LIGHTING: FUNDAMENTALS, PRACTICE, AND INTEGRATED SYSTEMS

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Keywords: Daylighting, Efficacy**,** Electric lighting, Energy, Fenestration, Fluorescent, Illuminance, Incandescent, Lighting, Luminance, Mesopic vision, Metal halide, Photopic vision, Scotopic vision, Sustainable, Visible spectrum, Watts

Contents

Summary

Lighting—the presence of light, the design of light, and the system of installed light. This chapter discusses these various aspects of lighting. Light is the great enabler. It profoundly influences health, wellbeing, and productivity. When used properly, designed properly, and/or installed and maintained properly, lighting will not burden our energy infrastructure and Earth's environment. Fundamentals of light and vision are introduced as a foundation for appreciating design decisions and use patterns. Key design parameters of illuminances, luminances, color characteristics, energy, costs, and maintenance are discussed and put into relative context. Throughout, footnote references are added where technical and research details may be of interest, particularly on aspects that heretofore were considered simply aesthetic in nature. A

short bibliography includes texts on the broader topics of lighting design, lighting engineering, daylighting, and facility management.

Architecture is an, if not the most important, integral component of lighting. Geometry and function of spaces, finishes of room surfaces, and number, position, and orientation of daylight apertures influence efficiency and integration of lighting. These aspects are reviewed along with the basic mechanics of electric lighting—lamps. The most efficient white–light lamps are advanced for respective applications.

Practice trends are presented in the form of do's/don't's checklists. Based on the discussions of design parameters and architectural aspects of light, concise practice suggestions are made for residential, hospitality, work, and institutional situations.

1. Introduction

Light is sustenance. It feeds our plants and animals, our bodies, minds, and souls. It nearly single-handedly gives people the potential to do most anything – from recognition to reading and writing to precisely articulateing body movements that constitute life, art, and work. As much as light contributes to our way of habitation, it is wreaking havoc on our planet. Poorly planned daylighting and electric lighting, misguided lighting criteria and inappropriate priorities, and misunderstanding of the principles of light and vision, result in misuse of our natural resources and lead to greater air pollution and greater landfill burden.

So it is then, that an appreciation of the fundamentals of light and vision is necessary when making decisions about lighting, lighting design, and lighting systems. Here, fundamentals are reviewed and references for additional information are cited. The practice of lighting design is introduced here as a means of addressing a multiplicity of requirements, not just limited to simplistic illuminance (lux) requirements. However, an understanding of the lighting fundamentals and knowledge of lighting practice cannot assure a situation that meets the needs of the human physiological and psychological condition while minimizing the impact on planet earth's condition. The architectural setting in which lighting is placed will affect its benefits, and may erase them. Room finishes, geometry, configuration of furnishings, and integration or lack thereof with other building systems greatly influences the success of any lighting design.

Vision is experienced when light (wavelengths of energy from about 380 nm to about 770 nm) reflects from objects and/or transmits through transparent or translucent objects, impinges on the retina of a sighted person, and, finally, stimulates brain activity culminating in recognition.(Gary Steffy, 2002) Figure 1, illustrates the visible spectrum within the context of the electromagnetic spectrum. A small but extremely significant portion is visible to humans. This is highlighted at 10^{-6} meters (visible radiation is typically reported in nanometers, or 10^{-9} meters—so 700 nm (deep red) is also 700×10^{-9} meters or 0.7×10^{-6} meters). These wavelengths are natural phenomena that can be created by the sun (directly [solar disc], semi-directly [partly cloudy and cloudy conditions], or indirectly [moonlight]) or by light sources fashioned by humans (flame [from wax, wood, gas, animal-fat or oil sources] or electric [from wind, solar, water, oil, coal, gas, or nuclear sources]). Several aspects of light greatly influence its success – color qualities, intensity, and distribution. The color qualities and intensity of light primarily influence visibility – how well people see. Distribution of light influences comfort and subjective impressions – how people feel.

The relative strength of various wavelengths results in very significant color shifts of light, influencing color temperature (whiteness) and color rendering. When all wavelengths are present (reasonably evenly distributed from 380 nm to 770 nm) or when reasonably equitable shares of three key wavelengths—short (blue), medium (green/yellow), and long (orange/red) wavelengths—are present, white light results. A preponderance of shorter wavelengths (380 nm to about 550 nm) results in cooler-toned light. High concentrations of wavelengths of the midrange (550 nm to 600 nm) yield neutral white light.

