IMPACT OF CORRELATED COLOR TEMPERATURE OF HEADLAMPS ON VISIBILITY

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ABSTRACT

The purpose of this project was to provide an initial investigation into the effects of different light source correlated color temperatures (CCT) on detection and color recognition of roadway objects and pedestrians. This project included an investigation of both the light source spectrum from the overhead lighting spectrums as well as correlated color temperature from vehicle headlamps.

The detection of pedestrians and small objects along the roadway edge was measured on the Virginia Smart Road. Here the objects were located at specific points along the roadway and participant drivers performed a detection task. The point of first detection was recorded and the detection distance calculated. The objects appeared under high-pressure sodium (HPS) and light-emitting diode (LED) overhead lighting systems, as well as headlamps filtered to resemble LED and the amber overhead HPS sources.

The primary results from this investigation indicate that: 1) There is not a significant difference in terms of pedestrian detection and targets located immediately alongside the roadway between the correlated color temperature of the vehicle headlamps within the range selected ; 2) Overhead lighting is a significant factor in the detection and color recognition of pedestrian clothing, but results indicate that it is the intensity – not necessarily the color – of the lighting that makes it a significant factor;

The tasks considered in this investigation were primarily foveal, meaning that pedestrians were within the line of sight of the driver. However, most spectral impact is expected to be in the periphery of the visual field. Part of this investigation considered the extent to which peripheral vision plays a role in object detection for a driver. Further investigation using a more extensive peripheral detection component is required to more fully explore the impact of the light source to the periphery.

As light sources transition to new technologies, light source spectrum is becoming a significant safety aspect of the roadway environment. The impact of the correlated color temperature of the headlamp is not significant in the foveal detection of pedestrians and objects within the range investigated. Further investigation of the peripheral impact of these light sources on pedestrian and driver safety is ongoing.

INTRODUCTION

While traditional roadway lighting utilizes high-pressure sodium (HPS) light sources, the source provides an amber color that does not allow object color to appear correctly. The light source spectral output (i.e., the wavelength by wavelength emission of the light source) is heavily weighted in the yellow and red portions of the spectrum of visual light. With the advent of applying light-emitting diode (LED) technology to roadway lighting, the concept of a more broad spectral distribution of light potentially provides additional benefits to the driver. Recent research has shown a benefit of broad-spectrum light in the detection of objects along the side of a roadway when compared to traditional narrow-

spectrum light sources (Lewis, 1999). The potential benefit is such that a lower light level may provide the same visual performance under a broad spectrum source (such as LED) as compared to a higher light level under a narrow band source (such as HPS). Lower lighting level will reduce energy usage and the potential number of luminaires required for a roadway lighting scene. Further benefits might also include better object color recognition and higher visual comfort. This project provides an initial investigation of these effects.

In addition to overhead lighting, vehicle headlamp technology has also significantly changed in recent years. With the advent of new light source technologies, such as LED headlamps, the same considerations of possible benefits must be made in terms of spectral output.

PURPOSE AND SCOPE

The purpose of this project was to identify the impact, if any, of different spectral distributions and their intensities on the detection and color recognition of objects in the roadway. Based on the results of the current study, future phases will incorporate factors such as detection and color recognition of objects and pedestrians located peripherally to the driver.

METHODS

Experimental Design

The experimental design used in this project consisted of a 2x2x5x4 mixed-factors design. The factors and the levels are described below.

- Participant Age (2 levels): Younger (25-35 years old) and Older (65 years old and above). The younger and older age groups were selected to investigate the changes in vision and perception that may occur with increasing age.
- Roadway Type (2 levels): High speed roadway (55mph) and Low speed roadway (35mph). A low speed roadway condition is instrumental in applications of street lighting where pedestrians are most often to be encountered. A high speed condition was selected for application on highways.
- Overhead Lighting (5 levels): 2700 Kelvin HPS luminaires (150W) and 6000 Kelvin LED luminaires (the CCT was measured to verify the performance). Both types of luminaires were dimmable, adding an additional level, such that participants experienced LED High and LED Low, as well as HPS High and HPS Low. The High levels for both luminaires resulted in an average roadway illuminance of approximately 4 lux. The Low levels for both luminaires resulted in an average roadway illuminance of approximately 1 lux. A fifth condition of no overhead lighting was also included in the study.
- Headlamp Type (4 levels): White/blue-filtered headlamps and white/yellow-filtered headlamps. The basic high-intensity discharge (HID) headlamp was filtered to emit both the white/blue and white/yellow colors. The white/blue color was used to create the correlated color temperature similar to an LED headlamp, while white/yellow was used to simulate halogen output. In addition to this, filters were designated as High and Low in terms of their transmittance level.

