Spring 2023

Designing Exterior Lighting for Safety and Comfort While Minimizing Light Pollution, Energy Consumption, and Cost

Stephen Michael Simmons

Missouri University of Science and Technology

Recommended Citation

Simmons, Stephen Michael, "Designing Exterior Lighting for Safety and Comfort While Minimizing Light Pollution, Energy Consumption, and Cost" (2023). *Masters Theses*. 8149.
https://scholarsmine.mst.edu/masters_theses/8149

DESIGNING EXTERIOR LIGHTING FOR SAFETY AND COMFORT WHILE MINIMIZING LIGHT POLLUTION, ENERGY CONSUMPTION, AND COST

by

STEPHEN MICHAEL SIMMONS

A THESIS

Presented to the Graduate Faculty of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN CIVIL ENGINEERING

2023

Approved by:

Stuart W. Baur, Advisor
William L. Gillis III
Devin M. Burns
Heath A. Pickerill

ABSTRACT

Artificial light at night brings many benefits to society. However, these benefits do not come without costs. One environmental issue that is often overlooked in the design of public spaces and infrastructure is light pollution. At the expense of large amounts of energy, light pollution causes numerous harmful effects on human health, ecosystems, and the night sky. Today, the problem is becoming more widespread, especially with the increasing use of bright, white LED luminaires. Thus, it is imperative for designers and engineers to create smarter lighting designs that not only allow for safety and comfort at night but also promote human health and environmental stewardship.

This research focused on creating healthier, more sustainable outdoor lighting designs. First, the harmful effects of artificial light at night were reviewed, and general design recommendations were made for mitigating these consequences. Next, a multi-criteria decision analysis framework was developed and used to optimize illuminance and spectrum for functionality, perception, light pollution reduction, energy use, and cost. Finally, virtual reality technology was utilized to aid in adopting smarter designs that require less illumination to make public spaces feel safe and comfortable at night.

The findings of this research will help lead to a more conscious use of artificial light in the future. Additional research is encouraged to further refine and develop lighting designs that promote a proper balance of human, environmental, and economic factors. With careful consideration of both the benefits and drawbacks of lighting, designers can work towards a solution to light pollution.

ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Stuart Baur, for enabling me to pursue my long-time goal of writing a master's thesis on light pollution, and for all his support and guidance along the way. I would like to thank Drs. William Gillis, Health Pickerill, and Devin Burns who supported me as members of my committee and assisted with the conduction of research and writing of publications. I would like to especially acknowledge Dr. Gillis for helping me get started along this path more than five years ago, when he helped me prepare a presentation on the topic during my first year as a Missouri S&T undergraduate.

I would like to acknowledge Dr. Suzanna Long for her mentorship and contribution to this research during my enrollment in her Advanced Research Methods course this past spring. I would also like to recognize Dr. Joel Burken, as well as Jody Seely and Jeannie Werner, who represent our department well and helped make my education at Missouri S&T meaningful and worthwhile.

I cannot finish this section without expressing my great gratitude to my parents, whose constant love and support has brought me to where I am today, to my sister who has also supported me and helped me improve this research, to my many friends who have kept me energized and motivated along the way, and foremost to our Lord, creator of the stars of night, who has given me everything I have.

TABLE OF CONTENTS

Page

ABSTRACT iii

ACKNOWLEDGMENTS iv

LIST OF ILLUSTRATIONS ix

LIST OF TABLES xi

SECTION

1. INTRODUCTION 1
    1.1. BACKGROUND 1
    1.2. OBJECTIVE 2
    1.3. THESIS OUTLINE 2
2. UNDERSTANDING AND MITIGATING THE HARMFUL EFFECTS OF OUTDOOR LIGHTING 4
    2.1. INTRODUCTION 4
    2.2. FUNCTIONALITY AND PERCEPTION 6
    2.3. HUMAN HEALTH 8
        2.3.1. Melatonin Suppression 8
        2.3.2. Cancer. 10
        2.3.3. Depression 10
        2.3.4. Diabetes, Obesity, and High Blood Pressure. 10
        2.3.5. Eye Damage. 11
    2.4. THE NIGHT SKY 12
    2.5. ANIMALS 14

2.6. PLANTS 16

2.7. UNKNOWNS 18

2.8. LIGHTING DESIGN RECOMMENDATIONS 19

3. OPTIMIZING AN EXTERIOR LIGHTING DESIGN FOR HUMAN, ENVIRONMENTAL, AND ECONOMIC FACTORS 22

3.1. BACKGROUND AND OVERVIEW 22

3.2. METHODOLOGY 23

3.2.1. Defining and Weighting Design Criteria. 23

3.2.2. Quantifying Relative Performance of Lighting Alternatives. 27

3.3. RESULTS 32

3.3.1. Illuminance. 32

3.3.2. Spectrum. 35

3.3.3. Interaction Effects. 36

3.3.4. Final Design Recommendation. 36

3.3.5. Limitations. 37

3.4. CONCLUSION 37

3.5. SUPPLEMENTAL MATERIALS 38

3.5.1. List of Items for Criteria Weight Survey. 38

3.5.2. Method of Weighting Functionality and Perception Subcriteria. 40

3.5.3. Color Perception Survey. 41

3.5.4. Data Used for Illuminance Utility Scores. 45

3.5.4.1. Functionality. 45

3.5.4.2. Perception. 48

3.5.4.3. Human health, animals, and plants. 49

3.5.4.4. Night sky. 51

3.5.4.5. Energy. 52

3.5.4.6. Cost. 53

3.5.5. Data Used for Spectrum Utility Scores. 54

3.5.5.1. Functionality. 54

3.5.5.2. Perception. 55

3.5.5.3. Human health. 55

3.5.5.4. Night sky. 56

3.5.5.5. Animals. 56

3.5.5.6. Plants. 58

3.5.5.7. Energy. 58

3.5.5.8. Cost. 59

4. DESIGNING LIGHTING FOR IMPROVED PUBLIC PERCEPTION AND REDUCED LIGHT POLLUTION USING VIRTUAL REALITY 61

4.1. INTRODUCTION 61

4.1.1. Lighting for Enhanced Public Perception. 62

4.1.2. Application to Sustainable Lighting on a University Campus 64

4.1.3. Using Virtual Reality to Test Perception of Lighting. 64

4.2. RESEARCH METHODS 65

4.2.1. Simulation of Lighting Design Alternatives. 65

4.2.1.1. Simulation of existing exterior lighting. 66

4.2.1.2. Simulation of dimmed existing lighting. 70

4.2.1.3. Simulation of experimental lighting design. 72

4.2.1.4. Simulation of dimmed experimental design. 74

4.2.2. Presentation of Simulations to Participants. 76

4.2.3. Gauging of Perception. 76

4.3. RESULTS....................77

4.3.1. General Perceptions of Each Simulation. 83

4.3.1.1. Existing design at full brightness. 84

4.3.1.2. Dimmed existing design. 84

4.3.1.3. Experimental design at full brightness. 85

4.3.1.4. Dimmed experimental design. 86

4.3.2. Limitations. 86

4.4. IMPLICATIONS FOR FUTURE LIGHTING DESIGNS 88

4.5. CONCLUSION 89

BIBLIOGRAPHY 90

VITA....................100

LIST OF ILLUSTRATIONS

Page

Figure 2.1 Aerial view of lighting at the Missouri University of Science and Technology campus in 2017 4

Figure 2.2 Unshielded lights and bright reflections from shielded lights 9

Figure 2.3 Skyglow seen on a clear night....12

Figure 2.4 Warm-colored light 16

Figure 2.5 Leaves still present in early December on trees exposed to LED lighting at Missouri S&T....18

Figure 2.6 Human photopic and scotopic spectral sensitivity, melatonin suppression action spectrum, and photosynthesis action spectrum 21

Figure 3.1 Sample survey question 25

Figure 3.2 Illustrations approximating illuminance orders of magnitude 29

Figure 3.3 Simulated spectrum alternatives 30

Figure 3.4 Simulated photos for the perception survey....42

Figure 3.5 Composite feelings of safety and comfort scores 44

Figure 3.6 Gender-separated survey scores....44

Figure 3.7 Estimated crime and collision rates vs. illuminance 46

Figure 3.8 Obstacle size with 95 percent detection probability vs. illuminance 47

Figure 3.9 Time required to navigate through an egress route under emergency lighting....47

Figure 3.10 Perceived safety vs. illuminance 48

Figure 3.11 Perceived lighting quality vs. illuminance....49

Figure 3.12 Melatonin suppression vs. photopic illuminance....50

Figure 3.13 Visible stars vs. artificial sky brightness....51

Figure 3.14 Required luminaire wattage to achieve a desired lumen output 52

Figure 3.15 Capital cost vs. rated luminaire wattage of several product lines..................53

Figure 3.16 Relative crime and collision rates vs. spectrum..54

Figure 3.17 Obstacle size with 50 percent detection probability vs. color temperature of light source 55

Figure 3.18 Average melatonin suppression index vs. spectrum 56

Figure 3.19 Average star light index index vs. spectrum..57

Figure 3.20 Average wildlife index vs. spectrum...57

Figure 3.21 Average induced photosynthesis index vs. spectrum....................................58

Figure 3.22 Luminous efficacy vs. spectrum 59

Figure 3.23 Relative luminaire capital cost vs. spectrum...60

Figure 4.1 Starting view, looking south from the observation point................................67

Figure 4.2 View looking west from the observation point...68

Figure 4.3 View looking east from the observation point..69

Figure 4.4 Images from simulation of dimmed existing lighting design 70

Figure 4.5 Images from simulation of experimental lighting design at full brightness 73

Figure 4.6 Images from simulation of dimmed experimental design...............................75

Figure 4.7 Composite feelings of safety and comfort/aesthetics ratings for each design and brightness level 78

Figure 4.8 Gender-separated ratings...79

Figure 4.9 Visualization of interaction effects 82

LIST OF TABLES

Page

Table 3.1 Final calculated weights of objectives and design criteria. 27

Table 3.2 Scores for illuminance alternatives. 33

Table 3.3 Scores for spectrum alternatives..34

Table 3.4 Pairwise comparisons for design criteria weight survey. 38

Table 3.5 Functionality and perception subcriteria and their weights..............................41

Table 3.6 Color perception survey data...43

Table 4.1 Perception survey data...78

Table 4.2 Variables and their categories analyzed in the mixed effects model................81

Table 4.3 Results of the linear mixed effects model for safety perception. 81

Table 4.4 Results of the linear mixed effects model for comfort/aesthetics. 82

1. INTRODUCTION

1.1. BACKGROUND

Outdoor lighting is ubiquitous in modern civilization, illuminating our streets, buildings, walkways, and other public spaces to better allow society to function after dark. Its many benefits, including visibility, safety, and increased usability of spaces, make artificial light an important part of the infrastructure today and in the future. Indeed, its use is expanding, and the rise of light emitting diodes, or LEDs, has allowed for a greater amount of illumination with less energy consumption and for smarter designs than were possible with previous technologies.

However, at the same time, the problem of light pollution is growing, shrouding the night sky from more and more people and threatening both human health and the livelihood of ecosystems. Furthermore, even with increased efficiency, artificial light is not free but carries substantial financial cost, consumes large amounts of energy, and produces significant greenhouse gas emissions.

Due to the consequences of artificial light at night, there is the need to take action to ensure that lighting designs in the future strike a balance between fulfilling the needs and wants of today's society, protecting natural darkness at night, and reducing energy consumption, carbon emissions, and monetary expense. This research helps pave the way towards achieving this goal by addressing the problems associated with artificial light at night and exploring more sustainable, human-centric designs aimed at creating a (figuratively) brighter future.

1.2. OBJECTIVE

The objective of this research is to gain a greater understanding of the causes and effects of light pollution, and to design sustainable outdoor lighting that reduces these impacts while being functional, well-perceived by the public, energy efficient, and cost effective. The design optimization portion of this research focuses on the exterior lighting at the Missouri University of Science and Technology campus in Rolla, Missouri. However, the general findings as well as the framework established in this research can be applied towards other settings and applications in the future and can be modified as necessary to fit different objectives.

1.3. THESIS OUTLINE

This thesis consists of four sections. This first section is the introduction, which describes the background and objective of this research and provides an outline of the thesis.

The second section includes a comprehensive literature review of the known impacts of light pollution and provides general lighting design recommendations for mitigating these impacts. It is based on the paper "Informing Lighting Designs Through a Comprehensive Review of Light Pollution Impacts." The research for this paper was presented at the International Conference on Light Pollution in September 2022, and the paper is intended to be submitted to a journal in the field for publication.

The third section includes research aimed at balancing the objective of light pollution reduction with functionality, public perception, energy consumption, and cost in an exterior lighting design through a practical framework. It is based on the paper

"Optimizing an Exterior Lighting Design for Human, Environmental, and Economic Factors." This conference paper was accepted by and presented at Light Symposium 2022 in Copenhagen, Denmark and has been published in *IOP Conference Series: Earth and Environmental Science.* It will be submitted to the journal *Re-Thinking Lighting Design in a Sustainable Future*, a special issue of *Sustainability.*

The fourth section contains research involving the evaluation of proposed lighting design best practices using virtual reality simulations. This work is aimed at boosting the public's perception of outdoor lighting while reducing its environmental and economic costs through strategic design decisions. This research will be presented at AEI Conference 2023 in Denver, Colorado and is intended to be submitted to the *Journal of Architectural Engineering* for publication.

2. UNDERSTANDING AND MITIGATING THE HARMFUL EFFECTS OF OUTDOOR LIGHTING

2.1. INTRODUCTION

Outdoor lighting provides numerous real and perceived benefits to society. These can include increased visibility at night for drivers and pedestrians, as well as easier navigation stemming from a better sense of place and direction. Illumination of public spaces can enable better surveillance of an area, which could reduce the likelihood of certain crimes being committed; it can also make people feel safer and more comfortable, increasing the appeal and usability of spaces after dark. Designed correctly, lighting can

Figure 2.1 Aerial view of lighting at the Missouri University of Science and Technology campus in 2017, showing a mixture of LEDs and older lighting technologies.

also enhance the aesthetics of the built environment, bringing a sense of order and visual appeal to structures, streets, walkways, parks, and landmarks.

Lighting up the night, however, does not come without cost. The U.S. Department of Energy estimates that outdoor lighting in this country uses 380 billion kWh of energy per year, amounting to a price tag of roughly $10 billion and matching the consumption of 35 million homes or 49 million passenger vehicles [1, 2]. With the still widespread use of fossil fuels this translates into significant greenhouse gas emissions and contributes further to climate change.

In addition to energy consumption, financial expense, and climate change, outdoor lighting brings another major drawback: light pollution. While often dismissed as an issue of secondary importance or even completely neglected in the design of lighting systems, light pollution has serious, far-reaching impacts on human health, the environment, and the night sky. Artificial light at night suppresses melatonin in humans and other animals triggering numerous negative effects, interferes with the natural growth and dormancy patterns of plants, and veils the natural night sky, sometimes to a great degree, over large parts of the Earth.

In recent years, LED lighting has been rapidly rising to dominance over other lighting technologies, as seen in Figure 2.1. In 2019, almost half of all light sources were LED, a number that is expected to grow to over 75 percent by 2025 and to almost 90 percent by 2030 [3]. Fortunately, this lighting technology can allow for the reduction of energy usage, cost, and light pollution. However, LED luminaires are often brighter than necessary due to a rebound effect caused by their increased energy efficiency and lower costs [4, 5]. A study in 2017 found that both the brightness and extent of artificial light at night is increasing globally by about 2 percent every year [4]. LEDs also frequently emit a more blue-rich spectrum of light, which can be much more harmful at night than other wavelengths.

This research compiled numerous sources to describe and quantify the impacts of artificial light at night on humans, the night sky, animals, and plants. The effects of varied brightness and spectrum are covered, as well as the impacts of light directionality and shielding. The effects of light pollution on the environment and possible mitigation strategies have been summarized previously [6]. However, with the recent proliferation of LED lighting, as well as the publication of more recent studies on light pollution, this topic should be revisited.

Based on the findings of this comprehensive literature review, lighting design recommendations are made to assist in maximizing the benefits of outdoor lighting while minimizing harm to humans, animals, and plants. Some of the unknowns of light pollution are also discussed, including research gaps and uncertainties that could be studied in the future. This review will provide a foundation for creating better lighting systems that account for health, safety, and the environment.

2.2. FUNCTIONALITY AND PERCEPTION

Brighter, more uniformly distributed light at night has been shown to promote greater feelings of safety [7, 8]. The use of white light with a color temperature around 4000K may boost safety perception as well, based on data from a survey given by the author to university students in 2022 [9]. However, lighting can also create a feeling of danger when it is excessive or poorly designed [10]. It also must be remembered that perception of safety is just that: perception. The question remains whether brighter, more neutral-colored light increases actual safety. A study of crime and road collision rates by Rebecca Steinbach and colleagues [11] found no evidence that switching off or dimming lights increases crime or collisions at night, and even found weak evidence that lowering light levels decreases crime rates. A later study linked a decrease in visibility to a reduction in vehicle crime, hypothesizing that criminals may opt for better-lit streets to see what they are stealing and commit their crimes without the use of a flashlight, which could draw attention [12]. While light can assist victims and law enforcement in spotting threats, it can also enable criminals to spot their targets and can conceal their actions with glare, resulting in an increase of crime [10]. Regarding the color of light, Steinbach's study found no evidence that switching from amber to white light decreases the number of collisions, and only weak evidence that it would reduce crime rates [11].

The use of bright artificial light at night carries additional risks besides enabling crime. Glare can cause discomfort and impair drivers' vision [13, 14]. Illuminated billboards, particularly newer video billboards, can distract motorists, especially the young and elderly [14, 15]. The recent proliferation of blue-rich light also brings safety and visibility concerns, as it has been shown that blue light produces more glare than other colors [16] and causes increased pupil constriction, potentially reducing foveal vision [17]. Blue-rich light may be less useful for visibility among the elderly population due to decreasing lens transparency for this portion of the spectrum in this age group [18]. Pavement surfaces are also less reflective of shorter wavelengths of light, resulting in 6-11% less luminance from roadways when white LED light is used compared to amber high pressure sodium lighting [18].

Finally, the aesthetic appeal of outdoor spaces can suffer when areas are overlit or when blue-rich light is used. A book by Navaz Davoudian published in 2019 advises creating a well-designed hierarchy of light while avoiding bright, glare-causing light in pedestrian areas [19]. In the survey of students mentioned earlier in this section, a color temperature of 2700K was associated with greater feelings of comfort and aesthetics than 5000K or amber light, suggesting that a warm white appearance similar to incandescent light may be most appealing to the public.

2.3. HUMAN HEALTH

Light pollution affects human health in numerous ways. Light at night strays into bedroom windows and disturbs people's sleep by suppressing melatonin, causing an array of ill effects. Melatonin suppression has been linked to certain cancers such as breast cancer and prostate cancer [20]. In addition, evidence exists that exposure to light at night, particularly blue light, causes depression and anxiety, diabetes, obesity, high blood pressure, and other disorders. Effects on human health may even extend to retinal damage due to chronic exposure to blue light coupled with a lack of red light.

2.3.1. Melatonin Suppression. A principal negative effect of light pollution on human health is suppression of melatonin and disruption of the circadian rhythm. This disturbance can cause numerous health problems from the altering of sleep and wake cycles, eating patterns, and metabolism, to its effects on mental alertness, mood, reproductive processes, heart rate and blood pressure, hormone production, body temperature, and the immune system [21]. Approximately 100 lux (~ 10 fc) of white fluorescent light was shown to cause 50 percent of the maximum melatonin suppression

Figure 2.2 Unshielded lights and bright reflections from shielded lights, as seen from a dormitory window.

response in humans, as well as a melatonin phase shift of 1.5 hours [22]. Much smaller amounts of light can still cause circadian disruption, including levels commonly spilling into bedrooms in urban areas [23], illustrated in Figure 2.2. A lack of complete darkness at night can also prevent cell repair [21].

While the amount of light exposure affects the degree of melatonin suppression, spectrum is likely a more critical factor, as the circadian system is most sensitive to blue wavelengths of light, similar to the color of a clear sky at noon [14, 21, 23, 24]. In one study, it took a mere 0.4 lux (0.04 fc) of blue-violet (440 nm) light to evoke 50 percent of the maximum suppression response, whereas about 10 times as much blue-cyan (480 nm) light, 100 times as much green (530 nm) light, and 1000 times as much yellow-orange (575-600 nm) light was required to evoke the same response [25]. Additionally, the angle of light matters strongly as well; only light entering the eye in the upper half of the visual field causes melatonin suppression, while light in the lower portion does not [21].

2.3.2. Cancer. Another major health impact of light pollution is its link to cancer. For decades now, circadian rhythm disruption from nighttime lighting and shift work has been associated with an increased risk of certain types of cancer, particularly breast cancer and prostate cancer [20, 26]. This link may be explained at least partially in that disrupting melatonin production affects the regulation of natural killer cells, which fight tumors [27]. A natural cycle of blue light during the day followed by darkness or long wavelength light at night appears to be important for the prevention of this potentially deadly condition.

2.3.3. Depression. Artificial light at night and circadian disruption is also linked to effects on mood. Evidence supports a linkage between even dim levels of light and depression and anxiety [28]. A significant relationship was found between bedroom light exposure of 5 lux (0.5 fc) or greater and depressed mood in the elderly [29]. Evidence also exists that constant artificial light exposure for premature infants might prevent proper circadian rhythm development [30] and increase the risk of developing mood disorders in life [26].

2.3.4. Diabetes, Obesity, and High Blood Pressure. The health effects of light pollution do not stop with cancer and depression. Research shows that restriction of sleep and circadian disruption can also cause metabolic disorders. In a research study conducted in 2012, sleep loss combined with circadian rhythm disruption result in a slowed resting metabolic rate, a reduction in insulin secretion, and hyperglycemia [31]. A study by Obayashi *et al.* demonstrated a significant relationship between light at night of greater than or equal to 3 lux (0.3 fc) and a higher body weight and BMI, greater risk of obesity, higher triglyceride levels, higher LDL and lower HDL cholesterol levels, and greater risk of dyslipidemia in elderly individuals [32]. Obayashi *et al.* later linked light at night to higher nighttime blood pressure in the elderly population, claiming a 6.1 percent increase in mortality as a result [33]. These studies suggest that light entering bedrooms through windows may be sufficient to contribute to an increased risk of diabetes, obesity, high blood pressure, and other related disorders.

2.3.5. Eye Damage. Light of a high enough intensity can damage the retina; blue light particularly has the ability to cause harm, as the threshold for damaging levels is lower with shorter wavelengths [19]. Short-wavelength-sensitivity (SWS) cones are also more likely to sustain damage [19]. A study conducted by Núñez-Álvarez *et al.* in 2018 showed that blue light exposure can cause retinal pigment epithelial mitochondria malfunction and oxidative stress, suggesting that chronic blue light exposure is associated with age-related macular degeneration [34]. To further this concern, a recent study by Li *et al.* found that chronic exposure even to low levels of blue light, such as those found in electronics, can cause retinal tissue structural and functional damage [35]. Based on these findings, it is possible that blue light exposure from streetlights and other artificial sources could contribute to retinal damage and macular degeneration over time. Núñez-Álvarez *et al.*'s study also found that red light exposure can help attenuate damage caused by blue light, suggesting that long wavelengths of light at night can conversely be beneficial to ocular health.

2.4. THE NIGHT SKY

The consequences of light pollution on humans reach beyond eye damage, sleep loss, and circadian disruption with its associated impacts. Manmade lighting, especially poorly designed lighting, deprives humanity of its view of the stars and milky way at night primarily in two ways: first, by directly and indirectly shining into eyes and preventing dark adaptation; second, and more critically, by scattering in the atmosphere and brightening the entire sky. This scattering, often called skyglow and shown in Figure 2.3, can obscure the views of the night sky even in locally dark regions and can extend over 100 km (~ 60 mi) from its source(s) [18].

