Factors Influencing the Performance of Visual Distress Signals

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Abstract

The present paper summarizes efforts undertaken to review the performance characteristics of visual distress signals using light emitting diodes that might replace pyrotechnic-based flare distress signals in the future. Field photometric measurements were made on board a rescue vessel and near the shore at a coastal station to ascertain typical visual environments under which visual distress signals might be viewed, and to understand the visual tasks associated with searching for and detecting these signals. With this information in mind, the literature was systematically reviewed to identify the factors that are likely to influence the performance of visual distress signals, and to provide preliminary guidance regarding the design of visual distress signals constructed with lighting emitting diodes.

KEY WORDS: *Visibility, Color vision, Effective intensity, Visual search*

Introduction

Similar to aid-to-navigation lights (IALA 2011), visual distress signals need to be viewed in the maritime environment under a wide variety of conditions by search and rescue personnel aboard watercraft and aircraft such as helicopters. By their nature, the locations of visual distress signals are not known before they are detected. Thus it is likely that the initial visual task, *detection*, will occur when the signal is located in the visual periphery. However, simple detection of a possible distress signal is not sufficient for proper and reliable identification, because the location(s) under search might also contain aid-to-navigation lights, lights from other vessels and lights from nearby shore areas that could serve as distractors. Thus, another important component of the visual is *recognition* of the detected light as a visual distress signal. Most likely, recognition is performed using central (foveal) vision following a searcher's initial detection of the signal light (Rea et al., 2009).

Detection and recognition of a visual distress signal are perhaps the key visual tasks associated with these devices. Once a searcher has detected and recognized the signal, it is possible to estimate a vector along which the distressed individual(s) or vessel might be located. If the vessel that has detected the distress signal will subsequently assist in the rescue of the individual/vessel deploying the signal, a secondary visual task of maintaining visual fixation might be performed, since currents and weather could result in the rescue being in a different location from that where the distress signal was initially detected.

The necessary distances at which visual distress signals must be detected and recognized can vary considerably in the search-and-rescue environment. For the present paper, a maximum distance of about 8 km is assumed.

Environmental Factors

The range of conditions under which visual distress signals must be detected and recognized can also vary considerably. Primary searchers will be Coast Guard personnel aboard vessels such as the 47-ft motor life boat (MLB). In order to obtain information about the search process and one example of the environmental and operational conditions under which search operations are conducted, a field visit to Coast Guard Station Point Judith in Narragansett, RI was made on 13 November 2012. Measurements and observations were made aboard an MLB and at the grounds of the Point Judith Lighthouse.

Field Visit Procedure

In both locations, illuminance and luminance measurements were made. Illuminance measurements provided an indication of the ambient lighting conditions (from the sky and/or adjacent light sources) in each location. A Gigahertz-Optik X9 illuminance meter was used. Luminance measurements were performed to provide information about the potential of on-board lights (such as cockpit displays) to detract from visual searching, and to provide information about the level of visual adaptation needed to identify visual elements in the field of view. A Minolta LS-110 meter, with a measurement aperture of 0.33^{o}, was used for measuring luminance.

Illuminance is a measure of the luminous flux density of light from a light source of a given intensity falling on a surface, such as on a horizontal work station or on a vertical plane located at an observer's eyes, and is measured in lux (lx, SI unit) or in footcandles (fc, British unit). As illustrated in Figure 1, illuminance from a light source is proportional to its luminous intensity and the distance between the source and the surface to be illuminated. All illuminances in the present document are reported in lx (10.76 lx = 1 fc; this is often simplified to 10 lx ≈ 1 fc). Luminance is a measure of the density of luminous intensity in the specific direction of measurement, and is measured in units of candelas per square meter (cd/m^2), sometimes called nits. Luminance is somewhat analogous to the perception of brightness of a surface. For example, a typical horizontal desktop illuminance in an office is 500 lx. The luminance (and approximate brightness) of white paper on a gray desktop will be higher than the desktop even though both have an incident illuminance of 500 lx, because the paper reflects more of the incident light than the desktop. Figure 1 shows an approximate calculation method for luminance of an illuminated surface based on its reflectance (white paint typically has a reflectance of 0.8) and the incident illuminance.

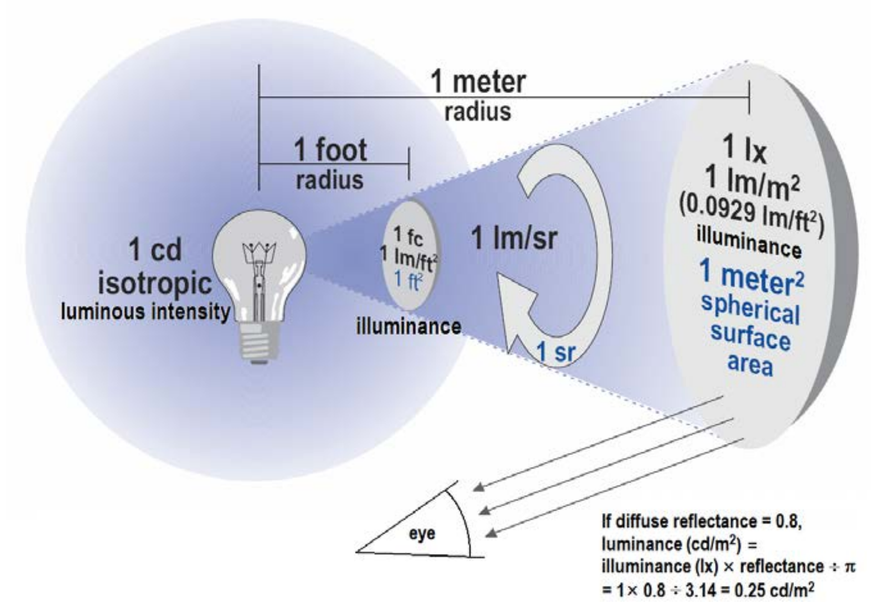

Figure 1: Relationships among luminous intensity, illuminance and luminance.

While conducting measurements on board the MLB, informal discussions with the Officer in Charge helped to describe operating, searching and scanning procedures during search and rescue operations.

On-Board Measurements

Measurements on-board the MLB were conducted while the boat was docked adjacent to a fishing boat dock, between 17:30 and 18:30, after the end of nautical twilight and during a new moon. Conditions were cloudy with periods of light rain, but little to no fog or haze was present. Lights from the fishing dock and boats were present during measurements, but were shielded or blocked by shadows to the extent possible. The brightness levels of cockpit instruments were adjusted by the Officer in Charge to the level that would normally be used during search and rescue operations. The officer explained that during search operations, the brightness level would be reduced to the lowest level possible while still maintaining legibility. Most other sources of illumination were switched off, as would be done during these operations. The motor lifeboat contains two bridges, an open, upper bridge used under most conditions, and an enclosed, lower bridge that would be used only when weather conditions made it impossible to work from the upper bridge. Measurements were made at both bridges.

