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**The National Surface Transportation Safety
Center for Excellence**

**Assessment of the Impact of
Color Contrast in the Detection
and Recognition of Objects in a
Road Environment**

Final Report

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Lighting	Technology
Fatigue	Aging

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LIST OF ABBREVIATIONS AND SYMBOLS

ADT	Achromatic detection threshold
ANOVA	Analysis of variance
BAT	Brightness Acuity Tester
BSM	Binocular simultaneity
CCT	Correlated color temperatures
DART	Data Analysis and Reduction Tool
HCBM	Heterochromatic brightness matching
HPS	High-pressure sodium
IESNA	Illuminating Engineering Society of North America
LED	Light-emitting diode
MH	Metal halide
NSTSCE	National Surface Transportation Safety Center for Excellence
OD	Optical density
RT	Reaction time
SNK	Student-Newman-Keuls
ST	Search time
STV	Small target visibility
VL	Visibility level
VTTI	Virginia Tech Transportation Institute

CHAPTER 1. INTRODUCTION

The National Highway Traffic Safety Administration's Fatality Analysis Reporting System database reveals that nearly 43% of all highway deaths in 2010 occurred at night with or without roadway lighting.⁽¹⁾ In 2007, the Federal Highway Administration reported that 50% or more of fatal crashes over the previous 25 years occurred at night despite the smaller number of vehicles on the roadway.⁽²⁾ Nighttime driving poses many unique hazards that are not present during the day, such as reduced visibility and contrast sensitivity.⁽³⁾ The reduction of these necessary components of nighttime vision impairs a driver's ability to detect and identify roadway objects and potentially hazardous situations.⁽⁴⁾ Nighttime driving uses both the rods and cones of human vision, referred to as *mesopic* vision.⁽⁵⁾ During nighttime driving, the eye must use mesopic vision to take in all available light and still control for glare and discrimination of objects.

Currently, most roadway lighting uses a high-pressure sodium (HPS) light source. Designers choose HPS because it is efficient in output per watt of input power, but it provides a yellow-colored light that has very poor color-rendering properties. The color-rendering properties of HPS lamps can be improved by increasing the sodium vapor pressure, but this would require a greater expense and a loss of efficiency in terms of lumens per watt.⁽⁶⁾ While an HPS light source is more efficient photopically than white light sources that have better color-rendering properties, the ambient light conditions present during nighttime driving situations prevent the human eye from operating in a photopic condition. Photopic vision is mainly responsible for color and is dominated by the use of cones in the retina. Conversely, scotopic vision is used for low light levels and is dominated by the use of rods located in the fovea. Mesopic vision is in the region between photopic and scotopic (at around 0.001 cd m^{-2} and 10 cd m^{-2}).⁽⁷⁾

While the literature has frequently considered white light to provide a benefit to mesopic lighting levels, the impact of color contrast provided by a high color-rendering source has not been considered. This project considers the impact of color contrast in the driving environment.

RATIONALE

This investigation compared the performance of a driver in two activities related to vision: a detection task and a color recognition task. These tasks were performed under three different lighting systems: two light-emitting diode (LED) systems with differing color temperatures and a fluorescent system.

The two LED lamps have correlated color temperatures (CCT) of 3500 K and 6000 K. A studio lamp has a CCT of approximately 3500 K while 6000 K is closer to the CCT of typical daylight or an electronic flash.^(6,8) It is expected that the 6000-K LED luminaire will have more ambience and better color-rendering properties than its 3500-K counterpart, particularly in the blue portion of the spectrum. The fluorescent bulbs have a 4200-K CCT, a value between the CCTs of the two LEDs.

The purpose of this research is to compare the overall efficiency of object detection during nighttime driving using the two LED light sources and the fluorescent source. This research will then be utilized for future designs and technologies.

RESEARCH OBJECTIVES

1. To determine the visual performance in the detection of an object while driving under each of the three light sources.
2. To determine visibility among different color objects and different illuminance levels while driving under each of the three light sources.

CHAPTER 2. BACKGROUND

VISION

Dim or reduced lighting has major impacts on visual acuity and detection capabilities. Thus, driving at night reduces the ability to detect contrast and poses visual obstacles such as night-time glare. According to Stephenson⁽⁹⁾, even someone with 20/20 vision is not necessarily immune to poor contrast sensitivity, which makes distinguishing foregrounds and backgrounds more difficult because similar colors tend to blend.

NIGHTTIME DRIVING

New technology has allowed for nighttime driving to be studied via eye-trackers. Eye-trackers typically involve cameras that follow the pupils of the human eye and, based on an algorithm, can predict where the individual is gazing. Not surprisingly, eye-tracker studies indicate that the longer the gaze, the more time the looker needs in order to obtain the information necessary to make sense of the environment or situation. These longer gazes likely signify the looker's inability to see and identify targets confidently. Well-lit areas, which promote high visibility, require shorter gazes because information within the roadway is easy to detect. Conversely, dimly lit stretches of road require longer gaze points and thus entail slower reaction times.⁽¹⁰⁾

Current roadway lighting is designed for the foveal view, or the driver's center view.⁽¹¹⁾ However, peripheral information is also required for safe driving.⁽¹²⁾ As Bullough and Rea⁽¹³⁾ explain, off-axis targets may not always be an immediate concern to the driver, but it is better to detect potential hazards even a little bit sooner rather than a short time later when there is less time to avoid potential danger.

At night the eye uses mesopic vision, in which both the cones and the rods are active in the retina to produce the visual response. Mesopic vision shifts the color sensitivity of the eye in two ways. The influence of the rods shifts color sensitivity toward blue. Additionally, reduced cone usage and increased usage of the monochromatic rods reduces color sensitivity, shifting sensitivity toward color blindness. These factors must be considered when reviewing the performance of a driver under a broadband light source.

MESOPIC VISION

There are two major light-sensitive photoreceptors in the human eye known as rods and cones. Photopic sensitivity utilizes cones while scotopic sensitivity utilizes mainly rods. Photopic vision is responsible for the perception of color because the cones respond to light of wavelengths between 360 nm and 760 nm (blue to red). Photometry relies on the photopic luminous efficiency function (V_λ) to represent output from a light source. Cones are mainly found in the fovea of the eye, which is responsible for visual acuity. Scotopic vision is necessary for pitch-black or very low light levels, in which the rod receptors are sensitive to wavelengths of 400 nm to 610 nm (violet to orange).⁽¹⁴⁾ Rods are concentrated mainly in the periphery, which is responsible for achromatic vision and detection. Most lit roadways and parking lots fall within the mesopic range.⁽¹⁴⁾ Table 1 summarizes the differences in rod and cone vision.

Table 1. Comparing rods to cones.⁽¹⁵⁾

Rods	Cones
Used for scotopic vision	Used for photopic vision
Light sensitive; sensitive to scattered light	Not light-sensitive; sensitive only to direct light
Loss causes night blindness	Loss causes legal blindness
Low visual acuity	High visual acuity; better spatial resolution
Not present in fovea	Concentrated in fovea
Slow response to light, stimuli added over time	Fast response to light, can perceive more rapid changes in stimuli
Have more pigment than cones, can detect lower light levels	Have less pigment than rods, require more light to detect images
20 times more rods than cones in retina	20 times fewer cones than rods in retina
Confer achromatic vision	Confer color vision

There are currently not as many reliable models available for defining mesopic visual levels as there are for photopic and scotopic visual levels. There have been several attempts to contrive a visual model for mesopic vision, but ultimately it becomes too difficult to establish consistency, according to Alferdink, 2006.⁽⁵⁾ Yunjian He was an early pioneer in the attempt to establish a unified system of photometry. He sought to form a connection between the photopic efficiency function and the scotopic efficiency function, whose interstice defines the mesopic function region.⁽¹⁶⁾

Eloholma et al.⁽¹⁷⁾ provided an overview of mesopic models that had been characterized by their performance in nighttime driving. There were 15 models listed, 10 of which utilized heterochromatic brightness matching (HCBM) as their method. The visual angles for all 15 of the models varied between 2 and 10 degrees. The models that did not use HCBM used reaction time (RT), binocular simultaneity (BSM), search time (ST), or achromatic detection threshold (ADT).

Rea and Bullough⁽¹⁸⁾ have urged the international community to create a unified system of photometry. In a widely publicized 2007 memorandum, they acknowledge that an effort has been made by the MOVE consortium⁽¹⁹⁾ as well as by the Illuminating Engineering Society of North America (IESNA). When comparing several models for mesopic vision, Rea and Bullough⁽²⁰⁾ mention that the underlying difference between each model is whether or not they follow Abney's Law of Additivity. The example given by the law is that if there are four stimuli and **A** matches **B**, **C** matches **D**, and **(A+C)** matches **(B+D)**, then **(A+D)** matches **(B+C)**.⁽²¹⁾ Rea and Bullough⁽²⁰⁾ stress that this law, the cornerstone of photometry, must be upheld for a unified system of photometry to warrant merit. The methods that do not use Abney's Law of Additivity tend to use psychophysical tests, such as brightness matching, which ignore Abney's law.

In 2010, the Commission Internationale de L'Eclairage (CIE) published a final model that is the combination of the MOVE and the Unified System of Photometry derived from the work of He et al.⁽⁷⁾

It is important to note that the mesopic effect occurs primarily in the periphery of the eye. The fovea contains no rods, so the shift to a mesopic light level is not evident in the fovea.

COLOR CONTRAST

The other effect of the nighttime light levels is the change in color sensitivity. The color appearance of an object also influences the ability of a person to see it. The mesopic effect is strictly a change in the visual performance due to a change in the eye's sensitivity and is related to luminance contrast. Color contrast refers to the chromatic difference of an object from its background. This effect is primarily effective in the fovea of the eye, where most of the color determination of the visual system is evident.

Very little research has been performed relating to the effect of color contrast on object visibility. Eastman⁽²²⁾ discusses an experiment in which color targets were considered in relationship to their visibility. The impact of the color contrast was evident only at low luminance contrast levels and showed an impact of only 5% at higher luminance contrast levels. It is important to note that no human participants made any assessments in this investigation; rather, a visibility metric was used to perform the assessment. It is also important to note that the lighting levels were 100 lux and above. These results may have little or no impact at low lighting levels and in a dynamic environment as that experienced in a nighttime driving situation.

The Eastman paper did show an interesting effect that might need to be considered in the analysis of the color contrast results: small-target tritanopia. There are fewer blue cones in the fovea of the retina than red or green so, for very small objects, the fovea has a limited blue sensitivity.

Freiding et al.⁽²³⁾ explain that the ability to detect a target at night without necessarily being able to identify its color is referred to as *achromatic threshold detection*. Detecting a target or potential hazard is the first step toward taking an appropriate driving action to avoid it. Results by Freiding et al. indicate that the detection threshold for color in the periphery increased as the luminance in the mesopic region decreased. Also, the blue targets had a smaller contrast threshold than the red and green targets for all background luminances used in the study (0.01, 0.1, and 1 cd/m²). This means that the blue targets were more easily identifiable. These results are expected due to the reduction in background luminance which causes increased spectral sensitivity to shorter wavelengths. Szalmas et al.⁽²⁴⁾ add that the shorter reaction time to blue could be caused by the spectral sensitivity of rods. Another explanation proposed by Szalmas et al. for the higher mesopic luminance only, compared to that of red or green, might be the greater visual "conspicuity" of blue light. When the equivalent brightness formula is applied to achieve equal luminance for each of the three colors (green, red, and blue), the difference in reaction times between blue and either green or red becomes smaller.

AGE EFFECTS

Age is an important factor in nighttime driving and mesopic vision. Older drivers (55+) make up nearly one-fourth of all fatal crash victims and nearly one-fourth of all drivers involved in a fatal crash.⁽¹⁾ Horswill et al.⁽²⁵⁾ found a correlation between age and hazard perception response time, as older drivers responded more slowly to traffic conflicts. The contrast sensitivity variable had the most significant impact on hazard perceptions because several of the participants in that study had severe cataracts. Horswill et al. also found that the useful field of view was crucial for hazard perception, as any reduction of vision within the useful field of view makes traffic

conflicts more difficult to detect. A separate study ⁽²⁶⁾ used foam roadway objects to represent hazards. The study showed that elderly participants were surprised by the foam objects regardless of the lighting level, while the two younger age groups identified the objects and avoided them. They hypothesize that the age-related decrease in target detection is likely due to the diminished visual systems in older drivers, including contrast sensitivity.

As the eye ages, changes occur in the optical density (OD) of the crystalline lens. When this occurs, the lens alters the wavelengths of light entering it. With age, the lens becomes more yellow, which affects the perception of hue and contrast.⁽²⁷⁾ This could cause an older driver to have a preference for the yellow hue of the HPS lighting as opposed to the blue light of the LED lighting.

The ability of older drivers to respond to the presence of roadside pedestrians at night is considerably weaker than that of younger drivers. In a 2005 study by Wood et al.⁽²⁸⁾, older drivers detected and recognized only 59% of pedestrians whereas younger drivers recognized 94% of pedestrians. Older drivers also recognized pedestrians much later than did the younger drivers.

Owens and Tyrell ⁽²⁹⁾ found that steering accuracy for older drivers in low-luminance settings was poorer than that of younger drivers. However, Owens et al. ⁽²⁶⁾ found that older drivers tended to drive more cautiously in a low-luminance setting than did the younger drivers.

COMPARING LIGHT SOURCES

Color temperature describes the color of a radiating source at a particular temperature. The temperature does not relate to the heat radiating from the source; instead, it is the absolute temperature of a blackbody radiator having a color equal to that of the light source. CCT is the absolute temperature of a blackbody whose color most nearly resembles that of the light source; in the case of this study, the two LED systems and the fluorescent system. Color temperature is often used to define the color performance of a light source. This may not always be effective because the same color temperature can be reached by a variety of spectral output characteristics.⁽¹¹⁾

The light source has been shown to have a significant impact on visual performance. In a laboratory trial, Rea (30) compared HPS light sources and metal halide (MH) sources, each at two luminance levels (0.1 and 1.0 cd/m²). Participants completed a discrimination task with these two light sources. HPS and MH lamps lit opposite portions of an isolated roadway. Participants were asked which end of the street appeared brighter and which end they would feel safer walking along at night. The participants perceived the MH lamps to be much brighter and safer for walking along at night. The study suggests that white light, in this case produced by the MH lamps, appear brighter than the light from the HPS lamps of the same luminance.⁽³¹⁾

Three studies suggest that color recognition is greater for white light sources than for HPS or yellow light sources.^(32,33,34) The lamp type (white or HPS) and the amount of luminance affected color recognition. Two of the three studies suggest that the color rendering for a white light source with a luminance of 0.1 cd/m² is almost equal to or better than the color rendering for an HPS source with a luminance of 1.0 cd/m², a 10-times greater luminance.⁽⁷⁾

A nighttime driving study by Rea et al.⁽³⁵⁾ found that reaction times to off-axis targets were shorter under an MH lamp than under an HPS lamp. Ratings of overall visibility and peripheral reaction times were also greater under the MH illumination.

A study by Akashi et al.⁽³⁶⁾ used off-axis targets and found that MH light sources were responsible for shorter reaction times versus HPS lamps of the same photopic light levels. This study also demonstrated that task performance improves with unified luminance. In addition, under unified luminance, objects on- and off-axis could be detected much more quickly without increasing energy requirements. Akashi et al. also point out that an increased peripheral view may not be appreciated by drivers and may not change their driving behaviors.

Light sources that improve mesopic visual ranges, like those that produce white light, may also have negative consequences, such as increased glare in fog and snow conditions.⁽³⁷⁾ Also, because white light increases luminance on the immediate roadway as well as in the periphery, falling snow could be a possible distraction to the driver.

The IESNA Lighting Handbook⁽¹¹⁾ states that the color rendering properties of lamps (for example, between a low-pressure sodium lamp and a yellow fluorescent lamp) will be much different compared to daylight. Under sodium lamps, objects will lose their daylight appearance and appear as one hue. Under the yellow fluorescent lamp, more hues can be recognized, but the colors will still differ considerably from those seen in daylight alone.

It is important to note that the studies described here typically have a limited assessment of the impact of color on performance.

CHAPTER 3. EXPERIMENTAL METHODOLOGY

EXPERIMENTAL DESIGN

A 2x3x2x2 mixed factors experiment was used to investigate the relationship of color contrast to object detection and recognition in the roadway environment. The factors are shown in Table 2.

Table 2. Experimental design.

Variable	Levels
age	younger, older
lighting	LED (3500 and 6000 K), fluorescent (4200 K)
object/color	targets (red, green, blue, gray), pedestrians (blue-clothed, black-clothed)
lighting level	12 lux, 6 lux vertical

Independent Variables

As shown in the experimental design, this study included many variables. Independent variables included age, light level, object, object color, and lighting type. There were two age groups: younger (25-34 years) and older (55 years and up). The vertical illuminance on the object of interest was the basis for determining the two light levels chosen: 12 lux and 6 lux. The fluorescent systems were not able to achieve the 12-lux level, so their scenarios included objects lit at only 6 lux. Objects, as will be discussed later, were pedestrians and square, wooden targets. Lighting type comprises the three lighting systems tested in the study: the 3500 K LED, the 6000 K LED, and the fluorescent system.

Dependent Variables

This experiment used two dependent variables: the initial detection of the object placed along the roadway and the point where the object's color is recognized.

This study operationally defines detection distance as the distance between the onset of verbal detection and physically passing the object in the vehicle. Detection distance is an important factor in determining an object's visibility. Logically, if a participant can see an object, then it is visible. The distances at which a participant can see objects corresponds to the objects' visibility at those distances.

