

Evaluation of women's perceived safety after dark using VR (Virtual Reality) technology

by

Maryam Kazemidemneh

B.S., Shahid Beheshti University, 2012

M.S., Tarbiat Modares University, 2016

M.S., KTH Royal Institute of Technology, 2020

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Abstract

The development of public lighting has changed the appearance of cities and opened opportunities to extend daily activities into the night. The quality and quantity of lighting has a significant impact on people's participation in nighttime activities, and in particular, their sense of safety and security in public areas such as streets and sidewalks. This research looks at how lighting design can increase the perception of safety for women.

This study investigated the effect of certain types of lighting design on women's perceived safety after dark in an outdoor urban environment, using virtual reality (VR) technology. Eight distinct lighting scenarios were created, which included variations in lighting height (bollard and pole), color temperature (warm and cool), and façade lighting (upper and lower). A within-subject experimental design was employed, where each participant experienced all lighting scenarios. The experiment was divided into two separate 2x2 factorial design studies. The first experiment explored the effect of color temperature and lighting height on perceived safety, with participants experiencing four scenarios that combined warm and cool color temperatures with bollard and pole lighting. The second experiment introduced upper and lower façade lighting and its effect when paired with bollard and pole lighting.

The simulated site was a representation of a residential street in a medium-sized city in the United States. Fifty female volunteers were recruited to participate in the study. Each participant wore a VR headset and after virtually walking through the eight lighting scenarios, they rated their perceived safety using a Likert scale.

After collecting the data, statistical analyses, including ANOVA and post-hoc tests, were performed to assess the main and interaction effects of lighting type, color temperature, and façade lighting on women's perceived safety. The main effects examined how each factor—color

temperature, lighting height, and façade lighting—individually influenced perceived safety. The interaction effects, on the other hand, examined whether the combination of these factors produced a different impact on perceived safety, indicating how the effect of one factor might change depending on the level of another.

In the first experiment, the results indicated that participants felt safer in scenarios with bollard lighting, and combining bollard lighting with pole lighting significantly enhanced their perceived safety. However, t-test calculations showed that the effect of color temperature on perceived safety was not statistically significant, and the ANOVA test results revealed no significant interaction effect between lighting height and color temperature, indicating that the influence of lighting height on perceived safety was not dependent on the color temperature.

The second experiment showed that lighting height and façade lighting had a significant main effect on perceived safety. Façade lighting on the lower part of buildings made participants feel safer compared to upper façade lighting, and similar to the first experiment, bollard lighting when combined with pole lighting, significantly increased perceived safety. However, the ANOVA test did not reveal any significant interaction effect between lighting height and façade lighting, indicating that the influence of lighting height on perceived safety was independent of the type of façade lighting, and vice versa.

The results of this study provide valuable insights into the effectiveness of various lighting design strategies for enhancing women's perceived safety in urban environments after dark. Policymakers, including organizations such as the Illuminating Engineering Society (IES), the International Dark-Sky Association (IDA), the U.S. Department of Energy (DOE), transportation planners, and public works staff can utilize this information to develop regulations and guidelines

to promote effective lighting solutions that will enhance perceived safety, which can lead to increased walkability in urban areas, contributing to the vibrancy of public spaces.

In addition to policymakers and organizations, the findings of this study are equally beneficial for architects, urban designers, and lighting professionals. These practitioners can integrate insights into their design processes to create urban spaces that prioritize safety. Architects, in particular, can apply these results to design buildings with exterior elements that thoughtfully incorporate lighting, enhancing both the architectural aesthetic and the overall sense of safety in the surrounding environment. This research shows that thoughtful lighting design can significantly influence human health and well-being by fostering a sense of security that encourages individuals to engage in outdoor activities, ultimately creating healthier, more active communities.

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Approved by:

Major professor

Anne Beamish

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After collecting the data, statistical analyses, including ANOVA and post-hoc tests, were performed to assess the main and interaction effects of lighting type, color temperature, and façade lighting on women's perceived safety. The main effects examined how each factor—color

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Dedication

To my beloved family—my parents and brothers—whose endless love, encouragement, and belief in me have been my greatest source of strength and inspiration.

Chapter 1 - Introduction

Lighting plays a crucial role in public spaces, such as streets and sidewalks because it not only enhances our ability to see but also affects our perception of the environment and our sense of safety and security (Boyce et al. 2000, Dastgheib 2018). A safe city allows more people to participate in outdoor activities at all times, including the night, which makes the city come alive; and in turn encourages people to participate in outdoor activities. More people outside at night also increases the perception of safety, and the cycle repeats itself. While it is generally agreed that increased lighting increases people's sense of safety (Boyce et al. 2000), much less attention has been given to the quality and type of lighting provided. Therefore, this research project assesses users', and in particular women's, perception of nighttime safety in an urban area and how it relates to façade lighting, street lighting height, and light source color temperature (CCT).

1.1 Problem

People's participation in nighttime activities usually drops significantly after dark (Boomsma and Steg 2014) and one of the most crucial reasons is related to safety (Dastgheib 2018). Past research, policies and design for nighttime environments have tended to focus on the experience of white males, with little attention paid to other groups, such as women, the elderly, people of color, and people with disabilities who experience the city differently and often feel less safe at night. As a result, women's social activities drop drastically after the dark, and they feel less safe compared to men (Blöbaum & Hunecke 2005, Loewen et al. 1993, Boomsma and Steg 2014). For example, women, on average, are three times more fearful of being a victim of sexual violence at night on campus compared with college men (Fisher and Sloan 2003). Because women avoid certain places and situations that they perceive as unsafe, their daily activities can be restricted (Keane 1998,

Valentine 1989, Mitra and Bardhan 2017), which may affect their ability to participate in physical activity such as walking outdoors (Valentine 1989). This significant inequity in nighttime access to the city for vulnerable groups has restricted their opportunities to participate in nighttime activities, socialize, and enjoy the urban environment.

Also, past and current lighting regulations, standards, and design are mostly vehicle-oriented, which may further decrease perceived safety for all pedestrians. This vehicle-oriented approach encourages car use and discourages walking, leading to a decline in pedestrian activity. A lack of pedestrians reduces natural surveillance, often making public spaces feel isolated and unsafe. This sense of isolation lowers perceived safety, which further discourages walking, reinforcing a cycle where fewer pedestrians lead to even less perceived safety.

It is essential to address the inequity and create a more inclusive and safer urban environment that caters to the needs of all members of the community, fosters a sense of community and belonging while promoting social cohesion, and improves the overall quality of urban life. Some of this inequity can be addressed by improved nighttime public lighting. Therefore, this research focuses on women as the target group and aims to assess their perception of safety and lighting with the long-term goal of designing urban spaces that allow them to participate more fully in urban areas after dark. While the focus of this research is to increase a sense of nighttime safety for women through lighting, it can also positively affect walkability for all groups, for if an environment is perceived as safe, people are more willing to walk, cycle or use public transport instead of individual cars. The research intends to contribute to the creation of lighting guidelines that prioritize pedestrian safety and enhance walkability, thus facilitating a safer and more sustainable urban environment for all.

1.2 Importance

Lighting has been identified as a crucial factor in enhancing perceived safety (Boyce et al. 2000, Trop et al. 2023), and there has been extensive research on the lighting characteristics which can enhance the perception of safety. For example, lighting intensity (Bhagavathula and Gibbons 2020, Lin et al. 2023; Svehkina et al. 2020), lighting distribution (Hamsa et al. 2009, Lindh 2013), uniformity (Bullough et al. 2020), color temperature (Johansson et al. 2014; Peña-García et al. 2015), visibility (Dastgheib 2018, Boyce et al. 2000) and glare (Dastgheib 2018, Kohko et al. 2015, Zhu et al. 2013) were among the lighting characteristics that influenced perceived safety. In addition, individual factors such as gender (women) and visual acuity (visually impaired) were found to affect perceived safety (Johanson et al. 2011, Loewen et al. 1993, Knight 2010).

Despite substantial research on women's perceived safety and related lighting design characteristics, there is still a debate among experts regarding the relation between the color temperature of the light source, lighting fixture height, and façade lighting on perceived safety. Hence, conducting research to fill these gaps in our knowledge is of utmost importance because it will be useful for policy makers such as Illuminating Engineering Society (IES), International Dark-Sky Association (IDA), U.S. Department of Energy (DOE) and designers such as urban planners, architects, and lighting designers in developing more effective lighting designs to enhance safety in urban environments.

Additionally, proper lighting is important because it can significantly enhance walkability by creating safe, welcoming, and visually appealing environments for pedestrians. Well-lit streets and sidewalks increase the sense of safety and encourage more people to walk rather than drive. This shift reduces reliance on vehicles, leading to lower fuel consumption and fewer greenhouse gas emissions, which contributes to a more sustainable and energy-efficient urban environment.

1.3 Purpose

As urbanist Jan Gehl argues, the city belongs to people, and it should provide opportunities for them to move freely and socialize (Gehl 1980), but research shows that users' activities vastly decrease after the dark (Boomsma and Steg 2014). Therefore, the purpose of this research is to increase people's, and in particular women's, participation in urban areas after dark by identifying lighting designs that increase their sense of safety. In addition, with a better understanding of a pedestrian's perception of lighting and safety, a more active nightlife can be promoted. To accomplish this, VR (virtual reality technology) was used to test the relationship between lighting design (including façade lighting and street lighting) and the perception of safety, with a focus on the color temperature and the position of the light source. By understanding this relationship, this research aims to provide insights that can contribute to developing more inclusive and user-friendly urban environments.

1.4 Objectives

The study aims to assess the effectiveness of different lighting conditions on women's perceived sense of safety, focusing specifically on the impact of different street lighting height (3 and 9 feet), color temperature of the light source (CCT), and the effect of illuminating different parts of the façade. The results of this study will provide insights into the importance of street lighting, façadelighting, and color temperature of the lighting source in promoting safety in urban areas and can help guide the development of policies and design guidelines that promote equitable access to safe and well-lit public spaces.

The effect of color temperature on perceived safety is a topic of debate in the lighting research community. While some studies (Maciejewski 2018, Bullough and Skinner 2015, Boyce et al

2000, Peña-García et al. 2015, and Knight 2010) have found that higher color temperature is directly linked to greater perceived safety, there are other studies (Saad et al. 2021, Liu et al. 2022) that suggest the opposite. This lack of consensus on the ideal color temperatures for safety highlights the need for further research in this area.

While pole lighting is the most common method used to illuminate streets, there is growing evidence that bollard lighting can significantly improve perceived safety in pedestrian areas (Vogel and Pettinari 2002, Bullough and Skinner 2015). This study aims to determine the impact of bollard lighting as a complement to pole lighting on perceived safety in urban areas.

Direct and reflected façadelighting is another factor that can play a crucial role in promoting perceived safety in public spaces (Dastgheib 2018, Wänström 2012). Currently, building façadelighting practices emphasize aesthetics and rarely consider the importance of perceived safety. In addition, studies of façade lighting (Neumann and Champa 2002) do not provide enough criteria or guidelines that can lead to improvements in perceived safety. Thus, the objective of this study is to provide more detailed information on the impact of façadelighting on perceived safety.

1.5 Research Questions

Based on the literature and identified gaps in our knowledge of lighting and perception of safety, this study investigated five main questions:

- 1- What is the effect of color temperature on women's perception of safety?
- 2- How does height of lighting (bollard with 3 feet/90 cm height + pole with 9 feet/270 cm height vs. only pole with 9 feet/270 cm height) affect women's sense of safety?
- 3- What is the effect of upper and lower façade lighting on women's perception of safety?

- 4- How does the relationship between the height of street lighting (3-foot bollard + 9-foot pole vs. only 9-foot pole) and color temperature of the light source (warmer 3000 K vs cooler 6500 K) affect the perceived safety in women?
- 5- How does the relationship between the type of façade lighting (lower part and upper part) and the height of street lighting (3-foot bollard + 9-foot pole vs. only 9-foot pole) affect the perceived safety in women?

The research questions were answered based on a within-subjects experimental study. In a “within-subject” designed experiment, each individual is exposed to more than one of the treatments being tested and differs from traditional experimental research which randomly assigns participants to a different experience with each participant only evaluating one treatment or condition. This type of study allowed us to test the specific and detailed lighting interventions that affect perception of safety on a more limited number of participants than in a traditional experimental design. In this study, participants compared their perceived sense of safety in eight different lighting scenarios. After experiencing each lighting scenario, participants filled out a five-point Likert scale survey to self-report their perceived safety.

Furthermore, based on the research questions, this study considered five main hypotheses:

1-Women’s perception of safety will increase with the higher/warmer color temperature (3000 K) lighting.

(Null hypothesis: There is no significant increase in women's perception of safety associated with higher/warmer color temperature (3000 K) lighting)

2- Women’s perception of safety will increase when bollard lighting is used as a complement to pole lighting.

(Null hypothesis: There is no significant increase in women's perception of safety associated with the use of bollard lighting.)

3- Women's perception of safety will increase when there is lighting on the lower part of the façade.

(Null hypothesis: There is no significant increase in women's perception of safety associated with the use of lighting on the lower part of a building façade.)

4- Women's perception of safety will increase when bollard lighting is combined with higher/warmer color temperature lighting.

(Null hypothesis: There is no significant increase in women's perception of safety associated with the combination of bollard lighting and higher/warmer color temperature lighting.)

5- Women's sense of safety will increase when bollard lighting is combined with light on the upper part of the building façade.

(Null hypothesis: There is no significant increase in women's sense of safety associated with the combination of bollard lighting and light on the upper part of the building façade.)

Chapter 2 - Literature review

2.1 Key Concepts

This section is divided into two parts. The first part defines the key concepts used in this research and lighting-related concepts to review our understanding of light. The second part examines the lighting characteristics that influence the perception of safety at night. To simplify the organization of this research, the first part (2.1) is referred to as “key concepts” and the second part (2.2) is termed as “research framework”.

2.1.1 Residential area and street

A residential street refers to a vehicular thoroughfare in an area with in which the predominant land use is housing (Gu and Gu 2009). Typically, these places see a reduction in social interaction and activity after dark compared to commercial and mixed-use areas (Dastgheib 2018). Though a lack of activity and social interaction tends to decrease the perception of safety in residential areas, lighting has been shown to increase it (Boyce et al. 2000).

Kevin Lynch, in his book *Image of the City* introduced five elements — path, edge, district, node, and landmark — that improve the “legibility” or “imageability” of a city, which refers to the urban characteristics that create easily-grasped images that then allow people to create a mental map (Lynch 1964). According to Lynch, a path is defined as a network of habitual or potential lines of movement, and therefore, based on the five elements, we can consider a residential street as a path, and where street lighting and building façade lighting can improve both its legibility and imageability (Davoudian 2019).

2.1.2 Activities in urban areas

Urbanist Jan Gehl emphasizes the importance of activities in urban spaces because without activity, human social interaction decreases or even disappears, and the boundary between isolation and social interaction becomes more distinct (Gehl 1980). In his book *Life between Buildings*, he defines “activity” as an element which makes it possible to “be among others,” “see and hear others,” “receive an impulse from others,” and have a “positive experience” without being necessarily with a specific person (Gehl 1980, 19).

Gehl proposes that there are three types of activities that take place in an urban environment: “necessary activities,” “optional activities,” and “social activities.” While “necessary activities” take place under any circumstances because they are essential, such as going to school, work, shopping and etc., “optional activities,” such as standing around and enjoying life, are the ones in which people participate when the time and place are pleasant. Lastly, “social activities” happen when people congregate in a place to socialize and include “greeting and conversation,” “communal activities,” and “seeing and hearing other people” (Gehl 1980). Gehl believes that in a poor-quality environment, the “necessary activities” are more dominant, while in a good-quality outdoor area, optional and social activities are more evident.

Although necessary activities are dominant in a residential street, optional and social activities can take place but depend on the quality of the environment. Perceived safety is one of the most important elements that affect the quality, and even existence, of these activities. A safe environment not only supports the “necessary activities,” but also encourages people to take part in “optional” and “social” activities. And research has shown that lighting is one of the most important elements in perceived safety (Boyce et al 2000, Dastgheib 2018). In this research the focus is to improve the conditions for these three types of activities to happen in a residential street.

2.1.3 Walkability

Hutabarat Lo defines “walkability” as the presence and continuity of sidewalks and pedestrian routes, accessibility of facilities to people with different abilities, directness of pedestrian paths, connectivity of the street network, connections to frequent transit services, ease and safety of crossings, visual interest, and perceived or actual security (Lo 2009). Walkability is also considered an important factor in promoting physical activity and improving public health (Frank et al. 2010).

There are different approaches to measuring walkability in urban areas. One traditional method involves measuring population density, street connectivity, and land use mix. Frank et al. expanded on this approach by developing a more comprehensive walkability index that included residential density, land use mix, street connectivity, and pedestrian infrastructure, and used these four components to calculate a single walkability score for a neighborhood (Frank et al. 2010). In contrast, Ewing and Handy argued that the traditional measures of walkability fail to capture subtle aspects of urban design that impact walking experience. To address this issue, they developed a new set of measures that incorporated a range of features that influenced walkability such as physical characteristics, urban design qualities and individual reactions to a place (Ewing and Handy 2009). Ewing and Handy (2009) as well as other researchers such as Lo (2009) considered perceived or actual safety as an essential factor that would increase walkability.

2.1.4 Lighting fundamentals

2.1.4.1 What is light?

Visible light is electromagnetic radiation with a wavelength ranging from 380 to 780 nanometers and lies between ultraviolet and infrared radiation. This segment of the electromagnetic spectrum

is what can be seen by humans because the photoreceptors in our eyes absorb energy within this wavelength range, which initiates the process of seeing (Boyce 2014). The visible light spectrum consists of seven colors that range from red to violet, and when these colors are combined, they create white light. Visible light has unique characteristics that significantly affect our perception. For example, when light comes in contact with an object, it can either be absorbed, reflected, refracted, transmitted, diffracted, or polarized.

Absorption occurs when the light energy taken in by the object is converted into other forms of energy, such as heat. Alternatively, the light can be reflected, which is when the light bounces off the object's surface and changes direction. Refraction occurs when the light changes speed as it passes through different materials, causing it to bend. Transmission takes place when light passes through an object made of transparent or translucent materials. Diffracted light is light that bends around objects, creating a pattern of interference or diffraction. Lastly, polarization is the orientation of light waves in a specific direction, which can affect how the light is absorbed or reflected (Cuttle 2008).