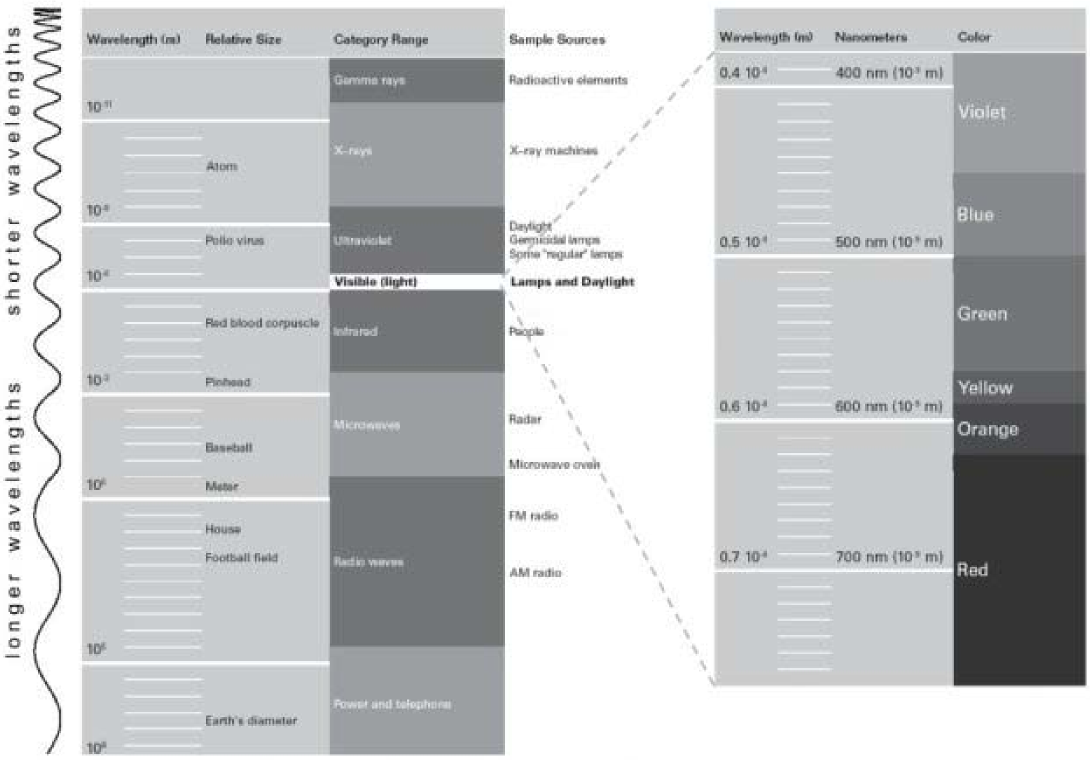

Figure 1: The electromagnetic spectrum is diagrammatically represented here. Resource: Electromagnetic Spectrum Chart, The Exploratorium (http://www.exploratoriumstore.com. © and excerpted with permission from Architectural Lighting Design, 2nd edition published by John Wiley & Sons, Inc.].

Finally, concentrations of longer wavelengths (600 nm to 770 nm) yield warmer-toned light. Whenever just a narrow band of wavelengths is present (e.g., only 500 to 550 nm), light sources are considered monochromatic, and exhibit undesirable light that renders nearly all surface colors poorly. So, light source selection should include an assessment of color characteristics, typically qualified by CRI (how well a particular light source renders or "brings out" the colors of materials and skintones, rated on a scale where 100 is best) and color temperature (how cool, neutral, or warm the light source appears when energized, rated on a scale of absolute temperature, K or Kelvin). Light sources that produce other-than-white light (e.g., shades of yellow, orange, or blue) and light sources that render colors strangely result in user dissatisfaction for all but entertainment applications.

Research indicates that light sources with some measure of shorter (bluer) wavelengths yield better vision in the low light situations that one might encounter outdoors after sunset (Yunjian He, et. al.,(1996), Alan L. Lewis, (1998), Alan L. Lewis, (1999), Yukio Akashi and Mark Rea, (2002)). So much so that the yellow pall of the ubiquitous roadway high pressure sodium lamps (with a color temperature of about 2100K) can be shown to be a quarter to half as efficient as the light from white-light lamps (3000K or greater) in nighttime exterior settings. The energy and safety/security ramifications are significant. Either a reduced light level (*As measured with a meter exhibiting a spectral response based on the CIE photopic standard observer curve.*) from white-light lamps suffices (with a corresponding reduction in energy use) or changing to white-light lamps of equal wattage increases the apparent light level (without any increase in energy use). So, in exterior lighting situations where any sort of people activity is expected to occur, higher color temperature lamps (lamps with some measure of shorter wavelengths) seem better.

