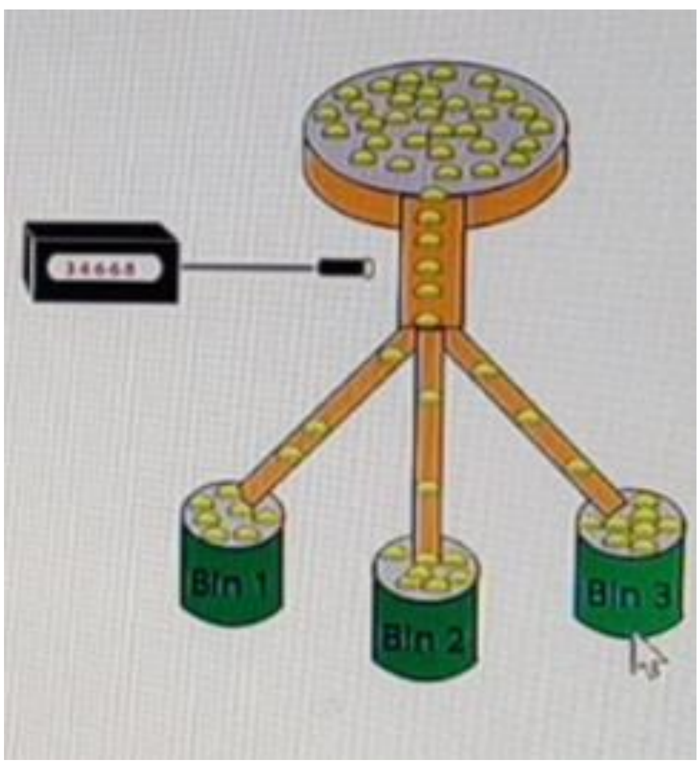


Fig. 13 Colour bin & Binning process of led manufacturing * *courtesy Prof Van Bomel

The color of an LED plays a crucial role in LED selection. LEDs typically emit light in a narrow spectrum, making their color specification important. The color emitted by an LED is determined by its peak wavelength (lpk), which represents the wavelength with the highest light output.
The color of an LED is primarily influenced by the semiconductor doping materials used and the chip fabrication process. Variations in the manufacturing process can result in slight deviations in the peak wavelength, typically within a range of around ±10nm. Figure 13 provides an example of color deviation due to these variations.
When choosing LED colors, it is important to consider that the human eye is most sensitive to hue or color variations in the yellow/orange region of the spectrum, specifically between approximately 560 to 600 nm. Even slight process variations can lead to noticeable differences in color, especially when using orange LEDs placed next to each other on a front panel. This consideration may impact color selection. Table 2 below serves as a guideline for color deviation and is commonly included in various product standards.

Table 2 Colour CCT Tolerance & Deviation

Sl. No	Nominal CCT[1)]	Target CCT and tolerance (K)	Target Duv and tolerance
(1)	(2)	(3)	(4)
1	2700 K	2725 ± 145	0.000 ± 0.006
2	3000 K	3045 ± 175	0.000 ± 0.006
3	3500 K	3465 ± 245	0.000 ± 0.006
4	4000 K	3985 ± 275	0.001 ± 0.006
5	4500 K	4503 ± 243	0.001 ± 0.006
6	5000 K	5028 ± 283	0.002 ± 0.006
7	5700 K	5665 ± 355	0.002 ± 0.006
8	6500 K	6530 ± 510	0.003 ± 0.006
9	Flexible CCT (2700 – 6500 K)	T[2)] ± ΔT[3)]	D_{uv}[4)] ± 0.006

13 COLOUR RENDERING

Color rendering is a measure of how accurately a light source reproduces colors compared to a reference light source. The reference light source is typically a blackbody radiator with a temperature suitable for the specific application. For example, a blackbody radiator with a spectrum at 4100 degrees Kelvin is often considered appropriate for office settings.

It is important to note that light sources with the same correlated color temperature may have the same color appearance, but this doesn't necessarily mean that surface colors will appear the same under these sources. The color of a surface is determined by the selective reflection of specific spectral wavelengths present in the light sources themselves. For instance, comparing monochromatic yellow light from low-pressure sodium lamps to that from an incandescent lamp with a yellow filter, even though the color appearance of the two light sources is the same, object colors can be distinguished much better under the light of incandescent lamps compared to sodium light where it becomes nearly impossible. This distinction is more evident when the light source is a thermal radiator, displaying a continuous spectrum with all wavelengths represented. However, for selective discharge lamps and solid-state lighting that emit selective spectral lines, color rendering may differ.

The color rendering capability of a selective radiator is determined by the number, arrangement, and relative intensity of spectral lines or bands present in its visible spectrum. These factors collectively determine how faithfully a range of surface colors can be reproduced under that particular light source. This capability is quantitatively assessed using the CIE's method, which involves eight test colors (R1 to R8). The color appearance of each test color under the light source is calculated as a percentage of its appearance under a blackbody radiator with the same color temperature. The average result of the eight samples is referred to as the color rendering index (Ra), which can range from 0 for monochromatic sources to 100 for blackbody radiation. However, values below 25 on the color rendering index scale typically have no practical significance. To account for additional mixed color object recognition, the CIE introduced six additional special color samples (R9 to R14) to complement the assessment.