2.1.4.2 Light and vision

Our visual system is comprised of two distinct parts that work together to allow us to perceive light: the optical system and the image processing system (Boyce, 2014). The optical system is responsible for creating an image on the retina of the eye, while the image processing system extracts various features of the image and sends them to the visual cortex for interpretation. In the retina, there are two types of photoreceptors responsible for vision: rods and cones. Cones are primarily responsible for color vision and detecting fine details in bright light conditions, while rods are more sensitive to low levels of light but do not provide any information about color. Based

on the activity of rods and cones, there are three types of vision: photopic (in bright light), mesopic (in moderate light), and scotopic (in dim light) (Barbur and Stockman 2010)

Photopic vision is dominated by cone photoreceptors. It is responsible for distinguishing colors and details, and it is active during the day on luminance higher than 5 candelas per square meter (cd/m^2). Scotopic vision occurs in very low light conditions when only the rods in the retina are active. During scotopic vision, visual acuity is reduced, and color perception is impaired or nonexistent. Scotopic vision works on luminance less than 0.005 cd/m^2 . Lastly, mesopic vision occurs in conditions of moderate lighting, where both rods and cones are active. Mesopic vision is characterized by reduced visual acuity and color perception compared to photopic vision, but better visual performance than scotopic vision. In mesopic conditions, both the rods and cones work together to provide a balance of visual sensitivity and acuity, and they are active on luminance between 0.005 and 5 cd/m^2 (Tregenza and Loe 2013).

2.1.4.3 Light pollution

Light pollution is a very serious problem in the outdoor environment due to the excessive use of artificial light (Hollan 2009) and takes place in three forms: sky glow, light trespass, and glare, each with its own unique characteristics. Sky glow is the most prevalent and is defined as an increased brightness of the night sky, beyond what can be attributed to natural sources like moonlight. This results in a flattened illuminated dome that is visible above most cities and towns. Trespass occurs when light crosses property boundaries and creates illumination in areas where it is not necessary or desired. Glare, on the other hand, refers to bright light sources that cause visual discomfort, making it difficult to see or concentrate. (Boyce 2014).

To quantify the level of light pollution, we use the Bortle scale, which focuses on the observability of celestial objects and the interference caused by light pollution. The nine-level

numeric scale measures the brightness of the night sky at a specific location (Bortle 2001) and ranges from 1 (the darkest skies) to 9 (the brightest skies). The Bortle scale has proven to be a useful tool for evaluating the impact of light pollution and identifying areas that are suitable for dark sky preservation efforts.

Light pollution has some extremely negative consequences for both humans and animals. First, it can reduce the visibility of stars and other astronomical features (Boyce, 2014). In the *First Atlas of Artificial Night Sky Brightness* “they showed that more than 60% of world population lives under light polluted skies (99% of the population of USA and Europe) and almost one-fifth of world terrain is under light polluted skies” (Falchi et al. 2011, 2715). Meanwhile, exposure to light at night decreases the secretion of melatonin which regulates human circadian rhythms, which in turn causes a reduction in performance and alertness, sleep and metabolic disorders, and an increased growth of some type of cancer (Glickman et al. 2002, Stevens et al. 2007). Finally, the excessive use of artificial light can disrupt the natural rhythms of animals and plants, which can lead to behavioral changes and affect the growth and survival of plants, as well as disrupt orientation or disorientation, foraging, reproduction, communication etc. of wildlife (Longcore and Rich 2004).

To limit this type of pollution several effective practices have been identified. One involves the lighting fixture design to control the direction, intensity, and distribution of artificial light. Shielding luminaires is one of the most effective strategies, as it prevents direct upward light emission and minimizes glare, particularly at low angles above the horizon, which significantly contributes to skyglow. However, even with proper shielding, some light pollution remains due to reflection and atmospheric scatter. Light that strikes surfaces, such as roads or buildings, can be diffusely reflected upward, further illuminating the night sky. Therefore, choosing fixtures that

minimize unwanted reflections is essential to reducing overall light pollution. To address these challenges, regulatory measures are necessary, including enforcing the use of fully shielded fixtures to minimize wasteful and harmful light spill (Falchi et al. 2011, Küçük and Ekren 2021). Another effective method to decrease light pollution is to avoid over lighting. This means only using lighting levels that are required for the task, rather than using unnecessary higher levels. By doing so, less light is produced, which reduces the amount of light pollution. Additionally, illumination should be limited to the area where it is required and during the time it is needed. This helps to reduce the amount of light that is emitted and ensures that the light is not wasted in areas where it is not needed (Falchi et al. 2011).

2.1.5 Urban planting and lighting

Urban planting such as trees and shrubs, and street lighting affect the perceived safety after dark (Jansson et al. 2013, Maas et al. 2009, Boomsma and Steg 2014, Sreetheran and Van den Bosch 2014, Johansson et al. 2011). The relationship between urban greenery, lighting and perceived safety can be explained by the prospect-refuge theory (Appleton 1984, Fisher and Nasar 1992). Based on this theory, every urban space should reduce hiding spots for potential offenders (concealment) and create a better view of the surroundings (prospect) while improving the visibility of escape routes (escape).

Rahm et al. asked participants about the effect of urban greenery and lighting and found that participants viewed green spaces positively during the day, but many avoided such areas after dark. They concluded that poorly maintained green spaces “unkept greenery” in urban areas with inadequate street lighting might restrict pedestrians' options for routes at night, requiring them to take detours. Therefore, to ensure cities are accessible to everyone, green spaces must be well-lit and designed with safety as a priority (Rahm et al. 2021, 49).

Other researchers have also weighed in on the role of vegetation and safety. For example, Sanders concluded that walking trails need to balance vegetation needs with lighting in order to decrease the amount of foliage blocking light and enhance perceived safety and physical safety. (Sanders 2016). In another study, Vrij and Winkel suggested that the amount of foliage in a given area can play a role in people's fear of crime. They proposed that a balance should be struck between providing enough greenery to improve the aesthetics and livability of an area, while also ensuring that the foliage does not block lighting and obstruct visibility. In other words, when individuals are able to see more light in their environment due to the removal of obstructions, their perception of danger may decrease (Vrij and Winkel 1991).

2.1.6 A brief history of street lighting

Because people didn't have access to artificial lighting in the Middle Ages, their activities were limited to daylight hours (De Beer 1941). Bouman states that torches were still a very common means of outdoor illumination and when a city ordinance required citizens to place a light in front of their home, lantern was the first choice (Boumam 1984). But light at night was so important that in the sixteenth century, "many English provincial towns did have laws requiring lanterns in windows, while the responsibility varied" (Boumam 1984, 99). In this regard, Tarr believes "The impetus for providing improved street lighting derived from several factors, the most important of which was the perception that it would enhance public safety" (Tarr 2020, 106).

In the mid- seventeen century many European cities such as Paris, Berlin, Amsterdam, Vienna etc. used oil lamps for street lighting (Stone 2022) and the first streetlights installed by many American cities burned whale oil (Tarr 2020). Later in the mid-nineteenth century, oil lamps began to be replaced with gas lamps, which needed a connected network of pipes to distribute the gas through the streets (Tarr 2020). There were also other advantages of using gas lamps over oil

lamps, such as duration as well as easier usage (all lights could be ignited simultaneously) and later the ability to control all lights simultaneously (Neumann and Champa 2002).

During the mid- and late-1800s, cities experienced a significant period of expansion and growth, and the introduction of electric street lighting helped to illuminate these expanded cities. At this time, the cities were illuminated by different types of lighting such as oil, gas, and electric lighting. “The Census reported that in 1890, 323 cities with an aggregate population of almost 17 million possessed more than 300,000 streetlights. Of these, 61 percent (186,359) were coal gas streetlights; 19 percent were electric (42,927 Arc and 14,256 incandescent); and 20 percent were ‘All others’ (62,142)” (Tarr 2020, 107).

In 1911, tungsten filament incandescent electric lamps became the primary source of street lighting and gradually replaced other lighting types such as gas, gasoline, naphtha, and arc lamps. It is worth noting that the widespread adoption of electric lighting only occurred once the extremely high level of illumination in the early arc lamps was reduced to a level comparable to that of gas lighting (Neumann and Champa 2002). From 1950, streets were mostly illuminated by mercury vapor lamps and sodium vapor lamps, none of which had a good rendering quality, and the low-pressure sodium lamps created a monochromatic yellow light. After 1960 these were replaced by high-pressure sodium lamps because they produce a brighter light (Holden 1992). Today, LEDs are replacing the older types of streetlights as there are several advantages of using LEDs, including better color rendering (Jin et al 2015), energy efficiency and associated cost savings (Pattison et al. 2018), controllability (Srivatsa et al. 2013), and a reasonable lifetime (Timinger and Ries 2008). Although LED lights solved many of the problems of traditional lamps, they were not popular until their initial cost decreased, and today, they are the main type of street lighting.

2.1.7 A brief history of façade lighting

Architectural illumination and fireworks at night have been a common feature of public and private festivals in Europe since the Renaissance era (Salatino 1995). “Among the often cited and well-illustrated examples are the spectacular illumination of the canals in the Versailles garden of 1674” (Neumann and Champa 2002, 8). Initially, torches were used for illumination, but as oil and gas lamps became more common, architectural lighting was combined with these newer types of lighting (Schivelbusch 1995). The first place that we see lighting as a form of art and a new building material and not just as an illumination, was in world fairs. In many cases, “the structures at the fairs adapted their architecture to the illumination scheme. Materials, colors, and surfaces were selected according to their appearance under artificial light, and the placements of the outline lighting were carefully planned with the architects” (Neumann and Champa 2002, p 12). The entire buildings in these world fairs were illuminated by the “outline lighting” method. Search lighting was also very popular in world fairs during the early 20 century (Neumann and Champa 2002).

Apart from the world fairs, façade lighting was mostly seen in large cities such as New York and Chicago where there was a competition among companies to accentuate their own unique building in a way that each new constructed building was taller than the previous ones. To bring attention to their building at night, they started to add light layers to the building façade. Floodlighting became popular in American large cities during the 1920s and 1930s (Neumann and Champa 2002) because it provided an opportunity to bring more attention to the building by creating a pool of lights on the buildings’ façades. The great advantage of floodlighting compared to outline lighting was that floodlighting doesn’t leave traces during the daytime, and all lighting fixtures could hide behind the setbacks (Neumann and Champa 2002).

The next generation of façade lighting was a mobile system with color-changing floodlights using the primary colors of light (blue, red, and green). The use of artful illumination temporarily stopped twice, once during World War II and another time after the energy crisis of 1973. Before WW2, the purpose of the façade lighting was to bring attention to and highlight the uniqueness of the building, which was accomplished by adding pools of very bright light. However, little attention was paid to users' perception and comfort. After WW2, lighting designers began to focus more on users' perception and acceptance of lighting design. As a result, words such as joyful, interactive, and users' perception were incorporated into the vocabulary used in lighting design. (Neumann and Champa 2002). For example, after WW2 in war-damaged cities, it was recommended to “light outline the streets, replace the non-existent upper floor of buildings, create squares and define open spaces, outline and emphasize the buildings that are reconstructed” (Rosenberg 1953, 271). This helped to create a sense of security and to make the town look less like a shanty town or a bomb site as it was during the day.

Color-changing façade lighting has received more attention since 1980 because of computer-based technologies, which can provide color and light sequences far more complex than what was available during the 1920s and 1930s (Neumann and Champa 2002). The newer technology in façade lighting is the media façade which doubles as a form of entertainment. In this type of lighting, designers consider the building as a canvas on which to project images that people can interact with (Haeusler 2009). This brief history of façade lighting illustrates how lighting strategies have been changed from the early examples that used light to advertise and highlight the uniqueness of the building, to today where light is a medium which people can interact with, and perception, joy, and interactivity became part of lighting designers' terminology.

The façade lighting has traditionally focused on large buildings, with much less attention on medium-sized buildings. Recently, however, there has been some research on the importance of façade lighting on smaller buildings and considered façade lighting, or vertical illumination, as an important factor in the perception of safety (Dastgheib 2018, Wänström 2013).

2.2 Research framework

This section is intended to lay the groundwork for the research framework by reviewing key relevant literature. This study focuses on the perception of safety using virtual reality technology as a research tool. Therefore, the research framework has two parts. The first part investigates the concept of safety and the lighting characteristics that are crucial in creating a sense of safety. The second part investigates the use of virtual reality as a research tool to study safety perception. The following diagram shows the research framework.

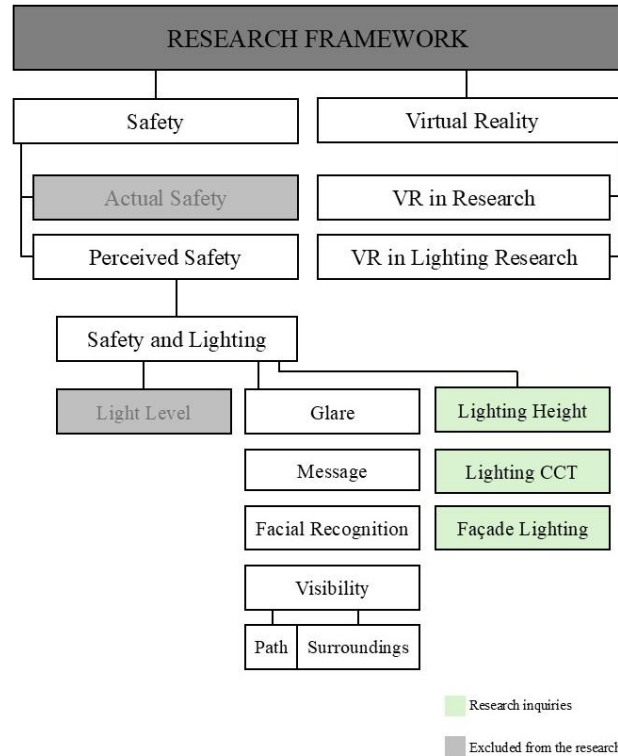


Figure 1: This diagram illustrates the research framework, divided into two parts: safety and VR research. The lighting criteria related to safety are categorized into three groups. Light level is excluded from the study, while glare, message, facial recognition, and visibility inform the survey questions. Meanwhile, lighting height, lighting CCT, and façade lighting address the research inquiries.

2.2.1 Safety

Boomsma and Steg define safety as “protection or the feeling of being protected against danger caused by or threatened to be caused by human actions in the public sphere” (Boomsma and Steg 2012, 194). Safety can affect our physical, social, and mental well-being, and it is one of the most important factors in evaluating a public space (Dastgheib 2018). Many researchers, such as Boomsma and Steg (2012) distinguish safety into “actual” and “perceived” safety. Actual safety is the actual crime rate, and perceived safety is defined as “a person’s immediate sense of security, and an absence of anxiety of becoming victimized, when traveling through a particular environment” (Haans and de Kort 2012 343, Blöbaum and Hunecke 2005, Park et al 2008). While

actual safety and perceived safety are two connected terms, one does not necessarily lead to the other one. This means that a place might be perceived as safe when it is not really safe and vice versa. This research focuses solely on the perception of safety; actual safety is another topic that would need to be addressed in another study.

2.2.1.1 Vulnerable Groups and Safety

The perception of safety depends on several factors, such as gender, age, memories, and the relationship between an individual and the space (Ceccato 2012). Dymen and Ceccato claimed that, as “individuals are exposed to different environments at different times, their victimization propensity and safety perception also vary over time and space” (Dymen and Ceccato 2012, 313). Generally, vulnerable groups such as women, the elderly, people of color, and people with disabilities often feel more unsafe in urban environments. For example, research shows that women’s social activities drop drastically after the dark because they feel less safe compared to men (Blöbaum & Hunecke 2005, Loewen et al. 1993, Boomsma and Steg 2014). In another study, the writers found that college women are, on average, three times more fearful of being a victim of sexual violence at night on campus compared with college men (Fisher and Sloan 2003). As a result, women often avoid certain places and situations that they perceive as unsafe, resulting in a restriction of daily activities (Keane 1998, Valentine 1989, Mitra and Bardhan 2017), which may affect their ability to participate in physical activity such as walking outdoors (Valentine 1989). Furthermore, another study by Roman and Chalfin found that age (older) and gender (female) were associated with an increase in fear (Roman and Chalfin 2008). The low level of participation in day and nighttime outdoor activities by vulnerable groups illustrates the severe inequality and injustice that takes place in urban spaces (Dastgheib 2018) and is an issue that needs urgent attention from stakeholders, planners, and designers.

2.2.1.2 Safety and Lighting

The design of the environment can decrease or increase the perception of safety. Jacobs (1961), Newman (1973), and Jeffery (1971) all discuss the relationship between criminal behavior and environmental design. Research has also shown that crime is not randomly distributed but rather concentrated in specific areas, often referred to as “hot spots” that can often be attributed to specific environmental design features (Sherman et al. 1989, Weisburd et al. 1992). As a response to these findings, the theory of Crime Prevention Through Environmental Design (CPTED) was developed (Cisneros 1996), which emphasizes the importance of designing and managing the built environment in a way that reduces the opportunity for criminal activity. CPTED principles include territoriality, surveillance, access control, target hardening, image and maintenance, and activity support (Cozens et al. 2005). In this regard, street lighting has been identified as a way to increase surveillance (Cozens et al. 2005).

There are two contradictory opinions about the effect of lighting on actual safety. According to Atkins et al., there is no substantiated proof to suggest that better street lighting decreases reported criminal activities. Their study indicated that although some specific types of crimes and certain areas showed a decrease in nighttime offenses compared to daytime offenses, the overall pattern did not change significantly (Atkins et al. 1991). On the other hand, some studies found more reported crime in the presence of street lighting (Welsh and Farrington 2009). While there are contradictory opinions about the relation between lighting and actual safety, research shows that lighting has a direct effect on perceived safety (Tien et al. 1977, Fotios et al. 2015, Van Cauwenberg et al. 2012). Tien et al. were among the first to investigate the impact of street lighting on fear of crime by conducting an attitude survey that looked at 15 streets in different cities in the US. The study was limited to street lighting projects that had been installed with the

intention to reduce crime and that had been implemented in the United States between 1953 to 1977. Their results were straightforward, with 66 to 82 percent of the questioned residents and police officers reporting feeling “somewhat or much safer” after the installation of street lighting (Tien et al. 1977). In another study by Fotios et al., they reported that 39 out of 53 participants mentioned lighting as a reason for feeling safe while walking on a street after dark (Fotios et al. 2015).

2.2.1.3 Lighting factors related to safety

2.2.1.3.1 Visibility (path and surroundings)

Lighting has both direct and indirect effects on improving perceived safety. Directly, lighting primarily enhances visibility and promotes natural surveillance. Studies have shown that people's perception of safety drops significantly after dark when visibility is impaired, and fear increases when fewer people are around (Taner and Tiesdell 1997, Dravitzki et al. 2003). And because darkness limits visibility, it provides offenders with opportunities for concealment and makes it harder for people to find escape routes (Wu and Kim 2016). Furthermore, the perception of safety is indirectly influenced by lighting as a well-lit space communicates the message that the area is valuable and worth designing, which can foster a sense of care and security (Fotios et al. 2019).