Figure 2.3 Skyglow seen on a clear night approximately 7 miles from the center of Jefferson City, Missouri, a town of around 40,000 people.

A major contributor to skyglow is poorly aimed (and typically wasted) light. Light that shines between 0 and 45 degrees above the horizontal plane results in the most pollution of the sky due to its long path length through the atmosphere, and light between 0 and 10 degrees below horizontal can also be problematic due to shallow reflection upwards off pavement [18]. Thus, along with limiting the amount of artificial light to only what is needed, proper shielding and aiming of light fixtures is essential for minimizing the degradation of the night sky.

Additionally, as with human health, limiting the amount of blue light and utilizing long-wavelength light protects the night sky. White light can produce 2.5 to 15 times the amount of skyglow as amber light [17] due to increased atmospheric scattering of shorter wavelengths compounded by the higher scotopic sensitivity of human eyes to blue light [17, 18]. Thus, while converting to full cutoff fixtures can reduce the amount of skyglow by about half, simultaneously switching from previously popular high pressure sodium lighting to white LED can counteract the benefits of shielding and result in a greater amount of skyglow [36]. For example, when Hung *et al*. measured changes in skyglow after an LED retrofit [37], it was found that the amount of skyglow measured from the ground increased even though the lights were fully shielded, illuminance was reduced by about 50 percent, and the bulbs were predominantly of a warm white (3000K) color temperature, a temperature approved by the International Dark Sky Association (IDA) as night sky friendly [38]. The IDA now generally recommends the use of 2200K, amber, or blue-filtered light [39].

Another, more subtle but very concerning source of skyglow is the increasing number of satellites orbiting the earth in recent years. A study led by Kocifaj in 2021 found that satellites and space debris have already increased sky brightness by about 10 percent over natural background levels, a figure that is expected to increase in the coming years [40]. This could result in unacceptable levels of light pollution for professional astronomical observations and give a light-polluted status to even the most pristine dark skies on earth. Thus, the days of a natural night sky may be permanently coming to an end.

2.5. ANIMALS

Artificial light at night impacts different animal species in the environment, including insects, birds, turtles, and fish, in many ways. The vast number of species and the diversity between them results in a plethora of individual effects, but the overall result appears to be negative – the disruption of ecosystems.

Like humans, animals' circadian rhythms can be affected by the presence of light at unnatural times [6, 41]. Animals that rely on perceived daylength to time their reproduction, migration, and feeding [6, 41] could be confused into performing these behaviors at the wrong times by artificial light. The light can also impair their efforts when they do carry out these essential functions [21], potentially leading to population decline and disrupting food chains. For species relying on moonlight patterns for certain activities [41], light pollution can interfere by masking these cycles of relative brightness and darkness at night [42]; cloud cover can also amplify light pollution by 10 times, resulting in much brighter skies when natural light would be at its dimmest [43]. Light can disrupt pollinators [21], kill threatened or endangered sea turtles by discouraging nesting and luring hatchlings away from the ocean [44], and can even raise the risk of introducing invasive species by attracting insects to ports and ships [45]. Light at night can also increase rates of West Nile virus among birds, potentially leading to more outbreaks among people [46, 47]. Additionally, artificial light can cause animals to avoid otherwise good habitats [48], expanding the area of the natural environment that is degraded by human development.

Horizontally aimed light can cause greater disruption by traveling for longer distances compared to other angles [6]. Properly shielding light and reducing brightness where possible would minimize the area affected by light pollution [6]. However, animals would still likely be disrupted near light sources regardless of dimming, as certain species are sensitive to light several orders of magnitude lower than what is required for human vision [6, 49].

The impact of light spectrum on animals is less straightforward than with humans and the night sky. Shorter wavelengths of light have been shown to attract moths more strongly, with UV light possibly playing a strong role [50]. Other species shown to be more sensitive to short wavelength light include bees [51] and songbirds [52]. Sea turtles can be sensitive to both short- and long-wavelength light [51], but narrowband amber lighting is used to minimize impacts and help protect hatchlings from disorientation. To the contrary, there is evidence that some insects such as moths and aphids experience greater impacts from amber light sources compared to white light, at least under certain circumstances [53]. A study last year found that dim, amber light could interfere with moths' color perception, inhibiting pollination and possibly leaving the moths more susceptible to predation [54]. Despite exceptions such as this case, however, Longcore *et* *al.* found that blue light is more disruptive for wildlife collectively, and recommends the use of amber light followed by warm white [51], as demonstrated in Figure 2.4.

Figure 2.4 Warm-colored light (simulated here in a color-corrected photograph) is ideal for protecting human health, the environment, and the night sky.

2.6. PLANTS

Finally, light pollution affects the health of plants. Light can induce photosynthesis, affect growth and flowering, and shift when trees bloom in the spring and drop their leaves in the fall. These changes can cause negative impacts on the environment and on crops and can disturb normal plant and animal interactions.

Plants are most sensitive to red wavelengths of light as well as blue and violet [23, 55]. Light in these wavelengths can more readily induce photosynthesis and prevent repair following stress, as well as interfere with flowering and growth by disturbing plants' circadian rhythms and detection of daylength [55]. Previous studies show that less than 5 lux (0.5 fc) can be sufficient to cause impacts and that light containing a large proportion of red light and a high red to far red ratio may be most disruptive, at least for certain species [56-58]. As a result of the interference caused by artificial light, crops can be damaged, as shown in two recent studies linking light trespass from roadways to delayed soybean development and reduced yield [59, 60]; in the second study, the authors recommend restricting light spilling into fields to less than 2.2 horizontal lux (0.2 fc) to allow for an acceptable harvest, at least for the HPS and 4000K LED lamps included in the study [60].

Studies have linked the addition of artificial light into the nighttime environment to earlier budding of plants in the spring [61, 62] and delayed dropping of leaves in the fall [62-64], as substantiated in Figure 2.5. These studies show that artificial light at night, even at low levels typically found outdoors, can cause trees to bloom about a week earlier and then retain leaves longer by a month or more compared to natural lighting conditions. One of these studies [62], published this year, showed a more complicated relationship between light and leaf fall, claiming that in a warming climate the effect of light could eventually be reversed. Regardless, the shifting of natural periods of dormancy can disrupt ecosystems by putting plants out of sync with pollinators, seed carriers, and herbivores, and can leave plants more susceptible to frost damage in colder parts of the year [55, 65].

Figure 2.5 Leaves still present in early December on trees exposed to LED lighting at Missouri S&T. Fall foliage in this region typically should peak around late October.

2.7. UNKNOWNS

While much is now known about the effects of light at night, more research is still needed. Conclusive evidence is needed regarding the relationship between light and safety, in terms of visibility, crime, and accidents. Further study of this issue would allow for more effective lighting designs and could increase the public's peace of mind.

Future research should continue to explore the effects of brightness and spectrum on human health, seeking to uncover any additional negative impacts and investigating the potential for lower thresholds of harm. Research regarding plants and animals is likely a much more complicated task due to the vast number of species that could be affected in different ways by different lighting conditions. Less-studied regions of the world could be experiencing severe effects from light pollution that have not yet been discovered by researchers. While uncovering all potential ramifications is practically impossible, general lighting recommendations to minimize overall impacts can be further refined and tailored to local ecosystems, and particular attention could be paid to endangered species, as is currently being done with sea turtles.

2.8. LIGHTING DESIGN RECOMMENDATIONS

In the design of outdoor lighting systems, multiple criteria must be considered. These include visibility, safety, and public perception, as well as light pollution impacts, energy usage, economics, and any additional factors determined to be important for a particular case. Assessing the relative importance of these criteria and designing a lighting system to maximize overall benefits can be very complicated. Here, general design recommendations are given based on the impacts of artificial light covered in this review.

The benefits of artificial light at night can be realized while minimizing its negative impacts by using light only when and where it is warranted, at an appropriate brightness for a given purpose. Providing higher illumination levels than required increases light pollution, energy usage, and cost. Following minimum illuminance guidelines can achieve acceptable functionality while avoiding excessive light. Further research could explore whether even these minimum levels are overly conservative and if lower levels could be used without causing disproportionately negative effects. Studies show that illuminance dropping below about 2 lux (0.2 fc) results in visibility being degraded at an increasing rate, but that levels on the order of 0.1 lux (0.01 fc) may still be adequate for obstacle detection while walking at night [66, 67]. A well-thought-out design placing the right amount of light at strategic locations, such as at the edges of a space at eye level, could allow for lower illumination levels while increasing peoples' sense of direction, feelings of safety, and comfort [19]. Additionally, timers and motion sensors can be used where practical to dim or extinguish lights when they are not necessary. Light levels could be fine-tuned for weather conditions, such as the presence of highly reflective snow, and for ambient lighting present, such as moonlight or other artificial light.

In addition to limiting the amount of light, the harmful impacts of light at night can be further reduced by designing and installing luminaires so that no light shines directly above the horizontal plane. Minimizing light emissions above 10 degrees below the horizontal will cut back on glare and low-angle reflection to the sky [18]. LEDs' directionality, along with proper shielding, can be utilized to control distribution and avoid light spillage into areas where light is not needed or wanted.

The spectrum of light is also a critical design consideration. Spectral power distribution can be optimized to provide good visibility for humans in an energy-efficient and cost-effective manner while minimizing health and environmental impacts. Emission of wavelengths shorter than 550 nm causes greater harm, as this portion of the spectrum produces greater skyglow from scattering and scotopic sensitivity and causes the most melatonin suppression [23]. Wavelengths between 550 nm and 610 nm, on the other hand, contribute less to these undesirable effects but are still highly effective for photopic vision [23]. This portion of the spectrum also retains effectiveness for mesopic and scotopic vision [68] which become more relevant at lighting levels on the order of 1 lux (0.1 fc) or below [69]. Animals, at least collectively, will not be affected as adversely by these longer wavelengths, while plants will experience less harm due to the minimization of both blue and red light. Relative spectral impacts on vision, melatonin, and photosynthesis, as well as the recommended range for outdoor lighting of 550 to 610 nm, are displayed in Figure 2.6. The exact spectrum can be tailored to maximize aesthetics and public perception, as well as efficiency and cost, at least to the extent allowed by available lighting technology. Fortunately, the versatility of LED technology could allow for an idealized spectrum not possible in the past.

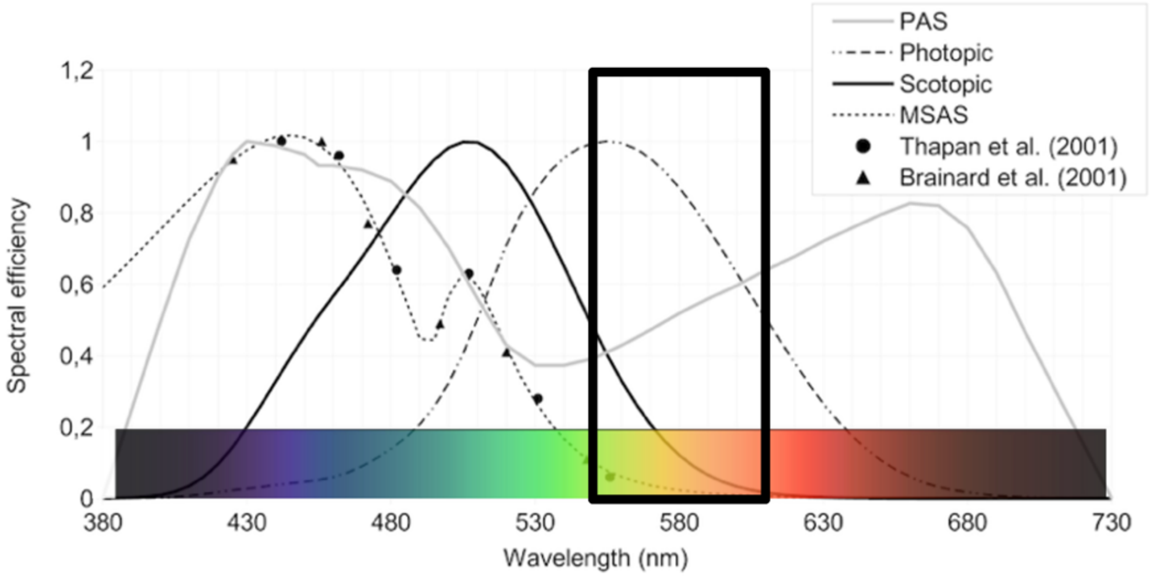


Figure 2.6 Human photopic and scotopic spectral sensitivity, melatonin suppression action spectrum (MSAS), and photosynthesis action spectrum (PAS), adapted from [23, 70-72]. A box has been drawn around the optimal wavelengths for outdoor lighting.

3. OPTIMIZING AN EXTERIOR LIGHTING DESIGN FOR HUMAN, ENVIRONMENTAL, AND ECONOMIC FACTORS

3.1. BACKGROUND AND OVERVIEW

In the previous section, the numerous harmful impacts of artificial outdoor lighting were outlined, and generalized design considerations were given for achieving a reduction of these effects. However, these blanket recommendations do not provide a thorough means of balancing potentially conflicting lighting design objectives such as ensuring visibility on walkways and protecting the night sky. They also do not provide a design optimization framework that could be applied to a particular case, accounting for specific priorities or requirements and incorporating available lighting products. Development of such a framework is important for creating safe, navigable spaces while properly accounting for objectives such as light pollution reduction, public perception, energy efficiency, and cost, bringing the greatest benefits to both people and the planet.

This research optimizes the design of an exterior pedestrian LED lighting system at the Missouri University of Science and Technology (Missouri S&T) campus for human, environmental, and economic factors. Several methods of optimizing lighting designs for multiple criteria already exist in the literature [74-76]. These all make use of different forms of a multi-criteria decision analysis (MCDA) to select an ideal solution among many possible design alternatives. While an exterior lighting design algorithm has been created that includes light pollution as a principal criterion [74], it does not address factors such as light spectrum. It also does not score alternatives for the illuminance and light pollution criteria, but instead simply eliminates those deemed unacceptable. This research addresses these shortcomings by utilizing the analytic hierarchy process (AHP) and multi-attribute utility theory (MAUT) to compare lighting alternatives in a quantifiable manner, as has previously been done for interior lighting [76], and by incorporating more criteria to cover all major light pollution impacts as well as public perception. The framework used for this case can be used for other exterior lighting design applications and can be modified as necessary to fit different design objectives.

3.2. METHODOLOGY

To create an optimized outdoor lighting design, all significant design criteria were defined and weighted according to their relative importance. After determining the weighted criteria, different alternatives for illuminance and spectrum were scored according to their performance relative to each other and to a baseline. On the condition that they provide an acceptable level of visibility, the alternatives scoring the highest were considered to represent ideal lighting specifications. While not pursued in this study, minimum standards for other criteria could be established as well.

3.2.1. Defining and Weighting Design Criteria. The following eight design criteria were used in this analysis:

- Functionality – public safety, visibility
- Perception – feelings of safety, comfort and aesthetics
- Human health – melatonin suppression, linked to a multitude of ailments [20, 21]
- Night sky – veiling of stars due to skyglow
- Animals – interference with or harm of various species
- Plants – interference with growth, dormancy period, etc.
- Energy – estimated energy usage of a lighting system
- Cost – capital, operation, maintenance

These criteria were associated with three main objectives: utility (functionality, perception); light pollution reduction (human health, night sky, animals, plants); and economy (energy, cost).

The analytic hierarchy process (AHP) [77], a common method used in multi-criteria decision analyses [76, 78-80], was used in this study to weight the design criteria. This method involves setting each criterion against all others with pairwise comparisons and allowing decision makers to indicate how favorable one is over the other. The fundamental scale of 1/9 to 9 was used, with a score of 1/9 indicating extreme unfavorability of the first criterion over the second, 1 indicating equal preference, and 9 indicating extreme favorability of the first over the second. Intermediate values indicate lesser degrees of favorability or unfavorability.

For this study, a survey containing pairwise comparisons of the design criteria was distributed to students in the university's Civil, Architectural, and Environmental Engineering department. The survey set items representing the criteria against each other—for example, "functionality vs. perception" was represented with the phrases "actually being safe" vs. "feeling safe." For each pair, respondents were asked to indicate which item they believed was more important, and to what degree. To provide simplicity and reduce survey fatigue, a 5-point Likert scale was used and converted to the 1/9 to 9 scale after collecting responses. The choices included the following: "equal importance," corresponding to a 1; "somewhat more important," corresponding to either 1/5 or 5; and "much more important," corresponding to 1/9 or 9. A sample survey question is included in Figure 3.1, and the complete list of pairwise comparisons is included in 3.5.1. The average response among participants was used for the final analysis. It was assumed that if a criterion was ranked “much more important” by all respondents, this would truly indicate extreme importance and merit a 9 on the AHP scale.

	Much more important	Somewhat more important	Equal Importance	Somewhat more important	Much more important	
Actually being safe	○	○	○	○	○	Feeling safe

Figure 3.1 Sample survey question.

The survey structure and questions were reviewed internally and by a third party [111], then a pilot run was conducted in which responses were collected from members of a lighting design course within the department (n = 20, 50% female). The results of the pilot survey were analyzed for inconsistencies, and modifications were made to certain questions to provide a more consistent, equitable representation of all criteria throughout the survey. Next, the survey was opened to all students in the department (~ 500 students) and received a response rate of around 10% (n = 53, 53% female). Participation was voluntary and anonymous, and no compensation or incentives were offered in exchange for participation. Responses were screened for credibility with the assistance of an interquartile range outlier analysis, and any spurious responses were removed. Using the average of all valid responses from the final run of the survey, an AHP Excel template was used [81] to determine the weights of the eight design criteria. Due to the nature of the 1/9 to 9 scale, each criterion always receives a nonzero score, and thus the total weight related to each objective (utility, light pollution, and economy) is affected by the number of associated criteria. To correct for this, the survey questions were also grouped by objective to separately determine the objectives' weights (using the AHP template) and then adjust the criteria weights in proportion to them. The weights of the objectives and the adjusted weights of the design criteria are given in Table 3.1. In addition, functionality and perception were divided into subcriteria, the weights of which were approximated as detailed in 3.5.2.

There was greater than a 95% consensus between the pilot and final survey results. However, there were some noteworthy differences that could not be attributed to any modifications that were made. Specifically, the weights of human health and functionality declined while those of energy and cost increased. This disparity could be due to differing values among students in the lighting class compared to the department in general. The results of the final survey were assumed to represent the views of a large portion of the student body and were taken as a valid source for designing outdoor lighting for Missouri S&T's campus.

The calculated consistency ratio of the collective survey response was 0.076 for the three objectives and 0.174 for the eight criteria. Typically, a consistency ratio of 0.10 or lower is considered acceptable. However, the threshold is sometimes set at 0.20 [82]. In this case, since the results stem from the mean of more than 50 respondents, the likelihood of inconsistencies due to individual human error or poor judgment is lower. Rather, inconsistencies are more likely caused by the variation of items representing each criterion. For instance, the perception criterion was rated more favorably when represented by feelings of safety as opposed to comfort or aesthetics. Since great care was taken to ensure a balanced overall representation of all criteria, the results are considered acceptable. In addition, between-participant consistency was analyzed for all survey responses except for two that were incomplete (n = 51) using SPSS Statistics software (Version 28). The intraclass correlation coefficient (ICC) was calculated as 0.885 (95% CI: 0.818–0.937) based on a mean-rating, absolute agreement, two-way random model, representing good to excellent reliability [83].

Different methods of determining criteria weights, as well as the employment of this method towards other lighting applications and demographics, can be addressed in future research.

Table 3.1 Final calculated weights of objectives and design criteria.

Utility		Light Pollution				Economy	
0.221		0.306				0.473	
Functionality	Perception	Human Health	Night Sky	Animals	Plants	Energy	Cost
0.156	0.065	0.120	0.042	0.073	0.071	0.249	0.224

3.2.2. Quantifying Relative Performance of Lighting Alternatives. The following lighting attributes and design alternatives were analyzed in this study:

- Illuminance—alternatives ranging from 0.01 fc (0.1 lx) to 10 fc (~100 lx)
- Spectrum—alternatives ranging from amber to 5000K correlated color temperature (CCT)

Illuminance alternatives are illustrated in Figure 3.2. These illustrations were derived from an image taken at the Missouri S&T campus at night. Construction drawings provided by the university for this location [98] were used to estimate the actual illuminance in the photo (~2 fc or 20 lx), and the image was corrected to match different illuminance levels generated using a LIFX brand light bulb which has a logarithmic dimming profile [108].

Spectrum alternatives are illustrated in Figure 3.3 and were derived from the same image as was used for illustrating illuminance alternatives. The actual CCT is known to be 5700K from the construction drawings [98]. The photo was color corrected to simulate each spectrum alternative by comparison with the original photo displayed on a screen running f.lux software, which allows for the screen to be set to a specific CCT.

For both illuminance and spectrum, an MCDA was performed to compare several alternatives representing a wide range of possible design choices. In addition, significant interaction effects (i.e., variation in one attribute leading to altered performance of a different attribute) were studied.

To score the alternatives relative to each other, multi-attribute utility theory (MAUT) [76, 84] was employed. Each alternative was given a utility score ranging from 0 to 1 for each of the design criteria, with 0 representing no utility and 1 representing an ideal alternative.

Instead of determining utility curves via expert judgements as was done in [76], this study calculated utility scores mathematically using data from the literature where possible or from other practical methods (e.g., survey research, analysis of market prices and specified product luminous efficacy). This provided a simplified, more objective process of scoring the alternatives and helped avoid any bias caused by arbitrarily assigning utility values. Regression models were used to estimate missing data points

a b c d

Figure 3.2 Illustrations approximating illuminance orders of magnitude. a) 0.01 fc (0.1 lx). b) 0.1 fc (1 lx). c) 1 fc (~10 lx). d) 10 fc (~100 lx).

Figure 3.3 Simulated spectrum alternatives. a) 5000K. b) 4000K. c) 3000K. d) 2700K. e) 2200K. f) amber (~1800K).

where necessary. The survey research used to determine the perception utility for light spectrum is detailed in 3.5.3.

Utility scores for positive design criteria (where a maximum value is desirable, e.g., visibility, feelings of safety, comfort) were calculated using Equation (1):

$$u_i = \frac{x_i}{x_{max}} \tag{1}$$

where u_i is the utility score of an alternative for criterion *i,* x_i is the value of the metric used to score the alternative for that criterion, and x_{max} is the maximum value of that metric for all tested alternatives.

Utility scores for negative design criteria (where a minimum value is desirable, e.g., crime rate, light pollution impacts, cost) were calculated using Equation (2):

$$u_i = 1 - \frac{x_i}{x_{max}} \tag{2}$$

Using this scoring system, for positive criteria a score of 1 was assigned to the best case achievable among the alternatives analyzed (e.g., best visibility, feelings of safety and comfort, and energy efficiency within alternatives), and a score of 0 represents the absolute worst case possible (e.g., zero visibility, feeling very unsafe/uncomfortable, zero energy efficiency); for negative criteria a score of 1 represents the theoretical best case possible (e.g., no crime/accidents, no light pollution, no cost) and a score of 0 was assigned to the worst values found among the alternatives studied (e.g., highest crime/accident rate, greatest light pollution impacts, and highest cost). The possible scores for each criterion thus range from a baseline of the maximum or minimum theoretically possible value to an extreme value found within the range of alternatives. In some cases, several subcriteria were combined to derive the score for a criterion, and thus neither the 1 nor 0 point may appear among the alternatives. Due to the nature of this scoring system, the score of each alternative should primarily be interpreted relative to other alternatives rather than as an absolute measure of utility. The formulation of different possible scoring systems for this analysis could be the topic of future research.

