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Spectral Effects of High-Intensity Discharge Automotive Forward Lighting on Visual Performance

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ABSTRACT

Recent studies have shown that high-intensity discharge (HID) headlamps provide visual benefits to the vehicle operator that may lead to increased nighttime driving safety. An experimental field investigation is described that further investigates the visual performance aspects of HID forward lighting systems to isolate and examine the role of lamp spectral distribution under realistic nighttime driving conditions.

This study examines lamp spectral distribution by direct comparison of HID source spectra to one that simulates a conventional halogen source. Two additional lamp spectra are also included in this study, a “cool” distribution with a high percentage of short wavelength visible light and a “warm” distribution with a high percentage of long wavelength visible light. Subjects perform a visual tracking task, cognitively similar to driving, while seated in the driver's seat of a test vehicle. Simultaneously, small targets located at various angles in the periphery are activated and target detection reaction time is recorded. Reaction times greater than 1 second are considered misses. Target illuminances are kept constant between the HID and halogen simulating systems, allowing the effects of spectrum to be identified and isolated.

From the results, comparisons are made among the four lighting conditions. The differences in visual performance as a function of light spectrum are discussed. The potential implications of the results on driving safety and on the development or refinement of HID forward lighting systems are also discussed.

INTRODUCTION

BACKGROUND

HID headlamps provide benefits to off-axis visual performance that may lead to greater nighttime safety.[1][2][3][4][5] HID lamps differ from conventional halogen headlamps in two important aspects: total light output and spectral composition. It is these differences that most likely explain the relative benefits seen in visual performance as compared to halogen systems. HID lamps generally produce two to three times as much overall light than halogen lamps and often have spectral distributions weighted more toward shorter visible wavelengths.[6] However, the relative contribution of each factor, or how important a role spectral composition plays with respect to the total light output, is unknown. It has been shown that depending on the visual conditions light spectrum can moderately or greatly increase efficiency.[7][8]

There are two types of photoreceptors in the human eye: cones that are used for daytime vision, and rods that are used at night. In the retina cones are mostly found in the fovea, or central viewing area, while rods are only found in the periphery. At high light levels, above 3 cd/m^2, the cones suppress the rods and dominate visual performance. As light levels are reduced the control of the cones diminishes and rods begin to play a more dominant role.[7]

Important in this study, the shift in photoreceptor activity with light level is accompanied by a shift in spectral sensitivity in the peripheral retina. The peak spectral sensitivity of the cones is at 555 nm; for rods the peak sensitivity is at 507 nm. The luminous efficiency function of the fovea, $V_?$, remains essentially constant at any light level since there are no rods in the center of the fovea.[7] However, the luminous efficiency of the peripheral retina gradually shifts toward shorter wavelengths as light levels are reduced.[9][10] At very low light levels only rods are functioning.

Under nighttime driving conditions light levels typically range from 0.3 - 0.01 cd/m^2. In this mesopic region both rods and cones are active.[11] Some recent studies show much larger effects of lamp spectra on off-axis visual performance in this region than would be deduced from theory.[8][12] Changes in spectral sensitivity of the visual system under mesopic light levels can not alone explain changes in visual performance.

The explanation for the differences in results lies in the response characteristics of visual performance. Visual performance is dependent upon various stimulus parameters, such as target size and contrast, as well as characteristics of the area surrounding the target. Depending on the light level, changes to these parameters can have small or large effects on visual performance. These visual parameters interact to affect visual performance. It is because of this fact that a field study is needed to determine if any spectral effects from HID systems can be seen in realistic conditions.

SCOPE OF PAPER

An experimental field investigation is described that investigates visual performance aspects of HID forward lighting systems as it relates to spectral distribution. This study is an extension of earlier research. The goal here is to isolate and examine the role that lamp spectral distribution plays on visual performance under realistic nighttime driving conditions.

This paper is divided into three main sections. The first reviews the experimental methods employed in the study. This includes a description of the experimental geometries, procedures, and subjects used.