Upper Bridge

Ambient light levels measured on the upper bridge (while shielding light from the adjacent fishing dock) ranged from 0.1 to 0.2 lx in the horizontal plane at work-plane height (approximately 1 m above the floor). With lights and displays switched off, the vertical illuminance was approximately 0.1 lx at eye height (approximately 1.5 m above floor level) when standing about 0.6 m behind and in front of the chart plotter (the plotter is shown near the center of Figure 2). This value includes the contribution of the ground-based lights ahead of the boat shown in the background of Figure 2. The 0.6 m distance was chosen because the upper bridge was relative open and this was the approximate viewing distance to the plotter when standing behind it.

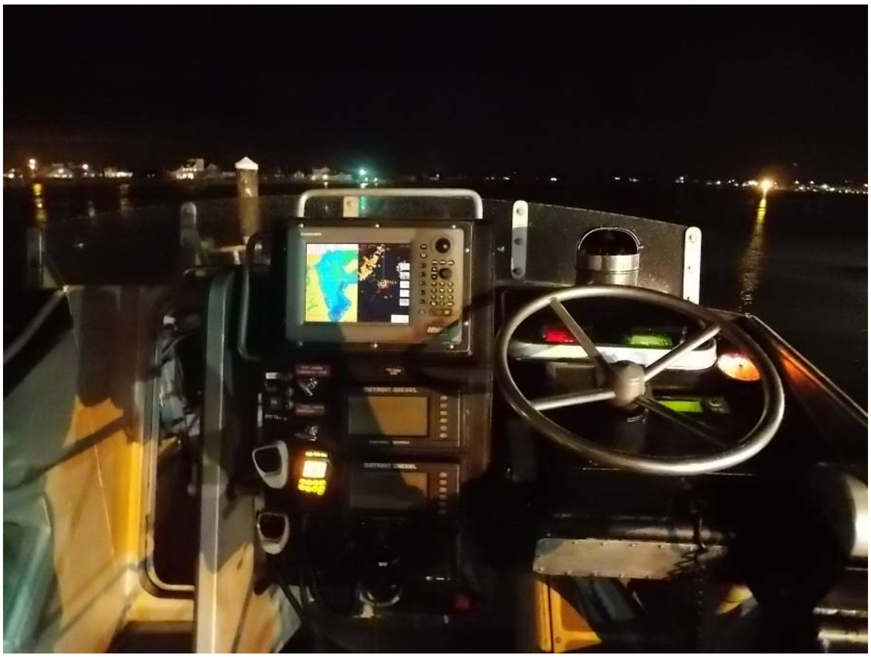

Figure 2: Forward view of upper bridge cockpit.

The maximum luminance of the plotter screen (displaying a white color) was 0.45 cd/m^2. The luminance of the plotter screen when displaying a black color was 0.02 cd/m^2. The luminance of the graphite-colored bevel around the plotter screen was between 0.03 and 0.05 cd/m^2. When the plotter screen was switched off, its luminance was 0.01 cd/m^2. The luminance of the small red display behind the steering wheel to the right of the plotter was 0.62 cd/m^2. The luminance of the small green display adjacent to the red one was 0.99 cd/m^2. Below the chart plotter was a small radio microphone with an illuminated yellow display. The luminance of this display was 7.45 cd/m^2.

Lower Bridge

Ambient light levels in the lower, enclosed bridge, measured while shielding light from the adjacent fishing dock ranged from 0.06 to 0.1 lx in the horizontal plane at work-plane height. With on-board lights and displays off, the vertical illuminance at eye height was 0.1 lx about 1 m directly behind the chart plotter (the plotter is near the center of Figure 3). The 1 m distance corresponds to the location of the seat position in the lower bridge.

The luminance of the white portion of the chart plotter screen was between 1.39 and 1.57 cd/m^2, and the darkest, black portion of the screen was 0.02 cd/m^2 when shielding light from the adjacent fishing dock. The luminance of the smaller, amber display screen to the lower right of the plotter was 2.12 cd/m^2. The luminance of the blue display screen to the right of the amber display was 0.57 cd/m^2, and the luminances of the green and red displays above the blue one were 7.65 cd/m^2 and 8.42 cd/m^2, respectively. The luminance of the blue-gray display to the lower left of the plotter was 0.74 cd/m^2, and the luminances of the gray display screens above the white display, to the left of the plotter, ranged from 0.15 to 0.20 cd/m^2.

Figure 3: Forward view of lower bridge cockpit.

Ground-Based Measurements

Between 18:30 and 20:00 on the same night, photometric measurements were made on the grounds of the lighthouse at Point Judith Station, which has a 180^o+ panoramic view of the Block Island Sound and Rhode Island Sound, including Narragansett, Block Island, Newport, Jamestown and the Newport Bridge (see Figure 4). Conditions were cloudy with periods of light rain, with little to no fog or haze evident. The lighthouse remained in operation; when the light was on, the ambient illuminance was between 0.1 and 0.15 lx in the horizontal plane at ground level. When the light was off the ambient horizontal illuminance was reduced to 0.01 lx. Although the ambient illumination changed considerably, there were no measurable differences in the luminances of dark areas of the sea, land or sky when the lighthouse was either on or off.

When measuring the dark area toward the southeast of the observation location, the sky had a luminance of 0.01 cd/m^2 and the water had a luminance between 0.01 and 0.03 cd/m^2. When placing the luminance meter measurement spot (0.33^o) over the steady-burning green and amber lights of a ship estimated to be about 10 km offshore from Point Judith, the maximum luminances ranged from 0.03 to 0.07 cd/m^2.