Fisher and Nasar (1992) identified three safety-related environmental elements or characteristics, namely prospect (having an overview), escape (perceived escape possibilities), and refuge/concealment (perceived hiding places for offenders). The prospect-refuge theory was first introduced by geographer Jay Appleton, who proposed that humans prefer places that offer both prospect and refuge (Appleton 1984). Potential offenders seek a hiding place from which they can attack victims, which means that a place with a low level of concealment is preferable in the case of perception of safety. In contrast, people are looking for a place with a high level of prospect that

provides an overall view of space. Lastly, it is important for the built environment to offer escape routes in case of an attack by a potential offender.

This prospect-refuge theory allows the evaluation of a designed environment and assesses whether it provides a high level of safety. A good lighting design enhances these characteristics and improves the perceived safety of the designed built environment. It can reduce hiding spots for potential offenders (concealment) and create a better view of the surroundings (prospect) while improving the visibility of escape routes (escape). Conversely, inadequate or poor lighting creates areas of darkness in which potential offenders may hide, reduces prospect by causing glare, and impedes the visibility of escape routes (Dastgheib 2018).

Improved visibility not only creates a sense of safety but also encourages outdoor activities, resulting in an increased presence of people in an area. This aligns with Jane Jacobs' theory that the presence of people leads to better natural surveillance, as it increases the number of “eyes on the street.” (Jacobs 1961). According to Jacobs, a well-used city street tends to feel safer due to the increased presence of people, whereas a deserted one is likely to be unsafe. She further argued that lighting plays a crucial role in enhancing visibility and attracting more people to urban areas, thereby resulting in activity and more eyes on the street. She argued that there are four types of visibility – physical, social behavioral and temporal. Physical visibility involves clear sightlines and allows people to see and be seen. Social visibility depends on the presence of diverse activities that draw people into public spaces. Behavioral visibility highlights the role of individuals actively observing and interacting with their surroundings. And lastly, temporal visibility ensures consistent activity throughout the day and night.

It is worth noting that the design guidelines for residential roads, as outlined in lighting standard books such as IES, CIE, and British Standard Institution, primarily focus on horizontal

illuminance (lighting on the path) as the main concern. However, recent studies have shown that pedestrians' sense of security can be influenced not only by lighting on the path but also on the surrounding areas. For instance, Cellucci et al. (2016) demonstrated that the lighting in the surrounding areas such as vertical planes near the path can affect pedestrians' sense of security. Moreover, both Dastgheib (2018) and Wänström (2012) have proposed that illuminated visual spatial boundaries, such as building façades and surrounding areas, play a crucial role in enhancing perceived safety.

2.2.1.3.2 Message (communication)

Lighting has an indirect effect on the perception of safety because a well-lit space sends the message that someone cares about this place, and it is worthy of being designed (Fotios et al. 2018). Additionally, light encourages people to use places after dark, leading to increased social presence and interaction, which enhances the perception of safety because the presence of others makes individuals feel more secure since they potentially can help them in case of danger (Jacobs 1961, Warr 1990). Moreover, the presence of others has a calming effect under conditions of threat and provides a sense of security (Mikulincer et al. 2003). Boyce (2014) argues that light has the potential to create attractive places that people would want to visit after dark. Dastgheib (2018) also asserts that lighting affects the perception of safety through "visibility" and "message" factors.

2.2.1.3.3 Glare

Glare refers to a bright and intense light that causes discomfort or reduces visibility. There are two common forms: direct glare and indirect (reflected) glare (Boyce 2014). Direct glare is the presence of a bright light source in the visual field and indirect glare is caused by bright reflections off, of smooth or shiny surfaces that are located in the same visual field as the observer (Boyce 2014). Several studies have focused on perceived safety and glare. For example, Peña-García et

al. conducted a survey using 275 pedestrians to evaluate perception of safety and considered glare as one of the factors related to safety and concluded that uniform lighting without glare makes people feel safer (Peña-García et al. 2015). Similarly, Knight (2010) considered glare as one of the important factors related to perceived safety. Portnov et al. (2020) studied the impact of public space lighting (PSL) on pedestrians' feeling of safety (FoS) in urban areas after dark. They too found that glare led to a reduction in the feeling of safety among pedestrians. Also, Boyce et al. (2020) found that the presence of glare matters to the perception of safety (Boyce et al. 2000). And lastly, Dastgheib (2018) proposed a table of lighting criteria to evaluate the perceived safety and considered glare as one of the factors. Given the extensive research, we can state that the presence of glare negatively affects people's perception of safety.

2.2.1.3.4 Facial recognition

Facial recognition is the ability to recognize facial features and is valuable in understanding the intention of an approaching person (Dastgheib 2018). Boyce determined that the minimum distance required for facial recognition is 4 meters (13 feet), while the optimal distance is 10 meters (32 feet) (Boyce 2014). Numerous other studies have established a conclusive relationship between facial recognition and the perceived level of safety (Boyce et al. 2000, Lin and Fotios. 2015, Calleri et al. 2019, and Li et al. 2023). Knight (2010) recognized facial recognition as a crucial factor in people's perception of safety and investigated the relationship between lamp distribution patterns and facial recognition, as did Yang and Fotios (2015). In addition, Painter (1996) and Wänström (2013) have also emphasized the importance of good lighting in improving facial recognition, which increases the sense of being watched over (eyes on the street) and therefore causes people to feel safer.

Several factors have been identified that can improve facial recognition. For example, studies by Boyce (2014) and Cozens et al. (2003) have found that the presence of vertical illuminance can enhance facial recognition, while positioning light sources at a lower height can also facilitate recognition by avoiding harsh shadows on faces, as noted by Wänström (2012). Additionally, Li et al. (2023) have studied the critical role that 2D (image) and 3D (modeling) information plays in pedestrians' ability to recognize facial expressions. The study found that accuracy in recognizing facial expressions is likely to improve when 3D information is available.

2.2.1.3.5 Light level

Based on the IES, visibility is the quality or state of being perceivable by the eye, either under daylight or artificial light, or both and light level is directly associated with visibility (Illuminating Engineering Society 2020a). As visibility increases, we see an improvement in perceived safety. Calvillo et al. examined the relationship between emotions (such as fear and joy) and urban outdoor lighting and found that the amount of perceived visual information has an influence on people's emotions. When little visual information was available and the intensity of lighting was low, more respondents reported feelings of fear (Calvillo et al. 2016).

Though the level of illumination plays an important role, there is little consensus on how much light is needed. Boyce et al. found that people feel safer when the lighting level (lux) is closer to daylight. They evaluated the perceived safety in a parking lot and suggested that a 30 lux level would be close to daylight and would ensure a sense of safety (Boyce et al. 2000). More recent studies suggest that a lower light level would be adequate. Svehkina et al. surveyed 106 participants in three cities in Israel. Participants evaluated 257 survey points at different hours, in 10 neighborhoods in total. They concluded that higher levels of illumination don't necessarily lead

to a rise in the perception of safety and suggested that a 5 to 10 lux level was enough for the perception of safety in outdoor areas (Svechkina et al, 2020).

Another study by Liu et al., concluded that a satisfactory level of feeling of safety was reached with illumination levels of 5–17 lux (Liu et al. 2022). Additionally, Vogel and Pettinari found that excessive brightness in lighting could create a "fishbowl effect," which means that people can be easily seen by potential offenders, while potential escape routes may not be as visible to those seeking safety (Vogel and Pettinari 2002). In all of these studies, the light level and uniformity were considered together, with many scholars showing that even a uniform light level is perceived as safer than varying light levels (Fotios et al. 2019). In addition, people prefer to have light in their immediate surroundings rather than on the path that lies ahead (Haans and de Kort 2012).

It is important to clarify the relationship between light level and the theory of “eyes on the street” by Jane Jacobs (1961). We need less light when we have active eyes on the street (Dastgheib 2018), and a parking lot is a place with fewer potential active eyes. Furthermore, in the studies by Svechkina et al., they concluded that the required light level is not the same in all urban settings, and the “one-size-fits-all” is a misconception (Svechkina et al. 2020). Boomsma and Steg also established a relationship between light levels and social safety, which is defined as protection or the feeling of being protected against danger caused by human action. According to their research, the perceived level of social safety mediates the effects of lighting levels on acceptability. This means that when people feel socially safe and their safety is not threatened, they tend to accept lower lighting levels. (Boomsma and Steg 2014).

The IES has some very specific recommendations for the level of illumination depending on the age of and the type of task they could be undertaking.

Category	Recommended illumination targets (Lux)			Typical application and task characteristics	
	Visual ages of observers where at least half are				
	<25	25 to 65	>65		
Interior and exterior application	A	.5	1	2	• Dark adapted situations • Basic convenience situations • Very low activity situations • Slow paced situations • Low density situations • Slow to moderate paced situations • Moderate to high density situations • Moderate to fast paced situations • High density situations • Some indoor very subdued circulation situations • Some indoor social situations
	B	1	2	4	
	C	2	4	8	
	D	3	6	12	
	E	4	8	16	
	F	5	10	20	
	G	7.5	15	30	
	H	10	20	40	
Interior and exterior	I	15	30	60	• Congested and significant outdoor intersections, important decision points, gathering places, and key points of interest. • Some indoor social situations • Some indoor commerce situations

Table 1: IES required light levels for interior and exterior spaces. (Source: Illuminating Engineering Society. *The Lighting Handbook: Reference and Application* 2011)

2.2.1.3.6 Color temperature

The impact of color temperature on perceived safety is a topic of debate in the lighting research community. Maciejewski (2018) found that participants prefer environments characterized by cooler light and higher color temperature. Bullough and Skinner claimed that white light appears brighter, and consequently safer, than yellowish light (Bullough and Skinner 2015). Other researchers found similar results and considered higher color temperature a better source of perceived safety. (Boyce et al 2000, Peña-García et al. 2015, Knight 2010).

While several studies concluded that higher color temperature is directly correlated with higher perceived safety, there are other studies that show the opposite. For example, Saad et al. (2021) found that uniformity and warm color light (lower color temperatures) were considered important factors in the perception of safety. Liu et al. also concluded that people feel safer if nighttime light is warm and uniform (Liu et al. 2022). This lack of agreement on the ideal color

temperatures for safety is the reason why it was important to include this variable in this research project.

2.2.1.3.7 Height of street lighting (bollard and pole lighting)

Street lighting is a critical aspect in promoting safety in urban areas, but not all lights are the same. Different patterns of light distribution are created by varying the spacing and height of lamp posts as well as the configuration of optical components in a lighting fixture (Fotios et al. 2015). The height of street lighting, which traditionally ranges from 8 to 50 feet, plays a crucial role in visual performance and shaping our perception of a given area, which in turn affects our perceived safety. Dastgheib (2018) and Scorpio et al. (2020), found that the height of the light fixture was an important element which impacted visual performance and consequently perceived safety.

There are several studies focusing on lower (approx. 3 feet high) lighting and perceived safety in an illuminated exterior environment. Vogel and Pettinari concluded that low-pole lighting created “people-scaled illumination in dark corners” in areas around transit stations (Vogel and Pettinari 2002). Paskovic also claimed that bollard lighting in pedestrian areas creates “an inviting public realm” (Paskovic 2012). In still another study, the researchers found that the use of bollard lighting led to a significant increase in the perception of safety compared to the pre-existing pole lighting (Bullough and Skinner 2015). And another study by Rensselaer Polytechnic Institute looked at the relationship between bollard level lighting and safety at crosswalks and focused on wayfinding and navigation aspects. Paskovic also reported that bollard lighting in pedestrian areas created continuous movement leading to an inviting public realm (Paskovic 2012). However, most of these studies mainly focused on the safety of pedestrians from vehicles and less on the perception of safety.

While pole lighting is the most common way of illuminating streets, there is growing evidence that bollard lighting can significantly impact perceived safety in pedestrian areas, which is the reason that this study compares the impact of bollard and pole lighting on perceived safety in urban areas.

2.2.1.3.8 Façade lighting

Research has shown that light on façades can also play a crucial role in promoting perceived safety in public spaces. According to Dastgheib, illuminating vertical spatial boundaries, such as building façades, is an important factor in perceived safety (Dastgheib 2018). Similarly, Wänström suggested that illuminating vertical visual borders can create a feeling of safety (Wänström 2012). Though the studies found that illuminating the façade of buildings can enhance perceived safety, they did not provide specific criteria or guidelines for façade lighting.

Generally, we can divide a building's façade into three parts: lower, middle, and upper. The lower part, being closer to human scale, has the most interaction with people, while the middle part emphasizes the building's architectural elements (Neumann and Champa 2002). The upper part is crucial in highlighting the spatial boundaries of the building and the surrounding area. This study's objective was to provide more detailed information on the impact of façade lighting on perceived safety and focused on lighting the the lower and upper parts of the building façade.

2.2.1.4 IES and safety

The perception of safety, as defined by the Illuminating Engineering Society (IES), includes the notion of reassurance, which refers to the alleviation of worry, fear, and doubt, leading to the restoration of confidence that is critical to pedestrians' willingness to engage with their surroundings after dark. It is important to note that if a space is unsafe during the day, lighting conditions at night are unlikely to make it safe, but high-quality lighting can help mitigate the

decline in reassurance that often occurs after dark. The perceived safety and security of an area are more closely associated with the quality, rather than the quantity, of lighting. Exterior environments that are comfortable and well-defined, with distinct "zones of recognition" where individuals' faces can be clearly identified, are often considered secure. Proper illumination of these spaces allows pedestrians to have sufficient reaction time to avoid or escape potential threats. In extreme threat circumstances, quality lighting aids pedestrians in identifying safe places or escape routes. Security lighting aims to reduce the fear of crime by enhancing the perception of safety. It is crucial for users to detect potential threats as early as possible, affording them enough time to make informed decisions and react accordingly (Illuminating Engineering Society 2020c). The following image shows the hierarchical process of designing quality lighting in outdoor environments and location of reassurance in this process.

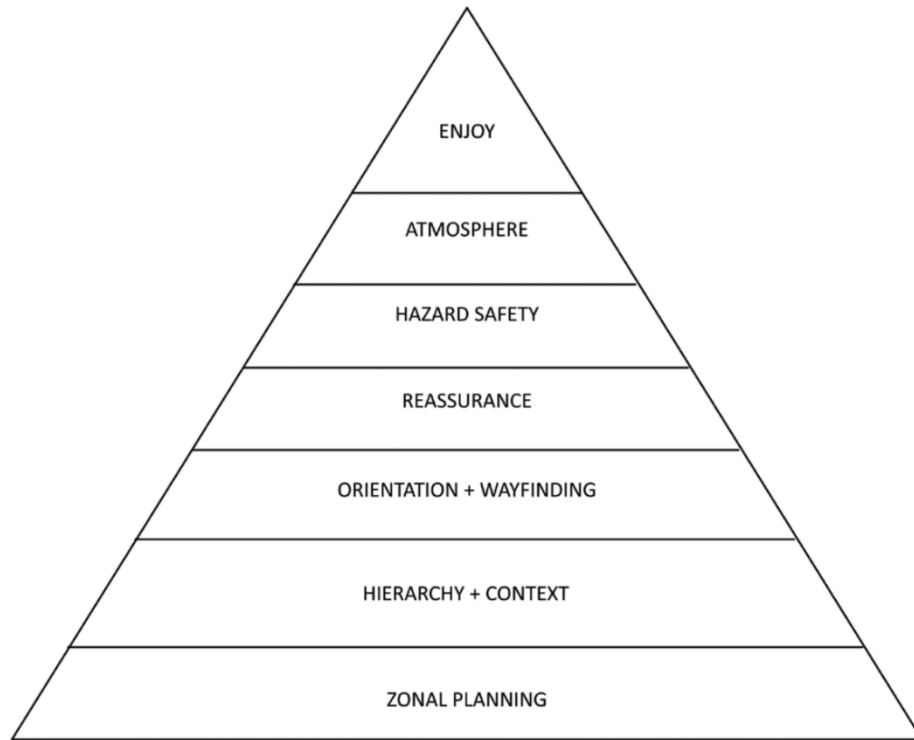


Figure 2: Hierarchical process of designing quality lighting for people in outdoor environments. (Source: Illuminating Engineering Society 2020c)

According to the IES, facial recognition is regarded as an essential aspect of lighting design that contributes to a sense of reassurance and the key to creating this feeling is to illuminate the faces of approaching strangers. When pedestrians have a reduced ability to detect others or perceive potentially threatening activities, it significantly diminishes their overall experience. In some cases, this may even lead them to avoid public spaces entirely. Another critical factor that improves the perception of safety is an absence of glare (Illuminating Engineering Society 2020c).

The type of lighting fixture is another important element influencing reassurance. For example, human-scale lighting with low-glare properties and designed for pedestrian zones will increase reassurance. Conversely, taller poles that more suitable for roadways because they

provide illumination for vehicles will not. In summary, when designing a lighting system that promotes a personal and human-centric environment, it is better to position the light source closer to people's heads rather than placing it high above them. Lower positioned light sources, in general, contribute to the generation and reinforcement of a human-centric atmosphere (Illuminating Engineering Society 2020b).

The IES also highlights the importance of vertical illumination and façade lighting in shaping perceptions of safety. This type of lighting can help in three ways. First, the light that escapes from windows, doorways, and façades along the path adjacent to buildings can effectively illuminate the pathway. Second, illuminating vertical surfaces produces a silhouette effect on approaching strangers that enhances visual cues and assists in evaluating potential threats. Façade lighting can show spatial boundaries which are directly connected to perception of safety. In this context spatial boundaries refer to the visual or perceptual cues that define the edges or limits of a space, such as the boundaries between buildings. And finally, vertical illuminance plays a crucial role in facilitating facial recognition, further enhancing the overall effectiveness of the lighting design (Illuminating Engineering Society 2020b).

2.2.2 Virtual reality (VR) as a research tool

2.2.2.1 Definition

Of the five senses, sight is by far the most dominant and the main way that we perceive and understand the world around us (Bruce et al.1996, Rose 2022). Different research tools, such as photographs, films, and virtual reality (VR) use this sense to evaluate the environment. As useful as photographs and film have been, the important advantage of virtual reality is that it is immersive and can help users experience a place rather than simply viewing it. Because virtual technologies allow researchers to create immersive and interactive experiences that can be used to design and

simulate urban environments, we now have access to a wide range of virtual locations, situations, transactions, and relationships through these representations (Portman et al. 2015).

There are several definitions for virtual reality with nuanced differences. The Collins dictionary states that VR is a “computer-generated environment that, to the person experiencing it, closely resembles reality” (Collins Dictionary 2014). Other definitions emphasize the participatory aspect, where VR is “experienced,” as opposed to “viewed.” Regenbrecht and Donath defined VR as a computer-generated synthetic space where users are incorporated as a vital part of the system and where they can interact with virtual objects, environments and other users as if they were in the physical world (Regenbrecht and Donath 1997). In another definition, VR is described by its characteristics of the five “i”s consisting of: “intensive, interactive, immersive, illustrative and intuitive” (Sherman and Judkins 1992). One of the more inclusive definitions of VR states that, VR enhances three-dimensional computer-generated models by incorporating immersive and interactive elements, enabling users to explore and engage with the models in ways that were previously impossible with conventional forms of representation (Burdea and Coiffet 2003).

