Brightness/Luminous Intensity Values for Blue, White, and Green Aviation Signal Lights Using Light-Emitting Diodes

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16. Abstract

Signal lights at airports and along runways serve a variety of functions, including helping pilots locate the airport, assisting pilots in orienting the aircraft to the appropriate landing runways, and aiding pilots with taxi maneuvers on the airfield. Anecdotal pilot reports suggest that light-emitting diodes (LED) used as signal lights in and around airports are perceived as brighter than comparable signal lights using incandescent sources at the same measured intensity. These subjective reports are consistent with previously published psychophysical data. In general, saturated colors, similar to those produced by LEDs, appear brighter than less saturated lights, similar to those produced by incandescent sources. This technical note describes a series of experimental investigations to quantify the brightness of blue, white, and green LED signal lights relative to incandescent signal lights within the same Federal Aviation Administration (FAA) color boundaries. Both types of signal lights were compared against dark and dimly lighted backgrounds and through simulated fog. The results confirm that LED signal lights are perceived as brighter than incandescent signal lights at matched luminous intensities. Brightness relationships were unaffected by signal light intensity, background light level, or the number of signal lights viewed. The simulated fog reduced the relative brightness difference between the incandescent and the LED signal lights due to light scattering in the fog that desaturated the signal light colors. The results of the present study were not accurately predicted by two previously published models of brightness appearance, but this is most likely due to differences in experimental conditions. A new model was developed for this study that could be used to predict signal light brightness perception for FAA blue, white, and green signal light colors. Except for very short-wavelength blue signal lights, the model was able to accurately predict brightness perception data obtained in the present study as well as those presented in an independent study published 30 years ago. This independent validation lends confidence to the generality of the model for predicting blue, white, and green signal light brightness.

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AC	Advisory Circular
B/L	Brightness-to-luminous intensity ratio
CCT	Correlated color temperature
cd	Candelas
CIE	Commission Internationale de l'Eclairage
FAA	Federal Aviation Administration
LED	Light-emitting diode
LRC	Lighting Research Center
lx	A unit of illumination equal to 1 lumen per square meter
PWM	Pulse width modulation
SPD	Spectral power distribution
VD-RS	Vector distance-relative saturation

EXECUTIVE SUMMARY

Signal lights at airports and along runways serve a variety of functions, including helping pilots locate the airport, assisting pilots in orienting the aircraft to the appropriate landing runways, and aiding pilots with taxi maneuvers on the airfield. Signal light colors have different meanings and are typically perceived from different distances; therefore, they have different color and luminous intensity specifications.

Anecdotal pilot reports collected by the Federal Aviation Administration (FAA) suggest that light-emitting diodes (LED) used as signal lights in and around airports are perceived as brighter than comparable signal lights using incandescent sources at the same measured intensity. These subjective reports are consistent with previously published psychophysical data. In general, saturated colors, similar to those produced by LEDs, appear brighter than less saturated lights, similar to those produced by incandescent sources. This technical note describes a series of experimental investigations to quantify the brightness of blue, white, and green LED signal lights relative to incandescent signal lights within the same FAA color boundaries.

Both incandescent and LED signal lights were compared against dark and dimly lighted backgrounds and through simulated fog. The results confirm that LED signal lights are perceived as brighter than incandescent signal lights at matched luminous intensities. Brightness relationships were unaffected by signal light intensity, background light level, or the number of signal lights viewed. The simulated fog reduced the relative brightness difference between the incandescent and the LED signal lights due to light scattering in the fog that desaturated the signal light colors.

The results of this study were not accurately predicted by two previously published models of brightness appearance, most likely due to differences in experimental conditions. A new model was developed for this study that could be used to predict signal light brightness perception for FAA blue, white, and green signal light colors. Except for very short-wavelength blue signal lights, the model was able to accurately predict brightness perception data obtained in the present study as well as those presented in an independent study published 30 years ago. This independent validation lends confidence to the generality of the model for predicting blue, white, and green signal light brightness.

INTRODUCTION

PURPOSE.

The purpose of this evaluation was to conduct a series of experimental investigations to quantify the potential impact of blue, white, and green light-emitting diode (LED) signal lights on perceived brightness under a range of viewing conditions emulating signal lights perception during nighttime flight operations. The research was conducted by the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute under contract FAA/05-C-AT-RPI granted through the Federal Aviation Administration (FAA) Airport Safety Technology Research and Development Section of the FAA William J. Hughes Technical Center in Atlantic City, New Jersey.

BACKGROUND.

Anecdotal pilot reports collected by the FAA indicate that runway signal lights using LEDs appear brighter than conventional incandescent (and filtered incandescent) signal lights of the same nominal color at the same luminous intensities. Both technologies generate light within the prescribed FAA chromaticity boundaries, but the filtered incandescent signal lights appear less saturated (i.e., whiter) than the LED signal lights of the same color. It has been well established in the color science literature that saturated signal lights (e.g., red) will appear brighter than desaturated signal lights (e.g., pink) of the same photometric luminance [1 through 3]. Three neural channels in the brain combine to construct perceptions of signal light brightness: (1) one achromatic channel (i.e., the luminance channel) and two color channels, (2) the red versus green (r-g) channel, and (3) the blue versus yellow (b-y) channel [4].

In addition to the achromatic channel response (i.e., luminance), saturated signal lights will appear brighter than desaturated signal lights because they have a stronger contribution to brightness perception from one or both of the color channels. Thus, consistent with theoretical expectations, the more saturated LED signal lights will appear brighter than the desaturated, filtered incandescent signal lights at the same luminous intensity. Although several quantitative models of brightness perception exist, and they all suggest than signal lights of greater saturation will appear brighter for the same luminous intensity, their predictions of brightness are not in total agreement due to differences in viewing conditions and experimental protocols underlying those models.

SIGNAL LIGHT LUMINOUS INTENSITIES AND COLOR REQUIREMENTS. Signal lights at airports and along runways serve a variety of functions, including helping pilots locate the airport, assisting pilots in orienting the aircraft to the appropriate landing runways, and aiding pilots with taxi maneuvers on the airfield. Signal light colors have different meanings and are typically perceived from different distances; therefore, they have different color and luminous intensity specifications.

FAA Advisory Circular (AC) 150/5345-46B [5] summarizes the luminous intensity requirements for signal lights of different colors and configurations. Table 1 lists the specifications for blue, white, and green signal lights. The large range of luminous intensities for each signal light color in this table represents the different distances from which the signal lights are expected to be viewed for their respective purposes. For example, green in-pavement threshold signal lights have a luminous intensity of 5000 candelas (cd), because these signal lights help pilots identify the runway orientation when flying an approach to the airport. In comparison, green in-pavement taxiway signal lights have a luminous intensity of only 20 cd. These signal lights are viewed by pilots after the aircraft has landed, and thus are viewed from relatively close distances.

Table 1. Minimum Luminous Intensities of Blue, White, and Green Signal Lights

Signal Function	Minimum Intensity (cd)
Blue	
In-pavement runway threshold/end (nonprecision instrument flight rules)	2
Elevated taxiway edge	2
In-pavement runway edge	75
Elevated runway edge (precision instrument flight rules)	200
White	
Elevated runway edge (visual flight rules)	15
Elevated runway edge (nonprecision instrument flight rules)	75
In-pavement runway centerline	5,000
In-pavement runway touchdown zone	5,000
In-pavement land and hold short	5,000
In-pavement runway edge	10,000
In-pavement runway edge (precision instrument flight rules)	10,000
Green	
Elevated runway threshold/end (visual flight rules)	10
In-pavement taxiway centerline (high visibility)	20
In-pavement taxiway centerline (curved section, low visibility)	100
In-pavement taxiway centerline (straight section, low visibility)	200
Elevated runway threshold/end (nonprecision instrument flight rules)	300 or 600
Elevated runway threshold/end (precision instrument flight rules)	3,200
In-pavement runway threshold/end	3,300
In-pavement threshold (medium-intensity approach lighting system)	5,000

FAA AC 20-74 [6] contains specifications for signal light chromaticities. These specifications ensure that signal lights are reliably identified by pilots. Although chromaticity relates to color matching not to color appearance, chromaticity coordinates can be useful for communicating color appearance.

Figure 1 shows the FAA chromaticity boundaries, as plotted in the Commission Internationale de l'Eclairage (CIE) chromaticity space [4], for blue, white, and green signal lights. Signal lights having chromaticities within a boundary should appear to have the same nominal color for blue, white, or green. Approach signal lights that are designed to operate on a range of voltages have multiple chromaticity coordinate values. The arrows show the shifts in chromaticity as the voltage increases (note that for the green signal lights measured, with the chromaticity at the lowest voltage, is outside the color boundary).

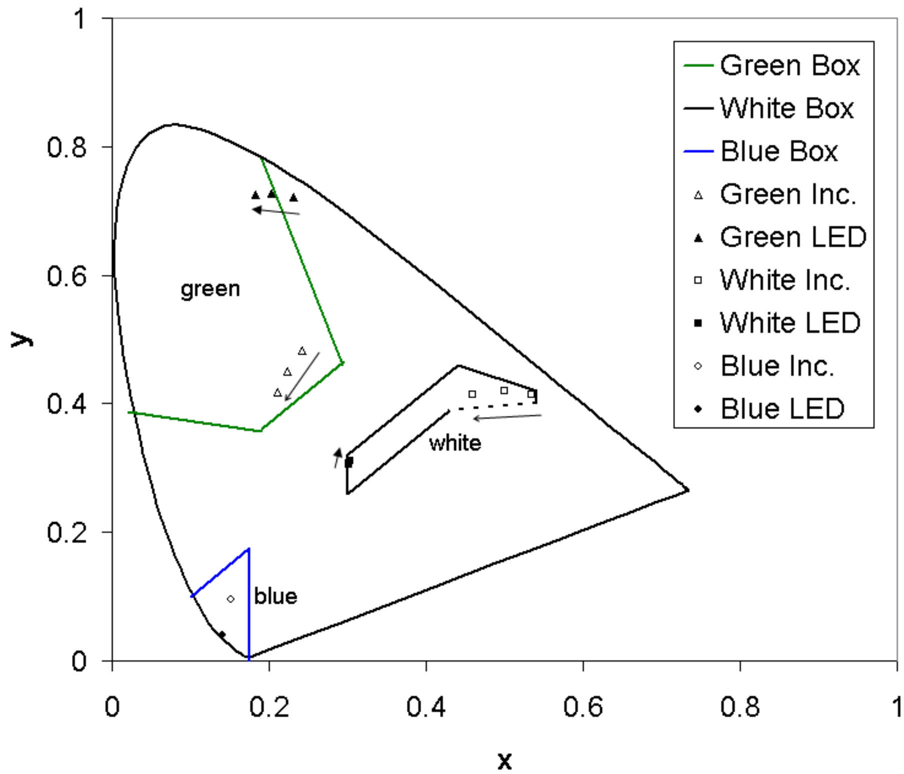

Figure 1. Specified FAA [6] Color Boundaries and Chromaticity Coordinates

Representative chromaticity coordinates of several blue, white, and green signal lights operated at different luminous intensities are also shown in figure 1. The incandescent sources are shown as open symbols, and the LED sources are shown as filled symbols. These chromaticity data were provided to the Lighting Research Center (LRC) by FAA personnel for available and prototype products and from sample measurements performed at the LRC. These chromaticities are representative of the light emitted by different technologies used as signal lights but are not necessarily typical of signal lights on airfields. They merely illustrate the magnitude of differences in the chromaticities between filtered and unfiltered incandescent light sources and comparable LED light sources [7]. Generally speaking, the two technologies generate lights of different, distinct chromaticity groupings within the FAA chromaticity boundaries. White LED signal lights typically appear bluer than incandescent signal lights and colored LED signal lights typically appear more saturated (i.e., less white) than filtered incandescent signal lights. As a result, LED signal lights, both white and colored, appear brighter than incandescent signal lights within the same FAA chromaticity boundary.

BRIGHTNESS AND CHROMATICITY. A number of studies [1, 2, and 8 through 15] have compared the brightness appearances of colored lights of different chromaticities. A common metric employed in many of these studies is the brightness/luminance or brightness/luminous intensity ratio (B/L). To illustrate this metric, suppose two light sources have respective B/L values of 1.0 and 2.0. The measured luminance (or luminous intensity) of the former light source would have to be increased by a factor of 2.0 to match the apparent brightness of the latter light source. Conversely, the luminance of the latter light source would have to be decreased by a factor of 0.5 (that is, 1/2.0) to match the brightness of the former light source.

Both Harrington [16] and Alman [10] showed that white light sources with chromaticities corresponding to high correlated color temperatures (CCT) (appearing bluish-white) tend to appear brighter than those with low CCTs (appearing yellowish-white) at the same luminance, within the CCT range of 2800 to 6500 K. Outside this range, lights no longer appear white; therefore, this generalization is not necessarily valid for lights of higher or lower CCT values. Moreover, it should be noted that even lights with the same CCT can have very different chromaticities [17] and will not necessarily appear to have the same apparent brightness.

Viewing conditions also affect B/L values. For example, absolute radiance (adaptation level) apparently affects the relative B/L values for two lights [2]. Guth and Lodge [2] postulated that, as the magnitude of the color channel signals increase with radiance, their contributions to brightness increase; thus, the B/L values for any two lights will be affected. Individual differences also play a role in B/L values [9 and 18], which is the reason experiments with multiple participants are used to obtain representative B/L values [1, 8, 11, 12, and 19]. In addition, studies using a side-by-side comparison of stimulus brightness tended to have more stable results than studies using sequential presentations [20] because a subject's memory of brightness becomes unstable once a light stimulus is extinguished.

Two important models, one by Guth and Lodge [2] and one by Ware and Cowan [3], were developed to predict B/L values of light stimuli having different chromaticity coordinates. Both are commonly used in studies of brightness perception [21].

The Guth and Lodge [2] and the Ware and Cowan [3] models result in qualitatively, but not quantitatively, similar predictions of B/L values:

- Light stimuli with chromaticity coordinates closer to the spectrum locus have higher B/L values.

- White light stimuli have the lowest B/L values.

- Light stimuli with chromaticity coordinates tending toward the yellowish portion of the chromaticity space tend to have lower B/L values than those tending toward other portions of the chromaticity space (i.e., reddish, greenish, and bluish).

Although quantitative predictions differ for the two models, both models would generate predictions consistent with the anecdotal pilot reports collected by the FAA regarding the brightness appearance of LED signal lights relative to incandescent signal lights. The former signal lights tend to be more saturated in appearance than the latter and, thus, will appear brighter. Using the data in figure 1 as a guide, it is reasonable to expect that, following experimental testing, the B/L values obtained for LED signal lights would be higher than those obtained for the incandescent signal lights. To quantify these effects under viewing conditions representative of nighttime flight conditions, a series of experiments were performed and are described in the following sections.

OBJECTIVES

The objectives of this research were to

- determine if signal lights with different chromaticities but equal luminous intensity can have different brightness characteristics.
- develop a model for objectively measuring this perceived difference.
- note any caveats for applying this model in practice.