Dependent Variables As a measure of the visibility, the distances at which participants could see pedestrians and wooden targets were recorded. When a participant could first see a pedestrian or target, he/she would verbally identify it by saying “pedestrians” or “target” depending on the object presented. The in-vehicle experimenter would press a button when the participant identified the object correctly and again when the participant verbally identified the color of the object correctly. Finally, the in-vehicle experimenter would press a button when the vehicle reached the object presented. These buttons flagged the data so, during later analyses, the distance traveled between these points could be determined. These distances were called the Detection Distance and the Color Recognition Distance for those particular instances.

Participants

Thirty-two participants were selected to participate in this study. Participants were selected from two age categories: younger (25-35 years old) and older (65+). Sixteen participants from each age group performed the study. Each group of participants consisted of an even number of males and females. Virginia Tech Institutional Review Board (IRB)

approval was obtained prior to recruiting subjects. Subjects were paid $30/hr. and were allowed to withdraw at any point in time, with compensation adjusted accordingly.

Facilities and Equipment

Virginia Smart Road The experiment took place at the Virginia Tech Transportation Institute (VTTI) and on the Virginia Smart Road in Blacksburg, VA. The Smart Road is a 2.2-mile two-lane controlled access road. The Smart Road is equipped with a 0.75 mile long variable overhead lighting system. There are three luminaires on each lighting pole that can be individually turned on and dimmed. The lighting poles can be spaced at 40, 60, 80 and 120 meters and can be varied in height between 11 and 15 meters.

Participants drove the entire road, through both lighted and unlighted sections of the road.

Pedestrians and Targets Pedestrians were clothed in scrubs of blue, gray, black, or red depending on the order of the experimental design. Targets were 18cm by 18cm wooden objects painted blue, gray, green, or red and also presented based on the order of the experimental design. Pedestrians and targets were stationary and positioned 60cm outside the white line of the vehicle's travel lane. The experimental design also included an off-axis pedestrian located approximately 18 meters off the roadway, also clothed in the blue, gray, black, or red clothing (depending on the experimental design).

Overhead Lighting 150 Watt HPS and 6000K LED luminaires installed on the Smart Road were equipped with dimming mechanisms. The luminaires were mounted at 15 meters high and spaced at 80 meters. The HPS and LED overhead luminaires were characterized using a mobile measurement system developed by VTTI. The dim levels for each of the lighting conditions were established so that the average illuminance on the roadway was equivalent between the two lighting systems. Target and pedestrian locations were carefully selected throughout the test area in order to ensure equal illuminance under both the HPS and LED luminaires.

Test Vehicles Participants drove one of two 1999 or 2000 Ford Explorers with four HID low beams capable of being filtered to output white/blue or white/yellow light. Lee-brand filters were selected and combinations of filters with headlamps were classified as either "High" or "Low." The High filter level along with the four HID low beams resulted in approximately the same amount of light as one would see with a typical two-headlamp system. The Low filter level resulted in an approximately 30% reduction in light level. Levels of transmittance, correlated color temperatures (CCT), and specific filter identification number combinations used are shown below in Table 1.

Table 1.
Headlamp Filter Specifications

Color	Intensity	Transmittance	CCT	Filters
White/Yellow	High	0.4883	2926	205 223 298
White/Yellow	Low	0.3821	2910	205 223 209
White/Blue	High	0.4367	5357	202 218
White/Blue	Low	0.3130	5120	202 218 298

An in-vehicle experimenter rode in the passenger seat for the duration of the study. The vehicle was equipped with a Data Acquisition System (DAS) which recorded vehicle network data and four camera views inside and around the vehicle. The DAS recorded the driving distance and the button presses for the Detection Distance calculations. The DAS also recorded information entered by the experimenter such as the participant's age, subject number, and button presses. In addition, each vehicle was equipped with a luminance camera system which took specialized photos throughout the study. These photos allowed for the measurement of the luminance of any object captured in the forward view of the vehicle. These photos also allowed for a post-hoc analysis of object contrast.

