Lighting Fundamentals for the Undergraduate Science, Technology, Engineering and Mathematics (STEM) Student

Kevin B. Martin[1] and William J. Mills, III[2]

Department of Technology, Northern Illinois University, DeKalb, IL 60115 USA

[1] corresponding author Email: kbmartin@niu.edu Phone: 815-753-1345

[2]Email: wmills11@niu.edu Phone: 815-753-5366

ABSTRACT

Light is the most dominant human sense and plays a very important role in how humans perceive and interact in every environment. Numerous professions benefit from an understanding of the fundamentals of light due to the ubiquitous nature of light. This paper provides a set of engaged/active experiments to help students 1) gain an understanding of the proper measurement and interpretation of light data; and 2) determine the operational characteristics and capabilities of current commercially available lighting technology. The hands-on activities and provided questions for reflective thought result in the development of critical thinking skills regarding lighting issues. To fully prepare the student prior to the experiments, preparatory research questions and resources are also provided.

KEYWORDS

Spectral Power Distribution (SPD), Photometry, Photopic vision, Scotopic Vision, Color Correlated Temperature (CCT), illuminance

1. Background

A very simple definition of visible light (light) is “visually perceived radiant energy” (DiLaura D., 2011). It is important to note that the part of the electromagnetic spectrum visual to humans is a small section (400-700 nm) of the broad radiant energy range that includes X-rays, ultraviolent and infrared energy, micro-waves and radio waves (IOHA, 2010). Light is the most dominant human sense and plays a very important role in how we perceive and interact in every environment. Light which consists of shorter wavelengths appears violet while light with longer wavelengths appears red, with all other colors falling in between. Light which consists of all visible wavelengths in relatively equal intensities will appear white. However, there are numerous combinations of wavelengths which can produce white light with the same perceived shade. The color of an object can also appear to change depending on the spectral power distribution (SPD) illuminating its surface. For example, a blue shirt can appear black if a filter is used to remove blue from the light source. A related parameter to SPD is the correlated color temperature (CCT) ("Standard CIE S 017/E:2011 ILV: International Lighting Vocabulary.," 2011). The SPD of a blackbody radiator provides the basis for the simplified parameter which can be used to compare the visually perceived color (CCT) produced by light sources. The International Commission on Illumination (CIE) is the international standards setting body for lighting issues ("Standard CIE S 017/E:2011 ILV: International Lighting Vocabulary.," 2011). CIE has developed so-called “color spaces” or chromaticity diagrams that relate the human perceived color to wavelengths (or combinations of wavelengths) and include a black body radiator locus for comparison. The two major chromaticity diagrams in use today are the 1931 and 1976 versions (Schanda & Danyi, 1977). Several calculators/converters are available that allow the x,y,z coordinates for the CIE color space to be provided for a given CCT (Ledtuning.nl; Lindbloom).

One weakness of using a simplified approach in describing the color of a light is that numerous light sources with different SPDs can all have the same CCT although they would visually appear to be much different (Borbély, Sámson, & Schanda, 2001). Due to how simple tungsten filament incandescent lamps produce light, they are limited to producing light with a single yellow white CCT (2800K). Fluorescent lamps are commercially produced with approximately 4 different fixed, white CCTs which vary from a “warm” 3500K, “cool” 4100K, “bright white” 5000K, up to “daylight” 6500K. LED lamps are generally produced in either of two ways. The first method entails using blue LEDs coated in a phosphor which emits a yellow light when illuminated by some of the produced blue light. When the yellow light is combined with the remaining blue light from the LED, the mixture produces a perceived white light. The other method entails combining light from typically two LEDs in the case of white only color tunable lamps, or three LEDs (red, green, blue) in the case of color tunable lamps capable of producing nearly every color. It is important to note that even though a light source may appear white, the effects on the human body, including hormone levels and emotional state, may vary based on the actual SPD (T. Bedrosian & Nelson, 2013; Edwards & Torcellini, 2002; LRC, 2013; M. Rea, Figueiro, Bierman, & Hamner, 2012; M. S. Rea, 2011).

