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A Dual Approach to Evaluating the Physical and Perceptual Impact of Exterior Lighting Renovations on Denver's Historic 16th Street Mall

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by

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Thesis directed by Dr. Walter Beamer IV

Denver's 16th Street Mall was first introduced as the retail and commercial heart of the city in the 1980s through the distinctive design of I.M. Pei and Partners. However, in recent years, the need for a revitalization through an ambitious urban renewal plan has become apparent as years of "wear and tear" combined with rapid urban growth and development have begun to take a toll on the beloved mall. In recent years, the City of Denver has allocated funds to renovate this Central Denver corridor, in an effort at revitalizing this urban area. One of the central components of this urban renewal plan is the replacement of the existing, out-of-date lighting fixtures with new, LED replica fixtures. This document provides an in depth analysis of the impact of the 16th Street lighting retrofit installation through the extensive documentation of both pre and post installation lighting conditions.

The purpose of this study is to document the changes that occur as a result of the installation and draw a conclusion about the impact of the new lighting on the mall from both an objective and subjective point of view. The objective components of the study included taking extensive lighting measurements on the mall both before and after the installation to document the physically calculable changes to the lighting on the mall. These measurements included horizontal illuminance, vertical illuminance, and luminance via High Dynamic Range (HDR) images. The subjective, or human factors, components of the study included surveying users of the mall before and after the installation, in order to get an understanding of user preferences and opinions with the goal of understanding of how peoples perceptions of the light has changed. This component focused on understanding the changes in lighting characteristics which impact the perceptions of the user such as light quality, reassurance or perceived safety, and visual performance. Together, the objective and subjective results were combined to gain a comprehensive understanding of the effect that the new lights have had on the mall and those who use it.

This results of this study are that the overall light levels on the mall decreased as a result of the new lighting installation. However this decrease was not perceived by the mall uses likely because perception of brightness was shown to have increased. The subjective analysis revealed that the visual performance of mall users increased despite the reduced light levels. The increased perception of brightness and the improved ability to perform visually may have been caused by the dramatic colorimetric changes that resulted from transitioning from High Pressure Sodium to LED light sources. This resulted in a significant increase in both color temperature as well as color rendering ability although the subjective analysis did not reflect these changes. The new lighting was also showed to have improved the distribution of light on the mall, making it more uniformly distributed on the sidewalk. The increased uniformity, along with the changes in color properties, may be the cause of the increased feelings of perceived safety and reassurance on the mall. The new lighting did not show any changes in visual comfort, perceptions of luminous atmosphere, or general mall usage. This study serves as a starting point for more in-depth studies of a similar nature as well as an outline for other studies that wish to observe similar, large-scale, exterior lighting changes.

Dedication

To Samuel Lamar Lucas:

A loving grandfather, brilliant engineer, and godly man who taught me to never stop “churning butter.”

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Chapter 1

Introduction

1.1 Motivation

Lighting in urban spaces has long been declared a necessity of urban design, but within recent years it has been more and more widely accepted as a tool to be used to create an engaging and stimulating user experience. Lighting has been found to have a large impact on the ways that pedestrians interact with the built environment - ranging from the perception of safety and street usage [31] to impacting physical comfort [22].

The primary driving factor for this study is to better understand what impact a new lighting installation in Denver's celebrated 16th Street Mall has on the surrounding urban environment. The impact of the installation is to be measured in two different ways. The first way to measure the change in lighting conditions is through measuring the objective aspects of the lighting before the installation and after the installation to measure how dramatically the lighting has changed. From this quantifiable analysis this study aims to understand how factors such as the overall lighting levels, light distribution, uniformity, and light quality have changed. One of the ways that this study sought to do this is through the use of HDR (High Dynamic Range) images which can be used by lighting researchers to accurately understand the luminous setting as a whole. By measuring and comparing these qualities before and after the installation, the objective components of the change in lighting on the mall can be quantified and a conclusion can be drawn concerning the magnitude of the impact with the change in the environment.

The second way that this study seeks to understand the change in lighting is from a subjective or human factors point of view. Through the use of surveying methods before and after the installation, this study seeks to understand how the users of the space perceive the lighting to change. Specifically, this study seeks to understand how peoples' perceptions of reassurance (or perceptions of safety), visual performance and comfort, and perceptions of the overall quality of the light have changed over the course of the installation. This study sought to accomplish this task by developing a single, comprehensive survey that would be handed out to random users of the mall over the course of several days both before and after the installation. Then, by comparing how the general answers have changed, a conclusion on the impact that the change in lighting had on the perceptions of the users of the space can be drawn. The results of this comparison will help to answer questions such as "Do people feel safer walking on the mall with the new lights?", "Is the mall more visually or aesthetically pleasant?" and "Are visual tasks easier to perform?" Ultimately, the magnitude of change in perception that is documented will help to determine if the installation was perceptually impactful.

At the conclusion of the study, the goal is to have two separate evaluations on the impact of the changes of the lighting on the Mall. An attempt will be made to connect the objective lighting changes to the perceptual and subjective trends. From the combination of these two evaluations, this study seeks to determine if the installation can be considered impactful and if so, to what degree. It is possible that the lighting could undergo a significant technical or measurable change while having a very minimal perceptual effect or vice versa. This study will seek to explore these options and draw a conclusion which will help inform future, similar lighting installations.

1.2 Contents

This document is broken up into 10 Chapters, beginning with this introduction. The next chapter provides background information on the history of the 16th Street Mall and documents the installation project itself. This chapter will help also to set the stage for the study by describing the physical aspects of the mall such as the layout and key design elements. The third chapter is a literature search which begins with a basic introduction to lighting terms, measurement strategies, and technical information that will be directly related to the objective component of the study. The rest of the literature search consists of studies which focus on various aspects of lighting research specifically human factors and perception studies as well as studies which consist of surveying methods and strategies. Chapter 4 will outline the overall set up of the 16th Street Study, giving a scope overview of the study and detailing the thought process behind some of the major design elements and set-up of the investigation. Chapter 5 will begin outlining the objective components of the research by describing the measurement process and observations. Chapters 6 will present the objective results and summarize the findings. Chapter 7 will complete the objective component of the study by analyzing the results of Chapter 6 and drawing a conclusion about the measurable impact of the lighting from a technical perspective which is independent of the subjective components of the study. Chapters 8, 9, and 10 will follow the same structure as the preceding Chapters by detailing the process of the objective measurements, the results, and then drawing a conclusion about the perceptual impact of the lighting on the mall users. Chapter 11 will combine the two perspectives into a single, overarching impact analysis which will be the final result of the study.

Chapter 2

Mall Renewal Project and Lighting Installation Background

2.1 Background of the 16th Street Mall

The following information about the background of the 16th Street Mall was found in the 16th Street Urban Design Plan which serves as the basis for the new lighting installation project.

Denver's 16th Street had been central retail destination since the 1890's but by the 1960's the mall was experiencing a noticeable decline in popularity. This decline was heightened in the early 1980's, as the collapse of the energy boom of the 70's which resulted in the departure of retail and department stores and an increase in vacancy in the downtown districts [14]. As part of a larger scale revitalization plan, it was decided that I.M. Pei and Partners, a highly renowned architecture firm of the time, would redesign the 16th street into a 13-block shopping mall complete with bus transfer stations and a shopping and entertainment "Pavillion." The mall would incorporate mixed use buildings and sidewalk cafes along a central promenade with patterned paving, fountains, and benches. The mall was pedestrian-centered with a "common identity" to protect the malls "distinctive personality". This mall became an iconic part of the city breathing new life into the heart of the downtown district [14].

However, in the early 2000s, it became apparent that the mall was no longer upholding the original vision established upon its creation. Dramatic changes to the buildings and businesses surrounding the mall combined with the expected wear and tear and more stringent health standards and ADA compliances had left the City of Denver with an obvious need for a dramatic update of the mall. In 2008, the Urban Land Institute assessed the mall and developed a set of guidelines to which the new remodeling should adhere to. These guidelines called for many improvements and alterations but also stated that any improvements to the mall should honor the original design intent and identity set by I.M. Pei [14].

These guidelines formed the basis of a rehabilitation and renovation plan which involved the Regional Transit District, the City and County of Denver Public Works, Downtown Denver Partnership, and Downtown Denver Business Improvement District [14]. The eventual result of this partnership and an extensive amount of research was the Urban Design Plan which would call for an all-encompassing renovation of many key elements of the mall, bringing them up to code, but still maintaining their historical charm.

2.2 Lighting Background

The lighting on the mall was to be a central component of the mall's "identity." Howard Brandston, the renowned lighting designer responsible relighting the Statue of Liberty in 1986 and creating the master lighting plan for Detroit's business district [5], was hired to design a completely unique fixture which would enhance the pedestrian experience and help to establish the mall aesthetic. In his 1977 lighting report Brandston claimed that "Lighting for Malls must respond to the way walking humans see and move." [5]. He focused on introducing lighting that would cater not only to the physical safety of the pedestrian but to the mental satisfaction as well. He chose to light the mall with "full spectrum" halogen sources that would ensure excellent color rendering properties [5]. He also designed the mall with a strong emphasis on different layers of light with each layer serving a different purpose. The pedestrian lights would have an uplighting component to highlight the tree canopies, a "twinkle" light ring that would give vertical illumination, and downlight to provide light on the path below. The original intent was that these pedestrian fixtures would interact with the storefronts and other lighting on the mall to create a richly layered, and textured lighting atmosphere.

However, over the years, Brandston's vision was not entirely met. The highly inefficient halogen sources were replaced with more efficient high pressure sodium options, resulting in an orange/yellow color temperature and changing the color rendering properties of the lamps. The twinkle light element, which was too hard to maintain, was removed. The shop storefronts were turned off after closing hours, removing a critical component of Brandston's layers of light design. Over the years, 44 of the 179 fixtures were removed due to vehicle impact and other damage [5]. The mall lighting experience pedestrians have today is very different than the original design of the mall.

The analysis revealed through Denver's Urban Design Plan made it quite evident that the pedestrian lights were to be one of the mall elements which would be addressed and revitalized. The plan outlined three " alternatives" for the lights. The first alternative was to renovate the existing lights by installing new components. The second alternative was to replicate the fixtures with entirely new materials and technology but striving to maintain the original design. The third alternative was to replace the assemblies with modern, non-custom, fixtures. After much consideration, the second option was selected to be the best solution and new, LED replicas were created to replace the old light fixtures [5].

Chapter 3

Background Knowledge and Literature Search

The following Chapter will begin with a brief section dedicated to relevant background knowledge. This section will include a short overview of fundamental lighting concepts and traditional measurement techniques. These concepts will be foundational to the objective analysis of the study. Next, a general outline of High Dynamic Range (HDR) imaging will be introduced. The goal of this segment will be to introduce the reader to the technology and process of HDR photography as well as summarize the luminance calibration process. The final background knowledge component will address the sociological methods of data collection that were utilized in this study.

The second half of this Chapter will be devoted to prior research and consist of a literature search which addresses the human factors components of the study. The research outlined in this section will give a generic overview of some other studies which address various perceptual and sociological facets of lighting design. A particular emphasis will be placed on case studies which examined exterior lighting installations (as opposed to interior applications or lighting simulations) as well as before-and-after type comparison studies and studies that utilized questionnaires with perceptual components.

3.1 Lighting Fundamentals

The objective component of the study will require a fundamental knowledge of lighting concepts and terms. A few important definitions can be found below:

Light can be defined as “visually evaluated radiant energy” or the “amount of electromagnetic energy that can be emitted, transferred, or received in the form of radiation" [12] and then evaluated visually. This study will employ two major metrics of light illuminance and luminance. The Illuminating Engineering Society (IES) defines illuminance as "the density of photopic luminous flux (lm) incident on a point on a surface". In short, illuminance is the amount of "light" arriving on a surface. It has units of lumens per area, Lm/ft^2 or Lm/m^2 which are referred to as Footcandles, Fc, or lux, lx. Illuminance is often measured using an illuminance meter, see figure 3.1.

Figure 3.1: Konica Minolta T-10A Illuminance Meter [21]

3.1.1 Illuminance

This study will be looking at three "types" of illuminance: horizontal illuminance (E-h), which is illuminance incident to a horizontal plane; vertical illuminance (E-v), illuminance incident to a vertical plane; and semi-cylindrical illuminance (E-sc). Semi-cylindrical illuminance can be described as the average illuminance on a curved surface of an upright half cylinder. This form of illuminance is often used as a representation of the faces of pedestrians in exterior lighting environments because it can approximate the human face as a curved surface instead of a flat plane. Unfortunately, calculating semi-cylindrical illuminance is much more complicated in real world lighting applications than in computer software simulations where it is most often used. To evaluate semi-cylindrical illuminance, this study will approximate it through cubic illuminance. Cubic illuminance measurements are simply a set of six measurements that correspond to the six sides of a cube centered at a point (see Figure 3.2). Although cubic illuminance can be measured using a specialty six-photocell cubic illumination meter, a more straightforward way is to simply mount a cubic form to a level surface at the preferred mounting height, and then use a traditional illuminance meter to measure the light incident to each surface. These measurements can then be converted into a variety of forms of illuminance including semi-cylindrical illuminance through a series of transformations developed by Cuttle [11].

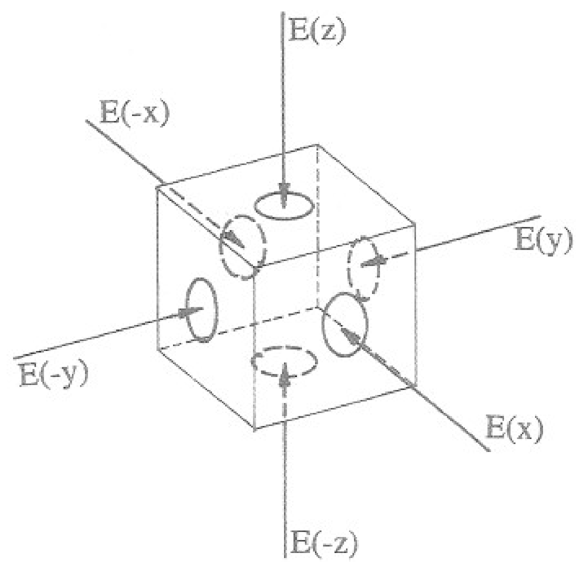


Figure 3.2: Cubic Illuminance Diagram [11]

3.1.2 Luminance

The next measurement this study will utilize is luminance. Luminance is the amount of photometric power or luminous intensity per unit solid area emitted from a surface in a given direction. Luminance is a directional quantity which is dependent on the position of the surface relative to the viewing point (the human eye, a camera lens, luminance meter, etc.) It is expressed in Candelas (luminous intensity) per unit area and is quite often associated with the human perception of brightness. This is not an entirely accurate comparison because the perception of brightness is subjective, depending on each person, while luminance is an objective value. Luminance is often measured through the use of a luminance meter (see figure 3.3) which is aimed at a specific spot on the surface to measure the luminance of that point.

Figure 3.3: Konica Minolta Model LS-100 Luminance Meter [27]

3.1.3 Color Temperature

The correlated color temperature (CCT) is the term used to describe the color appearance of “white” light emitted from light sources. CCT values generally range from 2700K to 6500K. “Warm” lamps have a CCT that generally falls below 3200 K and can be described as yellow-white or orange-white while “Cool” sources generally have a CCT greater than 4000K and tend towards blue-white shades. “Neutral” white CCT can generally be found between these two values. See figure 3.4 for a diagram of the color temperature spectrum.

3.1.4 Color Rendering Index

The Color Rendering Index (CRI) is a rating index that is used to represent how accurately a light source renders the color of objects that it illuminates when compared to an ideal source. A perfect CRI value of 100 would indicate a source which renders colors exactly as an ideal source would render them. High pressure sodium sources, such as the ones on the 16th Street Mall are

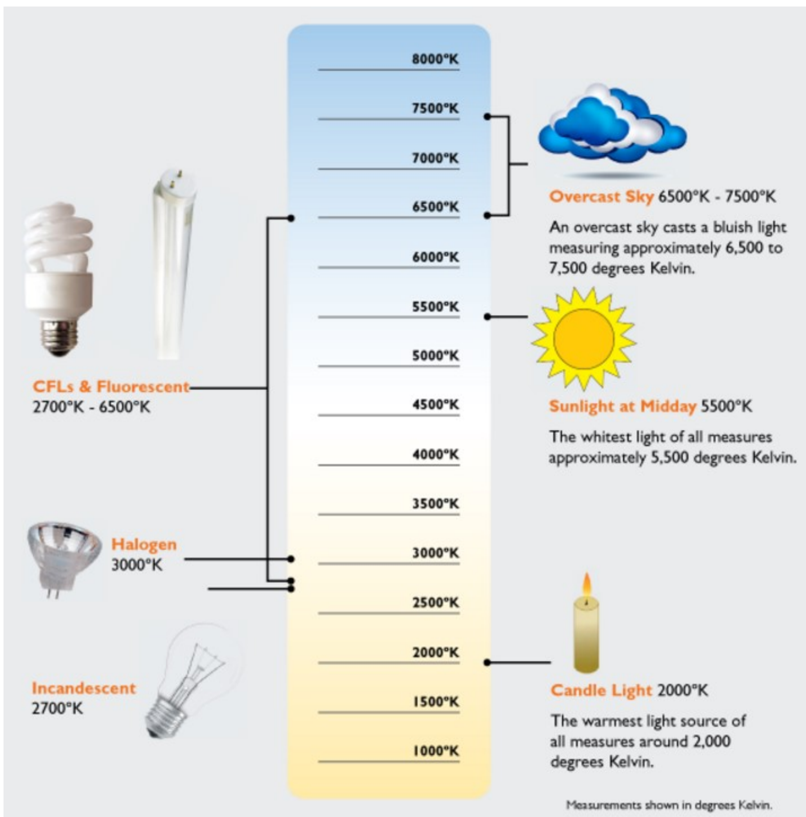


Figure 3.4: Correlated Color Temperature Diagram [7]

known for their low color rendering ability. The following table 3.5 from the Lighting Research Center displays typical CRI values for traditional lamp sources.

Source	CRI
Incandescent	95
T8 Linear Fluorescent	75 - 85
Cool White Linear Fluorescent	62
Compact Fluorescent	82
Standard Metal Halide	65
Standard HPS	22

Figure 3.5: Color Rendering Index Examples [10]

LED technology has been changing dramatically in recent years as manufacturers have been pushing to develop an LED that can replace the incandescent in color quality while maintaining high energy efficiency. Many factors can influence the CRI of an LED such as if the LED is uses multichip or phosphor-based technology [29]. In general, most LEDs fall into a CRI range between 80 and 90.

3.2 High Dynamic Range Imaging

3.2.1 Terms and Definitions

A more recent method of measuring luminance is through "luminance mapping" which utilizes HDR imaging. HDR imaging is performed by using a camera to take a series of LDR (low dynamic range) images of the same scene with varying exposures. Cameras can vary the exposure of the image in two ways. The first way is to vary the size of the lens aperture. The larger the aperture, the more light is allowed to pass through the lens and strike the camera sensor, and the more exposed (washed out) the image will be. Likewise, a small aperture size will result in less light and a less exposed (darker) image. The second method is to vary the shutter speed. A fast shutter speed will let less light in producing a less exposed image while a slow shutter speed lets in more light and produces a more exposed image. This is demonstrated in figure 3.6.

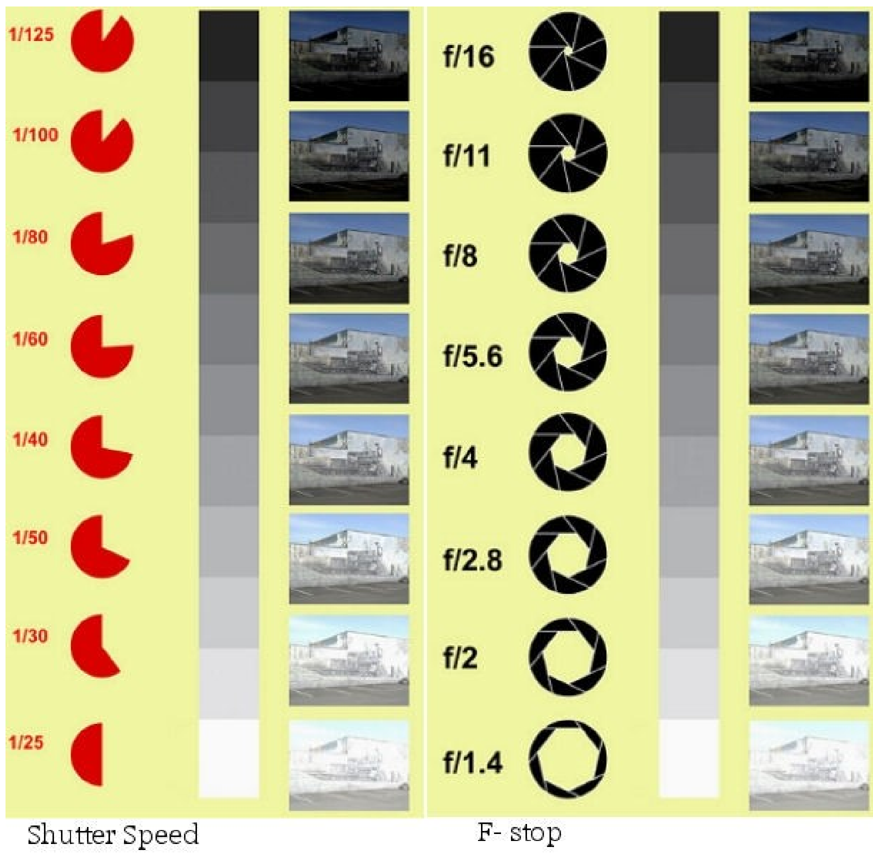


Figure 3.6: Exposure Varying Techniques for HDR Images [15]

Each of the individual LDR images contains only a small range of luminance data but as a group, the images contain a much larger range of luminance information for any particular scene. Through the use of HDR computer software, they can be "stitched" or compiled together to form a single image which contains the full range of luminance data in the scene. The image below, figure 3.7, demonstrates this concept. The bottom three images are the LDR images which contain the luminance information at three different exposure settings. After they have been compiled they result in the image at the top. This compiled image contains a full range of luminance data.

Figure 3.7: HDR Image Compilation Example [25]

These compiled images are sometimes used as "luminance maps" because they provide luminance data on a pixel by pixel level, allowing for the user to easily understand lighting conditions such as uniformities, contrast ratios, and light distributions in an entire scene. The advantage of this methodology is that it allows for an analysis of the spacial distribution of the full luminous scene which is analogous to the human visual experience as opposed to only getting bits and pieces of the overall picture, such as is provided by the luminance meter alone.

3.3 Experimental Methods

3.3.1 Likert Analysis

The final area of background knowledge necessary to understand the set-up for this study falls into the realm of experimental methods and measurement procedures for survey-type research. A common form used to measure feelings and opinions in contemporary studies is done through the use of a Likert scale. The Likert scale was created by Rensis Likert and was first documented in his 1932 paper "A Technique for the Measurement of Attitudes." Likert sought to develop a statistically sound technique for measuring attitudes, character traits, and personal opinions. His goal was to take qualitative responses and transform them into quantitative data which could then be analyzed from a mathematical viewpoint [26]. His questionnaire design has now evolved into the Likert-type scale which is a very widely used strategy in questionnaires and survey research today.

In modern research, a typical Likert scale consists of a "Likert item" followed by a range of responses to that item. A Likert item is often a statement which is given to a survey recipient who is then asked to evaluate their level of agreement or disagreement. Thus, the responses are easily transformed into quantifiable data which can then be statistically analyzed to better understand the opinions of the survey recipients.

3.3.2 Semantic Differential Analysis

The semantic differential is an alternate type of rating scale which was developed by Charles Osgood in 1957 which can also be used to measure qualitative and subjective concepts and opinions. As opposed to the Likert scales which provide information on the respondents level of agreement with the statement, a semantic differential scale uses polar (opposite) adjectives to measure a persons connotations (or suggestive significance) of a certain word or concept. Modern research often utilizes semantic differentials as a method of quantifying changes in attitudes and opinions.

Both the semantic differential scale and the Likert scale are highly intuitive, requiring little explanation and are common choices for survey and questionnaire type research such as the 16th Street Mall Study.

3.4 Literature Search

The following literature search will focus primarily on the human factors and perception side of lighting research. This section will outline several studies which include components (be it methodology, theory, or findings) which can be in some way applied to the objective portion of the 16th Street Mall Study. This literature search is not exhaustive and is only meant to briefly touch on some of the more directly relevant findings.

3.4.1 Perception of Safety

Since safety and perception of safety is something that greatly impacts the overall atmosphere and usage of an urban environment, it was selected as one of the components that would be used to draw a final conclusion on the overall impact of the 16th Street lighting installation. If people feel safer or more reassured after dark, they are more likely to stay longer, visit more often, and have a better, overall experience. There have been countless research studies devoted entirely to this topic below are a few of the more pertinent studies.

Traditionally, studies which attempt to correlate lighting improvements and crime rate have had very mixed results. In 1976 James Tien conducted an expansive study which analyzed 15 different street light projects over time and eventually determined that there was no significant change in crime which can be attributed to lighting [42]. This is contrary to the later findings of Kate Painter and David Farrington in 1997 who conducted a study which showed that "improved" street lighting did decrease the overall amount of crime through the use of victimization surveys. Painters research concluded that when compared to the 12 months prior to the new lighting installation, the total number of "victimizations" was found to have decreased by 23 percent [32]. Painters conclusion proposes that the lighting improvements provided a "catalyst for behavioral change" in the environment of interest which in turn resulted in less crime. The lighting was believed to "enhance natural surveillance" on the streets in other words, increased lighting resulted in more people spending time on the street resulting in an atmosphere with more people to act as witnesses which in turn deterred the criminal activity [32].

However, most studies find that attempting to find a connection between crime and lighting is very difficult due to the numerous uncontrollable variables that impact crime. Factors like demographics, geography, time of day, and other social and economic factors combined with the fact that a crime focused study would require months or even years of monitoring trends in crime in the area of interest is enough to make many lighting researchers avoid attempting to directly linking lighting to crime and safety. However, studying the perception of safety as opposed to safety itself is a much more feasible and popular area of research. The perception of safety, often referred to as reassurance [43] or in some cases simply called fear, is an area of study that has direct and quantifiable ties to lighting. In general, it is thought that the perception of safety in a space is almost or just as important as the actual safety of people inhabiting the space. Just as Painter found that improved lighting reduced crime through behavioral change, the perception of safety in an environment could in turn produce similar behavioral changes which would impact the overall safety or general atmosphere of an urban environment. Even Tien acknowledged that increased lighting decreases the fear of crime and suggested that this effect could have been caused by increases in lighting uniformity[42].

In 1996, a year prior to the aforementioned crime study, Painter sought to evaluate the impact of street lighting at several locations on not only crime but also fear of crime; and pedestrian street usage [31]. This was a "before and after" study where three different "dangerous" or crime-"likely" streets were selected to undergo lighting enhancements. These enhancements included changing the light source, increasing the amount of light, and increasing the uniformity of the light. Instead of using surveys, Painter conducted interviews which occurred before the installation, 6 weeks after, and 12 months after the changes had been made. Painter found a significant reduction of criminal "incidents", increased feelings of personal safety, a reduced fear of crime, and a significant increase in the number of people that used the streets [31].

One such study which built off of the research of Painter was Boyces study from January 2000 entitled "Perceptions of safety at night in different lighting conditions." This study is the compilation of four field studies which aimed to determine exactly "how much light is needed to provide the perception of safety at night?" and "How important is the light spectrum to that perception?" [3].

The first two field studies focused on establishing a specific illuminance value that would be needed in order to produce the perception of safety. In these studies, illuminance (both vertical and horizontal) data was collected at multiple sites in New York City. Then people were introduced to the space and asked to rate their opinions of the lighting in the space on 5-point scales. The results of the surveyed answers were used to determine a definition of "good" security lighting or "bad" security lighting. From these responses, certain sites were established as having "good" light. Boyce found that a horizontal average illuminance of 40 lux or 3.7 fc is necessary for security lighting to be considered "good" [3].

The third study specifically focused on perception of safety and took place in both urban and suburban parking lots. People were brought to several sites both during the day and during the night and asked questions that were on a 7 point scale from very dangerous to very safe. A similar strategy as the earlier studies then compared the results of the surveys to determine perceived "goodness of security lighting" and from that, determined the corresponding illuminance values. In this study, the results found that 20lux (1.86 fc) were needed in urban parking lots and only 10 lux (0.93 fc) in suburban parking lots [3].

The fourth study sought to compare perceived safety for different light sources. A single parking lot was fitted with different sources (HPS and MH) and different light outputs. Surveys were again distributed to volunteers who were brought to the space. After analyzing the results of the survey, Boyce found that illuminance is much more important to the perception of safety than the light spectrum and color rendering of the source. However, Boyce also concluded that at lower light levels, other factors like glare and uniformity play a much larger role in perceptions of safety while illuminance decreases in importance [3].

There have been several other studies which also sought to connect lamp spectrum to perception of safety. A study by Colette Knight to compare HPS sources to MH sources in a before and after installation study across different sites in European cities. As the sources changed, the color temperature increased while the distribution and output stayed constant. Knights work also included a face-to-face interview component similar to Painters study which was used to understand the respondents perceptions of safety and comfort. This component of the study used open ended questions as well as five point scales to gather the necessary information. Knights research showed that cooler light (higher CCT) was perceived to be brighter, safer, and more comfortable than warmer, yellow light. It is important to note that cooler light was perceived to be brighter even when it wasnt at a higher output than the warmer light[22].

A secondary component of Knights study was to understand the impact of lamp spectrum on facial recognition - a component that is studied widely in perception of safety studies. The theory is that if a person can easily recognize the face of someone approaching them, they will be able to determine if it is a friend or stranger; as well as if they have good intentions. The sooner the face is recognized, the more time the person has to escape if necessary. The ability for a person to recognize an approaching face is tied to the amount of light shining on their face in other words, the amount of vertical illuminance [22]. Ultimately, Knights results were inconclusive in this area. However, other studies, such as that done by van Bommel and Caminada found that the ability to recognize a face at a distance was related to the amount of light shining on the face (semi-cylindrical illuminance) [6]. There have also been studies that suggest that factors such as SPD, color rendering, and color temperature also impact the ability to recognize faces. For example, Raynham and Saksvikronning found that “white” light sources that had high color rendering allowed for better facial recognition [34].

3.4.2 Other Subjective Lighting Studies

Even though perception of safety plays a large role in the overall approval or disapproval of a lighting installation, the overall impact of lighting on an exterior space is more than just the changes in perceived safety. Other factors such as visual performance, brightness perception, and visual comfort, all play a role in determining the overall impact that lighting may or may not have on a space.

A study done by Fotios, Cheal and Boyce explored the topic of brightness perception and visual performance in 2005. This goal of this study was to once again explore how light source SPD effected pedestrian perceptions of brightness as well as visual performance. Brightness, Fotios argued, is important to the pedestrian because it is “a fundamental visual perception which experience tells us is related to the amount of light present, and that in turn is related to how well we can see where we are going and what is happening around us.” [39]. Thus brightness, both the perception of brightness and the luminance in a space, is very critical to understanding the quality of lighting to the user. Also, as mentioned earlier, brightness can be related to reassurance and perception of safety and can also aid in facial recognition [22]. Fotios has done several studies since his 2005 study which specifically seek to explore the impact of the lamp spectrum on perception of brightness and visual performance. The second study, which focused on brightness, found that many sources which have a more desirable lamp spectrum which renders colors well as well as lamps which produce “whiter” light are both perceived as much brighter than “yellow” high pressure sodium lamps [17].

Visual performance, on the other hand, is important because it impacts the ease with which the pedestrian interacts within the environment. Visual performance can range from essential visual tasks like recognizing key elements of the surroundings to “desirable” tasks such as detecting a friend approaching on the street. In the first part of Fotios and Cheals 2007 study, visual performance was separated into the following categories: Off-axis detection (which is necessary for all tasks), visual acuity, contrast sensitivity, and the ability to discriminate colors. All of these categories are needed for satisfactory visual performance and as such, a light source or lighting condition which allows for the pedestrian to perform better visually will be considered “better” lighting [16]. It was suggested by Fotios that SPD can play a large role in performance of visual tasks, but because of the wide variety of outside factors which influence these tasks, there have been very mixed findings in this area.

The study which has had the most impact on the design of the subjective components of the 16th street study was done by Romnee and Bodart in 2014. Romnee conducted a field study to expose which factors or impacted a pedestrians “appreciation” of street lighting. To accomplish this he developed a series of “indicators” of certain perceptual concepts. The concepts studied were “feelings of visual comfort,” “feelings of safety,” and “perceptions of luminous atmosphere.” [1]. His method included a questionnaire in which each question corresponded to certain indicators. For example, the question about the ability to recognize a friend approaching you would correspond to the “people appearance” indicator which would in turn correspond to the concept of feeling of safety. After gathering the necessary data, Romnee used it to create a satisfaction index which would determine which of the indicators were the most important in determining what constitutes high quality street lighting. He then was able to determine which physical lamp characteristics, such as source, influenced safety, visual comfort, and perception of luminous atmosphere. His study ultimately found that the type of source directly influence the feelings of safety, visual comfort, and the perception of the luminous atmosphere. Specifically, he found that LED lighting is always preferred to HPS lighting [1]. He also found that age and gender play a role in these three categories with women tending to be more adamant in their appreciation of the lighting change and people who are older feel safer and more visually comfortable you are. Most directly relevant to our study is the claim that the “quality of public lighting should consider quantitative variables and qualitative variables” [1]. Romnee suggests that street lighting standards should include information concerning not only the brightness and uniformity of the light but also feelings of safety and other human factors. This study directly confirms the need and relevance of the 16th Street study. Although the 16th Street study will not be going so far as to create a satisfaction index to measure the change in satisfaction of the installation, it will be utilizing a very similar questionnaire design in which questions correspond to specific lighting concepts indicators which in turn provide information on larger perceptual categories.

