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16. Abstract

Various new light sources, such as light emitting diodes (LEDs) and neon, have recently been adopted for signal lamps, or are being considered for such use. These sources expand the range of spectral power distributions (SPDs) that are of concern for automotive applications. This report reviews the interactions of such SPDs with visual conditions that are of special importance in driving and that might have spectrally selective effects. Such conditions include spectrally selective windshields, weather conditions (fog and rain), and certain visual conditions of drivers (color blindness, yellowing of the lens of the eye with aging, and wearing of sunglasses). Most of the effects of SPD can be expected to be minor. Generally speaking, even though the chromaticity constraints that are applied to signal lamps allow a range of SPDs, the chromaticity constraints are sufficient to ensure that visual performance will be predictable. A few exceptions are noted.

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Introduction

Standards for signal lamps were developed at a time when it was generally assumed that the light sources would be incandescent bulbs. Because such bulbs produce light by heating a metal filament, the spectral power distributions (SPDs) they produce are very constrained. Figure 1 shows the SPD of a tungsten-halogen (TH) bulb. Because the filament of the TH bulb is operated at a higher temperature than that of the tungsten bulb, its SPD corresponds to a slightly higher color temperature. But the SPDs of the two sources are nevertheless very similar to each other, and each is similar to the spectrum of a black body radiator of the corresponding temperature.

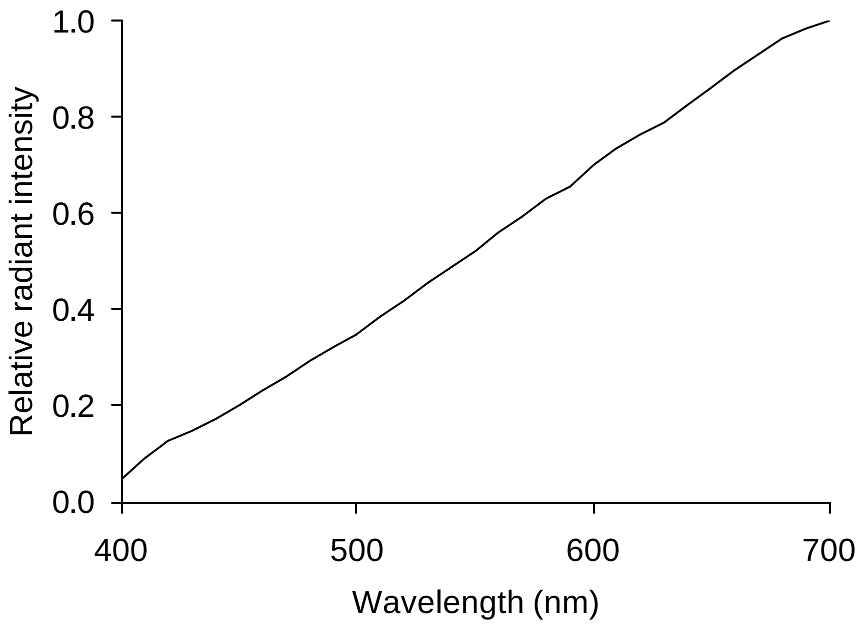

Figure 1. Spectral power distribution of a tungsten halogen (TH) lamp.

Colors for signal lamps have traditionally been produced by filtering light from incandescent bulbs. Most filtering materials are constrained in their transmittance functions, so that the resulting lamp SPD (the source SPD filtered by a colored material) is also highly constrained.

Recently, however, a variety of nonincandescent sources have been used (or are being considered for use) in automotive signal lamps. These sources include light emitting diodes (LEDs), neon sources, and high-intensity discharge (HID) sources.

These nonincandescent sources have a much greater variety of SPDs than can be produced by filtered incandescent bulbs, raising new issues about the visual effects of the new sources. In particular, it seems possible that environmental factors—like filtering from sunglasses and windshields, scattering by fog and rain, or variation in the response characteristics of the eye—may have different effects on these sources than they would have on filtered incandescent lamps.

Standards for signal lamps have generally specified ranges of chromaticity values to ensure that the colors of the lamps will function as desired. Although it was well understood that a particular chromaticity could be achieved in a variety of ways using different mixtures of wavelengths (i.e., metamers, which will be discussed later), most signal light sources were tungsten-filament lamps, and their spectral characteristics were fairly homogeneous. Thus, with an explicit constraint on chromaticity, and an implicit constraint on the light sources, the choice of filter to achieve the desired chromaticity was indirectly constrained as well. Consequently, little variation in SPD was possible between any two signal lights—that is, not until innovative light sources with their different SPDs began to compete with incandescents. The introduction of the new sources has raised the issue of whether some consideration of SPD, beyond simply chromaticity, is necessary.

This document reviews the roles of chromaticity and SPD in determining visual performance, the varieties of source spectra that may be encountered in signal lamps, the influence of atmospheric conditions on SPD, and the range of driver spectral sensitivities that must be considered (including the effects of color blindness and aging). Finally, we quantify the combined effects of some of these factors, and discuss the question of whether effects of SPD beyond chromaticity must be considered.

Basic Facts about Color Vision

To understand how the SPD of a light source produces the sensation of color, we need to recognize that the transformation of light to neural responses on the retina of the eye always involves considerable information loss. As a consequence of this loss, even perfectly normal color vision is, in a sense, largely colorblind. To be specific, color vision is made possible by specialized receptors called cones that do the work of transforming light energy into electrical energy. There are three types of cones, each with a particular response sensitivity function to different wavelengths of light; they are often referred to as short-wavelength, medium-wavelength, and long-wavelength (or blue, green, red) receptors, based on their peak spectral sensitivities.

With such a system, color is registered by the relative responses of the receptor types to light of a particular wavelength. Red light produces one pattern of responses, green produces another, and a difference in color is seen. Of course, light that reaches our eye is not just one wavelength. It most often is a mixture of different wavelengths at different intensities. Each wavelength contributes to the stimulation of each cone type, in relation to the cone's sensitivity to that wavelength. The perceived chromaticity of light is the result of the relative output of the three types of receptor. As a consequence, the visual system is blind to the component wavelengths that make up a mixture of light. A light could contain one, two, or hundreds of different wavelengths and appear to be the same color, so long as the relative output of the cones were the same. (This is in marked contrast to the human auditory system that can readily discern component frequencies in a complex sound wave.) Lights that are made up of different mixtures of wavelengths but which give rise to the same perception of color are referred to as *metamers*.

Thus, although light spectra are helpful in understanding the physical properties of light, they do not directly identify the color or brightness that is seen by an observer. For that, we also need to factor in the response characteristics of the human visual system using color-matching functions to determine the color of the light that is seen, and the luminous efficiency function, $V(l)$, to determine apparent brightness of the light.

Color-matching functions are a way of characterizing the different response characteristics of the three cones in a normal eye to light of different wavelengths. The Commission Internationale De l'Èclairage (CIE), using data from a color-matching task, established standard color-matching functions for three selected primaries. In the task, an observer is presented with a circular field divided in half. On one side, a monochromatic light of a selected wavelength is presented. On the other, the observer is asked to make adjustments in the mixture by controlling the relative intensities of three primaries, so that the two halves of the visual field are indistinguishable from each other. For people with normal (i.e., "trichomatic") color vision, it turns out that three primaries are just the right number to allow them to make these matches. Two is not enough, and any set of four will have one primary that can be dispensed with.

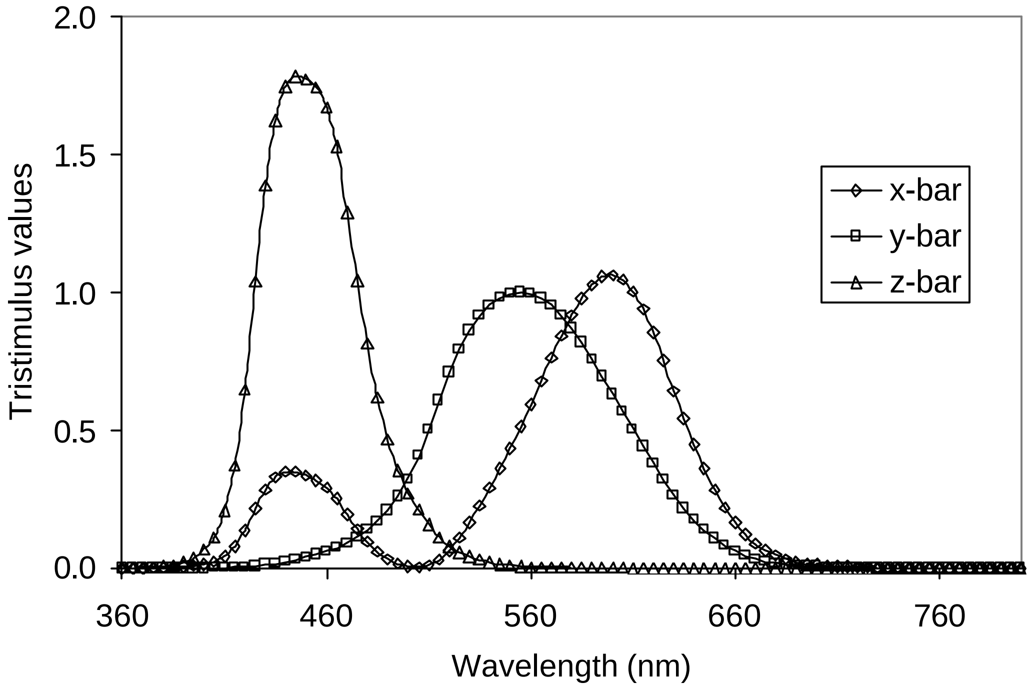

Figure 2. CIE color-matching functions for each of three primaries.

The relative amounts of each primary required to match a given wavelength establish one data point for the color-matching function of each selected primary. Measures are taken of the mixture of primaries across the visible spectrum. The resulting color-matching functions are depicted in Figure 2. For a given wavelength of light, the functions show the relative contribution of each primary needed to produce the corresponding color. (The data in Figure 2 actually show the relative amounts required for a set of *imaginary* primaries, and are derived from data on matching with real primaries. The imaginary primaries have been selected so that all of the required values are positive. With real stimuli and real primaries, the amounts of the primaries required to achieve a match in the two halves of a divided field will sometimes be negative. In practice, this means that the "negative" primary would be switched to the other side of the field.)

The color-matching functions model the trichromatic response of the eye, allowing one to compute the resulting perceived color. To do this for a given mixture of wavelengths, the responses of each primary channel to each wavelength in the light mixture are summed within each channel, to produce the summed channel outputs, *X*, *Y*, and *Z*:

$$X = \int S_{\lambda} \bar{x} d\lambda ,$$
$$Y = \int S_{\lambda} \bar{y} d\lambda , \qquad (1)$$
$$Z = \int S_{\lambda} \bar{z} d\lambda$$

where S_{λ} represents the spectral power distribution of the sample light, and $\bar{x}$, $\bar{y}$, and $\bar{z}$ are the color-matching functions. The relative contribution of *X* and *Y* are then determined to produce *x, y* chromaticity coordinates:

$$x = \frac{X}{X+Y+Z},$$
$$y = \frac{Y}{X+Y+Z}, \qquad (2)$$
$$z = \frac{Z}{X+Y+Z}$$

Because the value of z is completely constrained by x and y ($x + y + z = 1$), it is usually ignored and omitted in the CIE chromaticity diagram (Figure 3) which plots x and y in a color space. This diagram is used widely in standard specifications of color. For example, SAE J578 references this diagram to define color boundaries for red, yellow, green, blue, and white. The diagram also shows the variety of light mixtures that can map to the same chromaticity coordinate. For example, if any point in the chromaticity space is selected and a line is drawn through that point to intersect the boundaries of the diagram's horseshoe, that line defines a mixture of two monochromatic lights that can produce that particular chromaticity. If the line is rotated about the point, other mixtures of two monochromatic lights can be found that produce the same chromaticity.

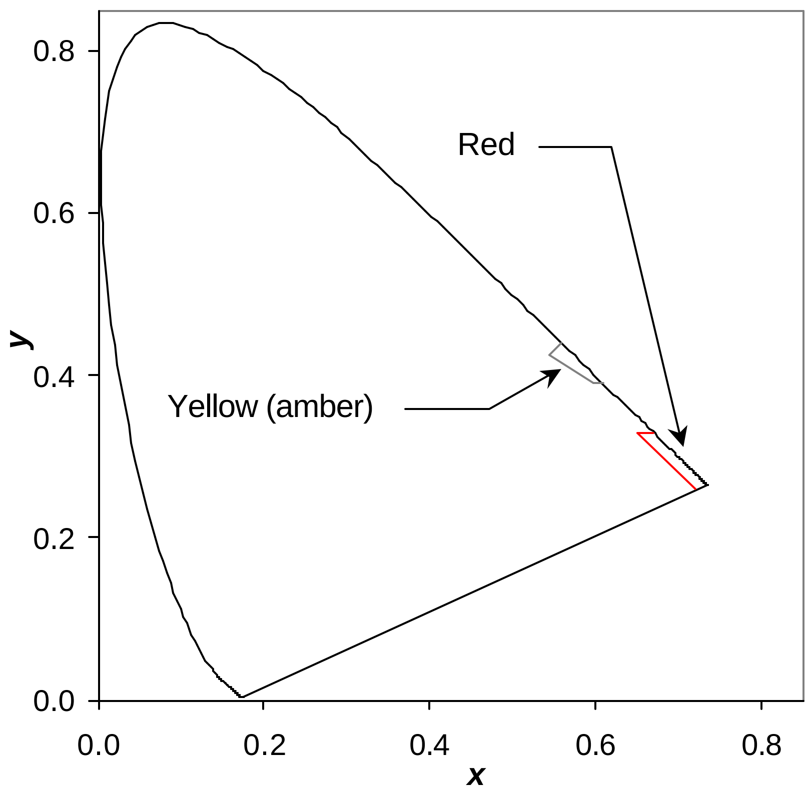

Figure 3. CIE 1931 chromaticity diagram identifying SAE J578 color boundaries for red and yellow (amber).

