POTENTIAL OF USING LED MODULES AS PRIMARY LIGHT SOURCES FOR OFFICE BUILDINGS

by

PENGXIANG JIANG

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Major Professor
Fred Hasler

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Abstract

This paper discusses the potential of using LED modules as the primary light source for office buildings' lighting systems. The LED lamps are the newest mass-produced lamps today; they have many insurmountable advantages compared to other light sources, like long lamp life, high efficacy, and low heat emission. Because of these advantages, owners and occupants of buildings can benefit greatly from the application of LED luminaires. The main focus of this paper is in 4 categories, which include the reliability of published data, occupant comfort, energy efficiency, and the life cycle costs of building lighting systems. LED light sources are compared to other primary light sources, which include fluorescent and incandescent lamps, of low ceiling office spaces from these 4 categories.

The reliability of published data discussion covers color rendering index (CRI), correlated color temperatures (CCT), lamp life, and efficacy of the different type of lamps. The criteria of LED lamps are the most emphasized point of this section. The current CRI, efficacy, and lamp life evaluation systems are not suitable for LED lamps, and this paper discusses the practical value of each of these published data in office lighting system design. Some technical reports presented in this paper show that high CRI values of LED light sources do not directly link to excellent color rendition. However, LED light sources can have similar spectrum power distributions as natural light, and offer adequate visual comfort. Efficacy and lamp life are in the same situation. Even though, the published values do not necessarily reflect the real life performance of LED lamps, they often still have the longest lamp life and highest efficacy.

Human comfort is the second factor discussed. Engineers and lighting designers consider illuminance level, color rendering ability, and glare of lighting systems to be deciding factors of human comfort from a lighting design perspective. However, many medical studies show that the

human is much more sensitive to the correlated color of light sources. Light sources must vary output luminous flux and correlated color temperatures over time to help occupants reach optimum office task productivity and maintain health and visual comfort. LED lamps are the only light source that can practically change both the output luminous flux and correlate color temperature without heavy extra investments in equipment, which makes it the perfect candidate for this category.

Energy efficiency is the third discussion point presented in this paper. Efficacy is a widely adopted term for evaluating the energy efficiency of a lamp, which describes the ratio of the output illuminance and input power. Because the output illuminance of LED lamps is decided not only by the illuminant bodies, but also many other electronic components in the lamps, some experts suggest that using efficacy to judge LED lamps is biased. This paper states the author’s position on whether efficacy can adequately describe the efficiency of LED lamps.

Costs are also an inevitable point of this paper. LED lamps have the reputation of being the most expensive type of light source, but marketing data shows that the price of LEDs has been dropping dramatically recently. Moreover, Haitz’s law predicts that the price of LEDs will drop even more in the future. In this paper, the lifecycle costs of a light system have also been addressed across different types of light sources.

Some crucial drawbacks of LED lamps, such as narrow photometric distribution and thermal damage control, are also addressed in this paper. Scientists and engineers still have not found the perfect solution to these drawbacks, but they are not significant enough to jeopardize the application of LED lamps in most architectural lighting design cases.

According to the finding of this paper, LED lamps are the mainstream light source of future office lighting systems. The author also gives some suggestions for using LED lamps as primary light sources in office lighting system design applications at the end of the paper.

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Moreover, my father and mother, for being a pair of wonderful parents, and supporting me for many years without complaint.

Dedication

To Manhattan KS, because you have given me a wonderful college memory.

Chapter 1-Brief Introduction of LED Light Source

Using filament and fluorescent lamps as the major light sources of artificial light inside buildings has more than 100 years of history (Niki, 2007). A long time of developing their production technologies gives them the advantages of having mature markets, low production costs, and a high average of quality. Occupants, building owners, and lighting-system designers are all familiar with using filament and fluorescent lamps as primary light sources.

In the past fifteen years, light-emitting diode (LED) type lamps became more and more common. This type of lamp has longer lamp life, higher efficacy, and is easier to control than any other types of lamps; people are starting to believe that LED lamps will replace other lamps and become the mainstream light sources inside buildings. This paper will compare LED lamps with other common lamp types, and discuss whether LED lamps have the potential to be the primary light sources in commercial buildings. Since office buildings contain more than 54% of floor space among all commercial buildings, this paper will only focus on the lamp applications of office-building lighting systems (U.S.EIA, 2012).

History of LED lamps

Even through LEDs are still considered a new lamp type, LED lamps actually have a very long history. The first officially recorded LED-type light emission process happened as early as 1907. Henry Joseph Round observed an electroluminescence from a piece of silicon carbide. However, the light's emission was too weak to have any practical usage, and the process was very difficult to control; nobody paid attention to it (Henry, 1907). However, this discovery directly led to the invention of LED lamps. Later, in 1920, a Russian scientist called Oleg Losev constructed a solid-state light-emitting device by using silicon carbide; this device can be considered the first LED lamp in history. Because the greenish light of this device was also too weak to have any feasible value, it did not attract much attention. However, Oleg Losev conducted detailed research on the light emission mechanism of the device and published his research result in a Russian science journal (Oleg, 1928).

The previously mentioned solid-state light emission devices are only the prototypes of LED lamps; they had no commercial value. In 1962, American engineers Dr. James R. Biard and Gary E. Pittman invented the first genuine LED lamp (US Patent 3293513, 1966). This LED lamp uses a diode as the light source instead of a piece of raw semiconducting material; it is the first modern LED lamp and the master template of all current LED lamps. However, this LED lamp was an infrared radiation lamp, which does not emit visible light. Later that same year, Dr. Nick Holonyak invented a red-light LED lamp, which was the first LED lamp that emitted visible light.

Even though scientists and engineers achieved many breakthrough technologies for LEDs in 1968, LEDs still could not emit enough light for illuminating large areas. The first commercial LEDs were from Hewlett Packard laboratories; they were used only for indicator lights (HP, 1968). The wide application of these LEDs drew more and more people’s attention; it became the model behind many later LED technological innovations and largely shaped current LEDs. Later, George Craford’s invention of the first yellow light LED and Herbert Maruska and Jacques Pankoyes’s invention of the first violet light LED also have made significant contributions to develop of LED technologies. Shuji Nakamura became one of the Nobel Prize in Physics winners of 2014, because of his bright blue LED invention at 1979. Figure 1.1, indicates some major milestones in the history of LEDs.

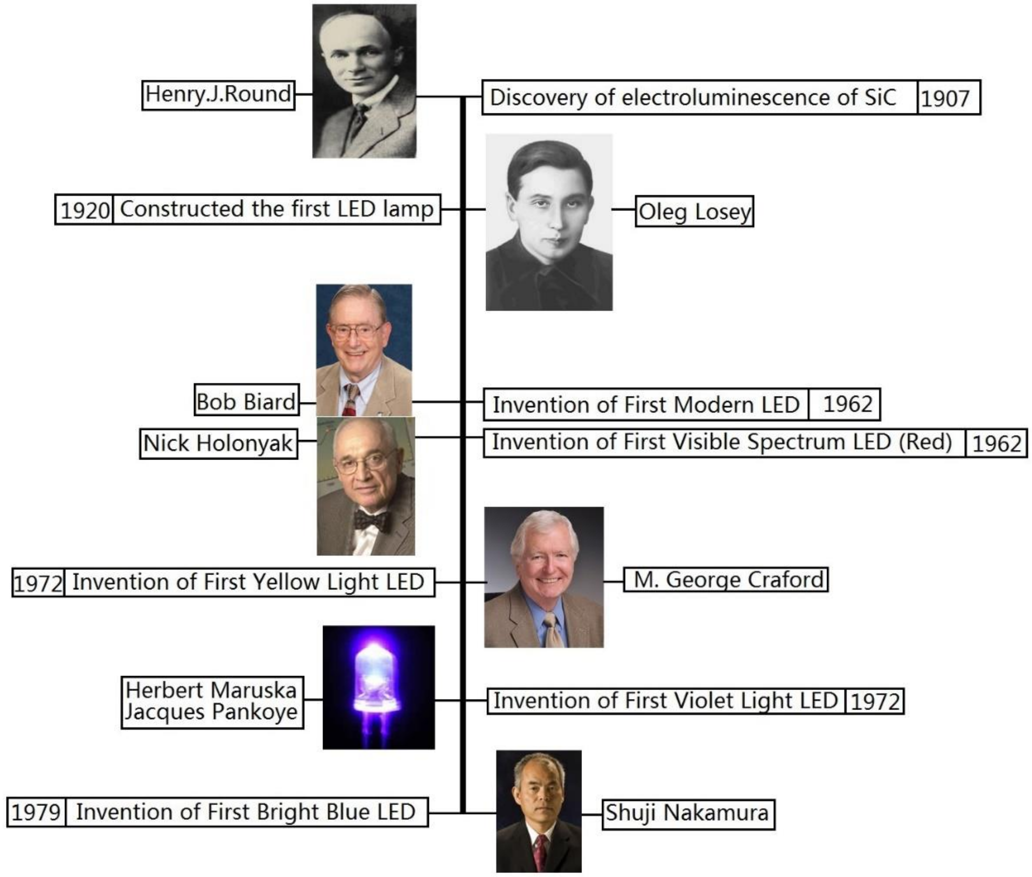

Figure 1.1 Brief History of LEDs (Information and images from *LEDs*, Edison Tech Center, 2013; *World+Dog hails 50th birthday of the LED*, T. Smith, 2012; *ECE Professor Leads Way to Nobel Prize*, Texas A&M Univeristy, 2014)

What is light?

Light is one of the most familiar and useful elements of our life; humans have a long history of researching light. Many assumptions about the definition of light have been made during the past several hundred years. Some of them have the support of scientific evidence, but none of them can disprove all others and become the only official explanation. Two of these assumptions have worldwide recognition and are being considered as the best solutions. They are the electromagnetic wave theory and the photon theory.

Electromagnetic Theory

Electromagnetic theory comes from the work of J.Clerk Maxwell and subsequent developments (Eugene, 2002). It describes light as a form of traveling transverse waves, and these transverse waves consist of a pair of orthogonal and interlocked magnetic and electric waves, referred to as electromagnetic waves (EMW). Since the magnetic wave aspect of EMW are irrelevant to light, this paper will choose to ignore it in the discussion. Figure 1.2 is an example of electromagnetic waves.

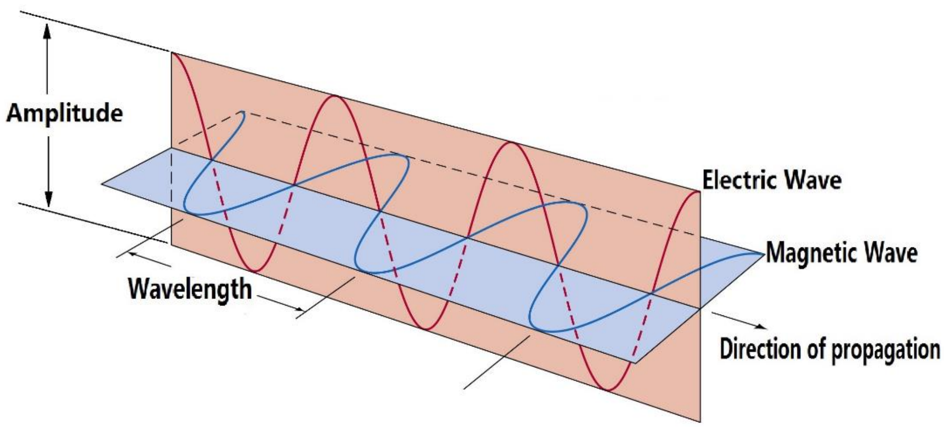

Figure 1.2 Electromagnetic Wave (EMW)

EMW is the same as any other transverse wave; it is defined by its wavelength (λ), frequency (ν), and amplitude (E). The wavelength of an EMW decides its display color and visibility. The wavelength range of light that can be detected by the human eye is called the visible spectrum. Visible spectrum of human being is from λ=390nm to 700nm. Light with a short wavelength tends to have "cool" tone colors, such as violet (390nm); light with a long wavelength tends have "warm" tone colors, such as red (700nm).

Since the linear speed of EMW (V) is defined as V= ν•λ, the wavelength and frequency of light together decide the propagation speed of EMW. The amplitude of EMW is directly proportional to the energy of the wave.

The propagation rule of EMW is also the same as any transverse waves. Multiple beams of light waves can travel in a superposed state, and they will not interfere with each other if they are not fully coherent. Hence, multiple beams of light with different wavelengths can emit from the same source and always keep their characteristics of specific wavelengths unchanged. This is very important for the color production of LED lamps, which will be discussed later.

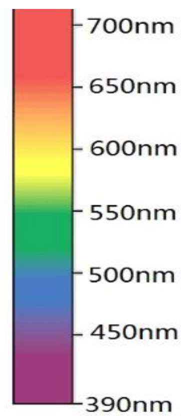

Figure 1.3 The Visible Spectrum

Photon Theory

Photon theory is a relatively newer theory. This theory is widely adapted to quantum electrodynamics study, it prescribes that light consists of a collection of massless energy-carrying particles, referring to them as photons. Photon theory is practical in quantum physics research, but it is not practical in optics studies, nor is it always apparent. Since this paper is about optic and light's architectural impacts, the photon theory will not be pursued further in this report.

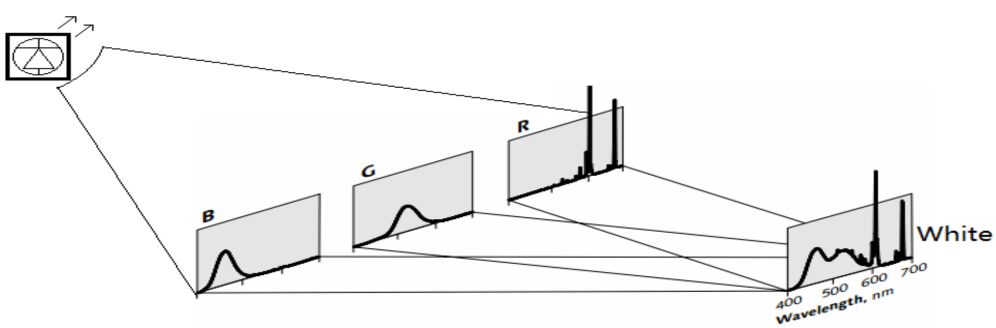

Figure 1.4 LED Color Reproduction (Reproduced from *Digital Video and HDTV* , Charles A. Poynton, 2012). This figure demonstrates that a single LED lamp can emit light beams contain multiple colors light, and all keep their characteristic.

How LEDs Work

A light-emitting diode is one of many different types of diodes; it shares the same characteristics as any other diodes. Diodes have two poles; the poles generally are denoted as anode and cathode, which are available for electric current entry. All diodes are semiconductors; they have the character of letting electric current flow through their bodies easily in one direction and forbidding or applying massive resistance if the electric current tends to flow in an opposite direction. Figure 1.5 shows some symbols of diodes in an electric circuit's diagrams. The direction of the arrows indicates the direction of the flow of electrons, which is opposite to the direction of the current.

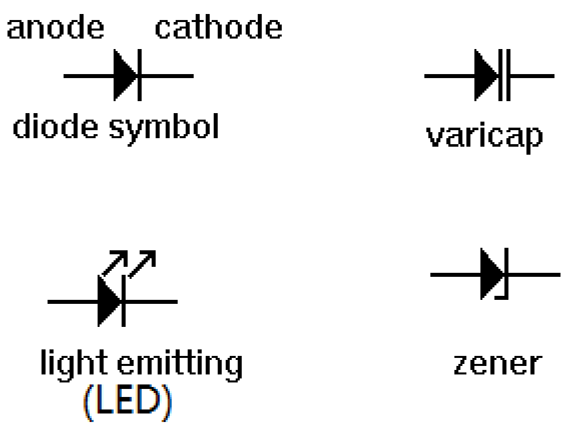

Figure 1.5 Diodes Symbols

Light-emitting diodes use positively charged material (p-type) and negatively charged material (n-type) as their two poles; p-type and n-type materials are connected to junction layers, or what are sometimes referred to as active regions. Atoms of n-type materials are charged with extra electrons, and atoms of p-type materials have fewer electrons than in their equilibrium state or describe as charged with electron holes. When electric current is applied to an LED, the current pushes the atoms of both poles towards the active region; this action gives the opportunity to p-type atoms to take electrons from n-type atoms; this phenomenon is called doping. Because p-type atoms take electrons from n-type atoms, the electron holes are neutralized by accepting electrons; the orbit energy of electrons in n-type atoms is higher than in p-type atoms. Therefore, the process of transferring electrons will emit extra energy in electromagnetic wave form. If the electromagnetic waves happen to have a wavelength of 390 to 700 nm, they become the light that humans observe from LED lamps. The applied currents offer free electrons for the n-type atom, and offer energy to create electron holes for the p-type atom, and keep pushing these two types of atoms toward the active region; then the applied current will maintain the light-emitting process. This is supplying negative charges to the n-type sides, forcing electrons flow to the p-type sides, a process called forward bias.

LEDs depend on a doping process to emit light and forward bias to maintain the continuum of the process. Figure 1.6 shows the mechanism of doping and forward bias process. The colors of the emitted light depend on the semiconducting materials, and different materials will emit different colors of light. The first LED lamps, constructed by Henry. J. Round, use silicon carbide (SiC) and emit yellow light; some old LED technologies use gallium phosphide (GaP), gallium arsenide phosphide (GaAsP), and aluminum gallium arsenide (AIGaAs) to produce wavelengths from red to yellowish-green light. Unfortunately, all of these materials only emit very low-intensity light efficiently; they will produce excessive heat if applied with a large current to push out high-intensity light. Nowadays, these material are mainly used for indicator lights in manufacturing.

High-intensity LED lamps use different materials, such as aluminum indium gallium phosphide (AllnGaP) and indium gallium nitride (InGaN). AllnGaP emits “warm” color light, and InGaN emits “cool” color light; together, they can emit any color of light on the spectrum (Jonathan, 2010). Even though modern high-intensity LED lamps mainly use InGaN and

AllnGaP as emissive materials, some other materials are also applicable due to different technologies from a variety manufacturers.

LED lamps are known for their ability to change intensity levels and colors. The rate of light emission of the doping process is directly proportional to the input power of LED light sources. Less input of free electrons and energy will result in less light emission, and vice versa; it is a common characteristic of the electroluminescence effect. Therefore, intensity variation is achieved by controlling the input wattage.

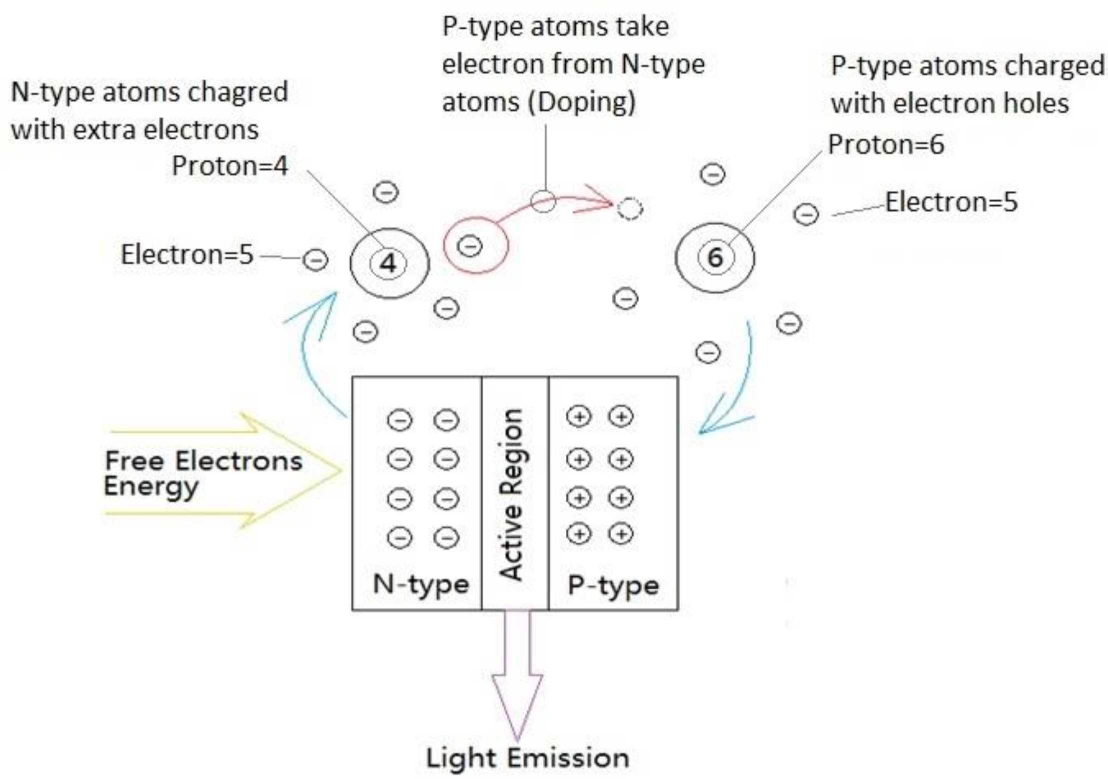

Figure 1.6 Doping & Forward Bias Process

LED lamps change colors by using additive color models. Additive color models obey the additive reproduction law, and the law states that adding light with different colors will produce light with new colors. A good additive color model is able to produce millions of different colors with correct mixing. The most common additive color model is the red-green-blue (RGB) model. Figure 1.7 is an example of an RGB model and its common color-mixing results.

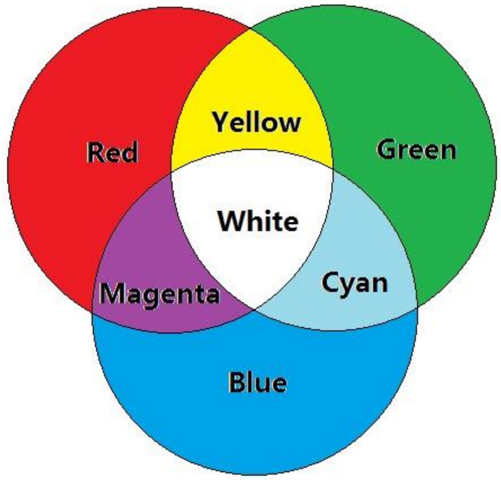

Figure 1.7 RGB Color Model

The mixing of RGB (trichromatic primary colors) will obtain millions of different colors, but these colors are still far fewer than the total number of colors that can be detected by the human eye. In 1931, the International Commission on Illumination (CIE) defined the spectrum range of the human eye; it is also known as color space. Figure 1.8 is a model of the color space diagram. LED lamps cannot reproduce all the colors in the diagram. However, they can reproduce all the colors inside the RGB triangle. Therefore, LED lamps' color variation can be achieved by installing light emission modules with different materials in the lamp and varying the light intensity of each module to change the formula of RGB addition to obtain different colors.

The most common light color in office applications is white because white light renders different color accurately, and it is the most common light color in the nature. For these reasons, the ability to produce high-quality white light is very significant for any light source. LED light sources have three methods of producing white light. Using an RGB color model (RGB-W LED) to produce white light is the one of the three methods. Figure 1.7 shows that adding all three primary colors will produce white light; adding colors that contain all primary colors will also have same effect. This method has the highest efficiency, because the light additive reproduction process involves no energy transformation.