Chapter 4

Study Set Up

4.1 Overview of Study

This study will build off of the research mentioned earlier and use two different approaches to try and quantify the overall impact of the 16th Street Mall installation. The first analysis will be an objective analysis that will compare the measureable qualities of the light before and after the installation. This approach will include a comprehensive comparison of the illuminance, both horizontal and vertical, over the area surrounding the pedestrian light. The results of these measurements will give a basic understanding of the amount of light that is being provided by the fixtures as well as the uniformity of the light. The objective component of the study will also include a luminance analysis by using the relatively novel method of luminance mapping through the use of High Dynamic Range (HDR) imaging. This strategy will provide a more comprehensive idea of uniformity along the path as well as an understanding of the color qualities Correlated Color Temperature (CCT) and Color Rendering Index (CRI) and the impact that these factors have on the surrounding environment.

The second component of the study is a "before and after" questionnaire which will provide a subjective analysis of the lighting installation. This aspect of the overall study will asses the impact of the lighting installation from a human factors point of view. This approach will measure the perceptual response to the lighting change by administering a survey to random mall users over the course of several days. These surveys will measure impact through four different categories which have been influential in prior research: visual comfort and performance, perception of safety/reassurance, and perception of luminous atmosphere, and mall usage. Through a comparison of the before and after survey responses this component of the study aims to understand how the lighting has impacted the perceptions of the users of the mall.

4.2 Selection of Sites and Obstacles

Originally, two sites on the mall were selected to be used for the study. The original Downtown Denver, 16th Street Mall covers 12 blocks from Market St. on the west end to Cleveland Pl. on the east end. The Mall was extended in 1994 to Wynkoop St. to include the lower downtown blocks and again in 2012 to Union Station, however the lighting only occurs on the original Mall segment. This study will only focus on the original Mall blocks.

Figure 4.1: Map of 16th Street Mall

The lighting on the mall was originally designed with two different main layouts a symmetric layout, figure 4.2 and an asymmetric layout, figure 4.3. The “bookend” blocks from Market Street to Arapahoe St and from Tremont Pl. to Cleveland Pl have the asymmetric layout where the lights are located on the middle median as well as on the NE sidewalk. The symmetric layout is found an all of the blocks between Lawrence St to Tremond Pl. and has lights only on the central median in a very regular pattern.

The two sites that were selected for the study were two of the symmetric blocks because of their design consistency and central location on the mall. The two spots were chosen to be on opposite sides of the mall in areas that were near commonly used areas or areas of high foot traffic. The measurements and surveys were conducted on the NE sidewalk, not on the central median, because the sidewalks on either side of the median experience the most amount of foot traffic and

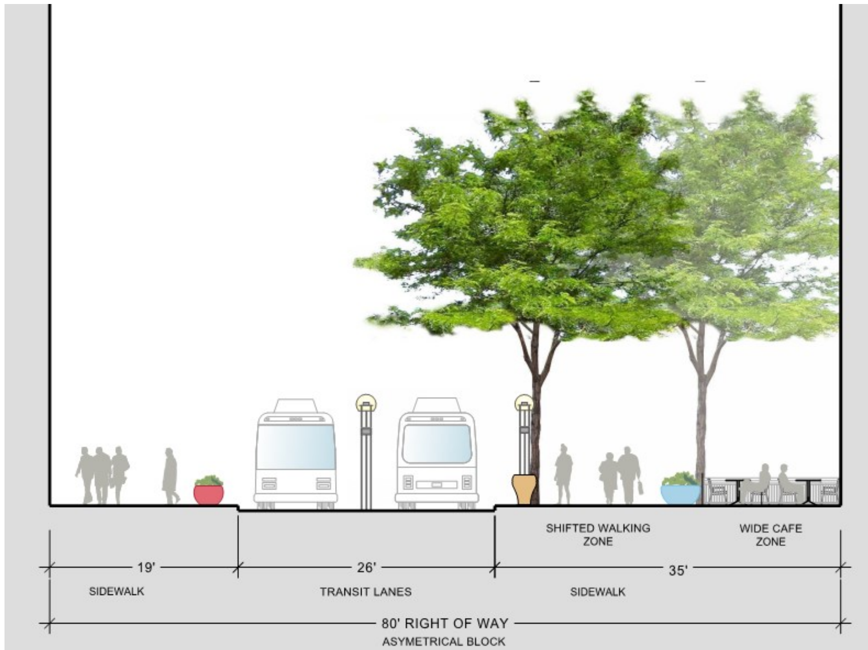


Figure 4.2: Asymmetric Mall Section View [14]

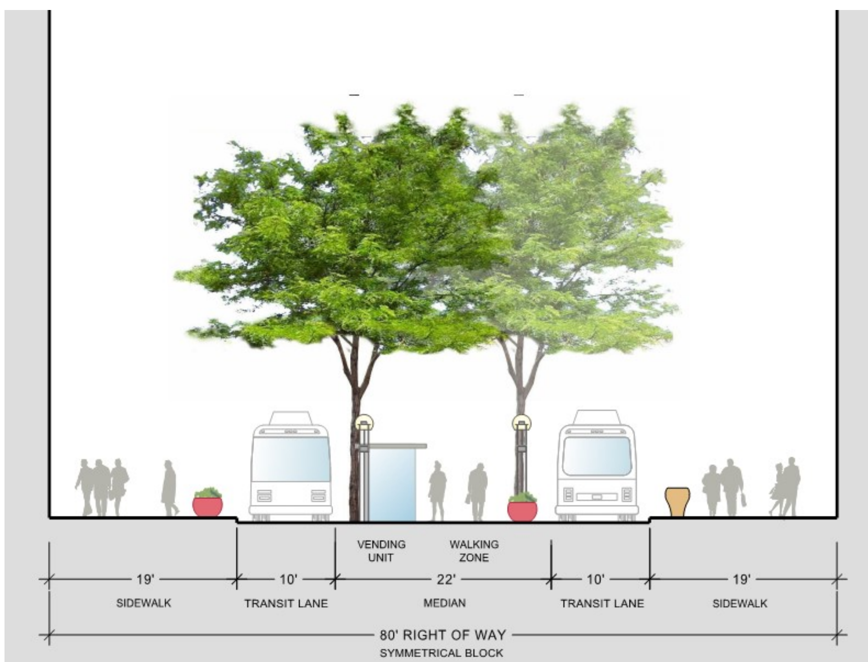


Figure 4.3: Symmetric Mall Section View [14]

considerably less obstacles than the central median area.

Site 1 was located on the NW side of the mall on the block between Arapahoe St. and Curtis St. right outside of Rock Bottom Restaurant and Brewery. The location was selected because of the many late-night restaurants nearby as well as the fact that the buildings nearby were set back further from the street itself which provided a good opportunity to understand the uniformity and distribution of the lights while also minimizing lighting contributions from nearby facades. Site 2 was located on the SE side of the mall on the block between Glenarm Pl. and Tremond Pl. right outside of Cook's Fresh Market. This spot was selected because of its proximity to the Denver Pavilions, an extremely high traffic area which include many evening activities such as the cinema as well as several restaurants. Both locations are marked on the map above in figure 4.1 with yellow stars.

Unfortunately, because the installation took place later than expected and took a considerable amount of time to remove the fixtures (which included removal of the existing fixture, renovation of the granite pavers, rewiring, etc.) the timeline of the study had to be shifted back, starting later in the Summer. Pre-installation measurements were taken at both sites, but the installation (which started on the West side of the mall) had not yet reached the other end of the mall before it became too cold to take measurements and surveys on that end. So, the bulk of the analysis could only be completed for Site 1 on the West side of the mall. Luckily, this location was the more used of the two sites. Since this was the location where the adjacent stores were set back from the mall, it provided a better understanding of the uniformity and distribution of the lights, thus making it the more ideal location of the two sites and ensuring that the accuracy and reliability of the study remained intact. In the following chapters, only information pertaining to Site 1 will be included.

4.3 Time and Date

Beside the selection of the sites, several other decisions had to be addressed before proceeding to take measurements such as selecting the appropriate dates and times for the various measurements. First, it was estimated that multiple days of surveying would be necessary in order to gather enough data to have sufficient power to detect a statistically significant relationship if one exists. To minimize the contributions from the moon and stars, the measurements and surveys would need to be conducted during a period of the lunar cycle that minimized sky contribution. In other words, as near to the new moon period as possible. Because the new moon period only occurs once a month, this significantly reduced the available dates to take measurements. In the interest of time, it was decided that the measurements would be conducted over the course of a single week as opposed to having month-long breaks between measurement nights. It was determined that three, consecutive days would be enough time to gather enough survey data to have enough power to detect any statistically significant relationships.

Ideally, all of the objective lighting measurements would be collected the same day(s) as the surveys would be administered. However, the amount of data that needed to be collected made this impossible (see for discussion on the window of time needed for data collection). Instead, it was decided that the objective lighting measurements would be taken the day prior to the three surveying days. Furthermore, measurements would be conducted during the week as opposed to the weekend because the number of people on the mall and the subsequent sidewalk congestion during the weekend made taking measurements very difficult. The final solution was to gather the bulk of the objective data on the Monday that fell closest to the new moon period and then conduct surveys on the following Tuesday, Wednesday, and Thursdays.

4.4 Survey Preplanning

Several surveillance trips to the mall were made with the goal of understanding usage patterns and general trends. The observations made on these trips determined that the mall experienced a consistent amount of foot traffic until around 10:30. This could be contributed to the fact that most of the shops close at 8pm and many restaurants close at 10pm. The overall amount of users on the mall begins to drop off consistently until around 11:00. By 11:15, the atmosphere of the mall had dramatically changed many of the people left on the mall are in a hurry to get home with the exception of those who are frequenting the late-night bars and pubs. There are no families traveling the mall and very few women. These observations made it clear that the survey component of the study would need done before it became too late. Also, as a safety precaution, any measurements, objective or subjective, that were taken on the mall would have to be completed before 11:00 and done in groups. Unfortunately, during the summer hours, it doesn't get completely dark until much later in the evening, making finding a time window to take measurements difficult. In the summer it doesn't get completely dark until the end of astronomical twilight (when night technically begins) which occurs between 9:30 to 10:00. Waiting until the beginning of night would not have allowed us enough time to complete either set of measurements, so it was decided that any measurements that were needed would begin during astronomical twilight, ensuring that there would be enough time to finish before 11:00.

Chapter 5

Objective Study Process and Observations

5.1 Objective Data Collection Process

The pre-installation lighting measurements took place on Monday, August 1st. During this time a team of three people visited each site on the mall to take various sets of lighting measurements at the two designated sites. The first set of measurements were horizontal ground plane illuminance measurements. All illuminance measurements were taken with a Konica Minolta T-10A illuminance meter. The ground plane horizontal illuminance measurements were taken at 8' ft. spacing in a line down the "sidewalk" of the mall in an East-West orientation as seen in figure 5.1. These locations coincided with the center point of the light colored pavers on the path as depicted in figure 5.2. This spacing was done to intentionally make measurement replication easier and to minimize error. A smaller spacing was not necessary because the purpose of these measurements was to gain a broader understanding of the light over a very large area with the purpose of understanding the general trends of the light distribution. Three measurements were taken at each measurement location. At each site, 7 measurement locations were used along a single line 4ft from the curb (referred to as the "front row" of measurements) and then three more measurements were taken 6ft back from the front row pavers (the "back row" measurements). Taking the second row of measurements allowed us to get a more comprehensive look at the distribution, uniformity, and the "drop off" of the light along this path. See figure 5.1 below for layout of measurements.

In addition to horizontal measurements taken on the ground plane, vertical illuminance measurements were also taken. To accomplish this, a small cube (approximately 6" x 6" x 6")

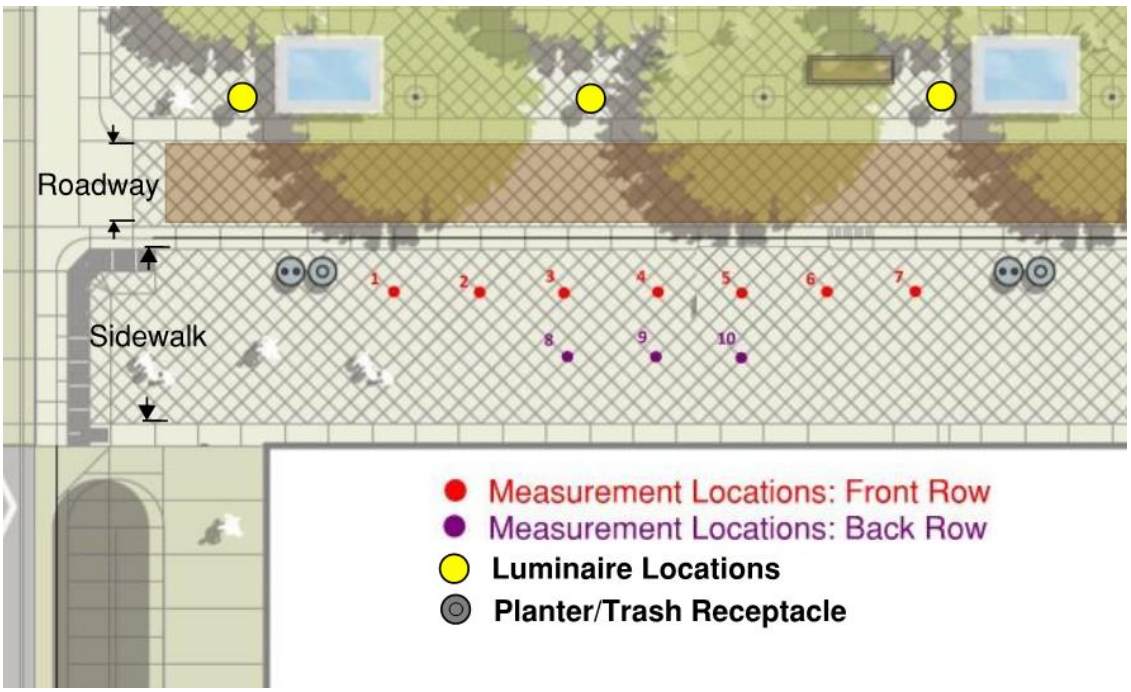


Figure 5.1: Locations of Objective Measurements [14]

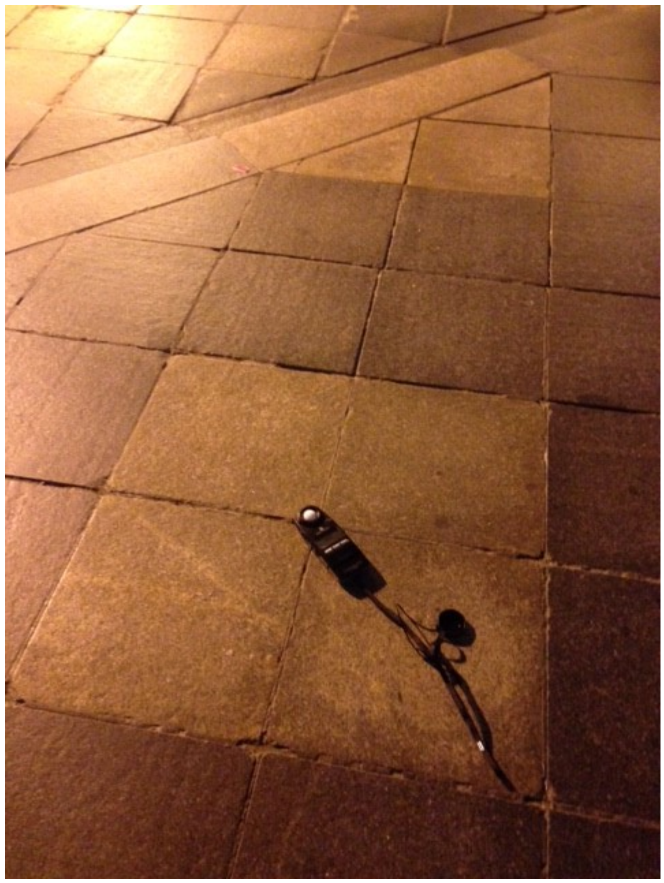


Figure 5.2: Horizontal Illuminance Measurements

was mounted to the top of a tripod at a height of 4'-4". The tripod was placed at Location 4 (see figure 5.1) and illuminance measurements were taken on each of the 6 faces of the cube as shown in figure 5.3. Just as with the ground plane measurements, 3 sets of measurements were taken at each of the 6 faces. Then, the tripod was moved to Location 5 and Location 3 and the process was repeated.

Figure 5.3: Cubic Illuminance Mounting Set Up

The final component of the lighting measurements was the luminance measurements. These measurements would be taken through the use of the luminance mapping HDRI process described in the background information section 2. The tripod was moved back to Location 4 and the mounting height remained the same at 4'-4". Then the HDRI system (this analysis used a Nikon D5200 model camera) was mounted to the tripod and aimed down the length of the mall. The camera used in these measurements was the same camera that was used by M. Stanley in her HDR work[41] with the 18mm Zoom lens. The decision to use this camera and lens was made so that during the vignetting analysis process the white balance function that Stanley had established could be utilized and the results of this analysis could be double-checked with her findings to ensure the accuracy of the vignetting correction process.

The camera was manually aimed down the mall and focused by hand. At some of the sites, in order to get the fixtures in the frame of the image, the camera had to be slightly aimed towards the fixture instead of directly in line with the mall as seen in figure 5.4. Once the camera was focused and locked in place, it was tethered to a computer. A software called Sofortbuild was used to create a bracketed series of images at a manually selected aperture size. The bracketed images varied only in shutter speed, ranging from at 1/125 sec. to 30 sec. shutter speeds with an aperture size of f/5.6. This resulted in a large range of images of sequentially differing exposures. This process was repeated twice, with two different apertures sizes. Then, the camera was rotated 180 degrees to get a view of the mall from the opposite direction. The same bracketed set of images at the two aperture settings were taken for this view as well.

In order to digitally calibrate the images, "spot" luminance measurements also had to be taken with a luminance meter, a Konica Minolta LS-100 meter, while the pictures were being taken with the camera. Three spots on the mall were identified with brightly colored tape. Spot 1 was 14' away from the tripod. Spot 2 was 16' and shifted 2' towards the curb while spot 3 was 22' away from the tripod (see figure 5.5). While the camera was taking the bracketed images, the luminance meter was held next to the camera lens and aimed at the marked spots. Three measurements were taken at each spot and these values were recorded so that the final compiled HDR pictures could later be calibrated based on these values.

5.2 Data Processing

The horizontal and vertical illuminance analysis would be just a simple comparison between the pre and post average illuminance values. The HDR images, however, needed to be processed before they could be analyzed. Figure 5.6 demonstrate four of the LDR images that were collected

Figure 5.4: HDR Camera Mounting Set Up

Figure 5.5: Luminance Measurement Marker Locations

with the f/5.6 apertures size. In total, each HDR image was compiled of 13 total images with a range of exposures similar to these.

Figure 5.6: LDR Image Array Sampling

The first step of the image processing procedure was to compile the images into a single HDR image. To do this, a piece of software called HDRgen was used. After compiling all of the sets of bracketed LDR images into single HDR images, the new individual HDR images were passed through a custom Matlab script that would apply a predetermined vignetting function to the images which would neutralize the effect of vignetting on the image. Vignetting is the effect that occurs in photographs where the brightness of the image gradually falls-off from the center of the image towards the image boundaries. This effect can be countered by applying a vignetting function to the image. The vignetting function is a mathematical function that is unique to the lens type and the aperture size used. See Appendix B for vignetting function code. The Matlab script applies the appropriate vignetting function and then output a new HDR image which has been corrected for vignetting. This new HDR image was then used in the final analysis. However, before any comparisons could take place between the pre and post installation the images needed to be calibrated. A program called HDRscope [23] allows for a specific area of the image to be selected and then assigned a luminance value. Then the program will calibrate the entire image based on that value. The luminance measurements gathered at the mall through the use of the luminance meter were used for this calibration. After the images had been calibrated, the pre-installation and the post-installation images can be compared and information such as uniformity and contrast can be analyzed.

5.3 Observations and Sources of Error

Safety was the number one priority of the team during this measurement process. This includes not only safety of the team but of the equipment also. A minimum of three people were needed to take the objective measurements: one person to take the measurements, one person to record the values, and one person to guard the rest of the equipment. As mentioned in Chapter 4, all measurements had to be taken during the window between the beginning of Astronomical Twilight and 11:15 pm. After 11:15 pm, the security of the team and the equipment became more of a concern because of the overall shift in the atmosphere of the mall. The most difficult component of this process was completing all of the measurements during this brief time window. This time constraint limited the overall amount of measurements that could be taken.

Another difficult part of this process was avoiding the amount of foot traffic in the measurement area. Because our interest was in the light levels along the most commonly used sidewalk, the measurements were taken in areas that experienced high volumes of foot traffic. There was also quite a bit of traffic on the adjacent street due to bicyclists, police, maintenance vehicles, and the regularly scheduled "mall ride" tram. This pedestrian traffic was a concern not only because of the inconvenience of having people walk around the measurement site, but because as people passed between the measurement locations and the street where the lights were located, they cast shadows over the meters which threw off the measurements. Additionally, as vehicles and trains drove by their headlights shined more light on the measurements while also shadowing light from nearby street lights resulting in very large variances in the data. So, measurements had to be taken in short "spurts" of time when there were no people or vehicles nearby. This slowed the overall progress and further added complications to the measurement process. However, the decision to take measurements during the weekday as opposed to during the weekend helped to minimize the amount of pedestrian traffic in the area.

One notable source of potential error in the process was the dramatic change that the mall underwent in the period between the pre and post-installations. A little more than two months passed between pre and post-measurement. During this time the signage on the mall was changed; temporary structures and vendors were moved, removed, and replaced; and the vegetation grew and was eventually replaced when it got cold. Although these changes had very little effect on the illuminance measurements, it made the HDR image analysis difficult since many of the changes resulted in changing the colors of many elements in the "scene".

Another potential source of error in this part of the process came through the location of the markers where luminance measurements were taken during the HDR imaging component. Because of the geometry of the mall and the location of the lights in relation to the sidewalk, the camera was angled slightly towards the lights in order to get a "view" which included all of the desired visual elements. Unfortunately, this meant that the location of the squares which marked the luminance measurements were no longer centered in the camera frame. Centering the markers would have required putting them in the street right in the path of the mall bus and other vehicles. As a result, the final HDR images were calibrated to a point that is off-center in the image. This is not expected to drastically affect the study because the factors like color rendering, color temperature, uniformity, etc. do not require precise luminance values. The only aspect of the HDR analysis in this study that utilizes the measured luminance values is the calibration of the images for the luminance mapping component, which is a relatively small part of the HDR image investigation. So even though this could possible introduce error into the absolute values found in the luminance maps, the HDR process will still allow for reliable and valuable relative and observable information.

Finally, as mentioned in Chapter 4, the unfortunate circumstance of only having a single site to analyze reduces the comprehensiveness of the study but does not refute the quality of the process outlined or the reliability of the results found at the single site. Future studies which seek to use a model similar to that outlined in this study should attempt to observe multiple sites if possible.

Chapter 6

Objective Results and Discussion

The following chapter compiles the results of the objective measurements and provides a brief discussion about how the data can be best interpreted.

6.1 Horizontal Illuminance Results and Analysis

Figure 6.1 displays the pre and post installation horizontal illuminance values measured on the ground along a section of the 16th and Curtis block. Recall that the location index coordinates can be found in figure 5.1. The illumination levels remained very consistent over the course of the measurement period. This would imply that other factors that may influence lighting conditions, such as faade lighting or sky conditions, remained constant over time.

As you can see, the pre-installation illuminance values are noticeably different than the post-installation illuminance values. The pre-installation measurements (marked above in red and purple colors) are not only much higher than the post-installation measurements (blue and green), but they also display a very dramatic variance within themselves. Recall that measurements at location 1-7 were taken along a straight line spaced 8' apart from each other while locations 8, 9, and 10 were 6' set back (away from the curb) adjacent to points 3, 4, and 5 respectively. This provided us with a large "grid" which covered a significant portion of the mall, allowing us to get a broad look at the uniformity of light along the sidewalk. This graph demonstrates that as you walk down the block prior to the installation, the illuminance at the ground varies sharply in both the East-West direction (the path of travel along the mall) and the (North-South) directions. After

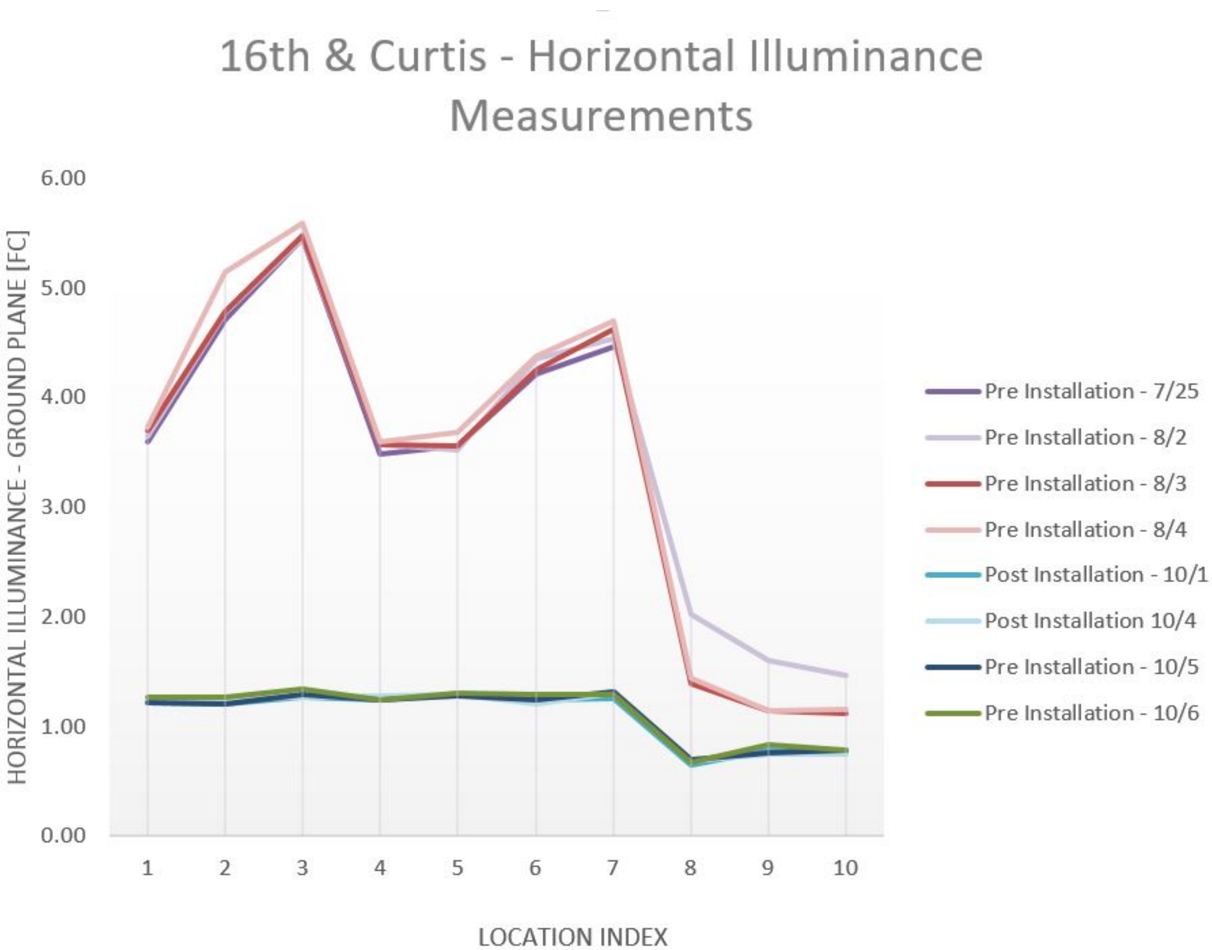
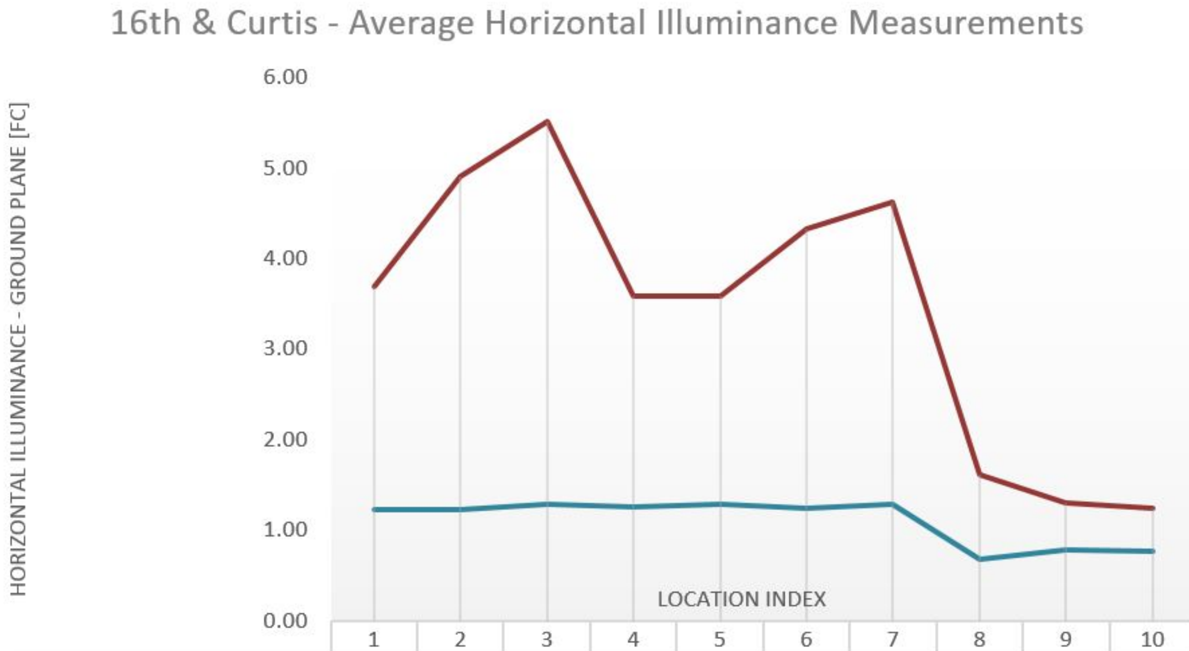


Figure 6.1: 16th and Curtis - Horizontal Illuminance Measurements

the installation, however, the illuminance was significantly more uniform in both directions.



	1	2	3	4	5	6	7	8	9	10
Pre Installation Average Illuminance (fc)	3.69	4.90	5.51	3.58	3.59	4.33	4.62	1.62	1.30	1.25
Post Installation Average Illuminance (fc)	1.229	1.231	1.290	1.250	1.291	1.247	1.290	0.674	0.780	0.766

Figure 6.2: 16th and curtis - Average Horizontal Illuminance Measurements

By looking at the averaged illuminance values at each point (figure 6.2), the dramatic rate of "drop off" in the North-South direction as seen by observing shift in illuminance from points 3-5 to points 8-10. The illuminance at the ground drops off by as much as 3.86 fc (or 70%) between points 3 and 8, which is quite dramatic over such a compact area. After the installation, this change in illuminance between these two points was only 0.616fc which is much more desirable in such a space of this size.

The average illuminance uniformity across the ground plane can also be calculated by using these averaged values. Table 6.1 displays the changes it uniformity for the area. Note that, when looking at each measurement "row" individually, in would appear that the area underwent a very minimal change in uniformity. However, when looking at the space as a whole, the overall uniformity underwent a much more significant change - decreasing from a 4.42:1 max:min to 1.91:1 max:min (a 56.8% increase in uniformity) across the measurement area.

Table 6.1: Horizontal Illuminance Uniformity

Measurement Location	Uniformity Categorization	Pre-Installation Uniformity	Post-Installation Uniformity
Front Row	Max:Min	1.54:1	1.05:1
Back Row	Max:Min	1.30:1	1.16:1
Total	Max:Min	4.42:1	1.91:1
Front Row	Ave:Min	1.21:1	1.03:1
Back Row	Ave:Min	1.11:1	1.10:1
Total	Ave:Min	2.76:1	1.64:1

6.2 Vertical Illuminance Results and Analysis

The following graphs (fig. 6.3, fig. 6.4, fig. 6.5) display the illuminance values measured at a height of 4'-4" on each face of a cube at each tripod location.