Light sources with some measure of shorter (bluer) wavelengths have also been shown to influence vision in low-to-moderate light situations that one might encounter in some interior settings, including some offices (S.M. Berman, (1992),S.M. Berman, et. al., (1992),Mojtaba Navvab, (2002)). Here, higher color temperature lamps appear to influence visual clarity or crispness of objects, and also appear to influence the sensation of brightness. Bluer light evokes an improved sense of clarity or crispness and a perception of greater brightness. So, in interior lighting situations where visual clarity and/or a perception of greater brightness are desired, higher color temperature lamps seem better.

For most applications interior or exterior, a general rule is to look for lamps that exhibit CRIs of 70 or greater, and that exhibit a color temperature in the range from 2700K to 4100K. Such lamps offer greatest color clarity and contrast, produce a color of light that is considered pleasing and acceptable by most people, and generally exhibit the best efficacies. Lamps with poorer CRI and out-of-range color temperature characteristics may result in less comfortable, less attractive, and less productive settings, which, indeed, are a waste of earth resources (used in making such lamps and all of the architectural materials and furnishings), financial resources (used in buying the lamps and their luminaires, buying the architectural materials and furnishings, and paying people to work, if a workplace), and energy (since user dissatisfaction might be expected to result in lower productivity, more energy may be expended to achieve an equal level of performance).

More research remains, however. For example, there is some concern that lamps exhibiting color temperatures greater than 3500K may adversely impact thermal comfort. The cooler-toned light may cause users to feel a bit cooler than the actual ambient temperature (F.H. Rohles, et. al.,1981). At these higher color temperatures, users may be reminded of less-comforting institutional places. In interior settings where people are more likely to spend much of their time, visibility benefits teased from lamps exhibiting color temperatures greater than 4100K may be offset by these possible shortcomings, and by the lower efficacy of most lamps exceeding 5000K.

Light intensities influence how well people see. Generally, older populations (over 40 years of age) require more light for seeing. Because of their inherent character, some tasks require more light for seeing. For example, where typewriter ribbons, printer ribbons, or printing presses are poorly maintained, or where low contrast paper (e.g., darker colored paper or gray paper) is used in preparing material, more light will likely be necessary to read the material at an acceptable level of accuracy at a reasonable rate or speed. The energy impact could be significant. Properly maintaining printers, inks, ribbons, and/or using lighter colored papers, is preferable and more environmentally appropriate than expending more capital and energy to buy, install, and operate more lighting. So, changing the characteristics of the task may be easier and more environmentally sound than adding more light in order to better see a task.

Light intensities also influence people's biological cycles and health. Circadian rhythms and seasonal affective disorder (SAD) are related to light intensities and the duration of exposure to those intensities (Gary Steffy, (2002). The circadian rhythm is "set" when the eyes absorb light. Here, intensities of thousands of lux are necessary to trigger the circadian rhythm. However, the absence of light during the sleep period is just as important as the exposure to high doses of light during the wake period in order to maintain the rhythm. During the winter months, insufficient exposure to high doses of light during the wake cycle can result in SAD. Treatment is generally successful where patients are exposed to high doses (up to 10,000 lux) for relatively short periods during the wake cycle. Of course, the most effective and sustainable method of introducing people to such high doses of light is through exposure to high intensities of daylight for at least 30 minutes a day. It is important to reiterate that high doses of light are needed to affect people's health. Further, it is noteworthy that the spectral distribution of light has little effect on circadian rhythm and on SAD. Therefore, so–called full–spectrum lamps, particularly at normal room-lighting intensities, offer insignificant benefit, and may actually contribute to a waste of capital and energy resources (Jennifer A. Vietch, (1994).

Visibility achieved with light intensity and task characteristics is of little use if people do not wish to be in an environment. Lighting influences people's subjective impressions. How light is distributed throughout a space or an area influences how people feel in and/or react to the environment (John Flynn, (1973),Dale Tiller, (2002),Belinda Collins, (1993),John E. Flynn, et. al., (1973)). Here, too, the energy implications are significant. If lighting is uncomfortable or creates an undesirable setting, then the resources and energy used to manufacture, transport, install, and operate the lighting is mostly wasted. Generally, downlighting or direct lighting alone in any setting is undesirable. Here, the horizontal work and/or floor surfaces exhibit luminance while the other surfaces go dark, thereby creating a confined, cavelike effect. Adding some wall lighting, maintaining light colored surfaces, and/or using some uplighting introduce a sense of brightness in the fields of view of most occupants. These techniques also act to minimize the glare effects so prominent with downlighting.