Apart from chromaticity, the human visual system can also be characterized by its overall responsiveness to light of various wavelengths. This is defined by the luminous efficiency functions for photopic (daytime) and scotopic (nighttime, low-light) vision, *V(l)* and *V'(l)*, respectively. The functions are derived from empirical work using a variety of perceptual tasks, including heterochromatic flicker photometry (HFP). In this task, observers are asked to adjust the intensity of a selected wavelength of nearly monochromatic light to match the luminance of a standard reference light to eliminate the appearance of flicker when the two sources are rapidly alternated. The functions depict the relative sensitivity of the visual system to the complete range of visible light, and allow one to assess the relative effect of changes in spectral characteristics of a light source on its overall appearance of brightness to an observer. The differences between *V(l)* and *V'(l)* (Figure 4) are a consequence of the different spectral absorption characteristics of the cone receptors versus the rods. Because rods are less sensitive to the longer wavelengths, a shift in the relative brightness of red versus blue can be seen when changing from photopic to scotopic vision. This effect is called the Purkinje shift.

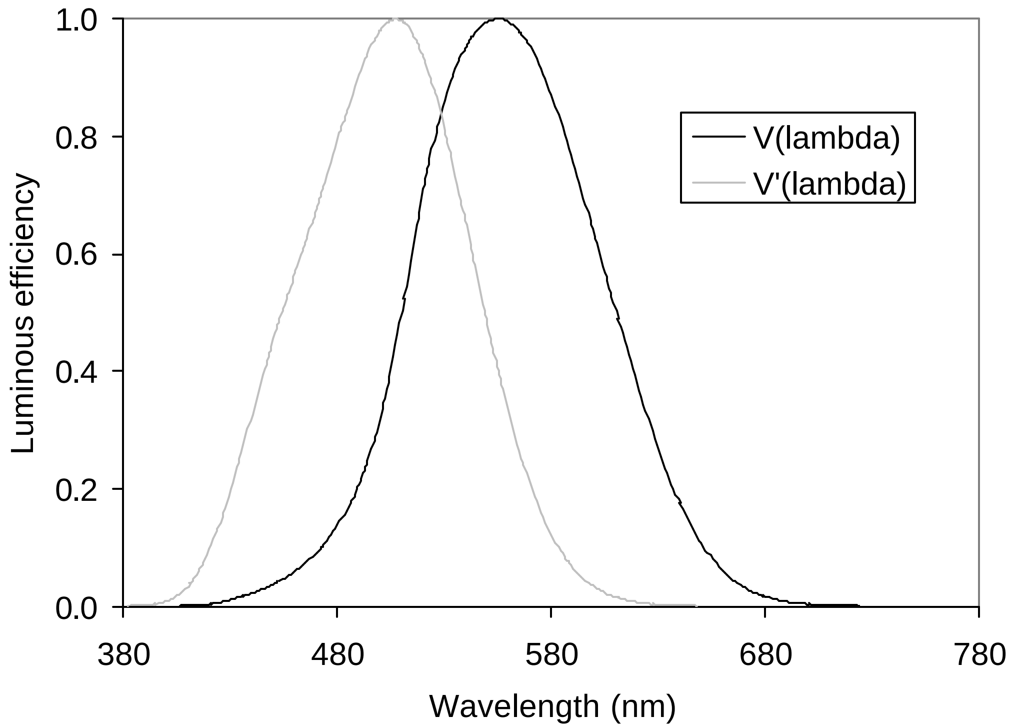

Figure 4. Photopic (daytime), *V(l)*, and scotopic (nighttime), *V'(l)*, luminous efficiency functions.

Chromaticity Ranges of Signal Lamps and SPD

Standards for signal lamp colors are commonly specified in terms of the CIE 1931 chromaticity diagram. The SAE J578 boundaries for red and yellow[1] (amber) are depicted in Figure 3.

Although chromaticity highly constrains the SPD of a light source, it does not determine it. As noted earlier, two stimuli that are metamers have the same chromaticity (i.e., they look the same to a human observer with normal color vision) but different SPDs. As long as they are viewed directly, lights that are metamers of each other can be considered visually equivalent. However, if they are viewed through filtering materials (like tinted windshields, colored sunglasses, or colored lenses) or viewed as reflected light from colored surfaces, metamers will often be affected differently.

Furthermore, human spectral sensitivity can be expected to vary in certain ways that could result in different overall appearance of metamers. Chromaticity constraints only apply to color-normal observers and cannot guarantee that metamers will look similar to a color-anomalous observer. Moreover the perceived intensity of a signal lamp may also be different for these observers.

[1] Throughout this report, the terms *yellow* and *amber* are used equivalently.

LEDs and Incandescent Sources. By using the color-matching functions and luminous efficiency functions described earlier, we can compute how chromaticity and brightness are affected differently by the different SPDs of the light source. We begin by comparing an incandescent red signal light to a red light emitting diode (LED).

Unlike incandescent light sources, LEDs emit very narrow SPDs. The light is strongly saturated and nearly monochromatic. Figure 5 shows a sample LED (from McKinney, 1986) with a peak wavelength of 660 nm with a bandwidth of ± 20 nm at 50% peak intensity.

Because incandescent sources emit a broad spectrum, they are filtered to produce light at the desired chromaticity. To produce a red light, a filter is used to remove most of the shorter wavelengths emitted by the incandescent source. As an illustration, we matched the chromaticity of the LED described by McKinney (1986) to a filtered incandescent light source, and plotted the SPDs of both sources, normalizing for brightness (Figure 5). Although the two spectra are obviously different, they have nearly identical chromaticity: (x, y) for the LED is (.680, .320); and the incandescent source is (.678, .320).

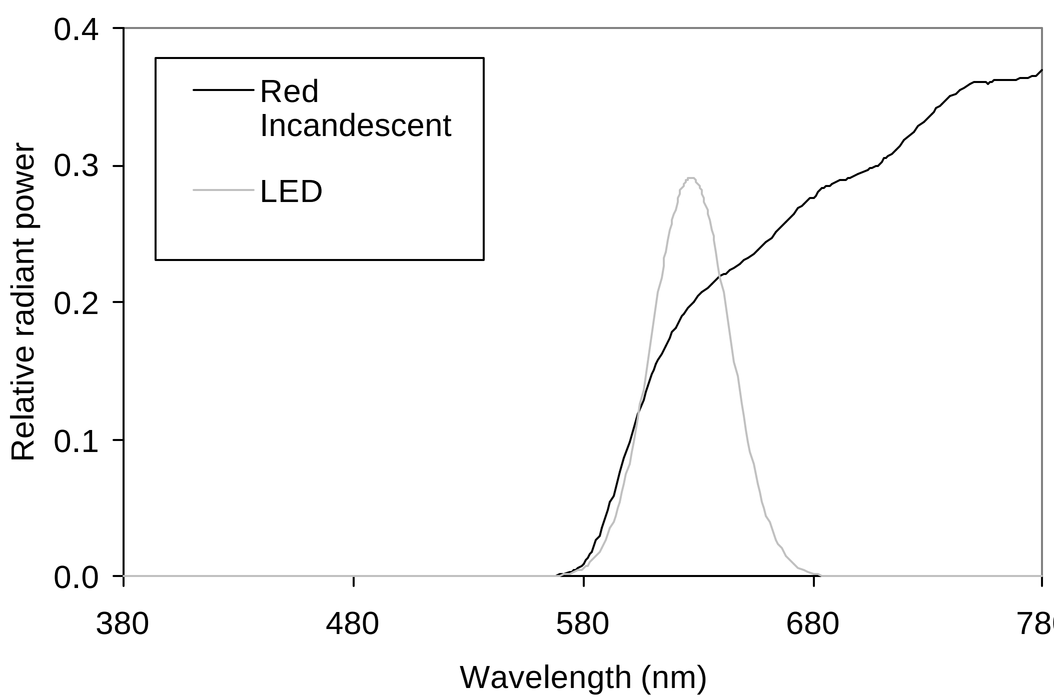

Figure 5. Spectral power distribution of LED and incandescent red light source. Each waveform is scaled to produce the same overall perceived brightness.

If we look at these sources a little differently, weighted by the photopic luminance efficiency function, we can see the extent of each wavelength's contribution to the visual system's overall experience of brightness. This is shown in Figure 6. If viewed in this way, the seemingly large differences between the incandescent and the LED light sources are sharply reduced. The incandescent source's power in the longer wavelengths is of no real significance to the observer, since the observer is largely insensitive to it. One implication of this way of looking at the spectral differences between the sources is that the two light sources are unlikely to be differently affected by *any* environmental factors such as filtering or atmospheric scatter.

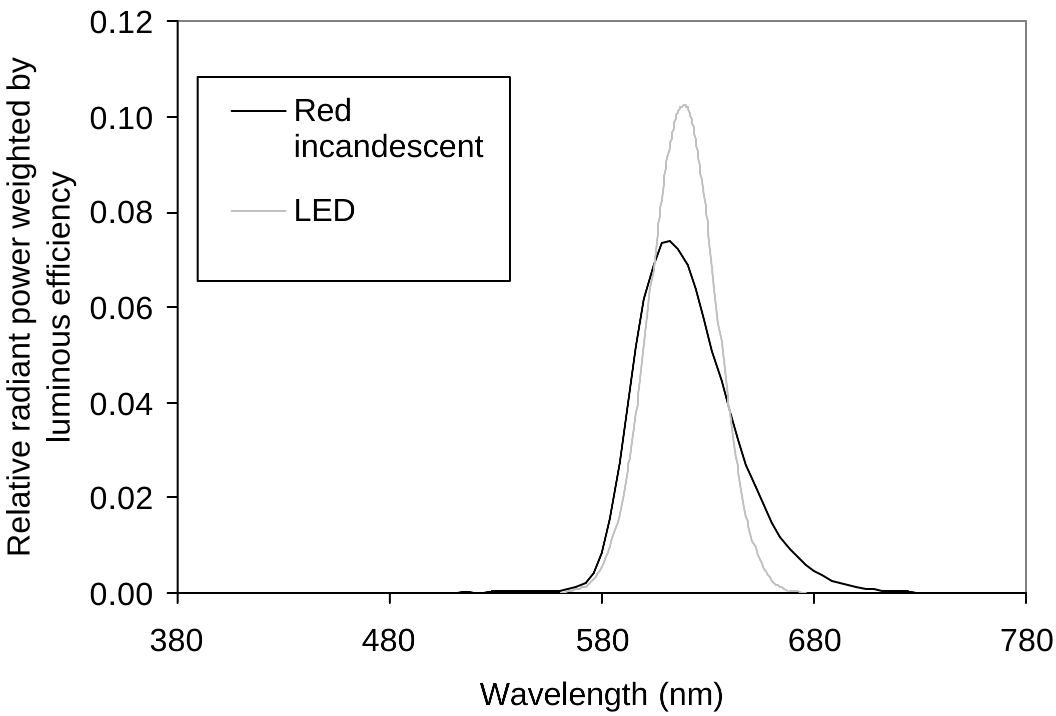

Figure 6. Spectral power distributions of red LED and incandescent sources weighted by the photopic luminous efficiency function, *V(l)*. Each distribution is scaled so that their integrals sum to one.

It should be noted that in this example, the LED was deep red. To make an equivalent color incandescent light, heavy filtering was required to eliminate wavelengths below 580 nm. The incandescent source was thus limited by filtering on the short wavelength side, and by the small weighting of the long wavelengths by *V(l)* on the long wavelength side. If the selected color were a more orange-red, there would be less similarity between the LED and the incandescent source.

If we next look at amber LED and incandescent sources, we see a more marked difference in their spectra even when weighted by *V(l)*. Figure 7 shows the SPD of an LED and an incandescent amber light source (*x,y* coordinates are [.572, .427] and [.573, .423], respectively). Figure 8 shows the same lights weighted by *V(l)*. Note that the LED is characteristically peaked, compared to the relatively broad spectral distribution of the incandescent light, even after the *V(l)* weighting is applied.