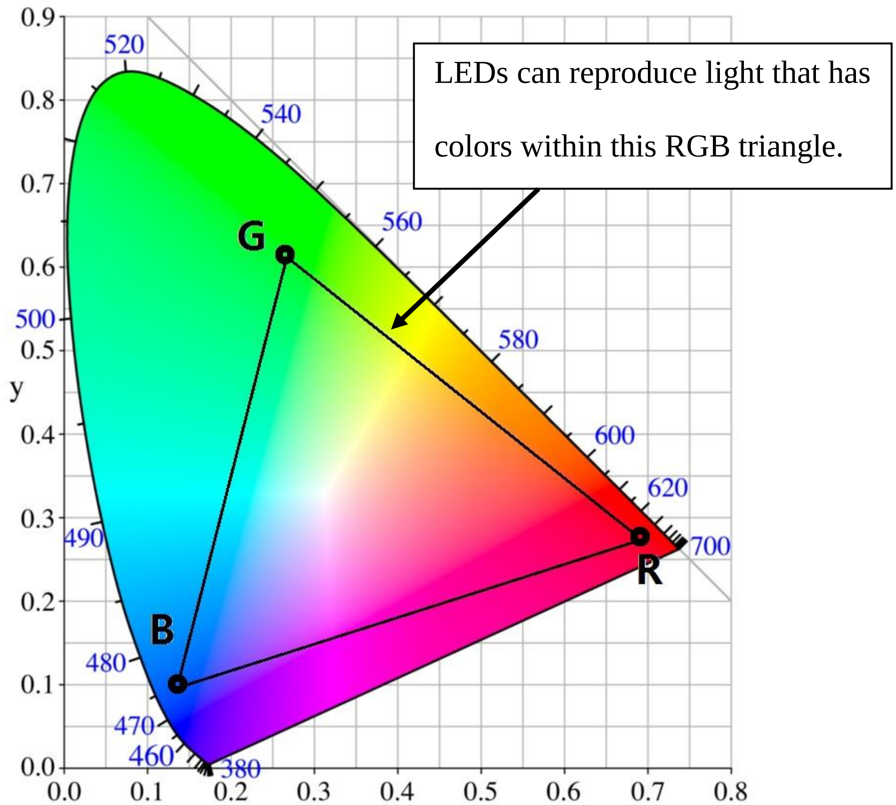

Figure 1.8 Color Space (Reproduce from *CIE 1931 Standard Colorimetric Observer*, International Commission on Illumination, 1931)

The second method uses phosphorus-coated, short-wavelength, light-emissive materials. This type of LED is called phosphorus-coated white LED (p-W LED). Short-wavelength light-emissive materials emit light with wavelengths shorter than 460 nm, such as UV light and blue light. The “cool” color light that is generated inside an LED will go through a layer of yellowish phosphorus coating and be partially converted to yellow or other “warm” color light. The unconverted “cool” color light and converted “warm” color light will combine to produce white light (Philips, 2011).

Combining p-W LEDs with red LEDs is the third method of producing white light (p-W+R LED). Instead of purely depending on generating “warm” color light from the phosphorus coating, red LED will add “warm” color light into the combining light beams. This approach gives the p-W LEDs the ability to change light color (Philips, 2011).

All these methods enable LED lamps to change colors while operating; this ability is referred to as dynamic color shifting; LED lamps are the only type of lamp which has a realistic dynamic color-shifting ability.

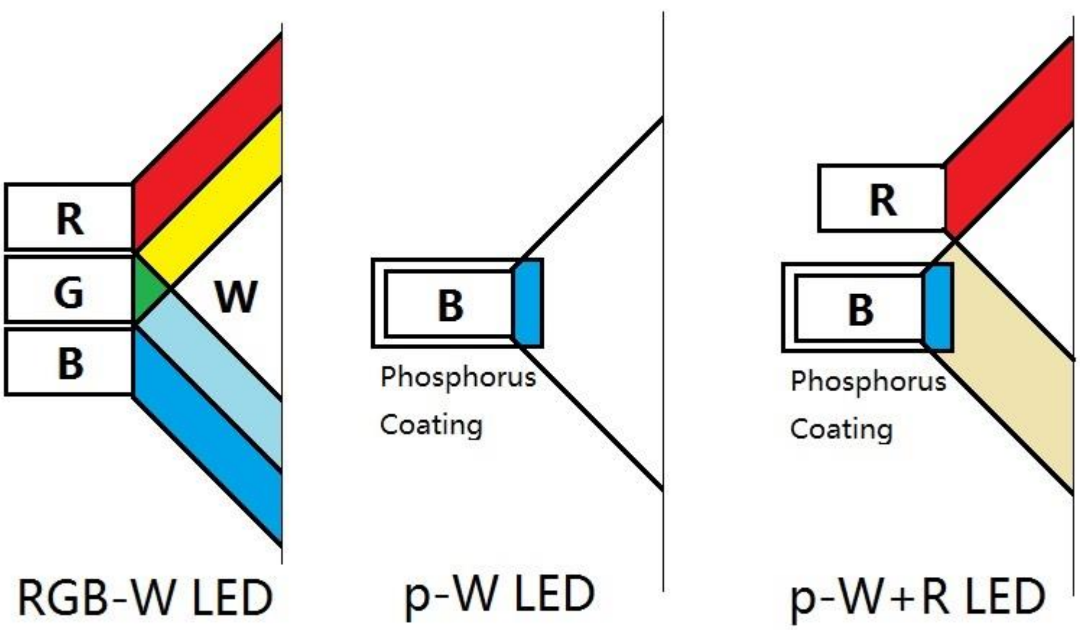

Figure 1.9 Three Types of White LED

LED Structure

Modern LED luminaires that are produced by different manufacturers have large variations in the details of their structure; however, the main structure of an LED luminaire is similar. Figure 1.10 is the main structure example of modern LED luminaires.

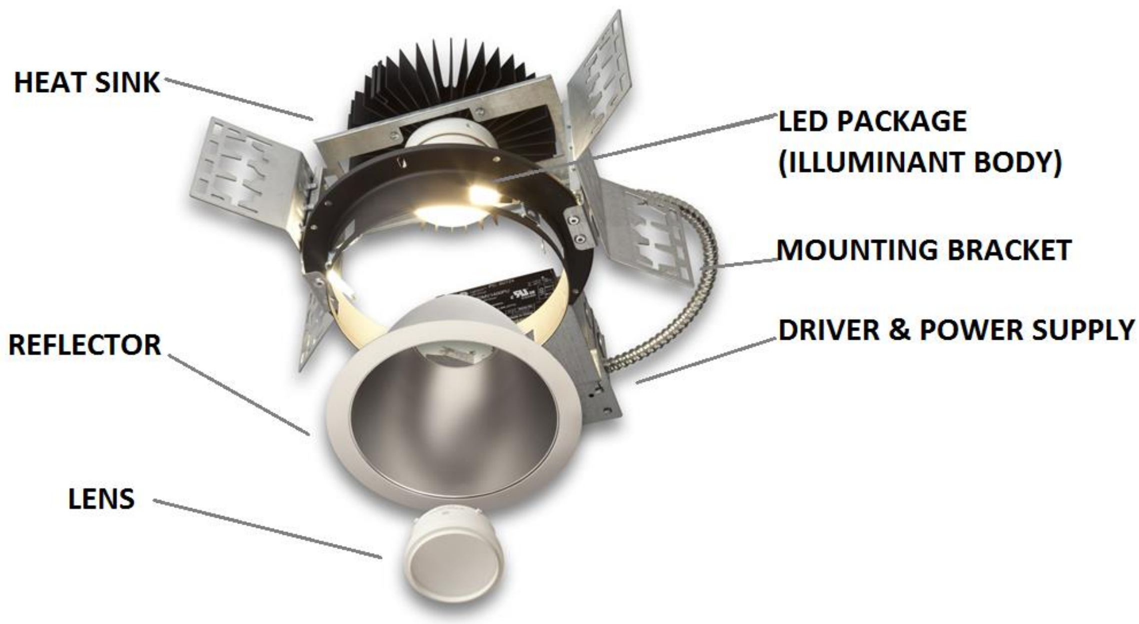

Figure 1.10 Typical Structure of LED Luminaires (Figure from *GE Lumination™ LED DownLight modules*, GE Lighting, 2014)

The core of this structure is the LED package. Two types of LED packages are commonly installed inside LED modules; these are the standard LED and the surface-mounted LED. The standard LED is the conventional type of LED; the first visible spectrum LED from 1962 and the first commercially available LED from 1968 are both classified as standard LED. The standard LED consumes less energy than any type of illuminant bodies and is cheap to produce; unfortunately, it cannot emit high-intensity light. It

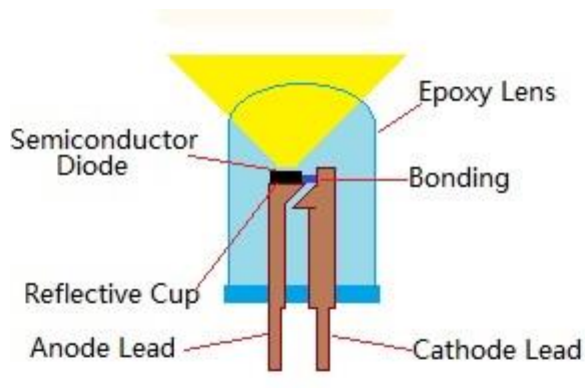

Figure 1.11 Standard LED Structure (Information from *LED Lighting Explained*, Philips Lighting,

is good to use as an indicator light, but it is not ideal for illuminating large areas.

Surface Mounted LED (SML) is a newer type of LED; it also known as high-brightness LED. This type of LED is able to handle relatively higher input power than standard LED, and it also emits higher intensity light. The structure of this type of LED can vary slightly, but they all share a similar, basic structure (See Figure 1.12). This structure is based on a semiconductor chip, also referred as a "die." A substrate layer supports the die, and thermal pads directly contact the substrate for maximum heat conduction. The silicone lens provides basic protection for the die and diffuses the emitted light preliminarily.

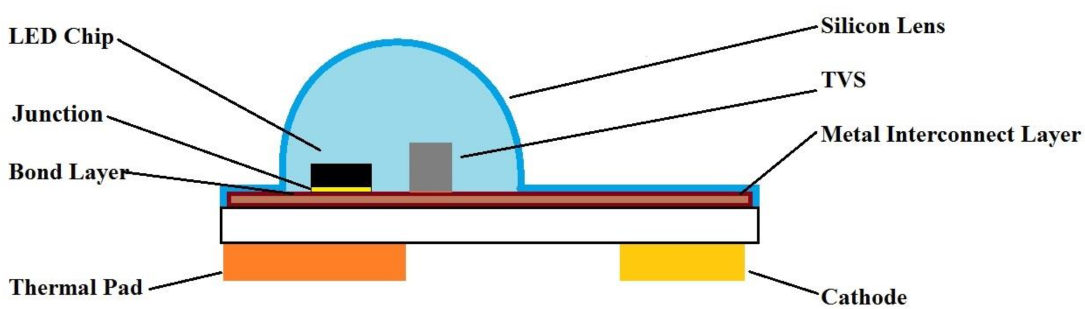

Figure 1.12 Surface Mounted LED (SML) Structure (Information from *LED Lighting Explained*, Philips Lighting, 2010)

LED Application Analysis

Incandescent and fluorescent lamps are the mainstream light sources of architectural lighting system designs for the past one hundred years and in the present day (Niki, 2007). However, LED lamps display many unique and supreme advantages over any other types of lamps, such as dynamic color shifting, long lamp life, and efficacy. All these advantages make points for the discussion that LED has the potential to be the primary light source for commercial buildings.

Since, this paper only focus on lighting systems of office buildings, all the discussion categories are strictly based on design considerations for that type of application. First, whether the published data of lamps are trustable and can be applied in the design is discussed. Then, lighting system costs and visual comfort of occupants are the primary concerns of an office lighting system design, which is heavily addressed in this paper. Lastly, environmental friendly design, ease of control, and many other factors are secondary concerns, which are also discussed.

Published photometric data of lamps are the references of lamps' performance in lighting system design. The published data that is significant to design process include CRI, CCT, lamp life, and costs; they are the key characteristics of lamps. After an introduction, they are discussed from rating systems, determining methods, and reliability aspects for LED, incandescent, and fluorescent lamps.

The visual comfort of an office lighting system is defined as offering a lighting environment for occupants that fulfills their visual task requirements and help them achieve optimum productivity. The first part of the visual comfort discussion is about the technical parameters of the correct lighting environment; the second part is comparing which lamps can reproduce the environment.

An environment-friendly design is one of the major considerations of every type of industrial and commercial design since environmental issues are too severe to ignore. This paper's discussion of this aspect is not limited to low energy consumption; it will also include lamp manufacturing pollutions, disposal pollutions, and recyclability.

The discussion and comparison of costs are not only limited to the initial costs, but also include the maintenance and operational costs. All the lighting systems will be required to achieve the necessary functions of a modern lighting systems. Such systems shall have preset scene, dimming, and sensor controlling functions. All the costs of devices that are required to achieve these functions are counted as initial costs. The energy efficiency of the systems, necessary maintenance frequency and complexity, and lamp life will all become deciding factors in the maintenance and the operational costs.

The results of comparisons and discussions may present that LED is not the ideal candidate for current technologies; however, if technical reports show that LED has a potential to overcome its drawbacks in the next few years, the idea of using LED as a major light source is still applicable.

Chapter 2- Important Aspects of Light Sources in Office Lighting Systems Design

This chapter introduces the different characteristics of a lamp in an architectural lighting design and how they relate to LED lamps. Using efficacy, color rendering index, and other technical terms to evaluate the quality of lamps is widely adopted; nevertheless, using them to evaluate LED lamps can be imprecise. Because the light emission mechanism of LED lamps and the emitted light combinations are greatly divergent from other lamps, there may need to be new and exclusive measuring methods. This chapter discusses whether the results from the current measuring method is reasonable.

Introduction of Key Characters

Different types of building projects emphasize different characteristics of lighting systems. For instance, storage building projects value the costs and efficacy of lighting systems more than other characteristics; hospitality building projects emphasize aesthetic and visual comfort aspects. However, five characteristics are most commonly emphasized. They are correlated color temperature, color rendering index, efficacy, lamp life, and costs. The Illumination Engineering Society of North America (IESNA) has defined all these terms; the following is a brief introduction of them.

Correlated color temperature

Correlated color temperature (CCT) is a standard that is used to describe the color of the light source when it is operating as intended, and IESNA defines CCT as "*the absolute temperature of a blackbody whose chromaticity most nearly resembles that of the light source*" (DiLaura, 2011). A blackbody is an idealized opaque object that absorbs all incident EMW; it will also radiate EMW with different wavelengths based on its surface temperature. When the surface temperature of the blackbody is uniform, it will only emit one wavelength of the EMW; the EMW becomes visible light when its wavelength is inside a visible spectrum. The color of the light is correlated with the surface temperature and represented by the temperature in Kelvin.

Typically, CCT of lamps ranges from 1000 to10000 Kelvin (K), lower temperatures represent warmer colors and the higher temperature cooler colors. Figure 2.1 is the color temperature correlation of some common light sources, which is defined by the International Organization for Standardization (ISO).

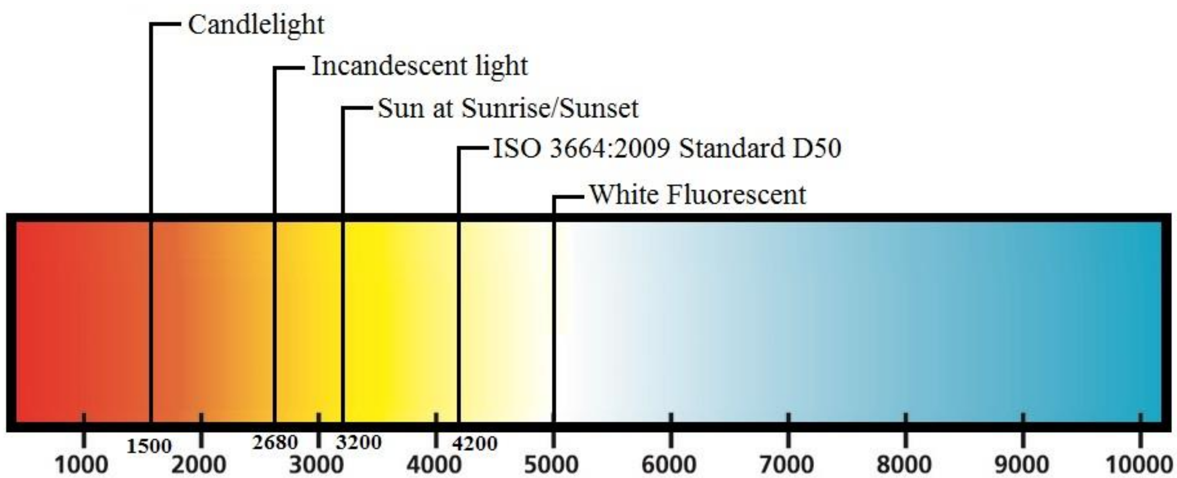

Figure 2.1 Color Temperature Correlation (Information from *ISO file 3664:2009*, International Organization for Standardization, 2009)

Color rendering index

The color rendering index (CRI) quantitatively measures how precise a light source can present colors of different objects compared to a reference light source. IESNA defines it as *"a measure of the degree of color shift objects undergo when illuminated by the light source as compared with the color of those same objects when illuminated by a reference source, of comparable color temperature."* (IESNA, 2011a)

CRI has a rating scale from 0 to 100. Reference sources have perfect color rendering ability, with a CRI equal to 100. Natural light is a reference light source for high CCT sources. Incandescent lamps have a continuous and steady spectrum curve. Therefore, they often are considered as a reference source for low CCT sources. Table 2.1 contains information on some common lamps. Because the current widely adopted CRI rating system is not sufficient to rate CRI of LED lamps, they are not listed in this table. CRI rating issues of LED lamps are further discussed in later chapters.

Source	**CRI**
Incandescent	95-100
T8 Linear Fluorescent	75 - 85
Cool White Linear Fluorescent	62-70
Compact Fluorescent	82-95
Standard Metal Halide	65-68
Standard Sodium-Vapor	22-30

Table 2.1 Common Lamps CRI Data (Information from *Color Rendering Index, CRI,* Lighting Research Lab, accessed date 12-24-2014)

Efficacy

Efficacy is the ratio of total emitted luminous flux and total input power of lamps; the unit of efficacy is lumens per watt (lm/w). Efficacy measures energy efficiency of lamps; a high efficacy value does not always mean a high luminous output. Conventional incandescent lamps generally have the lowest efficacy of all lamp types due to the large amounts of energy wasted in thermal energy. Fluorescent lamps have higher efficacy than incandescent, and metal halide and high -pressure sodium have the highest efficacy. The efficacy of LED lamps can be higher or lower than that of fluorescent and high-intensity discharged (HID) lamps depending on the manufacturing quality.

Source	Efficacy (Lm/W)
Incandescent	5-20
Tungsten Halogen	18-28
Halogen infrared	20-30
Mercury Vapor	25-48
Compact Fluorescent	65-68
Linear Fluorescent	65-100
Metal Halide	45-100
High-Pressure Sodium	45-110

Table 2.2 Efficacy of Various Lamps (Information from *High-wattage Compact Fluorescent Lamps*, Lighting Research Center, 2006 accessed date 12-24-2014)

Lamp Life

Lamp life is "*estimated through industry-standard lamp rating procedures. Typically, a large, statistically-significant sample of lamps is operated until 50% have failed; that point, in terms of operating hours, defines 'rated life' for that lamp*" (DOE, 2009). Different lamps have very different lamp life, and this is also controlled by many different factors. Incandescent lamps have the shortest lamp life, and their lamp life is controlled by the manufacturing quality and the operating voltage (dimming). Fluorescent lamps have a lamp life 10 times longer than that of incandescent lamps and their lamp life is controlled by manufacturing quality and the burn times of lamps (Department of Energy, 2013). Metal halide and high-pressure sodium lamps have even longer lamp life, although they are usually applied to high ceiling spaces because of their intensity.

The lamp life of LEDs is different from that of other lamps because LED lamps will not fail because of long operating times; they only infinitely depreciate their luminous flux output. The rule in defining the lamp life of LED is that when an LED lamp has greater than 30 percent of output luminous flux depreciation, it is considered as passed the end of its useful life. Even though, the lamp life of LED is defined by its useful life, they still have the longest lamp life.

Source	Lamp Life (Hours)
Incandescent	750-2500
Fluorescent	7000-24000
LEDs	10000-50000+

Table 2.3 Lamp Life of Primary Light Sources of Low Ceiling Office Buildings

(Information *from Solid-State Lighting Research and Development Multi-Year Program Plan*, U.S. Department of Energy,2014)

Costs

Costs of different types of lamps vary widely because of rated input power and manufacturing techniques. Generally, LED lamps have lower rated input power and higher costs than fluorescent and incandescent for similar applications, and incandescent lamps have the highest rated input power and lowest cost. However, LED lamps have high efficacy. LED lamps may emit similar or even more luminous flux than incandescent or fluorescent lamps that have higher input power. For this reason, comparing the costs per emitted luminous flux is more practical. U.S dollars per a thousand lumens ($/klm) will be used to compare sources in the cost comparisons.

Incandescent lamps have the longest history. Meanwhile, they have the lowest $/Klm value. Nowadays, fluorescent lamps already have similar $/klm as incandescent lamps. Because LED lamps are a new type of light sources, their related manufacturing technologies, available production lines, and markets are not as developed as incandescent and fluorescent lamps. The $/klm value of LED lamps is higher than that of incandescent and fluorescent lamps in most cases. Table 2.4 is $/klm data of some common lamps.

Source	Price ($/klm)
Halogen Lamp (A19-43W, 750 Lumens)	$2.5
CFL (13W, 800 Lumens)	$2
LED Lamp (A19-12W, 800 Lumens)	$16
Linear Fluorescent Lamp w/ Ballast System (F32T8)	$4

Table 2.4 Lamp Initial Costs Comparison (Information *from Solid-State Lighting Research and Development Multi-Year Program Plan*, U.S. Department of Energy,2014)

Determination of Characteristics and Comparison Methods

The comparison methods and reliability of published data of the key characteristics of light sources are discussed in this section. Suggestions that are related to office lighting system design are given based on the summary of the comparison.

Color Rendering Index

In order to explain the relationship between CRI and visual comfort, the color perception of the human eye needs to be briefly introduced first. A colored surface is only able to reflect one certain wavelength of light efficiently, and the color of reflected light represent the color of the surface (Martin, 1996). For instance, the incident light in Figure 2.2 is an example of the reference light, and the dominated portion of reflected light is a green light. Hence the color of the surface is green.

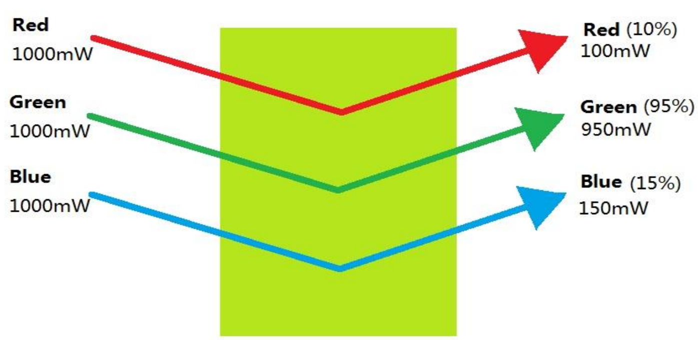

Figure 2.2 Surface Color Reflection (Information from *An introduction to the visual system*, Martin Tovee, 1996)

The human eye detects colors and intensity of light by using photoreceptor cells. Cone cells are more sensitive to bright light, and are able to detect red, green, and blue light; in contrast, rod cells work best in dim light, and are not responsive to red color light. These photoreceptor cells will send signals about the intensity of light and quantity of red, green, and blue color photons to nerve systems; nerve systems will analyze the signals and decide the intensity and color of the light.