2.2.2.2 VR in research

The use of VR for design and research has increased in the past decade because designers and planners can “enter” three-dimensional digital simulations (models) of planned or existing buildings, cities, and landscapes. (D’Souza et al. 2011, Stouffs et al. 2013, Pietsch 2000, Pittman 1992, Simpson 2001 and Portman et al. 2015). For design research, virtual reality (VR) technology enables designers to show their concepts and assess their design criteria (Rahimian and Ibrahim 2011, Chen and Schnabel 2009) such as materials and lighting. And as the use of VR has increased, so too has research on its reliability.

To ensure that VR is a useful tool in research, it is important to consider not only how users think and act in virtual environments but also how their experiences compare to real-life environments. In other words, we need to examine the extent to which VR is an accurate representation of the real world in terms of user perception and overall experience. (Kuliga et al. 2015). There have been several studies that focus on direct comparisons between real and virtual environments, and how cognitive and affective environmental appraisal and human movement patterns correspond in both environments (Westerdahl et al. 2006, Kort et al. 2003, Bishop and Rohrmann 2003, Skorupka 2009, Haq et al. 2005, Dalton 2003, Witmer et al. 1996). Kuliga et al. concluded that VR has the potential to be a valuable research tool for studies in a human–environment (Kuliga et al. 2015). In another study by Newman et al., they concluded that experiences of VR presentations fell between real and video presentations, and more realistic VR environments evoked more positive affective responses, as well as a greater sense of presence (Newman et al. 2022). In another research, Shin concluded the same results and highlighted the importance of the immersive properties of a VR scene in promoting the perception that the scene is real and live (Shin 2018). Based on these studies, it has been shown that virtual reality technology (VR) is dependable and can be effectively utilized as a research tool.

2.2.2.3 VR in lighting research

Bellazzi et al. compared lighting conditions in VR and real environments by studying 33 manuscripts which looked at the properties of light, including brightness, correlated color temperature (CCT), distribution, contrast, evenness, and glare in VR and real environments. The overall results showed that a virtual lit environment was perceived as similar to the real one in terms of the perception of the lighting appearance and lighting level in both daylit and electrically lit environments (Bellazzi et al. 2022). In another study by Chen et al., they investigated the validity

of using Virtual Reality for lighting research and concluded that VR could present lighting attributes, and human subjects were most satisfied with VR reproductions (Chen et al. 2019). In still another study, Scorpio evaluated the possibility of using VR to represent lighting characteristics such as brightness, correlated color temperature and distribution, and found that VR could be used to evaluate different lighting scenarios (Scorpio 2020).

Maciejewski conducted an experiment to examine the validity of using Virtual Reality to evaluate perceived safety in different lighting conditions, which demonstrated that “VR can be used in research on quantifying the relation between lighting parameters and the perceived personal safety” (Maciejewski 2018). Bhagavathula et al. also showed that there is no statistical difference between the real and virtual environments for participants’ intention to cross the street, estimation of distances, and perceptions of safety and risk. However, statistically significant differences between real and virtual environments were observed in the estimation of speed. (Bhagavathula et al. 2020).

Chapter 3 – Research design

3.1 Methodology

This study employed an experimental design using two independent two by two factorial designs (Table 2 and 3). A within-subjects design was employed, meaning that each participant experienced all eight lighting conditions (Charness et al., 2012), and because every participant experienced all lighting scenarios, any individual differences that may have affected the results were assumed to be constant across all conditions. Also, this design helped to reduce data variability, increased the results' precision and accuracy, and enhanced the statistical power of the experiment. However, to ensure the validity and reliability of the results, it is crucial to consider some essential factors.

One crucial factor was the order in which participants experience the lighting scenarios. To minimize the effects of order, a counterbalanced design has been used, whereby the four scenarios in each of the two parts were presented in a different sequence to different participants. This approach was used to reduce the risk of response bias or practice effects, where participants become more familiar or fatigued with the task as the experiment progresses. To control for the fatigue effect, participants had a five-minute break between the two parts of the experiment.

Furthermore, to ensure the validity and reliability of the results, each participant was provided with clear instructions on how to navigate the virtual environment, and they had a chance to practice navigating the virtual environment before starting the experiment. Additionally, to minimize any potential measurement errors, the survey used to measure perceived safety was pre-tested on a small group of participants to ensure that the questions were clear and understandable.

Pole lighting with WarmCCT	Pole lighting with CoolCCT
Bollard lighting+ Pole lighting with WarmCCT	Bollard lighting+ Pole lighting with CoolCCT

Table 2: First part of the experiment with four lighting scenarios in a 2 by 2 factorial design.

Pole lighting with Lighting on lower part of the façade	Pole lighting with Lighting on upper part of the façade
Bollard lighting+ Pole lighting with Lighting on lower part of the façade	Bollard lighting+ Pole lighting with Lighting on upper part of the façade

Table 3: Second part of the experiment with four lighting scenarios in a 2 by 2 factorial design.

Participants were asked to wear a VR headset, navigate the VR environment, and experience a series of lighting scenarios. For each, they were asked to rate their perception of safety as a dependent variable in different lighting conditions using a Likert scale.

To analyze the data collected from the experiment, R Studio and Python statistical analysis programs were used. In order to determine the main effects and interaction effects of the independent variables (light height, light source color temperature in the first experiment and, façade lighting and light height in the second experiment), a repeated measures analysis of variance (repeated measures ANOVA) were conducted. The main effects of these two independent experiments include the effects of height of light source (3-foot bollard + 9-foot pole vs. only 9-foot poles), light source color temperature (CCT), and façade lighting on perceived safety, each

analyzed separately. Furthermore, the interaction effects reveals whether the height of light source (3-foot bollard + 9-foot pole vs. only 9-feet poles) had a different impact on perceived safety depending on the CCT level (warmer vs. cooler), and whether the height of light source (3-foot bollard + 9-foot pole vs. only 9-foot poles) has a different impact on perceived safety depending on the different façade lighting conditions. Overall, a two-way repeated measures ANOVA for each factorial design allowed for a comprehensive analysis of the data and the identification of significant effects. Figure three shows the research variables.

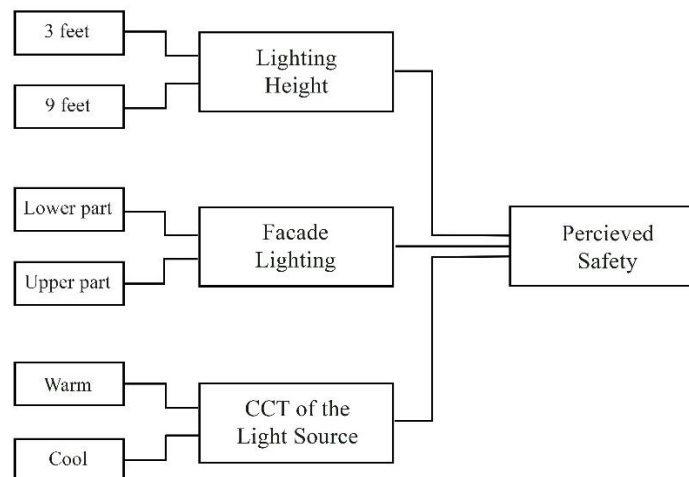


Figure 3: Conceptual diagram shows the research variables.

3.1.1 Advantages of using VR (Virtual Reality) Technology

The most accurate way to study users' perception of safety is to actually build the environment and lighting conditions on a real scale. Participants would have the opportunity to walk, feel, and assess different lighting conditions and their effect on perceived safety. While this would provide more precise results, the considerable cost of building an actual model makes this method impractical.

Another method would be to use existing and already-built spaces. Though less expensive, this method also has some limitations. First, it would be almost impossible to find all the lighting conditions in existing places, and even if it was possible to find appropriate sites, asking participants to travel to each place would be impractical.

Another established method among scholars is to use photographs, videos, and 3D renderings as a way to depict and analyze the built environment. While these methods have many advantages, such as being relatively cheap, quick, and easy to access, they cannot present a precise feeling of reality. Bishop and Rohrman conducted a study to compare people's evaluations of an outdoor environment in a real outdoor space and a recorded video of the same environment, during both daytime and nighttime conditions. The results showed that the video simulated environment did not produce similar outcomes as the real environment (Bishop and Rohrman 2003). There are also several other studies that found that photographs cannot show the complexity and dynamics of a real environment (Toet and van Schaik 2012, Austin et al. 2007)

In contrast, developing technologies such as VR, are able to provide a higher level of reality and have begun to be used by designers and researchers (D'Souza et al. 2011, Stouffs et al. 2013, Pietsch, 2000, Pittman 1992, Simpson 2001 and Portman et al. 2015). The important advantage of this method is that each person experiences a more reliable version of reality (Burdea and Coiffet 2003). To do so, users wear a high-resolution display screen that provides a stereoscopic view, mounted on a headset worn on their head, which allows the user to perceive a 3D environment.

VR allows researchers to create a controlled environment that can be manipulated to simulate a wide range of lighting conditions, which would be impossible to achieve in the real-world. Participants feel like they are fully immersed in the virtual environment, which can help to elicit more accurate responses and feedback. Furthermore, conducting research in VR is often far

more cost-effective than conducting real-world studies. Researchers can create multiple lighting scenarios and conduct a large number of experiments in a shorter amount of time, with no need to travel or set up equipment in different locations. This flexibility allows researchers to test a variety of hypotheses and lighting scenarios, helping to advance the understanding of how lighting impacts people's lives. In summary, this method to analyze the environment not only provides a more precise version of reality and gives participants this opportunity to explore and feel the space but also is relatively inexpensive, quick, and flexible for the researcher.

As advantageous as VR applications are, they also present some challenges. They require high processing power and graphics capabilities and require specialized computers that meet certain specifications. A VR-ready computer typically has a high-end graphics card, a powerful processor, and a sufficient amount of RAM, which means that they are significantly more expensive than regular photographs, videos, and rendered 3D modeling equipment.

3.2 Method and procedure

This research aimed to investigate how different lighting scenarios affect users' perception of safety. The study involved 50 female volunteers who participated in an experimental design with a within-subjects factor. A simulated urban residential street was created using Revit software and imported into Twinmotion rendering program to produce eight distinct lighting scenarios, each with different street lighting height, light source color temperature and façade lighting (See table 2 and 3). Participants navigated the virtual street and experienced each of the eight lighting scenarios. There was also a baseline environment in which participants walked through before experiencing these eight lighting scenarios. The baseline scenario consisted of only traditional pole lighting normally used for illuminating street for vehicles. After each walk-through, participants completed a survey to self-report on their perceived levels of safety (See Appendix one).

To investigate the impact of different lighting scenarios on perceived safety, this study employed two separate two by two factorial designs. The first design examined the effects of four lighting conditions: pole lighting with high CCT (6500 K), pole lighting with low CCT (3000 K), bollard lighting + pole lighting with high CCT (6500 K), and bollard lighting + pole lighting with low CCT (3000 K). The second design explored the effects of lighting placement on different building façades, with four lighting scenarios: pole lighting with lighting on the lower part of the façade, pole lighting with lighting on the upper part of the façade, bollard lighting + pole lighting with lighting on the lower part of the façade, and bollard lighting + pole lighting with lighting on the upper part of the façade. In the second experiment the CCT of both the façade and street lighting was considered around 5000 K to produce a neutral natural white (neither warm nor cool).

A residential street with five-story apartment buildings has been modeled for simulation. The street is 32 feet wide, consisting of two car lanes, and is bordered by two sidewalks, each 5 feet wide. To create a more realistic environment and enable participants to assess facial recognition quality, a layer of people has been added to the model. As a result, the overall simulation represents a residential street with a moderate level of activity and human presence. The spacing of lighting fixtures depends on several factors, including pole height, light distribution pattern, required illuminance levels, uniformity ratio, and surrounding environmental conditions (IES 2018). Taller poles typically allow for wider spacing, whereas shorter fixtures, such as bollard lights, need to be placed closer together to maintain adequate illumination. Additionally, the type of luminaire, its beam spread, and the reflectance of surrounding surfaces influence how light is distributed and perceived (IES 2018). In this model, pole lighting was arranged at 36-foot intervals to ensure consistent illumination along the walkway. Additionally, for the bollard lighting scenarios, two bollard lights were positioned between each pair of poles.

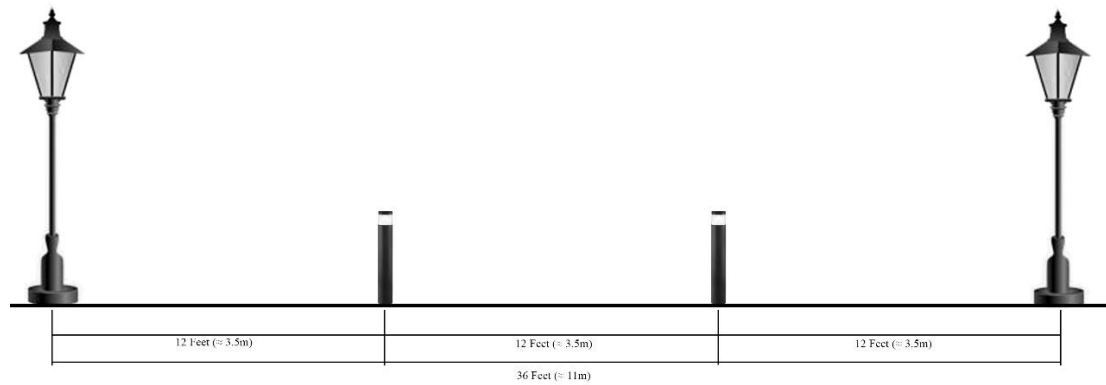


Figure 4: Lighting fixtures spacing.

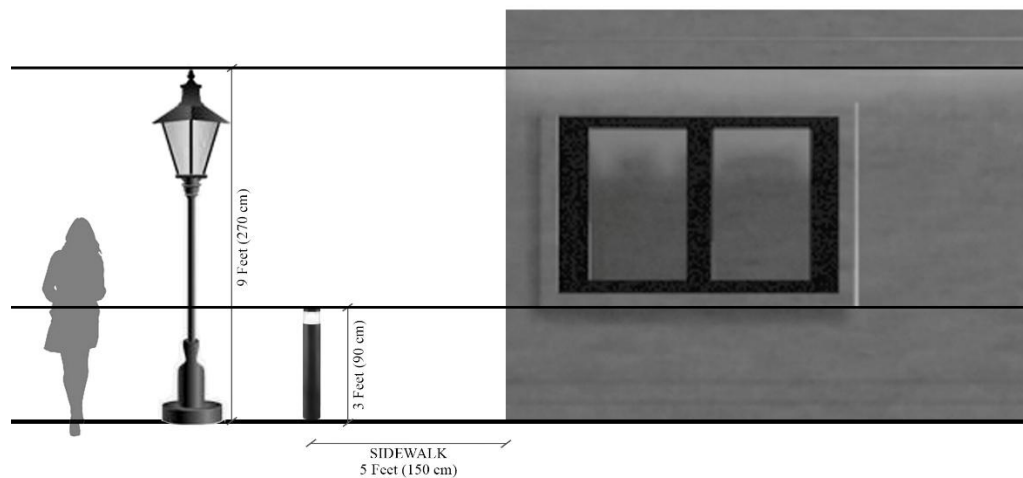


Figure 5: Lighting fixtures height.

In Twinmotion simulation, the primary lighting control available is lumen intensity, as the software does not provide direct lux level adjustments. Converting lumens to lux depends on factors such as beam angle, area coverage, and mounting height. Since Twinmotion is a rendering program, not a precise lighting calculation tool, it does not determine exact lux levels. However, for a 9-foot pole light, which covers approximately 250 ft², the lumen output was set around 150 lumens to achieve an estimated 6 lux (residential street with moderate activity) (IES 2018). In scenarios involving 3-foot bollards, the lumen level was set at 50 lumens, while pole-mounted

luminaires in bollard scenarios were adjusted to approximately 70 lumens to ensure a comparable lighting effect. For Experiment Two, which included façade lighting scenarios, a soft light with 20 lumens was directed onto the façade to minimize its impact on the overall light level, ensuring that the primary illumination remained controlled by the pole and bollard lights. Each participant experienced all nine combinations of lighting scenarios in a within-subjects design. Figures 6 to 14 show these eight lighting conditions alongside the baseline lighting scenario in Twinmotion.



Figure 6: Baseline lighting scenario.



Figure 7: Bollard lighting with CoolCCT.



Figure 8: Bollard lighting with WarmCCT.



Figure 9: Pole lighting with CoolCCT.

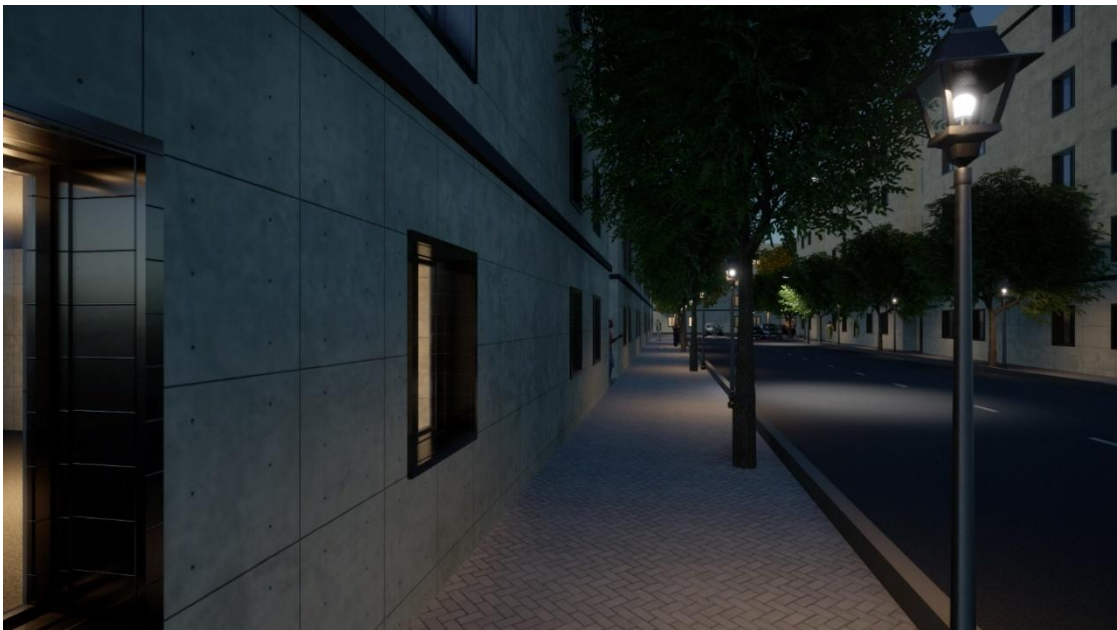


Figure 10: Pole lighting with WarmCCT.