In the International System of Units (SI), the time rate flow of light is measured in lumens (lm) (BIPM, 2006) ("Lighting Terminology," 2009). One (l) lm is equal to one candela (cd) of luminous intensity uniformly across a solid angle of one steradian (sr). The lumen output of a light source will have only one value. The more commonly used parameter when specifying and measuring (also referred to as photometry) appropriate lighting conditions is illuminance, defined as the areal density of the luminous flux incident at a point on a surface. The SI unit for illuminance is the lux (lx). A lux is defined as 1 lm m^2. This is due to illuminance being more easily measured in the field. The measurement of lumens for a light source (and thus lux) also takes into account the human eye’s response (luminosity function) to the spectrum produced by the light source. CIE has established two luminosity functions that are commonly used to measure human eye response (Roufs, 1978). The photopic (P) luminosity function approximates human eye response primarily from the three types of cones in the human eye and has a peak relative sensitivity at 555 nm. The scotopic (S) luminosity function takes into account the contribution from the rods in the human eye and has a peak sensitivity at 498nm. Plots and tables of luminous efficiency functions have been plotted and made available by the Colour and Vision Research Laboratory (CRVL). Standard CIE S 017/E:2011 published by CIE, is the International Lighting Vocabulary (ILV) ("Standard CIE S 017/E:2011 ILV: International Lighting Vocabulary.," 2011). Several easy to use and more understandable websites are available for general lighting terms and principles including the Lighting Research Center (LRC) ("Lighting Terminology," 2009), J.W. Speaker("5 Lighting Terms You Should Know," 2014), Lowell (Lowell, 2008), Regency Lighting (Lighting, 2017) and the Illuminating Engineering Society (IES) (IES, 2017).

In the United States (US), artificial lighting represents about 8% of all electricity usage (USEIA, 2017). Light exposure (or lack thereof) has been shown to have positive and negative effects on biota (including humans) (OED) physiology and performance (LRC, 2013). For example, lower than optimal exposure to light can cause eye strain, affect mood (T. Bedrosian & Nelson, 2013), and harm plants (CCOHS, 2017; "Light and Moisture Requirements For Selected Indoor Plants," ; Trinklein, 2016). Over exposure to light can cause sleep disturbances (T. A. Bedrosian, Fonken, & Nelson, 2016; Dominoni, Borniger, & Nelson, 2016), circadian rhythm disruption (including an associated increase in certain cancers) (Davis, Mirick, & Stevens, 2001; Erren et al., 2010; Fritschi, 2009; Kantermann & Roenneberg, 2009; R. G. Stevens, 2009; Richard G Stevens, Brainard, Blask, Lockley, & Motta, 2013), increased light pollution (Contín, Benedetto, Quinteros-Quintana, & Guido, 2016; Kocifaj & Aubé, 2014; Luginbuhl, Boley, & Davis, 2014; Olsen, Gallaway, & Mitchell, 2014; Pun, So, Leung, & Wong, 2014), and wastes energy (Ho, Lin, & Huang, 2012; Sánchez de Miguel, Zamorano, Gómez Castaño, & Pascual, 2014).

The ubiquitous nature of light results in various professions benefitting from at least a minimum level of basic knowledge of the properties of light and artificial lighting technologies. Specifically, natural science professionals, environmental health and safety (EHS) managers, environmental scientists, energy engineers, architects, and building management majors may utilize or manage lighting as part of their job responsibilities. It is important that these professionals have some understanding of the nature of visible light, how to measure it and limitations of some parameters and restrictions of current standard (i.e., photopic) light meters (or photometers).

To help develop a basic understanding of light basics, student preparatory questions and five laboratory exercises are provided so that students can perform applied experiments to 1) gain an understanding of the proper measurement and interpretation of light data; and 2) determine the operational characteristics and capabilities of current commercially available lighting. In order to ease the incorporation of lighting basics into an established curriculum, materials and methods for the construction of a low cost experimental setup are also provided.

2. Benefits of Engaged Learning

Many educational institutions have historically used lecture based learning for the bulk of their science and engineering courses (Freeman et al., 2014). However, there is strong evidence that lectures are often not the most effective way for students to learn. As an example, a recent article included an illustration with a painting of a lecture (from *the 1350's!)* that showed students in varying degrees of dis-engagement from the lecture (Reese, 2013). Finkel's conclusion is that "What is transmitted to students by lecturing is simply not retained for any significant amount of time" (Finkel, 2000). Numerous studies and publications have shown a need for a more learning-centered basis of teaching (Ambrose, Bridges, DiPietro, Lovett, & Norman, 2010; Bransford, Brown, & Cocking, 1999). Studies such as those from the National Survey of Student Engagement's (NSSE) (Kinzie, 2017; Kuh, 2001, 2003; "NSSE Findings,") have emphasized the need for student engagement. The use of engaged (or active) learning in the sciences, engineering and technology has shown an increased retention of subject material and improvement in critical thinking skills compared to lecture based learning (Freeman et al., 2014).

Several experiments emphasizing student engagement that have been developed and used by the authors at Northern Illinois University (NIU) to teach lighting basics are provided. These experiments utilize engaged/active and cooperative learning techniques through preparatory research, utilizing hands on activities (experiments) and providing questions for reflective thought (analysis). All of these steps result in the development of critical thinking regarding lighting issues.

