SPECTRAL QUALITIES OF LIGHT: EFFECTS ON HUMAN PERCEPTION AND THE HUMAN VISUAL SYSTEM

by

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Abstract

By definition, light is a metric created solely for the visual response of human beings. As a result, nearly every lighting metric is weighted to accurately depict human responses. The first human visual response function was adopted in 1924 by the CIE, V(λ), and is still the primary function weighting for all other lighting metrics. However, V(λ) has obvious limitations, one being that it only includes contributions from long- and medium-wavelength photoreceptors. Therefore, V(λ) cannot accurately provide indication to visual acuity (VA). Because vision is a sense that humans rely so heavily on, causes for optimal vision are valued in order to create artificially lit spaces that emulate qualities on which the human visual systems thrives.

One factor of VA is pupillary diameter, which is dictated by many factors ranging from light spectra to emotional states. The formula $P(S/P)^x$ was derived to predict how average pupil size is influenced by general light spectra. Generally, the smaller the pupil, the greater VA. Per the formula, increased scotopic (V'(λ)) lumens result in smaller pupils. A rearrangement of the $P(S/P)^x$ formula provided a mathematical means for quantifying an illuminance reduction, later established by the IES as Equivalent Visual Efficiency (EVE) Factors. In theory, acceptable reduced illuminance levels result in less energy consumed. Not everyone saw the benefits of spectrally enhanced lighting though; the practicality, extent of application, and actual preference of light sources that allow the usage of EVE Factors remain a polarized subject.

Intrinsically photosensitive retinal ganglion cells (ipRGC) were discovered in 2002, after the derivation of the $P(S/P)^x$ formula. However, they are known to play a role in pupil size. Emotional and ipRGC contributions to pupil size are ambiguities that prove a weak point in the argument for reducing illuminance levels.

Overall, this report compiles and analyzes research over the past century. Initially, background information on light, metrics, light sources, and human biology is introduced. Then specifics on human vision follow. Arguments for and against IES EVE Factors are presented, and ultimately, a recommendation is provided on the implementation of EVE Factors. The Appendix houses example EVE calculations and values.

Table of Contents

List of Figures

List of Tables

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I would like to thank everyone at Mercer-Zimmerman, Inc. as well for the incredible introductory experience into the lighting industry. I could not have had a better first internship and it influenced me to fully pursue lighting. Also, a thank you to Kate Wimer at Mercer-Zimmerman is necessary for writing a letter of recommendation for me to enter the graduate school at Kansas State University, which led to the writing of this paper. I appreciate the friendships made and I acknowledge that my experience at Mercer-Zimmerman was a major factor in my success in academic and professional endeavors. Thank you all.

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Dedication

I dedicate this paper to my family, and specifically, my parents Dan and Shelley Wheeler. I am eternally grateful for your support and endless belief in my abilities and potential. I am fortunate to have such wonderful and successful role models and teachers; I aspire to be like the both of you.

Chapter 1 - Introduction

From the advent of human-controlled illumination with fire to the semiconductors that are becoming prevalent today, there have been enormous advances in the methods in which we as a species illuminate our surroundings. Many technologies have influenced how work was conducted and how social interactions commenced; now there is a greater interest in understanding and appreciating the physiological and biological impacts light has on people.

However, to most people, light is ubiquitous. Unless it stands out as exceptional or exceptionally poor, it often goes unnoticed. Therefore, many take light for granted and rarely think of its true value or implications. We understand that lighting is needed in and on buildings, vehicles and other means of transportation such as planes and trains, for streets and various pathways, but beyond that initial recognition of application, there is little else. Translating to the architectural design industry, we accept the designs that work, and replicate them for similar successes. Many times, final measurements and surveys are not conducted to identify issues, and even if they are, it can be difficult to understand the cause of the problems without dedicated investigation.

Indeed, light is not created equally, or rather, perceived equally. The vast majority of lighting design is intended to complement human activity. Therefore, it is critical as a lighting designer or engineer to understand the operation characteristics and processes of the visual and biological systems for those in which the lighting is designed. Spectral qualities affect how well light is processed in the visual system of humans, so given lighting designs can be perceived as too great or too little illumination depending on the specific lighting qualities. Moreover, there are numerous other bodily responses to light: circadian (biological sleep-wake cycles), neuroendocrine (physiological), and neurobehavioral (behavioral). The intention of this paper is to investigate the visual system of human beings to better understand perception and visual performance. The illumination adjustment factors, presented in the literature of the Illuminating Engineering Society (IES) entitled *The IES Lighting Handbook, 10th Edition* and *An Optional Method for Adjusting the Recommended Illuminance for Visually Demanding Tasks Within IES Illuminance Categories P through Y Based on Light Source Spectrum* (IES TM-24-13) are recognized. Additional literature and research are presented to understand the validity of these factors through the exploration of human biology and physiology, history, and light source characteristics.

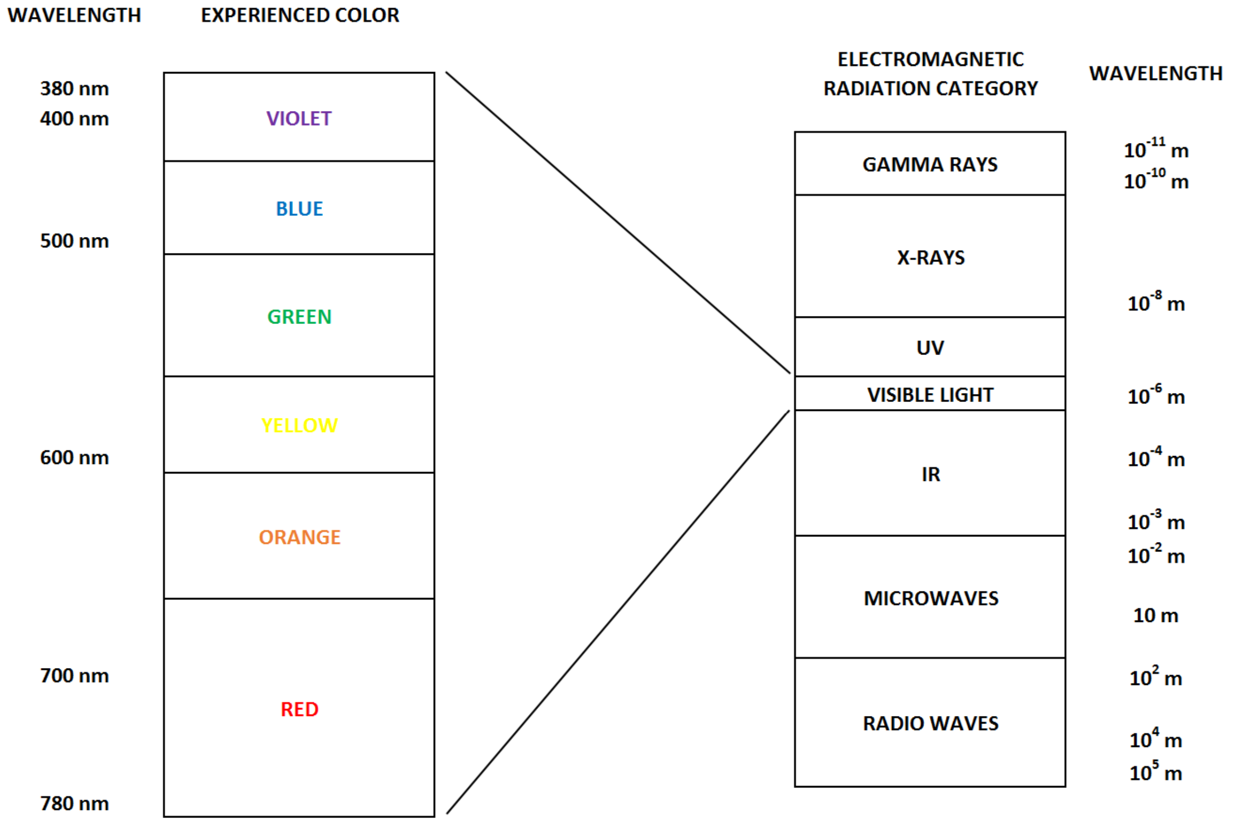
First, this paper begins with the definition of light, as well as metrics associated with the concept. Light metrics are a crucial component to understanding information presented in this document, and as such, these metrics are further explained in Chapter 3. Sequentially, Chapter 4 expands upon the spectral characteristics of light sources, which inherently lays the foundation for Chapter 9 where the discussion shifts from theory to implementation and design practice. Chapter 5 presents the basis for light and human biology and physiology, building further into higher-order body responses in Chapter 6 and Chapter 7. Light level altering factors are introduced and discussed in Chapter 8. This introduction teams with the light source and light metrics covered earlier in the report to conceive practicality out of theory in Chapter 9. Minor disputes are presented over the theory and application of factors changing light levels, in both Chapters 8 and 9, and these discussions are further explored in Chapter 10, in addition to the outcomes of the report and the author's recommendation for the subject of such factors. Finally, the factors themselves are documented and exemplified in Annex A, thus ending the rhetoric of this report.

Chapter 2 - Light and Metrics

Light is defined as optical radiation entering the eye that provides visual sensation in humans (IES, 2011). Optical radiation is a radiant energy that exists only between the wavelength boundaries of 100 nanometers and 10,000 nanometers (DiLaura et al, 2011). Dimensionally, light is the optical radiation that falls within the wavelength range of 380 to 780 nanometers; the shorter the wavelength, the greater the energy of the radiation. A depiction of the visible spectrum and its relation to the electromagnetic spectrum is given in Figure 2.1. Although countless living organisms are reactive and dependent to the effects of light and other regions of optical radiation, humans are only visually reactive to wavelengths between 380 nanometers and 780 nanometers. Therefore, the premise of light metrics and dimensions are exclusively dependent on the visual effect on humans. Thus, if the human species were to become extinct and replaced by another intelligent species, the definition of light as we know it would have to be rewritten. Optical radiation is a physical quantity, a wave-particle duality, whereas light is referencing a portion of optical radiation that stimulates the visual system; it is a psychophysical quantity, a perception (DiLaura et al, 2011). For the purpose of this publication, and the majority of illumination engineering, light will be classified as a wave only.

First and foremost, as a wave, light must incept from a source and propagate outwards until an object or force alters the direction of travel and quantity of light traveling through some sort of interaction. Such an interaction could include the forces of gravity that will bend light, transmission through different material densities, and reflection off of objects. The amplitude of light waves is an indication of power propagated, which can be integrated over the time of one wavelength to propagate for the time-average power, the aspect of radiant power required to characterize it for human vision, in addition to wavelength (DiLaura et al, 2011).

Figure 2.1: Electromagnetic and Visible Spectrums



Radiometry and Photometry

Photometry is a pertinent part of lighting design; it is technically the main category used for general illumination within a space. Photometry is a type of radiometry that refers only to the measurement of light. Radiometry, on the other hand, is the measure of all radiation. Both are typically programmed into the measuring capabilities of light meters and other detectors of optical radiation. Photometry is unique in that it is a combination of the spectral power distribution (SPD) of light with the Commission Internationale de l'Eclairage's (CIE) Standard Photopic Luminous Efficiency Function, V(λ), which is discussed in detail in Chapter 6 of this publication. In general terms, V(λ) provides indication of human sensitivity to various wavelengths within the visible spectrum at photopic light levels. The summation of weighted spectral power distribution measurement provides the luminous flux definition (DiLaura et al, 2011).

Spectral Qualities, Color Temperature, and Color Rendering

Spectral power distribution (SPD), also referred to as spectral power concentration in the international scene, expresses the radiant power emitted by a source over a range of wavelengths (DiLaura et al, 5.3). Spectral qualities and proportions are directly correlated with color temperature and color rendering. Color temperature and correlated color temperature (CCT) are discussed in Chapter 3 of this publication, and generally refers to the color appearance of the light source. Color rendering, on the other hand, refers to the ability of light to accurately display the colors of object(s) it is illuminating. This is measured by the color rendering index (CRI) and through the Illuminating Engineering Society's (IES) technical memorandum TM-30-15, *IES Method for Evaluating Light Source Color Rendition*. Despite the importance of color rendering abilities of light sources, it is generally beyond the scope of this publication. Rather, it is intended to introduce the concept of color rendering for general knowledge and the occasional reference throughout this discourse. Measuring spectra of light sources is accomplished through the use of spectroradiometers. These instruments come in numerous shapes and sizes, as well as sensitivities, but all accomplish a reading of types and quantities of various wavelengths of light.

Luminous Flux

Luminous flux, measured in lumens, is a common unit in lighting that is a time rate of flow of the quantity of photopic light emitted by a source (DiLaura et al, 2011). There are both photopic luminous flux and scotopic luminous flux variations, but the scotopic luminous flux is so uncommon that the term luminous flux will refer to the photopic luminous flux in this writing. However, scotopic luminous flux is integral to the method of determining a reduction in illuminance target values. In such cases, each type of luminous flux will be referred to specifically to avoid confusion. The important concept to internalize is that a lumen is a lumen. The only qualifier to categorize such as scotopic or photopic is the wavelength that the light wave exhibits, which will elicit a specific visual response in the human retina and, subsequently, the visual system. Human visual sensitivities to different wavelengths are covered in Chapter 6.

Light Source Efficacy

Light source efficacy is a term that refers to the effectiveness at which a light source can convert electric power into luminous power. This value is presented as a quotient of lumens emitted by the light source to the wattage consumed by the light source, thus providing a metric of lumens per watt (lm/w or LPW). Throughout this publication, the term light source efficacy will be referred to simply as efficacy.

Luminance versus Illuminance

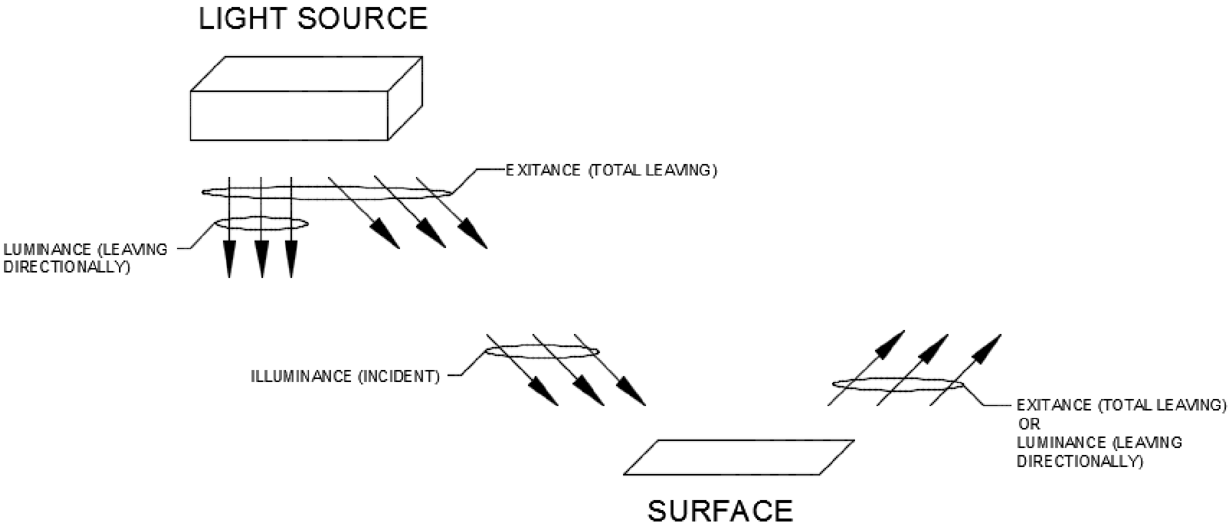
Luminance and illuminance are metrics in lighting that are easily confused. Figure 2.2 was created to aid in clearing the confusion. Luminance is a measure of light emitting power of a surface per unit area, in a particular direction (DiLaura et al, 2011). Illuminance, conversely, is the luminous flux density incident on a surface per unit area. Hence, there are two main differentiators: incidence versus emittance and directionality versus non-directionality. Luminance is only for the light emitting power of a surface (i.e. the light we see when we look at a given surface), while illuminance is only for the light that is falling on the surface. Moreover, luminance deals with a specific direction, much like a vector, causing the units to be luminous intensity per area, most commonly candela per square meter (cd/m^2). A candela is the unit used for light density and is the equivalent of light leaving a source with a density of one lumen per steradian. A steradian has an area such that there are always 4π steradians in a given sphere

(Russell, 2012). The use of a steradian for luminance is highly practical because light propagates out spherically, so the lumens passing through the steradian is constant despite the increasing size of the imaginary sphere. Illuminance does not take this directionality into consideration, and is thus lumens per area, lux (lx or lm/m^2) for Standard Internationale (SI) units and footcandles (fc or lm/ft^2) for the non-SI units. The footcandle unit for illuminance is most common in the United States. Unit conversion between lux and footcandles is a quotient of lux by 10.764 or a simple estimation of dividing by ten often suffices.

Exitance

Exitance is similar to illuminance in the fact that it has the same units (lm/ft^2 or lm/m^2) and has no indication to direction, but differs by referring to a different portion of light with respect to a surface. As stated previously, illuminance is the luminous flux density incident (falling) on a surface; exitance is the luminous flux density exiting (leaving) a surface. This is often used to quantify how bright a surface may appear, although it could be misinterpreted due to the fact that it does not take into account a direction. As a consequence, a specific viewing direction could vary from the quantification if the surface is not diffuse in nature. To ensure a more accurate representation of the brightness that a surface may appear, the luminance should be consulted. The interrelationships between such metrics are shown in Figure 2.2.

Figure 2.2: Diagram of Applicability of Common Light Metrics



Chapter 3 - Correlated Color Temperature

First and foremost, there should be a clarification of color temperature and correlated color temperature. Color temperature is an absolute measurement of the temperature of a blackbody radiator, an element that will be discussed in the following section. Correlated color temperature (CCT) is used to denote the color appearance of a light source with relation to the absolute metric of color temperature. The CCT is achieved by evaluating the proximity of the chromaticity of the light to that of the blackbody locus, which will also be discussed in the following section and can be seen in Figure 3.1. Therefore, color temperature is the absolute temperature of a blackbody radiator and CCT is the relation of chromaticity of a light source to that of the blackbody radiator absolute temperature in degrees Kelvin.

The Color Temperature Concept

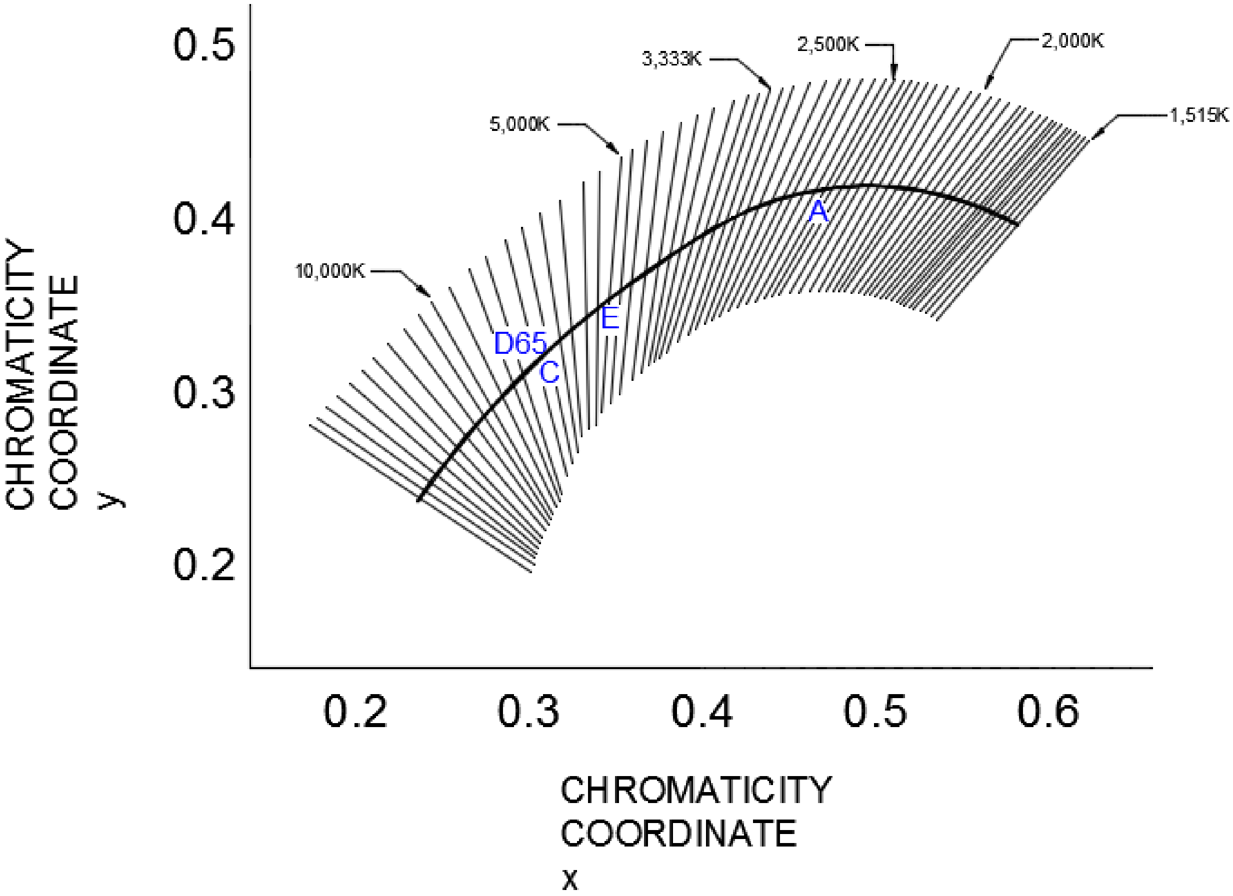
The color temperature metric revolves around the concept of a mental construct referred to as a blackbody radiator. This fictitious element is a theoretical metal that is heated to the point of incandescence. Spectral irradiance of the blackbody radiator varies as a function of temperature; thus, a system can be utilized to quickly and easily distinguish spectral qualities of light. The temperature of the theoretical blackbody radiator, in degrees Kelvin, is used as the metric to express the wavelengths of light produced.