Therefore, the entire process of how humans detect the color of an object has 3 steps. The first step is the light incident on the target object; in the second step, the human eye perceives the reflected light; and in the last step, the photoreceptor cells interpret the light information into neuroelectric pulse signals and transfer to the nerve systems to process. The nature of incident light is the most critical part of this process; it directly changes the decisions of nerve systems.

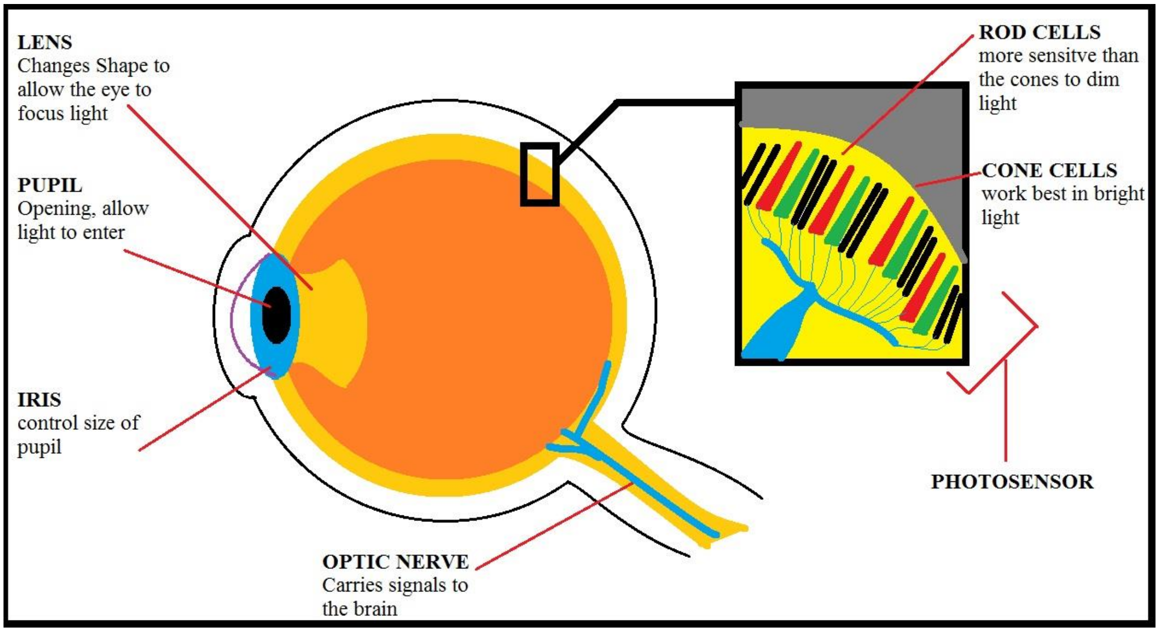

Figure 2.3. Vision System (Information from National Library of Medicine, retrieved from http://www.livescience.com/32559-why-do-we-see-in-color.html)

Even though our nerve systems need only one wavelength of light to decide on the color of an object, small amounts of all other colors of light are still necessary to ensure that our nerve system made the correct decision. For instance, if a red surface is put under pure, red light, the human vision system will only be able to collect the red light from the reflected light, and the nerve systems will think that the surface is white. Hence, the human vision and nerve systems work best under the light with continuous and balanced Spectral Power Distribution (SPD).

Natural light or sunlight is treated as a reference light source; it has a continuous and balanced spectrum (See Figure 2.4). Our nerves can process colors of objects under light sources precisely with this type of SPD; in contrast, if the curve of the SPD has gaps or large and sudden variations, our nerve system will be confused and will find it difficult to process the colors (LRC, 2005).

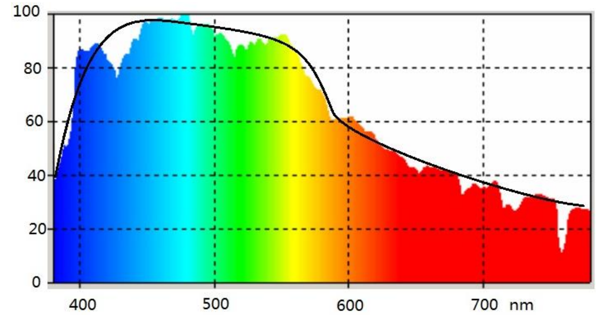

Figure 2.4 Daylight Power Distribution

The color detection devices, such as chroma meters, which are used in CRI determination tests, detect colors in a different way as compared to humans. They are able to locate one color on a UV-mapped color space accurately by collecting one wavelength or light. Therefore, some light sources may have very high CRI, but humans still interpret the color quality as poor.

CRI Determination Method

CRI of a lamp is determined by measuring the color shift of an eight color sample board that is illuminated by this lamp and comparing results to reference light sources. The eight colors are selected from the CRI Test Color Samples Library (TCSL), which consists of 15 Munsell Color System color, denoted as TCS01 to TCS15. Based on the CCT of the target lamps, eight colors are selected from the library to form the eight color sample; colors TCS01 to TCS08 are the most often selected colors. Table 2.5 is an example of the TCSL.

NAME	Appr. Munsell	Apperance Under Reference Light Sources	Swatch
TCS01	**7,5 R 6/4**	**Light greyish red**	
TCS02	**5 Y 6/4**	**Dark greyish yellow**	
TCS03	**5 GY 6/8**	**Strong yellow green**	
TCS04	**2,5 G 6/6**	**Moderate yellowish green**	
TCS05	**10 BG 6/4**	**Light bluish green**	
TCS06	**5 PB 6/8**	**Light blue**	
TCS07	**2,5 P 6/8**	**Light violet**	
TCS08	**10 P 6/8**	**Light reddish purple**	
TCS09	4,5 R 4/13	Strong red	
TCS10	5 Y 8/10	Strong yellow	
TCS11	4,5 G 5/8	Strong green	
TCS12	3 PB 3/11	Strong blue	
TCS13	5 YR 8/4	Light yellowish pink	
TCS14	5 GY 4/4	Moderate olive green	
TCS15	1 YR 6/4	Asian skin	

Table 2.5 CRI Test Color Sample Library, Red & Bold name color samples are the most often used (Information from *Color Rendering Index CRI*, A.C.Lighting Inc., accessed date 12-28-2014)

All the colors from the TCSL can also be located in the color space model in figure 1.8, and the color shift is also measured on this model. Because the color space model is an imaginary three-dimensional model, it needs to be transformed into a more realistic two-dimensional model in order to quantify any color shift distance. The 3-D to 2-D transformation is called UV mapping. XYZ coordinates will be mapped onto UV coordinates; this process is like mapping a globe onto the world map. Figure 2.5 is a graphic representation of the UV mapping of color space.

The first step of CRI calculation is locating all the 8 sample colors on the UV-mapped color space by their appearance under the reference light source. The next step is relocating them by their appearance under the target lamp; the distances between the first time location and the second time location are the color shifts. However, the distances (Ei) that represent color shifts are the same as distances in XY 2-dimensional coordinates; all the UV coordinates' distances are Euclidean and much more complicated to calculate. The third step of CRI calculation is finding the special color rendering index, which is denoted as Ri, by using following the formula (Wyszecki& Stiles, 1982):

$$\boldsymbol{R_i = 100 - 4.6\Delta E_i} \qquad \textbf{Equation 1}$$

Where R_i=Special Color Rendering Index

ΔE_i=Euclidean Distance of Color Shifts

The final step is finding the mean of all the eight sample colors' special color rendering index, that is

$$\boldsymbol{R_a = \frac{1}{8}\sum_{i=TCS01}^{TCS08} R_i} \qquad \text{Equation 2}$$

Where R_a=Color Rendering Index

The mean of the special color rendering index is the CRI.

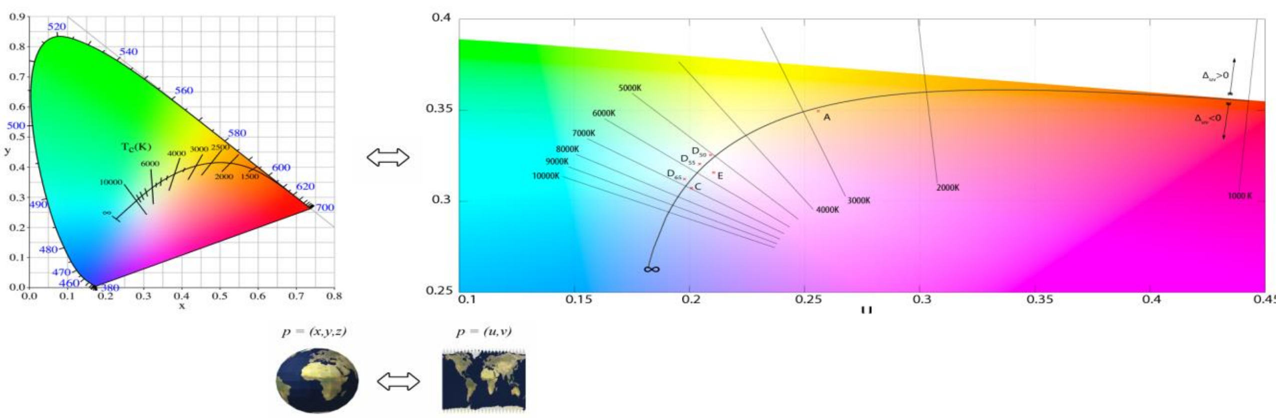

Figure 2.5 Color Space UV Mapping (Image from *Color Space*, CIE,1931 and 1960,)

Reliability of Published Data of CRI

The CRI rating system has been used to rate the color quality of fluorescent lamps and high-intensity discharge lamps for over 40 years (Department of Energy CRI, 2008). Manufacturer published data can, therefore, be considered reliable. However, the CRI rating system is not ideal for LED lamps; the CIE even suggests the following statement in its technical report 177:2007,

> "The conclusion of the Technical Committee is that the CIE CRI is generally not applicable to predict the color rendering rank order of a set of light sources when white LED light sources are involved in this set."

They also indicate that they are developing a new color rendition rating system for LED lamps.

The current CRI rating system is not ideal for LED lamps for two reasons. The first reason is that LED lamps with high CRI scores may not always be able to maintain visual comfort and color fidelity; the second reason is that some LED lamps have a dynamic color shift function.

Incandescent lamps have similar SPD as daylight; they also are often considered as reference light sources. Because these type of light sources have near perfect SPD, they can score extremely high to perfect CRI from the perspective of color detection devices; at the same time, humans can easily distinguish colors under them.

Another indoor primary artificial light source, fluorescent, has tempestuous changing and largely unbalanced SPD curves; some of them even have intermittent SPD curves. This type of light is not comfortable to human view, nor is it able to score high in CRI. The only way to improve the CRI is to change the blending of phosphor coating inside the bulb. This change will improve the color rendering ability of fluorescent lamps by making the SPD more balanced and closer to daylight SPD. Figure 2.6 shows some examples of spectrum variations of fluorescent lamps from US. Patent 7391148B1 Report; the differences of spectrums are tremendous from different phosphor blending.

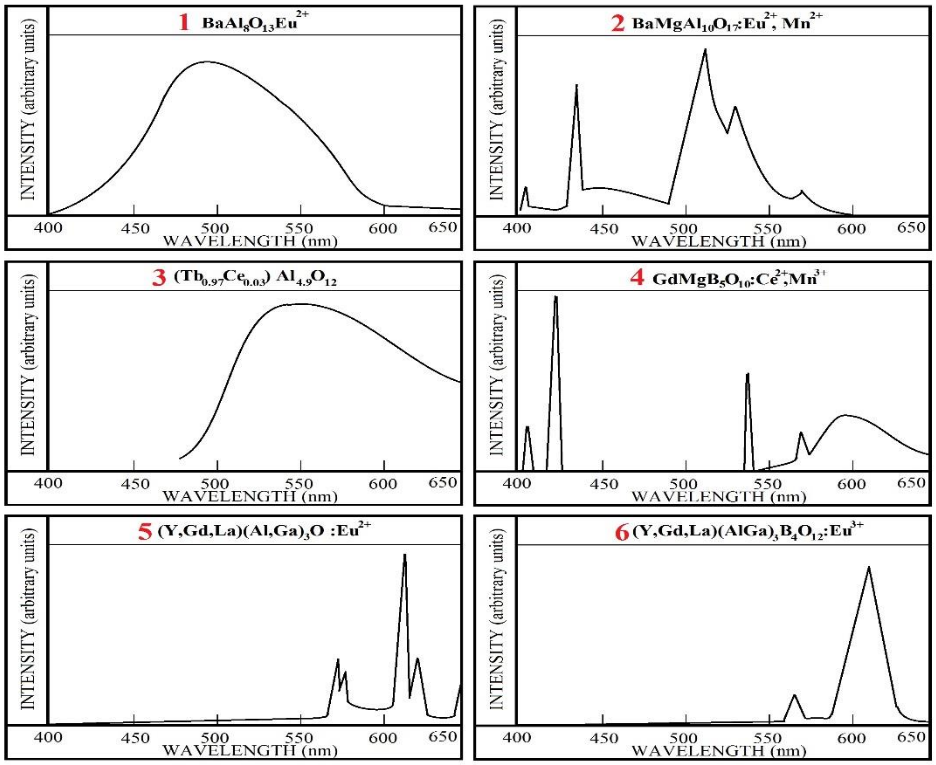

Figure 2.6. Example of Fluorescent Lamps with Different Phosphor Coatings (Information from US. Patent 7391148B1,2008)

Blending Sample 3 has the most balanced SPD. The CRI test result of this sample is 89, which is good for any type of office task applications (US.Patent 7391148B1, 2008). It offers light with a wavelength from 480 nm to above 750 nm. This wide and even SPD also offers visual comfort to human beings. In fluorescent lamps, a higher CRI means better visual comfort and color fidelity.

LED lamps often have spiky and unbalanced SPDs, like fluorescent lamps. Instead of tuning their SPD to become more balanced and closer to daylight SPD, LED lamps are able to tune their SPD to become even spikier to score high in the CRI rating.

As mentioned previously, color detection devices, which are used in the CRI rating test, are able to locate one color from one wavelength of light precisely, and the eight-color sample is the only color rendering tester. Hence, lamps only need to emit eight wavelengths of light that have the same color as the eight-color sample to score an excellent CRI rating; LED lamps are easily able to achieve this. Figure 2.7 is an example of SPD of LED lamps. This SPD has a spikier curve than the fluorescent lamp sample 3 from Figure 2.6. However, its CRI rating is 93.6, which is much higher than that of sample 3.

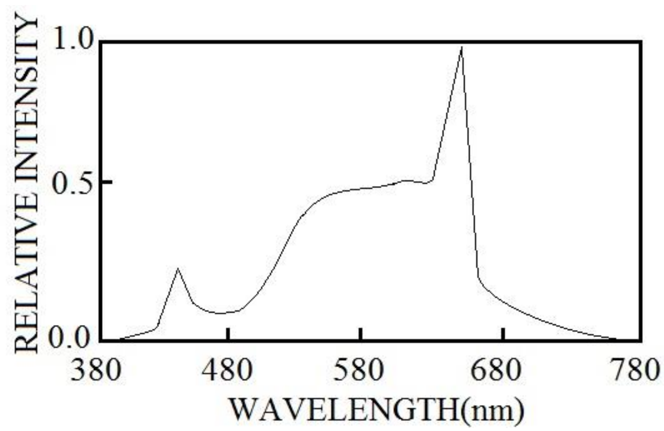

Figure 2.7 LED Lamp SPD (Figure from *LED white Lights with high CRI and high luminous efficacy*, He el at. 2010)

Incandescent lamps are considered as reference light sources, and their CRI ratings are generally rated from 94 to 100. Therefore, the 93.6 CRI rating of the previously mentioned LED lamp is extremely high; however, it cannot provide a comfortable and natural visual environment for humans. Its SPD puts too much emphasis on the certain color of light that has identical colors to primary colors. Its light will overly render the true colors of objects, and objects will appear to have oversaturated color surfaces. The nature and vividness of the object will be lost due to oversaturated colors; it will cause visual discomfort to humans. In that case, the high CRI rating of LED lights only implies high color fidelity, but not visual comfort.

CIE has updated their 8-color sample to a 14-color sample to avoid the narrow hue range problem for the LED CRI rating (CIE, 1995). Even though this update has only appeared in CIE's report and CIE never recommended this update to the public, it is widely adopted by most manufacturers, scholars, and designers. These 14-color samples are TCS01 to TCS14 from TSCL, which have a relatively wider hue range; however, it only helps polish the CRI rating system for LED lamps slightly. Figure 2.8 is an example of the comparison of CRIs that are rated by 8-color and 14-color samples. The rating results from the two systems only varies by 0.6.

Robertson's Calculated CCT			2650	K		
McCamy ESTIMATED CCT			2851	K		
1931 2 DEG COLOR SPACE						
	X	Y	Lumens	Rad Watts	Multipier	% Light
pump 452nm	0.1504	0.0317	1.61	0.03987236	0.9	0.50%
pump 458nm	0.1438	0.0425	2.11	0.03989233	0.9	0.70%
pump 493nm	0.072	0.3479	15.2	0 07670785	1.8	4.80%
direct 634nm	0.6953	0.3016	38.4	0.21269359	7.1	12.20%
phosphor 24nm	0.2821	0.6318	49.6	0.10126437	0.9	15.70%
phosphor 73nm	0.4753	0.5153	124.51	0.27172125	1.8	39.50%
phosphor 600nm	0.5541	0.4431	841	0.25784827	1.5	26.70%
Composite SPD	0.446	0.40361	315.5	1		100.00%
CRI R8=	**97.4**					
CRI R14=	**96.8**					

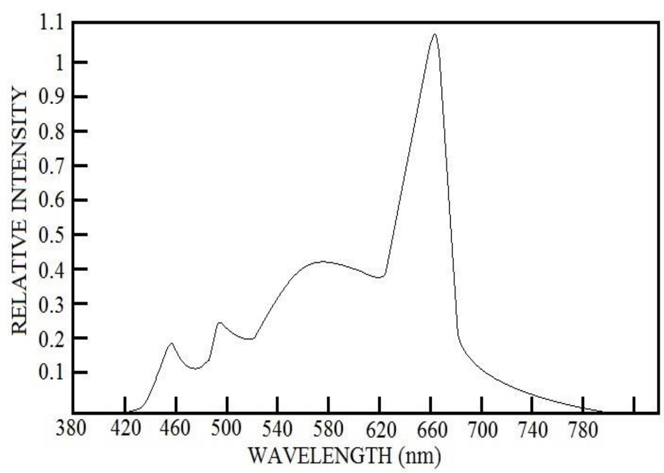

Figure 2.8. SPD and CRI Rating of an LED Lamp (Information from *Achieving High CRI from Warm to Super White*, E. Balley and E. Tormey, 2007)

The second reason why the CRI rating system is not ideal for LED lamps is that the CRI rating system does not accommodate rating of light sources with various CCTs. The reference light sources are unconditionally considered as having the perfect CRI for any CCT; even their color rendering ability is severely degraded at some extreme CCTs (NIST, 2015). LED lamps' CCT have a very wide range. Some LED lamps are even able to change CCT while operating, and it makes the CRI rating system very difficult to quantify the CRI rating of LED lamps.

Scholars have proposed other improved measuring methods for LED lamps to remedy the deficiencies of CRI rating system, and many of these are valid. For instance, the color quality scale (CQS) measuring method is one successful example. CQS was proposed by scholars Yoshi Ohno and Wendy Davis of National Institute of Standards and Technology; it is not an alternative method of CRI, but an add-on of CRI. This method has eliminated many shortcomings of current CRI ratings; the most significant advantages include three aspects.

The first aspect is that CQS uses 15 color samples instead of eight for CRI. Fifteen color samples have a noticeably wider hue range than an eight-color sample. Just like the 14-color sample does not improve the practical value of CRI of a LED light source a great deal, 15 color samples will not offer a large improvement either. However, a wider hue is always better than a narrower one.

The second advantage is that the CQS includes the CCT of light sources as one of the deciding factors (NIST, 2015). The CQS provides a weighted CCT factor scale from 0-100, and it is the multiplication factor of the CRI. It avoids light sources with extremely high CRI color scores. For instance, an extremely red color lamp may score a CRI in the conventional CRI rating system if it can render the color red very precisely. However, it cannot efficiently render objects with colors other than red. The high CRI rating becomes misleading information. With the CCT factor included in the final multiplication, the resulting CRI rating has more practical value.

The third advantage is that the CQS uses the root-mean-square value of each special CRI as the average CRI. This is a great improvement; the light source can then avoid using high special CRI scores of some color samples to compensate for others' low special CRI. Then lamps that can only render a few colors well cannot score high CRI ratings.

CQS also offer many other advantages, like eliminating CRI score reduction in chroma increase, the negative value in the CRI, etc; it has improved the practical value of the CRI. Unfortunately, high scores in the CRI and CQS combined test still do not indicate great visual comfort.

Suggestions and Summary of CRI Comparison

Most incandescent lamps have perfect CRI and offer great visual comfort for people; that incandescent lamps are supreme in this category is beyond all doubt. Manufacturer-published CRI of fluorescent lamps is trustable data, and a higher CRI of the lamps typically indicates better visual comfort.

LED lamps are different. The manufacturers' published CRI data is genuine; however, a high CRI of LED lamps is not directly linked to good visual comfort due to the deficiency in the CRI rating system. All the current alternatives or enhanced methods do not have significant improvements. Hence, engineers and designers need to consult the SPD of LED lamps to decide if they should be used in the design. Officials of the Department of Energy have made the following recommendations about how to choose a LED with good color rendition in their document "LED Measurement Series: Color Rendering Index and LEDs," which appears feasible.

"Specifically, we recommend the following:

1. Identify the visual tasks to be performed under the light source. If color fidelity under different light sources is critically important (for example in a space where color or fabric comparisons are made under both daylight and electric lighting), CRI values may be a useful metric for rating LED products.

2. CRI may be compared only for light sources of equal CCT. This applies to all light sources, not only to LEDs. Also, differences in CRI values of less than five points are not significant, e.g., light sources with 80 and 84 CRI are essentially the same.

3. If color appearance is more important than color fidelity, do not exclude white light LEDs solely on the basis of relatively low CRI values. Some LED products with CRIs as low as 25°C still produce visually pleasing white light.

4. Evaluate LED systems in person and, if possible, on-site when color fidelity or color appearance are important issues."

Correlated Color Temperature

Correlated Color Temperature is the least questionable characteristic of lamps. The industrial standard method of determination is established and widely adopted; the published data is trustable.

CCT Determination Method

The lighting industry has used Color Space System from CIE as a basis for predicting and calculating the colors of light sources for many years (LRC V8I1, 2004) since the discovery of trichromatic system (RGB). Manufacturers may use different equipment for collecting data from light sources. However, the method of color determination must obey the mathematic rule of CIE color space and trichromatic system.