3. Preparatory Research

The authors recommend requiring the students to perform some preliminary research on lighting issues prior to performing the experiments. When students have performed the experiments without preparation it has been found that they often worked inefficiently and had to repeat work. The preliminary research can incorporate the use of educational institution or public library resources and resources generally available via the internet. For the use of the internet, the authors have found that it is important for students to understand the difference between primary (RUSA, 2015) and secondary sources (SCC), as well as exhibiting some critical thinking as to the reliability of the internet source. The following list covers the preliminary research that we ask the students to perform on an individual basis prior to the laboratory.

1. Perform a web search for “the Pacific Northwest Tree Octopus”.
    a. What did you find?
    b. Do you think this website is reliable? Why or why not?
    c. What does this exercise tell you about information on the internet?
2. Perform web searches for the following organizations and briefly explore the website for information on light, lighting or photometry. We also request a specific website address for a specific topic. In order to reinforce the importance of exhibiting critical thinking, we require them to provide a proper scientific citation for the website requested.
    a. Lighting Research Center

        i. Lighting terms
    b. Bureau of International Weights and Measure
        i. Photometric units
    c. Canada Center for Occupational Health & Safety (CCOHS)
        i. Lighting /Lighting ergonomics
    d. National Institute for Science and Technology (NIST)
        i. Photometry
    e. Illuminating Engineering Society (IES)
        i. The Lighting Handbook

3. Using library and internet resources, answer the following questions:
    a. What is the Electromagnetic spectrum?
    b. What is visible light?
    c. Lighting terms and Units of measurement
        i. What is Illuminance? What is the SI unit for this?
        ii. What is the Lumen? What is it a measure of?
        iii. What is Spectral Power Distribution? What is an example of this?
    d. What is difference between scotopic and photopic vision?
    e. Provide a basis for each of your answers. What is your source of information? Why do you consider it reliable?
4. Using library and internet resources, look up SPD examples for
    a. Sunlight
    b. High pressure sodium (HPS) lamps
    c. What is your source? Why do you consider it reliable?
5. Using library and internet resources, answer the following questions:
    a. What is biota? What is your source?
    b. What are some health effects of lighting on biota for the following:

   i. Low light level (provide at least 3, with proper scientific citation for each)
   ii. Light during day (provide at least 3, with proper scientific citation for each)
   iii. Light at night (provide at least 3, with proper scientific citation for each)

c. What is light pollution? Why should we care?

4. Experimental Setup

The required equipment to complete the experiments is provided in Table 1.

Table 1: Required Experimental Equipment

Dimmable Compact Florescent Lamp (CFL)	Adjustable Arm Lamp Base (luminaire) with Dimmer Switch	Standard "Photopic" Light Meter (photometer)
Dimmable Single CCT Light emitting diode (LED) Lamp	Inline Electricity Monitor	Hand Held Spectrometer
Dimmable RGBW LED Lamp	Ruler (in cm)	Dark Box

To reduce barriers for adoption, the provided series of experiments utilizes a low-cost setup consisting of residential scale equipment. The CFL and LED lamps can be obtained at various consumer retailers along with the inline electricity monitor (e.g., Kill-A-Watt® or Watts-Up? electricity monitors). The specific selection of the red, green, blue, white (RGBW) LED lamp will depend on the control system selected for the lamp. Such lamps can be controlled either using a specific remote or through various communication hubs. The hubs are connected to the internet which receive commands via an app on a smartphone or tablet. The authors have used the Lightify® system from Osram. It is suggested that the single-color LED lamp be approximately equal to the CFL CCT value.

A suggested construction method for the dark box entails using foam board panels (90 cm x 120 cm) covered in black felt attached to a wood frame using velcro^{tm}/staples/nails. Black felt, which can be purchased at an arts and crafts store, provides a nearly non-reflective surface which aids in the directionality measurements. The combination of foam board and black felt also creates a medium which blocks external light from entering the measurement chamber.

A low-cost, standard light meter which does not have a cosine correction filter (e.g. LX-1010B) and a spectrometer light meter capable of visually demonstrating the spectral power distribution (SPD) and provide both the scotopic and photopic illuminance are also required. A "cosine correction" feature which consists of a diffuser which is placed over the sensor and filter which corrects the angle of collection is essential (e.g., Gigahertz-Optik BTS256-E). Prior to the laboratory, students are provided with background material on the basics of light and lighting terms and perform some preliminary research on the topic. The authors have found that a short quiz prior to beginning the laboratory is often helpful as a motivation for the students to properly prepare for the laboratory experiments. The authors have found that running the experiments with groups of 2-4 students provides an optimum size for cooperative learning to take place.