2. Lighting Practice

Lighting is a design discipline and a building system – it is an art and a science. It is responsible in large part for how we interact with and respond to other people and our environment. For these reasons, the practice of lighting encompasses many criteria. The success of a lighting design is then dependent on the depth and breadth of criteria used in its planning and design. Simple one or two step processes that result in a regular array of cheap, glary lights cannot address all of the salient issues. Lighting criteria include illuminances, luminances, color characteristics, productivity and satisfaction, power/energy budgeting, initial and life‒cycle costs (including sustainability aspects), and maintenance (Eric Teicholz, ed.,2001). Understanding these and helping the client to prioritize these criteria are crucial to developing a lighting system that meets the needs of its users but also limits negative impact on our ecosystem.

2.1 Illuminances

Illuminances can be categorized as horizontal and vertical. Horizontal illuminances are those intended for horizontal planes, such as tables and desks, laps, and floors. Vertical illuminances are those intended for vertical planes, such as people's faces, objects of interest on walls, walls themselves, merchandise, and computer screens. Horizontal illuminances are responsible for visibility of tasks on horizontal surfaces, while vertical illuminances are responsible for visibility of tasks on vertical surfaces. Additionally, vertical illuminances are responsible for subjective impressions. In residential and hospitality settings, illuminances set the scene for leisure and social activities. In work settings, illuminances set the scene for productivity. Check national lighting standards, guides, and/or codes or guidelines of the Commission Internationale de l'Eclairage (CIE at http://www.cie.co.at/cie/) for specific illuminance criteria. Some guidelines offer ranges of illuminance for various tasks, where the lower end of the range is intended for younger people (typically under 40 years of age), the middle of the range is intended for middle‒aged people (typically 40 to 60 years of age), and the upper range is intended for older people (typically over 60 years of age). Where ranges are not provided, it is possible that the cited illuminances are intended for younger people (such should be confirmed) and, if this is the case, then consideration should be given to increasing the cited illuminance 50 percent for middle‒aged people, and to doubling the cited illuminance for older people (Gary Steffy,2002). Obviously this has significant impact on the size and cost of the lighting system, both initial and life‒cycle. So, carefully determining the intended users and their intended tasks is important.

2.2 Luminances

Luminances can be categorized based on the elements reflecting or transmitting light. Luminaire luminances are those emitted by the luminaire or luminaires in a space. Surface luminances are those emitted by walls, ceilings, art objects, desks, tables, windows, skylights, and the like. Luminaire luminances influence glare. If the solar disc or a luminaire is too bright, the effect is direct glare. If the sun or a luminaire causes extremely bright reflections from nearby surfaces, the effect is reflected glare. Surface luminances influence comfort and the degree to which daylight or luminaire luminances are problematic. For example, a bright luminaire viewed against the background of a black ceiling will create direct glare for most observers. The same luminaire against a white ceiling will create direct glare for fewer observers. In residential and hospitality settings, luminances set the scene for leisure and social activities. In work settings, luminances set the scene for comfort and productivity. Check national lighting standards, guides, and/or codes, or guidelines of the Commission Internationale de l'Eclairage (CIE at http://www.cie.co.at/cie/) for specific luminance criteria.

2.3 Color Characteristics

Discussed previously, color temperature and color rendering also influence how well people see. To promote a sense of normalcy, white light sources ranging from 2700K to 4100K are preferable and generally most efficacious. For tasks with any inherent color, visibility is enhanced when CRI exceeds 70. In residential and hospitality settings, light source color temperature of 2700K to 3200K and CRI approaching 100 set the scene for leisure and social activities. In work settings, color temperature can range to the upper end of 4100K and CRI can range to the lower end of 70 to set the scene for productivity.

2.4 Power and Energy Budgets

To limit electricity used for lighting, the power or watts required should be limited in absolute value and in duration of use. Daylighting should be explored as an alternative to some or all of the electric lighting for some or all of the time. Efficient, low–wattage lamps should be used. Conveniently located switches controlling lights in the immediate vicinity of a user or small group of users is preferable to centralized switches that control lighting over large areas. Photocells, motion sensors, and timeclocks can limit the duration of electric light use. Check national lighting standards, guides, and/or codes or guidelines of the Commission Internationale de l'Eclairage (CIE at http://www.cie.co.at/cie/) for specific power and/or energy budget criteria.