The second section presents the experimental results. This includes both reaction time and number of missed signals as a function of target location, target contrast, and lighting condition.

The last section analyzes the data. Potential implications on driving safety and on the development or refinement of forward lighting standards are discussed.

METHODS

EXPERIMENTAL GEOMETRY

This experiment was designed to measure off-axis visual performance under four vehicle frontlighting conditions in which the same photopic illuminance was produced on the roadway, but with different spectral distributions. One HID headlamp system was used to produce all four lighting conditions through filtering. The system used is considered relatively “high quality” and uses DS1 lamp to produce a beam pattern corresponding to SAE J1383 standards. The measured intensity distribution for the right HID headlamp is shown in Figure 1 (the distribution for the left was similar). This intensity distribution is for the lamp before filtering. Filtering the system lowers the intensity values but does not appreciably alter the shape of the beam distribution. Although the intensity values are lowered the filtered beam used in this study still meets SAE J1383 photometry standards.

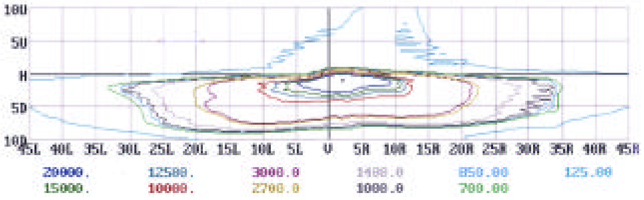

Figure 1. Intensity distribution of right HID test headlamp.

Two target contrast levels were used, a high contrast with a reflectance of approximately 40% and a low contrast with a reflectance of approximately 20%. Subjects were shown the off-axis targets lit with the test headlamps and asked to respond as soon as the target was seen. If no response was given within 1 sec the target was considered missed. This process was repeated many times and the subject reaction times and numbers of missed signals were recorded.

In order to increase application validity this experiment was performed in the field. A disused runway at Schenectady County Airport in Scotia, NY was chosen as the study location. This location offered a straight, flat, paved surface with little stray light. The average background illuminance was less than 0.1 lx. The tarmac is asphalt and exhibited reflection characteristics similar to a typical roadway surface.

The experimental geometry, shown in Figure 2, is as follows. The subject sits in the driver position in a stationary test vehicle. A tracking task is placed ~15 m away from the front of the test vehicle directly in the subject’s line of sight. Six targets are placed at a consistent distance of 60 m from the vehicle. The targets have a 5^o angular separation, with four to the right of the driver and two to the left. In both directions the targets start at 2.5^o from the line of sight. This geometry results in targets at the angular positions shown in Figure 2, where negative angles indicate to the left of the driver and positive to the right.

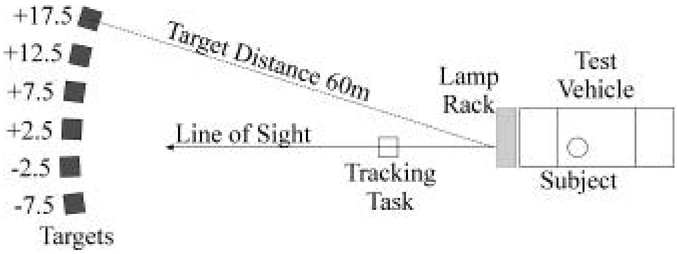

Figure 2. Schematic diagram of experimental geometry.

The headlamp system was placed on a rack in front of the car. It was constructed on a frame that could be adjusted for aiming and mounted on the rack fixture. The rack with headlamp assembly is shown in Figure 3.

Figure 3. Headlamp rack assembly with filters.

The subject could not see the rack from the driver's position so it appeared the lighting was from the vehicle. Headlamps were mounted at the correct vehicle height and separation. The HID system was powered directly from the test vehicle battery. Care was taken to aim the headlamps to the line of sight every time they were mounted on the rack or adjusted. Aiming was performed visually using a screen 10 m from the lamps.

