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ABSTRACT

Recently, there has been a proliferation of commercially available lamps with spectral light output differing from conventional halogen lamps for use in vehicle headlighting systems. For the last 20 to 30 years halogen lamps have been used as the standard source in most headlamp applications. These lamps produce the familiar blackbody-like continuous-spectrum output light. In the last ten years, high-intensity discharge (HID) light sources have come onto the market place with their characteristic discrete spectra and higher correlated color temperature (CCT). Even more recently, coated "blue" halogen lamps have become available which reduce the amount of long-wavelength light and shift the light output to higher CCTs. Currently, halogen lamps are under development that have glass envelopes doped with neodymium, which acts similarly to the coated lamps in reducing long-wavelength light and shifting the CCT to higher values. With all of these new headlamp sources being used with different spectral light output the question arises about the appearance of common roadway objects under different headlamp illumination.

A laboratory study is presented that examines subjective color preferences under different types of headlamp illumination. Side-by-side and sequential viewing of targets illuminated by headlamp bulbs was performed by subjects. Neodymium, HID, "blue"-coated, and conventional halogen lamps were compared. Since traffic signs are among the most important colored objects along the roadway, common sign materials were used to make up the test targets. Several color viewing properties were examined, including color naming, specific color comparison preference, overall color comparison preference, and overall preference. The implications of the results to driving performance and aesthetics are discussed.

INTRODUCTION

This report describes a study performed by the Lighting Research Center (LRC) to determine the subjective color preference, if any, of bulbs used in automobile headlamps. The present study examines subjective color preferences under different types of headlamp illumination. Side-by-side and sequential viewing of targets illuminated by headlamp bulbs was performed by subjects. Neodymium, HID, "blue"-coated, and conventional halogen lamps were compared. The spectral power distribution for each of the lamps is provided in Figure 1. Each of the curves was normalized for relative comparison.

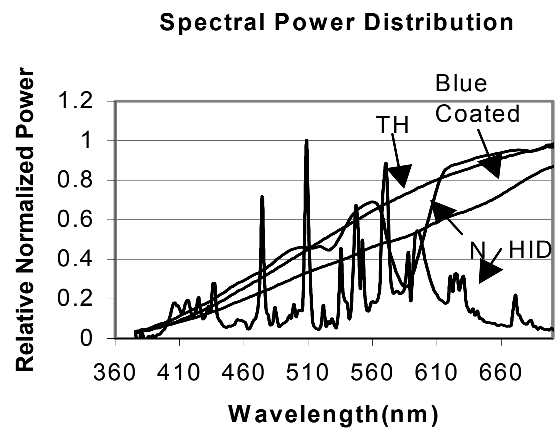

Figure 1. SPD of the lamps used in the study.

The luminance values of traffic signs at night is somewhere between 0.5 cd/m^2 and 15 cd/m^2 [1,2,3] The present study was conducted at two different luminance levels within this range to determine whether subject preference was correlated with luminance. A white reflectance standard was used to measure the luminance levels for each lamp in both the high and low luminance level studies. The luminance levels measured from the white reflectance standard were 11.6 cd/m^2 and 63.2 cd/m^2. The luminance of the colored sign materials ranged between 0.5 cd/m^2 and 15 cd/m^2 when the luminance of the white reflectance standard was 11.6 cd/m^2.

The implications of the results to driving performance and aesthetics are discussed.

METHOD

Volunteers were recruited to participate in this experiment. The subjects were asked to answer questions about their color preference when comparing two identical boxes in which identical color targets were placed. Each box was illuminated using different lamps at approximately the same luminance. The subjects were asked questions about the two boxes including color naming, color comparison, preference between boxes and overall preference of the boxes illuminated by the four different lamps. The study was run twice using two different luminances. The first study was conducted at a lower luminance with 22 subjects participating. The second study was conducted at a higher luminance with 20 subjects participating.

The following procedure was utilized for each subject. The subject is asked to take a color vision test. The subject sits in a chair and the room lights are dimmed. The study begins with a curtain in front of the two scenes to be compared. Two of the lamps are turned on and the curtain is lifted after a waiting period of 15 to 20 seconds. The subject is asked questions relating to color naming, side-by-side color preference, and overall color preference. The curtain is lowered and the lamps are turned off and the next set of lamps is turned on. The curtain is lifted after a waiting period of 15 to 20 seconds and the same questions are asked. This cycle continues for a total of eight comparisons. The last question is a sequential comparison. A single lamp is turned on and the curtain is lifted after a waiting period of 15 to 20 seconds. The curtain is lowered, the lamp is turned off, the next lamp is turned on, and the curtain is lifted after the 15 to 20 second waiting period. This procedure is repeated for all four lamps. Then the subject is asked to rank the four lamps in order of preference.