Following scoring by criterion, the total score of each lighting alternative was calculated by taking the sum of the score for each criterion multiplied by that criterion's weight, as shown in Equation (3):

$$U = \sum w_i u_i = w_1 u_1 + w_2 u_2 + \cdots + w_n u_n \tag{3}$$

where U is the total score for the alternative, w_i is the weight of criterion i, u_i is the utility score of the alternative for criterion i, and n is the total number of criteria ($n = 8$). The total scores of the illuminance and spectrum alternatives analyzed in this study, as well as the scores for each criterion, are given in Tables 3.2 and 3.3. The data used to score the alternatives are included in 3.5.4 and 3.5.5.

3.3. RESULTS

Based on the total scores calculated for the illuminance and spectrum alternatives, an ideal lighting design was determined by incorporating the alternatives scoring the highest. This design provides the best balance between the eight design criteria considered in this study. Additional considerations which could affect the feasibility of implementing this design are also discussed.

3.3.1. Illuminance. The illuminance alternative scoring the highest relative to the others is 0.01 fc (0.1 lx), or approximately the brightness of a full moon [85]. This lighting level is more than two orders of magnitude lower than typical illuminance values

Table 3.2 Scores for illuminance alternatives.

Criterion	Functionality	Perception	Human Health	Night Sky	Animals	Plants	Energy	Cost	**Total**
Data Source	[11, 67, 86, 87]	[7]	[23, 86, 88, 89]	[90, 92, 98]	[88, 89]	[55]	[93, 98]	[93, 100]	
Weight	0.156	0.065	0.120	0.042	0.073	0.071	0.249	0.224	
10 fc (~100 lx)	0.600	0.730	0.000	0.000	0.000	0.000	0.000	0.000	**0.141**
5 fc (~50 lx)	0.587	0.892	0.089	0.038	0.076	0.076	0.564	0.468	**0.418**
2 fc (~20 lx)	0.571	0.876	0.207	0.133	0.176	0.176	0.820	0.681	**0.559**
1 fc (~10 lx)	0.560	0.741	0.297	0.248	0.252	0.252	0.906	0.752	**0.612**
0.5 fc (5 lx)	0.555	0.627	0.386	0.398	0.328	0.328	0.950	0.789	**0.651**
0.2 fc (2 lx)	0.617	0.515	0.491	0.622	0.428	0.428	0.977	0.811	**0.701**
0.1 fc (1 lx)	0.599	0.446	0.556	0.775	0.504	0.504	0.986	0.819	**0.723**
0.01 fc (0.1 lx, approx. full moon)	0.462	0.255	0.772	0.973	0.697	0.697	0.994	0.826	**0.755**

Table 3.3 Scores for spectrum alternatives.

Criterion	Function-ality	Perception	Human Health	Night Sky	Animals	Plants	Energy	Cost	**Total**
Data Source	[11. 66]		[23, 110]	[23, 110]	[51]	[23, 110]	[94, 101, 105]	[99, 100, 106]	
Weight	0.156	0.065	0.120	0.042	0.073	0.071	0.249	0.224	
5000K	0.652	0.914	0.000	0.000	0.000	0.018	1.000	0.291	**0.477**
4000K	0.641	1.000	0.194	0.092	0.065	0.000	0.993	0.290	**0.501**
3000K	0.601	0.965	0.467	0.289	0.155	0.000	0.955	0.285	**0.530**
2700K	0.593	0.931	0.563	0.370	0.187	0.030	0.933	0.282	**0.540**
2200K	0.583	0.850	0.696	0.571	0.244	0.045	0.880	0.247	**0.542**
PC Amber	0.557	0.764	0.924	0.825	0.302	0.111	0.744	0.153	**0.524**
Narrowband Amber	0.558	0.764	0.971	0.921	0.515	0.435	0.461	0.000	**0.468**

recommended for public lighting systems [107]. Levels below 0.01 fc were excluded from this analysis due to a greater potential for insufficient hazard detection at night [67], which is taken to be a critical factor for good quality lighting.

Despite its selection as the optimal alternative, a light level of 0.01 fc could present a design dilemma, as it provides a minimal level of obstacle detection capability [67] and – despite reduced illumination being associated with lower crime rates in the study used for this analysis [11] – is associated with negative safety perception [7]. If greater visibility and perceived safety is deemed to be necessary, higher illumination levels may be called for. An interesting detail to note is that an illuminance of 0.2 fc (2 lx) scores highest for functionality in this analysis. In [66, 67], approximately 0.2 fc is identified as an inflexion point below which visual performance drops steeply, at least for a surface reflectance of 0.20. As certain assumptions were made in the calculation of the utility indices and surface reflectance can vary in real-world scenarios, this finding could be flawed to some extent, and the ideal illuminance could be different for specific cases. A more precise study of how illuminance affects visibility and safety perception for case-specific conditions and demographics, as well as the determination of minimum acceptable illuminance, should be topics for future research.

3.3.2. Spectrum. The spectrum alternative scoring the highest is 2200K, with 2700K following closely behind. Considering the estimated uncertainty in the criteria weights, assumptions made in the calculations, and a lack of complete and/or statistically significant data in the literature for some of the metrics, 2200K and 2700K can be considered virtually tied. 2200K better fulfills the objective of light pollution reduction compared to 2700K, but 2700K would include benefits of better utility and economy.

Color temperatures higher than 2700K increase light pollution significantly while not providing much benefit to utility or economy, whereas amber light would further reduce light pollution but bring greater drawbacks to functionality, perception, energy efficiency, and cost. It is important to note that if the energy efficiency and cost effectiveness of amber LEDs increase enough in the future, narrowband amber would become the preferred alternative.

3.3.3. Interaction Effects. An interaction effect between illuminance and lamp spectrum was found where visibility declined more steeply at low illuminances (< 0.2 fc) when warmer-colored lighting was used [66]. As 2000K HPS lighting was used to compute visibility vs. illuminance in the literature used for this analysis [67], the use of a higher color temperature could result in lower required illumination levels for acceptable visibility. Another interaction effect was found in data from [66] where visibility dropped more significantly for elderly subjects than for younger subjects with reduced illuminance; however, this effect was only pronounced below 0.2 fc. This should be taken into consideration when designing lighting systems for other applications with a greater proportion of elderly people. Other possible interaction effects between illuminance and spectrum were not analyzed in this study but could become the topic of future research.

3.3.4. Final Design Recommendation. Based on the results of this multi-criteria design optimization, the recommended LED lighting design for the exterior pedestrian areas of the Missouri S&T campus is an illuminance on the order of 0.01 fc and a color temperature of 2200K or 2700K. A lighting level above 0.2 fc is not recommended, as it would increase energy usage, cost, and light pollution without increasing functionality.

3.3.5. Limitations. There are several limitations of this research that could be addressed in future studies. The survey data collected for weighting the design criteria and gauging public perception of different light spectra is limited in scope and represents the collective opinion of a specific group of people. The utility scoring system, while it provides consistency and objectivity through a mathematical model, scores alternatives in a somewhat relative manner. The data used to evaluate alternatives were often limited and sometimes inconclusive, and assumptions had to be made in several instances. This research also determined optimal lighting attributes independently of each other, not formally accounting for any interaction effects. Other alternatives such as filtered LEDs or non-LED technologies were not accounted for as well, nor were other lighting attributes such as distribution and mounting height.

3.4. CONCLUSION

This research addresses the lack of a comprehensive lighting design that adequately factors in people, the environment, and economics. Through a multi-criteria decision analysis consisting of AHP and MAUT methods, ideal illuminance and spectrum specifications for an exterior pedestrian LED lighting design were determined based on functionality, public perception, health and environmental impacts, energy use, and cost. The findings of this study support a lower illuminance level than conventional recommendations prescribe, as well as the use of a warm white spectrum. This design is anticipated to be acceptable for visibility while minimizing light pollution, energy consumption, and cost. Future research should study the applicability of these findings for different lighting applications. This methodology can also be used as a framework for other design optimization problems.

3.5. SUPPLEMENTAL MATERIALS

This subsection contains additional materials from this study, including details from the survey research conducted, the methodology for weighting subcriteria for functionality and perception, and the data used for scoring the lighting alternatives.

3.5.1. List of Items for Criteria Weight Survey. All pairwise comparisons from the criteria weight survey are shown in this section in Table 3.4.

Table 3.4 Pairwise comparisons for design criteria weight survey.

Criterion	*Survey Item*	*vs.*	*Survey Item*	*Criterion*
Functionality	Actually being safe		Feeling safe	Perception
Perception	Aesthetically pleasing lighting		Lighting that provides good visibility	Functionality
Functionality	Having well-illuminated walkways		Being able to sleep well at night	Human Health
Human Health	Reduced cancer and depression risk		Reduced crime and trip/fall risk	Functionality
Functionality	Safety and visibility while walking at night		Seeing the stars and milky way	Night Sky
Functionality	Safety and security at night		Protection of animals and insects	Animals
Plants	Benefiting the health of trees		Finding your way around at night	Functionality
Functionality	Good lighting for walking at night		Energy efficient lighting	Energy

Table 3.4 Pairwise comparisons for design criteria weight survey. (cont.)

Criterion	*Survey Item*	*vs.*	*Survey Item*	*Criterion*
Cost	Lower tuition		Added safety at night	Functionality
Perception	Feeling more secure outside at night		Being able to sleep better	Human Health
Night Sky	Beautiful stars		Beautiful lighting	Perception
Perception	Aesthetically pleasing lighting		Animal friendly lighting	Animals
Plants	Protecting plants and trees		Feeling secure walking at night	Perception
Perception	Lighting that makes you feel secure		Energy efficient lighting	Energy
Cost	Cost effective lighting		Aesthetically pleasing lighting	Perception
Human Health	Receiving good quality sleep		Seeing a star-filled sky	Night Sky
Human Health	Healthy people		Healthy animals	Animals
Human Health	Healthy people		Healthy plants	Plants
Energy	Reduced energy consumption		Reduced depression and cancer risk	Human Health
Human Health	Better sleep at night		Lower tuition	Cost
Animals	Protecting animals		Protecting the night sky	Night Sky
Night Sky	Protecting the night sky		Protecting trees	Plants
Energy	Energy efficient lighting		Night sky friendly lighting	Night Sky

Table 3.4 Pairwise comparisons for design criteria weight survey. (cont.)

Criterion	*Survey Item*	*vs.*	*Survey Item*	*Criterion*
Night Sky	Night sky friendly lighting		Cost effective lighting	Cost
Animals	Protecting animals		Protecting plants	Plants
Energy	Energy efficient lighting		Animal friendly lighting	Animals
Animals	Protecting animals		Saving money	Cost
Energy	Conserving electricity		Protecting trees	Plants
Plants	Plant/tree friendly lighting		Cost effective lighting	Cost
Cost	Saving money		Saving energy	Energy

3.5.2. Method of Weighting Functionality and Perception Subcriteria. Due to the limited extent of the survey, which was designed to directly weight only the eight primary design criteria, subcriteria weights for functionality and perception were estimated using Equation (4) instead of conducting separate AHP calculations.

$$w_k = w_i * \frac{\overline{a_k} * \overline{v_j}}{\sum(\overline{a_k} * \overline{v_j})} \tag{4}$$

where w_k is the weight of subcriterion *k* of criterion *i*, w_i is the final weight of criterion *i*, $\overline{a_k}$ is the average preference (from 1/9 to 9) of subcriterion *k*, and $\overline{v_j}$ is the average unadjusted weight of opposing criteria *j* in the pairwise comparisons containing subcriterion *k.* As an illustration, the feelings of safety subcriterion of the perception criterion was paired against functionality, human health, plants, and energy (average unadjusted weight = 0.152) in the survey and was preferred by a factor of 0.567. The other perception subcriterion, comfort/aesthetics, was compared against functionality, night sky, animals, and cost (avg. unadjusted weight = 0.118) and preferred by a factor of 0.275. The estimated weight of the feelings of safety (FoS) subcriterion is thus given as follows:

$$w_{FoS} = 0.065 * \frac{0.567 * 0.152}{0.567 * 0.152 + 0.275 * 0.118} = 0.047$$

which is about 73% of the weight of the entire perception criterion. The subcriteria weights for functionality and perception are given in Table 3.5.

Table 3.5 Functionality and perception subcriteria and their weights.

Criterion	*Subcriterion*	*Weight*
Functionality	Crime/Collisions	0.058
	Visibility (Safety)	0.059
	Visibility (Wayfinding)	0.039
Perception	Feelings of Safety	0.047
	Comfort/Aesthetics	0.018

3.5.3. Color Perception Survey. The perception utility scores for light spectrum were determined through a survey given to university students, predominately from the Missouri S&T Civil, Architectural, and Environmental Engineering department. Participation was voluntary, and no compensation or incentives were offered in exchange for participation. The survey consisted of three pictures simulating 5000K, 2700K, and amber (~1800K). These pictures, shown in Figure 3.4, were created using the method described in 3.2.2. Pictures were displayed in a random order to prevent bias.

a b c

Figure 3.4 Simulated photos for the perception survey. a) 5000K. b) 2700K. c) 1800K.

Respondents were asked to rate their agreement on a 5-point Likert scale with the following statements:

- “I would feel safe walking around in this area”
- “This lighting is aesthetically pleasing and comfortable to be around”

Next, the three pictures were shown side by side, and respondents were asked to indicate which light color would make them feel the safest and the least safe, as well as which color is most and least aesthetically pleasing and comfortable to be around. An opportunity to explain these preferences or indicate no preference was given. Responses were vetted for consistency, and any instances where the Likert scale ratings were inconsistent with the preferences given in the side-by-side comparison were removed. A total of 56 responses were received, of which six were removed for the feelings of safety

(FoS) portion and nine for the comfort and aesthetics portion (FoS: n = 50, 55% female; Comfort: n = 47, 48% female). Between-participant consistency was measured by calculating the ICC in SPSS software for all responses with complete data for both portions (n = 42). The calculated ICC (0.858, 95% CI: 0.642–0.976) represents moderate to excellent reliability between participants [83].

Results were obtained by averaging the responses for each portion. In addition, a separate analysis was performed after separating data by gender to understand any differences that may be present based on this demographic. Results are assumed to provide a valid data source for designing lighting for Missouri S&T's campus. The overall and gender-separated results are shown in Table 3.6 and Figures 3.5 and 3.6.

Table 3.6 Color perception survey data. Scoring ranges from -2 to 2, with a value of 0 representing a neutral response.

	CCT	*5000K*	*2700K*	*1800K*
Feelings of Safety	Composite	1.080	0.980	0.480
	Male	1.182	1.091	0.636
	Female	1.000	0.852	0.296
Comfort/ Aesthetics	Composite	0.149	0.532	0.000
	Male	0.208	0.542	-0.250
	Female	0.091	0.500	0.182

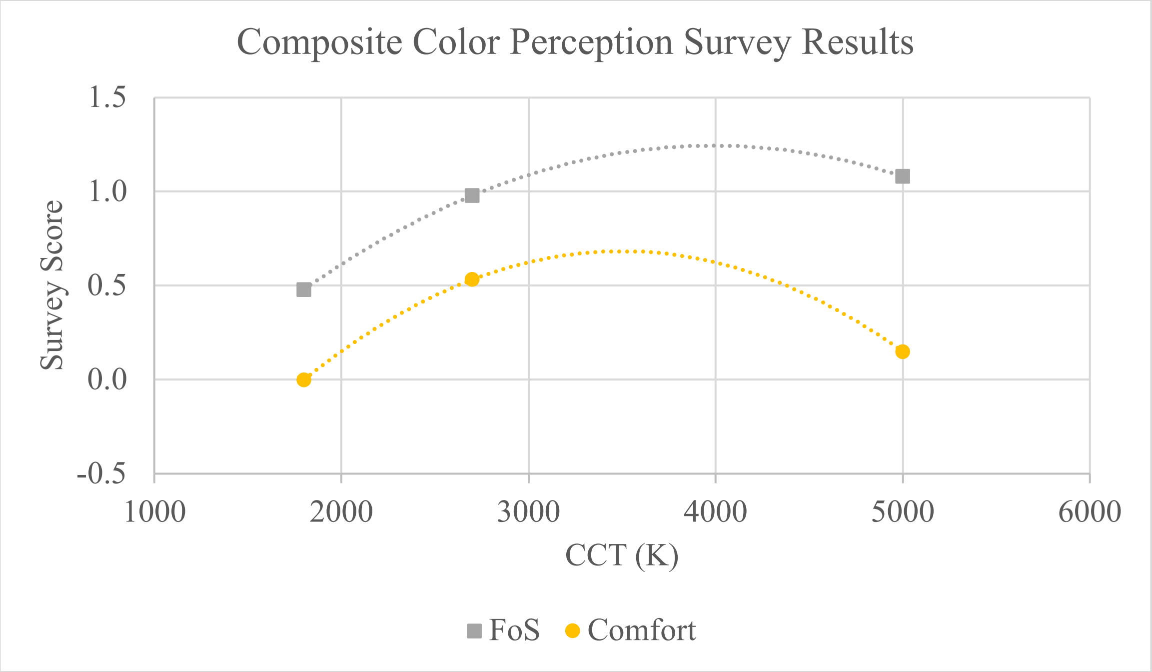


Figure 3.5 Composite feelings of safety (FoS) and comfort scores, with interpolated values between tested color temperatures.

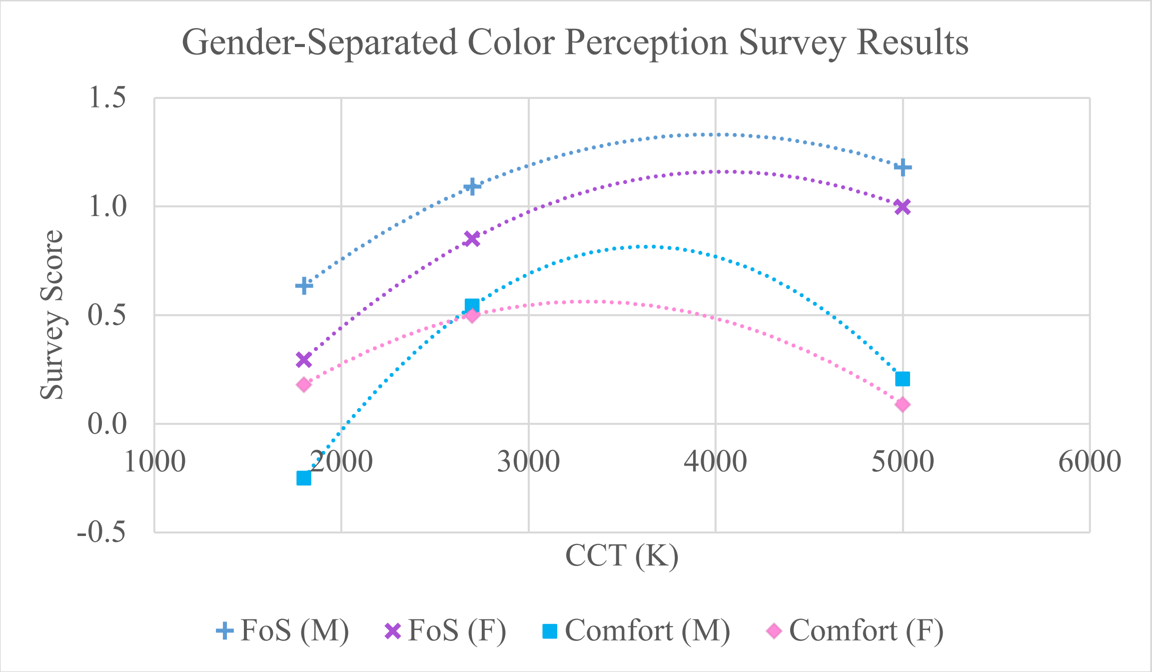


Figure 3.6 Gender-separated survey scores, with interpolated values between tested color temperatures.

3.5.4. Data Used for Illuminance Utility Scores. The data used to determine the utility scores for illuminance alternatives are discussed in this section. Where necessary, data were interpolated or extrapolated to determine utility scores for unknown illuminance values.

3.5.4.1. Functionality. Functionality was determined using three subcriteria: crime and collisions, visibility for safety, and visibility for wayfinding.

Aggregate crime and collision rate ratio data from [11] was used for the first subcriterion. This study covered more than 60 jurisdictions over multiple years and found weak evidence of reduced crime with dimming. A literature review on the topic of lighting and crime shows several studies with conflicting data, linking various street lighting interventions such as increased illuminance with reduced crime rates [109]. However, of those studies directly linking increased street lighting to reduced crime, none cover as large a sample size as the study used in this analysis. Furthermore, it should be noted that the recommended design alternatives from this research do not change if crime and collision data are neglected.

When interpreting crime and collision data, full brightness was assumed to be 8 lx (0.7 fc), as 2-15 lx is recommended for residential roads per the British Standards Institution (BSI) [86]. “Dimmed” lights were assumed to be at half of this brightness (4 lx). Data is shown in Figure 3.7. Crime and collision rates for levels greater than 8 lx were assumed to be equal to those at 8 lx.

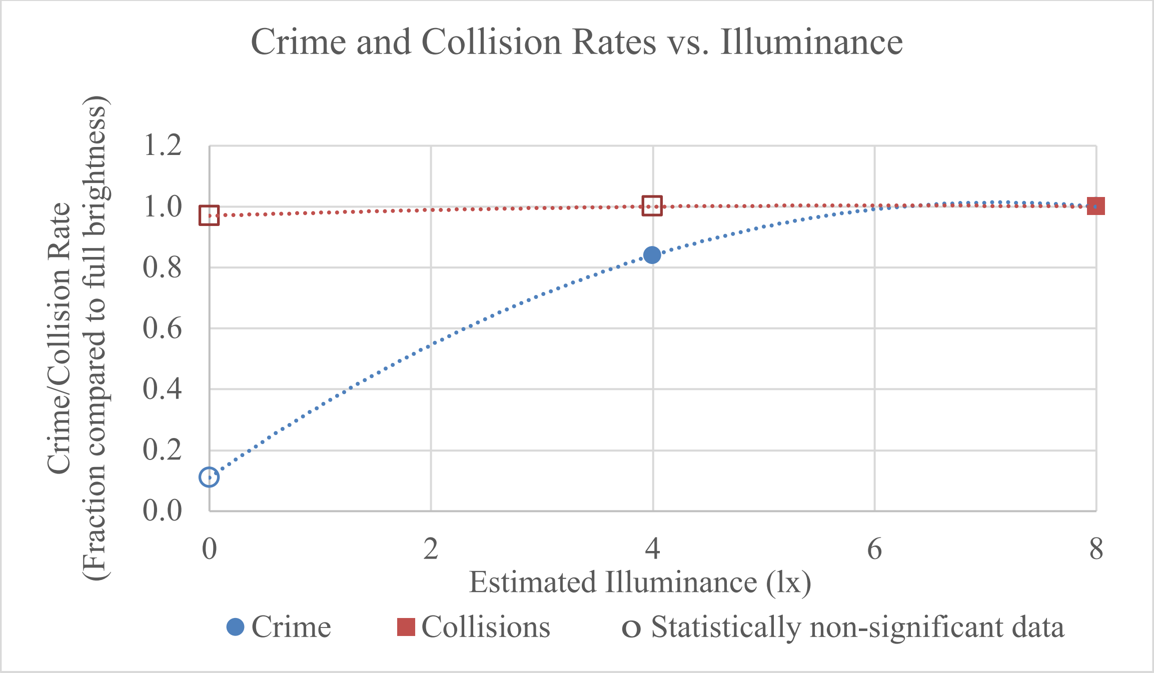


Figure 3.7 Estimated crime and collision rates vs. illuminance, from [11].