Experimental Procedure

Participants were initially screened over the telephone, followed by an initial in-person screening visit. This initial visit included participants reading the Informed Consent form and completing vision-related tests. These vision tests included an evaluation of useful field of view (UFOV), visual acuity, color vision, and contrast sensitivity. If

eligible for the study, a time was scheduled for testing. Participants were instructed to meet an experimenter at VTTI in Blacksburg, VA. Participants were scheduled in pairs. Upon arriving at VTTI, each participant was asked to re-read and sign the Informed Consent form, and fill out a W-9 tax form, a health questionnaire, and a pre-drive questionnaire.

Once all forms and vision tests were complete, the experimenter would orient the participant to the study. Experimenters would explain to participants what was meant by the detection and color recognition of objects, and what participants were to say at such instances.

Once participants had been oriented to the study, each in-vehicle experimenter would escort his/her assigned participant to the experimental vehicle. The in-vehicle experimenter would familiarize the participant with the vehicle controls, such as seat and mirror adjustments. When the participant and computer systems in each vehicle were ready, the experimenters would instruct the participants to exit the parking lot and drive to the Smart Road.

Participants drove a practice lap in order to become familiar with the vehicle and the route they would be driving on the Smart Road. In addition, the in-vehicle experimenters would answer any questions the participants had. No pedestrians or targets were presented during the practice lap, and participants were not asked to identify any objects.

After the practice lap was complete, the test laps began. Each participant drove eight test laps during which they identified pedestrians, targets, and their respective colors. Participants then drove an additional eight laps on a following night, in order to decrease the impact of fatigue. Participants were asked to drive at 35 mph or 55 mph depending on the order of the experimental design for the evening. Participants would pause and park the vehicle in turnaround sections of the road in order to complete questionnaires. This would also allow experimenters the opportunity to change overhead lighting and headlamp configurations based on the experimental design for the evening.

Once all laps were completed, participants were instructed to exit the Smart Road and return to the VTTI parking lot. From there, the experimenters escorted each participant back inside. Participants were then given a copy of the informed consent form and a receipt showing their time of participation and how much compensation they would receive. Participants earned $30 per hour, and were paid with cash following their final night of participation.

Data Analysis

Recorded data were reduced using VTTI's Data Analysis & Reduction Tool (DART) in order to isolate distances associated with participant detections and color recognitions of objects. Images recorded at the moments of detection and recognition through the luminance camera system were also analyzed, resulting in luminance and contrast data for pedestrians and targets.

RESULTS

Pedestrians – Detection (Overhead Lighting Present) The Detection Distance was considered in an Analysis of Covariance (ANCOVA) considering all of the experimental design parameters. The actual speed of the vehicles was considered a covariate as it was a continuous variable that was controlled for, capable of influencing detection and recognition distances. In order to determine the relationships only when overhead lighting was present, results do not take into account data collected from the dark or un-illuminated section of the road. The results from this ANCOVA (a significance level of 95% (α=0.05)) are summarized in Table 2. The significant factors are denoted by an asterisk and the associated F values are shown.

Table 2.
ANCOVA Results for Pedestrian Detection Distance

Source	F Value	Pr > F
Age	7.78	**0.0092***
Headlamps	0.57	0.5674
Age*Headlamps	0.64	0.5329
Pedestrian Clothing Color	4.27	**0.0073***

Age*Pedestrian Clothing Color	0.71	0.5494
Headlamp Color and Intensity*Pedestrian Clothing Color	0.44	0.8513
Age*Headlamp Color and Intensity*Pedestrian Clothing Color	2.09	0.0573
Overhead Lighting Color and Intensity	5.55	**0.0023***
Age*Overhead Lighting Color and Intensity	1.13	0.3461
Headlamp Color and Intensity*Overhead Lighting Color and Intensity	0.42	0.8648
Age*Headlamp Color and Intensity*Overhead Lighting Color and Intensity	1.58	0.1741
Pedestrian Clothing Color*Overhead Lighting Color and Intensity	2.1	**0.0327***
Age*Pedestrian Clothing Color*Overhead Lighting Color and Intensity	0.55	0.8371
Headlamp Color and Intensity*Pedestrian Clothing Color*Overhead Lighting Color and Intensity	0.77	0.7131
Age*Headlamp Color and Intensity*Pedestrian Clothing Color*Overhead Lighting Color and Intensity	0.75	0.7041
p < .05 significant		

Within this analysis, participant age, pedestrian clothing color, overhead lighting color and intensity, and the interaction of pedestrian clothing color and overhead lighting color and intensity were found to be significant. It is to be expected that there would be a significant difference between the ages of participants due to the differences in visual acuity between the ages. This difference is shown in Figure 1 with younger participants significantly detecting pedestrians from further away than did older participants.