5. Description of Experimental Studies

5.1. Experiment 1: Lighting measurement techniques

Learning Outcomes: To understand the differences between light meter types by investigating cosine theta correction and reviewing the spectral power distributions of various light sources.

Background: Light meters are used to confirm that lighting requirements are met prior to occupation of a building or usage of an outdoor space. They are also routinely used to audit lighting systems for lighting performance and to optimize light levels to reduce energy consumption while meeting regulations or other targets (e.g., optimal lighting conditions for agriculture or productivity for certain work tasks). Most industrial light meters utilize silicone photodiode sensors as the measuring element. Photodiodes are photovoltaic cells which generate a current proportional to light exposure. As photons of light strike the diode, electrons are created which flow towards the cathode creating a photocurrent. As more photons strike the diode, a higher total current occurs. The current is converted to a light corresponding measurement with a selected unit. The design of many light meters forces the light to enter the meter at the incorrect angle which can cause measurement errors of up to 25%. Light at the point of measurement should be proportional to the cosine of the angle at which the light is incident.

Procedure:

1. Setup the adjustable arm luminaire with a CFL lamp, connected to the electricity monitor, in the dark box.
2. Initially set the lamp to “off” and place the standard (photopic) light meter directly under the lamp (e.g., lamp is at 90^o to light meter sensor) at approximately 30 cm (measure with a ruler or tape measure). If the light meter being used is capable of being operated remotely (via wired or wireless interface), the dark box can be closed off with a foam panel lined with black felt. The authors use a simply velcro^{tm} closure. If this is not possible, the authors recommend dimming lights as much as possible and turning the dark box away from any remaining light sources (windows, lights, etc.) where possible.
3. Measure and record the background illuminance in lux.
4. Set the dimmer at 100% (i.e., full) power and measure and record the illuminance in lux (lx) and power demand in watts (W).
5. Keeping the light meter in the same location below the lamp, tilt the light meter sensor to approximately 45 degrees relative to the direction to the lamp. Measure and record the illuminance (lx).
6. Repeat steps 2, 3, 4, 5, but use a spectrometer. If the spectrometer has the ability to provide scotopic and photopic lux, these should be recorded.
7. Repeat steps 1-6, but use the single CCT LED (note: of approximately same CCT as the CFL).

8. Repeat steps 1-6, but use the RGBW LED set at green color and adjust the CCT to approximately same CCT as the single-color LED and CFL value.

Analysis:

1. How did the measurement of the light levels change between background (0%) and full (100%) power on the dimmer?
2. Calculate and compare the lux/watt values for the three different lamps. Which one appears to provide the highest value for this ratio?
3. How did the measurement of the light levels change as you rotated the standard light meter?
4. How did the measured light level and spectrum change as you rotated the spectrometer?
5. Was there a significant difference in behavior between the meters?
6. Plot the spectral power distribution (SPD) for the CFL, single CCT LED, and RGBW LED using MS-Excel^{tm}.
    a. How do the SPDs compare with each other?
    b. With other published SPD?

5.2. Experiment 2: Light Intensity and Distance

Learning Outcomes: To understand the relationship between light intensity and distance.

Background: As the distance between an observer and a light source changes, the intensity of incident light from the source adjusts as the total amount of light is dispersed over a changing area. The incident intensity or brightness of light as a function of the distance from the light source follows an inverse square relationship. Therefore, as the distance doubles, the light intensity decreases to one-fourth of the original value. Consider a light bulb centered inside a balloon; as it is being inflated, the amount of light produced is being spread over an ever-larger amount of area. As the area of the sphere is calculated by Equation 1,

$$A = 4\pi r^2 \quad \text{Equation 1}$$

by doubling the distance r between the balloon surface and the light bulb, the surface area has increased by four times. The same amount of light spread over an area four times greater results in each unit of area receiving one-fourth the intensity as before.

Procedure:

1. Setup the adjustable arm luminaire with a CFL lamp in dark box.
2. Set the dimmer at 100% (i.e., full) power and place the standard light meter directly under the lamp at approximately 15 cm (measure with a ruler or tape measure), measure and record the illuminance in lux.
3. Repeat step 2 for the CFL at 30 cm.
4. Repeat step 2 for the CFL at 45 cm.
5. Change the CFL to the single CCT LED or RGBW LED. Set the dimmer at 100% (full) power and place the standard light meter directly under the lamp at approximately 15 cm (measure with a ruler or tape measure), measure and record the illuminance in lux.
6. Repeat step 5 for the LED at 30 cm.
7. Repeat step 5 for the LED at 45 cm.
8. (Optional) repeat steps 5-7 for the second type of LED lamp.

