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ABSTRACT

Many individuals believe that yellow headlights are preferable to white headlights when driving at night during a snowfall. Although evidence exists to support the claim that yellow light can be perceived as less "glaring" or "distracting" than white light of equal luminance, it is not clear whether backscattered light of different colors are differentially effective for driver comfort or for driver performance. This study investigates a potential mechanism that could support the supposed benefit of yellow headlamps for reducing the detrimental effects of backscattered light to drivers at night. The results suggest that under low light levels when the visual field is dominated by a dynamic field of visual "noise" (like that caused by backscattered light from falling snow), performance of a tracking task similar to driving is reduced in accordance with the scotopic (rod-stimulating) content of the visual noise. Contrary to conventional understanding, rods might affect performance up to luminances of 65 cd/m^2.

INTRODUCTION

Roads in North America and Europe range from multilane interstate highways to narrow country roads; from roads with extensive roadway lighting to those with none. Because of this variability and because roadway lighting is not always properly maintained, forward lighting is used on vehicles so that drivers can see parked vehicles, pedestrians, or other objects. Even when lighting from utility poles is provided, headlights can improve the visibility of potential hazards (as well as make the vehicle itself more conspicuous).

Light reflected from particles in perturbed atmospheres (such as falling snow, rain and fog) impairs visibility because it acts as a luminous veil in the case of fog, or as visual "noise" in the case of falling rain and snow. Snow plow operators cite reflected light from precipitation as an important problem while performing their jobs, and many drivers utilize their own solutions to counteract this problem. One solution commonly offered by operators is the use of yellow fog lamps[1]. For many years, vehicles in France were required to use yellow headlamps, based on early research performed there[2,3] claiming that scattered light in perturbed atmospheres is less when the light is yellow rather than white. Subsequent research and basic physics have eliminated this claim from serious consideration.

Nevertheless, many individuals still believe that yellow light is preferable to white light when driving in inclement conditions. While evidence exists to support the claim that yellow light can be perceived as less "glaring"[4,5] or "distracting"[6] than white light of equal luminance, whether the spectral effects of backscattered light can be measured psychophysically in a driving situation has not been established. This paper provides data that supports the belief that yellow headlamps can be, in fact, superior to white light of the same intensity in reducing the detrimental effects of backscatter. A mechanism to explain these results is offered.

BACKGROUND

The main purpose of headlighting is to provide forward visibility. Although a headlighting configuration may be adequate during clear conditions, reflected light from falling snow, rain or fog particles will obscure the roadway (or objects on it) that the driver wishes to see. Some of the light from headlamps will be reflected from falling rain and snow[7,8] back toward the driver. This reflected light reduces visibility, in part, by decreasing the contrast of objects. Also, distracting visual "noise" is created by the continually flickering objects (raindrops or snowflakes) in the field of vision. Such objects appear brighter than static objects of equal luminance[9,10], and may contribute to discomfort or fatigue over time, possibly increasing the likelihood of road accidents[11]. Reports from snowplow operators, who spend significant amounts of time driving during inclement weather conditions, indicate that backscattered light from falling snow results in a sensation of glare[1].

Rayleigh scattering has been offered as an explanation for anecdotal preferences for yellow headlamps in perturbed atmospheres. Rayleigh scattering pertains to very small scattering particles (whose size is no larger than the wavelength of light passing through them); the amount of scatter is inversely proportional to the wavelength of the light. Thus, short-wavelength (blue) light will be scattered more than long-wavelength (red) light, and white light will be scattered more than yellow light, which has a lower proportion of short-wavelength energy. This was the primary basis of recommendations by Mouton[2] and Monnier[3] for yellow headlamps in France. However, raindrops, snowflakes, and even most fog particles, with average diameters of 8000 nm[12,13], are at least an order of magnitude larger than visible wavelengths between 400 and 700 nm[14]. Under these conditions, Rayleigh scattering is negligible.

Although never discussed in terms of backscattered light, another possible explanation for preferences for yellow headlamps lies in the visual response to lights of different colors. Several studies have been conducted to determine the effect of spectral power distribution (SPD) on brightness perception, which could be related to subjective judgments of brightness and discomfort, and to poorer performance with backscattered light. Although the photopic luminous efficiency function is used to define luminance, this quantity predicts subjective judgments of brightness perception only under limited conditions. The effect of SPD on brightness perception has been documented by Kaiser[15], Alman[16], Alman *et al.*[17] and Hunt[18]. For example, saturated colors tend to appear brighter than desaturated colors at the same luminance.

Of the two kinds of photoreceptors in the human visual system (rods and cones), rods are relatively more sensitive than cones to shorter visible wavelengths, with a (scotopic) peak sensitivity at 507 nm, compared to the combined (photopic) peak sensitivity of foveal cones at 555 nm. (There are three types of cones with peak spectral sensitivities around 570, 540 and 440 nm; a simple weighting of cone input in proportion to their relative densities in the fovea results in a photopic peak sensitivity of 555 nm.) It is traditionally thought that cones are the primary photoreceptors at luminances higher than 3 cd/m^2 and that rods are the primary photoreceptors below about 0.034 cd/m^2 [14]. Between these luminances (called the mesopic region) both cones and rods combine their responses. Figure 1 shows the photopic luminous efficiency function and the scotopic luminous efficiency function.