The tracking task used consisted of an LED "bar graph", shown in Figure 4. This was a linear series of LEDs that mimicked a moving bar graph. The lights started lit in the middle and light a random distance up or down. The subject has a knob controlling the LEDs and is instructed to turn them off till they reach the center again. Once the center is reached the LEDs light in a random direction again. The subject is asked to perform the tracking task throughout the experiment. This ensures that the subject's line of sight is fixed.

Figure 4. LED bar graph.

Figure 5 shows the targets used in this experiment. They are a 177.8 mm x 177.8 mm grid of "flip dots". The flip dots are small 12.7 mm diameter electromagnetic disks that are white on one side and black on the other. When a current is applied the disks flip completely within 20 ms, showing the white or black face. The dimensions and relative position on the targets were constructed to match other studies of roadway visibility.[13][14]

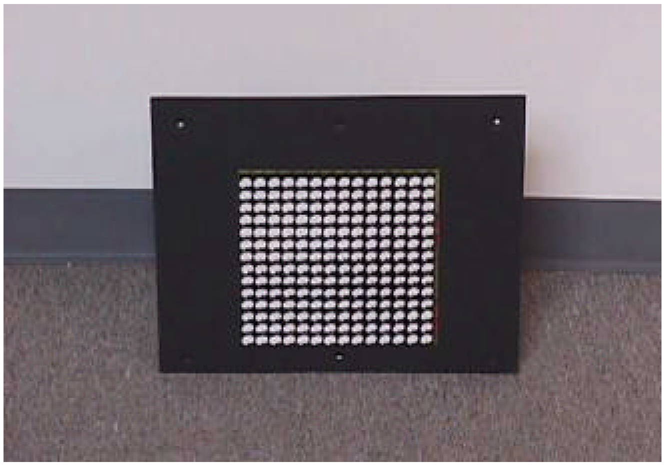

Figure 5. Flip dot target.

Changing the target contrast was accomplished by placing neutral density filters over the targets. For high contrast the target was used with no filter. The lower contrast condition was accomplished by placing a 0.15 optical density filter over the target. This resulted in a contrast level of ~50%. The filters were placed over the target at an angle so that any light reflected directly from the filter would not return to the subject.

The illuminance levels were measured at the top and bottom of the targets each time the headlamps were mounted. Figure 6 shows the average target illuminance as a function of angular target position. The study was performed over two sessions; each point represents the average target illuminance (top and bottom) averaged over the two sessions with the error bar length equal to twice the standard deviation.

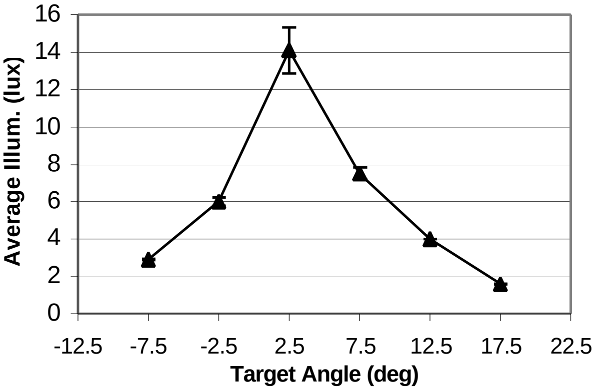

Figure 6. Plot of average target illuminance.

SPECTRAL DISTRIBUTION

The goal of this study is to isolate and examine the role that lamp spectral distribution plays on visual performance under realistic nighttime driving conditions. To accomplish this a series of headlamp systems were tested that produced similar total light output and spatial distributions but had varying spectral compositions. The systems were compared on the basis of scotopic to photopic (S/P) ratio. S/P ratio is defined as the ratio of a source's light output as determined using the scotopic luminous efficacy function, to the source's output as determined using the photopic luminous efficacy function. S/P ratio provides a good indication at how effective a light source is at stimulating the rod photoreceptors, and thus provides a relative comparison between light sources to determine how effective they are for low light level off-axis vision. HID sources typically have slightly higher S/P ratios (~7% higher) than halogen sources and thus will theoretically result in greater mesopic visual performance.

