Aviation Signal Lighting: Impacts of Lighting Characteristics on Visibility

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ABSTRACT

This paper summarizes research on visual responses to colored light signals in the aviation and roadway environment and on government requirements for lighting along airfields. The objective is to identify gaps in the knowledge about how individuals process visual information in order to inform subsequent studies of requirements for visual signaling or airfield lighting, particularly when existing standards are unlikely to be met and when visual conditions are likely to be difficult.

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INTRODUCTION

Aviation signal lights are a crucial element to the safety of pilots and their passengers and cargo. As lighting technologies for signal lights evolve through the increased use of light-emitting diodes (LEDs) over less efficient and shorter-lived incandescent lamps, their color, electrical and life characteristics are changing. Limitations of earlier technologies might no longer apply to aviation signal lighting. For this reason, it seems fruitful to review information about human responses to signal lighting characteristics in order to assess whether future requirements for these systems should be changed. The present paper briefly describes previously published research on responses of pilots, drivers and others to colored signal lights with the objective of identifying gaps in knowledge and possibly, to identify potential areas where new standards might be helpful.

Parameters of light signals and observers affecting visibility
This section briefly discusses previous research on the detection and visibility of colored light signals in a variety of transportation related applications. Research issues are grouped into intensity-, spectral-, distribution-, time-, weather-, and user-related factors.

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Intensity

As might be expected, the greater the luminous intensity of a signal light, the easier it is detected in the field of view. This increase in visual detection, however, should be tempered by the need to avoid discomfort glare under nighttime viewing conditions.

As luminous intensity increases, reaction time to a signal light decreases according to a power function with an exponent having a value often close to -0.33 [1-5]. Also as luminous intensity increases, detection probability increases in a curvilinear manner [6].

Discomfort glare from a signal light of white color [7] increases as a function of illuminance at the eye, decreases as a function of background luminance, and decreases as a function of angular location of the signal light from the line of sight. A ratio between the threshold intensity of a light and the level at which it produces glare is stated to be approximately 1:4000; Pearson [8] recommends that any signal light should not have an intensity more than 1000 times its threshold.

A luminous intensity of 10 cd near the horizontal plane, and of 4 cd throughout the upper hemisphere of a obstruction light for aviation applications is stated to be more than sufficient [9] for this application. It is stated that an intensity of 350 cd is required for a signal light to be visible from 0.125 miles away in conditions corresponding to a runway visual range of 0.125 miles [10].

Spectrum

While there is no advantage to any color that is attributable to the ability of light of any particular color to penetrate fog, rain or snow, when the signal luminance is close (or lower) to the background luminance, signal colors with greater saturation (e.g., blue and red) will be detected more rapidly than those with less saturation (e.g., white and yellow). Under most nighttime viewing conditions, the signal luminance can be assumed to be well above the background luminance, and in such cases, the signal color is a relatively unimportant factor. With regard to discomfort glare, light sources containing substantial short-wavelength light produce more discomfort than those of equal intensity but less short-wavelength content.

When the signal luminance is much higher than the background luminance, signal color does not affect reaction times but as the signal luminance approaches and is lower than the background luminance, increases in reaction time are exhibited for wavelengths near the middle of the visible spectrum [6, 11, 12].

More saturated red signal colors will tend to result in shorter reaction times than less saturated red signal colors for color normal observers [13]. There is little effect of wavelength on scatter by fog particles in the atmosphere [14]. Shallenberger and Little [15] stated that there is little difference in the visibility distance of white objects than for colored objects, especially in smoke and haze conditions. The nearly monochromatic color of low pressure sodium lamps is stated to be more resistant to color filtering by the atmosphere than broadband sources [16].

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Discomfort glare from signal lights is dependent upon the color with green resulting in more discomfort than red and yellow [17]. Shorter-wavelength content is generally associated with increased discomfort [18-20].