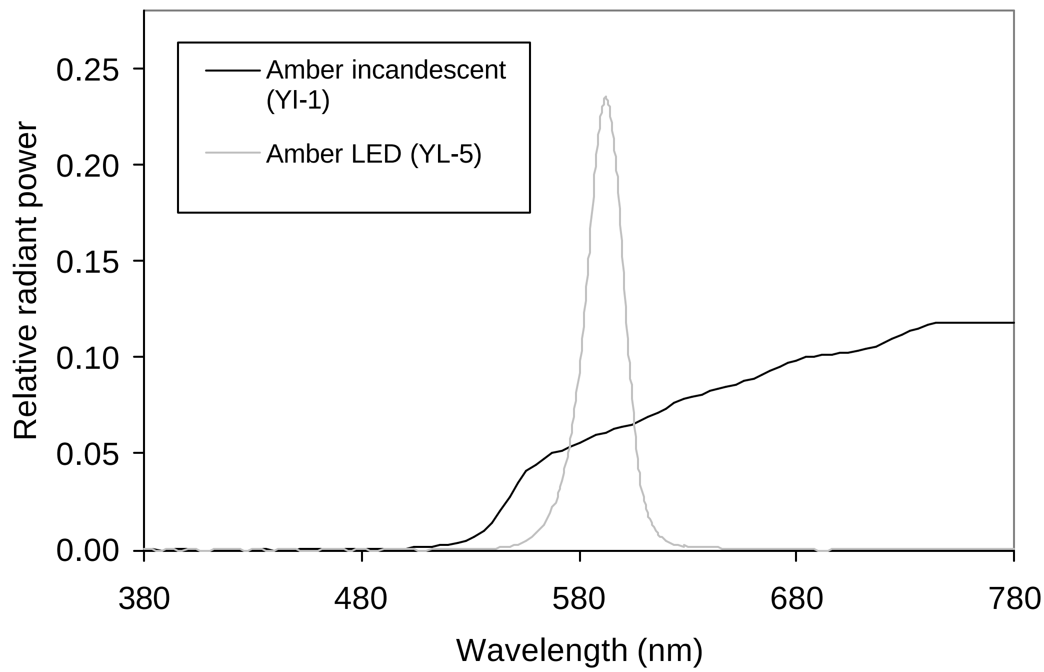

Figure 7. SPDs of amber LED and incandescent light sources of equal luminance.

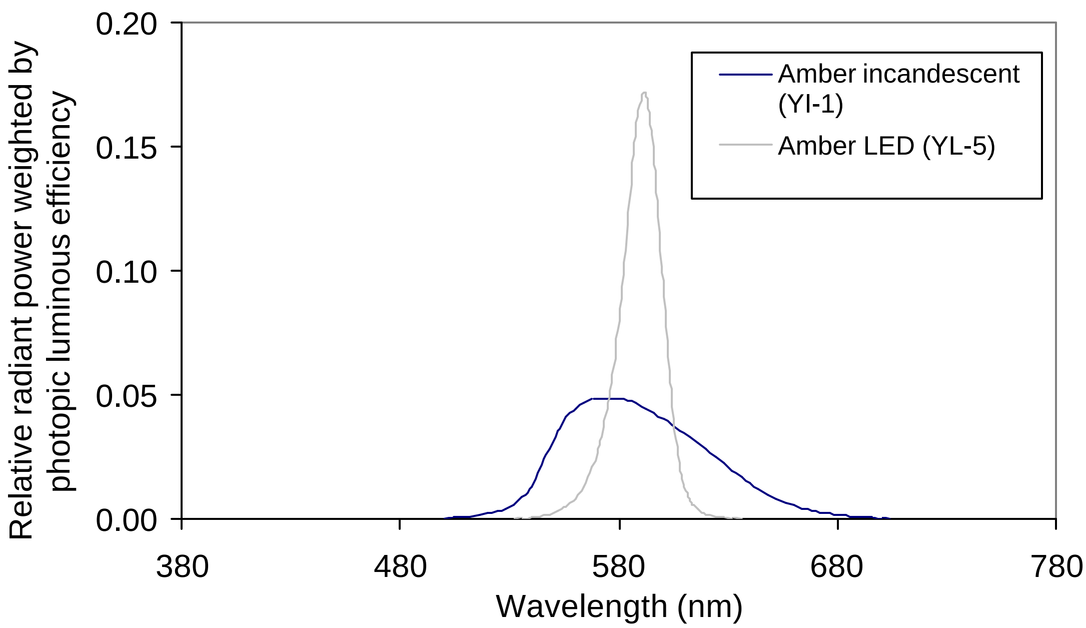

Figure 8. Amber LED and incandescent light sources weighted by $V(l)$.

Because the spectral power of an LED, compared to that of an incandescent source, is concentrated in a narrow range of wavelengths, it may also be less susceptible to a chromaticity shift when a colored filter is interposed. Suppose we have an LED and an incandescent light source with the same dominant wavelength. (The dominant wavelength is that wavelength which most closely resembles the color of a light source.) If we have a filter that is maximally dense at that dominant wavelength, it would reduce the apparent brightness of the LED more than it would if applied to an incandescent source. On the other hand, it would shift the color of the incandescent source significantly. This happens because filters can only absorb wavelengths emitted by a light source. If that source emits only a narrow range of wavelengths, then there is little potential for a chromaticity shift—no amount of filtering will turn a red LED into blue. If the filter affects the light at all, its main effect will be to reduce intensity. In contrast, with a broadband light source, energy is distributed across many more wavelengths. If a filter absorbs some part of the spectrum, energy transmitted from the other parts of the spectrum will determine chromaticity. Thus, a shift in chromaticity is likely. This same transmitted energy will also tend to keep the intensity of broadband light higher than the narrow-band. In a sense, narrow-band light viewed through a colored filter is less susceptible to a color shift, at the expense of a greater potential loss in overall luminance. Broadband sources are less susceptible to luminance loss, at the expense of chromaticity shifts. This characteristic will be discussed in more detail when we consider the filtering effects of sunglasses and tinted windshields, later in this report.

Neon Light Sources. The color of neon light is orange-red, and is produced by a characteristic line spectrum. (Other colors can be produced by the introduction of coatings that fluoresce at different wavelengths and alter the color.) Figure 9 illustrates the SPD of a red neon source. It differs from LED spectra in that it is more broadly distributed, but unlike incandescent sources, it is distributed across somewhat discrete wavelengths. Like an incandescent source, a filter that absorbs a neon light's peak wavelength would not attenuate the light's overall brightness as much as an LED, because its energy is distributed more broadly than an LED's. On the other hand, the light may be vulnerable to greater shifts in chromaticity.

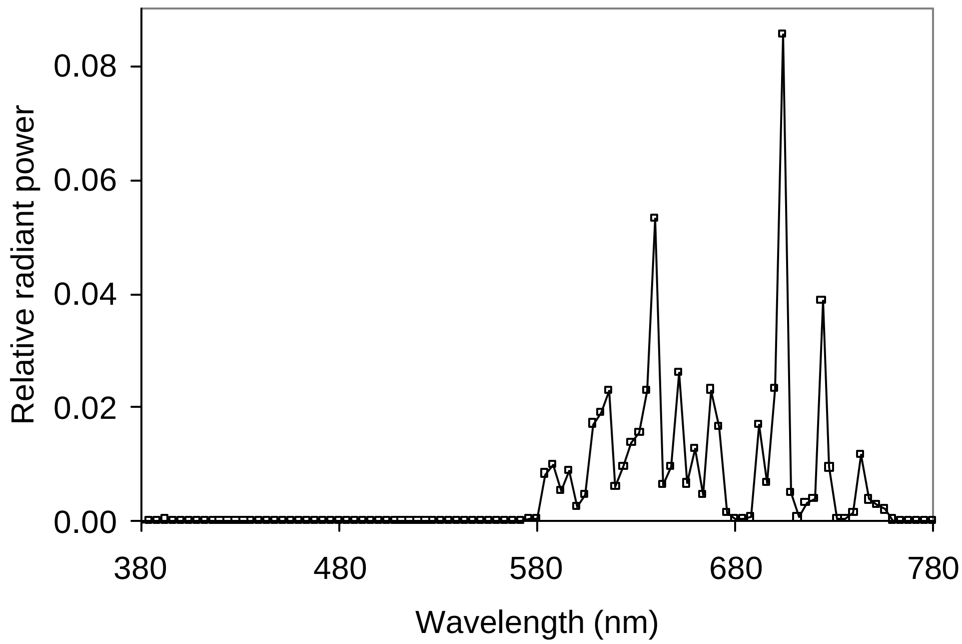

Figure 9. SPD of a red neon source.

Visual Conditions of Drivers

Color blindness

Color blindness is an imprecise term applied to many forms of color vision that deviate from normal. It is most commonly found in males. There are varieties of trichromatic (found in 5.9% of males), dichromatic (2% of males), and monchromatic (.003 % of males) color blindness. Anomalous trichromats, the most common, fall into two general groupings: the protanomalous (1% of males), who exhibit a lack of sensitivity to long wavelengths, and the deuteranomalous (4.9% of males), which match normal sensitivity, but deviate from normal in color-matching functions (Hsia & Graham, 1957). Less than one half of one percent of females exhibit any kind of colorblindness. Dichromats can be classified as protanopes, deuteranopes, or tritanopes. They require only two primaries to make a color match. Protanopes appear to be lacking the cone pigment most sensitive to long wavelengths; deuteranopes appear to be lacking the mid-wavelength cone pigments; tritanopes appear to lack cone pigments sensitive to short-wavelength. For our purposes, we look at changes in apparent brightness associated with differences in the luminous efficiency of color-blind observers. These differences are illustrated in Figure 10 where it is apparent that protanopes are less sensitive to the longer wavelengths, and deuteranopes and tritanopes have about the same spectral efficiency as color normals.

As will be seen, for protanopes the shape of the SPD of the light source matters less than the wavelength where the spectral power is concentrated. Deuteranopes and tritanopes show little sensitivity to differences in the SPDs of the light sources.

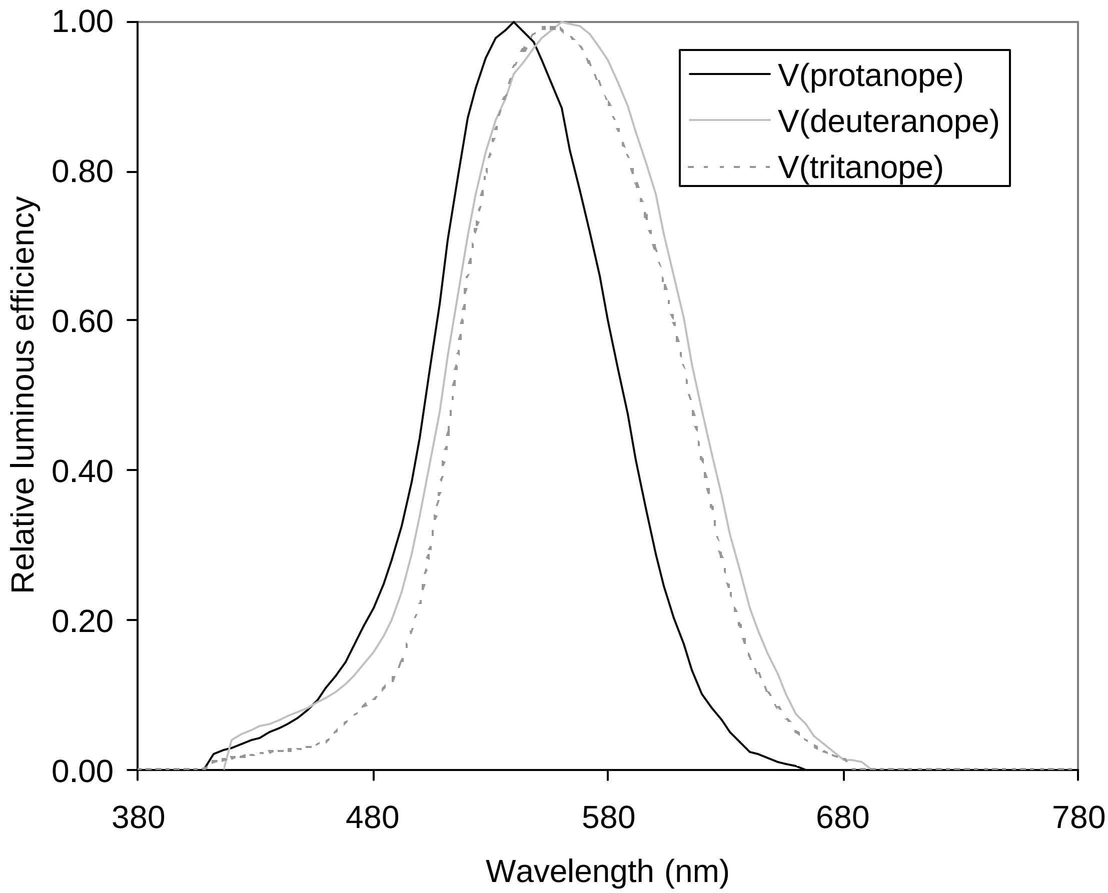

Figure 10. Luminous efficiency functions of dichromats (from Wyszecki & Stiles [1982], Table 4[5.14.2], p. 470.) Note that the protanopes show a marked shift in their peak wavelength sensitivity.

Analysis. The following analysis provides a picture of how dichromats are differently affected by the SPDs of red incandescent, neon, and LED light sources. Although dichromats are not the majority form of colorblindness, we used them in the following analysis for several reasons. The nature of their color deficit is less variable than anomalous trichromats, and consequently reliable luminous efficiency measures that can be used in determining the apparent luminosity of light sources are available for them. They also represent worst case conditions and thereby provide the best chance to observe differing effects of light sources. Finally, anomalous trichromats would likely display similar, albeit milder, effects if compared to their dichromat counterparts.