Figure 11: Bollard lighting with lighting on lower part of the façade.



Figure 12: Bollard lighting with lighting on upper part of the façade.



Figure 13: Pole lighting with lighting on lower part of the façade.

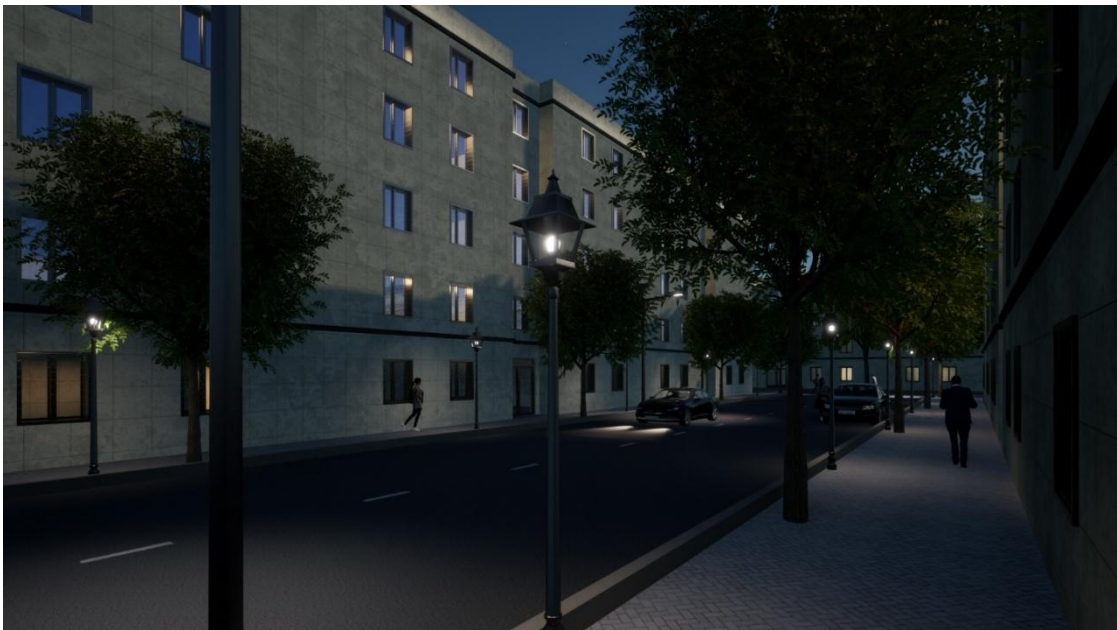


Figure 14: Pole lighting with lighting on upper part of the façade.

To recruit participants, an announcement was made in the Kansas State University e-newsletter "K-State Today," inviting female volunteers aged 18-65 with any educational or

professional background to participate in the study. The maximum age for participants was set at 65 because age-related macular degeneration, which can blur the central vision, is most common in those over age 65 (Chader and Taylor 2013). The study participants resided in Manhattan, Kansas, a relatively small and safe college town compared to more densely populated cities. It is important to note that participants' definition of perceived safety may differ from those living in larger cities, and this distinction could potentially impact the overall findings of the study. Participants received a \$17 gift card for their time and the entire experiment was approximately 60 minutes.

Although no severe side effects were expected with VR, some people do experience mild dizziness, headache, and motion sickness (Park and Lee 2020) from exposure to the immersive virtual environment and head-mounted display. In addition, some people find the simulated lighting environment reminiscent of unpleasant past experiences, which may cause discomfort. In this study, there were two participants who felt uncomfortable and couldn't finish the experiment. Participation was entirely voluntary, and participants could withdraw from the study at any time. The study used a convenient sampling method, which may limit the generalizability of the findings. However, the within-subjects design can increase the statistical power of the results. Data were collected and analyzed with strict adherence to ethical guidelines and institutional review board (IRB) protocols.

A survey was designed to gather participants' perceptions of safety in different lighting scenarios using a Likert scale. Participants were instructed to complete the survey after experiencing each of the eight lighting scenarios in the virtual environment. The survey consisted of six questions — the first five survey questions were based on the literature review and the last question asked directly about participants' perceived safety (See Appendix 1).

After the data was collected, R studio and Python statistical software were used to analyze the data using statistical methods to determine if there were significant differences between the different lighting scenarios in terms of participants' perceptions of safety. This analysis included descriptive statistics to summarize the data and inferential statistics to determine the significance of any differences found.

3-3-Tools

The equipment required to collect the data for this study included a high-performance workstation with the capability of supporting software programs such as Revit and Twinmotion for modeling and rendering the virtual environment. The computer also needs to meet the specifications necessary for VR applications, including a high-end graphics card, a powerful processor, and sufficient RAM. To achieve full immersion in the virtual environment, the HTC VIVE Pro 2 VR headset with navigators and sensors were used.

The VR headset is a high-resolution display device that fits on the head and provides a fully immersive experience of the virtual environment. The headset is connected to the workstation and displays a stereoscopic view of the 3D model. Navigators, or handheld controllers, were used to interact with the virtual environment. In addition to the navigators, sensors were placed around the room to track the participant's physical movements and location. It is essential to ensure that all equipment functions correctly and is calibrated before starting the experiment to ensure accurate data collection. Moreover, participants received instructions on how to use the equipment and navigate the virtual environment to avoid any issues that may affect the data collection process.

During the experiment, participants were asked to complete the survey by scanning a barcode on their phone. The survey questions were created using the Qualtrics app, and the collected data transferred to the Excel statistical software for analysis.

3.4 Survey questions

The literature revealed that there are five key attributes of light that significantly impact perceived safety — visibility of the path, visibility of the surroundings, presence of glare, facial recognition, and the message conveyed by the lighting. Additionally, research has demonstrated that specific factors such as lighting fixture height, color temperature of the light source, and the presence of façade lighting can influence perceived safety. Each of these variables has the potential to alter one or more of the lighting attributes, thereby impacting the overall perception of safety. To provide a clearer understanding of this study's framework, the following image shows a conceptual map and structure to illustrate the interrelationships among the lighting attributes, as well as the impact of the variables on perceived safety.

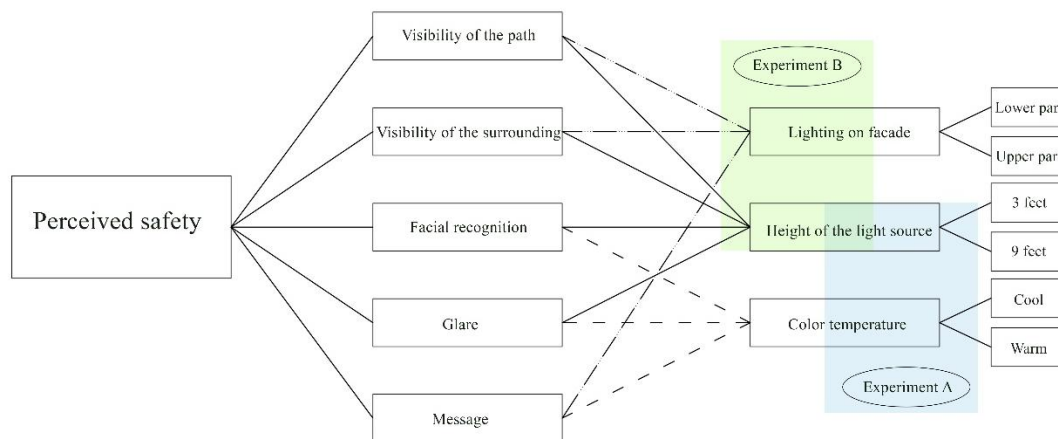


Figure 15: Conceptual map and structure of the research study.

The experiment involved eight distinct lighting scenarios, each of which followed by participants completing a survey to assess their perceived safety. Before participating in the actual experiment, participants first experienced a baseline level, which involved walking through a residential street with pole lighting solely on the vehicle lane. Subsequently, participants filled out a survey comprising nine questions (three demographic related questions and six perceived safety related questions). The initial three questions inquired about the participants' age, ethnicity, and frequency of walking habits. This demographic information was crucial to collect because previous studies, such as Ceccato (2012) and Roman and Chalfin (2008), suggested that older individuals tend to feel less safe. Other, such as Dastgheib (2018) highlighted the potential influence of ethnicity on perceived safety.

Following the testing of the baseline scenario and answering demographic questions, participants proceeded to the actual experiment, where they encountered the eight lighting scenarios. After each scenario, participants were asked to complete a survey consisting of six questions that measured their perceived safety. On each question participants rated their agreement from 1 (lowest agreement) to 5 (highest agreement). Questions one to five evaluated perceived safety based on the criteria extracted from the literature review. Additionally, there was one question that directly asks about the participants' overall perceived safety in the scenario. Table four shows the operational construct of the variables and table five clarifies the definition of each variable using the pervious literature.

Perception of safety	Independent variables	Variables	Attributes	Operationalization	Type	Data source
		Light source height	Visibility of the path	Presence of dark spot on the path	Ordinal	Survey
			Visibility of the surrounding	Presence of dark spot on the surrounding	Ordinal	Survey
			Glare	Presence of bothering light source on the visual field	Ordinal	Survey
			Facial recognition	Ability to recognition of facial expression	Ordinal	Survey
			Message	Willingness to stay in the place	Ordinal	Survey
		Light source color temperature	Facial recognition	Ability to recognition of facial expression	Ordinal	Survey
			message	Willingness to stay in the place	Ordinal	Survey
			Glare	Presence of bothering light source on the visual field	Ordinal	Survey
		Lighting on façade	Visibility of the path	Presence of dark spot on the path	Ordinal	Survey
			Visibility of the surrounding	Presence of dark spot on the surrounding	Ordinal	Survey
			Message	Willingness to stay in the place	Ordinal	Survey
	Confounding variables	Age	Young/ old	Counting age	Interval	Baseline level Survey
		Ethnicity	White/ African or Black/ others		Nominal	Baseline level Survey
		Walking habits (frequency)	Low to high	Frequency of walking	Ordinal	Baseline level Survey

Table 4: Operational construct of the variables

Perception of safety	Visibility of the path	-Prospect (having an overview) (Fisher and Nasar 1992) -Scape (perceived escape possibilities) (Fisher and Nasar 1992) -Concealment (perceived hiding places for offenders) (Fisher and Nasar 1992)
	Visibility of the surrounding	-Prospect (having an overview) (Fisher and Nasar 1992) -Scape (perceived escape possibilities) (Fisher and Nasar 1992) -Concealment (perceived hiding places for offenders) (Fisher and Nasar 1992)
	Glare	-Presence of a bright light source in the visual field (Boyce 2014)
	Facial recognition	-Understand the intention of an approaching person by his or her facial features (Boyce et al. 2000, Lin et al. 2015, Calleri et al. 2019, and Li et al. 2023)
	Message	- The message conveyed by lighting refers to the emotional or psychological impact of the lighting environment on individuals' perceived safety and whether the place is attractive and encourages people to visit after dark (Boyce 2014).

Table 5: Definition of each variable in the context of this research.

The survey questions were:

- 1) Which option represents your age the best.
18 to 30/ 31 to 50/ 51 to 65
- 2) How many times per week do you walk to commute.
Never/ Rarely/ Sometimes/ Often/ Always
- 3) Which categories describe you the best.
White/ Black or African/ others
- 4) I can see the pedestrian path clearly under this lighting condition (1: strongly disagree, 5: strongly agree)
- 5) The lighting enhances my ability to perceive the surrounding buildings and environment (1: strongly disagree, 5: strongly agree).
- 6) I am able to recognize facial expressions on people on the sidewalk clearly under this lighting condition (1: strongly disagree, 5: strongly agree).
- 7) I find the lighting is bothersome and the light source is in my field of view (1: strongly disagree, 5: strongly agree)

8) The lighting creates a welcoming and inviting atmosphere and encourages me to spend more time here (1: strongly disagree, 5: strongly agree).

9) I feel safe walking under this lighting condition (1: strongly disagree, 5: strongly agree).

Question	Source from literature review
No 1 and 2	Taner et al. 1997 Dravitzki et al. 2003 Fisher and Nasar 1992 Appleton 1975 Dastgheib 2018 Cellucci et al. 2016 Wänström 2012
No 3	Dastgheib 2018 Boyce 2014 Lin et al. 2015 Calleri et al. 2019 Li et al. 2023 Knight 2010 Yang and Fotios 2015 Painter 1996 Ulrika 2013
No 4	Peña-García et al. 2015 Knight 2010 Portnov 2020 Dastgheib 2018 Boyce et al. 2000
No 5	Fotios et al. 2018 Boyce 2014 Dastgheib 2018

Table 6: Extracted references of the five survey questions from the literature review.

3.5 IRB

This study aimed to recruit 50 female volunteers aged between 18 and 65 to participate in the experiment to evaluate their perceived safety under different lighting scenarios. To ensure ethical considerations of the experiment, informed consent was provided to the participants prior to their involvement. They were fully informed about the nature of the study, potential risks and benefits of participation, and their right to withdraw from the study at any time. Participants' confidentiality was ensured by anonymizing their responses and using only aggregate data in the analysis. The experiment was considered low-risk, and any potential side effects were mild and transient, such as a mild headache. In light of these considerations, the Kansas State University IRB approved the study.

Chapter 4 – Results

4.1 Summary of experiment and procedure

The study was conducted from January to April 2024, with the primary objective of investigating how different lighting conditions influence individuals' perception of safety. Given the constraints of a limited participant pool, a within-subject design was adopted, wherein each participant experienced all lighting scenarios (Charness et al., 2012). This approach allowed for a comprehensive examination of participants' responses across varied lighting conditions.

Fifty (50) female volunteers were recruited to engage in a virtual reality (VR) experiment. Each participant wore a VR headset and navigated through a simulated urban residential street featuring eight distinct lighting scenarios. These scenarios were differentiated by factors such as street lighting height, light source color temperature, and façade lighting. Participants were instructed to walk from the beginning to the end of the street, a journey typically lasting between one to two minutes.



Figure 16: Each participant wore a VR headset and navigated through the simulated environment.

The experiment was structured into two parts, employing two separated two-by-two factorial design. In the first part, participants experienced variations in lighting color temperature and height, while the second part involved changes in lighting height and façade illumination. Prior to exposure to experimental scenarios, participants were exposed to a baseline level featuring standard pole lighting typically found in current urban street settings. Following each simulation, participants were asked to complete a survey assessing their subjective perceptions of safety. The eight lighting scenarios were:

Bollard lighting + cool color temperature of the light source (CoolCCT)

Bollard lighting + warm color temperature of the light source (WarmCCT)

Pole lighting + cool color temperature of the light source (CoolCCT)

Pole lighting + warm color temperature of the light source. (WarmCCT)

Pole lighting + lighting on the lower part of the building façade (LowerBLDG)

Pole lighting + lighting on the upper part of the building façade (UpperBLDG)

Bollard lighting + lighting on the lower part of the building façade (LowerBLDG)

Bollard lighting + lighting on the upper part of the building façade (UpperBLDG)

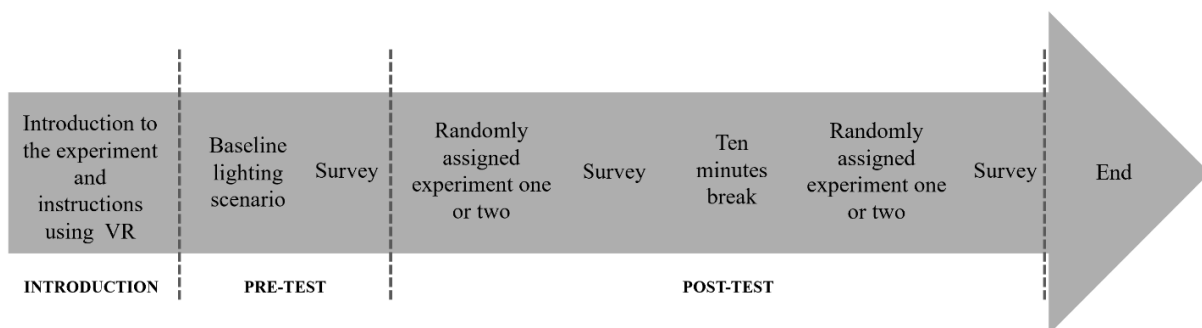


Figure 17: Experiment process.

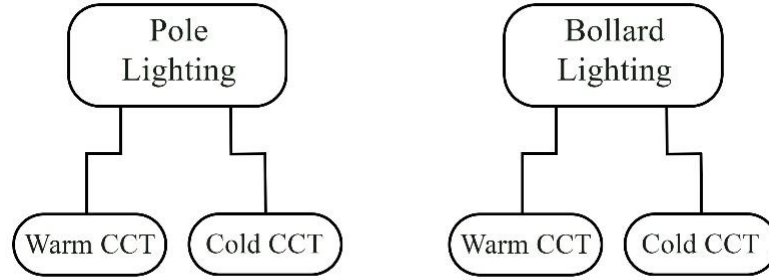


Figure 18: Experiment one with four lighting scenarios.

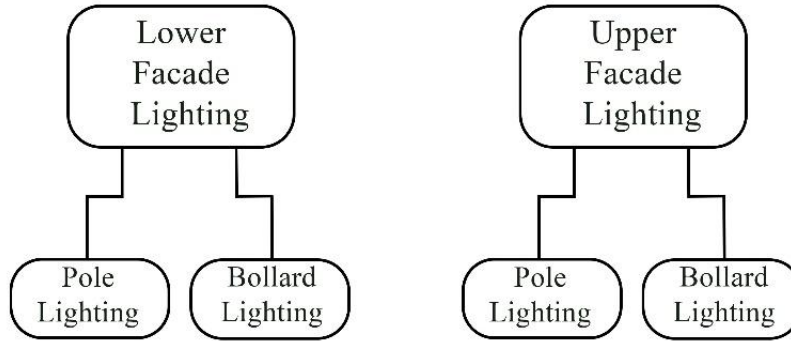


Figure 19: Experiment two with four lighting scenarios.

The survey comprised of six questions designed to assess participants' perceived safety using a Likert scale (1=Strongly disagree, 2=Disagree, 3=Neutral, 4=Agree, 5=Strongly agree). Five of these questions indirectly sought to assess perceived safety by employing criteria extracted from the literature review, while one question directly inquired about participants' perceived safety by prompting them to self-assess their perceived safety. The inclusion of both direct and indirect questions aimed to evaluate the reliability of the survey questions and assess the alignment between responses to indirect queries and the direct inquiry regarding perceived safety.