Spatial Distribution

For very small signal lights (for practical purposes, any signal seen from a distance of a mile or more can be considered to be very small), there can be assumed to be a direct tradeoff between size and luminance such that luminous intensity is the appropriate photometric characteristic when considering airfield approach lighting systems. Because of the loss of size information when viewing small signal lights, an array of lights is required to provide closure information to approaching observers.

For foveal signals up to about 7 minutes of arc in size, and for peripheral signals (from 8° to 20° off axis) up to about 1° of arc in size, luminance and size of a signal light can be traded off (Riccò's Law) such that a signal twice the luminance but half the area of another will appear equivalent at threshold [21]. For peripheral signals (from about 10° to 24° off axis) between about 1° and 8° in visual size, luminance and the square root of the size of a signal light can be traded off (Piper's Law) such that a signal twice the luminance but one-fourth the area of another will appear equivalent at threshold [21].

An assumption that a very small light source has a relatively larger image in the field of view because of optical limitations in the visual system was used by Horman [22] to develop a model for reliable detection of signal lights in the field of view as a function of its intensity and the background luminance.

An additional small array of lights at the entrance to the runway can help a pilot align the airplane to the entrance [8]. For signal lights to be viewed as a particular shape (triangle, arrow, symbol), a maximum-to-minimum luminance ratio of 5:1 is recommended [23]. To detect rate of closure, an array of multiple point sources is more effective than a single point source [24].

An aircraft beacon optical design was presented with a maximum luminous intensity in the range very close to the horizontal, perhaps about 1° above horizontal, representing an important viewing angle for aviation approach applications [25]. A cutoff of 15° above horizontal was given as the limit that can be perceived by a pilot because of the design of aircraft cabins [10].

A wider spread of light from ground-based signal lights might be necessary for remote airfields than for airports with facilities for radio communication and other aids to flight [16]. Signal lights in the runway touchdown surface itself are desired by some pilots to avoid the "black hole" effect whereby the surface upon which an airplane would land is dark, relative to other parts of the visual field [10]. Floodlighting the runway surface itself is desired by some pilots as another means to avoid the "black hole" effect [26].

Temporal Factors

When flashing lights are employed (e.g., to increase conspicuity), sources with rapid onset times provide modest reaction time benefits. Steady-burning sources provide superior guidance regarding closure detection than flashing lights.

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For foveal and peripheral signals up to several degrees of arc in size, luminance and duration can be traded off (Bloch's Law) such that a signal twice the luminance but presented for half the duration of another will appear equivalent at threshold [21]. Well above visual threshold, the 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 effective intensity [27]. When the intensity of a signal light is reduced such that it approaches the visual threshold, the relationship between steady-burning and flashing signals is reversed in opposition to effective intensity [27].

Close to visual threshold, fast-flashing signals are detected more readily than slow-flashing signals (for the range from 3 flashes/s to 0.33 flashes/s) [28]. Because of their shorter onset times, LED and neon signal lights are detected more quickly [29, 30] than incandescent signal lights, but they are not detected more reliably within 1 second [31, 32]. Signal onsets consisting of "sweeping" whereby the signal area gradually increases will increase conspicuity because of dynamic presentation [23, 33] but decrease detection performance characterized by reaction times and missed signals [13, 30].

For a deep red, low-contrast signal subtending 6.5^{o} the temporal frequency most readily detected was around 10 Hz [34]. Steady-burning signal lights will result in improved closure detection performance relative to flashing and strobing lights [35, 36].

Different flash rates of signal lights between 60 and 100 flashes/min. are reported not to impact visual detection. In any case, strobe lights provided poor closure and vehicle speed information compared to slower-flashing incandescent lights [37]. Subjective brightness of a short flash can be higher (briefly) than for a longer flash because the visual system lags in processing time relative to the flash duration [38]. Rinalducci and Higgins [39] conclude that increasing the duration of the flash for signal lights longer than 0.2 s will not appreciably improve its conspicuity.