We consider only apparent brightness of the sources, since it is unclear how to compare color-normal chromaticity to that of dichromats. To compare brightness, the intensity of each light source was normalized to appear to be the same brightness *to a* *color normal observer.* We used a white source with an equal-energy spectrum as a basis for normalizing luminance changes for each dichromat condition. That is, we assumed that an equal-energy white light of a selected brightness could be used as a reference against which the relative brightness of the red lights for dicromats could be evaluated. Each SPD was convolved with the luminous efficiency function of the associated dichromat to compute a luminance value, which was then normalized to the luminance value of the white light. Thus, we assume that the brightness of an equal-energy white light for a normal would be the same as for a dichromat. We selected representative samples of red signal lamps, including two incandescent sources (designated RI-1 and RI-2), four LED sources (designated RL-1, RL-2, RL-3, and RL-4 [R/O]), and one neon source. SPDs for each of the lamps are presented in Figures 11 and 12. All light sources had chromaticity coordinates within the SAE J578 red boundaries.

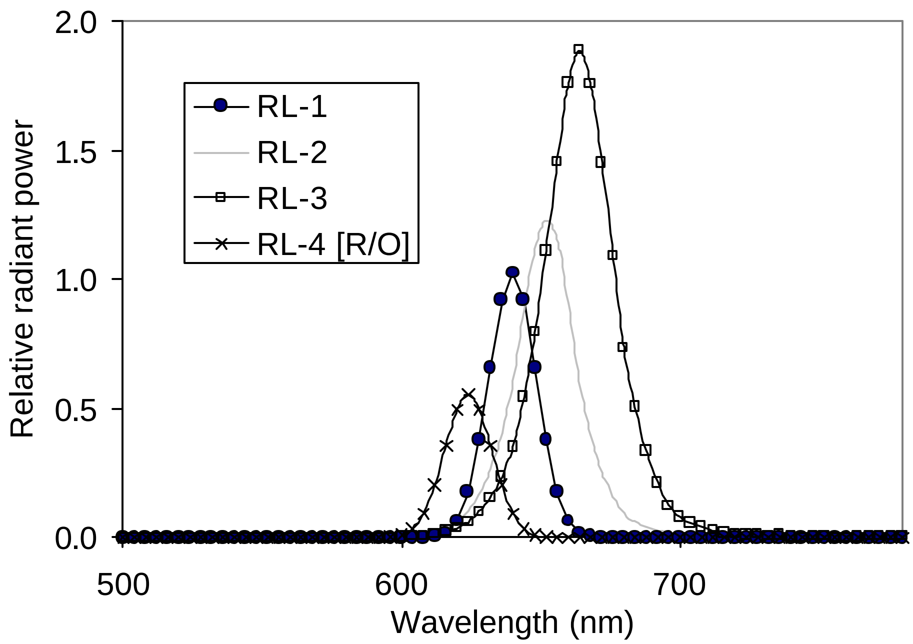

Figure 11. SPDs of four red LEDs. RL-1, RL-2, and RL-3 are deep red LEDs. RL-4 is a red-orange LED.

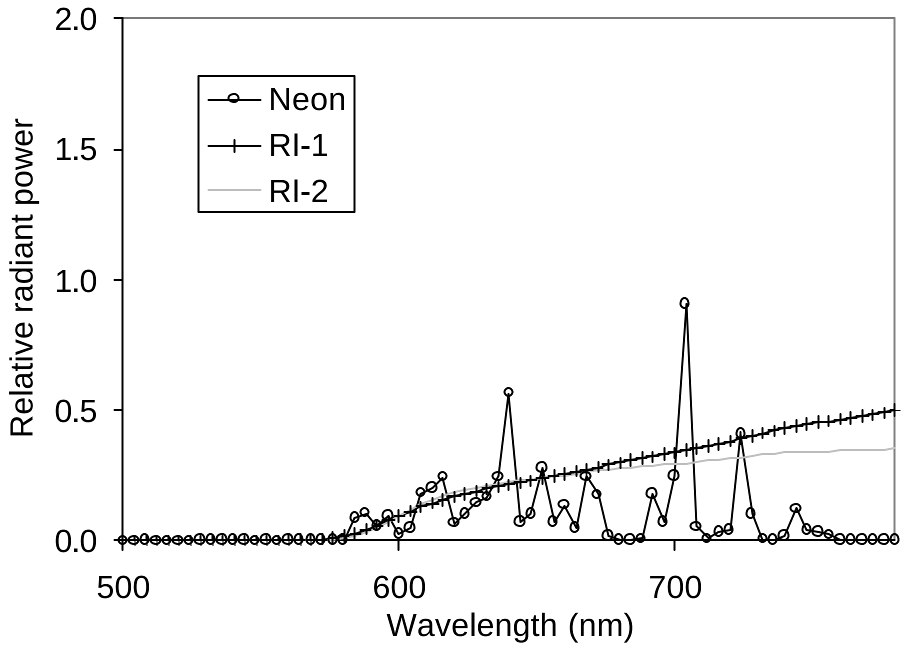

Figure 12. SPDs of two red incandescent sources and one neon source.

The relative luminances of the stimuli are shown in Figure 13. For deuteranopes and tritanopes, the red stimuli do not differ greatly from the equal-energy white (all the ratios to equal-energy white are close to 1.0). The protanopes show a marked decrease in sensitivity to all of the red stimuli, but the reduction for the three deep-red LEDs is greater than for the other red sources. The extent of the luminance reduction is directly related to how much of a light's SPD is concentrated in the long-wavelength part of the spectrum (see Figure 11 and Figure 12). Because the SPD of RL-4 [R/O] is shifted toward the shorter wavelengths, its effect on protanopes is comparable to the incandescent light sources; because RL-3 contains predominantly longer wavelengths, it is less visible to protanopes. Neon differs very little from the two incandescent sources.

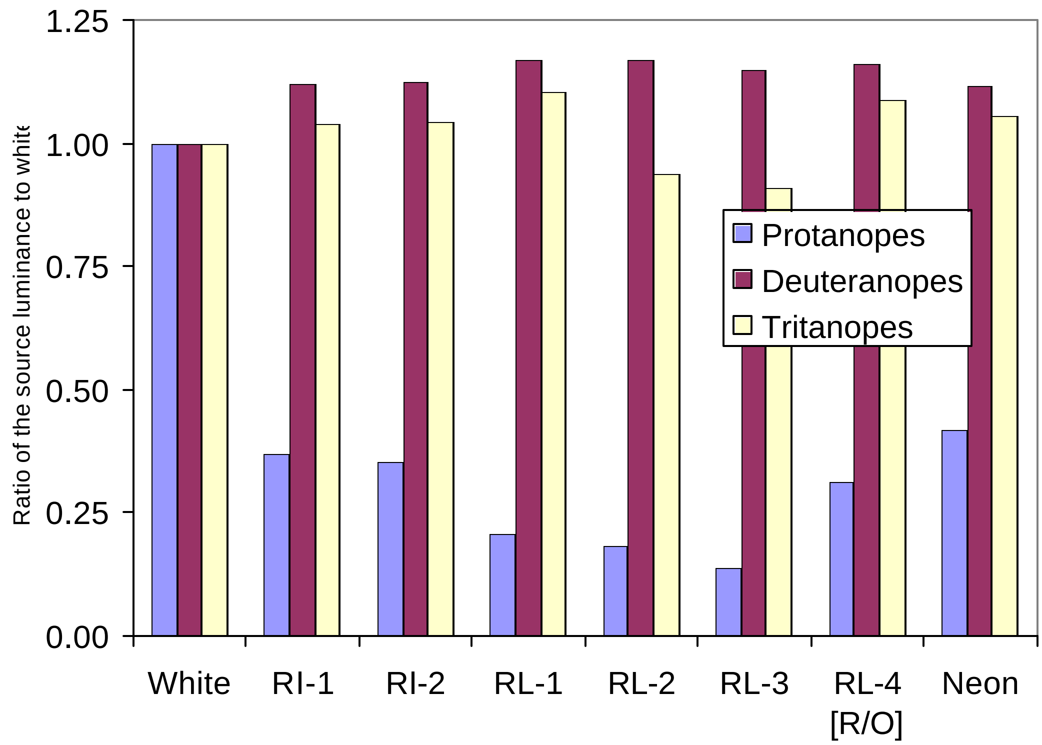

Figure 13. Ratios of the luminances of red light sources to equal-energy white. RI-1 and RI-2 are red incandescent sources; RL-1, RL-2, and RL-3 are relatively deep red; RL-4 [R/O] is red-orange.

Effects of aging

The aging of the visual system has been chiefly characterized as a broad decline in sensitivity to light caused by changes in the cornea, aqueous humor, lens, vitreous humor, and the receptors on the retina (Werner, Peterzell, & Scheetz, 1990). Part of this decline is a direct consequence of less light reaching the retina. There are three major mechanisms of light loss. First, less light enters the eye because pupil size is smaller with increasing age (Lowenfeld, 1979). Second, the lens of the eye yellows with age and absorbs short-wavelength light. Third, there is more scatter in the eye as a consequence of increasing turbidity of the ocular media. That is, the cornea, aqueous humor, lens, and vitreous humor contain particles that scatter light. Sensitivity may also decline as a consequence of changes in receptor number and individual sensitivity. Werner, Peterzell, and Scheetz (1990) have estimated declines in the short, middle, and long wavelength cones to be 0.12, 0.14, and 0.14 log units per decade respectively. Although this result implies a uniform decline in spectral sensitivity, declines in the shorter wavelengths are more commonly reported.

Because some of these changes in vision appear to be spectrally selective, there is a possibility that innovative light sources could present special problems for the vision of an aging population. We note, however, that even if an age-related change in spectral sensitivity can be demonstrated in a component of the visual system (e.g., the lens), it does not necessarily mean that the visual system as a whole reflects this change. For example, although Hemenger (1996) reports that scatter by the lens is wavelength-dependent, others using psychophysical methods (Whitaker, Steen, & Elliott, 1993; Wooten & Geri, 1987) find little evidence of wavelength dependence. Perhaps other sources of scatter outside of the lens (e.g., corneal scatter, and/or scatter in the aqueous and vitreous) simply obscure the wavelength-dependent effect. Likewise, although the aging lens yellows and increases in density to blue light (Werner, 1982), it appears that this change has little effect on color perception. Schefrin and Werner (1993) compared old and young observers in a task that required them to judge the percentages of fundamental hues in sets of broadband colored stimuli. Young and old observers were indistinguishable in their use of hue names. Similarly, Werner and Schefrin (1993) examined changes in the location of the white point with age. The white point is a coordinate in color space judged to be white by adjusting a mixture of short and long wavelength light. If the yellowing of the lens with age attenuates short wavelength light, it is expected that progressively more short wavelength light would be needed to produce the same white point. Instead, the white point does not appear to change substantially with age. In another study (Verriest, 1963), color discrimination performance on the Farnsworth-Munsell 100-hue test in elderly observers was mimicked by young observers wearing short-wavelength absorbing filters, suggesting a short wavelength deficiency with age. However, the same short-wavelength deficiency was also mimicked by reduction in illuminance level for young observers (Knoblauch et al., 1987), suggesting that the decline in retinal illuminance accounts for the difference.

It seems clear that the visual system does an extraordinarily good job maintaining color perception as it ages. Some have suggested that it does some rebalancing so that sensitivity of receptors is reduced in proportion to their activation (Enoch et al., 1999), preserving color constancy throughout the lifespan. With this in mind, it seems reasonably accurate to characterize the aging visual system as comparable to the performance of a younger visual system under reduced illumination. Consequently, it is unlikely that the spectra of innovative light sources would possess any features that uniquely affect an aging population.

Effects of External Filtering

Although signal lights are normally thought of as being viewed directly, the widespread use of tinting in sunglasses, spectacles, contact lenses, and windshields suggests we should consider how these filters interact with innovative light sources, and whether such differences affect signal visibility in significant ways. A case in point is the dramatic reduction in brightness produced when certain yellow LEDs are viewed through certain sunglasses (Arens, 1996a; Alferdinck, 1997). In this case, the sunglass lens in question strongly filtered out a narrow band of light that coincidentally matched the peak wavelength of a particular yellow LED. The same lens, if used with a broad-spectrum light source (or a light with a slightly displaced SPD), would have had less effect. The particular LED, if viewed through a more conventional sunglass lens (having smooth, continuous transmittance characteristics), would likewise have been less affected. In this analysis, we investigate how the transmittance characteristics of six representative windshields (five tinted [Figure 14] and one clear), seven sunglass lenses ([Figure 15], as well as no lenses), and the combinations of those windshields and sunglasses, affect the perceived brightness and chromaticity of 16 different light sources: 8 red sources (two incandescent [Figure 12], four LEDs [Figure 11], and two neon [Figure 19]), and 8 yellow sources (1 incandescent [Figure 7] and 7 LEDs [Figure 22]).