Obstacle size that can be detected with 95 percent probability [67] at a given illuminance, shown in Figure 3.8, was used to score alternatives with regards to visibility for safety. Visibility was calculated as the reciprocal of the obstacle size. In [67], an illuminance of 0.10 lx (0.01 fc) was required to achieve 95 percent detection of an obstacle with a height of 25 mm (~1 in) from a distance of approximately 2 paces (1200 mm, ~3.94 ft). For this analysis, 0.01 fc was thus taken to be the minimum acceptable illuminance for safety. Future research could more precisely determine the minimum required illuminance for visibility at night in different settings.

The visibility for wayfinding subcriterion was scored using navigation speed, which was taken as the reciprocal of the time required to navigate through a space with varying levels of emergency lighting [87], shown in Figure 3.9.

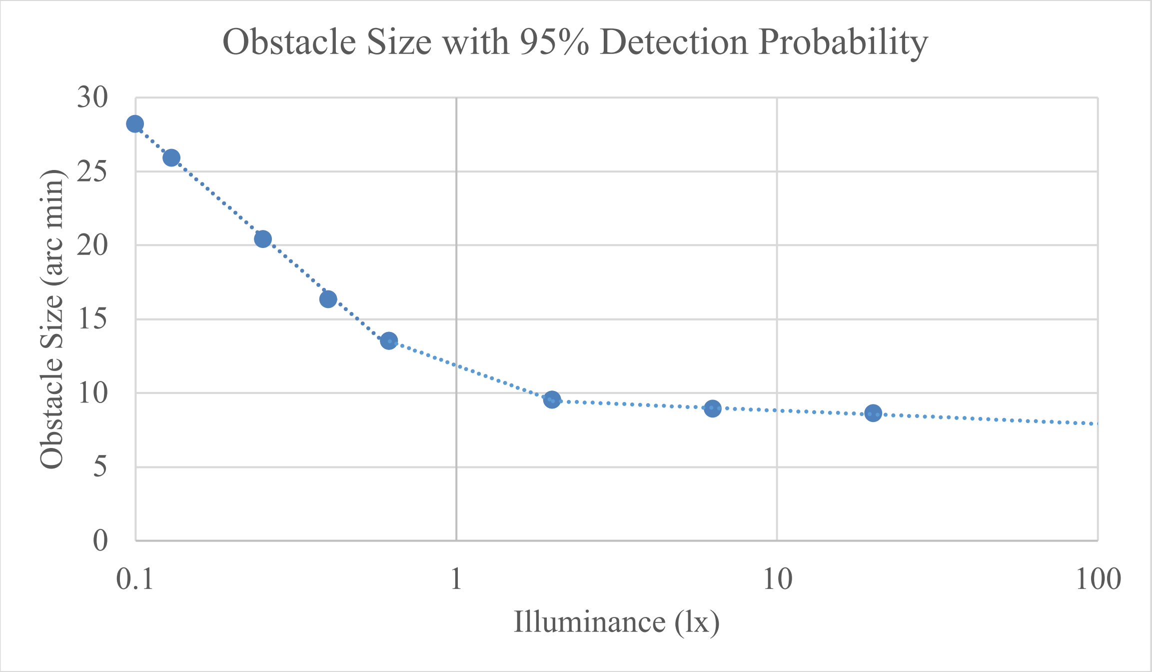


Figure 3.8 Obstacle size with 95 percent detection probability vs. illuminance, from [67].

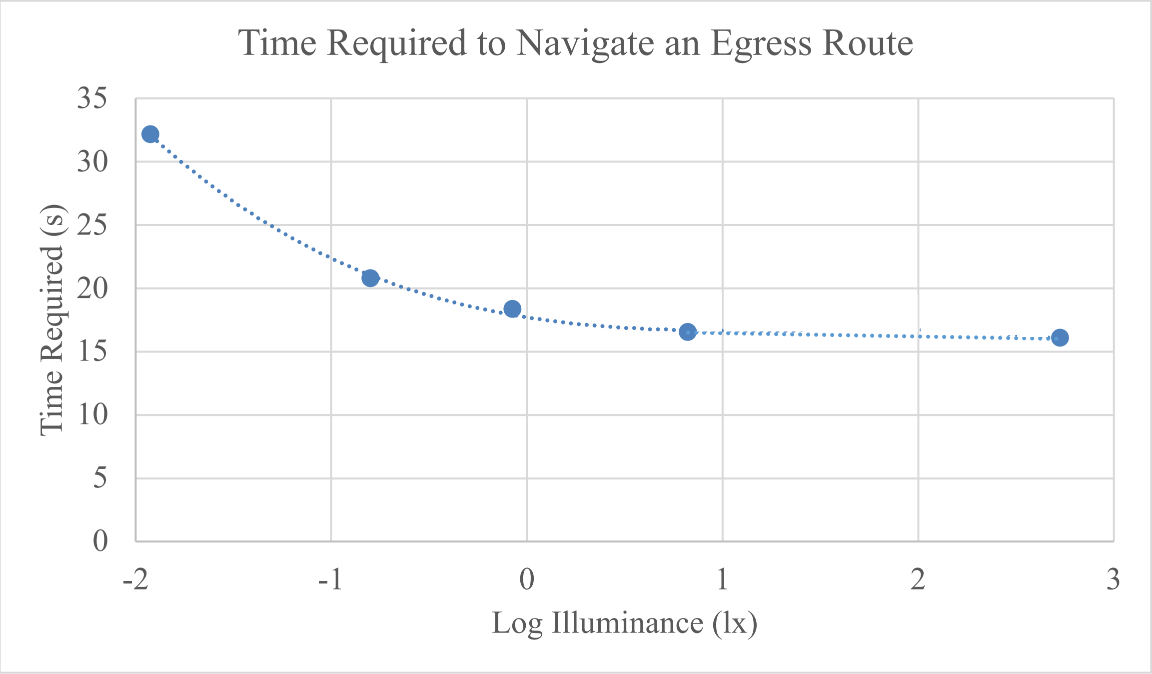


Figure 3.9 Time required to navigate through an egress route under emergency lighting, from [87].

3.5.4.2. Perception. Perception was determined using two subcriteria, feelings of safety and comfort/aesthetics. Perceived safety vs. illuminance, obtained via survey data in [7], was used for the first subcriterion and is shown in Figure 3.10.

Perceived lighting quality vs. illuminance, obtained via survey data in [7], was used for the comfort/aesthetics subcriterion and is shown in Figure 3.11. Data was extrapolated for lower and higher illuminance levels, using zero as the lowest possible value.

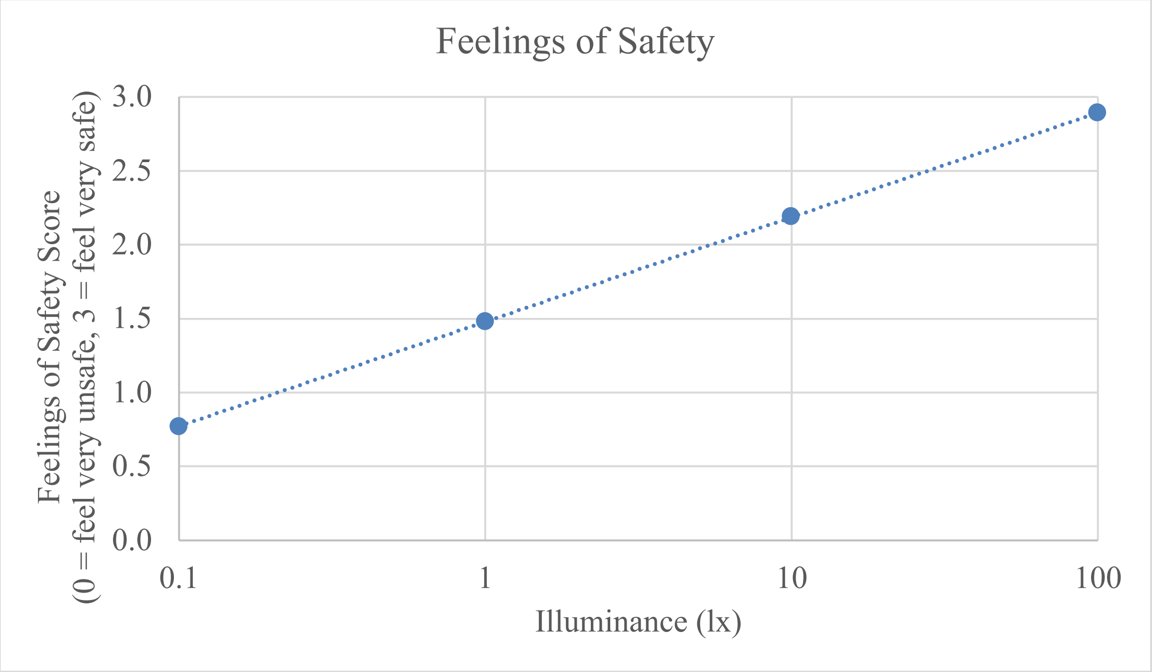


Figure 3.10 Perceived safety vs. illuminance, from [7].

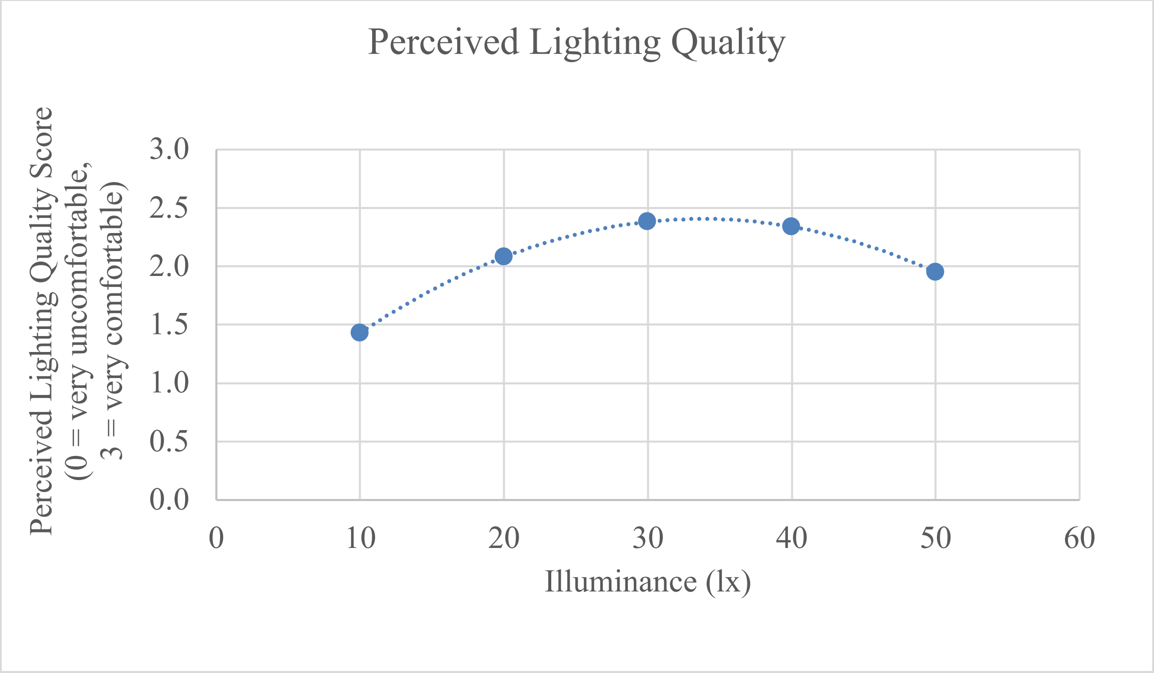


Figure 3.11 Perceived lighting quality vs. illuminance, from [7].

3.5.4.3. Human health, animals, and plants. The impact of illuminance on human health was assumed to be primarily caused by melatonin suppression. It was assumed that illuminance in bedrooms would be a more accurate gauge of people's exposure to light at night than outdoor illuminance. In this analysis, bedroom illuminance was approximated as 25 percent of outdoor illuminance, based on an observation of approximately 2 lx in urban bedrooms by [23] and an estimated 8 lx typical outdoor lighting levels per BSI standards [86], which recommend 2-15 lx for residential roads. Data relating melatonin suppression and photopic illuminance was gathered from [89], as shown in Figure 3.12, showing an approximately logarithmic relationship.

Impacts on animals were also assumed to be predominately caused by melatonin suppression, based on [88]. It was assumed that the relationship between illuminance and melatonin suppression is the same with animals as it is with humans, and that 100 percent of the outdoor illuminance affects wildlife.

Impacts on plants were assumed to follow the same approximately logarithmic relationship as melatonin suppression, based on data in [55] linking changes in spring budburst timing to artificial illuminance levels. Therefore, the utility score for plants was assumed to be equal to the score for animals.

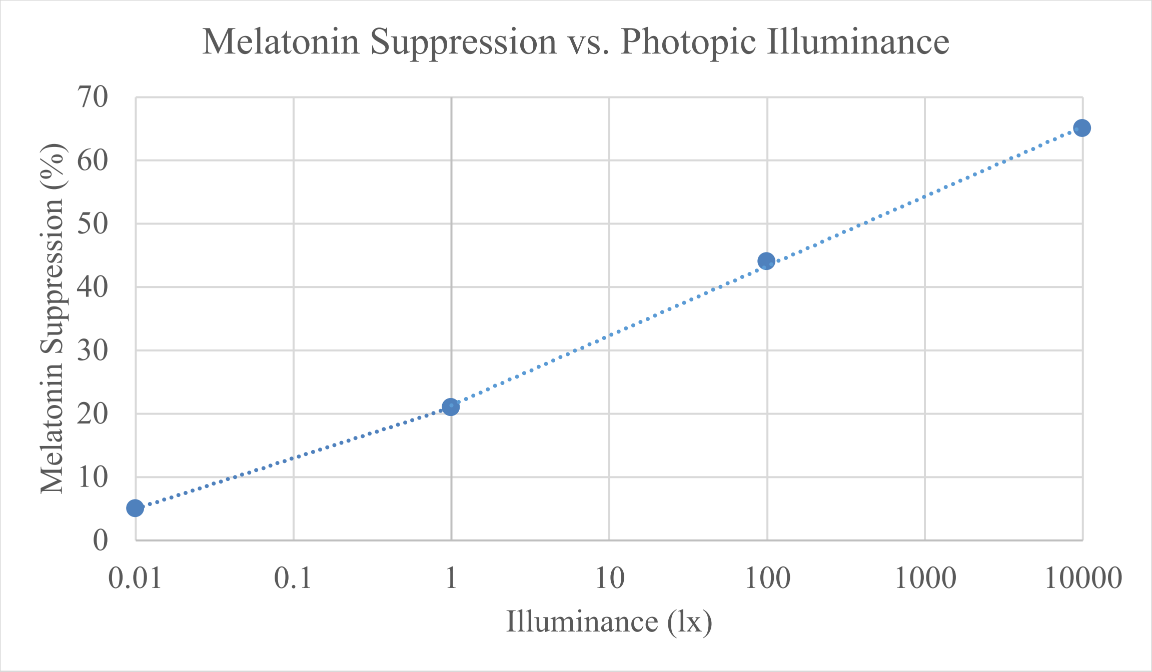


Figure 3.12 Melatonin suppression vs. photopic illuminance, from [89], showing an approximately logarithmic relationship.

3.5.4.4. Night sky. The estimated number of visible stars in the sky was used for the night sky utility score. The relationship between visible stars and sky brightness, shown in Figure 3.13, was estimated based on data included in [90]. Illuminance at the Missouri S&T campus was estimated as 2 fc based on the provided lighting plans [98]. The artificial sky luminance was estimated as 1.450 mcd/m^2 in this location using an atlas of artificial brightness [92]. Supported by [91], sky brightness corresponding to other illuminance alternatives was determined by assuming a directly proportional relationship between ground illuminance and artificial sky brightness.

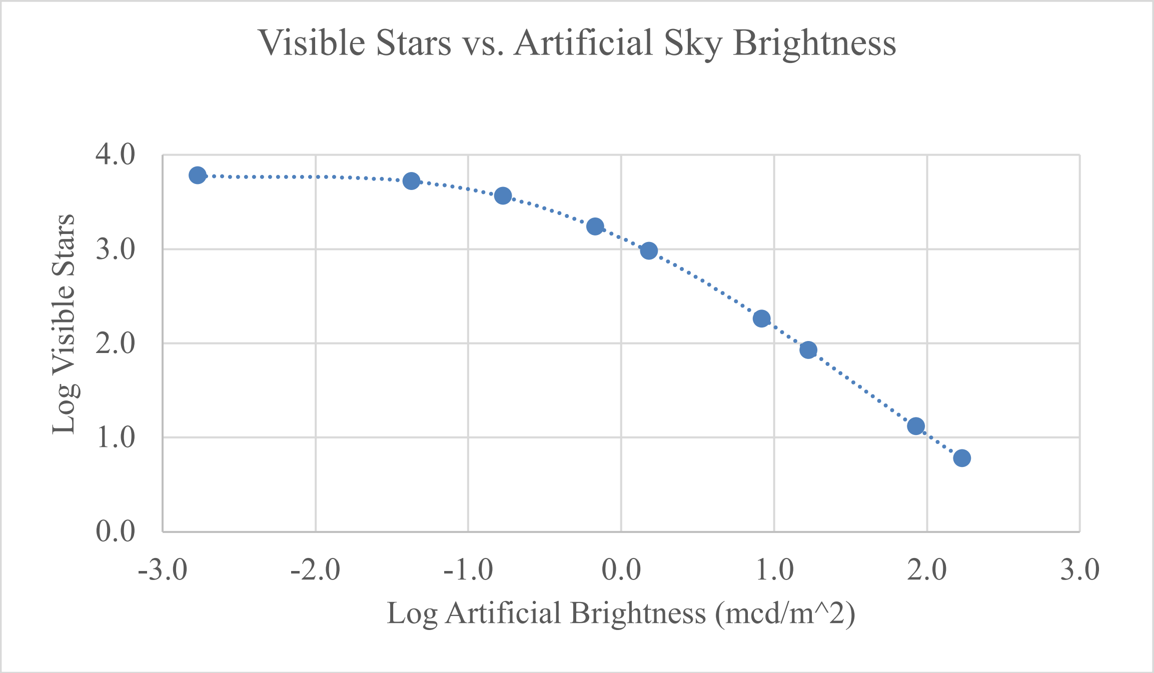


Figure 3.13 Visible stars vs. artificial sky brightness from data in [90].

3.5.4.5. Energy. Required wattage to achieve a target lumen output, shown in Figure 3.14, was determined using product data [93-97]. Assuming 10 luminaires per acre (estimated using campus lighting plans [98]), the required luminous flux was calculated using Equation (5):

$$\Phi = E * A/LMF \tag{5}$$

where Φ is the required lumens, A is the area to be illuminated and LMF is the lumen maintenance factor, assumed to be 0.85 based on a selection of product specifications [93-96]. Based on campus lighting plans [98], a density of 10 luminaires per acre was used when calculating total wattage.

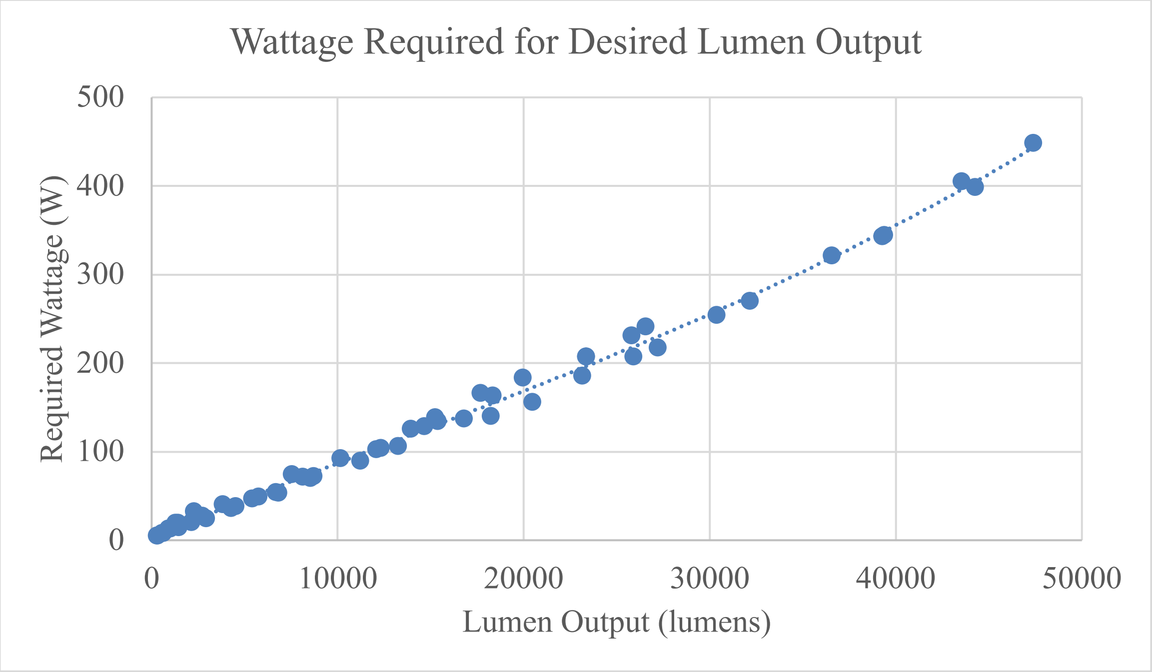


Figure 3.14 Required luminaire wattage to achieve a desired lumen output, from [93-97].

3.5.4.6. Cost. Capital and 20-year energy costs, assumed to be the primary costs of LED luminaires, were used for the cost utility score. The calculations accounted for a 1-acre area to be illuminated with 10 luminaires. Capital cost was calculated based on the average cost vs. rated luminaire wattage of several product lines, shown in Figure 3.15. Energy costs were determined using local electricity rates for street and outdoor customer-owned area lighting [99] and required wattage as previously determined for energy index.

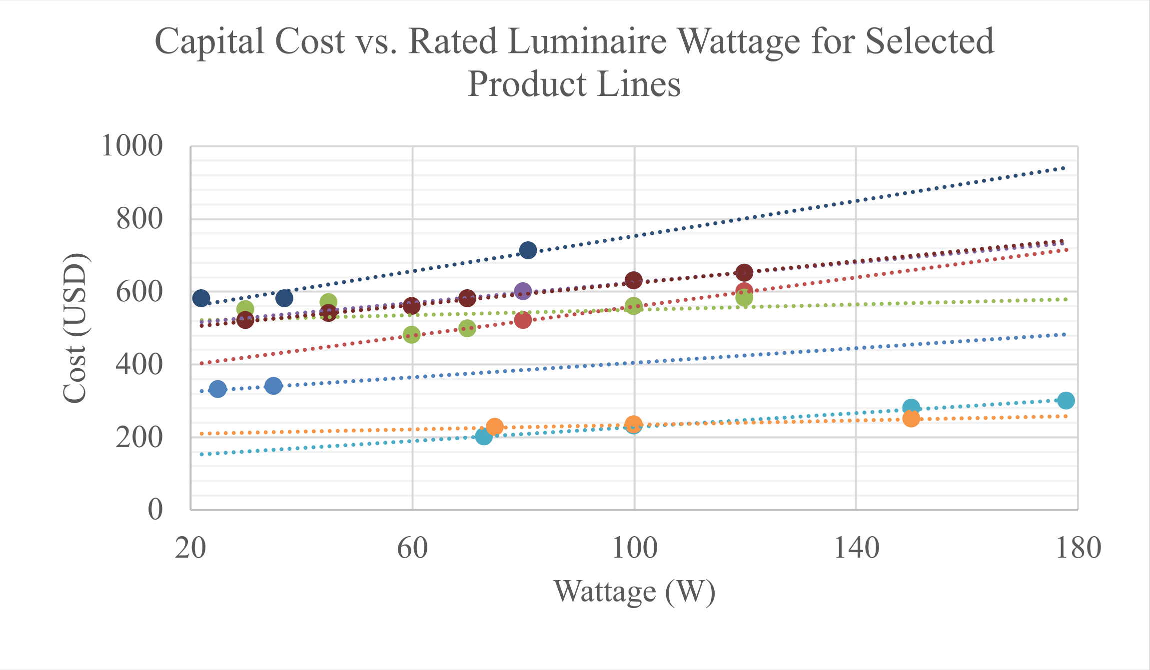


Figure 3.15 Capital cost vs. rated luminaire wattage of several product lines from [100]. The average cost from this data was used in determining the cost utility.