The previous section mentioned that all colors can be expressed as the combinations of primary colors (RGB); for example, pure red color can be written as R-100%, G-0%, B-0%, or color cyan can be written as R-0%, G-50%, B-50%. Light combinations of light sources are obtained from their SPD. Manufacturers use the ingredient summary of the light sources in terms of RGB to locate a correlated color in color space. The located color represents the appearance color of the light source.

Reliability of CCT Published Data

The method of determination of CCT is analyzing the emitted light from the light sources to obtain results; the light source types are irrelevant in this process. Therefore, this method is applicable to any types of light sources. The only possible errors of this testing process are testing equipment errors. However, IESNA documents have precise requirements of acceptable equipment errors range (2011). For these reasons, the published data about CCT is considered as reliable data.

Suggestions and Comparison Summary of CCT

All types of lamps can produce light for millions of different colors. However, only LED lamps can achieve dynamic color shift and vary CCT gradually. In this category, comparing different lamps' CCT is meaningless, choosing light sources with different CCT should only depend on the preference of designers and building owners.

Efficacy

The method to determine the efficacy of conventional light sources is accurate, and the published data has high practical value. However, both the methods of determination and published data are questionable for LED lamps.

Efficacy Determination Method

IESNA has published detailed methods of determining the efficacy for different types of light sources in their document "IESNA Approved Method"; even though the testing procedures and conditions of different light sources has small variations, the testing mechanism is the same for all light sources. Equation 3 describes this mechanism (IESNA-LM-79-08,2008).

$$\eta_v = \frac{\phi_{TEST}}{P_{TEST}} \qquad \text{Equation 3}$$

Where, η_V is the luminous efficacy

Φ_{test} is the visible flux

P_{test} is input power

Φ_{test} and P_{test} are testing results that are collected from the defined conditions in the *IESNA Approved Method*. For incandescent, fluorescent, and LED light sources, the defined conditions include ambient conditions, power source conditions, and instrumentation conditions.

The ambient conditions for all three types of major indoor light sources are the same; they require ambient temperatures be maintained at 25±1°C (77±2°F), air movement be less than 13.1 ft/min, and the environment vibration and external light be kept to a minimum (IESNA LM-45-91, 1991).

The power source requirements are different for all three types of light sources. Incandescent lamp testing requires that voltages of both direct current (DC) and alternative current (AC) power sources vary less than 0.1% during continuous operations. Fluorescent lamp testing only requires that the root-mean-square voltage of AC power source be less than 0.1% variation since they only use AC power sources; however, they have specific requirements related to ballasts (IESNA LM-66-2000, 2000). LED testing requires that voltages of both direct current (DC) and alternative current (AC) power sources vary less than 0.2%.

All the instruments involved in the testing process shall have a tolerance value less than 0.25%, and all the data shall be recorded after the lamps have reached thermal and electric equilibrium.

Reliability of Efficacy Published Data

The *IESNA Approved Method* is extremely thorough and precise for all conventional light sources, and all the defined conditions and test results from the testing procedures have been considered accurate and useful for many years; therefore, it is safe to conclude that the manufacturer published efficacy data of incandescent and fluorescent lamps are reliable and practical. However, the published efficacy data on LED lamps has very limited usefulness.

The U.S. Department of Energy has stated why the efficacy of LED lamps is less meaningful in its report "*LED Measurement Series: Luminaire Efficac*y":

"1) There is no industry standard test procedure for rating the performance of LED devices or packages.

2) The luminaire design and the manner in which the LEDs are integrated into the luminaire have a material impact on the performance of the LEDs."

Even though IESNA defines all the required testing conditions and procedures in its document, the document has never become the industry standard; it is not practical. The illuminant bodies of LED lamps are LED packages, also known as LED modules; other parts of LED luminaires are supportive parts for maintaining the continuous operation of LED modules, and they are not involved in the light emission process. Therefore, LED manufacturers measure the efficacy of their products only based on the testing results of the LED module alone.
The *IESNA Approved Method* requires data after the light sources have reached a thermal and electric stabilized state with the ambient temperature set at 25±1°C (77±2°F) (1991,2000). It

involves the lamp preheat and stabilization process; however, manufacturers estimate the luminous flux output of LED modules based on a short pulse of power while holding LED modules and ambient temperature at 25±1°C (77±2°F), and the testing time duration typically is less than 1 second (Department of Energy, 2009). Because the heat impact of LED modules will severely damage the device, LED modules cannot operate for a long period of time without a heat sink system and proper air flow. Thus, the manufacturer-published luminous flux output data is generally listed as “minimum value” or “approximate brightness”.

The second factor becomes crucial when efficacy testing is performed on LED lamps. The real-life performance of lamps is different from lab-rated performance; manufacturers need to take performance prediction into consideration when they publish their data. Conventional lamps have long development times, and all real-life data is well-documented and reliable; this makes the performance of conventional lamps more predictable, and published data has higher real-life value in any condition. However, LED lamps are relatively newer light sources, and real-life data is still inadequate; therefore, the performances of different lamp structures and application of lamps in different work environments varies greatly, even if they share the same LED module. For instance, a luminaire is designed to operate with a specific LED lamp. If that original and specific LED lamp fails and is replaced with a different type of LED lamp with the same efficacy, the same wattage, and the same socket fitting, but with a different lamp structure, it may cause the heat sink of the new LED lamp to work inefficiently, and it will compromise the performance of the new lamp.

In conclusion, manufacturer-published efficacy data about conventional light sources has much higher real-life value than that about LED lamps.

Suggestions and Comparison Summary of Efficacy

Even though the previous section already has concluded that the published efficacy data of LED lamps has less practical value, LED lamps are still recommended. LED lamps have much higher efficacy compared to any other lamps, and this advantage is too great to dismiss because of the performance reduction caused by thermal energy issues. This point will be further addressed in the Sustainable and Environmental-Friendly Design section.

Lamp Life

The rated lamp life of fluorescent and incandescent lamps has reference value for the purpose of designing lighting systems. Because lamp life of solid state light sources depends on the operating environment, the designer always take light source location conditions, LED lamp housing, and lamp life rating standard in consideration when designing lighting systems.

Lamp Life Determination Method

IESNA has published its approved method of determination for each type of light source in its document series "*IESNA Approved Method for Life Testing*."(1994) These *IESNA Approved Methods* also define testing environments and lamp selections. Manufacturers need to select lamps and set up testing environments according to IESNA requirements, keep the lamps operating under testing conditions, and then find the rated life based on the operating duration of the selected lamps before half of them have failed. The lamp selections and testing environments are defined similar to that of efficacy testing, and the lamp operating methods are defined differently according to the different life characteristics of different light sources. For instance, the lamp life of fluorescent lamps will be shortened by high-frequency ballast striking; hence, their lamp life can be maximized through continuous operation. In order to obtain the most practical and valuable results, IESNA requires all testing of fluorescent lamps to operate in an

"180 minutes on / 20 minutes off" cycle (IESNA LM-65-01, 2001).

Reliability of Lamp Life Published Data

Most lamp manufacturers obtain the rated life of their conventional light sources based on *IESNA Approved Methods for Life Testing.* These methods have been used to examine the rated life of conventional light sources for many decades; therefore, these methods are well-developed, and the outcomes are reliable and useful. However, the data for LED lamps is a different situation. Because no industry standard testing method for the lamp life of LED light sources is established, the published LED lamp life is not a good reference for designers and owners. Two deficiencies make published LED life data less valuable; first, the definition of "end of lamp life" is unclear for LED lamps, and second, the manufacturer's lamp life testing environments have insufficient practical value.

The definition of end of lamp life for conventional light sources is very clear; when an incandescent or fluorescent lamp failed while operating under testing environments that were defined by an *IESNA-approved method*, then it had reached the end of lamp life. IESNA also defines that when 50% of the select lamps have failed, the operating duration is defined as the lamp life of that lamp; this rule is also known as B_{50}, and most lamp manufacturers have adopted it. Unfortunately, this rule cannot be applied to LED lamps because LED lamps will not fail under normal conditions; they will only depreciate their output of luminous flux over time.

Manufacturers and scientists propose that end of lamp life for LED light sources occurs when the output luminous flux of a LED lamp depreciates to a visually unacceptable level. However, "visually unacceptable level" is a vague definition. Some manufacturers use a 30% depreciation as a criterion for lamp life rating, and others use a 50% depreciation instead (N. Narendra, 2013). Moreover, some visually intense tasks, such as graphic design, have strict requirements for task plane light intensity; a 30% depreciation is detrimental to the performance of these tasks.

Good testing environments may have differences with real-world environments, however, their testing outcomes should reflect the real-world performance of the products that are tested. This is not true for LED lamps. The testing environments of LED lamps are too idealized, and the testing results vary greatly from a product's real-life performance. For instance, in 1997, many manufacturers generally estimated that AlGaInP LEDs (a type of LED modulus of white LED lamps) would last for 100,000 hours before they depreciated to their 70% initial output; however, a test shows that 5-mm-type white LEDs only last for 6,000 hours before they depreciate to their 50% initial output.

Because of the deficiencies of the lamp life rating process, manufacturers' published rated life data of LED lamps contain less practical value than that of conventional light sources.

Suggestions and Summary of Lamp Life Comparison

The situation for published rated life data is the same as that for efficacy data. However, the low practical value of published data does not indicate that LED lamps have a short lamp life. Actually, the lamp life of LED lamps is far superior to conventional lamps; this great advantage cannot be diminished by the drawbacks of published data and testing processes.

The previous section states that the real lamp life of AlGaInP LEDs already has surpassed incandescent lamps since 1997. After more than a decade of LED technology development, the actual lamp life of LED lamps has increased. For instance, white LED lamps from Philips Inc. have a rated life of 35,000 to 50,000 hours, and their end of life is defined at 70% of initial output luminous flux (Philips, 2010). Table 2.6 shows the rated life comparison between LED lamps and other light sources.

Modern LED lamps have a longer rated life than incandescent lamps are beyond doubt. Most LED lamps that from reputable manufacturers like Philips Lighting, GE Lighting, or Osram Sylvania even have long rated lamp life than most fluorescent lamps. And the lamp life of LED lamps are still improving. However, designers should always use extra caution in selecting LED lamps based on their published data; if the designer's project involves visually intensive tasks, the designer should always find out which depreciation level the rated lamp life is based on.

Light Source	**Typical Range (Hours)**
Incandescent	750-2000/Rated Life
Halogen Incandescent	2000-4000/Rated Life
CFL	8000-10000/Rated Life
Metal Halide	7500-20000/Rated Life
Linear Fluorescent	20000-30000/Rated Life
White-light LED	35000-50000/Rated Life

Table 2.6 Rated Lamp Life Comparison (Information from Philips, *Understanding LM-80, Lumen Maintenance, and LED Fixture Lifetime*, 2010)

Chapter 3- Visual Comfort and Health

This chapter presents discussions related to the human visual comfort and personal health requirements for a lighting environment. The discussions center on three aspects: how our bodies react to light, what is the perfect light for us, and which type of light source is able to emit the "perfect light" or has the potential to produce it. The business benefit of maintaining good visual comfort in a lighting environment will be presented first.

LoBusiness Value of Visually Comfortable Lighting System

Since the main focus of this paper is lighting systems in office buildings, and office buildings are mainly used for commercial purposes, whether companies benefit from maintaining visual comfort is the key question.

Influence of Employee's Productivity on Companies' Profit

More than 60% of companies' spending is on employee payroll (Richard, 1985). For this reason, most administrators want to increase the profit versus salary ratio to maximize the company's profit, and the most obvious way is to improve employee productivity. Improving employee productivity is also the most feasible way to increase a company's profit; Dr. Albert D. Bates points out that a "1% improvement in employee productivity has approximately the same impact on profit as a 10% reduction in rent expense or a 25% reduction in interest" in his article "*A profit equation: rethinking employee productivity*."(Albert, 1994)

Lighting's Effects on Employee Productivity

Employees' productivity is improved through two methods, adequate training programs and creating good working environments. Lighting is one of the most crucial element of good working environments; it affects employees' perception of working tasks, emotions, motivational states, and even circadian rhythms (Katzev, 1992). Training programs may improve employees' productivity by refining their skills and giving them more experiences, but training programs are often expensive and not always necessary for every employee. In comparison, lighting is one the least expensive and always necessary factors that affect human productivity at work.

The effects of lighting on employees' productivity are not only inexpensive and necessary but also instant and efficient. For instance, task plane illuminance, which is the most mentioned character of a lighting system, has dramatic effects on human performance. The National Lighting Bureau's (NLB) report "*Lighting and Human Performance: A Summary Report*" states:

> "A four-year study of workers who stamped out leather shapes for handbags showed that increasing illuminance from 32 foot-candles to 93 foot-candles resulted in an average performance improvement of 7.6 percent. In another study, workers who checked original copy against a computer printout showed a dramatic 30 percent reduction in work output when illuminance was reduced from 93 foot-candles to 46 footcandles" (NLB, 1989)

The NLB also expands the application case studies to many other tasks, such as map reading and measuring the diameters of bolts; all their results reflect that better illuminance improves productivity dramatically.

In addition, better lighting environments assist the performance of aged eyes. Senior employees often are the most knowledgeable groups and have the highest authority; they are the most productive and make important decisions for the company. For this reason, offering them a visually comfortable environment will influence the profit of the company significantly.

All these discussions show that one of the most effective ways to increase the profit of companies is improving the productivity of employees, and maintaining visual comfort for employees is the most direct and low-cost way to improve productivity. Therefore, investing in the design and installation of lighting systems that can maintain visual comfort is worthwhile.

How Our Bodies React to Light

The eyes are the primary light perception organs of humans. However, this does not mean that the eyes are the only organs that are affected by light. Human brains and internal body systems are all influenced by light; in addition, light also exerts a deep and subtle influence on human mood, motivation, and circadian rhythm. This paper will present a detailed discussion on how our bodies react to light.

The Eye's Reaction to Light

The section on color perception in Chapter 2 has already given an introduction of how human eyes and brains detect colors; for this reason, this part will be very brief. The published technical document "*Light, Sight, and Photobiology*" of the Rensselaer Polytechnic Institute states a very brief but accurate explanation of how human eyes react to light.

> "The human eye is a light-sensing system with a pupil and a photoreceptive medium called the retina. The retina contains two photoreceptors: rods and cones. Cones (which see photopic lumens or bright light) are responsible for day vision. Rods (which see scotopic lumens or dim light) are associated with night vision…Studies at UC Berkeley Laboratories by Dr. Sam Berman, senior scientist, have proven that pupil size and brightness perception at typical office levels are, in fact, strongly affected by rod activity within the retina of the eye."

> "Light reaching the retina of the eye is converted into electrical signals that are transmitted by the optic nerve. Most of these signals end up in the visual cortex of the brain and produce our sense of vision. (Light, Sight, and Photobiology 1998)."

Internal Body Systems' Reaction to Light

Human bodies are very complicated chemistry reacting furnaces; the various and continuous chemistry reactions support human life. All these reactions are partially controlled and regulated by perception of different wavelength of light (Edwards, 2002). Light is involved in almost all human system operations, such as endocrine systems and circadian rhythms

Endocrine system

Zoologists always use artificial lights to stimulate reptiles kept captive because reptiles' skins can use sunlight for vitamin D formulations. Similarly, human skin can also incorporate light, and different wavelengths of light will stimulate the human endocrine system differently through the skin. For instance, a light wavelengths and human health related study shows short wavelengths of light, like 470nm or 525nm, suppresses formulation of melatonin greatly (Wright and Lack, 2001). The effects of light can be categorized into two types: modifying individual endocrine or hormone and regulating metabolic states. Some examples of the effect of light in humans are the formulation of Vitamin D and the dissociation of bilirubin.

The effect of light on our endocrine system is indispensable. L. Edwards and P. Torcellini made a statement in their paper, "*A Literature Review of the Effects of Natural Light on Building Occupants*."

> "Danzig, Lazarev, and Sokolov…contend that physiological disorders may occur in the human system if the human skin does not receive some exposure to solar radiation, either direct or diffused, for long periods of time. They believe there will be a vitamin D deficiency followed by weakened body defenses and an aggravation of chronic diseases."

Circadian Rhythm

Circadian rhythms are the most fundamental "internal body schedules" for most intelligent animals or even plants; they guide an approximately 24-hour cycle based on physical, mental, and behavioral changes in the body. In the natural organism world, circadian rhythms are reactions to a variation of lighting conditions. Inside the human brain, a group of nerve cells, called the Suprachiasmatic Nucleus (SCN), act as the "master clock" of circadian rhythms. The SCN only reacts to the lighting signal that is sent from the human vision system; it controls circadian rhythms based on the light intensity and light wavelengths. In 1980, scholar Bickford states that exposure to cool white (5000k or higher CCT) fluorescent lights might cause abnormal circadian rhythms because SCNs need all the color frequencies of light to form a healthy circadian rhythm pattern (National Institute of General Medical Science, 2012).

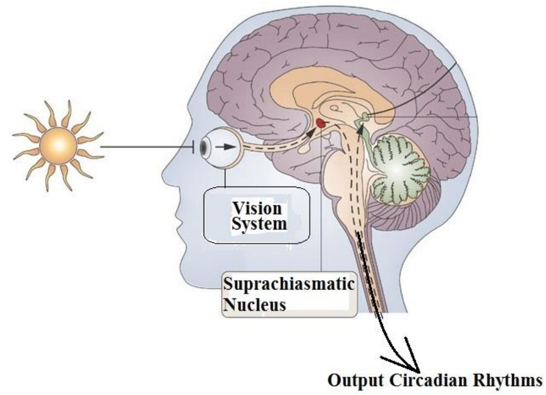

Figure 3.1 SCN and Circadian Rhythms Output (Reproduced from Nature Reviews Nephrology, date accessed 12-28-2014)

Circadian rhythms are particularly significant to homeothermic animals, such as human beings. Humans rely on circadian rhythms to adjust body temperatures, sleeping cycles, and metabolism speeds. Therefore, abnormal circadian rhythms exert a severe negative impact on human bodies. Jet lag is an example of body discomfort caused by abnormal circadian rhythms. During an airplane flight, humans cannot perceive natural light sufficiently, which causes SCNs to not form healthy circadian rhythm patterns, and it sequentially causes abnormal body core temperatures, sleeping cycles, and metabolisms. This is the major reason passengers always feel cold, drowsiness, and apocleisis during long flights.

Nerve Systems' Reaction to Light

Most office tasks are dominated by nerve systems; human nerve systems control mood, memory, and other psychological functions, which directly affects the productivity of employees. Scholars and researchers have done many experiments on light's effect on human nerve systems; many of them proved that color and intensity of light can impact the nerve systems of humans.

Psychological Performance and Memory

Igor Knez describes an interesting experiment on the relationship between human mental performance and the color and intensity of the lighting condition in his research paper "*Effects of Colour of Light on Nonvisual Psychological Processes*," which reflects how human nerve systems react to light (Igor, 2001).

The goal of this experiment was to obtain data from humans' moods, short-term memory, long-term memory, and problem-solving ability under different light conditions, with different intensities and colors. Participants were also required to give evaluations about the quality of the lighting condition.

The participants of this experiment were 108 high school students, with a 1:1 ratio of females and males. The setting of this experiment was a windowless chamber 3.9 x 3.8 x 2.5 m in size, and the lighting system included three different sets: an Osram 36W linear fluorescent lamp with CCT=3000K, CRI=95 (warm light); an Osram 36W linear fluorescent lamp with CCT=4000K, CRI=95 (cool light); and an Osram 36W linear fluorescent lamp with CCT=5000K, CRI=95 (daylight).

This experiment consisted of five parts. The first part was a mood evaluation, in which participants needed to record the changes in their moods under the influence of different light sources. The second part was the perceived room light evaluation, in which participants evaluated the quality of the indoor lighting condition of each lighting system using a 5-point scale. The third part was "Short-term Recall." A sequence of 16 random words was presented to the participants, with each word having an exposure duration of 1.5 seconds. Participants had to write down the words they could remember. The fourth part was "Long-term Recall." A seven-page text was given to each participant; after 90 minutes, they answered six general questions and 18 multiple-choice questions on the text. The last portion was "Problem Solving," where participants needed to solve a set of 32 abstract figure questions.

Even though Igor Knez thought "no significant results were obtained" for the "Mood" portion of the experiment, other results still reflect the human nerve system's reaction to different colors or intensities of light. Figure 3.2 shows the results of these experiments. Participants intuitively felt that cool light offered a better indoor lighting environment while warm light offered the best intensive and prolonged environment for mental performance. However, females require "daylight" (5000K) to achieve their best problem-solving abilities. Because the illumination level was fixed for all lighting systems other than in the first part of the experiment, this experiment can conclude that colors of light will influence human nerve systems.

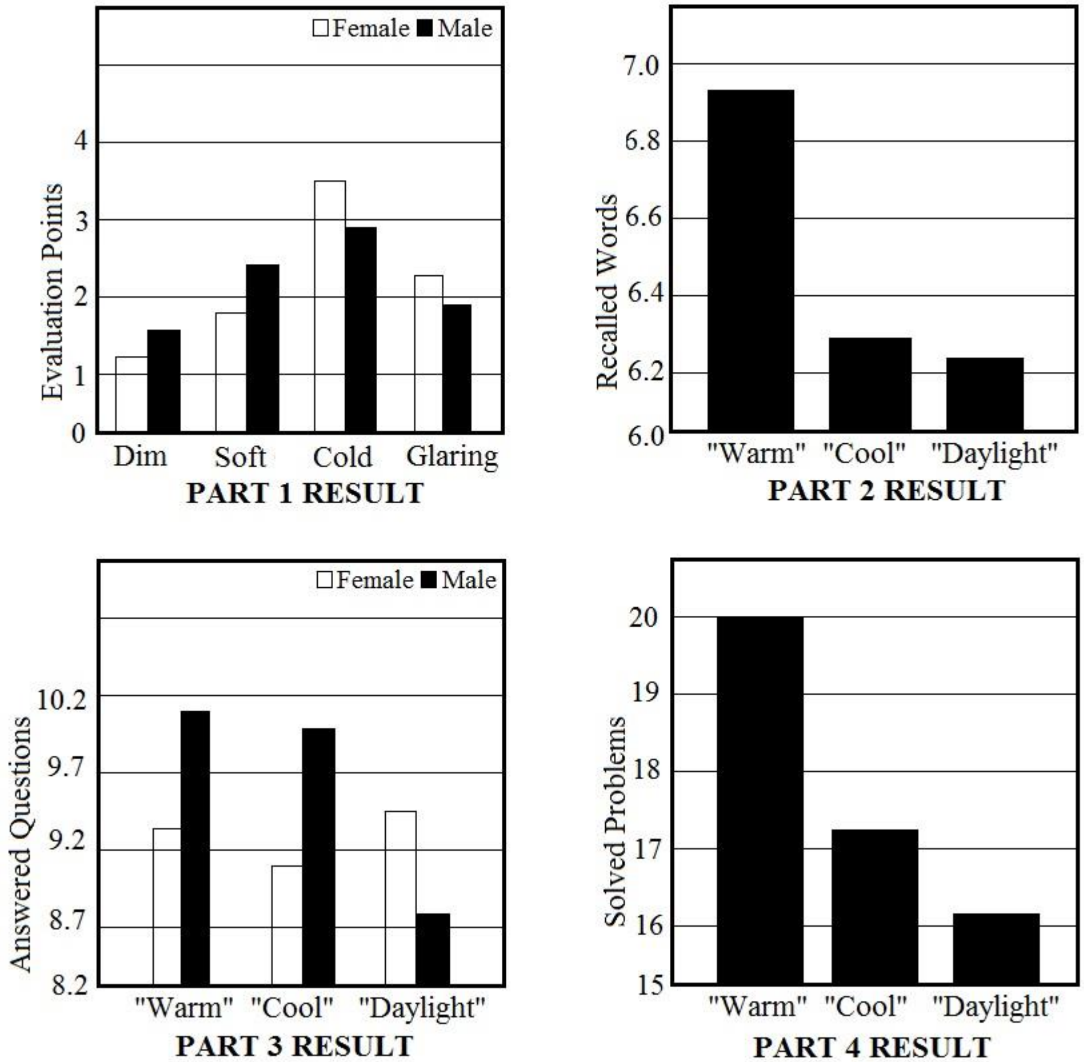

Figure 3.2 Igor Knez's Experiment Results (Information from *Effects of Colour of Light on Nonvisual Psychological Processes*, Igor Knez, 2001)

Many other scholars have done case studies and experiments on light's effect on human nerve systems. For instance, J.Y. Park, B-Y. Min, and other scholars have done extensive research on illumination influences on the human nerve system by using the electroencephalogram testing system. Even though their research used much more advanced technologies than Igor's, they all come to one conclusion, which is that lighting conditions have a great impact on the human nerve system.