Weather and Ambient Condition Factors
The ambient conditions (clear weather, haze, fog) as well as the ambient light level conditions (day versus night) certainly affect the visibility of light signals. Intensity requirements are higher when ambient conditions result in higher background luminances or in reduced atmospheric transmission.

Using a nomogram based on Allard's law [40, 41] the visibility range of a signal light (in miles) can be determined from the signal luminous intensity (in cd) and the atmospheric condition, such as clear, haze or fog. (Presumably, this nomogram pertains to white light signals only.) Under fog and snow conditions, visibility of signals is restricted to a limited range, for practical purposes [8].

In fog and haze conditions, the increase of signal luminous intensity under difficult viewing conditions is proposed [42] as a means to increase visibility that would otherwise be decreased. A dimming range down to 0.3%-0.1% is recommended to allow a light to remain comfortably visible under differing ambient conditions [8]. As visual noise (the presence of additional stimuli in the field of view) increases, the distance at which a stimulus can be seen is reduced [43].

User Factors
A significant proportion of the population (0.1% of females, 8% of males) have some form of color deficiency that affects not only color perception but brightness perception of lights of certain colors. Since pilot licensing requirements prohibit persons with color deficiencies from flying, these issues may be less important in an aviation context. On the other hand, age of an observer plays an important role in visual performance.

Unlike color-normal observers, more saturated red colored signals result in longer reaction times in protan (color-deficient) observers [44]. The CIE [45] has published chromaticity recommendations to ensure satisfactory visibility of red signal lights by protans. The average 50-year-old person receives only half the retinal illuminance as a typical 20-year-old person, because of decreased lens transmittance and reduced pupil area [46].

Existing models
This section briefly discusses important models and formulae used to predict visibility of signal lights, particularly with respect to aviation and navigation contexts. The primary focus of the present paper is on detection and visibility of lights seen from generally long distances (when the signal can be assumed to be a point source), and under nighttime viewing conditions. Douglas and Booker [47] provide excellent guidance in investigating the visibility of extended-size sources (of a given luminance) in higher-light-level ambient conditions, such as daytime viewing.

Visual Range
Douglas and Booker [47] summarize the development of equations and formulae for determining the distance at which a signal light of a given luminous intensity can be seen, or conversely, the luminous intensity of a signal light needed for it to be seen from a given distance.

The threshold illuminance (E_t) at the eye required to detect a signal light with high certainty is given dependent upon the background luminance [47]. Using Allard's law [40], the luminous intensity I (in cd) required to detect a signal light can be determined from the following equation:

$$I = V^2 E_t / T^V$$

where V is the required distance at which the signal should be seen (in m), E_t is the threshold illuminance at the eye (in lx), and T is the transmissivity of the atmosphere (per m).

The threshold illuminance values given by Douglas and Booker [47] apply only when the observer knows exactly where the light signal in question is to be found. When this is not the case and when the observer is expected to relatively easily detect the signal, the threshold illuminance should be increased by a factor of 5 to 10. Even larger increases are necessary if the signal light is supposed to attract one's attention (when the signal is unexpected); it is assumed that for the present application, the signal is expected.

CIE 48
The Commission International de l'Éclairage (CIE) published a report [23] on recommendations for photometric characteristics of signal lights for traffic control. Despite the specific focus upon

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road traffic control for this report, the data within can be particularly useful in the evaluation of signal lights for other applications.

For the application of signal lights in roadway applications, research by Cole and Brown [48] on the optimum luminous intensity I_d for red traffic signal lights viewed under daytime conditions from a distance of 100 m (where the size of the signal light is such that is can be treated as a point source) was conducted. The optimum was defined as the luminous intensity above which response times or the proportion of missed signals did not decrease appreciably, and was found to be about 200 cd for red signal lights.

Using the assumption that the optimum luminous intensity is proportional to the background luminance (about 10,000 cd/m² for daytime viewing conditions), lower optimum intensities (I_d, in cd) can be estimated using the equation [23]:

$$I_d = 2 \times 10^{-6} d^2 L_B$$

where d is the viewing distance (in m) and L_B is the background luminance (in cd/m²).