To become better familiarized with the blackbody radiator concept, one should think of the behavior of a heated metal. When the metal is heated to the point where the metal itself is discharging heat, no light can be seen by the human eye. Indeed, electromagnetic radiation is propagating from the metal, but in the form of infrared light. Heated further, the metal will begin to produce dark red light. It is at this point that the radiator is capable of discharging enough energy that the wavelengths are shifting from the infrared portion of the electromagnetic spectrum to the visible spectrum. As more heat is added, the light produced will continue to change from the dark red to a red-orange, then orange, yellow-orange, yellow, and so on. As one can see, the addition of heat to the blackbody radiator increases the amount of energy that the fictitious element releases. Thus, the irradiance follows the electromagnetic spectrum in a predictable manner of lower level irradiance (infrared light) to increasingly higher levels of visible light. This path of irradiance is called the Planckian locus, or also referred to as the blackbody locus. It is upon this locus that metrics of light are related to.

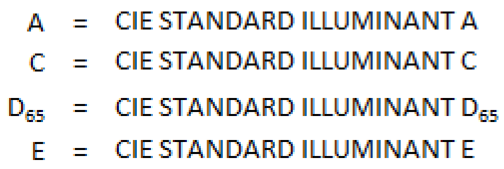
Correlated Color Temperature, CCT

Not all sources are heated to incandescence, however. Accordingly, there must be a metric to classify light from sources that is not characteristic of its temperature only. The correlated color temperature (CCT) is that metric. The CCT is conjured by referencing the Planckian locus that was discussed in the previous section. The Planckian locus is a function of chromaticity coordinates as a relationship to temperature. Therefore, if the chromaticity coordinates of a light source are represented on the Planckian locus, then the color temperature is simply used to describe color appearance of the light. If the chromaticity coordinates do not land on the Planckian locus, then the color appearance must be made with CCT. This is done by drawing lines that intersect the Planckian locus, referred to as iso-temperature lines, and quantifying the light chromaticity coordinates as the closest CCT iso-temperature line in degrees Kelvin (Boyce, 2003). The CCT metric is based on the chromaticity of the light emitted from the source and it will not always accurately characterize how “warm” or “cool” the light will appear. Figure 3.1 illustrates the Planckian locus (the bold curved line in Figure 3.1) and iso-temperature lines used for CCT quantification. Areas beyond the endpoints of the iso-temperature lines are areas exempt from CCT evaluation; these areas will return inaccurate results in actual color appearance versus the CCT value.

Figure 3.1: Diagram of the Planckian Locus and Associated CCTs (created from information in Boyce, 2003; Cuttle, 2015; DiLaura et al, 2011; Malacara, 2011; Rea, 2011)



A misleading notion with CCT is that two light sources of identical CCT values will be identical in appearance in light emitted. This statement is false. In referencing Figure 3.1, the iso-temperature lines extend on both sides of the Planckian locus. The length of the iso-temperature lines cross through numerous color regions that have a direct influence on the appearance of the tint that the light source appears to have. Therefore, light sources of equivalent CCT values but different chromaticity coordinates will display different appearances of light. Figure 3.1 also indicates chromaticity coordinates of standard illuminants. The standard illuminants will be covered at the conclusion of this chapter.



A = CIE STANDARD ILLUMINANT A
C = CIE STANDARD ILLUMINANT C
D_{65} = CIE STANDARD ILLUMINANT D_{65}
E = CIE STANDARD ILLUMINANT E

Chapter 4 - Light Sources and Their Characteristics

Man has harnessed light since the discovery of fire to perform visual tasks. Since then, numerous light source technologies have been founded and improved. For starters, fire was improved from igniting animal fat in hollowed out rocks to candles and oil lamps. Gas lamps were the next step in lighting technology, shortly followed by electric sources of incandescence and arc lamps. At the time of this writing, light emitting diode (LED) and organic light emitting diode (OLED) technologies are becoming more commonplace for illumination. Additionally, due to the extensive history mankind has had exposed to the sun and various light technologies, those relationships have defined evolutionary and perceptual traits associated with vision that people innately have today. Specifically, these traits are connected with spectral qualities of light and CCT, which will be discussed for each light source below.

Even before the advent of human-controlled fire, there was the sun. Primal peoples understood the value of the light that the sun provided – entire civilizations were built upon the premise of solar diurnal and seasonal characteristics, one of the most well-known being the ancient Egyptians. Without the sun and the precise relationship between the sun and Earth, sight, seasons, and even life would be absolutely altered, if not absent altogether. Therefore, it is imperative that the light from the sun is covered in this light source breakdown, especially since so many of the electrical sources are intended to mimic the characteristics of the sun.

The Sun

Located 92,905,807 miles from the earth, also termed an astronomic unit (AU), light from the sun takes about eight minutes and twenty seconds to traverse the distance (DiLaura et al, 2011, Loe & Tregenza, 2014; Michels, 1996). Our sun generates energy in the form of light, heat, and other radiation through nuclear fusion in the sun's core, a process of fusing hydrogen

(H) molecules to helium (He) and energy through immense pressure and temperature. That energy, in the form of light and heat, disperses from the core and after many redirections from collisions with densely packed atoms in the sun, arrives at the photosphere, the visible surface of the sun, where the energy finally propagates into space. The sun radiates energy across a majority of the electromagnetic spectrum, ranging from X-rays to radio waves, including the ultraviolet light (UV), visible spectrum, and infrared light (IR).

The sun is full of various types of elements and isotopes. This is important to the radiation produced by the sun. A myriad of temperatures exist throughout the sun; the characteristics of light emitted is dependent on both the type of atom and the temperature to which it is exposed to. Moreover, the absorbance of photons and the re-emittance of them at lower frequencies by solar plasma further affects the radiation qualities. The plethora of radiation types is the contributing factor to the vast coverage of the electromagnetic spectrum. Furthermore, the radiation will be refracted and reflected when interacting with the atmosphere of the Earth before finally reaching the planet's land and water. The Earth's atmosphere removes much of the harmful radiation from the sun, acting like a filter.

The atmosphere also contributes to the CCT of sunlight on Earth. Sunlight as we experience it on Earth is one of the most versatile in the sense of CCT variation. For instance, the CCT of sunlight at dawn or dusk can be valued around 2000K and at high noon the CCT could easily reach values around 10,000K during the same day. The variations in CCT of sunlight throughout the day are cyclical realities that humankind has experienced for thousands of years. Therefore, it has become a part of how people have evolved, and thus, necessary to reinforce circadian rhythms. Moreover, the spectral qualities of light during the middle of the day couple with the high illumination levels to provide a framework for which human physiology optimizes visual processes, largely due to the nature of the human species to perform a majority of tasks with illumination from the sun. As a result, humans are diurnal creatures.

Gaseous Light Sources

Gaseous light sources were used in both theatrical lighting installations and street illumination in the 19th century and prior. This source of light is accomplished through the combustion of a fuel in gas form, often sparked manually with a flame. Although different gases produce unique CCTs, most often the CCT is warm in nature, usually less than 3000K. Furthermore, CCT is likely to vary with intensity as well.

Incandescent Sources

All incandescent sources operate off the premise of running an electric current through a metal filament, usually tungsten, within a glass enclosure. The remaining space inside the glass enclosure is either a vacuum or halogen gas of some sort to aid in lamp longevity. Light is emitting from the filament once enough current is applied; the metal filament incandesces, hence the term incandescent. The greater the current, the higher that the temperature is and the greater quantity of visible light emitted from the lamp. Although this light source provides visible light, some UV light is transmitted but a great majority of the electromagnetic radiation that is emitted resides within the IR region of the electromagnetic spectrum. It is because of that reason that the energy notoriety of incandescent light sources exists – most of the output is heat instead of visible light. The amount of visible light that is emitted varies as a function of the quantity of current that is allowed to flow through the filament, but, generally speaking, when there is a maximum allowance of current flowing through the filament, CCT values typically range from 2700K-3500K with the CCT decreasing as the current is reduced and the light output is dimmed.

High-Intensity Discharge (HID) Sources

High-intensity discharge (HID) sources require a ballast for operating, which initiates and maintains voltage and current to obtain electricity arcing between two electrodes in a quartz arc tube. There are different types of gases and metals (halides) that can be mixed within the lamp envelope that alter the characteristics of the light emitted, efficacy and lamp life. These gases are types that are easily ionized at low temperatures, such as argon, xenon, and neon. Most HID sources are employed as illuminants of large areas, indoors and outdoors alike, due to the nature of large quantities of luminous flux. Regardless of specific HID technology, the spectral qualities of each remain fairly constant despite any change in intensity.

High Pressure Sodium (HPS)

High pressure sodium (HPS) light sources used to be more common prior to widespread metal halide and LED usage, but it is still relevant at the time of this writing. An electric current is passed through a blend of sodium and mercury, which is vaporized during operation, to produce optical radiation. When the HPS lamp is initially energized, it appears as slightly yellow-white in color. As it continues to heat, the light becomes warmer (more yellow-orange components) until operating temperatures have been reached and the color temperature stabilizes. The CCT options for HPS sources are limited, and all are within the range considered warm, approximately 2000K to 2800K. As the life of the lamp increases, the CCT typically decreases, producing an increasingly warm light.

Spectral qualities of HPS sources is dependent on the pressure at which the lamp is operating. Low pressure sodium (LPS) is a type of HID source, but due to the near extinction of this technology, it has been determined an irrelevant light source for practical design. However, mention should be made about the spectral qualities of LPS for comparison and greater understanding of spectral qualities of sodium HID sources as a function of lamp operating pressure. LPS light sources were commercially available as early as the 1930s, and the SPDs are nearly monochromatic; there is a double spectral peak at 589 nanometers and 589.6 nanometers (DiLaura et al, 2011). These values are in the section of the visible light spectrum that would be identified as orange. In a standard HPS lamp, spectral emission is dense in the region of 560 nanometers to 620 nanometers (yellow to red-orange), while even higher sodium pressures, sometimes referred to as super high pressure sodium, will not have any spectral emission around the 589 nanometer section that was inherent with the LPS sources (DiLaura et al, 2011). Instead, there are two major peaks in the SPD on either side of the 589 nanometer area, providing light in both the yellow-white and red-orange regions of the visible spectrum (DiLaura et al, 2011).

Metal Halide

Metal halide HID sources are the most common, and output large quantities of light so they are typically used for large areas both indoor and outdoor. The quartz arc tube is relatively small, which integrates with simply constructed complementary optical systems. The wavelengths of light produced can vary. A myriad of molecules and atoms can be configured to be excited by electrical current for the operation of metal halide lamps. Such could include sodium, scandium, tin, cesium, lithium, thulium, holmium, dysprosium, thallium, calcium, and others (DiLaura et al, 2011). The spectral characteristics of metal halide light are highly variant with regard to the metals that are employed in the irradiance process; each metal has a unique spectral radiation characteristic and the combination of all metals' unique outputs sums the entire light emitted from the source. A coating, or phosphor, can be used on the interior of the outermost glass envelope of the lamp. The phosphor can increase color rendering properties, but more often it absorbs ultraviolet light that is invariably a byproduct of metal halide radiation.

Although CCT values can range, typically 3200K to 8000K, the most common perceived color is a neutral or cool white. Metal halide lamps are the subject of a phenomenon referred to as color shift and color variance. Color shift is a matter of lamp life and lamp operating conditions, while color variance is more closely related to the manufacturing process. Color variance refers to the difference in spectral uniformity between newly operating metal halide lamps. Challenges in manufacturing that could affect color variance include electrode gap sizes, arc tube geometries and volumes, heat reflection, and halide density (DiLaura et al, 2011). Conversely, similar metal halide lamps of different operating times and operating conditions can appear different due to color shift. Factors that contribute to color shift are: tungsten transport as a result of reactions with impurities such as oxygen and water, reactions between the halide dose or arc tube walls or electrodes, and sodium ion diffusion through the arc tube wall (DiLaura et al, 2011). The point to take away from this section is that metal halide can produce light in multitudinous spectral forms that are dependent on manufacturer, CCT selection, color variance, and color shift.

Ceramic Metal Halide

Ceramic metal halide (CMH) is very similar to the operation and component characteristics of metal halide. The biggest difference between the two, however, is the construction of the arc tube within which the electrical arc emits light. For CMH sources, the arc tube is made of ceramic, hence the name. Moreover, the ceramic arc tube is commonly in an ovoid-type shape, which is only sometimes true for the quartz arc tubes of metal halide lamps. Ultimately, CMH lamps have better luminous efficiency, color rendering and color stability (greater resistance to color shift) due to the higher arc tube temperatures, which are possible because of the ceramic arc tubes (DiLaura et al, 2011).

Fluorescent Sources

At the time of this writing, fluorescent light sources are the most versatile and popular means of illuminating the surrounding world. From office spaces to classrooms, restrooms to signage, transition spaces to gyms, fluorescent reigns as a top contender. This is due to a few factors. First, the usage of fluorescent lamps has existed in the commercial lighting scene since the 1930's – a substantial amount of time. Therefore, the technology is heavily entrenched in the design and construction markets. Improvements in the technology have been continuously developed and built upon. Additionally, fluorescent light sources are incredibly versatile; multiple configurations of tubular fluorescents are used in recessed linear and troffer luminaires, as well as low and high-bay applications. Meanwhile, compact fluorescent lamps are easily installed in downlights, pendants, and some track lighting. The compact fluorescent light sources are ideal in replacing the shorter lived A-lamp incandescent light sources. Also, fluorescent lighting is capable of good color rendering and available in multiple lumen outputs. Lastly, a factor that is on every facility owner or manager's mind: cost. The cost for a fluorescent lamp is a few dollars and has a life span over 20,000 operating hours to improve the deal further. Overall, fluorescent lighting is a dominant force in the lighting market, although LED sources are starting to convert some of the fluorescent applications into markets for solid state technology.

Fluorescent light sources operate as a discharge lamp source type and require a ballast for operation. Electrodes on either end of the tube fire electrons that collide with mercury, often causing an electron in the mercury atom to "excite" and reach a higher energy level. As the electron returns to the lower energy level, a photon is emitted, usually with a wavelength that would classify it as UV light. Phosphors coat the inside of the tube envelope and absorb the UV light and release light in the visible spectrum as a product. The types of phosphors used in fluorescent lighting determines the spectral qualities of the light emitted from the lamp. As one can imagine, there are numerous phosphors that can be used to coat the inside of the fluorescent tube, providing a wide range of CCTs that a fluorescent lamp can exhibit. CCT ranges that are easily acquired for fluorescent lamps range from 2700K to 6500K in commercial practice. Furthermore, the CCT and spectral qualities of fluorescent sources are independent of luminous flux.

Induction Sources

Induction sources are similar to those of fluorescent. The main differences are that the tube is larger in diameter and there are no electrodes. Instead, it is subjected to an electromagnetic (EM) field. This increases the expected life by roughly a factor of three. Again, like fluorescents, phosphors are used to convert UV light to visible light. Therefore, the spectral qualities of the light is dependent upon the phosphors that are used. The author has seen CCT values commonly range from 3000K to 6000K for induction-based sources, and similar to fluorescent sources, the CCT is rarely influenced by the intensity of the light source.

Solid-State Light (SSL) Sources

Solid-state lighting sources are those that exhibit electroluminescence in operation. Electroluminescence is an optical and electrical phenomenon where a phosphorous material emits light when electricity is introduced to the material, either in the form of an electrical current or electrical field. There is great variance within the family of SSL light sources, but luminescence from a solid state is the binding characteristic between them all.

Light Emitting Diode (LED)

The light emitting diode (LED) is a solid state technology that has been used since the 1960s. However, it was primarily only capable of miniscule light output, about enough to operate as an indicator function rather than an illumination function. It was not until the twenty-first century that this semiconductor-based lighting technology reached a capability of adequate luminous flux to where it could be used as a compelling means for illumination.

LED technology is based upon injection luminescence. A semiconductor diode is a component that conducts electric current in only one direction, and whose resistivity potentially alters under the influence of electricity. The semiconductor crystals terminate on electrical terminals that create a positive negative (p-n) junction. This junction has been "doped" with positive and negative silicon variances to encourage the flow of electrons. When a forward biased voltage is applied to the p-n junction, electrons are injected into the positive region and holes – areas absent of electrons that otherwise electrons could be present – are injected into the negative region (DiLaura et al, 2011). Electron-hole recombination is a result of this unbalance of energy and light emission is the product. Ultimately, the type of materials that the diodes are constructed out of determines the spectral qualities of photon emissions.

LEDs, by nature, have very narrow bands of spectral wavelength characteristics. These narrow spectral regions of emission are combined and/or altered with phosphors to produce a fuller spectrum of light for common lighting applications. Typically short wavelength light is transformed into longer wavelength light with phosphor technology. LEDs commonly emit light in the shorter wavelength regions of the visible spectrum, and often some in the UV spectrum as well. Even with the addition of a phosphor, the emission tends to remain deficient in the longer wavelength regions. These are home to red wavelength visible light and R9, one of fourteen pigment values for determining color rendition (however only the first eight, R1 through R8, are used for the Color Rendering Index, CRI). To conquer this deficiency, multiple phosphors are combined and the resulting light is one of greater coverage throughout the entire spectrum.

Mixed or combined LED sources are another option for producing more usable optical radiation. In this scenario, multiple LED chips are used and the phosphor is omitted entirely. While both mixed LEDs and phosphor options operate through color addition methods, the mixed LED option requires more effort in the optics department of the chip. However, the mixed LED technologies allow for electronic control of color change through the enhancing or dimming of each colored chip. Moreover, there is no worry for phosphor degradation, which can become an issue if the LED with a phosphor is emitting too harmful of UV radiation. Also, mixed LED sources allow for more concentrated spectral power distributions, which reduce the visual losses of optical radiation invariably emitted with phosphor based technology, but may also reduce the overall coverage of the visible spectrum to peaks of spectral power at a small band of wavelengths that each LED is concentrated to emit. Regardless, the larger the number of chips that are added to the mixed LED option, the better the color rendition because the number of spectral power "peaks" are increased. For example, a three-chip RGB (red, green, blue) LED is likely to have three spectral power "peaks": one in the red, one in the green, and one in the blue region of the visible spectrum. Compare that to a four-chip RGBA (red, green, blue, amber) LED where there are four spectral power "peaks", each in the respective region of the visible spectrum as the color implies. The greater the coverage in the spectral power distribution (SPD) of a light source, the better the color rendition will be. Additionally, the CCT is dependent on relational quantities of light wavelengths in one region versus others.

Lastly, there is a hybrid choice of combining mixed LEDs with phosphors. In this installation, there is usually an LED chip for short-wavelength light (blue) and an LED chip for long wavelength light (red). The middle of the visible spectrum is covered by utilizing phosphors that alter a portion of the short-wavelength light to green and yellow emissions.