Mood

Controlling human mood is one of the most important functions of nerve systems. Scientists divide all human emotions into two categories, which are positive moods and negative moods. Positive moods are always associated with happiness, excitement, and joy; in contrast, negative moods are related to depression, anxiety, and grief.

Even though the direct incentives of moods are not lighting, lighting can induce different moods and help maintain moods. Dr. Igor Knez did not obtain conclusive data about the relation between mood and lighting in the experiment mentioned previously. However, he and Ingela Enmarker gathered some useful data about mood variation under light with different CCT in their 1998 research (Knez, 1998).

This research used the same setting as the previously mentioned experiment (excluding the 5000k lamp set). The participants were 20 males and 20 females from their local college. Participants were presented 20 items that represent positive and negative moods; then they were asked to answer a series of questions.

Their results show that warm light (3000K) helps preserve positive moods and induce the least number of negative moods for males. In contrast, females favor cool light (5000K or above) more than warm light in terms of preserve positive moods.

The Perfect Light for Humans in an Office Setting

Human vision systems need a continuous and balanced spectrum of light to perform well. The internal body systems need a full spectrum of light to moderate our internal chemical reacting processes. Humans need to perceive different colors of light to regulate the nerve systems. All the facts conclude that humans need a balanced, full spectrum light to maintain our well-being, and sunlight (natural light) seems to fit all the requirements. Many scientists and scholars recommend that maximization of natural light integration for office buildings is beneficial to the companies and employees. However, natural light has both advantages and disadvantages when used in an office lighting application.

Natural Light

The advantages of natural light in an office lighting application are very notable, which include three aspects. The first one is that natural light helps in maintaining health in the office. A study conducted by Franta and Anstead shows that daylight helps to reduce the rate of occurrence of headaches, seasonal affective disorder, and eyestrain (Franta and Anstead, 1994). Natural light also helps to reduce stress; in contrast, a completely natural light-free environment will increase the stress level. Moreover, the previous section explained that human bodies rely on light to adjust our internal body systems. Since humans evolved around sunlight for millions of years, natural light will keep human conditions regulated.

The second advantage of natural light for an office application is that natural light increases the productivity of employees. In 1983, designers of Lockheed Martin Inc.'s Sunnyvale, CA, Division used a daylight-integrated open-office layout for their office building; this action brought a 15% increases in contract productivities to their companies (Romm and Browning, 1994).

The last advantage is that natural light helps decrease absenteeism. This point does not have direct scientific explanation yet; however, many facts have confirmed its validity. For instance, the Lockheed Martin division mentioned earlier also observed a 15% decrease in overall absenteeism in the office since they moved to the daylight-integrated building.

Unfortunately, the drawbacks of natural light are as notable as its advantages. First, natural light applications have building layout and landscape limitations. Natural light applications are not always a viable option for all locations, especially for cities with high people density. For instance, most modern Chinese commercial buildings are high-rise buildings, and these buildings often combine a commercial office section, hotels, and a residential section in them for maximum selling profit. Nevertheless, the Chinese Residential Building Code requires buildings to be spaced widely enough so that the lowest level of the building has 1 hour of daylight during winter days (Residential Building Code, 2006). An hour of light is not sufficient for any office space.

It is difficult to distribute natural light evenly to an entire office space. Uniform illumination is one of the key factors required to achieve visual comfort (Hernandez et al., 2011). IESNA recommends maintaining 150-300 lumens per square meter for most office areas. Even though this is only a recommendation, designers always try to reach the optimum working efficiency for occupants (IESNA, 2011). The natural light intensity of a task plane will decrease as one moves further away from the windows of a building, and using daylight harvesting systems to maintain a relatively uniform illumination is restricted to the shapes and interior layouts of the buildings.

One of the most critical drawbacks of daylight is that it contains harmful elements to human beings. Solar radiation that arrives on the surface of the earth ranges from 250 nm to more than 2300 nm; the human visibility spectrum range is only a small portion of it. Solar radiation also contains ultraviolet A and B rays (UVA and UVB), which range from 320 to 400 nm and 290 to 320 nm; both rays are harmful to human skin (John and Stephen, 2014). UVA rays damage skin cells and accelerate the aging process. UVB rays are the primary cause of many skin diseases.

No commercially available sunlight harvesting devices can completely filter out UVA and UVB rays.

Another critical drawback is that using daylight increases the solar load on the HVAC system. Daylight is introduced into buildings from building envelope openings, such as windows, skylights, and roof daylight harvesting devices. These openings usually have the least thermal insulation of building envelope components. Introducing a large amount of daylight in buildings increases the peak cooling load of air conditioning systems and overall energy consumption of the buildings.

Natural light is good for humans in various conditions; it provides many health benefits and improves productivity. However, office lighting systems need to stimulate the optimal productivity of employees, and, at the same time, maintain the health of the occupants. Previous studies show that neither females nor males can reach their peak productivity in a daylight environment.

Better than Natural Light

The perfect lighting condition for every individual varies slightly. However, the goals of creating great lighting conditions for a particular gender and age group are clear. Younger people require lower task plane illumination to work efficiently, and older people require a higher value. Females favor a cool color scheme more than males in order to increase productivity and maintain a positive mood.

Philips Lighting Inc. has offered some valuable materials accredited by the Royal Institute of British Architects related to the best light color patterns throughout the day for human health and wellbeing (Matthews et al., 2012). These materials indicate that cool blue light introduced in the morning and warm yellow light in the evening achieve optimum human comfort.

For this reason, ideal lighting conditions for achieving the highest productivity in the office and maintaining employee health needs the following requirements. It shall be a continuous and balanced spectrum of light and able to deliver light uniformly to every task plane; it will change colors and intensity based on time of day and individual requirements; and it cannot emit UVA and UVB rays.

The Ideal Lamp Type for Office

Since incandescent, fluorescent, and LED lamps are the primary light sources for indoor office applications, they shall be compared one by one in terms of fulfilling requirements of creating an ideal lighting condition for the office environment.

Incandescent and Fluorescent Lamps

Incandescent lamps can emit a well-balanced and continuous light spectrum, and they are known to be reference light sources in CRI tests as previously mentioned. A good lamp housing design and overall lighting system design will help incandescent lamps deliver light to every task plane uniformly. Dimming can be easily accomplished with incandescent lamps. The luminous flux output of incandescent lamps is decided by the voltage of electric currents that are delivered to the filament of an incandescent bulb. For this reason, voltage control dimming switches will enable them with the dimming function. Moreover, dimming will prolong the lamp life of incandescent sources (Light Research Center, 2012). Incandescent lamps are sufficient to render a high-quality lighting condition.

Unfortunately, incandescent lamps have crucial drawbacks. The color of light that is emitted by incandescent lamps is determined by the filament material. This characteristic makes the dynamic color shift impossible for all incandescent lamps. Only theatrical lighting applications will change the output colors of incandescent sources; this is achieved by adding different colors of gels or color filters, which is not practical for architectural daily lighting applications.

Fluorescent lamps are not CRI reference lamps. However, with long time development of technology and manufacturing capabilities, fluorescent lamps have adequate CRI for all types of office tasks. In the perspective of rendering high-quality lighting conditions, fluorescent lamps are at the same level as incandescent lamps.

Unlike incandescent lamps, fluorescent lamps can change CCT during operation. The dynamic color shift of fluorescent lamps is accomplished using two techniques. The first one is using electric pulses to excite a "*mercury-rare gas discharged utilizing phosphor combination*" as a luminous body, and the second one is alternating mercury UV radiation selectively to excite particular phosphors coating the segment (Ravi and Maya, 2000). The mechanism of both techniques is the use of different electric pulses or UV radiations to excite different types of phosphors to emit a variety of colors of light. However, the color changing process is rigid and

Brand	Type	Energy Used (Watts)	Light Output (Lumens)	Life (Hours)	Label
Incandescent Light Sources					
General Electric	Reveal	75	830	750	1
Great Value	Soft White	75	1170	750	2
Philips	Soft White	75	1180	750	3
Halogen Light Sources					
General Electric	Reveal	75	850	3000	4
Philips	Soft White	75	1120	3000	5
Unshielded CFL Light Sources					
Feit	Ecobulb plus	18	1100	10000	6
N:Vision	Daylight	19	840	10000	7
N:Vision	Bright White	19	1100	10000	8
N:Vision	Soft White	19	1200	10000	9
Sylvania	Soft White	19	1200	8000	10
Shielded CFL Light Sources					
General Electric	Energy Smart	15	850	8000	11
Philips	Soft White	14	800	8000	12

Table 3.1 Selected Lamps for UVA and UVB Emission Measuring (Information from AD Nuzum-Keim and RD Sontheimer, *Ultraviolet light output of compact fluorescent lamps,2009*)

sudden, and the total color quantities are very limited. The CCT variation process cannot represent the natural-light color-changing process throughout the day. Figure 3.3 shows an example of the emission spectrum of variable CCT fluorescent lamps. It combines the spectra emitted by exciting $LaPO_4$: Ce and Tb and $2O_3$: Ce and Eu to emit a variable color spectrum. The combined spectrum is extremely spiky and missing all the transaction colors.

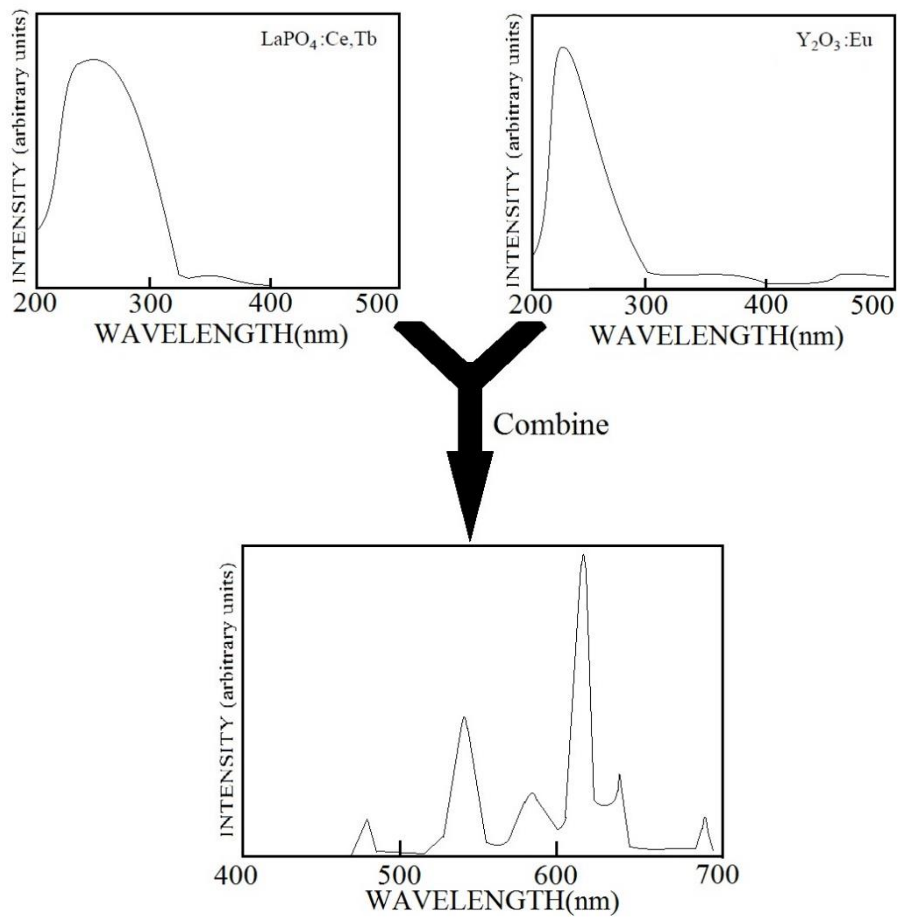

Figure 3.3 Variable CCT Fluorescent Lamp (Figures from J.Ravi and J.Maya, *Variable color temperature fluorescent lamp*, 2000)

Fluorescent lamps and incandescent lamps both present a potential threat to health by emitting UVA and UVB rays. AD Nuzum-Keim and RD Sontheimer have done research on the ultraviolet light output of fluorescent and incandescent lamps. They measured the ultraviolet emission of many common incandescent and fluorescent lamps, and their data shows that both types of light sources emit UVA and UVB rays. The lamps that they used in the test are indicated in Table 3.1, and their associated measured results are presented in Figure 3.4. The average UV irradiance that is measured at 50 cm is approximately 0.0005 Watts/cm^2 (5000mW/m^2), which seems to be a very low value. However, UV irradiance of a clear sunny day is generally less than 500mW/m^2, the 5000mW/m^2 is actually a dangerously high number. (Smithsonian Environmental Research Center, 2015)

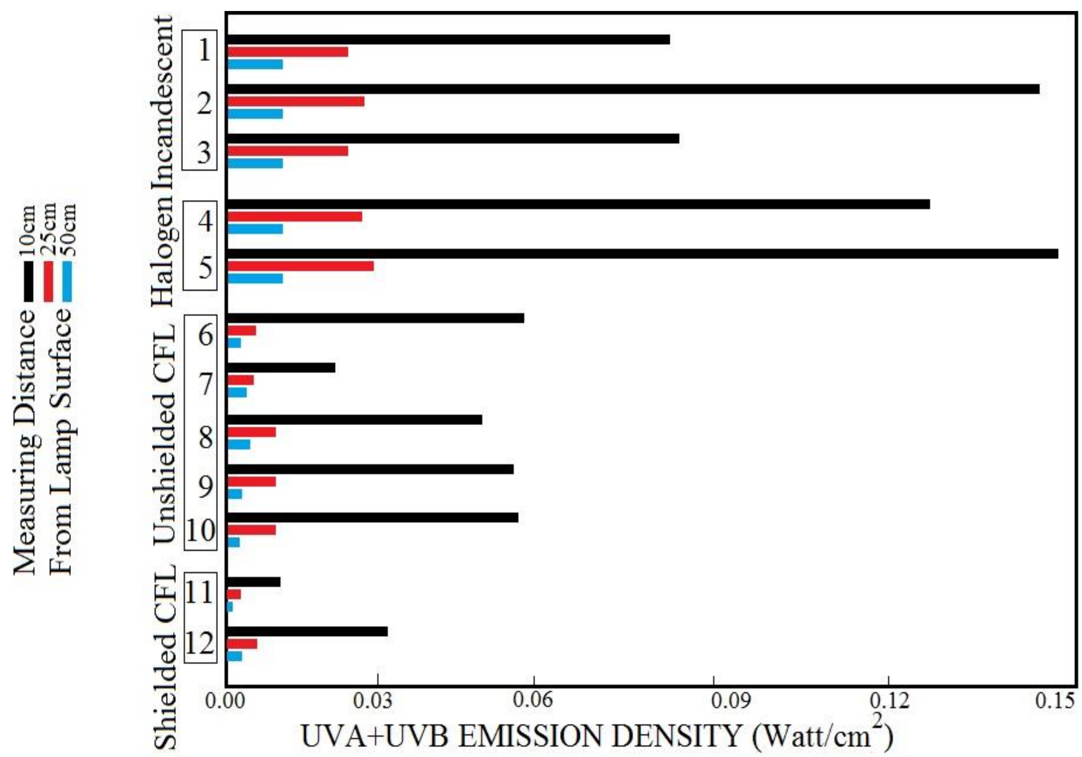

Figure 3.4 UVA and UVB Emission Measuring Results (Table from AD Nuzum-Keim and RD Sontheimer, *Ultraviolet light output of compact fluorescent lamps,2009*)

LED lamps

All the previous discussions and data show that the ideal light for the office needs to be the same quality as natural light, have a tunable CCT, be dimmable, and not emit UVA and UVB rays. Incandescent and fluorescent lamps cannot vary CCT gradually like LED lamps. Fluorescent lamps are more difficult to dim than LED. Incandescent and fluorescent lamps both emit UVA and UVB rays. In contrast, LED lamps can fulfill all of the requirements.

LED lamps are known for their ability to dim, dynamic color shift, and controllable emission spectrum. The technology of varying CCT's and dimming function for solid state light sources is mature and reliable; even non-professional-grade LED products can achieve such function. For instance, “HUE” LED lamps from Philips are consumer-grade products; these lamps can dim with integrated drivers, and each individual lamp can emit over 16 million colors (HUE Philips, 2014).

A Chinese company called Yueyang Xiuri applied for a patent simulating natural light by using LED lamps in 2013 (Wu, 2013). Their purpose was to use LED-simulated "natural light" to cure office workers' sick building syndrome, which is induced by a lack of natural light in the working environment. This LED light source-related invention extends the function of a lighting system from a level of providing visual necessity and visual comfort to a 360-degree, full occupant health and comfort maintenance system.

The inventor of this patent and his team propose a natural light CCT and illuminance variation pattern based on a time-of-year and time-of-day cycle. This pattern is used to guide the CCT and illuminance variation of office lighting systems. However, it incorporates sensor systems, processing systems, sound systems, and air conditioning systems (A/C system) to co-function and interact with the lighting systems to achieve the most vividly natural light and environment simulation. Figure 3.5 show the relationship between each system. For instance, occupants decide to create a noon, forest, summer environment in the lounge room of their office building. After the Central Micro Processing Unit (CPU) receives orders from the occupants, it will correspond air conditioning, lighting, and sound to the space. Moreover, sensors detect the room conditions and send calibration data to the CPU for further adjustment. Finally, this system can offer occupants a lounge room with summer like “warm” and bright lighting environment with cool and dry air condition, and birds singing in the background.

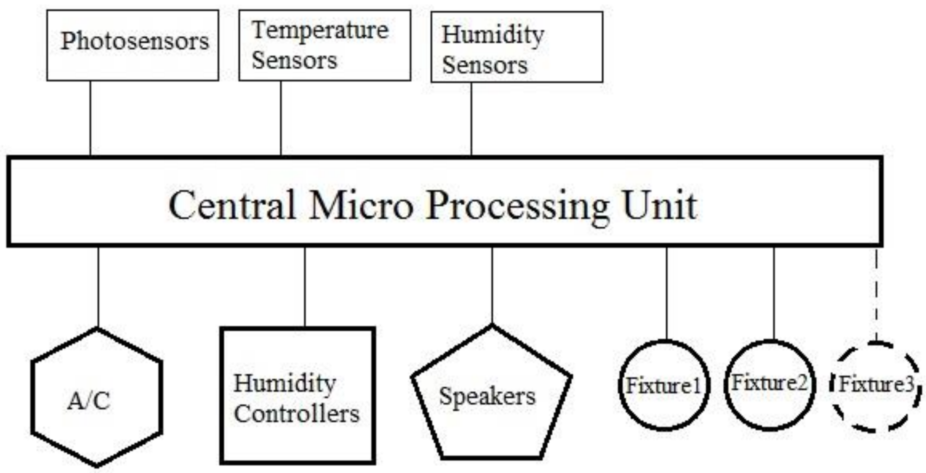

Figure 3.5 LED Light Sources Natural Light Simulating System

(Information from Chinese Patent CN201310158992, 2013)

However, this paper will only focus on the lighting control part of this patent and its effect on occupants. In their pattern specifications, they specifically point out that this system can help occupants control their endocrine processes by emitting different colors and intensities of light. For instance, it can help occupants stay focused by emitting light with a high intensity and CCT, and it can also help occupants relax by emitting light with a low-intensity and CCT. This function is compatible with the results of Igor Knez's research.

Recreating a natural-light environment indoors has remained an unsolved subject for years; many scientists and engineers have tried to accomplish it but without success. The systems that they built to render natural light cannot provide light that feels realistic to the occupants. However, this LED dominant system is different from others; it is the only known direct solution to this subject.

In comparison to fluorescent and incandescent lamps, LED lamps do not emit harmful UV rays (Excluding LED lamps that are built to emit UV rays, such as full spectrum aquarium LED lamps). The emitted spectrum of LED light sources is tunable to every detail; manufacturers can eliminate the ultraviolet emission of lamps easily. For instance, Philips Lighting Inc. claims that its LED lamps do not emit harmful UV and IR rays.

The only possible drawback of using LED lamps as light sources to produce the "ideal light" is their CRI rating. However, the discussions and evidence that are presented in Chapter 2 indicate that LED lamps can have excellent color rendering ability; the problem is that the CRI rating systems are not sufficient to judge LED lamps' color rendition.

For these reasons, LED lamps are the only practical candidates to emit the "ideal light" in offices.

Chapter 4 – Sustainable and Environment-Friendly Design

Using sustainable and environment-friendly designs in building construction and industrial product manufacturing is more than a new rising global subject; it is an inescapable responsibility for every person, and it is the only way to preserve a better living condition for future generations. In this chapter, the sustainable and environment-friendly design aspect of office lighting system will be discussed, and LED, fluorescent, and incandescent lamps will be compared in terms of this aspect.

Energy Efficiency

Saving energy is a crucial element in environment-friendly designs, and designing systems with better efficiency are always the best solution. Lamps are the primary power consumers of lighting systems. Their efficacy dictates the overall efficiency of the entire system. Chapter 2 has a brief explanation and discussion of this point. This chapter will extend this discussion and focus on LED lamps because their performance sways with the variation of their operating environments.

Efficacy of LED lamps

The term that is used to describe the efficiency of lamps is efficacy (lm/w). Generally, LED lamps have higher efficacy than fluorescent lamps, and incandescent lamps have the lowest efficacy. The change in incandescent and fluorescent lamps' efficacy due to varying operating environments is negligible. However, the efficacy of LED lamps can change significantly under varying operating environments. The operating environments of LED lamps are the luminaires. Luminaires can decrease the efficacy of LED lamps or module in two ways: heat dissipation and driver losses.

Heat dissipation is the major reason efficacy decreases. Even though LED lamps do not emit infrared rays, they still generate heat. Heat generation is caused by electrons and electron holes combining at junction (Refer to figure 1.12 Surface Mounted LED (SML) Structure) of an LED lamp, and the temperatures at the junctions determine the efficiency of EMW emissions. The typical junction temperature of LED lamps during operation is around 60°C (140°F), and luminaires must dissipate the heat that is generated by the LED lamps to maintain their anticipated performance. Nevertheless, a bad heat-dissipating system design can raise the junction temperature to above 100°C (212°F), causing up to a 15% drop in efficacy.

