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Nonincandescent Source Aviation Signal Light Colors

October 2012

DOT/FAA/TC-TN12/45

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16. Abstract

Aviation signal lighting systems are increasingly replacing filtered and unfiltered incandescent lamps with light-emitting diode (LED) sources to create various signal light colors. As LED sources produce spectral distributions that can differ in color appearance from incandescent signal lights, it is important to understand how the characteristics of LEDs influence color identification.

The objective of this research was to provide chromaticity regions for aviation signal lights that maximize the likelihood of correct identification while minimizing the potential for confusion with other colors.

Three color identification studies of aviation signal lights were conducted to produce white, yellow, red, blue, and green colors using filtered and unfiltered incandescent lamps and LEDs. The objectives of these studies were to (1) identify chromaticity regions resulting in a high probability of correctly identifying aviation signal lights as white; (2) compare the color identification performance of color-normal and color-deficient observers in response to incandescent and LED signal lights of each nominal color (white, yellow, red, blue, and green); and (3) identify chromaticity regions resulting in a high probability of correctly identifying aviation signal lights as yellow, red, or blue.

Based on the results of these studies, recommendations for each of the nominal signal colors are provided in the Commission Internationale de l'Éclairage 1931 chromaticity space.

17. Key Words

Aviation signal lighting, Color vision, Light-emitting diodes, Color identification

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LIST OF ACRONYMS

ANSI	American National Standards Institute
CAD	Colour Assessment and Diagnosis
CAMI	Civil Aerospace Medical Institute
CCT	Correlated color temperature
cd	Candela
CIE	Commission Internationale de l'Éclairage (also Commission on Illumination)
FAA	Federal Aviation Administration
ICAO	International Civil Aviation Organization
K	Kelvin unit
L	Long wavelength
LCD	Liquid crystal display
LED	Light-emitting diode
LRC	Lighting Research Center
lux	Luminous flux (measurement)
M	Medium wavelength
MALSR	Medium-intensity approach lighting system with runway alignment indicator lights
mlx	Millilux
nm	Nanometers
PAPI	Precision approach path indicator
RPI	Rensselaer Polytechnic Institute
SAE	Society of Automotive Engineers
SLG	Signal light gun
W	Watt

EXECUTIVE SUMMARY

Aviation signal lighting systems are increasingly replacing filtered and unfiltered incandescent lamps with light-emitting diode (LED) sources to create various signal light colors. As LED sources produce spectral distributions that can differ in color appearance from incandescent signal lights, it is important to understand how LED characteristics influence color identification. Using this more efficient light source (i.e., LEDs produce more light with less heat than incandescent lights), color regions can be refined to avoid confusion among colors at all intensities and to provide an improved visual cue to the user at reduced energy and maintenance costs. This technical note summarizes the Federal Aviation Administration studies conducted to assess color identification across the different light sources and presents recommendations for the specification of LED signal lights.

The objective of this research was to provide chromaticity regions for aviation signal lights that maximize the likelihood of correct identification while minimizing the potential for confusion with other colors.

Three color identification studies of aviation signal lights were conducted to produce white, yellow, red, blue, and green colors using filtered and unfiltered incandescent lamps and LEDs. These studies were to (1) identify chromaticity regions resulting in a high probability of correctly identifying aviation signal lights as white; (2) compare the color identification performance of color-normal and color-deficient observers in response to incandescent and LED signal lights of each nominal color (white, yellow, red, blue, and green); and (3) identify chromaticity regions resulting in a high probability of correctly identifying aviation signal lights as yellow, red, or blue.

Based on the results of these studies, recommendations for each of the nominal signal colors are provided in the Commission Internationale de l'Éclairage 1931 chromaticity space.

INTRODUCTION

PURPOSE.

Aviation signal lighting systems are increasingly replacing filtered and unfiltered incandescent lamps with light-emitting diode (LED) sources to create various signal light colors. LED sources produce spectral distributions that can differ in color appearance from incandescent signal lights; therefore, it is important to understand how the characteristics of LEDs influence color identification. This technical note summarizes several Federal Aviation Administration (FAA) studies conducted to assess color identification across different light sources and presents recommendations for the specification of LED signal lights. This research is intended to provide chromaticity regions that maximize the likelihood of correct identification while minimizing the potential for confusion with other colors.

BACKGROUND.