EXPERIMENTAL GEOMETRY

The study was conducted in a darkened laboratory. Figure 2 shows a photograph of the laboratory where the study took place. Figure 3 shows the view of the boxes with a curtain in front. The curtain is raised and lowered between each cycle and the lamps are switched before raising the curtain again. Figure 4 shows the scene that the subjects are comparing. Each box contains 16 color chips taken from traffic signage material provided by 3M. Figure 5 shows a subject looking at the boxes and answering questions.

Figure 2. Study setting.

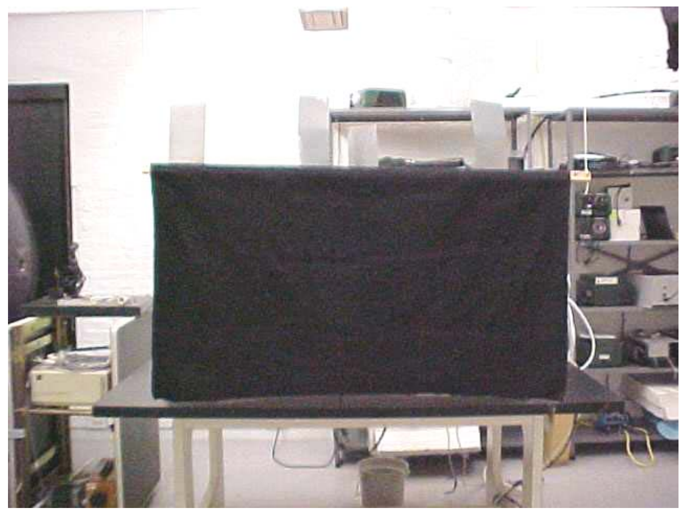

Figure 3. View of test boxes with curtain lowered.

Figure 4. Test scene as seen by subjects.

Figure 5. Subject performing experiment.

LIGHTING CONDITIONS

Four types of lamps were used in the studies reported herein. The types of lamps used in the studies are summarized in Table 1.

Table 1. Lamp Information.

Lamp	Manufacturer Info	Acronym used
Standard tungsten halogen	Commercially available 9007	TH
Xenon or metal halide HID	Commercially available	HID
Neodymium doped tungsten halogen	Prototype from Corning Inc.	N
Blue coated tungsten halogen	Commercially available 9007	Blue coated

Two separate studies were conducted. The difference between the two studies was the luminance used. The luminance was set by measuring the luminance on a white reflectance standard on the back wall of each box for each lamp using a spectroradiometer. Table 2 shows the luminances for each lamp in each box for each study and lists the lamps used in both studies.

Future references to the low luminance study and the high luminance study refer to the studies where the average luminance of the boxes is 11.8 cd/m^2 and 63.2 cd/m^2, respectively. The Illumination Engineering Society of North America (IESNA) suggests in order to perceive a difference in luminance, the ratio should be greater than 2:1 [4]. The largest ratio in the low luminance study is

$$\frac{12.8\,\text{cd/m}^2}{9.9\,\text{cd/m}^2} = 1.3$$

The largest ratio for the high luminance study is

$$\frac{68.0\,\text{cd/m}^2}{60.2\,\text{cd/m}^2} = 1.1$$

Table 2. Lamps in each box and luminance values for each lamp in the low luminance study and the high luminance study.

	Low Luminance		**High Luminance**	
	Lamps	Luminance (cd/m^2)	Lamps	Luminance (cd/m^2)
Box 1	Tungsten halogen	9.9	Tungsten halogen	60.2
	Blue filtered tungsten halogen	12.5	Blue filtered tungsten halogen	63.0
	Neodymium doped tungsten halogen	12.3	Neodymium doped tungsten halogen	62.1
	Mean	11.6	Mean	61.8
Box 2	Tungsten halogen	10.8	Tungsten halogen	68.0
	Metal halide	12.5	Metal halide	64.2
	Neodymium doped tungsten halogen	12.8	Neodymium doped tungsten halogen	61.8
	Mean	12.0	Mean	64.7
	Overall Mean for Study 1	11.8	Overall Mean for Study 2	63.2

Both of these ratios fall well within the 2:1 ratio suggestions and therefore, the subjects should see no perceivable differences among the luminance levels of the scenes.