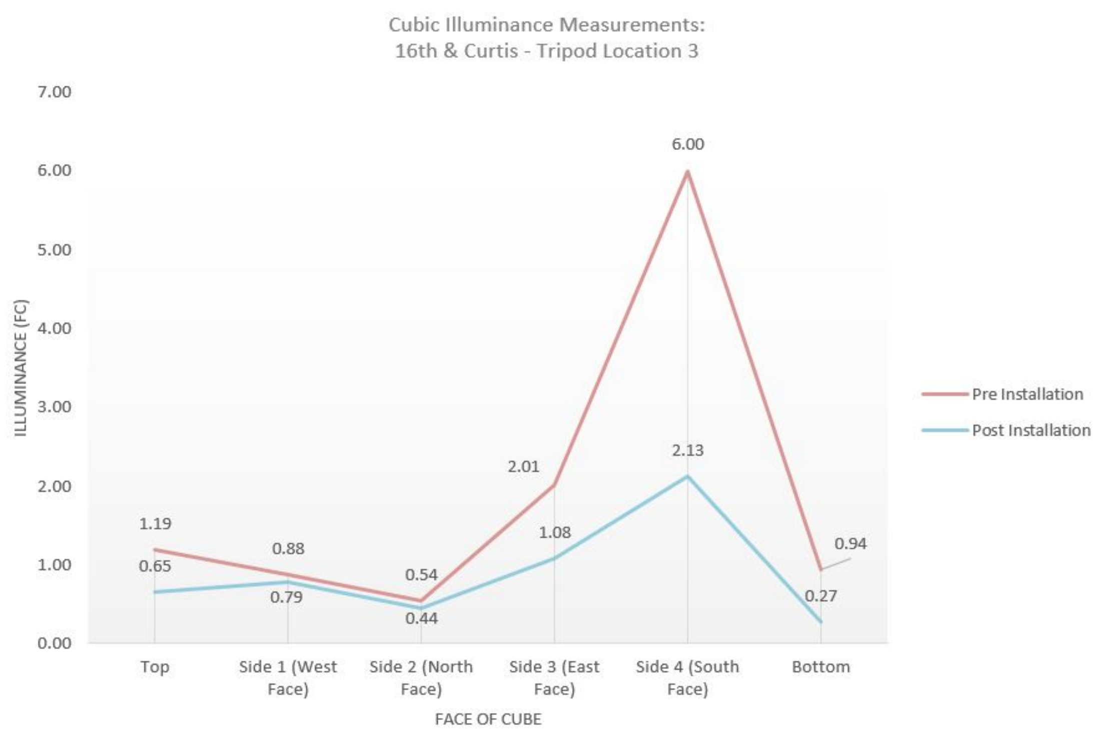


Figure 6.3: Cubic Illuminance Measurements - Tripod Location 3

Tripod location 3, as seen in the horizontal illuminance analysis, is the location direct adjacent to one of the luminaires and experiences the highest illuminance levels (figure 6.3). Just as this location produced the most dramatic illuminance characteristics in the ground plane analysis, it also has the most notable results in the vertical illuminance analysis. The most obvious thing that this graph reveals is a dramatic change in vertical illuminance on the South face of the cube. This is the face that is oriented toward the luminaires. As one might have predicted after looking at the data from the ground plane analysis, there is a significant decrease in vertical illuminance on this face, a 64.5% decrease from 6fc to 2.13 fc. All of the other sides undergo a much less dramatic decrease in illuminance with the West and North face of the cube experiencing very minimal change.

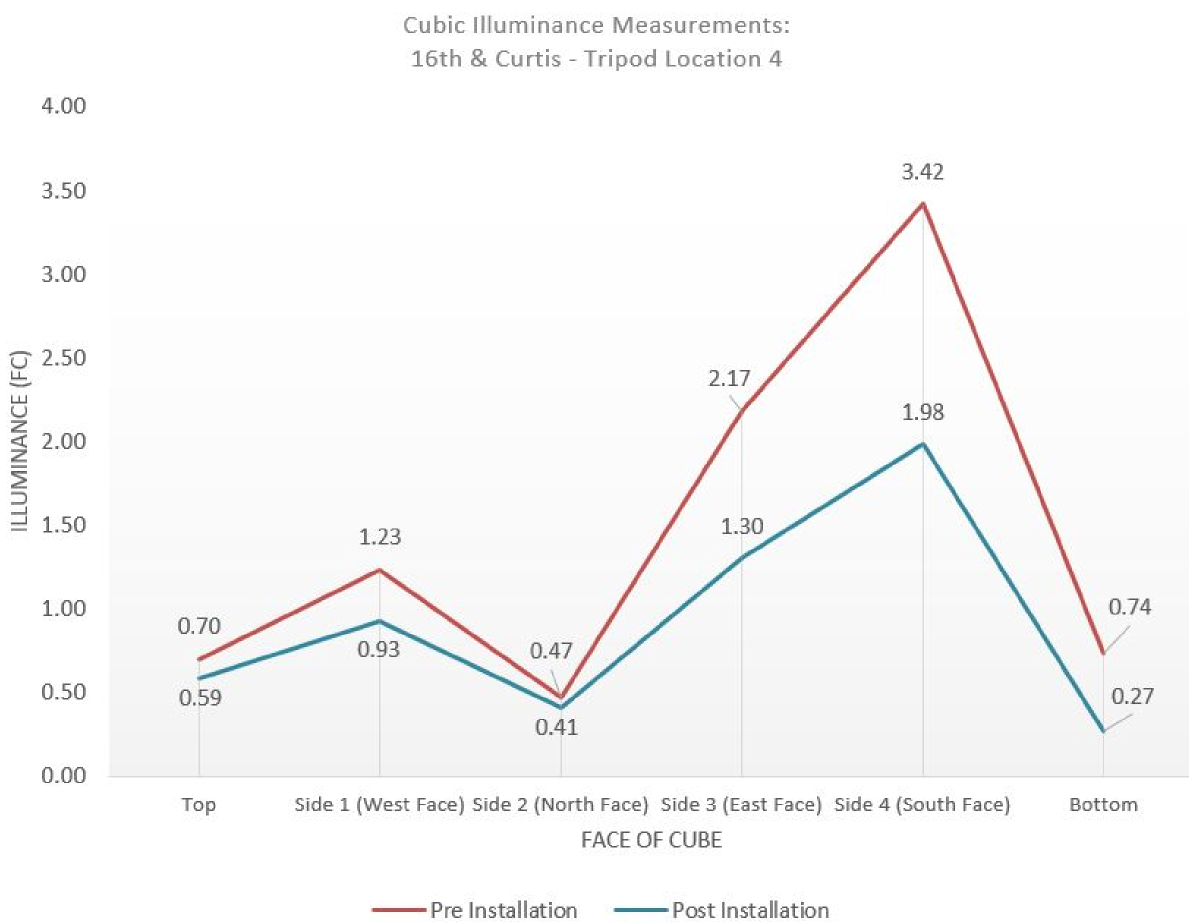


Figure 6.4: Cubic Illuminance Measurements - Tripod Location 4

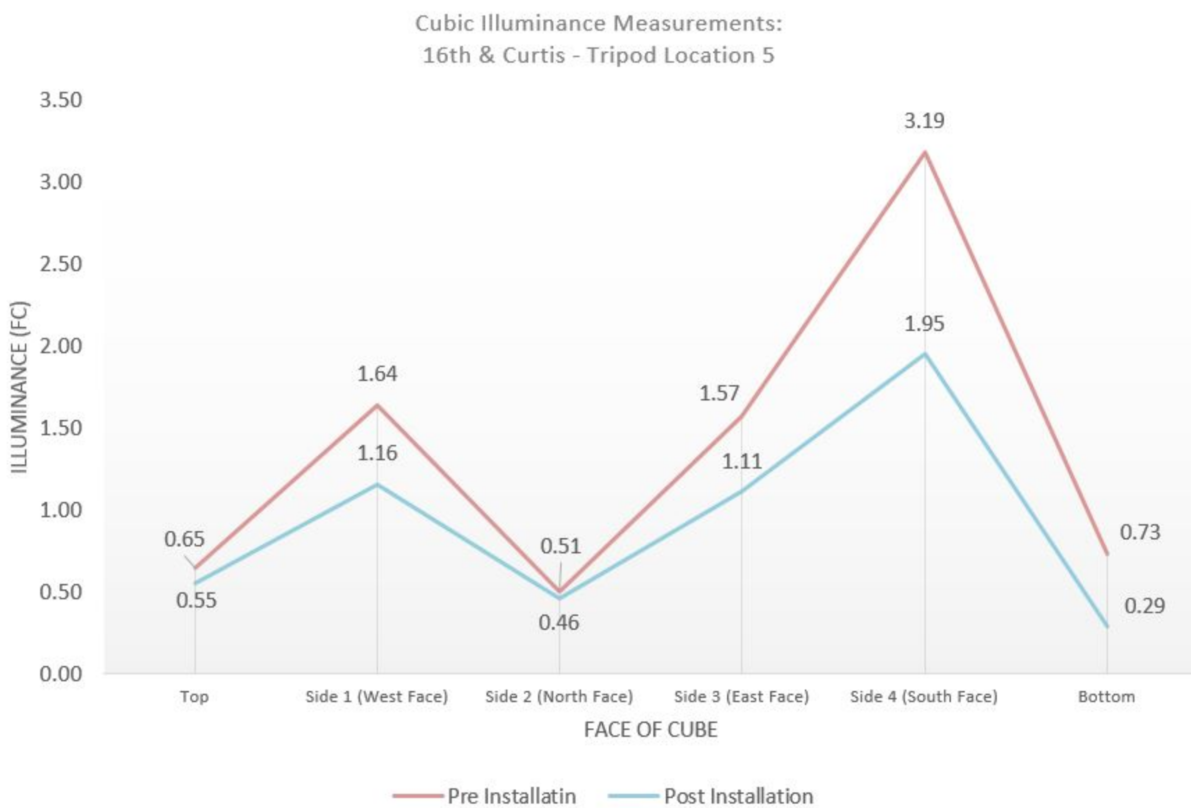


Figure 6.5: Cubic Illuminance Measurements - Tripod Location 5

Results from the other two tripod locations are presented in figure 6.4 and figure 6.5. Again these locations exhibit the same trends as found at location 3, however the effect at these locations was not as dramatic. The illuminance at each face of the cube decreased of less than 1 fc except for at the South face which experienced a 1.44fc (42.1%) and 1.24 fc (38.9%) decrease in illuminance at tripod locations 4 and 5 respectively. This confirms that the trend observed at location 3 is consistent all along the sidewalk although the magnitude of the effect does vary. It would appear that the South face consistently experienced dramatic decreases in illuminance while the other faces experienced much less (or no) change.

6.3 Semi-Cylindrical Illuminance Results and Analysis

The cubic illuminance measurements presented in the last section can also be transformed into semi-cylindrical illuminance (see appendix for calculations based on Cuttle's method) [11]. Figure 6.6 and figure 6.7 display the semi-cylindrical illuminance values for each tripod location both before and after the installation. The two plots show the average illuminance on a curved surface of a half cylinder located at a reference point which is defined as the center of the cubic measurements. The two plots represent the two conditions which characterize the orientation of this semi-cylinder facing the East and facing the West. The calculated semi-cylindrical illuminance values can be used to approximate the illuminance hitting the face of a person standing at the location of the tripod when viewed by an approaching pedestrian from either the west or the east. For reference, these plots also displays the "facial recognition threshold" determined by Fotios [38]. The threshold values demonstrate the minimum amount of semi-cylindrical illuminance necessary to recognize a face at various distances from the vertical facial plane. Fotios found that 0.7lx (0.065 fc) were needed to recognize facial features at a distance 4m (approx. 13ft) and that 7lx (0.65 fc) were needed to recognize a face at a distance of10m (approx. 33ft). As you can see, both the pre and post installation values for both directions of travel fall above these thresholds despite the reduction of illuminance found in the post-installation as compared to the pre-installation.

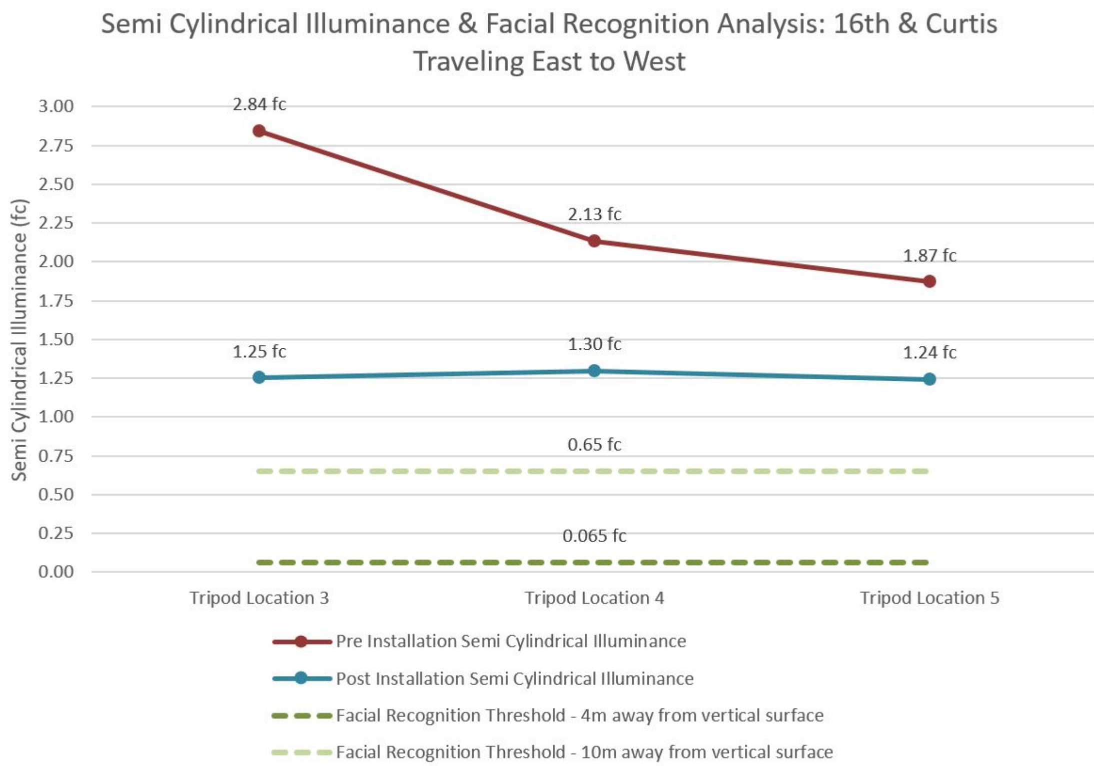


Figure 6.6: Semi-Cylindrical Illuminance Measurements: East to West

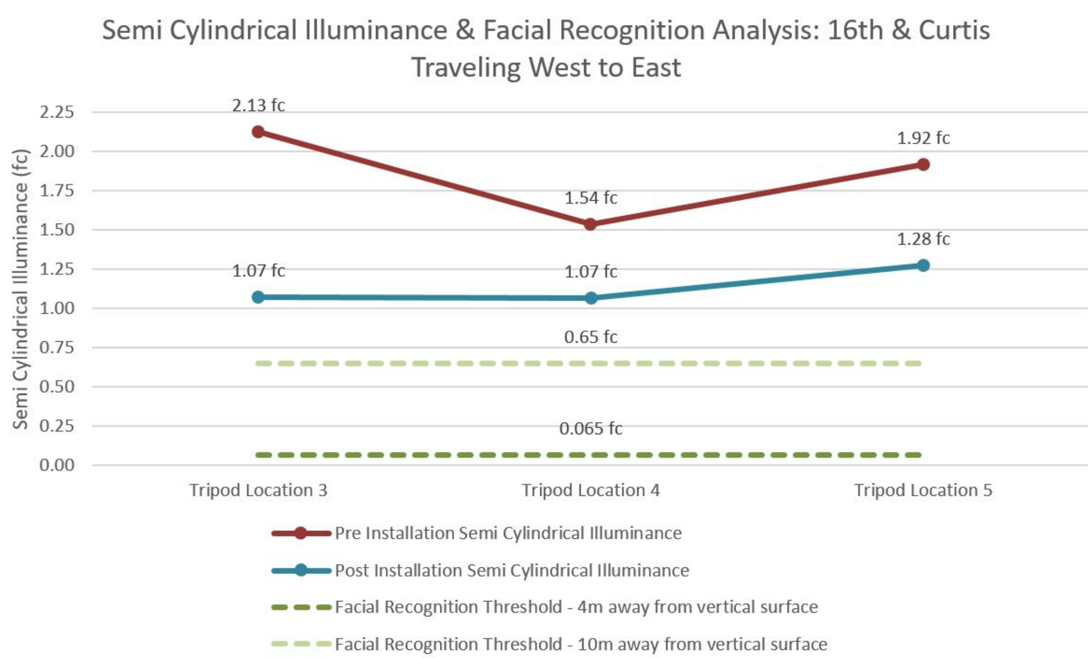


Figure 6.7: Semi-Cylindrical Illuminance Measurements: West to East

6.4 HDR Image Results and Analysis

The final component of the objective data collection process was through the use of HDR photography. Figures 6.8, 6.9, 6.10, and 6.11 below are the final results of the compiled HDR images for both the pre and post installation conditions.

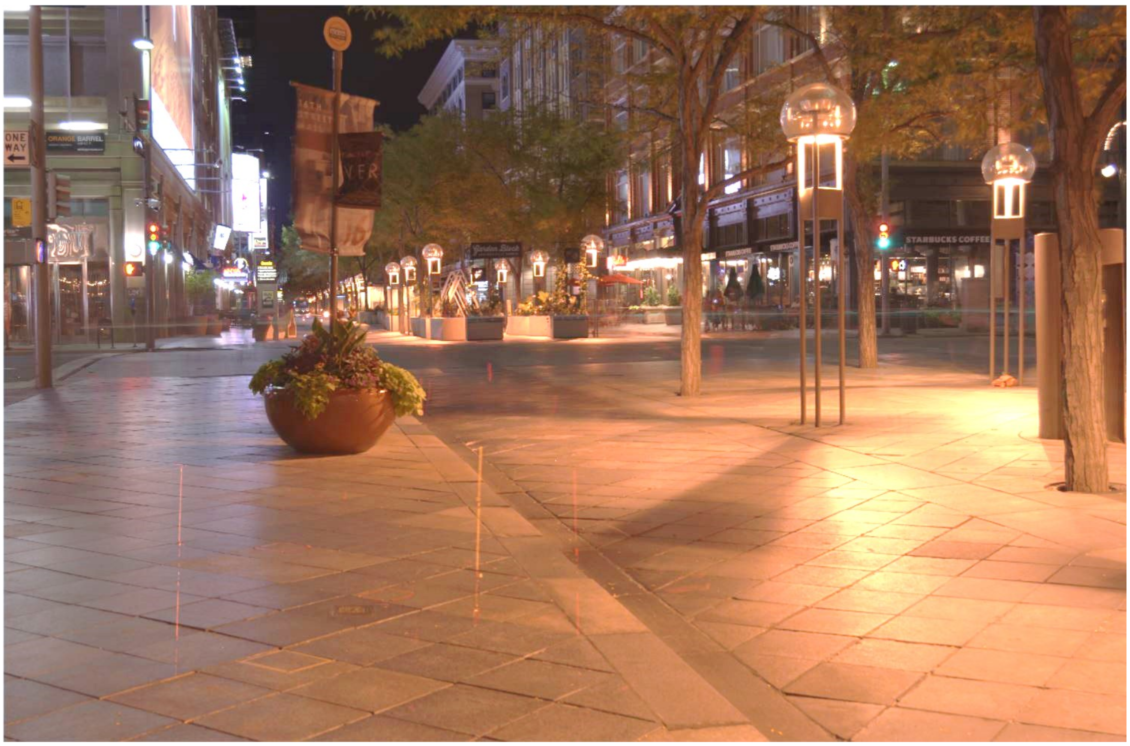


Figure 6.8: Compiled HDR Image: 16th and Curtis - East View, Pre-Installation

Some of the differences between the images are quite dramatic while other differences are very subtle. This report will briefly touch on some of the valuable applications of HDR image analysis.

6.4.1 Color Temperature

Perhaps the most visible difference between the two images is the change in color temperature of the lamps. As previously noted, the pre-installation lamps were high-pressure sodium technology, known for their high efficiency and high light output. However, high-pressure sodium lights are also known for their low correlated color temperature (CCT). Traditionally HPS sources have a CCT

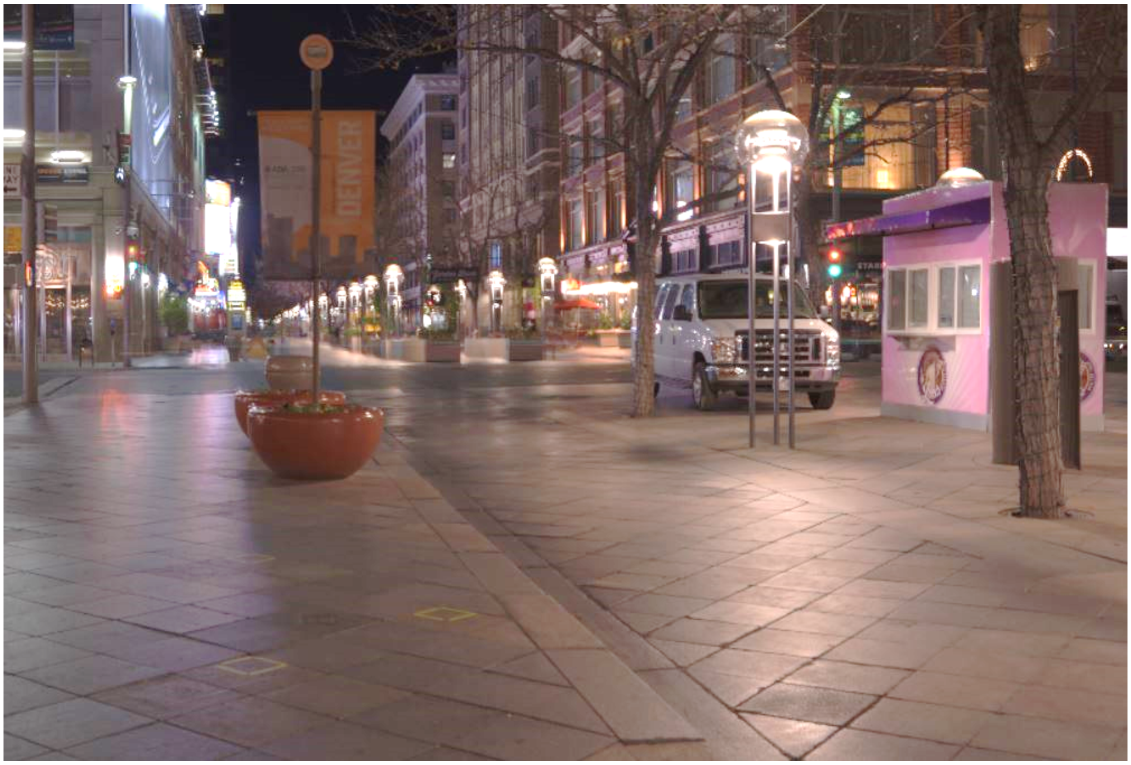


Figure 6.9: Compiled HDR Image: 16th and Curtis - East View, Post-Installation

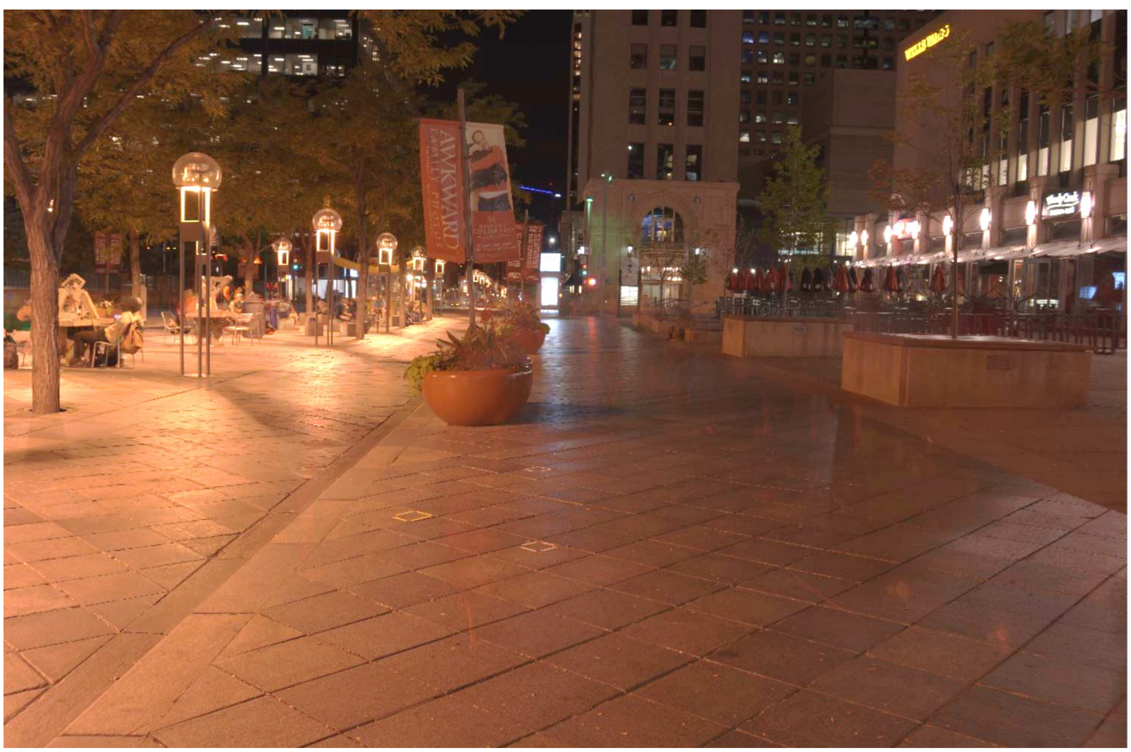


Figure 6.10: Compiled HDR Image: 16th and Curtis - West View, Pre-Installation

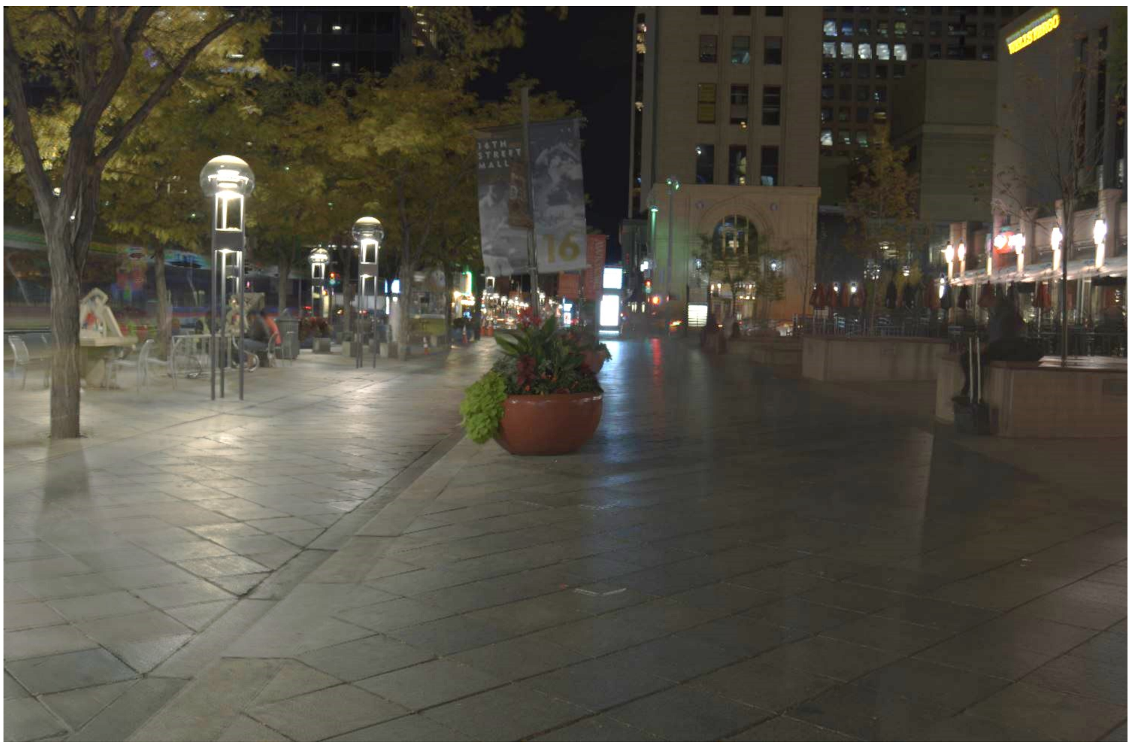


Figure 6.11: Compiled HDR Image: 16th and Curtis - West view, Post-Installation

value of 1900K. LED's, on the other hand, can be found in a wide spectrum of color temperatures ranging from very warm to very cool. A simple visual analysis of the two HDR images above (figure 6.10 and figure 6.11) reveals a very dramatic shift in color temperature. The new LED sources appear to be much "cooler" in color, however they do not appear to be very "blue," a trait commonly associated with LED sources.

Quantifying this shift in color temperature can be accomplished through chromaticity measurements taken by an illuminance spectrophotometer. Several measurements were taken on the mall from a small sampling of both the existing and the new lights. The spectrophotometer was a model Konica Minolta CL-500A and provided a large variety of information, but specifically revealed the average correlated color temperature of the sources. These measurements revealed that the average correlated color temperature from the pre-installation lights was approximately 1875 K while the post installation CCT was approximately 3134 K. To provide a reference for this shift, candle light is considered to be around 1850 K to 1900 K while a traditional "cool white" linear fluorescent has a CCT of about 4200 K and daylight generally falls around 6500K 6.12. Generally light sources that are used for common applications range from 2700K to 4000K. This knowledge reveals that pre-installation lamps had an extremely warm color temperature akin to candle light whereas the new lights falls more in the range "neutral white" or "bright white" albeit on the warmer side of these ranges. The chart below in figure 6.12 can be used to better put these values into context.

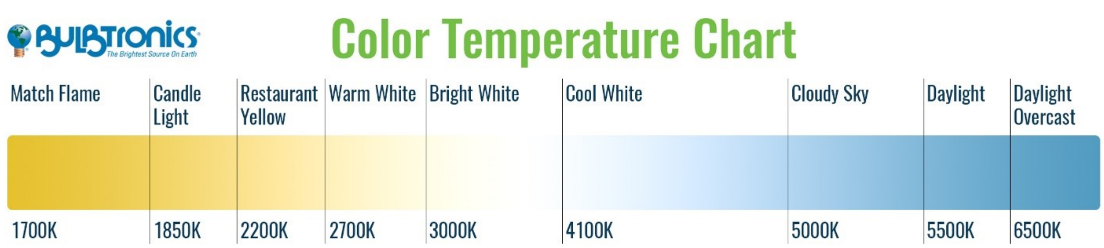


Figure 6.12: Color Temperature Chart [8]

6.4.2 Color Rendering

Another change that these before and after images bring to attention is the color rendering of the light sources. As mentioned earlier, color rendering (described by the CRI of a source) is a rating which reveals how accurately a light source renders colors. The photos of the site, seen in figures 6.13 and 6.14 are a useful tool for displaying this property. Note the changes in coloring that can be found in the vegetation in the images.

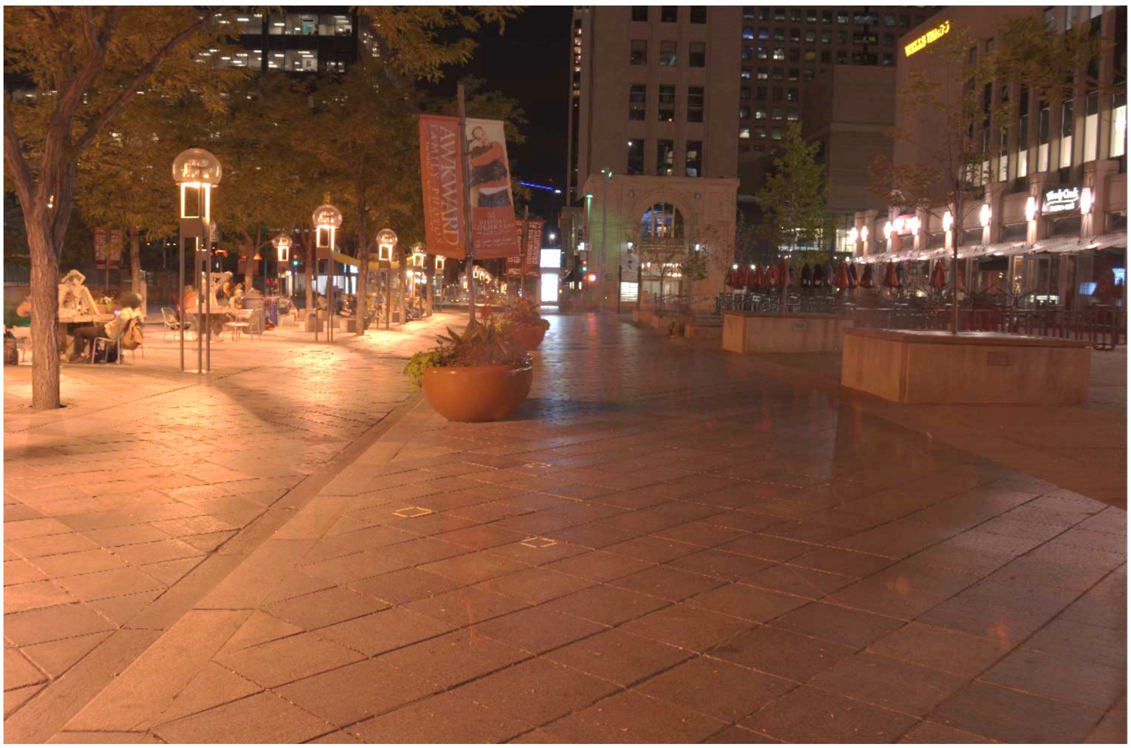


Figure 6.13: 16th and Curtis Pre-Installation - West View: CRI Display

The leaves on the trees are noticeably more green and the vegetation in the potted plant more vivid and intense in the image of the new installation as opposed to the old installation. (Note that the signage above the potted plant was changed between the pre-installation period and the post-installation period, so these two features cannot be compared). Just as with the color temperature, the illuminance spectrophotometer was used to quantify and confirm this observed change. Figure 6.15 shows the average R values found in the old luminaires compared to the new.