Typically, this results in superior efficacy and color rendering than the other options, but, regardless, CCT is still a value of selection and manipulation.

With the numerous combinations and methods with which LEDs can emit different wavelengths of light, the possibilities are immense when it comes to CCT and spectral qualities. As it was mentioned earlier, the CCT of LEDs can be altered electronically via signal from a driver for automatic, seamless dynamics. Therefore, to have a more accurate prediction on the human visual, circadian, neuroendocrine, and neurobehavioral responses, spectral qualities of each LED source must be evaluated.

Organic Light Emitting Diodes (OLED)

Similar to LED technology, organic light emitting diode (OLED) technology struggled to generate enough luminous flux to be a contender in the selection of light sources used for illumination. Even now, there is not a great amount of light emitted by the OLED sources themselves when compared to multiple other sources. However, the efficacy is improving to around 30 lumens per watt, which does not rival that of its SSL cousin LEDs, but does trump that of conventional incandescent light sources.

OLEDs are comprised of multiple organic, semi conductive layers instead of the non-organic positive and negative junctions in an LED. The organic material is the engine behind the production of electrons and the electron holes – it is a natural process that is capitalized upon to provide visible light. The layers that complete the OLED are incredibly thin – about three millimeters thick – and flexible. Each side of the outermost layers need a protective shield. The shield on the light emission side must be a clear material that allows light to pass. In between the shields are four layers: the cathode, the emissive layer, the conductive layer, and the anode, listed from top to bottom. The cathode and anode are where the voltage is applied to create the flow of electricity. Once this starts, the emissive layer, adjacent to the cathode, gains electrons while the conductive layer, adjacent to the anode, loses electrons. In other words, the emissive layer becomes negatively charged and the conductive layer becomes positively charged, which creates a similar scenario to the p-n junction in an LED. When the electron holes in the conductive layer are filled with electrons in the emissive layer, a photon is released – the OLED emits light.

As for CCT of OLEDs, it is customizable. Fibers and other filters can be added to the layers in the OLED module to manipulate the emitted light as desired.

Standard Light Sources versus Standard Illuminants

After covering many common light sources, it is important to introduce standard illuminants and differentiate them from standard light sources. Everything previously mentioned in this chapter, both naturally and electrically occurring, are standard light sources – they physically exist in reality. Standard illuminants, instead, are numerical descriptions of ideal light sources categorized by their SPD's; they do not physically exist. Malacara writes in *Color Vision and Colorimetry* that, "the absolute value of their spectral radiance is not important. The important factor is variation with the wavelength, so that it can be multiplied by any desired arbitrary constant, and thus the relative spectral radiances can be obtained" (Malacara, 2011, p. 35). Three standard illuminants were initially recommended by the Commission Internationale de l'Eclairage (CIE), termed illuminants A, B, and C. Illuminant B was intended to mimic noon sunlight while illuminant C was intended to demonstrate an average daylight, although it does not have equivalent quantities of UV compared to average daylight (Malacara, 2011). Because of such great fluctuations in the experienced sunlight on Earth for various times of the day or year, or any time weather depending, proved too great a feat for illuminants B and C to adequately represent; they were discontinued. The cure for the absence of daylight standard illuminants came in the form of D-series illuminants. Three were recommended by the CIE as D_{55} (5500K), D_{65} (6500K), D_{75} (7500K). The D_{65} illuminant represents average daylight, similar to the previous illuminant C, but has improved characteristics to better align representation (Malacara, 2011). There are also F-series illuminants that fluorescents are modeled after. Overall, illuminants are important to standard light source technology, as well as the impending colorimetry and color control. For the sake of this writing, a brief knowledge is preferred to better understand the relationship between standard light sources and standard illuminants. Standard illuminants A, C, and D_{65} are shown in Figure 3.1 in relation to the Planckian locus and CCT iso-temperature lines.

Common CCTs and Applications

As one should notice from the light sources previously listed, there are a multitude of options when it comes to choosing a source to illuminate a space. And there are even more options of CCT and CRI values and specific spectral qualities. Yet when it comes to common spaces, such as a classroom, office, library or waiting room, specific lighting characteristics come to mind. This is even truer when we inspect residential lighting. Although we are seeing a shift in technology preferences, especially in commercial applications, many older technologies are entrenched in western culture design philosophies and expectations. For example, residential applications almost always employ warm CCT lighting; we expect this type of feeling in a residential setting. Much of this is attributed to the history of how residential properties were illuminated. From the firelight of candles and oil lamps to the incandescent lamp, all early sources of light were generally radiating longer wavelengths of light that are associated with the warm part of the visible spectrum, many spilling into the infrared portion as well. At the time of this writing, compact fluorescent and LED replacement A-lamps are becoming more commonplace in residential illumination. Despite this shift in technology, our affinity with warm CCTs still exists because of the familiarity with them; light of longer wavelengths has a tendency to make a space feel more intimate and calm. Although part of this phenomenon is due to the historical familiarity, other parts can be attributed to the neuroendocrine effects and a calming perceptual association that the lack of short wavelength light produces in the human body. Overall, residential applications have, and will, typically use light sources that are capable of producing light with CCT values within a range of about 2600K to 3500K.

Commercial applications are much more skewed. Indeed, 3000K to 4000K is a frequent CCT range for many common lighting applications in the commercial world. But this range was not as broad as it is at the time of this writing. It was not uncommon for many commercial applications, such as offices and classrooms, to have fluorescent lighting with a CCT of 3000K in the 1990's – some offices and schools still have this type of light in use. But as time trudged on, cooler CCT values became more favorable, maybe with slight coincidence as the timing coincided with the publishing of scientific studies about human productivity and circadian system impact with shorter-wavelength optical radiation. It is the author's understanding that nearly all commercial applications that are used for learning and immediate conduct of business standardize a range of CCT values from 4000K to 5000K; all of such spaces that the author has worked on designing have landed within this range. Studies continue to be produced that determine human compatibility and preference with CCT values in various spaces. Multiple studies will be elaborated in later sections in this document.

Street lighting has evolved over the years as well. From the beginnings of street lighting employing gas with manual ignition to high-pressure sodium, the CCT has historically been relatively warm. The lack of adequate color rendition with high-pressure sodium sources, however, has led to the increasing transition to metal halide and LEDs to illuminate streets and pedestrian pathways. Both metal halide and the LEDs that are specified are of cooler CCTs, commonly around 4000K-5000K. Therefore, it is becoming more common to see street, site, and pathway lighting that is a crisp white.

Chapter 5 - The Human Visual System

Light is necessary for people to see. Vision has been dubbed one of the most complex human senses, and perhaps one that is most vital to the navigation and interaction with the world. The human visual system is not exclusive to the eyes or brain; rather, it relies on the unity between the two. Thus far, qualities of light have been covered in order to build a foundation upon which an understanding of biological systems can exist. Now this chapter will introduce and delve into the components, operations, and perceptual characteristics of the human visual system.

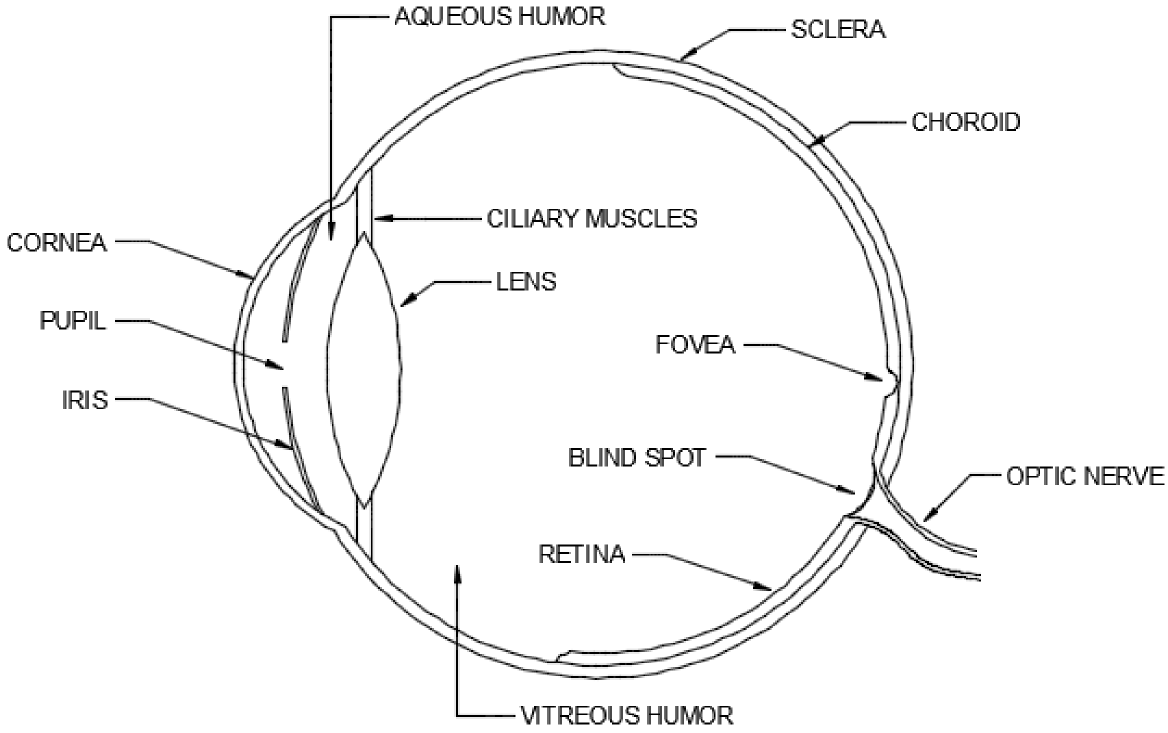
Structure of the Human Visual System

As mentioned in the previous paragraph, the human visual system is comprised of both eyes and brain, connected by the optic nerve. Therefore, there are many components that collaborate to produce the visual images that can be understood, contemplated, acted upon, and so forth. The structural breakdown will commence just as the visual system works: first with the eye, followed by the optic nerve, optic chiasm, and optic tract, finishing with numerous components in the brain.

The Human Eye(s)

The frontally mounted eyes of the human species provide significant overlap of the two visual fields, which results in exceptional depth perception. As one can expect, there are many optical and processing components that work in unison to translate photic (light) signals into decipherable electrical signals for the rest of the visual system to transmit and process. As the components of the eyes are announced and detailed, their individual contributions to the functionality of the optical and visual system will be better understood. Reference to Figure 5.1 will enhance the understanding of locations and geometries of optical components in the eye.

Figure 5.1: Diagram of the Human Eye



Sclera

Starting at the most exterior of the eye, is the sclera. The sclera is an opaque, relatively thick and tough, white outer layer of the eye that contains blood vessels (DiLaura et al, 2011). This component is the first line of defense in the protection of the eye.

Cornea

The cornea is an extension of the sclera at the front of the eye, one that is clear so light can pass through. Unlike the sclera, however, the cornea has no blood vessels but instead houses nerve receptors to help protect the eye from danger. Moreover, it is curved to provide about two-thirds of the eye's focusing abilities (DiLaura et al, 2011).

Choriod

The choroid resides just inside the sclera covering most of the back portion of the eye. The choroid is a thin, dark layer and brings the blood from the sclera into the interior of the eye. It is important that the choroid is dark; the pigment epithelium causes the layer to be dark and results in a high absorption rate of light, mitigating any reflectance that would cause light to scatter across the inner part of the eye (DiLaura et al, 2011).

Ciliary Body and Aqueous Humor

As the choroid approaches the front of the eye, it gives way from the sclera to the ciliary body. This component of the eye is responsible for producing a fluid between the cornea and the lens, which forms the aqueous humor. The aqueous humor provides oxygen and nutrients to the cornea and lens, and takes away their waste (Boyce, 2003). Consequentially, the aqueous humor is continuously absorbed and regenerated.

Iris and Pupil

The iris consists of two layers, an inner one with blood vessels and an outer one with pigments (Di Laura et al, 2011). Together, it forms a circular opening into the eye, referred to as the pupil. The pupil dilates and contracts based on the size of object(s) in the field of view, amount of light, emotions, and spectral qualities of light that enters the eye. This is controlled through two different sets of muscles that communicate with the brain, which gets its information from photoreceptors in the eye. It is a self-perpetuating and reactive cycle. The size of the pupil is unique to each person. For instance, if two people are in the same space experiencing the same retinal illuminances and spectral compositions of light, the diameter of one individual's pupils could very well be different from that of the other's. A truly accurate calculation of a specific person's pupil diameter is not possible until actual measurements have been taken to see the limits of the individual's iris' dilation and constriction to each lighting scenario. Even then, the emotional state of that individual could differ, independent of the lighting, and skew the calculations predicting actual pupil size. A typical pupil diameter for young people ranges from three millimeters to eight millimeters (DiLaura et al, 2011).

Lens

The lens is located directly behind the pupil and is a multilayered, double convex structure (DiLaura et al, 2011). It bulges or flattens to change its focal length for optimal dynamic focusing. For close range focusing, the lens flattens; conversely, the lens bulges for focusing at great distances. This is achievable from connected ciliary muscles that contract or relax.

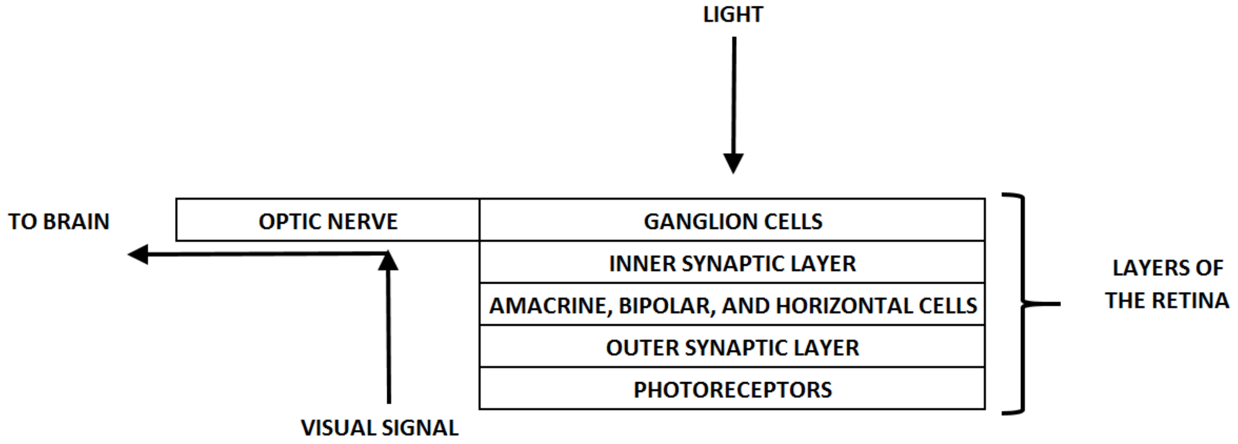
Vitreous Humor

Similar to the aqueous humor, the vitreous humor is a fluid chamber. While the aqueous humor is clear, watery, and located at the front of the eye, the vitreous humor is jelly-like, less clear, and located at the back of the eye. The combination of the amount of fluid in the aqueous humor and vitreous humor result in a pressurization on the surrounding eye structures (Di Laura et al, 2011).

Retina

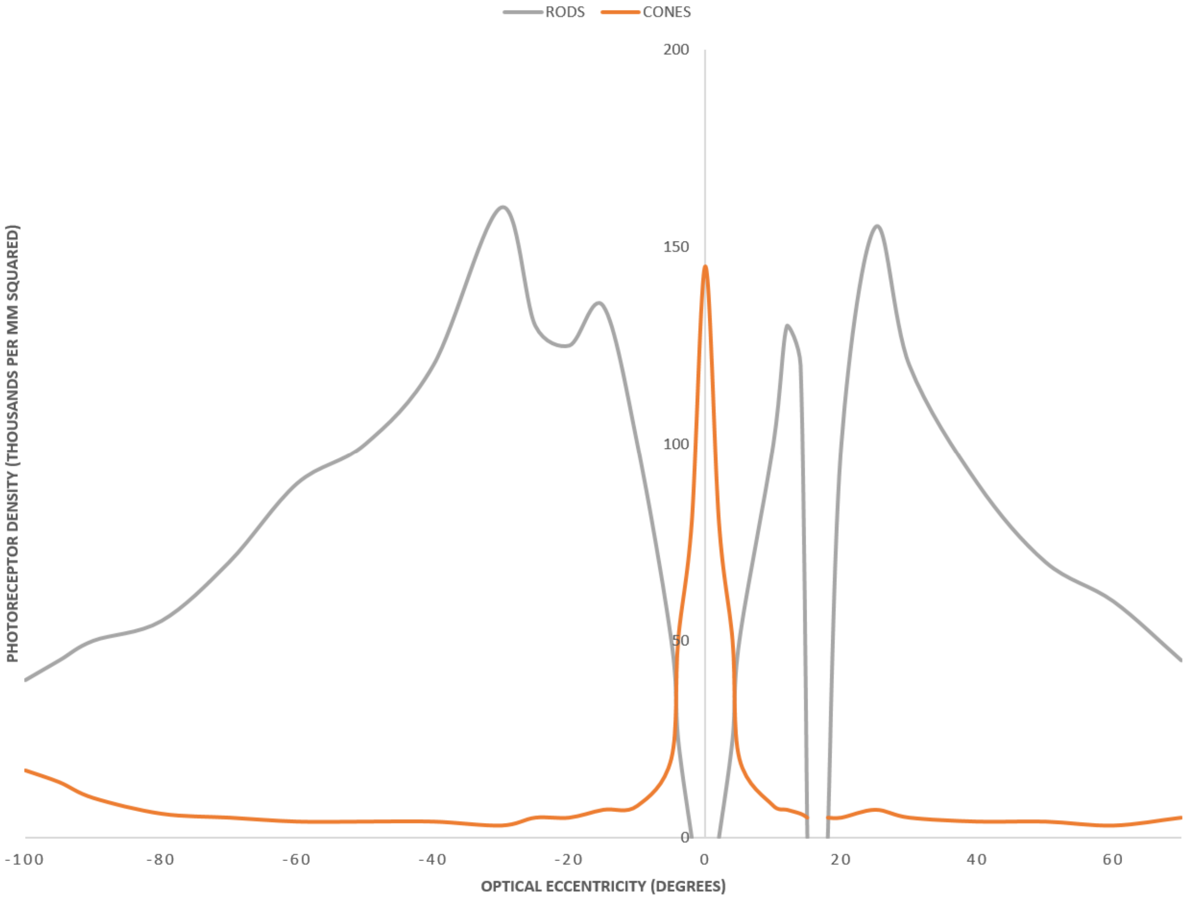
The retina is where the optical pathway ends and the visual pathway begins. The retina is a complex structure in the visual system, and is often considered an extension of the brain. This is due to the direct connection with the brain via the optic nerve and the ability of the retina to perform initial processing of photic signals before dispatching it to the brain for further processing. The retina is located at the back of the eye and consists of many hundreds of millions of photoreceptors, horizontal cells, amacrine cells, bipolar cells, and ganglion cells, all

Figure 5.2: Schematic of Light Signals Translated and Transported as Electrical Visual Signals



composing several layers of the retina (IES, 2011). The construction and orientation of the retinal layers is schematically depicted in Figure 5.2, as well as the direction of light and visual signals. The central part of the retina, which is described as a pit and is located from zero to around two degrees from the optical axis, is termed the fovea. This small region is very dense in cones – approximately 8 million – but has a complete absence of rods. Instead, the rods are located along the peripherals of the retina, peaking at about eighteen degrees. Bridging the fovea and peripherals is the macula – it houses a mix of both rods and cones. Locale densities of photoreceptors is approximated in Figure 5.3. There are many more rods than there are cones, about 120 million in total (IES, 2008). The greatest visual resolution is possible in the fovea, which is completely attributed to the density of cone photoreceptors and the proportion of cones to ganglion cells in the fovea. The fewer cones that are supplying information to the ganglion cell, the smaller the receptive field, which increases spatial resolution (IES, 2011). Photoreceptors and ganglion cells will be covered in upcoming sections. The visual system works in such a way that rods detect motion on the peripherals of the visual field, which creates a response to turn the head and/or move the direction of the eyes in order for the cause of the rods' detection to be translated onto the fovea for visual processing. Obviously, the macula and entire retina are involved in the visual process, but the center of vision, the fovea, is the location that the optical components in the eye aim to project the image.