To satisfy all of the possible comparisons with four lamps, six combinations are required. Two null conditions were included for a total of eight comparisons for each subject. The order of the lamp comparisons was balanced over the subjects to counter balance any order effects.

The signage material was indirectly illuminated, i.e. the color chips were not looked at under retroreflective operation. The color coordinates were measured for each colored piece of sign material used under retroreflective illumination and indirection illumination. The difference in color coordinates was not significant. Indirect lighting of the color chips was achieved by mounting the lamp in the corner of the box away from the back wall. A metal shield was placed in front of the lamp. The shield was lowered or raised to obtain the desired luminance levels.

One example of the order of the eight combinations of lamps is shown in Table 3.

Table 3. Lamp comparison order shown to one subject.

Comparison	Box 1	Box 2
1	Tungsten halogen	Tungsten halogen
2	Neodymium	Metal halide
3	Tungsten halogen	Neodymium
4	Tungsten halogen	Metal halide
5	Blue coated tungsten halogen	Neodymium
6	Blue coated tungsten halogen	Tungsten halogen
7	Blue coated tungsten halogen	Metal halide
8	Neodymium	Neodymium

Incidentally, a warm-up time was included in the study, because the HID lamps required approximately 15 seconds to reach a stable luminance level. So that all of the comparisons were the same except the lamps being used, the curtain was lowered and raised between each comparison.

SUBJECTS

The subjects were asked to take a color vision test. Only those individuals having normal color vision were used in the study. Demographic details of the subjects are given in Table 4.

The subjects were all volunteers. The subjects were not required to participate in both studies; however, many subjects did.

Table 4. Demographic details of the subjects.

Demographic detail of the subjects		
Low Luminance		
# of Subjects	22	
Age (years)	Mean = 32	Range = 22 to 46
Gender	Males = 12	Females = 10
Corrective Lenses	Yes = 16	No = 6
High Luminance		
# of Subjects	20	
Age (years)	Mean = 35	Range = 22 to 61
Gender	Males = 12	Females = 8
Corrective Lenses	Yes = 12	No = 8

QUESTIONS

The study was conducted at two luminances. Each subject was asked the same set of questions for both luminances.

COLOR NAMING

For each combination of lamps, the subject was asked to name the 16 colors in each box (i.e. the subject named the colors in the left box under the illumination of one of the lamps and then the subject named the colors in the right box under the illumination of another lamp). The colors used were colors as specified in Standard Highway Signs as specified in the Manual of Uniform Traffic Control Devices [5]. The subjects were shown a sheet with a list of colors and they were told to limit the names of the color chips to this list of colors. The list of colors is given in Table 5. The name selected by the subject was recorded.

Table 5. List of colors provided to subjects.

Color Names
Black
Blue
Brown
Green
Orange
Red
White
Yellow
Fluorescent yellow-green

SIDE-BY-SIDE PREFERENCE

For each lamp combination, the subjects were asked to choose the box in which they preferred the illumination of the color chips. This information was recorded by giving the box they preferred a value of one and the other box a value of zero.

OVERALL PREFERENCE

Finally, the subjects were asked their overall preference of the illumination of the colored sign material and were shown the scene illuminated with each of the four lamps sequentially. After they viewed the four scenes, they were asked to rank the boxes from one to four in order of preference.

RESULTS AND DISCUSSION

The results of this study show that subjects preferred the color rendering provided by the neodymium lamps to all of the other lamps. This preference for the neodymium lamps was significant for both side-by-side comparisons and when the each of the lamps was shown to the subjects sequentially. The other studies such as color naming and color difference did not show any favorable or unfavorable results for any of the lamps. In other words, the number of color naming errors was spread equally across all of the lamps.

ANSWERS TO QUESTIONS

COLOR NAMING

The results of the color naming portion of the study show that all of the lamps resulted in few errors in naming the colored chips. In other words, all of the lamps provided adequate lighting to correctly name the colors. As expected, certain colors were named incorrectly more often than other colors. Namely, one of the yellow color chips was often incorrectly named brown. Also, red was often incorrectly named brown. However, there were no significant differences among lamps in the color naming portion of the study. The numbers of color naming errors for each lamp in the low luminance study and the high luminance study are shown in Figure 6 and Figure 7. There is no statistical significance between the number of errors and the type of lamp illuminating the colored chips. What this means is that the colors of the highway signs will be equally correctly identified regardless of the lamp being used to illuminate it.

