

## **Characteristics of Light-Emitting Diode Sources: Relevance for Visual Signal Detection**

John D. Bullough, Ph.D.;\* Yiting Zhu, Ph.D.; Nadarajah Narendran, Ph.D.

Lighting Research Center, Rensselaer Polytechnic Institute

21 Union Street, Troy, NY 12180 USA

Tel. +1.518.687.7100, Fax +1.518.687-7120, \*Corresponding Author Email [bulloj@rpi.edu](mailto:bulloj@rpi.edu)

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### **Abstract**

Visual signaling devices using light-emitting diodes (LEDs) are increasing in number. LED sources have a number of characteristics that are particularly well suited for signal applications: very rapid onset and offset times, straightforward temporal control of luminous intensity through adjustment of current or voltage properties, saturated color that provides relatively high perceived brightness, and robust performance resulting in long useful lives, with appropriate thermal design. With specific emphasis on the capabilities and unique properties of LED light sources, the relevance of human-factors research findings from various signal lighting applications to visual warnings and alerts for fire and emergency protection are discussed, including environments where visual effectiveness can be reduced, such as in smoke or fog. Some preliminary guiding principles regarding the visual effectiveness of signal and warning devices for fire protection using LEDs are also summarized. Considerations and criteria for effectiveness will include ensuring detection, minimizing response times, providing an ability to locate a warning signal or device, and helping ensure that the warning or signal can be identified and interpreted properly.

### **Introduction**

Light-emitting diodes (LEDs) are growing in use for a number of visual signaling applications, including vehicle signals (Bullough et al. 2001, 2007a), road traffic signals (Bullough et al., 2000, 2005), aviation signal lights (Bullough et al. 2007b; Radetsky et al. 2009; Skinner and Bullough 2011; Skinner and Greenfield 2011), and work zone lighting (Bullough et al. 2011a). They are also being considered for visual signaling applications in fire and emergency alarm systems in building interiors. In this paper, the characteristics of LEDs and potential implications for various visual responses are briefly described.

### **LED Technological Characteristics**

LED sources have undergone rapid increases in luminous efficacy (lm/W) and in light output in recent decades, making them viable alternatives for such applications. Table 1 summarizes the photometric, colorimetric and temporal characteristics of LEDs along with those of other sources that might be used in some visual signaling applications.

It can be seen from Table 1 that tungsten filament lamps such as incandescent have relatively low luminous efficacies. The relatively large source size of fluorescent and compact fluorescent lamps, and their relatively long “warm-up” times can make them less suitable for many signaling applications. Issues with long warm-up and re-strike times of metal halide lamps are exacerbated even further. Xenon strobe lamps are the most common sources for fire alarm visual signals, but

the high efficacy, rapid onset time and long operating life of LED sources are making them attractive alternatives to consider for this application.

*Table 1. Light Source Characteristics*

<b>Light Source</b>	<b>Efficacy (lm/W)</b>	<b>Life (hours)*</b>	<b>Correlated Color Temperature (K)</b>	<b>Onset Time<sup>†</sup></b>
Tungsten filament lamp	12-20	750-4000	2700-3200	0.1-0.3 s
Fluorescent (incl. compact)	60-100	10,000-30,000	2700-7500	1-60 s
Metal halide	80-110	10,000-20,000	2800-5000	60-300 s
Xenon	30-60	1000-5000	5000-6000	1 $\mu$ s
Light-emitting diode (white)	90-130	50,000-100,000	3000-8000	10-20 ns

\*Assuming steady operation.

<sup>†</sup>Time to reach 90% of maximum light output.

In addition to the characteristics listed in Table 1, the light output of LED sources can be manipulated in a fairly straightforward manner through changing the current through the LEDs, or using pulse-width modulation (PWM) where the LED is modulated at a very high frequency above the critical fusion frequency of around 100 Hz (De Lange 1958; Kelly 1961; Bullough et al. 2011b), and the duty cycle is adjusted so that the apparent output is linearly correlated with the duty cycle.