This study defines recognition distance the same way, with recognition distance being related to color. After the participant detects the object, he/she then recognizes its color and states it aloud. The recognition distance is the distance between the point of recognition and the physical passing of the object.

EXPERIMENTAL EQUIPMENT AND SETUP

This experiment required a variety of equipment and vehicles, including the visual targets, the test track, and the measurement systems.

Smart Road Testing Facility

The research was conducted at the Virginia Tech Transportation Institute (VTTI) and on the Virginia Smart Road. The Smart Road is a 2.2-mile test track with guard rails and pavement markings. Dispatchers control entry to the facility. The Smart Road has one intersection with a signal, which was not used for this study. The Smart Road also has three bridges. No tasks or events related to the study occurred on or near the bridges.

Figure 1 illustrates the Smart Road test track. The blue numbers indicate the stations along the road where targets and pedestrians were placed. The orange section of the road is the lighting test bed containing the LED and fluorescent lights. The Smart Road has five turnarounds, one on each end and three in the middle. This study used turnarounds 2 and 3.

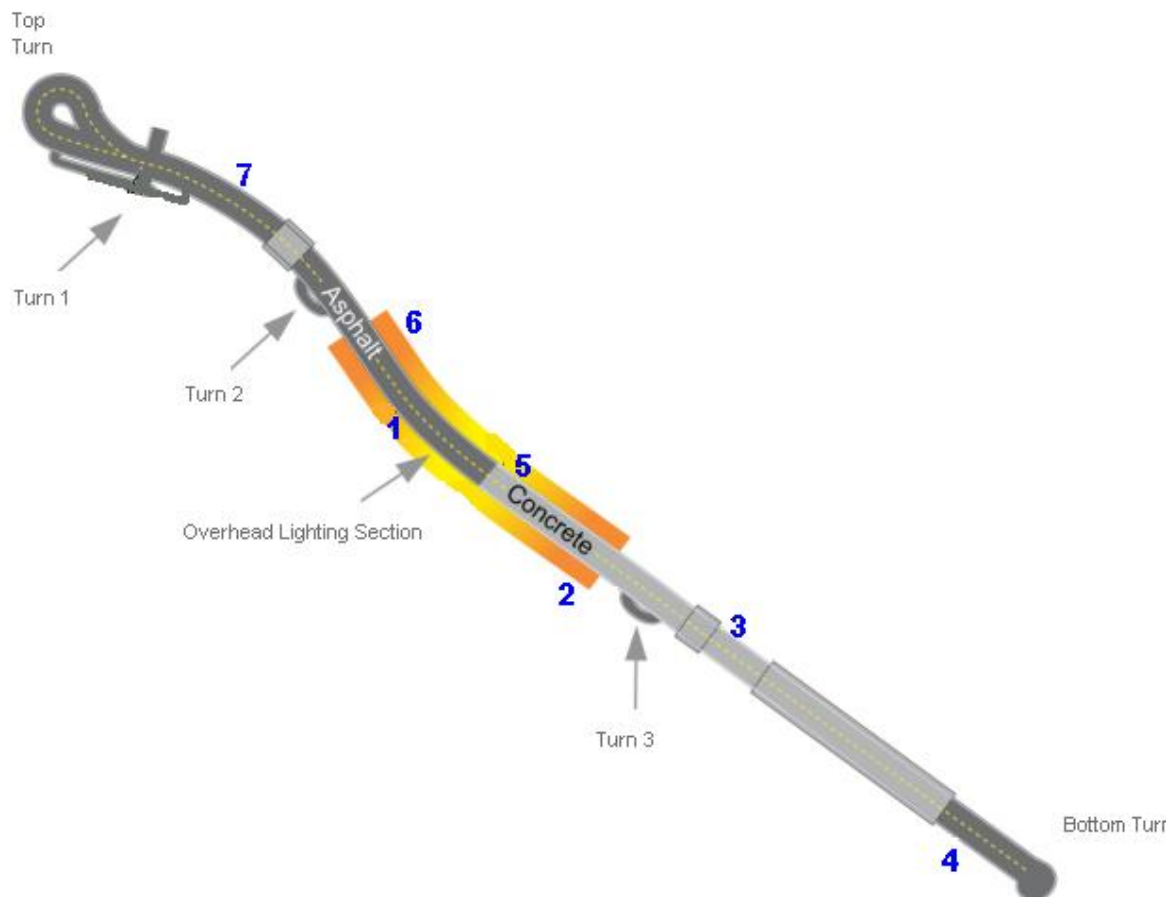


Figure 1. Smart Road test track.

The lighting system on the Smart Road used for this testing was spectrally measured using an Ocean Optics S2000 spectroradiometer. Figure 2 presents the results.

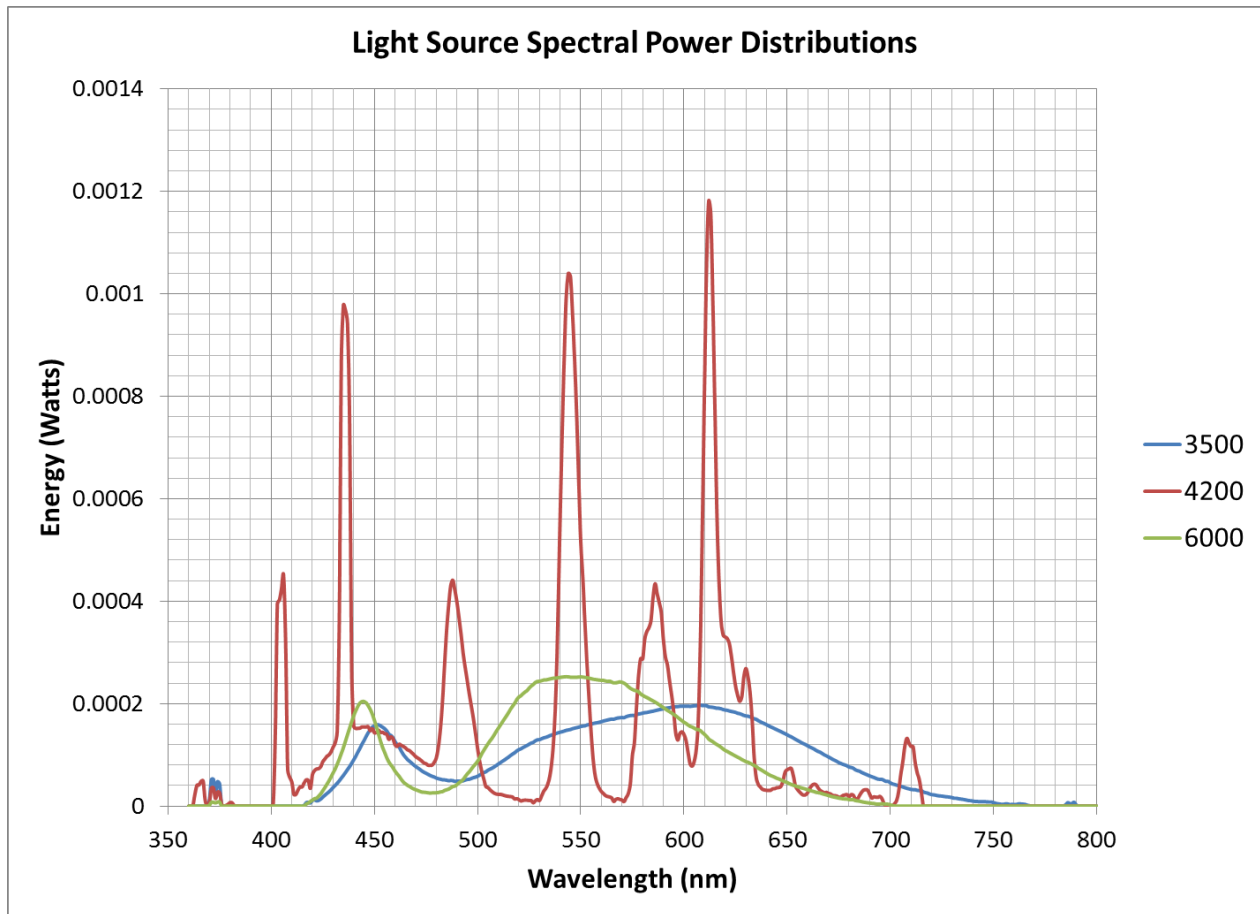


Figure 2. Spectral power distributions of the test lighting systems.

Pedestrians and Targets

The roadside objects for participant detection were pedestrians and painted wooden targets. Vehicles striking pedestrians at night is an obvious concern. Pedestrians in the study wore all-denim scrubs (because denim is a commonly worn type and color of clothing) or all-black scrubs to represent a worst-case scenario for a pedestrian at night. The pedestrians stood on the right side (outside) of the shoulder line on the roadway and remained static as the experimenting vehicles passed.

The wooden targets measured 18 cm by 18 cm. Many roadway obstacles fall within this size range. As Figure 3 shows, each target was uniform in color and had a flat face, which facilitated gathering luminance data from the targets. Determining the contrast of an obscurely shaped object – such as pedestrians who vary as to size and shape – is much more difficult than with a flat, smooth surface such as the wooden targets. The four colors for the targets—gray, blue, green, and red—were chosen based on their contrast to the roadway and the color sensitivity present with the two different kinds of light sources. Gray is a neutral color while blue, green, and red are additive primaries.

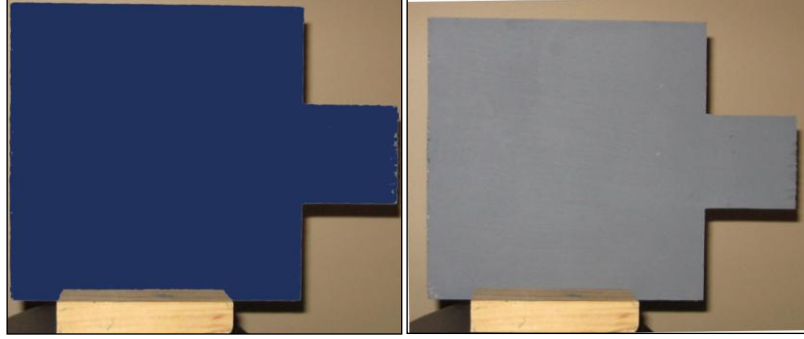


Figure 3. Targets.

The wooden targets were designed to break on contact if a participant mistakenly ran them over. They were placed two feet outside the right-hand white edge line on the roadway, upright, facing oncoming vehicles. The targets were presented at locations of equal illuminance for both light sources (6 and 12 lux). The participants were asked to drive toward the targets and identify 1) the presence of a target, and 2) the color of the target. Once the participant identified the target, the in-vehicle experimenter pressed a button to record within the data stream when the identification was made. A button press was also recorded when the color of the target was identified by the participant. A third button press was recorded when the participant vehicle passed the object. These button presses were used to generate algorithms that measured the distance of detection from the actual target. In-vehicle experimenters kept notes to decipher the button presses if they did not follow the order of identification and recognition. Each video file for every participant was also reviewed during data analysis to more precisely determine the moment of identification, recognition, and passing of the object.

Figure 4 depicts a red off-axis target. Note that red off-axis targets were not actually used in the study's protocol, but the figure depicts the size and shape of the off-axis targets used. Colors for off-axis targets were blue and gray. These targets were placed just beyond the right guardrail to represent objects that were potential hazards instead of immediate ones. These objects were placed to appear in the peripheral vision of the driver to assess how the two LED lighting systems and the fluorescent system affected ambient detection. The targets were mounted on tripods so drivers could see them over the guardrail and still recognize their shape. The silver legs of the tripod were covered in a black plastic bag so that they would cast no reflection that might give away the target's presence and location.



Figure 4. Off-axis target.

It is important to note that these targets adhere to Adrian's⁽³⁸⁾ small target visibility (STV) model. The model suggests that the ability to detect a standard small target (~18 cm square) propped vertically on the road is a quality measure for assessing the visibility made available by a particular roadway lighting system. The visibility level (VL) is computed as the ratio between the contrast between the target and its background and the detection threshold. The greater the VL, the more visible the target.⁽³⁹⁾

The target reflectance was measured spectrally using the same Ocean Optics S2000 spectroradiometer. The spectral reflectance of each target is shown in Figure 5. Note that yellow, which is included in Figure 5, was not a target color used in the current investigation. The content in Figure 5 was generated prior to this current study.

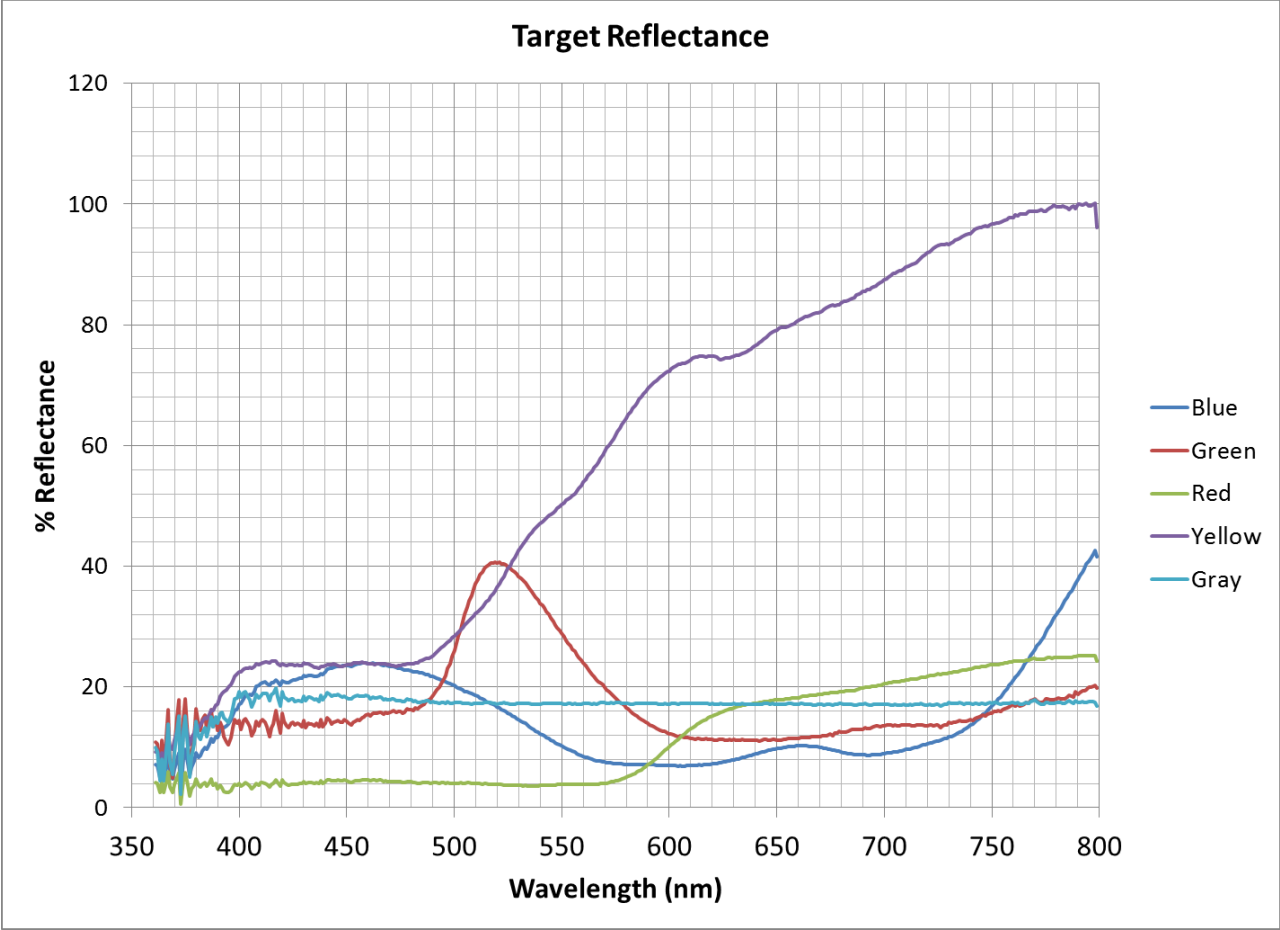


Figure 5. Target spectral reflectance.

Figure 6 shows the location of each of these targets in the CIE color diagram. This figure shows the targets as a reference reflectance and the target colors as they would appear under each of the light sources. Here, the target color is indicated by the marker color, and the color temperature of the light source is indicated by the marker shape. It is noteworthy that the color appearance of the red target is relatively unchanged by the light source, with the exception of the 6000-K LED. The gray target remains relatively close to the Planckian locus and would remain generally spectrally neutral. The blue target is pulled to the spectrum locus under the 6000-K LED light source but retains a blue appearance under the other light sources.