3.5.5. Data Used for Spectrum Utility Scores. The data used to determine the utility scores for spectrum alternatives are discussed in this section. Data were interpolated or extrapolated when necessary for determining utility scores. Where data on narrowband amber LED was lacking, this alternative was assumed to be equivalent to low pressure sodium (LPS) lighting.

3.5.5.1. Functionality. As with illuminance, aggregate crime and collision data from [11], shown in Figure 3.16, was used to score the crime and collisions subcriterion. "White" light was assumed to be 2200K-5000K LED, whereas the two amber alternatives were categorized as "non-white."

Obstacle detection data from [66], shown in Figure 3.17, was used to determine visibility vs. spectrum. Data was extrapolated for higher and lower color temperatures.

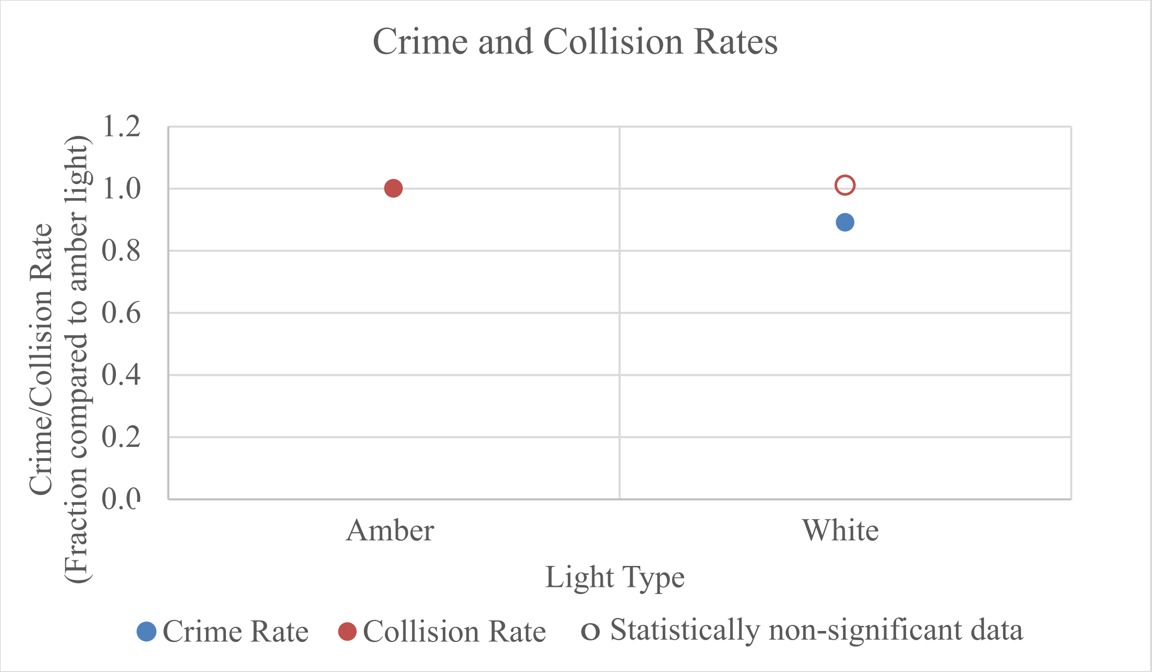


Figure 3.16 Relative crime and collision rates vs. spectrum, from [11].

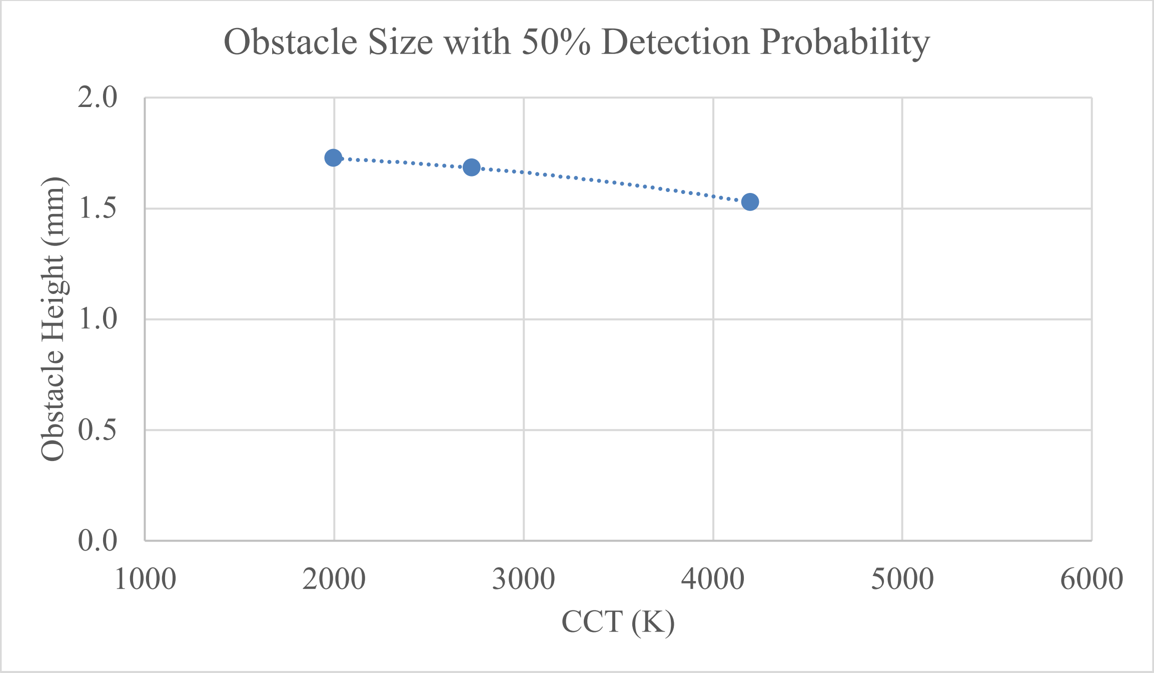


Figure 3.17 Obstacle size with 50 percent detection probability vs. color temperature of light source, from [66].

3.5.5.2. Perception. For perception, the feelings of safety and comfort/aesthetics subcriteria were scored using the composite data from the color perception survey, shown in Figure 3.5 in 3.5.3. Data were interpolated between the three color temperatures included in the survey, resulting in an estimated optimal color temperature of roughly 4000K for safety perception and 3500K for comfort and aesthetics.

3.5.5.3. Human health. The melatonin suppression index formulated by Aubé, Roby, and Kocifaj [23] was used to score spectrum alternatives with regards to human health. An average index value for each spectrum alternative, shown in Figure 3.18, was taken from multiple products included in a database stemming from their research [110]. Actual product specified color temperatures vary up to ±200K from the alternative they represent. Narrowband amber LED was assumed equivalent to LPS.

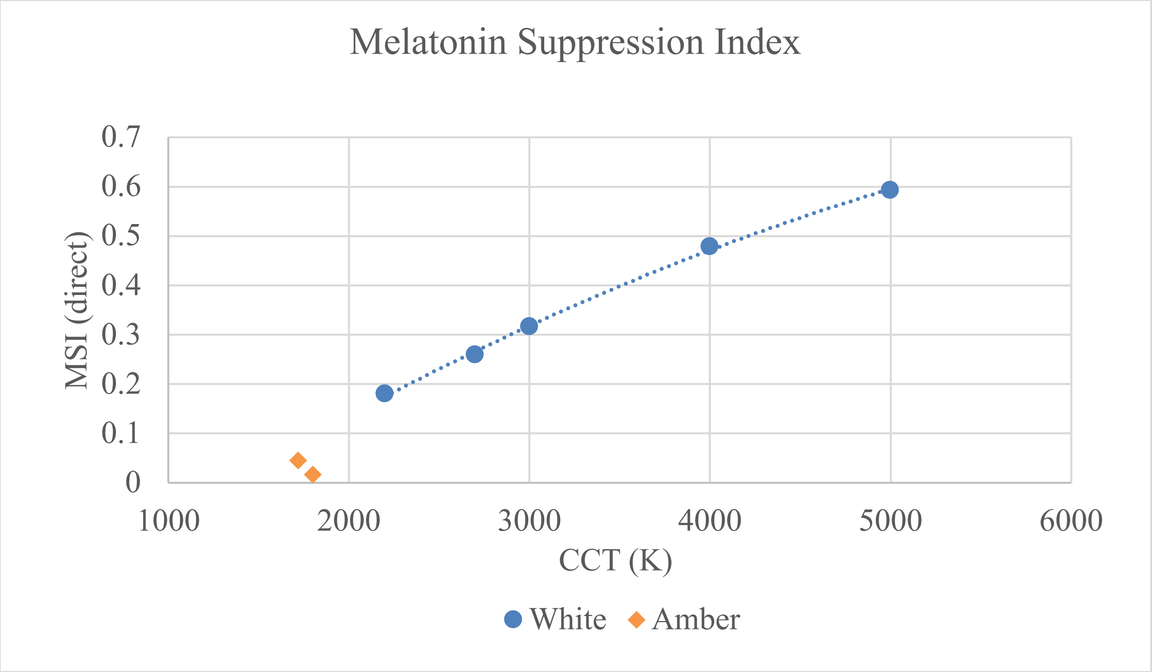


Figure 3.18 Average melatonin suppression index (MSI) vs. spectrum, from the Lamp Spectral Power Distribution Database (LSPDD) [110].

3.5.5.4. Night sky. The star light index (clear sky, 0 km distance) [23] was used to calculate the night sky utility. Average values of the direct star light index for multiple products representing each spectrum alternative, shown in Figure 3.19, were calculated from data included in [110] and corrected for atmospheric scattering based on data found in [23]. Actual product specified color temperatures vary up to ±200K from the alternative they represent. Narrowband amber LED was assumed equivalent to LPS.

3.5.5.5. Animals. The wildlife index formulated by Longcore *et al.* [51] was used to calculate the animals utility. Data for the spectrum alternatives is shown in Figure 3.20. Narrowband amber LED was assumed equivalent to LPS.

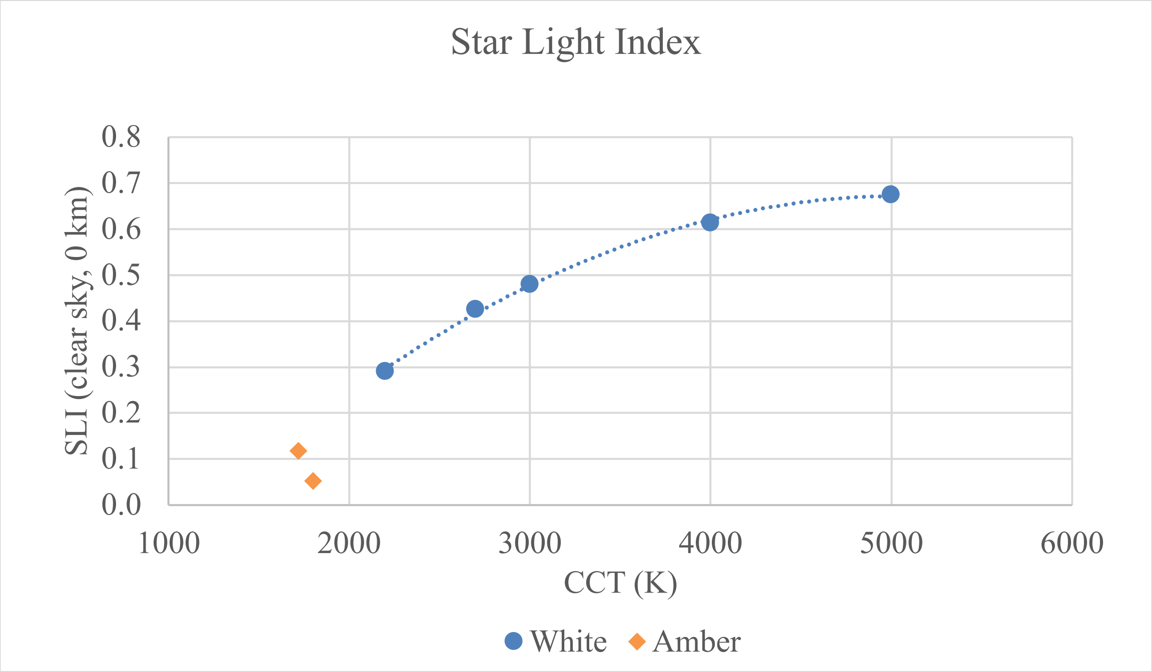


Figure 3.19 Average star light index index (SLI) vs. spectrum, from the Lamp Spectral Power Distribution Database (LSPDD) [110].

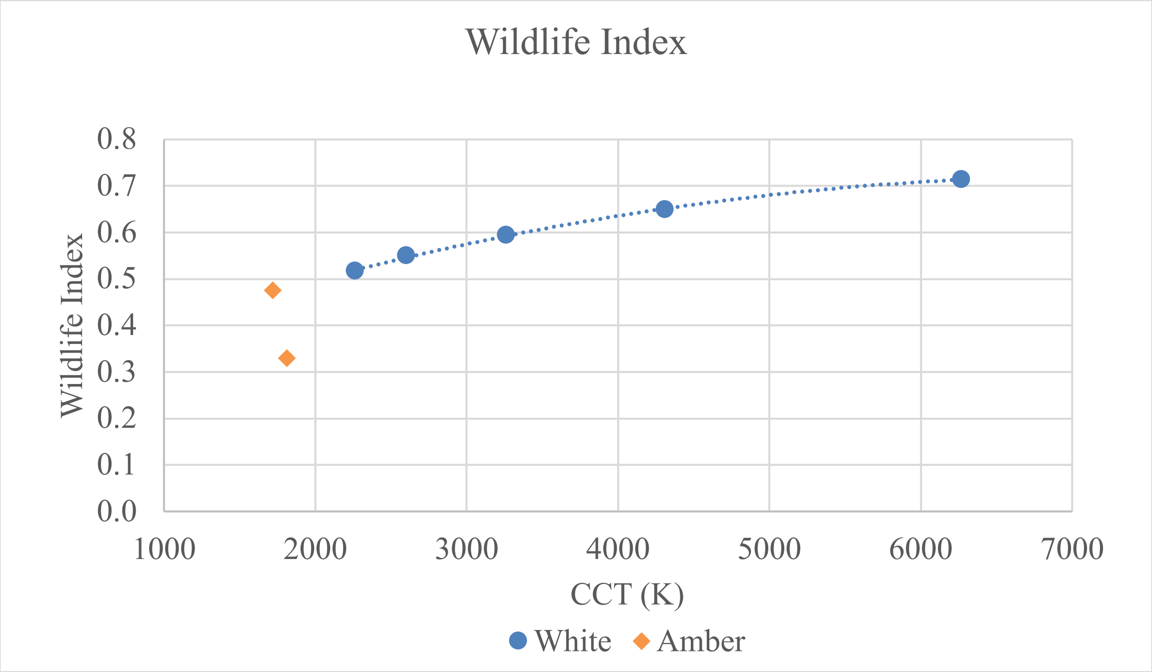


Figure 3.20 Average wildlife index vs. spectrum, from [51].

3.5.5.6. Plants. The induced photosynthesis index [23] was used to calculate the utility score for plants. Average values of the index from multiple products representing each alternative, shown in Figure 3.21, were taken from data in [110] Actual product specified color temperatures vary up to ±200K from the alternative they represent. Narrowband amber LED was assumed equivalent to LPS.

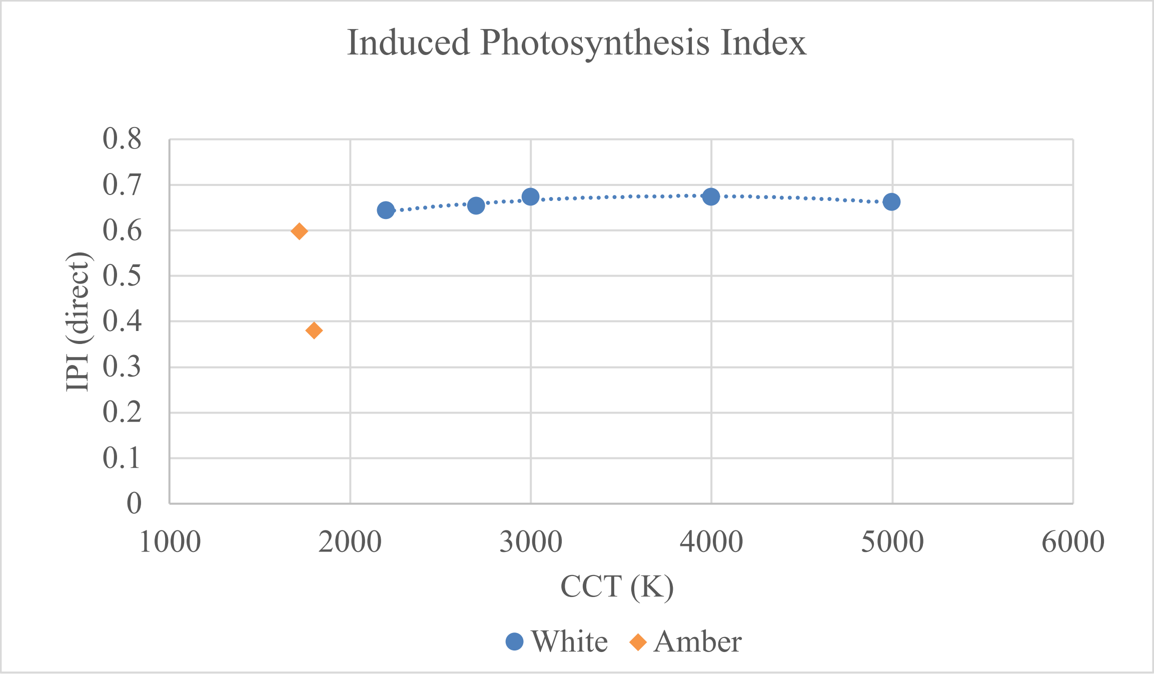


Figure 3.21 Average induced photosynthesis index (IPI) vs. spectrum, from the Lamp Spectral Power Distribution Database (LSPDD) [110].

3.5.5.7. Energy. Luminous efficacy was obtained from available product data [94, 101-105] to determine the energy utility for spectrum. Efficacy of each spectrum alternative is shown in Figure 3.22.

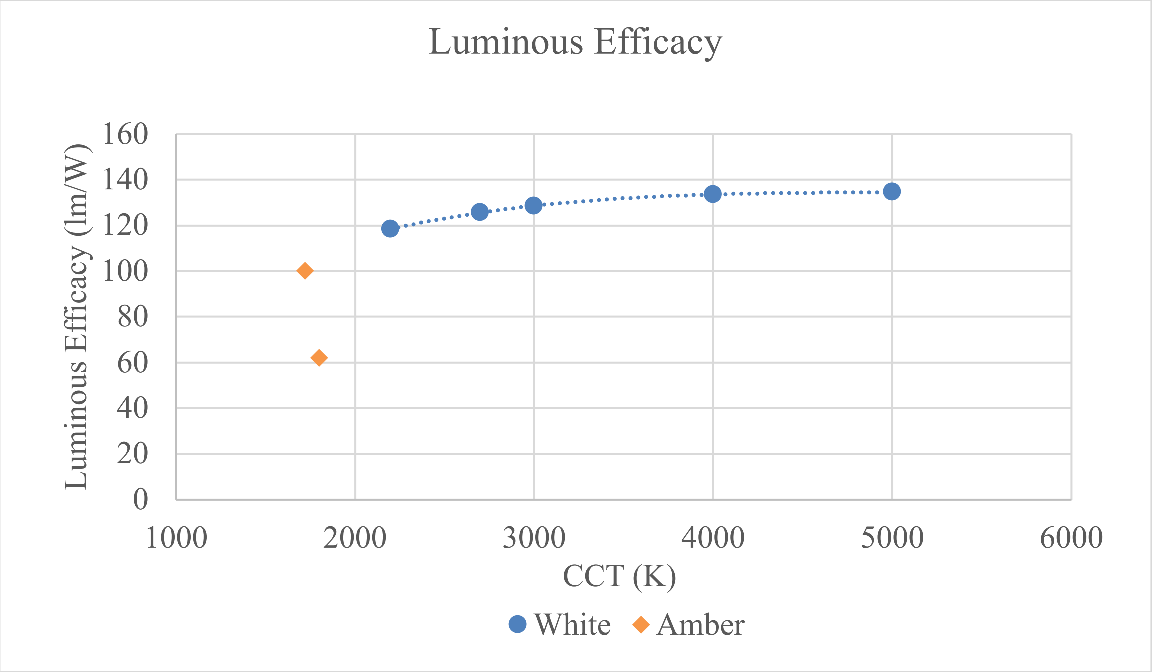


Figure 3.22 Luminous efficacy vs. spectrum, from product data [94, 101-105].

3.5.5.8. Cost. Estimated capital and 20-year energy costs [99, 100, 106] were used to determine the cost utility for spectrum. The relative capital cost of spectrum alternatives, shown in Figure 3.23, was calculated or obtained from suppliers [100, 106] and adjusted for the wattage required to achieve constant illuminance using data from [100]. Relative energy costs were determined using local electricity rates for street and outdoor customer-owned area lighting [99] and required wattage. For calculation purposes, it was assumed that ten luminaires of 8,000 lumens each would be used in a design.

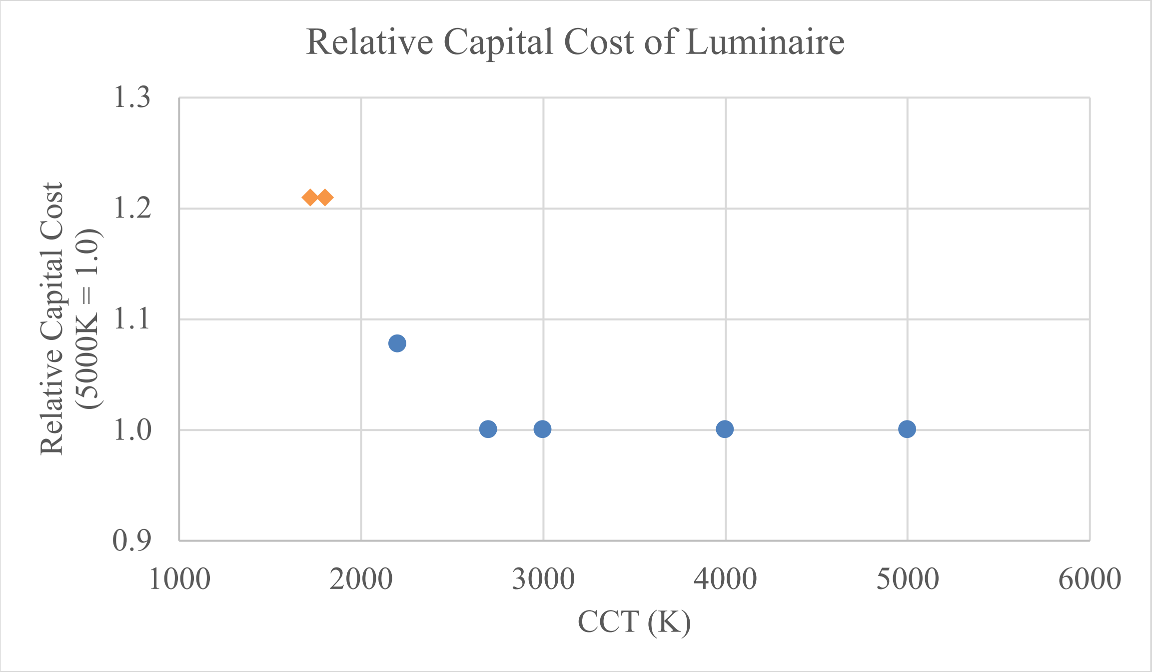


Figure 3.23 Relative luminaire capital cost vs. spectrum, from [100, 106].