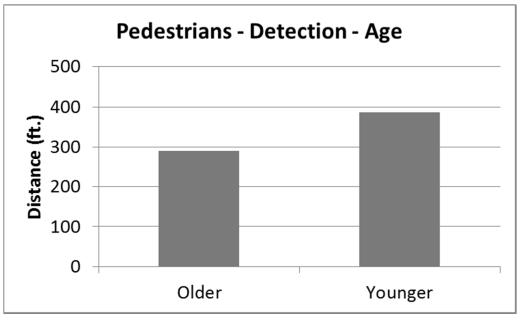

Figure 1. Mean detection distance of pedestrians by age.

The other significant effects are detailed along with the results of pedestrian color recognition.

<u>Pedestrians – Color Recognition (Overhead Lighting Present)</u> The Color Recognition Distance of pedestrians was also considered in an ANCOVA with the vehicle speed as a covariate. The results from this ANCOVA (a significance level of 95% (α=0.05)) are summarized in Table 3.

Table 3.
ANCOVA Results for Pedestrian Color Recognition Distance

Source	F Value	Pr > F
Age	7.42	**0.0108***
Headlamp Color and Intensity	1.22	0.3016
Age*Headlamp Color and Intensity	0.68	0.5131
Pedestrian Clothing Color	28.67	**<.0001***
Age*Pedestrian Clothing Color	2.02	0.1172
Headlamp Color and Intensity*Pedestrian Clothing Color	1.62	0.1464
Age*Headlamp Color and Intensity*Pedestrian Clothing Color	1.45	0.2004
Overhead Lighting Color and Intensity	1.62	0.1963
Age*Overhead Lighting Color and Intensity	1.13	0.3453
Headlamp Color and Intensity*Overhead Lighting	0.83	0.5532

Color and Intensity		
Age*Headlamp Color and Intensity*Overhead Lighting Color and Intensity	1.74	0.1385
Pedestrian Clothing Color*Overhead Lighting Color and Intensity	2.06	**0.0379***
Age*Pedestrian Clothing Color*Overhead Lighting Color and Intensity	0.36	0.9535
Headlamp Color and Intensity*Pedestrian Clothing Color*Overhead Lighting Color and Intensity	0.43	0.9549
Age*Headlamp Color and Intensity*Pedestrian Clothing Color*Overhead Lighting Color and Intensity	0.46	0.9161
p < .05 significant		

Similar to the results of the pedestrian detection, participant age, pedestrian clothing color, and the interaction of pedestrian clothing color and overhead lighting color and intensity were statistically significant. However, in contrast to pedestrian detection results, overhead lighting color and intensity was not a significant factor in pedestrian color recognition. Regarding the significance of participant age, this may be expected as the lens of the human eye undergoes a physical yellowing with increased age (Coren and Girgus, 1972).

With the interaction of pedestrian clothing color and overhead lighting color and intensity being significant in terms of both detection and color recognition of pedestrians, a focus on these factors is displayed in Figure 2. Here, the impact of overhead lighting color on each pedestrian clothing color is similar between lighting types. In general, all of the pedestrians were more visible under the HPS light source with the gray-clothed pedestrians performing at the highest detection distance. The red-clothed pedestrian was less visible under the HPS than under the LED and took a more substantial decrement than did the other object types.