After completing the study, participants received \$17 as compensation and appreciation for their participation. However, during the course of the study, two volunteers experienced dizziness,

a known side effect of using virtual reality (VR) and were unable to finish the experiment. Consequently, surveys from these incomplete sessions were excluded from the analysis and two more participants were added.

4.2 Descriptive statistics of subjects' demographics

The study recruited volunteers from Manhattan, Kansas, ensuring a diverse pool of participants with varied backgrounds and walking habits based on self-reported information. Participants were stratified into three distinct categories: 18-30, 31-50, and 51-65. The distribution included 27 individuals in the 18-30 age group, 17 in the 31-50 range, and 6 in the 51-65 category. Additionally, the sample encompassed a mix of 21 international and 29 American volunteers. In terms of ethnicity, the majority of participants, comprising 45 individuals, identified as white, while 5 participants identified as African American or “other.” Furthermore, participants were classified into five distinct walking habit categories, based on self-reported frequency. Figures 20 to 23 show the participants' demographic distribution.

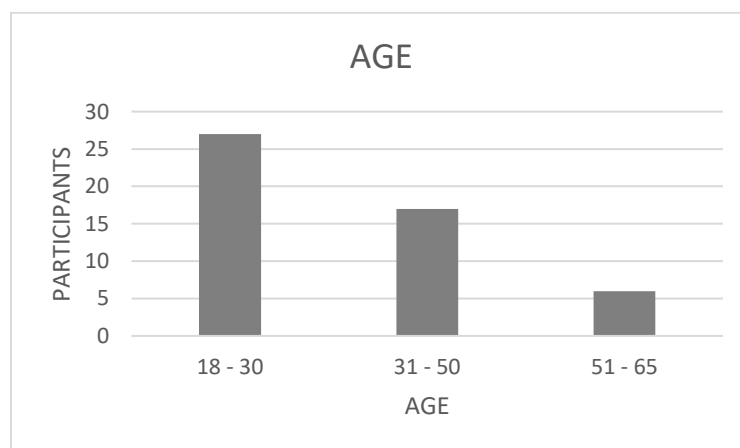


Figure 20: Distribution of participants ages in the study sample.

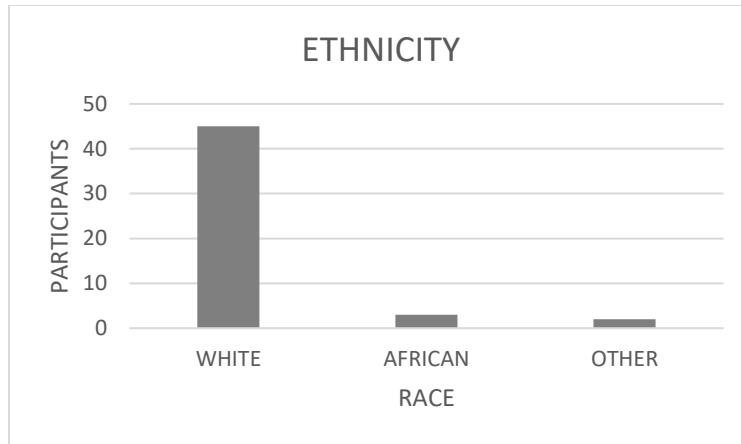


Figure 21: Ethnic distribution among study participants.

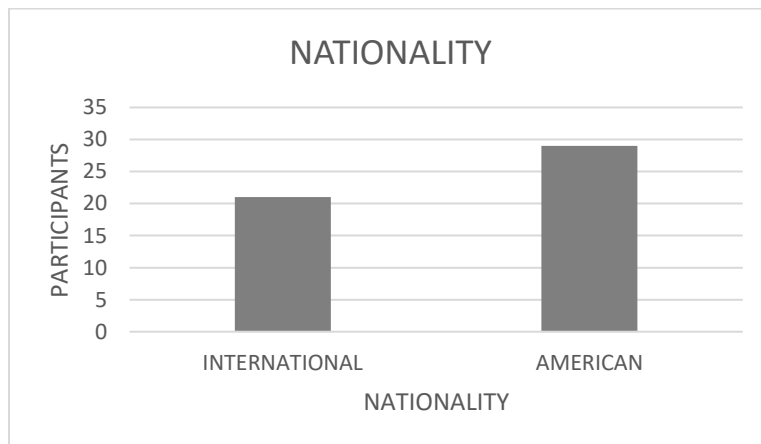


Figure 22: Nationality distribution among study participants.

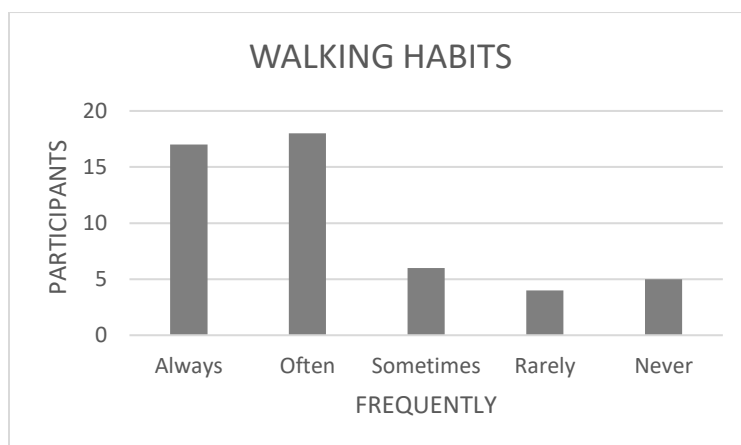


Figure 23: Frequency of walking habits among study participants.

The following two tables illustrate the variations in perceived safety across each lighting scenario, analyzed according to different demographic groups among participants. These tables provide insights into how these factors influence participants' safety perceptions in response to each lighting condition.

Demographic Information			Safety score - EXP1				
		Total Number	Baseline	Pole+ CoolCCT	Pole+ WarmCCT	Bollard+ CoolCCT	Bollard+ WarmCCT
Age	18-30	27	2.096	3.215	3.230	3.644	3.978
	31-50	17	2.282	2.953	3.376	3.682	3.718
	51-65	6	2.167	3.167	3.600	3.867	4.367
Nationality	International	21	2.248	3.190	3.238	3.581	3.705
	American	29	2.107	3.071	3.350	3.729	4.071
Walking habits	Always	17	2.106	3.111	3.333	3.733	3.911
	Often	18	2.167	3.118	3.188	3.647	3.976
	Sometimes	6	2.510	3.400	3.367	3.467	3.801
	Rarely	4	2.150	2.700	3.150	3.750	3.602
	Never	5	2.000	3.100	3.840	3.840	4.450

Table 7: Safety score among different demographic groups in experiment one.

Demographic Information			Safety score - EXP2				
		Total Number	Baseline	Pole+ LowerBLDG	Pole+ UpperBLDG	Bollard+ LowerBLDG	Bollard+ UpperBLDG
Age	18-30	27	2.096	4.207	3.104	4.519	3.422
	31-50	17	2.282	4.035	3.153	4.494	3.447
	51-65	6	2.167	4.600	3.467	4.833	4.033
Nationality	International	21	2.248	4.324	3.295	4.438	3.324
	American	29	2.107	4.093	3.043	4.614	3.586
Walking habits	Always	17	2.106	4.289	3.267	4.600	3.322
	Often	18	2.167	4.094	3.106	4.471	3.541
	Sometimes	6	2.510	3.914	3.114	4.486	3.829
	Rarely	4	2.150	4.300	2.750	4.450	3.000
	Never	5	2.000	4.600	3.450	4.850	4.100

Table 8: Safety score among different demographic groups in experiment two.

Tables nine and ten present the descriptive analysis, including metrics including mean, standard deviation, and other relevant statistics, for experiments one and two. These tables provide a detailed summary of the safety perception data across the various lighting scenarios for each experiment.

Lighting scenario		Mean	Median	Mode	Standard Deviation	Minimum	Maximum	Confidence Level
Pole Lighting	WarmCCT	3.324	3.4	4	0.825	1.4	4.6	0.313
	CoolCCT	3.120	3.2	3.4	0.850	1	4.6	0.326
Bollard Lighting	WarmCCT	3.936	4	4	0.707	2.2	5	0.268
	CoolCCT	3.684	3.9	4	0.747	2.8	4.8	0.283
Baseline		2.168	2.2	1.8	0.435	1.4	3	0.165

Table 9: Descriptive analysis for experiment one.

Lighting scenario		Mean	Median	Mode	Standard Deviation	Minimum	Maximum	Confidence Level
Pole Lighting	UpperBLDG	3.164	3.2	3.4	0.695	1.4	4.6	0.264
	LowerBLDG	4.196	4.2	4.4	0.466	3	5	0.177
Bollard Lighting	UpperBLDG	3.504	3.5	3.6	0.710	2	5	0.319
	LowerBLDG	4.548	4.6	5	0.463	2.8	5	0.176
Baseline		2.168	2.2	1.8	0.435	1.4	3	0.165

Table 10: Descriptive analysis for experiment two.

4.3 Statistical Analysis

4.3.1 Validity and reliability of the scales

A Cronbach Alpha test was conducted to assess the internal consistency or reliability of the survey. This test quantifies the extent to which the items in a scale measure the same underlying construct or concept. In other words, Cronbach's alpha indicates how closely related a set of items are as a group, with higher values suggesting greater consistency (Christmann and Van Aelst, 2006). Typically, a Cronbach's alpha value exceeding 0.70 is internally consistent (Peterson, 1994). The analysis was performed using R Studio version 2023.12.1+402 and resulted in a Cronbach's alpha coefficient of 0.83 for the two experiments and baseline.

Additionally, a Confirmatory Factor Analysis (CFA) was used to validate the measurement model for perceived safety across lighting scenarios. CFA is a statistical technique used to test whether a set of observed questions or indicators accurately measures an underlying concept or "latent variable," such as perceived safety. In this research, CFA was applied to verify if the

specific safety-related questions consistently represent the overall concept of perceived safety in different lighting scenarios.

The survey responses to five questions (Q1–Q5), designed to measure the latent variable "perceived safety," were analyzed to assess whether the observed variables reliably represent the underlying construct. CFA was employed because it allows for the evaluation of the relationship between observed variables (survey questions) and their associated latent variable, ensuring the survey validity. A good model fit is achieved when the chi-square (χ^2) $p > 0.01$, the comparative fit index (CFI) > 0.90 , the Tucker Lewis index (TLI) > 0.95 , the root mean square error of approximation (RMSEA) < 0.08 , the standardized root mean square residual (SRMR) < 0.08 (Hooper et al. 2008, Kline 2023). To conduct the analysis, R Studio was used, and the results indicated an acceptable model fit. The Chi-square value was 7.022 with a p-value of 0.219, the CFI value of 0.931 and the TLI value of 0.952, the RMSEA value was 0.030, and the SRMR value was 0.012.

Additionally, correlation analysis was used to evaluate the relationship between the perceived safety metrics derived from the literature review and participants' overall perception of safety. Five questions in the survey assessed perceived safety based on criteria extracted from the literature, while an additional question requested participants to self-evaluate their perceived safety under each specific lighting condition. By analyzing the correlation between each of the first five questions and the sixth, the aim was to determine if the individual criteria effectively measure the overarching concept of perceived safety.

The correlation test quantifies the strength and direction of the relationship between two variables, generating a correlation coefficient ranging from -1 to +1. This coefficient indicates the presence of a strong positive or negative relationship or the absence of one (Taylor 1990).

Accompanied by a p-value, the test determines whether the observed correlation is statistically significant, thereby discerning if the relationship is likely due to chance. Table 11 shows the results of Spearman's Rank Correlation Coefficient.

Survey question	Survey question	Spearman's Rank Correlation Coefficient
Q6 (overall perceived safety reported by participants)	Q1 (visibility of the path)	0.708/ P-value (< 0.01***)
	Q2 (visibility of the surrounding)	0.804/ P-value (< 0.01***)
	Q3 (facial recognition)	0.753/ P-value (< 0.01***)
	Q4 (Glare)	0.475/ P-value (< 0.01***)
	Q5 (welcoming message)	0.831/ P-value (< 0.01***)

***Significant at the 1% level

Table 11: Correlation analysis between reported overall perceived safety and each of the survey questions.

In correlation analysis, a commonly used guideline is that correlation coefficients above 0.7 indicate a strong relationship, suggesting that changes in one variable closely predict changes in another. Coefficients between 0.4 and 0.69 suggest a moderate relationship, where variables are linked but less predictably, while values near zero (0 to 0.39) represent a weak correlation, indicating little to no association between the variables (Taylor 1990).

In this study, correlation coefficients were calculated between the reported overall perceived safety and each of the survey questions revealing consistent and strong correlations. The positive correlation coefficient indicates that as scores on questions 1 to 5 increase, scores on question 6 also tend to increase. The correlation showed high coefficients and low p-values, consistently below the standard significance threshold of 0.01. This suggests that the observed correlations are statistically significant and not merely a result of random chance.

4.3.2 Comparison between baseline condition and proposed lighting scenarios

In this experiment, there was a baseline condition or scenario representing typical street lighting commonly found in U.S. cities — pole lighting that illuminated both the street and sidewalk. In this condition, no specific lighting was designated for the sidewalk, representing a common scenario in urban environments where lighting is primarily focused on vehicular areas rather than pedestrian pathways. Each participant initially walked through this baseline condition before experiencing the other lighting scenarios, which provided a reference point for their subsequent experiences with alternative lighting scenarios. The primary objective was to discern any disparities in perceived safety between the baseline level and each subsequent lighting scenario.

Following the baseline assessment, participants were exposed to a series of distinct lighting scenarios, each designed to manipulate various factors such as lighting height, color temperature, and façade lighting. By comparing participants' perceptions of safety across these different scenarios to their experiences in baseline condition, I sought to discern any discernible differences or improvements in perceived safety.

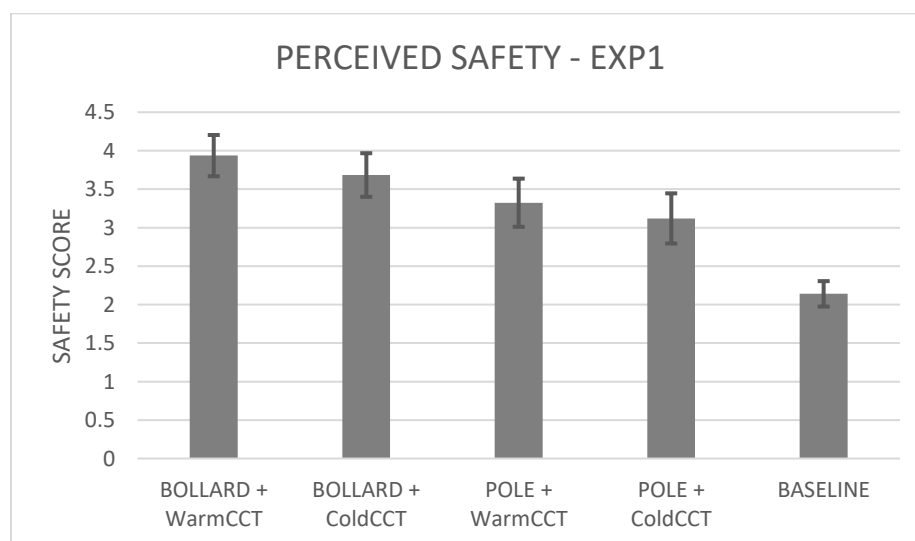


Figure 24: Comparison between baseline safety score and the four lighting conditions in experiment one.

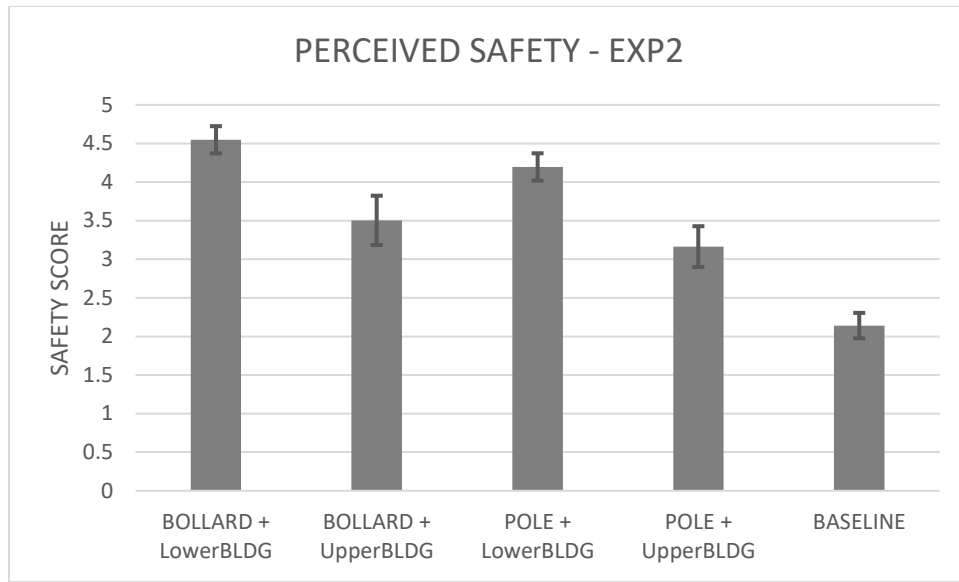


Figure 25: Comparison between baseline safety score and the four lighting conditions in experiment two.

To compare the eight different scenarios, repeated measures ANOVA were used, which is a statistical technique used for analyzing data where multiple measurements are taken on the same subjects under different conditions or time points. This method is well-suited for experimental designs involving within-subject factors, where participants are exposed to various treatments or conditions (Bergh, 1995). By employing repeated measures ANOVA, it was possible to determine whether the observed differences in perceived safety scores across the various lighting scenarios were statistically significant. The mean safety scores across different conditions were compared to determine if there were significant differences attributable to the lighting conditions rather than to random variations among subjects. The analysis was performed using Phyton. Python is a programming language widely used for statistical analysis due to its robust libraries that allow users to process data and perform statistical tests. Table 12 presents the Repeated Measures ANOVA results for both experiment one and experiment two.

	F value	Num DF	Den DF	Pr > F (P-value)
Experiment One	55.155	4	196	< 0.01***
Experiment Two	137.110	4	196	< 0.01***

***Significant at the 1% level

Table 12: Repeated measure ANOVA results for experiment one and two.

The null hypothesis indicates that there is no statistically significant difference between the mean scores of the various lighting conditions. In other words, it suggests that any observed differences in perceived safety scores across the different lighting scenarios could be due to random chance rather than actual effects of the lighting conditions. In this case, the calculated p-value from the statistical test is smaller than 0.01. This result indicates that the likelihood of observing such a significant difference in mean scores under the assumption of no true effect (if the null hypothesis were true) is very low. As a result, the null hypothesis is rejected, which means, there is a statistically significant difference in perceived safety scores among the various lighting conditions.