All the spectral distributions were generated by filtering the HID headlamp system. Table 1 shows the test lighting conditions characteristics used in this study. The HID condition uses neutral filters to reduce the intensity but leave unaltered the spectral composition. The "halogen simulating" condition uses slightly yellowish filters to reduce the S/P ratio such that it is comparable to a standard halogen lamp. The difference in S/P ratios between the HID and halogen simulating conditions corresponds to the difference that actually exists in these types of headlamps. The warm condition uses filters with greater absorption in the short-wavelength region to reduce CCT and S/P ratio to values lower than that of typical halogen headlamps. The cool condition uses long-wavelength-absorbing filters to increase CCT and S/P ratio. All conditions create "white" light that falls within the color box for white as defined by SAE J578 (Figure 7).

Characteristic	**Filtered Lighting Conditions**			
	Warm	**Halogen simulating**	**HID**	**Cool**
S/P ratio	1.02	1.57	1.69	2.04
Transmission	57%	59%	58%	58%
CCT	2740K	3755K	3884K	5037K
Chromaticity (x,y)	0.47, 0.44	0.40, 0.40	0.39, 0.38	0.35, 0.36

Table 1. Characteristics of the filtered lighting conditions.

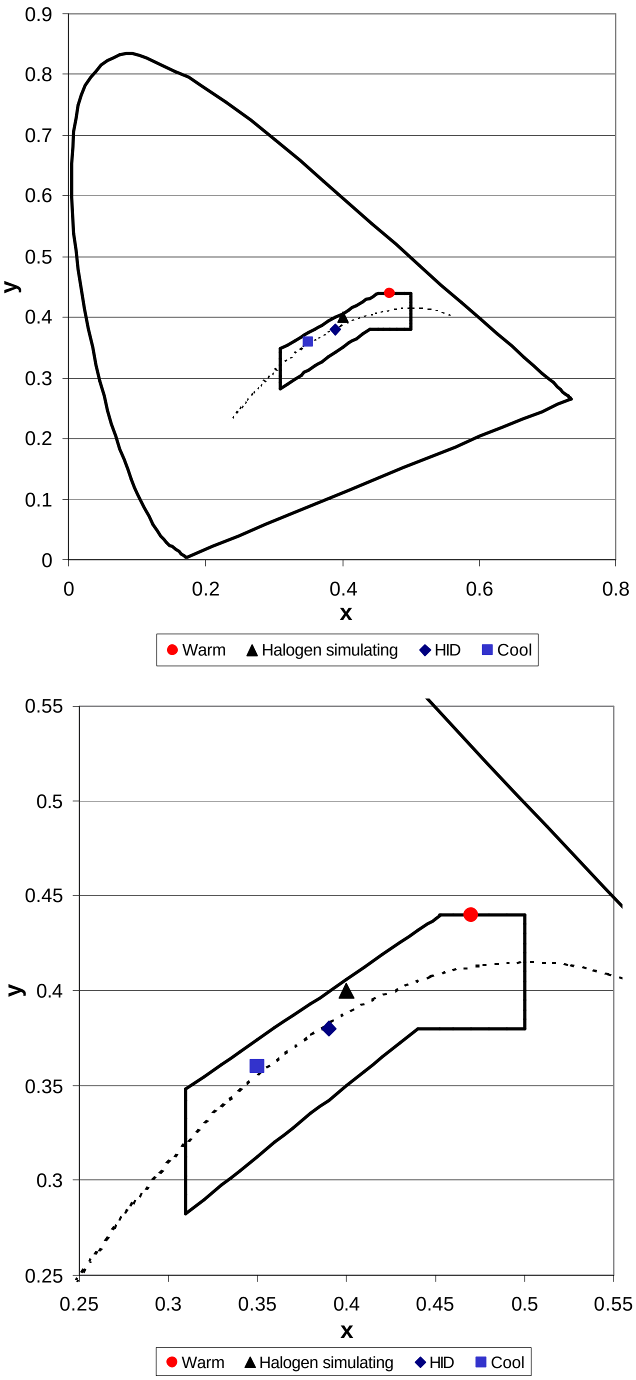

Figure 7. 1931 x,y chromaticity coordinates of the test lighting conditions. All the conditions fall within the SAE white box (also shown).