Windshields. Existing American standards establish a minimum transmittance of 70% for windshields (FMVSS Standard No. 205, ANSI Z26.1 incorporated by reference). Because strong windshield tinting would reduce transmittance to an unacceptably low level, windshield tinting is, on the whole, relatively neutral. As the sample of windshields in Figure 14 demonstrates, filtering is typically relatively flat over the middle wavelengths with a sharp decrease in the ultraviolet area and a gentle roll-off in the high wavelengths, presumably to reduce heat transmission and thereby keep the vehicle cooler. Notably, the chromaticity of Illuminant D_{65} (a standard representation of natural daylight) when filtered through any of the sample tinted windshields remains within the SAE J578 definition of white.

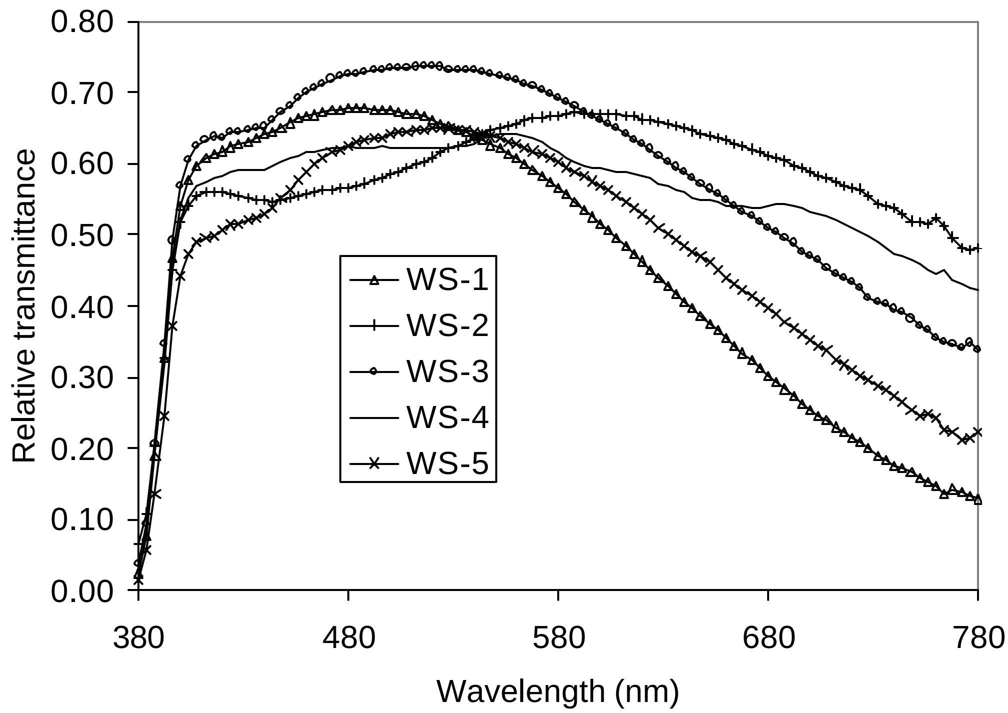

Figure 14. Transmission characteristics of five sample tinted windshields at a 60 deg rake angle.

Sunglasses. A standard also exists for sunglasses (ANSI Z80.3-1986) which sets minimum limits on the transmittance and chromaticity of sunglass lenses with particular regard to traffic signal visibility. The standard evaluates sunglass lenses against standard traffic signals that are based on filtering of Illuminant A, a standard representation of an incandescent source. It stipulates acceptable transmittance for red (8%), yellow (6%), and green (6%) traffic signals and establishes chromaticity boundaries for green and yellow signals. Compliance with the standard is voluntary, and the above guidelines do not apply to sunglasses regarded as “special purpose.”

The ANSI standard did not anticipate the spectral characteristics of innovative sources like LEDs and neon. Recently, some researchers have noted certain circumstances in which sunglass lenses that comply with the standard reduce the visibility of certain LED signal lights to an unacceptably low level (Arens, 1996b; Alferdinck, 1997; Mellerio & Palmer, 1997). It should be noted that each author cites very similar circumstances. The sunglass lenses in question all seem to employ neodymium, a rare-earth metal that absorbs a narrow band of wavelengths around 584 nm (see Figure 15, SG-2 and SG-7). Neodymium filters are commonly used in glassworking to filter out the intense yellow light emitted by hot glass, but they were also briefly introduced into the mainstream sunglass market in the mid-90s, and then apparently withdrawn. The yellow signal lights cited are nearly monochromatic yellow LEDs with a peak wavelength that is near the same wavelength as the notch in the neodymium filter. Thus, the circumstances required to produce an undesirable effect might be characterized as unusual; no other combinations of filter and light source have emerged as similarly deficient.

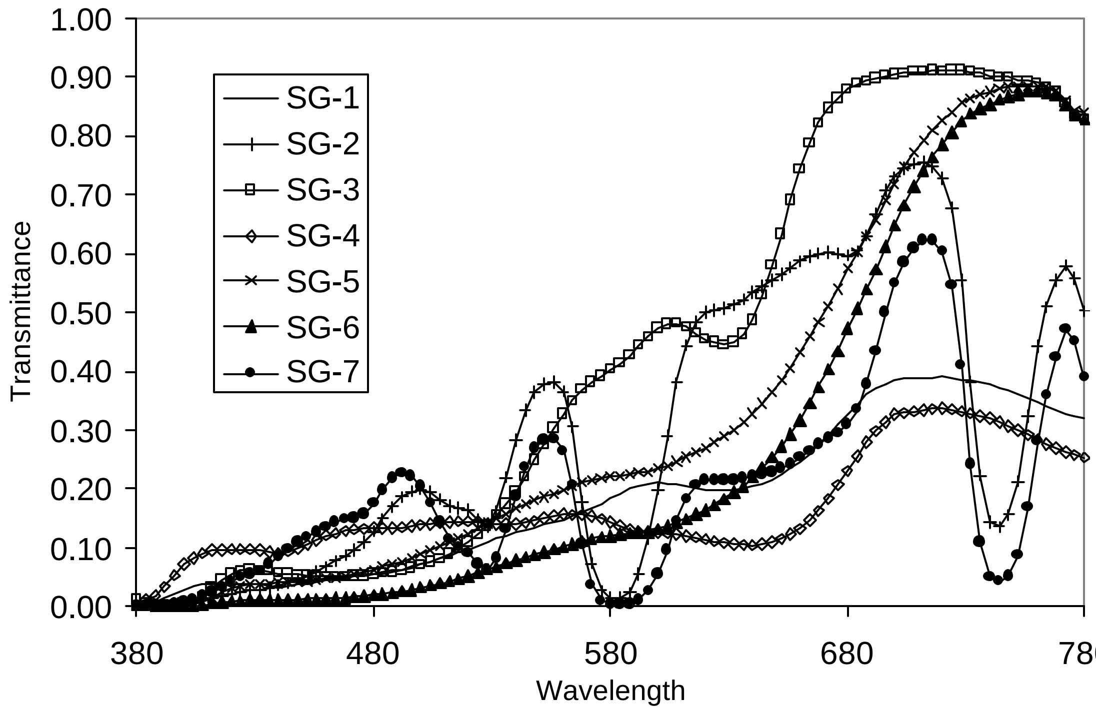

Figure 15. Transmittance characteristics of seven sample sunglass lenses (from Alferdinck, 1997). SG-2 and SG-7 are characteristic of filters containing the rare-earth metal neodymium.

To obtain a more comprehensive picture of how the filters and the light sources interact, we will evaluate the chromaticity change and transmittance of various signal lights through each filter combination. Chromaticity change will be calculated geometrically using u', v' distances (a rescaled x, y coordinate system that takes *perceived* color change into account). Transmittance will be represented as density of the filter with respect to the light source, computed as $-\log_{10}(t)$, where t is percent transmittance. A scatter plot of chromaticity versus density is used to portray their joint effects (Figure 16). On this plot, the nearer a point is to the origin (the bottom left), the less the filter has altered the light in chromaticity and brightness. For simplicity, only the light sources will be explicitly distinguished in each plot. The sunglass-windshield combinations that are in turn combined with the light sources to arrive at the points plotted in the figures will not be identified except to highlight specific circumstances where they play a role.

Results

Red Signal Lamps. Figures 16, 17, and 18 show plots for incandescent, LED, and neon red signals, respectively. Comparing the figures, we see that they behave approximately the same with respect to density: about 10% of the incandescent points and 10% of the LED points fall outside of the ANSI red-signal transmission limit; for neon, 14% are outside. All of these outlier points involve sunglasses *and* a tinted windshield; all the sunglasses, by themselves, meet the ANSI standard.

Chromaticity shifts for LEDs (Figure 17) are small, largely because of their narrow spectra. Neon and incandescent sources both show larger susceptibility to chromaticity shifts (Figure 16 and Figure 18) because of their broader spectral distributions of energy. For the red incandescent sources, chromaticity shifts exceeding 0.04 are produced by the SG-2 and SG-7 (neodymium) sunglass lenses. With the neon sources, the largest chromaticity shifts were also observed with filters SG-2 and SG-7, but only with the light source, RN-2. RN-1 did not show a similar chromaticity shift (Figure 18) because, compared to RN-2, it has less power in the range of 580-590 nm (Figure 19), the area of the neodymium notch.

Thus the pattern of results indicate that red LEDs are resistant to chromaticity change, all red sources appear equally susceptible to attenuation effects through sunglasses, and the two neon sources differ in degree of chromaticity shift related to differences in their spectra.

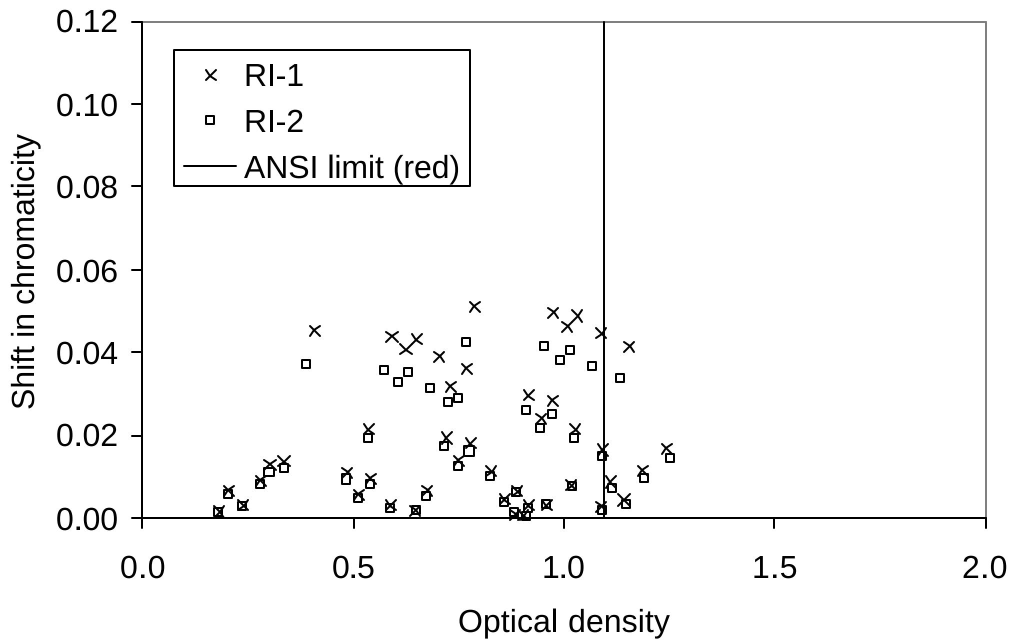

Figure 16. Chromaticity shift and density for red incandescent light sources viewed through tinted windshields and sunglasses. The ANSI minimum red-signal transmittance is indicated (vertical line, 8% transmittance, corresponding to an optical density of 1.1).

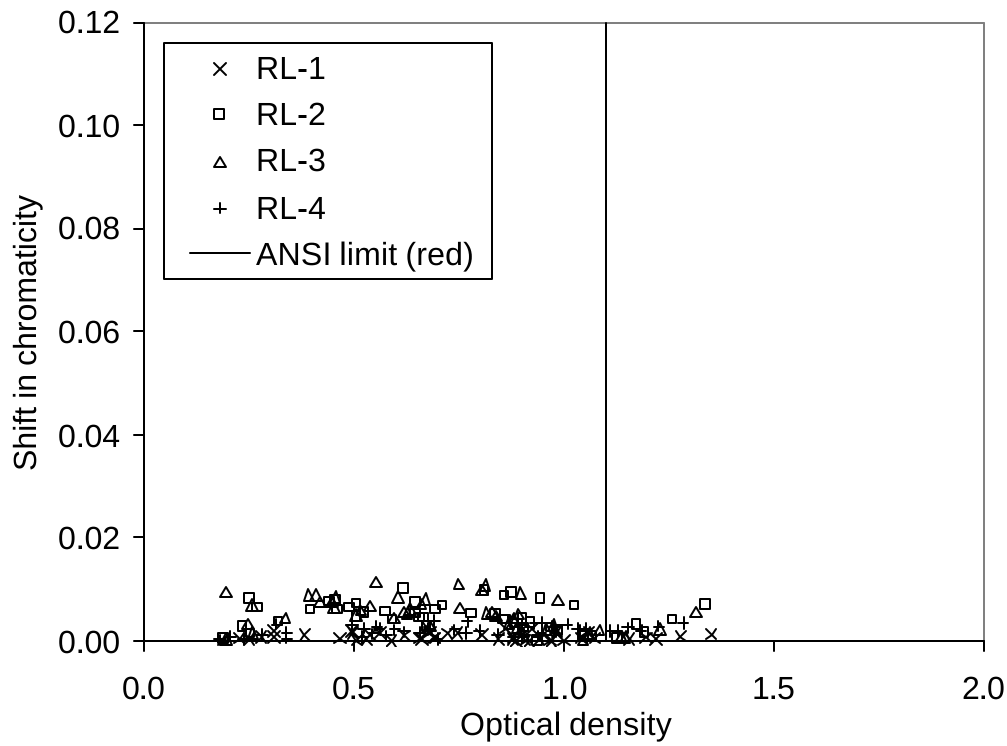

Figure 17. Chromaticity shift and density for red LED light sources viewed through tinted windshields and sunglasses. The ANSI minimum red-signal transmittance is indicated (vertical line, 8% transmittance, corresponding to an optical density of 1.1).