After conducting a repeated measures ANOVA, which showed significant differences in safety perceptions across different lighting conditions, post-hoc tests were performed to determine which specific conditions differed significantly from each other. Post-hoc tests or follow-up tests, are statistical analyses conducted after an ANOVA when the initial results show statistically significant differences and are used to identify exactly which pairs of group means (average value) are significantly different from each other. The primary goal of post-hoc testing is to explore and confirm where the differences lie between group levels, especially when multiple groups or conditions are compared (Wilkerson, 2008).

Pairwise T-tests were used as a post-hoc test. In addition, to the Bonferroni correction was applied to the p-values obtained from these multiple comparisons. The Bonferroni correction is a

method used to adjust the threshold for statistical significance, ensuring that the findings remain robust against Type I error (Napierala, 2012). By reducing the likelihood of falsely identifying significant differences, this correction method enhances the precision of the results and increases confidence in the observed differences being genuine rather than chance occurrences. The analysis was performed using Python. Table 13 shows the results of the pairwise T-test for experiment one and two.

Proposed lighting conditions		t-statistics	P-value	Adjusted P-value (Bonferroni correction)
Experiment One				
Baseline lighting condition	BOLLARD + CoolCCT	13.15	< 0.01***	< 0.01***
	BOLLARD + WarmCCT	15.78	< 0.01***	< 0.01***
	POLE + CoolCCT	7.53	< 0.01***	< 0.01***
	POLE + WarmCCT	9.36	< 0.01***	< 0.01***
Experiment Two				
Baseline lighting condition	BOLLARD + LowerBLDG	19.08	< 0.01***	< 0.01***
	BOLLARD + UpperBLDG	10.35	< 0.01***	< 0.01***
	POLE + LowerBLDG	18.15	< 0.01***	< 0.01***
	POLE + UpperBLDG	9.47	< 0.01***	< 0.01***

***Significant at the 1% level

Table 13: Pairwise T-test results for comparison between baseline and experiment one and two.

The results from both experiments clearly demonstrate that each of the proposed lighting conditions significantly differed in perceived safety when compared to the respective baseline lighting conditions. This is evidenced by the valid p-values in both the raw and Bonferroni-adjusted columns, indicating strong statistical significance in all comparisons.

4.3.3 ANOVA results for Experiment One

After confirming the validity and reliability of the experiment and assessing the effectiveness of the lighting conditions compared to the baseline condition. The next step was to examine the potential main and interaction effects for experiment one. A two-by-two factorial design was

employed for two independent variables (lighting type and color temperature of the light source), each with two levels. This type of experimental design allows for the exploration of both main effects, which represent the impact of each independent variable on the dependent variable, and interaction effects, which denote the combined influence of the independent variables. Figure 26 shows the perceived safety scores for experiment one.

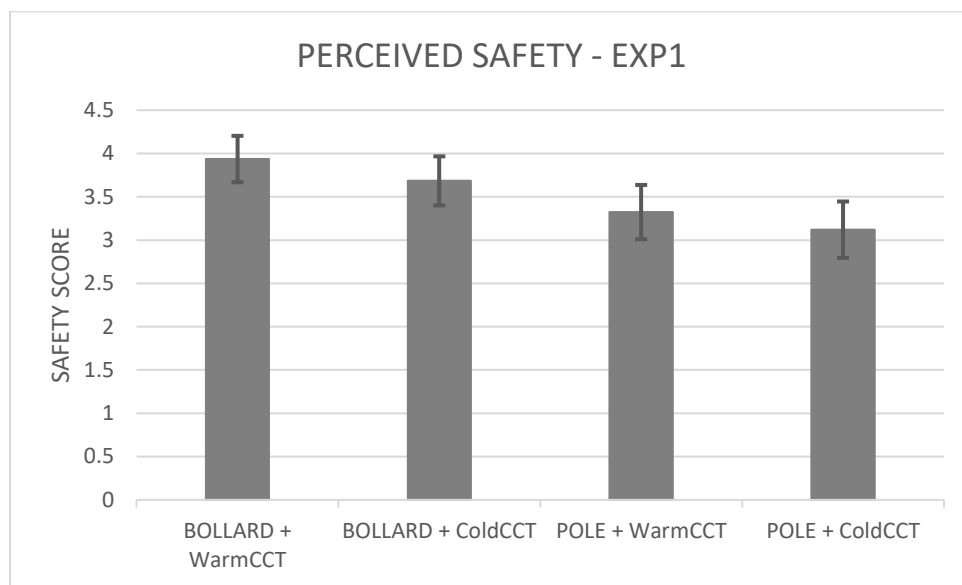


Figure 26: Perceived safety scores for experiment one.

As outlined, the four lighting conditions included bollard lighting with warm color temperature (Bollard + WarmCCT), bollard lighting with cool color temperature (Bollard + CoolCCT), pole lighting with warm color temperature (Pole + WarmCCT), and pole lighting with cool color temperature (Pole + CoolCCT). Through these conditions, the aim was to examine the main effects of color temperature and light height on perceived safety. Additionally, the interaction effect was investigated, which determines whether changes in color temperature, in conjunction with lighting height, impacted perceived safety differently. Essentially, the interaction effect assessed whether the influence of color temperature on perceived safety varies with the lighting

height specifically, whether it differs between bollard-mounted and pole-mounted lighting configurations.

To assess the presence of both main and interaction effects, a repeated measures ANOVA was employed, which is a statistical technique ideally suited for our experimental design. In this study, where each participant explored all lighting conditions, repeated measures ANOVA prove particularly valuable as it accounts for the repeated observations made on each subject. This method quantifies the main effects attributed to factors such as color temperature and light height as well as the potential interaction between these factors, by analyzing the variance within the data.

ANOVA is used to examine whether there are any significant differences between the means of these independent groups. In this context, ANOVA was able to evaluate the impact of color temperature and light height on perceived safety across multiple lighting conditions. By comparing the variance within the data to the variance between different lighting groups, ANOVA determines whether the observed differences in perceived safety scores are statistically significant and not merely due to random variability or chance. Table 14 and 15 show the mean values (perceived safety scores) and the results of the repeated measure ANOVA for experiment one.

Lighting scenario (experiment one)	Mean value (perceived safety score)
Bollard + WarmCCT	3.936 (0.707)
Bollard + CoolCCT	3.684 (0.747)
Pole + WarmCCT	3.324 (0.825)
Pole + CoolCCT	3.120 (0.850)

Note: values are mean (min: 1; max: 5), with standard deviation inside parentheses.

Table 14: Mean values of experiment one.

	F value	Num DF	Den DF	Pr > F	η^2
COLOR (main effect)	6.117	1.00	49.00	< 0.01***	0.020
HEIGHT (main effect)	27.852	1.00	49.00	< 0.01***	0.124
COLOR: HEIGHT (interaction effect)	0.084	1.00	49.00	0.772	0.0002

***Significant at the 1% level

Table 15: The main effect and interaction effect results for experiment one.

The results of the repeated measures ANOVA indicated that the p-values for both color and height are less than the predetermined significance level of 0.01, which suggests that there is a potential main effect of color and height on perceived safety. In other words, variations in the color temperature and the height of the lighting fixtures may independently influence participants' perceptions of safety.

However, the p-value associated with the interaction between the independent variables (color temperature, and height of the lighting fixtures) is significantly higher than 0.01. This implies that the interaction effect between color temperature and height does not exert a statistically significant influence on the dependent variable (perceived safety). In simpler terms, the combined impact of color temperature and height of the lighting fixtures does not significantly affect participants' perceptions of safety beyond what can be attributed to color temperature and height individually.

Meanwhile, the analysis indicated that height exerts a more pronounced influence on perceived safety compared to color. This inference is drawn from the eta-squared values, where height demonstrates a significantly larger effect size ($\eta^2 = 0.124$) compared to color ($\eta^2 = 0.020$). Conversely, the interaction between color and height shows negligible impact on the dependent variable, as reflected by its very small eta-squared value ($\eta^2 = 0.000237$). This implies that any

combined effect resulting from the interaction of color and height does not significantly contribute to the overall variance in the perceived safety.

Following the ANOVA test, which revealed the potential main effects of color and height on the participants' perception of safety, the next step was to conduct a post-hoc test to make pairwise comparisons between group means. Post-hoc tests are essential when the ANOVA indicates significant differences, as they allow us to identify specifically which groups differ from each other. This is crucial when the ANOVA indicates significant differences, then we need to pinpoint where those differences lie. Given the absence of an interaction effect in the ANOVA results, post-hoc tests were conducted exclusively for pairs that exhibited a main effect.

Therefore, paired t-tests with Bonferroni Correction were conducted as a post-hoc analysis to examine differences in perceived safety scores across various lighting conditions. This choice of statistical test was appropriate given the repeated measures design of our experiment, where each participant provided scores under multiple lighting conditions. The paired t-test calculated the difference between pairs of related observations and determined whether these differences are statistically significant.

Additionally, the Bonferroni correction was applied to our paired t-tests to uphold statistical rigor when making multiple comparisons between different lighting conditions. With participants experiencing several combinations of lighting height and color temperature, perceived safety scores were compared between these pairs using paired t-tests. Because multiple comparisons heighten the risk of Type I errors (false positives), the Bonferroni correction adjusts the significance threshold accordingly. By doing so, we can ensure that any significant findings are genuinely meaningful and not merely the result of random chance. Python was used to conduct the paired t-tests, and the results are presented in Table 16.

Comparison	t- statistics	P-value	Adjusted P-value (Bonferroni correction)
WCCT + BOLLARD vs. WCCT + POLE	4.637	< 0.01***	< 0.01***
WCCT + BOLLARD vs. CCCT + BOLLARD	2.305	0.0253	0.152
WCCT + POLE vs. CCCT + POLE	1.494	0.141	0.848
CCCT + BOLLARD vs. CCCT + POLE	3.893	< 0.01***	< 0.01***

***Significant at the 1% level

Table 16: Paired T-test comparison results for experiment one.

Table 16 presents the results of paired t-tests comparing different combinations of lighting height (BOLLARD vs. POLE) and color temperature (WarmCCT vs. CoolCCT) on perceived safety, with both unadjusted and Bonferroni-adjusted p-values. The comparisons "WarmCCT + BOLLARD vs. WarmCCT + POLE" (t-statistic: 4.64, adjusted p-value: < 0.01) and "CoolCCT + BOLLARD vs. CoolCCT + POLE" (t-statistic: 3.89, adjusted p-value: <0.01) are statistically significant after adjusting for multiple comparisons, indicating that the perceived safety scores between these combinations differ significantly. This implies that lighting height has a notable impact on perceived safety, regardless of color temperature. The ANOVA analysis revealed a potential main effect of color temperature on perceived safety. However, upon further examination using paired t-tests, no statistically significant differences between pairs were observed, indicating that the effect of color temperature did not yield significant variations in perceived safety scores.

4.3.4 ANOVA results for Experiment Two

In the second part of the study, the focus shifted to four distinct lighting conditions: bollard lighting with lower façadelighting (Bollard + LowerBLDG), bollard lighting with upper façadelighting (Bollard + UpperBLDG), pole lighting with lower façadelighting (Pole + LowerBLDG), and pole lighting with upper façadelighting (Pole + UpperBLD).



Figure 27: Perceived safety scores for experiment two.

This setup constituted a within subjects two-by-two factorial experiment, where all participants experience each lighting condition. Similar to the first part, the objective was to assess the presence of main effects and interaction effects. Main effects included examining the impact of lighting height and façade lighting on perceived safety separately. Additionally, the study sought to evaluate interaction effects to determine whether the influence of lighting height on perceived safety varies based on the type of façade lighting employed. Here the interaction effect serves to assess whether the relationship between lighting height and perceived safety is contingent upon the specific façade lighting arrangement. Through a comprehensive examination of main and interaction effects, the study aimed to discern how different combinations of lighting height and façade lighting influence participants' perceptions of safety in urban environments.

To assess the presence of potential main and interaction effects, a repeated measures ANOVA was conducted followed by a post hoc test, mirroring the methodology employed in the previous part of the study. The post hoc test becomes imperative once the ANOVA identifies significant main effects or interaction effects. This test facilitates pairwise comparisons between group means, enabling us to pinpoint the specific groups that differ from each other. The following

tables present the mean values (perceived safety scores), results of the repeated measures ANOVA and paired T-tests conducted using Python.

Lighting scenario (experiment two)	Mean value (perceived safety score)
Bollard + LowerBLDG	4.548 (0.463)
Bollard + UpperBLD	3.504 (0.710)
Pole + LowerBLDG	4.196 (0.466)
Pole + UpperBLD	3.164 (0.695)

Note: values are mean (min: 1; max: 5), with standard deviation inside parentheses.

Table 17: Mean values of experiment two.

	F value	Num DF	Den DF	Pr > F	η^2
FAÇADE LIGHTING (main effect)	140.278	1.00	49.00	< 0.01***	0.403
HEIGHT (main effect)	16.1652	1.00	49.00	< 0.01***	0.069
COLOR: HEIGHT (interaction effect)	0.005	1.00	49.00	0.940	0.00002

***Significant at the 1% level

Table 18: The main effect and interaction effect results for experiment two.

Comparison	t- statistics	P-value	Adjusted P-value (Bonferroni correction)
LowerBLDG + BOLLARD vs. LowerBLDG + POLE	4.393	< 0.01***	< 0.01***
LowerBLDG + BOLLARD vs. UpperBLDG + BOLLARD	8.362	< 0.01***	< 0.01***
LowerBLDG + POLE vs. UpperBLDG + POLE	9.309	< 0.01***	< 0.01***
UpperBLDG + BOLLARD vs. UpperBLDG + POLE	5.335	< 0.01***	< 0.01***

***Significant at the 1% level

Table 19: Paired T-test comparison results for experiment two.

The results of the repeated measures ANOVA revealed the potential presence of a main effect, suggesting that both the height of the lighting fixture and the location of façade lighting may indeed influence perceived safety. However, the analysis did not uncover any significant

interaction effect between the height of the lighting fixture and façadelighting on perceived safety. This suggests that the relationship between lighting fixture height and perceived safety is not influenced by the presence or absence of façadelighting. In other words, the effects of lighting fixture height on perceived safety remain consistent regardless of whether façadelighting is present or not. The results from experiment one similarly suggested the influence of lighting height on perceived safety.

Meanwhile, the "façade" factor exhibits a substantial impact, with a partial eta-squared value ($\eta^2 = 0.403$). Similarly, the "height" of the lighting fixture also emerges as a significant predictor, albeit to a lesser extent, with a η^2 value of 0.069. However, the interaction between façadelighting and fixture height appears to have minimal influence, as evidenced by the very small η^2 value of 0.00002. This suggests that any combined effect resulting from the interaction of these factors does not substantially contribute to the overall variance in the perceived safety.

Since the repeated measures ANOVA analysis did not reveal any interaction effect, the post hoc table exclusively displays pair comparisons for the main effect. The paired t-test with Bonferroni-adjusted p-values highlighted that lighting height significantly influences perceived safety under each type of façadelighting. Furthermore, comparisons across different lighting types demonstrated significant differences, indicating that the placement of façadelighting also significantly impacts perceived safety.

Chapter 5 – Discussion and Conclusion

5.1 Discussion

Experiment one examined the influence of both color temperature and the height of lighting fixtures on perceived safety. Within the realm of lighting design, there has been an ongoing debate regarding the impact of color temperature on perceived safety. Some experts suggest that warmer color temperatures create a greater sense of safety (Saad et al. 2021, Liu et al. 2022), while others argue that cooler color temperatures are more conducive to feelings of safety (Bullough and Skinner 2015, Boyce et al., 2000, Peña-García et al. 2015, Knight 2010).

The first research hypothesis stated that women's perception of safety will increase with the warmer color temperature lighting. The results of the ANOVA test in this study hinted at the potential influence of color temperature on perceived safety. However, further analysis through post hoc testing did not uncover any statistically significant differences among the pairs related to color temperature. Despite this, the initial indication of color temperature's influence underscores the complexity of factors at play in urban lighting design and the importance of considering color temperature alongside other design elements. Moreover, it's worth noting that the effect size of color temperature on perceived safety, when compared to the effect size of lighting fixture height, was relatively low. This suggests that while color temperature may have some impact on perceived safety, its magnitude is not as substantial as the influence exerted by the height of lighting fixtures.

In this research, the results didn't approve the hypothesis and indicated that color temperature does not significantly impact perceived safety, and **although color temperature can influence the mood of a space, it does not dramatically change perceived safety in tested women volunteers.**

However, although the post hoc test did not reveal any significant connections, it is still prudent to consider further investigation. This is especially important given the initial indication of significance from the ANOVA results. While the post hoc test did not yield statistically significant differences among the pairs related to color temperature, it is possible that this outcome could be attributed to limitations such as sample size constraints.

Still, there may be other good reasons to choose warmer colors. For example, the International Dark-Sky Association (IDA) and the Illuminating Engineering Society (IES), provide guidelines to reduce light pollution while ensuring effective outdoor illumination. These principles advocate for using light only when necessary, choosing the appropriate brightness to avoid over-lighting, directing light precisely to areas that need it, minimizing harmful blue light emissions by favoring warmer color temperatures, and prioritizing energy-efficient fixtures. Therefore, although the results showed no significant differences between warm and cool light in terms of perceived safety among the recruited volunteers, **warm light is still preferred because it would reduce light pollution and minimize disruption to both human circadian rhythms and wildlife, without compromising safety.**

The next research hypothesis stated that women's perception of safety will increase when bollard lighting is used as a complement to pole lighting. The lighting fixture height emerged as an important variable in both experiment one (different color temperature and lighting height) and experiment two (different lighting height and façade lighting). In experiment one, the statistical analysis unveiled a significant effect of lighting fixture height on perceived safety. The robustness of this finding was underscored by the results of the ANOVA, which provided evidence of the influence of lighting fixture height on perceived safety. Moreover, the subsequent investigation using a post-hoc test yielded consistent and strongly valid results, further confirming the

significance of lighting fixture height in shaping perceptions of safety in urban environments. Indeed, the post-hoc tests for the pairs related to lighting fixture height yielded statistically significant results. Additionally, the analysis of effect size reaffirmed the importance of the effect of lighting fixture height on perceived safety.

Based on the results from the post-hoc analysis, participants reported feeling safer in scenarios where bollard lighting was added as a complement to pole lighting. For example, in experiment one, the scenarios that included bollard lighting consistently resulted in higher perceived safety scores, regardless of the color temperature. Similarly, in experiment two, scenarios incorporating bollard lighting also yielded higher safety scores, irrespective of the different façade lighting configurations. These findings approve the hypothesis and indicate that **the presence of bollard lighting contributes significantly to the perception of safety, suggesting that its use, in conjunction with traditional pole lighting, can enhance the overall sense of safety in urban settings.** It is also important to note that the light levels were kept consistent across all scenarios. Thus, the overall illumination remained the same whether pole lighting or a combination of both was used.