Figure 5.3: Approximate Density of Photoreceptors in the Retina (created from information provided in Boyce, 2003; IES, 2011; Malacara, 2011)



Photoreceptors

Photoreceptors absorb optical radiation and transform it into electrical signals. There are two main types of photoreceptors in the human eye: rods and cones. Both rods and cones continuously increase their electrical activity in dark conditions, known as *depolarization*. However, when light is absorbed by a photoreceptor, they stop firing, which is referred to as *hyperpolarization* (IES, 2011). The change in electrical signals is what creates visual information.

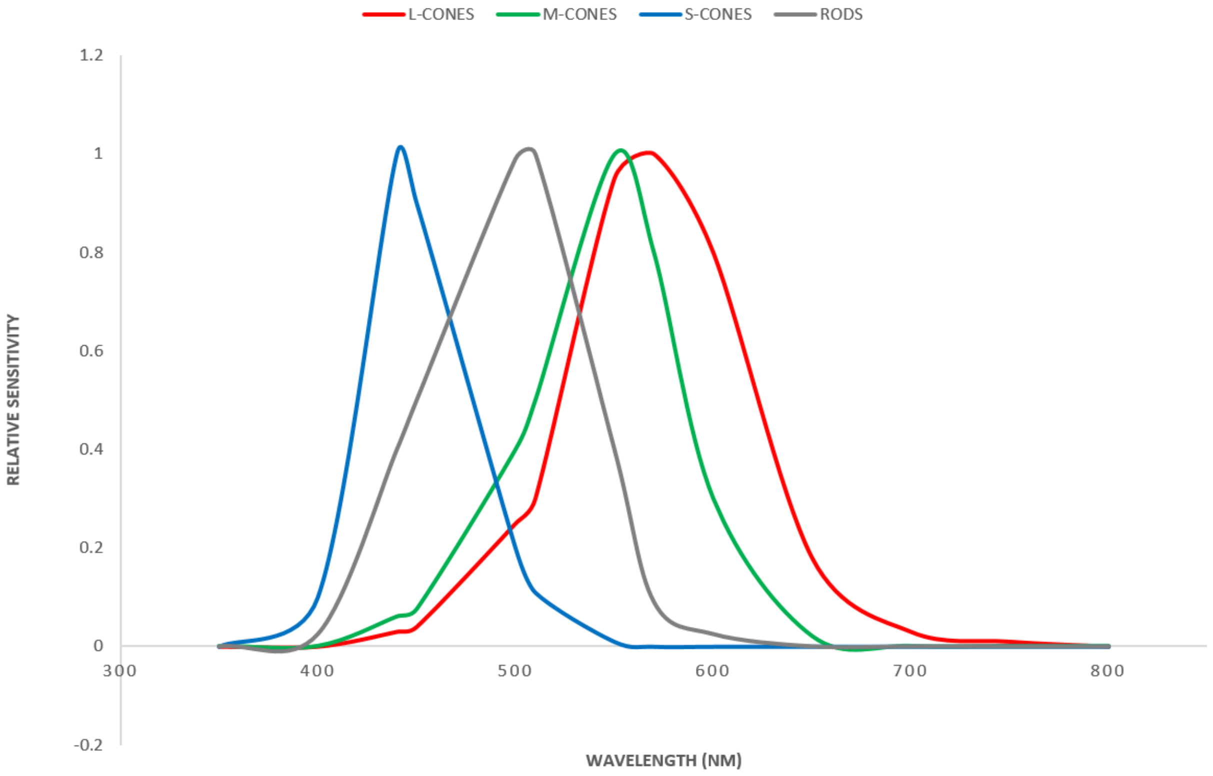
Rods

In total, there are between 100 and 120 million rods in the retina, depending on the source from which the information is retrieved. These photoreceptors provide input to ganglion cells through collector cells at scotopic and mesopic light levels (IES, 2011). During photopic light levels, the rod signals are prevented from reaching the ganglion cells by the cone photoreceptors. All rods contain the photopigment rhodopsin, which has a peak spectral sensitivity at 507 nanometers (IES, 2011), which can be seen in the relative luminous sensitivity functions in Figure 5.4. Because all rods have this photopigment and respond equally to light, rods can only provide an indication of bright versus dark and movement. Therefore, scotopic vision appears monochromatic and is deficient in spatial resolution. But rods are large and sensitive to light changes. Although they provide little detail to the viewer, rods do indicate a direction of where to focus vision for greater acuity.

Cones

Cones are small photoreceptors that are active in photopic and mesopic light levels to provide detail and color vision. The human eye has three types of cones: short (S), medium (M), and long (L). Classification of each is determined by the photopigment that it contains. Short (S) wavelength-cones contain cyanolabe photopigment that peaks in relative sensitivity at 437 nanometers; medium (M) wavelength-cones have chlorolabe photopigment that peaks in relative sensitivity at 533 nanometers; and long (L) wavelength-cones contain erythrolabe photopigment that peaks in relative sensitivity at 564 nanometers (IES 2011). The differences in spectral sensitivity of the three types of cones is illustrated in Figure 5.4. The ratio of L-, M-, and S-cone quantities in and around the fovea is 32:16:1 (DiLaura et al, 2011). Sometimes the L-, M-, and S-cones are referred to as red, green, and blue cones, respectively, referring to the color experience that each type of cone is most sensitive to. L- and M-cones are mainly concentrated in the fovea, while the S-cones are absent from the fovea. Instead, S-cones peak in density just outside the fovea, the macula. It is due to these three types of cones that color vision is possible and relatively large amounts of detail can be distinguished.

Figure 5.4: Relative Sensitivity Functions of Rods and Cones (created from information provided in Cuttle, 2015; DiLaura et al, 2011; IES, 2011)



Horizontal, Amacrine, and Bipolar Cells

Horizontal, amacrine, and bipolar cells collect neural signals from the photoreceptors and process the information. Signals from the rods and cones are collected by bipolar and horizontal cells and transmitted to the ganglion cells (DiLaura et al, 2011). Similarly, the amacrine cells and some horizontal cells distribute signals across bipolar cells as inputs for ganglion cells

(DiLaura et al, 2011). Horizontal cells provide photoreceptors with feedback about firing rates to adapt to photic signals, which is crucial to visual adaptation. That phenomenon is discussed in Chapter 6 of this report.

Retinal Ganglion Cells

Retinal ganglion cells can be categorized into two main types: regular and intrinsically photosensitive retinal ganglion cells (ipRGCs). Regular retinal ganglion cells collect the neural information in the retina and transmit it to the brain while ipRGCs are sensitive to optical radiation themselves and therefore do not receive information from photoreceptors.

Regular Retinal Ganglion Cells

What will be referred to as the regular retinal ganglion cells are the type that collect signals from the bipolar, horizontal, and amacrine cells, conforms them, and sends the signals through its axon (DiLaura et al, 2011). It should be remembered that bipolar, horizontal, and amacrine cells receive information from photoreceptors. See Figure 5.2. The axon of the ganglion cell travels along the optic nerve, in a process that will be discussed in the following sections. Regular retinal ganglion cells vary in coverage, which affects the quality of vision. In the fovea, there is a higher concentration of ganglion cells; therefore spatial resolution is best because there is a smaller proportion of cones sending signals to a single ganglion cell (IES, 2011). Alternatively, in the periphery of the retina, several hundred cones could send signals to a single retinal ganglion cell, which results in large perceptive fields with poor spatial resolution (IES, 2011). Regular ganglion cells that receive visual information from several different types of cone photoreceptors have one of two types of receptive fields: opponent center-surround or achromatic (Boyce, 2003). The opponent center-surround receptive field displays spectral opponency, either blue-yellow (b-y) or red-green (r-g) channels (IES, 2011). The b-y channel has the blue provided by S-cones while the yellow is a combination input from L- and M-cones; similarly, the r-g channel has the green provided by M-cones and the red is a combination of L- and S-cones' information (IES, 2011). The achromatic receptive field combines electrical input from L- and M-cones to produce a luminance signal; however, both the achromatic and opponent center-surround receptive fields play an important role in brightness perception, and is covered in greater detail in Chapter 6 of this publication (Boyce, 2003).

Intrinsically Photosensitive Retinal Ganglion Cells (ipRGCs)

Intrinsically photosensitive retinal ganglion cells (ipRGCs) account for only 0.2%-3% of all ganglion cells, which is partially why they were not discovered until the early 2000's (IES, 2011). These ipRGCs contain the photopigment melanopsin, which has a peak spectral absorption between 480 nanometers and 490 nanometers – generally the sensitivity gradually increases in wavelength as age of the viewer increases throughout adulthood – which would be described as blue in color. Both the cell bodies and dendrites are photosensitive and they depolarize in response to light, which is opposite of the hyperpolarization of rods and cones (IES, 2011). Although a minority of the ipRGC axons lead to the lateral geniculate nucleus, and eventually the visual cortex for input with brightness perception, most travel to the suprachiasmatic nucleus (SCN) for contribution to the production of hormones and other circadian functions (IES, 2011). Other axons still connect with the olivary pretectal nucleus (OPN), a nerve center in the brain that controls pupillary light reflex (Boyce, 2003). It is this nerve center that plays a large role in visual acuity through pupil response.

The Human Brain

The human brain is an intricate structure. Vision alone requires complex interconnections within the brain, which leads to more than just optical vision. Circadian, neuroendocrine, and neurobehavioral responses are all factors that are influenced by the optical radiation that is transformed into electrical pulses in the retinas and transferred to the brain by the optic nerve. The optic nerve and optic tract are highways of fibers that lead from the eyes to portions of the brain for processing, while the optic chiasm can be viewed as an interchange. In total, there are seven paths of information from the eye to the brain, referred to as visual subsystems (Kolb & Whishaw, 2009). One path is to the suprachiasmatic nucleus, another to the olivary pretectal nucleus, third is to the pineal gland, fourth is to the superior colliculus, fifth is to the accessory optic nucleus, sixth is to the visual cortex, and the last is to the frontal eye fields portion of the brain (Kolb & Whishaw, 2009). Most will be differentiated and discussed in detail in the following text, especially in the section about the optic chiasm. The bundles of fibers are known to selectively converge and diverge between the eye and the optic chiasm, which becomes the reasoning for the organizational arrangement of the subsequent identification of visual subsystems and components. Figure 5.5 is a good reference to understand the basic interconnections within the visual system.

Optic Nerve

The axons of all the ganglion cells extend to a near-central back part of the eye to form a bundle that surrounds the main artery for the interior of the eye, and exit as the optic nerve (DiLaura et al, 2011). The connection point is at the back of the eye, slightly towards the nasal direction. Moreover, where the optic nerve connects with the eye is a blind spot, one that no photoreceptors exist. The blind spot can be seen in Figure 5.3 where there are neither rods nor cones. Therefore, any light that is focused onto this part of the eye cannot register an image in the brain of the viewer.

Optic Chiasm

The optic chiasm is the region where optic nerves from both eyes interconnect before making final connections to the brain. Fibers from each are diverted to the superior colliculus, located at the top of the brain stem that is responsible for controlling head and eye movements for visual imaging; other fibers are routed to the suprachiasmatic nucleus (SCN) in the hypothalamus region of the brain and the pineal gland, both responsible for circadian rhythm entrainment; some of the remaining fibers are sent to the lateral geniculate nuclei (Boyce, 2003; Kolb & Whishaw, 2009). More fibers still are divided and sent to the accessory optic nucleus, responsible for providing compensatory eye movements to head movements (Kolb & Whishaw, 2009). More eye movements are controlled from the frontal eye fields, located at the front of the cerebral lobes. The last group of fibers are destined for the visual cortex for visual processing. They have been split from their respective optic nerves and recombined so that the right side of vision for each eye travels on the optic tract to the lateral geniculate nuclei on the left side of the brain. Conversely, the fibers from the left side of vision are combined and travel to the lateral geniculate nuclei on the right side of the brain via the optic tract. Figure 5.5 schematically depicts the interchange of fiber stands in the optic chiasm.

Optic Tract

The optic tract is the highway between the optic chiasm and the lateral geniculate nuclei. After the fibers are selectively split and combined in the optic chiasm, the respective fields of vision are sent to that side of the brain. Therefore, there are two paths that the optic tract flows.

Optic Radiation

The optic radiation fibers connect the lateral geniculate nuclei to the primary visual cortex at the rear of the brain. Particularly, the striate cortex receives most of the lateral geniculate nuclei information (Kolb & Whishaw, 2009). It is very large in humans and functionally has a well-defined map of spatial information in human vision. This is the final major transport of visual information for interpretation and preliminary motor response.

Primary Visual Cortex

The primary visual cortex is located at the rear of both cerebral lobes and is relatively small in size. However, there are still approximately over 200 million neurons packed into the visual cortex and they are tasked with processing the visual information that has reached it, specifically the information from the central ten degrees of the retina (DiLaura et al, 2011). Color vision, depth and pattern perception, as well as various other visual processing tasks such as visual attention are the important feats that the visual cortex and its subcomponents perform.

Olivary Pretectal Nucleus (OPN)

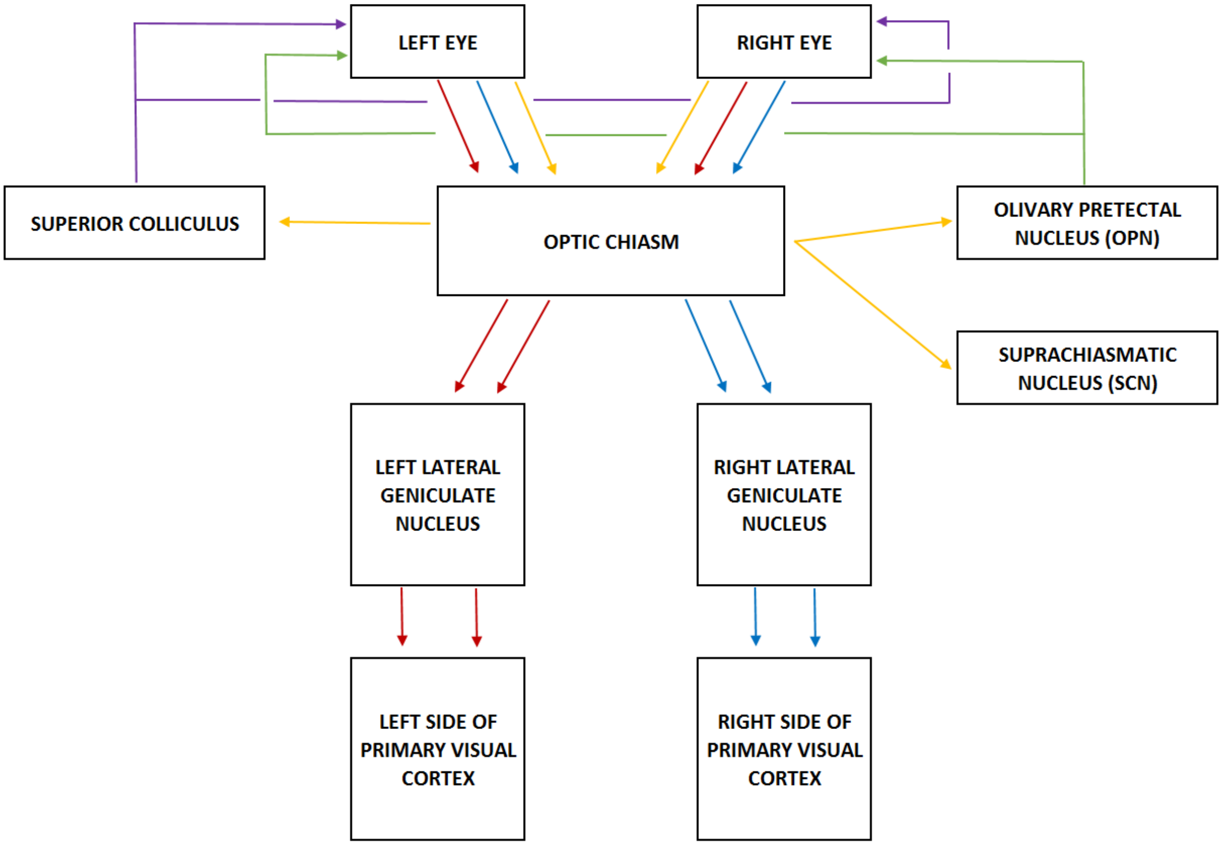
The olivary pretectal nucleus (OPN) is one of seven nuclei in the pretectum, a midbrain structure that participates in the subcortical visual system (Boyce, 2003). The OPN itself is involved in mediating behavioral responses to changes in light that arrive at the retina, specifically with the pupillary light reflex and optokinetic reflex (Boyce, 2003). Therefore, binocular information gathered from ipRGCs in the retina is internalized in the OPN, which then dictates pupil dilation or constriction. The effects of the change in pupil size are then immediately gathered by the ipRGCs and translated to the OPN, and the pupil adjusts again as needed. This is a self-balancing, perpetual cycle. As mentioned previously, ipRGCs have a peak spectral sensitivity of 480-490 nanometers, so wavelengths in the blue region of the visible light spectrum directly influence pupil size.

General Transference of Optical Information from the Eyes to the Brain

This sub-section is intended to piece together the process of visual information transference between the human visual components covered in this chapter, which will also decode the schematics of Figure 5.5. In Figure 5.5, there are different colored arrows to indicate different information being transmitted. The red arrows represent visual information from the right portion of vision of both eyes. Conversely, the blue arrows are visual information from the left portion of vision. The yellow is information that will not be processed for visual imaging. Rather, it is an indicator to sections in the brain to alter optical components for improved clarity, or other internal, non-visual processes such as hormone production. The yellow arrow reaching the OPN provides the necessary information that the OPN needs to operate the iris. Consequentially, the green arrows leaving the OPN and traveling to both eyes are command signals to the ciliary muscles to dilate or constrict the pupil according to the information that the OPN receives. Another yellow arrow arrives at the superior colliculus, to give indication on other optical needs. As stated previously, the superior colliculus controls eye movements, thus the purple arrows supply both eyes with such commands. The final yellow arrow feeds into the SCN as an external indicator with which the circadian rhythm can align.

Back at the optic chiasm, optical information from the right side of the visual field (red arrows) make way to the lateral geniculate nucleus on the left hemisphere of the brain, and the optical information from the left side of the visual field (blue arrows) traverse to the lateral geniculate nucleus on the right hemisphere of the brain; both make way via the optic tract. After the stop at the lateral geniculate nuclei, the information is sent via the optic radiation fibers to the primary visual cortex in the rear of the brain. This is the location where conscious visual processing, pattern and depth perception, and color vision takes place.

Figure 5.5: Schematic of the Basic Transference of Optical Information from the Eyes to the Brain



Chapter 6 - Human Vision, Perception, and Visual Responses

This chapter is dedicated to the combination of physiological and perceptual entities that form the basis of human visual functioning. It will also lay the necessary framework for later chapters about CCT and spectral qualities of light and how both impact the methods in which the optical and visual system as a whole react to optical radiation. This information can be capitalized upon by the lighting designer of certain project opportunities to have a more diverse design selection to solve illumination problems for human vision with visually demanding tasks.

Visual Acuity (VA)

Visual acuity (VA) is the ability to resolve minute and fine details through visual processes; the most common limiters of visual acuity are diffraction, aberrations, and photoreceptor density of the portion of retina that the image is entrained on (DiLaura et al, 2011). All of these limiters are due to optical components in the human eye. Diffraction occurs from the stretching and compressing of the lens, and can be negatively affected by diseases such as myopia that cause blurriness. Aberrations are light rays that do not converge after interacting with the lens. Pupil constriction is a good remedy to eliminating most light aberrations from reaching the retina, and thus, not interfering with visual processing. Location of the visual image with relation to photoreceptor density of the retina is dependent on the focusing of the lens; if the muscles controlling the lens perform correctly, the size and orientation of the lens is altered to project light onto the correct area of the retina, provided immediate feedback from the brain. Each person differs with VA though, and it is subject to change as a factor of age as well. Refer back to Chapter 5 of this publication for information regarding the lens, pupil, and retina and their integrative roles in VA.

Quantifying VA is attempted in a relative manner through the use of eye chart tests at ophthalmologist or optometrist offices. This is accomplished by testing the distance that a specific individual can accurately interpret an alphabetic letter, or other symbol, compared to the distance that an average observer can make out the same symbol. This quantity is expressed as a ratio. For example, someone with 20/20 vision is a person who can correctly identify a symbol from twenty feet away, the same distance it takes the average observer to correctly identify the identical symbol. Another example is a person with 20/40 vision is one who can correctly identify a symbol at a distance of twenty feet that an average observer can correctly identify at a distance of forty feet; the specific observer is below average in this example.