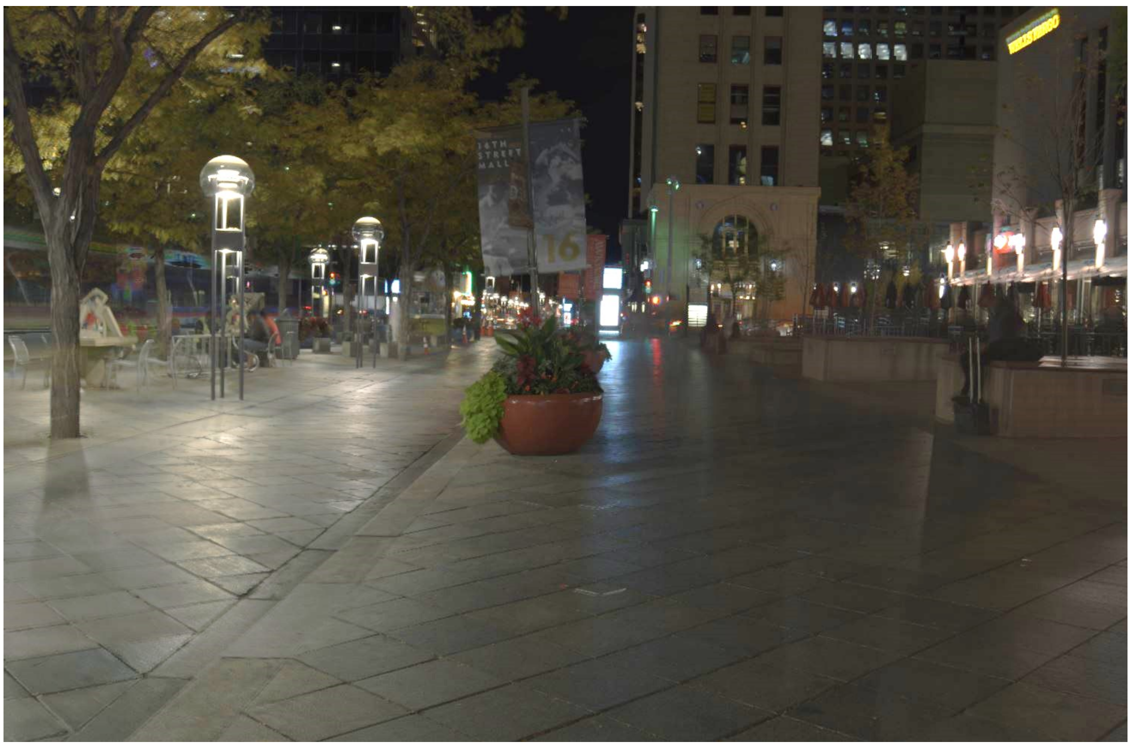


Figure 6.14: 16th and Curtis Post-Installation - West View: CRI Display

The pre-installation measurements are recorded as the left-hand bars while the post-installation measurements are recorded as the right-hand bars.

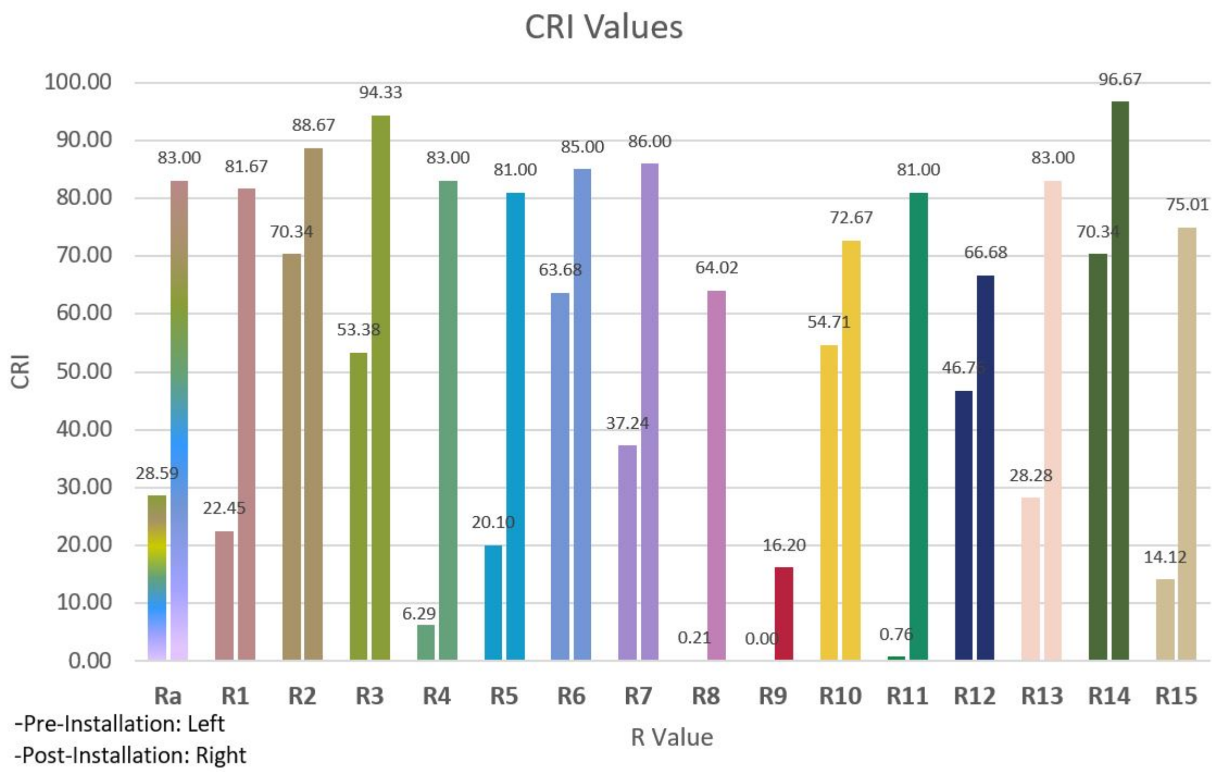


Figure 6.15: Pre and Post Installation CRI Comparison

Each of the color rendering indices (R's) correlate to a different Munsell color reference. (The Munsell color system is a commonly referenced color space which specifies colors based on hue, value, and chroma). The first eight references correlate to eight "general" color-rendering index which use low saturation colors with approximately equal hues. Ra is the average color rendering index which is made up of the averages of R1-R8. This is the value that is commonly recorded to explain the overall CRI of a source. The next seven numbers are the "special" color rendering indices which were added later by the CIE (the International Commission on Illumination). These values represent more "realistic" colors or colors that you would more likely encounter in everyday life. For example, R13 correlates to Caucasian skin color and R14 correlates to "leaf" green. This data reveals that there is a very significant change in the CRI of the new lights as compared to the old lights. The Ra value alone changes from approx. 29 to 83 a 65% increase in CRI. This confirms the visual observations found in the HDR image analysis.

It should be noted, however, that a considerable amount of research suggests that the CRI metric is not the best method for measuring the ability of light to render color. Other metrics (such as the color quality scale, CQS and the gamut area index, GAI), have been proposed as metrics which could supplement or even replace the CRI metric [36], [37], [13]. However, because CRI is still the main metric used within the lighting industry, it is considered more than sufficient for the purposes of this study.

6.4.3 Uniformity

It was already shown that there was an increase in uniformity on the mall through the horizontal ground plane illuminance measurements. However, these measurements were only taken on the sidewalk where the majority of the pedestrians walk. Figures 6.16 and 6.17 reveal a more dramatic shift in uniformity which occurred not on the sidewalk itself, but on the central median area. This area is used less often for transportation, and more for recreation and leisure. This area contains, benches, art installations, tables for playing chess, and often serves as a location for street performers and vendors on the mall. So, even though the other measurements were not taken in this area, it is still important for the lighting experience in this area to be pleasant. By observing the HDR images, it is seen that this area experiences a very dramatic shift in uniformity.

Notice how the dark “pinwheel” like shadows that occurred from the three luminaire poles which hold up the light have been washed out by the addition of a downlight component located about 3/4 of the way up the length of the fixture. This significantly reduced the appearance of shadows which extended across the central median of the street.

The final aspect of the HDR image analysis is the luminance mapping component which can be used to quantify these uniformity observations. A section of the scene has been calibrated and mapped in figure 6.18. These maps were created by HDRScope [23].

The advantages of HDR imaging come in to play quite dramatically for this analysis. The

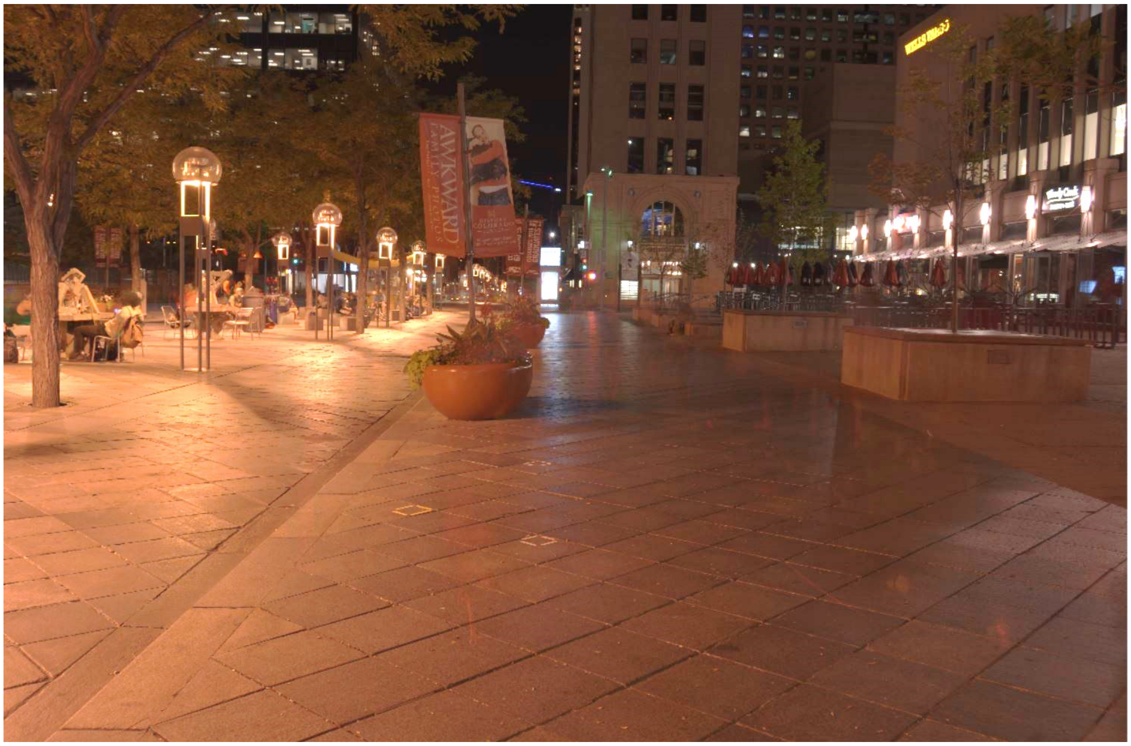


Figure 6.16: 16th and Curtis Pre-Installation - West View: CRI Display

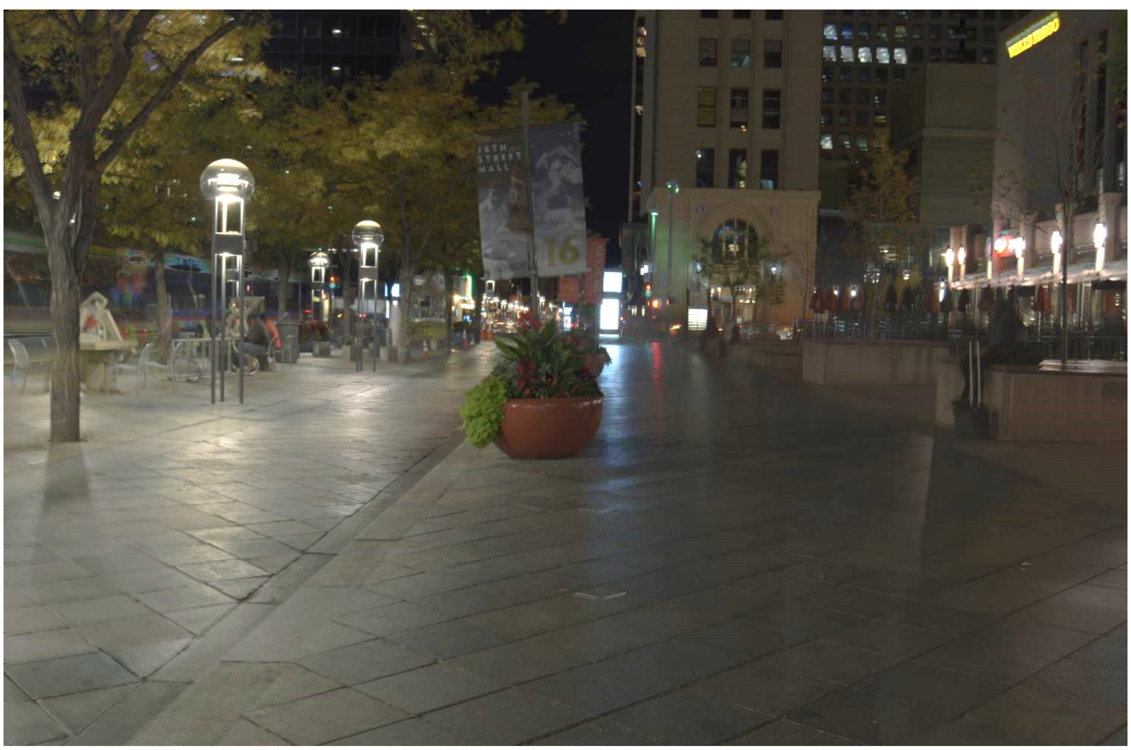


Figure 6.17: 16th and Curtis Post-Installation - West View: CRI Display

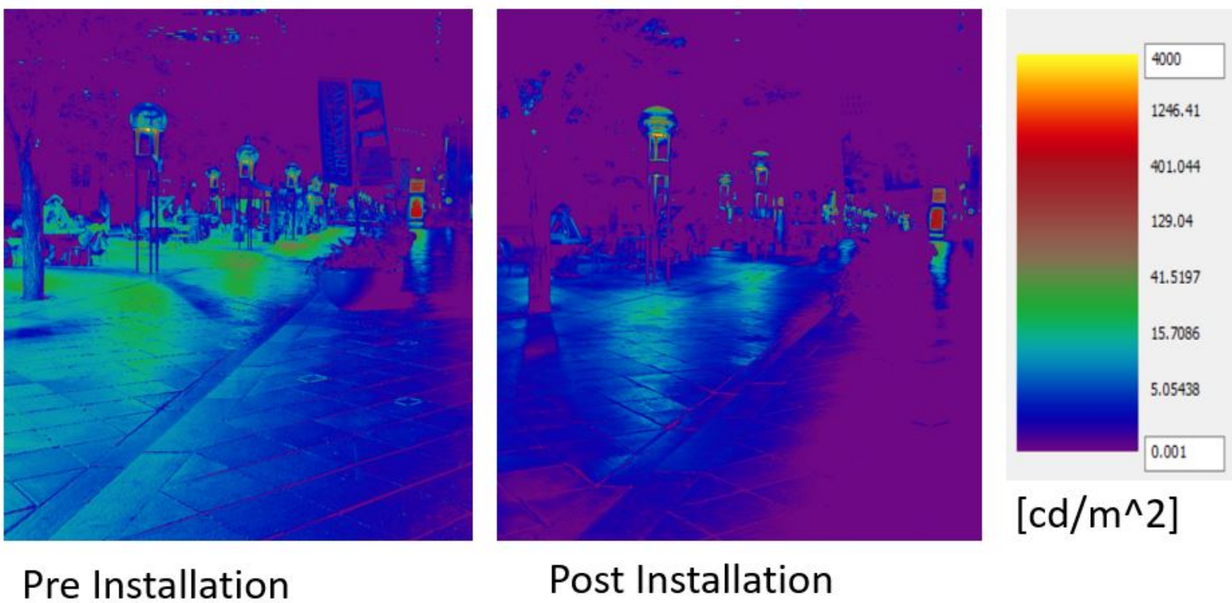


Figure 6.18: HDR Luminance Mapping Images

images were first calibrated based on luminance measurements taken at the marked locations on the ground. These values can be found in the appendix. Then the image processing software can accurately map the calibrated luminances of the image and be easily visualized through the false color rendering display. Both images utilize the same scale which is in cd/mˆ2. These images reveal that there was a definite decrease of luminance on the mall after the installation. However, the dramatic change of uniformity can also be observed. The pre-installation image reveals that the sidewalk area had a luminance level of approx. 10 cd/mˆ2 at the curb and less than 0.1 cd/mˆ2 approximately 12' away from the curb in the middle of the sidewalk. The post-installation luminance was reduced to approx. 5 cd/mˆ2 at the curb to about 0.01 cd/mˆ2 only 4ft away from the curb. In the central area of the median (around the "pinwheel" shadows), the luminance undergoes a considerable shift from as high as 120 cd/mˆ2 to as low as 5 cd/mˆ2 over a very small area. The post-installation uniformity demonstrates a much lower change shifting from a maximum of 40 cd/mˆ2 to less than 1 cd/mˆ2. In this analysis, the exact values are less important than the magnitude of luminance ratios that can be found in such a small space.

Chapter 7

Objective Measurements Summary

7.1 Horizontal Illuminance

The ground plane illuminance underwent a decrease in overall illuminance, which may result in a mixed conclusion regarding the effect of the lighting change on the mall. On one hand, the illuminance levels in the space have decreased, which may appear concerning because it is a common misconception that more light is always better and in some cases, such as feelings of safety - this has been found to be true [2]. However a decrease in light does not always mean that it is harder to see. According to the ANSI/IES Recommended Practice for Roadway Lighting, "Commercial areas in urban environments [with] high nighttime pedestrian activity" are recommended to have a horizontal illuminance level of 1-2fc depending on the amount of vehicle use. For lighting applications where vehicle conflict is not expected, the recommended average horizontal illuminance is around 0.5fc [19]. Depending on how this space is classified, the 16th Street Mall falls right within these ranges of recommended values and provides enough light to accomplish the visual tasks necessary for the mall. In fact, some studies would argue that if the purpose of the lighting is only to accomplish visual tasks, much lower light levels would suffice. Studies have shown that significantly raised paving stone can be detected 95% of the time with light between 0.1 and 0.62 lx (0.0092fc to 0.057fc) [4] and that only 1 lx (0.092fc) is sufficient amount of light for "smooth and steady movement in interior spaces" [30] (although this final study only observed interior spaces, the results which illustrate that hazards can be avoided under low-light conditions can be used to further understand low light level visual performance).

However, even though the amount of light does play an important role in determining "good" quality lighting [3],it is not the only factor that should be considered. A point worth noting is that even though the changes in illuminance are very small, Boyce found that at very low illuminance levels, changes in illuminance produced much larger changes in the perception of safety (and by extension comfort) than at higher illuminance levels [3]. Boyce found that between 0-10 lux (0-0.93fc) changes in light levels produced relatively large changes in perception of safety. Light levels between 10 lux and 50lux (0.93fc 4.6fc) that experienced changes in lighting resulted in much lower changes in perception of safety. Since the pre-installation to post-installation light level shift remained right on the threshold of this higher category, it can be implied that the reduction in light did produced a decrease in perception of safety but not nearly as dramatically as if the light levels would have decreased below 0.9fc. Further exploration is necessary to draw a conclusion in this area. Ultimately, it would appear that horizontal illuminance alone is not enough to determine the impact of the lighting on the mall.

7.2 Vertical Illuminance

The vertical illuminance (as seen through the cubic illuminance measurements) underwent a seemingly minor change as well, with the exception of the illuminance falling on plane directly facing the source. This face experienced the highest illuminance prior to the installation which dropped off very rapidly on the other three vertical planes. After the installation this face was still experienced higher light levels than the other three directions, but the difference was not so dramatic. Something to consider is that having such a high illuminance on only one side of the cube (which can be imagined as being roughly equivalent to a human face), would result in a very strong shadowing effect coming from that side. As anyone who has ever held a flashlight up to their face to make a scary face knows, casting shadows across the face can dramatically change a person's appearance and make reading facial expressions very difficult. Facial recognition is a large component in perception of safety. So, the pre-installation condition where the south face of the cube experienced high illuminance levels compared to the other faces, can be considered a much worse overall solution than the post-installation conditions were the vertical illuminance values are much more even. Even though this effect is not as strong at the other tripod locations, there is evidence that the post-installation condition can still be considered an improvement in this regard. According to RP-8-14, the high pedestrian conflict area recommends a vertical illuminance of 0.5-1 fc in both directions parallel to the flow of pedestrian traffic[20]. By this definition, the vertical lighting levels are high enough to be considered effective.

7.3 Semi-Cylindrical Illuminance

As mentioned in the above data section, Fotios conducted a study which sought to determine, among other things, how much light is necessary for accurate facial recognition. He found that 0.7 lux (0.065fc) of semi-cylindrical illuminance was needed at 4m while a minimum of 7lux (0.65fc) of semi-cylindrical illuminance was needed for facial recognition at a distance of 10m[38]. The measurements of the mall reveal that the new installation provides semi-cylindrical illuminance values of approx. 0.7fc which is right above the minimum value prescribed by Fotios for recognition at a distance of 10 m. To put this distance into context, 10m is approximately the distance between each light on the mall. This may seem like an uncertain conclusion since the amount of light it is right at the edge of the 0.65fc threshold, however when compared to other similar studies, Fotios' values are much higher. For example, a study by Rombauts found that only 3 lux (0.28 fc) was needed for 10m facial identification[33] while a study by Caminada van Bommel found an even lower value of 2.7 lux (0.25fc)[6]. With these values in mind, the post installation results seem very reasonable in fact much more reasonable to the excess amount of light provided from the pre-installation results.

7.4 HDR Images

7.4.1 Color Temperature

While the illuminance based investigations seemed to produce mixed results, the two color-based examinations produced much more dramatic and less debatable results. The color temperature measurements showed that the CCT changed from 1875 K with the old lights to 3134 K with the new lights. The new lights appear to be a comfortable, neutral/warm white color temperature. From prior research, is has been shown that cooler color temperatures tend to have a positive response in many settings when compared to warmer/orange sources. In general, studies have shown that whiter sources with a more full spectrum tend to produce a greater perception of brightness[17], [22] which in turn aids in feelings of security and comfort[35], [3]. This component, particularly the increased perception of brightness associated with the new color temperature, may counteract the decrease in illuminance measured on the mall.

7.4.2 CRI

The second color-based metric which underwent a dramatic shift was CRI. The average CRI value went from 29 to 83. Even though "excellent" CRI values are generally considered to be higher than 90, this standard should be put into context. CRI values of 90+ are often the most desirable in applications where it is very important to display colors accurately and vibrantly. (Art museums, retail shops, grocery stores, etc.) There is no need for such a high CRI value on the mall, so a CRI of 83 is perfectly adequate in this context. Visually, this shift results in the atmosphere becoming more visually appealing and the colors appearing more natural. Studies have found that high CRI values in street lighting applications serve as another way of increasing facial recognition[34]. In fact, many international lighting standards, such as the British and Italian standards of design, allow for lower illuminance values for street lighting that has a CRI above 60[4]. It is not farfetched to argue that the improved color metrics of the mall may be able to counteract the decrease in illuminance.

7.4.3 Uniformity and Luminance

The luminance mapping component reveals on one hand that the walkway has lower luminance, however it also reveals that the luminance is much more uniform over the entire walkway, street, and median. The decrease in luminance may be perceived as a darker (less bright) environment, however it has already been seen that the white color temperature and increased CRI may counter this effect, making the decrease in luminance less of a concern. The removal of the "pinwheel" shadows and subsequent increase in uniformity is a very desirable result of the new lighting. Increased uniformity has often been shown to be a quality of "good" exterior lighting. Both Painter and Romnee documented uniformity as one of the characteristics that were found in high quality lighting systems[31], [1]. Boyce identifies both the presence of shadows and poor-uniformity to be factors which impact of visual comfort[4]. According to Saunders, a min/max uniformity ratio that drops below 0.7 resulted in a much higher percentage of people that considered the lighting in an area to be "unreasonable"[40]. The min/max uniformity on the mall under the old lights was right at that threshold with a min/max ratio of 0.65 along the first row of measurements. The new lights were dramatically more uniform, at 0.95. The luminance mapping analysis confirms the dramatic decrease in the presence of shadows on the mall and the increase of uniform surfaces.

Aesthetically, although the distribution of the shadows created a repetitive patterning on the ground that could be considered visually interesting, the more uniform spread of light without the shadows helps to draw attention to some of the other, perhaps more nuanced, visual elements of the mall like the patterning and layout of the street pavers which was intentionally designed to pay homage to the local wildlife of Colorado by mimic the patterning on a rattlesnake.

Chapter 8

Subjective Study Observations and Process

The following sections will outline the subjective component of the analysis. These sections will first describe the survey creation process, followed by an explanation of the survey distribution procedure as well as briefly document the observations that were made during the distribution itself. Then, a brief summary of the general demographics will be presented. Finally, a more comprehensive analysis of both the semantic differential results as well as the Likert results will be described before a final conclusion will be made concerning the subjective results as a whole.

8.1 Survey creation Process

The subjective process began with the creation of the questionnaire. Ultimately the goal of this component of the study was to understand how the lighting impacted the users of the mall through the change in perceptual responses recorded by the mall users. Through the background research it was determined that both Likert type analysis surveys and semantic differential scales had both been successful ways of measuring subjective perceptual concepts[2], [28], [1]. The creation of the 16th Street Mall survey consisted of drawing from prior lighting and human factors research mentioned in the literature search to create a questionnaire which covered a variety of important lighting components

8.1.1 Categorization of Questions

As mentioned in Chapter 3, the heaviest influence on the creation of the questionnaire was Romnee's study (2014) which relied in a Likert type analysis where individual questions were grouped into a series of "category indicators." These category indicators were then correlated to larger categories which had been previously identified as important to the perception of high quality lighting[1]. This study used Romnee's structure as a starting point and developed 25 questions which were used to define the following category indicators and categories (see tables 8.1, 8.2, 8.3, 8.4, 8.5).

Table 8.1: Survey Question Categorization - Visual Performance

Question Category	Category Indicators	Survey Questions
Visual Performance	Distance Visual Tasks (Vert. Illuminance)	"I can easily read street signs from this location"
		"I can easily see the faces of pedestrians as they approach me"
		"I would be able to recognize a friend walking towards me"
	Distance Visual Tasks Horiz. Illuminance	"I can easily see curbs or objects in my path"
		"I can easily identify loose stones or cracks in the sidewalk"
	Color Rendering	"The color of the vegetation on the street looks natural"
		"The colors of objects around me looks unusual"
	Detail Tasks	"The print on this survey is difficult to read"

8.1.2 Category Explanations

Visual Performance This category seeks to answer the question "To what extent has the new lighting affected a person's ability to successfully perform visual tasks?" This category has been broken down into four different indicators, each correlating to a different contributing

Table 8.2: Survey Question Categorization - Visual Comfort

Question Category	Category Indicators	Survey Questions
Visual Comfort	Glare & Brightness Luminance	“The lighting on the street is too bright”
		“the mall lighting hurts my eyes”
		“The lights produce too much glare”
	Amount of Light	“This sidewalk appears dark”
		“There is not enough light on this path”
		“There is enough light for me to see my surroundings clearly”
		“There is too much light on the path”

Table 8.3: Survey Question Categorization - Perception of Safety/Reassurance

Question Category	Category Indicators	Survey Questions
Reassurance	Facial Identification (Vertical Illuminance)	“I can easily see the faces of pedestrians as they approach me”
		“I would be able to recognize a friend walking towards me”
	Color Rendering	“The color of the vegetation on the street looks natural”
		“The colors of objects around me looks unusual”
	Amount of Light	”This sidewalk appears dark”
		“There is not enough light on this path”
		“There is enough light for me to see my surroundings clearly”
		“There is too much light on the path”
	Distance Visual Tasks (Horizontal Illuminance)	“I can easily see curbs or objects in my path”
		“I can easily identify loose stones or cracks in the sidewalk”
	General Reassurance	”I feel safe walking on this sidewalk”
		“I would feel comfortable walking along this sidewalk alone”

Table 8.4: Survey Question Categorization - Perception of Luminance Atmosphere

Question Category	Category Indicators	Survey Questions
Perception of luminous atmosphere	Uniformity of light	"The light is evenly distributed all along the sidewalk that I am on"
		"There are a lot of shadows on the ground"
	Color rendering	"The color of the vegetation on the street looks natural"
		"The colors of objects around me looks unusual"
	Amount of light	"This sidewalk appears dark"
		"There is not enough light on this path"
		"There is enough light for me to see my surroundings clearly"
		"There is too much light on the path"
	Color of light	"The lighting on the street is too warm in color"
		"The lighting on the street is too cool in color"
	Quality of light	"The lighting on the street is too bright"
		"the mall lighting hurts my eyes"

Table 8.5: Survey Question Categorization - General Mall Usage

Question Category	Category Indicators	Survey Questions
Mall Usage	Mall Usage	"I am likely to continue shopping after the sun sets"
		"Eating on one of the nearby outdoor patios would be pleasant"
		"I am likely to return to the mall at this time of night in the future"
		"I enjoy walking up and down the mall at night"

factor to one's ability to perform visual tasks. These indicators are divided by task type and are as follows: distance tasks (horizontal illuminance), distance tasks (vertical illuminance), color rendering, and detail tasks. This is by no means an exhaustive list of factors which contribute to visual performance; however these were common themes among much of the research and could easily be distilled into simply worded questions. The two distance vision task indicators are each primarily influenced by the general amount of illuminance in the space, both vertical and horizontal. The questions in these two indicator categories assess one's ability to see well at a distance on both the horizontal and vertical planes. Color rendering is the indicator which correlates to a person's ability to accurately identify colors. The final category is detail tasks which addresses one's ability to perform close-up tasks which require the eye to see fine details.

Visual Comfort The indicators and questions in this category seek to answer the question "To what extent has the new lighting affected how comfortable it is for a person on the mall to perform visual tasks?" Light characteristics which would cause the user to strain, squint, or cause any other sort of visual discomfort would be assessed in this category. As such, there are two category indicators in this category: glare and brightness (luminance) and amount of light. The former category (glare and brightness) includes questions which relate to the perceptual construct of "brightness" which is most often attributed to the luminance in a particular direction. This indicator also includes questions of the amount of glare that is created by the lights and to what extent does this glare cause discomfort. The second indicator is amount of light. The amount of light, particularly if it was not high enough, would cause considerable visual discomfort and fatigue. These questions are relatively straightforward and seek to understand if the amount of light on the mall is too high, too low, or at a comfortable level.

Perception of Safety or Reassurance The third category seeks to answer the question "To what extent has the new lighting affected how safe or reassured people feel while walking on the mall?" This category drew from Romnee's study and the research mentioned in Chapter 2 and resulted in five different indicators. These indicators are facial identification (vertical illuminance), color rendering, amount of light, distance visual tasks (horizontal illuminance), and general reassurance. It should be noted that some of these category indicators and/or questions were used already in prior categories. However, the objective component of several of these indicators often impact more than one area which plays a role in creating a positive lighting atmosphere. For example, the indicator of distance visual tasks (horizontal illuminance) was included in the visual performance category to measure how well the mall user can perform visual tasks which rely on horizontal illuminance on the ground plane. The same indicator with corresponding questions were also in the reassurance category section because of the importance of identifying environmental factors on the horizontal plane and navigating the lit environment on reassurance[43]. The facial identification category indicatory is another example of repeated questions. In this case, the facial identification indicator is almost the same as the vertical illuminance question from the visual performance category except that it has been distilled to only include questions specifically related to facial identification a key component of pedestrian reassurance[22]. So, the facial identification indicator acts as a sort of subset of the vertical illuminance indicator.

Perception of Luminous Atmosphere Recall that this category was one of the categories in the Romnee's study. This category seeks to answer the question "To what extent has the new lighting affected how the pleasant or unpleasant the luminous atmosphere is perceived to be."[1]. Once again, some of the questions in this section can also be found in other categories, however, this category introduces indicators such as color of light (which addresses the correlated color temperature of the source) and uniformity of light (which addresses the distribution of the light and the amount of shadows that are thrown on the ground).

Mall Usage The final category is a small category entitled Mall Usage, which has no indicator, but simply seeks to understand if the usage patterns of the pedestrians on the mall have changed after the installation when compared to the usage before the installation. There are only four questions in this category and they attempt to understand trends in the mall usage independent of the characteristics of the lighting.

8.1.3 Length of Survey

Determining the length of the survey was done concurrently with the creation of the categories and indicators. The goal was to have a survey which was easy to understand and could be filled out in two to three minutes. However, it was also necessary to try and have more than one question per indicator category. Since there was a significant amount of data to collect and only a single "shot" at the surveys, the surveys were created to get as much data as possible in one visit. The survey creation process was very much an exercise in optimization trying to maximize the amount of information gained in order to get a full picture of the changes on the mall while also preventing the survey from becoming too long to be filled out quickly by participants. Some guiding factors in this area was that the survey could be no more than one page (including front and back). Also, since people of all ages and reading abilities would be taking the survey at night with only the help of the streetlights, it was important that the font size be large enough to see. (But not so large as to invalidate one of the questions which would reference their ability to read the text on the paper measuring their visual performance under the lights.) These two factors naturally helped to safeguard against creating a survey that was too long; however, a shorter survey would have been better received by many of the people on the mall.