2.5 Initial and Life–cycle Costs

During any design effort it is common and necessary to fret over initial costs. However, too many times the effort to limit initial costs is the single most important priority and other criteria suffer. Of more concern should be life–cycle costs, or all of the costs associated with the manufacture, purchase, installation, operation, and disposal of the lighting. The capital expended and the impact on earth to make, transport, sell, install, replace, and then frequently recycle a cheap, screwbase, incandescent lamp are very likely greater than the capital expended and the impact on earth resources to make, transport, sell, install, and less–frequently recycle a more expensive low–mercury fluorescent lamp. Assuming equal light output from each lamp, the cheap incandescent lamp might have a rated life of 2000 hours and might require three times the power, while the low–mercury fluorescent lamp might have a rated life of 24000 hours. On average, twelve cheap incandescent lamps will have to be made, bought, installed, and recycled or disposed for every fluorescent lamp. Further, triple the amount of energy will be used to operate the incandescent lamp. Finally, each of these lamp types contains undesirable heavy metal. The screwbase incandescent lamp contains some amount of lead solder while the low–mercury fluorescent lamp contains some amount of mercury. To be fair, a complete scientific analysis of the glass, metal, gases, and/or coating components used in each lamp and the amount of energy required to actually extract from the earth the necessary raw materials and then to make those various components and an analysis of environmental impact of the creation of the energy used to operate the light is needed along with a study of the recycling possibilities and/or the landfill impact of disposing all of the materials.

2.6 Maintenance

Maintenance can foil plans and can fail a lighting system. Alternatively, maintenance can minimize the resources used for a lighting system. Systems that will be appropriately maintained require fewer lamps, ballasts, and luminaires to achieve criteria. Here, the degradation effects of dirt buildup on luminaires and room surfaces are kept at bay. The degradation effects of spent lamps not being replaced in a timely manner need not be addressed where maintenance programs are developed and followed. Proper maintenance can reduce installed lighting hardware quantities by as much as 10 to 20 percent, depending on agreed–upon cleaning cycles and spot and group relamping procedures. This can have a profound effect on sustainability. Group relamping is a fine balance between relamping maintenance costs, energy costs, lamp lumen depreciation effects, and recycling costs. However, to maximize in–service use and to blunt the effects of prematurely disposing of great quantities of lamps, group relamping is implemented when lamps have burned for 85 percent to 95 percent of rated life. Note, however, that spot relamping will be an ever–increasing maintenance requirement once lamps have reached about 70 percent rated life.

Designing lighting to be easily maintained at the expense of any of the other lighting criteria is counterproductive. Maintenance should be implemented to prolong and maximize benefits from any lighting system. Significant dirt build up on room surfaces and the lighting equipment directly affects illuminances and luminances and reduces efficiency. Not replacing failed lamps and/or ballasts also affects illuminances and luminances and reduces people's comfort and productivity. Disposing of lamps and/or ballasts in a haphazard manner or in small increments typically has a negative impact on the earth's environment. Recycling spent lamps, ballasts, and other components is recommended, if not a legislated requirement. Check laws or codes for specific recycling and disposal criteria.

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Biographical Sketch

Gary Steffy received a Bachelor of Architectural Engineering degree with emphasis in environmental systems from The Pennsylvania State University (1977). Mr. Steffy worked initially in research and development on integrated ceiling systems at Owens Corning Fiberglas. He later took a senior lighting design position at the architectural engineering firm of Smith, Hinchman & Grylls in Detroit, Michigan, USA. In 1982 he established his design consultancy in Ann Arbor, Michigan.

Mr. Steffy has taught lighting design classes at Michigan State University, The Pennsylvania State University, the University of Michigan, and Wayne State University. He has been involved in Illuminating Engineering Society of North America (IESNA) committee work, including its Technical Review Council. He is Lighting Certified by the (US) National Council on Qualifications for the Lighting Professions. He was president of the International Association of Lighting Designers for the 1988–1989 term.

Mr. Steffy's expertise is typified by lighting design for such national landmarks as the Michigan State Capitol, the Ohio State Capitol, and the State of Ohio Supreme Court. His contemporary design work includes lighting for corporate headquarters and campuses. He has authored three lighting texts, including the most recent and popular *Architectural Lighting Design* 2nd edition published in 2001 by John Wiley & Sons. He serves on the editorial board of LEUKOS, the Journal of the Illuminating Engineering Society of North America. He edited *A History of Light and Lighting* by Professor David DiLaura.

Mr. Steffy is a Fellow of the International Association of Lighting Designers. He received the IESNA Presidential Award and the Distinguished Service Award in 2006.