Other forms of VA quantification exist as well. Probably the most meaningful is the angle subtended at the eye by the detail that can be resolved on half of the occasions that the symbol is presented, with the angle measured in minutes of arc (Boyce, 2003). One minute of arc is referred to as normal vision.

For the sake of lighting, there are three main types of VA that are of interest: resolution acuity, recognition acuity, and Vernier acuity (DiLaura et al, 2011).

Resolution Acuity

Resolution acuity is the visual capability of a person to properly distinguish the existence of multiple objects versus the appearance of one. Common examples include discriminating multiple stars in the sky versus many stars appearing as one, or the ability to see that there are many lines that make up a barcode, especially when viewing from a significant viewing distance, opposed to seeing one wide line.

Recognition Acuity

Recognition acuity is the ability to properly identify an object, especially when differentiating it from another similar object. An example could include the ability to properly distinguish an uppercase "O" from an uppercase "Q" when viewing from a distance, similar to the tests of an eyechart at an ophthalmologist or optometrist office.

Vernier Acuity

The IES Lighting Handbook, 10th Edition defines Vernier acuity as, "the ability to identify a misalignment between two lines" (DiLaura et al, 2011). Often, the stimulus is smaller than the spacing of photoreceptors in the retina, so it requires visual pooling of information to detect the difference. However, one can train themselves to improve their Vernier acuity, as several studies have found (McKee & Westheimer, 1978; Fahle & Edelman, 1993).

Visual Efficiency

Visual efficiency is termed in the *Dictionary of Visual Science and Related Terms* as, "the ability to perform visual tasks easily and comfortably" (Hofstetter et al, 2000). In order for visual efficiency to occur, certain factors must align to promote it. These include: type of task, size of the task, familiarity of performing the task, the light level and contrast of light provided for the task. Familiarity with the task is entirely independent of the lighting designer's efforts, and thus, is neglected from this analysis of visual efficiency. Visual efficiency should be the goal of those designing a space, and it should be acknowledged that it transpires when visual performance has ceased to increase further, and instead plateaus, regardless of any further incremental increases to any of the aforementioned variables (IES, 2013).

Visual Effort

Visual effort is related to the visual efficiency of a task. The more effort required to perform a visual task, the less efficient that the visual performance will be. The visual effort is an indicator of the relative level of difficulty that exists to perform the tasks. The higher the visual effort, the higher the difficulty to perform the task, which usually means that the VA is near a threshold – far from optimal. The VA insufficiency could be born from either lack of illuminance on the retina, insufficiencies in the spectral composition of the light reaching the retina, or a combination of the two. Regardless, minimizing visual effort through optimal VA is pertinent to reaching visual efficiency, and thus, ideal levels of visual performance.

Visual Performance

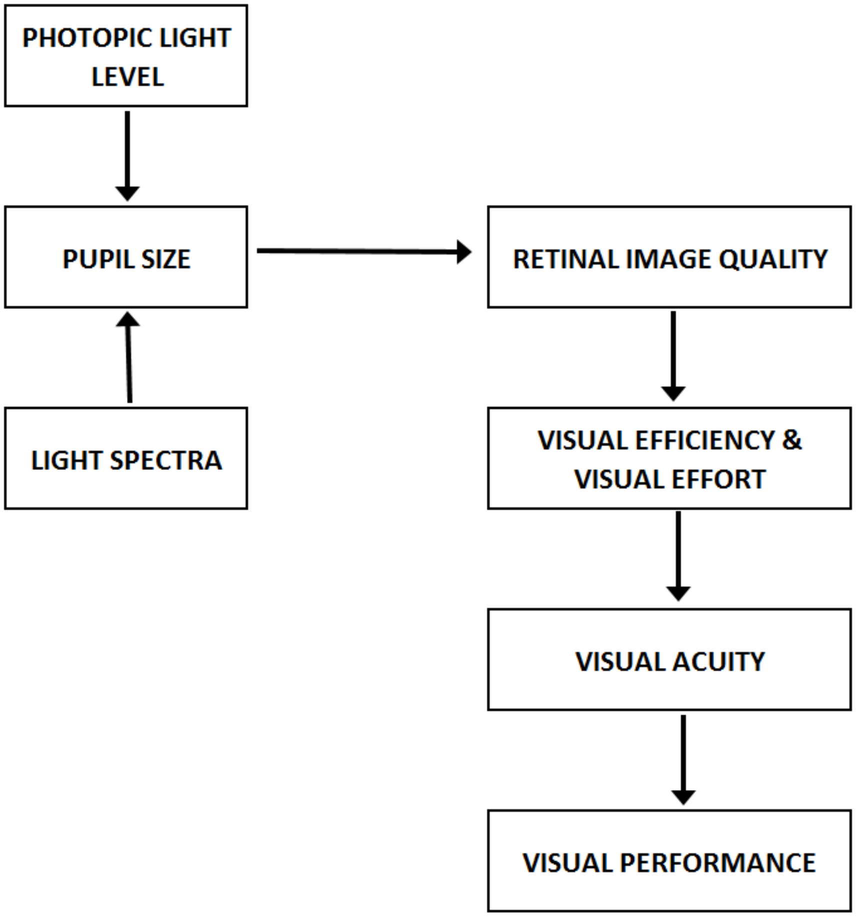
Visual performance refers to the speed and accuracy of processing visual information, which is usually evaluated by relating aspects of the visual environment to measurable human responses (Rea & Ouellette, 1991). Ultimately, the end goal is to understand the impacts of lighting on the human visual system in such an advantageous way that spaces can be designed to increase VA, increase visual efficiency, and decrease visual effort so that visual performance is optimized. Visual performance is not an equivalent of task performance, rather an addend of sorts. Task performance, similarly, can be viewed as an addend for productivity. Sequentially, lighting plays a major role in the productivity of tasks.

According to *The IES Lighting Handbook, 10th Edition*, there are three components to any task: visual, cognitive and motor (DiLaura et al, 2011, p. 4.19). It goes on to say:

> The visual component refers to the process of extracting [relevant] information [from the environment] . . . the cognitive component is the process by which these sensory stimuli are interpreted . . . the motor component is the process by which

the stimuli are manipulated to extract information and the consequential actions carried out.

Figure 6.1: Schematic of Light's Influence on Pupil Size, Ultimately Influencing Visual Performance (constructed from information in IES TM-24-13)



The mixture of visual, cognitive and motor quantities differs per task, but it should be noted that all exist in most tasks. It should also be noted that of the three components of a task, the primary component is that of vision; it precedes the functions of the other processes. Ergo, if the visual system is operating under conditions that increase visual effort because said conditions are not conducive to proper VA, then the entire system is either stressed to compensate or inoperable. The interrelationships between pupil size, VA, visual efficiency and visual effort, and ultimately, visual performance is schematically presented in Figure 6.1.

Adaptation

Visual adaptation is the term used to describe the dexterity of the human visual system to permit proper vision under varying lighting conditions. This is the phenomenon that allows such versatility in the human visual system to adequately see in extremely high light levels, such as outside at noon on a sunny day, yet navigate our surroundings in dim areas like a movie theatre. Visual adaptation to extreme changes is a feat that is impossible for neurons to pull off themselves; instead, most of the adaptation occurs at the eyes themselves, specifically the pupil and retina. Visual adaptation entails altering the size of the pupil, switching between photoreceptors (rods to cones or vice-versa), neural adaptation in the retina, and modification of the photochemicals within the photoreceptors themselves (Boyce, 2003). As photoreceptors fire, they are provided feedback information from the horizontal cells in the retina. The feedback allows the photoreceptors to alter their responsiveness to light levels, benefitting the individual with a flexible and wide range of viewing capabilities. This is how neural adaptation in the retina works; it is produced by synaptic interactions (Boyce, 2003). Small changes can be compensated for quickly by the entire visual system, but extreme changes in adaptation takes much longer.

There are two types of the extreme adaptation: dark adaptation and light adaptation. Dark adaptation is where the visual system switches from experiencing high retinal illuminance levels to low retinal illuminance levels. Per the example mentioned above, transitioning from outside at noon on a sunny day to a dimly lit movie theatre is a scenario of dark adaptation. As one may assume, dark adaptation is the transition of relying on cones to largely relying on rods for visual information. Similarly, pupils dilate in dark conditions to allow for more light to enter the eyes. Pupillary dilation is a slower phenomenon than pupil constriction, a difference by about a factor of five (DiLaura et al, 2011). For aging persons, the muscles controlling the pupil diameter are often not as responsive as that of a younger individual. Consequentially, it is common for dark adaptation to increase in transition time as the individual ages. Moreover, and regardless of age, the time longevity of rod adaptation is significant; it can take 60 minutes or more for rods to reach maximum sensitivity (Boyce, 2003).

Light adaptation is the scenario when one is changing from experiencing low retinal illuminance levels to much higher retinal illuminance levels. Conversely to that of dark adaptation, light adaptation is when visual information is becoming entirely dependent on cones, and the pupil is constricting to refrain excessive amounts of light from entering the eye. Because the pupil is constricting in size, the process occurs much quicker than dark adaptation. Also, higher light levels cause photopigment bleaching, a case where less photopigment is available to photoreceptors firing (Boyce, 2003). Photopigment bleaching is a phenomenon that contributes to a decrease in receptiveness to subtle light level changes at high light levels – this is a variable for the perception of brightness, which is discussed in the following section. Also, cones take about 10 minutes to reach maximum sensitivity, much quicker than rods (Boyce, 2003). The culmination of the information presented in this section provides the basis of which the human visual system can adapt to such a wide range of light levels, with light adaptation being the most expedient.

Brightness

What is referred to as brightness is merely a perceptual response to an object appearing bright, dim, or somewhere in between. Luminance is the main contributor to this perception, along with various relations of luminance. For example, contrast of luminance values between the object and surrounding objects plays an important role when distinguishing brightness versus dimness. The contrast of luminance values also contributes to visual adaptation, detailed in the previous section, which is another factor of brightness perception. It should be obvious that an individual adapted to mesopic surroundings, such as a movie theatre, would find a normal office space to appear bright, whereas someone adapted to the high light levels of the outdoors on a sunny day at noon would view the same office space as dim. Brightness is a perception based on comparison. Moreover, the human eye functions in such a way that lower adaptation luminance values require smaller changes in luminance to create much more noticeable changes in brightness, as opposed to higher adaptation luminance values. The luminance gradient is yet another luminance related factor of brightness perception. Luminance gradient refers to the change of luminance with each visual angle change (DiLaura et al, 2011). Mainly, this is affected by object edges, a change of material, or possibly due to uneven illumination. The higher the luminance gradient is, the greater difference in brightness perception will be noticed. That covers the luminance specific factors of brightness, but there are others. Spectral qualities of light is also a determinant in the perception of brightness and will be discussed in the following sub-section. Yet another factor is the angle of incidence that the light lands on the retina. This is termed the Stiles-Crawford Effect and covered in the respectively titled sub-section. The final factor contributing to brightness is the object size, specifically in comparison to other objects around it. Perceived brightness tends to increase as the size of an object increases, until a threshold is reached, at which point the perceived brightness plateaus as object size increases.

Light Spectra and Brightness

As it was mentioned before, light is not perceived equally; each wavelength will register as a color and brightness. Different types of receptive fields were introduced in Chapter 5 of this publication: achromatic and opponent center-surround (chromatic). The achromatic receptive field combines input from the L- and M-cones to produce a luminance signal sent via the magnocellular channel to the optic chiasm. While the magnocellular channel is a major contributor to brightness perception, it is not the only contributing channel. In fact, the two opponent center-surround receptive fields, the b-y and r-g channels, are chromatic fields that travel to the optic chiasm via the parvocellular channel and contribute to brightness perception as well. The proportion of information contribution is dependent upon retinal illuminance levels, for the various channels operate differently when exposed to different levels of light. For example, the b-y channel provides little input for brightness perception at low mesopic light levels, but begins to dominate in instances of much greater light levels (Rea, 2013).

While there are plenty of scientific studies that show S-cones do not play a role in luminance signals to the visual system, they do communicate chromatic information to the brain that concerns hue and saturation of the optical radiation (Boyce, 2003; DiLaura et al, 2011; IES, 2011; Malacara, 2011). Perceived saturation plays an enormous role in brightness perception, theorized in the Hemholtz-Kolrausch Effect (Wyszecki and Stiles, 1982). Generally, it states, "When two fields of different color but equal luminance are placed side-by-side, the one with greater color saturation will appear brighter" (Boyce, 2003. p. 201). It should also be understood that the Hemholtz-Kolrausch Effect is not constant; rather, it varies with colors. For example, primary colors (red, green or blue) have a much greater effect than those of secondary colors (Padgham and Saunders, 1975). Ware and Cowan furthered this notion by attempting to empirically quantify relative brightnesses of colors (Ware and Cowan, 1983). They succeeded for any color that has a chromaticity y-coordinate of greater than 0.02 on the CIE chromaticity diagram adopted in 1931. Overall, Equation 6-1 shows commonalities of the psychophysics relationship of perceived intensities versus actual intensities, coined the Weber-Fechner Law.

$$\boldsymbol{B = \log(L) + C} \qquad \textbf{Equation 6-1}$$

where,

B = relative brightness

L = luminance (cd/m^2)

C = conversion factor

The conversion factor (C) in Equation 6-1 can be empirically derived from Equation 6-2 succeeding. It should be evident from Equation 6-1 that equivalent luminances yield relative brightness perception to the conversion factor – the higher the conversion factor, the more saturated, and thus, brighter an object appears. To determine order of relative brightness for multiple light sources, sum the values of $\log(L) + C$ in Equation 6-1 (Boyce 2003).

$$\boldsymbol{C = 0.256 - 0.184y - 2.527xy + 4.656x^3y + 4.657xy^4} \qquad \textbf{Equation 6-2}$$

where,

C = conversion factor

x = x-coordinate in CIE 1931 chromaticity diagram

y = y-coordinate in CIE 1931 chromaticity diagram

It has been noted for some time that when concerned about brightness, V(λ) underrates sources with high S/P ratios and high CCT values (Cuttle 2015). V(λ) is covered thoroughly towards the end of this chapter. Rea proposes a system called “bright illuminance” in *Value Metrics for Better Lighting* where there would be a simplification in the relationship between the light source, illuminated object, and viewer. There would be three functions as follows: $V_{B3}(\lambda)$ for instances above 25 lux (2.5 footcandles); $V_{B2}(\lambda)$ for instances between 1 lux and 25 lux (0.1

to 2.5 footcandles); and V'(λ) for instances below 1 lux (0.1 footcandle) (Rea 2013). It will be shown towards the end of this chapter that the V'(λ) is the function to describe the human scotopic visual response. Rea shows in Section 4.2 and Tables 4.3 and 4.4 in *Value Metrics for Better Lighting* the benefits of using his proposed unified illuminance system. Similar to the factors for adjusting recommended IES illuminance targets that are covered in later chapters of this publication, Rea denotes the alterations of necessary light in relationship to relative power of utilizing the unified illuminance system (Rea, 2013).

There exists a final approximate brightness calculation outlined in *The IES Lighting Handbook, 10th Edition* where the brightness is directly related to the luminance. It is shown in Equation 6-3 and is referred to as the power law of Stevens (DiLaura et al, 2011). Equation 6-3 is only valid in instances of a single surface, so its practicality is limited. There are modified equations in *The IES Lighting Handbook, 10th Edition* to provide approximations of brightness with instances of multiple surfaces. Both the basic and modified equations presented in *The IES Lighting Handbook, 10th Edition* lack the ability to accurately demonstrate brightness of colored surfaces; highly saturated surfaces will be calculated as less bright than actually perceived while translucent surfaces will be calculated as brighter than they actually appear (DiLaura et al, 2011). Section 4.3.3 of *The IES Lighting Handbook, 10th Edition* should be consulted for further information regarding the basic Equation 6-3 shown in this publication, and the modified equations for multiple viewing surfaces.

$$\boldsymbol{B = \alpha * L^{0.33}} \qquad \textbf{Equation 6-3}$$

where,

B = approximate brightness

α = constant

L = luminance (cd/m^2)

The Stiles-Crawford Effect

Alluded to previously, the Stiles-Crawford effect refers to the influence that the angle of incidence of light on the retina has on brightness. After light is refracted by both the cornea and lens onto the retina, the totality of the paths of light differ as they travel to the retina. The different paths are due to difference in refraction angles, and thus produce different distances traveled (miniscule) and the angles of light incident on the retina (potentially significant). Light rays closest to the optical axis have the smallest angle of incidence on the retina; in fact, they are nearly perpendicular. The light rays at the perimeter of the pupils will have the largest angles of incidence on the retina. The light rays with larger incidence angles produce smaller brightness effects on the retina (Malacara, 2011).

The Effects of Age on Human Vision

Many components degrade with age and extended use – optical components in the human visual system are no different. For one, the cornea begins to harden and yellow. Years of exposure to the elements cause imperfections and inhomogeneities. This in turn causes imperfect refraction of light and light aberrations, as well as decreased access of light to reach the retina.

Another aging degradation includes iris muscle tightening and decreased responsiveness. Ultimately, the pupil size cannot change as quickly to a difference in lighting conditions and it cannot dilate or constrict to the same degree; its range of size capabilities decreases, especially with dilating. Older individuals tend to have much smaller pupil diameters, termed as senile myosis. The result is much longer adaptation rates and decreased abilities to see in lower illuminance conditions. To quantify the effects of senile myosis, an average fully dark adapted eye of a sixty year-old person admits less than half the amount of light that an average fully dark adapted eye of a twenty year-old (DiLaura et al, 2011).

In addition to the yellowing of the cornea, the lens yellows and clouds (cataract) as well. This combination further reduces light transmission to the retina, especially shorter wavelength light. An aging lens can cause further issues by "fluorescence". This is the phenomenon when the lens absorbs some UV radiation and short wavelength light and re-emits it as longer wavelength light (DiLaura et al, 2011). The product is inaccurate and scattered optical information absorbed by the retinal photoreceptors, by which the rest of the visual system has to attempt to compensate. The final issue with an aging lens is the loss of focusing power. As the lens gets older, it becomes less flexible to stretching and bulging – mainly stretching – and the ciliary muscles that control the lens degrade as well. The major loss is the ability to focus on tasks close to the observer. This circumstance is often epitomized by an older individual holding a book or other manuscript to read at an arm's length; by completely extending the arm the reader is attempting to compensate for the lack of near-range focusing abilities.

Types of Vision

The human visual system operates under various lighting conditions, but can be categorized based on luminance and operation of photoreceptors. The categories of vision can be defined as three: photopic, mesopic, and scotopic. In terms of commonality, photopic and mesopic lighting levels are the most prevalent in electric lighting designs. To be under true scotopic conditions requires such little light that it is impractical and highly unlikely to ever design for these conditions.

Photopic Vision

Photopic vision is the operating state of the human visual system in conditions that have luminance values greater than 3 cd/m^2 (IES, 2011). Under these conditions, cone photoreceptors dominate the visual response, meaning that a high level of detail and color are distinguished, specifically from the cones in the fovea. Because of the dominance of cones in this visual operating state, a function to describe spectral sensitivity can be derived; this function is referred to as the Standard Photopic Luminous Efficiency Function and will be covered in the section entitled *Luminous Efficiency Functions*.

Mesopic Vision

Mesopic vision is the visual operating state that is intermediate of the photopic and scotopic states, meaning that a combination of rods and cones provide visual information from the optical radiation reaching the retina. Luminance levels for mesopic vision ranges between 0.001 cd/m^2 and 3 cd/m^2 (Boyce, 2003). Between the top and bottom boundaries of this range is a shift that occurs between operation of rod and cone photoreceptors. As the luminance decreases, foveal contribution also decreases until it reaches a value of zero contribution, usually around the 0.001 cd/m^2 boundary, and only the peripheral regions of the retina react to optical radiation.

Scotopic Vision

Given the outlines of the photopic and mesopic visual operating conditions, scotopic vision is classified as a situation where the luminance is less than 0.001 cd/m^2 (Boyce, 2003). As it was mentioned in the mesopic vision, once the luminance has declined to the lower boundary of the mesopic visual operating condition and crosses into the scotopic visual operating condition, there is no input from the fovea. Instead, all photoreceptor responses are from areas outside of the fovea and are dominated by rod photoreceptors. Therefore, there are large receptive fields with no real perception of color. Similar to the photopic conditions, there is a function that can describe scotopic spectral sensitivity. It is referred to as the Standard Scotopic Luminous Efficiency Function and will be discussed in the following section entitled *Luminous Efficiency Functions*.