8.1.4 Incentivization

Another interesting component of the survey creation process was question of incentivization. Namely, if there should be some sort of incentive for filing out the survey and if there is what should it be? The surveyors needed to distinguish themselves from other survey "pushers" on the mall. Some possible forms of incentives that were considered were coffee gift cards or free drink coupons, a chance to win a "grand prize" through a raffle, or some sort of food that could be given away immediately. The last option was selected because it would provide immediate compensation and it was simple to acquire. Candy bars were selected as the incentive because they are something that many people would enjoy, are easy to obtain, and simple to transport.

8.2 Survey Distribution Process

8.2.1 Training of Survey Distributors

Great lengths were taken during the time prior to survey distribution to ensure that bias was minimized as much as possible. The nature of the study was such that two different teams of multiple people needed to be handing out surveys simultaneously. The more people who were present handing out surveys, the more data could be collected. However, this naturally increased the risk of introducing unintentional bias and human error into the experiment process. Specific concern was given to the potential for different survey distributors to unintentionally give too much away about the study as they interacted with the recipients. In order to minimize this effect, the surveyors were given an information packet beforehand which "briefed" them on the project ensuring that all of the surveyors were on the same page before beginning the process. Then, everyone involved was required to attend a brief meeting prior to the distribution to go over the information together, answer questions, and set a series of ground rules which would govern the survey process.

It was also necessary that each surveyor understand the proper etiquette for approaching people on the mall. Pedestrians were to be approached as they passed by with no distinction between age, race, appearance or any other defining characteristic. This would help reduce surveyor bias.

One of the most important parts of training the surveyors was to ensure that each person operated off of a "script" when approaching mall users. This was important for two reasons. First of all, it was critical that no person was given information about the study prior to completing the survey which might cause them bias. For example, if the surveyor approached a mall pedestrian asking them if they wanted to participate in a "before and after" study, it might bias the results of the survey. A psychological phenomenon called the Hawthorne effect (or observer effect) states that if individuals are aware that they are being observed, may change their response or behavior [24]. In other words, someone may answer the questions based on what they think the right answer is as opposed to what they actually believe because they are aware that they are being studied. For example, if someone on the mall was told that the survey was gathering information on the 16th Street Mall lighting post-installation condition, that person might automatically say that the lighting has dramatically improved because they think that that is what the surveyor wants to hear. This is one of the reasons that a single, constant team of respondents was not used both before and after the installation opting instead for a sampling of general mall users. To avoid this effect it was important that the surveyors only reveal certain amounts of information as they approached people on the mall. The goal was to ensure that the people answering the questions did not get any indication of how they were "expected" to answer the questions. The point of the survey was to gain information from people who were unaware of the installation and get their completely unbiased opinion.

8.2.2 Method of Distribution

Distribution took place at the two different locations on the mall (however only the data from the first site was used in the analysis). Six people were split up into two groups of three. The teams stayed near the area where the lighting measurements took place but they were encouraged to spread out as long as they stayed close to that section of the block and on the same side of the street. Surveys were handed out to passing pedestrians and upon completion of the survey the recipient could choose to take a candy bar of their own preference. If any respondents were in groups they were asked to not consult each other as they were filling out the survey. If they had questions about the study itself they were asked to wait until they (and other respondents nearby) had finished filling out the survey before any information about the study could be revealed. The survey process lasted for approximately 1.5 hours. At 10:30 the surveyors wrapped up what they were doing and took horizontal illuminance measurements in their area using the same process as was outlined in the objective section above.

8.3 Survey Distribution Observations and Sources of Error

8.3.1 Mall Demographics and the Effects of Incentivization

There were several things that were observed during the survey distribution process. One of the interesting things worth noting is the demographics of those on the mall were not as expected. Because of the late time of night that the surveys were handed out, the "audience" was primarily young (under the age of 40) with a significant amount of teenagers and adolescents. As was predicted, the age of the respondents increased as it got later. Very few middle-aged or elderly people were on the mall after 9:30, and those that were on the mall were not very willing to stop and talk let alone fill out surveys. The selected method of incentivization further affected these demographics. Free candy bars tend to attract more teenagers and adolescents than expected. Young professionals and older adults tended to not want to eat candy so they were less likely to stop and fill out the survey.

8.3.2 Safety of Surveyors

Another interesting observation was the amount of personal risk that was involved in the surveying process. Although the overall atmosphere on the mall should not be described as particularly hostile, the mood of the mall did become less friendly and more aggressive as the night wore on, particularly if any measurements crept past 11:00. The presence of officers on the mall did help to ease the tension; however there were a few periodic aggressive mall users who engaged in verbal confrontations with the surveying team. It became very important to make sure that all of the surveyors were aware of their surroundings, only surveyed in groups, and that everyone was aware that if they felt uncomfortable at any point they could leave.

8.3.3 Polarizing Opinions

Some of the most valuable observations came from the conversations that we had with the mall users upon completion of the questionnaire. Many people were very interested in the project after finishing their survey and desired to express their opinions after hearing more about the study. A prominent trend that emerged from these conversations is that the old mall lighting was very polarizing. People either greatly approved or greatly disapproved of the lighting. Upon hearing that the lighting would change because of the upcoming installation they were either very excited and encouraged, or they became very dismayed. In general, it seemed like out-of-town visitors were very excited to know that the lighting would change. They claimed that the “orange” color looked eerie and cast shadows. They thought that the new lighting would make the atmosphere more pleasant and inviting. On the other hand, it seemed like people who frequented the mall or “locals” were very upset and disheartened to see the lighting change. One young teenager was filming a home-video on the mall and loved the dramatic effect the lights gave to his films.

It was harder to get a feel for people’s opinions of the post-installation lights because the weather had become much colder. Respondents were less likely to stay and chat with the survey team after finishing the survey and often hurrying away to warm up. However, from the few conversations that were had, it seemed like the lighting was liked by both newcomers and locals and that the polarization had been reduced.

Chapter 9

Qualitative Results and Discussion

This chapter will document the results obtained from the subjective questionnaire process and give a brief discussion concerning the implications of these results.

9.1 General Demographics

However, before the pre and post data was processed, the general demographics that were gathered from the mall were recorded for reference. This simply gives an idea of composition of the people who took the survey. The questionnaire had many questions that all provided a wealth of information about the people on the mall, but below we have only included a very general overview of the gender, age, and frequency of visiting the mall. Only a small sampling of this data is shown in figure 9.1.

The first graph shows the gender demographics of the people who took the survey. The obvious trend is that compared to men, women were significantly less likely to stop and take the survey. This data validates the observations from earlier. Most of the women on the mall, especially women who were alone as opposed to traveling in a group, were very unlikely to stop and take the time to take the survey. This trend was magnified when the weather became colder. The low number of post-installation female surveys prevents us from drawing any statistically significant conclusions about male vs female trends.

Figure 9.2 displays the age distribution of the surveys. In both the pre-installation and post-installation the 20-39 age group made up the majority of the surveys collected.

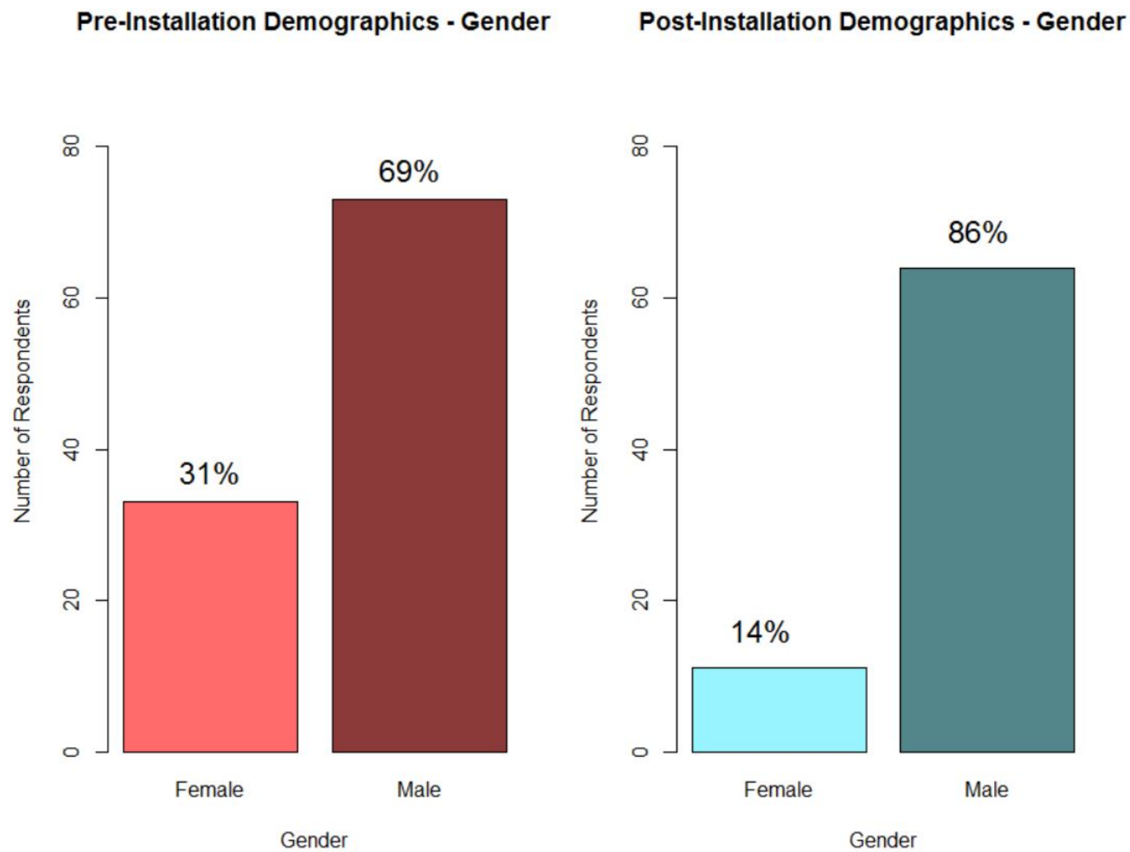


Figure 9.1: Gender Demographics Data

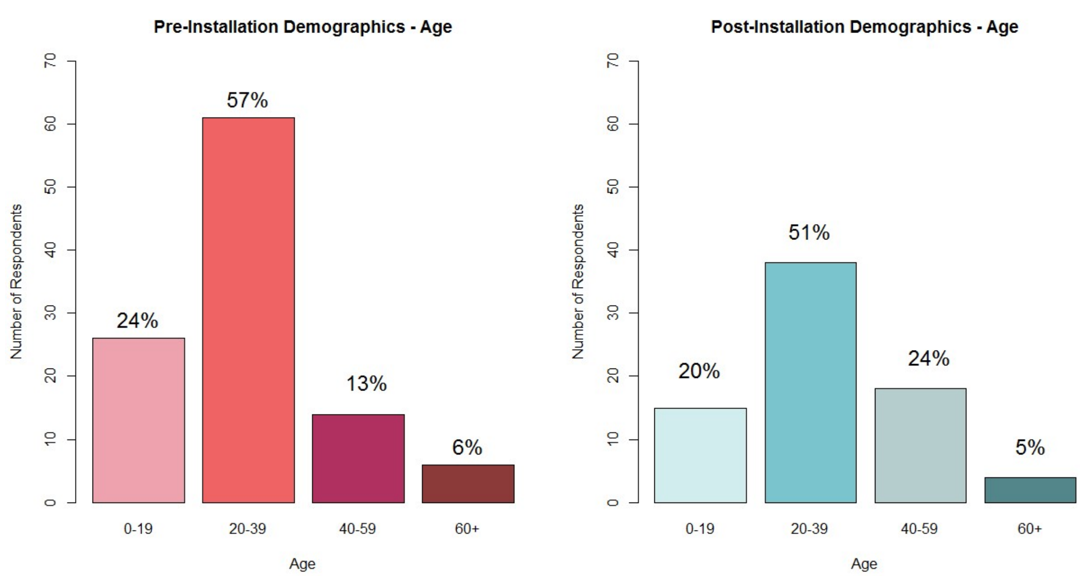


Figure 9.2: Age Demographics Data

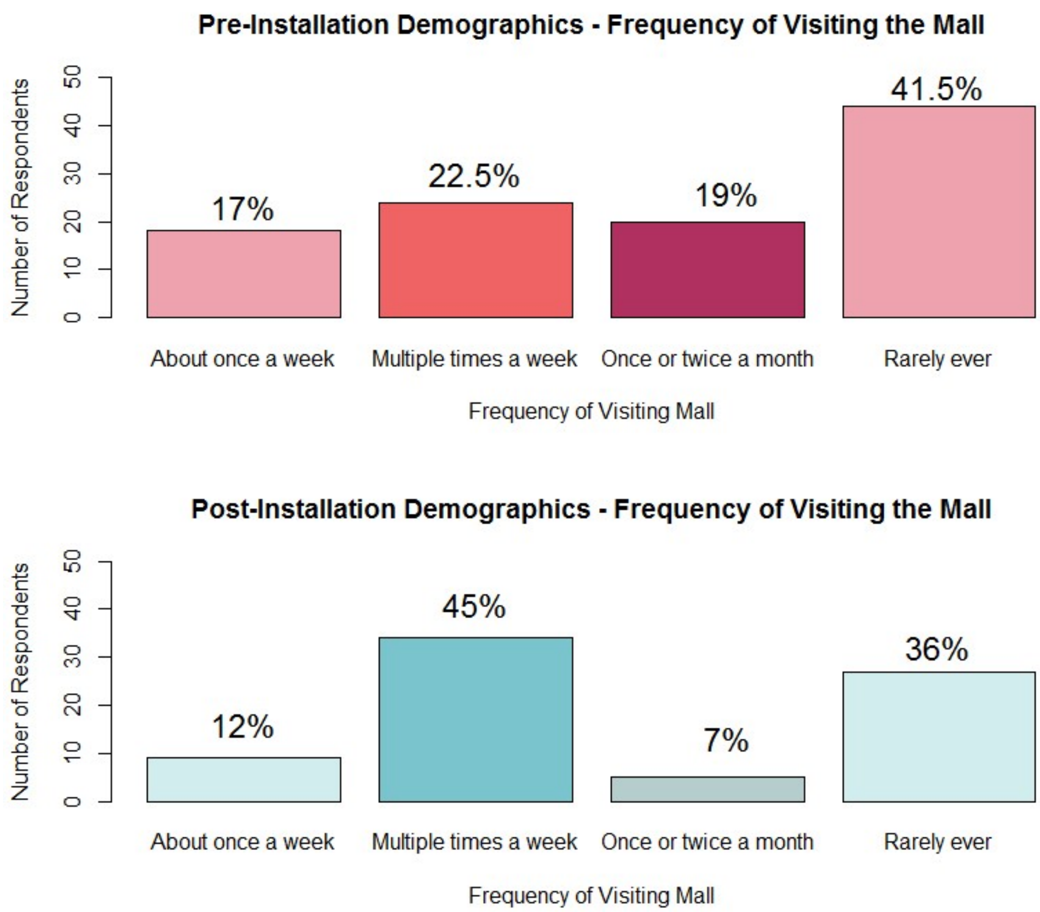


Figure 9.3: Frequency of Visit Demographics Data

Finally, figure 9.3 reveals how frequently the survey respondents visited the mall. This data is reassuring because there is a broad spread of data. It was observed that some of the people who stopped and filled out surveys were out of town visitors these people fell into the “rarely” ever category. It is beneficial to get the opinions of both “everyday” mall users as well as tourists and visitors because any given evening on the mall contains a mix of these two groups so an accurate sampling would allow for both groups to participate.

In this study, the demographic information collected was not used in any further investigation beyond the basic analysis shown above. However, the survey was designed so that a much deeper exploration could be executed. For example, one could take a single category, such as age or gender, and compare how the answers to the Likert questions varied when compared against for that single variable. This would be a deeper and more focused strategy of further study. Some interesting questions that could be answered using the demographic information in this study are:

- Did people who visit the mall often prefer the old lighting over the new lighting?
- Did people who visit the mall often more likely to rate certain questions higher?
- Do women feel more reassured in the new lighting than men?
- Did younger people rate the visual performance questions higher than older people?
- Is there a statistical difference in response between the different age groups?

These are just a few areas of further analysis. This paper does not attempt to answer these questions, but the data that was collected has the capacity to address questions such as these and more.

9.2 Semantic Differential

The first area of comparison between the pre-installation survey results and the post-installation survey results is the semantic differential analysis. This study included two different semantic differential components. The first section asked users to rate their current feelings while on the mall (“At the moment I am feeling”) while the second section asked users to rate the overall mall atmosphere (“The current atmosphere on the mall is”). The average responses to these two sections, both before the installation and after the installation, are demonstrated in Figures 9.4 and 9.5

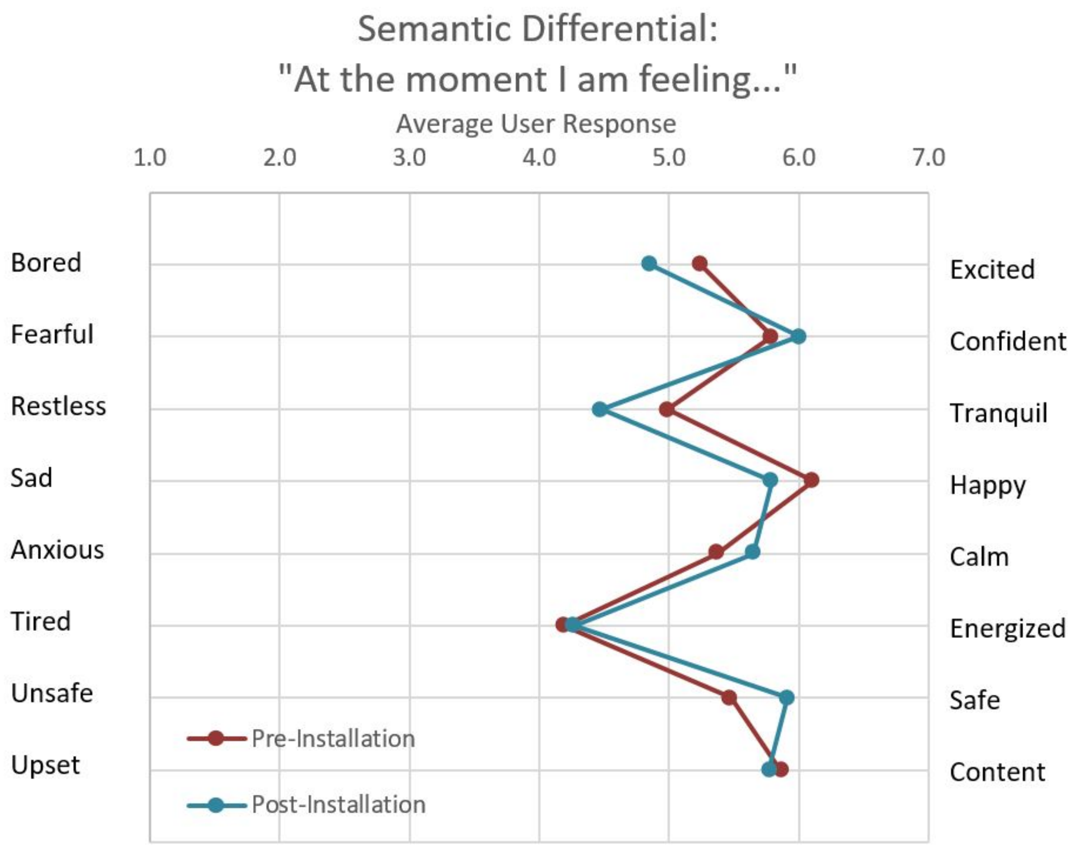


Figure 9.4: Semantic Differential Results - User Mood

The analysis for the first question (Figure 9.4) shows mixed results. Even though the majority of the changed responses proved to be positive (towards the more positive adjective), the largest change was negative 0.51 away from "Tranquil" towards "Restless." This question is the more "vague" of the two questions and so many other factors could have contributed any observed change in mall user "mood," and none of the changes were very large, thus it would appear that these recorded changes cannot, with any degree of certainty, be attributed to the change in lighting.

The second semantic differential chart, Figure 9.5, shows seemingly less significant results. It is apparent that very little change in the perceived atmosphere was recorded in this section, with the largest difference in average response being a very slight change of 0.23 in the "Unpleasant" direction.

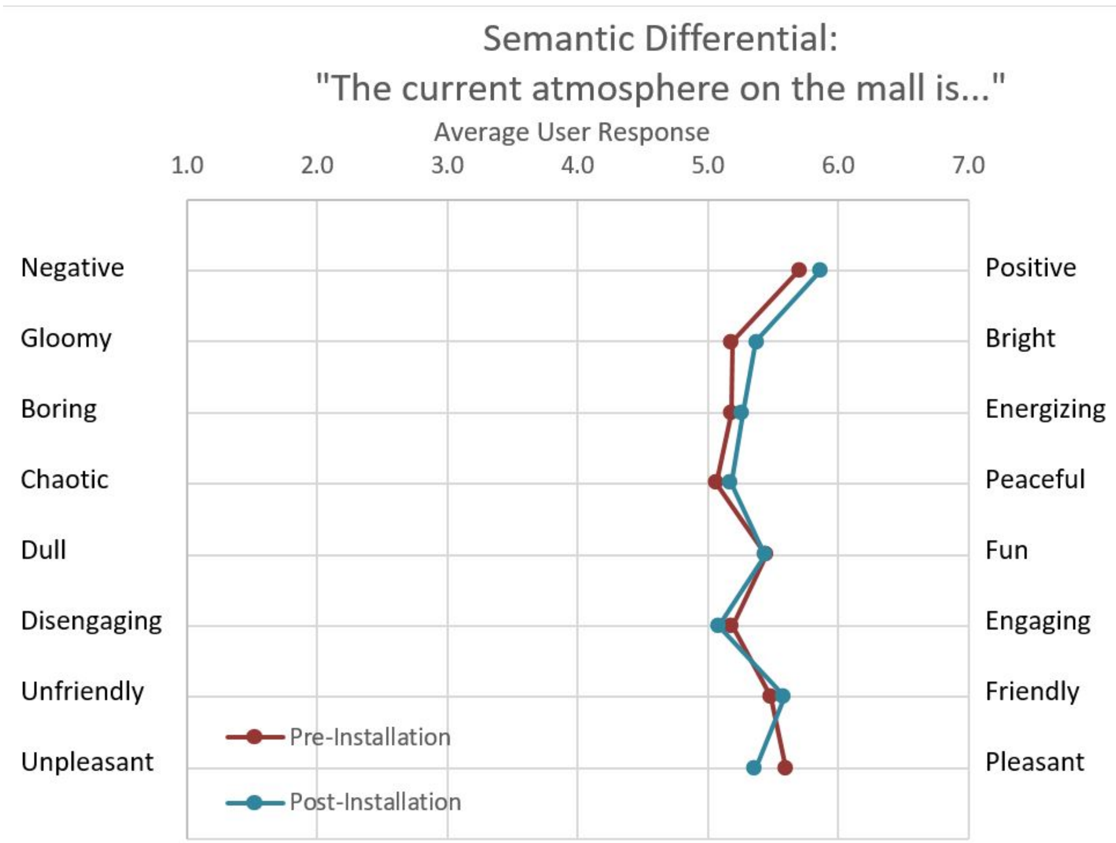


Figure 9.5: Semantic Differential Results - Mall Atmosphere

9.2.1 Semantic Differential Significance

To confirm that the semantic differential results were not significant, the semantic differential items were grouped together (much like how the questions were grouped into indicators and categories). After organizing the traits in this manner, a statistical t-test was run on each category as well as on the total combined groups. A t-test is a statistical analysis of two population means which can be used to reveal whether the change in average response is statistically significant or not and to what degree of confidence that can be claimed. A Welch's t-test will be used because the two sets of data are independent, have unequal sample sizes and variances. For this analysis, a standard alpha value of 0.05 will be used. The alpha value, or significance level, is the probability of rejecting the null hypothesis. A small alpha value indicates a more stringent test. For this analysis, the following hypothesis was established:

Null Hypothesis: $\sigma_{new} = \sigma_{old}$

Alternate Hypothesis: $\sigma_{new} \neq \sigma_{old}$

The results of this analysis can be seen in Table 9.1.

This results found in Table 9.1 reveals that, as expected, almost none of the categories which describe the mall users and the mall atmosphere demonstrated a significant pre to post change in average response. The only exception is the "Safe" category which consists of the two semantic differential pairs "Fearful Confident" and "Unsafe Safe." This analysis shows that the mall users felt safer under the post-installation lighting conditions than under the pre-installation lighting. However, considering the somewhat ambiguous nature of this type of analysis and the many other contributing variables that may have come into play, the results from this analysis should be compared with the results from the Likert Analysis before any final conclusions can be drawn.

9.3 Likert Analysis

The second part of the subjective analysis was the Likert analysis. As mentioned earlier, the questions which made up the Likert analysis were grouped into various category indicators

Table 9.1: Semantic Differential Significance Test Results

Semantic Differential Category	Semantic Differential	Pre Mean Response	Post Mean Response	P-Value
"Right now I am feeling"				
Excited	Bored Excited	4.638	4.528	0.5864
	Tired - Energizing			
Peaceful	Restless Tranquil	5.084	5.021	0.7456
	Anxious - Calm			
Happy	Sad Happy	5.808	5.683	0.5133
	Upset Content			
Safe	Fearful Confident	5.479	5.915	0.0117
	Unsafe - Safe			
Total		52.38	5.295	0.6582
"The mall atmosphere is"				
Stimulating	Gloomy Bright	5.115	5.234	0.476
	Boring Energizing			
	Dull Fun			
	Disengaging - Engaging			
Enjoyable	Negative Positive	5.333	5.444	0.5089
	Chaotic - Peaceful			
	Unfriendly Friendly			
	Unpleasant - Pleasant			
Total		5.249	5.342	0.5331

which each correlated to a different measureable lighting concept. Before we could begin any of the analysis moving forward, it was necessary to “invert” the negative questions responses so that the “strongly agree” value of 7 was always indicative of a positive aspect of the lighting. The assumption is that a selected rating of 6 on the question “There is not enough light on the path” would be equivalent to a score of 2 for the inverted question of “There is enough light on the path.” With all of the questions now “oriented” the correct way and sorted into their respective category indicator groups, an average “score” could be compiled for each individual survey response for each indicator. This indicator score would simply be the average response across each question in the specified indicator category. This would give us 107 average pre-installation and 75 post-installation scores for each category indicator. The value response of each question in each category was also averaged to get a final category score for each survey. These new sets of data could then be used to understand the changes between the pre and post data.

9.3.1 Cronbach’s Reliability Alpha

Before any of the responses could be analyzed, the data had to be organized in a way that was meaningful. Recall that the data was organized so that each respondent got an average response “score” for each category indicator resulting in an array of average indicator and category scores for both the pre and post installation which could then be compared against each other. The following plots, shown in (figure 9.6), show the pre and post installation average “scores” for the indicators within the Visual Performance category.

This box-plot analysis is important because it reveals how the pre and post installation data distributions compare against each other. In general, the average post-installation responses were slightly higher (more positive) than the pre-installation responses suggesting that on average the mall users indicated that the new lighting resulted in a more positive visual performance experience. In some cases, the data is more skewed in the positive direction, with the mean and median being higher and the standard deviation being small indicating a tighter distribution with less variability. The obvious exception to these trends is the fourth indicator category - detail tasks. In this category

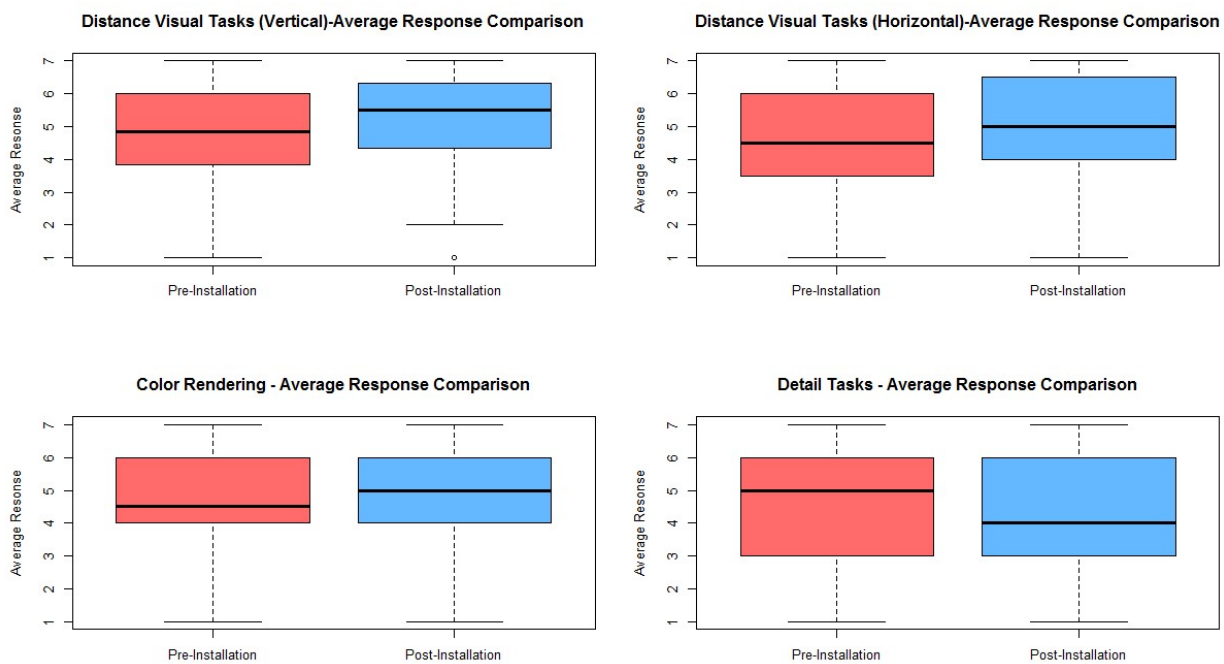


Figure 9.6: Visual Performance Pre and Post Installation Average Response Boxplot Analysis

Table 9.2: Visual Performance Pre and Post Installation Statistical Data

	Mean Response		Median Response		Standard Deviation	
	Pre-Installation	Post-Installation	Pre-Installation	Post-Installation	Pre-Installation	Post-Installation
Distance Tasks Vertical	4.786	5.198	4.835	5.5	1.616	1.446
Distance Tasks Horizontal	4.447	4.932	4.5	5	1.665	1.558
Color Rendering	4.6875	4.973	4.5	5	1.47	1.295
Detail Tasks	4.485	4.357	5	4	2.033	1.919

the post-installation responses have a lower average value and a lower median. The behavior of this questions implies that it may not have been a good indicator for the overall category . This indicator, which only consists of a single question, “The print on this survey is difficult to read,” warrants further analysis along with the other indicators and categories.

The fact that this question shows such a distinctly different pattern from the other questions may suggest that the questions which form this indicator and by extension the category may not be internally consistent. In other words, people that answered high for certain questions may have answered low to other questions which were similar resulting in a contradictory overall trend. An analysis of the internal reliability of the established categorical system is necessary before any further analysis can be accomplished. This was accomplished through a Cronbach alpha test, which is simply a process which estimates the reliability of a scaled psychometric test such as the one in this study. The code and steps for this evaluation can be found in the appendix. Figure 9.7 demonstrates the internal consistency of the Visual Performance category.