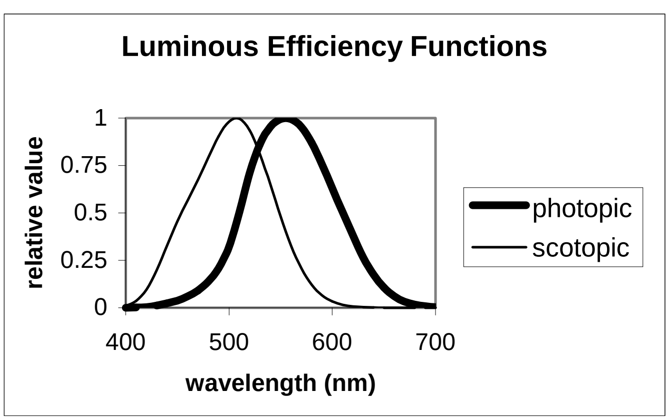

Figure 1. Photopic and scotopic luminous efficiency functions.

Since "yellow" light generally has less energy in the short wavelength region (below 550 nm) of the visible spectrum than "white" light of equal luminance, it will produce a relatively weaker rod response. One way to quantify the relative contribution of rods and cones to the visual perception of a lamp is called the scotopic/photopic (s/p) ratio[19,20]. A lamp's s/p ratio is the ratio of the scotopic and the photopic weighting of its SPD. A "blue" lamp will typically have a high s/p ratio and a "red" lamp will have a low s/p ratio. Table 1 lists several lamps and their associated s/p ratios. If rods play a dominant role in the discomfort glare response, then the s/p ratios of lamps might be useful in predicting the relative discomfort glare from different lamps.

Light source	**s/p ratio**
Incandescent	1.41
Yellow-filtered incandescent	1.25
High pressure sodium	0.62
Low pressure sodium	0.23
Warm white fluorescent	1.00
Cool white fluorescent	1.46
Clear mercury vapor	0.80
Metal halide (sodium-scandium)	1.49

Table 1. Common light sources and their s/p ratios.

Independent studies by Ferguson *et al.*[4] and by de Boer and van Heemskerck Veeckens[5], using similar experimental methods, suggest that rods may play a role in discomfort glare. Ferguson *et al.*[4] asked subjects to assess the glare from 10 x 22 cm patches of light from low pressure sodium (LPS) and from mercury lamps against a background luminance of around 3 cd/m². The luminance of the LPS patch was fixed at 68,000 cd/m² while the mercury patch luminance was adjustable. On average, the luminance of the mercury patch was reduced to 1/3 that of the LPS patch in order for the two patches to appear equally glaring.

de Boer and van Heemskerck Veeckens[5] compared the glare from unfiltered incandescent and yellow-filtered incandescent light sources in streetlighting installations. They asked subjects to observe streetlight installations against a background luminance of about 1 cd/m², and changed the source luminance until the luminance reached a "just permissible" level in terms of discomfort. On average, the luminance of the yellow-filtered incandescent source at the just permissible discomfort level was 25% higher than the luminance of the unfiltered incandescent source at the same discomfort level.

By estimating the *ratio of the s/p ratios* for two lamps, one can compare the relative scotopic and photopic contributions for the two lamps[19]. Using Table 1, the ratio of the s/p ratios for incandescent and yellow-filtered incandescent lamps is 1.1 (1.41/1.25), and the ratio of the s/p ratios for mercury and LPS lamps is 3.5 (0.8/0.23). These values correspond closely with the luminance ratios at which 50% of the observers in each study rated these sources as equally glaring: about 1.25 for yellow and unfiltered incandescent[5] and about 3 for

LPS and mercury[4], as shown in Figure 2. The similarity between these pairs of ratios perhaps implies that the relative scotopic output of a lamp might predict its potential for causing discomfort glare when the background luminance is in or near the mesopic range.

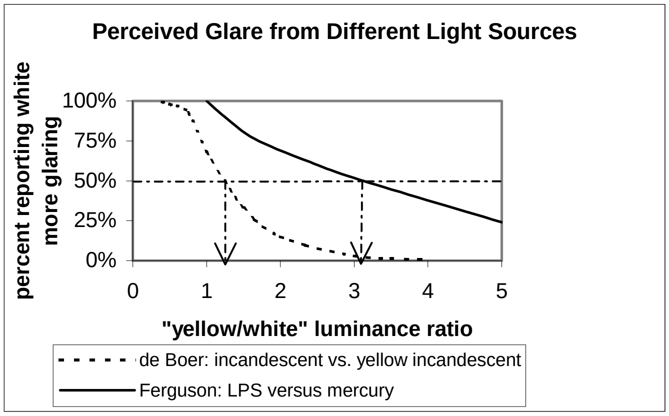

Figure 2. Relationship between yellow/white luminance ratio and percentage of people rating white more glaring than yellow in two studies. The horizontal line indicates when the lights were perceived as equally glaring, when the yellow/white ratio was about 1.25 and 3.