EVALUATION METHOD

Experimental trials were conducted with two stacked enclosures; the incandescent enclosure, located on the bottom of the setup, served as the reference signal light(s), and the LED enclosure, served as the test signal light(s) in all trials. Figure 2 shows the LED and incandescent enclosures, displaying blue signal lights through the central apertures.

Figure 2. Light-Emitting Diode (top) and Incandescent (bottom) Enclosures

<u>PROFILE OF EXPERIMENT SUBJECTS</u>.

A total of 15 subjects (12 males and 3 females) participated in the series of experiments. The ages of the subjects ranged from 21 to 56 years (mean 33 years and median 30 years). The subjects reported normal color vision and wore corrective lenses if needed. There were between 6 and 11 subjects in every experiment. The subjects signed informed consent forms approved by Rensselaer's Institutional Review Board.

After signing the consent form and having the experiment explained to them, the subjects entered the laboratory and adapted to the lighting condition for 5 minutes. The subjects were seated at a desk with their head positioned in an adjustable chin rest 2 m away and perpendicular to the front surfaces of the two enclosures holding the simulated light signals. The incandescent signal light was switched on and remained on during the session. A series of 30 test signal lights was randomly presented (six test signal intensities and five replications at each luminous intensity).

The subjects used a joystick that was fastened to a desk and connected to a personal computer to record their judgments of brightness. The subjects responded to the question "Which signal light is brighter?" by moving the joystick up (test light brighter) or down (reference light brighter). The subjects were instructed to respond either up or down (to guess) even if the signal lights looked equal in brightness. The subjects could take as long as they needed to make each judgment. Typically, each session of 30 brightness judgment trials took no longer than 5 minutes. After the last trial for a given session, the incandescent reference signal light was extinguished.

EXPERIMENTS.

Four experiments were performed to assess the B/L characteristics of white, green, and blue LED signal lights relative to incandescent signal lights. Schematic diagrams of the stimulus conditions in these four experiments are shown in figure 3. The following are descriptions of each experiment:

- Experiment One: Subjects compared the brightness of a single incandescent signal light to an adjacent LED signal light against a dark background.

- Experiment Two: Subjects compared the brightness of an array of three incandescent signal lights to an array of three LED signal lights against a dark background.

- Experiment Three: Subjects compared the brightness of a single incandescent signal light to a single LED signal light against a dim background.

- Experiment Four: Subjects compared the brightness of a single incandescent signal light to a single LED signal light against a dark background, but both were seen through a simulated fog medium that scattered the light from both signal lights.

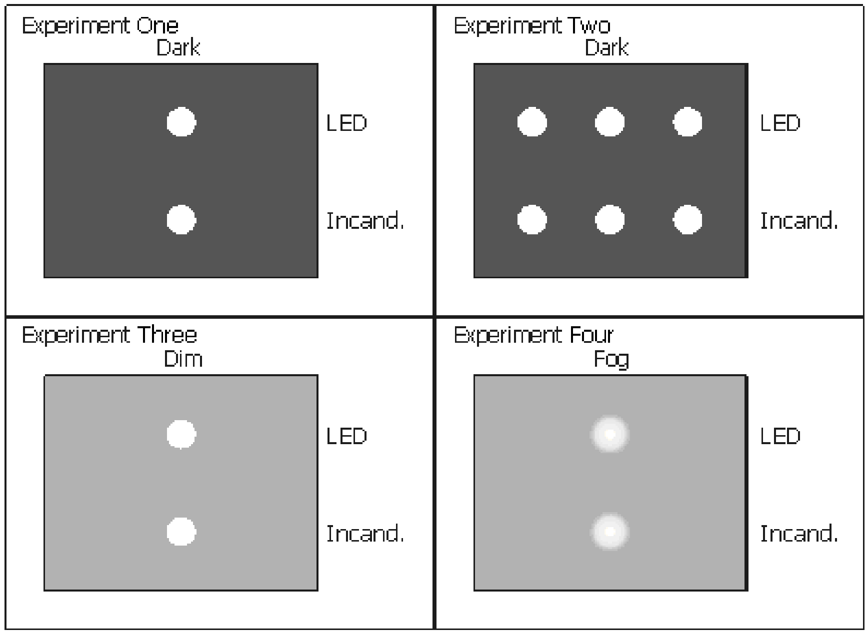

Figure 3. Schematic Representation of Each Experiment

APPARATUS.

The apparatus providing the incandescent and the LED signal lights to the subjects was the same in all four experiments. Laser-cut holes (0.6 mm in diameter) served as light-emitting apertures in the experiments. Three of these apertures, 51 mm apart, were affixed to the front of several matte-black aluminum enclosures that housed either the incandescent or LED sources.

One enclosure housed three small pin-based incandescent lamps (35 W), each positioned directly behind an aperture (figure 4). Incandescent lamps with large filaments were used so that the entire aperture, when the subjects viewed the signal lights 2 m from the front of the apparatus, was completely filled by the luminous filament. Given the high temperatures generated by the incandescent lamps, this enclosure was cooled with forced air (not shown in figure 4). The pinhole apertures shown in figure 4 were 0.6 mm in diameter.

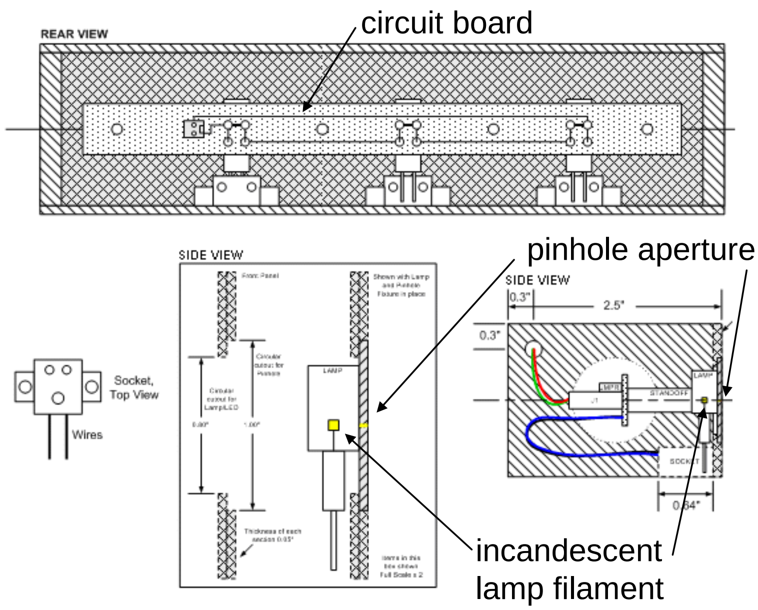

Figure 4. Schematic of Aluminum Enclosure Containing the Incandescent Lamps

A combination of glass and/or plastic gel filters was positioned in front of the apertures to provide the blue or green signal lights. For the blue signal lights, glass blanks (Schott, BG25) were used to meet FAA requirements [6]. For the green signal lights, glass blanks (Schott, BG7) were used in combination with a plastic gel filter (Lee, Filter 730) and neutral density filters (Lee, Filter 210) to meet the FAA requirements [6].

Several other enclosures were employed to house the blue, white, and green LEDs. Each enclosure housed three 1-W LEDs (figure 5). The pinhole apertures shown in figure 5 were 0.6 mm in diameter.

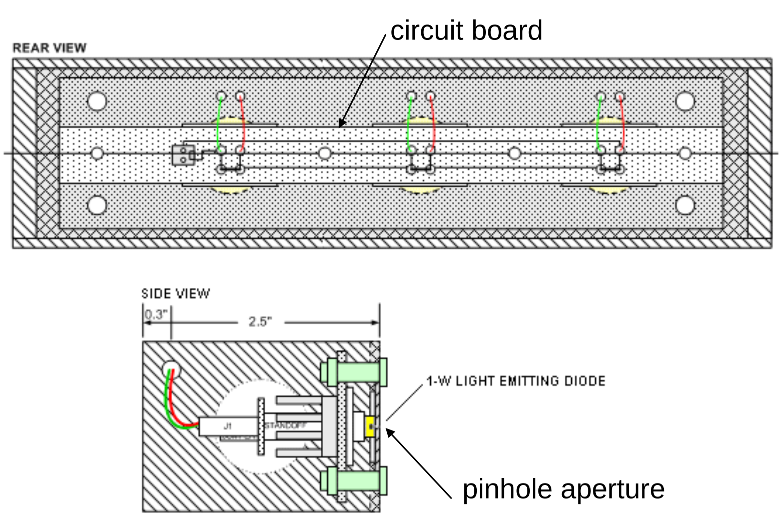

Figure 5. Schematic of Aluminum Enclosures Containing the LEDs

The LED light source was square, 0.95 mm on a side, and like the incandescent filaments, completely filled an aperture when illuminated. The LED test colors are denoted Blue 1 and 2, White 1 and 2, and Green 1 through 5. The chromaticities of the signal lights are given in table 2 for every experimental condition.

Table 2. Chromaticity Coordinates for Each Reference and Test Lighting Condition

Color	Chromaticity Coordinates (High)		Chromaticity Coordinates (Medium)		Chromaticity Coordinates (Low)	
	x	y	x	y	x	y
Blue 1 Test	-	-	0.156	0.023	0.160	0.019
Blue 2 Test	-	-	0.133	0.067	0.134	0.065
Blue Reference	-	-	0.148	0.079	0.152	0.095
White 1 Test	0.306	0.311	0.304	0.296	0.303	0.289
White 2 Test	0.418	0.404	0.417	0.391	0.411	0.383
White 1 Reference	0.473	0.413	0.499	0.416	0.534	0.420
White 2 Reference	0.481	0.414				
Green 1 Test	0.072	0.480	0.069	0.466	0.064	0.463
Green 2 Test	0.079	0.525	0.076	0.518	0.072	0.510
Green 3 Test	0.089	0.598	0.085	0.586	0.076	0.583
Green 4 Test	0.144	0.705	0.136	0.705	0.133	0.696
Green 5 Test	0.189	0.722	0.183	0.713	0.175	0.709
Green Reference	0.268	0.439	0.269	0.441	0.270	0.442

The LEDs and incandescent lamps were mounted to circuit boards. Jumper wires were used to vary the number of energized light sources in the enclosure. Power supplies (Hewlett-Packard), controlled by computer software (Labview™), provided calibrated voltages for the incandescent lamps or 1000 Hz pulse width modulation (PWM) duty factors for the LEDs.

A wide range of signal light intensities are specified by the FAA for different runway situations (table 1). For long viewing distances (e.g., in-pavement runway edge lights), high intensities are specified; but for short distances (e.g., elevated runway edge lights), much lower intensities are specified. From a pilot's viewing position in the cockpit, it can be reasonably assumed that signal lights are perceived as point sources. Therefore, an intensity specified in table 1 can be used to calculate a corresponding illuminance at the eye for a known distance. For example, a signal light having an intensity of 5000 cd and viewed at 200 m will provide an illuminance of 0.125 lux (lx) at the eye.

The visual sensation from this signal light will be identical to that generated by a 0.5-cd signal light viewed at 2 m because both signals provide 0.125 lx at the eye. Since the 0.6-mm luminous aperture sizes viewed by the subjects from a distance of 2 m corresponds to a visual angle of 1 minute of arc, the simulated signal lights were effectively perceived as point sources. Table 3 lists the illuminances at the plane of the subject's corneas at a distance of 2 m from the simulated signal lights for every color used in these experiments. Because of the wide range in luminous intensities specified for the signal lights by the FAA (table 1), a range of representative corneal illuminances were selected for Experiment One. These were categorized as high, medium, and low intensities (table 3). For the other three experiments, only the medium intensities and a subset of colors (Blue 1, White 1, and Green 1) were used.

Table 3. Illuminances at a 2-m Distance for Each Lighting Condition in the Experiments

<table>
<tr><th rowspan="2">Color</th><th colspan="3">Nominal Intensity
(lx)</th></tr>
<tr><th>High</th><th>Medium</th><th>Low</th></tr>
<tr><td>Blue 1-2</td><td>-</td><td>0.036</td><td>0.006</td></tr>
<tr><td>White 1</td><td>0.216</td><td rowspan="2">0.072</td><td rowspan="2">0.018</td></tr>
<tr><td>White 2</td><td>0.120</td></tr>
<tr><td>Green 1-5</td><td>0.108</td><td>0.027</td><td>0.002</td></tr>
</table>

Illuminances were measured on an optical bench using calibrated, highly accurate illuminance meters (Gigahertz-Optik X9 and LMT; the latter instrument varies from the photopic standard observer by less than 3% at all wavelengths above 420 nm). Spectral power distributions (SPD) of the signal lights were measured using a reflectance standard and a spectroradiometer (PhotoResearch, SpectraSpan® System PR-705).

Chromaticity coordinates were then calculated from the SPDs (table 3) and plotted, as shown in figure 6. There was relatively little shift in the LED chromaticities at different PWM levels, a finding that is consistent with research by Dyble et al. [22] and Gu et al. [23]. It should be noted that dimming with PWM or with voltage modulations produce opposite color shifts [23]. This effect is shown by comparing the color shift for the Green 5 LED with voltage modulation in figure 1 compared to PWM in figure 6. The incandescent signal lights show large changes in chromaticity (as shown in figure 6), but this is consistent with what would be experienced with actual signal lights at the airport due to voltage modulation. The arrows show shifts in chromaticity as the nominal intensity is increased from the low to the high value (for blue, the shift from low to medium is shown).

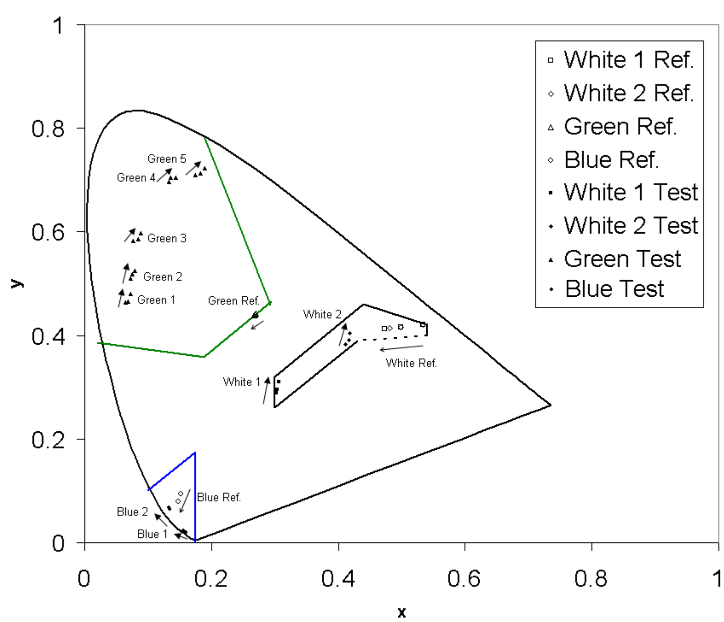

Figure 6. Chromaticity Coordinates of all Test and Reference Lighting Conditions

For Experiment Three (dim background), a 60- by 76-cm sheet of white paper was positioned behind the LED and incandescent enclosures and illuminated with a 60-W incandescent lamp positioned behind and slightly to the side of the subject. During the trials, the signal lights were surrounded by a 0.2-cd/m² uniform luminous background. This luminance corresponds to Illuminating Engineering Society of North America standards for roadway illumination on collector roads [24].