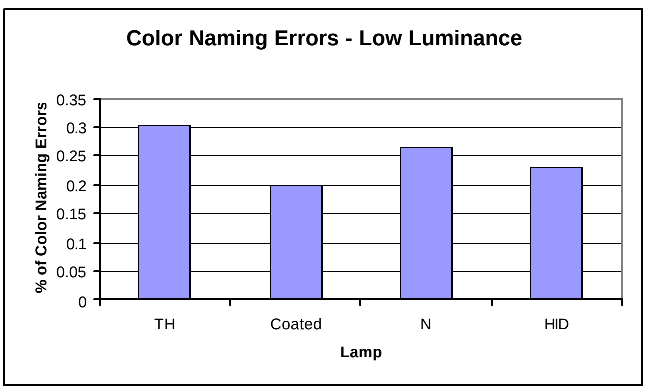

Figure 6. Number of color naming errors for each lamp under low luminance.

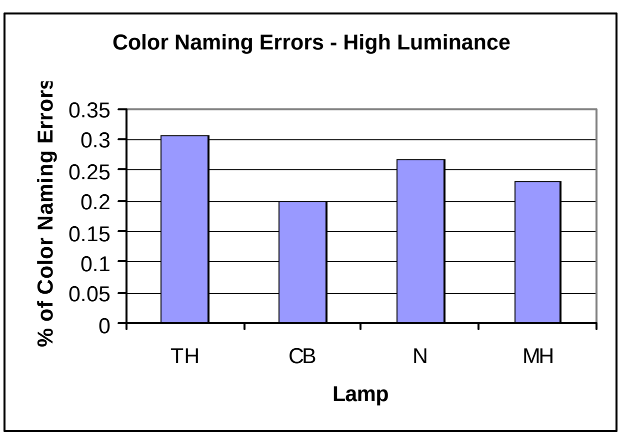

Figure 7. Number of color naming errors for each lamp under high luminance.

SIDE-BY-SIDE PREFERENCE

The results of both the low luminance and the high luminance studies are illustrated in Figure 8 and Figure 9. These graphs show that the neodymium lamps were chosen over all other lamps in both the low and high luminance studies. These graphs represent all of the data from the side by side comparisons in one figure for each study. Each lamp was shown three times to each subject in each study. In Figure 8, the neodymium lamp was shown a total of 66 times (three side by side comparisons were shown to 22 subjects). The neodymium lamp was chosen 61 times or 92%. The standard tungsten halogen (TH) was chosen 20 times out of a total of 66 times it could have been chosen. The difference between the number of times the neodymium lamp was chosen over the three other lamps is statistically significant such that there was less than a 0.5% chance that the preference was due to chance. Note that this graph includes the comparisons where the standard tungsten halogen was compared to the HID, i.e. the data for ALL of the comparisons is included here for the low luminance study.

In Figure 9, the neodymium lamp was shown a total of 60 times and was chosen 95% of the time for the high luminance study.

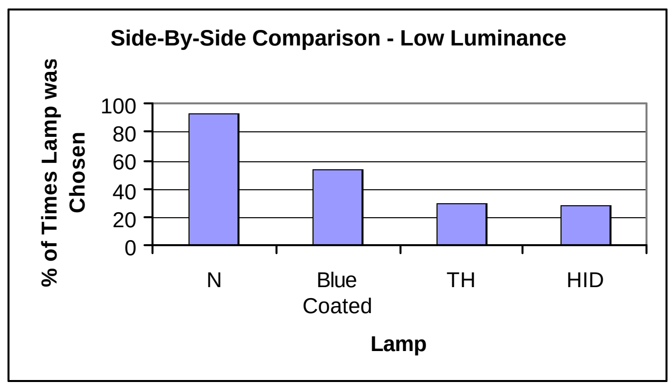

Figure 8. Side by side comparisons in the low luminance study show that neodymium was chosen over all other lamps.

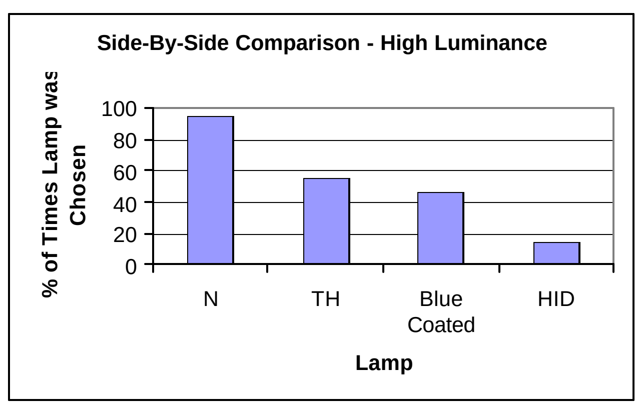

Figure 9. Side-by-side comparisons in the high luminance study show that neodynium was chosen over all other lamps.