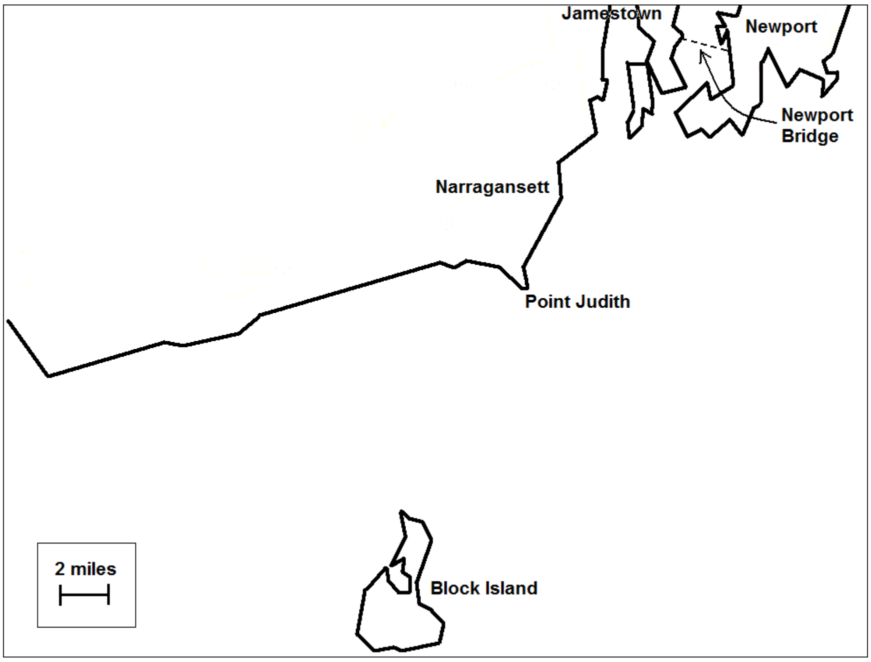

Figure 4: Map of ground-based measurement location and surrounding areas.

In and around Newport many of the lights had the characteristic yellowish color of high pressure sodium (HPS) lamps. Lights along the Newport Bridge were white, with red flashing obstruction lights (1 Hz) on the bridge pillar tops. There was also a flashing green light (0.5 Hz) visible near Newport. Above Newport, the luminance of the sky glow (similar in color to an HPS lamp) above the city was between 0.03 and 0.07 cd/m^2. The luminance of the sea in front of Newport ranged between 0.02 and 0.03 cd/m^2. Portions of the dark terrain in the vicinity of Newport had luminances of 0.01 to 0.02 cd/m^2. When measuring the luminance of (and adjacent to) the lights on the Newport Bridge, the maximum luminance was 0.10 cd/m^2. When measuring the luminance of (and adjacent to) the HPS lights in and around the Newport vicinity, the maximum luminance was 0.41 cd/m^2.

Around Narragansett (see Figure 5), many HPS sources were visible, as well as a visible sky glow with the same color as HPS. A steady-burning green light was also present near Narragansett. The luminance of the water in front of Narragansett was 0.04 cd/m^2. When measuring the luminance of (and adjacent to) the HPS lights in and around Narragansett, the maximum measured luminance was 9.8 cd/m^2.

Around Block Island, a few HPS sources were faintly visible, but no visible sky glow was present. There was also a steady-burning white light source, an amber flashing light (0.25 Hz) and a red flashing light (1 Hz) present around Block Island. A red flashing buoy with a frequency of 0.25 Hz was visible to the left of Block Island. When measuring the luminance of (and adjacent to) the steady-burning white light near Block Island, the maximum measured luminance was 0.15 cd/m^2.

Figure 5: View of lights around Narragansett (in the left portion of the photograph) as seen from the measurement location.

Field Visit Summary

The measurement data are summarized in Table 1. These data can be used to define some representative viewing conditions experienced by search and rescue personnel when conducting search operations.

Table 1: Summary of Field Visit Photometric Measurements

On-Board Measurements (Ambient Illuminance: 0.06 – 0.2 lx, horizontal at work plane)	
Location	**Luminance Range (cd/m^2)**
Chart plotter	0.02 (minimum, black) – 1.57 (maximum, white)
Chart plotter bevel	0.03 (minimum) – 0.05 (maximum)
Radio microphone display	7.45 (maximum)
Various displays	8.42 (maximum)
Ground-Based Measurements (Ambient Illuminance: 0.01-0.15 lx, horizontal at ground)	
Location	**Luminance Range (cd/m^2)**
Sky	0.01 (minimum) – 0.07 (above Newport with sky glow)

Sea	0.01 (minimum) – 0.04 (in front of Narragansett)
Terrain	0.01 – 0.02
Lights near Newport*	0.10 (bridge) – 0.41 (maximum, city/town lights)
Lights near Narragansett*	9.8 (maximum, city/town lights)
Lights near Block Island*	0.15 (maximum, steady-burning white light)
Lights on stationary ship*	0.03 – 0.07 (maximum, steady burning green/amber lights)

**Value within 0.33^o viewing angle.*

Range of Environmental Conditions

The photometric characteristics described above and summarized in Table 1 do not characterize the range of conditions under which distress signals can be viewed in the operational environment. During the on-board field measurements the MLB was docked adjacent to nearby fishing boats, and during both the on-board and ground-based measurements, the weather was largely clear and the sea was relatively calm. No moonlight was present, but in combination with swelling and crests of the sea, moonlight and other lighting might create highlights and reflections of visual "noise" superimposed upon the visual search area. In particular, the detrimental effects of outdoor shore-based lighting such as streetlights and parking lot lighting, advertising lights, and other outdoor systems for recreational use has been recognized as a severe and growing problem for visibility of navigational lights by the National Academy of Sciences (Benson et al., 1971) and by the International Association of Lighthouse Authorities (IALA, 2011).

For this reason, the literature review included in the present paper addresses visual conditions of greater complexity than those characterized during the site field visit.

The primary on-board source of light that is likely to create problems for personnel during search operations is the chart plotter. Bright objects in the field of view create scattered light within the eye's optical media that reduces the contrast of objects in the field of view. The amount of scattered light can be expressed as a location-dependent *veiling luminance* that is superimposed onto the scene being viewed (Fry, 1954). The veiling luminance (L_v, in cd/m²) from a glare source producing an illuminance E (in lx) at the eyes, and located θ degrees from the line of sight, is estimated by the equation:

$$L_v = 9.2E/[\theta + (\theta + 1.5)] \quad (1)$$

Consider, for example, a chart plotter containing an all-white display with a luminance of 1.57 cd/m², matching the highest chart plotter luminance measured during the site visit, having dimensions of 0.2 × 0.25 m, and located 1 m from an observer's eyes 15^o from the primary line of sight. The approximate illuminance at the observer's eyes from the plotter would be 0.08 lx and the veiling luminance would be less than 0.003 cd/m². This is less than 30% of the lowest-measured sky, sea or horizon luminance measured under visually clear, moonless conditions (0.01 cd/m²) and is considered by the Illuminating Engineering Society (IES, 2000) a value unlikely to contribute to substantially reduced nighttime visibility.

Signal Light Performance Characteristics

In the present section of this paper, the characteristics of light signals are discussed with emphasis on how these characteristics should be defined to ensure adequate visibility under an appropriate range of visual conditions. Literature from the vision sciences, transportation engineering, illuminating engineering and psychology was consulted.

Luminous Intensity

Perhaps the most important parameter related to the visibility of a distress signal is its luminous intensity. As illustrated in Figure 1, it is the luminous intensity, in conjunction with the distance, which determines the illumination from a signal light at an observer's eyes.