Aviation signal lights that use LED sources differ from their counterparts using filtered or unfiltered incandescent lamps, to generate specific colors or unfiltered to produce white light, in several important ways. Colored LEDs produce narrowband spectral output with highly saturated color appearance that meets FAA chromaticity requirements, but has different chromaticity values from filtered incandescent sources. Because of this, incandescent light sources usually produce less saturated colors than LEDs. Additionally, white LED sources are available in higher correlated color temperatures (CCT) than incandescent filament sources. These differences can have implications for color identification of aviation signal lights.

In using this more efficient light source (i.e., LEDs produce more light with less heat than incandescent lights), color regions can be refined to avoid confusion among colors at all intensities and to provide an improved visual cue to the user at reduced energy and maintenance costs.

SCOPE.

The studies described in this technical note are laboratory studies of color identification under varying conditions and in response to different incandescent and LED light sources.

Three color identification studies of aviation signal lights were conducted to produce white, yellow, red, blue, and green colors using filtered and unfiltered incandescent lamps and LEDs.

This technical note presents the results from three studies, discussion of related literature on color identification of signal lights varying in chromaticity, and recommendations for, for white, yellow, red, blue, and green signal lights chromaticity regions.

STUDY 1: CHROMATICITY BOUNDARY FOR AVIATION WHITE LIGHT

INTRODUCTION.

Several aspects are involved in the recognition of an aviation signal light source's color, including chromaticity, the configuration of the sources that comprise the signal system, and the chromaticity of neighboring light sources (i.e., whether they are signal sources or illumination sources). The FAA currently uses the Society of Automotive Engineers (SAE) standard AS25050 [1] to define the chromaticity limits, or boundaries, for recognition of various aviation signal colors. Chromaticity standards for signal light sources applicable to air travel operations are also currently maintained by the Commission Internationale de l'Éclairage (CIE) [2] and by the International Civil Aviation Organization (ICAO) [3].

The chromaticity values used by the FAA for aviation white, as defined by SAE AS25050 [1], were created nearly 50 years ago [4] using incandescent light sources as a basis. The SAE standard's blue boundary for the aviation white color ($x = 0.360$) presently excludes certain LED color bins that may be perceived as white, potentially causing hardship and expense in adopting many new, energy- and maintenance-saving LED products for this application. While phosphor-converted white LEDs are available in a range of chromaticities, covering a large range of CCT values, the least expensive and highest-efficiency products typically have CCT values well over 5000 Kelvin units (K) due to the method of obtaining white light and the nature of available phosphors. As a result, only a small subset of commercially available white LEDs meets the current chromaticity requirements for aviation white. The white boundaries of SAE AS25050 may need to be redefined independently of the color limitations of incandescent light sources to better coincide with the colors that people identify as white, thereby removing any unnecessary restrictions that limit LED or other new light sources from being considered.

This technical note describes a study conducted by the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute (RPI) that investigated the chromaticity region, or boundaries, that define what people naturally identify as white in the context of the current standards. A range of test sources were evaluated having chromaticity points both within and outside the current aviation white boundaries. From these evaluations, recommendations were developed for aviation white boundaries that can include newer LED technology.

BACKGROUND.

HISTORY OF AVIATION SIGNAL COLOR REQUIREMENTS. According to Breckenridge [5], the first document for use in the United States that specified aviation colors was AN-C-56 [6], which was introduced in 1942. This original standard required that signal colors be "similar" to the specified standard filters. The chromaticity specifications that constituted what "similar" meant were eventually incorporated into the document [5], which later became MIL-C-25050A [4].

Federal Standard No. 3 [7] defined the chromaticity limits of various aviation colors using boundaries drawn in the CIE 1931 chromaticity space but also retained guidance on filter selection for obtaining suitable colors using incandescent sources. MIL-C-25050A [4] provided only the chromaticity limits of the color boundaries and did not reference filters. MIL-C-25050A was eventually adopted by the SAE and has since become SAE AS25050 [1], which is in use today and has remained unchanged since 1963.

Concurrent to the standards-setting activities taking place in the U.S. in 1948, the CIE recognized the importance of unifying the signal color specifications on an international basis. A committee to research and recommend chromaticity boundaries for the various signal colors was established. Before the committee issued its final findings, ICAO solicited interim recommendations for the establishment of its own standards. Accordingly, ICAO and CIE standards have been consistent with each other [5].