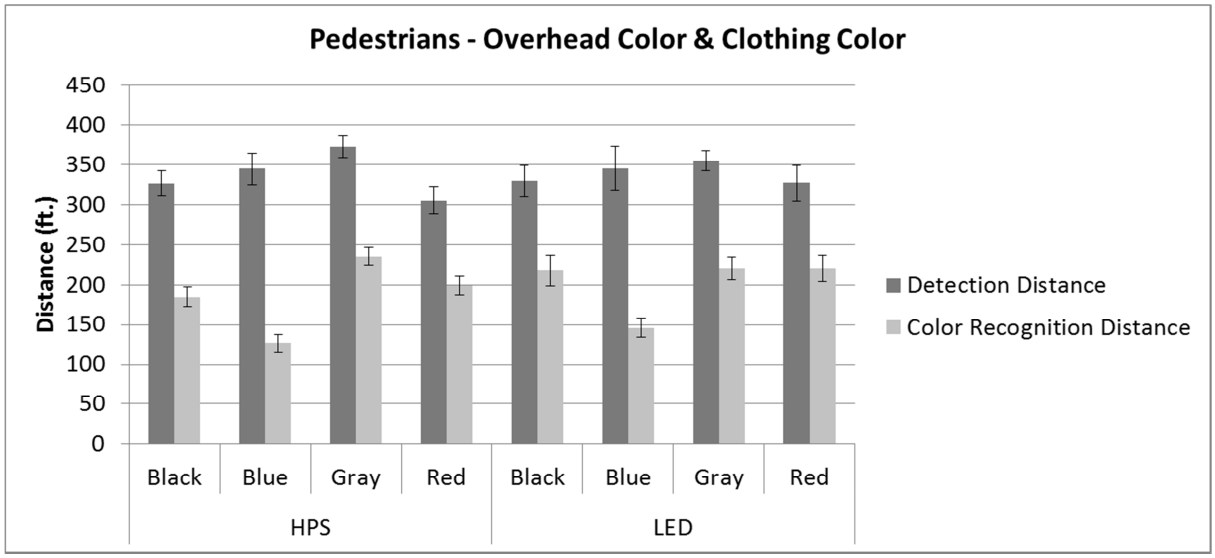

Figure 2. Mean detection and color recognition distances of pedestrians by clothing color and overhead lighting color.

In terms of the interaction between lighting source type and lighting level and light source, participants both detected and recognized pedestrian clothing color from further away when under the LED lighting than they did when under the HPS, but only for the higher intensity condition. As the factor of overhead lighting color and intensity was a pooled factor, and seeing the similarity between lighting types in Figure 2, this leads one to believe that the significance of this factor in the resulting ANCOVA table is due more to the intensity aspect than the color aspect. In other words, any differences in participants' ability to

detect or recognize pedestrian clothing color are more likely due to the differences in intensities between LED and HPS and not necessarily their differences in spectral color output. In order to highlight the role that intensity is playing in the significant effects of overhead lighting, Figure 3 shows the interaction where it can be seen that the LED outperformed the HPS at the high intensity level but HPS performed at a higher level in the low intensity condition. This inversion in performance of overhead light source as the intensity is decreased remains an area for future research. It is also noteworthy that this was only evident for the detection distance.

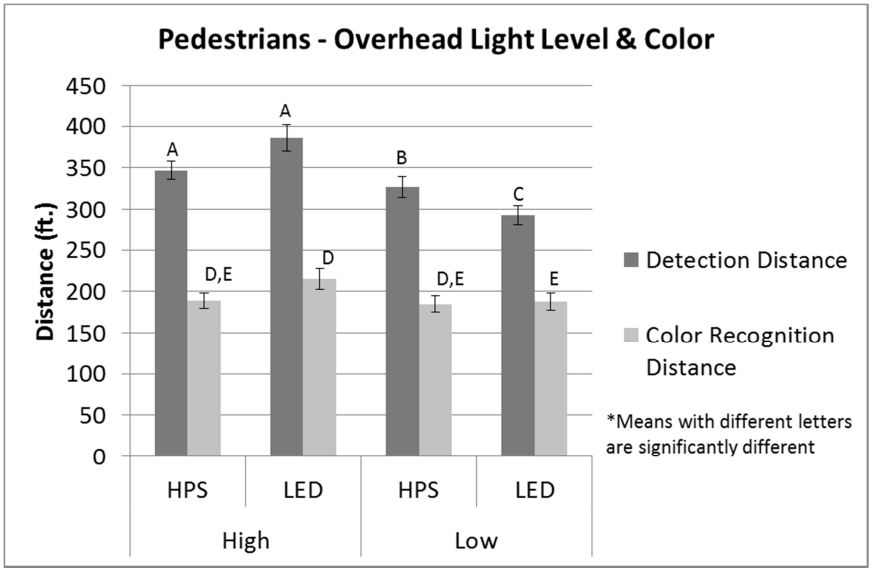

Figure 3. Mean detection and color recognition distance of pedestrians by overhead light.