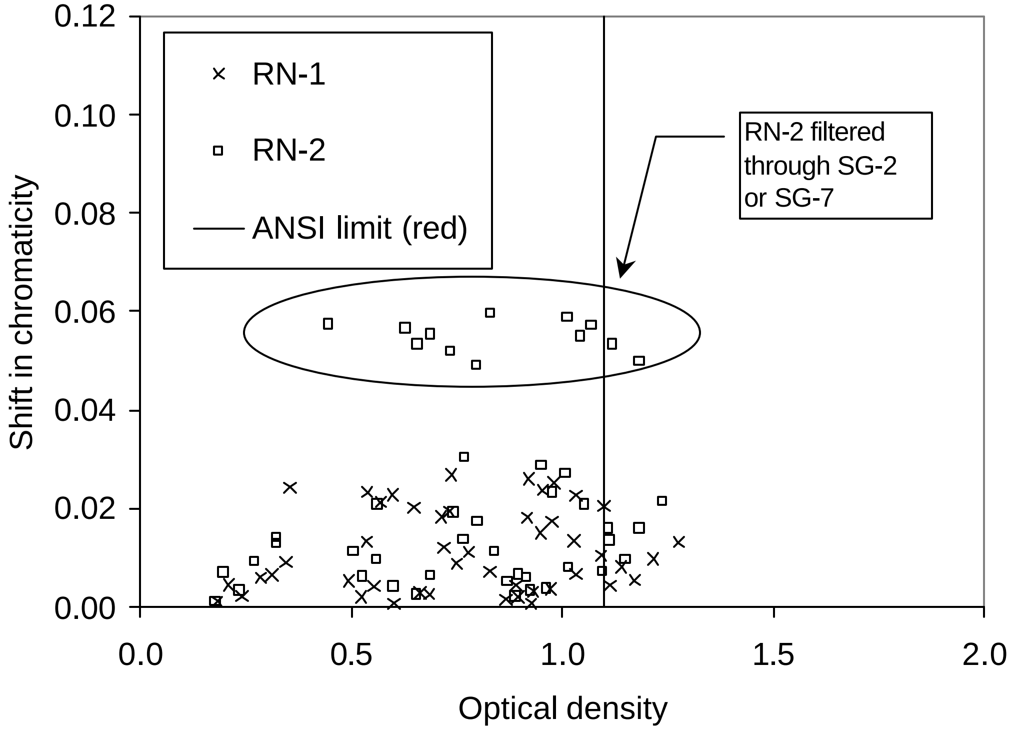

Figure 18. Chromaticity shift and density for red neon light sources viewed through tinted windshields and sunglasses. The ANSI minimum red-signal transmittance is indicated (vertical line, 8% transmittance, corresponding to an optical density of 1.1). The largest chromaticity shifts (greater then 0.04) are caused by SG-2 and SG-7.

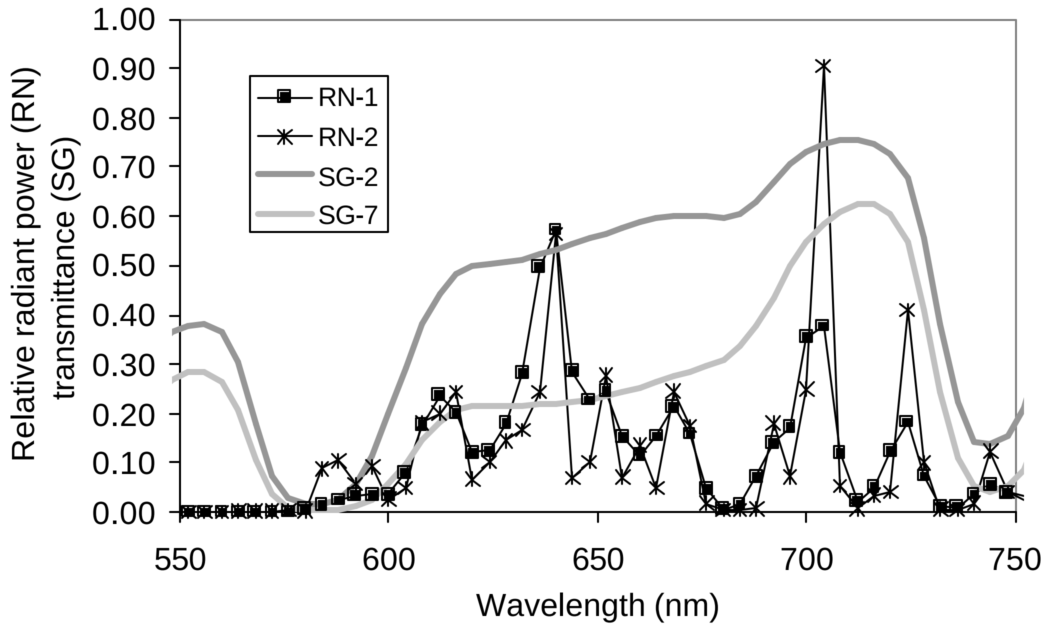

Figure 19. SPDs of sample red neon signal lights and the transmittance of SG-2 and SG7. Note that RN-2 contains more power in the range of 580-590 nm than RN-1.

Yellow Signal Lamps. For yellow signal lamps, we review incandescent and LED sources (no yellow neon samples were available for this analysis). In Figure 20, we see the transmission effects for a sample yellow incandescent source. Notably, all points fall within the transmittance limits (6%, optical density 1.2) established by the ANSI sunglasses standard, despite the added filtering from the tinted windshields.

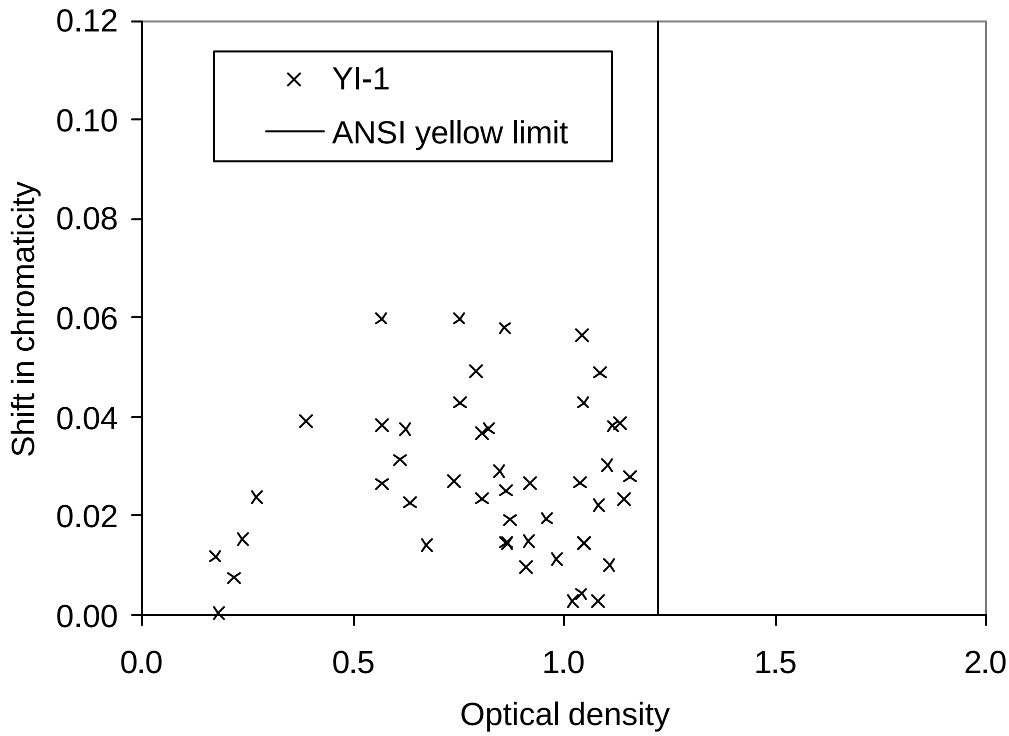

Figure 20. Chromaticity shift and density of a yellow incandescent light source viewed through tinted windshields and sunglasses. The ANSI minimum yellow-signal transmittance is indicated (vertical line, 6% transmittance; 1.22 optical density).

Turning to the LEDs (Figure 21), we see a very different pattern. Instead of the scatter of points characteristic of the incandescent sources, we see a tight cluster of points along the optical density axis, below a value of about 1.2, suggesting almost no chromaticity change. This is similar to the results for red LEDs in Figure 17, and again illustrates the resistance of LEDs to shifts in chromaticity, even at fairly high optical densities. However, unlike Figure 17, in Figure 21 we also see a secondary pattern in which large (greater than 0.01) chromaticity changes are present at large (mostly greater than 1.0) optical density levels. These are caused exclusively by the SG-2 and SG-7 sunglass lenses (the "notched" neodymium filters). In contrast, as shown in Figure 20, the yellow incandescent source showed large chromaticity shifts for most of the sunglass lenses and in combination with some windshields. The reason for this becomes evident if one considers that the yellow LED sources have spectral peaks in the region of 590 to 600 nm. The SG-2 and SG-7 lenses distinguish themselves from the other lenses by their minimal transmission in this same region (see Figure 22).

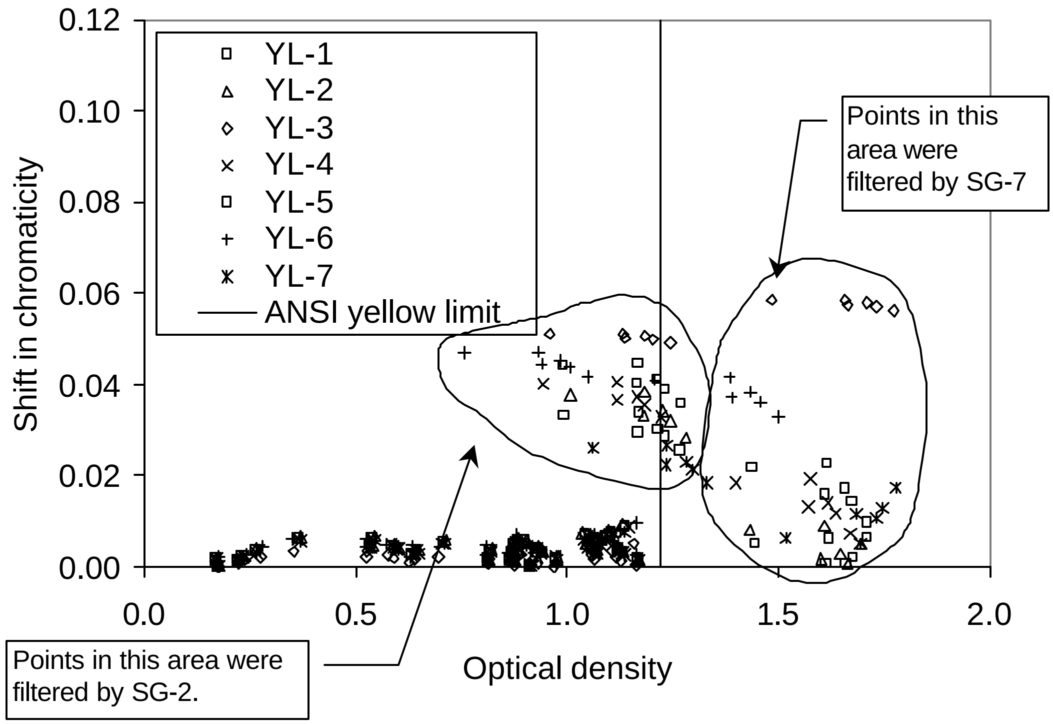

Figure 21. Chromaticity shift and density of a yellow LED light source viewed through tinted windshields and sunglasses. The ANSI minimum yellow signal transmittance is indicated (vertical line, 6% transmittance; 1.22 optical density).

Two LEDs tended to show larger chromaticity shifts: YL-3 and YL-6. Unlike the other yellow LEDs in the sample which peak around 592 nm, YL-3 and YL-6 peak at 596-600 nm and are slightly more offset from the filter notch at 584 nm than the other LEDs (see Figure 22). As a consequence, their spectra are filtered more asymmetrically than the other LEDs, producing a shift in color. The effects of SG-2 and SG-7, weighted by $V(l)$, are shown in Figure 23 and Figure 24, respectively. Note that the peak wavelength of most of the LEDs has been shifted towards the longer wavelengths. For comparison, Figure 25 shows the effect of one of the more usual sunglass filters, SG-1—there, little peak shift is evident. Note that if the LED spectra were shifted an additional 20 nm away from the filter notch, the effect would be substantially smaller.