Figure 9.8 presents the alpha values which were calculated for the visual performance category. The alpha value for the entire category for the pre-installation survey results (marked in the above graph as the dark red horizontal line) is 0.75. This is a very high alpha value which indicates that, overall, the questions which were included in this group were well correlated to one another. As a general rule of thumb, alpha values that are above 0.7 are considered to represent good reliability [18]. The post-installation alpha (marked as the dark blue horizontal line) is also high at 0.72 - further demonstrating that the questions in this category are well correlated. However, because it was shown earlier that the detail category was acting in opposite ways from the other indicators (Figure 9.6), it is not enough to just look at the category alpha value alone. Along with the overall category alpha value, each question can be individually examined to see how they interact with the group as a whole. Figure 9.8 demonstrates this analysis. Each vertical bar represents how the overall alpha for the category would change if each question were dropped from the group. For example, the pre-installation visual performance category alpha is 0.75, but if the first question “I can easily read street signs from this location” was to be dropped, the overall alpha would decrease

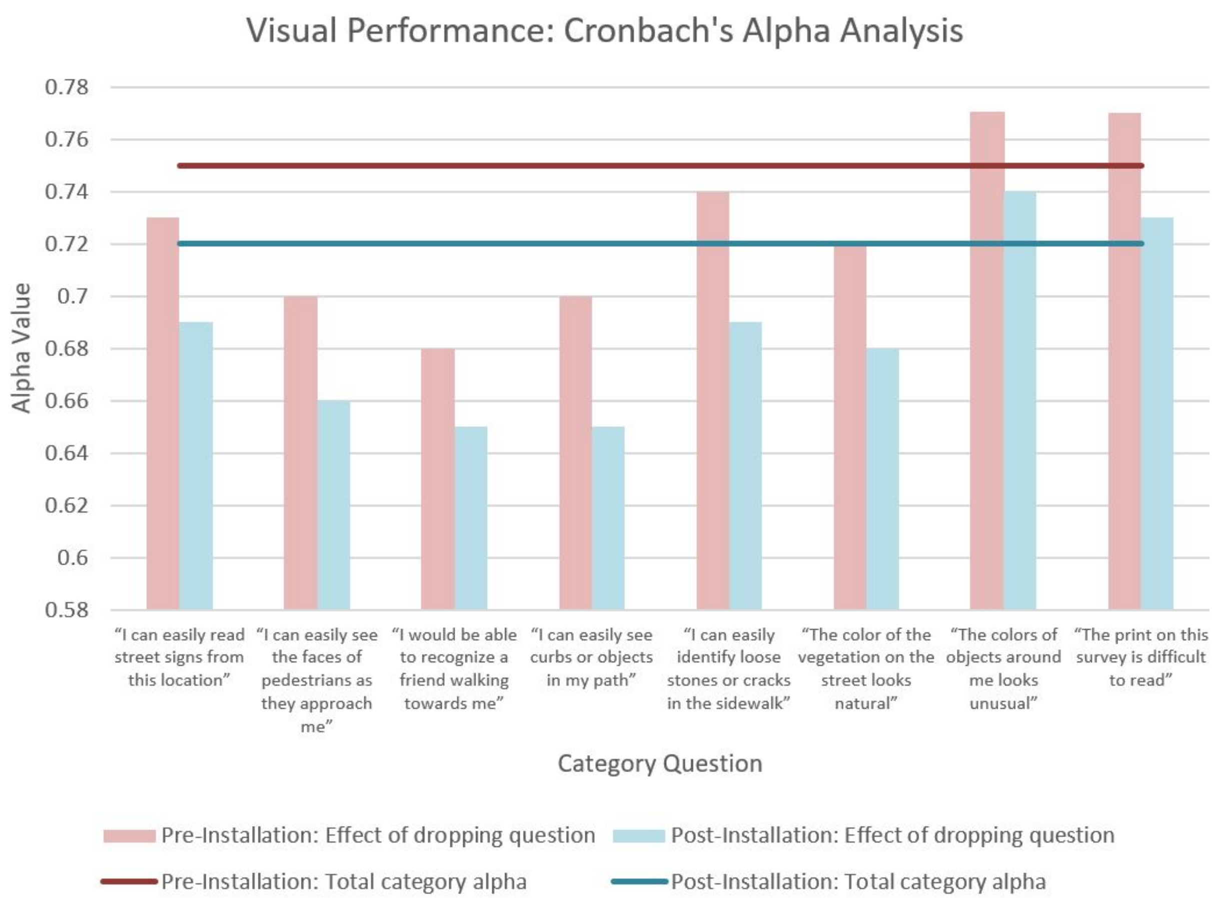


Figure 9.7: Visual Performance: Cronbach's Alpha Analysis

to 0.73 (the top of the bar). Since a larger alpha value indicates a better correlation, we would not want to remove this question. On the other hand, removing the final question "The print on this survey is too difficult to read," which is the question that correlates to the detail category indicator, the alpha value would increase to 0.77. Removing this question would have a similar positive effect on the post-installation data as seen on the pre-installation data. So, it can be concluded that in both cases, this question acts contrarily from the other indicators just as seen in the boxplots from earlier. In other words, people who answered positively to the other questions in this category answered negatively to this question. This final question, which correlates to the negative trend observed in the final boxplot in Figure 9.6, was removed from further analysis. The second to last question, "The colors of objects around me looks unusual" was not removed because the other questions in that category indicator did not display sufficient evidence that it impacted the overall category in such a strong way.

All of the other categories underwent a similar alpha analysis. Figures 9.8, 9.9, 9.10, 9.11 were then created.

One of the first, and most important, takeaways from these graphs is that the alpha value for each category, both before and after the installation, is over 0.7. This is a highly desirable outcome because it implies that all of the categories are composed of questions which are internally consistent with each other, despite occasional outliers. Another item worth noting is that even though there are questions which, if removed, would result in higher overall categorical alpha values; there are no questions (beyond those found in the Visual Performance category) that display this quality for both pre-installation and post-installation. In order to justify removing a question based on the alpha value, it would have to impact both the pre and post installation alphas in the same way. This, combined with the fact that all of the other category alphas were over a value of 0.7, indicates that none of the other questions should be removed from the analysis. The rest of the analysis can continue with confidence that the question composition of each category is reliable.

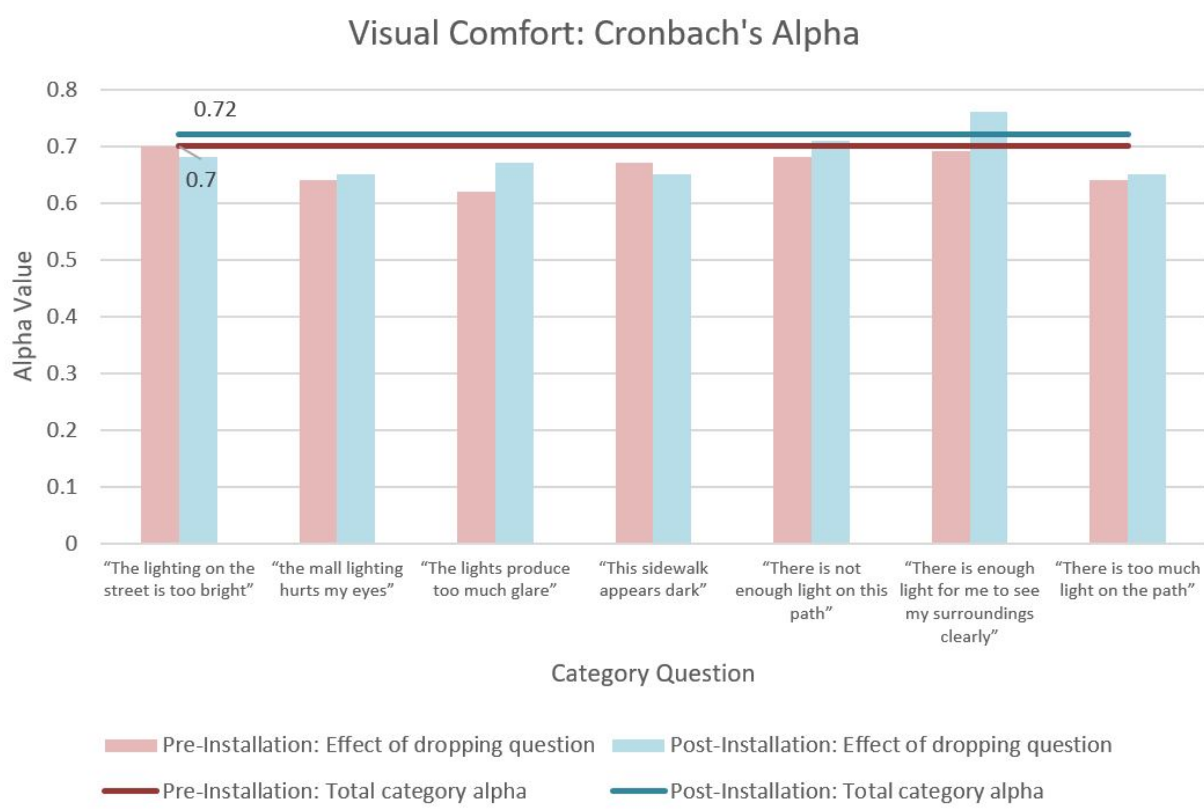


Figure 9.8: Visual Comfort: Cronbach's Alpha Analysis

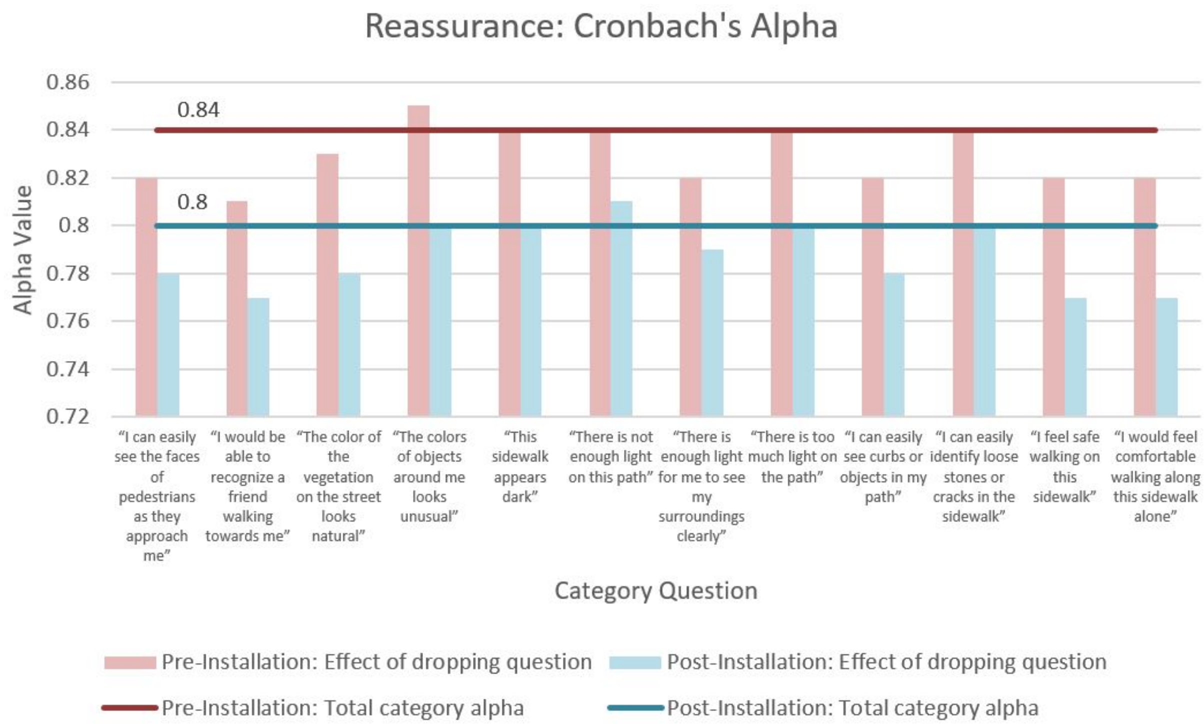


Figure 9.9: Reassurance: Cronbach's Alpha Analysis

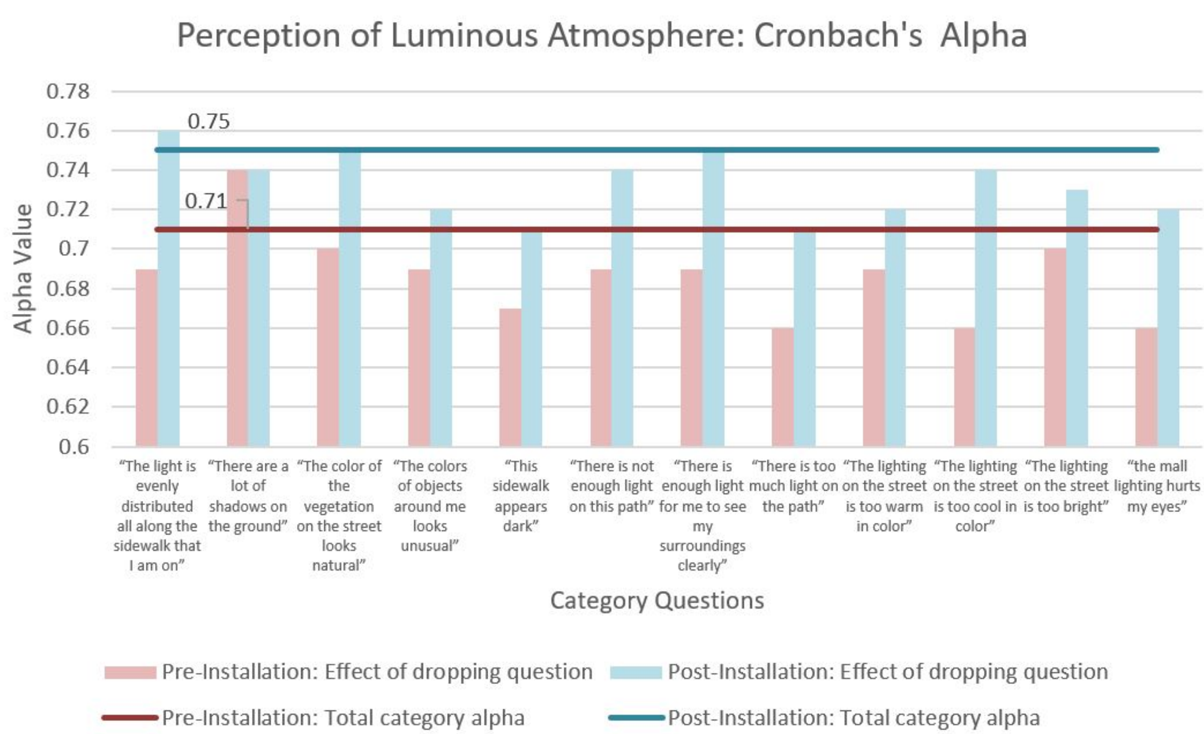


Figure 9.10: Perception of Luminous Atmosphere: Cronbach's Alpha Analysis

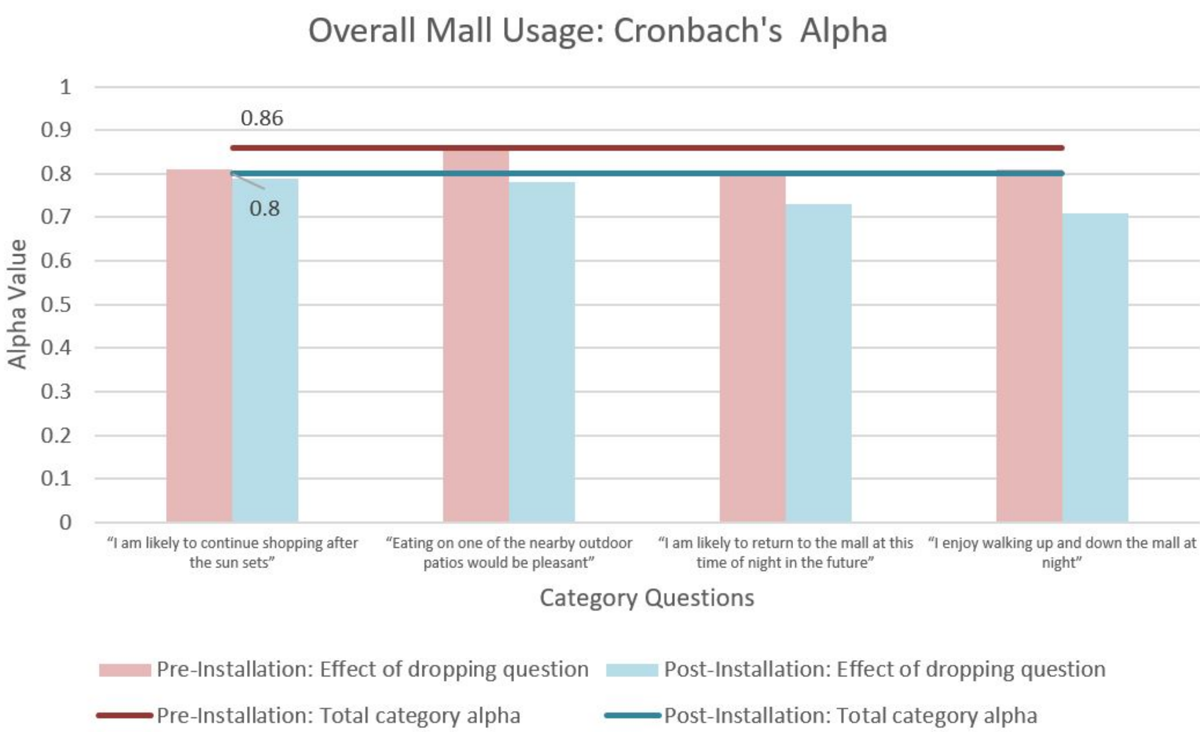


Figure 9.11: Overall Mall Usage: Cronbach's Alpha Analysis

9.3.2 Data Plotting

The following plots (figure 9.12) show the difference in the average response for each of the five categories. These histograms show the density of each average response with the pre-installation data plotted in red and the post-installation data plotted in blue. Note that for the remainder of this analysis the visual performance category no longer contains the detail task category indicator.

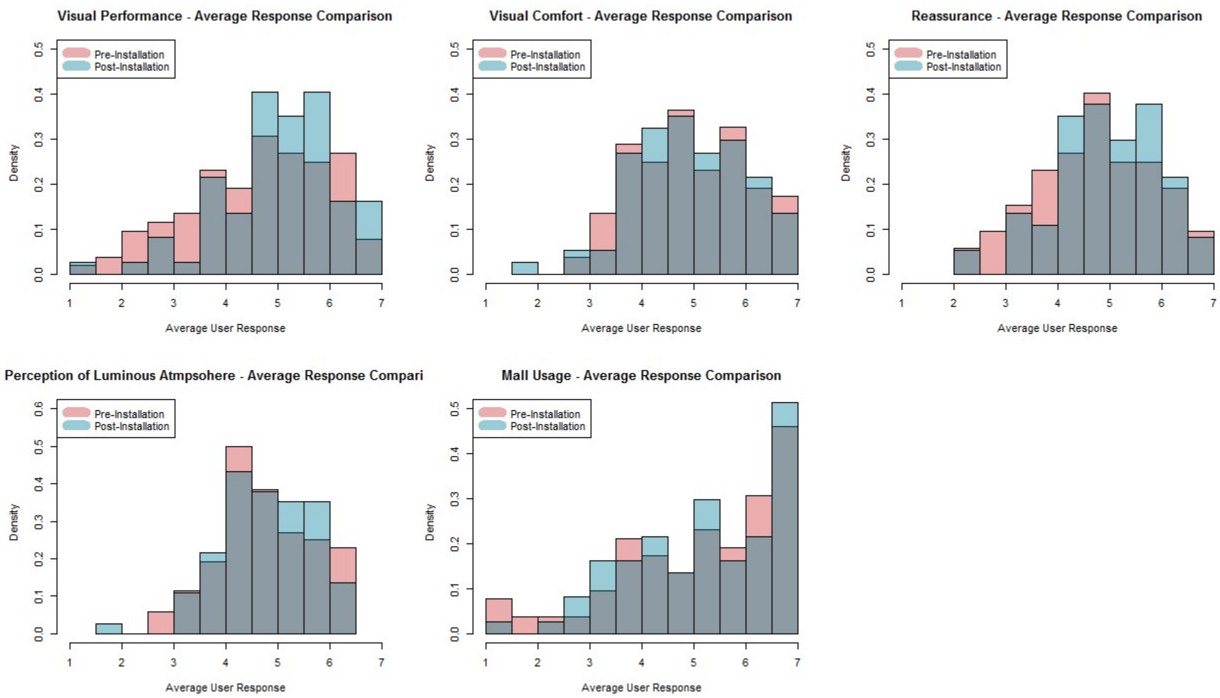


Figure 9.12: Average Category Response Histograms

Table 9.3: Visual Performance Category Indicator Statistical Results

	Pre-Installation Mean Response	Post-Installation Mean Response	Pre-Installation Std. Deviation	Post-Installation Std. Deviation
Visual Performance	4.66	5.07	1.298	1.133
Visual Comfort	4.98	4.97	1.072	1.071
Reassurance	4.765	5.01	1.143	1.011
Perception of Luminous Atmosphere	4.79	4.83	0.899	0.914
Overall Mall Usage	5.23	5.31	1.585	1.413

Most of these plots appear to be relatively normal distributions which are skewed towards the right. The skewed characteristic demonstrates that the users of the mall tended to answer questions more positively than negatively, indicating that neither the old lights nor the new lights were considered by the mall users as particularly negative. The means of each distribution, shown in table 9.3 shows that in every case the average user response increased with the exception of the Visual Comfort which essentially remained constant. The standard deviation for each case was reduced except for Perception of Luminous Atmosphere. These results indicate a positive post-installation trend; however, it appears that none of the categories (except perhaps visual performance) underwent any particularly large changes. It would appear that further analysis is necessary in order to draw significance from this analysis.

9.3.3 Statistical Significance

A statistical t-test on each set of categorical data can be used to compare the before and after changes in average user response. Just as with the earlier significance test, an alpha value of 0.05 will be used.

For the following t-test the following hypothesis was established:

Null Hypothesis: $\sigma_{new} = \sigma_{old}$

Alternate Hypothesis: $\sigma_{new} \neq \sigma_{old}$

Table 9.4 reports the relevant values computed from the t-test. A P-Value less than our alpha (0.05) indicates that the null hypothesis should be rejected indicating a statistically significant change in mean response. The 95% confidence interval states that there is a 95% probability the difference in mean responses can be found within these bounds.

The results seen in Table 9.4 indicate that the only category which contained a change in average responses that can be considered statistically significant is Visual Performance. (Reassurance, having a P-value of 0.1354 is next most significant category). The mean response in the visual performance category changed by 0.41 which is a substantial change when considering the responses were on a 7 point scale. From this analysis alone, it would appear that the new lighting only

Table 9.4: Subjective Category T-Test Results

	Pre-Installation Mean Response	Post-Installation Mean Response	Confidence Interval	P-Value
Visual Performance	4.66	5.07	[-1.76176, -0.0382]	0.03045
Visual Comfort	4.98	4.97	[-0.3124,0.3314]	0.9537
Reassurance	4.765	5.01	[-0.5644, 0.077]	0.1354
Perception of Luminous Atmosphere	4.79	4.83	[-0.3166, 0.2289]	0.7511
Overall Mall Usage	5.23	5.31	[-0.3166, 0.2289]	0.7

impacted this category in any sort of meaningful way.

9.3.3.1 Indicator Analysis

A more comprehensive analysis was done to gain an understanding of what indicators were contributing to each category's significance (or lack thereof). Figure 9.13 display the comparison of the average responses which make up each indicator in the Visual Performance category; Vertical Distance Tasks, Horizontal Distance Tasks, and Color Rendering. These three plots are shown below with the total Visual Performance category at the end.

Just as the pre and post installation categories underwent a statistical t-test, each category indicator underwent the same test. This analysis demonstrates which mean response for each category indicator underwent a statistically significant change. The same alpha value and hypothesis was used in these analyses as in the above analysis. Table 9.5 provides the results of this analysis

Table 9.5: Visual Performance T-Test Results

	Pre-Installation Mean Response	Post-Installation Mean Response	Confidence Interval	P-Value
Color Rendering	4.688	4.73	[-0.6969, 0.126]	0.1726
Distance Tasks: Horizontal	4.447	4.9923	[-0.966,-0.004]	0.0482
Distance Tasks: Vertical	4.479	4.932	[-0.966, 0.004]	0.07565

The results seen in Table 9.5 shows that both of the distance task categories underwent

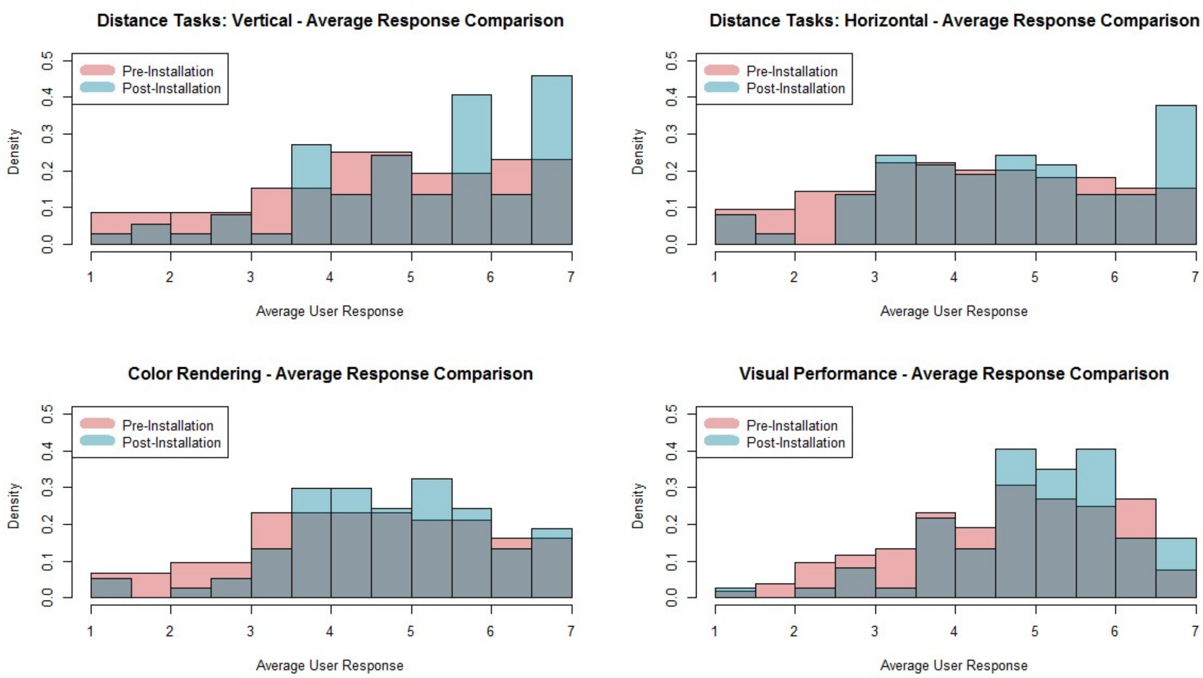


Figure 9.13: Visual Performance Category Indicator Histograms

a statistically significant increase in means (the vertical tasks can only be considered marginally significant because it is slightly over the 0.05 threshold). The color rendering category did not undergo a significant change.

However, some of the other categories are not as cut and dry as the visual performance category. The below plots and t-test reveals the pre and post mean comparison for the Visual Comfort category.

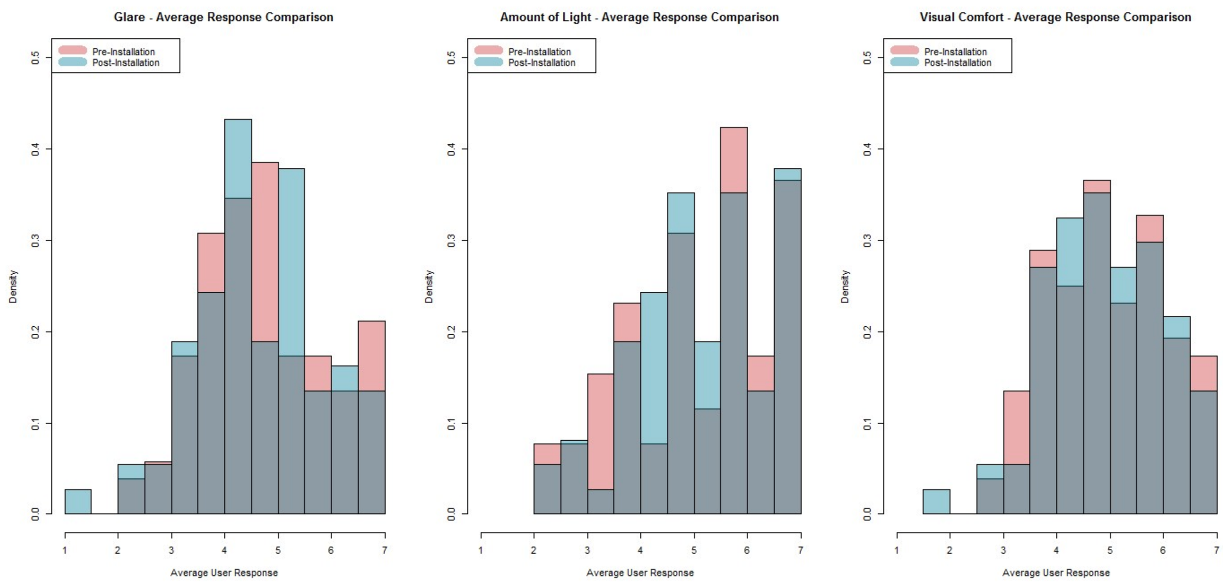


Figure 9.14: Visual Comfort Category Indicator Histograms

Table 9.6: Visual Comfort T-Test Results

	Pre-Installation Mean Response	Post-Installation Mean Response	Confidence Interval	P-Value
Glare	4.847	4.775	[-0.3124, 0.3314]	0.9534
Amount of Light	5.157	5.223	[-0.452,-0.3206]	0.7367

None of these category indicators underwent a statistically significant change in means.

The comparison plot for the Reassurance category is displayed in Figure 9.15. Recall that this category underwent a borderline significant change in mean responses (9.4). A closer look at the indicator categories gives more insight into this scenario.

Even though the change observed in total Overall Reassurance category could not be considered

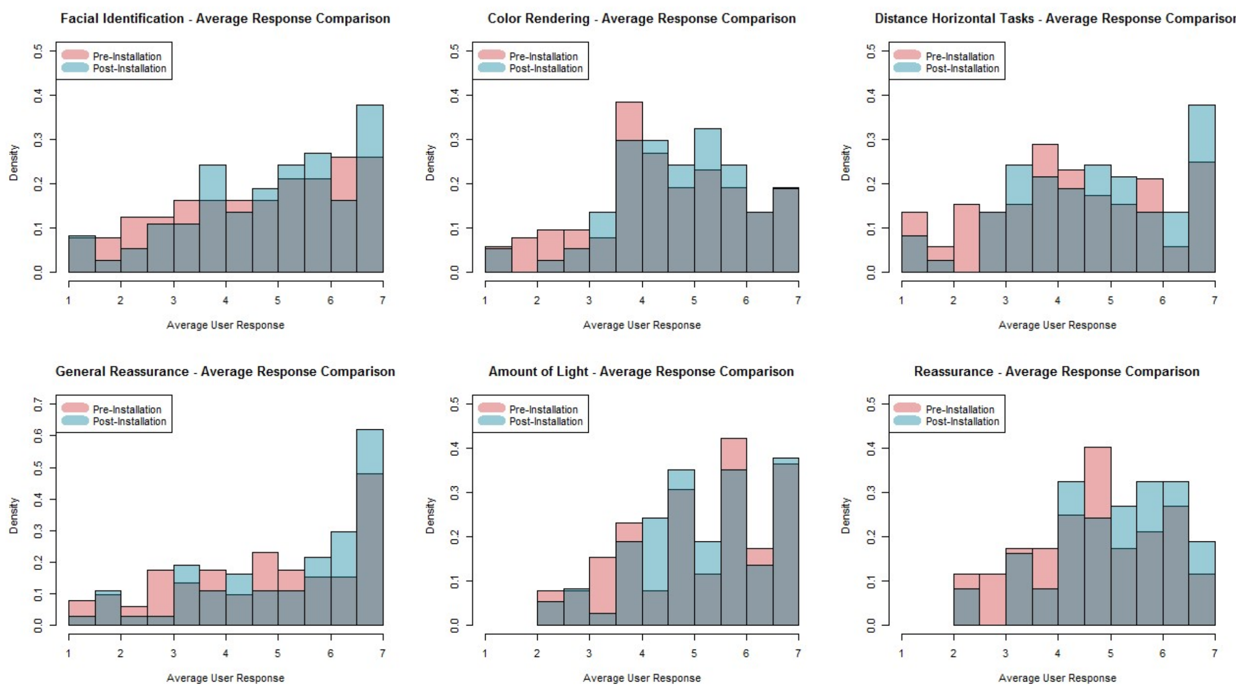


Figure 9.15: Reassurance Category Indicator Histograms

Table 9.7: Reassurance T-Test Results

	Pre-Installation Mean Response	Post-Installation Mean Response	Confidence Interval	P-Value
Facial Identification	4.788	5.088	[-0.7858, 0.187]	0.226
Color Rendering	4.6875	4.973	[-0.6969, 0.126]	0.1726
Distance Tasks: Horizontal	4.447	4.9923	[-0.966,-0.004]	0.0482
Amount of Light	5.157	5.223	[-0.452,-0.3206]	0.7367
General Reassurance	4.9663	5.4662	[-1.0036, 0.00387]	0.05176

statistically significant, several of the category indicators in this category did experience significant changes in means. Distance Horizontal Tasks and General Reassurance both underwent significant changes.

Again, Perception of Luminous Atmosphere underwent the same analysis, as reported in Figure 9.16 and Table 9.8.

Table 9.8: Perception of Luminous Atmosphere T-Test Results

	Pre-Installation Mean Response	Post-Installation Mean Response	Confidence Interval	P-Value
Uniformity	4.155	4.453	[-0.737, 0.063]	0.7511
Color Rendering	4.6875	4.973	[-0.6969, 0.126]	0.1726
Amount of Light	5.157	5.223	[-0.452,-0.3206]	0.7367
Color of Light	4.9757	4.6486	[-0.1188, 0.773]	0.1493
Quality of Light	5.236	5.338	[-0.53, 0.3255]	0.6375

Here, Table 9.8 none of the category indicators can claim to have experienced a statically significant change in mean responses. Uniformity, however, could be considered moderately significant since it did fall below 0.1.