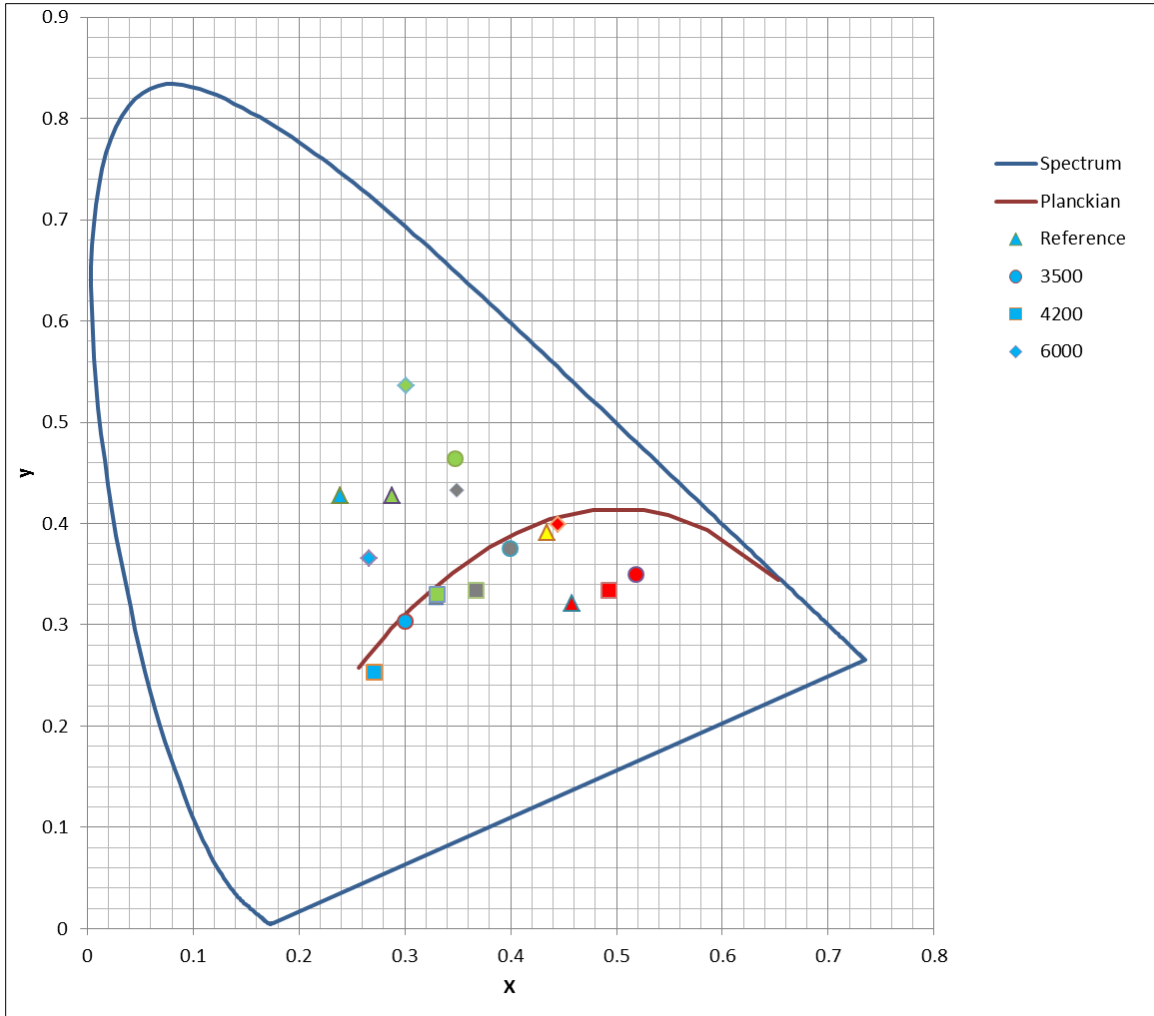


Figure 6. CIE diagram with target colors highlighted. (7)

Vehicles

Figure 7 shows one of the two vehicles used for the study; two SUVs: a 1999 Ford Explorer, and a 2000 Ford Explorer. Each vehicle was similarly instrumented for data collection. The data collection equipment includes digital audio and video recorders, luminance and eye-tracking cameras, small monitors, and keyboards.



Figure 7. Ford Explorer.

The headlamps of both vehicles had been characterized for their spectral and luminance contribution to objects along the roadway. The headlamps for both were aligned prior to the study to control the angle of light coming from the vehicles. Each vehicle was equipped with a color camera and a luminance camera mounted to the windshield to record luminance data throughout the length of the study (Figure 8). For every target and pedestrian detection, the luminance and color data are captured from the time the in-vehicle experimenter presses the button. The cameras had undergone a successful calibration with a relatively high level of accuracy based on comparisons to other known luminance values. The calibration study for the luminance camera was conducted at VTTI in 2009 and has been published by The National Surface Transportation Safety Center for Excellence (NSTSCE).⁽⁴⁰⁾



Figure 8. Luminance and color cameras.

PARTICIPANTS

The 40 participants were selected from the VTTI subject database, an in-house database that stores contact information, demographical information, and previous experience at VTTI for willing participants, on the basis of age. Nineteen participants between the ages of 25 and 34 years made up the younger participant group, and 21 participants 55 years and older made up the

older participant group. The younger age group averaged to 29.1 years old while the older averaged to be 58.5 years old. Because contrast sensitivity diminishes with age⁽²⁶⁾, it was important to compare the abilities of the two age groups to detect objects under each lighting condition. The populations chosen for this research study reflect different driver characteristics, including visual and physiological characteristics. For example, older drivers benefit from their driving experience. However, visual and physiological changes may occur with age, which may result in different amounts of discomfort and disability glare. Younger drivers more often have normal vision. However, they may react to glare sources in a different manner.

Because of the three different light types being tested in the study, each participant was asked to return to VTTI on three separate nights (one night per light source).

Screening criteria for participant selection included:

- 1) Must hold a valid driver's license.
- 2) Must not have more than two moving violations in the past three years.
- 3) Must have normal (or corrected to normal) vision.
- 4) Must be able to drive an automatic transmission vehicle without assistive devices.
- 5) Must not have caused an injurious accident in the past three years.
- 6) Females must not be pregnant.
- 7) Must not have lingering effects of heart condition, brain damage from stroke, tumor, head injury, recent concussion, or infection. Must not have had epileptic seizures within 12 months. Must not have current respiratory disorders, motion sickness, inner ear problems, dizziness, vertigo, balance problems, diabetes for which insulin is required, or chronic migraine or tension headaches.
- 8) Must not currently be taking any substances that may interfere with driving ability, cause drowsiness, or impair motor abilities.
- 9) Must be eligible for employment in the United States.
- 10) Must drive at night at least two times per week.
- 11) Must not have had eye surgery.

Participants were compensated \$20 for every hour they participated in the study, including time spent filling out questionnaires.

The two age groups were chosen on the basis of driving experience and age characteristics that can affect vision. The younger participants (25-34) typically had similar driving experience, drove frequently at night, and did not usually have a notable yellowing of their lenses. The older participants (55 and up) had much more driving experience, may still have driven a substantial amount at night, and had a greater likelihood of lens discoloration. Coren and Gurgis⁽⁴¹⁾ found that the yellowing of the lens starts at birth and becomes more rapid around ages 45-50 years. These results indicate that the older age group was anticipated to have more difficulty detecting contrast than the younger age group due to changing optical density with age.

EXPERIMENTAL METHODS

Participant Orientation

Once the participants arrived at VTTI, they were taken into the conference room to be briefed and screened. The in-vehicle experimenter recorded the time the participant arrived on the participant's receipt and asked to see the participant's driver's license to verify its validity.

The participant was then asked to carefully read and sign the appropriate informed consent form. The eye-tracking participant had a separate informed consent form. Once the participant had read and signed the informed consent form, the participant was asked to complete a W-9 tax form as well as a brief medical questionnaire. Once these were completed, the participant was ready to begin the vision tests.

Pre-Drive Vision Tests

Snellen

The Snellen test was the first vision test given to participants after the completion of their paperwork. Using both eyes, participants were required to read the smallest line of print they could on the Snellen chart. This vision test is the only test that could disqualify a participant from the study. All participants were required to score a 20/40 or better with both eyes at once. The Snellen eye chart exam is the most commonly used form of testing for obtaining a driver's license in the United States.⁽⁴²⁾

Color Vision

The color vision test was given using an Ishihara Color Vision Exam. The participants were asked to identify the numbers on each of seven slides. The researchers were interested to see how participants with poor color vision would fare during the driving study; perhaps one light would make a clear difference in their abilities to identify the colors of the targets and pedestrians. No one failed the color vision test.

Brightness Acuity Test

Although glare was not a construct built into the study, participants were tested using a Brightness Acuity Tester (BAT) to determine their sensitivity to glare. The BAT is a handheld device that a participant places over one eye while covering the other. A light inside the eyepiece adjusts the amount of glare directed toward the lens of the eye. While doing this, participants were asked to read lines off of the Snellen eye chart, and their scores were recorded for each eye. Participants could not be disqualified based on this exam, but the data from the exams were recorded to examine possible correlations between the two light sources.



Figure 9. Brightness Acuity Tester (BAT).

Contrast Sensitivity

This test was particularly important to the study because contrast sensitivity plays a major role in the differentiation between objects and their backgrounds. The test itself is a chart with various contrast ratios between grated lines.



Figure 10. Contrast sensitivity chart.

Lines at the top of the chart are darker and thicker, thus providing more contrast than the lower rows that consist of thinner and lighter lines. Participants were asked to look across each row and identify the orientation of the lines in each circle until the lines disappeared. The lines slant left or right or are completely vertical. The participants completed the test for each eye while covering the other.

Vehicle Familiarization and Practice Run

Each participant was shown to their experimental vehicle by the in-vehicle experimenter. The experimenter demonstrated to the driver how to correctly adjust the seat, steering wheel, and mirrors. The side mirrors in the study were covered with a felt cloth to prevent the driver from being distracted by potential headlamp glare from the other participant vehicle. The rearview mirror remained uncovered, and the participant could adjust it. The experimenter also gave instructions on how to operate the headlamps and other dashboard operations. It was important to make all these adjustments so that the driver was in a normal, comfortable position prior to the movement of the vehicle.

Once the eye-tracker was calibrated for the participant selected to use the eye-tracking device, the in-vehicle experimenters instructed both participants to enter the Smart Road. Upon entering the Smart Road, the participants were told to drive to Turn 2 (see Figure 1). Once both vehicles arrived at Turn 2 and the on-road experimenters verified that the road was clear, the participants began a practice lap on the section of the road where they would soon perform four test laps. The purpose of this practice lap was to familiarize the participants with the upcoming experimental tasks, remind them of the speed limit (40 mph), and make them more comfortable with the vehicle. Once the practice lap was completed, both vehicles returned to turnaround 2 for a brief questionnaire.

Two participants partook in the study simultaneously but were routed so they never needed to pass each other throughout the road course. Both participant vehicles used Turn 2 as a starting point. The first vehicle departed from Turn 2 and traveled to the bottom turn and returned to Turn 2 for a single lap. The second vehicle departed Turn 2 shortly after the first vehicle and followed the path of the first vehicle, except that it turned at Turn 3 and traveled to the Top Turn and back down. Once the second vehicle passed Turn 2 on the way toward Turn 3, a lap had been completed. For every lap, both participants saw the same targets and pedestrians placed in the lit portion of the road, as this part of the road was shared. The unlit portions of the road were different in terms of number of targets and pedestrians; however, the colors of these objects were counterbalanced. The participants were also counterbalanced for what end of the course they drove (top or bottom) and the order they drove them in. The participant vehicles never approached each other throughout the experimental session.

When participants returned to VTTI on subsequent nights for the other light sources, the same protocol was followed for entering the road and completing the practice lap and four test laps. On the second night, once participants returned to the building, they were administered the “Night Two” questionnaire, which asked them to compare the lighting of the current night to the lighting from their previous visit. The third visit was similar. Participants were administered a questionnaire that asked them to compare the lights from all three visits. Each questionnaire also asked the participant to rate their own abilities to accurately remember the previous visits.

Data Collection

The participants drove four test laps consisting of one lighting condition each night (6000 K LED, 3500 K LED, or fluorescent). The subsequent nights included a different lighting scenario under the same protocol so that each participant received each type of lighting type paired with

each scenario. Light presentation order was counterbalanced. Participants were asked to verbally identify targets, target color, pedestrians, and pedestrian color as they drove with the in-vehicle experimenter pressing the button that triggered the data recorder. Upon completion of the four test laps, both vehicles met in turnaround 2, and the participants were administered a Post-Scenario Questionnaire. The same protocol was followed for the second and third nights for every participant.

Experimental Procedure

As participants drove up and down the Smart Road, they passed a certain number of the seven stations located alongside the road depending on which end of the course they drove. Confederate experimenters were at each station to either place a target or pose as a pedestrian. The confederates had order sheets that instructed what object and color they were to present for each lap. The orders were counterbalanced across all three light sources so that, on subsequent nights, participants were less likely to expect a particular object or color. Experimenters also attempted to alternate each participant's end-of-the-road course (top or bottom) on each night. However, there were instances when this was not possible given the availability of participants and their previous route. All participants did experience each end-of-the-road course at least once in their three nights.

Using a computer in the passenger's seat of the vehicle, the in-vehicle experimenter pressed a button as the participant verbalized an identification to flag the instance in the data to be reviewed later. After verbal color recognition, the participant would again press the button to flag the instance. As the vehicle passed the object, specifically when the object was parallel to the passenger, the experimenter pressed the space bar to advance the program to the next object. Speed and the time between button presses determined the detection distance between verbal recognition and the object.

QUESTIONNAIRES

Once the five laps and the post-task questionnaires were completed, both vehicles returned to VTTI. The participants were allowed to use the restroom. On the second and third nights, they were then administered different questionnaires which were more comprehensive questionnaires of the entire study. Once these were completed, the participant's end-time was logged, and the participant was paid based on his/her time engaged in the study. Participants who completed all three nights received a \$30 bonus, which had been explained to them in their recruitment.

DATA ANALYSIS

The data analysis was performed in series of steps: video reduction to determine the detection and color recognition distances, a luminance analysis, and the statistical analysis.

Video Reduction

VTTI uses in-house software, Data Analysis and Reduction Tool (DART), to reduce videos taken from experimental vehicles. This tool is specific to the data collected in the vehicle and records several variables, including speed, object distance, time, and when an experimenter flagged a participant's identification of an object and its color.

Reducing a video with this software tool requires aligning the frame number of the video to the data and observing the video for when the experimenter pressed a button to flag an event. These instances are made obvious in the data. The data reductionist watches this segment of video to more precisely determine the point of identification and the point that the object was passed by the vehicle. The difference between the point of detection and the point where the vehicle passed the object was used as the detection distance. Similarly, the point of proper color recognition and passing point were used to calculate the recognition distance.

TARGET LUMINANCE ANALYSIS

The contrast and luminance of the targets and pedestrians were assessed using a program created in MATLAB® for luminance as part of an NSTSCE endeavor. This reduction used the still images taken by the luminance cameras mounted on the windshield of the vehicle and traced the target image at the frame number associated with the detection or recognition. Once the image was traced, the reductionist verified the image's validity and the program calculated the luminance of the target object, and the contrast of the image as well using the surrounding elements outside of the trace.

The program was created to utilize a number of different contrast metrics, including CIE95, Michelson, IESNA, RSS, PSS, and Doyle. This project did not use these metrics, but additional information about them can be found in Meyer and Gibbons, 2011.⁽⁴³⁾ This study, as well as most other studies that use the program, use the Weber Contrast metric, which is the comparison of a target of uniform luminance to its background of uniform luminance. This metric incorporates negative contrast, which many other metrics do not. The ones that do not use negative contrast instead convert the negative values into absolute values. The Weber metric was selected because true negative contrast is important in this study.

The equation below is used to calculate Weber Contrast.

Equation 1: Weber Contrast

$$\text{Weber contrast} = \frac{\Delta L}{L_{bkg}}$$

Where:

ΔL = Luminance of a target – Luminance of the background

L_{bkg} = Luminance of the background

After each cutout is assigned a luminance value for the target image and its surrounding elements, it is automatically uploaded to a database that places the contrast and luminance information on the same line as the object's identification and color recognition distances.

STATISTICAL ANALYSIS

After DART was used to reduce the data from its raw state, a statistical program analyzed the findings. SAS Enterprise Guide 4.2® was used to design an analysis of variance (ANOVA) to determine the various effects of the treatment conditions. The ANOVA highlighted the interactions that were found to be statistically significant regarding the varying combinations of object color, lighting level, lighting type, age, contrast, and detection and recognition distance.

Separate ANOVAs were used for targets and pedestrians because each shared different traits, such as color and size. Separate ANOVAs were also used to differentiate the significance of the object detection distance and the significance of the color recognition distance. The Student-Newman-Keuls (SNK) test was also used to determine the levels of significance between each interaction.

The results for the off-axis targets and the questionnaires were not analyzed for this project. These analyses will be undertaken at a later time.

CHAPTER 4. RESULTS

INTERACTIONS

Table 3 shows the list of interactions highlighted by the ANOVA analysis.

Light type was significant for both the detection of targets and pedestrians. The few significant effects may be due to the complexity of the study's design although it is not unexpected to have few significant factors in an actual driving experiment. Comparisons of interest are highlighted and discussed in this section.

Table 3. Interactions and main effects.

<u>SIGNIFICANT INTERACTIONS</u>				
<u>BETWEEN</u>	Target Detection	Pedestrian Detection	Off- Axis Target	Off- Axis Peds
Age				
<u>WITHIN</u>				
Lighting Level				
Lighting Level by Age				
Target Color				
Target Color by Age				
Lighting Level by Target Color				
Lighting Level by Target Color by Age				
Lighting type	X	X		
Lighting type by Age				
Lighting Level by Lighting type				
Lighting Level by Lighting type by Age				
Target Color by Lighting type				
Target Color by Lighting type by Age				
Lighting Level by Target Color by Lighting type				
Lighting Level by Target Color by Lighting type by Age				

DETECTION OF TARGETS

The results for the target detection are presented below. In these figures, participant age categories are denoted by O and Y for older and younger, respectively.

The impact of the lighting system and the target color have to be considered in two different analyses, the first at high levels of vertical illuminance and the second at low levels of vertical illuminance. This is necessary because the experimental design was unbalanced in the green

target category (as mentioned earlier, the green target only appeared at the low luminance level for the fluorescent lighting system).

Figure 11 indicates the significant main effects of lighting type and detection distance regardless of target color, age, or lighting level ($df=2$, $F\text{-Value}=6.91$, $p=0.0025$). These results are significant in terms of the average distance at which a driver can identify a target's presence. The fluorescent lighting provided a longer detection distance than either type of LED lighting.