4. DESIGNING LIGHTING FOR IMPROVED PUBLIC PERCEPTION AND REDUCED LIGHT POLLUTION USING VIRTUAL REALITY

4.1. INTRODUCTION

In the previous section, data from the literature and survey research were used to optimize outdoor lighting for human, environmental, and economic design criteria at Missouri University of Science and Technology based on the priorities of a sample of students. It was determined that by using a minimal amount of light (0.01 fc), adequate functionality in terms of visibility and safety could still be achieved while reducing the harmful impacts of light pollution, energy consumption, and financial expense. However, despite being selected as the ideal alternative among those tested, a brightness of 0.01 fc is associated with a negative perception of safety and with discomfort among the general population according to a study by Liu *et al.* published this year [7]. In fact, in that study even an illuminance level ten times greater (0.1 fc) was found to roughly correspond to only neutral feelings of safety and comfort, with a significant portion of the population still feeling insecure. This presents a large obstacle to implementing a design with such low levels of illuminance, as exterior lighting is often used to create an environment where people can comfortably move around after dark.

Facing this dilemma, lighting designers are presented with the challenge of giving spaces an acceptable level of perceived safety and comfort at night while also having due concern for the consequences of artificial light at night. Smarter design approaches will be necessary to make lighting systems more human and environmentally friendly while concurrently providing the comfort and sense of security desired by society.

4.1.1. Lighting for Enhanced Public Perception. Work by Dr. Navaz Davoudian provides considerable insight into how such lighting designs could be created going forward. Davoudian's book, *Urban Lighting for People* [19], describes several lighting design techniques for creating more comfortable, navigable spaces while also reducing light pollution. Some of the key concepts emphasized in the text include:

- Designers should engage with people of different demographic groups through observations and interviews to determine how a particular space is used, rather than making assumptions and mindlessly following design standards.
- A visual hierarchy should be created at night through varied lighting levels to give a sense of place and direction, avoiding uniform lighting which both detracts from orientation and increases light pollution.
- Vertical illuminance should be prioritized over horizontal illuminance; minimal light is needed to walk, but the ability to see other people is important for feeling secure and judging an area.
- A space should be defined with light through illumination of façades, boundaries, pavement edges, landmarks, trees, and hazards such as steps. The ability to see the edges and recesses of a space boosts safety perception by eliminating places where others could lurk in the shadows. Ambient lighting can be provided indirectly, avoiding harsh, overly bright light.

Urban Lighting for People also describes case studies showing ways in which these concepts have been implemented to create successful lighting designs. One of these is Granary Square in London, where the book mentions four key elements that combine to create a friendly space for people to enjoy at night. First, the Granary Building's façade is illuminated with uplights, and is brightest towards the bottom to visually ground the building. Second, a series of water pools featured in the area are sometimes left dark and tranquil but can be activated to create a public spectacle of colorful, lighted fountains. Third, trees are illuminated with uplights to make the space more inviting for pedestrians in the area. Finally, the general lighting in this space is not excessively bright and is provided by secondary reflector systems that avoid glare and do not obstruct the view of the building. An illuminance map provided in the text for this area shows most of the space under less than 0.5 fc of horizontal illuminance, yet it was stated that the area is perceived as safe and is well-visited at night.

Other case studies analyzed in this work show mixed results, with the spaces sometimes not being as well-perceived as designers would have hoped. Bright islands of light on the ground and uplit benches, for example, were observed to be avoided by many people. Lighting was also not the only determinant of the popularity and usage of these spaces, as other important components such as open shops in the area and availability of comfortable seating also had a noticeable impact.

Looking at these case studies, it is clear that lighting can have a real positive or negative impact on outdoor areas, influencing how people behave and how they use a space after dark. It is also acknowledged by Davoudian that several other factors, such as available amenities as well as location and reputation, can affect how a space is perceived and used by the public. While lighting cannot be used as a tool in and of itself to make a bad area good, it can be employed strategically through informed design choices to boost the public's perception of a space and increase its usability after dark.

4.1.2. Application to Sustainable Lighting on a University Campus. This research aims to determine whether a university campus such as Missouri S&T could successfully implement a more human-centric, environmentally friendly exterior lighting design that both reduces the harmful impacts of light pollution and boosts public perception of safety, comfort, and aesthetics at night. Principles from *Urban Lighting for People*, such as the creation of a visual hierarchy, are evaluated in comparison to the lighting currently in place. As many university campuses feature multiple buildings and large outdoor spaces owned and operated by a single entity, such a setting could be an ideal location to employ a master-planned lighting design that incorporates buildings, open spaces, and other elements together into a well-designed nighttime environment.

4.1.3. Using Virtual Reality to Test Perception of Lighting. With the development of virtual reality (VR) technology in recent years, a new and exciting method of conducting research has emerged. The ability to immerse people into a simulated scene has great potential to be used for applications such as lighting design optimization, particularly when gauging public perception of multiple design alternatives for a single location, and numerous studies employing VR technology to this end have already been conducted [113]. While the use of virtual reality includes certain limitations, it allows for a controlled comparison of lighting designs and can be used to eliminate confounders such as changes in location, people and other traffic present in the scene, and weather. This current study involves the showing of several VR lighting design simulations set on a portion of the Missouri S&T campus to a selection of students, and collection of feedback for the purpose of evaluating the effectiveness of the different designs.

4.2. RESEARCH METHODS

In this study, multiple lighting designs for an area of the Missouri S&T campus were created and displayed to a selection of students at the university through a virtual reality headset. For each simulation, participants were asked questions about how safe they felt and how comfortable and aesthetically pleasing the lighting was to them, and then they were given the opportunity to elaborate on the reasons for their responses. Responses were analyzed to determine the feasibility of implementing a more environmentally friendly lighting design while achieving an acceptable level of comfort and security among students.

4.2.1. Simulation of Lighting Design Alternatives. The simulations of lighting alternatives for the Missouri S&T campus were built using a multistep process enlisting several software programs. First, as-built drawings of the campus [114] were obtained from the university and viewed using Autodesk AutoCAD 2023. A portion of the drawings containing the area of interest was then imported into Autodesk Revit 2023 software, where the topography, walkways, building façades, lamp posts, and other relevant features were modeled. A point was selected on campus as the spot where participants would virtually view the simulations, and the model was designed to provide a realistic scene from this vantage point. After creating the model in Revit, the scene was then imported into Twinmotion software (versions 2022.2.2 and 2022.2.3) in Epic Games. Here, realistic material textures were added to the scene, and features such as trees and other landscaping were placed. Next, luminaires were modeled to mimic the existing lighting scenario on campus. Interior lighting shining through certain windows and other details such as a projector left on in one of the rooms were also modeled to create a more realistic experience for participants. Additionally, computer-generated people were placed within the simulation, although the area was kept sparsely crowded.

After creating the simulation of campus as-is, three other simulations were built to showcase alternative exterior lighting scenarios. In these other simulations, only the brightness, color, placement, and distribution of exterior luminaires were varied. Interior lighting visible through windows, ambient natural lighting, the night sky, landscaping, people, and other details remained constant in all four simulations to avoid any confounding variables.

4.2.1.1. Simulation of existing exterior lighting. The first simulation was designed to mimic the existing lighting layout on the area of campus analyzed in this study. Visual observations and photographs taken of campus at night were used in the creation of this simulation. Existing lighting mainly consists of daylight LED pole-mounted area luminaires (predominately 5700K correlated color temperature per campus lighting plans [98]). Poles are generally spaced at intervals of 25 to 50 feet, and typical ground-level horizontal illuminance on paved areas ranges from 0.5 to 5 footcandles. Darker areas of around 0.1 to 0.5 footcandles exist, mainly in grassy and landscaped areas near building faces. Images of the simulated existing lighting and photos of campus at night are provided in Figures 4.1-4.3. The simulated light distribution does not exactly match the lighting present on campus, with lower uniformity and a lack of indirect or reflected light occurring in the simulated view. A more thorough discussion of simulation inconsistencies can be found in 4.3.2.

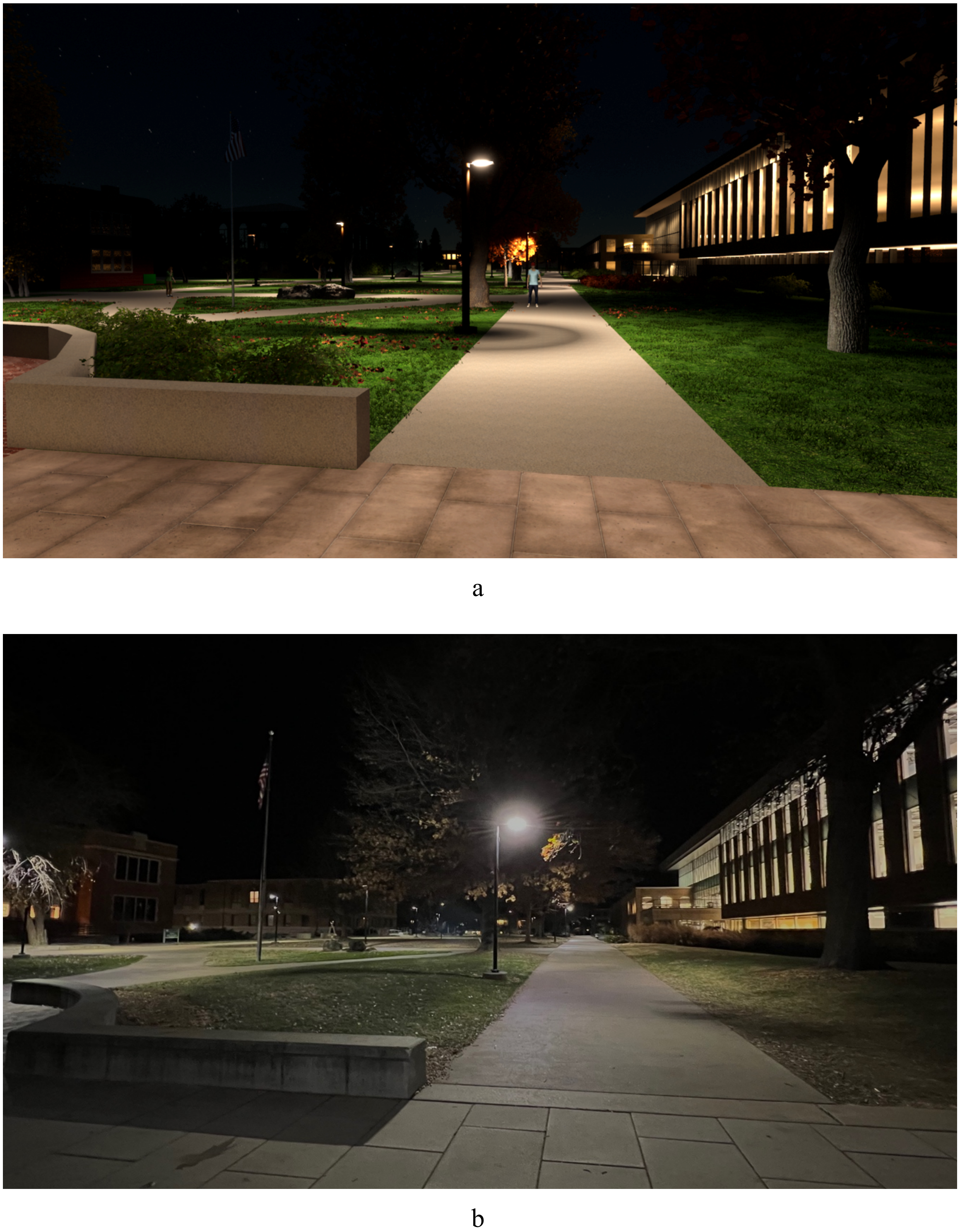
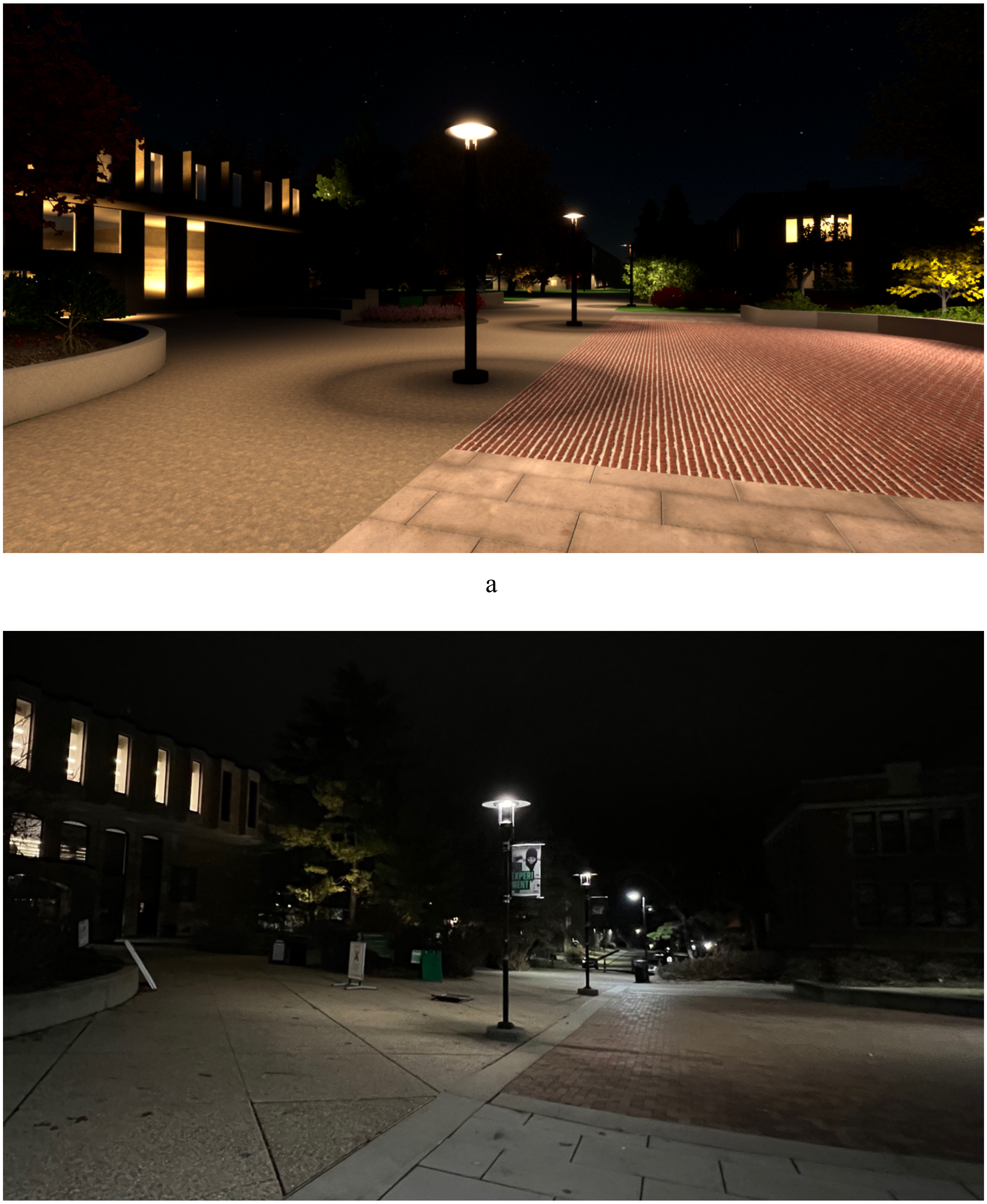


Figure 4.1 Starting view, looking south from the observation point. a) Simulation.
b) Photo of the area.

a

b

Figure 4.2 View looking west from the observation point. a) Simulation. b) Photo of the area, with a burnt-out luminaire affecting the brightness level.



a

b

Figure 4.3 View looking east from the observation point. a) Simulation. b) Photo of the area.

4.2.1.2. Simulation of dimmed existing lighting. The second simulation, shown in Figure 4.4, was generated by decreasing the illuminance of all exterior light sources in the existing scenario to 25 percent of their original levels. As perception of brightness approximately follows a square law curve [115], it was assumed that this would represent a drop in perceived brightness by about half. No other changes to the simulation were made.

a

Figure 4.4 Images from simulation of dimmed existing lighting design. a) Looking south. b) Looking west. c) Looking east.

b

c

Figure 4.4 Images from simulation of dimmed existing lighting design. a) Looking south. b) Looking west. c) Looking east. (cont.)

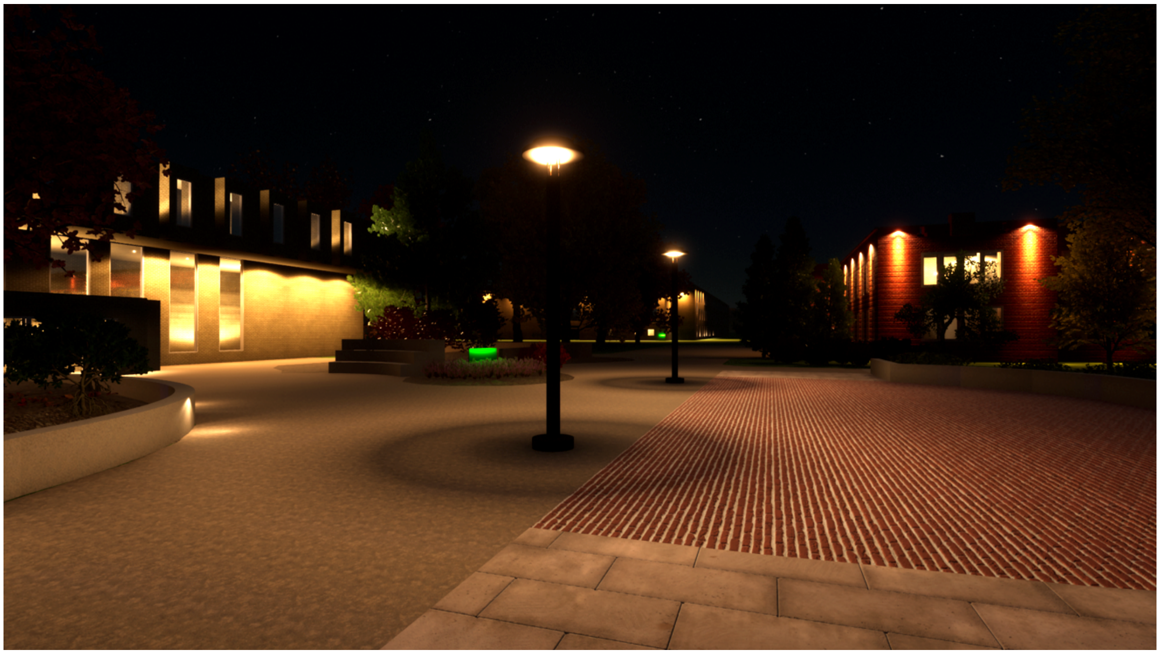
4.2.1.3. Simulation of experimental lighting design. An experimental lighting design was simulated to test the principles promoted in *Urban Lighting for People*. Overhead direct illumination was sharply reduced, and the majority of light poles were removed. Instead, lights were mounted on the faces of buildings to define the boundaries of the space and provide soft, indirect lighting to walkways and green spaces. Unlike the case studies included in *Urban Lighting for People*, lighting in this design was aimed downwards instead of upwards to minimize light pollution. Additional lighting was provided on stairways to assist with hazard detection, as well as on the concrete knee wall near the library entrance to add to the definition of the space and the creation of a visual hierarchy. Finally, green accent lights (representing the school colors) were placed to illuminate the information signs located near building entrances and provide reference points throughout the space.

In this design, the total exterior luminous flux was kept the same as the existing lighting scenario at full brightness; only luminaire type, placement, distribution, and spectrum were changed. Color temperature was lowered to a softer 2700K-3500K on the building faces and 4000K for the area luminaires, with diversity in lamp spectrum further contributing to the definition of buildings and open spaces. Views from this simulation are included in Figure 4.5.

a

b

Figure 4.5 Images from simulation of experimental lighting design at full brightness. a) Looking south. b) Looking west. c) Looking east.



c

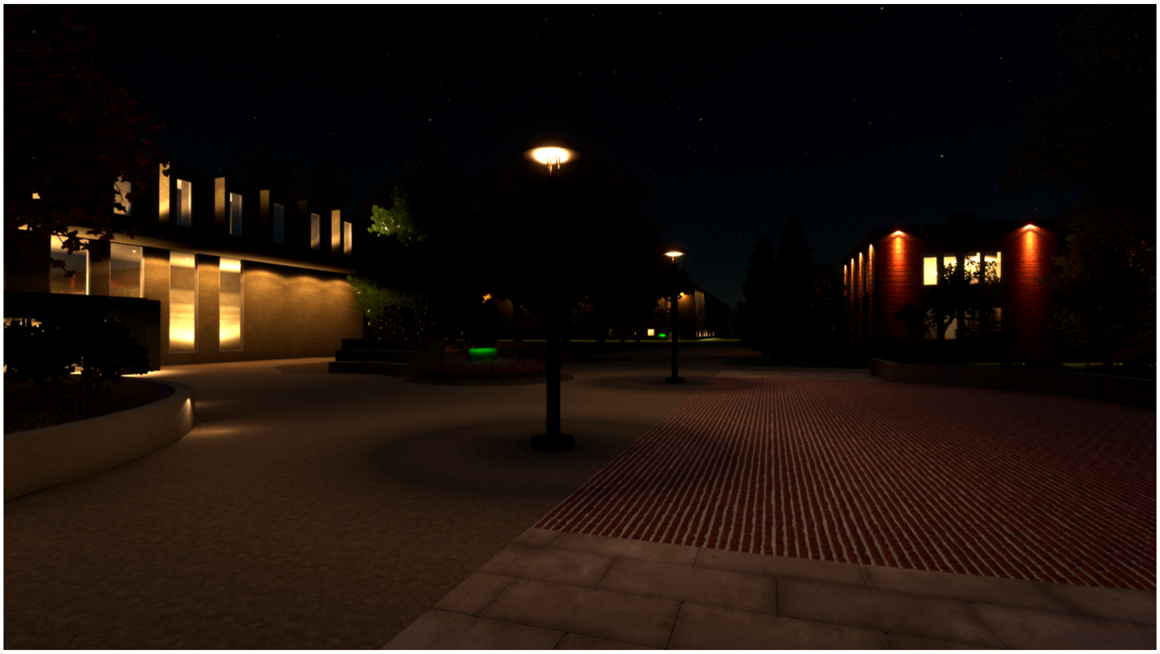
Figure 4.5 Images from simulation of experimental lighting design at full brightness. a) Looking south. b) Looking west. c) Looking east. (cont.)