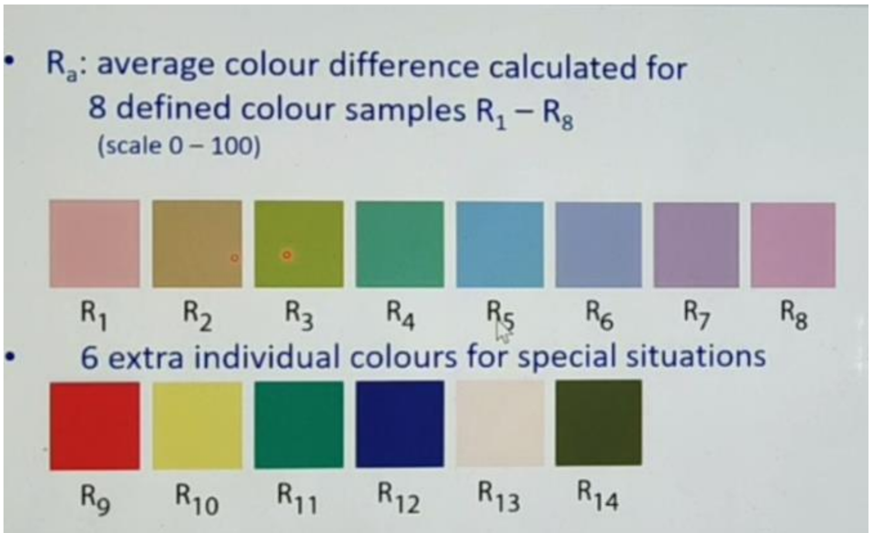


Fig. 14: CIE Colour Chart

For lighting application, classification guideline of colour rendition as follows
100- perfect match with black body

- 90 Excellent

80 to 89 Very good
70 to 79 Good
60 -69 Fair
50 o 59 Poor

14 IES TM 30 -2018 (Updated), CIE 2017 NEW METHOD OF COLOUR RENDITION

CIE 1965 method was working good for discharge lamps but not future proof with led lighting. With led light, the need of more quantification demanded. IES TM 30 able to remove the deficiencies of CIE old method. IESNA published TM30 IN 2015. Then further revised TM30 2018 published. The TM30 is now widely accepted.

IES colour rendition have three parts

a) FIDELITY Index Rf;
b) Gamut Index Rg; and
c) Colour Graphics/ Picture.

15 THE FIDELITY INDEX is a new index for color rendering, and it shares the same scale as the CIE system, ranging from 0 to 100. The calculation procedure for the Fidelity Index in the IES system has been improved by considering a three-dimensional color space, whereas the CIE system only considers two dimensions, as discussed earlier. The Fidelity Index incorporates 99 evenly distributed color samples within the color space, excluding extremes in saturation or darkness. The color fidelity index for each of these samples is obtained by calculating the color deviation. The overall color fidelity index is determined by averaging the results of the 99 individual test colors, referring to the CIECAM02-UCS model for guidance.

Fig.15 99 TM -30 COLOURS

Rg Gamut index characteristics “colour saturation”.
All colour spaces and chromaticity diagrams are designed so that so that more saturated colours are located outwards and unsaturated colours inwards. The saturation aspects of colour rendering of a specific light source is thus directly dependent on the direction of the colour shift of colour sample: shift outwards increses saturation and shift outwards decareses the saturation. The area obtained by connecting the chromaticity points of the colour samples when illuminated with a specific light source is called the gamut area. Larger the gamut area larger the saturation of colour obtained with that light source relative to reference light source.

In TM30, The **Gamut area Index, Rg** is the percentage of the gamut area of the test source relative to the area of the reference source. This is basically based on comparisons of a light source with that of a reference source, the same light source used for Rf value. TM30 gamut area based on chromatically coordinates of 16 colours (based on practical possibility) groups or colour bins and deviation is taken into account for calculations of CIECAM02-USC colour space.
When there is no shift the Rg value is 100. Rg value > 100 means increased saturation, Rg <100 means decreased saturation. Practically Rg scale is 60 to 140 for all lamps with Rf > 60.
Below colour graphics will give clear idea of saturation

16 IES COLOUR GRAPHICS

Below picture is termed as Colour Graphics or colour vector graphics. Here both test lamps have same Rf of 70 but one test samples colour vector graphics gone outside which is more saturated and other test lamp inside the reference lamp graphics hence have lower saturation.