Much of the literature on the threshold intensities for light detection against background luminances varying in value are for stimuli having relatively large angular dimensions (Blackwell, 1946; Boff et al., 1986). Visual distress signals, being generally portable devices suitable for hand-held use, are likely to have point-source sizes when viewed from a km or more away. For white point-sources viewed against a white (achromatic) background, Hill (1947) reported that up to a background luminance of 0.1 cd/m², the threshold illuminance from the point source was nearly constant, and an illuminance of about 0.1 microlux (μlx) was needed for threshold (50%) detection; triple this value provided highly reliable (90%) detection. Above a background luminance of 0.1 cd/m², the threshold illuminance increased along a logarithmic function to nearly 400 μlx at a background luminance of 10,000 cd/m², the maximum likely to be experienced outdoors during the daytime. At this luminance, highly reliable detection required double the threshold illuminance, about 800 μlx.

For nighttime viewing conditions, Rea et al. (2009) investigated the necessary intensity of an array of four flashing lights viewed against mostly dark backgrounds (with some rival lights to simulate rural villages) to be reliably and confidently detected and identified. A scotopic luminous intensity of 20 cd for a simulated viewing distance of 8 km was determined as a value at which detection and confidence were both high. This corresponds to a scotopic illuminance at the eye of approximately 0.3 μlx, which (leaving a discussion of the difference between scotopic and photopic units to later in this paper) is largely consistent with the threshold for highly reliable detection measured by Hill (1947).

Even when a light source is highly reliably detected, increases in luminous intensity will result in shorter reaction times to the onset or presence of a light. Under most conditions, reaction times to stimuli decrease with increasing luminous intensity according to a power function with an exponent value near -0.33 (Vaughan et al., 1966; Pollack, 1968; Lit et al., 1971; Vicars and Lit, 1975; He et al., 1997).

Influence of Background Complexity

As described above, increased background luminances require increased threshold luminous intensities for a light signal to be detected. Much of the work on thresholds has been conducted using visually simple backgrounds (Hill, 1947), or backgrounds of fixed complexity (Rea et al., 2009). In addition to the data presented above on field measurements, Worthey (1988) conducted several sets of photometric measurements in the New York City harbor area, a highly built up location, and found typical lights (mostly judged to be streetlights using HPS or mercury vapor sources) to produce 10 μlx from distances ranging between about 1 and 15 km away.

A number of researchers have investigated the role of the background complexity itself on detection and identification of signals. For example, Haines (1968) found that detection of a point source of light increased from 0.5 to 0.8 s when it was displayed against a simulated star-field background, and to 1.7 s when a high-luminance (about 188,000 cd/m^2) glare source subtending 0.3^o was located 27^o off axis. Langmuir and Westendorp (1931) reported that the presence of 30 irrelevant steady-burning lights increased detection times of a flashing light by 30% when they were similar in intensity to the signal light, and by 100% when their intensity was 100 times higher than the signal.

An outdoor experiment was conducted in the 1960s by the Applied Psychology Corporation (APC, 1962) to evaluate the impact of city-light backgrounds on the detection of signal lights, using a location overlooking Tucson, AZ. Flashing signal lights were located such that from a subject's viewing location, they could be superimposed over dimly and brightly lighted sections of the city. Significant impacts of background complexity were found. Against little background lighting, detection times averaged about 2 to 5 s; against backgrounds with intermediate complexity, average detection times were between 7 and 9 s. Against the brightest backgrounds, detection times averaged more than 12 s.

Several attempts to quantify the relationship between signal light detection and the number of irrelevant lights have been made. Crawford (1962, 1963) found that with no irrelevant lights, detection times to steady and flashing lights averaged about 0.8 s, but with 21 irrelevant lights present, the times increased to 1.3-2.6 s. Different increases were found for different combinations of the signal and irrelevant lights being flashing and steady-burning. When the signal was flashing and the irrelevant lights were steady-burning, the shortest detection times were found. Flashing signal lights among flashing irrelevant lights had the longest detection times.

The IALA (2008) recommends that when minor background lighting is present, the luminous intensity of aid-to-navigation lights should be increased by a factor of 10, and when substantial background lighting is present, the luminous intensity should be increased by a factor of 100.

Spectral Distribution (Color)

When a light signal has a much higher luminance than the background against which it is seen, and when it has sufficient intensity for its color to be identified (Hill, 1947), the color plays relatively little role on the speed and accuracy of detecting the signal (Ueno et al., 1985). When the background luminance approaches the intensity of the signal light, such as when it is viewed against a bright daytime sky, the color will strongly influence the reaction times elicited by the signals (Ueno et al., 1985; Bullough et al., 2000).

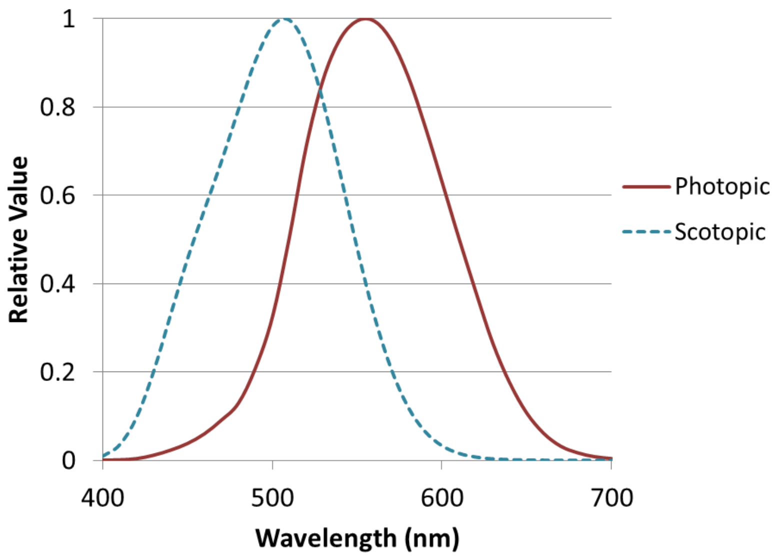

Figure 6: Photopic and scotopic luminous efficiency functions.

When the background illuminance is very low, and when the signal light intensity is low enough that its color cannot be readily ascertained, the spectral sensitivity of the visual system is best characterized by the *scotopic* luminous efficiency function, in contrast to the *photopic* luminous efficiency function used to define conventional photometric quantities (Figure 6). As the average background luminance decreases below about 1 cd/m^2, the spectral sensitivity of the human visual system shifts from a peak spectral sensitivity at 555 nm (yellow-green light), the combined sensitivity peak for the eye's cone photoreceptors, toward 507 nm (blue-green light), the peak sensitivity of rod photoreceptors (He et al., 1997; Rea et al., 2004). Under dark nighttime conditions background luminances can be as low as 0.01 cd/m^2 (see Table 1) and it is reasonable to assume that the spectral sensitivity for faint light signals would be characterized by the scotopic sensitivity curve in Figure 6. At intermediate luminances, the so-called *mesopic* spectral sensitivity is characterized by a weighted average of the photopic and scotopic functions (Rea et al., 2004).