Similar to ballast losses in fluorescent lamps, driver losses are inevitable in LED light sources. LED modules require drivers to convert alternating currents to direct currents to operate correctly. Typically, LED drivers only have 85% operating efficiency; they sequentially decrease the efficacy of LED lamps.

The driver losses and heat-dissipation issues become more severe as the lumen output of a LED light source increases. However, if LED lamps or modules are installed and operating in luminaires specifically design to accommodate them, the efficacy depreciation that are caused by the driver losses and heat-dissipation is generally acceptable.

Efficacy Comparison of Different Types of Light Sources

The U.S. Department of Energy estimated that the average value of all the available LED luminaires in the market would reach 100 lm/w by the year 2012 (DOE, 2012). Its 2014 report shows that its estimate was reached, and the current average is about 120 lm/w (DOE, 2014).

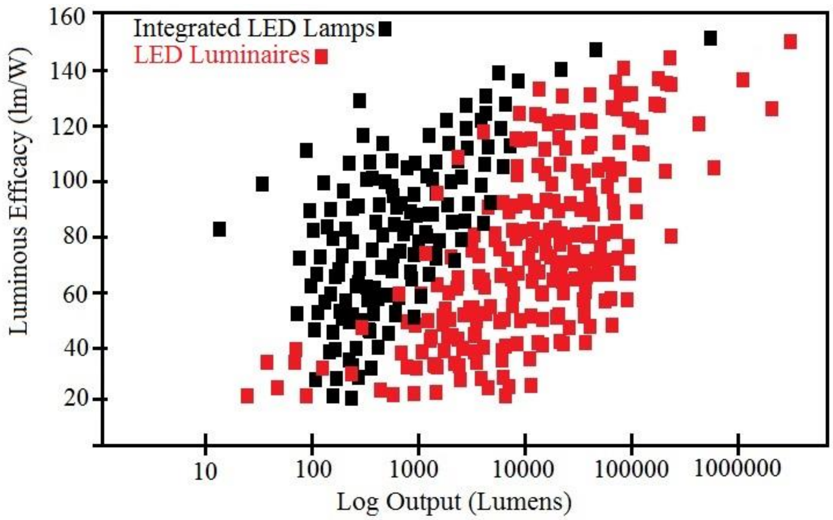

Figure 4.1 Efficacy of Integrated LED Lamps and LED Modules Integrated LED Lamps are drivers, heat-sink, and base "all-in-one" lamps, like A19 LED lamps. LED Modules are commercial LED modules, like GE fusion LED modules. (Information from Department of Energy, *Energy Efficiency of LEDs*, 2013)

Since the efficacy of LED luminous always has lower efficacy then their LED modules, comparing the efficacy of LED luminaries to other types of light sources is also meaningful. Table 4.1 shows the efficacy comparison table of common light sources from the U.S. Department of Energy's 2014 report. Incandescent lamps remained as the least efficient light sources. Linear fluorescent systems have slightly higher efficacy than integrated LED lamps. However, commercial LED light sources are the most energy-efficient light sources.

Product Type	Luminous Efficacy (in lm/W)
LED A19 lamp	94
LED PAR38 lamp	78
LED troffer 2X4	131
LED high/low-bay	119
High intensity discharge system	115
Linear fluorescent system	108
High intensity discharge system	104
Compact fluorescent lamp	73
Halogen	20
Incandescent	15

Table 4.1 Efficacy Comparison of Different Light Sources (Information from Department of Energy, *2014 DOE SSL Multi-Year Program Plan*, 2014)

Environmental Pollution and Recycling

Incandescent lamps cannot be considered as environment-friendly light sources due to their huge deficiency in efficacy. The efficacy of fluorescent lamps are very close to and can even surpass LED lamps. However, fluorescent lamps are still considered as environment hazards.

Fluorescent lamps contain the heavy metal element mercury, which is toxic to living beings and is a severe pollutant to the environment. 620 million fluorescent lamps are discarded yearly in the U.S.; only 20% of them are recycled (Michale et al., 2004). Mercury not only will damage the immune system, enzyme system, and nerve system of living beings, it also will effect the environmental biology sequence by damaging the natural food chain (USGS, 2000).

If fluorescent lamps are broken indoors, they will present even more serious conditions. The Minnesota Pollution Control Agency (MPCA) suggests that people and pets should evacuate from the room of broken fluorescent bulbs, and the room shall be ventilated for at least 15 minutes before re-entering (MPCA, 2015). The MPCA may consider that mercury leakage of broken fluorescent lamps will diminish to a safe level to humans after 15 minutes. However, the mercury leakage will last for a much longer time. Michael Aucott and his colleagues have conducted an experiment about mercury released from broken fluorescent lamps. They assume that an average burned-out fluorescent lamp contains 4.5 milligrams of mercury, and a typical new lamp contain 20 milligrams each. They found that the broken fluorescent lamps will keep releasing mercury into the air for at least 8 hours; in some conditions, the release time can even reach 340 hours.

Because LED lamps consist only of solid and hard parts, breaking LED lamps accidentally is a rare occurrence. LED lamps contain no toxic and hazardous materials; therefore, broken LED lamps present minimum health and safety threat to humans. Moreover, most parts of LED lamps are electrical components, and more than 90% of LED lamps or luminaire parts are recyclable and reusable (Philips, 2011).

All data shows that LED light sources are more preferred from the perspective of sustainable and environment-friendly design. They pose the least pollution to the environment, and LED lamps have the highest efficacy. U.S. Department of Energy estimates that the efficacy of LED lamps will reach 200 lm/w by the year 2020. It means that the energy efficacy of LED lamps will be superior, compared to any other light sources.

Chapter 5 – Costs

Since most countries in the world have market economies, the cost of any design is an eternal topic; it is necessary to devote an entire chapter to discussing the costs of office lighting systems. This chapter will not only compare the initial costs of lamps and luminaires but also compare the life cycle costs of systems with different light sources.

Initial Costs Comparison

Packaged LED luminaires are generally cheaper than LED lamps with third-party fixtures with the same power consumption, lumen output, and functions. For this reason, the initial costs comparison will only compare the initial price of different types of lamps.

LED lamps have long been known for their high initial cost. In the past, LED lamps were only used in places where dynamic color shifts or dimming functions were necessary to the design of the project. For instance, LED lamps are very popular in theaters and exhibition centers. These spaces place more emphasis on the lighting system's ability to render correct moods than on initial cost. When the advantages of LED lamps, such as high energy efficiency and ease of control, become more and more conspicuous, the industry will start to think LED lamps can also be used as mainstream light sources inside buildings. However, the high initial cost of LED lamps is still an obstacle. In 2000, Dr. Roland Haitz proposed his famous *Haitz's law*, which is related to the trend in the price and efficacy of LED lamps (Haitz, 2000). *Haitz's law* states that "every 10 years, the price of LEDs decreases by a factor of 10, while the performance (measured in flux per unit) increases by a factor of 20." Figure 5.1 shows the estimated LED price and output luminous flux trend of *Haitz's Law*. The cost per lumen and output luminous flux per package figure that was measured by Ronald Haitz and Philips

Lumileds proved the truth of *Haitz's law*.

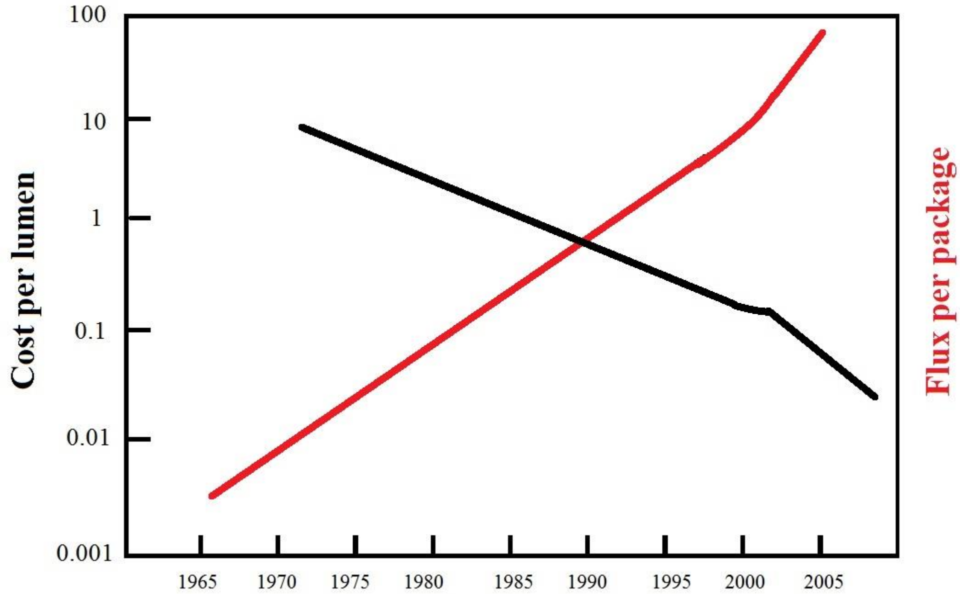

Figure 5.1 Haitz's Law (Information from LED Lighting Group LLC, *Haitz's Law and Its Implications for LED Lighting*, 2005)

In Haitz's publication, the forecasted efficacy of LED lamps was 100 lm/w by the year 2010 and 200 lm/w by the year 2020. This coincides with the estimate of the U.S. Department of Energy. A DOE-sponsored IESNA publication from 2002 also indicated that the estimated average lumen cost of commercially-available LED lamps (U.S. dollar per kilolumen or $/klm) would be 300$/klm and that this number would decrease to 5$/klm by 2012 (2002). The 2014 publication of DOE proves that their previous estimate was correct. Table 5.1 shows the IESNA's estimate of the price and performance trend of LED lamps in 2002.

Technology → [*date*] →	*SSL-LED 2002*	*SSL-LED 2007*	*SSL-LED 2012*	*SSL-LED 2020*	*Incandescent 2002*	*Fluorescent 2002*
Luminous Efficacy (lm/W)	25	75	150	200	16	>85
Lifetime (khr)	20	>20	>100	>100	1	>20
Flux (lm/lamp)	25	200	1000	1500	1200	3000
Input Power (W/lamp)	1	2.7	6.7	7.5	75	32
Lumens Cost ($/klm)	300	20	<5	<20.4	1.5	
Lamp Cost ($/lamp)	5	4	<5	<3	0.5	5
Color Rendering Index (CRI)	75–90	80–90	80–90	80–90	100	>80
Chip Temperature (°C)	100	300–600	500–750	600–1000		
Input Power Density (W/cm^2)	100	300–600	500–750	600–1000		

Table 5.1 LED Lamp Performance as of 2002 and at Projected Target Dates (Information from IESNA report, 2005)

Because incandescent lamps are one of the oldest types of light sources, their global manufacturing lines and markets are well-developed, they have the lowest initial costs. The cost of LED light sources continues to decrease over time. However, even by the year 2020, the average targeted cost of LED lamps is not significantly less than that of fluorescent lamps. Moreover, the average output luminous flux of LED lamps will not reach or exceed that of fluorescent lamps. LED lamps do not have an advantage on initial costs compared to other light sources.

Life Cycle Costs Comparison

The overall life cycle costs of an office lighting system involve many factors, such as maintenance labor costs, replacement costs, operation costs, and initial costs. Labor costs vary greatly based on different areas. Excluding lamps, other components of lighting systems can be completely different based on the preference of designers and owners. For these reasons, the comparison of life cycle costs in this section will only be based on the lamps' initial cost, energy consumption, and replacement cost. Prashant K Soori and Fafaa Alzubaidi from Heriot-Watt University conducted a real-life case study on the energy efficiency of an office building's lighting systems (2011). They chose an office space in the United Arab Emirates as their case study sample. The dimensions of this office space were 12 m x 30 m x 3 m, and it had two north-facing windows. They found that the reflectance of the walls, floor, and ceiling were 0.57, 0.2, and 0.7, respectively. The luminaires which they chose for this case study are ceiling mounted-down lights from the ERCO Quintessence Series. These luminaires have three light source options, which are LED, fluorescent, and incandescent. Because, these luminaires are from the same series, they have the same exterior appearance and shall be applied for the same design applications. However, internal structures of them are varied to fit different types of light sources. The average lamp life that they adopted in their publication is 1,500 hours for incandescent lamps, 17,000 hours for fluorescent lamps, and 62,500 for LED lamps. The design reference illuminance that they adopted for the office space is similar to the illuminance recommended by the IESNA office (2011). Table 5.2 shows the design references for various similar spaces.

Area/location	Lux (lx)
Open plan office mainly screen based work	300
Open plan office mainly paper based work	500
Deep plan core area (more than 6m from window)	500
Cellular office-mainly screen based work	300
Cellular office-mainly paper based work	500
Graphics workstations	300
Dealing rooms	300- 500
Executive offices	300- 500

Table 5.2 Design Reference UAE

(Information from P.K.Soori et al., *Study on improving the energy efficiency of office building's lighting system design*, 2011)

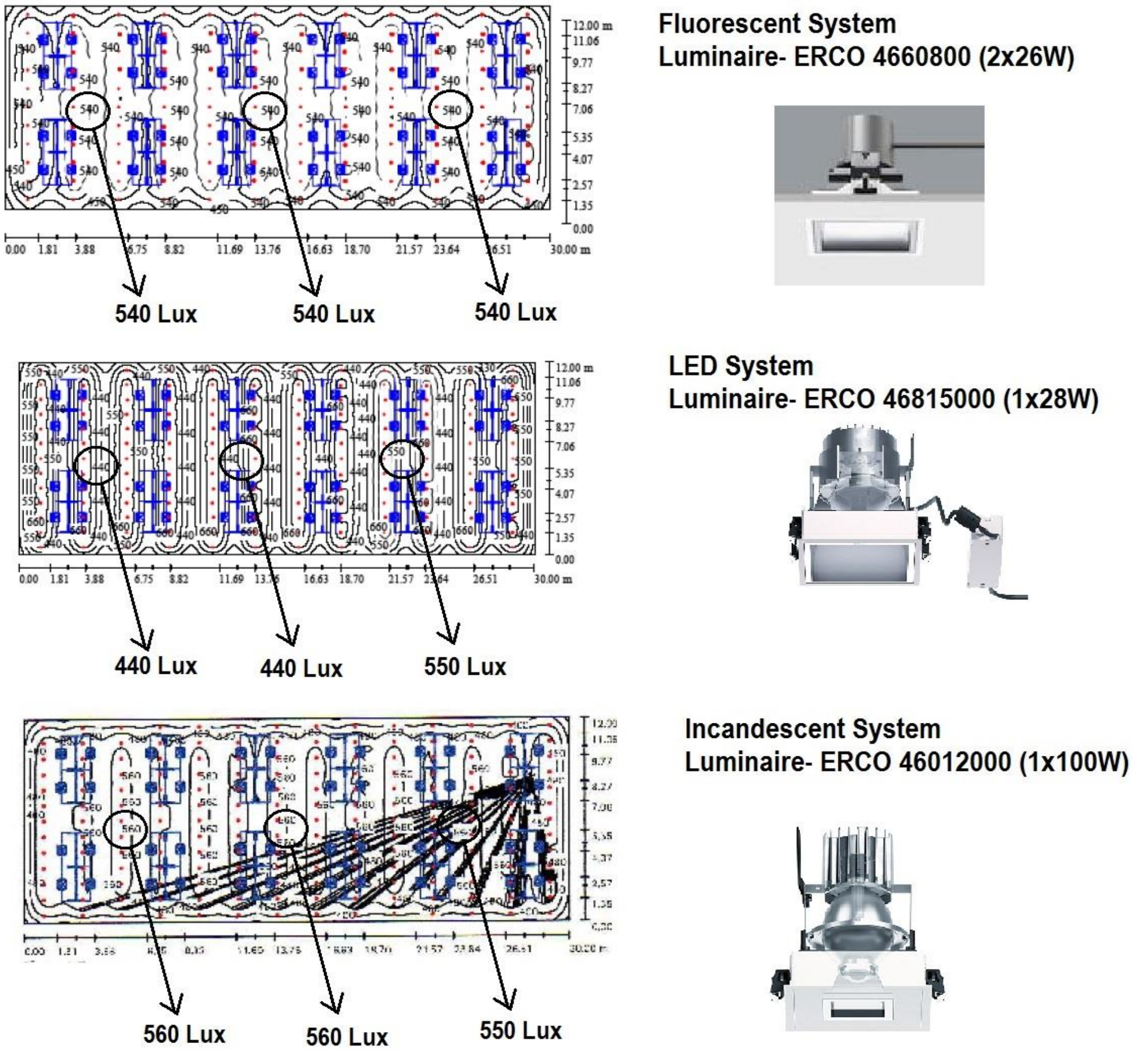

Figure 5.2. Design Results of UAE Office (From P.K.Soori et al., *Study on improving the energy efficiency of office building's lighting system design*, 2011)

Because the office space is a cellular office—a mainly paper-based workspace—the researchers tried to achieve 500 lux uniformly across the entire task plane. Figure 5.2 shows information related to the design results. The final results of selected points vary by a maximum of 80 lux; therefore they can be considered acceptable.

Table 5.3 shows the luminaire quantities, power consumption, and cost results. The initial cost of LED luminaires is at least three times as much as that of other light sources. Meanwhile, the power consumption of incandescent lamps is much more than that of other light sources.

Type of Lighting System	No. of individual Luminaire	Power Consumption (Watts)	Power Desity (Watts per Square-meters)	Individual Luminiare Price (Dollar)	Individual Lamp o/ LED module Price (Dollar)	Total System Luminaire cost
CFL	132	6864	19.07	400	25	52800
LED	156	4368	12.13	1000	95	156000
Incandescent	182	18200	50.56	225	15	40950

Table 5.3 Final Results of UAE Office Study Case (Information from P.K.Soori et al., *Study on improving the energy efficiency of office building's lighting system design*, 2011)

Common expected life for office lighting system is 20 years. It is assumed that the office lighting system will be kept on for 10 hours per day and that the office operates 300 days a year. The total life cycle duration for this system is 60,000 hours. In the UAE, electricity costs 0.11 dollars per kilowatt-hour ($/kWh). Therefore, the total life cycle costs of each system can be estimated by using equation 4. All the labor costs, such as installation, maintenance, and replacement, are not included in this equation. This equation also does not include life span and aging performance depreciation factors of luminaires components other than the lamps or LED modules.

$$LCC = \mathrm{A} + T \times B \times u + \left(\frac{\mathrm{T}}{t}\right) \times C$$ **Equation 4**

Where, LCC = Life Cycle Costs

T=Total Life Cycle Operating Duration in hours

t= Rated Lamp Life of the Installed Lamps

A=Initial Costs

B=Power Consumptions

C=System Lamps or LED Modules Costs

u=Electricity Costs per kWh.

Many critical costs factors, such as labor and luminaire drivers' replacement costs, are not included in this calculation method. Since this paper only addresses the comparison between LED, fluorescent, and incandescent lamps, the calculated results of this equation are still valuable but not realistic. The life cycle costs of incandescent, fluorescent, and LED lamp systems are $267,460, $118,096, and over $184,829, respectively. Fluorescent lamp systems, therefore, have the lowest life cycle costs.

Because the calculation method is not realistic, this result cannot be used to predict the results of other office lighting design situations. However, that fluorescent lamps are still a viable choice in terms of costs currently is true for most cases. Nevertheless, all research shows that LED lamps have the potential to become the most cost-efficient lighting system in the future.

Chapter 6 – Unique Drawbacks of LED Lamps

Narrow Distribution of Light Issue

Even though, LED, fluorescent, and incandescent lamps all have different structures, that of LED lamps diverge greatly from those of the other two. The illuminant body of the incandescent lamp is the filament. The individual size of the filament is usually large compared to the size of the entire lamps; the only direct obstacle of the illuminant body’s emission is the lamp base, it only blocks a small portion of the illuminant body's (filaments) surrounding area. For these reasons, the emitted light distribution (ELD) of incandescent lamps is wide. Meanwhile, the illuminant body of a fluorescent lamp is the entire bulb, excluding the lamp bases, therefore emitting light at 360 degrees. Hence, the ELD of fluorescent lamps is also wide.

In contrast, the illuminant body of a common LED lamp is the LED module. The individual size of the LED modules is very small compared to the size of the lamp. All LED modules are installed on the top of the bases of LED luminaires, and they only emit light from the front face of the modules. For commercial LED light sources, LED modules are even much smaller in size compared to other components of the luminaires; the available lamp emission space is even smaller. Therefore, the ELD of LED lamps is usually very narrow and only covers the space directly in front of the modules.

The technical term used to describe the distribution of the emitted light of lamps and luminaires is "photometric data." Photometric data is usually in polar coordinates form. The lamp that is being described is put in the center of the polar coordinates. The polar coordinates are treated as one of the vertical cross section areas of the lamps when it is operating. The distance from a plotted point to the center of coordinates indicates the intensity of the emitted light at that point. A greater distance reflects higher intensity light. Figure 6.1 is a general photometric data comparison of incandescent, fluorescent and LED light sources.

Emitted light intensity of incandescent and fluorescent lamps are distributed evenly for wide degrees. These types of lamps can deliver light evenly to task plane without strict requirements on luminaire lenses and reflectors. In contrast, LED lamps have narrow distribution planes. They often rely on luminaire lenses and reflectors to diffuse the emitted light. If the reflectors or lenses are not carefully designed for these types of LED light sources, direct glare is inevitable.

Viable Improvements

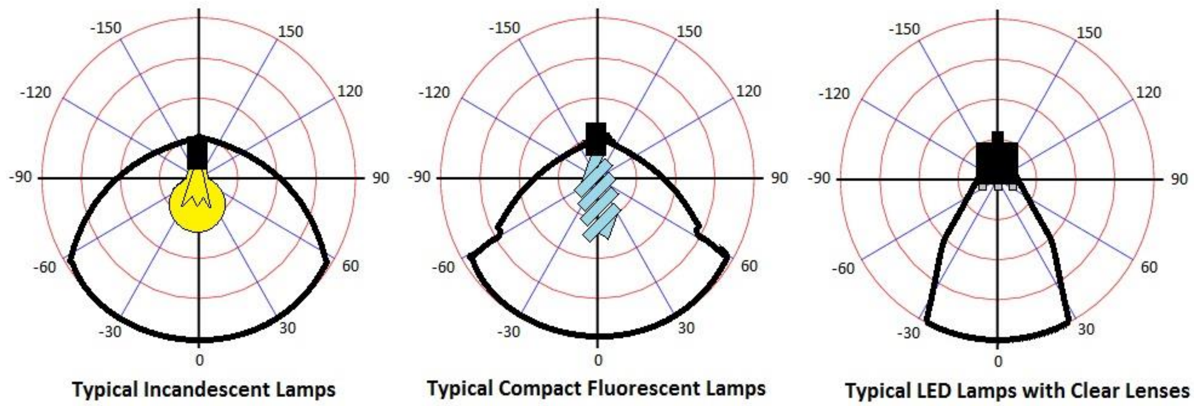

Figure 6.1. Photometric Data Examples

Instead of only relying on luminaires to solve the LED lamps' ELD drawback, scientists and engineers have proposed some remedies for improving the narrow distribution issue. These remedies include changing the flat LED modules mounting surface to a curved surface or adding integrated reflectors. Of all of the remedies, adding well-designed lenses is the most popular and viable method.