When the tungsten halogen lamp and the HID lamps are compared, the tungsten halogen is strongly preferred over the HID at the higher luminance; at the lower luminance, the tungsten halogen is preferred only slightly as shown in Figure 10.

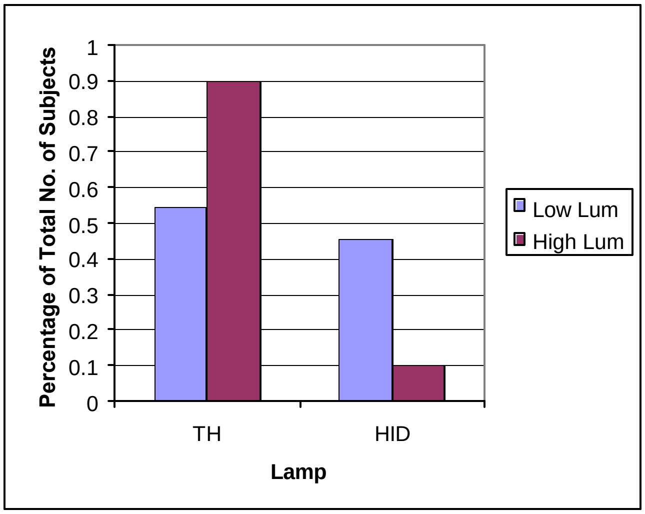

Figure 10. Preference for tungsten halogen vs. HID lamps and the change in preference depending on luminance level.

OVERALL LAMP PREFERENCE

The subjects were asked to select the lighting they preferred when they were shown the lamps sequentially. The order of the lamps shown to each subject was chosen from a balanced list. The results show that the neodymium lamps were chosen overwhelmingly over all of the other lamps. The results for the low luminance study and the high luminance study are shown in Figure 11 and Figure 12, respectively. The values in the graph are given as the percentage of the number of times the neodymium lamp was picked compared to the total number of times a selection was made. For example, in the low luminance study, the neodymium lamp was chosen first by 14 subjects out of 22 total subjects. As another example, in the high luminance study, the HID lamps was chosen last by 13 subjects out of 20 total subjects.

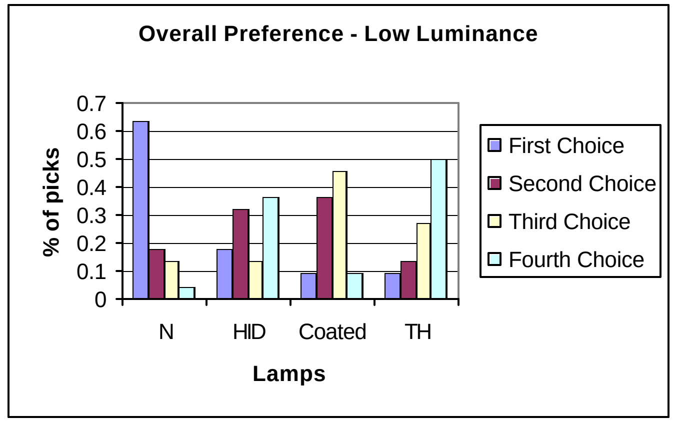

Figure 11. In a sequential comparison at the low luminance level, the neodymium lamps were preferred 64% of the time.

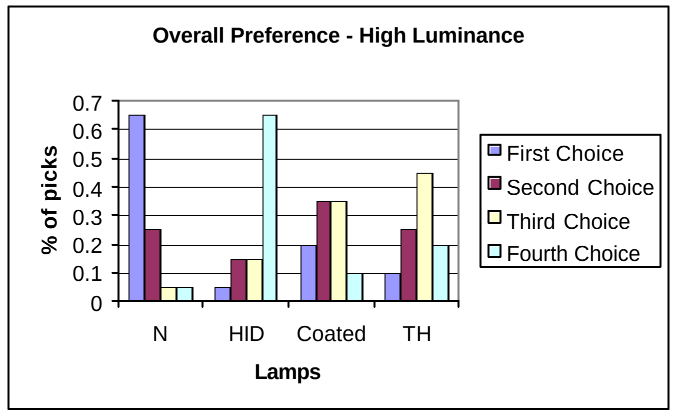

Figure 12. In a sequential comparison at the high luminance level, the neodymium lamps were preferred 65% of the time.