Luminous Efficiency Functions

The advent of the Standard Photopic Luminous Efficiency Function, V(λ), adopted by the CIE in 1924, marked a time when the scientific community attempted to standardize the visual sensitivity of humans. Nearly a century later we are still attempting to standardize metrics that accurately quantify the human visual response to light. In the years following the CIE adoption of V(λ), it was discovered that this function alone is inadequate in representing true human vision characteristics. To remedy this, several other functions have been proposed, and some have been adopted by the CIE as well. This section will introduce and explore several of these extra luminous efficiency functions.

Standard Photopic Luminous Efficiency Function, V(λ)

As stated above, the Standard Photopic Luminous Efficiency Function, V(λ) was adopted by the CIE in 1924. It is based off of psychophysical methods of Gibson and Tyndell where the visual field was restricted to the central two degree field of view (Boyce, 2003). This two degree field of view represents less than one percent of the solid angle of the full field of view that human eyes are normally exposed to. Therefore, all optical radiation interacts with only the fovea: M- and L-cones. S-cones, rods and ipRGCs are neglected from the V(λ) function. As a result, V(λ) does not predict pupillary size changes due to different spectra without altering light level. The luminous response is illustrated in Figure 6.2. Due to its longevity of existence, V(λ) has become entrenched in commerce, as it rightfully should. Moreover, it is the function that light meters are calibrated upon. However, for the lighting engineer, designer, or other relevant profession, the underlying physiology and applicability to lighting designs is crucial to understand; a notion that V(λ) is the only function, especially in mesopic and scotopic conditions, is fallacy. A final note is that this function is only applicable for conditions where optical radiation exceeds 3 cd/m^2; anything less will not elicit a response that coincides with what is indicated in the V(λ) function (IES, 2011).

Standard Scotopic Luminous Efficiency Function, V'(λ)

The Standard Scotopic Luminous Efficiency Function, V'(λ) was approved by the CIE in 1951 for representation of human visual response in dim lighting conditions. V'(λ) is based off of the work of Wald and Crawford, using an area that covered the central twenty degrees of the visual field with a luminance of approximately 0.00003 cd/m^2 (Boyce 2003). The dim lighting conditions that were described in the V'(λ) function is for theoretical and experimental work. Typically, the light level appropriate for V'(λ) is starlight, and thus, not common in electric lighting; any mesopic lighting condition is not in accordance with V'(λ). The V'(λ) function is graphed in Figure 6.2.

Judd-Vos Correction, $V_M(\lambda)$

The Judd-Vos Correction, $V_M(\lambda)$ is corrective measure for V(λ). Although nearly identical to the V(λ) function, the $V_M(\lambda)$ correction does indicate a slightly enhanced sensitivity to short-wavelength light in central two degree foveal vision. The minute discrepancy has been adopted by the CIE for accuracy measures, however, it does not play a significant role in understanding central two degree foveal vision in people, nor does it significantly affect efforts in illuminating standard spaces.

Ten Degree Photopic Luminous Efficiency Function, $V_{10}(\lambda)$

As the name implies, the Ten Degree Photopic Luminous Efficiency Function, $V_{10}(\lambda)$ is a function that represents the sensitivity of the central ten degrees of the human retina. This larger area of coverage incorporates the inputs from all photoreceptors: L-, M-, and S-cones, rods, and ipRGCs. As a result, $V_{10}(\lambda)$ is a more accurate representation of true human vision.

Mesopic Luminous Efficiency Function, $V_{mes}(\lambda)$

In 2010, the CIE recommended $V_{mes}(\lambda)$ as a linkage between $V(\lambda)$ and $V'(\lambda)$ functions, as shown in Equation 6-4. The value 'X' in Equation 6-4 is a function of light level and the light source's SPD, which is characterized by the S/P ratio. The S/P ratio is covered at the conclusion of this chapter. Overall, $V_{mes}(\lambda)$ is intended to represent the visual response that a person has when interacting with various spectral qualities of light within the operation of mesopic light levels.

$$\boldsymbol{V_{mes}(\lambda) = [X * V(\lambda)] + [(1 - X) * V'(\lambda)]} \qquad \textbf{Equation 6-4}$$

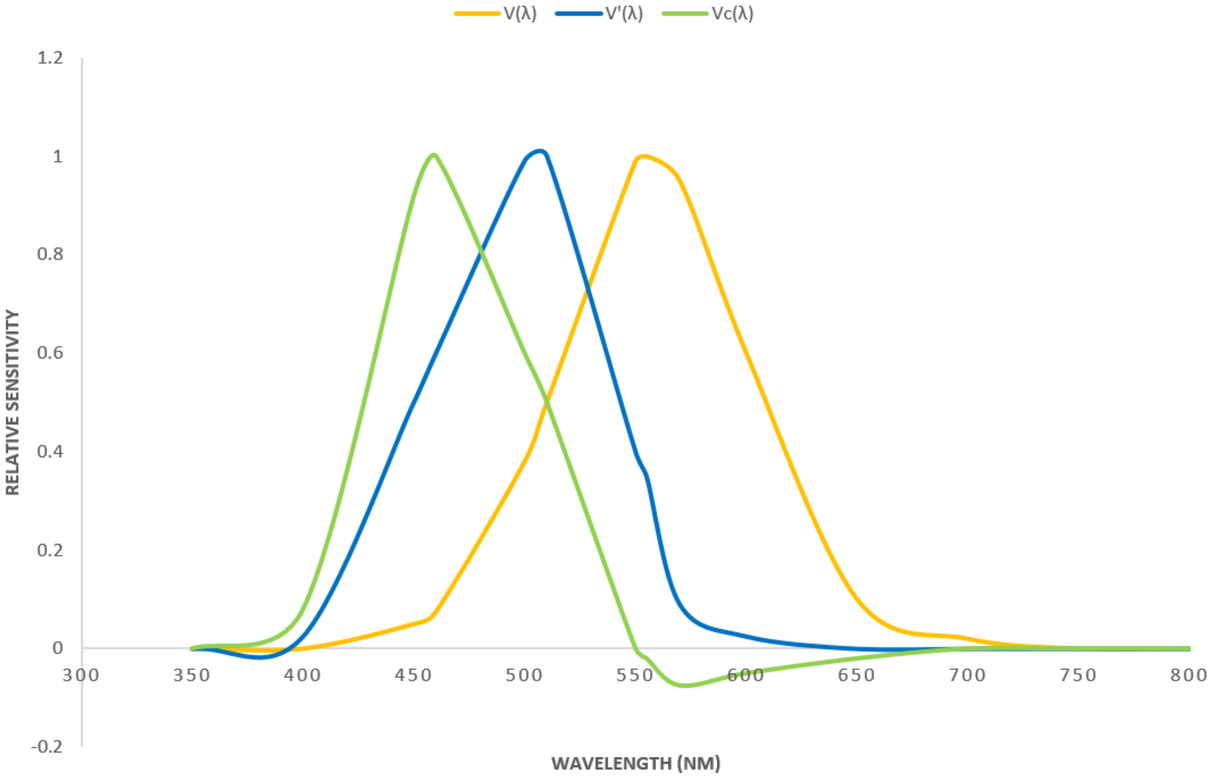
where,

X = proportion of photopic spectral sensitivity

Human Circadian System Efficiency Function, $V_C(\lambda)$

The Human Circadian System Efficiency Function, $V_C(\lambda)$, represents a response that does not necessarily play a role in vision. Rather, this function indicates the amount of response that the human circadian system has with various wavelengths of radiation from the visible light spectrum. One defining characteristic of the $V_C(\lambda)$ function is that there is a negative region – this is not an occurrence on any other of the efficiency functions. This can be seen in Figure 6.2. The negative region reflects a subadditive portion of circadian phototransduction with wavelengths greater than 507 nanometers (Rea, 2013). $V_C(\lambda)$ is a product of the total information contribution from rods, cones, and iPRGCs in the retina. Particularly, the b-y channel provides input to ipRGCs; the ipRGCs combine the b-y information with their own photosensitive response before sending the information to the biological master clock located in the SCN (Rea, 2013). The $V_C(\lambda)$ function peaks around 460 nanometers (Rea, 2013).

Figure 6.2: Relative Luminous Efficiency Functions for V(λ), V'(λ), and $V_c(\lambda)$



Proposed Luminous Efficiency Function for Brightness, B(λ)

The B(λ) function is not a standardized or adopted function. Rather, it was proposed by academics to better represent the response of the human visual system to perceived brightness (Rea et al, 2011). Currently, the V(λ) function is derived from the response of L- and M-cones in the fovea. This interpretation of visual response to light is inaccurate in the contribution of S-cones and rods. B(λ) more accurately depicts the brightness perception that one would experience with a broader field of view, similar to the $V_{10}(\lambda)$ function mentioned in a previous sub-section. The B(λ) function is formulated in Equation 6-5. The 'g' variable is the short-wavelength gain factor; its value increases when the light level increases (Rea et al, 2011). Increasing the value of 'g' is due to the Bezold-Brücke Effect. The Bezold-Brücke Effect is a phenomenon where the perceived hue of a color changes with respect to different light intensities. At greater intensity levels, the shift directs towards blue, if below 500 nanometers, or yellow, if over 500 nanometers. This is due to the increased input value of the b-y channel at higher light levels, as mentioned in Chapter 5.

$$\boldsymbol{B(\lambda) = V(\lambda) + [g * S(\lambda)]} \qquad \textbf{Equation 6-5}$$

where,

B(λ) = luminous sensitivity function for brightness

V(λ) = standard photopic luminous sensitivity function

g = short-wavelength gain factor

S(λ) = luminous sensitivity function for s-cones

The Scotopic/Photopic Ratio (S/P)

The scotopic/photopic ratio (S/P) has raised interest recently with its impact of human visual acuity effects. Boyce defines the S/P ratio as, "[a calculation] by taking the relative spectral power distribution, in radiometric units, of the light source and weighting it by the CIE [V(λ) and V'(λ)] and expressing the resulting scotopic lumens and photopic lumens as a ratio" (Boyce, 2003, p. 27). This is meant to assess the effectiveness of light sources with rods' and cones' sensitivities. Consequently, a higher S/P value will result in the rods being stimulated more compared to a light source with a lower S/P under conditions of equal photopic luminous flux (Boyce, 2003). S/P ratios are only meaningful when examined for light sources that do not have SPD's that change with intensity level. The reader should recall light source information from Chapter 4 and recognize that most of the electric light sources that mankind uses can derive accurate meaning from utilizing the S/P ratio. Only incandescent and specialty LEDs that change SPDs are fallible sources. Additionally, the sun's light is not an accurate source to apply S/P ratios to; constant variations throughout a day, season, and year makes it impractical.

The S/P ratio is a foundation for adjusting recommended photopic light levels in Section 4.12.3 of *The IES Lighting Handbook, 10th Edition* and the publication IES TM-24-13, *An Optional Method for Adjusting the Recommended Illuminance for Visually Demanding Tasks Within IES Illuminance Categories P through Y Based on Light Source Spectrum*. Furthermore, S/P ratios are values that can often be acquired from manufacturer data sheets, upon request of the manufacturers, or from independent testing facilities. The idea and implementation of adjusting IES recommended illuminance levels will be further explored in the coming chapters of this publication.

Chapter 7 - CCT and Spectral Quality Effects on Humans

It was mentioned in Chapter 1 that this publication is about using the spectral components of light that affect human vision for advantageous use in design applications. All of the previous chapters provided the necessary background information to build up to this chapter and the forthcoming chapters. This chapter delves into the exploration of the effects that CCT and, specifically, spectral qualities have on the visual system of human occupants in a designed space.

The Daily Natural Light CCT Cycle

The versatility of sunlight CCTs experienced on Earth was introduced and detailed in Chapter 4 of this publication. Any range from 2000K to 20,000K is reasonable to visually experience in any given day from dawn to dusk, dependent on global location. Seasonal positions of the sun's arc in the sky, due to the Earth's tilt and rotation, are another factor of CCT variation of sunlight on Earth. Moreover, the latitude on Earth at which a viewer is stationed impacts the angle at which the light from the sun is delivered. It is the angle of the relationship between the Earth's atmosphere and the solar position that has the greatest impact of CCT variation. A combination of reflection and refraction of solar rays in the Earth's atmosphere allows and prohibits certain radiation waves to reach the Earth's surface. Refraction and reflection are dependent on the angle of incidence of the solar radiation waves, thus describing the outcome of fluctuating CCT values of natural light. It should be inherently understood that changing selectivity of reflection and refraction of solar radiation due to the Earth's rotation is indicative of differing spectral qualities of light throughout the course of a day, season, and year. The greater that the angle of incidence of sunlight interacting with the Earth's atmosphere, the greater quantity of short-wavelength light that is denied transmission to the Earth's surface. That is why sunrises and sunsets are warm reds, pinks, and oranges in human vision, the long-wavelength light is the majority of the light transmitted through Earth's atmosphere. But because the Earth is always in motion relative to the sun, and the combination with different atmospheric conditions, CCT from natural light is in a constant state of change.

The luminous quality of the sky on Earth is due to a phenomenon termed Rayleigh scattering, where sunlight is reflected, refracted, and diffused through interaction with air molecules, particles of water vapor, and other particulate matter in the atmosphere (DiLaura et al, 2011). This paves way to the blue sky nature, which is attributed to the atmosphere's capability of diffusing shorter wavelengths of light. Also, the presence of clouds greater diffuses light from the sun, although with little impact on spectrum; generally, one can expect a natural CCT around 5500K on an overcast midday (DiLaura et al, 2011).

Manipulating CCT of Electric Light Sources

As stated in Chapter 4 of this publication, it is often desired to create light sources that emit spectral power distributions that are comparable to the sun. Besides the ideal color rendering aspect of this goal, there is also the historical notion that the light from the sun is what the human visual system has evolved with. Therefore, it is logical to assume that qualities of light from an electric source that mimic the natural optical radiation that arrives on Earth (while understanding some non-visual radiation can be quite harmful) would legitimize the electric light source for ages – it produces environments that allow visual optimization for humankind.

Analogous is the logic that the variance of light spectra induced upon human beings is conducive to visual, neuroendocrine, and neurobehavioral systems in the human body. It is upon this concept that the idea of electrically altering light source spectra becomes a desired outcome. Therefore, light sources with the capability to alter its emitted light spectra, and additionally its CCT, are gaining popularity in architectural applications. Primarily SSL light sources are capable of accomplishing this function, all through electrical information transmitted from a controller to a driver that regulates the SSL. Because of the popularity of LED light sources in architectural applications, the reference of electronically altering CCT and light spectra will only concern LED sources in this publication.

Such LED types are referred to as tunable LEDs, particularly white-tunable LEDs in the case of this discourse. They operate one of two ways. The first is by utilizing two sets of controllable phosphor-coated LEDs, one possessing a warm-white CCT and the other possessing a cool-white CCT (DOE, 2012). The other method is with three LEDs, or more, each being a primary color and utilizing additive color mixing to produce the white color that is desired. The second method has a greater ability to follow the Planckian locus for CCT values than that of the first method (DOE, 2012).

Effects of Light Spectra and CCT on VA

Introduced in Chapter 6, $V(\lambda)$ and its variants were created to standardize the sensitivities at which the visual and circadian systems responded to optical radiation. The functions that relate to photopic vision – namely $V(\lambda)$, $V_M(\lambda)$, and $V_{10}(\lambda)$ – do not represent changing pupil sizes, thus leaving an absence in representation for VA. As it was discussed in Chapter 6, pupil size plays a large role in the VA of an individual; typically, VA increases with a decrease in pupil diameter, until a point of plateau that occurs around 2-3 millimeters of pupillary diameter.

Pupils dilate to allow more light into the eye when there is an insufficient amount reaching the retina per the adaptation state needs. Conversely, they constrict to remove excess and non-central aberrant light rays. Excess light rays exist in extremely high retinal luminance cases, as well as when the adaptation state of the retinal photoreceptors is lower than necessary for newly encountered lighting circumstances; also, removing aberrant light rays reduces blurred images. The collaboration between the optical components upstream of the retinal photoreceptors is crucial to the VA of the entire optical system; the quality of the optical image reaching the retina trumps the actual retinal resolution capabilities. It does not matter how resolute the photoreceptors are if the information they are receiving is indecipherable. Light levels related to adaptation states, however, play a smaller role in pupillary sizes than one may think.

Spectrally Driven Pupil Sizes

$V(\lambda)$, $V_M(\lambda)$, and $V_{10}(\lambda)$ do not approximate pupil sizes. Instead, they only correlate with the spectral sensitivities of rod and cone photoreceptors. V'(λ) is closer to predicting pupillary extents, but still with some degree of error. For years formulae were derived using the S/P ratio of ambient lighting to predict pupil size (IES, 2013). But in 2003 it was announced that a new photoreceptor that operated at photopic light levels was discovered, and subsequent studies confirmed the existence of the ipRGC (Gamlin et al, 2007, IES 2013, McDougal and Gamlin, 2010). The newly discovered iPRGCs demonstrated a direct connection to light spectra controlling pupil size, especially when photopic light levels remained constant (IES, 2013). Close to the spectral peak of 507 nanometers of V'(λ) is the spectral peak of melanopsin-filled iPRGCs around 480-490 nanometers, which is the accountant for the degree of error in predicting pupil size based off the V'(λ) function.

There is an empirical formula correlating both V(λ) and the SPD of a light source. It is quantified as the $P(S/P)^x$ formula, where 'P' represents the photopic light level, and 'x' is an exponent that depends on specific conditions of observation, but was approximated to be valued at 0.78 for subjects with a full field of view in a spectrally flat white environment and a fixation point of one meter in length (IES, 2013). This formula was empirically derived by Berman and shows how spectrum and light level combine to predict the average variation of pupil size, rather than predict absolute pupil size (Berman, 1992; IES, 2013). As discussed previously in this publication, absolute pupil size is a result of many categories of inputs, and varies on an individual level. Therefore, it is practically impossible to predict an absolute pupil size. Berman, instead, aimed to empirically predict the average variation of the pupil size, which is a more realistic derived prediction. Moreover, Berman illustrated the importance of field size with pupillary size. In 1997 he tested subjects in an observation where they had a full field of view, but the self-illuminated task was approximately the subtended solid angle size of the fovea, resulting in an 'x' value equal to 1.0 in the $P(S/P)^x$ formula (IES, 2013). This means that the photopic light levels cancel out and the pupillary response is solely dependent on the scotopic luminous efficiency function. It should be noted that the formula was derived prior to the discovery of the ipRGCs, and thus, neglects direct and definite contribution from such cells. Indeed, the scotopic function does better depict wavelengths of increased sensitivity in ipRGCs, but enough understanding of ipRGC responses to light elude scientific knowledge at the time of this writing. For the time being, the $P(S/P)^x$ formula provides information that leads the designer in the right direction for human pupillary responses.

In Rea's book, *Value Metrics for Better Lighting*, he offers a spectral sensitivity function for human circadian response $V_C(\lambda)$ (Rea, 2011). Because ipRGCs serve as nonvisual information providers to brain structures that regulate circadian, neuroendocrine, and neurobehavioral responses, the $V_C(\lambda)$ function can serve as an estimated representation of wavelengths of light that pupillary response is most sensitive to. It should be noted, however, that the pupillary response governed by the OPN in the brain does not have subadditive nature like the circadian response does; therefore, there is no negative sensitivity that can be correlated to pupillary response. At the time of this writing, there is not an official spectral sensitivity function for ipRGCs that could accurately provide pupillary response information to light spectra. Therefore, it is recommended that a general idea can be generated from the positive left portion of the $V_C(\lambda)$ function while an improved measurement results from the $P(S/P)^x$ formula.

General Design Implications

To the lighting designer, the information in this chapter is empowering. Understanding the fluctuating nature of CCT from the sun, especially as it relates to geographical positioning on the Earth, is a feature that can be mimicked in artificial lighting design. Advances in technology give greater allowances of achieving such design strategies. If budgeted for, tunable LED sources can be researched and specified to deliver specific wavelengths of light at different times during the day, which can reinforce an occupant's internalization of time, or circadian entrainment. Also, shorter-wavelengths of light that correspond with scotopic and ipRGC responses can be implemented to constrict pupil sizes for visual acuity improvement. As it will be covered in the remainder of this report, numerous potential benefits are linked with the inclusion of lighting designs utilizing shorter-wavelength light. Various lighting schemes, illuminance variance, and electrical consumption are some of the resultants of shorter-wavelength light in architectural installations. A detractor of shorter-wavelength lighting is occupant preference, which this discourse covers both sides of that debate.