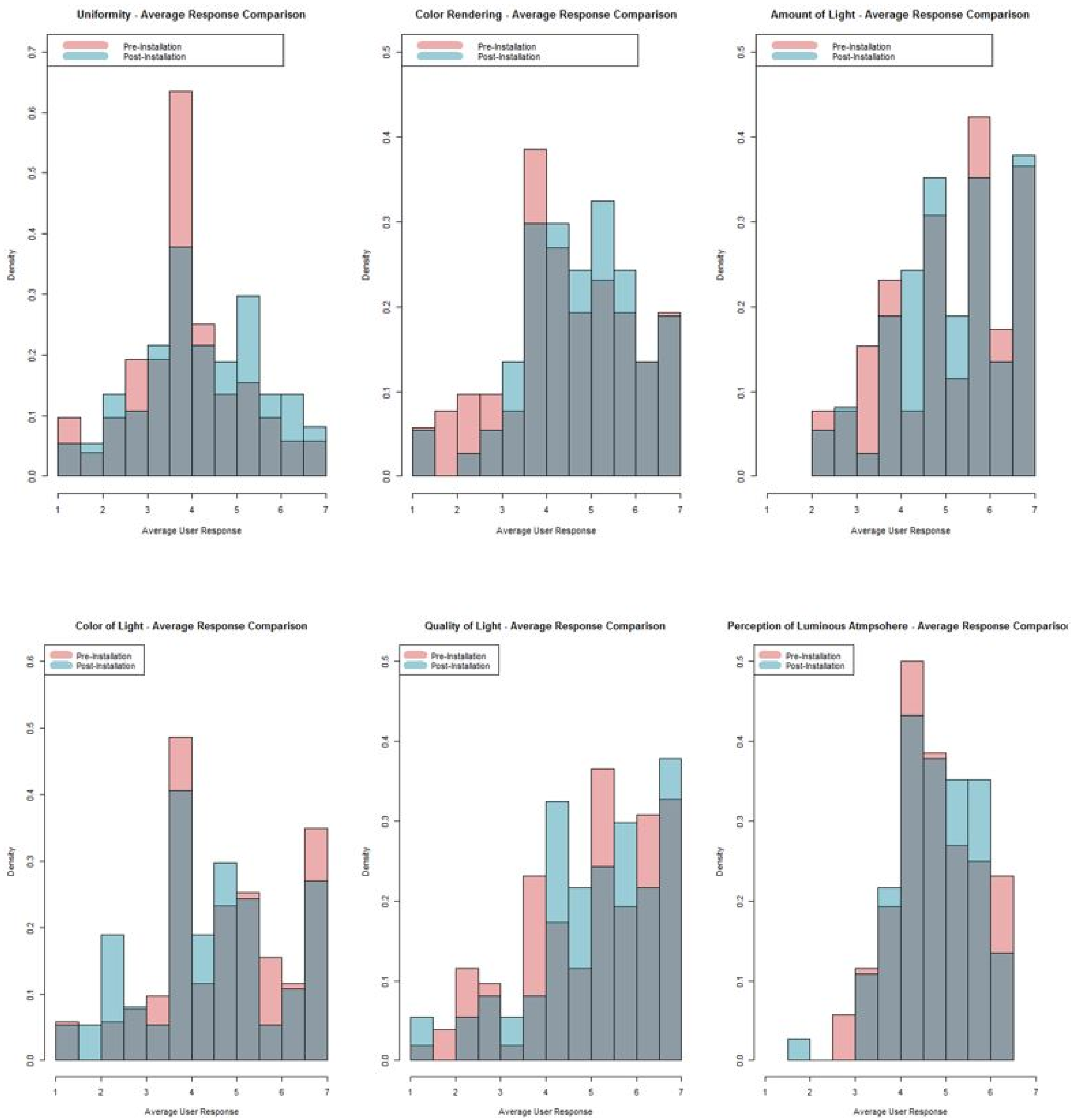


Figure 9.16: Perception of Luminous Atmosphere Category Indicator Histograms

Chapter 10

Subjective Measurements Summary

This chapter will provide a brief summary of the results and conclusions drawn from the data recorded in Chapter 8 and the discussion of Chapter 9.

10.1 General Demographics

As mentioned earlier, the general demographics serve primarily to validate the observations that were taken during the survey distribution. It also provides a wealth of information for further, more specialized analysis.

10.2 Semantic Differential

Overall, the only really valuable thing that the semantic differential results reveal is that the overall atmosphere of the mall and the overall "mood" of the pedestrians on the mall were both skewed towards the positive side of the differential. This reveals very little about the lighting installation; however, the City of Denver can take heart in that the people using the mall are, on average, more happy and satisfied than not, and that the atmosphere is perceived to be more positive than negative. This type of analysis would likely be more useful with a more controlled experiment. For example, if the same group of people were taken to two different sites and then asked to fill out the semantic differential questions in each controlled setting, the semantic differential may have produced stronger results. Another way this analysis might have been more successful is if the questions were more specifically tailored to the lighting installation. For example, the question:

“At the moment I am feeling” could have been changed to: “The lighting on the mall makes me feel”. This strategy was not adopted for this particular study because the questions were kept intentionally broad so as to not bias any of the individuals taking the survey and for the possible goal of relating the broad semantic differential questions back to the more specific Likert questions. However, further research which hopes to get more out of a semantic differential component should include much more precise questions and may get more significant results from them.

10.3 Likert Analysis

10.3.1 Cronbach’s Alpha

The first component of the Likert analysis, the Cronbach’s alpha value investigation, reveals quite a bit about the data gathered in this study. Primarily, it reveals that the survey questions and categories are well correlated increasing the reliability of the study as a whole.

The most important result of this analysis was information revealed about the “detail tasks” category indication with the question: “I can easily read the words on this survey” This category indicator was removed from the analysis because there was strong evidence that this question could have been misinterpreted and was not a good indicator for the overall category.

The actions of this question could indicate that people genuinely couldn’t see detail as well under the post installation conditions as compared to the pre (which doesn’t seem very likely when compared to the average responses to other questions in this category). A more likely explanation is that this question is either not a good representation of the overall category (i.e. reading the print on the survey is not a good indicator of visual performance) or that the question was simply misunderstood by many people. Since this was one of the questions that was specifically worded in an inverted way so that 7 indicated a highly undesirable response as opposed to 7 being a desirably outcome, it is very possible that this question was simply not understood well by those taking the test. For this reason, it this question out of the visual performance category analysis.

10.3.2 Statistical Significance

Up front, the t-test results revealed that there were very few areas that experienced any sort of statistically significant change in average response between the pre and post installation conditions. The only category that experienced significant change was the Visual Performance category. After breaking up the data, the only category indicators that experienced any significant (or moderately significant) change were the two visual task categories, general reassurance (the category indicator, which is different than the overall Reassurance Category), and uniformity. This may come across as a bit of a surprise considering the dramatic nature of some of the lighting changes on the mall, revealed in the objective analysis. However, certain categories, specifically those relating to the color properties of the lights, do not warrant themselves well to this sort of an analysis. It is difficult to measure the perceptual change in color characteristics without some sort of a reference. Mall users may need something to compare the current color qualities to in order to make an accurate assessment of the color quality of the lights and how well the lights render colors around them. Thus, it would make sense that these may not exhibit large changes in responses relative to other categories that are more easily observed. Because these questions were a large component of several of the categories, this could be part of why the change in responses for the categories were so low.

Another thing to note is the “amount of light” category indicator. This was the largest category indicator because the amount of light on the mall is perceptually easy to observe and measure and it is arguably one of the most important lighting component having a significant impact on the ability to perform visual tasks. The results of the subjective study demonstrate that there was no statistically significant change in how much light was perceived to be on the mall. However, the objective measurements showed that the amount of light on the mall actually decreased. So, the fact that there was no perceivable change is actually a very good thing. It implies that even though the actual amount of light on the mall decreased; this decrease was not perceptible by the mall users.

This category indicator is the only indicator where no change in average response can be considered a positive result. Since all of the other indicators operate under the assumption that a negligible change in the mean can be considered neither good nor bad, this indicator category can provide misleading results. An interesting experiment would be to understand how removing this category indicator from each category would impact the final significance of each category. A brief analysis on only the Reassurance category shows that removing this category indicator results in a categorical P-value reduction from 0.1358 to 0.03815. This is a dramatic shift which classifies the change in mean response for the Reassurance category from insignificant to significant. Even though this analysis was only examined for the Reassurance category, it can be assumed that removing the Amount of Light indicator would have the same effect on other categories.

The removal of this indicator is only an exploratory analysis, however. It is not good practice to change the definition of each category to achieve a certain result. This investigation primarily demonstrates the importance of establishing the initial categories and indicators with care prior to the beginning of the study. Even though the amount of light category indicator acted in a different way than the other indicators, it still plays a large role in providing a "full picture" of several of the categories, thus removing it from these groups cannot be justified. For example, the amount of light is very important to understanding the visual comfort of the lighting and without this indicator, the only component of the visual comfort category would be the questions pertaining to glare. This would not be enough to fully understand how the change in lighting affected the average pedestrians' visual comfort. Ultimately, the way that the questions and indicators are created and grouped has a large effect on the "success" and "failure" of the final installation. This study seeks to group them in a logical way based on factors that have been identified in prior research, though, that is not to say that future studies may not benefit from a different category "structure." Further research may want to explore the effect of reorganizing these variables to ensure that the final outcome best represents the focus on the study. Likewise, for a study similar to this one that seeks to gather data from two, independent groups of people (pre-installation mall users and post-installation mall users), colorimetric questions and other similar inquiries that require references to be best understood should be separately categorized or omitted altogether.

Overall, it can be concluded that the subjective analysis produced mixed results. Questions pertaining to specific tasks, specifically concerning to the amount of horizontal and vertical illuminance in the area, showed statistically significant improved user responses. This is made even more impressive considering that the overall amount of light on the mall decreased. This implies that despite the fact that the overall light levels were lower, it was easier for mall users to complete visual tasks such as recognizing faces, reading signs, and locating obstacles. The statistically significant increase in overall reassurance demonstrates that even though the category of reassurance did not show statistical significance (largely due to the impact of the amount of light indicator), people on the mall perceived themselves to be safer when asked outright. Finally, the increased in average responses towards the perceived uniformity indicator is affirmation that the improved uniformity on the mall is significant even though the overall perception of luminous atmosphere was not found to have changed after the installation as it was before the installation.

On the other hand there was no significant change in perceptions pertaining to color rendering, color temperature, and glare. There was also no change in the overall mall usage category. This does not indicate that there were no changes to these factors on the mall, only that any changes were not perceived by the public.

Chapter 11

Final Conclusion

11.1 Impact of Lighting Installation on Visual Performance and Comfort

One of the greatest factors that determines one's ability to perform well visually is the presence of sufficient light [3]. Visual tasks do become easier as the amount of light in a space increases, however, additional light is only valuable to a certain point [9]. Not to mention, too much light in the space is wasteful and economically irresponsible. The new light installation on the mall considerably decreased both horizontal and vertical illuminance on the sidewalk, but the overall light levels were not decreased enough so as to prevent the users' from accomplishing basic visual tasks. There was enough light to meet the IES recommended design criteria for exterior spaces [19]. However, even though the light levels decreased, the questionnaire results revealed that this change was not perceived by the mall users and there is evidence that it was actually easier to perform visual tasks after the new lighting installation. This indicates that horizontal and vertical illuminance alone is not enough to determine the impact of the lighting installation on the users' ability to perform visually.

This seemingly paradoxical conclusion could very well be a result of the increase of perceived brightness. Studies show that perceptions of brightness can be increased due to changes in lamp spectrum, color temperature, and color rendering [22], [35]. The results of the objective measurements and the HDR images reveal a very dramatic improvement in color temperature and color rendering. The new lights are much "whiter" and render color significantly better than the old lights. Improvements such as this have been shown to increase people's perception of brightness, which could possibly be perceived as higher light levels thus explaining the contradiction between the objective and subjective results in this area.

Visual comfort did not appear to have been influenced by the new lighting installation. Several of the variables which were used to define visual comfort demonstrated no significant change between pre-and post-installation. Specifically, the presence of glare did not show any changes according to the subjective analysis and although HDR imaging has been suggested as a good tool for glare studies, it was not utilized in this way for this study.

11.2 Impact of Lighting on Reassurance

Like visual performance, reassurance and feelings of safety are strongly influenced by the amount of light, specifically the amount of vertical illuminance which directly impacts facial recognition. The objective study revealed that there was more than enough semi-cylindrical illuminance on the faces of pedestrians to achieve accurate facial recognition at a distance of 10m [38]. The results of the subjective analysis not only confirm that there is enough light for facial recognition but that facial recognition tasks are actually easier to accomplish. This could be due in part to the increase in uniformity across the vertical illuminance measurements which result in less shadowing effects found on the faces, making them easier to identify and thus resulting in increased feelings of safety. Survey questions which directly pertained to feelings of reassurance experienced a statistically significant increase in average responses; yet the overall reassurance category did not undergo a significant change. This can be greatly attributed to the presence of the "Amount of Light" category. This category experienced no change in response which is a desirable result considering the decrease of illuminance on the mall, but an undesirable result when incorporated into a group of other factors. The removal of this indicator would have resulted in a statistically significant increased in positive average reassurance responses.

There are also studies which show that transitions from warm color temperatures to more neutral/cool white colors as well as improved color rendering both produce greater feelings of safety [22]. Even though the subjective analysis did not reveal any changes in the colorimetric aspects of the lighting, there were enough objectively measureable changes in CRI and color temperature that the increased feelings of reassurance on the mall can still be partially attributed to these traits. The dramatic change in color temperature in particular could very well have produced greater feelings of safety.

11.3 Impact of Lighting on Luminous Atmosphere

According to Boyce, positive luminous atmospheres tend to include lighting that is "bright", "even," and comfortable [3]. Perceived brightness was shown to have improved after the installation, however changes in visual comfort were negligible. That leaves uniformity was one of the remaining important factors which influence the luminous atmosphere

As mentioned earlier, the objective results also show a measureable increase in uniformity on the mall. Both the horizontal illuminance measurements and the HDR images reveal a more uniform distribution of light on the ground which can be attributed to the additional downlight incorporated into the bottom of the light fixture. This increase in uniformity was also reflected in the subjective survey responses, although the observed shift in user responses was found to be only slightly statistically significant. It is possible to connect the change in mall lighting uniformity to the subjective user responses yet the lack of strong significance may imply that questions concerning uniformity may need a reference to be accurately answered. In other words, people may not be able to accurately gauge the uniformity of a surface without having something to compare it to. Ultimately, however, the strong observations found through the objective analysis are enough to state that the new lighting produced a more uniformly lit environment, and thus positively impacted the luminous atmosphere despite the apparent lack of subjective evidence.

11.4 New Lighting and Howard Brandston's Vision

An area of examination that has yet to be strongly considered is how well the new lighting adheres to the original vision of Howard Brandston. First and foremost, the decision to use replica lights instead of re-designed lights already prove that remaining true to the original design intent was a high priority on this project. According to Denver's 16th Street Urban Design Plan, Brandston intended for the lighting on the mall to address both the "psychological comfort and satisfaction, as well as physical safety" of the mall [14], [5]. Although results in the area of comfort and satisfaction were more inconclusive, the areas of safety (or at least perceived safety) were shown to have improved, thus remaining true to Brandston's vision. Brandston specifically design the fixtures to utilize "full spectrum sources which produce a color rendition as close to that of daylight as possible." [5]. This original design goal was most definitely achieved through the switch to LED sources. Not only were the new LED lights found to have a much higher CRI, but Brandston originally specified that the mall lights should NOT be high pressure sodium [14]. This shift in and of itself demonstrates that the new installation is more aligned with the original vision than the old lights were.

One of the most important aspects of Brandston's design that was achieved through the new lights was the light levels themselves. One of Brandston's original design strategies was that "lighting levels must be no higher than necessary to be achieve the lighting goals" thereby not over-lighting the space [5]. The objective study demonstrates that this goal was met by showing that in many cases the lighting was reduced to levels which were much closer to the minimum amount of light necessary to perform visual tasks.

Even though there are still areas of Brandston's design which remain incomplete, such as the in-grade pavement lights and coordinated nature of the surrounding retail lights [14], the new lighting installation is much more closely aligned with Brandson's vision than the old lighting installation.

11.5 Value and Integrity of Study and Further Research

The purpose of this study was not to condemn or commend a specific lighting decision, but to better understand the impact that this change had on the mall environment. The value of this study is that it can objectively look at many areas of possible impact as individual components and then draw unbiased conclusions by grouping these components together in logical ways. This study is also valuable because of its flexibility. Not only does it provide a big-picture view of the change in lighting conditions, but it allows for the different aspects of the design to be analyzed separately for individual merit. Additionally, one of the most important aspects of this study is the fact that it contains the potential to observe many more aspects of the lighting than was explored. The objective study holds great potential in the HDR analysis alone. A glare study, in particular, could have been explored in attempts to further understand the change in visual comfort. The HDR analysis also holds great potential for more luminance-based explorations. The subjective analysis also holds great potential for further statistical analysis, particularly, a more in depth observation of demographics and how these factors have influenced the lighting. A regression analysis could easily have been carried out on the subjective variables as well. In short, it is important to understand the great flexibility of this study. Different locations may benefit from altering the type of measurements. In particular, the subjective categorization structure may be adjusted for varying locations and scopes.

The main source of integrity within the study is the system of checks that is employed by analyzing certain lighting component from both an objective and subjective point of view. Changes that were measured through the objective components and then shown to be statistically significant through the subjective analysis are by default more robust than conclusions drawn from only one of the studies. That is not to say that observations and conclusions formed from either the objective or subjective components by themselves are not valid. Color rendering, for example, underwent a very significant increase that was clearly seen in the objective measurements but not the subjective. This is likely the result of the nature of the subjective study which lends itself more to certain lighting aspects than others. However, the study is made more legitimate by the ability to observe both the objective and subjective results as one comprehensive whole.

In conclusion, Denver's 16th Street Mall lighting installation had a measurable and statistically significant impact on the users of the mall as well as the general environment itself. Even though not all results could be demonstrated through both objective and subjective studies, it stands that the new installation had a net positive impact on the Mall, and it can be anticipated that this change will continue to benefit the City of Denver as the 16th Street Mall continues to change and grow.

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Appendix A

Subjective Analysis Questionnaire

Please complete the following survey about your current experience at the 16th street mall by answering the questions as accurately as possible.

Age	0-19 ○	20-39 ○	40-49 ○	50-59 ○	60+ ○
Gender	Male ○	Female ○	Other ○	Prefer not to answer ○	
How often do you visit the 16th street mall for leisure or recreation	Multiple times a week ○	About once a week ○	Once or twice a month ○	Rarely ever ○	
What sort of activities do you do on the mall (check all that apply)	Shop ○	Dine ○	Sight see ○	Attend events ○	Other ○
What time of day do you usually visit the mall	Morning ○	Afternoon ○	Evening ○	Night ○	Varies ○
Are you usually afraid to walk alone during the day?	Always ○	Sometimes ○	Rarely ○	Never ○	
Are you usually afraid to walk alone at night?	Always ○	Sometimes ○	Rarely ○	Never ○	
What is your favorite part of visiting the 16th street mall					

Fill in the bubble that you feel best completes the following statements concerning your current experience at the 16th street mall.

"At the moment I am feeling..."			*"The current atmosphere on the mall is..."*		
Excited	○ ○ ○ ○ ○ ○ ○	Bored	Negative	○ ○ ○ ○ ○ ○ ○	Positive
Fearful	○ ○ ○ ○ ○ ○ ○	Confident	Bright	○ ○ ○ ○ ○ ○ ○	Gloomy
Restless	○ ○ ○ ○ ○ ○ ○	Tranquil	Boring	○ ○ ○ ○ ○ ○ ○	Energizing
Happy	○ ○ ○ ○ ○ ○ ○	Sad	Peaceful	○ ○ ○ ○ ○ ○ ○	Chaotic
Calm	○ ○ ○ ○ ○ ○ ○	Anxious	Fun	○ ○ ○ ○ ○ ○ ○	Dull
Tired	○ ○ ○ ○ ○ ○ ○	Energized	Disengaging	○ ○ ○ ○ ○ ○ ○	Engaging
Safe	○ ○ ○ ○ ○ ○ ○	Unsafe	Unfriendly	○ ○ ○ ○ ○ ○ ○	Friendly
Content	○ ○ ○ ○ ○ ○ ○	Upset	Pleasant	○ ○ ○ ○ ○ ○ ○	Unpleasant

Figure A.1: Questionnaire - Front

Fill in a bubble that best represents your opinion on a scale from 1 to 7 where:
1 = *I strongly* ***disagree*** *with the statement*
7 = *I strongly* ***agree*** *with the statement*

		Strongly Disagree 1	2	3	4	5	6	Strongly Agree 7
1	"I can easily read street signs from this location"	O	O	O	O	O	O	O
2	"The lighting on this street is too bright"	O	O	O	O	O	O	O
3	"The light is evenly distributed all along the sidewalk that I am on"	O	O	O	O	O	O	O
4	"The lighting on the street is too warm in color"	O	O	O	O	O	O	O
5	"There are a lot of shadows on the ground"	O	O	O	O	O	O	O
6	"I can easily see the faces of pedestrians as they approach me"	O	O	O	O	O	O	O
7	"The mall lighting hurts my eyes"	O	O	O	O	O	O	O
8	"I can easily see curbs or objects in my path"	O	O	O	O	O	O	O
9	"The color of the vegetation on the street looks natural"	O	O	O	O	O	O	O
10	"I feel safe walking on this sidewalk"	O	O	O	O	O	O	O
11	"This sidewalk appears dark"	O	O	O	O	O	O	O
12	"I am likely to continue shopping after the sun sets"	O	O	O	O	O	O	O
13	"The lighting on the street is too cool in color"	O	O	O	O	O	O	O
14	"There is not enough light on the path"	O	O	O	O	O	O	O
15	"I would be able to recognize a friend walking towards me"	O	O	O	O	O	O	O
16	"Eating on one of the nearby outdoor patios would be pleasant"	O	O	O	O	O	O	O
17	"The lights produce too much glare"	O	O	O	O	O	O	O
18	"There is enough light for me to see my surroundings clearly"	O	O	O	O	O	O	O
19	"I would feel comfortable walking along this sidewalk alone"	O	O	O	O	O	O	O
20	"There is not enough light for me to easily read the print on this survey"	O	O	O	O	O	O	O
21	"I am likely to return to the mall at this time of night in the future"	O	O	O	O	O	O	O
22	"There is too much light on the path"	O	O	O	O	O	O	O
23	"I enjoy walking up and down the mall at night"	O	O	O	O	O	O	O
24	"The colors of objects around me looks unusual"	O	O	O	O	O	O	O
25	“I can easily identify loose stones or cracks in the sidewalk”	O	O	O	O	O	O	O

Figure A.2: Questionnaire - Back

Appendix B

Vignetting Correction Matlab Code

```
\%Vignetting correction takes a raw HDR image and a vignetting correction
\%function and applies the correction to output a new HDR image corrected
\%for vignetting.
\%By Mio Stanley
\%Sept. 22, 2015

\%Adapted by Shelby White
\%Aug. 31st, 2016

\% clc
\% clear

Filename='DenverHDR/102516_16curtis_east_f9_compiled';
type=2;
\%Please specify if the image is a fisheye or not. 1= fisheye or 2=rectangular image are
\%the accepted options.
image=hdrread(sprintf('\%s.hdr',Filename));
\%Reads in the HDR image to a 3D matrix named 'image'.
[rows,columns,pages] = size(image);
```

```
\%Gets dimensions of HDR image matrix.

\%Cfile =  'coeffs_Z18_0308.txt'; \% Coefficients for f56
Cfile =  'coeffs_Z18_0309.txt'; \% Coefficients for f9
coeffs = dlmread(Cfile, '\t');

\%VF='%NF_f14_JPEG_VF.txt';
\% [coefs]=textread(VF,'\%f');
\%Read in vignetting function text file and assigns the values to variables
sizeCoeffs=length(coeffs);

if type==1
cp=[3000,2006];
maxRad=1575;
else
cp = [round(columns/2),round(rows/2)];
maxRad = sqrt(cp(1)\^2 + cp(2)\^2);
end

VCimage = zeros(rows,columns,pages);
for i=1:rows
for j=1:columns
x=j-cp(1);
y=i-cp(2);
r=sqrt(x\^2+y\^2)/maxRad; \% radius normalized
\%Radius of pixel.
if r>1
```

```
VCimage(i,j,:)=0;
else
V=0;
\%Starts calculation for correction factor.
for k=1:sizeCoeffs
V=V+coeffs(k)*r\^(sizeCoeffs-k);
\%Calculates the vignetting loss for calculated radius.
end
CF=1/V;
\%Calculates the correction factor, which is the reciprocal of the
\%vignetting loss.
VCimage(i,j,:)=CF*image(i,j,:);
\%              VCimage(i,j,1)=CF*image(i,j,1);
\%              VCimage(i,j,2)=CF*image(i,j,2);
\%              VCimage(i,j,3)=CF*image(i,j,3);
\%Applies correction factor to pixel.
end
end
end
figure
imshow(VCimage)
hdrwrite(VCimage, sprintf('\%s\%s',Filename,'-VCorrected.hdr'))
```

Appendix C

Demographics Analysis - R Code

```
#16th street mall general demographics analysis

##Processing Part 2
##16th Street Mall
library(ISLR)
library(leaps)

#load in data
pre.data = read.csv("~/SurveyResultsFinalFormatted.csv",header = TRUE,
na.strings = "N/A")
pre.data.west = pre.data[pre.data\$Side.of.the.Mall =="West Side",]

post.data = read.csv("~/Survey Results Post Interim.csv", header = TRUE,
na.string = "N/A")


#Gender information
par(mfrow = c(1,2))
```

```
barplot(table(pre.data.west\$Gender), main = "Pre-Installation Demographics -
Gender",
col = c("indianred1","indianred4"), ylim = c(0,90))
barplot(table(post.data\$Gender), main = "Post-Installation Demographics -
Gender",
col = c("cadetblue1","cadetblue4"),ylim = c(0,90))

#Date information
par(mfrow = c(1,2))

barplot(table(pre.data.west\$Age), main = "Pre-Installation Demographics - Age",
col = c("lightpink2","indianred2","maroon","indianred4"), ylim = c(0,70))
barplot(table(post.data\$Age), main = "Post-Installation Demographics - Age",
col = c("lightcyan2","cadetblue3","lightcyan3","cadetblue4"),ylim = c(0,70))

#Visiting frequeny information

par(mfrow = c(2,1))
barplot(table(pre.data.west\$How.often.visit), main = "Pre-Installation Demographics-
Frequency of Visiting the Mall",
col = c("lightpink2","indianred2","maroon"), ylim = c(0,50))
barplot(table(post.data\$How.often.visit), main = "Post-Installation Demographics-
Frequency of Visiting the Mall",
col = c("lightcyan2","cadetblue3","lightcyan3"),ylim = c(0,50))

#afraid
#par(mfrow = c(2,2))
```

```
#hist(table(pre.data.west\$Afraid...day), main = "Pre-Installation Demographics-
Afraid of Walking Alone: Day",
# col = c("lightpink2","indianred2","maroon"), freq = F)



#barplot(table(post.data\$Afraid...day), main = "Post-Installation Demographics-
Afraid of Walking Alone: Day",
# col = c("lightcyan2","cadetblue3","lightcyan3"),ylim = c(0,80))

#barplot(table(pre.data.west\$Afraid...night), main = "Pre-Installation Demographics -
 Afraid of Walking Alone: Night",
# col = c("lightpink2","indianred2","maroon"), ylim = c(0,80))

#barplot(table(post.data\$Afraid...night), main = "Post-Installation Demographics -
 Afraid of Walking Alone: Night",
# col = c("lightcyan2","cadetblue3","lightcyan3"),ylim = c(0,80))
```