### **Visual Responses to LED Signal Lights**

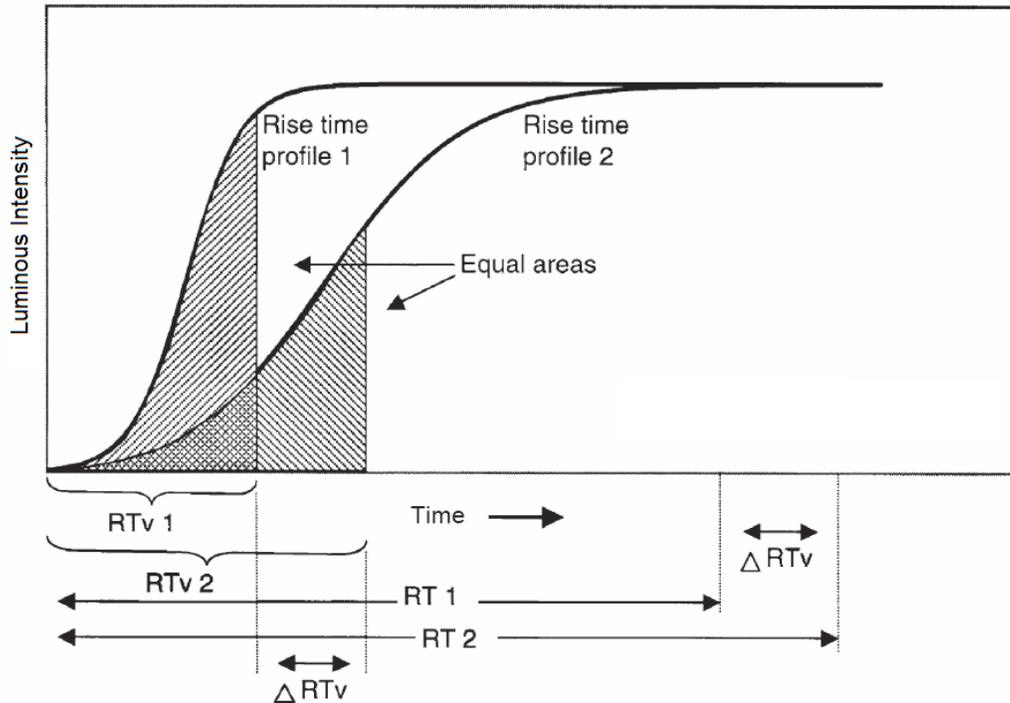
As described above, LEDs have been used in a wide range of visual signaling applications and there is a substantial body of research relating the characteristics of LED signal lights to various visual responses, each with varying degrees of relevance to visual signals for fire alarm systems.

#### *Rapid Signal Detection*

A key visual response for nearly any signal light is the ability to detect it with sufficiently high probability and with a reasonably short reaction time. Bullough et al. (2000) measured the reaction times of individuals to the onset of simulated road traffic signals viewed against a bright background such as the daytime sky. The signal sizes were such that they subtended the same visual angle as a 200-mm-diameter traffic signal viewed from a distance of 100 m. For each of the three road traffic signal colors (red, yellow and green), the reaction times, when plotted as a function of the luminous intensity of the signal, followed a power function where reaction times decreased sharply as a function of increasing intensity at low intensity values, but leveled off to asymptotic values at higher intensities.

There were also differences among the colors. Reaction times to the red signal lights were shorter than to yellow and green signals of the same luminous intensity under simulated daytime conditions with bright backgrounds. In comparison, at much lower background light levels, Ueno et al. (1985) found little difference among colors. Because the red signal color used by Bullough et al. (2000) was highly saturated in appearance relative to the yellow and green signals, the increased chromatic information may have helped in providing more rapid detection when the

relative intensity difference between the signal light and its background was smaller, such as during daytime viewing conditions. For darker background conditions, where the intensity difference between the signal light and its background is much larger, the ability to detect the signal rapidly appears to depend mainly on its luminous intensity regardless of color. White signal lights are not saturated in terms of color, so it might be expected that reaction times to the onset of white flashing lights would be longer than for signal lights of equal intensity but colored appearance when the background light level is high, as during daytime in spaces illuminated in part by daylight.