The improvement related to well-designed and diffuse lenses is enormous. Scholars of Pacific Northwest National Laboratory (SPNWL) have prepared a report called "*Application Summary Report 21: Linear (T8) LED lamps*" for the U.S. DOE (DOE, 2014). This report is about the practicality of using linear LED lamps as a substitute for fluorescent T8 lamps in design applications. They pointed out the distribution drawback of LED lamps. However, they also found that diffuse lenses can improve the distribution of LED lamps dramatically. They made the following statement in their paper:

> "Although none of the LED products were close to matching the fluorescent benchmark—which had relatively uniform intensity at all vertical angles—the data did reveal a distinct difference between lamps with a clear lens and lamps with a frosted lens. The beam angle is twice the vertical angle at which the intensity is 50% of maximum intensity."

Figure 6.2 is the comparison result for multiple linear LED lamps and fluorescent T8 lamps. Fluorescent lamps have evenly distributed light distribution; the light intensity from angle 0 to 180 degrees are similar. On the other hand, all the LED lamps have uneven distribution with most of the luminous flux output at the center 0 degree. However, the improvement that comes

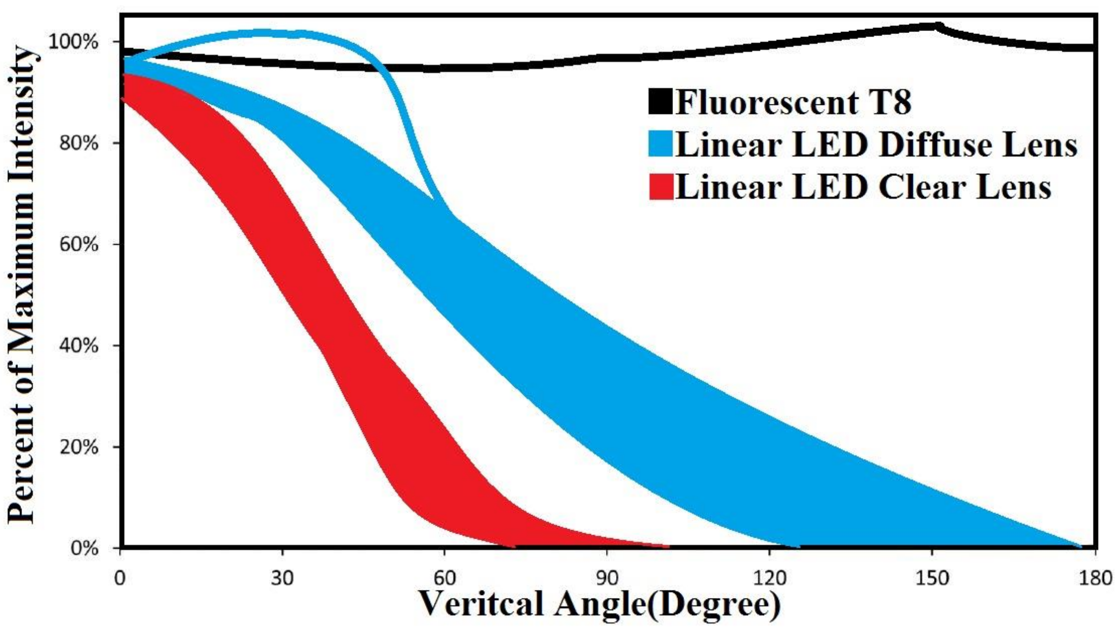

Figure 6.2 Comparison Results of Emitted Light Distribution

(Information from the Department of Energy, *Caliper Application Summary Report 21: Linear (T8) LED Lamps* ,2014) from using diffuse lenses is significant. Almost no light is detected at a 90-degree vertical angle for all the clear-lens LED lamps; about 30% to 50% of the light is still detected at the same vertical angle for all the diffuse-lens lamps.

Using diffuse lenses to help obtain wider luminous flux distribution is also a very common method that is used in current-on-market commercial LED light sources. For instance, General Electric Company (GE, or GE Lighting) uses diffuse lenses on their LED products to obtain a wider and more even distribution. *Infusion LED Module* is a commercial LED light source from GE lighting. This module only includes LED arrays, LED module housings, reflectors, lenses, optical interfaces, and necessary electrical and mechanical bases. Figure 6.3 is the example of the front and back view of an *Infusion LED Module* (Not including housing and lens).

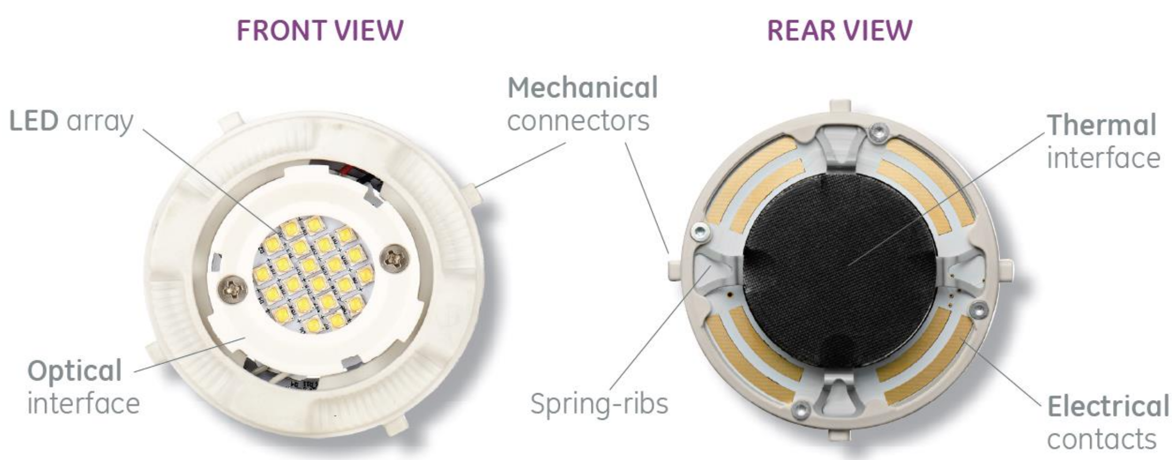

Figure 6.3 Infusion LED Module (Figure from the GE Lighting, *Infusion LED Module cut sheet*, 2015)

This series of LED Modules has clear lenses and diffuse lenses option. Their published data shows that diffuse lenses create wider distributions. Figure 6.4 shows how housings, reflectors, and lenses are installed on LED arrays and bases, and it also shows graphical results of modules with both types of lenses when they project light to parallel surfaces.

The graphical results may not show a big visual difference. However, the quantitative differences from photometric data are very clear when these modules are applied to their compatible luminaires. “Lumination LED Luminaires” series from GE Lighting is one of the viable luminaires using “Infusion LED Modules.” The photometric data example in figure 6.5 shows the quantitative data differences that are created by using clear and diffuse lenses.

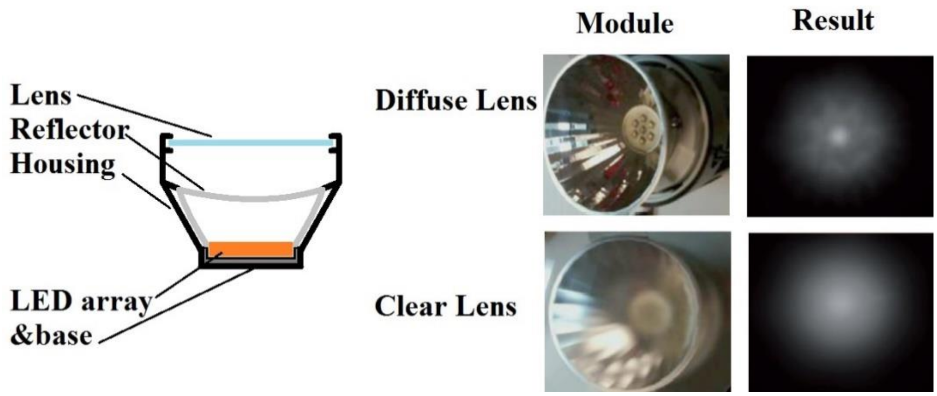

Figure 6.4 Comparison of Visual Results (Figures and information from *Infusion LED Module cut sheet*, GE Lighting, 2015)

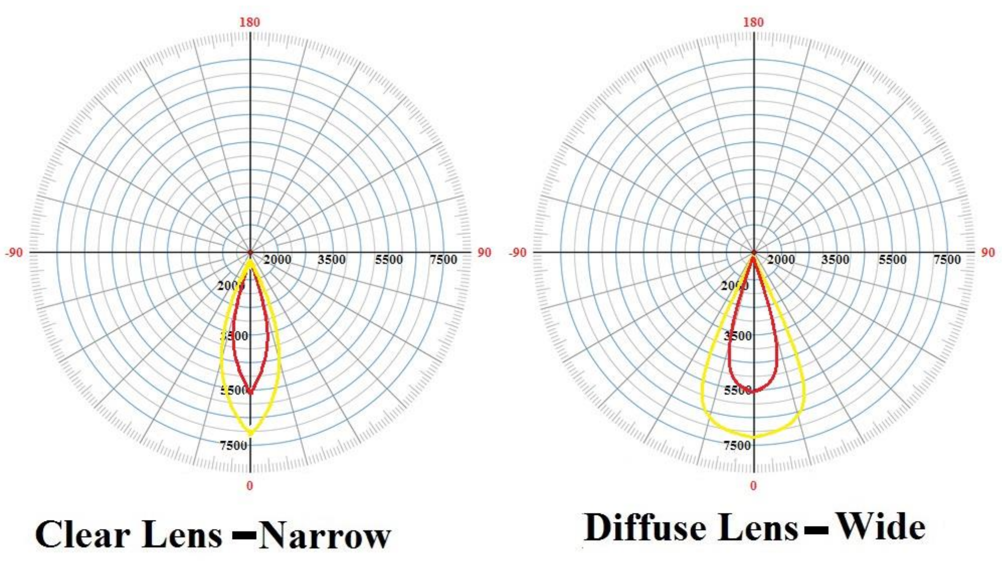

Figure 6.5 Comparison of Graphical Results (Figures and information from *Infusion LED Module cut sheet*, GE Lighting, 2015)

Visual Experiment

No visual representation of the lamp distributions are provided in the SPNWL report. GE LED modules and luminaires' example did not provide vertical light source projection examples. For these reasons, a simple experiment is conducted to understand the importance of diffuse lenses; this experiment is only for obtaining visual data, and no quantitative data is acquired.

The lamps that are used in this experiment are generally used in residential applications. However, frosted lenses are used as diffuse lenses on both commercial and residential light sources; the propagating principle of EMWs are the same when they are traveling. For this reason, this experiment is still valuable to help understand the significance of using diffuse lenses.

This experiment is to observe the emitted light distribution patterns that are projected on a flat white wall from diffuse- and clear-lens LED lamps. The equipment and devices needed for this experiment include a power-supplying socket, 1 diffuse-lens (frosted-lens) LED lamp, 1 clear-lens LED lamp, and a flat white surface; Table 6.1 shows their detailed specifications.

Device	Specification
Power Supplying Socket	120V 60Hz, 60W rated max available power
Diffues (Frosted) Lens LED lamp	General Electric, A19-LED11DAV3,11W, LED lamp
Clear Lens LED Lamp	Titan, Energy Efficient 7-LED, 0.45W, LED Lamp
Wall	Flat and white wall, no reflectance available
Camera	8 megapixel iSight camera

Table 6.1 Specifications List

The LED modules of both lamps are mounted on the flat surface of the bases, and both lamps are non-CCT-variable, white-color LED lamps. The power supply socket is 5.5 inches from the wall, and it points upward, standing parallel to the wall. Figure 6.6 shows more details about the setups and both lamps, and figure 6.7 is the result visual data. Appendix A shows a 3-dimensional view of this experiment set up, and appendix B and C are the cut sheets of the lamps that are used in this experiment.

Figure 6.6. Set-ups and Lamp Details

The experiment includes five steps:

1. Place the power supply socket 5.5 inches away from the wall and adjust the socket to an erect position.
2. Place the camera 20 inches away from the wall, making sure the center of the aperture is in line with the top of the socket.
3. Install the clear lens LED lamp and turn it on. Take a picture of the light projection pattern it emits on the wall. Then, remove the clear lens LED lamp.
4. Repeat step three for the diffuse lens LED lamp and the diffuse lens LED lamp without a lens.
5. Compare the results.

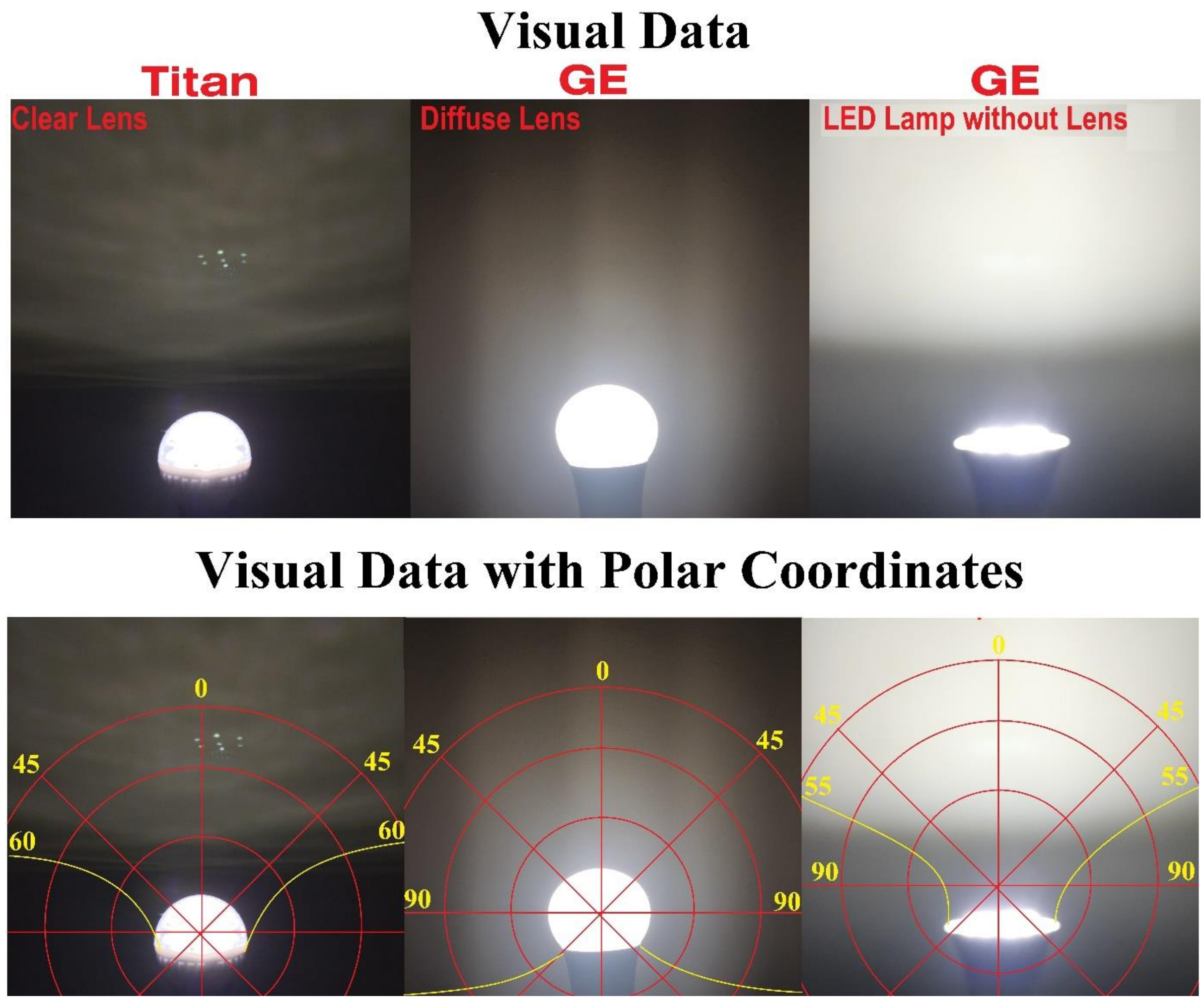

Figure 6.7 Acquired Visual Data

Visual data shows the majority of output luminous flux for the clear lens, and no lens LED lamps are concentrated above 60 degrees, and the diffuse lens LED lamp has flux distribution for almost 360 degrees. This result indicates that the diffuse lens LED lamp has a more even and wider light distribution pattern than the clear lens LED lamp. The improvement that results from using a diffuse lens is a leap forward. Even though these distribution patterns cannot be considered as photometric data, they resemble the shape of photometric curves. Using a diffuse lens to improve the ELDs of LED lamps can be considered a mature and viable method.

Heat Dissipation Issue

The efficacy and lamp life discussions of Chapter 2 have already indicated that fluorescent and incandescent lamps are affected mildly by their operating environment; the associated efficacy and lamp life reduction are negligible. However, the heat significantly decreases the actual efficacy and lamp life of LED light sources. This section discusses some solutions for this heat issue.

LED lamps rely on a doping process that occurs in the junction of LED modules to emit light, and the doping process emits more light for limited amounts of current in cooler environments. Figure 6.8 shows the relationship between light output and junction temperatures of some common LED light sources. Red, blue, and white LEDs can emit more light than their rated value for the rated power input in low-temperature conditions (below 25°C or 77°F), and the value decreases below 100% if the temperature surpasses 25°C (77°F).

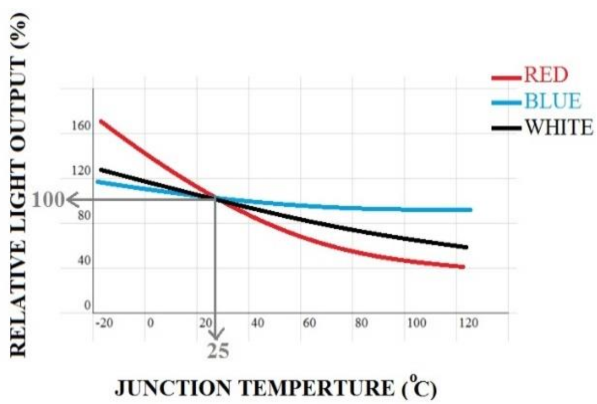

Figure 6.8 Light Output and Junction Temperature (Information from Lighting Research Center, *LED Lighting Systems*, 2003) The tested LEDs are supplied with their rated current and voltage input

One of the ways to keep LEDs emitting their rated light output is increasing the input power. Some manufacturers install temperature sensors on the backside of the junction, and program the LED drivers in such a way that the drivers will increase the power input if temperature sensors detect the junction temperature rise above a certain temperature. This solution avoids output light depreciation from heat issues; however, it excessively decreases the lamp life and efficacy of the light sources. This method was quickly abandoned by all the manufacturers.

Another solution is installing heat-dissipating systems (also refer as thermal management systems or heat-sinks) on lamps. This method ensures that LED light sources emit constant amounts of light by regulating the junction's temperature; it is the most popular method used today. The thermal management systems are made from a fine heat conducting material such as ionized metal, and they are designed with multiple fins to maximize their available thermal conducting area. In most cases, these thermal management systems rely on convective airflow to take heat energy from their surface. Therefore, the fins' orientation becomes one of the most important factors in their effectiveness. Figure 6.9 shows some example of heat-sinks' effectiveness in different orientations. The effectiveness of heat-sinks can vary by up to 40% depending on the orientations of their fins (John, 2013), and heat-sinks are most effective when

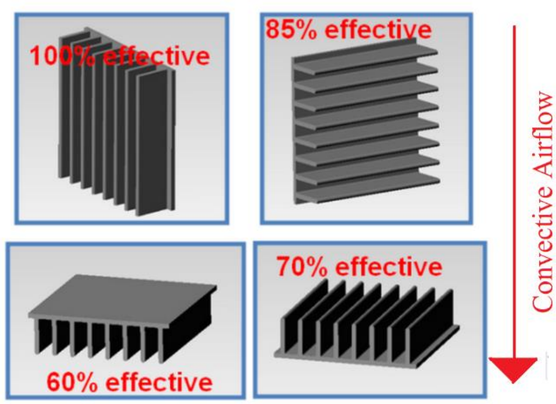

Figure 6.9 Effectiveness of Heat-Sinks of Different Orientations (Figure reproduced from *understanding LED Technology Part 2: The Limitations of LED Lighting*, J. Curran, date accessed 1-20-2015)

their fins are parallel to the convective airflow.

Commonly, LED lamps can eliminate the heat dissipation issue by using their dedicated and correctly installed heat-sinks. For instance, GE Lighting Infusion, the example LED modules

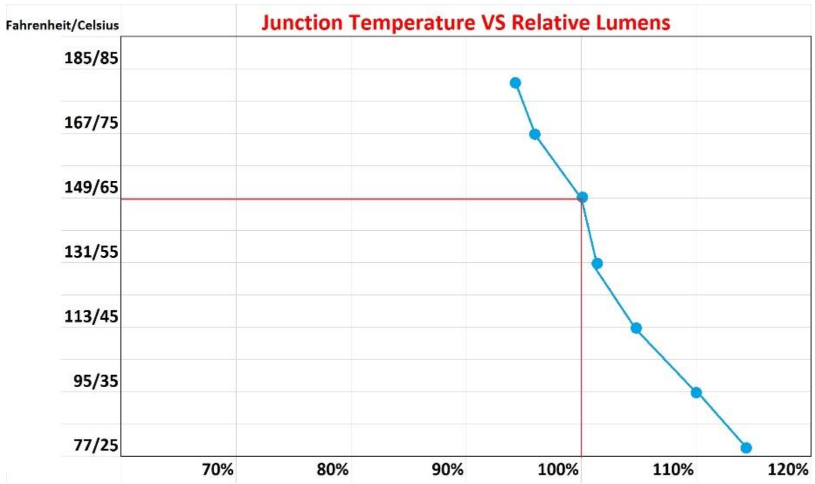

Figure 6.10 GE Lighting Infusion Lumen Depreciation by Heat (Figures from *Infusion LED Module cut sheet*, GE Lighting, 2015)

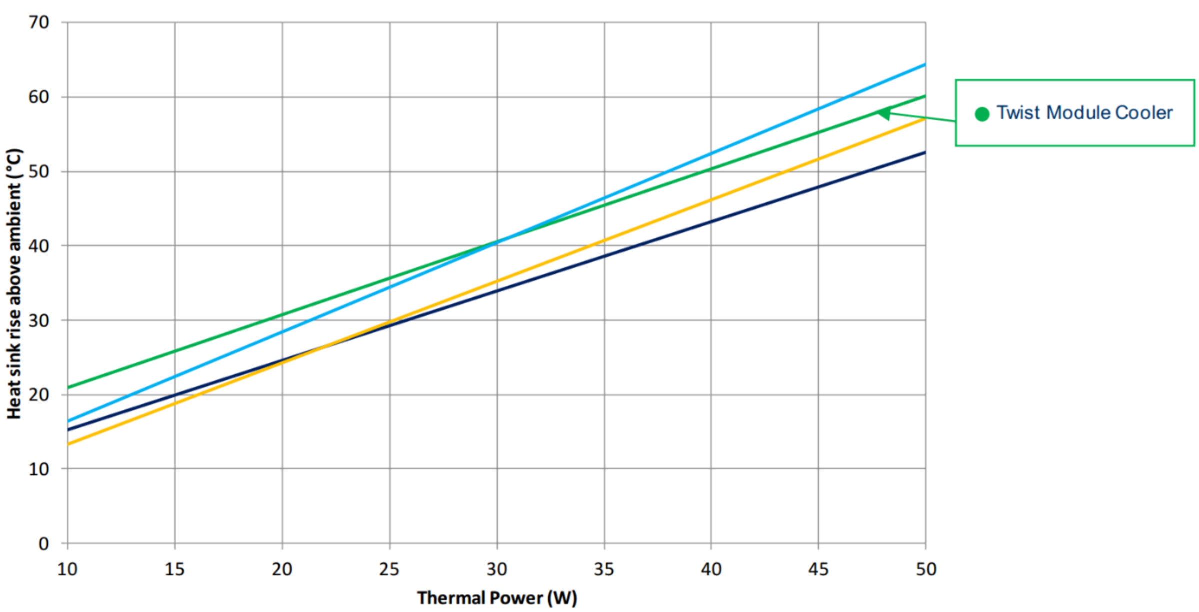

Figure 6.11 Nuventix Twist Module Cooler Performance Data (Figures from *Twist Module Cooler Heat Sink Data Sheet*, Nuventix, 2015)

from the previous section, can keep emitting 100% of their rated light if their junction temperature is kept under 65^{o} C (149 ^{o}F). Figure 6.10 shows the detailed relationship between their relative light output and junction temperatures.