<u>Off-Axis Pedestrians – Detection and Color Recognition</u> The Detection Distance and Color Recognition Distance of pedestrians located in an off-axis position were considered in an ANCOVA considering all of the experimental design parameters. However, participant detections and color recognitions of the off-axis pedestrians resulted in a small subset of the data collected. Final results indicate that participants failed to detect off-axis pedestrians 77% of the time and failed to recognize pedestrian clothing color 82% of the time. While no meaningful statistically significant conclusions can be drawn from this sample of data, mean distances were compared and are shown in Figure 4.

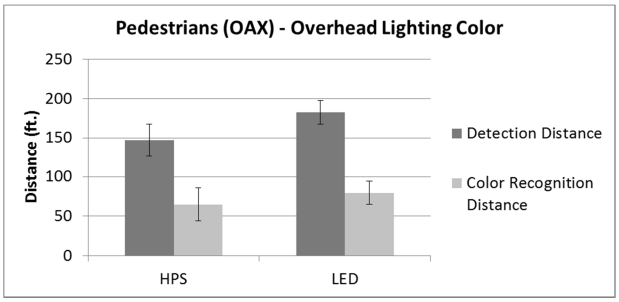

Figure 4. Mean detection and color recognition distance of off-axis (OAX) pedestrians by overhead light.

Pedestrians located peripherally off the roadway were detected from a further distance, on average, when under the LED lighting than when under HPS. This also applied to distances at which color of pedestrian clothing was recognized. While not significantly different, there may be a spectral aspect related to these differences in performance. This would be consistent with expectations of the human eye in conditions of the bluer light of the LED as compared

to the yellow light of HPS. The eye is more sensitive to the blue light of the LED in such mesopic and scotopic driving conditions as this. With the location of these pedestrians in the periphery there is more of a contribution by rods than cones in detection and color recognition. As rods and cones have different response functions to light, the contribution of rods changes the maximum light wavelength sensitivity of the human eye. In a daylight – photopic – scenario the eye would be most sensitive to green light at 555nm. However, in this nighttime scenario, the contribution of rods makes the eye most sensitive to the bluer color of 505nm; therefore, more sensitive to the bluer LED color than the higher yellow wavelength of HPS (CIE, 1951). This might allow those pedestrians located in the periphery under the bluer LED light to be detected from slightly further away than they are when under the yellow HPS light.

Targets – Detection (Overhead Lighting Present) The Detection Distance of targets was considered in an ANCOVA. Similar to the analysis of the pedestrians, only data recorded from the overhead illuminated section of the road are included in this analysis of targets. The results from this ANCOVA (a significance level of 95% (α=0.05)) showed that the main effect of Target Color ($F=12.35$, $p<0.0001$) was significant.

The specific differences among the target colors are discussed in conjunction with the color recognition of targets in Figure 5.

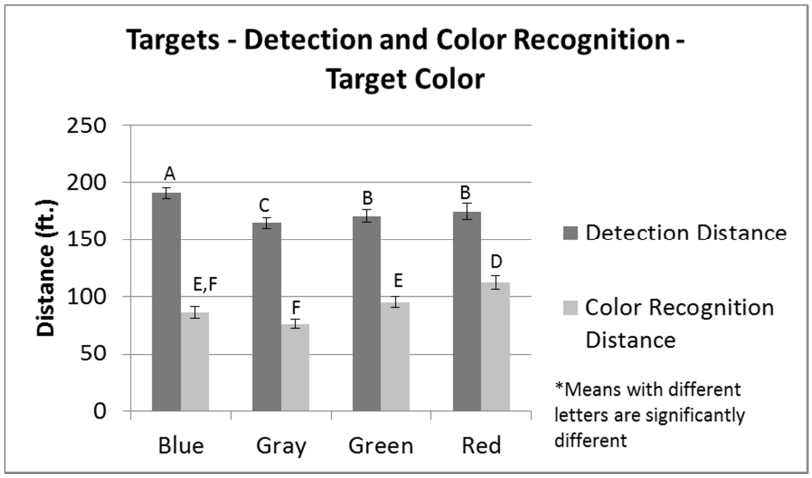

Figure 5. Mean detection and color recognition distances of targets by target color.