The U.S. established a National Committee to participate in the CIE international committee on the color of signal lights. After the CIE issued its official recommendations on signal colors, the U.S. committee worked to develop a tentative U.S. standard for signal colors, which was based on the use of standard filters with incandescent sources. The use of standard filters was chosen because colorimeters capable of reliably measuring chromaticity were not commonly available [5]. This tentative standard never replaced MIL-C-25050A [4].

SIGNAL LIGHT CHROMATICITY STANDARDS AND DEFINITIONS. The definition of aviation white for signal lights was largely based on the capability and limitations of the available technology at the time, which was limited to incandescent filament sources. The chromaticity boundary of white as specified by Federal Standard No. 3 [7] is presented first because it is referenced by SAE AS25050 [1].

Figure 1 shows the chromaticity boundaries of SAE AS25050 drawn on the CIE 1931 chromaticity diagram pertaining to white signal sources. There are three important features of this region. First, it follows the black body, or Planckian, locus (which is the path the color of an incandescent black body would take in a particular chromaticity space as its temperature changes). Second, separate regions are provided for white and variable white. Third, the distance from the black body locus depends on the x-chromaticity value in the following manner: $y-y0 = 0.3x$.

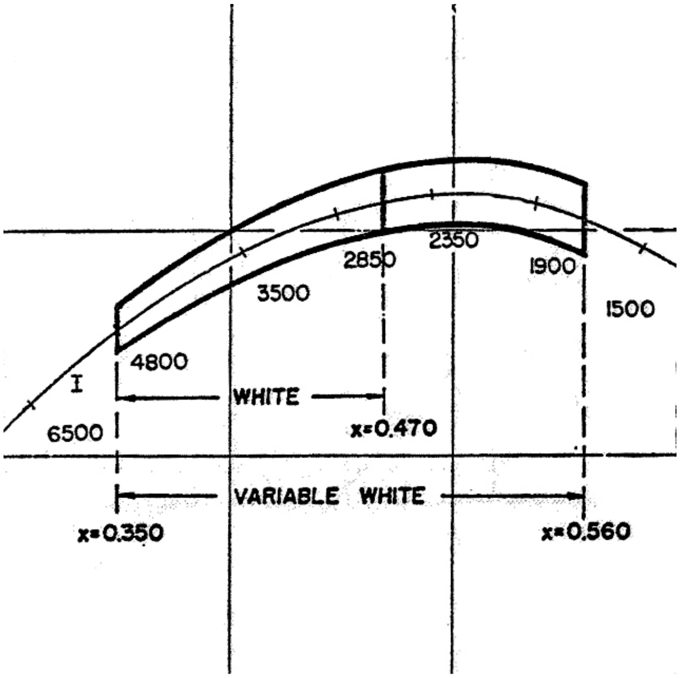


Figure 1. Chromaticity Limits for White Signal Lights Defined by Federal Standard No. 3 [7] Shown on CIE 1931 Chromaticity Space

Figure 2 shows the aviation color limits as defined by SAE AS25050 [1], which are the same as those defined by MIL-C-25050A [4]. The biggest changes for aviation white between Federal Standard No. 3 [7] and SAE AS25050 [1] are (1) the right boundary is moved from x = 0.560 to x = 0.540; (2) the permitted deviation from the Planckian radiator is redefined to be y-y0 = 0.01, which is not x dependent; (3) there is no distinction between fixed and variable white.

The CIE also maintains a signal color specification, CIE S 004-2001 [2], with the chromaticity boundaries shown in figure 3. Note that CIE S 004 contains two regions for the color “white.” Class A whites (IJKL) provide higher identification reliability and are the only whites specified for use in a five-color system in which yellow is present. The Class B whites (JJ'K'K) offer diminished reliability and are easily confused with yellow light sources. The CIE permits only the use of Class B whites in four-color systems in which yellow is not used.