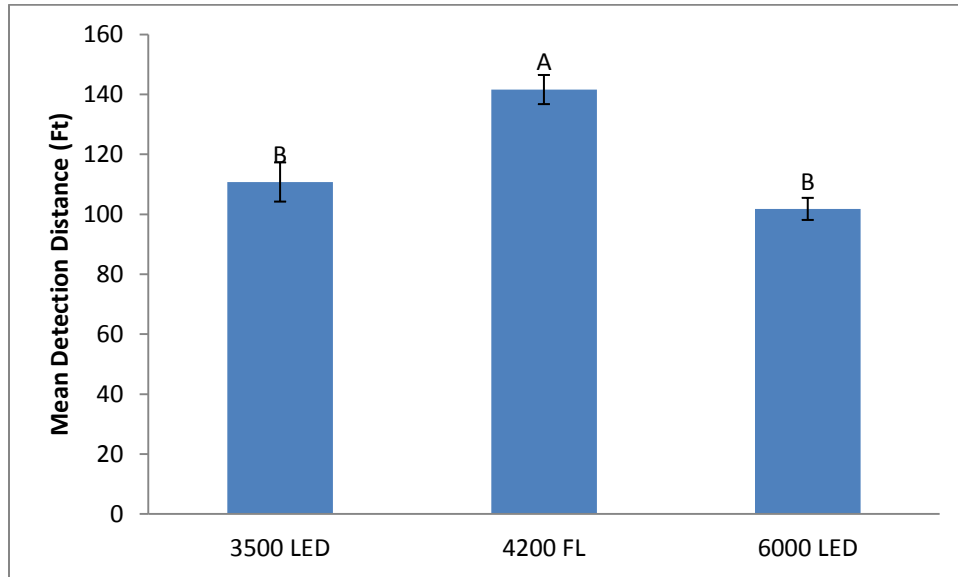


Figure 11. Target detection by light type.

Figure 12 depicts the interaction that lighting level and target color have on detection distance. The overall impact of the vertical illuminance level is that the targets under the lower illuminance level were detected sooner than those at the higher illuminance. This is likely due to the contrast of the target. The higher illuminance may have actually decreased the targets' contrast and, therefore, reduced their visibility. These findings were not significant ($df=5$, $f\text{-value}=1.67$, $p=0.165$).

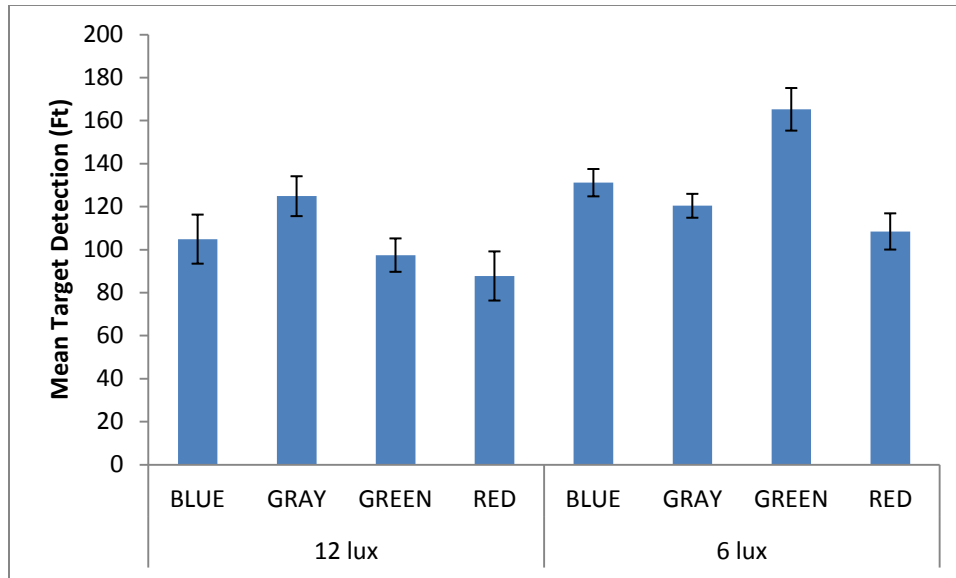


Figure 12. Target detection: Target color and lighting level by mean detection distance.

The scatter plots shown in Figure 13, Figure 14, Figure 15, and Figure 16 employ Weber's Contrast formula. The contrast axis (left) depicts 0 through 1 as positive contrast (brighter target than background) and 0 through -1 as negative contrast (brighter background than target). It is important to note that the contrast increases from negative to positive as the distance decreases. This is a result of the onset of the headlamp lighting. As the vehicle approaches the object, the illuminance from the headlamps increases the luminance and, therefore, makes the target's contrast more positive. This transition typically takes place around 150 to 200 ft, which is a typical distance for the reach of headlamps.

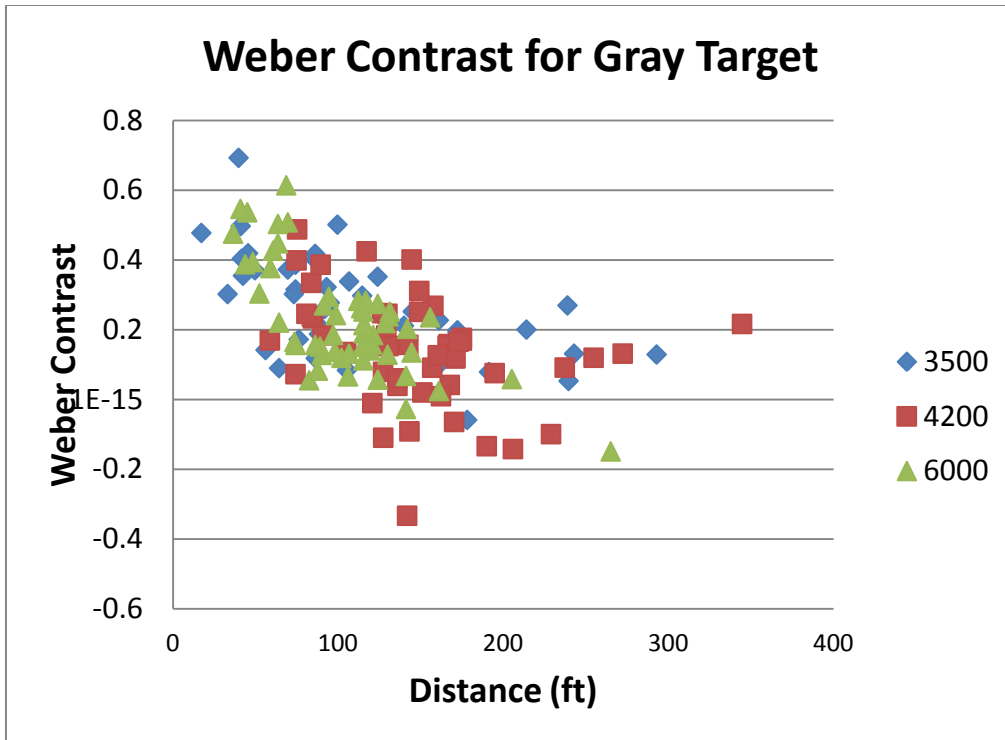


Figure 13. Target detection: Weber Contrast for gray target.

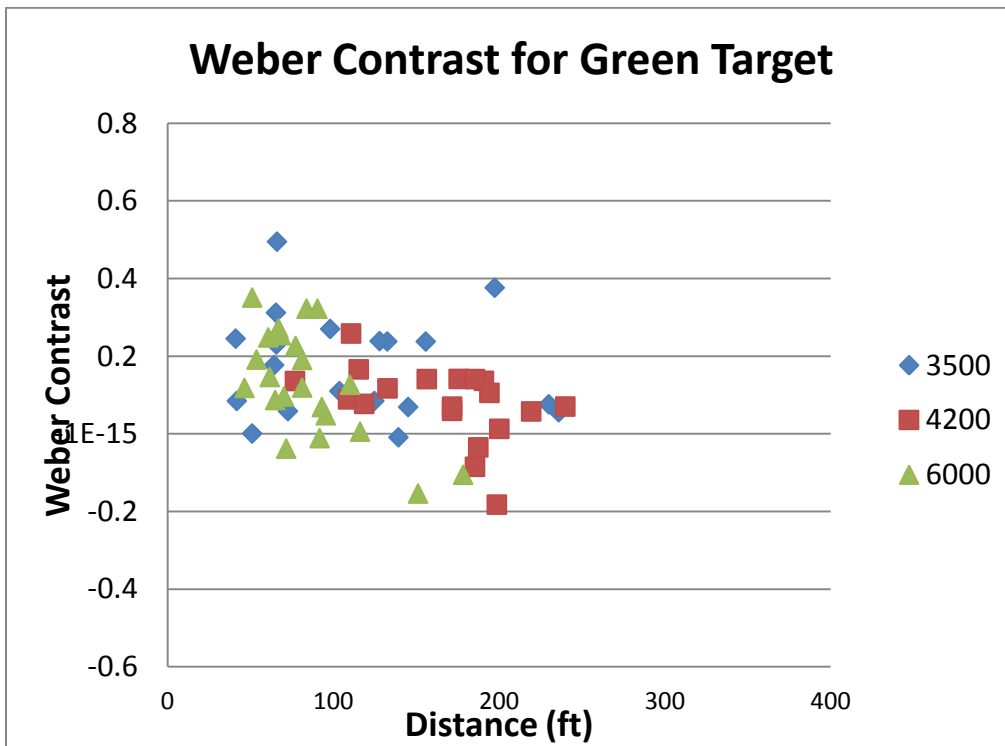


Figure 14. Target detection: Weber Contrast for green target.

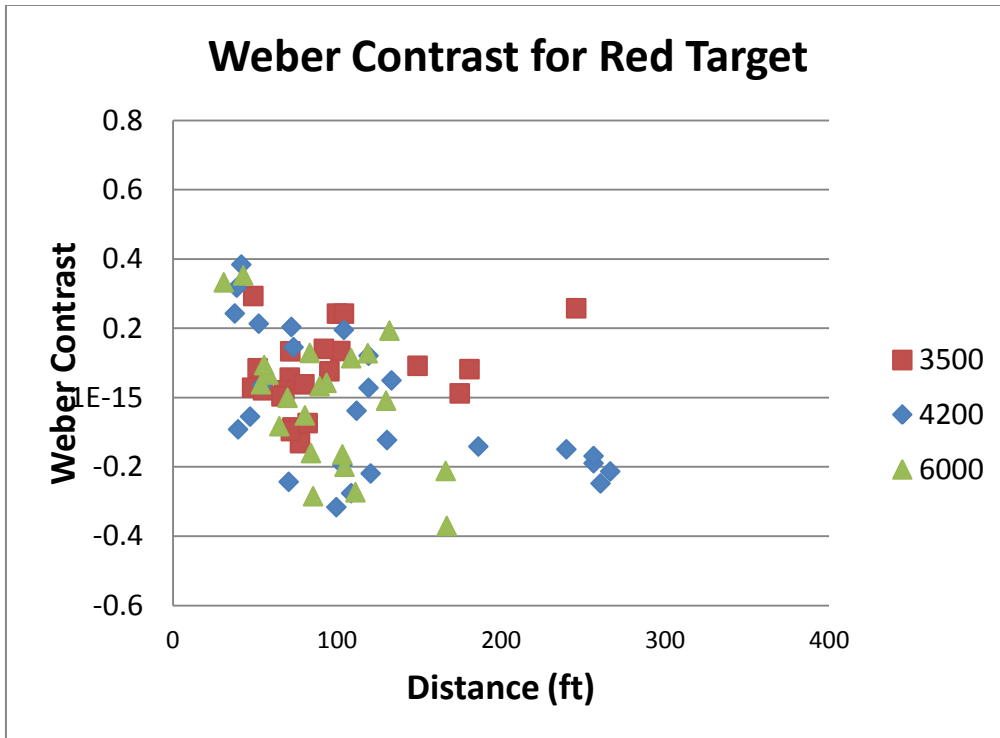


Figure 15. Target detection: Weber Contrast for red target.

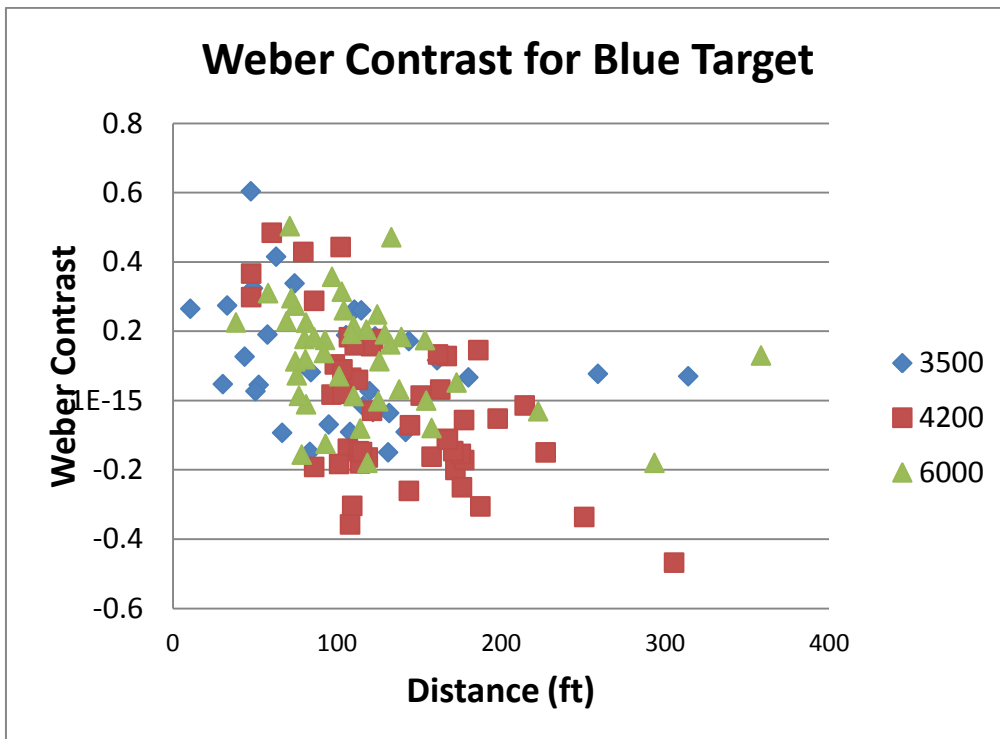


Figure 16. Target detection: Weber Contrast for blue target.

DETECTION OF PEDESTRIANS

The analysis of the pedestrian detection results is shown below. The primary factor is the main influence of the lighting system type.

Figure 17 indicates the significant effects of lighting type and detection distance regardless of pedestrian color, age, or lighting level ($df=2$, $F\text{-value}=10.83$, $p=0.002$). These results show that lighting types 3500 K LED and 6000 K LED are significant in terms of the average distance at which a driver can identify a pedestrian and provide a longer detection distance than the fluorescent lighting.

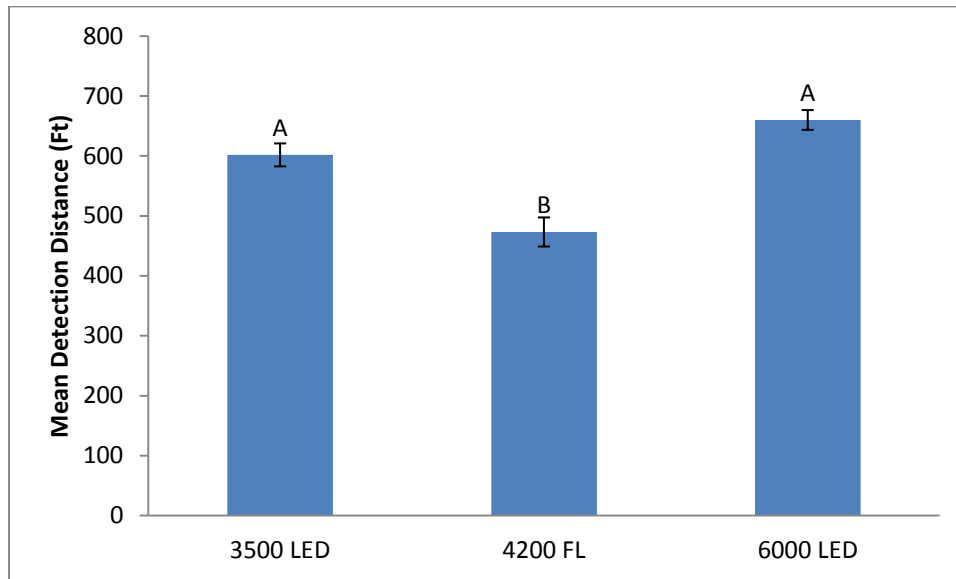


Figure 17. Pedestrian detection: Mean detection distance by lighting type.

The interaction of clothing color, lighting type, and age was found to be non-significant. However, Figure 18 shows that detection distance of pedestrians for older participants was shorter under fluorescent lamps. Mean detection distances under both the fluorescent lamps and the 6000 K LED lamps slightly dropped off from black clothing to denim clothing. However, the 3500 K LED lamps slightly increased the mean detection distance. Of interest, however, is the comparison of the performances of younger and older drivers. Figure 18 shows the results for younger drivers, who had longer mean detection distances of the denim-clothed pedestrians compared to the black-clothed pedestrians. This increase was not evident for the older participants. The blue clothing, particularly blue clothing under a bluer light source such as the 6000-K LED, had a shorter detection distance among older participants. This was likely due to the yellowing of the lenses of the older participants.