Data from Rea et al. (2009) on the detection of dim flashing light signals varying in color (red, yellow, white, green and blue) illustrate this phenomenon (Figure 7). For the same low background luminance conditions, equal luminous intensities from each of these colors do not elicit equal response times. Higher luminous intensities are needed for red and yellow signal lights relative to green and blue ones, consistent with the relative sensitivity to light for these colors in Figure 6. However, once the luminous intensity were 50 cd or higher, the response times would be asymptotic and there would be little difference among the colors.

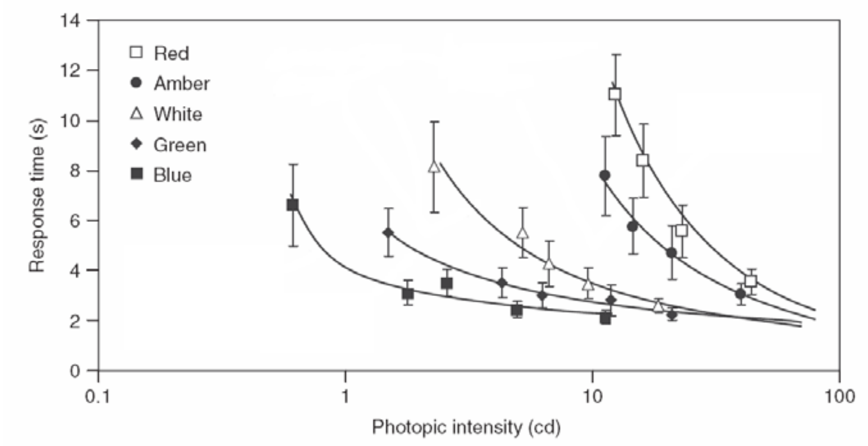

Figure 7: Response times to signal lights varying in color under dark background conditions (Rea et al., 2009).

Another interesting finding from Rea et al. (2009) is that the identification of the orientation of signal light arrays (and not merely their detection) appeared to be more related to the photopic intensity of the lights than their scotopic intensity, even when the background luminance was very low. This suggests that detection and identification might be served by two visual channels: one channel in the visual periphery with a spectral sensitivity similar to the scotopic luminous efficiency function, and one channel in the central (and rod-free) visual field where only cone receptors exist, with a sensitivity matching the photopic luminous efficiency function in Figure 6.

Visual sensitivity in the peripheral retina at all light levels under which cone photoreceptors respond (photopic and mesopic) also appears to have a substantial short-wavelength lobe (Weale, 1953; Wooten et al., 1975) suggesting that blue light signals might be effective for peripheral detection during daytime and nighttime.

Regarding the potential for light sources of different colors to be scattered by the atmosphere to different extents, Boelter and Ryder (1940) reported that in fog, the amount of backscattered light was nearly the same for a wide range of colored light beams from blue (short wavelengths) to red (long wavelengths). This finding is consistent with the conclusion from Middleton (1952) that no special theory of visual range for colored signal lights through even a clear atmosphere is needed, relative to white signal lights. Over long distances, however, the scattering properties of the clear atmosphere will tend to result in greater extinction of short wavelengths so that color appearance can shift slightly toward yellower or redder appearance (Middleton, 1952).

Temporal Characteristics

Flashing lights are often employed for warning and signaling applications over steady-burning lights because of observations that flashing increases the conspicuity or attention-getting properties of a light source. Published literature confirms such observations (Goldstein and Lamb, 1967). However, when viewed well above the visual threshold (suprathreshold conditions), detection of a signal light that is steady burning is improved over a flashing signal light (with a maximum intensity equal to that of the steady-burning signal), in a manner consistent with predictions of the calculated effective intensity (Gerathewohl, 1953). Near the visual threshold, faster-flashing signals are detected more readily than slower-flashing signals, for a flash frequency range between 0.33 and 3 Hz (Gerathewohl, 1957). De Lange (1958) reported peak temporal sensitivity for small stimuli at low light levels around 3 Hz. Low duty cycles (the percentage of time a flashing light is on) also appear to be more effective than higher ones (IALA 2008).

When flashing lights are employed to increase conspicuity, sources having more rapid onset times will provide modest benefits in terms of response times. Because of their shorter onset times, LED and neon signal light onsets are detected more quickly (Sivak et al., 1994; Bullough et al., 2001a) than incandescent signal light onsets, but are not necessarily detected any more reliably, at least within 1 s (Bullough, 2005). And although steady burning lights are often less conspicuous than flashing signal lights, steady-burning light sources can provide superior visual information regarding closure detection than flashing lights (Bullough et al., 2001b). For foveal and peripheral signals up to several degrees of arc in size, the integrated product of the luminance and the duration of a flash of light (i.e., the light-energy) can be traded off as illustrated in Figure 8 (Bullough, 2005). For example, a signal that is double the luminance but with a flash duration that is half of another will appear equivalent at threshold (Baumgardt, 1972).

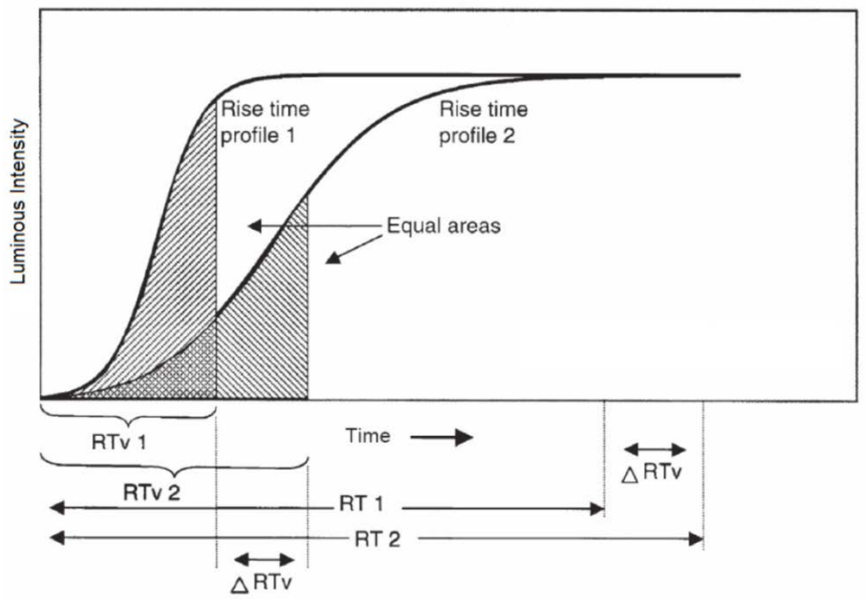

Figure 8: Two sources with different onset profiles will elicit response times based on the amount of time required to achieve a criterion level of light-energy (Bullough, 2005).