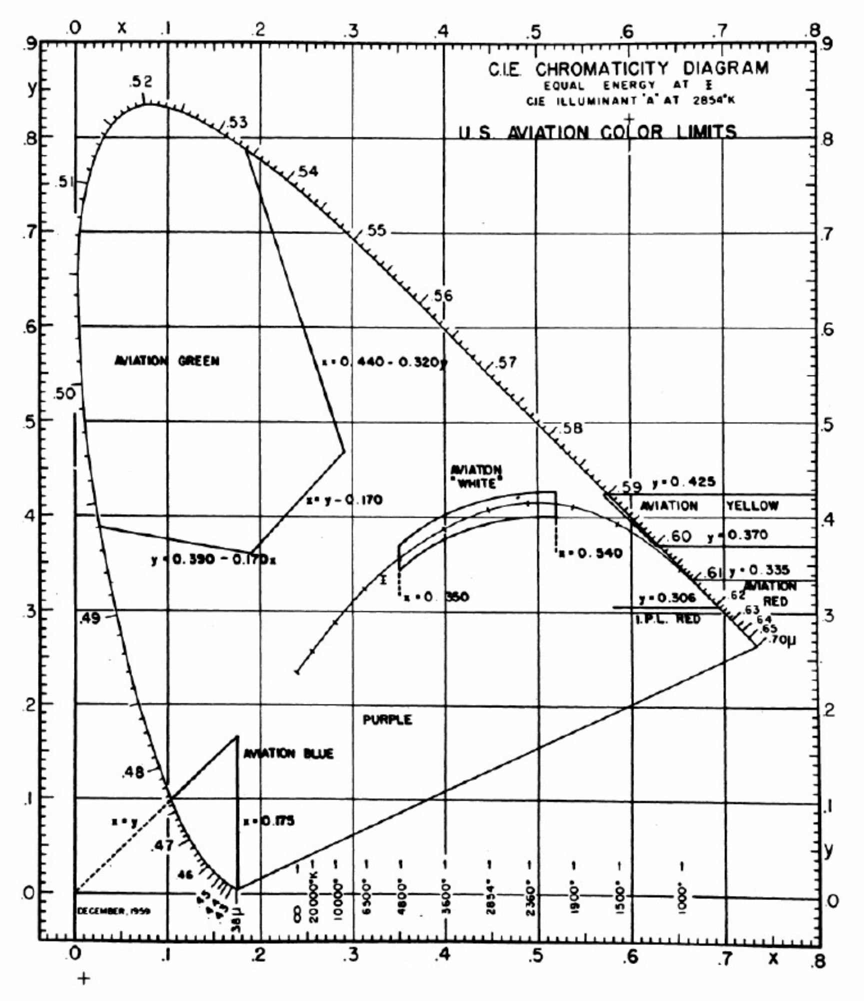


Figure 2. Chromaticity Boundaries for all Signal Colors as Defined by SAE AS25050 [1] Plotted on CIE 1931 Chromaticity Diagram

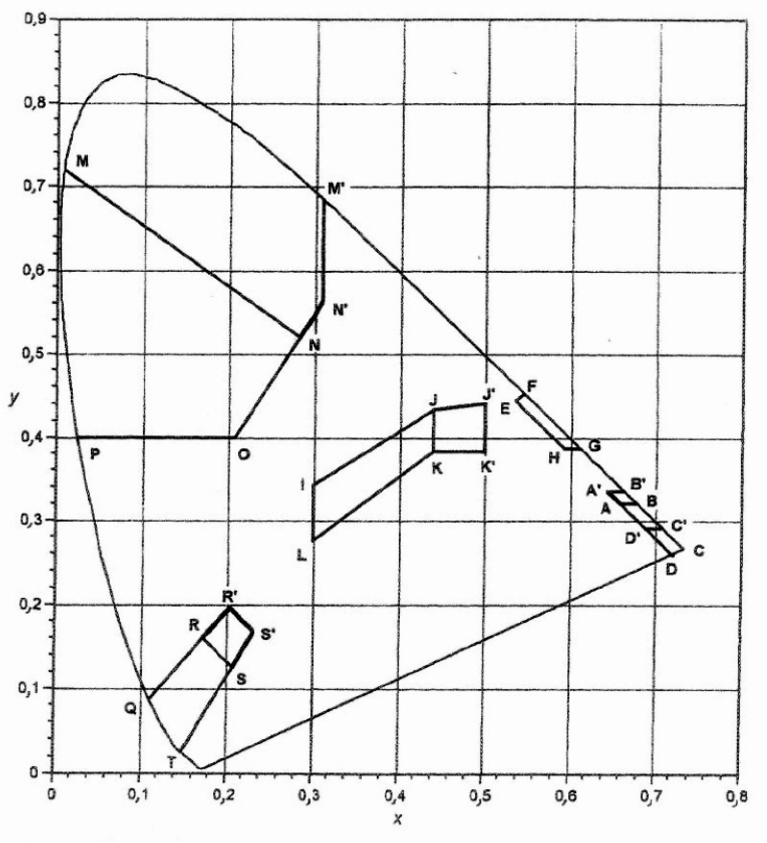


Figure 3. Chromaticity Boundaries for all Signal Colors as Defined by CIE-S 004 [2] Plotted on CIE 1931 Chromaticity Diagram (The region IJKL denotes the Class A White region, and JJ'K'K denotes the region for Class B whites.)