PROCEDURE

The experiment was conducted as follows. Subjects were asked to sit in the driver's position of a stationary car with the scene already illuminated by the HID system appropriately filtered to produce one of the four test lighting conditions. Subjects did not see which filters were being used. Once seated the subject was given a control box. It contained a knob to control the LED tracking task and a reaction time switch.

After a trial run to get acquainted with the controls the actual test was started. The subject held the reaction time button down while performing the tracking task. Targets were presented in a random order at random time intervals. Subjects were asked to release the reaction time button when a target was seen. If the subject did not respond in 1 sec to the target presentation it was considered missed. The reaction time and number of missed signals was automatically recorder by a computer. In one data collection period each target was presented to the subject four times.

The data collection periods were repeated within two groups of five subjects. Each subject performed the experiment at one lighting condition and the targets at one contrast level. The contrast level was then changed, either higher or lower, and each subject performed the experiment again. After each subject in the group performed the experiment for one lighting condition at both contrast levels the filter was changed and the process repeated.

Care was taken to randomize the order of the lighting conditions and target contrast levels presented. This was done to counterbalance any order effects. Therefore, in total, eight data collection periods were completed by each subject, four spectral distributions and two target contrast levels. In each data collection period 24 data points were collected (4 for each target). So, for each subject 192 data points were collected.

SUBJECTS

Ten subjects were used in total. The subjects ranged in age from 23 years to 42 years, with an average age of 33 years and a standard deviation of 10 years. Each subject was tested to ensure they had at least 20/20 corrected acuity and no color blindness.

RESULTS

REACTION TIMES

Figure 8 shows reaction time versus target location for all lighting conditions. The y-axis shows reaction time in milliseconds. The x-axis shows target location in degrees. Each reaction time data point is the average of all subjects and the errors bar length corresponds to twice the standard deviation. Reaction times are shown for both target contrasts. The impacts of target location and target contrast on reaction time were found to be statistically significant for these data ($p<0.05$). There is also a significant interaction ($p<0.05$) between target contrast and target angle. Additionally, there is significant interaction ($p<0.05$) between target contrast and lighting condition, as will be explained in the following sections.

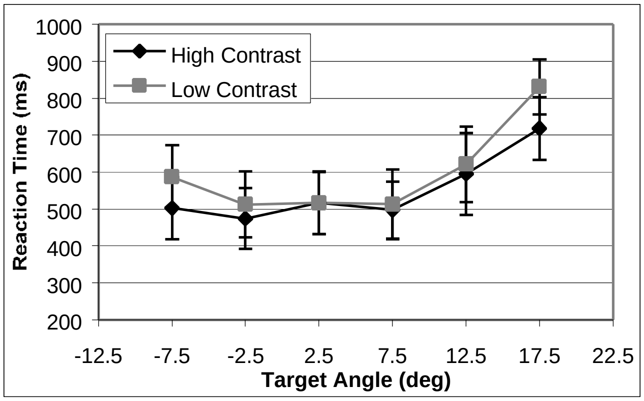

Figure 8. Average reaction times for all lighting conditions.

Several things are evident from the graph in Figure 8. Generally, reaction times are lowest at the small angle targets where illuminance is highest and reaction time increases as the target angle increases and the illuminance decreases. For both target contrast levels reaction times are statistically similar at small angles. As the angles increase the reaction times for each contrast condition begin to separate. This is particularly evident at the -7.5° and 17.5° target locations.

High Contrast

Figure 9 shows the average reaction times for the high contrast targets as a function of lighting condition. The y-axis shows reaction time in milliseconds. The x-axis shows target location in degrees. Each reaction time data point is the average of all subjects and the errors bar length corresponds to twice the standard deviation. The impacts of spectral distribution (S/P ratio) on reaction time were *not* found to be statistically significant for these data ($p>0.05$).