The values for the above equation pertain to signal locations about 3° from the line of sight. For larger offsets, a multiplication factor for I_d is given by:

$$(\theta/3)^{1.33}$$

where θ is the offset angle (in degrees). This equation does not apply to smaller offset angles [23].

Effective Intensity
Much of the work previously cited within this section involves steady-state intensity of signal lights that are static in appearance. A number of studies have suggested that flashing lights increase the conspicuity of a signal relative to a steady-burning signal light, but flashing lights, by virtue of their reduced total light energy, can have disadvantages relative to steady-burning signals as well. In particular, several efforts have been underway during the past century to quantify the impact of flash characteristics on the visibility of signal lights, using a concept of effective intensity, where the effective intensity is the intensity of a steady-burning light providing the same visual effect as the flashing one.

The Blondel-Rey equation for effective intensity relates the effective intensity of a flashing square wave light (I_e, in cd) to the intensity of the square wave and its duration using an equation of the form:

$$I_e = It/(a + t)$$

where I is the intensity of the flash (in cd), t is the duration (in s) and a is a constant found empirically in several studies [49] to have a value close to 0.2.

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The Blondel-Rey formulation is poor for predicting the visibility of trains of flashes separated by short (less than 1 s) periods of time [50]. For very short flashes (less than 100 ms in duration) the total energy of the flash (intensity times duration) appears to determine its threshold for visibility [49, 51].

Other formulations for effective intensity include one based on differential equations developed by Allard [40] and a method known as the form-factor method developed by Schmidt-Clausen [52]. All methods appear to give similar results for fairly simple flash waveforms; however, complex and rapidly modulating flash waveforms, such as those that can be achieved with LED or other discharge sources, give very different predictions of effective intensity [53]. Organizations such as the Trinity House Lighthouse Service have utilized all three methods in the past with success but also have noted recently with new light sources that the methods do not always agree [54].

Government standards
Of course not only are the luminous intensities of the various elements of the runway lighting system deemed to be important, but also the color, location, spacing and layout of the lighting. Runway edge lighting in particular is considered as most important in providing visual guidance for aircraft landing, and elevation of lights is likely a necessary feature for remote facilities because of potentially unstable ground conditions. It is noted that generally, the specifications for such lighting are designed to make such lights readily visible and clear to oncoming pilots.

Other standards for signal lighting in a navigation context are relevant to remote airfield lighting. These are briefly discussed below.

The Government of Germany [55] proposed a multi-level standard for inland navigation lights; the minimum luminous intensity to be visible from 1.8 km is stated to be 1 cd, from 3.7 km is 5 cd, from 5.6 km is 15 cd, from 9.3 km is 65 cd and from 11.1 km is 118 cd. The Port of London Authority [56] utilizes similar requirements for preventing collisions between ships at sea, based on the following equation:

$$I = 3.43 \times 10^6 TD^2 K^{-D}$$

where I is the required luminous intensity (in cd), T is the threshold illuminance (in lx, defined for navigation to have a value of 2×10^{-7}), D is the range (in mi.) of the signal light, and K is the atmospheric transmissivity (per mi., defined for navigation to have a value of 0.8).

Evaluations of lighting systems
A number of evaluation studies have been conducted to investigate the effectiveness of various lighting schemes on pilot visibility, preference and confidence as they approach a landing. Other similar studies have been performed in a navigation context. This section briefly summarizes several of those evaluation studies and discusses their relation to the literature summarized above. While many of the studies outlined in this section are empirical in nature, they tend to confirm the findings of controlled, parametric research studies.

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Flashing lights are often used to help pilots identify when a runway might have another aircraft upon it, so as to avoid collisions. So-called wig-wag lights having different flash rates (35 to 50 flashes/min.) were evaluated by pilots [57]. Generally, pilots preferred the faster flashing rate, consistent with research by Gerathewohl [28].