Analysis:

1. Plot the intensity versus the distance and confirm the inverse relationship.
2. Is there a difference in the relative reduction between the lamp types?
3. How do you think the relationship would change if the light meter was moved along an axis perpendicular and near the center of a linear fluorescent lamp?

5.3. Experiment 3: Directionality of various lighting technologies

Learning Outcomes: To understand the directionality of various light sources.

Background: Lighting has a wide variety of sources including incandescent, LED, fluorescent, and many other types. Although light emitting diodes (LEDs) are not inherently directional, they are typically manufactured to produce a directional light beam which can be utilized to illuminate only select areas, reducing wasted light. Incandescent and fluorescent lamps produce light in an omnidirectional manner which typically results in the use of a fixture housing or reflector to direct the light beam to the specified area. However, much of the light can be lost within the luminaire, escape in an unwanted direction, or even be reabsorbed by the lamp. Certain LED replacement lamps attempt to mimic the light encompassing nature of more traditional lamps (e.g., incandescent, metal halide, sodium vapor) by encapsulating the LED(s) in a globe or producing a “corn cob” lamp with LEDs packaged along the perimeter of a cylinder. However, lighting designers are increasingly utilizing the directional nature of LED lighting to reduce the installed wattage of lighting to meet regulations and reduce light pollution.

Procedure:

1. Setup the adjustable arm luminaire with a CFL lamp in the dark box.
2. Place the standard light meter directly under the lamp at approximately 30 cm (measure with a ruler or tape measure). This is the 0-cm position.
3. Set the dimmer at 100% (i.e., full) power and measure and record the illuminance in lux.
4. Move the standard light meter 15 cm to the right side of the lamp measure and record the illuminance in lux. This is the +15-cm position.
5. Move the standard light meter 30 cm to the right side of the lamp measure and record the illuminance in lux. This is the +30-cm position.
6. Move the standard light meter 15 cm to the left side of the lamp measure and record the illuminance in lux. This is the -15-cm position.
7. Move the standard light meter 30 cm to the left side of the lamp measure and record the illuminance in lux. This is the -30-cm position.
8. Repeat steps 1-7 using the single CCT LED.

9. (Optional) If it is possible, safely remove any optical globe on the LED lamp to expose the LEDs and repeat the measurements.

Analysis:

1. Plot the measured light intensity from -30 to +30 cm for both the CFL and single CCT LED lamp.
2. How does the directionality of the two lamps compare?
3. If it was possible to safely remove any optical globe on the LED lamp and repeat the measurements, how did the results change?

5.4. Experiment 4: The relationship among dim level, light output, and power usage

Learning Outcomes: To determine how LEDs and CFLs behave at reduced power levels.

Background: The ability to reduce the amount of light produced by a luminaire has many advantages including: energy savings, increased visual task performance, enhanced ambience, fewer light sources to specify/maintain/stock, enhanced space flexibility and satisfaction, demand response load shedding, and potentially improved light source efficacy and lifetime. LEDs are typically supplied power through a driver which adjusts to changes in the electrical properties of a LED as its temperature changes. Drivers can either provide a constant current or constant voltage. Constant current drivers provide more consistent brightness and avoid providing currents beyond the specified maximum, avoiding burnout and thermal runaway. Constant voltage drivers are a more common and lower cost technology but must be used with LEDs which have a current-limiting resistor in line. Although LEDs are inherently dimmable, doing so changes the behavior of the driver and the LED.

Procedure:

1. Setup the adjustable arm luminaire with a CFL lamp, connected to the electricity monitor, in the dark box and place the standard light meter directly under the lamp at approximately 30 cm (measure with a ruler or tape measure).

2. Set the dimmer at 100% (i.e., full) power and measure and record the illuminance in lux and power demand in watts.
3. Measure and record the illuminance in lux and power demand in watts for 75%, 50%, 25%, 10%, 0 dimmer settings.
4. Repeat steps 2 and 3 using the single CCT LED (note: of approximately the same CCT as the CFL).
5. Repeat steps 2 and 3 using the RGBW LED set at green color and adjust the CCT to approximately the same CCT as the single-color LED and CFL value.
6. Repeat steps 1-5 using a spectrometer and record the SPD or, in the alternative, the wavelengths for the five most intense peaks.

Analysis:

1. Graph the power demand versus percent dim level for all lamps.
2. How are the trends different?
3. Calculate the lux/watt ratio for each dimness value for both the CFL and LED.
4. Graph the calculated values versus the percentage dim value.
5. Describe the trends.