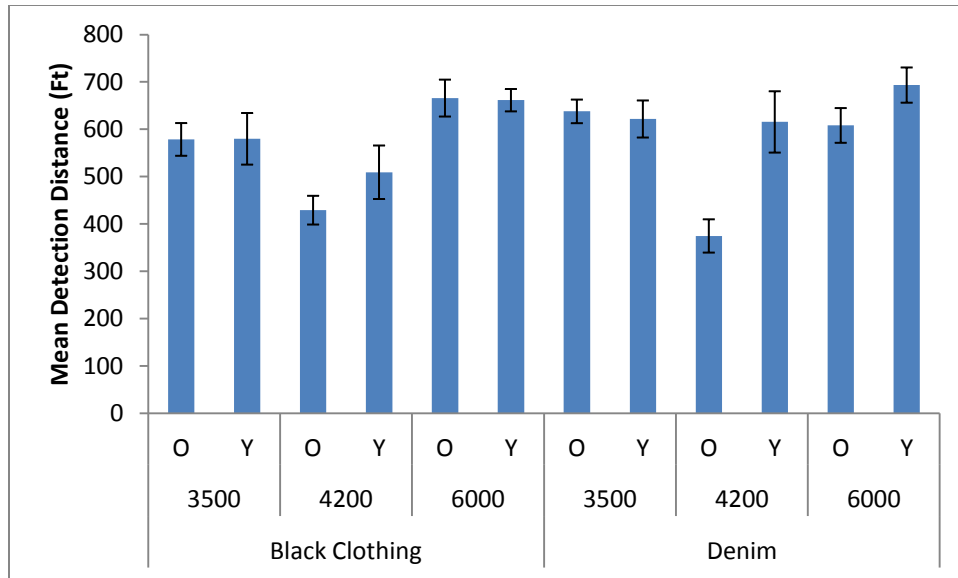


Figure 18. Pedestrian detection: Clothing color and lighting type by age.

Figure 19 and Figure 20 show the contrast results for the pedestrians. Here the influence of the headlamps is not seen. Of primary interest is that the contrast for the black-clothed pedestrians is more negative than that of the denim-clothed pedestrians.

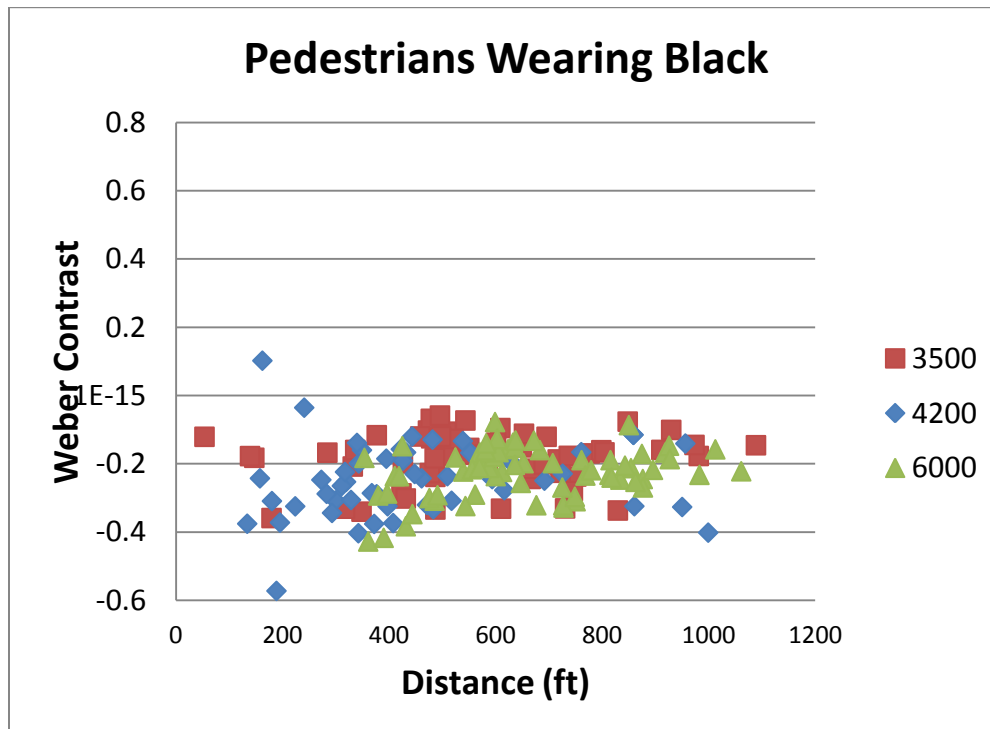


Figure 19. Pedestrian detection: Weber Contrast for pedestrians wearing black.

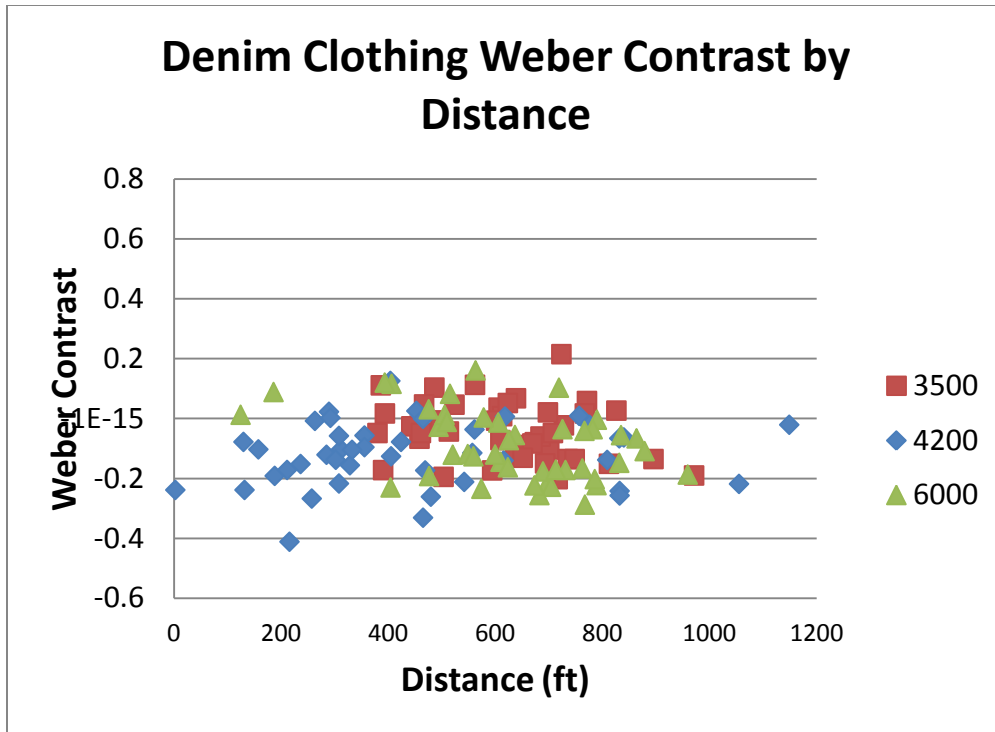


Figure 20. Pedestrian detection: Weber Contrast for pedestrians wearing blue (denim).

DETECTION OF OFF-AXIS TARGETS

Figure 21 shows the results for the detection of off-axis targets ($df=2$, $F\text{-value}=0.10$, $p=0.9016$). Gray was the only color used for off-axis targets. Results for this interaction between lighting and age were non-significant; however, the figure displays younger participants as identifying the presence of off-axis targets sooner under both LED light types as compared to the fluorescent.

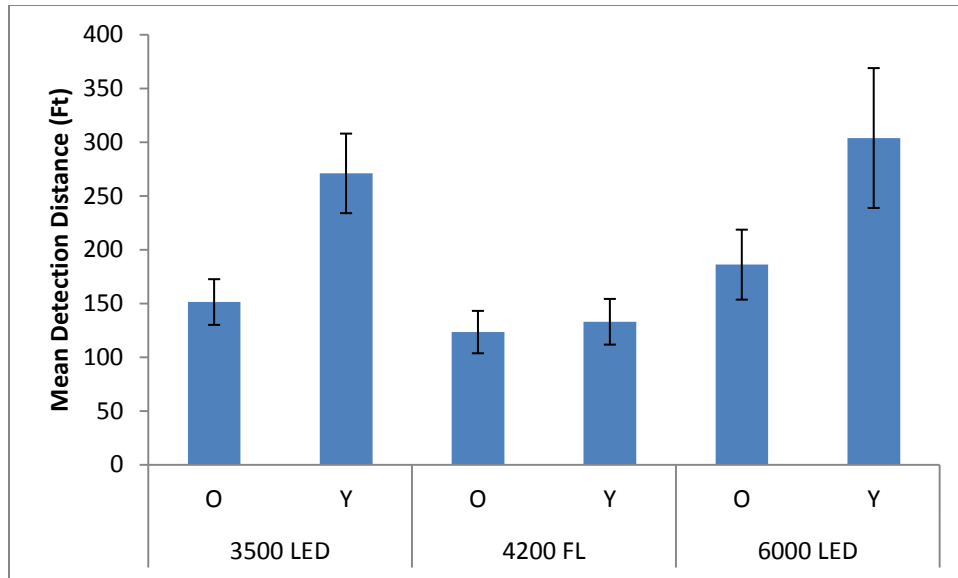


Figure 21. Target detection: light type and age.

DETECTION OF OFF-AXIS PEDESTRIANS

Figure 22 illustrates the results found for the interaction of light type and age in the detection of off-axis pedestrians ($df=2$, $F\text{-Value}=1.15$, $p=0.3285$). Denim was the only color used for the off-axis pedestrians. These findings were not significant; however, younger participants could detect the presence of off-axis pedestrians more quickly under 6000 K LEDs. All other interactions produced similar results between 200 and 250 ft. Younger participants under 6000 K noticed off-axis pedestrians at approximately 300 ft.

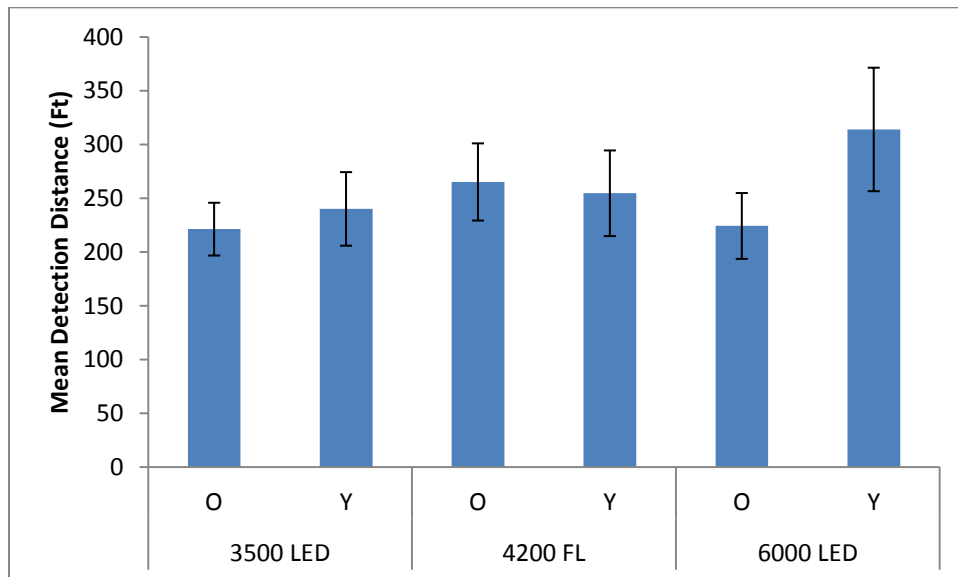


Figure 22. Off-axis pedestrian detection: light type and age.

COLOR RECOGNITION

Overall, the ANOVA (Table 4) showed that age and light level were significant factors for the recognition of pedestrian clothing color. Light type was a significant factor for the recognition of both target color and pedestrian clothing color. Lighting level and light type had a significant effect for target color recognition. Lighting level, light type, and age had a significant effect for pedestrian clothing color recognition. The color of the pedestrian’s clothing combined with light type had significance in the recognition of the pedestrian clothing color.

The multiple significances found for pedestrian clothing color recognition may be due to the greater luminance levels between the two clothing colors as opposed to the similar luminance found between the four different target colors. The reflectance for a black-clad pedestrian is only 3% as opposed to 18% for denim which provides a higher luminance level and confounds the luminance and color contrast metrics. For the targets, the paint that was used to cover the targets had similar reflectance values no matter the color (See Figure 5).

Table 4. Color recognition ANOVA results.

<u>BETWEEN</u>	Target Recognition	Pedestrian Recognition
Age		X
<u>WITHIN</u>		
Lighting Level		X
Lighting Level by Age		
Target Color		
Target Color by Age		
Lighting Level by Target Color		
Lighting Level by Target Color by Age		
Lighting type	X	X
Lighting type by Age		
Lighting Level by Lighting type	X	
Lighting Level by Lighting type by Age		X
Target Color by Lighting type		X
Target Color by Lighting type by Age		
Lighting Level by Target Color by Lighting type		
Lighting Level by Target Color by Lighting type by Age		

TARGET COLOR RECOGNITION

Figure 23 represents the results for target color recognition compared by light type. The results were significantly in favor of the 4200 K fluorescent light type. An SNK test paired the LEDs into a “B” grouping and assigned the fluorescent light a stand-alone “A” grouping (df=2, F-Value=4.48, p=0.0172).

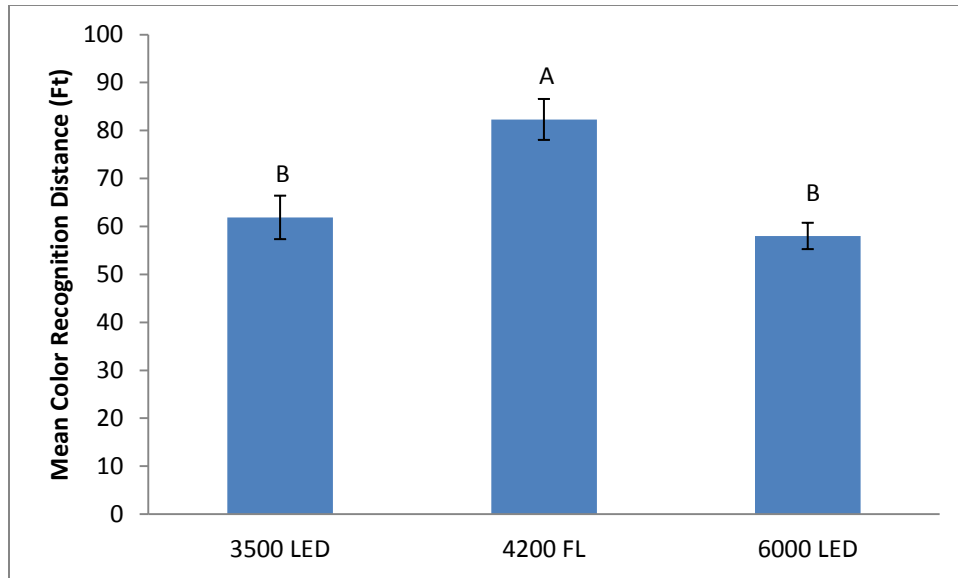


Figure 23. Target color recognition: light type.

Figure 24 illustrates the results of the interaction of light type and light level for target color recognition ($df=1$, $F\text{-Value}=11.66$, $p=0.0189$). The results were found to be significant. Note that there were no 12-lux events for the fluorescent lighting. The results indicate that the fluorescent light type performs well under 6 lux and much better than either LED. The results also indicate that the two LED light types perform oppositely per lighting level.

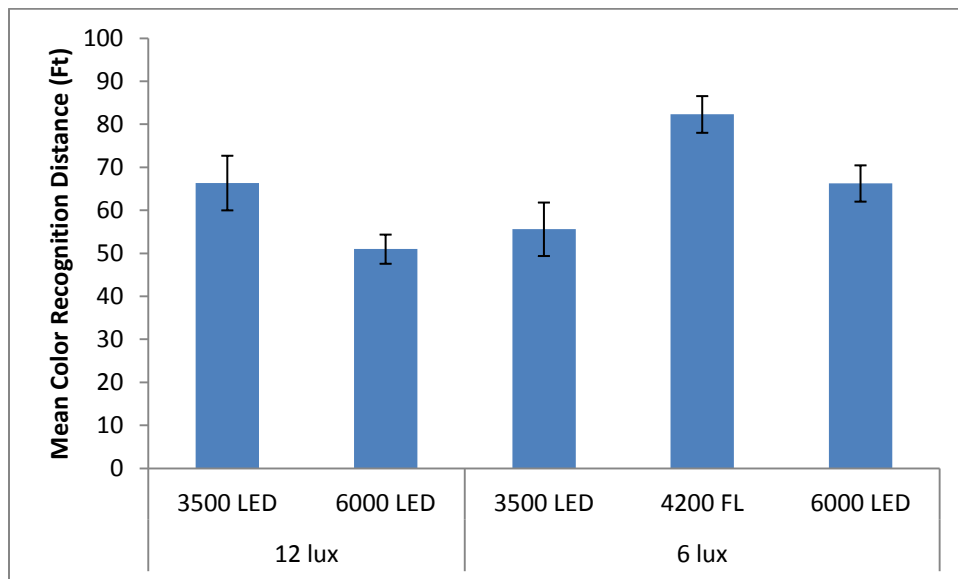


Figure 24. Target color recognition: Light level and light type.

PEDESTRIAN CLOTHING COLOR RECOGNITION

Figure 25 shows the age group comparison in the recognition of pedestrian clothing color ($df=1$, $F\text{-Value}=10.96$, $p=0.0022$). The younger age group significantly outperformed the older age group in the recognition of pedestrian clothing color by approximately 150 ft.