At the very least, the analysis described above indicates that photoreceptors with peak spectral sensitivities near 555 nm, or longer than 555 nm, would be very unlikely candidates for predicting the discomfort glare response with dark backgrounds. However, of the three cone types in the retina, short-wavelength cones, with a peak spectral sensitivity near 440 nm, might also be considered as the photoreceptor responsible for the discomfort glare response. This photoreceptor has been considered in predictive models of brightness perception[21], so a possible role for short-wavelength cones in discomfort glare would not seem unreasonable. It is possible to calculate a *short-wavelength-cone/photopic (c_s/p) ratio* for a lamp, like the s/p ratio, that characterizes the relative contribution of short-wavelength cones and foveal cones to visual perception of a lamp. If the *ratio of the c_s/p ratios* are calculated for the lamps used by de Boer and van Heemskerck Veeckens[5] and by Ferguson *et al.*[4], they are 3.5 for the yellow and unfiltered incandescent lamps, and 260 for the LPS and mercury lamps. These ratios differ greatly from both the equal-glaring luminance ratios found by de Boer and van Heemskerck Veeckens[5] and Ferguson *et al.*[4], and from the ratios of the s/p ratios calculated above, suggesting that short-wavelength cones are probably not the primary inputs for glare under these conditions, or at least, that if they do contribute to glare, their role is complex.

The role of SPD in discomfort glare might be further enhanced by considering the flickering and moving nature of light from falling snowflakes or raindrops, which increases its perceived brightness[9,10]. The human visual system can be segregated into two channels[22]: the sustained channel and the transient channel. The sustained channel is responsible for color vision and for discriminating fine details. The transient channel, on the other hand, is achromatic, has poor spatial resolution and is more sensitive to temporal luminance changes in the peripheral visual field, such as those that would be caused by falling snow or rain. Interestingly, the influence of short-wavelength cones under such conditions seems unlikely because these cones are known to have very slow temporal resolution[23,24], and are less sensitive than other photoreceptors to transient stimuli such as those that would be created by falling snow or raindrops while driving during inclement weather. He *et al.*[25] demonstrated that at mesopic luminances, the transient channel response, characterized by reaction time to small (2^o disc), flashed, peripheral (15^o off-axis) targets, was increasingly dominated by rods as luminance decreased. Conversely, as luminance increased, the influence of rods decreased up to a point where their influence disappeared and the photopic cone response alone accurately characterized the stimulus. For these reasons it appears unlikely that short-wavelength cones are primarily responsible for discomfort glare under conditions of visual noise.

Breitmeyer and Williams[6] investigated people's motion perception, another transient channel response, when viewing near-peripheral (about 1.7^o off-axis), sequentially displayed high-contrast stimuli (0.3^o x 0.95^o angular size), slightly displaced from one another (0.9^o angular displacement). Colored backgrounds (red, green or gray) were used at a low photopic luminance of 4 cd/m². Subjects rated the strength of motion perception as they viewed the sequential targets. Their ratings were significantly lower when the background was red than when the background was green or gray, suggesting that the transient channel is less sensitive to long-wavelength light. Breitmeyer and Williams[6] considered the possibility that rod intrusion in the transient channel occurs at low luminances (partially explaining reduced motion perceptions with the red background), since rods can be active even above 3 cd/m² under certain conditions[26] and since there is a significant rod population even at 1.7^o from the center of the fovea[14]. Presumably, this effect would be mitigated as the background luminance increases, reducing the influence of rods, although this concept has not previously been tested.

Since nighttime driving is a task primarily performed at low photopic and medium-to-high mesopic luminances between 0.1 and 1 cd/m² [14,25], the degree to which drivers perceive light backscattered from continuously-moving snowflakes or raindrops in the forward scene could depend upon the SPD of the forward illumination. Presumably, the s/p ratio of backscattered light, as it affects the perceived magnitude of visual noise, should also predict both the impact on driving performance and subjective ratings. It can be hypothesized then, based on the evidence discussed above, that backscattered light with a low s/p ratio will degrade visual performance and subjective ratings *less* than backscattered light with a high s/p ratio.

METHOD

Using manufacturer-reported photometric data on the illuminance distribution from headlamps, information about the areal concentration of snow in the atmosphere during snowfall[27], the spectral reflectance of snow particles[28], and field measurements of object contrast along roadways[29], it was determined that an average background luminance of approximately 1 cd/m^2 and a target contrast of 0.55 (contrast is defined here as the absolute difference between the target and background luminance, divided by the larger of the target or background luminance) represent "typical" values encountered in the visual scene while driving during a snowfall at night.