Chapter 8 - Factors to Adjust IES Illuminance Recommendations

One of the assumptions that is made when designing for the recommended illuminance values provided in *The IES Lighting Handbook, 10th Edition* is that the S/P ratio is equal to 1.4 – this value is synonymous with 3500K fluorescent lamps. In Section 4.12.3 of *The IES Lighting Handbook, 10th Edition*, however, it does acknowledge that spectral composition of light can have an adverse perceptual effect on the actual illuminance values due to the shift to mesopic adaptation – visual information absorbed by both the rods and the cones (DiLaura et al, 2011). As the reader may recall from the section about mesopic light conditions, it occurs as an intermediary condition between photopic and scotopic conditions. That is why Section 4.12.3 of *The IES Lighting Handbook, 10th Edition* declares that factors to adjust illuminance values in mesopic adaptation conditions are only allowable if the luminance is at or below 3 cd/m^2 (DiLaura et al, 2011). Further information about the mesopic multipliers can be gathered from Figure 4.27 and Table 4.2 of *The IES Lighting Handbook, 10th Edition*.

IES TM-24-13, *An Optional Method for Adjusting the Recommended Illuminance for Visually Demanding Tasks Within IES Illuminance Categories P through Y Based on Light Source Spectrum* further contributes to the notion of illuminance reduction. In this publication, there are supporting models for altering the recommended illuminance targets for visually demanding tasks, a major step further than the factors regarding mesopic vision in *The IES Lighting Handbook, 10th Edition*. The factors that will be introduced and explained in the remainder of this publication are not requirements, nor are they recommendations. Rather, if all prerequisites to allow sensible deployment of adjusting illuminance values are met, then applying the appropriate factor is an option. As one may expect, there may be situations where prerequisites for adjustment factor usage is met, but the actual purpose of the space or type of occupants in a space would not benefit, and in some cases detriment, from the actual adjustment of recommended illuminances. Such prerequisites for usage and circumstances to reject usage of the adjustment factors are outlined in the following sections of this chapter.

Applications Allowed to Use Illuminance Adjustment Factors

The adjustment factors for illuminance values have certain requirements in order to be considered for use. The first is that the application must be for a visually demanding task in interior IES Categories “P” through “Y”. For starters, a visually demanding task is defined as, “tasks that are based on the ability to discern visual detail to ensure speed and/or accuracy” (IES, 2013, p. 1). Therefore, it should be understood that a visually demanding task is dependent on detailed vision only. Next, IES Categories “P” through “Y” are displayed in Table 4.1 in *The IES Lighting Handbook, 10th Edition*. The categories themselves range from common, small-scale visual tasks to unusual, minute visual tasks that include: social, education, commerce, sports, industrial, and health care applications (DiLaura et al, 2011). Another requirement is that the application must allow the viewer a full field of view to perform the task with luminance ratios not exceeding the Default Luminance Ratio Recommendations in Table 12.5 of *The IES Lighting Handbook, 10th Edition* (IES, 2013). The Default Luminance Ratio Recommendations cover the maintenance of task attention, visual comfort, and minimizing veiling reflections (DiLaura et al, 2011). The last condition for illuminance adjustment consideration is that the visual task background luminance is 50 cd/m^2 or more (IES, 2013). Altogether, these requirements dictate the first step into acceptance for implementing the illuminance adjustment factors.

Applications Not Allowed to Use Illuminance Adjustment Factors

As the previous section noted, the illuminance adjustment factors are allowed for consideration in IES Categories “P” through “Y” only; this means that the remaining IES Categories of “A” through “O” are prohibited for inclusion. Converse to the recommended illuminance targets for IES Categories “P” through “Y” are the significantly lower recommended targets for IES Categories “A” through “O”. The difference in recommended illuminance target values is due to the nature of the applications and associated tasks; IES Categories “A” through “O” are primarily common, large-scale tasks, which deviate from the definition of visually demanding tasks.

The intended audience plays a vital role in the consideration of illuminance value factor usage. The main issue is with regard to the visual capability of the intended viewers. For example, applications that require the elderly to perform visually demanding tasks should be considered under careful scrutiny. It was discussed in Chapter 6 of this publication that the range of pupillary movements is far decreased in the elderly and their pupils remain more constricted than that of a younger person so they are already at a disposition to low light levels. Also, the yellowing of the cornea and lens reduces the amount of shorter wavelength light, thus eliminating the purpose of trying to capitalize off of human visual responses to short wavelength light once it is absorbed by the retina. A counter argument could be made contending that the older individuals are covered in illuminance targets by *The IES Lighting Handbook, 10th Edition* because illuminance targets are categorized into three age groups per application: less than 25 years of age, between 25 and 65 years of age, and over 65 years of age. The illuminance targets for the viewers over 65 years of age far exceed the illuminance targets of the other two age categories. Therefore, an adjustment factor applied to the target illuminance of the age group over 65 years of age would reflect a response of the viewer to the largest group of illuminance targets. The counter-argument to that has two points. First, the age group illuminance target values are applicable in *The IES Lighting Handbook, 10th Edition* where there is an anticipation of at least half of the occupants fall within the respective age range. Therefore, an occupant population in a space could consist of 60% of viewers are in the age group of less than 25 years of age while the remaining 40% could be in the category of over 65 years of age. A rushed or uninformed designer could easily discount the 40% by merely accepting the fact that the majority of the occupant population is under the age of 25, thus designing for significantly lower illuminance targets. Besides, the middle age group of 25 to 65 years of age is the default illuminance targets for designing a space, especially if it seems to be a fairly common scenario in a familiar application. This is not uncommon for many education applications, such as high schools and universities, where the student population far trail the age of the educator. If there is not extra or supplementary lighting in the front of the learning environment (frequently where the instructor is) and at his or her desk, then the illuminance values could possibly be too low for the instructor to perform visually demanding tasks with visual efficiency and low visual effort, especially if the illuminance values have been decreased due to spectral composition of the light. Secondly, even if the light levels are designed properly for the age of occupants performing visually demanding tasks, the reduced capabilities of the visual system of an elderly person limits the visual physiological response one can have to light spectra. Therefore, designing lighting for spaces that harbor elderly or other individuals of visual impediments should be done so with care, and reducing light levels for visually demanding tasks based on light spectra should be scrutinized intensely.

Equivalent Visual Efficiency (EVE)

The Equivalent Visual Efficiency (EVE) calculation is a concept introduced in the IES TM-24-13, *An Optional Method for Adjusting the Recommended Illuminance for Visually Demanding Tasks Within IES Illuminance Categories P through Y Based on Light Source Spectrum*. The EVE calculation title provides adequate information as to the nature of the concept: visual efficiency is equivalent between the IES recommended illuminances and the factored IES recommended illuminances given certain light spectra. The concept for EVE is outlined in the IES TM-24-13, *An Optional Method for Adjusting the Recommended Illuminance for Visually Demanding Tasks Within IES Illuminance Categories P through Y Based on Light Source Spectrum* publication as:

> Given a photopic light level 'A' under an illuminant 'x' of a known S/P value ($A_{(x)}$), there may be an alternative illuminant 'y' with a different S/P value that can provide the same level of visual acuity but with a different photopic light level 'B' ($B_{(y)}$). The two different photopic light levels ($A_{(x)}$) and ($B_{(y)}$) are then providing equivalent visual efficiency.

Based on the concept, EVE factors provide no claimed effect on overall visual performance. However, the concept does claim equivalent visual efficiency, which is a contributing component to visual performance. The excerpt from the IES TM-24-13 publication recently mentioned can be numerically described as shown in Equation 8-1.

$$\boldsymbol{P_1}[(\boldsymbol{S}/\boldsymbol{P})_1^{\mathbf{0.78}}] = \boldsymbol{P}_2[(\boldsymbol{S}/\boldsymbol{P})_2^{\mathbf{0.78}}] \qquad \textbf{Equation 8-1}$$

where,

P_1 = any conventional lighting metric based on V(λ) of the original (baseline) light source

P_2 = same conventional lighting metric as P_1 (based on V(λ)) of the new (proposed) light source

$(S/P)_1$ = the scotopic/photopic ratio (S/P) for the original (baseline) light source

$(S/P)_2$ = the scotopic/photopic ratio (S/P) for the new (proposed) light source

Equation 8-1 is a derivation of the $P(S/P)^x$ formula that was introduced near the end of Chapter 7 in this publication. The usage of this equation is to either solve for a new S/P ratio for equivalent visually efficiency or solve for a new illuminance level (or other V(λ) based lighting metric) of a different, but known, S/P value for equivalent visual efficiency.

The EVE multiplier factors are deducted in a straight forward calculation, shown as Equation 8-2 in the following text. Equation 8-2 is the method for obtaining the EVE factors that are recorded in Appendix A of this publication, which partially mirrors the information provided in Table 1 of the IES TM-24-13, *An Optional Method for Adjusting the Recommended Illuminance for Visually Demanding Tasks Within IES Illuminance Categories P through Y Based on Light Source Spectrum* publication. Moreover, an example EVE multiplier calculation is provided in Appendix A of this publication to illustrate usage of Equation 8-2.

$$\frac{\boldsymbol{P_2}}{\boldsymbol{P_1}} = \left[\frac{(\boldsymbol{S/P})_1}{(\boldsymbol{S/P})_2}\right]^{\mathbf{0.78}} \qquad \textbf{Equation 8-2}$$

where,

$\frac{P_2}{P_1}$ = the EVE multiplier, with each 'P' value representing a photopic light level

The technical memorandum IES TM-24-13 replaces the exponent of 0.78 with a rounding to 0.8 instead to match the level of accuracy inherent in the empirically derived formula (IES, 2013). Equation 8-2 should look familiar, as it is a reorganization of Equation 8-1 in this publication; the structure of the equation has merely been rearranged in order to solve for the EVE multipliers. The EVE multipliers can be applied directly to IES recommended illuminance targets as long as the application meets all of the requirements to be applicable for adjusting IES recommended illuminance targets and that extra consideration is taken to ensure that occupants will not be disadvantageous to the implementation of adjusted IES target illuminance values, both covered earlier in this chapter. Also noted earlier in this publication is the notion that an S/P ratio of 1.4 is the baseline value. This value is closely associated with S/P values of common 3500K fluorescent lamps, as well as common halogen incandescent lamps. Throughout the years, both sources have enjoyed long reigns of standard use in spaces where visually demanding tasks were performed. To this day, 3500K fluorescent light source luminaires are quite common in applications of performing visually demanding tasks, such as offices and schools.

It should be realized that the higher the S/P ratio – compared to the 1.4 baseline – the lower the EVE multiplier becomes, thus reducing the illuminance value in the space. The increased presence of scotopic wavelengths versus photopic wavelengths increases the contribution of short-wavelength photoreceptors, including the increased VA from the constriction of the pupil due to ipRGC electrical signals to the OPN in the brain, coalescing to provide an empirically derived equivalence in visual efficiency. Theoretically, the average human eye provides the same visual efficiency under lower light levels of light with higher scotopic values when compared to higher light levels of an S/P ratio of 1.4.

Chapter 9 - Implementing EVE Factors in Design

The evolution of lighting design and subsequent implementation in the commercial market has been shifting from warm CCTs to those with more neutral values. This is primarily evident in fluorescent and LED illuminated work spaces of office dwellers and educational facilities. It was mentioned earlier in this writing that the crossover from incandescent to fluorescent sources was viable with respect to economics and energy usage. Human historical preference, particularly of western cultures, of artificial illumination had tended to favor the warm CCT values; from fire, gas, oil, and incandescent sources, warm CCTs were always the output. Therefore, many believed that to better motivate the switch from incandescent to fluorescent lighting in commercial applications, warm CCT values were offered, 3000K being a common option. That value has started to increase into cooler ranges, those that are usually classified as a neutral CCT. The step in popularity to 3500K provided the initial inertia needed to implement cooler CCT values, and at the time of this writing, the author has experienced the commercial standard CCT equaling 4100K. Given the past trail of CCT values, the future trajectory would seem to imply further cooler CCT values, such as 5000K, 6000K, 6500K and so on.

Such a trajectory, though, cannot be sustained. At some reasonable point the trend must slow until finally plateauing. A potential plateau could be around the 6500K value; the oldest form of illumination that man has evolved with is the sun, and the illuminant D_{65} mimics the average daylight on Earth, with a CCT value of 6500K. Another potential point is 5000K, which is already used extensively in some foreign markets. Others do not believe that cooler CCT values are wise. Instead, they argue, that a space illuminated with cool CCTs looks cold and sterile rather than inviting. One such phenomenon is termed the Kruithof Effect, discussed in the following section.

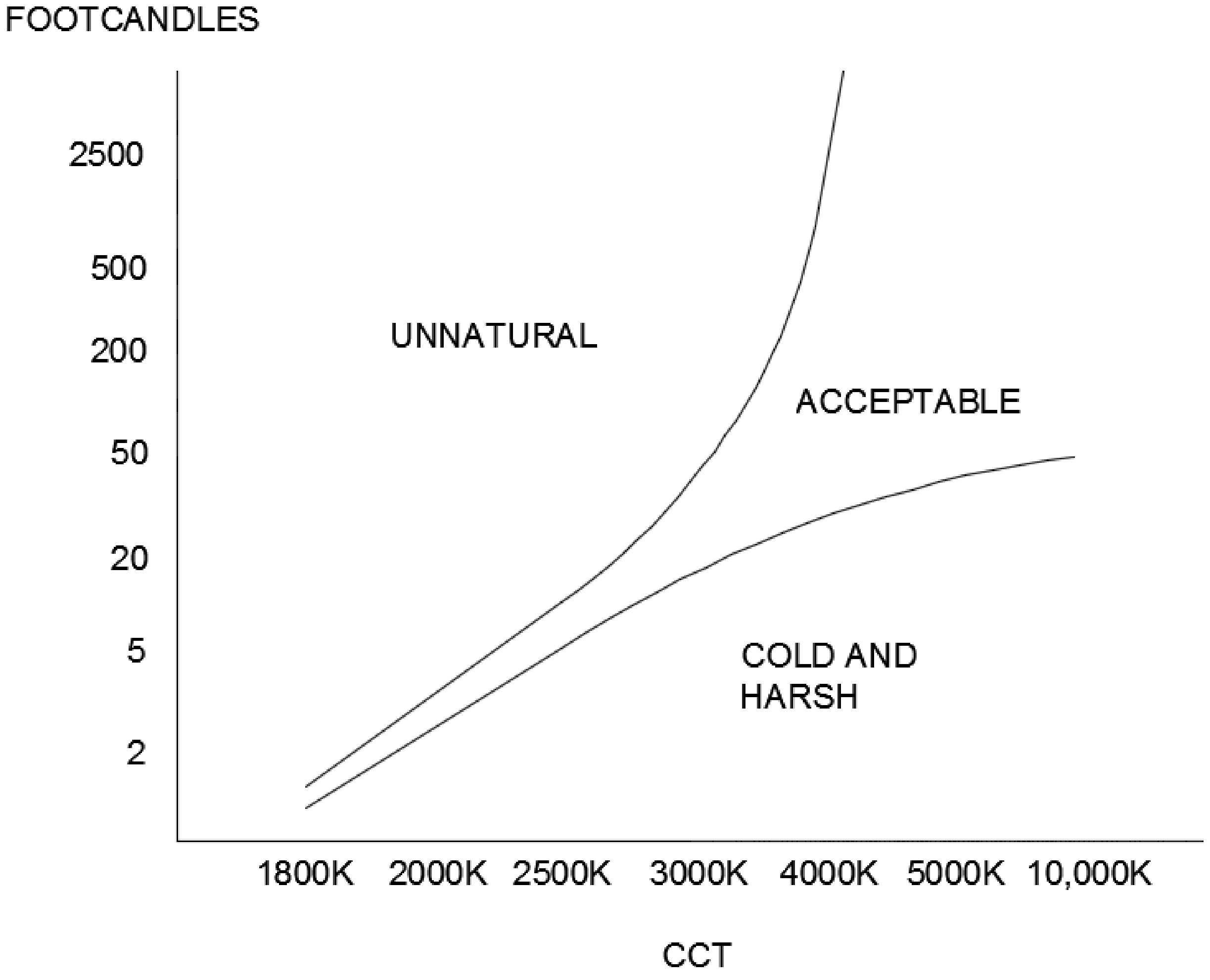
Kruithof Effect

Alluded to previously, the Kruithof Effect is the name for the theory that cooler CCTs make a space appear cold and dim. Kruithof was a lamp development engineer for Philips Lighting who performed informal visual observation tests in the 1940s for observers using different light CCT and illuminance value (Cuttle, 2015). Although much of the Kruithof findings are not well documented, a chart indicating observer preference remains. It shows a band of deemed acceptable light levels with relation to CCT: in general, as the CCT value increases so do the acceptable illuminance values. Not only do the acceptable illuminance values increase, but so do the amount of illuminance levels for a given CCT value – the range of illuminances expands. An approximation of Kruithof's curve is shown in Figure 9.1 where the expansion of illuminance values and ranges of values is demonstrated per the increase of CCT.

Kruithof had limited reliable sources for CCT; at the time there were only incandescent and early fluorescent lamps. For warm color temperatures, Kruithof switched incandescent lamps from series to parallel, but was limited to about 2800K; higher CCTs were achieved through Philips fluorescent lamps that were under development, and the range of phosphor elements were likely restricting (Cuttle, 2015). Moreover, Kruithof extrapolated for figures that were outside the abilities of electric lighting, such as provisions from the sun. Combining all of these methods produced the Kruithof curve.

Albeit the lack of precise data from the Kruithof experiments, what does exist elicits a potential reason as to the outcomes: historical preferences. Per the Kruithof curve, 1-2 footcandles of illumination matches up with about 1800K in CCT; greater values, such as those

Figure 9.1: Approximation of the Kruithof Effect Curve (created from information in Boyce, 2003; Cuttle, 2015)



experienced in an office, of around 10-50 footcandles garners a CCT range of 3000K to 4000K (DiLaura et al, 2011). Anything below this acceptable range was described as cold and harsh while anything above the acceptable range was called unnatural, illustrated in Figure 9.1 (Kruithof, 1941). It is likely to reason that because most street and area lighting in the 1940s time period was LPS sourced. There is potential that the low CCT values of LPS (around 2000K) and the accompanying low illuminance value in the majority of exterior lighting created an expectation within viewers: certain CCTs were supposed to be used at certain illuminance levels. Regardless of the potentialities of the cause of the Kruithof curve, the outcome is noted:

viewers prefer cooler CCT values for high illuminances and warmer CCT values for low illuminances.

A Case for Cool CCT Acceptance

Despite the potential outcome of the Kruithof Effect, there is a resiliency to the cause for altering the illuminance values for visually demanding tasks. For instance, different cultures boast different customs and acceptances. An example is the Japanese culture, which frequently uses 5000K fluorescent and LED sources for office illumination. This further indicates the potential for observers to acclimate to new lighting conditions, and thus, change their preferences in the process. Stan Walerczyk has performed many retrofits where he tackles historical familiarity and preference in illumination for offices. One of his case studies will be covered in the following section.

A direct contradiction to the Kruithof Effect was recorded in two more extensively documented tests that did not have the extrapolations and limitations that Kruithof endured. IES TM-24-13, *An Optional Method for Adjusting the Recommended Illuminance for Visually Demanding Tasks Within IES Illuminance Categories P through Y Based on Light Source Spectrum* documents the reports of the research conducted by Davis and Ginther in 1989 and Boyce and Cuttle in 1990 (Boyce & Cuttle, 1990; IES, 2013). They found:

> The advice limiting the use of high [CCT] lamps in rooms lit to low illuminances is unnecessarily restrictive. The research results obtained suggest that, provided the occupants are fully adapted to the lighting, the [CCT] of the lamp has little effect on people’s impressions of the lighting in the room.

The greater validity of the findings of these studies, as opposed to the Kruithof Effect, gives greater support to the option of altering IES recommended illuminance targets for visually demanding tasks based on light spectra.