Effective Intensity

One method used extensively across transportation modes to quantify the visual effectiveness of flashing signal lights has been through the luminous intensity of a steady-burning signal light with equal effectiveness, a concept known as effective intensity. One of the most commonly used formulations for effective intensity is the Blondel-Rey formulation based on studies conducted by Blondel and Rey (1912). According to this formulation, the effective intensity (I_e, in cd) of a flashing signal light at near-threshold viewing conditions is defined as follows:

$$I_e = \int_{t1}^{t2} I \, dt/(a + t_2 - t_1) \qquad (2)$$

where I is the instantaneous luminous intensity (in cd) at any moment between times t_1 and t_2 (both represented in s); and a is a constant (in units of s) determined experimentally by Blondel and Rey (1912) to have a value near 0.2.

Various studies on the perception of flashing lights have confirmed that the Blondel-Rey (1912) formulation is reasonably predictive of the effectiveness of flashing light signals (such as visual range or relative brightness) under a wide range of conditions (Neeland et al., 1938; Projector, 1957; Williams and Allen, 1971; Howett, 1979; IALA, 2008; Vandewoorde, 2009; Bullough et al., 2013; Bullough and Skinner, 2013). This is significant because different light source technologies can produce a wide range of temporal waveforms of light output as a function of time (Lomer, 1970).

Values for the constant a in the Blondel-Rey equation have been found to be different depending upon factors such as the overall intensity of the light, for either near- or supra-threshold (Toulmin-

Smith and Green, 1933; Hampton, 1934; Neeland et al., 1938; Rinalducci and Higgins, 1971; Schmidt-Clausen, 1971; Chander et al., 1991), the color of light (Schmidt-Clausen, 1971; Ikeda and Nakayama, 2006) and spatial configurations of the light (Schmidt-Clausen, 1971; Saunders, 1971; Wagner and Laxar, 1996; Bullough et al., 2015). Bullough et al. (2013) found different values of *a* for different response types (apparent brightness, conspicuity or overall visibility). Reviewing a number of findings from the literature, Projector (1957) suggested the published data contained sufficient imprecision that the value of *a* should be kept at 0.2 in order to facilitate comparisons between different flashing lights.

Thus, despite alternative formulations for effective intensity (Ohno and Couzin, 2003), the formulation proposed by Blondel and Rey (1912) remains largely accepted for use in a wide variety of contexts (IALA 2008) although it may not be suitable for predicting the relative effectiveness of very complex temporal waveforms, such as a rapidly alternating high-low sequence superimposed onto a sinusoidal temporal waveform of lower frequency (Ohno and Couzin, 2003).

Spatial Characteristics

Size

The spatial characteristics of aid-to-navigation lights have been investigated by the Coast Guard (Wagner and Laxar, 1996). However, given the requirements of visual distress signals to be relatively portable for possible handheld use during emergencies, and the large distances (i.e., 8 km) at which they must be detected and identified, it is not likely that visual distress signals can have a spatial extent large enough to render them as anything but point sources in the search and rescue operational environment.

Distribution

Visual distress signals are often expected to be seen by search personnel on waterborne rescue craft such as the MLB described previously in the present paper, or by mariners on nearby commercial or private vessels assisting in search operations. Thus, the primary distribution of light from visual distress signals will be in the horizontal direction. Search operations can also be conducted by aircraft, however, so it is also important for visual distress signals to produce light output at angles above horizontal.

According to the Addendum to the National Search and Rescue Supplement of the International Aeronautical and Maritime Search and Rescue Manual (Coast Guard, 2009), the recommended altitude when searching for distress signals is 1500-2000 ft (450-600 m). At a distance of about 10 km, an altitude of 0.6 km corresponds to an angle about 4^o above horizontal. As the aircraft approaches the signal the angle will increase if the search aircraft does not adjust its altitude. From about 4 km away, the same altitude corresponds to about 9^o above horizontal. Thus, an intensity distribution in the cone from 0^o (horizontal) to 10^o above horizontal might be a reasonable specification for the intensity distribution of a visual distress signal. This is similar to the distributions of aviation signal lighting (Loch, 1961; Schwartz, 1971; Bullough, 2011).

The lateral distribution of a visual distress signal should be as broad as possible because it is not clear to the user where search personnel will be located. However, because a visual distress signal might be a source of glare for the individual using it, it is recommended that the distribution contain a “notch” of reduced intensity in the direction of the user, perhaps as wide as 90^o in angle.

Observer Characteristics

Age

Most studies of visual performance and detection and identification of light signals have not specifically studied subject pools varying substantially in age. Because of changes in the thickness and yellowing of the crystalline lens in the human eye with age (Weale, 1961), and reductions in both the light- and dark-adapted pupil size, retinal illumination changes almost linearly between the ages of 20 and 60-70 years (Wright and Rea, 1984). By the time the age of 50 years is reached, the retinal illuminance is only half that of a 20-year-old. At the age of 60 years it is about one-third. Although generally not noticeable by individuals because of the gradual nature of this change, it does affect the necessary illuminance at the eyes for signal light detection relative to a younger observer.

Color Deficient Vision

About 8% of the male population and a very small percentage of the female population have some form of color vision deficiency, usually of the protan or deutan types (Rea, 2000). Protans have a missing or shifted long-wavelength cone pigment, with the result of being generally less sensitive to long wavelengths in the red portion of the visible spectrum. Deutans have a missing or shifted medium-wavelength cone pigment but do not exhibit reduced sensitivity to any particular wavelength region. Both groups may exhibit confusion of colors along the axis from green to yellow to red in the chromaticity diagram. To help protans and deutans with color identification of signal light systems that include red, yellow and green, some specifications require green signal lights to have a dominant wavelength between 500 and 510 nm rather than 520 to 530 nm, which provides some separation from the red-yellow-green axis and assists with discrimination (CIE, 2001).

To assist protans with the detection of red signal lights, it is suggested that dominant wavelengths for red signals be no longer than 615 nm, rather than 630 nm or longer. Such a restriction has been found (Huang et al., 2003) to permit reliable detection by protan individuals, while still ensuring that a signal will be identified as red by both protan and color-normal observers.