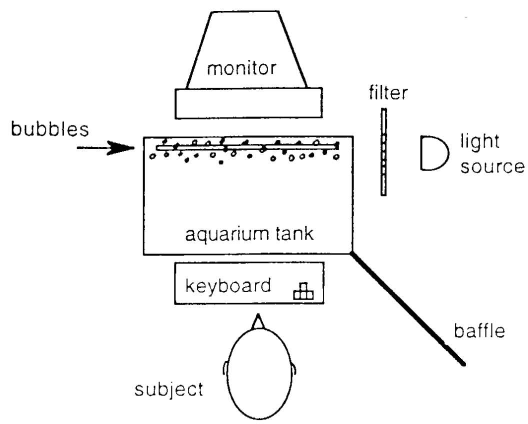

Figure 3. Plan view sketch of experimental apparatus.

To test the effects of SPD on perception under such conditions, a laboratory experiment was designed, using a simple apparatus (Figure 3) consisting of an aquarium tank filled with water and equipped with an agitator that created a uniform field of small bubbles (or a "visual noise" field) along the rear of the tank. The tank was 30 cm high, 50 cm wide and 25 cm deep and was mounted 95 cm above the floor. A halogen PAR-38 lamp, mounted approximately 30 cm from the right side of the tank, illuminated the bubbles from a nearly perpendicular angle to the subject's line of sight. Colored filter materials were placed in a cardboard, 48 x 35 cm frame containing a 23 x 18 cm rectangular aperture. These filters were mounted between the lamp and the tank to create each SPD condition. Colored filter materials used were:

- White SPD: 3M plain paper copier film, #PP2200, transmittance: 95%
- Yellow SPD: Roscolux color filter #11, light straw, transmittance: 82%
- Red SPD: Roscolux color filter #22, deep amber, transmittance: 26%
- Blue-green SPD: Roscolux color filter #370, Italian blue, transmittance: 31%

Two sheets of each colored filter was used in each cardboard frame. By changing the filters, the wattage of the lamp (50 W for the yellow and white filters and 100 W for the red and blue-green filters to account for the lower transmittance of those filters) and the angle of incidence of the beam from the light source onto the bubbles, the average luminance of the visual noise field could be adjusted. A baffle blocked subjects' direct view of the light source. The time-averaged luminance of the bubble field was measured for each condition in the direction of the subjects' line of sight.

A computer monitor with a 20 x 28 cm display was located behind the water tank. Subjects sat in front of the tank, and looked through the tank at the monitor; the monitor display was centered in the rear panel of the water tank. The monitor displayed a visual tracking task - a program similar to a simple road-racing video game whereby a keyboard-controlled icon is kept within the edges of a continuously-scrolling "roadway." Subjects were asked to keep the icon within the edges of the road for the duration of the task. The computer recorded the score, which was the percentage of time the icon was positioned between the edges of the road for each trial. For each SPD, the time-averaged luminance of the visual noise field was set to 10 cd/m^2 with the agitator on. With the agitator off, the background luminance was 2 cd/m^2. To create lower luminance conditions, dark glasses were used with a resulting visual noise field luminance of 1.2-1.3 cd/m^2. For the lowest luminances, two sets of glasses were mounted together to create a double pair with a resulting visual noise field luminance transmittance of 0.14-0.18 cd/m^2. There were a total of 12 combinations of 4 SPDs and 3 visual noise field luminances.

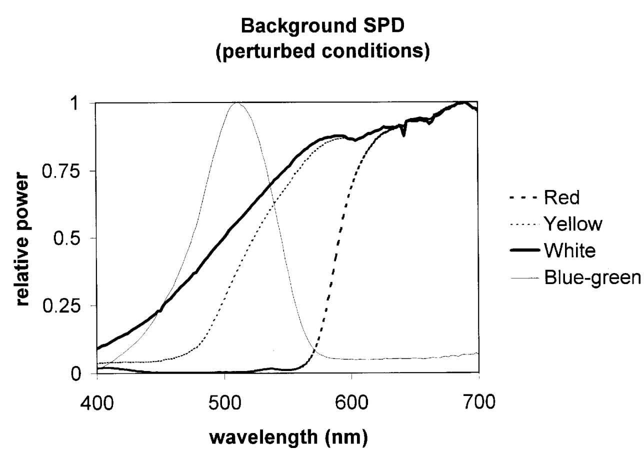

Figure 4. SPDs of the four visual noise conditions.

The four SPDs used to provide visual noise are shown in Figure 4. The (x,y) chromaticity coordinates of the background and targets and the luminance contrast and s/p ratios for each condition are listed in Tables 2, 3 and 4. The dark glasses were not perfectly spectrally neutral; thus, the s/p ratios for the backgrounds and targets shifted with lower luminances. However, the arithmetic differences among the s/p ratios remained nearly constant at each luminance. The s/p ratios of the targets and backgrounds differed slightly even in the clear conditions, because the filtered light source remained on during these conditions, and thus contributed a small amount of light to the overall SPD of the target and background.

Color/SPD:	Visual condition: clear	Visual condition: perturbed
blue-green	background: x=0.22, y=0.44 target: x=0.26, y=0.36	background: x=0.17, y=0.45 target: x=0.25, y=0.39
white	background: x=0.41, y=0.42 target: x=0.32, y=0.36	background: x=0.42, y=0.42 target: x=0.36, y=0.38
yellow	background: x=0.47, y=0.47 target: x=0.33, y=0.37	background: x=0.48, y=0.47 target: x=0.38, y=0.40
red	background: x=0.64, y=0.35 target: x=0.34, y=0.35	background: x=0.65, y=0.35 target: x=0.48, y=0.35

Table 2. Chromaticity (x,y) coordinates of background and target for clear and perturbed experimental conditions.