In another evaluation, a configuration of lights for reduced-size airports was evaluated by pilots [58]. The number of lights was reduced by reducing the overall length or by spacing lights less densely. Reducing the number of sequenced flashing lights by 40% from the standard configuration did not reduce pilots' ability to see and land aircraft. Similarly, Weis [59] evaluated a reduced configuration lighting system for helipad systems that would not hinder pilot performance.

Walker et al. [60] surveyed operators of commercial, military and recreational marine vessels to identify needs for navigation and found that signal lights were an important component of navigating, especially as the vessels approached land. Roberts [61] evaluated a navigational buoy consisting of 120 red LEDs with a Fresnel lens and found that the device was able to provide a nominal visibility range of 4 mi. Jones [62] compared the performance of helicopter pilots landing at a heliport outfitted with one of two systems: a conventional rotating beacon or a strobe light flashing the code for the letter "H" in Morse code. Pilots reported that both beacons, designed to be well above visual threshold, provided adequate guidance.

Ernst [63] evaluated helicopter pilots' responses to helipad lighting of various colors and noted that at nighttime, the use of green (525 nm maximum wavelength) light appeared to provide optimal visibility, consistent with an understanding of mesopic vision [5] at nighttime light levels. In an evaluation of sequential light signal systems by Luria [64], it was found that operators could identify sequencing and report sequence order reliably when the difference between sequential flashes was as short as 10 ms.

Evaluating navigational lights consisting of flashing elements, Wagner and Laxar [65] found that such flashing increased conspicuity relative to steady-burning lights, and that in complex environments with other lights present, flashing lights were negatively affected (in terms of search time) less than steady-burning lights. Schmidlapp [66] investigated the use of strobe lights for anticollision systems on aircraft and concluded that they provided little benefit for reducing collisions, presumably because of the reduced ability of flashing and strobing lights to give closure and relative speed information [36].

SUMMARY AND RECOMMENDATIONS

The literature reviewed briefly in this paper point to several tentative conclusions. With respect to the luminous intensity, the necessary intensity of a signal light to be reliably detected under a given light level from a given distance (and under a given ambient atmospheric condition) can be predicted using well-established formulae developed for these purposes. Since the ambient conditions in remote locations as well as the ready availability of power are likely to be quite challenging, it is likely that intensity of a system in the field will be limited by factors pertaining to the efficacy and power requirements of the light sources used.

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With respect to color or spectral power distribution, this factor is likely to be of overall secondary importance in comparison with luminous intensity. The data reviewed herein point to little difference between colors for most practical visual responses. There are practical reasons for avoiding specific colors such as red or blue to avoid presenting messages to oncoming pilots that conflict with safe landing. There could well be visual benefits associated with a signal color that is spectrally tuned to take advantage of shifted peripheral spectral sensitivity at nighttime light levels, such as green signal lights, but sources producing green illumination (through the use of colored filters or green light emitting diodes, for example) should also provide sufficient luminous intensity and might not be optimal.

There is less specific guidance to the designer with respect to the temporal characteristics of the corner lights to be proposed. Especially if the color used is white or yellow, there is a reasonable likelihood that such lights could be confused with lights in adjacent areas where a community is located. Even a small village is likely to have some lighting that will be maintained on throughout the nighttime period. Since the spatial configuration of such lights would be uncontrolled, the possibility of a chance arrangement similar to the corners of a runway cannot be eliminated. In such a case, both to improve conspicuity of signal lights and to differentiate them from other lights, the use of flashing patterns would appear to be beneficial.

Further, complex flash waveforms can be readily incorporated into solid state circuitry of low power lighting devices. Since some of these waveforms could offer advantages over simple flash patterns, especially near visual thresholds, and since the various methods for predicting the visual impact of these waveforms are currently in dispute, future study to investigate the characteristics of flashing - waveform shape, flash rate, duration and intensity of both the peak and the trough of the flash profile, could be of benefit in specifying a remote airfield lighting system.

ACKNOWLEDGMENTS

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