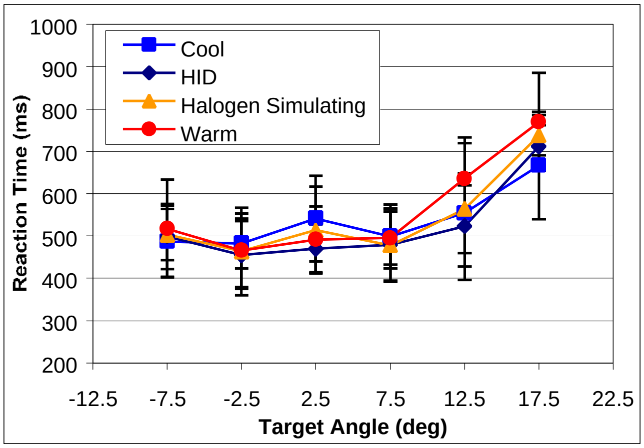

Figure 9. Average reaction times for high contrast targets.

Low Contrast

Figure 10 shows the average reaction times for the low contrast targets as a function of lighting condition. The y-axis shows reaction time in milliseconds. The x-axis shows target location in degrees. Each reaction time data point is the average of all subjects and the errors bar length corresponds to twice the standard deviation. The impacts of spectral distribution (S/P ratio) on reaction time *were* found to be statistically significant for these data ($p<0.05$).

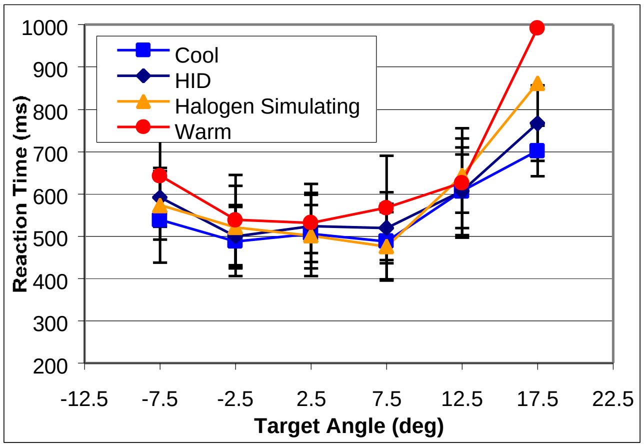

Figure 10. Average reaction times for low contrast targets.

The average reaction time has increased over the high contrast case. However, the same general trends are again seen. The trending is more severe with the low contrast targets than with the high contrast case. The reaction time increases more rapidly as the target angle increases and the target illuminance decreases. At -7.5^{o} and 12.5? the reaction times start to significantly increase.

Unlike the high contrast case, here the increase in reaction time is not equal for all of the lighting conditions. A definitive order is seen. The cool lighting condition produces the lowest reaction time. The HID condition and then the halogen simulating condition follow. The warm lighting condition results in the longest reaction time.

MISSED SIGNALS

Figure 11 shows a plot of missed signals vs. target location for all lighting conditions. The y-axis corresponds to the percentage number of totals targets missed. Each target is presented 4 times to the 10 subjects for a total of 40 possible target presentations to miss. The x-axis shows target location in degrees.

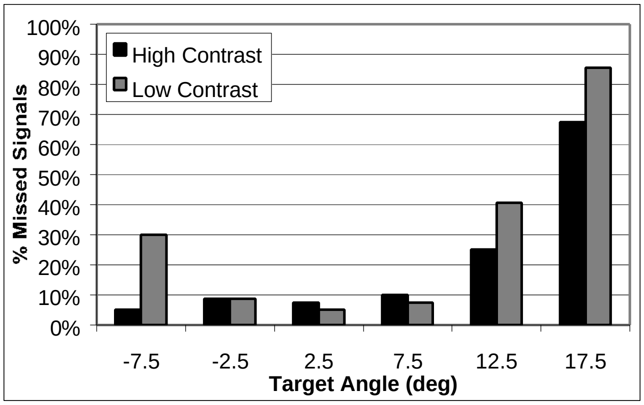

Figure 11. Percent missed signals for all lighting conditions.