For Experiment Four (fog), an acrylic aquarium tank was inverted and positioned between the subject's seating location and the signal light enclosures, forming an enclosed, clear volume through which the subjects viewed the signal lights (figure 7). A mixture of propylene glycol, glycerin, and water was heated inside a portable fog/smoke machine (Gemmy Industries, The Fog Machine®) and directed through a plastic tube into the aquarium until a density was attained that attenuated the illuminance from the signal lights to about 40% of the illuminance without the aquarium present. This level of attenuation corresponds to fog, defined as providing a nighttime visibility distance of 1 km [25] viewed at a distance of 0.25 km. When both the incandescent reference signal lights and the LED test signal lights were switched on and viewed through the aquarium, scattered light from both signal lights was superimposed over both signal lights, effectively reducing their chromaticity differences. Room lights were switched on to take the photograph shown in figure 7, but during the experiment, all room lighting was switched off.

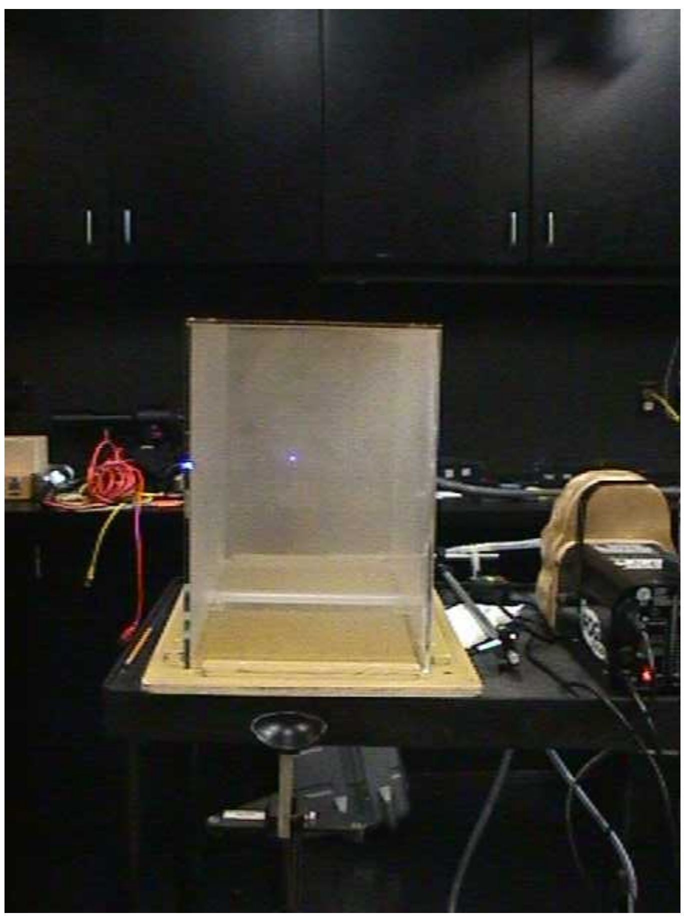

Figure 7. View of Signal Light Through the Aquarium Containing Fog for Experiment Four

It should be noted that none of the experimental conditions used a screen that would have simulated the spectral transmission of an aircraft windshield or of eyeglasses (particularly tinted sunglasses) that might be worn by a pilot in flight. A number of previously published studies have investigated colored signal light perception through tinted lenses and glasses, primarily focusing on traffic signal recognition for drivers wearing tinted sunglasses [26 through 29]. There are standards in place for minimum glass transmission characteristics to protect against color misidentification or poor detection of signal lights of certain colors [30 and 31]. It is assumed that such standards would ensure that the presence of windshields or eyeglasses would not result in chromaticity shifts large enough to affect the results of this study.

DATA ANALYSIS.

The brightness judgment data for each condition in each experiment were analyzed in a consistent manner. The values assigned to each brightness judgment trial (zero when the incandescent signal light was brighter, and one when the LED test signal light was brighter) were averaged for each lighting condition and for all the subjects participating in the trials for that lighting condition. This mean value, when multiplied by 100, was the percentage of times the LED test signal light was rated as brighter than the incandescent signal light.

These percentages, as a function of the intensity of the LED test signal light relative to the incandescent signal light, were then fitted to a four-parameter logistic (S-shaped) function having the form:

$$y = ((y_{min} - y_{max})/(1 + (x/a)^b)) + y_{max} \tag{1}$$

where x = the intensity of the LED signal light relative to the incandescent signal light.

y = the predicted percentage of times the LED signal light would be judged brighter than the incandescent signal light.

y_{min} = the smallest percentage of times that it would be possible to judge the LED signal light brighter than the incandescent signal light (fixed at 0%).

y_{max} = the largest percentage of times that it would be possible to judge the LED signal light brighter than the incandescent signal light (fixed at 100%).

a = the relative intensity of the LED signal light when it would be rated as brighter than the incandescent signal light half the time and less bright the other half.

b = the slope of the curve best fitting the x and y values.

This equation form has been commonly used to model a number of biological responses exhibiting a dose-response type of function [32]. It is particularly useful here because one would expect that when the LED test signal light is very dim relative to the incandescent signal light, the percentage of times that the LED signal light would be judged as brighter than the incandescent signal light would approach 0%; conversely as the LED signal light becomes very high in intensity, this percentage would approach 100%.

RESULTS

EXPERIMENT ONE.

In Experiment One, the brightness of a single incandescent signal light was compared with a single LED signal light against a dark background.

Appendix A shows the mean percentages (and standard errors of the mean) for the brightness judgments. The values of parameter b in the best fitting logistic functions were all close to one another, and its mean value (b = 4.68) was used to fit all data sets. The best fitting logistic functions and goodness of fit (r^2) coefficients (with the value of b fixed at 4.68) are also shown in appendix A. The goodness of fit of the data to the logistic functions was very high (r^2 from 0.94 to more than 0.99) in every case.

For each condition, B/L values of the LED test signal lights relative to the incandescent signal lights were calculated using the inverse of the value of parameter a (when expressed as a proportion). For example, if a = 50% (or 0.5 as a proportion), then the B/L value of the LED signal light is 2.0 (or 1/0.5) relative to the incandescent signal light.

The measured B/L values for each LED signal light color relative to its incandescent blue, white, or green reference are given in table 4. In general, the B/L values were similar for each nominal intensity (low, medium, or high); therefore, mean B/L values, averaging the values for all nominal intensities, are shown in this table. Differences were observed in B/L values among the different green signal light colors and between the white signal light colors, but not between the blue signal light colors.

EXPERIMENT TWO.

In Experiment Two, the brightness of an array of three incandescent signal lights was compared with an array of three LED signal lights against a dark background.

As described above, only the medium nominal intensity for the Blue 1, White 1, and Green 1 signal light colors were tested in this experiment, as well as in Experiments Three (dim background) and Four (fog). Appendix B shows the mean percentages (and standard errors of the mean) for the brightness judgments as well as the best fitting logistic function (with the value of b fixed at 4.68 as in Experiment One) and the goodness of fit (r^2) coefficients for each lighting condition in Experiment Two. As with Experiment One, the goodness of fit coefficients had very high values (r^2 from 0.97 to 0.98). The B/L values for Blue 1, White 1, and Green 1 were 1.66, 1.52, and 1.80, respectively.

EXPERIMENT THREE.

In Experiment Three, the brightness of a single incandescent signal light was compared with a single LED signal light against a dim (0.2-cd/m² luminance) background.

Appendix C shows the mean percentages (and standard errors of the mean) for the brightness judgments as well as the best fitting logistic function (with b fixed at a value of 4.68) and the goodness of fit (r^2) coefficients for each lighting condition in Experiment Three. As with Experiments One and Two, the goodness of fit coefficients had very high values (r^2 from 0.97 to 0.99). The B/L values for Blue 1, White 1, and Green 1 were 1.66, 1.78, and 1.86, respectively.

EXPERIMENT FOUR.

In Experiment Four, the brightness of a single incandescent signal light was compared with a single LED signal light against a dark background through a volume of simulated fog.

Appendix D shows the mean percentages (and standard errors of the mean) for the brightness judgments as well as the best fitting logistic function (with b fixed at a value of 4.68) and the goodness of fit (r^2) coefficients for each lighting condition in Experiment Four. As with Experiments One through Three, the goodness of fit coefficients had very high values (r^2 from 0.97 to 0.99). The B/L values for Blue 1, White 1, and Green 1 were 1.35, 1.45, and 1.42, respectively.

DISCUSSION

COMPARISON OF CORRESPONDING LIGHTING CONDITIONS.

Figure 8 shows the B/L values for the Blue 1, White 1, and Green 1 medium-intensity LED signal lights (relative to the blue, white, and green incandescent reference sources, respectively) determined from Experiments One through Four. Generally, the deviations in B/L values from Experiments One through Three were small and inconsistent. For example, the B/L value for the Blue 1 LED signal light was greater in Experiment Two (array) than in Experiment One (single light), but the opposite was true for the White 1 and Green 1 LED signal lights. Figure 8 shows that the influence of the array and the dim background conditions was small and inconsistent.

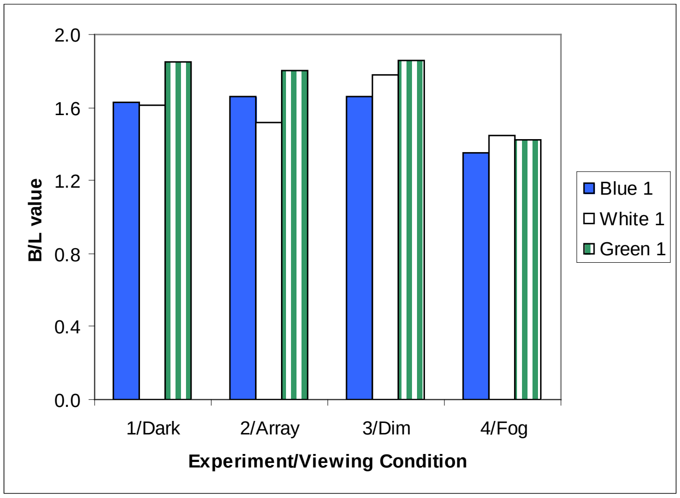

Figure 8. The B/L Values for the Blue 1, White 1, and Green 1 Medium-Intensity LED Signal Lights

This was not the case for the B/L values measured in Experiment Four (fog). As shown in figure 8, these B/L values were lower for all three LED signal light colors than in any of the other experiments. The illumination from both signal lights was scattered in the simulated fog, and stray light was superimposed over each signal light, which reduced saturation and chromaticity differences between the two signal lights and brought B/L values of the LED test signal lights closer to 1.

COMPARISON OF RESULTS FROM EXPERIMENT ONE TO MODEL PREDICTIONS.

Table 4 shows the predicted B/L values for each lighting condition in Experiment One, using the Ware and Cowan [3] and Guth and Lodge [2] models. (Both the low- and high-adaptation level models from the latter authors were used.) This table also shows the measured B/L values from Experiment One. Although the predicted and measured B/L values followed similar trends in terms of rank order, the predictions from those models were not consistent with each other or with the present data. These inconsistencies underscore the need for a new approach for B/L predictions under the conditions used in the present study. The values shown in table 4 are according to the model from Ware and Cowan [3] and the models (for low- and high-adaptation levels) from Guth and Lodge [2]. Also shown are the mean measured B/L values from Experiment One.

Table 4. The B/L Predictions and Measured Values for the Signal Color Chromaticities Listed in Table 2

Test Color	Ware and Cowan [3]	Guth and Lodge (Low) [2]	Guth and Lodge (High) [2]	Measured Values
Blue 1	1.10	1.27	3.55	1.47
Blue 2	1.05	1.16	1.51	1.48
White 1	1.14	0.97	1.04	1.62
White 2	0.98	0.98	0.96	1.17
Green 1	1.39	1.17	1.32	1.73
Green 2	1.34	1.16	1.28	1.80
Green 3	1.29	1.14	1.24	1.65
Green 4	1.23	1.09	1.15	1.48
Green 5	1.21	1.06	1.10	1.41

The data obtained from the series of experiments described in this technical note clearly show that the chromaticity of blue, white, and green signal lights, even within the FAA color boundaries [6] for these signal colors, influence the resulting brightness perception under a range of viewing conditions relevant to nighttime flight operations. Fundamentally, signal lights using LEDs in a range of chromaticity regions within the color boundaries had consistently higher B/L values than signal lights developed using incandescent lamps and for blue and green colored filters.

<u>DEVELOPMENT OF A NEW B/L MODEL</u>.

The previously published models [2 and 3] did not yield satisfactory B/L values for matching the results of the present study (table 4). This may be due to the differences in experimental methods used in measuring B/L values between the present study and the studies underlying those models. For example, none of the previous models used point source stimuli; and in previous studies, a nominally white light source was used as the reference light, rather than the colored signal lights (for blue and green) used as the reference lights (at least for the green and blue conditions) in this study. This is an important practical consideration, as the present study's objective was to identify brightness differences among signal lights of the same nominal colors, not the differences between different colors.

For this reason, the data from Experiment One were used as the basis for a new model to predict B/L values of any light within the blue, white, or green FAA color specifications [6] for these colors relative to an incandescent reference.

The model takes into account several factors:

- The difference in B/L values between a reference and a test light source will increase as the vector distance of the chromaticities increase. However, since the CIE (x,y) chromaticity diagram [4] is known to be nonuniform with respect to color differences [33], vector distances must be calculated using the more perceptually uniform CIE (u','v') chromaticity diagram [4]. Coordinates in (u',v') space can be calculated from coordinates in (x,y) space using the relationships $u' = 4x/(3 - 2x + 12y)$ and $v' = 9y/(3 - 2x + 12y)$.

- The difference in B/L values between a reference and a test light source increases with increased saturation of the reference source. The saturation of the reference source in turn is dependent upon the dominant wavelength of the test source relative to the reference source [34 and 4] and upon the relative position of the test source's chromaticity between the chromaticity of the reference source and the chromaticity of the dominant wavelength. The dominant wavelength is, therefore, the wavelength along the spectrum locus of the chromaticity diagram that is intersected by a line continuing from the reference source's chromaticity through the test source's chromaticity in (u',v') space [35].

The vector distance D_v (in the u',v' chromaticity diagram [4]) between the reference and test light sources can be calculated using the following equation:

$$D_v = [(u'_r - u'_t)^2 + (v'_r - v'_t)^2]^{0.5} \qquad (2)$$

where the chromaticity coordinates of the reference source are (u'_r, v'_r) and the chromaticity coordinates of the test source are (u'_t, v'_t).

Figure 9 shows the relationship between wavelength and relative saturation for a range of visible wavelengths [34]. The dashed curve is the average for two observers. The solid curves represent the two observers. For example, the saturation of light at 530 nm is about twice that at 550 nm, and the saturation of light at 470 nm is about six times that at 550 nm.