Discussion

The information summarized in this paper provides some guidance as to the characteristics of visual distress signals that can be reliably detected by rescue personnel during search operations:

- *Intensity:* A minimum scotopic intensity of 20 cd appears to be necessary for detection of a flashing light signal array (Rea et al., 2009) from 8 km away. Since a visual distress signal is a single source of light rather than an array, a higher intensity may be necessary to ensure reliable detection, but 20 cd is a reasonable lower value for a range of test conditions. Higher intensities might be necessary for reliable detection in visually complex environments with many irrelevant lights present.
- *Spectrum/Color:* A short-wavelength color may be most effective for peripheral visual detection (Weale, 1953) and detection under scotopic and mesopic conditions.
- *Temporal:* Flashing lights, or a profile with modulating intensity, will generally have increased conspicuity over steady-burning lights, and most background city and short lights are steady-burning. Frequencies of 3 Hz appear to be more effective than low frequencies such as 0.33 Hz (Gerathewohl, 1953). This also seems to be consistent with flicker sensitivity data from De Lange (1958). Duty cycles below 50% also appear to be more effective than higher duty cycles (IALA, 2011).
- *Spatial:* Visual distress signals should be compact in size for convenience, and their maximum intensity distribution focused between 0^o (horizontal) and 10^o above horizontal to ensure detection by water vessels and aircraft between 4 and 10 km away, based on Coast Guard (2009) search and rescue practices.

One potentially promising approach for visual distress signals could be to use alternating color and intensity simultaneously to provide a distinct spectral and temporal pattern. IALA (2011) suggests such an approach as a possible means to increase conspicuity. An alternating combination of short-wavelength (blue or green) and long-wavelength (yellow, orange or red) stimuli would provide both photopic and scotopic sensitivity.

A factor not heretofore discussed in this paper is the necessary electrical power supply for a visual distress signal using LEDs. Obviously, the performance of a visual distress signal would be constrained by the necessary power available to produce the signal light pattern. For example, a typical D cell battery will produce at least 10 W·hours of energy (Energizer, 2012). Assuming an LED light source system efficacy of 50 lm/W (including optical losses), a single D battery might be able to produce 500 lm·hours, say 250 lm for a duration of 2 hours. If the signal light had equal intensity in all directions around the source, the luminous intensity would be 20 cd in all directions for those 2 hours. The zone between 0^o (horizontal) and 10^o above horizontal covers about 8.7% of the inside surface area of a sphere, so concentrating the 250 lm (for 4 hours) in the present example to this 10^o band would permit the intensity to be approximately 230 cd. This equates to an illuminance of at least 3 μlx at an observer's eyes from 8 km away, which should be sufficient for a broad range of nighttime viewing conditions, based on the data reviewed in this paper.

The data summarized in this paper can assist the designers of visual distress signals using LED sources to ensure that they can be reliably detected by search personnel when necessary. Of course these data are also applicable to other signal lights for aviation, navigation and other modes of transportation that need to be seen and identified over long (several km or greater) distances.

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References

Applied Psychology Corporation. (1962). *Conspicuity of Selected Signal Lights Against City-Light Backgrounds.* Washington: Federal Aviation Agency.

Baumgardt, E. (1972). Threshold quantal problems. In *Handbook of sensory physiology*, Vol. VII/4. New York: Springer-Verlag.

Benson, W., Brown, J. L., Douglas, C. A., Riney, J., Taylor, J. H., & Duntley, S. Q. (1971). *The effects of background lighting on the usefulness of navigation lights*. Washington: National Academy of Sciences Committee on Vision.

Blackwell, H. R. (1946). Contrast thresholds of the human eye. *Journal of the Optical Society of America, 36,* 624-632.

Blondel, A., & Rey, J. (1912). The perception of lights of short duration at their range limits. *Transactions of the Illuminating Engineering Society, 7,* 625–662.

Boelter, L. M. K., & Ryder, F. A. (1940). Notes on the behavior of a beam of light in fog. *Illuminating Engineering, 35,* 223-235.

Boff, K. R., Kaufman, L., & Thomas, J. P. (1986). *Handbook of perception and human performance*. New York: Wiley-Interscience.

Bullough, J. D., Boyce, P. R., Bierman, A., Conway, K. M., Huang, K., O'Rourke, C. P., Hunter, C. M., & Nakata, A. (2000). Response to simulated traffic signals using light-emitting diode and incandescent sources. *Transportation Research Record*, *1724,* 39-46.

Bullough, J. D., & Skinner, N. P. (2013). Conspicuity of flashes of light: Interactions between intensity and duration. *Journal of Modern Optics, 60,* 1193-1199.

Bullough, J. D., Skinner, N. P., & Taranta, R. T. (2013). Characterising the effective intensity of multiple-pulse flashing signal lights. *Lighting Research and Technology, 45,* 377-390.

Bullough, J. D., Van Derlofske, J., & Yan, H. (2001a). Evaluation of automotive stop lamps using incandescent and sweeping neon and LED sources. Presented at the Society of Automotive Engineers World Congress, Detroit.

Bullough, J. D., Rea, M. S., Pysar, R. M., Nakhla, H. K., & Amsler, D. E. (2001b). Rear lighting configurations for winter maintenance vehicles. Presented at the Illuminating Engineering Society of North America Annual Conference, Ottawa.

Bullough, J. D. (2005). Onset times and the detection of colored signal lights. *Transportation Research Record, 1918,* 123-127.

Chander, M., Chandra, K., & Joshi, K. C. (1991). Effective intensity behaviour of flashing lights at reduced level. *Lighting Research and Technology, 23,* 111-112.

Commission Internationale de l'Eclairage. (2001). *Colours of signal lights,* S 004/E-2001. Vienna: Commission Internationale de l'Eclairage.

Crawford, A. (1962). The perception of light signals: The effect of the number of irrelevant lights. *Ergonomics, 5,* 417-428.

Crawford, A. (1963). The perception of light signals: The effect of mixing flashing and steady irrelevant lights. *Ergonomics, 6*, 287-294.

De Lange, H. (1958). Research into the dynamic nature of the human fovea-cortex systems with intermittent and modulated light, I. Attenuation characteristics with white and colored light. *Journal of the Optical Society of America, 48,* 777-783.

Energizer. (2012). *Product datasheet: Energizer E95*. St. Louis: Energizer.

Fry, G. A. (1954). A re-evaluation of the scattering theory of glare. *Illuminating Engineering, 49,* 98-102.

Gerathewohl, S. J. (1953). Conspicuity of steady and flashing light signals: Variation of contrast. *Journal of the Optical Society of America, 43,* 567-571.

Gerathewohl, S. J. (1957). Conspicuity of flashing light signals: Effects of variation among frequency, duration, and contrast of the signals. *Journal of the Optical Society of America, 47,* 27-29.