Color/SPD:	Light level: low	Light level: medium	Light level: high
blue-green	L_B=0.03 cd/m^2 (s/p ratio 4.39) L_T=0.22 cd/m^2 (s/p ratio 3.68) contrast=0.86	L_B=0.26 cd/m^2 (s/p ratio 3.85) L_T=1.8 cd/m^2 (s/p ratio 3.06) contrast=0.86	L_B=2 cd/m^2 (s/p ratio 3.34) L_T=15 cd/m^2 (s/p ratio 2.53) contrast=0.87
white	L_B=0.03 cd/m^2 (s/p ratio 2.42) L_T=0.22 cd/m^2 (s/p ratio 3.34) contrast=0.86	L_B=0.23 cd/m^2 (s/p ratio 2.01) L_T=1.8 cd/m^2 (s/p ratio 2.74) contrast=0.87	L_B=2 cd/m^2 (s/p ratio 1.66) L_T=15 cd/m^2 (s/p ratio 2.26) contrast=0.87
yellow	L_B=0.03 cd/m^2 (s/p ratio 1.61) L_T=0.22 cd/m^2 (s/p ratio 3.19) contrast=0.86	L_B=0.23 cd/m^2 (s/p ratio 1.40) L_T=1.8 cd/m^2 (s/p ratio 2.64) contrast=0.87	L_B=2 cd/m^2 (s/p ratio 1.21) L_T=15 cd/m^2 (s/p ratio 2.16) contrast=0.87
red	L_B=0.03 cd/m^2 (s/p ratio 0.22) L_T=0.22 cd/m^2 (s/p ratio 3.14) contrast=0.86	L_B=0.23 cd/m^2 (s/p ratio 0.22) L_T=1.8 cd/m^2 (s/p ratio 2.59) contrast=0.87	L_B=2 cd/m^2 (s/p ratio 0.22) L_T=15 cd/m^2 (s/p ratio 2.13) contrast=0.87

Table 3. Photometric characteristics of the clear experimental conditions (L_B=background luminance; L_T=target luminance).

Three subjects participated in the visual tracking experiment (1: male, 27 years old; 2: female, 37 years old; 3: female, 27 years old). All subjects had normal color vision and normal Snellen acuity from both 6 m and 50 cm. All subjects practiced the tracking task for at least 30 minutes before participating in the experiment. Each subject completed 12 sessions, one for each SPD/luminance combination. The order of combinations was randomized for each subject. Each session lasted about 45 minutes, and tasks were completed in the following order:

Color/SPD:	Light level: low	Light level: medium	Light level: high
blue-green	L_B=0.18 cd/m^2 (s/p ratio 4.75) L_T=0.41 cd/m^2 (s/p ratio 4.14) contrast=0.56	L_B=1.3 cd/m^2 (s/p ratio 4.25) L_T=3.0 cd/m^2 (s/p ratio 3.54) contrast=0.57	L_B=10 cd/m^2 (s/p ratio 3.77) L_T=24 cd/m^2 (s/p ratio 3.01) contrast=0.58
white	L_B=0.14 cd/m^2 (s/p ratio 2.22) L_T=0.36 cd/m^2 (s/p ratio 2.92) contrast=0.61	L_B=1.2 cd/m^2 (s/p ratio 1.85) L_T=2.9 cd/m^2 (s/p ratio 2.41) contrast=0.59	L_B=10 cd/m^2 (s/p ratio 1.53) L_T=24 cd/m^2 (s/p ratio 1.98) contrast=0.58
yellow	L_B=0.14 cd/m^2 (s/p ratio 1.46) L_T=0.34 cd/m^2 (s/p ratio 2.53) contrast=0.59	L_B=1.2 cd/m^2 (s/p ratio 1.28) L_T=2.8 cd/m^2 (s/p ratio 2.10) contrast=0.57	L_B=10 cd/m^2 (s/p ratio 1.12) L_T=24 cd/m^2 (s/p ratio 1.74) contrast=0.58
red	L_B=0.15 cd/m^2 (s/p ratio 0.17) L_T=0.36 cd/m^2 (s/p ratio 1.83) contrast=0.58	L_B=1.2 cd/m^2 (s/p ratio 0.18) L_T=2.8 cd/m^2 (s/p ratio 1.52) contrast=0.57	L_B=10 cd/m^2 (s/p ratio 0.18) L_T=24 cd/m^2 (s/p ratio 1.25) contrast=0.58

Table 4. Photometric characteristics of the perturbed experimental conditions (L_B=background luminance; L_T=target luminance).