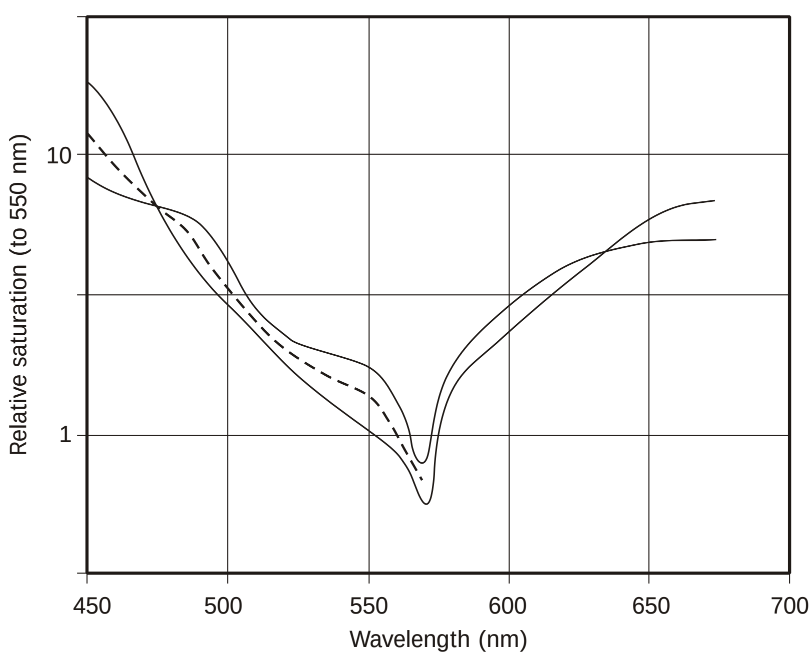

Figure 9. Relative Saturation (to 550 nm) of Light for Visible Wavelengths
(Adapted from reference 34.)

The solid lines represent data from two observers. The dashed line is the logarithmic mean and was used to approximate the relative saturation for dominant wavelengths between 450 and 570 nm, using the equation:

$$S_r = 10^{(5.5 - \lambda^{d/100})} \tag{3}$$

where S_r is the relative saturation and λ_d is the dominant wavelength (in nm) of the test light source relative to the reference light source.

Finally, a distance factor f is calculated by calculating the ratio between the value of D_v and the vector distance between the reference source and the monochromatic dominant wavelength (λ), using the equation:

$$f = D_v/[(u'_r - u'_{\lambda d})^2 + (v'_r - v'_{\lambda d})^2]^{0.5} \tag{4}$$

where the chromaticity coordinates of the reference light source as defined as in equation 2, and the chromaticity coordinates of the monochromatic dominant wavelength are $(u'_{\lambda d}, v'_{\lambda d})$.

When these three factors (D_v, S_r, and f) are multiplied together, the resulting products for each test light show consistent rank ordering with the mean B/L values measured for each test color in Experiment One. Except for the Blue 1 condition, these products are highly correlated (r^2=0.93) with the measured B/L values. For the Blue 1 condition, the measured B/L value was much lower than would be predicted from the product of D_v, S_r, and f.

There are several potential reasons for this discrepancy. One is that the lens of the human eye increases in absorption with decreasing wavelength [35], somewhat reducing sensitivity to light in this part of the visible spectrum. In addition, the relative saturation of light near 450 nm, close to the dominant wavelength of the Blue 1 LED signal light, has been shown in a series of studies using different methods (summarized by Kaiser et al. [36]) to be highly variable. In some cases, all wavelengths between 450 and 500 nm appear equally saturated.

This contradicts figure 9, which shows saturation increasing as wavelength decreases in this range of wavelengths. Furthermore, there are very few published data on brightness and color matching in the very short-wavelength region near 450 nm. Both the (x,y) and (u',v') color spaces are based on color matching data, and it is reasonable to suppose that either color space could be unsuitable to accurately represent differences in saturation and brightness in the very short-wavelength region of the spectrum. For this reason, the model described above, denoted the vector distance-relative saturation (VD-RS) model, was not used to predict the B/L value for this light source; instead, the empirical data from the present study were used.

Since the products of V_d, S_r and f were so highly correlated with the B/L measurements, predictions of B/L values can be made using a linear transformation of the products according the following equation:

$$B/L_{pred} = 2.32 D_v S_r f + 1.09 \tag{5}$$

Figure 10 shows the predicted and measured B/L values from the present study, plotted as a function of the predicted B/L values from the VD-RS model (excluding the Blue 1 test light).

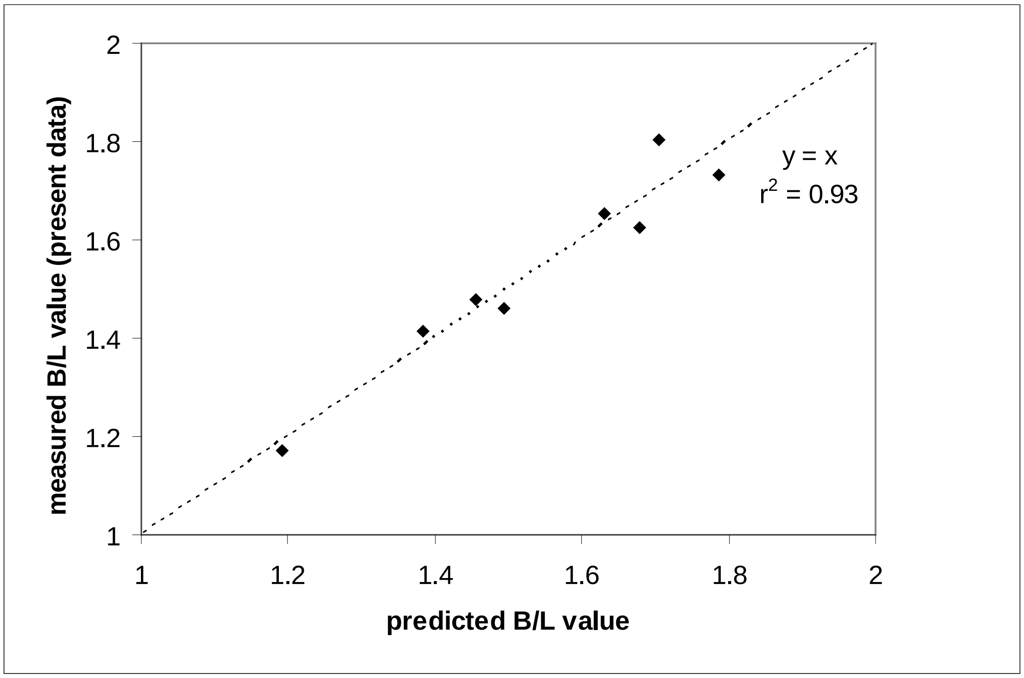

Figure 10. The Measured B/L Values

For the FAA blue color boundaries [6] transformed into the CIE (u',v') chromaticity space [4], figure 11 depicts contours (in steps of 0.2 units) showing predicted B/L values for all test light chromaticities within each color boundary plotted in the CIE (u',v') chromaticity space [4]. These values were calculated using the VD-RS model in equations 2 through 5 for Blue 2 and the empirical data for Blue 1. The same contours for white and green using the VD-RS model are shown in the graphs of figures 12 and 13, respectively. These same contours, when transformed back into the CIE (x,y) chromaticity space [4], are shown in figure 14.

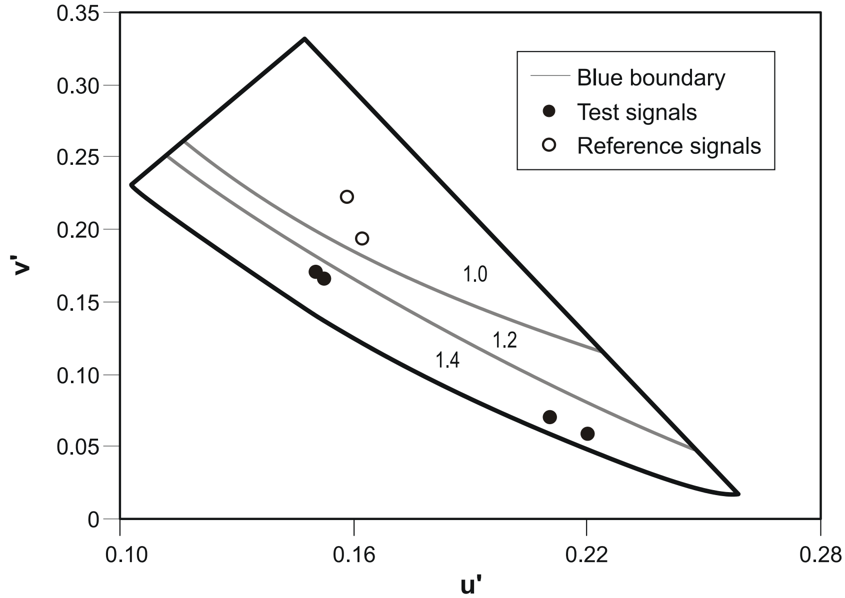

Figure 11. Contours Showing Regions of Equal Predicted B/L Values for Blue 1 and Blue 2

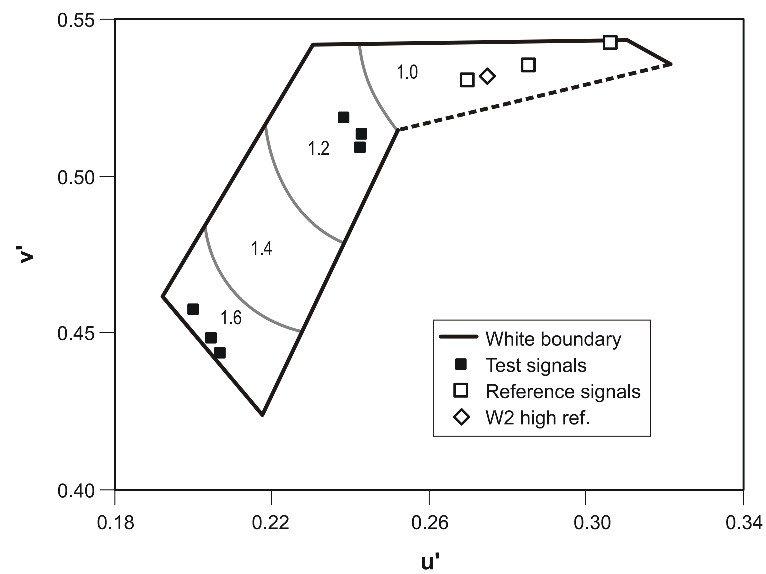

Figure 12. Contours Showing Regions of Equal Predicted B/L Values for White

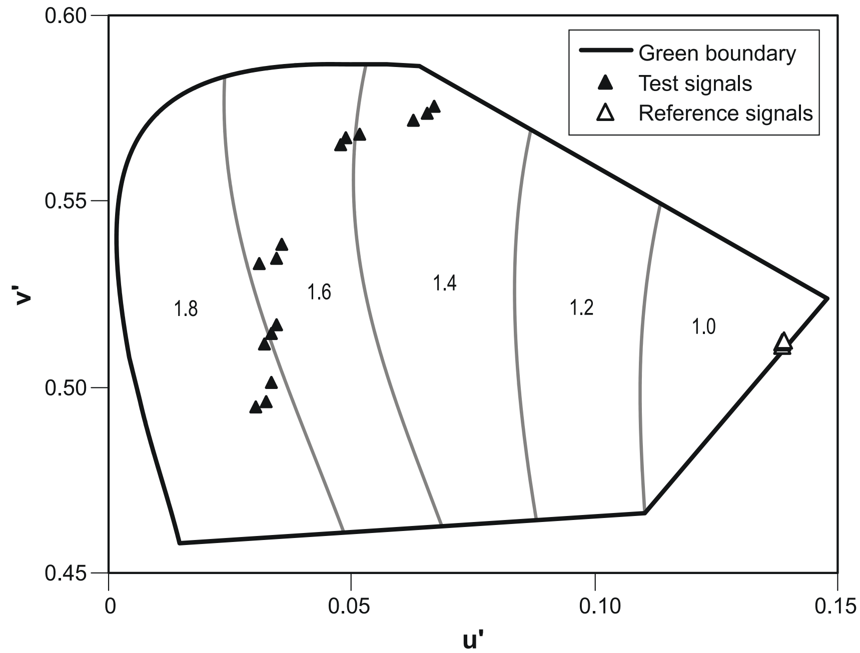

Figure 13. Contours Showing Regions of Equal Predicted B/L Values for Green

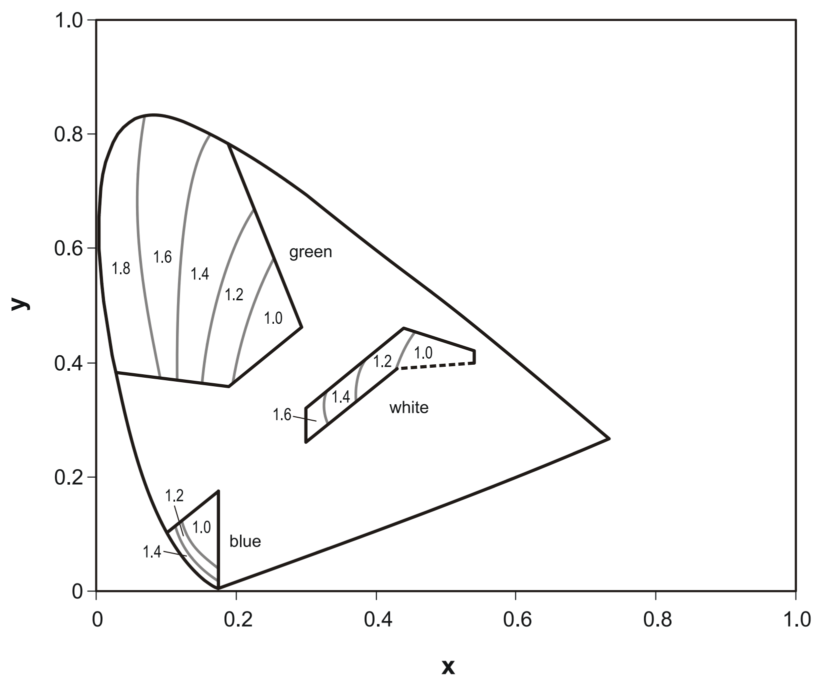

Figure 14. Contours Showing Regions of Equal Predicted B/L Values
(Plotted in the CIE (x,y) chromaticity space [4])

VALIDATION OF THE NEW B/L MODEL.

To test the utility of the model outlined in the preceding section, an independent set of B/L data for blue, white, and green colors [10] were analyzed using the VD-RS model. Alman [10] measured B/L values using a white incandescent light (2856 K) as a reference for a series of test light sources having various chromaticities. This was one of the few published studies that compared B/L values for white and colored stimuli and reported the stimuli characteristics in sufficient detail for reanalysis. B/L predictions were calculated for the test light sources used by Alman [10], according to equation 5.