5.5. Experiment 5: Advanced Energy Efficiency

Learning Outcomes: To understand the relationship between power demand and visually effective lux for various CCT and dimness combinations.

Background: Many building energy efficiency codes specify or recommend a maximum wattage per area. However, lighting designers have the flexibility to specify how to meet project requirements while complying with government regulations. Currently, the lighting industry is mass adopting LEDs to meet regulations as the cost has dropped significantly, while concurrently their efficacy (lm/W) has increased over the last few years. Additional energy efficiency and benefits can be realized by using human-centric lighting which considers how light is interpreted and perceived by humans. The human eye consists of rods and cones which respond to the visible light with varying intensity based on wavelength. Rods in the retina have a much higher absolute sensitivity to light with a peak response to shorter wavelengths of light in the visible blue region. These attributes also allow rods to function in reduced light levels. Traditionally, measured light levels considered the response primarily from cones which have a peak sensitivity to yellow light. However, lighting designers are currently adopting spectrally enhanced lighting which varies the spectral power distribution and intensity of the lamp. The adjustment of the SPD allows the intensity to be reduced, resulting in a lower power demand while maintaining an environment which provides equivalent visually effective lumens (VEL).

Procedure:

1. Setup the adjustable arm luminaire with using the RGBW LED, connected to the electricity monitor, in the dark box and place the spectrometer directly under the lamp at approximately 30 cm (measure with a ruler or tape measure).
2. Set the dimmer at 100% (i.e., full) power and set the color to blue (if possible) and 3500 CCT (if possible) and measure and record the SPD (if possible) and Scoptic (S) and Photopic (P) illuminance in lux and power demand in watts.
    a. Calculate the Visually Effective Lux (VELx) using Equation 2 below:

$$\text{VELx} = P*(S/P)^{0.78} \quad \text{Equation 2 -from (Berman, 1992)}$$

    and record this.

3. Keeping the color set on blue, adjust the CCT to 6500 K (or the highest possible CCT value).
    a. Calculate the VELx at this point.
    b. Adjust the dimness until the VELx is approximately equal to the P in step 2. Measure and record the SPD (if possible) and Scotopic (S) and Photopic (P) illuminance (lx) and power demand (W).

Analysis:

1. Calculate the change in power demand for the P in step 2 and the final VELx in step 3.

2. What is the % power change for question 1?
3. What does this illustrate?
4. What does this result tell you about the adequacy of photopic photometric measurements for LED lamps?

6. Conclusions

Humans interact with artificial lighting in many different environments. Therefore, an understanding of the basics of lighting is important for many different professions. The increasing adoption of LED lighting, with the associated recognition that photopic lux measurements are inadequate to characterize LEDs and the acknowledgement of the importance of the contribution of rods to the vision at ambient light levels in areas with artificial lighting, is creating the need to educate the various professions about lighting in more detail than in previous generations. The set of experiments provide an engaged learning opportunity for students to 1) gain an understanding of the proper measurement and interpretation of light data; and 2) determine some operational characteristics and capabilities of current commercially available lighting. These experiments have only been able to be developed at a low-cost due to the wider commercial availability of color adjustable and dimmable LED residential lamps, and the development of lower cost and smaller sized spectrometers.

7. Acknowledgements

The support of the authors' Department of Technology for the purchase of instrumentation and equipment is gratefully acknowledged. Dr. Janet Geisen from authors' Faculty Development and Instructional Design Center provided some helpful resources for engaged learning.

8. Disclaimer

The mention of any specific tradenames, equipment or instruments is for illustrative purposes only and does not constitute endorsement by the authors' or authors' university.

9. References

5 Lighting Terms You Should Know. (2014). Retrieved August 18, 2017, from https://www.jwspeaker.com/blog/lighting-terminology/

Ambrose, S. A., Bridges, M. W., DiPietro, M., Lovett, M. C., & Norman, M. K. (2010). *How learning works: Seven research-based principles for smart teaching*: John Wiley & Sons.

Bedrosian, T., & Nelson, R. (2013). Influence of the modern light environment on mood. *Molecular Psychiatry, 18*, 751-757.

Bedrosian, T. A., Fonken, L. K., & Nelson, R. J. (2016). Endocrine Effects of Circadian Disruption. *Annu Rev Physiol, 78*, 109-131. doi: 10.1146/annurev-physiol-021115-105102

Berman, S. (1992). Energy efficiency consequences of scotopic sensitivity. *Journal of the Illuminating Engineering Society, 21*(1), 3-14.

BIPM. (2006). SI Brochure: The International System of Units (SI) (8th ed.): Bureau International des Poids et Mesures.