- a 3-minute practice session allowing subjects to practice the task (without the visual noise field) and adapt to the conditions in the experimental room
- a 3-minute visual tracking task session with the lamp on but with the agitator off (without the visual noise field present; "clear" condition)
- a 30-minute visual tracking task session with both the light source and agitator on (with visual noise; "perturbed" condition)
- completion of a brief questionnaire pertaining to the 30-minute session on difficulty, distraction and discomfort
- a second 3-minute visual tracking task session with the light source but with the agitator off (clear condition)

For the questionnaire, subjects answered three questions using a scale ranging from -4 to +4. Subjects rated the difficulty of performing the tracking task, the level of distraction caused by the visual noise, and the maximum discomfort they experienced during the tracking task. The scores from both the clear and perturbed tracking tasks were recorded for subsequent analysis. Additional details of the experimental setup and apparatus can be found in Bullough[30].

RESULTS

TRACKING TASK - Figures 5 and 6 (solid lines) show the mean performance of all subjects for the clear and perturbed conditions in the first experiment, respectively. As Figures 5 and 6 indicate, there were large differences between these two conditions. These graphs also demonstrate the effect of background luminance on performance, which is seen for both clear and perturbed conditions. The effect of SPD is also seen on performance under the perturbed conditions (Figure 6, solid lines), especially at the lowest luminance, where the scores are correlated negatively with s/p ratio. Because the white and yellow SPDs had s/p ratios that were relatively close to one another (mean difference =

0.58), these two SPDs were essentially indistinguishable from one another in terms of performance.

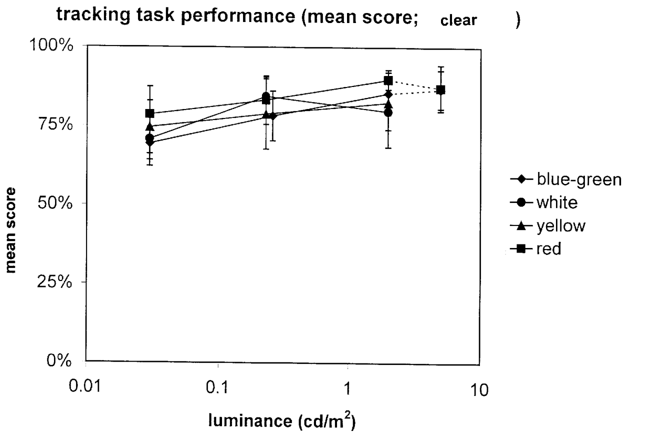

Figure 5. Mean tracking task performance (and standard deviations) under clear conditions for the first experiment (solid lines) and the second experiment (dotted lines). Luminance represents the background luminance of the screen.

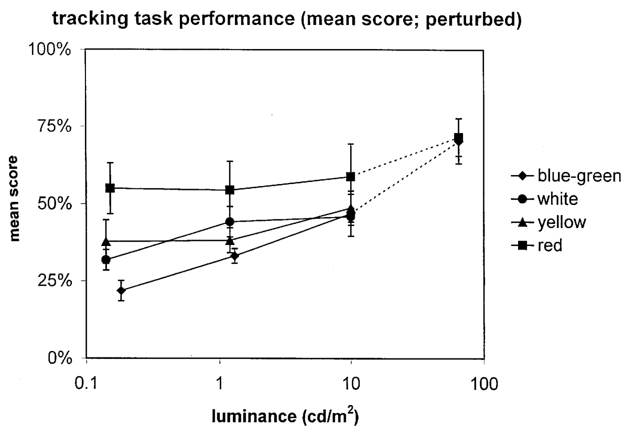

Figure 6. Mean tracking task performance (and standard deviations) under perturbed (visual noise) conditions for the first experiment (solid lines) and the second experiment (dotted lines). Luminance represents the background luminance of the screen plus the visual noise condition.

For the perturbed viewing conditions, a repeated-measures analysis of variance revealed a statistically significant ($p<0.01$) main effect of luminance. There was not a significant main effect of SPD ($p>0.05$), nor was the interaction between luminance and SPD significant ($p>0.05$), although the scores for each SPD appear to converge as luminance increases in Figure 6 (solid lines). The apparent effect of SPD under the perturbed conditions can be seen indirectly by plotting the difference in performance between the red and blue-green conditions at each luminance, as shown in Figure 7. The difference in performance is very nearly linearly related to the logarithm of the background luminance (correlation: $r^2=0.99$) from approximately 0.1 to 10 cd/m^2. This very high correlation implies that as rods become less effective at higher luminances, these scores would perhaps converge at some higher luminance [i.e., the difference in mean score between the red-SPD condition and the blue-green-SPD condition (the conditions with the lowest and highest s/p ratios, respectively) would be zero]. Visual estimation of the curve in Figure 7 indicated that this convergence should occur at about 100 cd/m^2.