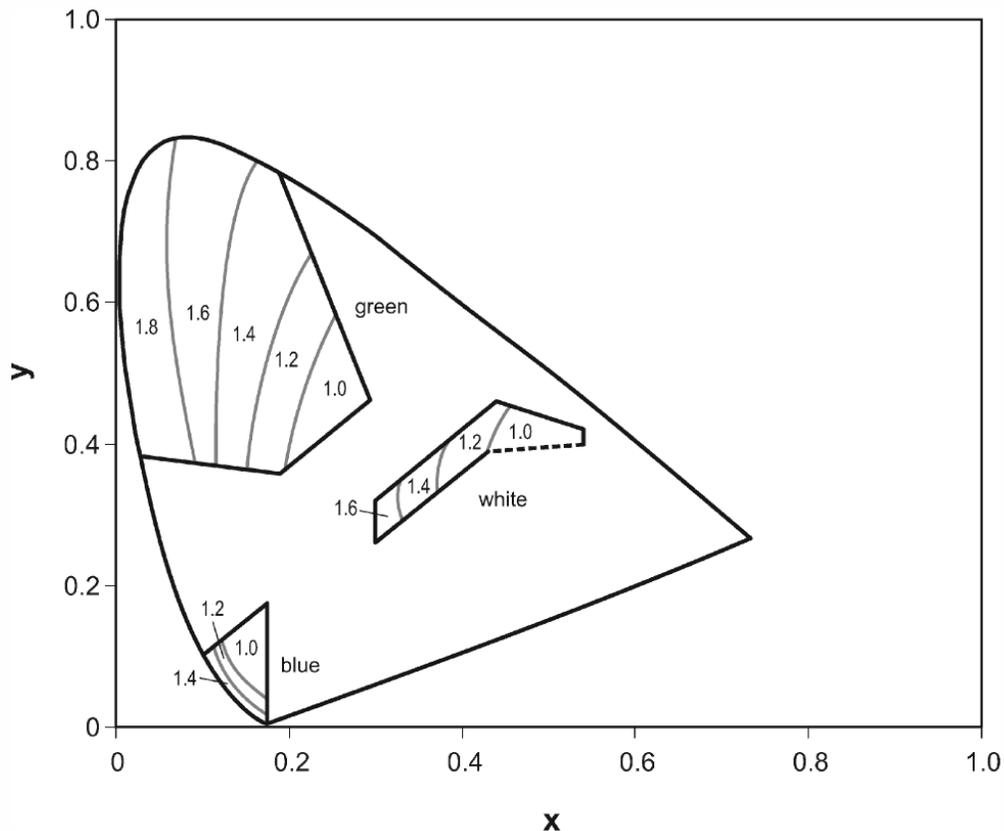


**Figure 1.** Illustration of the light energy threshold concept, plus a fixed nonvisual motor response time, used to predict reaction times to the onset of a signal light (Bullough 2005).

The onset time characteristics of LEDs, as illustrated in Table 1, are nearly instantaneous with rise times of 10-20 ns ( $1 \text{ ns} = 10^{-9} \text{ s}$ ). In comparison, tungsten filament sources can take up to 300 ms to achieve nearly-full light output because of the thermal mass of the incandescent filament as it is heated to produce light. Bullough (2005) reported the results of an experiment to measure reaction times to the onset of yellow and red signal lights with different rise times, ranging from about 20 to 200 ms. Interestingly, reaction times were predicted by a fixed light energy threshold (in  $\text{cd}\cdot\text{s}$ ) that depended upon the color, but not the onset time. Once the necessary light energy threshold (9  $\text{cd}\cdot\text{s}$  for yellow lights and 5  $\text{cd}\cdot\text{s}$  for red lights) was produced, a fixed nonvisual reaction time of 367 ms was added to the time needed to achieve the threshold light energy, to account for the physical motor movements involved in pressing a switch to indicate that the light was detected. For white light, the threshold light energy would be expected to be closer to that of yellow signal lights than for red, because of the lower saturation of white and yellow light compared to red light. Although the reaction times to signal lights with shorter onset times were systematically shorter, the probability of detecting the signal light within 1 s was not affected by the onset time.

## Brightness Perception

Fire alarm signal lights use white light to produce the necessary visual signal. If two lights have different correlated color temperatures (CCT), they can be judged to have different perceived brightness even if their luminous intensities (in cd) are identical. Ware and Cowan (1983), integrating the results from a large number of experiments, found that the perceived brightness of a saturated patch of light, or of a patch of light with a higher CCT, could be quantified in terms of the brightness/luminance (B/L) ratio relative to a standard white patch of light, such as from an incandescent source. A colored patch of light with a B/L value of 2.0 would need only 50% the luminance ( $1/2.0$ ) to be judged equally bright as the standard patch of light.