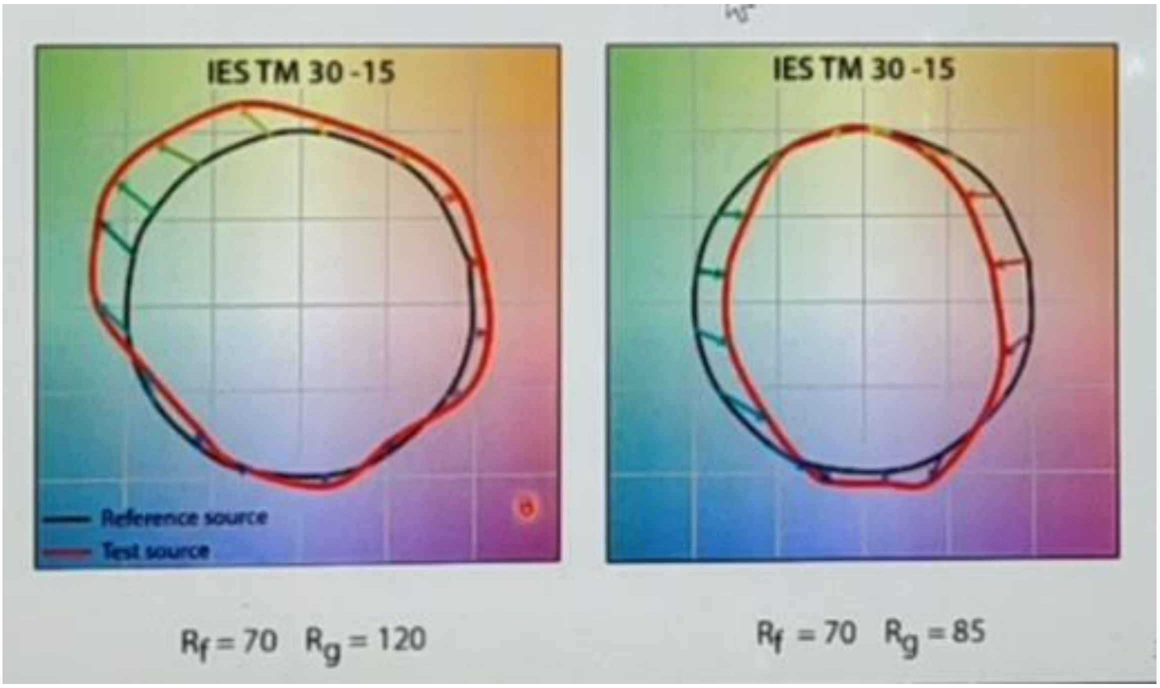


Fig. 16 Colour vector graphs visualizing the colour shift *

*courtesy Prof Van Bomel

Point to be noted that fidelity Index is suitable and mostly used in specification, regulation and standard but the gamut index is not used that way. This Rg tool is very important fr the lighting designer. The concept of these two helps them to blend best with colours of the object of the space to be illuminated.

> **Note:** So at the end in colour rendition both CIE & IESNA designation exist.
> Therefore, while defining the colour rendering index, one has to clarify which CRI is specifying. Is it CRI of CIE or CRI of IES system?

17 COLOUR DISCRIMINATION

This is a special aspects of colour rendering. It describes, whether slightly different colours, when seen simultaneously, can be distinguished as being different. These aspects of colour rendering is essentially there where colour difference can not be tolerated For example are in paint industry, the automobile damage repair sector and dentist practice. Farnsworth-Munsell 100 hue (FM100) test often used. Prof Wout van Bommel also developed a new colour measure of colour discrimination, Rd. It quantifies the number of cylindrical transpositions in the FM 100 test. Rd score of zero stands for superior colour discrimination, a score between 4 to 12 for average colour discrimination and a score of 16 or higher for poor colour discrimination.

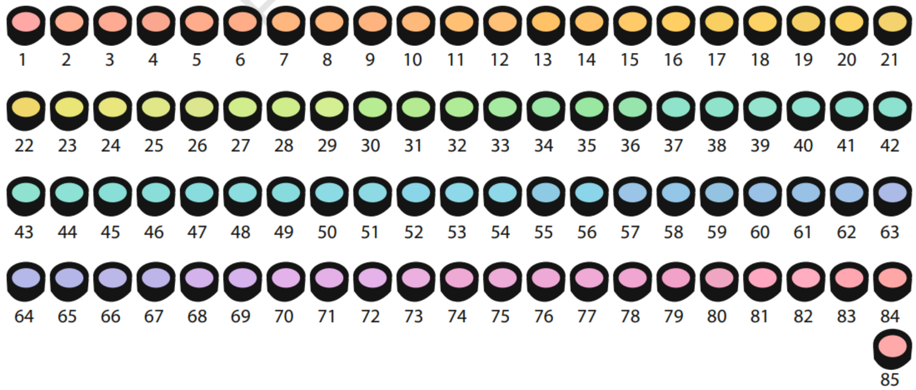


Fig. 17 Farnsworth-Munsell 100 hue (FM100) test cylinders *

***courtesy Prof Van Bomel

18 CONCLUSION

The physical characteristics of light is very important and complex to understand. Colour is not as simple matter due to the fact the way we perceive colour does not necessarily betray the way they are composed, and that both colour composition of light source and of the object which receive the light play a role. This is also very subjective and then lot of model/ theory based on majority of conscious decision.