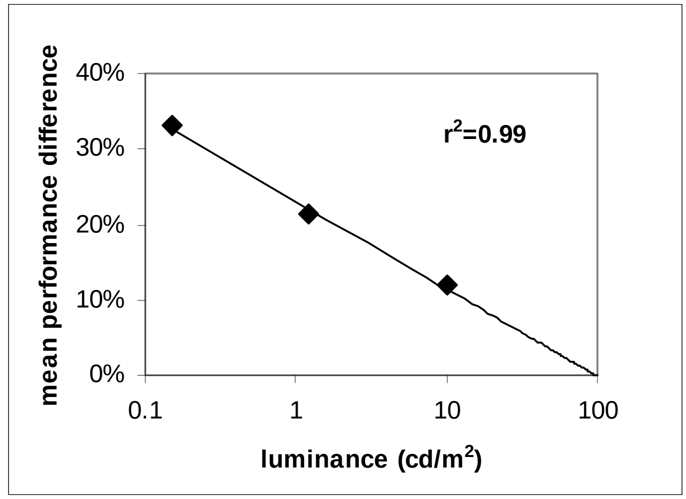

Figure 7. Mean difference in performance between the red and blue-green SPD conditions at background luminances of 0.1, 1 and 10 cd/m^2. The line is the regression function that reaches zero near 100 cd/m^2.

To test this inference, a second experiment using the same apparatus and same subjects, but testing only the red and blue-green visual noise conditions was conducted. The apparatus was modified so that a visual noise field luminance of 65 cd/m^2 was used (creating higher luminances was not possible with the apparatus). The background luminance for the clear conditions in this experiment was approximately 5 cd/m^2. Subjects did not wear sunglasses during this experiment. The order of presentation of the SPD conditions was randomized for each subject. Both performance scores and subjective ratings were collected at this high background luminance, as in the previous experiment.

The scores from this second experiment are shown in Figures 5 and 6 (dotted lines). There were virtually no differences in performance between the red and blue-green visual noise conditions under both the clear and perturbed conditions, implying that the convergence background luminance is around 65 cd/m^2 for this task.

SUBJECTIVE RATINGS - The ratings of difficulty, distraction and discomfort all followed similar trends, and were correlated with one another (difficulty-distraction correlation: $r^2 = 0.88$; difficulty-discomfort correlation: $r^2 = 0.37$; distraction-discomfort correlation: $r^2 = 0.46$). Because of these correlations, the subjective ratings were combined into overall mean ratings, shown in Figure 8. Two characteristics of the subjective ratings are:

- A relationship between the background luminance and the subjective ratings appears to exist (positive subjective ratings indicated less difficulty, less discomfort and less distraction).

- The blue-green visual noise conditions usually had the lowest (poorest) subjective ratings and the red conditions the highest, especially at the two lower luminances.

The combined mean subjective ratings in Figure 8 were consistent with the performance scores in Figure 6 (correlation: $r^2 = 0.76$). Like the performance scores, the ratings appear to both increase and converge as background luminance increases. Furthermore, the differences in subjective ratings between the yellow and white visual noise conditions were small, implying that the small difference in s/p ratios between these conditions was not large enough to be of much practical significance.

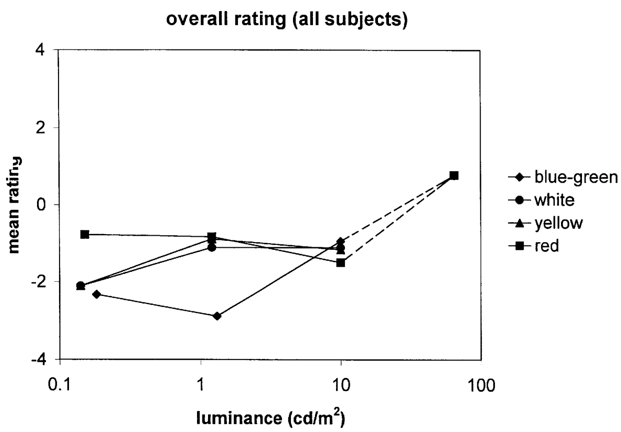

Figure 8. Mean subjective ratings of the tracking task under perturbed conditions for the first experiment (solid lines) and the second experiment (dotted lines). Luminance represents the background luminance of the screen plus the visual noise condition.

DISCUSSION

It is worth noting that the results above are qualitatively consistent with a hypothesis that short-wavelength cones rather than rods are primarily responsible for the differences in performance and subjective ratings that were found among SPD conditions in the present study. However, for the reasons outlined above in the Background section of this paper, it would seem unlikely that short-wavelength cones played a primary role in the experimental results, because of their slow temporal resolution[23,24] and because this cone type seems to have little impact on the perception of discomfort glare under nighttime conditions[4,5]. Furthermore, the performance scores measured in the present study converged at 65 cd/m^2. This implies that the photoreceptors primarily responsible for the differences among SPDs observed in the experiment cease to contribute to visual perception above this luminance. Certainly, all cone types actively contribute to visual perception at luminances much higher than 65 cd/m^2.[14,28]

The importance of the s/p ratio of the light sources for these results implies that the rods play a role in visual perception in the presence of visual noise, even at luminances well into a range traditionally considered as strictly photopic. Conventional understanding of the behavior of rods, which are commonly thought to be saturated above a luminance of about 3 cd/m², should be revised. As described earlier, however, the idea that the rods are active at levels traditionally considered photopic is not entirely new. When Breitmeyer and Williams[6] reported that the perception of movement against a red background was suppressed relative to green and white backgrounds, they discussed the possibility that rod responses were involved, noting that Stabell and Stabell[26] had found that the rods were active even above 3 cd/m². This was found to be true especially when the stimulus was dynamic rather than static[26]. In addition, Reeves[31] found that rods are very sensitive to extrafoveal stimuli much like the visual noise field used in the tracking task experiment. The results from this experiment fit well within the context of this previous research and suggest that rods can be active above 3 cd/m² for dynamic visual stimuli.