The CIE Class A white boundary is plotted with the current aviation colors (as defined by SAE AS25050 [1]) for comparison in figure 4. Note that the CIE color boundary extends much further to the blue than the current aviation white (x = 0.300 versus x = 0.350 for SAE AS25050). In addition, the yellow boundary for CIE S 004 [2] is more conservative and is located at x = 0.440, versus x = 0.540 for SAE AS25050 [1]. The other main difference between the two standards is that CIE S 004 permits a larger deviation in the vertical (y) direction than SAE AS25050.

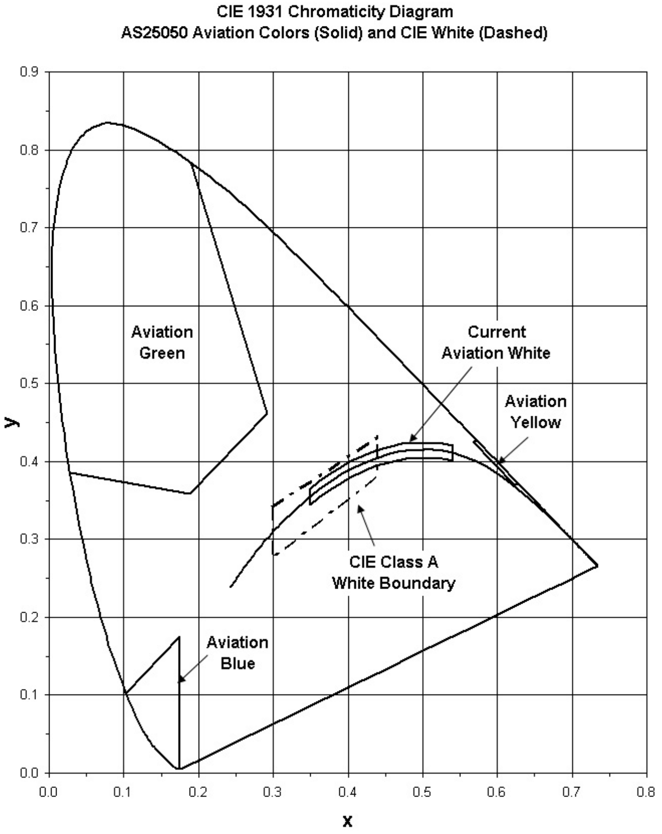


Figure 4. Chromaticity Boundaries for all Signal Colors as Defined by SAE AS25050 [1] (The Class A white boundary as defined by CIE S 004 [2] is plotted on CIE 1931 chromaticity diagram for comparison.)

LITERATURE REVIEW: STUDIES OF AVIATION SIGNAL COLOR. In 1994, the CIE published technical report CIE 107 [8]. This report provides an extensive list of references that were taken into consideration when formulating the CIE-recommended color boundaries of signal lights and suggesting revisions that were later incorporated into a revised standard S 004 [2]. The report also contains a bibliography that expands the topic to other related areas of color perception and identification. It was assumed that this reference list and bibliography satisfactorily captures the state of knowledge prior to 1994. Few additional papers were found on this topic post-1994.

This study is limited in scope to the white color boundaries of a five-color system (red, yellow, green, blue, and white) and further restricted to persons with supposed normal (trichromatic) color vision. A large portion of the literature concerns color identification for color-deficient observers with regard to the chromaticity regions defined for color-normal observers; it seems that at least some color boundary standards take this information into account by restricting the boundaries of certain colors beyond what is needed for color-normal observers. However, it can be argued that these modifications for color-deficient observers are only useful for three-color systems, such as the red/yellow/green traffic light standard or a red/green/blue system where dichromats, who perceive only two colors, do not have to distinguish white from the other colors [8]. Therefore, it is doubtful whether the results from experiments concerned with three-color systems could directly apply to the five-color system currently under consideration regarding utility for color-deficient observers.