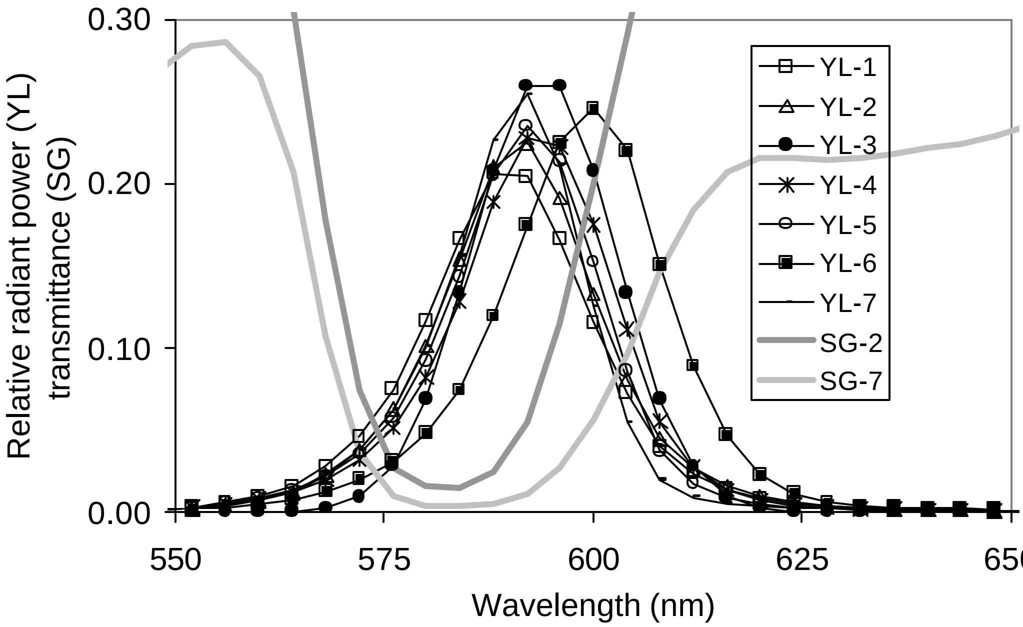

Figure 22. SPDs of sample yellow LED signal lights and the transmittance of SG-2 and SG7 in the spectral bands of the yellow LEDs.

If we examine the sunglass lenses involved in producing optical density values above 1.22 (6% transmittance; see the vertical line in Figure 21), we find that every point involves either SG-2 or SG-7. All the points above an optical density of 1.3 were produced by SG7. This is consistent with its overall low transmittance in the yellow range apparent from Figure 22. Below the 1.3 optical density, large shifts in chromaticity were produced by SG-2. Figure 23 illustrates the effect of SG-2. With its narrow notch, it reduces a small part of each LED's spectrum, causing a peak shift toward the longer (and less-attenuated) wavelengths. The amount of this shift is related to how aligned the notch is to the source spectrum. Note also that the magnitude of the shorter wavelengths (to the left of the notch) transmitted by the filter also influence chromaticity. These wavelengths will work to shift chromaticity towards green, possibly offsetting shifts toward red. The effect of SG-2 shown in Figure 23 is mainly to shift chromaticity toward red. The influence of the wavelengths around 560 nm is small relative to the peaks. In contrast, some of the LEDs in Figure 24 show two peaks of similar height straddling the filter notch. This LED/filter combination results in smaller chromaticity shifts and larger optical densities.

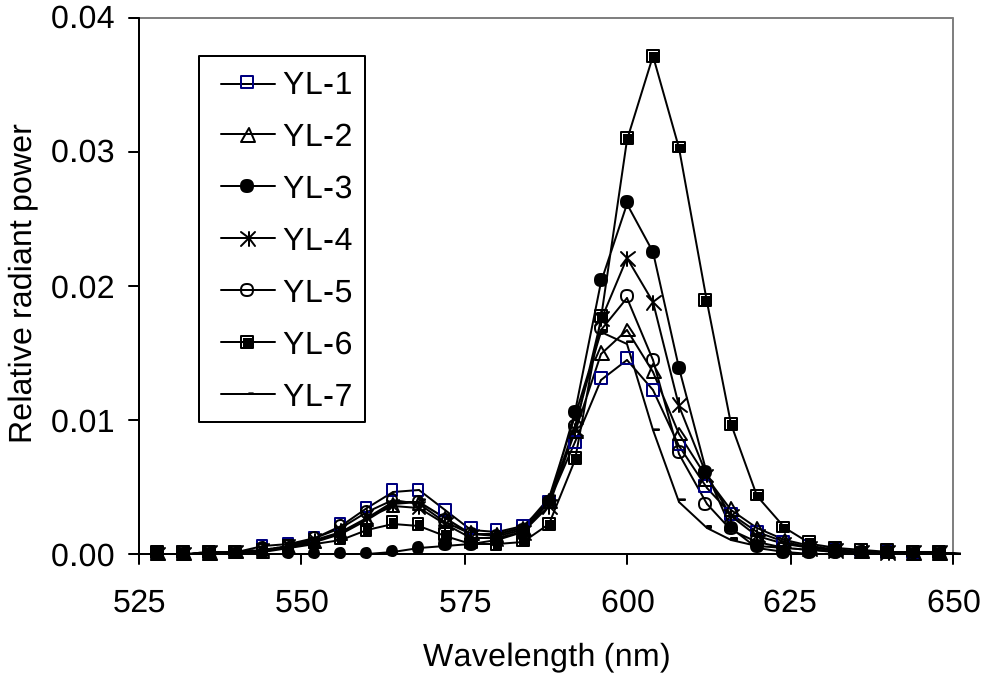

Figure 23. The relative radiant power of yellow LEDs filtered through SG-2 and weighted by *V(l)*.

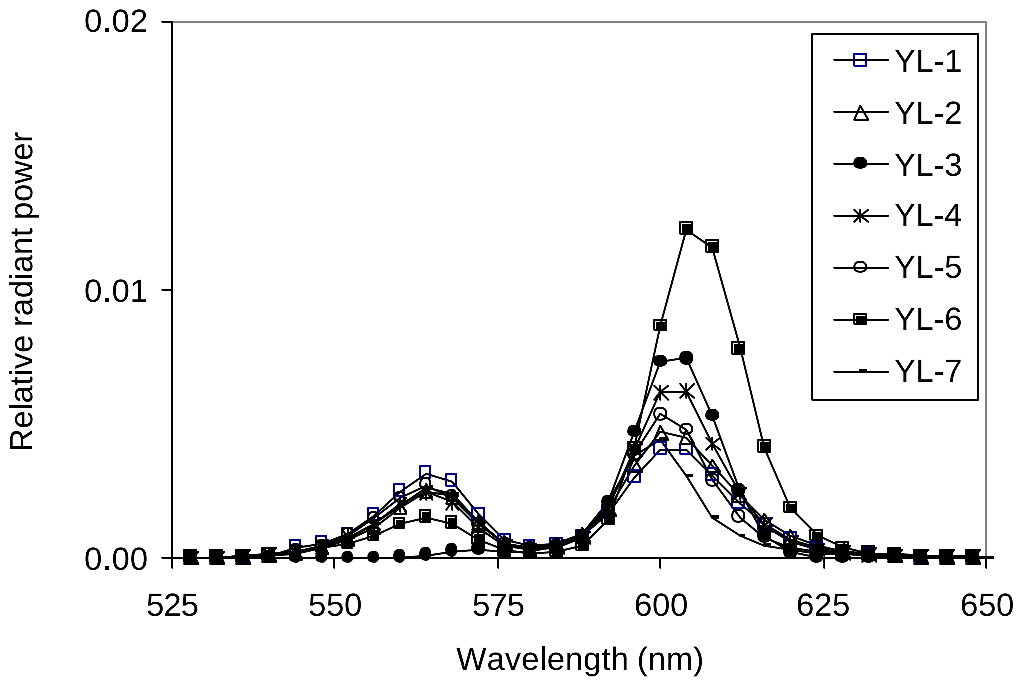

Figure 24. The relative radiant power of yellow LEDs filtered through SG-7 and weighted by *V(l)*.

So it seems that the yellow LEDs are reasonably well behaved, unless they are coincidentally paired with an unusual filter containing a sharply attenuated transmission region (a notch) near the dominant wavelength of the LED.

From this example we should note several things. First, it is unusual that a filter would contain a sharp notch about a small wavelength range. The transmission characteristics of most sunglass filters are only broadly selective. Second, it is also unlikely that such filter's notch would align with the narrow (±20 nm) wavelength span of an LED. The pairing this kind of filter and light source results in either a sharp attenuation of the light source intensity if the notch is aligned to the light's peak wavelength, or a chromaticity shift if they are slightly misaligned. It seems that there should be little concern about the use of LEDs for traffic signals as long as narrow wavelength notch filters remain relatively rare. As we noted earlier, the sale of at least some sunglasses with notch filters has recently been discontinued.

With the vast majority of sunglasses and tinted filters, LEDs are more resistant to shifts in chromaticity than are filtered incandescent sources. Whether this resistance translates into a true perceptual advantage is not immediately clear. At a relatively simple level, it would seem to be a good thing—for example, it makes it more likely that the light from a red or yellow signal lamp would remain within the SAE red or yellow chromaticity limits (Figure 3) even after filtering by sunglasses and windshields. However, because colored sunglasses or windshields cause a shift in chromaticity of a driver's entire visual field, it is important to consider whether a driver's color perception might generally readapt to such a shift. Such a change might naturally result in compensation for color shifts in signal lamps, even if they are filtered incandescent lamps, thus negating any potential advantage for LEDs.

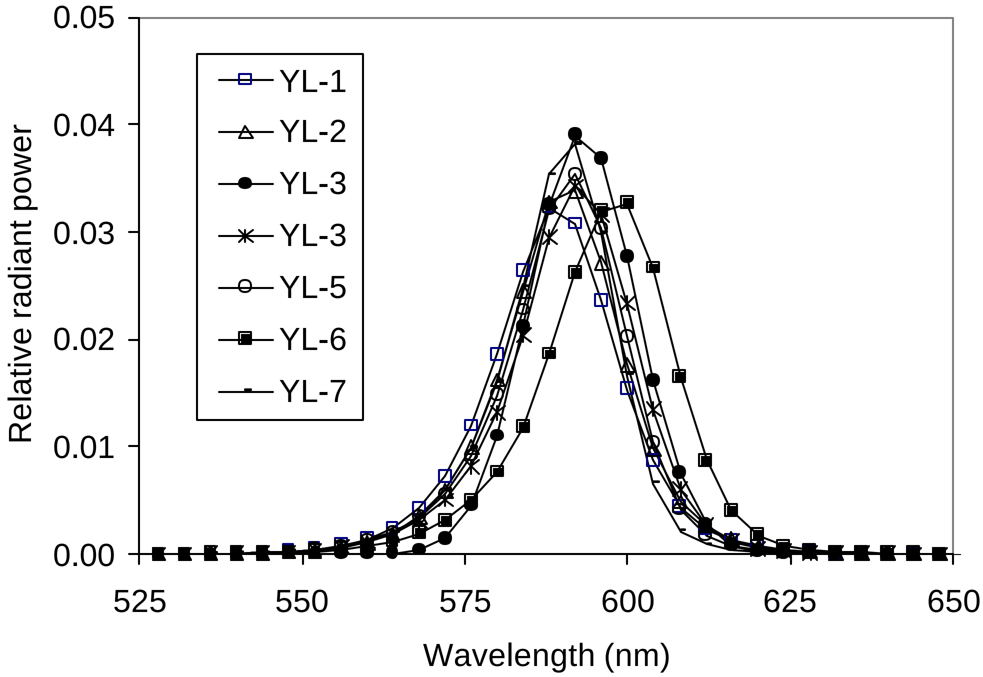

Figure 25. The relative radiant power of yellow LEDs filtered through SG-1 and weighted by *V(l)*. This filter has no notch in the yellow wavelength range.

Weather Conditions

Besides possibly passing through sunglass filters and windshields, light from signal lamps also travels through the atmosphere on the way to the eye. At different times this space may contain snow, hail, rain, fog, haze, and smoke. As light travels through these media, some of it may be absorbed, and some of it may be scattered. If the media affect the light in spectrally selective ways, then there may be circumstances in which innovative light sources are affected differently than incandescent lights.

Of the particulate matter lingering in the atmosphere, water droplets in fog and rain present special concerns for visibility. Indeed fog, in particular, has been the focus of many attempts to devise lighting countermeasures to reduce its detrimental effects on visibility. The safety concern has driven lighting manufacturers to devise alternative lighting systems. Such systems have involved repositioning lamps to help mitigate backscatter, and the use of colored lamps based on the presumed susceptibility of short wavelength light to scatter in fog. The latter strategy is the basis for the widespread use of yellow lamps in fog. It will be examined more carefully here inasmuch as it directly relates spectral properties of lamps to their ability to penetrate fog. What we will find is that common notions about special advantages of colored lights are not supported by objective evidence.