Similar to the present study, the B/L value for the most saturated blue light test source measured by Alman [10] was also lower than the values in equation 5 would predict. Clearly, the knowledge of brightness perception of very saturated blue signal lights presently is not well understood. Excluding this source from analysis resulted in a very high correlation (r^2=0.87) between the predicted B/L values calculated using equation 5 and the measured B/L values from Alman [10], as shown in figure 15.

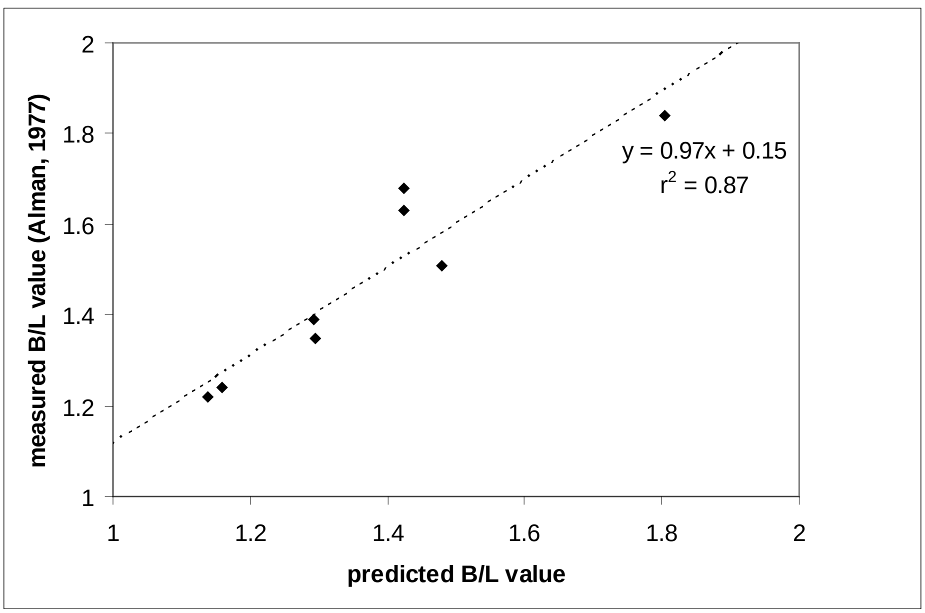

Figure 15. The Measured B/L Values From Alman [10]
(Excluding the most saturated blue test light used by Alman [10])

The high degree of agreement obtained using the VD-RS model with the B/L measurements is encouraging. However, the similar difficulties encountered in predicting B/L values for the most saturated blue signal lights underscores the need to rely on empirical data when making predictions of apparent brightness for signals of this color, until future study can provide a more refined model that addresses the unique brightness characteristics of highly saturated, short-wavelength blue lights.

SUMMARY

The results of the present study demonstrate that signal lights with different chromaticities, but within the same FAA color specifications [6], can have very different brightness characteristics even when they have the same luminous intensity. Viewing the signal lights in arrays, as is likely for runway aviation applications, or against dim rather than dark backgrounds, did not strongly affect B/L values. Nor did the absolutely intensity of the signal light strongly impact B/L values, within the ranges of signal luminous intensities studied.

The VD-RS model outlined in this technical note and the illustrated contours provide a model and a framework for identifying the B/L values for any signal lights within the blue, white, and green color specifications [6]. The approach used in the VD-RS model could also be used to test predictions of B/L values for signal lights having different colors, such as yellow, orange, or red.

Using the representative chromaticity data in figure 1, currently available products and prototypes are likely to correspond most closely with the test colors Blue 2, White 1, and Green 5. The B/L values for these colors (approximately 1.4, 1.6, and 1.4, respectively) may be most useful for preliminary LED-specific recommendations.

An important consideration when applying these values is the potential for desaturation of LED signal colors by light scatter in fog. The measured B/L values for the Blue 1, White 1, and Green 1 LED test signal colors in Experiment Four (fog) were lower than when the same signal lights were viewed in clear conditions. This implies that light scattered by fog can desaturate colors and therefore reduce the brightness advantage of saturated signal lights. Thus, if a more saturated signal light is reduced in luminous intensity to achieve equal brightness (in clear conditions) as a less saturated signal light, the former signal light can appear less bright than the latter signal when the two are viewed through fog.

Another factor regarding signal light perception, not directly addressed by the present study, is the speed and accuracy with which a signal light can be detected. Despite differences in brightness between signal lights with different degrees of color saturation, reaction times and detection probabilities for signal lights depend primarily on their luminous intensity, not their brightness, assuming the signal lights are brighter than the backgrounds behind them [7 and 37]. This assumption is certainly true during nighttime flight conditions and is also likely during the daytime as well. Thus, reducing luminous intensity of a saturated signal light to compensate for enhanced brightness can result in longer reaction times to, and lower probabilities of detecting, the more saturated signal lights.

Presumably, however, the luminous intensities of many signal lights for aviation applications are designed to be well above the visual threshold, even during daytime viewing conditions. Well above visual threshold, reaction times and detection probabilities are likely asymptotic [38], such that reductions in luminous intensity of saturated signal lights to achieve equal brightness as less saturated lights would not greatly impact visual performance. Thus, differences in luminous intensity may not be as important under many viewing conditions as is providing consistent brightness appearance of light signal patterns on the airfield, which may be used by pilots to appropriately align aircraft to runways during their approaches.

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APPENDIX A—RESULTS FROM EXPERIMENT ONE SHOWN IN BRIGHTNESS JUDGMENT PERCENTAGES BETWEEN INCANDESCENT AND LIGHT-EMITTING DIODE SOURCES

Figures A-1 through A-25 show the percentages of times the light-emitting diode (LED) signal lights were judged brighter than the incandescent signal lights for each lighting condition in Experiment One. The best fitting logistic functions to the data are also shown.