Nearly all the studies reviewed used a color-naming method to assess color identification. Color naming is useful because it emphasizes the perceptual appearance of colors (self-luminous) rather than other color vision tasks, such as color matching or color discrimination. Simple color-naming techniques are used because, as stated by Halsey [9], “If the system is to be widely applied, the colors chosen for signals must fall into the natural color classifications used by a majority of untrained laymen.” Acknowledging the large differences that exist between individuals, Halsey continues, “…the boundaries for signal lights must be restricted to conform to almost any individual’s color concepts.”

Even for the restricted group of color-normal observers, the white boundary is not a well-defined chromaticity region compared to the other signal colors found along the spectrum locus. For example, Halsey [9] had 100 color-normal observers name the colors of 50 low-saturation stimuli in the area of chromaticity space in and adjacent to the green, blue, violet, and white color boundaries. Colors were seen at two light levels of 18 and 6 microlux at the eye. As an indication of how variable the responses were, at the high light level, 33 of the 50 stimuli were named “white” by at least one subject, while only 9 stimuli were named “white” at least 50% of the time. Similar results were reported for the low light level condition with 34 of the 50 stimuli named “white” by at least one subject, and 7 stimuli named “white” at least 50% of the time. The highest agreement for any stimuli being named “white” was 80% for the high light level condition and 71% for the low light level condition. For comparison, a study by Soon and Cole [10] employing 60 subjects reported 100% consensus for naming certain red and green color stimuli that fell within the corresponding CIE S 004 color boundary [2]. In the same study, the four stimuli with chromaticity values within the CIE S 004 white region [2] varied widely on the percentage of observers naming them “white.” Stimuli in the Class B region (for use in a color identification system that does not include yellow) were more often identified as yellow than white. Stimuli in the Class A white region had “reasonably high probabilities” of recognition in the 80% to 90% range.

In CIE 107 [8], attempts were made to draw the 90% correct recognition boundaries in the CIE 1931 chromaticity diagram for the studies reviewed. Since most of the studies used only a few color stimuli in any one color area, these contours were approximate. Figure 5 shows the contours reproduced from the report for both daytime and nighttime viewing conditions. The signals seen under the nighttime viewing conditions were very bright (>1000 microlux at the eye), while those seen under daytime conditions had variable intensities (0.2 to 70,000 microlux at the eye).

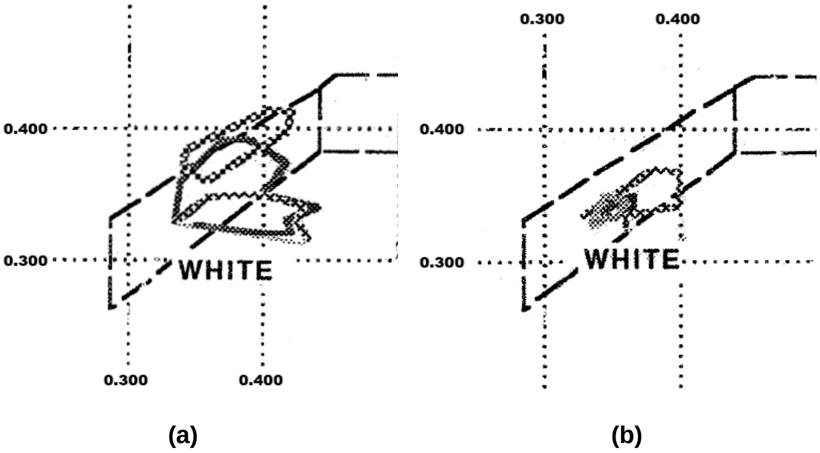


Figure 5. The 90% Recognition Contours in the CIE 1931 Chromaticity Diagram Reproduced From CIE 107-1994 for Both (a) Daytime and (b) Nighttime Viewing Conditions

As shown in figure 5, the 90% contours are much smaller than the defined color boundary, even the restricted CIE S 0004 Class A boundary. Also, the contours are all located near the center of the CIE S 004 Class A boundary at an x-value of approximately 0.35, corresponding to a CCT of 4835 K. Therefore, as the white signal chromaticity moves to either higher or lower CCTs, the probability of correct recognition can be expected to decrease. The current boundaries of the CIE S 004, as well as those of SAE AS25050, are based not only on high recognition probabilities, but also on the technology and practicality of achieving high luminous signal sources, and therefore, reduced identification performance is to be expected. This condition presents an opportunity for using LED sources to improve the identification probability of white signals by providing a high-intensity source in the optimum chromaticity region for white identification.