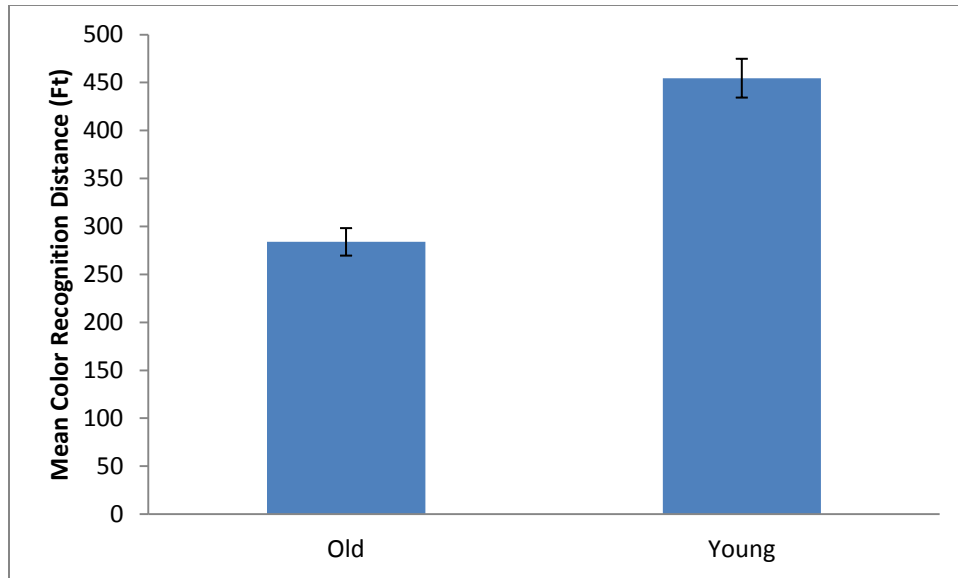


Figure 25. Pedestrian clothing color recognition: age.

Figure 26 shows the comparison of lighting levels for the recognition of pedestrian clothing color (df=1, F-Value =9.27, p=0.0049). The higher lighting level (12 lux) produced a greater recognition distance of pedestrian clothing color of approximately 100 ft more than the distance under 6 lux.

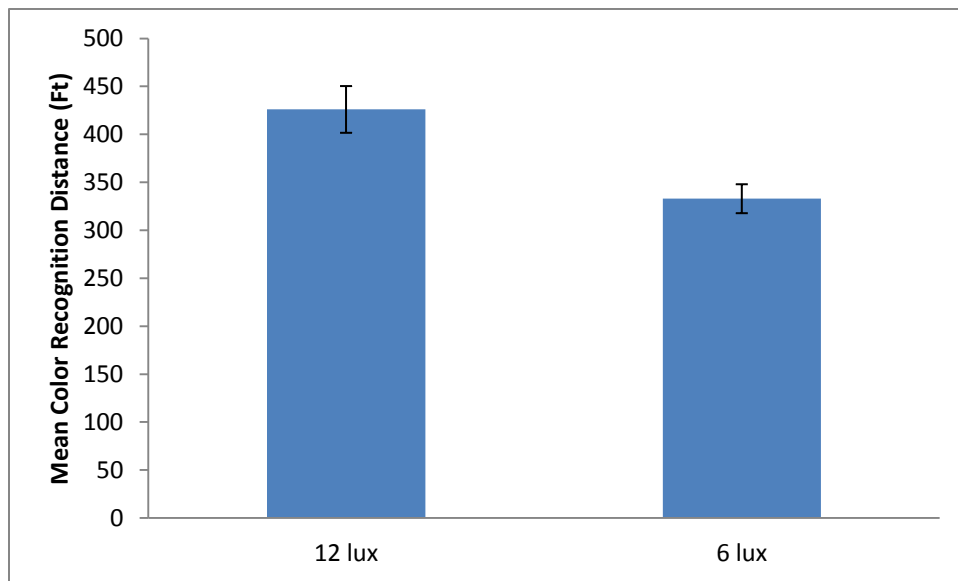


Figure 26. Pedestrian clothing color recognition: light level.

Figure 27 compares the light types by pedestrian clothing color recognition distance (df=2, F-Value=5.62, p=0.0071). The graph shows the 3500 K LED and the 4200 K fluorescent as being similar at approximately 300 ft of recognition distance. The 6000 K LED significantly outperforms these light sources with a recognition distance of approximately 450 ft.

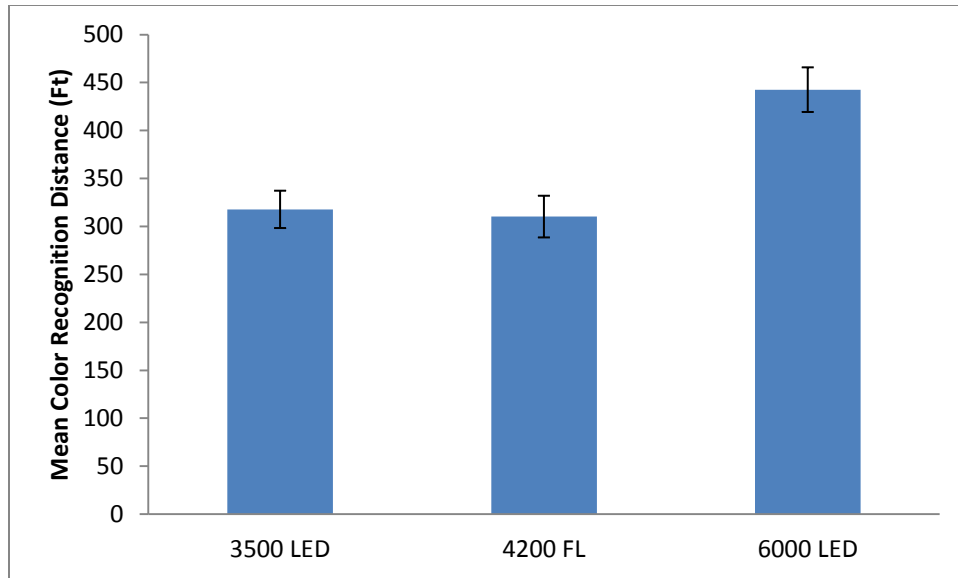


Figure 27. Pedestrian clothing color recognition: light type.

Figure 28 shows the significant interaction between light level, light type, and age for pedestrian clothing color recognition distance (df=2, F-Value=12.28, p=0.0067).

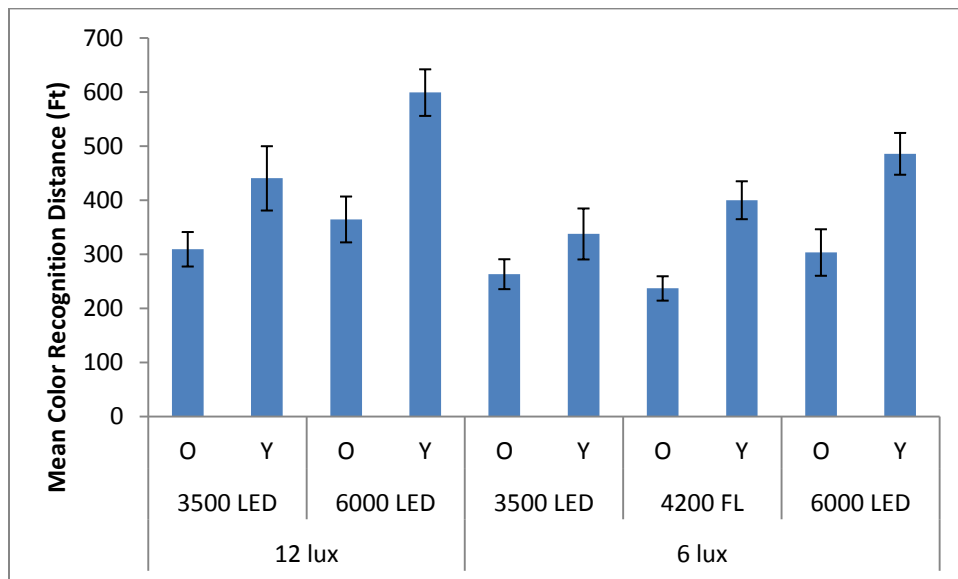


Figure 28. Pedestrian clothing color recognition: light level, light type, and age.

Figure 29 illustrates the significant interaction between clothing color and light type (df=2, F-Value =4.93, p=0.0182). The 6000 K LEDs performed best for both clothing colors. The fluorescent light had the biggest change in recognition distance from color-to-color. Denim-clad pedestrians had their clothing color recognized at a shorter distance than did black-clad pedestrians.

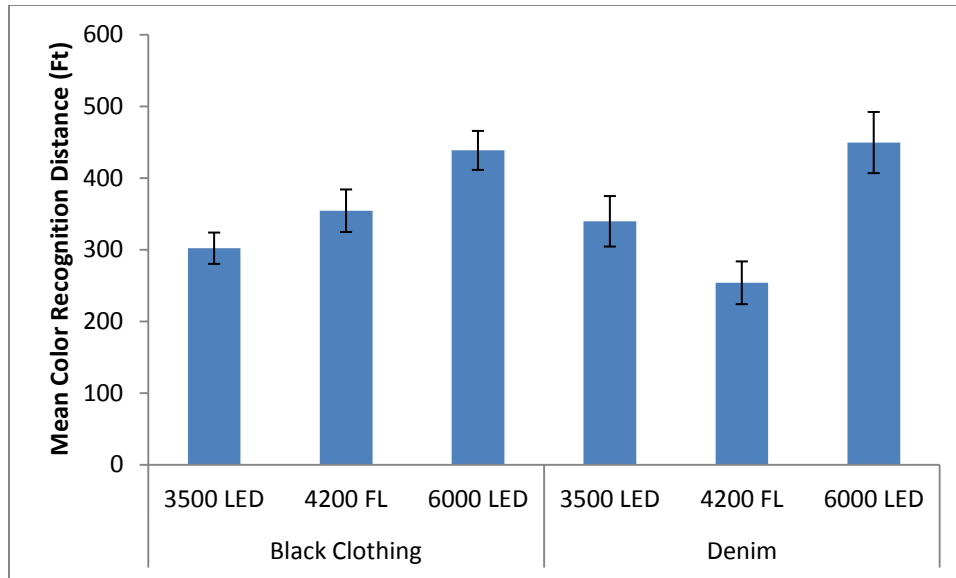


Figure 29. Pedestrian clothing color recognition: clothing color and light type.

WEBER CONTRAST

The Weber Contrast metric was used as a covariate for luminance contrast. Figure 30 shows the mean detection distance of targets for each light source paired with the Weber Contrast for each light source at those detection distances. These significant results indicate the fluorescent light source requires far less contrast to produce favorable detection distances for targets (df=2, F-Value=4.65, p=0.0149).

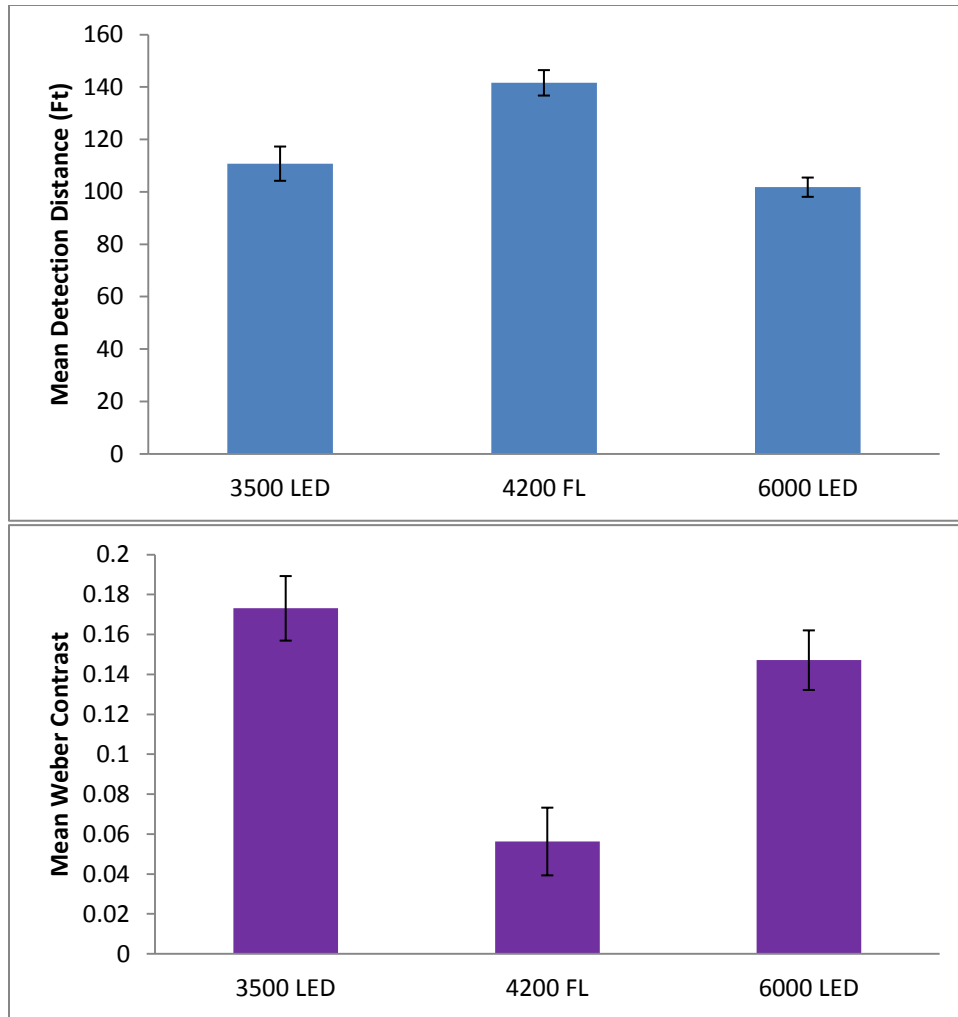


Figure 30. Target detection and Weber Contrast: light type.

Figure 31 shows the significant results for pedestrian detection distance paired with the Weber Contrast covariate. Opposite of target detection, the fluorescent light type required greater contrast to be visible from a distance less than that of either LED source ($df=2$, $F\text{-Value}=10.68$, $p=0.0002$).

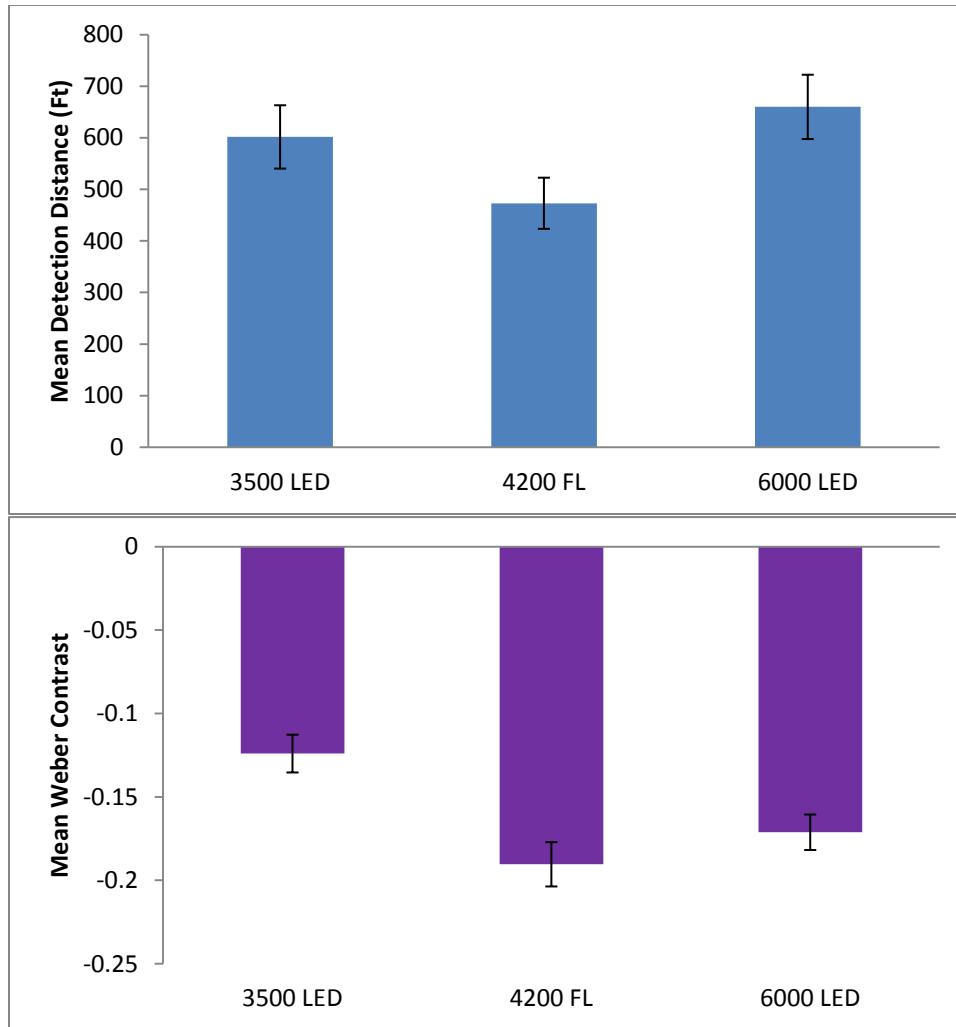


Figure 31. Pedestrian detection and Weber Contrast: light type.