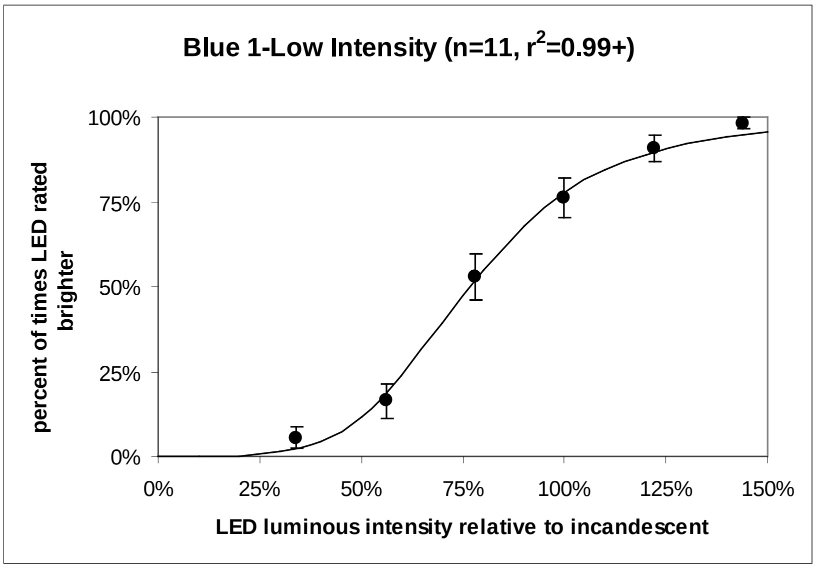

Figure A-1. Blue 1—Low Intensity

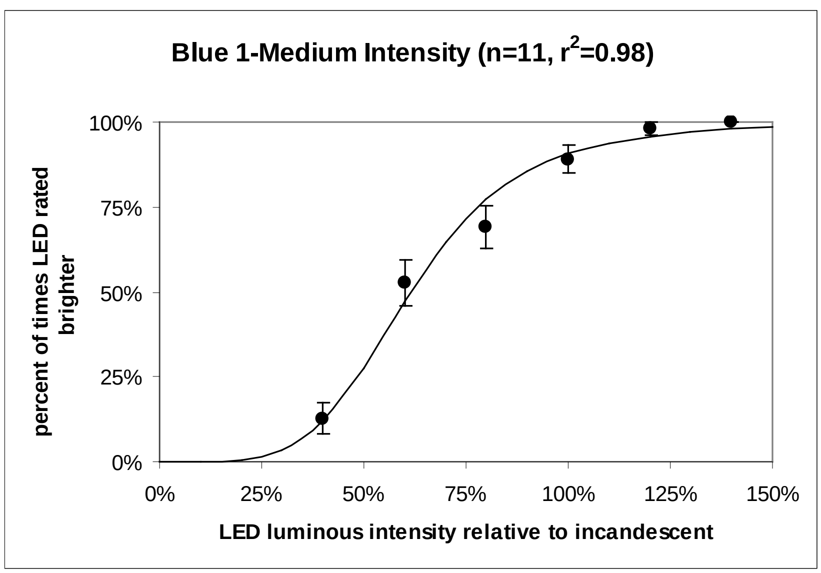

Figure A-2. Blue 1—Medium Intensity

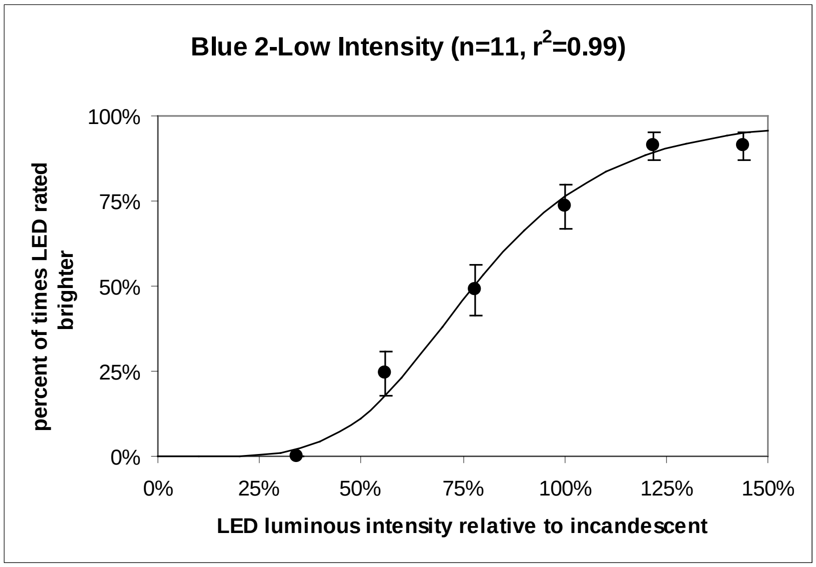

Figure A-3. Blue 2—Low Intensity

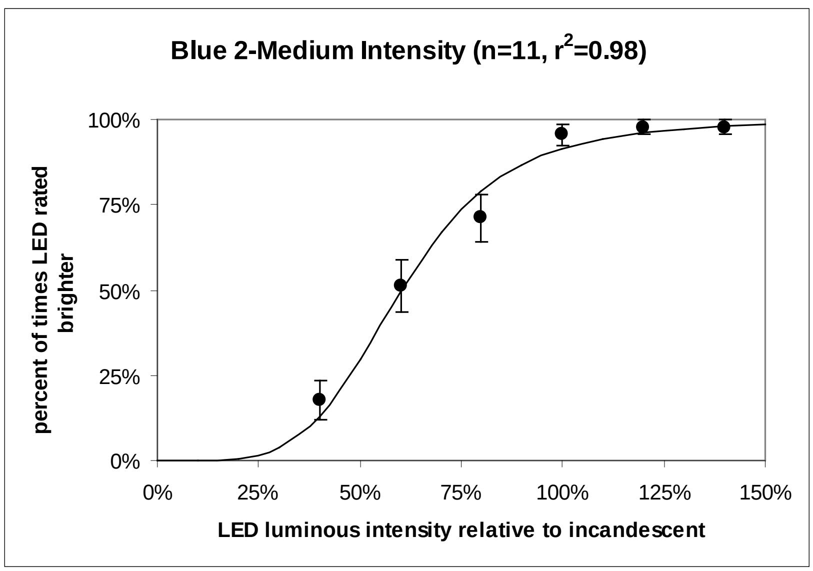

Figure A-4. Blue 2—Medium Intensity

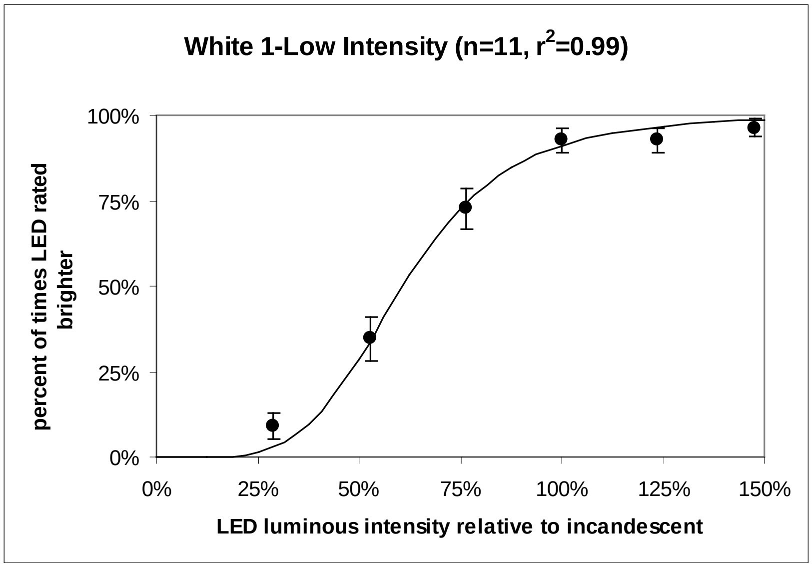

Figure A-5. White 1—Low Intensity

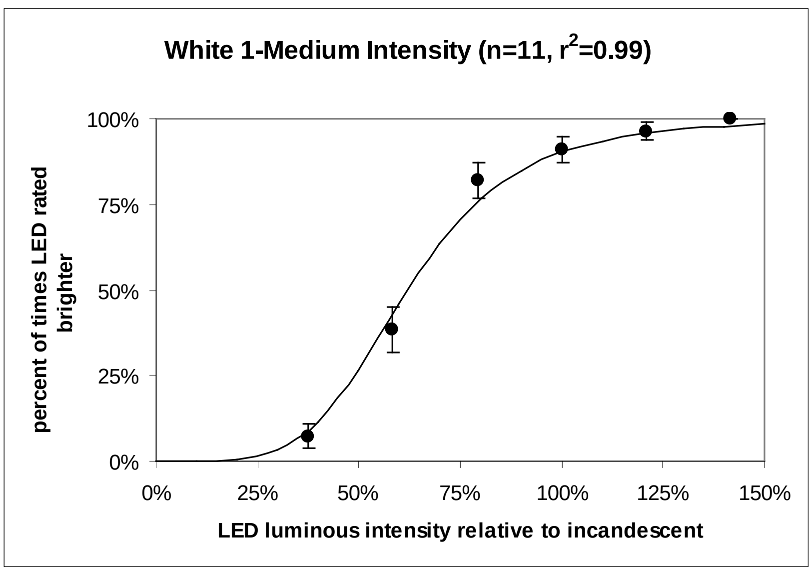

Figure A-6. White 1—Medium Intensity

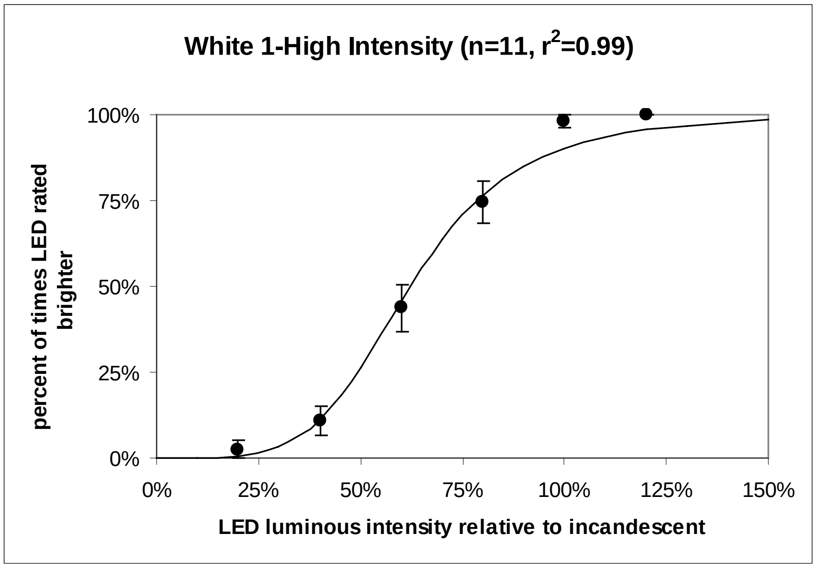

Figure A-7. White 1—High Intensity

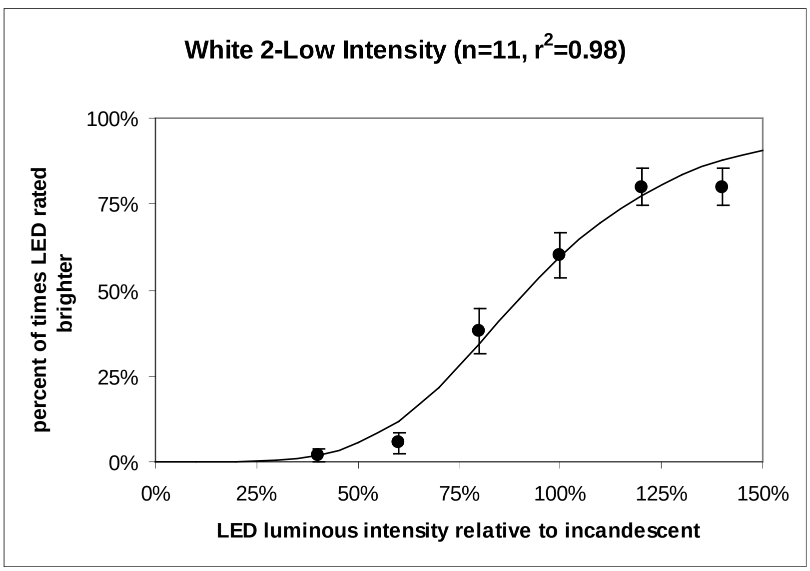

Figure A-8. White 2—Low Intensity

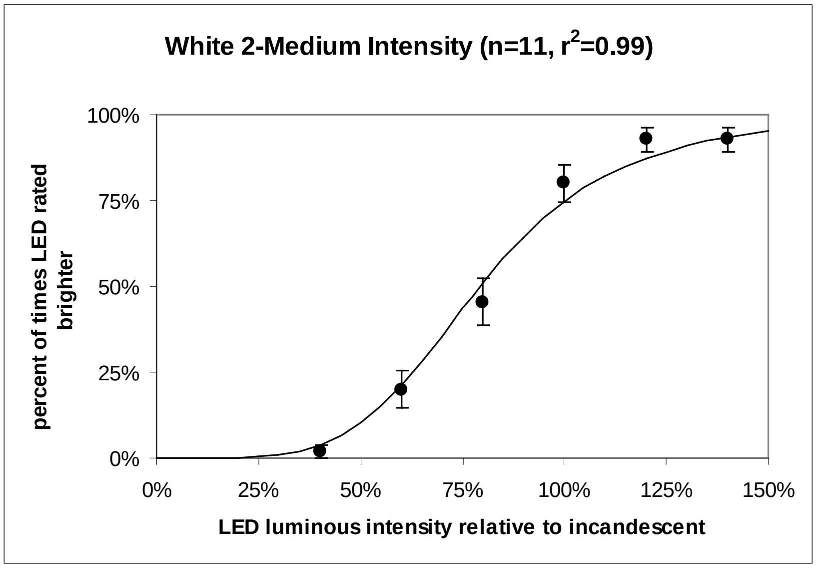

Figure A-9. White 2—Medium Intensity

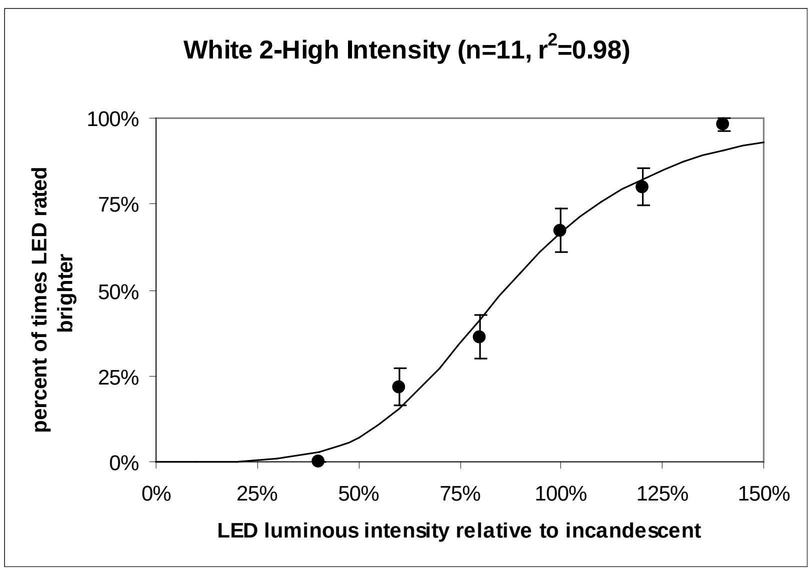

Figure A-10. White 2—High Intensity

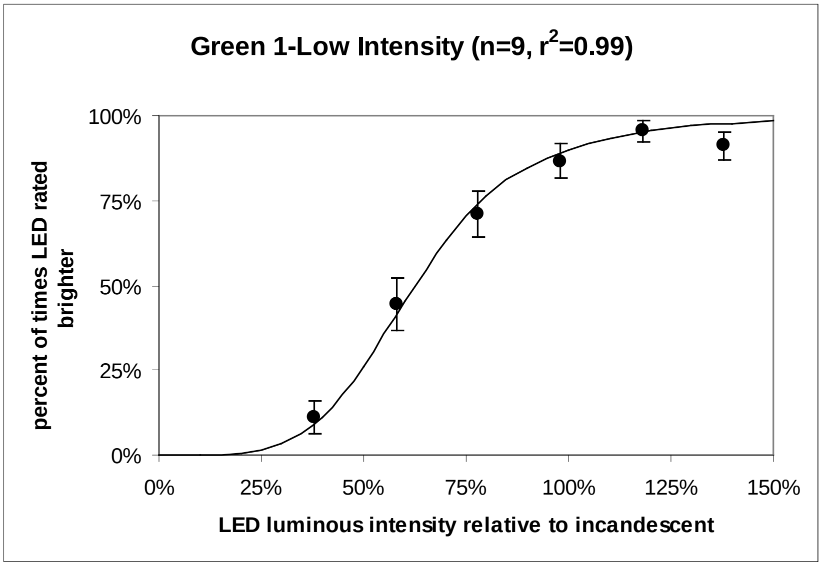

Figure A-11. Green 1—Low Intensity

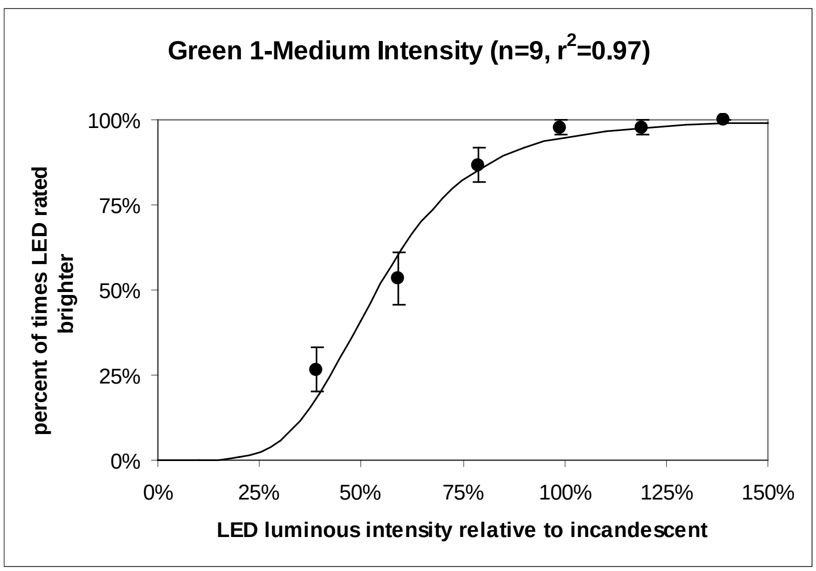

Figure A-12. Green 1—Medium Intensity

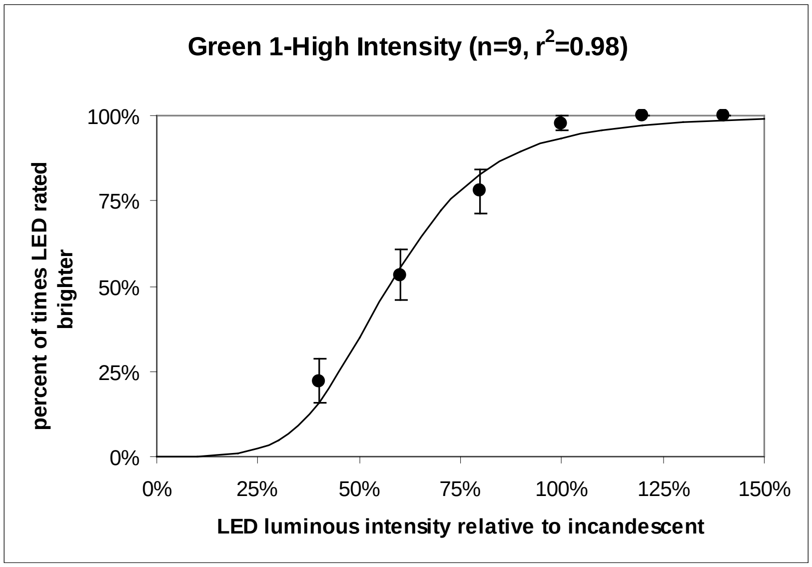

Figure A-13. Green 1—High Intensity

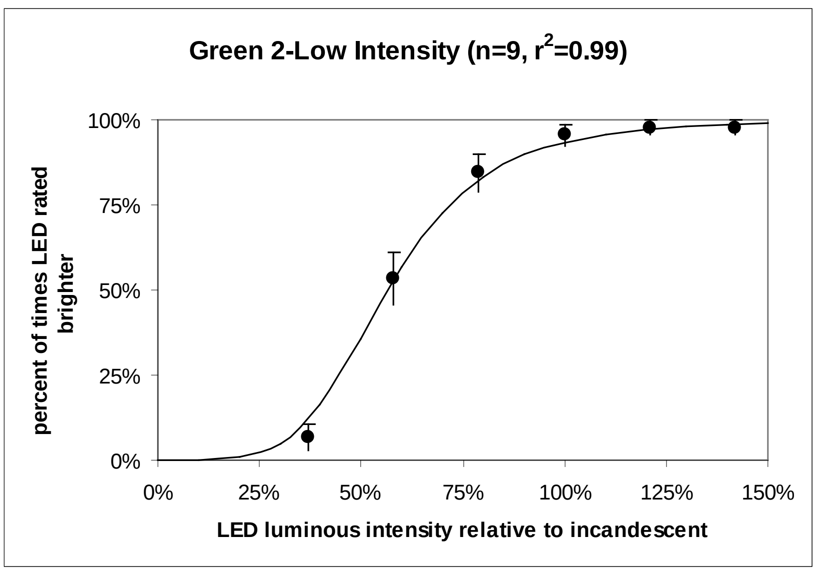

Figure A-14. Green 2—Low Intensity

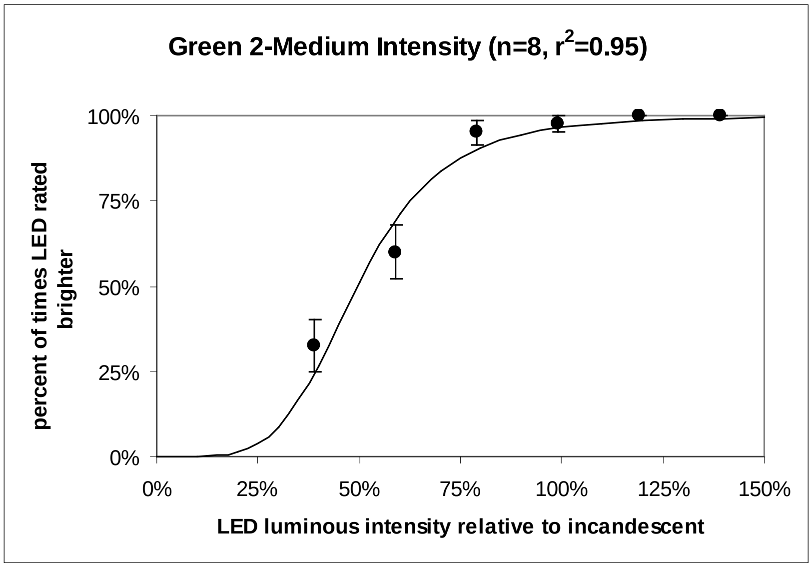

Figure A-15. Green 2—Medium Intensity