The fact that neodymium was chosen first over the other lamps is statistically significant as shown in Figure 13 and Figure 14, respectively. These graphs represent data about the ratings of the lamps. The subjects were shown each of the four lamps sequentially and asked to score their preference of the lighting of the color chips (1 worst – 4 best). The best score that could be given was a four. In the low luminance study, the neodymium lamp was given a score of 4 by 14 subjects, a 3 by four subjects, a 2 by three subjects and a 1 by one subject. The total is 75 out of a highest possible score of 88 (all 22 subjects giving N a rating of 4) that is a weighted ranking of 85% as shown in Figure 13.

The separation of the neodymium from the other three lamps is significant. The scores of the three lamps other than neodymium is not significant. The determination of the statistical significance was determined using the scaling methods outlined by Dunn-Ranken [6].

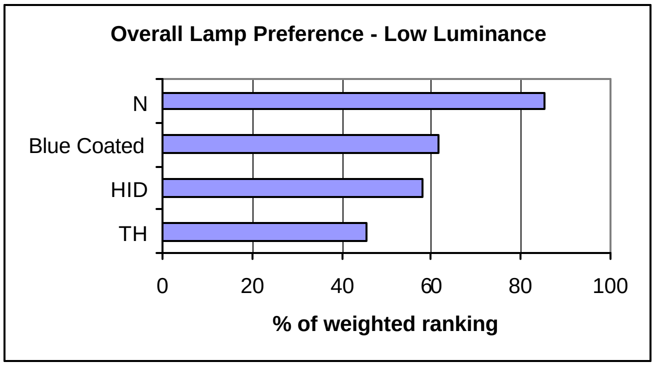

Figure 13. Low luminance lamp preference.

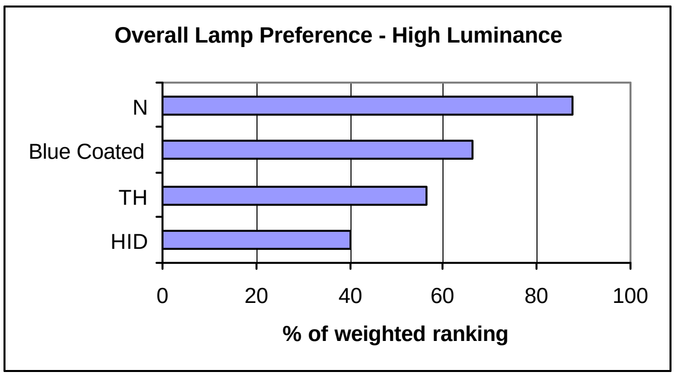

Figure 14. High luminance lamp preference.

CONCLUSIONS AND RECOMMENDATIONS

This study shows that roadway sign materials illuminated with tungsten halogen lamps with glass envelopes doped with neodymium were preferred in side-by-side and overall comparisons over standard tungsten halogen lamps, HID lamps and tungsten halogen lamps with glass envelopes coated with a blue absorptive coating. In the low luminance (11.8 cd/m^2) and the high luminance (62.5 cd/m^2) studies, the neodymium lamp was the first choice of 64% and 65% of the subjects, respectively for the overall sequential comparison. In the side-by-side comparison, for all of the times neodymium was shown, it was chosen 92% and 95% of the time for the low and high luminance studies, respectively.

Color identification was also considered in the study. It was found that all of the lamps provided illumination that allowed the subjects to equally correctly name the color of the roadway sign materials.

This study shows that people prefer illumination by the neodymium lamps. Subjects used words like “clearer”, “more vivid”, “brighter”, and “more natural” in comparison to the other lamps. This study does not provide any insight into whether this preference in any way relates to improved safety or ability while driving. More research is necessary to determine whether this preference translates into any safety benefits. However, the colors used in this study were very saturated. There is a possibility that the neodymium lamps provide better color rendering for colors that are not as saturated, for example, it may provide better color rendering to identify pink or salmon or rose, for instance.

Studies have shown that light sources that have more short wavelength light content do tend to improve off axis visual performance at low light levels [7]. More research is necessary to quantify the short wavelength light content in the neodymium lamps and to determine whether off axis visual performance is affected.

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