In the reaction time study by He *et al.*[25], the rods appeared to stop contributing to the visual response above a background luminance of about 0.6 cd/m², which is below even the commonly accepted photopic lower limit of 3 cd/m². However, the visual field used in that study was large, uniform and static with only an occasional small flashed target. It seems reasonable to assume that the rod response is more significant when the entire extrafoveal visual field contains motion, such as the visual noise field used in the tracking task experiment, falling snowflakes during a storm, or perhaps even the continuously moving field of vision that exists while driving in clear conditions.

Although the results of the present study are consistent with recommendations for using yellow lamps for perturbed atmospheres, the difference in s/p ratio between conventional tungsten-halogen lamps and yellow-filtered lamps is small, and therefore suggests that yellow-tinted headlamps would have only a small impact on performance or on subjective ratings. However, filters currently used in such lamps are not designed to optimize both transmittance and s/p ratio. It is possible to design a yellow or amber filter for a halogen headlamp that results in a higher transmittance and a lower s/p ratio than those used on existing products. Such a lamp-filter combination would need to have a low s/p ratio and relatively high photopic transmission to provide measurable performance benefits.

Of course, tungsten-halogen lamps are not the only viable technology available for automotive forward lighting. High-intensity discharge headlamps based on metal halide (MH) lamp technology are currently being sold on a number of automobile models[32]. The SPDs of MH lamps depend upon the concentration and chemistry of various halide mixtures that are added into the lamp's arc stream[33]. The correlated color temperature (CCT) of such lamps can range from less than 3000 K to over 7000 K. Estimates from MH headlamp manufacturers indicate that such systems produce twice the lumens as a halogen headlamp system of equal wattage[32].

The s/p ratios of several commercially available MH sources range from about 1.5 to 2.0[33], in comparison to a halogen headlamp's s/p ratio of around 1.5. While MH lamps alone do not seem to offer advantages over conventional headlamps with respect to their s/p ratio, their higher light output relative to halogen lamps means that such headlamps could perhaps be used with colored filters, providing low s/p ratios that would be less visually distracting than that from a halogen lamp while still having greater light output. Moreover, the chemical mixture of a MH lamp could be adjusted so that the s/p ratio could be greatly reduced.

Finally, it is important also to note that actual visual conditions while driving a vehicle in bad weather will depend on many additional factors (such as precipitation density, speed, size and ambient illumination conditions) that will not match the visual conditions used in this study. These factors will interact with one another in ways that cannot be predicted in the scope of this paper. For example, the effect of SPD when compared to other headlamp factors, such as mounting position and beam width[1,7,8,12,34-36], can be quite small. However, headlamp SPD could provide additional degrees of freedom to the automotive designer who does not have the flexibility to choose an unlimited array of mounting positions or beam angles.

CONCLUSIONS

The literature, experimental results presented here, and an analysis of those results indicate that under certain visual conditions, particularly at mesopic and low photopic light levels when a field of visual noise is present, performance of a tracking-type task, like driving, is related to the relative scotopic content (or s/p ratio) of the visual noise. Rods appear to be able to contribute to the transient visual channel up to luminances of 65 cd/m², or their contribution can disappear at luminances as low as 0.6 cd/m^2 [25], depending upon how much of the visual field is stimulated, contrary to conventional understanding. The s/p ratios of currently available yellow-filtered headlamps do not differ enough from conventional halogen headlamps for this effect to be significant in practical situations, but the design of filters that optimize both transmittance and s/p ratio might result in yellow- or perhaps orange-colored light that would provide a measurable benefit under perturbed atmospheric conditions.

The role of rods in the presence of glare should also be investigated. If the discomfort glare from oncoming headlamps could be mitigated by reducing the s/p ratio, the use of such headlamps might benefit drivers during inclement conditions. Of course, such benefits would have to be considered in parallel to possible drawbacks, such as reduced sensitivity to off-axis targets[25,37,38] such as bicyclists, pedestrians or animals in clear conditions.

Visual noise is a commonly experienced problem when driving at night during inclement weather. The results from this study indicate that filters can decrease the s/p ratio of light sources, and thus decrease the degree to which these sources can cause distracting visual noise. In real-world situations, other factors, such as driver alertness, color rendering, the spectral and spatial distribution of roadway lighting, or glare could possibly mitigate or intensify the s/p ratio's effect on overall performance. Given the promising results obtained from this preliminary study, it appears worthwhile to continue to investigate this problem. By extending this work in the laboratory and in the field, the practical value of such research can be more easily understood.

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