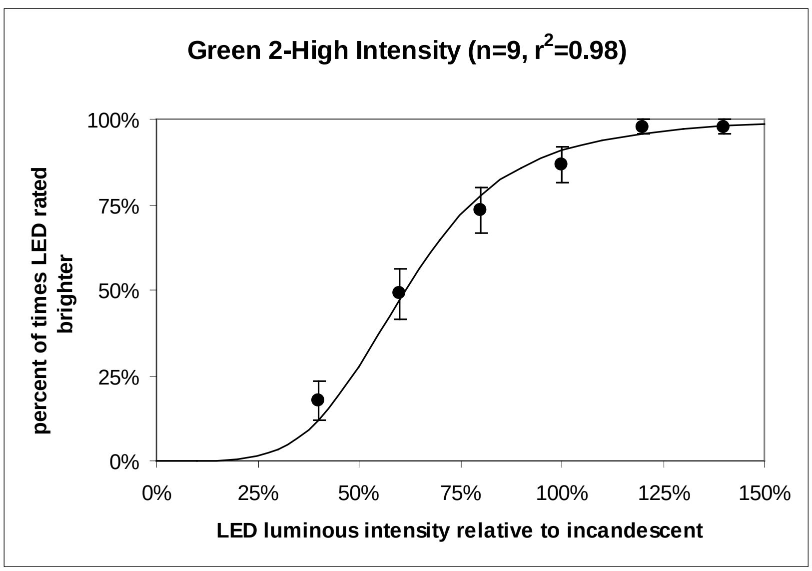

Figure A-16. Green 2—High Intensity

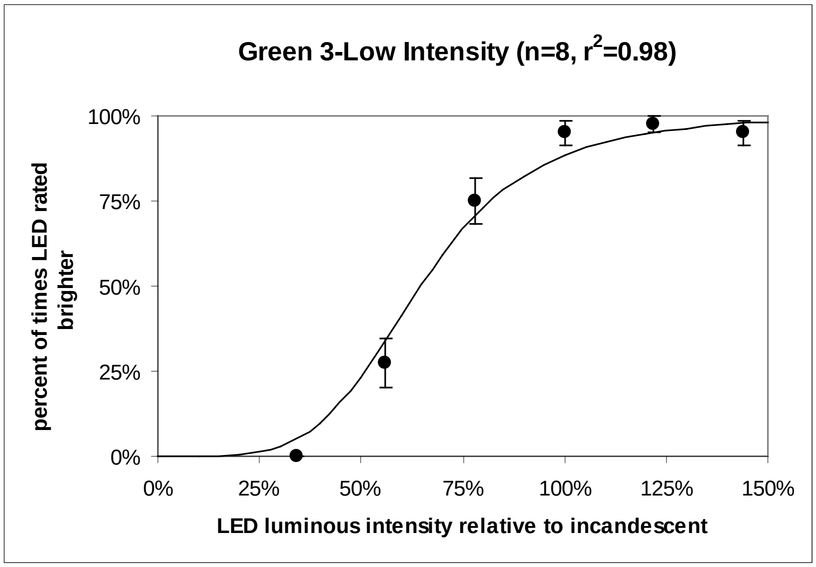

Figure A-17. Green 3—Low Intensity

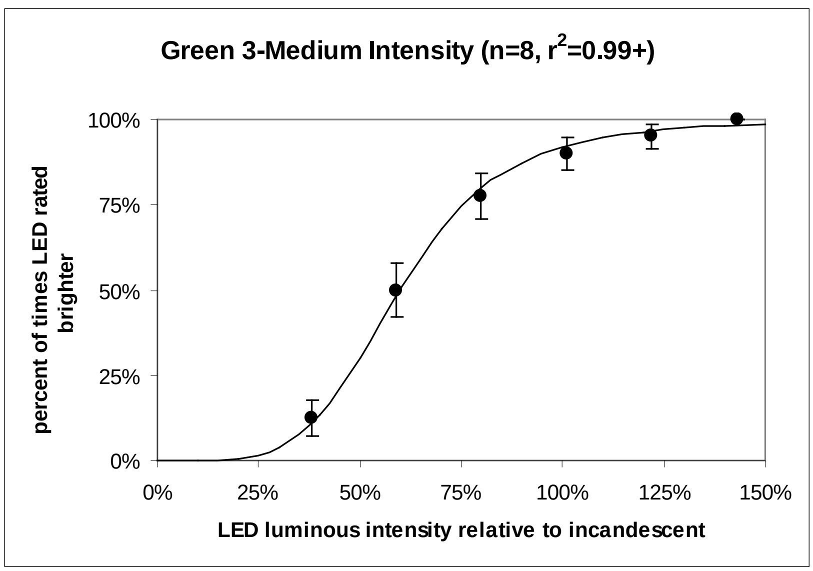

Figure A-18. Green 3—Medium Intensity

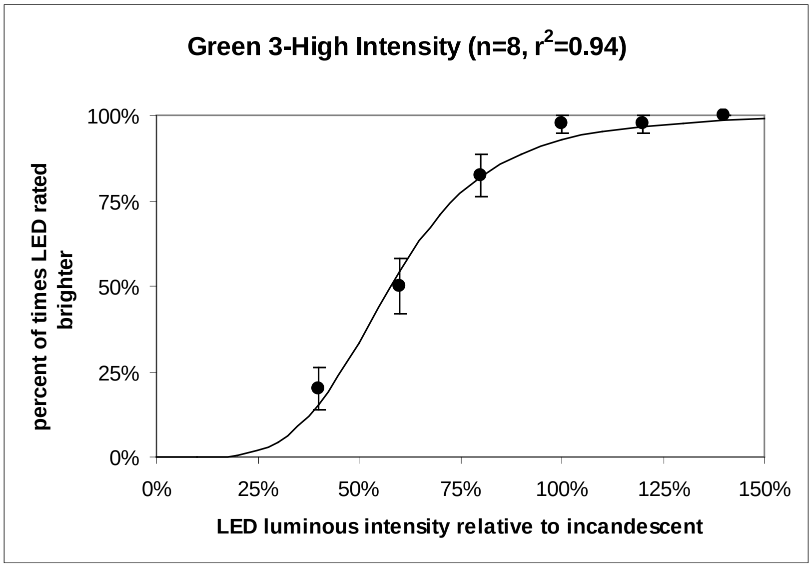

Figure A-19. Green 3—High Intensity

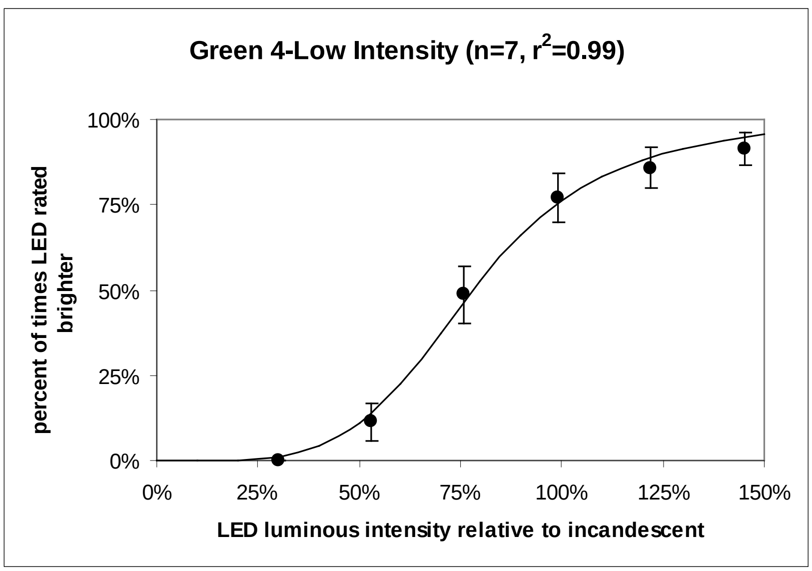

Figure A-20. Green 4—Low Intensity

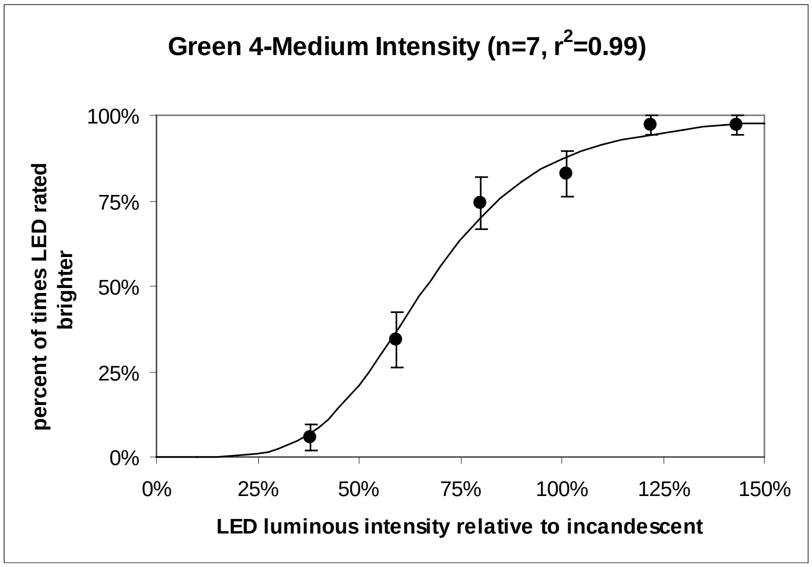

Figure A-21. Green 4—Medium Intensity

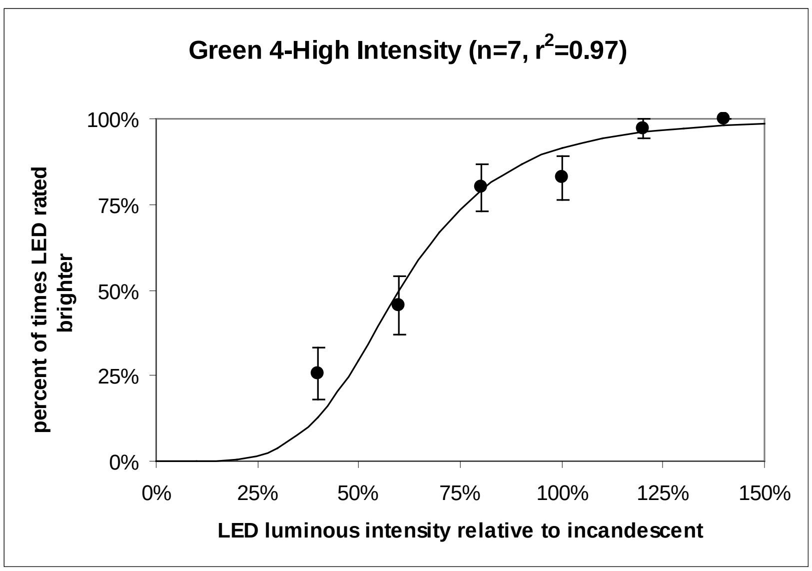

Figure A-22. Green 4—High Intensity

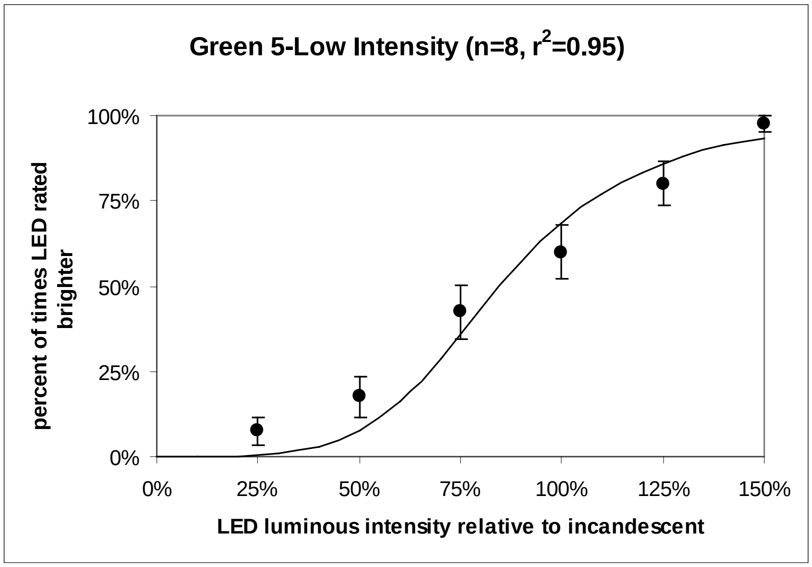

Figure A-23. Green 5—Low Intensity

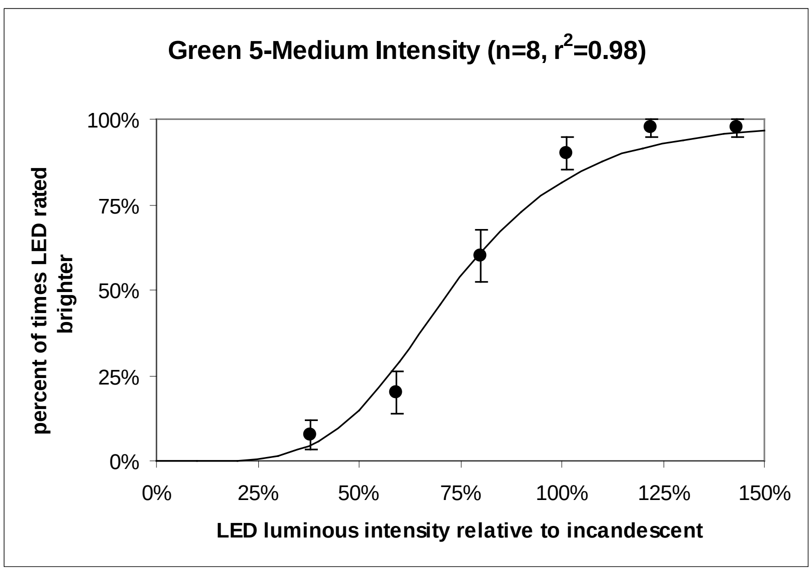

Figure A-24. Green 5—Medium Intensity

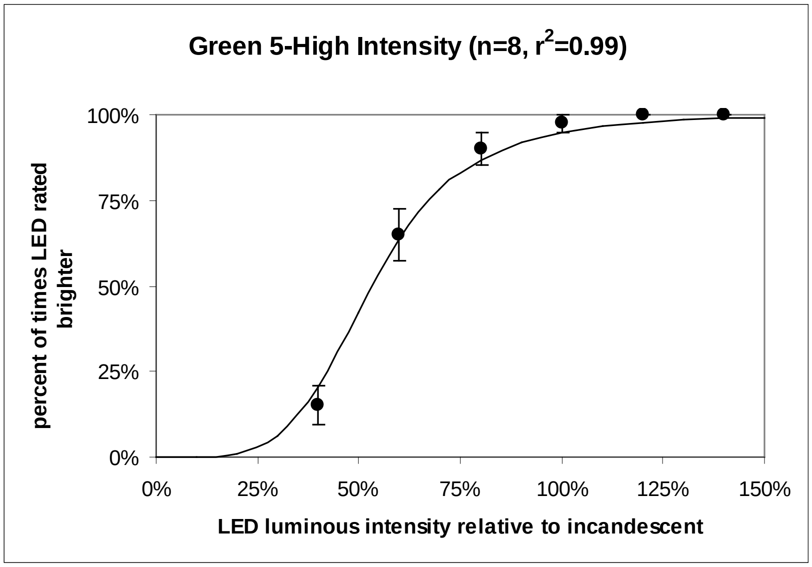

Figure A-25. Green 5—High Intensity

APPENDIX B—RESULTS FROM EXPERIMENT TWO SHOWN IN BRIGHTNESS JUDGMENT PERCENTAGES BETWEEN INCANDESCENT AND LIGHT-EMITTING DIODE SOURCES

Figures B-1 through B-3 show the percentages of times the light-emitting diode (LED) signal lights were judged brighter than the incandescent signal lights for each lighting condition in Experiment Two (array). The best fitting logistic functions to the data are also shown.