**Figure 2.** Measured B/L values for white, green and blue signal lights having different chromaticities (Bullough et al. 2007).

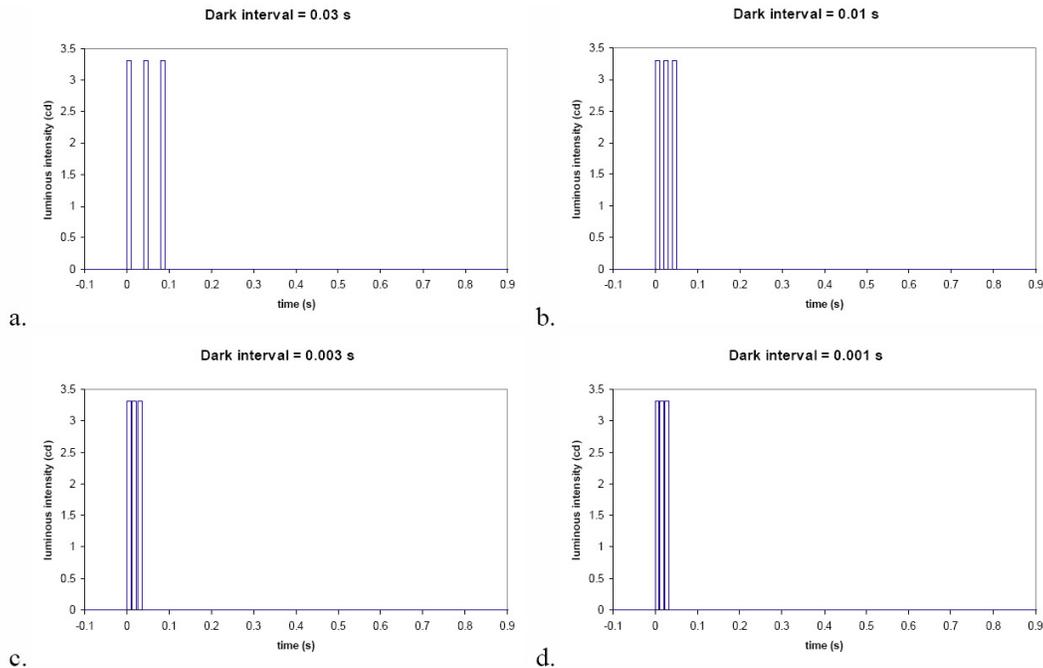
Because the B/L values from Ware and Cowan (1983) were based on patches of light, and not on points of light such as those seen when a signal light is viewed, Bullough et al. (2007b) compared the brightness/luminous intensity (B/L) values of point sources viewed under different conditions, including white signal lights varying in CCT. They found that a signal light with a higher CCT than incandescent (which is represented in Figure 2 by the white chromaticity region labeled 1.0) could have B/L values of 1.2 to 1.6, depending upon the CCT. To the extent that signal lights that appear brighter may be judged as more conspicuous, light sources with higher CCTs might increase conspicuity of white signal lights. For colored signal lights, perception of brightness seems to be related to the saturation of color. In Figure 2, blue and green signal lights

with the highest B/L values are those located closest to the spectrum locus, with the greatest saturation.

Another factor that may influence the brightness appearance of a flashing signal light is its effective intensity. Effective intensity of a flashing light is commonly defined as the luminous intensity of a steady-burning signal light that is judged as equivalent to the flashing light (IES 1964). Usually the judgment is assumed to correspond to threshold conditions when a signal light is just barely visible (Blondel and Rey 1912), but effective intensity is often applied to situations when a signal light is well above the visual threshold, primarily because there is presently no alternative to use. Fortunately, under many conditions, except for flashing lights with very complex waveforms, the effective intensity is at least useful in ranking various flashing lights correctly (Howett 1979). The most common formulation for effective intensity of a periodically flashing light comes from Blondel and Rey (1912) and is as follows:

$$I_e = \int_{t_1}^{t_2} I dt / (a + t_2 - t_1) \quad (\text{Eq. 1})$$

where  $I_e$  is the effective intensity (in cd),  $t_1$  and  $t_2$  (in s) are the time limits for the flash of light within a flash cycle,  $I$  is the instantaneous intensity of the signal light at any time between  $t_1$  and  $t_2$ , and  $a$  is a constant determined empirically by Blondel and Rey (1912) to have a value of about 0.2 s.