The same general trends as seen in the reaction time data are present in Figure 11. For both target contrasts few targets are missed at small angles. The missed targets shown in Figure 11 from –2.5^{o} to 7.5^{o} are probably the result of experimental noise. As the target angle increases, and the target luminance decreases, the number of missed signals increases. The increase in missed signals does vary between the target contrasts. The high contrast targets result in the least amount and the slowest increase of missed signals.

High Contrast

Figure 12 shows a plot of missed signals vs. target location for the high contrast targets as a function of the test lighting condition. The y-axis corresponds to the percentage number of totals targets missed. Each target is presented 4 times to the 10 subjects for a total of 40 possible target presentations to miss. The x-axis shows target location in degrees.

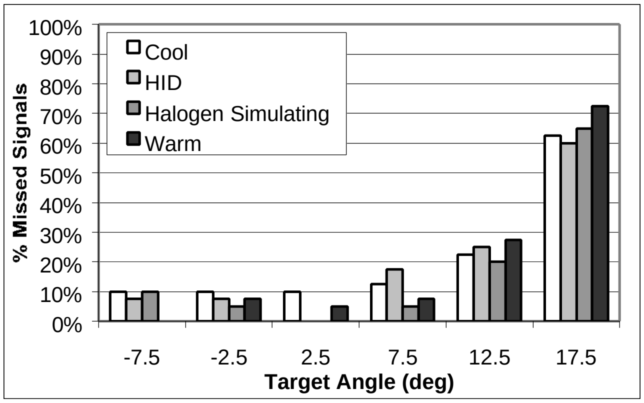

Figure 12. Percent missed signals for high contrast targets.

The same general trends seen in the reaction time data are present in Figure 12. For all headlamps, at small angles few targets are missed. The missed targets shown in Figure 7 from -7.5^{o} to 7.5^{o} are probably experimental noise. As the target angle increases, and the target luminance decreases, the number of missed signals increases.

Although the same general trends are seen for the high contrast target data, no specific conclusions can be drawn from these data regarding lamp spectra.

Low Contrast

Figure 13 shows a plot of missed signals vs. target location for the low contrast target case. The y-axis corresponds to the percentage number of totals targets missed. Each target is presented 4 times to the 10 subjects for a total of 40 possible target presentations to miss. The x-axis shows target location in degrees.

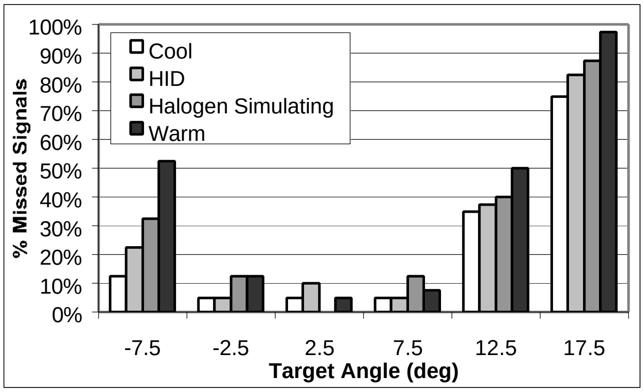

Figure 13. Percent missed signals for low contrast targets.

The total numbers of missed signals have increased over the high contrast case. However, the same general trends are seen again. As with reaction time, the trending is more severe with the low contrast targets than with the high contrast case. The numbers of missed signals increases more rapidly as the target angle increases and the target illuminance decreases. At -7.5^{o} and 12.5? the number of missed signals start to significantly increase.

Unlike the high contrast case, here the increase in missed signals is not equal for lighting conditions. A definitive order is seen. The cool lighting condition produces the fewest missed signals. The HID condition and then the halogen simulating condition follow. The warm lighting condition results in the most missed signals.