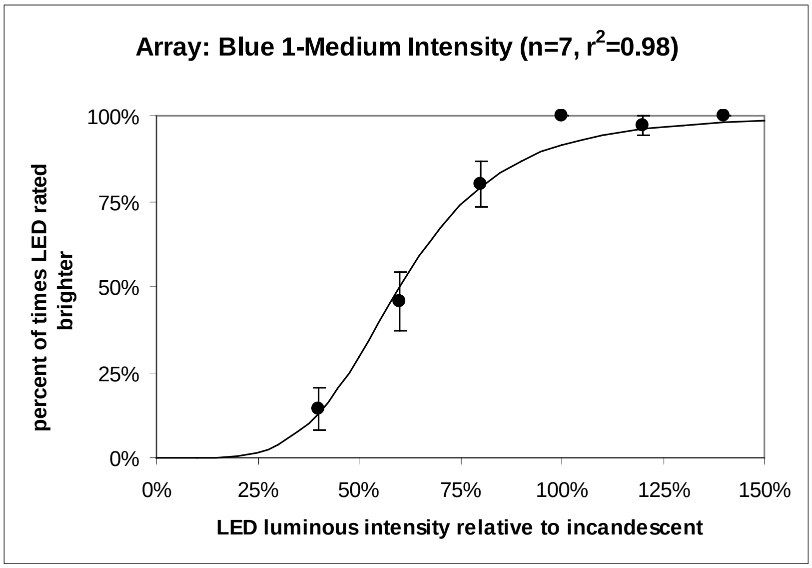

Figure B-1. Blue 1—Medium Intensity

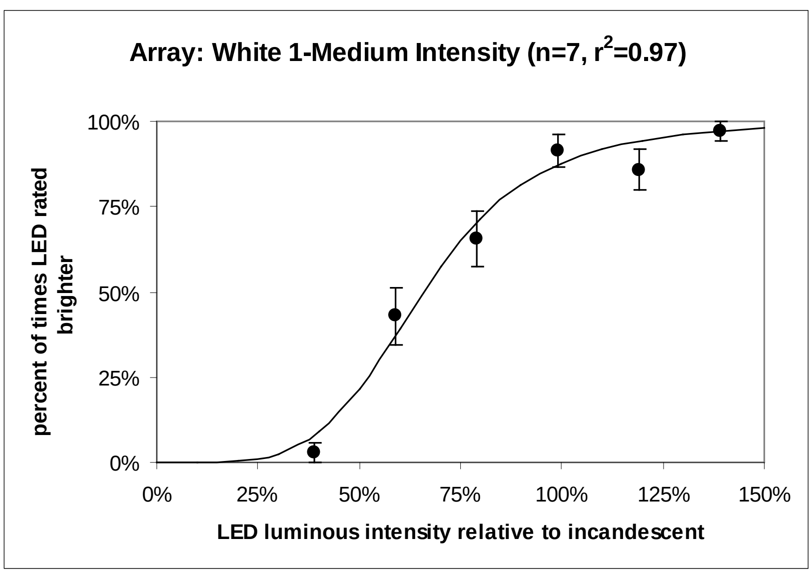

Figure B-2. White 1—Medium Intensity

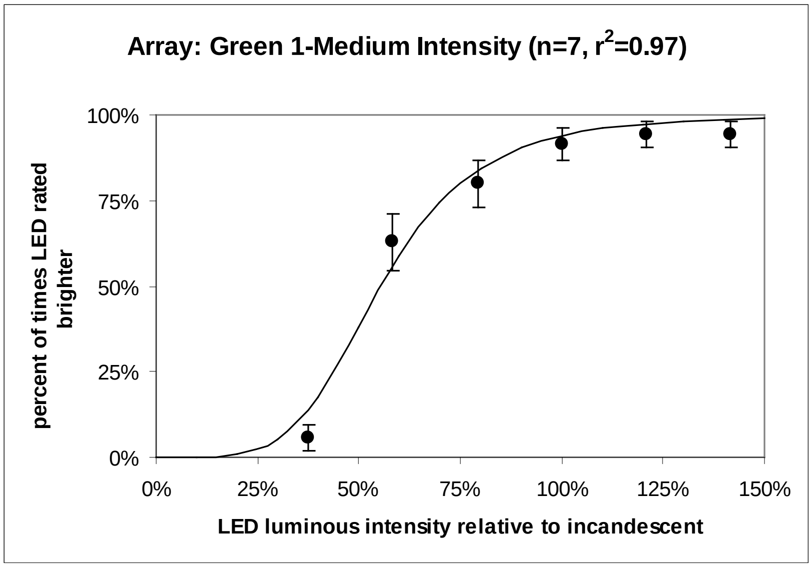

Figure B-3. Green 1—Medium Intensity

APPENDIX C—RESULTS FROM EXPERIMENT THREE SHOWN IN BRIGHTNESS JUDGMENT PERCENTAGES BETWEEN INCANDESCENT AND LIGHT-EMITTING DIODE SOURCES

Figures C-1 through C-3 show the percentages of times the light-emitting diode (LED) signal lights were judged brighter than the incandescent signal lights for each lighting condition in Experiment Three (dim background). The best fitting logistic functions to the data are also shown.

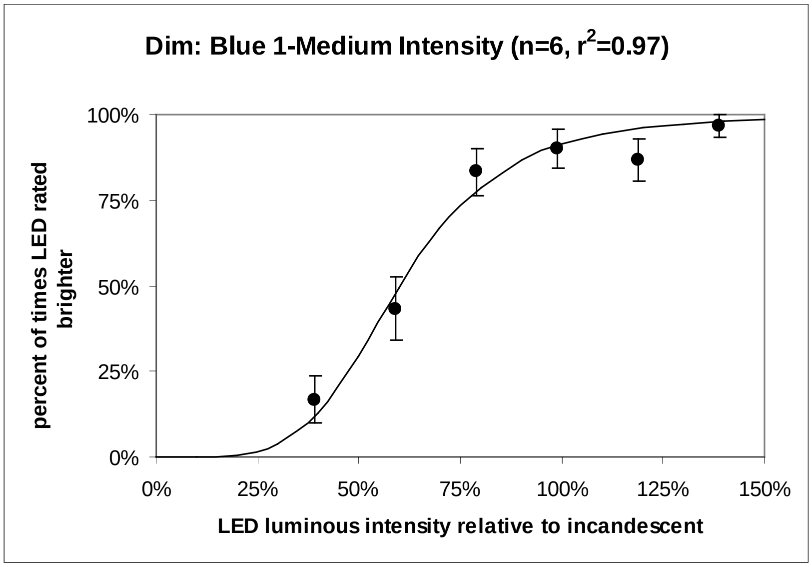

Figure C-1. Blue 1—Medium Intensity

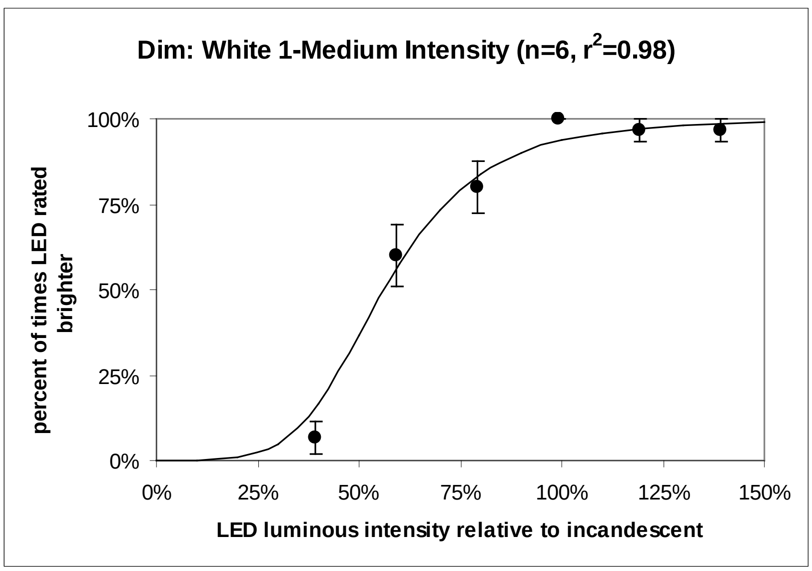

Figure C-2. White 1—Medium Intensity

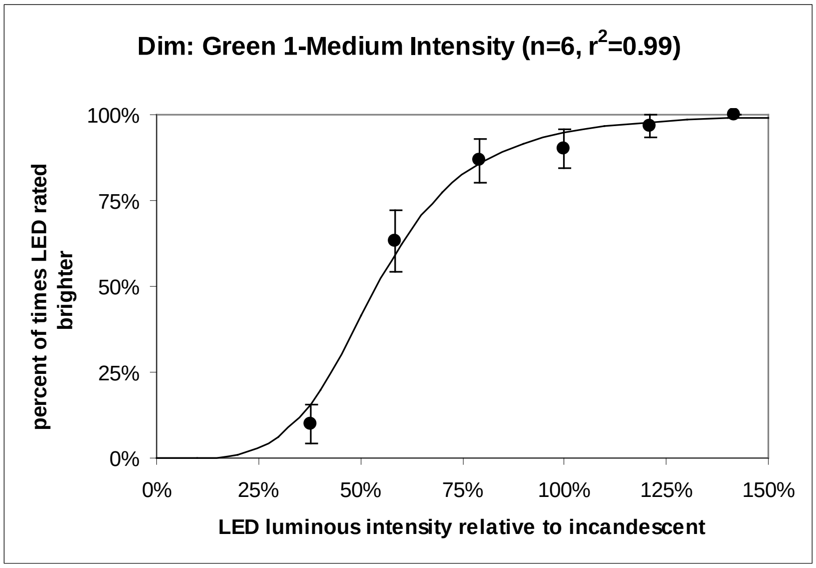

Figure C-3. Green 1—Medium Intensity

APPENDIX D—RESULTS FROM EXPERIMENT FOUR SHOWN IN BRIGHTNESS JUDGMENT PERCENTAGES BETWEEN INCANDESCENT AND LIGHT-EMITTING DIODE SOURCES

Figures D-1 through D-3 show the percentages of times the light-emitting diode (LED) signal lights were judged brighter than the incandescent signal lights for each lighting condition in Experiment Four (fog). The best fitting logistic functions to the data are also shown.

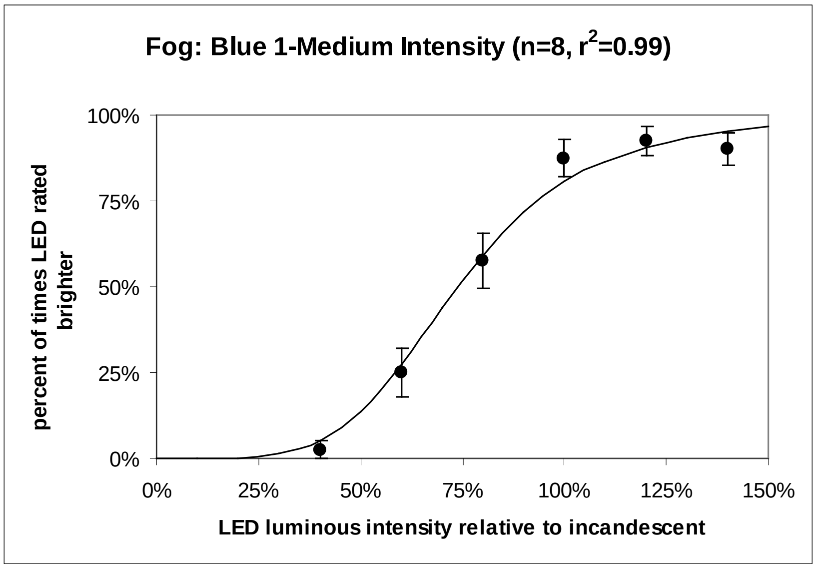

Figure D-1. Blue 1—Medium Intensity

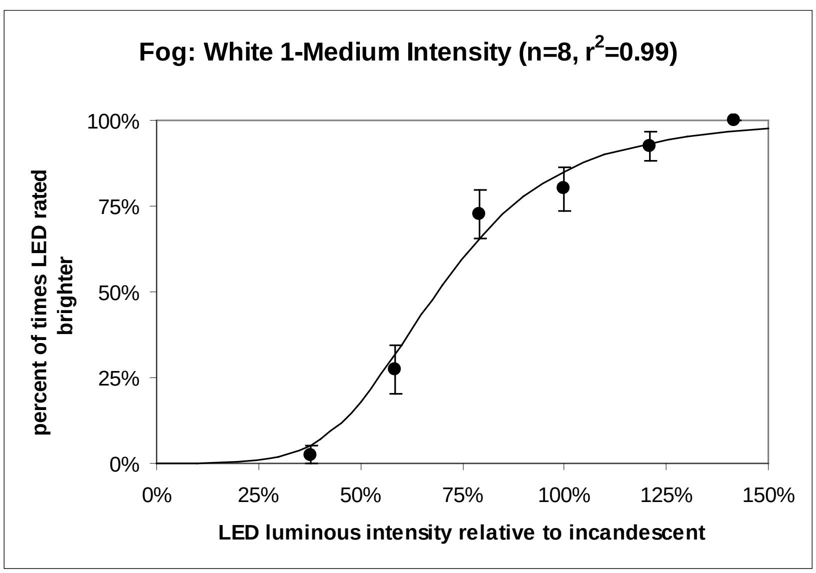

Figure D-2. White 1—Medium Intensity

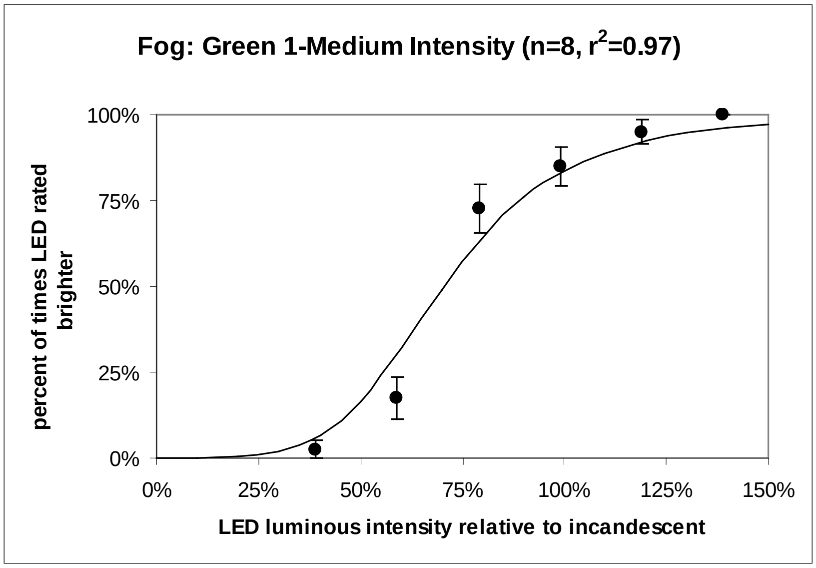

Figure D-3. Green 1—Medium Intensity