4.2.1.4. Simulation of dimmed experimental design. The final simulation, shown in Figure 4.6, was created by dimming all exterior light sources of the experimental design to 25 percent of their initial luminous flux. Thus, the total exterior luminous flux was made equal to that of the dimmed existing design while maintaining the experimental design changes implemented in the previous case.

a

b

Figure 4.6 Images from simulation of dimmed experimental design. a) Looking south. b) Looking west. c) Looking east.



c

Figure 4.6 Images from simulation of dimmed experimental design. a) Looking south. b) Looking west. c) Looking east. (cont.)

4.2.2. Presentation of Simulations to Participants. After building the four lighting simulations, each was exported from Twinmotion as a 360-degree panorama to be viewed through an HTC Vive Pro 2 virtual reality headset via SteamVR Media Player. Participants were obtained from among the students attending Missouri S&T; participation was voluntary, and no incentives were offered in exchange for participation or completion of the study. Simulations were presented in random order as determined by a randomizer to minimize order effects and prevent responses from being influenced by the overhearing of other participants.

4.2.3. Gauging of Perception. Determination of the overall perception of each lighting simulation was done in a similar manner to other studies, such as one conducted by Liu *et al.* where participants rated their feelings of safety and perceived lighting quality (comfort) at multiple locations in person [7]. During the presentation of each simulation, the following questions were asked:

- “On a scale from 1 to 5, how safe would you feel if you were walking around in this area?”
- “On a scale from 1 to 5, how comfortable and aesthetically pleasing is this lighting to be around?”

It was clarified to the participants that a score of “1” represents the worst perception (“very unsafe” or “very unpleasing”) and that a score of “5” represents the best perception (“very safe” or “very pleasing”). After responses were received for each question, participants were given the opportunity to explain why they gave the ratings they did, and notes were taken to record their explanations. After the showcasing of the virtual reality simulations concluded, respondents were given the opportunity to provide additional feedback about the simulations, the survey, and their general exterior lighting preferences.

4.3. RESULTS

Responses were obtained from a group of participants (n = 38, 42% female) from the Missouri S&T student body. The mean scores for safety perception and comfort/aesthetic appeal were calculated for the entire group and by gender. Composite and gender-separated perception scores for the four lighting simulations are given in Table 4.1 and Figures 4.7 and 4.8.

Table 4.1 Perception survey data. Ratings range from 1 (very poor) to 5 (very good). A value of 3 represents a neutral response

	Design	*Existing*		*Experimental*	
	Brightness	*100%*	*25%*	*100%*	*25%*
Feelings of Safety	Composite	3.868	3.026	3.737	2.079
	Male	4.045	3.591	3.909	2.636
	Female	3.625	2.250	3.500	1.313
Comfort/ Aesthetics	Composite	3.263	3.184	4.395	3.289
	Male	3.364	3.409	4.273	3.500
	Female	3.125	2.875	4.563	3.000

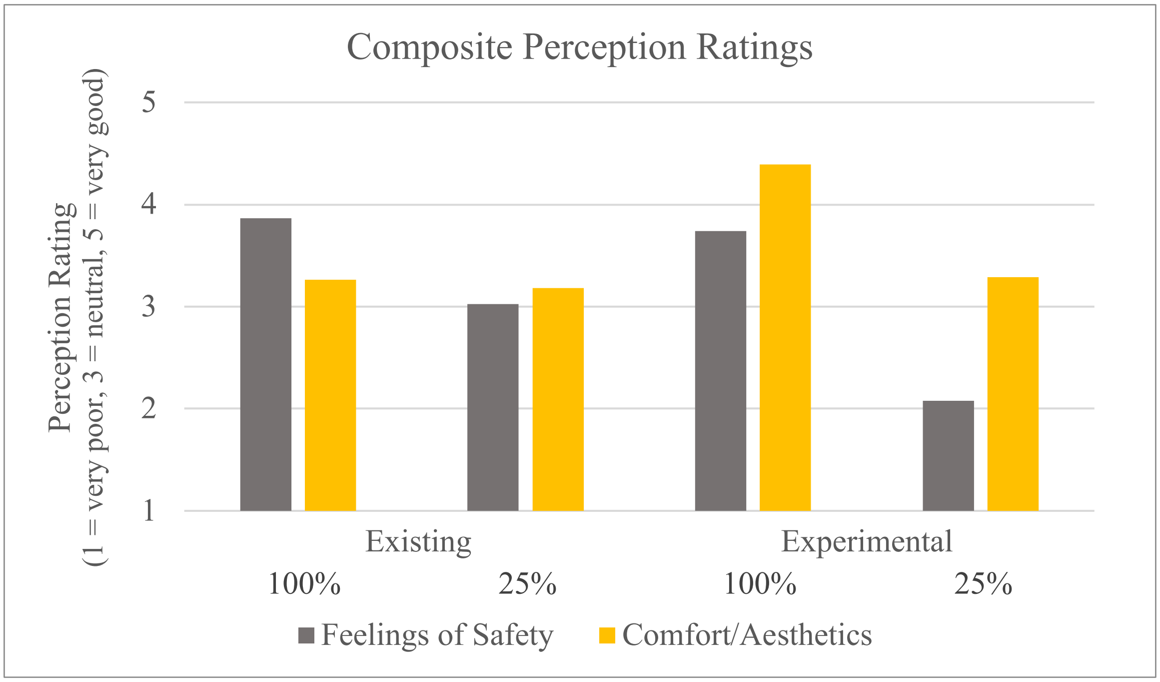


Figure 4.7 Composite feelings of safety and comfort/aesthetics ratings for each design and brightness level.

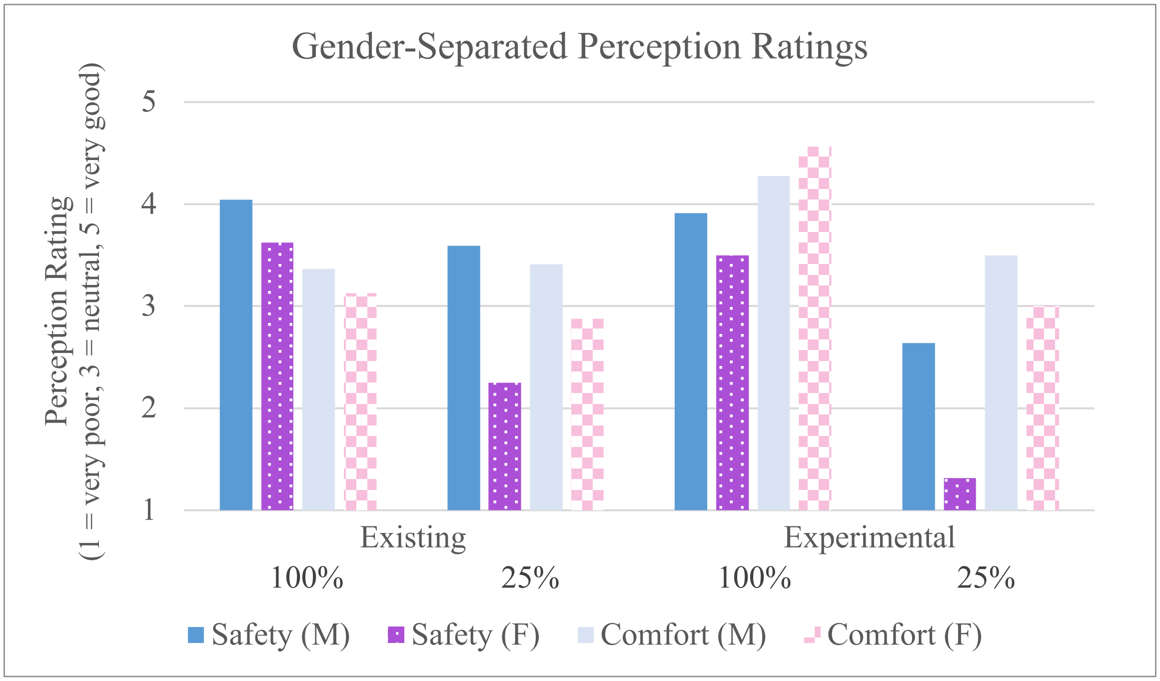


Figure 4.8 Gender-separated ratings.

Between-participant consistency was analyzed for the survey responses using SPSS Statistics software (Version 29). The intraclass correlation coefficient (ICC) was calculated as 0.935 (95% CI: 0.851–0.984) based on a mean-rating, absolute agreement, two-way random model, representing good to excellent reliability [83].

A linear mixed effects model was created to determine the significance of the following categories towards safety and comfort/aesthetics perception: design (existing vs. alternate), brightness (100 percent vs. 25 percent), gender, year in school, and major (Architectural Engineering majors vs. other majors). Participant ID was included as a random intercept to account for between-participant variability. Major was included because a significant portion (15 of 38 participants) were selected from an architectural engineering course offered in the researchers' department. Age was not included in this test, as all but one of the participants belonged to the 18 to 24 age group. It is assumed that participants' year in school at least somewhat corresponds to their age as well as to their familiarity level with campus at night. Variables and their categories are shown in Table 4.2. Data is assumed normally distributed based on an analysis of skewness and kurtosis.

As shown in Table 4.3, design, brightness, and gender are all significant predictor variables for perception of safety. Year in school and major were removed from the model due to non-significant effects. Additionally, interaction effects between design, brightness, and gender were tested. A significant interaction between brightness and gender was found where safety perception for women declined at roughly twice the rate as for men with a decrease in brightness. This interaction is demonstrated in Figure 4.9 (a).

Table 4.4 shows the results of a similarly designed linear mixed effects model for comfort and aesthetics. As with safety perception, year in school and major were removed due to non-significant effects. Brightness was determined to be a significant predictor variable, while design and gender were not. However, a significant interaction was found between design and brightness. As shown in Figure 4.9 (b), when raising the brightness of the lighting, comfort and aesthetic appeal increased by a much greater amount for the experimental design than for the existing design.

Table 4.2 Variables and their categories analyzed in the mixed effects model.

Variable	*Categories*
Safety Perception	1 = very unsafe, 2 = somewhat unsafe, 3 = neutral, 4 = somewhat safe, 5 = very safe
Comfort/Aesthetics	1 = very unpleasing, 2 = somewhat unpleasing, 3 = neutral, 4 = somewhat pleasing, 5 = very pleasing
Brightness	0 = full brightness (100%), 1 (ref.) = dimmed (25%)
Design	0 = existing design, 1 (ref.) = experimental design
Gender	0 = male, 1 (ref.) = female
Year	1 = freshman, 2 = sophomore, 3 = junior, 4 = senior, 5 = super senior, 6 (ref.) = graduate
Major	0 = Architectural Engineering (including dual majors), 1 (ref.) = other major

Table 4.3 Results of the linear mixed effects model for safety perception.

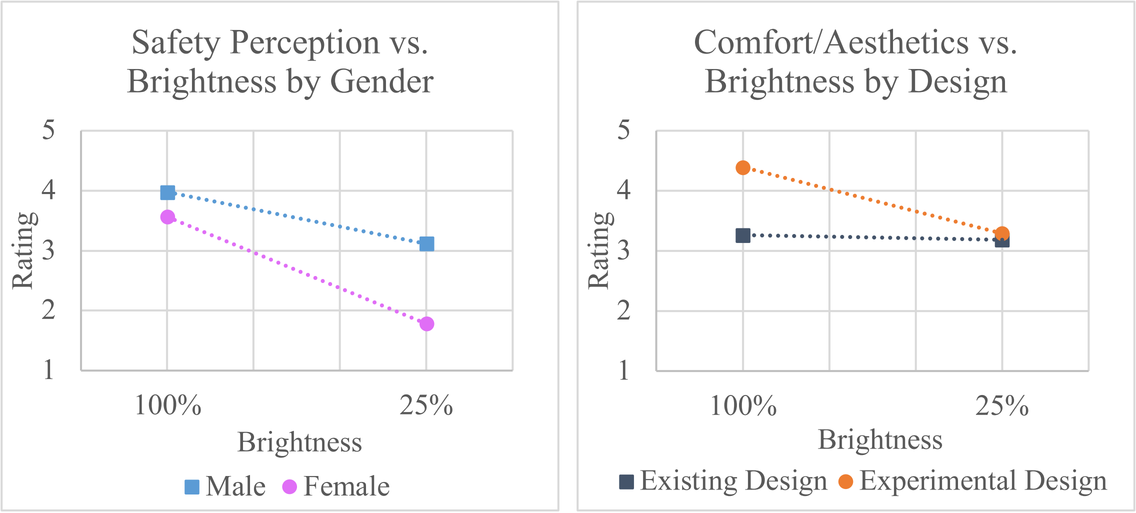
Parameter	*Estimate*	*t-stat*	*p-value*
Intercept	1.512	7.410	< 0.001*
Design = Existing	0.539	3.171	0.002*
Design = Experimental	0	–	–
Brightness = 100%	1.781	6.794	< 0.001*
Brightness = 25%	0	–	–
Gender = Male	1.332	5.468	<0.001*
Gender = Female	0	–	–
Brightness (100%) x Gender (Male)	-0.918	-2.663	0.009*

* = significant result ($p < 0.05$)

Table 4.4 Results of the linear mixed effects model for comfort/aesthetics.

Parameter	*Estimate*	*t-stat*	*p-value*
Intercept	3.147	16.583	< 0.001*
Design = Existing	-0.105	-0.455	0.650
Design = Experimental	0	–	–
Brightness = 100%	1.105	4.774	< 0.001*
Brightness = 25%	0	–	–
Gender = Male	0.246	1.482	0.140
Gender = Female	0	–	–
Design (Existing) x Brightness (100%)	-1.026	-3.134	0.002*

* = significant result ($p < 0.05$)



a

b

Figure 4.9 Visualization of interaction effects. a) Interaction between brightness and gender for safety perception. b) Interaction between brightness and design for comfort/aesthetics.

4.3.1. General Perceptions of Each Simulation. There were notable similarities and differences in perception between the four simulations, both in the composite and gender-separated data. The greatest perception of safety was associated with the existing campus lighting, although there was not a large difference between the existing lighting and the experimental design at full brightness. Feelings of safety declined for the dimmer scenarios, with the existing lighting layout receiving a roughly neutral rating and the experimental design receiving a negative one. It must be noted that walkway illuminance in the "full brightness" experimental design appears closer to that of the dimmed existing lighting than to its full brightness version due to differences in luminaire placement and distribution.

Ratings of comfort and aesthetics were positive for all simulations and were roughly the same for three of the four simulations. The experimental lighting design at full brightness, however, received notably higher ratings for this category than the others, with a composite score between 4 ("somewhat pleasing") and 5 ("very pleasing"). Considering both safety and comfort/aesthetics ratings, this alternative was the favorite among the participants.

In general, males felt safer in all four simulations compared to females, and this difference was most pronounced with the dimmed lighting scenarios. Men also perceived the lighting as more comfortable and aesthetically pleasing than women, except for the experimental design at full brightness where females provided higher ratings.

4.3.1.1. Existing design at full brightness. The simulation of the existing lighting on campus received a positive composite rating for feelings of safety and a roughly neutral rating for comfort and aesthetics. Favorable feedback on illumination levels and visibility was given by a majority of participants, with many of them commenting that the walkways were well lit. Several participants thought the lighting was too bright, at least in certain areas. A large portion of the negative remarks for this simulation were related to a lack of lighting uniformity, with complaints of "dark spots" and "shadows" being made by more than half of the participants. However, these complaints may be the result of simulation inaccuracy and might not reflect participants' views of existing campus lighting (see 4.3.2 for more details).

Regarding the ambiance and appearance of the lighting, a somewhat greater number of negative remarks were received compared to positive ones, with about a third of participants making comments such as "sterile," "bland," and "harsh." Others favored the appearance, labeling it as not too harsh, approving of the overhead lamp poles, or recanting their positive perception of safety under the lighting.

4.3.1.2. Dimmed existing design. The simulation of the existing lighting dimmed to 25 percent brightness received roughly neutral ratings for perception of safety and comfort. On average, males felt neutral to somewhat safe and comfortable, and females felt neutral to somewhat unsafe and uncomfortable. Close to half of the participants provided positive comments regarding visibility and brightness, many stating that the area was well lit at least on the main walkways, and several appreciating that the light did not appear excessively bright. Roughly the same number of participants shared negative opinions, calling the light too dim, especially near the buildings, and insufficient for recognizing the features on the people present in the scene. A handful of participants also expressed concern that “sketchy” activities or victimization could occur, especially in the dark areas. As with the existing lighting at full brightness, more than half of participants expressed a negative perception of the lighting uniformity due to the presence of dark areas. Again, this could be mainly due to inaccuracies in the simulation.

Lighting appearance received roughly the same number of positive and negative comments. Reasons for positive perception included the placement of luminaires, a brightness level that was not excessive or blinding, and a well-perceived illumination of the trees. Negative remarks were mainly due to a lack of illumination highlighting the buildings and poor aesthetics associated with the use of plain light poles.

4.3.1.3. Experimental design at full brightness. The experimental design at full brightness received a positive overall rating for feelings of safety and a strongly positive rating for comfort and aesthetics. Greater than half of the participants provided positive comments on the visibility and brightness level, frequently stating that they could see most if not everything around them; a few described the lighting as too dim. Comments regarding uniformity were roughly split between positive and negative – substantially better than with the first two simulations. Some of those providing positive feedback cited their ability to see beyond the walkways as well as an elimination of unpleasant shadows. Others disagreed, still finding there to be significant shadows or dark spaces.

The aesthetics of this design was very well received. About three quarters of the participants provided favorable remarks, some pleased by the illumination of the building faces and others describing the area as “comfortable” or “romantic.” Several comments were made showing a preference for the warmer-colored lighting used in this design.

4.3.1.4. Dimmed experimental design. The experimental design at 25 percent brightness received a negative response for feelings of safety, with males on average feeling neutral to somewhat unsafe and females feeling somewhat to very unsafe. For comfort and aesthetics, this scenario received a roughly neutral response. A majority of participants provided negative remarks on visibility and brightness level, giving descriptors such as “very dark,” “can’t see much,” and even “no lighting.” Uniformity was not commented on nearly as much as with the other three simulations.

Despite the negative safety perception, this design received positive remarks on comfort and aesthetics from almost two thirds of participants, with several of them stating an appreciation for the illumination of building faces and others expressing favorability towards the atmosphere created by the lighting. However, the lower brightness appeared to decrease the comfort and aesthetic appeal of this alternative compared to simulation three, at least for some. Several participants stated that their comfort level was negatively impacted due to a lack of visibility and/or perceived safety, giving comments such as “Aesthetics and safety go hand in hand.”

4.3.2. Limitations. There were several limitations to the virtual reality simulations that may have affected results. First, the simulations had to be viewed as 360-degree still images instead of as interactive, animated scenes, due to the inability of the computer to provide a smooth viewing experience with this option. This prevented participants from walking around within the scene, eliminated realistic features such as a flag blowing in the wind and leaves falling from the trees, and caused the people in the scene to appear motionless, which may have affected overall perceptions of safety and comfort. However, the still images also likely provided the best means of comparing simulations to each other, as all elements except the exterior lighting remained the same between them.

Another major limitation of the virtual reality simulations involved the illumination levels. While an effort was made to simulate the true distributions of the existing outdoor lighting, it was observed in the simulation of existing campus lighting that bright spots appeared brighter and dark spots appeared darker than in real life. Rendering of indirect or reflected lighting was poor, causing areas away from the direct lighting to appear deceptively dark. These errors, believed to be the result of the software and possibly the VR headset as well, led to unrealistically sharp shadows and dark spots in all the simulations. Notably, the experimental design at 25 percent brightness appeared nearly pitch black near the observation point. To partially correct for this, the ambient lighting level, which is adjustable in Twinmotion, was raised until the darkest areas of this simulation more closely resembled a photo of an area of campus experiencing a blackout, where ambient lighting provided some visibility even with the lights extinguished. This correction was applied to the other simulations to maintain comparability between them.

Inconsistencies were observed regarding the spectrum of light as well, with the color temperature appearing warmer in the simulations compared to the actual lighting on campus. This could be due to differences in spectral power distribution between the LED luminaires on campus and the computer-generated light sources in Twinmotion.

Finally, the simulations were limited in their extent of illumination. While lighting was provided for 250 feet or more from the observation point (nearly 1000 feet in the initial viewing direction), the simulated exterior lighting terminated at specific boundaries, leaving some dark areas in the distance. Additionally, certain luminaires such as a recently installed wall pack on one of the buildings were not included in the simulation. However, as the total exterior luminous flux was controlled and the same area was illuminated in all four simulations, these factors are not anticipated to affect differences in perception between them.

Due to the inconsistencies described above, safety perception and comfort/aesthetics ratings should primarily be interpreted relative to the other simulations. Future research could better determine students' true perception of the lighting currently installed on campus.

4.4. IMPLICATIONS FOR FUTURE LIGHTING DESIGNS.

The results obtained in this study are significant for guiding the design of exterior lighting that is healthy and sustainable while being well-perceived by the public. As shown in the data presented here, employing the principles promoted in *Urban Lighting for People* could increase the level of comfort and aesthetic appeal of public spaces at night, provided there is sufficient illumination and uniformity to make people feel reasonably safe.

These design principles could also reduce the total required luminous flux for adequate safety perception if employed strategically. While brightness was shown to positively affect feelings of safety in this study, it must be noted that in the "full brightness" scenario of the experimental design, horizontal illuminance on the pathways appeared to closely resemble the existing design at 25 percent brightness, yet safety perception was higher. An optimal combination of direct area illumination and lighting along the buildings and boundaries of a space could thus allow for less overall light at night, reducing light pollution and energy usage. Additionally, the use of warmer color temperatures compared to the currently used daylight LED spectrum could lead to both an increase in comfort and a reduction in light pollution.

4.5. CONCLUSION

A critical issue in the design of exterior lighting is public perception. While it was found previously that adequate functionality can be provided by minimal amounts of light, low illumination levels could cause many people to feel unsafe and uncomfortable walking around at night. However, strategic design choices could boost perception at lower brightness levels. This study used virtual reality technology to gauge the public perception of various simulated outdoor lighting design alternatives. Based on the responses of participants taking part in the study, it was determined that the illumination of building faces, boundaries of a space, points of interest, and hazards, as well as the use of warmer color temperatures, could increase the level of comfort and aesthetic appeal of outdoor areas provided there is enough light for people to feel safe. Future research should focus on optimizing luminaire type, distribution, and spectrum to create well-perceived spaces at night with as little light as possible.

BIBLIOGRAPHY

[1] U.S. Department of Energy, “Outdoor Lighting,” *State and Local Solution Center*, 2016, https://www.energy.gov/eere/slsc/outdoor-lighting (Accessed 25 Oct 2022).

[2] International Dark Sky Association, “Light is Energy: Estimating the Impact of Light Pollution on Climate Change,” 2022, https://www.darksky.org/light-is-energy-estimating-the-impact-of-light-pollution-on-climate-change/ (Accessed 25 Oct 2022).

[3] M. Placek, “LED lighting in the United States - statistics & facts,” *Statista*, 2021, https://www.statista.com/topics/1144/led-lighting-in-the-us/#dossierKeyfigures (Accessed 28 Oct 2022).

[4] C. C. M. Kyba *et al.*, “Artificially lit surface of Earth at night increasing in radiance and extent,” *Sci. Adv.*, vol. 3, iss. 11, 2017.

[5] N. Schulte-Römer, J. Meier, M. Söding, and E. Dannemann, “The LED Paradox: How Light Pollution Challenges Experts to Reconsider Sustainable Lighting,” *Sustainability*, vol. 11, iss. 21, no. 6160, 2019.