Targets – Color Recognition (Overhead Lighting Present) The Color Recognition Distance of targets was considered in an ANCOVA. The results from this ANCOVA (a significance level of 95% (α=0.05)) showed that the Main effect of Target Color ($F=3.6$, $p=0.0169$) and the interactions of Target Color, Overhead Lighting Color, and Intensity ($F=3.5$, $p=0.0018$) are significant.

Figure 5 shows the detailed comparison between specific target colors due to the significant impact of target color in both detection and color recognition.

The blue target was detected from significantly further away than were any of the other target colors, with the gray-colored targets having a significantly shorter detection distance than any other target color. In terms of color recognition, the red target had a significantly greater detection distance than did other targets. Similar to its short detection distance, the gray target had the shortest color recognition distance.

In the case of the significant interaction of Target Color and Overhead Lighting Color and Intensity, Figure 6 shows how the different target colors were recognized under each overhead lighting color.

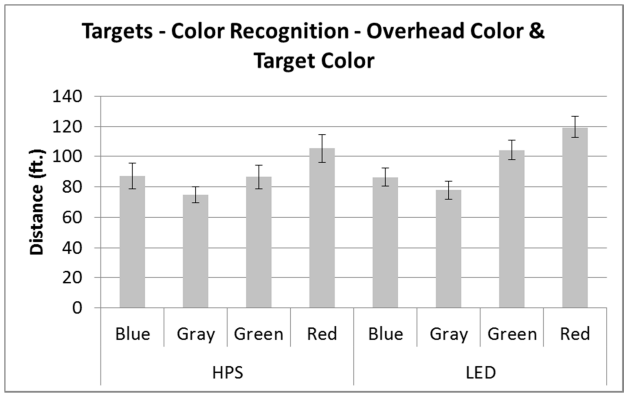

Figure 6. Mean color recognition distance of targets by overhead lighting color and target color.

In general, all of the targets were slightly more visible under the LED light source, with the Red target performing at the highest color recognition distance.

Summary

The combination of color and intensity of the overhead lighting was found to have an impact on the participants' ability to detect pedestrians, but not on their ability to recognize their clothing color. The significant interaction of pedestrian clothing color and overhead lighting on participants' ability to detect pedestrians may be related more to the intensity of the overhead lighting than to the color of the overhead lighting. In the cases of pedestrians located off-axis or in the periphery, while not statistically significant ,results indicate that color of the overhead lighting may also play a major role in determining when they are detected and when their clothing color is recognized. In general, based on statistical findings, the results show that headlamp color within the range tested had a minimal impact on the detection and color recognition of pedestrians and targets when such objects were located along the roadway with overhead lighting present.

In the case of targets, the combination of color and intensity of the overhead lighting was found to have an impact on the participants' ability to recognize the color of targets, but not on their ability to initially detect the targets. Finally, target colors were recognized from further away under the LED overhead lighting than under the HPS (particularly the lower intensity of LED lighting).

DISCUSSION

Off-Axis Pedestrian Color Recognition

In a comparison between pedestrians located along the roadway and those in the driver's peripheral vision (shown in Figure 7), overhead lighting color seemed to have a minimal impact on pedestrians located along the roadway.