COLOR CONTRAST

To determine the amount of color contrast contribution, a relationship between the color coordinate difference and threshold luminance contrast was investigated. Color coordinate difference refers to the coordinates of the XY chromaticity diagram in Figure 32. A gray target's threshold contrast, or luminance contrast (the amount of luminance contrast necessary before the target is visible) was measured and used as a multiple for the other target colors. The multiple "1" is the gray target that the other targets refer to under each light source (Figure 32). The graph shows that as the threshold luminance of the gray target is multiplied, the percentage of color coordinate difference also increases. The relationship suggests that color contrast has a positive impact on detection. The differences in target color coincide with the detection threshold of the target being separated from its background or, in this case, pavement.

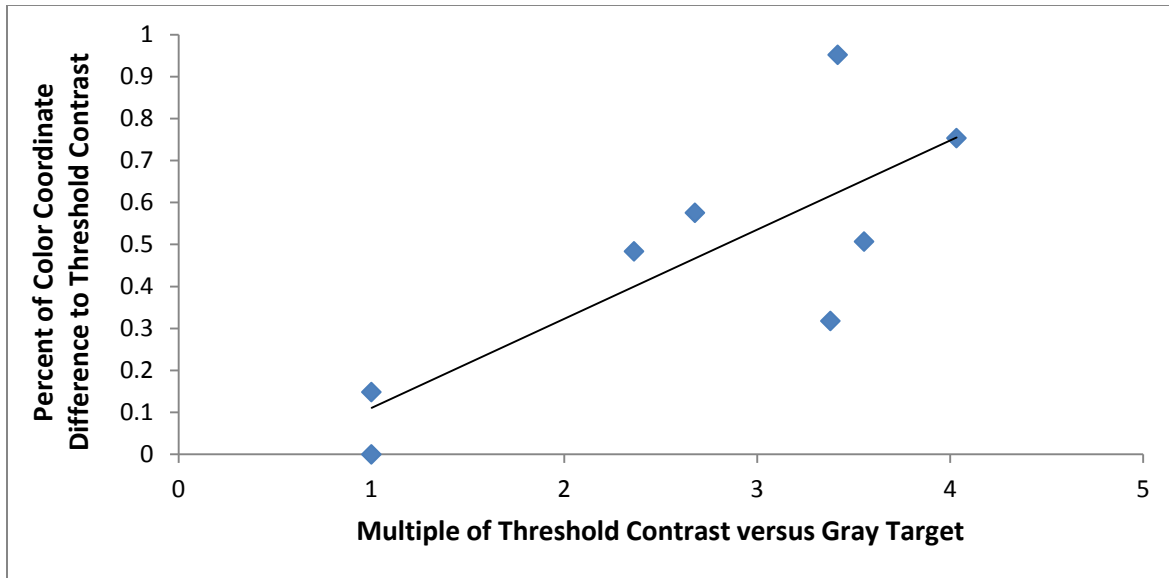


Figure 32. Threshold contrast versus gray target.

QUESTIONNAIRE RESULTS

Questionnaire data were coded and entered into a spreadsheet for further analysis. There were different modes of answering questions within the questionnaires; therefore, different analysis types were used.

One type of answering mode was a Likert-type scale, as found in all three questionnaires. The answers for the nightly questionnaire were analyzed using a non-parametric ANOVA. Likert-type questions were also analyzed using a non-parametric ANOVA; however, questionnaires that participants rated themselves low for remembering previous nights were removed from analysis. Questionnaires of participants who rated their abilities to remember previous nights below neutral were omitted. Participants who rated themselves as neutral (or 4) to very well (7) were kept for analysis. This method prevented participants who were not confident in their ability to recall previous light types from being included in the data pool. Twenty-four of 105 gathered questionnaires over the 3-night span of 40 participants were omitted due to low self-rating.

Of the Likert-type questions there were no significant results found in the responses, suggesting that participants did not consciously discover obvious differences among the light types while driving.

Another type of answering mode required the participant to check one answer from a list. The answer pool was consistent from question to question and required the participant to compare their experiences with the light types. The light types were referred to by their night orders so that participants were not required to know any details about the lights that were being tested. These answers were coded based on the light order the participants received and their ability to recall previous nights. Participants who rated themselves as 4 or above (when asked to rate their ability to compare the lights) were kept for data analysis, the rest were omitted. These answers were analyzed using frequency counts for when the two light types were preferred over the other or when the answer was neutral. There were no significant results found for this section;

however, the results can be found in Appendix A. The participants exhibited no clear preference for one light type in terms of how soon they could see targets or pedestrians, how well they could discern the color of targets or pedestrians, or for factors of glare.

Open-ended questions and comments sections were coded using content analysis. Content analysis is a method of research by which inferences are made based on textual data (Weber, 1990).⁽⁴⁴⁾ For each comment, the overall theme was assessed. Comments were first reduced for usability. If the researcher could not determine which light source the comment referred to or if the comment had no direct relevance to the study, it was removed from analysis. Questionnaires for which participants did not rate their ability to recall previous nights as a 4 or above were also stricken from analyses.

Figure 33 illustrates the results of the content analysis based on participant comments. There were no significant differences between light sources' negative or positive comments.

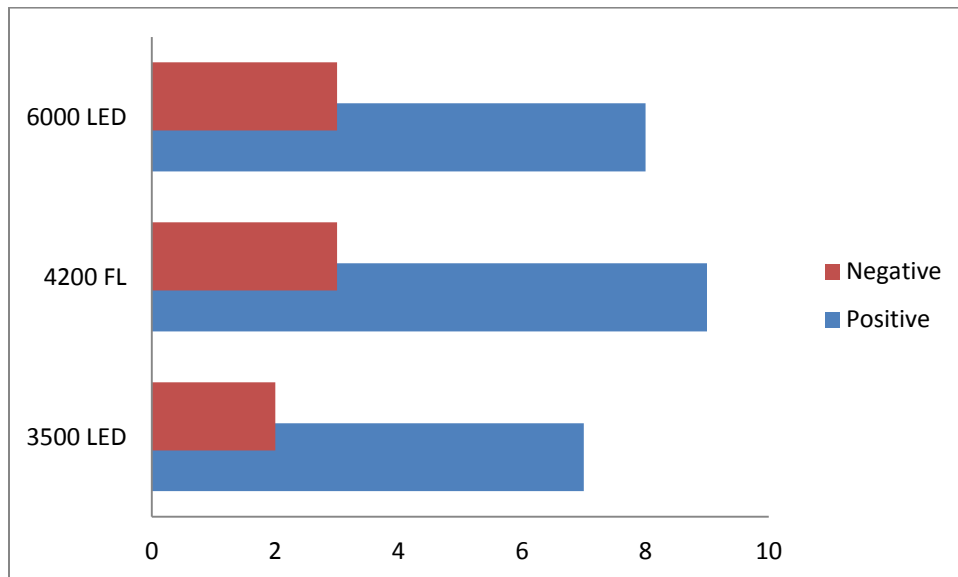


Figure 33. Content analysis results.

CHAPTER 5. DISCUSSION

In the assessment of the impact of color contrast, the detection results should be considered in terms of the measured photometric results. An object is detected through contrast against its background. Typically, that contrast is assumed to be the luminance contrast difference. In this analysis, the luminance contrast and the color contrast are associated with one another. Changing the light sources and the target colors will change both the color contrast and the luminance contrast. Comparing the results of the contrast measurements and the detection will allow for the development of the color contrast impact.

This discussion will consider the target and pedestrian objects. Figure 34 shows a side-by-side comparison of the detection distance and luminance contrast. The blue, green, and red targets required a lower luminance contrast level than did the gray target. This indicates that the color contrast provided by these targets, as compared to the gray target against its background, provided the additional information required for the equivalent or improved detection performance. It is important to note here that the impact of the color contrast is not equivalent across all of the color types and luminaire types. The red target had the lowest contrast level but was detected in the same region as the other targets. This indicates that the color contrast of the red target provided a boost to equalize its visibility of other targets despite lower luminance contrast. Similarly, the impact of the color contrast under the fluorescent system was much greater than that under the LEDs. As seen in the bottom chart in Figure 34, the change in the color contrast can improve object detection as much as 50% when comparing the blue and gray targets.

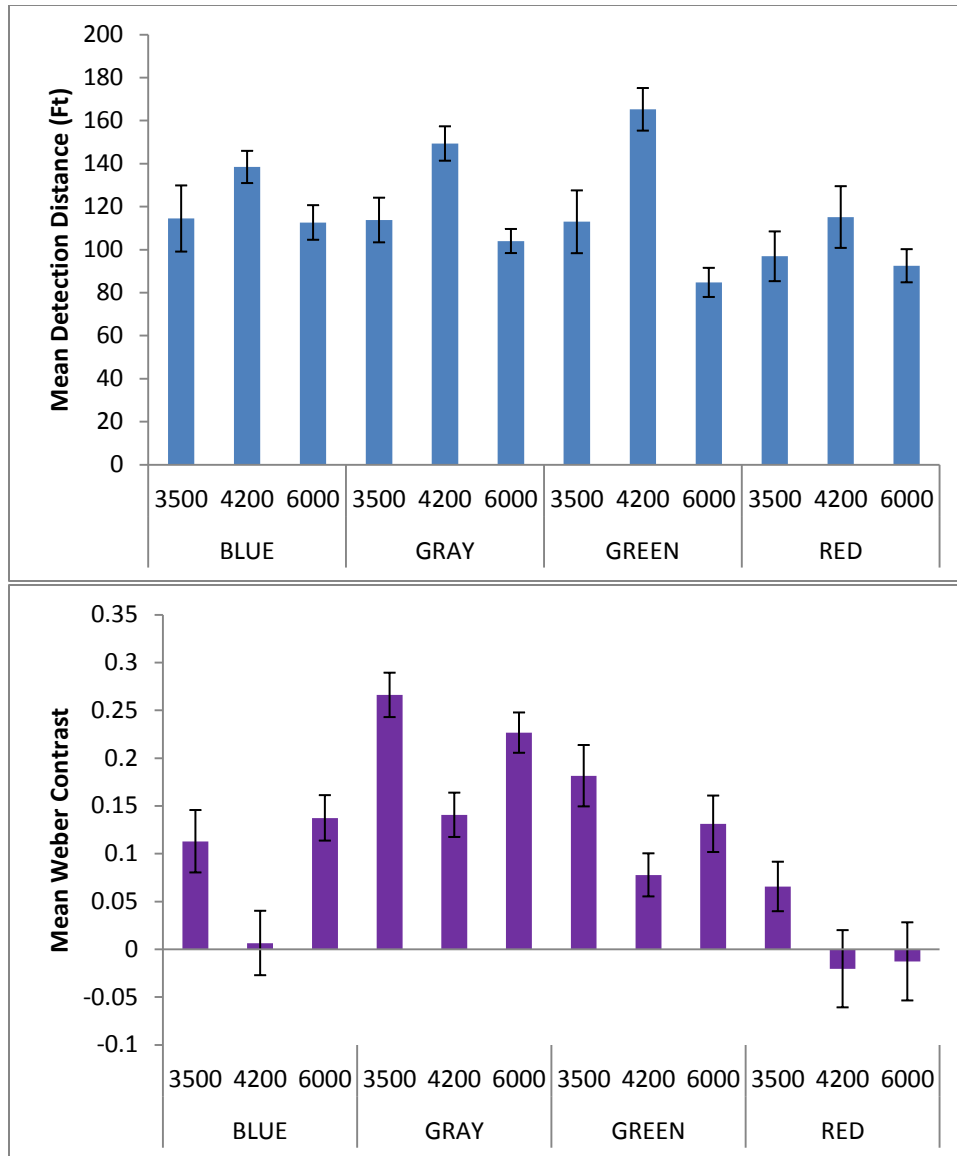


Figure 34. Target detection by lighting type and color detection distance and Weber Contrast.

The consideration of the age impacts is shown in the same format in Figure 35. Here, a higher contrast level was required for the older participants under the 3500-K LED and the 4200-K fluorescent as compared to the younger participants for equivalent detection distances. Under the 6000-K LED source, the younger participants needed a higher contrast than the older participants, indicating that a relationship exists between age and the effectiveness of color contrast as well.

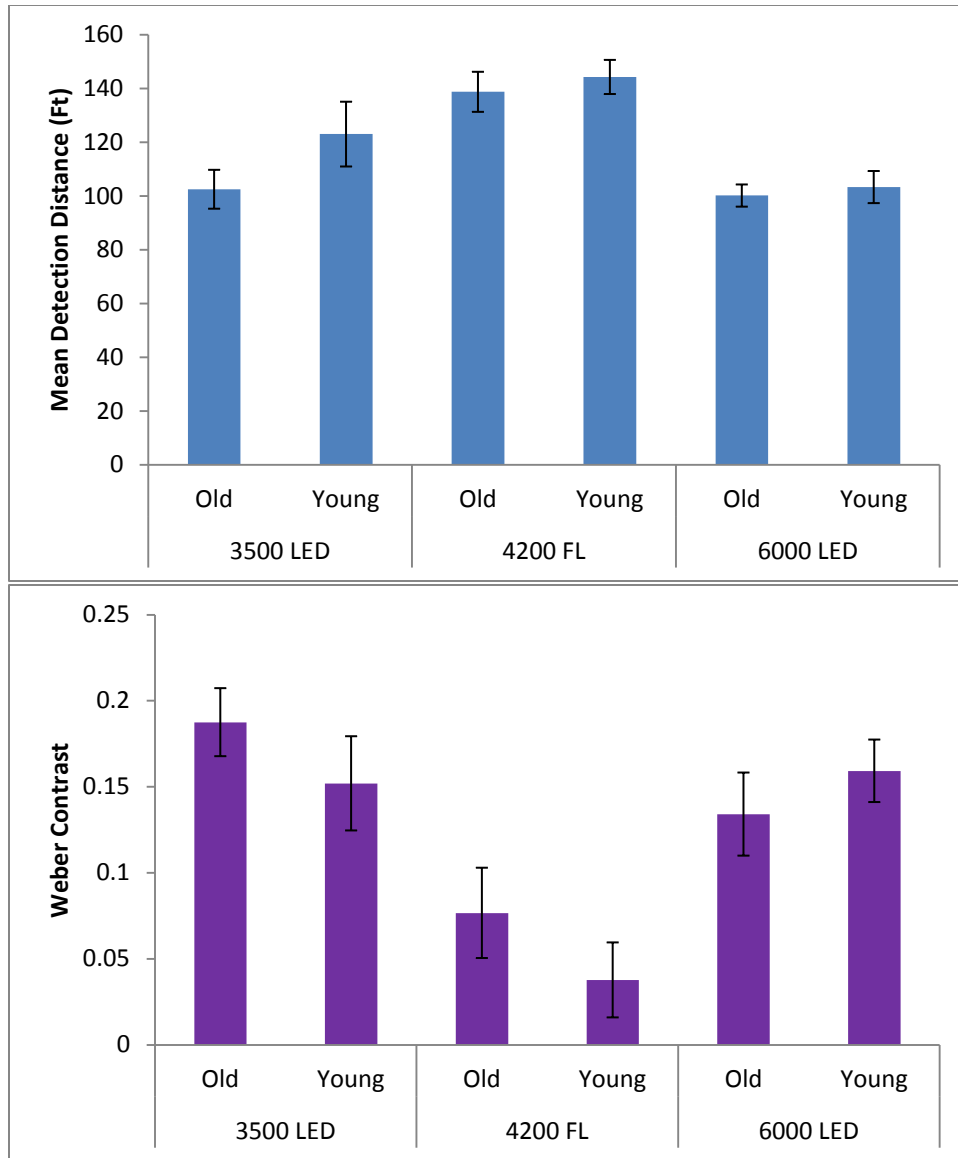


Figure 35. Target detection and Weber Contrast: Target detection by lighting type and age.

The final consideration is that of the lighting level. In comparing the required contrast results to the detection results, there is less of an effect than with the other conditions. The required contrast follows the same trend for all of the target colors across the varying lighting levels. With the exception of the contrast reversal for the red target, there is very little impact of the color as determined in the results.