As a beam of light travels through fog, water droplets absorb some light and scatter some in different directions. Both processes result in light reduction and are jointly referred to as *extinction* (van de Hulst, 1957). The amount of light absorbed by water is small in the visible spectrum, but orders of magnitude greater outside the near-UV and near-IR wavelengths (Killinger, Churnside, & Rothman, 1995). It is probably no coincidence that the absorption bands of chlorophyl and human (and animal) visual systems operate in the range in which absorption is limited. Compared to the effects of scatter, light loss due to absorption by water is comparatively minor.

Two kinds of light scatter have been distinguished: Rayleigh scatter and Mie scatter. Rayleigh scatter applies to light scattered by particles that are smaller than the wavelengths of light (e.g., atmospheric molecules) and accounts for why the sky is blue—short wavelengths are scattered more than longer wavelengths. Rayleigh scatter effects accumulate over large distances. We see a blue sky when looking through miles of atmospheric gases, but little scatter of blue light is evident when looking down a street. Rayleigh scatter is unlikely to significantly affect visibility over distances that matter for driving.

Mie scattering characterizes light scattered by particles equal to, or larger than the wavelengths of light. With increasing particle size, the influence of wavelength on scatter diminishes significantly (although the overall amount of scatter increases). Clouds, for example, are comprised of water particles that range in radius between 1µm and 100µm. The lack of spectral selectivity in the light scatter produced by water droplets in clouds is responsible for the appearance of clouds as white—all wavelengths are equally scattered.

Wavelength dependent scatter is illustrated in Figure 26 for several diameters of water particles using the efficiency metric. The distribution of water droplet size in various fogs have been measured, and most fall within the range of 2µm to 47µm (Zak, 1994, cited in Kontogeorgakis, 1997), with peaks around 10µm. These particle sizes are much greater than the range of wavelengths of visible light (.4 to .7 µm) and are clearly not subject to Rayleigh scatter. For this size droplet, scatter is largely independent of wavelength, as can be seen in Figure 26.

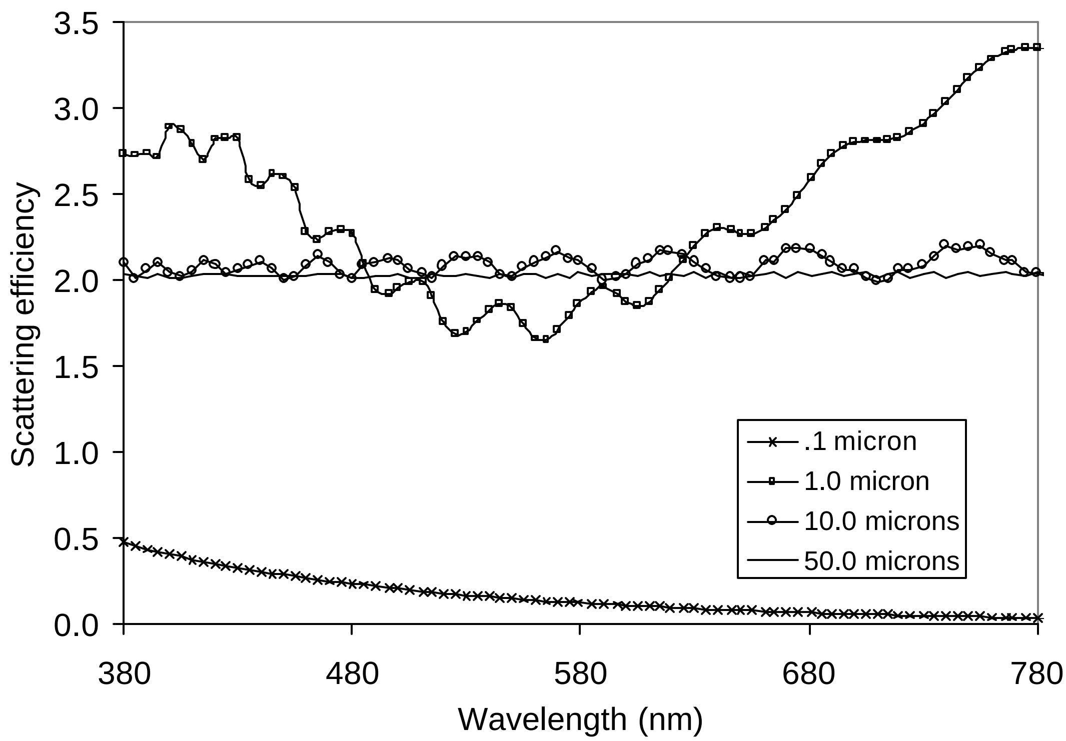

Figure 26. Scattering efficiency as a function of wavelength for four water droplet radii.

The droplet size of rain is much larger than fog, between 100µm and 9000µm (Measures, 1984 cited in Killinger, Churnside, & Rothman, 1995); snow and hail are similar in size or larger. Given these ranges of size, it seems reasonable to conclude that the particular spectral makeup of a light source should not influence the amount of scatter observed through fog, rain, or snow.

It should be noted that resolving questions about wavelength-dependent scatter in fog is far from addressing questions about *visibility* in fog. For example, we may find that some signal light colors are more visible in fog because there is better *color-contrast* between the signal lamp color and the background veiling luminance found in daylight fog, or in fog illuminated by headlamps. Wavelength-dependent scatter would have little to do with such an effect. Such effects would also be completely unrelated to the SPD of the source. As noted earlier, the color response of the eye is insensitive to the mixture of wavelengths in the source.

Conclusion

Perhaps the most important conclusion to be made in this report is that the spectral characteristics of innovative light sources are not likely to interact with the human visual system in ways that are markedly different from conventional incandescent sources. As we have seen, the visual system relays color information through three receptors, each responsive to broad and overlapping bands of spectral energy. Such a system lacks the ability to distinguish component wavelengths in broadband light. Thus, neon is indistinguishable from incandescent light provided their chromaticities and intensities are matched. If responses of individual receptors in the retina were selective to *narrow* bands of light, much like the auditory system's receptors are tuned to vibration frequency, a neon source would be readily distinguishable from an incandescent source, like the notes in a chord are distinguishable from an individual tone. But this is not how the visual system works. As Cornsweet (1970, p. 194) put it,

> "…A trained subject can, in fact identify the individual tones that make up a chord, but no subject, no matter how much training he has, can ever identify the particular wavelengths that are mixed together in grass. Wavelength information is present as the light passes through the media of the eye, but the media contain no machinery for detecting it, and, at the very first stage where quanta are detected, that is, where the quanta isomerize pigment molecules, a large part of the wavelength information is lost. It can never be recovered by the remainder of the subject's system."

Thus, the machinery of a normal eye is insensitive to spectral makeup. As discussed earlier, the same is also true for color-abnormal observers and aging observers. In our look at various sample red signal sources for dichromats, we found a large decline in protanope sensitivity to all red signal sources, ranging from 41% to 14%. The fact that many of the LED samples appear dimmest to protanopes is attributable to the dominance of long wavelengths in these samples and is not simply related to the narrowness of their spectra. The red-orange LED (Led R/O), which peaked in a shorter spectral range, was comparable to the incandescent sources. Neon affected protanopes no differently than incandescent sources. This lack of sensitivity to spectra is really not surprising. Dichromats are simply lacking one of the three receptors color normals have. Their remaining receptors probably function the same way as they do for color normals—each is sensitive to broad spectral bands that overlap in range of sensitivity. Thus, broadband light is mapped into the output of two receptors, rather than the normal three.

Aging observers are likewise not likely to be unusually sensitive to the spectral characteristics of innovative light sources. Although overall sensitivity to light appears to decline with age, color perception is well preserved and operates much like it does in young observers. The psychophysical evidence suggests that spectrally selective scattering and absorption measured in the lens affect vision very little. Thus, because of the non-selective, broad, smooth response of the receptors in the visual system to wavelength, we are incapable of distinguishing differences in the spectral makeup of different light sources.

When various filtering media like windshields and sunglasses are interposed between the eye and the light source, new opportunities arise for interactions between the source spectra and the filter. If filtering is broad and smooth, as is characteristic of most sunglasses and windshields, narrow-band sources like LEDs are less prone than incandescent (and neon) sources to produce a shift in perceived color. However, filters containing narrow-band notches may strongly interact with narrow-band sources if the notches in the filter align with spectral peaks in the light source. Although currently unusual, there is no guarantee that sunglass fashion will refrain from future experiments with notch filtering. Perhaps the ANSI sunglass standard should be revised to take more than just the visibility of incandescent light sources into account.

Finally, popular notions about spectrally selective effects of light in fog appear to be unfounded, based on what is known about the optics of scatter and absorption and the size of water droplets in fog. If LED or neon light sources possess real visibility advantages over incandescent light in fog, it must be for reasons other than differences in scatter.

References

Alferdinck, J. W. A. M. (1997). *The applicability of yellow LEDs at information carriers along the road in relation to the spectral transmission of sunglasses* (TM-97-C021). Soesterberg, The Netherlands: TNO Human Factors Research Institute.

American National Standards Institute. (1986). *American national standard for opthalmics–Nonprescription sunglasses and fashion eyewear–requirements.* (ANSI Z80.3-1986). New York, New York: American National Standards Institute.

Arens, J. (1996a). Beware the Ides of March — or — do your sunglasses pass muster? (FHWA-RD-97-010), *Transporter,* 5.

Arens, J. (1996b). The effects of notch-filtered sunglasses on the visibility of certain LED-based traffic control devices and tunnel entrances illuminated by low pressure sodium lamps. Personal communication.

Cornsweet, T. N. (1970). *Visual perception*. New York, NY: Academic Press.

Enoch, J. M., Werner, J. S., Haegerstrom-Portnoy, G., Lakshminarayanan, V., & Rynders, M. (1999). Forever young: visual functions not affected or minimally affected by aging: a review. *Journals of Gerontology. Series A, Biological Sciences & Medical Sciences, 54*(8), B336-351.

Hemenger, R. P. (1996). Dependence on angle and wavelength of light scattered by the ocular lens. *Ophthalmic & Physiological Optics, 16*(3), 237-238.

Hulst, H. C. van de (1957). *Light scattering by small particles.* New York: Wiley.

Killinger, D., Churnside, J., & Rothman, L. (1995). Atmospheric optics. In M. Bass, E. van Stryland, D. Williams, & W. Wolfe (Eds.), *Handbook of Optics* (Vol. I, pp. 44.41-44.50). New York, NY: McGraw-Hill.

Hsia, Y., & Graham, C. H. (1957). Spectral luminosity curves for protanopic, deuteranopic, and normal subjects. *Proceedings of the National Academy of Science U.S.A., 43*, 1011-1019.

Knoblauch, K., Saunders, F., Kusuda, M., Hynes, R., Podgor, M., Higgins, K. E., & deMonasterio, F. M. (1987). Age and illuminance effects in the Farnsworth-Munsell 100-hue test. *Applied Optics, 26,* 1441-1448.

Kontogeorgakis, C. (1997). *Millimeter through visible frequency waves through aerosols particle modeling, reflectivity and attenuation.* Unpublished Master of Science thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Lowenfeld, I. (1979). Pupillary changes related to age. In H. Thompson, R. Daroff, L. Friseen, J. Glasen, & M. Sanders (Eds.), *Topics in Neuro-Ophthalmology* (pp. 124-150). Baltimore, MD: Williams and Wilkins.

McKinney, W. (1986). *LED - Incandescent lamp perceived intensity comparison.* Anderson, IN: LED Task Force of the Signaling and Marking Devices Committee.

Measures, R. (1984). *Laser remote sensing*. New York: John Wiley & Sons.

Mellerio, J., & Palmer, D. A. (1997). *Conspicuity of LED's viewed through coloured lenses.* Paper presented at the Proceedings of the CIE Symposium on Standard Methods for Specifying & Measuring LED Characteristics, Vienna.

Schefrin, B., & Werner, J. (1993). Age-related changes in the color appearance of broadband surfaces. *Color Research Applications, 18*, 380-389.

Society of Automotive Engineers. (1988). *Highway vehicle standard SAE J578: Color specification (rev. May 1988)*. Warrendale, PA: Society of Automotive Engineers.

Verriest, G. (1963). Further studies on acquired deficiency of color discrimination. *Journal of the Optical Society of America, 3,* 185-195.

Werner, J. S. (1982). Development of scotopic sensitivity and the absorption spectrum of the human ocular media. *Journal of the Optical Society of America*, *72*(2), 247-258.

Werner, J. S., Peterzell, D. H., & Scheetz, A. J. (1990). Light, vision, and aging. *Optometry & Vision Science, 67*(3), 214-229.

Werner, J. S., & Schefrin, B. E. (1993). Loci of achromatic points throughout the life span. *Journal of the Optical Society of America A-Optics & Image Science, 10*(7), 1509-1516.

Whitaker, D., Steen, R., & Elliott, D. B. (1993). Light scatter in the normal young, elderly, and cataractous eye demonstrates little wavelength dependency. *Optometry & Vision Science, 70*(11), 963-968.

Wooten, B. R., & Geri, G. A. (1987). Psychophysical determination of intraocular light scatter as a function of wavelength. *Vision Research, 27*(8), 1291-1298.

Wyszecki, G., & Stiles, W. S. (1982). *Color science: concepts and methods, quantitative data and formulae* (2nd ed.). New York: Wiley.

Zak, J. (1994). Drop size distributions and related properties of fog for five locations measured from an aircraft. (NASA Contractor Report 4585). Hampton, VA: NASA.