The results of this part of the experiment align with the findings in the literature. Previous studies have emphasized the importance of bollard lighting in enhancing perceived safety. For example, Vogel and Pettinari (2002) concluded that low-pole lighting creates “people-scaled illumination in dark corners.” Another study conducted by Bullough and Skinner (2015) found that the use of bollard lighting led to a significant increase in perception of safety compared to pre-existing pole lighting. However, one key difference is that most of these studies primarily focused on safety from vehicles, while in this research, the focus was solely on the pedestrian's point of view. Another important difference in this study is that bollard lighting was used as a complement

to pole lighting, whereas previous research typically evaluated bollard lighting as an alternative to pole lighting. This complementary use appears to significantly enhance the sense of safety, suggesting that integrating both lighting types could be a more effective strategy for urban lighting design than relying on pole lighting alone.

As previous research suggests, one factor influencing participants' preference for bollard lighting could be related to the intentionality of the design because it can convey a sense that the lighting was thoughtfully planned and tailored to the environment. This intentional design can enhance the perception that the space is well-maintained and prioritized for safety. Furthermore, the presence of bollard lighting may create an impression that the path is important enough to warrant special attention and investment. This perception can contribute to a heightened sense of safety and comfort for pedestrians, reinforcing the idea that the area is considered valuable and deserving of meticulous design.

Another reason for the preference for bollard lighting is that it is on a more human scale, making it more relatable and acceptable to people. Because bollard lighting is closer to the ground and eye level, it creates a more intimate and approachable environment, which can enhance the feeling of personal safety and comfort, as it is perceived as more considerate of pedestrian needs. The proximity to human scale provided by bollard lighting can make spaces feel more welcoming, further contributing to its acceptability among users.

And still another good reason for bollard lighting is that it effectively illuminates the path where light is most needed, which aligns with the 5 Principles for Responsible Outdoor Lighting (Illuminating engineering society 2023), as it directs light precisely to the intended area, reduces light spillage, and improves visibility while minimizing light pollution.

This study also investigated the potential interaction effect between lighting height and the color temperature of the light source on perceived safety, and more specifically, whether the impact of lighting height on perceived safety depended on the color temperature. The research hypothesized that perception of safety will increase when bollard lighting is combined with warmer color temperature lighting. To explore this, an ANOVA test was conducted to check for any statistically significant differences in perceived safety when considering the effects of both variables simultaneously.

The results of the ANOVA test were not significant and didn't approve the research hypothesis. With the p-value exceeding the acceptance threshold, which indicates that, within the parameters of this research, there is no significant interaction effect between lighting height and color temperature on perceived safety. In other words, the effect of **lighting height on perceived safety does not depend on the color temperature of the lighting**. However, this finding could be influenced by the limitations of the study, and it is recommended that further investigations explore this potential interaction effect more comprehensively.

While experiment one focused on the impact of color temperature and lighting height and their interaction effect on perceived safety, the second experiment examined how lighting on different parts of the façade influenced perceived safety. Thus, in experiment two, lighting height and façade lighting were treated as independent variables.

The results from the second experiment confirmed the findings from experiment one regarding the impact of lighting height. The analysis consistently highlighted the importance of lighting height on perceived safety. In both experiments, lighting height was found to be a significant factor in how safe participants felt in different lighting conditions.

Similar to the first experiment, bollard lighting, when used as a complement to pole lighting, made participants feel safer compared to pole lighting alone. This finding suggests that bollard lighting provides a sense of security that is not achieved by pole lighting alone. The presence of bollard lighting appears to enhance the overall effectiveness of the lighting design.

Additionally, the main effect of façade lighting on perceived safety was statistically significant. This finding indicates that different types of façade lighting can alter the level of perceived safety. **Participants tended to feel safer when the lower part of the façade was illuminated.** These findings were in line with the research hypothesis stating that women's perception of safety will increase when lower façade lighting is used. These results may be due to the fact that lighting on the lower part of the façade tends to create a more human-scale lighting environment, which can make people feel that the lighting was intentionally designed, and giving them a sense of safety knowing that the path was deemed important enough to receive special attention and design. This finding underscores the significance of designing lighting that considers human-scale perception and the psychological impact of intentional design.

It is important to note that scenarios with upper façade lighting generally made participants feel safer compared to the baseline condition (pole lighting only) without any façade lighting. This suggests that we cannot overlook the importance of lighting on the upper part of the façade. Dastgheib (2018) argued that lighting on the upper part of the façade can make the spatial configuration clearer for people, thereby enhancing their sense of safety.

In experiment one, the focus was on color temperature and lighting height, which are closely tied to urban design and necessitate strategies at the urban level, which are primarily the concern of government policymakers. The goal was to understand how these factors, which are usually controlled by municipal regulations, can influence perceived safety in urban environments.

In contrast, façade lighting in residential areas intersects with both governmental policy and individual architectural design. Designers have some freedom to incorporate façade lighting based on aesthetic and functional considerations, while policymakers can establish regulations that mandate the inclusion of façade lighting to enhance public safety. This dual influence highlights the collaborative role of both designers and policymakers in creating safer urban and residential environments through thoughtful lighting design.

Another research question focused on the potential interaction effect between façade lighting and lighting height and whether the combination of façade lighting and lighting height influenced how safe individuals feel in an environment. Here, the research hypothesis stated that sense of safety will increase when bollard lighting is combined with light on the upper part of the building façade. Each of these factors independently affected perceived safety, but this study also investigated whether their interaction has a significant impact.

To explore this, an ANOVA test was conducted to assess any statistically significant differences in perceived safety based on the interaction between façade lighting and lighting height. This analysis is crucial as it helps identify whether the combined effect of these two variables is more significant than their individual effects. The results, however, were not statistically significant, and didn't approve the research hypothesis. The results indicated that the perceived safety levels, when varying façade lighting, do not depend on the changes in lighting height. In other words, the **impact of façade lighting on perceived safety appears to be independent of the lighting height.**

5.2 Analysis considerations

In this research, a Likert scale was used to measure perceived safety, which provided data on an ordinal scale. Traditionally, parametric statistics such as ANOVA and T-tests are considered appropriate for interval data, which assumes that the data points are spaced at equal intervals. However, the application of these tests to ordinal data, like that from Likert scales, has been debated (Kuzon et al., 1996).

Despite this, there is substantial evidence suggesting that parametric methods can be reliably used with Likert scale data. Norman (2010) argues that parametric methods such as ANOVA and T-tests are robust to typical violations of the assumptions of normality and linearity that arise with ordinal data. This robustness implies that these methods can still produce valid results when applied to Likert scale data. Therefore, using parametric tests in this study is justified and does not compromise the reliability of the results.

On the other hand, distribution normality and a large sample size are two common assumptions in many statistical tests to ensure the accuracy and reliability of results. Generally, larger sample sizes yield results that are closer to the true population parameters, increasing the generalizability of the findings. However, some researchers challenge these assumptions. Boneau (1960) highlights that parametric tests are robust even when the assumption of normality is violated, particularly when analyzing means and central tendencies. His work suggests that the robustness of these tests holds up under various conditions, thus supporting their continued use even when traditional assumptions are not fully met.

Norman (2010) further addresses the issue of small sample sizes in statistical analysis, criticizing the overly cautious approach that discourages the use of parametric tests with small

samples. He clarifies that there is no empirical evidence to support the idea that small sample sizes necessitate the abandonment of parametric methods. Norman emphasizes that the Central Limit Theorem plays a crucial role in mitigating the effects of non-normal distributions in small samples. According to this theorem, the distribution of sample means tends to be normal regardless of the shape of the original data distribution as the sample size increases. This suggests that even with smaller samples, parametric tests can still produce reliable and valid results.

However, for very small sample sizes, researchers should be aware of the increased risk of encountering Type I or Type II errors and the potential reduction in statistical power. Type I errors involve falsely rejecting a true null hypothesis (false positive), while Type II errors involve failing to reject a false null hypothesis (false negative). These risks are heightened when sample sizes are too small to reliably detect true effects. Thus, while it's generally acceptable to apply parametric tests with small samples, researchers should conduct a power analysis to assess the likelihood of detecting a true effect given the effect size, and significance level. By carefully considering these factors, researchers can ensure appropriate statistical handling and maintain the validity and reliability of their findings, even with smaller sample sizes.

For this project, based on available grant funding, I was able to recruit 50 volunteers for the investigation. According to various studies (Islam, 2018, Chang et al. 2006), a sample size greater than 30 is often considered the minimum threshold for achieving statistically significant data. Though the normality of the data was not tested for this investigation, I believe that the parametric statistics used in this research are robust and reliable, based on the research by Norman (2010) and others who have demonstrated that parametric methods, such as ANOVA and T-tests, can produce valid results even when the assumption of normality is not strictly met, especially with smaller sample sizes.

5.3 Conclusion and limitations

5.3.1 Conclusion

In the first experiment, which looked at the effect of lighting height and color temperature on perceived safety, the results indicated a potential main effect of both color temperature and lighting height on perceived safety, which suggested that each factor independently influences how safe participants feel under different lighting conditions. It also found that different lighting color temperatures were not associated with lighting height in influencing perceived safety. In other words, color temperature and lighting height affect perceived safety independently, without any significant interaction between the two variables.

The experiment also found that the height of the lighting fixtures had a notable impact on perceived safety. Participants consistently felt safer under lighting scenarios that included bollard lighting and using bollard lighting in combination with pole lighting significantly increased perceived safety. Meanwhile, based on the T-test calculations, the effect of color temperature on perceived safety was not significant.

The results of this part of the study have implications for urban design policies related to lighting. Both the color temperature of the light source and the height of the light source are factors that fall under the jurisdiction of municipal and government policymakers. It is recommended that urban design policymakers, transportation planners, and public works staff incorporate these findings into their regulations and guidelines and encourage the inclusion of bollard lighting in urban design to help create safer, more welcoming environments, which in turn can enhance the livability and walkability of city spaces.

The second experiment focused on the effects of both lighting height and façade lighting on perceived safety. This means that both the height of the lighting fixtures and the location of the façade lighting independently influenced participants' perceptions of safety. Participants felt safer under certain conditions of lighting height and façade lighting.

However, the ANOVA test did not reveal any interaction effect between lighting height and façade lighting, which means that the influence of lighting height on perceived safety did not depend on the type of façade lighting, and vice versa. In other words, changes in perceived safety due to variations in lighting height were consistent regardless of the specific façade lighting conditions. This suggests that these two variables independently contribute to perceived safety without interacting with each other. It also found that the presence of bollard lighting in conjunction with pole lighting significantly increased perceived safety, which aligns with the results from the first experiment, reinforcing the importance of lighting height in enhancing perceived safety.

Additionally, the results showed that façade lighting on the lower part of the buildings made people feel safer compared to lighting on the upper part, likely due to its impact on creating a more human-scale environment and better visibility of immediate surroundings

It is recommended that policymakers, transportation planners, and public works staff establish regulations mandating a minimum level of façade lighting to increase perceived safety. At the same time, architects should be given the freedom to interpret these regulations creatively, ensuring that the lighting meets both safety standards and enhances the visual appeal and character of the area. By balancing regulatory requirements with design flexibility, we can create safer and more visually engaging urban environments.

5.3.2 Limitations

The modeled residential area is based on five-story apartment buildings that are typically found in more densely populated cities in the USA where people might perceive their environment as less safe than those in smaller cities. However, due to limitations in time and budget, the experiments were conducted in Manhattan, Kansas, which is considered a relatively small and safe city. Participants in this study, many who came from other cities and country, may have a different definition and experience of safety, which could impact the results. Future studies should consider using participants who live in cities with characteristics similar to the modeled environment to obtain more accurate results.

Walking figures were added to the simulated virtual environment to assess facial recognition quality under different lighting scenarios. The presence, number, appearance, and activities of these figures can influence the perception of design and overall safety. Although, in this study, the entire layout of people—including their number, positioning, and activities—was kept identical across all lighting scenarios to ensure consistency, it is crucial to carefully control and consider their impact to ensure that the perceived safety results accurately reflect the effects of lighting rather than the influence of human presence in the model.

In this research investigation, the sample pool was limited due to financial constraints, allowing me to recruit 50 participants. Despite this limitation, it was possible to successfully engage volunteers and obtain valuable results. For future research, expanding the sample size is recommended, as larger samples tend to yield more reliable and generalizable results. Increasing the number of participants would enhance the statistical power of the study, potentially uncovering more subtle effects and providing a more comprehensive understanding of how lighting conditions impact perceived safety.

5.3.3 Recommendation for future research

This research focused on women's perception of safety at night, but there are other criteria to consider. Because the efficiency and sustainability of lighting solutions are becoming increasingly important in urban planning and design, energy consumption is a critical aspect of lighting. Although energy saving was not a primary focus in this research, consistent light levels were maintained across the different scenarios, ensuring that energy consumption did not vary significantly between them.

For future research, considering energy consumption as a key factor is highly recommended. Energy consumption can be influenced by factors like light levels, lamp efficacy, and fixture types. Efficient designs utilize high-efficacy lamps like LEDs, strategic layouts, and control systems such as dimmers and occupancy sensors to minimize unnecessary usage. It is essential to adjust findings and recommendations to ensure that lighting solutions not only enhance perceived safety but are also sustainable and cost-effective. By integrating energy consumption considerations, future studies can provide more comprehensive guidelines that balance safety, aesthetics, and sustainability in urban lighting design.

In this study, light levels were excluded as a variable. A significant body of research has focused on determining the minimum required light levels to enhance safety, and lighting standards have established specific illumination requirements based on various activities. Future research could benefit from exploring the interaction between different light levels and key lighting variables. For example, investigating the combined effects of varying light levels with color temperature or façade lighting could provide deeper insights and further refine the current findings.

This experiment was based on an analysis of quantitative data. Participants self-evaluated their perceived safety by filling out a survey, which was then analyzed using quantitative methods. While this approach provides valuable insights, it would be beneficial to complement it with qualitative methods to yield a more comprehensive understanding of the factors influencing perceived safety. This could be achieved by integrating qualitative methods such as focus groups. By engaging a larger pool of survey participants and selecting a smaller subset for focus group discussions, one could explore participants' perceptions in greater detail, providing richer and more nuanced information about the lighting conditions that most significantly affect perceived safety.

The benefits of using both qualitative and quantitative methods include a more holistic view of the research problem, validation of findings through multiple perspectives, and the ability to explore complex phenomena in depth. Qualitative data can add context to quantitative results, highlighting areas that require further investigation and offering explanations for observed patterns. Combining these methods would enhance the reliability and applicability of the findings, ultimately leading to better-informed decisions about lighting design and perceived safety.

The study used a specific type of residential area with five-story apartment buildings without a setback from the sidewalk. While the findings of this study may have implications for other residential areas with similar characteristics, further research is necessary to examine the impact of lighting on safety perceptions in different types of residential areas with varying population densities, design characteristics such as presence of setback and greeneries, building height, and levels of social activities. For example, Well-lit trees, shrubs, and other landscape elements can enhance visibility, create a sense of enclosure, and contribute to a more inviting nighttime environment. Strategic lighting of greenery can increase spatial legibility, potentially improving perceived safety. Investigating how different lighting techniques, such as uplighting or

integrated pathway lighting, influence perceptions could provide valuable insights for designing safer and more aesthetically pleasing urban spaces. This would allow for a more comprehensive understanding of the relationship between lighting and safety perceptions in diverse urban contexts.

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Appendix 1

Research survey for the baseline condition and the two experiments.

Default Question Block

Project Name. Pole lighting + WCCT

Q1. Which option represents your age the best.

- ☐ 18 - 30
- ☐ 31 - 50
- ☐ 51 - 65

Q2. How many times per week do you walk to work or school?

- ☐ Never
- ☐ Rarely
- ☐ Sometimes
- ☐ Often
- ☐ Always

Q3. Which of the following best describes you (select all that apply).

- ☐ White
- ☐ Black or African American
- ☐ American
- ☐ International
- ☐ Other

Q1. I can see the pedestrian path clearly under this lighting condition (1: Strongly disagree, 5: Strongly agree).

- ☐ 1
- ☐ 2
- ☐ 3
- ☐ 4
- ☐ 5

Q2. The lighting enhances my ability to perceive the surrounding buildings and environment(1: Strongly disagree, 5: Strongly agree).

- ☐ 1
- ☐ 2
- ☐ 3
- ☐ 4
- ☐ 5

Q3. I am able to recognize facial expressions of people on the sidewalk clearly under this lighting condition (1: Strongly disagree, 5: Strongly agree).

- ☐ 1
- ☐ 2
- ☐ 3
- ☐ 4
- ☐ 5

Q4. I find the lighting is bothersome, and the light source is in my field of view (1: Strongly disagree, 5: Strongly agree).

- ☐ 1
- ☐ 2

- ☐ 3
- ☐ 4
- ☐ 5

Q5. The lighting creates a welcoming and inviting atmosphere, encouraging me to spend more time here (or the lighting is not welcoming, and I don't use this path unless I have to) (1: Strongly disagree, 5: Strongly agree).

- ☐ 1
- ☐ 2
- ☐ 3
- ☐ 4
- ☐ 5

Q6. I feel safe walking under this lighting condition (1: Strongly disagree, 5: Strongly agree).

- ☐ 1
- ☐ 2
- ☐ 3
- ☐ 4
- ☐ 5

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Appendix 2

IRB Approval



TO: Anne Beamish
Landscape Archit & Comm Plan
Manhattan, KS 66506

Proposal Number: IRB-11813

FROM: Lisa Rubin, Chair
Committee on Research Involving Human Subjects

DATE: 09/25/2023

RE: Proposal Entitled, "Evaluation of women's perceived safety after dark using VR (Virtual Reality) technology.."

The Committee on Research Involving Human Subjects / Institutional Review Board (IRB) for Kansas State University has reviewed the proposal identified above and has determined that it is EXEMPT from further IRB review. This exemption applies only to the proposal - as written – and currently on file with the IRB. Any change potentially affecting human subjects must be approved by the IRB prior to implementation and may disqualify the proposal from exemption.

Based upon information provided to the IRB, this activity is exempt under the criteria set forth in the Federal Policy for the Protection of Human Subjects, **45 CFR §104(d), category:Exempt Category 2 Subsection ii.**

Certain research is exempt from the requirements of HHS/OHRP regulations. A determination that research is exempt does not imply that investigators have no ethical responsibilities to subjects in such research; it means only that the regulatory requirements related to IRB review, informed consent, and assurance of compliance do not apply to the research.

Any unanticipated problems involving risk to subjects or to others must be reported immediately to the Chair of the Committee on Research Involving Human Subjects, the University Research Compliance Office, and if the subjects are KSU students, to the Director of the Student Health Center.

Electronically signed by Lisa Rubin on 09/26/2023 1:00 AM ET