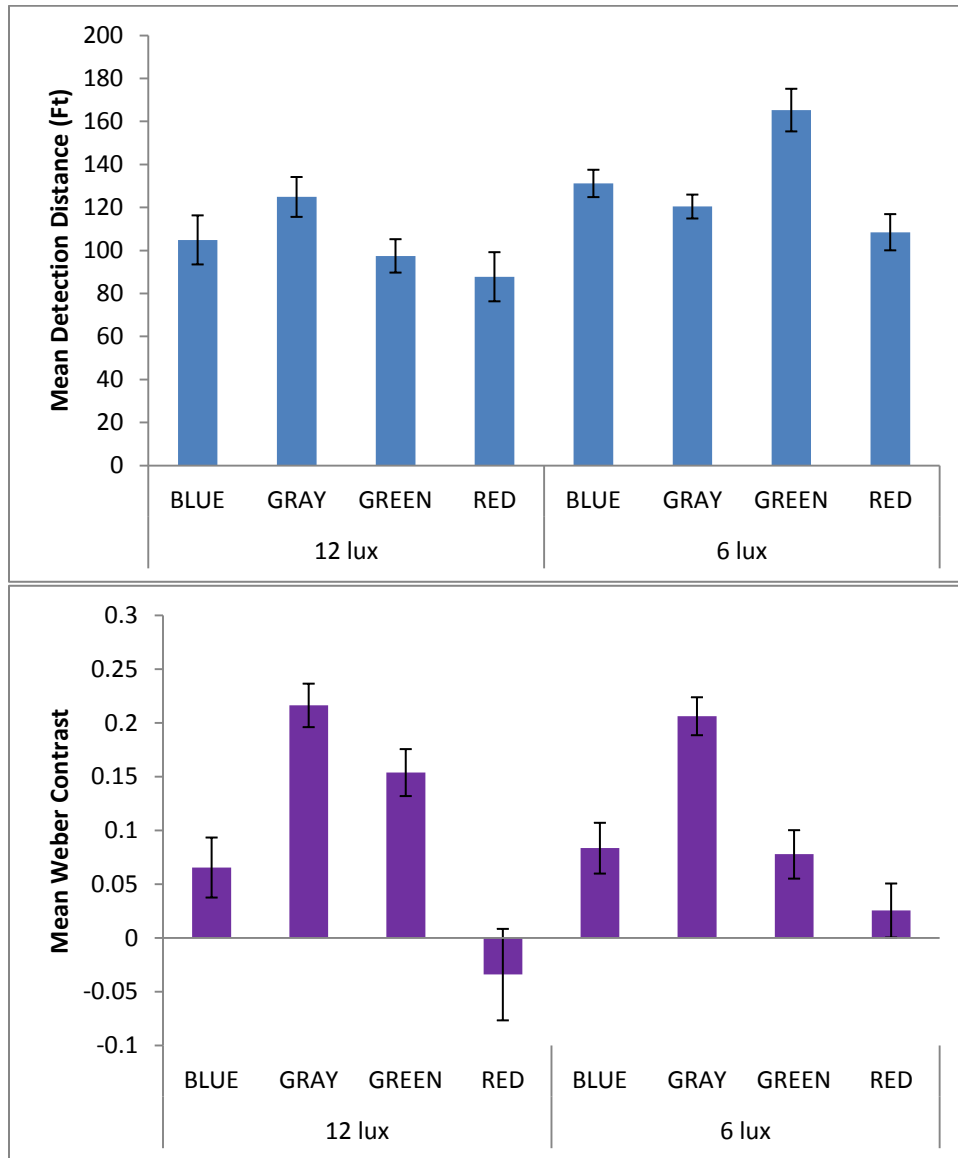


Figure 36. Target detection and Weber Contrast: Target detection by color and lighting level.

Regarding the pedestrian results, the impact of the color of the pedestrians' clothing was the primary consideration. The results point toward an interesting relationship between lighting type and clothing color in regard to detection distance and Weber Contrast. As Figure 37 shows, the relationship between detection distance and contrast appears to be inverse. The contrast for pedestrians is likely negative due to how far away they were detected on average (~460 ft to ~650 ft), which occurred before the light from the test vehicle's headlights contacted the object. All three light sources required less luminance contrast for denim-wearing pedestrians versus black-clothed; even though the detection distances were equivalent, luminance contrasts were not. This is another indication of the impact of color contrast. Here again, the impact may be as high as a 50% improvement.

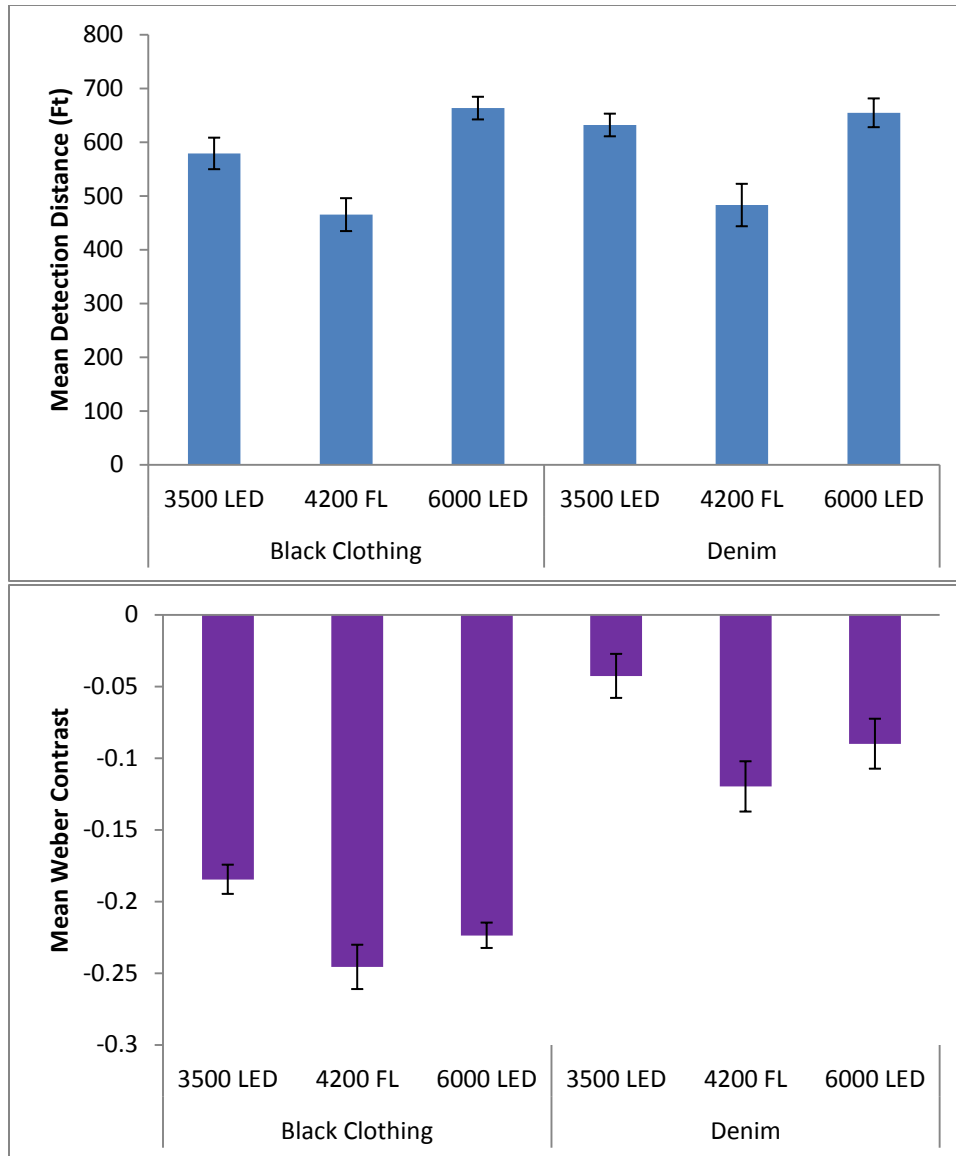


Figure 37. Pedestrian detection by lighting type and clothing color: Mean detection distance and Weber Contrast.

Considering the impact of the lighting level, the pedestrians show more of an effect than the targets do. In Figure 38 the impact of the color contrast and lighting level can be seen in the comparisons to the Weber Contrast. Under 12-lux, both black- and denim-clothed pedestrians were detected from similar distances across both light sources. However, their luminance contrasts are very different. The black-clad pedestrians' contrast was nearly 10 times greater than that of denim, yet both were detected at roughly the same distance. For the 6-lux condition, the required contrast was almost the same for equivalent detection distance performance. This indicates less of an impact of the color contrast at the lower lighting level.

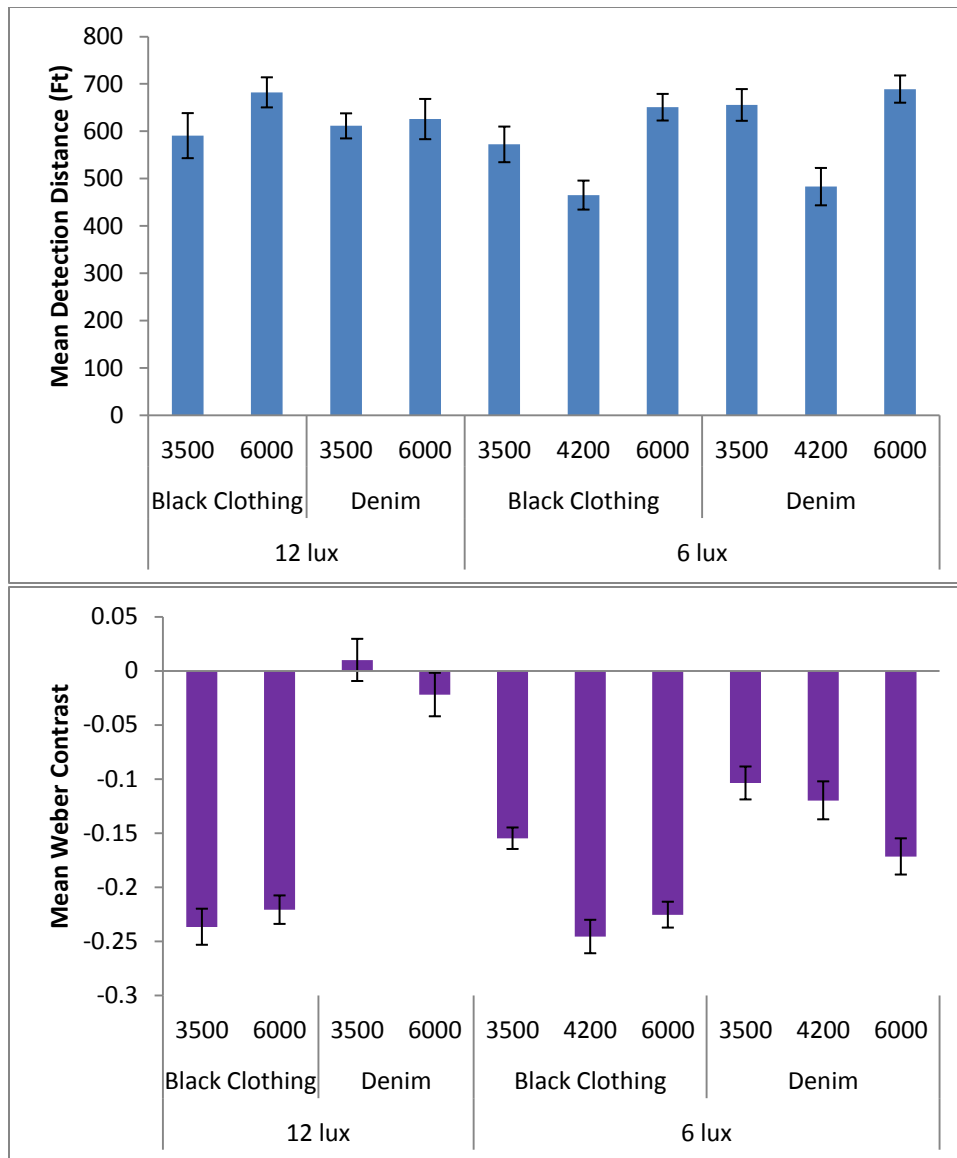


Figure 38. Pedestrian detection by lighting type and clothing color: Mean detection distance and Weber Contrast.

CHAPTER 6. CONCLUSIONS

The research results indicate that color contrast impacts the visibility of objects. The benefit provided by the color can be an object detection improvement as high as 50% (see Figure 35). However, the benefit does change based on the light source, the object being viewed, and the observer. The results also indicate that the impact of the color contrast may change with the luminance level of the object.

Given these considerations, care must be taken when applying a correction factor in lighting design. The results indicate that a blanket factor cannot be applied across all design scenarios. Any correction, however, must consider the lighting systems, the object being viewed, and the age of the observer. Further effort is required to determine the magnitude of these effects. To model them, the nature of the light source and the target interaction must be considered.

The fluorescent light source provided a greater detection distance of small targets than did either LED. However, for pedestrian detection, these results were just the opposite as the fluorescent light source had the least detection distance. This may be due to the color differences between targets and pedestrians and the spectral energy provided by the fluorescent light source. As seen in Figure 2, the fluorescent light source contains energy spikes which means that certain colors are highlighted, possibly making those more visible, whereas the full spectral distribution provided by the LED devices has a more complete distribution (which may perform better with certain other colors).

For color recognition, the fluorescent light type provided a significantly greater color recognition distance than did either LED for small targets. For pedestrian clothing color recognition, the 6000 K LED outperformed both the fluorescent and the 3500 K LED light type by approximately 130 ft. Due to the difference between the detection of pedestrians and the recognition of their clothing color, the results suggest that the 6000 K LED may be the superior light for rendering color.

LIMITATIONS OF THE STUDY

The results of this study are limited to the light sources and the targets tested in this investigation. Further effort must be considered to provide a more broadly applicable correction factor.

One of the primary assumptions of this investigation is that object detection is linearly related to contrast. Investigation into the metric that can be related to the object detection would also be required to develop the correction factor.

The study required participants to participate at least three times over the course of one to two weeks. Over time, the participants' memories of their previous scenarios begin to fade. When comparing the light sources in their questionnaires, the inconsistent time gaps between subjects participating in their three nights of the study serve as a weakness to the study's design, especially for questionnaire data.

This investigation did not consider the impact of glare.

Due to the study's focus and design, there were no color recognition tasks for off-axis objects. To fully explore the mesopic capabilities of these LED lighting systems, this must be explored.

A majority of the participants used in this study reside in the Blacksburg, Christiansburg, and Radford areas of Virginia. The driving and road-scanning behaviors of drivers from these rural areas may differ from those in more urban settings.

FUTURE RESEARCH

Further research is required to fully establish the impact of the color contrast. The nature of the light source, a wider variety of targets, and the impact of the headlamps all have to be considered in the development of the results. Similarly, a wider range of adaptation luminances is required for the evaluation of a final correction factor for the lighting design.

The LED luminaires and fluorescent luminaires should be compared directly to a conventional lighting system such as MH or HPS to construct more generalizable claims about their proficiency for safety.

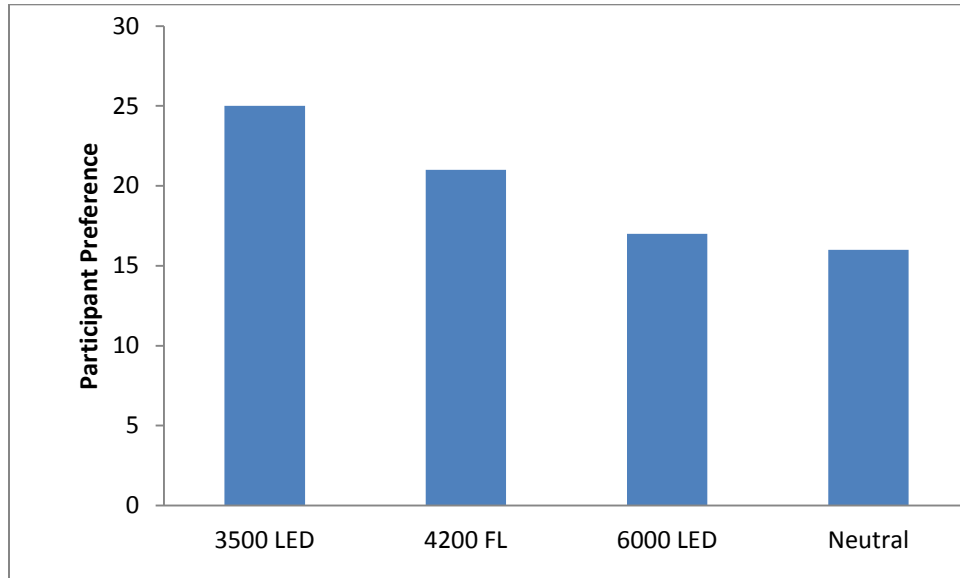
This study found that the 6000 K LED was able to provide comparable off-axis target detection with less contrast. This information may be a good starting point for lighting manufacturers as further research could delve into finding the perfect thresholds for identifying off-axis objects in regard to light power, CCT, and contrast. Also, future studies could tailor questionnaires to obtain more information about off-axis detection as well as potential over-lighting or light pollution caused by the luminaires.

The impact of glare was not calculated in this study; however, questionnaire data suggests that the fluorescent light type provided the most glare. Future research should consider the impact of glare of these three light types in terms of amount and comfort.

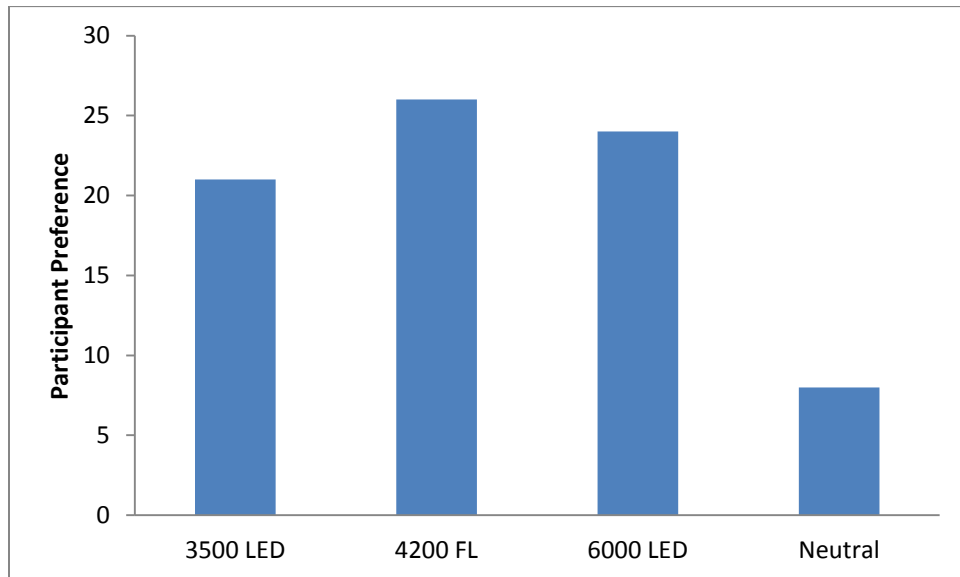
APPENDIX A.

QUESTIONNAIRE RESULTS

For questions regarding which light type allowed participants to see targets sooner.



For questions regarding which light type allowed participants to see pedestrians sooner.



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