Appendix D

Cronbach's Alpha Analysis - R Code

```
Appendix D  Alpha Code
##Survey Processing  Alpha Plots
##16th Street Mall
##Shelby White
library(ISLR)
library(leaps)
library(VIF)
library(RColorBrewer)
library(colorspace)
library(psych)

#read in data
pre.data = read.csv("~/SurveyResultsFinalFormatted.csv",header = TRUE,
na.strings = "N/A")
pre.data.west = pre.data[pre.data\$Side.of.the.Mall =="West Side",]

pre.data.means = read.csv("~/SurveyResultsFinalFormatted_PreMeans.csv",
header = FALSE, na.strings = "N/A")
```

```
post.data.means = read.csv("~/Survey Results Post Interim_means.csv",
header = FALSE, na.strings = "N/A")

#Visual Performance Indicators - Pre
distance.vertical.pre = pre.data.means\$V4
distance.horizontal.pre = pre.data.means\$V7
color.rendering.pre = pre.data.means\$V10
detail.tasks.pre = pre.data.means\$V12

#Visual Performance - Pre
visual.performance.pre = pre.data.means\$V13

#Visual Performance Indicators - Post
distance.vertical.post = post.data.means\$V4
distance.horizontal.post = post.data.means\$V7
color.rendering.post = post.data.means\$V10
detail.tasks.post = post.data.means\$V12

#Visual Performance - Post
visual.performance.post = post.data.means\$V13

#alpha testing
#pre data  visual performance
distance.vertical.pre.data =
data.frame(pre.data.means\$V1,pre.data.means\$V2,pre.data.means\$V3)
alpha(distance.vertical.pre.data, na.rm = TRUE)
```

```
distance.horizontal.pre.data =
data.frame(pre.data.means\$V5,pre.data.means\$V6)
alpha(distance.horizontal.pre.data, na.rm = TRUE)

color.rendering.pre.data =
data.frame(pre.data.means\$V8,pre.data.means\$V9)
alpha(color.rendering.pre.data, na.rm = TRUE)

total.individual.pre.data1 =
data.frame(pre.data.means\$V1,pre.data.means\$V2,pre.data.means\
$V3,pre.data.means\$V5,pre.data.means\$V6,
pre.data.means\$V8,pre.data.means\$V9,pre.data.means\$V11)
alpha(total.individual.pre.data1, na.rm = TRUE)

visual.performance.pre.data =
data.frame(distance.vertical.pre,distance.horizontal.pre,
color.rendering.pre,detail.tasks.pre)
alpha(visual.performance.pre.data, na.rm = TRUE)

#post data

distance.vertical.post.data =
data.frame(post.data.means\$V1,post.data.means\$V2,post.data.means\$V3)
alpha(distance.vertical.post.data, na.rm = TRUE)

distance.horizontal.post.data = data.frame(post.data.means\$V5,post.data.means\$V6)
alpha(distance.horizontal.post.data, na.rm = TRUE)
```

```
color.rendering.post.data = data.frame(post.data.means\$V8,post.data.means\$V9)
alpha(color.rendering.post.data, na.rm = TRUE)

total.individual.post.data1 =
data.frame(post.data.means\$V1,post.data.means\$V2,post.data.means
\$V3,post.data.means\$V5,post.data.means\$V6,
post.data.means\$V8,post.data.means\$V9,post.data.means\$V11)
alpha(total.individual.post.data1, na.rm = TRUE)

visual.performance.post.data =
data.frame(distance.vertical.post,distance.horizontal.post,
color.rendering.post,detail.tasks.post)
alpha(visual.performance.post.data, na.rm = TRUE)



#full comparison
par(mfrow = c(2,2))
boxplot(distance.vertical.pre, distance.vertical.post, main =
"Distance Visual Tasks (Vertical)-Average Response Comparison",
ylab = "Average Resonse",names = (c("Pre-Installation","Post-Installation")),
col = (c("indianred1","steelblue1")))

boxplot(distance.horizontal.pre, distance.horizontal.post, main =
"Distance Visual Tasks
(Horizontal)-Average Response Comparison",
ylab = "Average Response",names = (c("Pre-Installation","Post-Installation")),
```

```
col = (c("indianred1","steelblue1")))

boxplot(color.rendering.pre, color.rendering.post, main =
"Color Rendering -
Average Response Comparison",
ylab = "Average Response",names = (c("Pre-Installation","Post-Installation")),
col = (c("indianred1","steelblue1")))

boxplot(detail.tasks.pre, detail.tasks.post, main = "Detail Tasks -
Average Response Comparison",
ylab = "Average Response",names = (c("Pre-Installation","Post-Installation")),
col = (c("indianred1","steelblue1")))

boxplot(visual.performance.pre, visual.performance.post, main = "Overall Visual
Performance - Average Response Comparison",
ylab = "Average Response",names =
(c("Pre-Installation","Post-Installation")),col =
(c("indianred1","steelblue1")))

par(mfrow = c(1,2))
hist(visual.performance.pre, main =
"Overall Visual Performance - Average Response Comparison",
ylab = "Average Response",names =
(c("Pre-Installation","Post-Installation")),col = (c("indianred1","steelblue1")))

hist(visual.performance.post, main =
"Overall Visual Performance - Average Response Comparison",
```

```
ylab = "Average Response",names = (c("Pre-Installation","Post-Installation")),col =
(c("indianred1","steelblue1")))

###Visual Comfort - Pre
#Visual Comfort Indicators - Pre
glare.pre = pre.data.means\$V22
amount.light.pre = pre.data.means\$V17

#Visual Comfort - pre
visual.comfort.pre = pre.data.means\$V23

#Visual Comfort Indicator - Post
glare.post = post.data.means\$V22
amount.light.post = post.data.means\$V17

#Visual Comfort - Post
visual.comfort.post = post.data.means\$V23

#alpha testing - pre

glare.pre.data = data.frame(pre.data.means\$V14, pre.data.means\$V15,
pre.data.means\$V16)
alpha(glare.pre.data, na.rm = TRUE)

amount.light.pre.data =
data.frame(pre.data.means\$V18,pre.data.means\$V19,pre.data.means\$V20,
pre.data.means\$V21)
```

```
alpha(amount.light.pre.data, na.rm = TRUE)

total.individual.pre.data2
=data.frame(pre.data.means\$V14,pre.data.means\$V15,pre.data.means\
$V16,pre.data.means\$V18,pre.data.means\$V19,
pre.data.means\$V20,pre.data.means\$V21)
alpha(total.individual.pre.data2)

visual.comfort.pre.data = data.frame(glare.pre,amount.light.pre)
alpha(visual.comfort.pre.data, na.rm = TRUE)

#alpha testing - post

glare.post.data = data.frame(post.data.means\$V14,
post.data.means\$V15,post.data.means\$V16)
alpha(glare.post.data, na.rm = TRUE)

amount.light.post.data =
data.frame(post.data.means\$V18,post.data.means\$V19,post.data.means\$V20,
post.data.means\$V21)]
alpha(amount.light.post.data, na.rm = TRUE)

total.individual.post.data2 = data.frame(post.data.means\$V14,post.data.means\
$V15,post.data.means\$V16,post.data.means\$V18,post.data.means\$V19,
post.data.means\$V20,post.data.means\$V21)
alpha(total.individual.post.data2)
```

```
visual.comfort.post.data = data.frame(glare.post,amount.light.post)
alpha(visual.comfort.post.data, na.rm = TRUE)

total.individual.post.data2 =
data.frame(post.data.means\$V14,post.data.means\$V15,post.data.means\
$V16,post.data.means\$V18,post.data.means\$V19,
post.data.means\$V20,post.data.means\$V21)
alpha(total.individual.post.data2)



#analysis

par(mfrow = c(1,2))
boxplot(glare.pre, glare.post, main =
"Brightness/Glare-Average Response Comparison",
ylab = "Average Resonse",names = (c("Pre-Installation","Post-Installation")),
col = (c("indianred1","steelblue1")))

boxplot(amount.light.pre, amount.light.post, main =
"Amount of Light - Average Response Comparison",
ylab = "Average Resonse",names = (c("Pre-Installation","Post-Installation")),
col = (c("indianred1","steelblue1")))

boxplot(visual.comfort.pre, visual.comfort.post, main =
 "Overall Visual Performance - Average Response Comparison",
 ylab = "Average Response",names = (c("Pre-Installation","Post-Installation")),
 col = (c("indianred1","steelblue1")))
```

```
hist(visual.comfort.pre), main =
"Visual Comfort - Average Response Comparison", xlab - "Average User Response",
xlim = c(1:7), ylim = c(0,.5), freq = F)
hist(visual.comfort.post, xlim = c(1:7), ylim = c(0,.5), add = T)


###Reassurance
#Reassurance Indicators - Pre
facial.identif.pre = pre.data.means\$V26
#color.rendering.pre = pre.data.means\$V10/V29
#amount.light.pre = pre.data.means\$V17/\$V34
ease.of.tasks.pre = pre.data.means\$V37
overall.reassurance.pre = pre.data.means\$V40

#Reassurance - Pre
reassurance.total.pre = pre.data.means\$V41

#Reassurance Indicator - Post
facial.identif.post = post.data.means\$V26
#color.rendering.post = post.data.means\$V10/V29
#amount.light.post = post.data.means\$V17/\$V34
ease.of.tasks.post = post.data.means\$V37
overall.reassurance.post = post.data.means\$V40

#Reassurance - Post
reassurance.total.post = post.data.means\$V41
```

```
#alpha.testing pre

facial.identif.pre.data = data.frame(pre.data.means\$V24, pre.data.means\$V25)
alpha(facial.identif.pre.data, na.rm = T)

#color rendering alpha
#amount of light alpha

ease.of.tasks.pre.data = data.frame(pre.data.means\$V35, pre.data.means\$V36)
alpha(ease.of.tasks.pre.data, na.rm = T)

overall.reassurance.pre.data = data.frame(pre.data.means\$V38, pre.data.means\$V39)
alpha(overall.reassurance.pre.data, na.rm = T)

total.individual.pre.data3 = data.frame(pre.data.means\$V24,
pre.data.means\$V25,pre.data.means\$V27, pre.data.means\$V28,pre.data.means\$V30,
 pre.data.means\$V31, pre.data.means\$V32,
 pre.data.means\$V33,pre.data.means\$V35,
  pre.data.means\$V36,pre.data.means\$V38,pre.data.means\$V39),
  alpha(total.individual.pre.data3, na.rm = T)

reassurance.total.pre.data = data.frame(facial.identif.pre, color.rendering.pre,
amount.light.pre,ease.of.tasks.pre,overall.reassurance.pre)
alpha(reassurance.total.pre.data, na.rm = TRUE)

#alpha.testing post
```

```
facial.identif.post.data = data.frame(post.data.means\$V24, post.data.means\$V25)
alpha(facial.identif.post.data, na.rm = T)

#color rendering alpha
#amount of light alpha

ease.of.tasks.post.data = data.frame(post.data.means\$V35, post.data.means\$V36)
alpha(ease.of.tasks.post.data, na.rm = T)

overall.reassurance.post.data = data.frame(post.data.means\$V38, post.data.means\$V39)
alpha(overall.reassurance.post.data, na.rm = T)

total.individual.post.data3 = data.frame(post.data.means\$V24, post.data.means\$V25,
post.data.means\$V27, post.data.means\$V28,
post.data.means\$V30, post.data.means\$V31, post.data.means\$V32,
post.data.means\$V33, post.data.means\$V35, post.data.means\$V36,
post.data.means\$V38, post.data.means\$V39)
alpha(total.individual.post.data3, na.rm = T)

reassurance.total.post.data = data.frame(facial.identif.post, color.rendering.post,
amount.light.post,ease.of.tasks.post,overall.reassurance.post)
alpha(reassurance.total.post.data, na.rm = TRUE)


#analysis
```

```
par(mfrow = c(2,3))
boxplot(facial.identif.pre, facial.identif.post, main =
"Facial Identification - Response Comparison",
ylab = "Average Resonse",names = (c("Pre-Installation","Post-Installation")),
col = (c("indianred1","steelblue1")))

boxplot(color.rendering.pre, color.rendering.post, main =
"Color Rendering - Average Response Comparison",
ylab = "Average Resonse",names = (c("Pre-Installation","Post-Installation")),
col = (c("indianred1","steelblue1")))

boxplot(amount.light.pre, amount.light.post, main =
"Amount of Light - Average Response Comparison",
ylab = "Average Resonse",names = (c("Pre-Installation","Post-Installation")),
col = (c("indianred1","steelblue1")))

boxplot(ease.of.tasks.pre, ease.of.tasks.post, main =
"Ease of Tasks - Average Response Comparison",
ylab = "Average Resonse",names = (c("Pre-Installation","Post-Installation")),
col = (c("indianred1","steelblue1")))

boxplot(overall.reassurance.pre, overall.reassurance.post, main =
"General Reassurance - Average Response Comparison",
ylab = "Average Resonse",names = (c("Pre-Installation","Post-Installation")),
col = (c("indianred1","steelblue1")))

boxplot(reassurance.total.pre, reassurance.total.post, main =
```

```
"Reassurance - Average Response Comparison",
ylab = "Average Resonse",names = (c("Pre-Installation","Post-Installation")),
col = (c("indianred1","steelblue1")))


hist(reassurance.total.pre, freq = F, xlim = c(1,7),
ylim = c(0,0.5), main = "Reassurance - Average Response Comparison",
xlab = "Average User Response",col = rgb(.8,.2,.2, alpha = 0.4))
hist(reassurance.total.post, freq = F, xlim = c(1,7),
ylim = c(0,0.5), col = rgb(0,.5,.6,alpha = 0.4),breaks = 14, add = T)
legend ("topleft", c("Pre-Installation","Post-Installation"),
lwd =10,col =c(rgb(0.8,0.2,0.2,0.4),rgb(0,0.5,0.6,0.4)))


t.test(reassurance.total.pre, reassurance.total.post)

####Perception of luminous atmosphere
#Perception Luminous Indicators - Pre
uniformity.pre = pre.data.means\$V44
#color.rendering.pre = pre.data.means\$V10/V29/V47
#amount.of.light.pre = pre.data.means\$V17/V37/V52
color.light.pre = pre.data.means\$V55
quality.light.pre = pre.data.means\$V58

#Luminous - pre
luminous.perception.total.pre = pre.data.means\$V59
```

```
#Luminous indicators - post
uniformity.post = post.data.means\$V44
#color.rendering.post = post.data.means\$V10/V29/V47
#amount.of.light.post = post.data.means\$V17/V37/V52
color.light.post = post.data.means\$V55
quality.light.post = post.data.means\$V58

#luminous - post
luminous.perception.total.post = post.data.means\$V59

#perception luminous atmosphere alpha - pre

uniformity.pre.data = data.frame(pre.data.means\$V42,pre.data.means\$V43)
alpha(uniformity.pre.data, na.rm = T)

#color rendering alpha
#amount of light alpha

color.light.pre.data = data.frame(pre.data.means\$V53, pre.data.means\$V54)
alpha(color.light.pre.data, na.rm = T)

quality.light.pre.data = data.frame(pre.data.means\$V56, pre.data.means\$V57)
alpha(quality.light.pre.data, na.rm = T)

total.individual.pre.data4 = data.frame(pre.data.means\$V42, pre.data.means\$V43,
pre.data.means\$V45, pre.data.means\$V46, pre.data.means\$V48,
pre.data.means\$V49, pre.data.means\$V50, pre.data.means\$V51, pre.data.means\$V53,
```

```
pre.data.means\$V54, pre.data.means\$V56, pre.data.means\$V57)
alpha(total.individual.pre.data4, na.rm = T)

luminous.perception.total.pre.data =
data.frame(uniformity.pre, color.rendering.pre,
amount.light.pre, color.light.pre, quality.light.pre)
alpha(luminous.perception.total.pre.data)

#perception luminous atmosphere alpha - post

uniformity.post.data = data.frame(post.data.means\$V42,post.data.means\$V43)
alpha(uniformity.post.data, na.rm = T)

#color rendering alpha
#amount of light alpha

color.light.post.data = data.frame(post.data.means\$V53, post.data.means\$V54)
alpha(color.light.post.data, na.rm = T)

quality.light.post.data = data.frame(post.data.means\$V56, post.data.means\$V57)
alpha(quality.light.post.data, na.rm = T)

total.individual.post.data4 = data.frame(post.data.means\$V42, post.data.means\$V43,
post.data.means\$V45, post.data.means\$V46, post.data.means\$V48,
post.data.means\$V49, post.data.means\$V50, post.data.means\$V51, post.data.means\$V53,
post.data.means\$V54, post.data.means\$V56, post.data.means\$V57)
alpha(total.individual.post.data4, na.rm = T)
```

```
luminous.perception.total.post.data =
data.frame(uniformity.post, color.rendering.post,
amount.light.post, color.light.post, quality.light.post)
alpha(luminous.perception.total.post.data)

#analysis

par(mfrow = c(2,3))

boxplot(uniformity.pre, uniformity.post, main =
"Uniformity - Average Response Comparison",
ylab = "Average Resonse",names = (c("Pre-Installation","Post-Installation")),
col = (c("indianred1","steelblue1")))

boxplot(color.rendering.pre, color.rendering.post, main =
"Color Rendering - Average Response Comparison",
ylab = "Average Resonse",names = (c("Pre-Installation","Post-Installation")),
col = (c("indianred1","steelblue1")))

boxplot(amount.light.pre, amount.light.post, main =
"Amount of Light - Average Response Comparison",
ylab = "Average Resonse",names = (c("Pre-Installation","Post-Installation")),
col = (c("indianred1","steelblue1")))

boxplot(color.light.pre, color.light.post, main =
"Color Temperature of Light - Average Response Comparison",
```

```
ylab = "Average Resonse",names = (c("Pre-Installation","Post-Installation")),
col = (c("indianred1","steelblue1")))

boxplot(quality.light.pre, quality.light.post, main =
"Quality of Light - Average Response Comparison",
ylab = "Average Resonse",names = (c("Pre-Installation","Post-Installation")),
col = (c("indianred1","steelblue1")))

boxplot(luminous.perception.total.pre, luminous.perception.total.post, main =
"Perception of Luminous Atmosphere - Average Response Comparison",
ylab = "Average Resonse",names = (c("Pre-Installation","Post-Installation")),
col = (c("indianred1","steelblue1")))

hist(luminous.perception.total.pre, freq = F, xlim = c(1,7),
ylim = c(0,0.5), main =
"Perception of Luminous Atmpsohere - Average Response Comparison",
xlab = "Average User Response",col = rgb(.8,.2,.2, alpha = 0.4))
hist(luminous.perception.total.post, freq = F, xlim = c(1,7),
ylim = c(0,0.5), col = rgb(0,.5,.6,alpha = 0.4), add = T)
legend ("topleft", c("Pre-Installation","Post-Installation"),
lwd =10,col = c(rgb(0.8,0.2,0.2,0.4),rgb(0,0.5,0.6,0.4)))

##Mall Usage

#Pre
mall.usage.pre = pre.data.means\$V64
total.individual.pre.data5 = data.frame(pre.data.means\$V60, pre.data.means\$V61,
```

```
pre.data.means\$V62, pre.data.means\$V63)
alpha(total.individual.pre.data5, na.rm = T)

#Post
mall.usage.post = post.data.means\$V64
total.individual.post.data5 = data.frame(post.data.means\$V60, post.data.means\$V61,
post.data.means\$V62, post.data.means\$V63)
alpha(total.individual.post.data5, na.rm = T)

boxplot(mall.usage.pre, mall.usage.post, main =
"Overall Mall Usage - Average Response Comparison",
ylab = "Average Resonse",names = (c("Pre-Installation","Post-Installation")),
col = (c("indianred1","steelblue1")))

hist(mall.usage.pre, freq = F, xlim = c(1,7),
ylim = c(0,0.5), main = "Mall Usage - Average Response Comparison",
xlab = "Average User Response",col = rgb(.8,.2,.2, alpha = 0.4))
hist(mall.usage.post, freq = F, xlim = c(1,7),
ylim = c(0,0.5), col = rgb(0,.5,.6,alpha = 0.4), add = T)
legend ("topleft", c("Pre-Installation","Post-Installation"), lwd =10,col =
c(rgb(0.8,0.2,0.2,0.4),rgb(0,0.5,0.6,0.4)))


#Visual Performance - Adjusted


distance.vertical.pre = pre.data.means\$V4
```

```
distance.horizontal.pre = pre.data.means\$V7
color.rendering.pre = pre.data.means\$V10
detail.tasks.pre = pre.data.means\$V12

visual.performance.pre = pre.data.means\$V13

distance.vertical.post = post.data.means\$V4
distance.horizontal.post = post.data.means\$V7
color.rendering.post = post.data.means\$V10
detail.tasks.post = post.data.means\$V12

visual.performance.post = post.data.means\$V13

#alpha testing
#pre data
distance.vertical.pre.data =
data.frame(pre.data.means\$V1,pre.data.means\$V2,pre.data.means\$V3)
alpha(distance.vertical.pre.data, na.rm = TRUE)

distance.horizontal.pre.data = data.frame(pre.data.means\$V5,pre.data.means\$V6)
alpha(distance.horizontal.pre.data, na.rm = TRUE)

color.rendering.pre.data = data.frame(pre.data.means\$V8,pre.data.means\$V9)
alpha(color.rendering.pre.data, na.rm = TRUE)

total.individual.pre.data1.adjusted =
data.frame(pre.data.means\$V1,pre.data.means\$V2,pre.data.means\
```

```
$V3,pre.data.means\$V5,pre.data.means\$V6,pre.data.means\$V8,pre.data.means\$V9)
alpha(total.individual.pre.data1.adjusted, na.rm = TRUE)

visual.performance.pre.data =
data.frame(distance.vertical.pre,distance.horizontal.pre,
color.rendering.pre,detail.tasks.pre)
alpha(visual.performance.pre.data, na.rm = TRUE)

#post data

distance.vertical.post.data =
data.frame(post.data.means\$V1,post.data.means\$V2,post.data.means\$V3)
alpha(distance.vertical.post.data, na.rm = TRUE)

distance.horizontal.post.data = data.frame(post.data.means\$V5,post.data.means\$V6)
alpha(distance.horizontal.post.data, na.rm = TRUE)

color.rendering.post.data = data.frame(post.data.means\$V8,post.data.means\$V9)
alpha(color.rendering.post.data, na.rm = TRUE)

total.individual.post.data1 =
data.frame(post.data.means\$V1,post.data.means\
$V2,post.data.means\$V3,post.data.means\$V5,post.data.means\$V6,
post.data.means\$V8,post.data.means\$V9,post.data.means\$V11)
alpha(total.individual.post.data1, na.rm = TRUE)

visual.performance.post.data =
```

```
data.frame(distance.vertical.post,distance.horizontal.post, color.rendering.post,
detail.tasks.post)
alpha(visual.performance.post.data, na.rm = TRUE)
```

Appendix E

T-Tests and Histograms - R Code

```
#Processing Part T-Tests

#16th Street Mall

#Shelby White

library(ISLR)

library(leaps)

library(VIF)

library(RColorBrewer)

library(colorspace)

library(psych)


#Load in Data

pre.data = read.csv("~/SurveyResultsFinalFormatted.csv",header =

 TRUE, na.strings = "N/A")

pre.data.west = pre.data[pre.data\$Side.of.the.Mall =="West Side",]


pre.data.means = read.csv("~/SurveyResultsFinalFormatted_PreMeans.csv",header =

FALSE, na.strings = "N/A")

post.data.means = read.csv("~/Survey Results Post Interim_means.csv",header =
```

```
FALSE, na.strings = "N/A")


###Visual Performance


pre.data.rev1 = read.csv("~/PreMeans_NoDetail.csv",header =
FALSE, na.strings = "N/A")
post.data.rev1 = read.csv("~/PostMeans_NoDetail.csv",header =
FALSE, na.strings = "N/A")

distance.vertical.pre.rev1 = pre.data.rev1\$V4
distance.horizontal.pre.rev1 = pre.data.rev1\$V7
color.rendering.pre.rev1 = pre.data.rev1\$V10

visual.performance.pre.rev1 = pre.data.rev1\$V11

distance.vertical.post.rev1 = post.data.rev1\$V4
distance.horizontal.post.rev1 = post.data.rev1\$V7
color.rendering.post.rev1 = post.data.rev1\$V10

visual.performance.post.rev1 = post.data.rev1\$V11

###Visual Performance Analysis

t.test(visual.performance.pre.rev1,visual.performance.post.rev1, na.rm = TRUE)

par(mfrow = c(2,2))
```

```
hist(distance.vertical.pre.rev1, freq = F, xlim = c(1,7),
ylim = c(0,0.5), main = "Distance Tasks: Vertical - Average Response Comparison",
xlab = "Average User Response",col = rgb(.8,.2,.2, alpha = 0.4))
hist(distance.vertical.post.rev1, freq = F, xlim = c(1,7),
ylim = c(0,0.5), col = rgb(0,.5,.6,alpha = 0.4),breaks = 14, add = T)
legend ("topleft", c("Pre-Installation","Post-Installation"), lwd =10,col =
c(rgb(0.8,0.2,0.2,0.4),rgb(0,0.5,0.6,0.4)))

hist(distance.horizontal.pre.rev1, freq = F, xlim = c(1,7),
ylim = c(0,0.5), main = "Distance Tasks: Horizontal - Average Response Comparison",
xlab = "Average User Response",col = rgb(.8,.2,.2, alpha = 0.4))
hist(distance.horizontal.post.rev1, freq = F, xlim = c(1,7),
ylim = c(0,0.5), col = rgb(0,.5,.6,alpha = 0.4),breaks = 14, add = T)
legend ("topleft", c("Pre-Installation","Post-Installation"), lwd =10,col
 =c(rgb(0.8,0.2,0.2,0.4),rgb(0,0.5,0.6,0.4)))

hist(color.rendering.pre, freq = F, xlim = c(1,7),
ylim = c(0,0.5), main = "Color Rendering - Average Response Comparison",
xlab = "Average User Response",col = rgb(.8,.2,.2, alpha = 0.4))
hist(color.rendering.post, freq = F, xlim = c(1,7),
ylim = c(0,0.5), col = rgb(0,.5,.6,alpha = 0.4),breaks = 14, add = T)
legend ("topleft", c("Pre-Installation","Post-Installation"), lwd =10,col
 =c(rgb(0.8,0.2,0.2,0.4),rgb(0,0.5,0.6,0.4)))


hist(visual.performance.pre.rev1, freq = F, xlim = c(1,7),
ylim = c(0,0.5), main = "Visual Performance - Average Response Comparison",
```

```
xlab = "Average User Response",col = rgb(.8,.2,.2, alpha = 0.4))
hist(visual.performance.post.rev1, freq = F, xlim = c(1,7),
ylim = c(0,0.5), col = rgb(0,.5,.6,alpha = 0.4),breaks = 14, add = T)
legend ("topleft", c("Pre-Installation","Post-Installation"), lwd =10,col =
c(rgb(0.8,0.2,0.2,0.4),rgb(0,0.5,0.6,0.4)))

visual.performance.pre.t =
t.test(visual.performance.pre.rev1,visual.performance.post.rev1, na.rm = TRUE)
color.rendering.pre.t = t.test(color.rendering.pre,color.rendering.post, na.rm = TRUE)
distance.vert.t = t.test(distance.vertical.pre,distance.vertical.post, na.rm = TRUE)
distance.horiz.t = t.test(distance.horizontal.pre,
distance.horizontal.post, na.rm = TRUE)



###Visual Comfort


glare.pre = pre.data.means\$V22
amount.light.pre = pre.data.means\$V17


visual.comfort.pre = pre.data.means\$V23


glare.post = post.data.means\$V22
amount.light.post = post.data.means\$V17


visual.comfort.post = post.data.means\$V23


##Visual Comfort analysis
```

```
par(mfrow = c(1,3))
hist(glare.pre, freq = F, xlim = c(1,7),
ylim = c(0,0.5), main = "Glare - Average Response Comparison",
xlab = "Average User Response",col = rgb(.8,.2,.2, alpha = 0.4))
hist(glare.post, freq = F, xlim = c(1,7),
ylim = c(0,0.5), col = rgb(0,.5,.6,alpha = 0.4),breaks = 14, add = T)
legend ("topleft", c("Pre-Installation","Post-Installation"), lwd =10,col
= c(rgb(0.8,0.2,0.2,0.4),rgb(0,0.5,0.6,0.4)))

hist(amount.light.pre, freq = F, xlim = c(1,7),
ylim = c(0,0.5), main = "Amount of Light - Average Response Comparison",
xlab = "Average User Response",col = rgb(.8,.2,.2, alpha = 0.4))
hist(amount.light.post, freq = F, xlim = c(1,7),
ylim = c(0,0.5), col = rgb(0,.5,.6,alpha = 0.4),breaks = 14, add = T)
legend ("topleft", c("Pre-Installation","Post-Installation"), lwd =10,col
= c(rgb(0.8,0.2,0.2,0.4),rgb(0,0.5,0.6,0.4)))

hist(visual.comfort.pre, freq = F, xlim = c(1,7),
ylim = c(0,0.5), main = "Visual Comfort - Average Response Comparison",
xlab = "Average User Response",col = rgb(.8,.2,.2, alpha = 0.4))
hist(visual.comfort.post, freq = F, xlim = c(1,7),
ylim = c(0,0.5), col = rgb(0,.5,.6,alpha = 0.4),breaks = 14, add = T)
legend ("topleft", c("Pre-Installation","Post-Installation"), lwd =10,col
= c(rgb(0.8,0.2,0.2,0.4),rgb(0,0.5,0.6,0.4)))

glare.t = t.test(glare.pre, glare.post, na.rm = T)
```

```
amount.light.t = t.test(amount.light.pre, amount.light.post, na.rm = T)
visual.comfort.t = t.test(visual.comfort.pre, visual.comfort.post, na.rm = T)


##Reassurance
facial.identif.pre = pre.data.means\$V26
#color.rendering.pre = pre.data.means\$V10/V29
#amount.light.pre = pre.data.means\$V17/\$V34
ease.of.tasks.pre = pre.data.means\$V37
overall.reassurance.pre = pre.data.means\$V40

reassurance.total.pre = pre.data.means\$V41

facial.identif.post = post.data.means\$V26
#color.rendering.post = post.data.means\$V10/V29
#amount.light.post = post.data.means\$V17/\$V34
ease.of.tasks.post = post.data.means\$V37
overall.reassurance.post = post.data.means\$V40

reassurance.total.post = post.data.means\$V41

##Reassurance analysis

par(mfrow = c(2,3))
hist(facial.identif.pre, freq = F, xlim = c(1,7),
ylim = c(0,0.5), main = "Facial Identification - Average Response Comparison",
xlab = "Average User Response",col = rgb(.8,.2,.2, alpha = 0.4))
```

```
hist(facial.identif.post, freq = F, xlim = c(1,7),
ylim = c(0,0.5), col = rgb(0,.5,.6,alpha = 0.4),breaks = 14, add = T)
legend ("topleft", c("Pre-Installation","Post-Installation"), lwd =10,col
= c(rgb(0.8,0.2,0.2,0.4),rgb(0,0.5,0.6,0.4)))

hist(color.rendering.pre, freq = F, xlim = c(1,7),
ylim = c(0,0.5), main = "Color Rendering - Average Response Comparison",
xlab = "Average User Response",col = rgb(.8,.2,.2, alpha = 0.4), breaks = 14)
hist(color.rendering.post, freq = F, xlim = c(1,7),
ylim = c(0,0.5), col = rgb(0,.5,.6,alpha = 0.4), breaks = 14, add = T)
legend ("topleft", c("Pre-Installation","Post-Installation"), lwd =10,col
= c(rgb(0.8,0.2,0.2,0.4),rgb(0,0.5,0.6,0.4)))

hist(ease.of.tasks.pre, freq = F, xlim = c(1,7),
ylim = c(0,0.5), main = "Ease of Tasks - Average Response Comparison",
xlab = "Average User Response",col = rgb(.8,.2,.2, alpha = 0.4), breaks = 14)
hist(ease.of.tasks.post, freq = F, xlim = c(1,7),
ylim = c(0,0.5), col = rgb(0,.5,.6,alpha = 0.4),breaks = 14, add = T)
legend ("topleft", c("Pre-Installation","Post-Installation"), lwd =10,col =
c(rgb(0.8,0.2,0.2,0.4),rgb(0,0.5,0.6,0.4)))

hist(overall.reassurance.pre, freq = F, xlim = c(1,7),
ylim = c(0,0.7), main = "General Reassurance - Average Response Comparison",
xlab = "Average User Response",col = rgb(.8,.2,.2, alpha = 0.4), breaks = 14)
hist(overall.reassurance.post, freq = F, xlim = c(1,7),
ylim = c(0,0.7), col = rgb(0,.5,.6,alpha = 0.4), breaks = 14, add = T)
legend ("topleft", c("Pre-Installation","Post-Installation"), lwd =10,col
```

```
= c(rgb(0.8,0.2,0.2,0.4),rgb(0,0.5,0.6,0.4)))

hist(amount.light.pre, freq = F, xlim = c(1,7),
ylim = c(0,0.5), main = "Amount of Light - Average Response Comparison",
xlab = "Average User Response",col = rgb(.8,.2,.2, alpha = 0.4), breaks = 14)
hist(amount.light.post, freq = F, xlim = c(1,7),
ylim = c(0,0.5), col = rgb(0,.5,.6,alpha = 0.4),breaks = 14, add = T)
legend ("topleft", c("Pre-Installation","Post-Installation"), lwd =10,col
= c(rgb(0.8,0.2,0.2,0.4),rgb(0,0.5,0.6,0.4)))

hist(reassurance.total.pre, freq = F, xlim = c(1,7),
ylim = c(0,0.5), main = "Reassurance - Average Response Comparison",
xlab = "Average User Response",col = rgb(.8,.2,.2, alpha = 0.4))
hist(reassurance.total.post, freq = F, xlim = c(1,7),
ylim = c(0,0.5), col = rgb(0,.5,.6,alpha = 0.4),breaks = 14, add = T)
legend ("topleft", c("Pre-Installation","Post-Installation"), lwd =10,col =
c(rgb(0.8,0.2,0.2,0.4),rgb(0,0.5,0.6,0.4)))



facial.identif.t = t.test(facial.identif.pre, facial.identif.post)
color.rendering.t = t.test(color.rendering.pre, color.rendering.post)
ease.tasks.t = t.test(ease.of.tasks.pre, ease.of.tasks.post)
general.reassurance.t = t.test(overall.reassurance.pre, overall.reassurance.post)
amount.light.t = t.test(amount.light.pre, amount.light.post)
reassurance.total.t = t.test(reassurance.total.pre, reassurance.total.post)

#######Perception of luminous atmoshpere
```

```
uniformity.pre = pre.data.means\$V44
#color.rendering.pre = pre.data.means\$V10/V29/V47
#amount.of.light.pre = pre.data.means\$V17/V37/V52
color.light.pre = pre.data.means\$V55
quality.light.pre = pre.data.means\$V58

luminous.perception.total.pre = pre.data.means\$V59

uniformity.post = post.data.means\$V44
#color.rendering.post = post.data.means\$V10/V29/V47
#amount.of.light.post = post.data.means\$V17/V37/V52
color.light.post = post.data.means\$V55
quality.light.post = post.data.means\$V58

luminous.perception.total.post = post.data.means\$V59

##Perception analysis
par(mfrow = c(1,3))

hist(uniformity.pre, freq = F, xlim = c(1,7),
ylim = c(0,0.7), main = "Uniformity - Average Response Comparison",
xlab = "Average User Response",col = rgb(.8,.2,.2, alpha = 0.4), breaks = 14)
hist(uniformity.post, freq = F, xlim = c(1,7),
ylim = c(0,0.7), col = rgb(0,.5,.6,alpha = 0.4),breaks = 14, add = T)
legend ("topleft", c("Pre-Installation","Post-Installation"), lwd =10,col
= c(rgb(0.8,0.2,0.2,0.4),rgb(0,0.5,0.6,0.4)))
```

```
hist(color.rendering.pre, freq = F, xlim = c(1,7),
ylim = c(0,0.5), main = "Color Rendering - Average Response Comparison",
xlab = "Average User Response",col = rgb(.8,.2,.2, alpha = 0.4), breaks = 14)
hist(color.rendering.post, freq = F, xlim = c(1,7),
ylim = c(0,0.5), col = rgb(0,.5,.6,alpha = 0.4), breaks = 14, add = T)
legend ("topleft", c("Pre-Installation","Post-Installation"), lwd =10,col
= c(rgb(0.8,0.2,0.2,0.4),rgb(0,0.5,0.6,0.4)))

hist(amount.light.pre, freq = F, xlim = c(1,7),
ylim = c(0,0.5), main = "Amount of Light - Average Response Comparison",
xlab = "Average User Response",col = rgb(.8,.2,.2, alpha = 0.4), breaks = 14)
hist(amount.light.post, freq = F, xlim = c(1,7),
ylim = c(0,0.5), col = rgb(0,.5,.6,alpha = 0.4),breaks = 14, add = T)
legend ("topleft", c("Pre-Installation","Post-Installation"), lwd =10,col
= c(rgb(0.8,0.2,0.2,0.4),rgb(0,0.5,0.6,0.4)))

hist(color.light.pre, freq = F, xlim = c(1,7),
ylim = c(0,0.6), main = "Color of Light - Average Response Comparison",
xlab = "Average User Response",col = rgb(.8,.2,.2, alpha = 0.4),breaks = 14)
hist(color.light.post, freq = F, xlim = c(1,7),
ylim = c(0,0.6), col = rgb(0,.5,.6,alpha = 0.4),breaks = 14, add = T)
legend ("topleft", c("Pre-Installation","Post-Installation"), lwd =10,col
= c(rgb(0.8,0.2,0.2,0.4),rgb(0,0.5,0.6,0.4)))

hist(quality.light.pre, freq = F, xlim = c(1,7),
ylim = c(0,0.5), main = "Quality of Light - Average Response Comparison",
```

```
xlab = "Average User Response",col = rgb(.8,.2,.2, alpha = 0.4),breaks = 14)
hist(quality.light.post, freq = F, xlim = c(1,7),
ylim = c(0,0.5), col = rgb(0,.5,.6,alpha = 0.4),breaks = 14, add = T)
legend ("topleft", c("Pre-Installation","Post-Installation"),
lwd =10,col = c(rgb(0.8,0.2,0.2,0.4),rgb(0,0.5,0.6,0.4)))


hist(luminous.perception.total.pre, freq = F, xlim = c(1,7),
ylim = c(0,0.5), main =
"Perception of Luminous Atmpsohere - Average Response Comparison",
xlab = "Average User Response",col = rgb(.8,.2,.2, alpha = 0.4))
hist(luminous.perception.total.post, freq = F, xlim = c(1,7),
ylim = c(0,0.5), col = rgb(0,.5,.6,alpha = 0.4), add = T)
legend ("topleft", c("Pre-Installation","Post-Installation"), lwd =
10,col= c(rgb(0.8,0.2,0.2,0.4),rgb(0,0.5,0.6,0.4)))

uniformity.t = t.test(uniformity.pre, uniformity.post)
color.rendering.t = t.test(color.rendering.pre, color.rendering.post)
amount.light.t = t.test(amount.light.pre, amount.light.post)
color.light.t = t.test(color.light.pre, color.light.post)
quality.light.t = t.test(quality.light.pre, quality.light.post)
luminous.perceptin.t =  t.test(luminous.perception.total.pre,
luminous.perception.total.post)

#Mall usage
hist(mall.usage.pre, freq = F, xlim = c(1,7),
ylim = c(0,0.5), main =
```

```
"Perception of Luminous Atmpsohere - Average Response Comparison",
xlab = "Average User Response",col = rgb(.8,.2,.2, alpha = 0.4))
hist(luminous.perception.total.post, freq = F, xlim = c(1,7),
ylim = c(0,0.5), col = rgb(0,.5,.6,alpha = 0.4), add = T)
legend ("topleft", c("Pre-Installation","Post-Installation"), lwd =10,col
= c(rgb(0.8,0.2,0.2,0.4),rgb(0,0.5,0.6,0.4)))
```