Goldstein, D. A. & Lamb, J. C. (1967). Visual coding using flashing lights. *Human Factors, 9*, 405-408.

Haines, R. F. (1968). Detection time to a point source of light appearing on a star field background with and without a glare source present. *Human Factors, 10,* 523-530.

Hampton, W. M. (1934). The fixed light equivalent of flashing lights. *Illuminating Engineer, 27,* 46-47.

He, Y., Rea, M. S., Bierman, A., & Bullough, J. D. (1997). Evaluating light source efficacy under mesopic conditions using reaction times. *Journal of the Illuminating Engineering Society, 26,* 125-138.

Hill, N. E. G. (1947). The measurement of the chromatic and achromatic thresholds of coloured point sources against a white background. *Proceedings of the Physical Society, 59,* 574-585.

Howett, G. L. (1979). *Some psychophysical tests of the conspicuities of emergency vehicle warning lights*, NBS SP 480-36. Washington: National Bureau of Standards.

Huang, M. K., Bullough, J. D., Boyce, P. R., & Bierman, A. (2003). Detection and identification of light-emitting diode traffic signals by protan observers. *Transportation Research Record, 1844,* 52-58.

Ikeda, K., & Nakayama, M. (2006). Effective intensity of coloured monochromatic flashing light. *Journal of Light and Visual Environment, 30,* 156-169.

Illuminating Engineering Society. (2000). *American national standard practice for roadway lighting*, RP-8. New York: Illuminating Engineering Society.

International Association of Lighthouse Authorities. (2011). *Conspicuity of AtoN lights at night*, IALA Guideline No. 1073, Edition 1. St. Germain en Laye: International Association of Lighthouse Authorities.

International Association of Lighthouse Authorities. (2008). *Marine signal lights, part 4: Determination and calculation of effective intensity*, IALA Recommendation E-200-4. St. Germain-en-Laye: International Association of Lighthouse Authorities.

Langmuir, I., & Westendorp, W. F. (1931). A study of light signals in aviation and navigation. *Physics, 1,* 273-317.

Lit, A., Young, R., & Shaffer, M. (1971). Simple reaction time as a function of luminance for various wavelengths. *Perception and Psychophysics, 10,* 397-399.

Loch, C. H. (1961). Design and performance of an inset runway light. *Illuminating Engineering, 56,* 241-246.

Middleton, W. E. K. (1952). *Vision through the atmosphere.* Toronto: University of Toronto Press.

Neeland, G. K., Laufer, M. K., & Schaub, W. R. (1938). Measurement of the equivalent luminous intensity of rotating beacons. *Journal of the Optical Society of America, 28,* 280-285.

Ohno, Y., & Couzin, D. (2003). Modified Allard method for effective intensity of flashing lights. Paper presented at the Symposium on Temporal and Spatial Aspects of Light and Colour Perception and Measurement, Veszprem.

Pollack, J. D. (1968). Reaction time to different wavelengths at various luminances. *Perception and Psychophysics, 3*, 17-24.

Projector, T. H. (1957). Effective intensity of flashing lights. *Illuminating Engineering, 52,* 630-640.

Rea, M. S. (editor). (2000). *IESNA lighting handbook: Reference and application*, 9th edition. New York: Illuminating Engineering Society.

Rea, M. S., Bullough, J. D., Freyssinier-Nova, J. P., & Bierman, A. (2004). A proposed unified system of photometry. *Lighting Research and Technology, 36,* 85-111.

Rea, M. S., Yuan, Z., & Bierman, A. (2009). The unified system of photometry applied to remote airfield lighting. *Lighting Research and Technology, 41,* 51-70.

Rinalducci, E. J., & Higgins, K. E. (1971). An investigation of the effective intensity of flashing lights at threshold and suprathreshold levels. In *The perception and application of flashing lights.* Toronto: University of Toronto Press.

Saunders, R. M. (1971). Subjective brightness of a flashing light stimulus within the fovea as a function of stimulus size. In *The perception and application of flashing lights.* Toronto: University of Toronto Press.

Schmidt-Clausen, H. J. (1971). The influence of the angular size, adaptation luminance, pulse shape, and light colour on the Blondel-Rey constant a. In *The perception and application of flashing lights.* Toronto: University of Toronto Press.

Schwartz, A. H. (1971). Low profile optical system for an aircraft beacon. *Applied Optics, 10,* 358-362.

Sivak, M., Flannagan, M. J., Sato, T., Traube, E. C., & Aoki, M. (1994). Reaction times to neon, LED, and fast incandescent brake lamps. *Ergonomics, 37,* 989-994.

Toulmin-Smith, A. K., & Green, H. N. (1933). The fixed light equivalent of flashing lights. *Illuminating Engineer, 26,* 304-306.

U.S. Coast Guard. (2009). *U.S. Coast Guard addendum to the United States national SAR supplement.* Washington: U.S. Coast Guard.

Ueno, T., Pokorny, J., & Smith, V. C. (1985). Reaction times to chromatic stimuli. *Vision Research, 25,* 1623-1627.

Vandevoorde, J. C. (2009). *An updated method for calculation of flashing signals able to resolve existing issues in airport lighting,* VAWG/6-DP/13. Montreal: Visual Aids Working Group.

Vaughan, P. G., Costa, L. D., & Gilden, L. (1966). The functional relation of visual evoked response and reaction time to stimulus intensity. *Vision Research, 6,* 645-656.

Vicars, W. M., & Lit, A. (1975). Reaction time to incremental and decremental target luminance changes at various photopic background levels. *Vision Research, 15,* 261-265.

Wagner, S. L., & Laxar, K. V. (1996). *Conspicuity of aids to navigation: Spatial configurations for flashing lights,* NSMRL Report 1202. Groton: Naval Submarine Medical Research Laboratory.

Weale, R. (1953). Spectral sensitivity and wave-length discrimination of the peripheral retina. *Journal of Physiology, 119,* 170-190.

Weale, R. A. (1961). Retinal illumination and age. *Transactions of the Illuminating Engineering Society, 26,* 95-100.

Williams, D. H, & Allen, T. M. (1971). Absolute threshold as a function of pulse length and null period. In *The perception and application of flashing lights*. Toronto: University of Toronto Press.

Wooten, B., Fuld, K., & Spillmann, L. (1975). Photopic spectral sensitivity of the peripheral retina. *Journal of the Optical Society of America, 65,* 334-342.

Worthey, J. A. (1988). *Lights of New York harbor*. Washington: U.S. Department of Commerce.

Wright, G. A., & Rea, M. S. (1984). Age, a human factor in lighting. Presented at the International Conference on Occupational Ergonomics, Toronto.