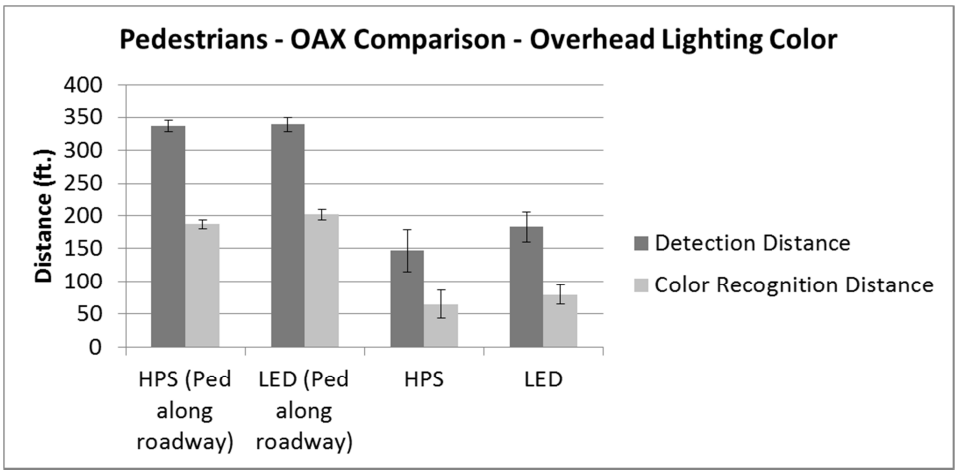

Figure 7. Comparison of pedestrians by location and overhead lighting color.

However, in the case of off-axis pedestrians located in the driver's peripheral vision, while not statistically significant, the LED overhead lighting allowed a greater detection and color recognition distance than did the HPS overhead source. This indicates a possible spectral component in how pedestrians located in the periphery are detected and recognized. This is consistent with the results when comparing pedestrian locations, taking into account the color of their clothing, as shown in Figure 8.

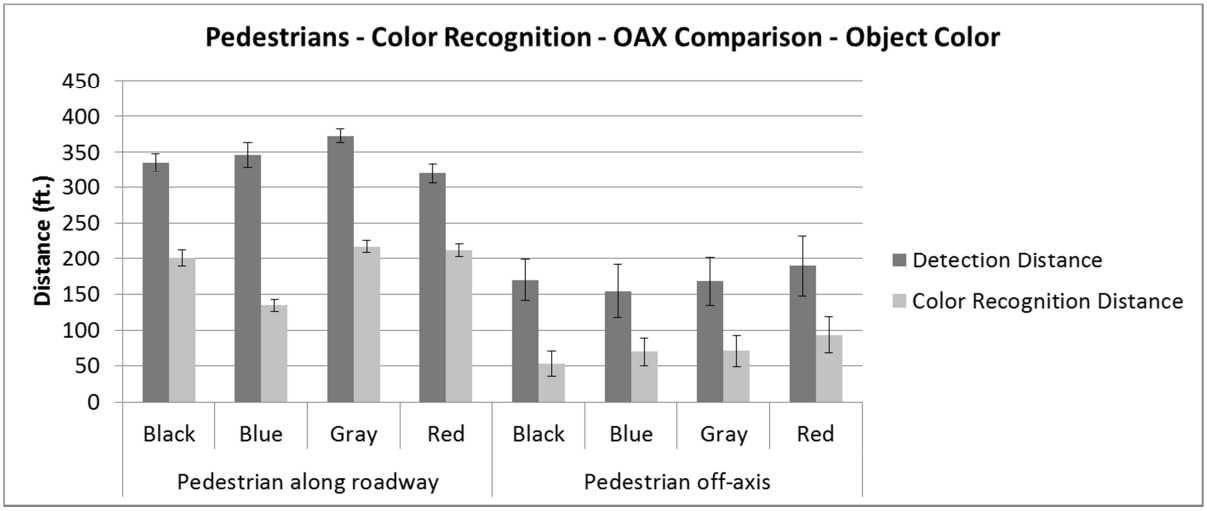

Figure 8. Comparison of pedestrians by location and clothing color.

Particularly worth noting is the significantly lower color recognition of the blue-clothed pedestrian when the pedestrian is located along the roadway. When the pedestrian location is changed to that of an off-axis location, the color recognition of this blue-clothed pedestrian is similar to that of any of the other clothing colors in the off-axis location. This is to be expected as human eyes become more sensitive to this blue color when in lower levels of light (the scotopic and mesopic lighting that comprises most night driving) and the rod-dominated areas of the periphery.

CONCLUSIONS

The conclusions from this investigation indicate that:

- Overhead lighting is a significant factor in the detection and color recognition of pedestrian clothing, but results indicate that it is the intensity, not necessarily the color, of the lighting that makes it a significant factor.
- Pedestrian clothing color plays a significant role in pedestrians being detected and their clothing color recognized.
- Target color plays a significant role in targets being detected and their colors recognized.
- Headlamp color within the range tested appears to have a minimal impact on detection and color recognition of pedestrians and targets in situations with overhead lighting present.
- The CCT of overhead lighting may play a much more significant role when pedestrians are located peripherally, as compared to pedestrians along the roadway.

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