[6] K. J. Gaston, T. W. Davies, J. Bennie, and J. Hopkins., “Reducing the ecological consequences of night-time light pollution: options and developments,” *J Appl Ecol.*, vol. 49, pp. 1256-1266, 2012.

[7] M. Liu *et al.*, “Evaluating Street Lighting Quality in Residential Areas by Combining Remote Sensing Tools and a Survey on Pedestrians’ Perceptions of Safety and Visual Comfort,” *Remote Sens.*, vol. 14, no. 826, 2022.

[8] B. A. Portnov, R. Sami, T. Trop, D. Kliger, and A. Svechkina, “Linking nighttime outdoor lighting attributes to pedestrians’ feeling of safety: An interactive survey approach,” *PLOS ONE*, vol. 15, iss. 11, no. e0242172, 2020.

[9] S. M. Simmons *et al.*, “Optimizing exterior lighting illuminance and spectrum for human, environmental, and economic factors,” *IOP Conf. Ser.: Earth Environ. Sci.*, to be published.

[10] B. Mizon, *Light Pollution,* Second ed. New York: Springer, 2012, ch. 5.

[11] R. Steinbach *et al.*, “The effect of reduced street lighting on road casualties and crime in England and Wales: controlled interrupted time series analysis,” *J Epidemiol Community Health*, vol. 69, iss. 11, pp. 1118-1124, 2015.

[12] L. Tompson *et al.*, “Absense of Street Lighting May Prevent Vehicle Crime, but Spatial and Temporal Displacement Remains a Concern,” *J Quant Criminol*, 2022.

[13] B. Wördenweber, J. Wallaschek, P, Boyce, and D. D. Hoffman, *Automotive Lighting and Human Vision*. Berlin: Springer, 2006, pp. 273-298.

[14] K. M. Zielinska-Dabkowska, “Critical Perspectives On Media Architecture: Is It Still Possible To Design Projects Without Negatively Affecting Urban Nighttime Environments And Will The Future Remain Dynamic, Bright And Multi-Colored?,” in *MAB ‘14*, Aarhus, 2014

[15] J. Wachtel, *Compendium of Recent Research Studies on Distraction from Commercial Electronic Variable Message Signs (CEVMS*), 2016.

[16] Y. Yang, R. M. Luo, and W. J. Huang, “Assessing glare, Part 3: Glare sources having different colours,” Light. Res. Technol., vol. 50, iss. 4, pp. 596-615, 2016.

[17] International Dark Sky Association, “Visibility, Environmental, and Astronomical Issues Associated with Blue-Rich White Outdoor Lighting,” 2010.

[18] F. Falchi and P. Cinzano, ‘Limiting the Impact of Light Pollution on Human Health, Environment and Stellar Visibility,” *J. Environ. Manage.,* vol. 92, iss. 10, pp. 2714-2722, 2011.

[19] N. Davoudian, *Urban Lighting for People*. London: RIBA Publishing, 2019.

[20] A. Garcia-Saenz *et al*., “Evaluating the Association between Artificial Light-at-Night Exposure and Breast and Prostate Cancer Risk in Spain (MCC-Spain Study),” *Environ. Health Perspect.*, vol. 126, iss. 4, no. 047011, 2018.

[21] K. M. Zielinska-Dabkowska, “Make lighting healthier,” *Nature*, vol. 553, pp. 274-276, 2018.

[22] J. M. Zeitzer *et al.*, “Sensitivity of the human circadian pacemaker to nocturnal light: melatonin phase resetting and suppression,” *J Physiol.*, vol. 526 pt. 3, pp. 695-702, 2000.

[23] M. Aubé, J. Roby, and M. Kocifaj, “Evaluating Potential Spectral Impacts of Various Artificial Lights on Melatonin Suppression, Photosynthesis, and Star Visibility,” *PLOS* ONE, vol. 8, iss. 7, no. e67798, 2013.

[24] D. Galadi-Enriquez, “Beyond CCT: The spectral index system as a tool for the objective, quantitative characterization of lamps.” *J Quant Spectrosc Radiat Transf*, vol. 206, pp. 399-408, 2018.

[25] G. L. Glickman, R. Levin and G. C. Brainard, "Ocular input for human melatonin regulation: Relevance to breast cancer," *Neuro Endocrinol. Lett.*, vol. 23, suppl. 2, pp. 57-60, 2002.

[26] R. Chepesiuk, "Missing the Dark: Health Effects of Light Pollution," *Environ. Health Perspect*., vol. 117, iss. 1, pp. A20-A27, 2009.

[27] J. E. Roberts, "Lighting and Human Health," in *Light Symposium*, Wismar, 2012.

[28] T. A. Bedrosian and R. J. Nelson, "Influence of the modern light environment on mood," *Mol Psychiatry*, vol. 18, iss. 7, pp. 751-757, 2013.

[29] K. Obayashi *et al.*, "Exposure to light at night and risk of depression in the elderly," *J. Affect. Disord.*, vol. 151, pp. 331-336, 2013.

[30] H. Ohta, A. C. Mitchell, D. G. McMahon, "Constant Light Disrupts the Developing Mouse Biological Clock," *Pediatr. Res.,* vol. 60, pp. 304-308, 2006.

[31] O. M. Buxton *et al.*, "Metabolic Consequences in Humans of Prolonged Sleep Restriction Combined with Circadian Disruption," *Sci Transl Med*, vol. 4, iss. 129, no. 129ra43, 2012.

[32] K. Obayashi *et al.*, "Exposure to light at night, nocturnal urinary melatonin excretion, and obesity/dyslipidemia in the elderly: a cross-sectional analysis of the HEIJO-KYO study," *J Clin Endocrinol Metab,* vol. 98, iss. 1, pp. 337-344, 2013.

[33] K. Obayashi *et al.*, "Association between light exposure at night and nighttime blood pressure in the elderly independent of nocturnal urinary melatonin excretion," *Chronobiol. Int.*, vol. 31, iss. 6, pp. 779-786, 2014.

[34] C. Núñez-Álvarez, C. Suárez-Barrio, S. Del Olmo Aguado, "Blue light negatively affects the survival of ARPE19 cells through an action on their mitochondria and blunted by red light," *Acta Ophthalmol,* vol. 97, iss. 1, pp. e103-e115, 2018.

[35] H. Li *et al.*, "Blue Light from Cell Phones Can Cause Chronic Retinal Light Injury: The Evidence from a Clinical Observational Study and a SD Rat Model," *Biomed Res Int.*, vol. 2021, no. 3236892, 2021.

[36] M. Aubé, A. Simoneau, R. Wainscoat, and L. Nelson, "Modelling the effects of phosphor converted LED lighting to the night sky of the Haleakala Observatory, Hawaii," *MNRAS,* vol. 478, pp. 1776-1783, 2018.

[37] L. Hung, S. J. Anderson, A. Pipkin, K. Fristrup, "Changes in night sky brightness after a countywide LED retrofit," *J. Environ. Manage*., vol. 292, no. 112776, 2021.

[38] International Dark Sky Association, “Outdoor Lighting Basics,” https://www.darksky.org/our-work/lighting/lighting-for-citizens/lighting-basics/ (Accessed 18 Aug 2022).

[39] International Dark Sky Association, “Board Policy on the Application of the Lighting Principles,” 2021.

[40] M. Kocifaj, F. Kundracik, J. C. Barentine, and S. Bará, “The proliferation of space objects is a rapidly increasing source of artificial night sky brightness,” *MNRAS*, vol. 504, pp. L40-L44, 2021.

[41] A. C. S. Owens and S. M. Lewis, The impact of artificial light at night on nocturnal insects: A review and synthesis,” *Ecol. Evol.,* vol. 8, 11337-11358, 2018.

[42] S. Bará, “Anthropogenic disruption of the night sky darkness in urban and rural areas,” *R. Soc. Open Sci.*, vol. 3, no. 160541, 2016.

[43] C. C. M. Kyba, T. Ruhtz, J. Fischer, and F. Hölker, “Cloud Coverage Acts as an Amplifier for Ecological Light Pollution in Urban Ecosystems,” *PLOS ONE,* vol. 6, iss. 3, no. e17307, 2015.

[44] Z. Hu, H. Hu, and Y. Huang, “Association between nighttime artificial light pollution and sea turtle nest density along Florida coast: A geospatial study using VIIRS remote sensing data,” *Environ. Pollut.*, vol. 239, pp. 30-42, 2018.

[45] S. M. Pawson and M. K.-F. Bader, “LED lighting increases the ecological impact of light pollution irrespective of color temperature,” *Ecol Appl*, vol. 24, no. 7, pp. 1561-1568, 2014.

[46] M. E. Kernbach *et al.*, “Light pollution affects West Nile virus exposure risk across Florida,” *Proc. R. Soc. B*, vol. 288, no. 20210253, 2021.

[47] M. E. Kernbach *et al.*, “Light pollution increases West Nile virus competence of a ubiquitous passerine reservoir species,” *Proc. R. Soc. B*, vol. 286, no. 20191051, 2019.

[48] A. R. Outen, “The possible ecological implications of artificial lighting,” *Hertfordshire Environmental Records Centre,* 1998.

[49] K. J. Gaston, J. Bennie, T. W. Davies, and J. Hopkins, “The ecological impacts of nighttime light pollution: a mechanistic appraisal,” *Biol. Rev.*, vol. 88, pp. 912-927, 2013.

[50] F. van Langevelde, J. A. Ettema, M. Donners, M.F. Wallis de Vries, and D. Groenendijk, “Effect of spectral composition of artificial light on the attraction of moths,” *Biol. Conserv.*, vol. 144, iss. 9, pp. 2274-2281, 2011.

[51] T. Longcore *et al.*, “Rapid assessment of lamp spectrum to quantify ecological effects of light at night,” *J. Exp. Zool.*, vol. 329, pp. 511-521, 2018.

[52] J. Q. Ouyang *et al.*, “Restless roosts: Light pollution affects behavior, sleep, and physiology in a free-living songbird,” *Glob Chang Biol*, vol. 23, pp. 4987-4994, 2017.

[53] H. A. S. Lamphar and M. Kocifaj, “Light Pollution in Ultraviolet and Visible Spectrum: Effect on Different Visual Perceptions,” *PLOS ONE*, vol. 8, iss. 2, no. e56563, 2013.

[54] E. S. Briolat *et al.*, “Artificial nighttime lighting impacts visual ecology links between flowers, pollinators and predators,” *Nat. Commun,* vol. 12, no. 4163, 2021.

[55] J. Bennie, T. W. Davies, D. Cruse, and K. J. Gaston, “Ecological effects of artificial light at night on wild plants,” *J. Ecol.*, vol. 104, pp. 611-620, 2016.

[56] C. M. Whitman, R. D. Heins, A. C. Cameron, and W. H. Carlson, “Lamp Type and Irradiance Level for Daylength Extensions Influence Flowering of *Campanula carpatica* `Blue Clips', *Coreopsis grandiflora* `Early Sunrise', and *Coreopsis verticillata* `Moonbeam,'” *J. Am. Soc. Hortic. Sci.*, vol. 123, iss. 5, pp. 802-807, 1998.

[57] A. R. Cathey and L. E. Campbell, “Effectiveness of five vision-lighting sources on photo-regulation of 22 species of ornamental plants,” *J. Am. Soc. Hortic. Sci.*, vol. 100, pp. 65-71, 1975, as cited in J. Bennie, T. W. Davies, D. Cruse, and K. J. Gaston, “Ecological effects of artificial light at night on wild plants,” *J. Ecol.*, vol. 104, pp. 611-620, 2016.

[58] A. R. Cathey and L. E. Campbell, “Security lighting and its impact on the landscape,” *J. arboric.*, vol. 1, pp. 181-187, 1975.

[59] M. Palmer *et al.*, “Roadway Lighting’s Impact on Altering Soybean Growth: Volume 1,” Illinois Center for Transportation, 2017.

[60] M Palmer, R. Gibbons, R. Bhagavathula, D. Holshouser, “Roadway Lighting’s Impact on Altering Soybean Growth – Volume 2: LED versus HPS Color Spectral Impact,” Illinois Center for Transportation, 2018.

[61] R. H. ffrench-Constant *et al.*, “Light pollution is associated with earlier tree budburst across the United Kingdom,” *Proc. R. Soc. B*, vol. 283, iss. 1833, no. 20160813, 2016.

[62] L. Meng *et al.*, “Artificial light at night: an underappreciated effect on phenology of deciduous woody plants,” *PNAS Nexus*, vol. 1, iss. 2, pp. 1-10, 2022.

[63] J. Škvareninová, *et al.*, “Effects of light pollution on tree phenology in the urban environment,” *Morav. Geogr. Rep.*, vol. 25, iss. 4, pp. 282-290, 2017.

[64] E. B. Matzke, “The effect of street lights in delaying leaf-fall in certain trees,” *Am. J. Bot.*, vol. 23, pp. 446-452, 1936.

[65] M. Gérard, M. Vanderplanck, T. Wood, and D. Michez, “Global warming and plant-pollinator mismatches,” *Emerg Top Life Sci*, vol. 4, iss. 1, pp. 77-86, 2020.

[66] S. Fotios and C. Cheal, “Obstacle detection: A pilot study investigating the effects of lamp type, illuminance and age,” *Lighting Res. Technol.*, vol. 41, pp. 321-342, 2009.

[67] S. Fotios and C. Cheal, “Using obstacle detection to identify appropriate illuminances for lighting in residential roads,” *Lighting Res. Technol.*, vol. 46, pp. 362-376, 2013.

[68] J. Hecht, “Photonic Frontiers: Color Measurement, Light Sources, and Vision: LED lighting makes new demands on color measurement,” *Laser Focus World,* Lasers & Sources, https://www.laserfocusworld.com/lasers-sources/article/16546933/photonic-frontiers-color-measurement-light-sources-and-vision-led-lighting-makes-new-demands-on-color-measurement (Accessed 23 Aug 2022).

[69] D. DiLaura, “Photopic and Scotopic lumens - 4: When the photopic lumen fails us,” https://www.visual-3d.com/Education/LightingLessons/Documents/PhotopicScotopiclumens_4%20_2_.pdf (Accessed 23 Aug 2022).

[70] J. J. Vos, “Colorimetric and photometric properties of a 2-deg fundamental observer,” *Color Red Appl,* vol. 3, pp. 125-128, 1978, as cited in M. Aubé, J. Roby, and M. Kocifaj, “Evaluating Potential Spectral Impacts of Various Artificial Lights on Melatonin Suppression, Photosynthesis, and Star Visibility,” *PLOS* ONE, vol. 8, iss. 7, no. e67798, 2013.

[71] G. Wyszecki and W. S. Stiles, *Color science: concepts and methods, quantitative data and formulae,* second edition. New York: Wiley, pp. 935, 1982, as cited in M. Aubé, J. Roby, and M. Kocifaj, “Evaluating Potential Spectral Impacts of Various Artificial Lights on Melatonin Suppression, Photosynthesis, and Star Visibility,” *PLOS* ONE, vol. 8, iss. 7, no. e67798, 2013.

[72] J. Ahlmann, “Humanly Visible Spectrum,” https://www.flickr.com/photos/65462440@N06/6146868258 (Accessed 26 Aug 2022).

[73] P. Tabaka, “Influence of Replacement of Sodium Lamps in Park Luminaires with LED Sources of Different Closest Color Temperature on the Effect of Light Pollution and Energy Efficiency,” *Energies*, vol. 14, no. 6383, 2021.

[74] P. Pracki and K. Skarżyński, “A Multi-Criteria Assessment Procedure for Outdoor Lighting at the Design Stage,” *Sustainability*, vol. 12, no. 4, no. 1330, 2020.

[75] M. Cristea, R. A. Tîrnovan, C. Cristea, and C. S. Pica, “A multi-criteria decision making approach in lighting technology selection for a production hall,” *MATEC Web of Conferences* vol. 184, no. 04007, 2018.

[76] O. Alshamrani, A. Alshibani, and M. Alogaili, “Analytic Hierarchy Process & Multi Attribute Utility Theory Based Approach for the Selection of Lighting Systems in Residential Buildings: A Case Study,” *Buildings*, vol. 8 iss. 6, no. 73, 2018.

[77] T. L. Saaty and L. G. Vargas, *Models, Methods, Concepts & Applications of the Analytic Hierarchy Process*, 2nd edn. New York: Springer, 2012.

[78] S. Madden, K. Alles, and Y. Demirel, “Measuring sustainability of renewable diesel production using a multi-criteria decision matrix,” *Biofuels, Bioprod. Bioref.*, vol. 15, pp. 1621-1637, 2021.

[79] T. Sangkakool, K. Techato, R. Zaman and T. Brudermann, “Prospects of green roofs in urban Thailand – A multi-criteria decision analysis,” *J. Clean. Prod.*, vol. 196, pp. 400-410, 2018.

[80] P. Jusakulvijit, A. Bezama, and D. Thrän, “Criteria prioritization for the sustainable development of second-generation bioethanol in Thailand using the Delphi-AHP technique,” *Energy, Sustainability and Society*, vol. 11, no. 37, 2021.

[81] K. D. Goepel, “Implementing the analytic hierarchy process as a standard method for multi-criteria decision making in corporate enterprises – a new AHP excel template with multiple inputs,” *Proceedings of the International Symposium on the Analytic Hierarchy Process*, 2013.

[82] D. Ho, G. Newell, and A. Walker, “The importance of property-specific attributes in assessing CBD office building quality,” *Journal of Property Investment & Finance*, vol. 23, iss. 5, pp. 424-444, 2005.

[83] T. K. Koo and M. Y. Li, “A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research,” *J. Chiropr. Med.*, vol. 15, pp.155-163, 2016.

[84] J. R. S. C. Mateo, “Multi-Attribute Utility Theory,” in *Multi-Criteria Analysis in the Renewable Energy Industry*. London: Springer, 2012.

[85] C. Kyba, A. Mohar, and T. Posch, “How bright is moonlight?” *Astron. Geophys.*, vol.58, iss. 1, pp. 1.31-1.32, 2017.

[86] British Standards Institution, *BS EN 13201-2:2015*. London: BSI Standards Limited, 2016.

[87] P. R. Boyce, “Movement under emergency lighting: the effect of illuminance,” *Lighting Res. Technol.*, vol. 17, iss. 2, pp. 51-71, 1985, as cited in P. R. Boyce, “Lighting for pedestrians,” in *Human Factors in Lighting*, 3rd edn. Boca Raton: CRC Press, 2014.

[88] M. Grubisic et al., “Light Pollution, Circadian Photoreception, and Melatonin in Vertebrates,” *Sustainability*, vol. 11, iss. 22, no. 6400, 2019.

[89] M. C. Giménez, O. Stefani, C. Cajochen, D. Lang, G. Deuring, and L. J. M. Schlangen, “Light Pollution, Circadian Photoreception, and Melatonin in Vertebrates,” *J. Pineal Res.*, vol. 72, no. e12786, 2022.

[90] M. Martínez-Ledesma, P. Sanhueza, C. Corco, H. R. Astudillo, R. Angeloni, G. Damke, F. Falchi, and G. Blanc, *Spectral and Zonal Restriction Justification – Review Process of DS043/2012 MMA (Ministry of Environment)*, 2019.

[91] M. Kocifaj and H. A. S. Lamphar, “Skyglow: a retrieval of the approximate radiant intensity function of ground-based light sources,” *Mon. Not. R. Astron. Soc.*, vol. 439, pp. 3405-3413, 2014.

[92] F. Falchi, P. Cinzano, D. Duriscoe, C. C. M. Kyba, C. D. Elvidge, K. Baugh, B. A. Portnov, N. A. Rybnikova, and R. Furgoni, “The new world atlas of artificial night sky brightness,” *Sci. Adv.*, vol. 2, iss. 6, no. 1600377, 2016, and https://www.lightpollutionmap.info/ (Accessed 3 May 2022).

[93] Lithonia Lighting, *D-Series Size 0 LED Area Luminaire, 2021.*

[94] Lithonia Lighting, *D-Series Size 1 LED Area Luminaire, 2021.*

[95] Lithonia Lighting, *D-Series Size 2 LED Area Luminaire, 2021.*

[96] Lithonia Lighting, *D-Series Pole Mount LED Area Luminaire, 2021.*

[97] Lithonia Lighting, *RADEAN Bollard LED Site Luminaire, 2022.*

[98] Antella Consulting Engineers Inc., *Campus Lighting – Toomey Hall*, 2016, construction drawings.

[99] M. C. Birk (Union Electric Company), *Electric Service*, 6th Revised, 2022.

[100] Access Fixtures, https://www.accessfixtures.com (Accessed May 2022).

[101] Lithonia Lighting, *D-Series Size 1 Amber Series LED Area Luminaire*, 2021.

[102] Crossroads LED, *Astrophile Series Narrow Band Amber Street Lights*, https://crossroadsled.com/lighting-products/narrow-band-amber-street-lights/ (Accessed Apr 2022).

[103] Crossroads LED, *Astrophile Series Phosphor Converted Amber Street Lights*, https://crossroadsled.com/lighting-products/phosphor-converted-amber-street-lights/ (Accessed Apr 2022).

[104] Crossroads LED, *Icon Series LED Acorn Retrofit Luminaires*, https://crossroadsled.com/lighting-products/retrofit-luminaires-for-acorn-and-post-top-fixtures/ (Accessed Apr 2022).

[105] Crossroads LED, *Prestige Series Luminaires for Decorative and Bell Shaped Fixtures*, https://crossroadsled.com/lighting-products/retrofit-luminaires-for-decorative-and-bell-shaped-fixtures/ (Accessed Apr 2022).

[106] Saint Louis Lighting Group (Acuity Brands), price quote, 28 Apr 2022.

[107] Illuminating Engineering Society (IES), as cited in Energy Trust of Oregon and Lighting Design Lab, *Footcandle Light Guide*, 2013.

[108] R. Crist (CNET), *Smart LED dimming curves: Linear vs. logarithmic*, 2019, https://www.cnet.com/pictures/smart-bulb-dimming-curves-linear-vs-logarithmic/ (Accessed Jul 2022).

[109] B. C. Welsh, D. P. Farrington, and S. Douglas, "The impact and policy relevance of street lighting for crime prevention: A systematic review based on a half-century of evaluation research," *Criminol Public Policy*, vol. 21, iss. 3, pp. 739-765, 2022.

[110] J. Roby, M. Aubé, A. Morin-Paulhus, W. Beauchesne, L. Cyr, and C. Laflèche, *LSPDD: Lamp Spectral Power Distribution Database*, https://lspdd.org/app/en/home (Accessed May 2022).

[111] S. Long, personal communication, 8 Mar 2022.

[112] R. Saad, B. A. Portnov, and T. Trop, "Saving energy while maintaining the feeling of safety associated with urban street lighting," *Clean Technol Environ Policy*, vol. 23, pp. 251-269, 2021.

[113] M. Scorpio, R. Laffi, M. Masullo, G. Ciampi, A. Rosato, L. Maffei, and S. Sibilio, "Virtual Reality for Smart Urban Lighting Design: Review, Applications and Opportunities," *Energies*, vol. 13, iss. 15, no. 3809, 2020.

[114] Missouri University of Science and Technology, *Campus As Built*, CAD file (Accessed Nov 2022).

[115] Illuminating Engineering Society of North America, “Lighting Control Strategies,” *The IESNA Lighting Handbook*, Ninth ed. New York: Illuminating Engineering Society of North America, 2000, ch. 27 – Lighting Controls.

VITA

Stephen Michael Simmons was born in Jefferson City, Missouri in 1998. He received his Bachelor of Science in Civil Engineering and his Bachelor of Science in Architectural Engineering from Missouri University of Science and Technology in December 2021. He received his Master of Science in Civil Engineering from Missouri University of Science and Technology in May 2023.