Borbély, Á., Sámson, Á., & Schanda, J. (2001). The concept of correlated colour temperature revisited. *Color Research & Application, 26*(6), 450-457. doi: 10.1002/col.1065

Bransford, J. D., Brown, A., & Cocking, R. (1999). How people learn: Mind, brain, experience, and school. *Washington, DC: National Research Council*.

CCOHS. (2017, Lighting Ergonomics - Survey and Solutions). Lighting Ergonomics - Survey and Solutions. Retrieved August 19, 2017, from https://www.ccohs.ca/oshanswers/ergonomics/lighting_survey.html

Contín, M. A., Benedetto, M. M., Quinteros-Quintana, M. L., & Guido, M. E. (2016). Light pollution: the possible consequences of excessive illumination on retina. *Eye, 30*(2), 255-263. doi: 10.1038/eye.2015.221

CRVL. Luminous efficiency functions. Retrieved August 19, 2017, from http://www.cvrl.org/lumindex.htm

Davis, S., Mirick, D. K., & Stevens, R. G. (2001). Night shift work, light at night, and risk of breast cancer. *Journal of the national cancer institute, 93*(20), 1557-1562.

DiLaura D., K. H., R. Mistrick, G. Steffy. (2011). *IES Lighting Handbook: Reference and Application* (10th Edition ed.). New York: Illuminating Engineering Society.

Dominoni, D. M., Borniger, J. C., & Nelson, R. J. (2016). Light at night, clocks and health: from humans to wild organisms. *Biol Lett, 12*(2), 20160015. doi: 10.1098/rsbl.2016.0015

Edwards, L., & Torcellini, P. (2002). *A Literature Review of the Effects of Natural Light on Building Occupants*. (NREL/TP-550-30769). NREL Retrieved from https://www.nrel.gov/docs/fy02osti/30769.pdf.

Erren, T. C., Falaturi, P., Morfeld, P., Knauth, P., Reiter, R. J., & Piekarski, C. (2010). Shift Work and Cancer The Evidence and the Challenge. *Deutsches Arzteblatt International, 107*(38), 657-662. doi: 10.3238/arztebl.2010.0657

Finkel, D. L. (2000). *Teaching with Your Mouth Shut*: Boynton/Cook Publishers.

Freeman, S., Eddy, S. L., McDonough, M., Smith, M. K., Okoroafor, N., Jordt, H., & Wenderoth, M. P. (2014). Active learning increases student performance in science, engineering, and mathematics. *Proceedings of the National Academy of Sciences of the United States of America, 111*(23), 8410-8415. doi: 10.1073/pnas.1319030111

Fritschi, L. (2009). Shift work and cancer: British Medical Journal Publishing Group.

Ho, C. Y., Lin, H. T., & Huang, K. Y. (2012). A Study on Energy Saving and Light Pollution of LED Advertising Signs. In D. Sun, W. P. Sung, & R. Chen (Eds.), *Frontiers of Manufacturing and Design Science Ii, Pts 1-6* (Vol. 121-126, pp. 2979-2984). Stafa-Zurich: Trans Tech Publications Ltd.

IES. 100 Significant Papers. Retrieved August 20, 2017, from https://www.ies.org/research/reports-and-papers/100-significant-papers/

IES. (2017). Illuminating Engineering Socieity-Education. Retrieved August 20, 2017, from https://www.ies.org/education/

IOHA. (2010). STUDENT MANUAL: Basic Principles in Occupational Hygiene (pp. 206): OHLearning.com.

Kantermann, T., & Roenneberg, T. (2009). Is Light-at-Night a Health Risk Factor or a Health Risk Predictor? *Chronobiology International, 26*(6), 1069-1074. doi: 10.1080/07420520903223984

Kinzie, J. (2017). The Use of Student Engagement Findings as a Case of Evidence-Based Practice. *New Directions for Higher Education, 2017*(178), 47-56. doi: 10.1002/he.20233

Kocifaj, M., & Aubé, M. (2014). Light pollution: Theory, modeling, and measurements. *Journal of Quantitative Spectroscopy and Radiative Transfer, 139*, 1-2. doi: https://doi.org/10.1016/j.jqsrt.2014.01.009

Kuh, G. D. (2001). Assessing What Really Matters to Student Learning: Inside the National Survey of Student Engagement. *Change, 33*(3).

Kuh, G. D. (2003). What We're Learning About Student Engagement From NSSE: Benchmarks for Effective Educational Practices. *Change: The Magazine of Higher Learning, 35*(2), 24-32. doi: 10.1080/00091380309604090

Ledtuning.nl. CIE convertor. from https://www.ledtuning.nl/en/cie-convertor

. Light and Moisture Requirements For Selected Indoor Plants. University of Arkansas Extension.