The Twist Module Cooler Series Heat-sinks from Nuventix Company are the dedicated heat-sinks for *GE Lighting Infusion LED Modules.* Figure 6.11 is the performance data of this series of heat-sinks. "Thermal power" is the heat generating rate of LED modules; it is always smaller than the input power, and "heat sink rise above ambient" indicates the maximum temperature increases of junctions compared to ambient temperature.

The highest rated input power of *Infusion LED Modules* is 45 watts, and the maximum thermal power is less than 35 watt. Hence, the highest possible temperature rise of the junction is 45^{o} C, and the average indoor temperature is 25^{o} C. The result is that the highest possible operating temperature of *Infusion LED Modules* that are served by *Twist Module Cooler Series* heat-sinks is 70^{o} C. According to figure 6.10, this series of LED modules can keep emitting more than 95% of their rated light output at this temperature condition. Therefore, this thermal management system shall be considered as a viable solution.

This example is only one of many current market available LED modules and heat-sink combinations. Other combinations may have small differences in term of actual performance; however, they shall always offer adequate performance.

Chapter 7- Suggestions and Summary

Some suggestions for using LED lamps as primary light sources in office lighting system designs will be given in this chapter. This chapter will also state a summary of data using LED lamps as primary light sources in office lighting systems, based on information and results from previous discussions.

Suggestions

All suggestions are given based on different lighting design application types. IESNA categorizes application types of office space into 14 categories (IESNA, 2011). This classification is too detailed for use in this chapter; application types with similar characteristics are combined into one type. For instance, drafting, IT, reading, and writing can be collectively referred to as office tasks. These may have slight differences in lighting condition requirements, but they have the same requirements in terms of light sources. All these types fall into 2 categories, which are public areas and private areas.

Public Areas

Building entrances and perimeters have fewer lighting requirements. However, these areas often require 24 hours of continuous lighting for security reasons; building entrances may even need to be much brighter for the occupant to identify visitors easily. Lamps installed in these areas do not necessarily need to have great color rendition, but they have to have long lamp life and high efficacy. Packaged LED Lamps are recommended in these areas since they always have the highest efficacy and lamp life.

For some buildings, owners may require their building entrances and perimeter lighting to have CCT-changing ability so that the light can change colors for various special events. RGB color changing LED light sources are recommended in these situations. Again, because perfect color rendition is not the primary requirements, these types of light sources provide the most economical solution and meet the requirements. For instance, *ColorBurst 6* series lamp from Philips Lighting can be perfect candidates for these types of areas (Philips, 2015). This type of light sources can achieve dynamic color shifts and have 70,000 hours of L_{70} lamp life.

Light sources for public bathrooms and locker rooms shall have similar characteristics as building entries. Because phosphor coated LEDs generally have the highest efficacy and longest lamp life of all white light LEDs, phosphor coated LED lamps are recommended in these areas.

Public areas include lobbies, corridors, and other transition space. The lighting systems in these areas do not necessarily need perfect color rendition. However, their color rendering ability needs to be good enough to achieve visual comfort. LED light sources shall have CRI over 80 from R14 test (Even though the R14 test is not the ideal CRI measuring, it is the best and most known worldwide).

Lobbies, corridors, and other transition areas are also perfect places to use LED light sources to render natural light conditions. These areas are usually adjacent to office task areas. Simulating natural light conditions in these areas can help reduce employees' sick building syndrome and offer much better visual comfort to all the occupants. In order to simulate a natural light condition, lighting systems need to have a dynamic color shift ability. However, the CCT variation range for natural light only ranges from 2000 to 8000 kelvin. For this reason, phosphor-coated LED lamps are more suitable than RGB LED lamps in this situation because they have better color rendition. Wu Wenchao mentions that they use 3 sets of dimmable and monochromatic LED lamps, which are 2000K, 5700K, and 7000K lamps, to simulate natural light in his patent report. This is a viable method, too.

The color and intensity shifting pattern is the key to successfully simulating natural light. In Wu's patent report, he gives a very detailed CCT and intensity shift pattern. Table 7.1 is the spring day lighting controlling pattern. Other seasons' lighting controlling patterns need to shift the hours forward and backward according to sunrise and sunset times.

Time of a Day	Shift CCT to	Illumination Level
0:00-5:00	>7000K	0%
5:00-7:00 Sunrise Time	3000K	0-50% (Opening Time)
7:00-9:00	6500K	50%-80%
9:00-12:00	5500K	80%-100%
12:00-15:00	6500K	100%-80%
15:00-17:00	5500	80%-60%
17:00-19:00 Sundown Time	2700K	60%-0% (Closing Time)
19:00-24:00	>7000K	0%

Table 7.1 Spring Day Controlling Pattern (Informations from Pattern CN 103237391A, Wu, 2013)

Food service, lounge, and other relaxing areas of building shall have the same controlling patterns and similar light source characteristics to lobbies and transitions areas. However, the light sources need to have good color rendition. Normally, most art and decorations are placed in these areas; lighting systems may need to function as accenting light. Light sources with good color rendition not only offer the benefit of visual comfort but also maximum esthetics. The color schemes of the controlling patterns can be warmer in these areas since people feel more relaxed in warm light conditions. CCT variable and dimmable packaged LED lamps are recommended for these areas.

Conference rooms have simple functions, which are conferences, discussions, and presentations. Lighting system requirements for conference rooms are simple, too. They need to have great color rendition and white or daylight color for the best working efficiency, and they need to be dimmable to have use flexibility. Therefore, white color or daylight color LED light sources are recommended.

Open office ambient light systems often only offer general illumination. It is not necessary to have great color rendition; in contrast, they should have great efficiency to reduce energy consumption. The office task lighting of each office cubicle are considered as private lighting.

Moreover, the ambient light of open offices spaces shall create an atmosphere to help maximize the productivity of employees. According to Igor Knez and Philips Lighting University RIBA accredited material, humans need to receive “cool blue” light in the morning and gradually shift to warm light to warm up our body internal systems; and generally, humans need warm CCT light to reach maximum productivity. Open office light control patterns may start as “cool blue” light in the morning, from 7:00-9:00 am, and have a shifting color to warm amber from 9:00 am onwards. For these reasons, open office lighting systems also need be able to change CCT. CCT variable packaged phosphor-coated LED lamps are recommended for this application.

Private Areas

Private areas include private office areas and cubes of open offices. Each private office must have its own luminaires and control points. In addition, each cubicle in an open office should have its own task luminaires and control points because previous stated research and discussions conclude that the most desirable colors of light vary by gender and the desired illumination levels vary by age. In most cases, warm light helps humans reach their maximum productivity; however, women demonstrate better problem-solving abilities in neutral light (5000k) or daylight. People in older age groups require high illumination levels to work efficiently. In contrast, people in younger age groups may feel disturbed and uncomfortable when the perceived light intensity is too high. The most important aspect is that the light sources need to have great color rendering ability.

Each private area needs to have a variable CCT and dimmable light sources with excellent color rendition and control points. Packaged phosphor-coated LED luminaires are also recommended for this application.

LED light sources are extremely versatile and controllable. To fully incorporate all the functions of LED light source systems, computerized controlling systems are recommended. Wu's patent report states that he uses central microprocessors to control lighting systems and to incorporate lighting systems with sound, air conditioning, and other systems. Due to the high complexity of controlling requirements, computerized controlling is a better choice than traditional controlling systems.

Summary

Currently, incandescent, fluorescent, and LED light sources are primary light sources for low-ceiling indoor lighting system design application. LED light sources are newer compared with the other two.

Incandescent light sources have perfect color rendition. However, they also have inferior efficacy. Many countries have instituted policies to phase out incandescent lamps. For instance, the U.S. started to partially phase out incandescent lamps in 2007 (An Act, 2007). The Chinese government plans to phase out most of its incandescent lamps usage by 2016 (Reuters, 2011). Incandescent lamps will inevitably become something of the past.

Fluorescent lamps have acceptable color rendition, excellent efficacy, and low initial costs. Unfortunately, they are still not the perfect lamps for office lighting design applications or for future applications. Despite causing heavy metal pollution to the environment, their efficacy has already been developed to the maximum. They also lack many features that are required for ideal future office lighting system designs, such as gradually shifting dynamic color. They may still be a viable choice in terms of cost. However, their initial cost will not likely decrease any more, and the increasing utility costs will diminish their advantages.

LED light sources have already demonstrated many advantages over other types of light sources. For instance, LED light sources appear to offer better visual comfort, have a higher efficacy, longer lamp life, and the least negative environmental impact than other light sources.

Reliability of Published data

In most cases, published correlated color temperature data is reliable. Because the method of determining CCT involves the entire emitted spectrum of the light sources, no holes exist in this method. The lamps types are irrelevant because the emitted spectrum is the only information required. Therefore, CCT data is, without a doubt, genuine.

The published color rendering index data of lamps is generally obtained from testing target lamps by following *the IESNA's approved methods*. These methods are well-developed for incandescent and fluorescent light sources; the CRI scores of these lamps are directly linked to light that the emitted light is visually comfortable to human beings. Incandescent and fluorescent light sources that have high CRI scores usually have well-balanced and continuous spectrum power distributions. However, *the IESNA's approved methods* are not suitable for rating LED lamps because LED lamps can tune their emitted spectrum to perform well in rating tests and still appear visually inferior to human. *IESNA approved methods* had provided an improved testing method for LED lamps to increase the practical value of testing results; this improved version uses a 14-color sample as a testing template instead of the 8-color sample that is used for incandescent and fluorescent lamps. Unfortunately, the improvement is negligible. Many scientists and scholars have proposed some other testing procedures as a supplement to *the IESNA approved methods,* but none of these testing procedures are widely adopted. However, LED light sources can emit light that appears visually comforting to humans. Due to imperfections of the rating system, designers should consult not only the published CRI value, but also the SPD of LED light sources to decide if the light sources are suitable for specific projects.

The published efficacy and lamp life data of incandescent and fluorescent light sources are trustable. However, the data for LEDs has the same shortcomings as for CRI. Determining methods for incandescent and fluorescent light sources are impeccable, and many years of industry using experience proves they are precise and reliable. However, due to insufficient real life data and lack of lab experiments, the determining methods of efficacy and lamp life for LED light sources have very limited practical value.

When consulting the rated efficacy value, designers must understand that the rated value is obtained from lab testing results, and the lab testing results cannot represent their actual performance. Because of the heat dissipation issue, the real life efficacy of LED light sources may decrease up to 15% from their rated value.

When consulting the rated lamp life of LEDs, designers should always find out what level of output light depreciation is applicable. Some manufacturers consider that light sources' output depreciated to 70% of their initial value is the end of lamp life, and others use 50% instead.

The Best Light Sources for Achieving Visual Comfort

In this paper, visual comfort is defined as using an adequate lighting environment to help occupants reach their peak productivity and maintain their health. Studies show that human beings need to perceive light with different colors throughout the day to regulate their internal body systems. Human beings also rely on light with various colors and intensities to tune their nerve systems to the best state. For instance, men and women can reach maximum productivity in a "warm" color light environment; men favor warm colors for preserving a positive mood, while women like "cool" color light environments.

In order to achieve all the requirements that were mentioned previously, an office lighting system needs to be able to vary CCT level and intensity gradually based on time patterns or occupants' demands. Incandescent light sources cannot practically vary CCT level. Therefore, they cannot meet the requirements. Fluorescent light sources can only vary CCT levels at very narrow ranges, and they cannot vary CCT levels gradually. For this reason, fluorescent lights cannot be considered a practical choice either. LED is the only type of light source that is able to vary both CCT level and intensity gradually. Hence, LED light sources are considered as ideal light sources for office lighting systems.

Environment-Friendly Design

Environment-Friendly design of office lighting systems means designing systems with high efficiency and low negative environmental impact. Incandescent light sources have the lowest efficacy; fluorescent light sources have much higher efficacy; and LED light sources have the highest efficacy. However, the efficacy difference between fluorescent and LED light sources is not significant. Some high-quality fluorescent light sources even have a higher efficacy than LED light sources. According to statistic material from the U.S. Department of Energy, the average efficacies of current incandescent, fluorescent, and LED light sources are approximately 18 w/lm, 85 w/lm, and 106 w/lm (U.S. Department of Energy, 2014).

Even though fluorescent light sources have a similar efficacy to LED light sources, they still cannot be considered as a viable choice for environment-friendly designs. Fluorescent lamps contain the heavy metal mercury; disposal of fluorescent lamps will cause severe environmental pollution. Moreover, recycling fluorescent lamps is a very complicated process; only 20% of discarded fluorescent lamps are recycled yearly. In comparison, LED light sources contain no hazardous material, and they present almost no threat to the environment.

As LED light sources have the highest efficacy and least environmental pollution, they will be considered the ideal light sources for environment-friendly design.

Costs

Costs of lighting systems include initial costs and life-cycle costs. Incandescent light sources have the lowest initial costs, those of fluorescent light sources are slightly higher, and LED light sources have the highest initial costs. IESNA's report shows that the lumen costs of incandescent, fluorescent, and LED light sources were 1.5 $/klm, 1.7 $/klm, and 5 $/klm by the year 2012. The lumen costs of incandescent and fluorescent light sources are similar, but those of LED light sources is almost four times that.

Because incandescent light sources have the lowest efficacy and lamp life, their life cycle costs usually are the highest. LED light sources appear to have a much longer lamp life than fluorescent light sources. However, fluorescent light sources have decent efficacy and low initial costs. For these reasons, fluorescent lighting systems still have the lowest life cycle costs in most cases. However, Haitz's law and many other scientists' theories predict that costs of LED light sources will keep decreasing and electricity costs will keep increasing. LED light sources will be the most economical type of light sources in the near future.

Drawbacks of LED Light Sources

LED light sources have two unique drawbacks, which are narrow photometric distributions and heat-dissipating issues. However, effective remedies are already available for these drawbacks.

The drawback of narrow photometric distributions is caused by LED modules emitting light in only one orientation. Manufacturers usually solve this issue by adding diffuse lenses for the light sources. This method is proven to be the most effective solution.

Because a high operating temperature will severely decrease the efficacy and lamp life of LED light sources, heat dissipating issues cannot be neglected. Manufacturers generally design a dedicated thermal management system for every LED module for heat dissipation. For most cases, the dedicated thermal management system can keep the LED light sources operating at their optimum performance.

Overall Summary

Overall, LED light sources have already demonstrated their superiority over incandescent and fluorescent lamps in maintaining visual comfort and environment-friendly designs. They also show a potential to be the most economical light source in the future. LED light sources can be the primary light source for office lighting system applications.

Future Study

The coloring rendering index of LED lamps is always questionable because the current worldwide adopted rating systems are not sufficient for LED lamps. Many scholars and researchers have proposed alternative rating methods in addition to the current method. However, none of these methods have gained global agreement and recognition. Future studies are required to find out the most appropriate CRI rating method.

The rated lamp life is also questionable for LED lamps. The reason is that the lamp life of LED lamps vary based on their operating environment; at the same time, no standard rating environment is set up as the industrial standard. Moreover, no industrial standard for the end of lamp life is defined. Future studies are required to discover the most appropriate definition of the end of lamp life and the rating environment.

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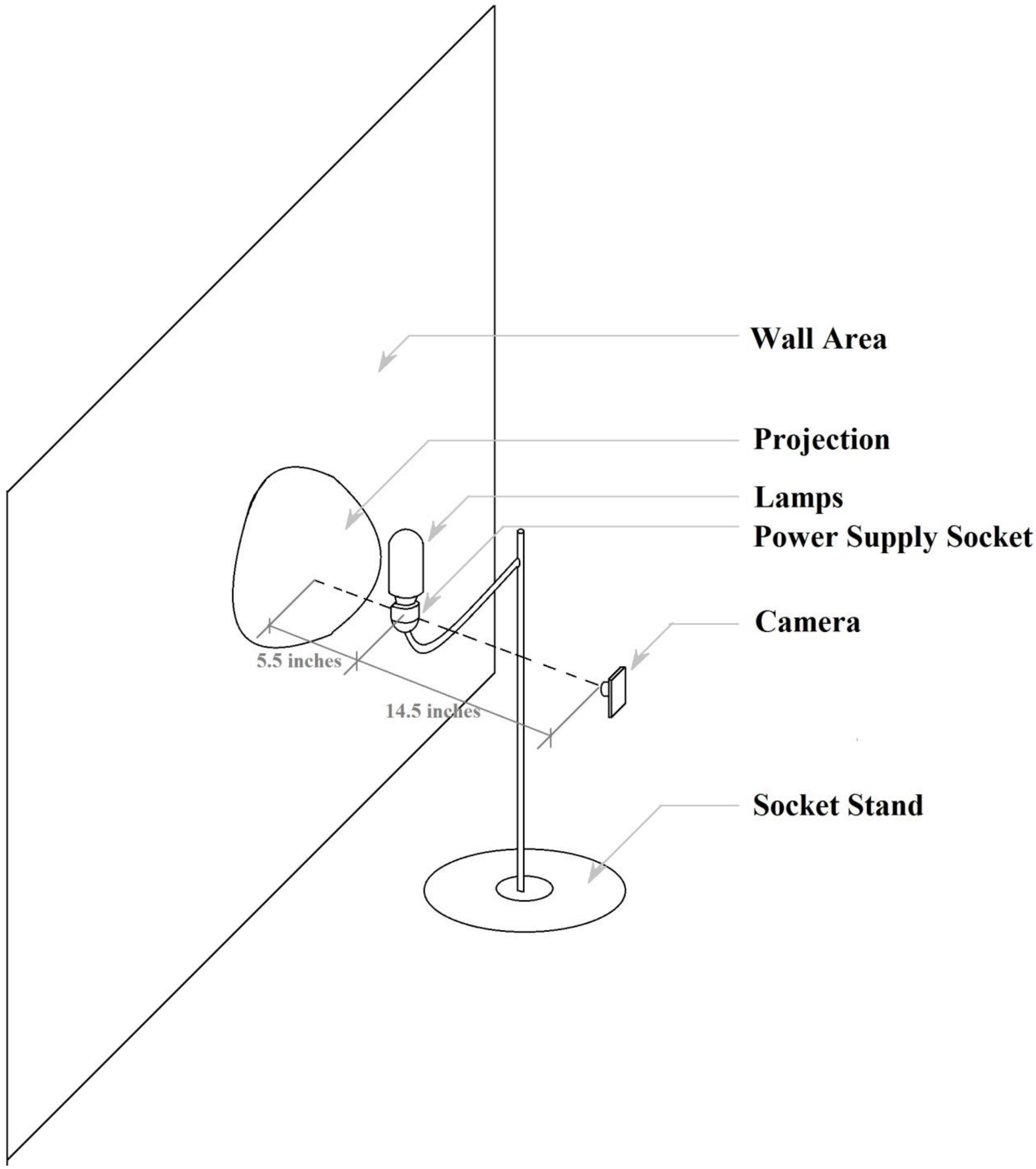
Appendix A-Visual Experiment Set-up



Appendix B-Cut Sheet, Visual Experiment Lamp 1

Titan 7LEDB

Brand	Titan LED
Item Weight	0.3 ounces
Product Dimensions	3.8 x 3.8 x 3.3 inches
Item model number	7LEDB
Shape	Bulb
Voltage	110 volts
Fixture Features	Instant on, Zero Mercury, Cool to the touch
Type of Bulb	LED
Base Type	E27
Wattage	0.45 watts
Incandescent equivalent	15 watts
Bulb Features	Instant On
Bulb Length	3 inches

Appendix C-Cut Sheet, Visual Experiment Lamp 2

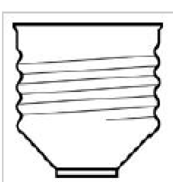
GE
Lighting

68015 - LED11DA19V-W/TP

GE LED 11 watt A19 1-pack

- The future of lighting is here. Unlike standard incandescents, GE energy smart LED general purpose bulbs last up to 15,000 hours--more than a decade at 3 hours per day use and equal to 15 incandescents. They also use 75% less energy, making them a brilliant idea for your budget. And, GE energy smart® LED bulbs provide soft white light instantly while fitting in many of the same fixtures as standard incandescent bulbs. Make the change to GE energy smart® LED general purpose bulbs today.
- Lasts 13.7 years based on 3 hours per day usage
- Estimated yearly energy costs $1.32 based on 3 hours per day $0.11 per kWh
- $81 in energy savings over the life of the bulb based on 3 hours per day usage
- A19 shape with medium base for use in table lamps

This product is no longer manufactured. Remaining stock will be sold.



GENERAL CHARACTERISTICS

Lamp Type	Replacement Lamps - A-line
Bulb	A19
Base	Medium Screw (E26)
Additional Info	White, Semi-Omni
Bulb Shape	A-19
Color	White
Dimming Capability	Operates on dimming circuits. See GELighting.com/dimming for further information
Equivalent Wattage (NOM)	65.0 W
Lamp Type	A-19
Life in Years (NOM)	13.7
Rated Life (NOM)	15000.0 h

PHOTOMETRIC CHARACTERISTICS

Color Rendering Index (CRI) (NOM)	80.0
Color Temperature (NOM)	2700.0 K
Initial Lumens (NOM)	800.0
Lumens per Watt (Efficacy) (NOM)	73.0 lm
Nominal Initial Lumens per Watt (NOM)	72.72727

ELECTRICAL CHARACTERISTICS

Estimated Energy Cost per Year (NOM)	1.32
Voltage (NOM)	120.0
Wattage (NOM)	11.0

DIMENSIONS

Bulb Diameter (DIA) (NOM)	2.375 in(60.3 mm)
Maximum Overall Length (MOL) (NOM)	4.430 in(112.5 mm)

PRODUCT INFORMATION

Product Code	68015
Description	LED11DA19V-W/TP
Standard Package	00-Case
Standard Package GTIN	10043168680155
Standard Package Quantity	3
Sales Unit	Unit
No Of Items Per Sales Unit	3
UPC	043168680158