EVE Factors and Energy Usage

EVE factors are intended to change the recommended target illuminance value, specifically, decrease the light level when designing to take advantage of high S/P ratios. Decreased illuminance values are commonly a product of light sources with lower wattages or fewer light sources. This in turn provides a potential for energy savings, which could prove financially beneficial after summing annual operations. Examples of this are demonstrated in the following case studies. Stan Walerczyk is one who retrofits existing installations. He replaces lamps of fluorescent light fixtures with cooler CCT fluorescent lamps, sometimes decreasing the number of lamps altogether. For example, a three-lamp fluorescent troffer could potentially be decreased to using only two lamps. Practically put, conditions that comply with the usage of EVE factors generally provide reductions in IES recommended illuminance targets by 10% for 4100K, 20% for 5000K, and 30% reductions for 6500K fluorescent sources; LEDs must be scrutinized more intensely because of the vast difference in spectral composition of SSL sources (IES, 2013). Furthermore, the Office of Energy Efficiency and Renewable Energy at the DOE has claimed on the energy.gov website that most retrofits it has studied range in energy savings between 20% and 40%.

Walerczyk outlines two energy savings strategies for lighting retrofits, while maintaining the same type of light source as the original installation: lamp for lamp and delamping opportunities (Walerczyk, 2014). These strategies mainly pertain to the usage of tubular fluorescent sources. The lamp for lamp method infers that the initial number of lamps used will be equivalent to the number of lamps used after the retrofit – the switch is literally a lamp for a lamp. Three scenarios of lamp for lamp comparisons are made in Walerczyk's book *Lighting and Controls: Transitioning to the Future*. First is a two-lamp 3500K luminaire using 32-watt T8 lamps and a ballast operating at a ballast factor of 1.15. The resulting energy consumption is 73-watts. This scenario could be referred to as the norm or baseline, it is common in application and the other options are deviations of the warmer CCT. Second is a two-lamp 4100K luminaire using 32-watt T8 lamps and a ballast operating at a ballast factor of 1.0; the resulting energy consumption is 64-watts. Lastly is a two-lamp 5000K luminaire using 32-watt T8 lamps and a ballast factor of 0.87, resulting in 54-watts consumed. The differences between the three scenarios are the CCT values and the ballast factors. Because there was an increase in each case in CCT value, and presumably the S/P ratio, there was not a need for as much light after applying a reductive factor. Therefore, a lower ballast factor was employed as a means for light reduction. As it can be observed from the comparison between the three scenarios, the final option with the 5000K CCT (assuming illuminance levels follow EVE factor guidelines) resulted in the least amount of energy consumed while presumably maintaining visual efficiency.

Walerczyk also outlines the possible delamping opportunity in *Lighting and Controls: Transitioning to the Future* as two scenarios. First is the baseline where a two-lamp 3500K luminaire using 32-watt T8 lamps and a ballast operating at a ballast factor of 0.77 results in 48-watts consumed. That is compared to a one-lamp 5000K luminaire using a 32-watt T8 lamp and a ballast factor of 1.15 where 38-watts are used. In this case, even though the second option is operating at a higher ballast factor, the fact that there is only a single lamp is enough to clinch the title as the option that consumes the least energy. Furthermore, the lamp catalogs of major fluorescent lamp manufacturers (GE, Osram-Sylvania, Philips) show that there is little difference in lumen output of comparable fluorescent lamps of different CCT values. Therefore, a reduction of two lamps to one lamp implies a significant reduction in illuminance, with presumed equivalent visual capabilities in this case.

Case Studies of Cool CCTs

Covered in the following pages are both general and specific characteristics of case studies performed by an independent lighting retrofitting contractor and the DOE. As the reader should notice, the case studies highlight the energy savings from the factored illuminance, while maintaining equivalent visual efficiency. Moreover, all scenarios fall within the IES Categories "P" through "Y" and can be defined as visually demanding tasks.

General Retrofitting of Existing Installations

Walerczyk claims that around 90% of his retrofits in the twenty-first century upgraded fluorescent CCT values to a minimum of 5000K, in concert with numerous other retrofitter contractors and energy service companies (ESCo) (Walerczyk, 2014). At the inception of a retrofit, Walerczyk emails the office workers that the retrofit will impact. In the email, he notifies them that there will be a lighting upgrade to a light appearance similar to daylight. He explains in his book *Lighting and Controls: Transitioning to the Future* that the prior sentence is selected intentionally: upgrade sounds better than retrofit and daylight appearance has a positive connotation. He continues in the email to the workers that the new lights are supported by the U.S. Department of Energy (DOE), and if anyone does not initially like the upgrade to please keep it to his or herself; if after a few weeks someone still does not care for the lighting upgrade, he or she is to contact him (Walerczyk, 2014).

Walerczyk primes the occupants to greater enhance the likelihood of a positive response. But after recording the instances of people entrenched in historical light sources and qualities because they are the status quo, it sounds like a reasonable method for proceeding to cooler CCT implementation. Even the findings of Boyce and Cuttle in the previous section give indication of this psychological adjustment where the researchers note that the occupants have no preference in CCT, provided they are fully adapted to the lighting. In psychology, such a situation could be deemed status quo bias. This bias is towards the current, or historically intimate, methodology. What is viewed as the status quo is intrinsically taken as a point of reference where any deviation from said point is perceived as a loss. Therefore, any change in lighting that intends to stand a chance as a potentially viable option may have to rely on priming. A counterargument could be made against this, though, claiming that the priming projects an ulterior bias towards the change in illumination.

A Case Study: The U.S. Forest Service

The case study for using lighting with high S/P ratios and reduced illuminances for the western regional headquarters of the U.S. Forest Service was conducted by the DOE and all background information can be found in a report by the DOE, cited in the bibliography of this publication (DOE, 2010a). Furthermore, the DOE terms cool CCT and high S/P ratio lighting as spectrally enhanced lighting (SEL). This case study and the following case study will use SEL terminology for synchroneity with reference.

The western regional headquarters of the U.S. Forest Service in California is a four-story, 119,000-square-foot office building. Pre-retrofit, the fluorescent lamps were around 3000K with CRI ratings in the 70’s. SEL was introduced with 5000K T8 lamps in a primarily parabolic troffer dominated open office space, improving CRI to an average of mid 80’s. Money was saved by installing new lamps and ballasts instead of entirely new luminaires, and the initial cost was recovered in less than four years. After completing the retrofit, the horizontal photopic illuminance levels were measured to be a reduction of 31% compared to the original installation. Occupants were surveyed before and after the retrofit and there was no significant change in their satisfaction with the lighting.

A Case Study: Washington Navy Yard

The case study for using lighting with high S/P ratios and reduced illuminances for the Washington Navy Yard was conducted by the DOE and all background information can be found in a report by the DOE, cited in the bibliography of this publication (DOE, 2010b).

The Washington Navy Yard lighting retrofit took place in a three-story police and security building with areas that had fluorescent lighting in ceiling recessed troffers. The majority of the fluorescent lamps were 4100K T8's that were switched out for 5000K T8 lamps with higher S/P ratios. Also, some of the retrofitted office spaces were discovered to originally be illuminated to levels of 80-100 footcandles, over twice the recommended illuminance values for such spaces. There were both fewer lamps and lamps with lower wattages and lumen outputs that replaced the old system so that average illuminance levels were closer to 50 footcandles. This was accomplished through the usage of existing recessed troffers. If the old troffer layout was modified, the new illuminance levels could have potentially been decreased further. Despite the drastic reduction of nearly 50% in illumination levels, it is reported that the occupants rated the new lighting as superior to the predecessor. Furthermore, energy consumption due to lighting decreased by 37.5%.

Chapter 10 - Conclusion

The compilation of every chapter of information previously covered in this publication leads to the potential viability of altering the IES recommended illuminance targets. The notion of such alteration is based upon equivalent visual efficiency (EVE), which promotes that the visual efficiency of the occupants will neither increase nor decrease when comparing the baseline lighting source of an S/P value equal to 1.4 with a light source of a significantly higher S/P value but reduced illuminance. In order to qualify for illuminance value alteration, prerequisites must be met. These include: the task must fall within the IES designated Categories "P" through "Y"; the task must be classified as a visually demanding task; tasks must be performed under a full field of view with relatively uniform lighting, as advised by Table 12.5 of *The IES Lighting Handbook, 10th Edition*; and visual tasks with a task background luminance equal to or greater than 50 cd/m^2.

A component of visual efficiency is visual acuity (VA) – when VA is optimized, there are greater potentials for visual efficiency to be optimized as well. Ingredients for VA include diffraction of light, light aberrations, and photoreceptor density where the optical image is formed on the retina. The diffraction of light is handled by the cornea and lens of the eye, while the optical image location on the retina is an integrative concert of contributions from various optical and non-optical components, such as face orientation, eye entrainment, lens diffractive response, and pupillary diameter. The diameter of the pupil also aids in removing the light aberrations that contribute to blurry images.

Pupillary movements that improve VA are a real phenomenon that can be influenced and predicted by light spectra. The $P(S/P)^x$ formula presented in this publication is supported by the IES, a world leader in standardizing and researching lighting. That formula is expanded upon to supply Equations 8-1 and 8-2 in this publication for obtaining the necessary S/P ratio, EVE factor, or illuminance. The pupillary diameter is also subject to ipRGC sensitivity and emotional states of the individual. The ipRGCs are relatively newly discovered cells in the retina (discovered in 2002) and are still not fully understood. This lack of certain understanding paired with the ambiguity of emotional states of viewers does contribute to a weakness in the support for EVE factor implementation.

Several arguments are noted in *Lighting Design: A Perception Based Approach* that the advantages attributable to the usage of high S/P light sources were exaggerated and too small to be worthwhile (Cuttle, 2015). Lighting for specific tasks are normally substantially over the visual threshold of the viewer to ensure that visual accuracy is experienced. Therefore, an argument against reducing the illuminance levels is the concern that the lower light levels are too near to the visual threshold. The nearer that the levels draw to the visual threshold, the greater probability of decreased visual efficiency, thus, accuracy. A citation of a study conducted by Wei and colleagues that surveyed office workers to obtain preference of office lighting was also demonstrated; the outcome was disfavor among office workers for high S/P light sources (Cuttle, 2015). However, the study only lasted two weeks – the first week was for adaptation to the new lighting and the second week was for assessment completion.

That short of a time period could be a reason for the negative assessments of the cooler CCT and higher S/P lighting. According to Walerczyk, a minimum of three weeks of adaptation to the new lighting is necessary before entertaining any complaints (Walerczyk, 2014). Moreover, Walerczyk primes the office occupants before the retrofit occurs, increasing psychological favor among the viewers. As mentioned before, this may be necessary to overcome status quo bias, but could potentially overstep into the region of manipulation.

Resulting from Walerczyk's methods are positive or neutral assessments of the "lighting upgrade".

To be irrefutable, more investigation into the ipRGCs and their characteristics must be explored, especially in areas of contribution to optical components responses to light absorbed by the ipRGCs. Then, a greater understanding will exist with respect to pupillary responses, which contributes to VA. Particularly, a standardized luminous efficiency curve to illustrate ipRGC response to light at different wavelengths adopted by international lighting authorities would prove beneficial, as well as provide consistent and familiar means for deciphering ipRGC behavior.

A Recommendation

After reviewing the culmination of research presented in this publication, it is advised that if a design application meets all of the criteria to allow illuminance target values to be reduced, then it should be considered. By no means is the objective of this report to promote blind acceptance of the EVE concept; arguments for and against both sides have been presented. Clearly, after assessing the arguments it seems that the notion of altering IES illuminance values is a polarized topic that is unlikely to be resolved soon, at least completely. Until that time, explore the option. Find inconsistencies in arguments for both sides. Form independent research. But the application and support of EVE factors is published by the leading lighting and energy organizations and government authorities of the world, so explore the concept. And after covering the energy savings realized in the DOE case studies, economic and environmental impacts could further incentivize the implementation of EVE factors. If given an opportunity to apply it in practice, and if deciding to do so, conduct post-design observations of the space(s). Budget permitting, employ tunable SSL products that occupants can control. Survey the occupants over short and extensive periods of time to provide more feedback about occupant preference and usage of such systems. Moreover, consider the possibility that this phenomenon is culturally and geographically influenced. It was mentioned earlier that it is common for Japanese offices to be illuminated with 5000K fluorescent and LED light sources. Moreover, it was also mentioned that the experience of daylight on Earth is largely dependent on geographical, specifically latitudinal, location. Not all people are used to the same quantities and qualities of natural daylight, and assuming that light from the sun developed evolutionary traits in living beings on Earth, it is logical to hypothesize that preference of light is influenced by comparisons to that of the natural.

Furthermore, remember that EVE factors are an option. There is no need to unnecessarily sacrifice warm CCT lighting designs. The EVE factors are not meant for warm CCT spaces. In fact, when calculating EVE factors using Equation 8-2 or referencing Table A.1 one will realize that the EVE factors for light sources with an S/P ratio less than 1.4 have EVE factors that correlate to larger illuminance targets, that is, the factors are greater than 1.0. As the S/P ratio declines, the EVE factor increases. But such designs are likely to have a presence for many years to come. The diversity of methods with which we as a species illuminate our surroundings brings aesthetic appeal and interest. Just because a space is used for visually demanding tasks should not give any finite indication to an absence of design.

Lastly, spend the necessary due diligence in design. All designs require professional diligence, it is ethically correct. But a new concept that is not entirely understood should foster additional scrutiny and care. Recall the scenario of designing the lighting for a space with visually demanding tasks where all prerequisites of using the EVE factors are validly met, but some of the occupants have less than average ocular health. In a situation like that, EVE factor implementation could prove detrimental. Obviously, designing to cover every possible scenario is infeasible, but the time spent to properly design a space to the best ability and understanding of the designer/engineer is time well spent.

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Appendix A - EVE Factors for Adjusting IES Recommended Light Levels for Visually Demanding Tasks in IES Categories P-Y

The EVE Factor concept is a major discussion in this publication. This appendix has been created to help further understand the EVE Factors, how they relate to one another, methodology of calculation, and ultimately, how they are used in photopic light metric calculations, specifically illuminance. Calculations are exemplified in the first section of this appendix.

The EVE Factors are tabulated in Table A.1 and is derived from Table 1 of IES TM-24-13, *An Optional Method for Adjusting the Recommended Illuminance for Visually Demanding Tasks Within IES Illuminance Categories P through Y Based on Light Source Spectrum* and other supporting information from that publication. A few words of navigational advice for the table. First, the example light sources listed on the left hand side are light sources that commonly demonstrate the S/P ratios that are located to the right of said light source. The point of the example light source is not to provide finite boundaries of reliance; rather, it is to give the user an indication to the characteristics of the associated S/P values. The actual S/P values of the light sources that the designer is locating on the table is obtained from the light source manufacturer or an independent light source testing facility. If the actual S/P value of the light source is not shown in Table A.1, then the designer has two options. The first option is to interpolate between values in Table A.1. The second option is to calculate the specific EVE Factor, which is demonstrated in the example calculations of this appendix.

Table A.1 differs slightly from the table in IES TM-24-13, *An Optional Method for Adjusting the Recommended Illuminance for Visually Demanding Tasks Within IES Illuminance Categories P through Y Based on Light Source Spectrum*. If you were to compare, it would be evident that there are two EVE Factor columns in Table A.1 and only one from the IES technical memorandum. As stated in Chapter 7 of this publication, the ‘x’ value in the $P(S/P)^x$ formula was empirically derived to equal 0.78 for subjects with a full field of view in a spectrally flat white environment and a fixation point of one meter in length. However, the IES rounds the ‘x’ value to 0.8 for simplification, claiming that it falls within the probability of error inherent with the initial approximation in the formula. To exhibit the difference in approximation between the two values, Table A.1 has columns that provide EVE Factors for both calculation methods. The officially accepted method by the IES is using ‘x’ as a value of 0.8, so that column is highlighted green to indicate the correct column to use. The column showing EVE factors when ‘x’ equals 0.78 in the $P(S/P)^x$ formula is only for comparison.

Lastly, the baseline S/P is a value of 1.4. That is both why the row with the S/P ratio equal to 1.4 is highlighted yellow to show the comparison baseline and why the EVE factor for that S/P value is equal to 1.0. There is no deviation from the baseline so the factor represents it as such.

Table A.1 EVE Factors for Visually Demanding Tasks (recreated from information presented in IES TM-24-13)

EXAMPLE LIGHT SOURCE	S/P RATIO	EVE FACTOR (USING X = 0.8)	EVE FACTOR (USING X = 0.78)
HPS	0.55	2.11	2.07
	0.60	1.97	1.94
	0.65	1.85	1.82
	0.70	1.74	1.72
	0.75	1.65	1.63
	0.80	1.56	1.55
	0.85	1.49	1.48
	0.90	1.42	1.41
WARM WHITE FLUORESCENT	0.95	1.36	1.35
	1.00	1.31	1.30
	1.05	1.26	1.25
	1.10	1.21	1.21
	1.15	1.17	1.17
	1.20	1.13	1.13
3000K FLUORESCENT	1.25	1.09	1.09
	1.30	1.06	1.06
	1.35	1.03	1.03
REFERENCE SOURCES: INCANDESCENT AND 3500K FLUORESCENT	1.40	1.00	1.00
3500K FLUORESCENT	1.45	0.97	0.97
	1.50	0.95	0.95
	1.55	0.92	0.92
4100K FLUORESCENT	1.60	0.90	0.90
	1.65	0.88	0.88
	1.70	0.86	0.86
	1.75	0.84	0.84
	1.80	0.82	0.82
5000K FLUORESCENT	1.85	0.80	0.80
	1.90	0.78	0.79
	1.95	0.77	0.77
	2.00	0.75	0.76
	2.05	0.74	0.74
6500K FLUORESCENT	2.10	0.72	0.73
	2.15	0.71	0.72
	2.20	0.70	0.70
	2.25	0.68	0.69
	2.30	0.67	0.68
	2.35	0.66	0.67
8000K FLUORESCENT, CIE SUN + SKY REFERENCE	2.40	0.65	0.66
	2.45	0.64	0.65
	2.50	0.63	0.64

Example Calculations

The following is a fictional situation, only procedures should be learned from it.

A typical classroom in a high school is currently illuminated by 3500K fluorescent lamps in recessed 2'x4' troffers. A comparison is made between the existing 3500K fluorescent lamps and a potentially new 5000K fluorescent lamp replacement. After checking the model with the lamp manufacturer, it was confirmed that the 3500K lamps have an S/P value of 1.4. The lamp manufacturer provides an S/P ratio of 2.0 for the proposed 5000K lamps. What is the EVE Factor and what does it mean?

First, recall Equation 8-2.

$$\frac{P_2}{P_1} = \left[\frac{(S/P)_1}{(S/P)_2}\right]^{0.78}$$

For the EVE calculation, the IES actually rounds the exponent of 0.78 up to 0.8. They claim that it falls within the probability of error for when the formula was empirically derived.

Identify the variables.

$$\frac{P_2}{P_1} = ?$$

$$(S/P)_1 = 1.4$$

$$(S/P)_2 = 2.0$$

Plug in values for variables and solve for the unknown.

$$\frac{P_2}{P_1} = \left[\frac{(S/P)_1}{(S/P)_2}\right]^{0.8}$$

$$\frac{P_2}{P_1} = \left(\frac{1.4}{2.0}\right)^{0.8}$$

$$\frac{P_2}{P_1} = 0.75 = \text{EVE Factor}$$

The EVE factor was calculated to be 0.75 for the classroom scenario, which means that only 75% of the illuminance level is necessary for equivalent visual efficiency when switching from the 3500K lamps to the 5000K lamps. If you look at the EVE Factors in Table A.1, you the notice that the EVE value for light sources with an S/P value of 2.0 is equal to 0.75, as it should.

Continuing this example, when searching for illuminance targets for a classroom, *The IES Lighting Handbook, 10th Edition* provides an average maintained value of 40 footcandles for the age group of 25-65 (although the high school classroom has students under the age of 25, the instructor and any other supplementary personnel are likely over the 25 years of age boundary. Because the average illuminance for the age group of 25-65 is larger than the under 25 category, it should be used to ensure adequate illumination for the instructor while there is an abundance of light for the students) in a general classroom where hardcopy and handwriting are the predominant tasks. Therefore, if the EVE factor is used, the new acceptable illuminance target is 30 footcandles, as calculated below.

$$E_2 = E_1 * \text{EVE Factor}$$

$$E_2 = (40\text{ fc}) * (0.75)$$

$$E_2 = 30\text{ footcandles}$$