Lighting, R. (2017). THE 2017 LIGHTING TERMS GLOSSARY.

Lighting Terminology. (2009). *Lighting Education Online.* Retrieved July 12, 2016, from http://www.lrc.rpi.edu/education/learning/intro.asp?mode=intro

Lindbloom, B. CIE Color Calculator. Retrieved August 19, 2017, from http://www.brucelindbloom.com/index.html?ColorCalculator.html

Lowell, R. (2008). Glossary of Lighting Terms. from http://lowel.tiffen.com/edu/glossary/

LRC. (2013). Initial Investigations of the Effects of Light on Human Health. Troy, New York: Lighting Research Center.

Luginbuhl, C. B., Boley, P. A., & Davis, D. R. (2014). The impact of light source spectral power distribution on sky glow. *Journal of Quantitative Spectroscopy and Radiative Transfer, 139*, 21-26. doi: https://doi.org/10.1016/j.jqsrt.2013.12.004

NSSE Findings. Retrieved August 20, 2017, from http://nsse.indiana.edu/html/findings.cfm

OED. biota. Retrieved August 20, 2017, from https://en.oxforddictionaries.com/definition/biota

Olsen, R. N., Gallaway, T., & Mitchell, D. (2014). Modelling US light pollution. *Journal of Environmental Planning and Management, 57*(6), 883-903. doi: 10.1080/09640568.2013.774268

Pun, C. S. J., So, C. W., Leung, W. Y., & Wong, C. F. (2014). Contributions of artificial lighting sources on light pollution in Hong Kong measured through a night sky brightness monitoring network. *Journal of Quantitative Spectroscopy and Radiative Transfer, 139*, 90-108. doi: https://doi.org/10.1016/j.jqsrt.2013.12.014

Rea, M., Figueiro, M., Bierman, A., & Hamner, R. (2012). Modelling the spectral sensitivity of the human circadian system. *Lighting Research & Technology, 44*, 386-396.

Rea, M. S. (2011). Human health and well-being: Promises for a bright future from solid-state lighting. In K. P. Streubel, L. W. Tu, H. Jeon, & N. Linder (Eds.), *Light-Emitting Diodes: Materials, Devices, and Applications for Solid State Lighting Xv* (Vol. 7954). Bellingham: Spie-Int Soc Optical Engineering.

Reese, H. (2013). Lectures Didn't Work in 1350—and They Still Don't Work Today: A conversation with David Thornburg about designing a better classroom. *The Atlantic*.

Roufs, J. A. J. (1978). CIE 041-1978: Light as a True Visual Quantity: Principles of Measurement.

RUSA. (2015). Primary Sources on the Web: Finding, Evaluating, Using. Retrieved August 20, 2017, from http://www.ala.org/rusa/sections/history/resources/primarysources

Sánchez de Miguel, A., Zamorano, J., Gómez Castaño, J., & Pascual, S. (2014). Evolution of the energy consumed by street lighting in Spain estimated with DMSP-OLS data. *Journal of Quantitative Spectroscopy and Radiative Transfer, 139*, 109-117. doi: https://doi.org/10.1016/j.jqsrt.2013.11.017

SCC. Identifying Primary and Secondary Resources. Retrieved August 20, 2017, from https://www.sccollege.edu/Library/Pages/primarysources.aspx

Schanda, J., & Danyi, M. (1977). Correlated Color-Temperature Calculations in the CIE 1976 Chromaticity Diagram. *Color Research & Application, 2*(4), 161-163. doi: 10.1002/col.5080020403

. Standard CIE S 017/E:2011 ILV: International Lighting Vocabulary. (2011). Vienna, Austria: CIE

Stevens, R. G. (2009). Light-at-night, circadian disruption and breast cancer: assessment of existing evidence. *International Journal of Epidemiology, 38*(4), 963-970. doi: 10.1093/ije/dyp178

Stevens, R. G., Brainard, G. C., Blask, D. E., Lockley, S. W., & Motta, M. E. (2013). Adverse health effects of nighttime lighting: comments on American Medical Association policy statement. *American journal of preventive medicine, 45*(3), 343-346.

Trinklein, D. H. (2016). *Lighting Indoor Houseplants*. Retrieved from http://extension.missouri.edu/explorepdf/agguides/hort/g06515.pdf.

USEIA. (2017, May 23, 2017). How much electricity is used for lighting in the United States? Retrieved August 19, 2017, from https://www.eia.gov/tools/faqs/faq.php?id=99&t=3