DISCUSSION

Previous studies indicate that HID systems can provide relative visual benefits for off-axis vision.[1][2][3] However, in these studies there were two factors that may have been responsible for the increased off-axis visual performance produced by the HID system: higher target illuminance and different light spectra. Since the test beam patterns were not controlled, the illuminances at the targets were as they would be in practice, and therefore was no way to distinguish between the two effects. For this reason, this study was performed to isolate and determine the specific role that spectral power distribution plays. This was done by using one headlamp system and filtering it to change the spectral output. In this way four spectral distributions were tested.

This study found that for the high contrast targets lamp spectra had no significant effect on visual performance. For the low contrast targets, however, lamp spectra resulted in a significant effect, with the “cool” headlamp spectral distribution resulting in increased visual performance over the “warm” distribution as measured by both reaction time and number of missed signals. These results are consistent with the plateau and escarpment characteristics of visual performance whereby the visibility of high contrast or large-sized targets is insensitive to lighting conditions (the plateau), but very sensitive to lighting conditions when the objects of interest are of low contrast or small size (the escarpment).[15] The HID and halogen simulating spectral distributions resulted in visual performance measures that fell between these two extremes and, although they were not significantly different from each other, the trending of the results followed what would be expected by comparing their S/P ratios. These results indicate that lamp spectra can influence low light level visual performance at off-axis angles that are relevant to driving tasks, particularly when the target has a low contrast.

To estimate the impact of spectrum on performance, consider the target illuminances required to provide equal criterion reaction times of 600 ms for the low contrast targets (Figure 10). For the "warm" source, the mean reaction time of 600 ms is reached between 7.5^{o} and 12.5^{o} toward the passenger side of the field of view; interpolating gives an approximate angle of 10^{o}. For the "cool" source, the same mean reaction time occurs at 12.5^{o} from the line of sight. It was found in a re-analysis of reaction time data under similar conditions that beyond 8^{o}-10^{o} from the line of sight, reaction times to targets did not degrade significantly as a function of angle, so it is assumed that the difference between 10^{o} and 12.5^{o} is unimportant for reaction times.[16] Interpolating from Figure 6, which displays the illuminances from the forward lighting systems as a function of angle, it is seen that an illuminance of approximately 6 lx is obtained at 10^{o}, and 4 lx at 12.5^{o}.

Thus, it is estimated that about 6 lx from the "warm" source gives equivalent visual performance as about 4 lx from the "cool" source; in other words, illumination from the "cool" source is approximately 50% more efficacious at eliciting detection than illumination from the "warm" source in the region from about 10^{o} to 12.5^{o}. As a first (and very rough) approximation, the mesopic efficacy of a particular source could be estimated as a weighted average of the photopic and scotopic efficacies from the source.[7] Assuming the photopic efficacy of both the "warm" and "cool" sources to be the same, and assuming the scotopic efficacy of the "cool" source to be about twice that of the "warm" source (based on its S/P ratio of about 2, compared to the S/P ratio of the "warm" source of about 1), the mesopic efficacy of the "cool" source could be approximated as about 1.5 times that of the "warm" source, or about 50% higher. The consistency between the empirical data in this study and the model of mesopic vision described by He *et al.* [7] indicates that this model provides a reasonably accurate prediction of the effects that can be found by changing the spectrum of forward lighting for the conditions in this study.

CONCLUSIONS

This study was performed to determine the role that HID lamp spectral distribution plays on visual performance. In as closely as the conditions simulated here are representative of typical real world driving, it can be generalized from this study that the spectral distribution of HID headlamps does produce a small, but measurable, improvement over halogen systems for off-axis visual performance. In other words, for the same photopic illuminance, HID is slightly more effective for off-axis low light level visual performance. Further, even "cooler" sources can be generated that can significantly increase the effectiveness of the light and "warmer" sources can be created that can decrease the light's effectiveness and worsen visual performance. The exact magnitude of the difference in performance depends on the off-axis angle and the target contrast.

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