**Figure 3.** Example light waveforms of multiple-pulse flashes of light, with pulses separated by different durations.

If there are multiple flashes of light in a flash cycle, and they appear as separate and distinct flashes, the effective intensity of each flash-pulse is calculated using Eq. 1 and the sum of the values is the effective intensity of the overall signal light. Some light sources can produce very rapid pulses of light so close together (typically separated by less than 0.03 s) that the pulses

appear to be a single flash of light. In this case, the integration should be performed over the duration of the entire train of pulses (IES 1964). Pulse trains with shorter intervals between them (see Figure 3) will have higher calculated effective intensities because the duration of the entire flash ( $t_2 - t_1$ ) is shorter when the interval between the pulses is shorter.

### *Color Identification*

Visual signals for fire alarm systems are supposed to be white; therefore, the ability to correctly identify the color may not be as directly relevant to such systems as for the correct identification of signal lights for roadway traffic control or for aviation signaling along airport runways and taxiways. However, it has been demonstrated that for relatively low CCT white light sources, such as incandescent lamps using tungsten filaments, these nominally white light sources can sometimes be identified as yellow (Bierman et al. 2009; Skinner and Bullough 2011). In contrast, when the CCT is higher, such as above 4000 K, the likelihood of an incorrect identification is much lower.

Skinner and Bullough (2011) also reported color identification data for both color-normal and color-deficient observers to incandescent (filtered) and LED signal lights varying in color (red, yellow, green, red and blue), and found that for both color-normal and color-deficient observers, the increased saturation generally resulted in improved color identification.

### *Distance/Location Judgment*

Some signal lights are meant simply to provide notification or detection (such as visual signals for fire alarm systems), whereas others may also require individuals to identify where the signal light is. For example, being aware that a vehicle's brake lights have been activated is an important visual response while driving, but it is also necessary to know from which vehicle the signal was produced, so that appropriate steering or braking maneuvers can be made. Such judgments can be more difficult when smoke, fog or snow is present because these materials scatter light throughout the field of view, and can obscure the location of a source of light.

With respect to flashing lights, Bullough et al. (2001) measured drivers' ability to detect when a snow plow truck, being driven ahead of the driver's vehicle during snowy weather, was beginning to slow down. Two rear lighting configurations on the snow plow truck were used: one was a pair of flashing lights, and the other was a pair of steady-burning lights mounted along the sides of the rear of the truck. In both conditions, the truck was also equipped with a rotating beacon light on the roof of the cab. Subjects in this study were able to detect the snow plow's deceleration sooner with the steady-burning lights than with the flashing lights. This is consistent with previous studies of people's ability to catch a thrown object under steady versus strobing illumination (Croft 1971), and of driver's recognition of flashing warning lights along highway work zones (Bullough et al. 2011). Tracking a moving object is more difficult when the visual information provided is intermittent.

## Preliminary Guiding Principles

It is clear that LED light sources have strong promise for a number of visual signaling applications. Their short onset times, range of available CCTs, long rated lives, and increasing luminous efficacy make them attractive for visual signaling. Of course, visual signaling for fire alarm systems has different requirements than for other signaling applications such as those for transportation, but the research literature on LED signal lights for transportation can lead to several guiding principles for optimizing visual responses.

- Response times to signals with short onset times (such as LEDs) are shorter than to those with longer onset times. Driving circuitry for LED signal lights should avoid using electrical components that will result in long (>10-20 ms) onset times in order to minimize visual reaction times.
- If LEDs will be used to produce multiple-pulse flashes of light, minimizing the duration between pulses will result in higher effective intensity values more likely to be judged as more conspicuous.
- White light sources with higher CCTs will be judged as brighter, and generally more conspicuous, than those with lower CCTs. They are also more likely to be identified as white, rather than yellow.
- If a flashing signal light is to be both detected and localized in the field of view, maintaining a steady-burning component will help people identify the location and distance of the light from the viewing location, especially in smoke or other perturbed atmospheres.

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