It is noteworthy that outside the field of signal lights, the perception of white has been studied for the video display industry. The manufacturers of televisions and computer monitors strive to create displays that produce a realistic white color under a range of different viewing conditions. Typically, the requirements for white are much stricter for this application, as the intent is to differentiate subtle differences in hue instead of just choosing between four or five color categories. Nevertheless, in studies such as the one conducted by Honjyo and Nonaka [11], the perception of pure white tends to correspond to CCTs ranging from 5,000 to 10,000 K. Consequently, nearly all televisions and other color displays have white point CCTs in this range [12].

METHODS.

Study 1 consisted of two separate phases of investigation. Phase I was intended to identify a region of interest on the CIE 1931 chromaticity diagram by presenting color samples from a large area in and around the current definition of aviation white. The results of Phase I were used to predict patterns of chromaticity acceptance as “white.” Care was taken to ensure precise color samples were displayed, but the context of their presentation was not representative of a pilot’s experience.

Phase II investigated the acceptability of chromaticity points identified in Phase I using various filtered and unfiltered LED sources to produce the samples. For this phase, the size, orientation, and intensity of the sample light sources were designed to be representative of a pilot's experience. Importantly, Phase II used actual phosphor-converted white LEDs to account for any spectral effects not captured in the measurement of chromaticity.

The experimental protocol was approved by the RPI Institutional Review Board.

PHASE I: APPARATUS. The experimental apparatus for Phase I consisted of a desktop computer with a calibrated red/green/blue (RGB), LED-backlit, liquid-crystal display (LCD) screen. The screen was chosen for its wide-gamut area specification and the assumed precision of its digital control. Software was written to create a specified color patch of uniform chromaticity and luminance on the screen. The values of luminance and chromaticity were controlled by the tester. The LCD and software were calibrated using a spectroradiometer (Photo Research, Inc., PR705 SpectraScan®) to produce chromaticity values accurate to 0.003 CIE 1931 x,y units on demand.

An additional computer program was used by the subjects to perform the test. It randomly selected 1 of 147 chromaticity values (see figure 6 for the chromaticity values in relationship to the FAA's aviation white boundary and the CIE boundary for a five-color signal system, which is similar to ICAO's boundary) and displayed it on the screen at a brightness specified by the tester. The chromaticity values of all test points are listed in appendix A. A shroud with a circular aperture shielded all parts of the screen from the subject except the region in which the color patch was being displayed.

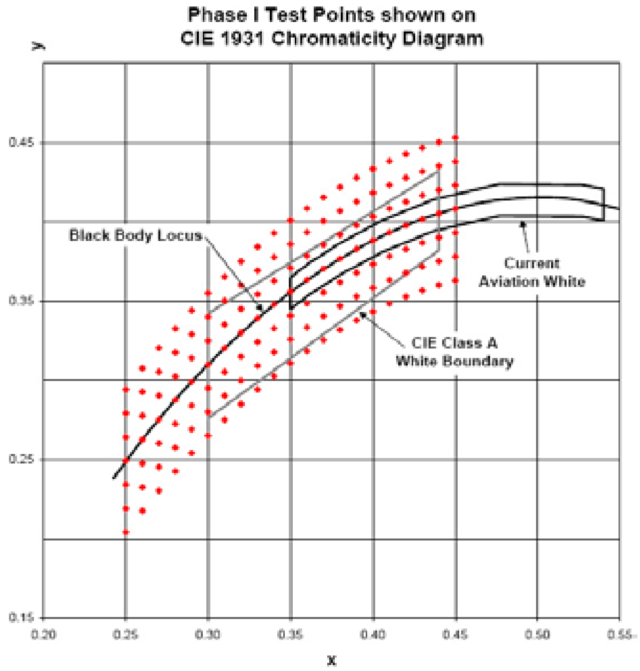


Figure 6. Phase I Experimental Test Points Shown on CIE 1931 Chromaticity Diagram

A schematic representation of the apparatus is shown in figure 7, and a subject participating is shown in figure 8. In both sessions, the subject was located at a distance of 10 ft from the 1.4 aperture. The screen's luminance was adjusted to provide the highest value of illuminance that a pilot would experience from a single source before passing the decision height of 200 ft. This value was calculated to be about 0.03 luminous flux (lux) per unit area at the eye based on the intensity requirements for approach lights, as defined on page 12 of FAA-E-2980 [13], and was equivalent to a 10,000 candela (cd) source at a 1900-foot line of sight.

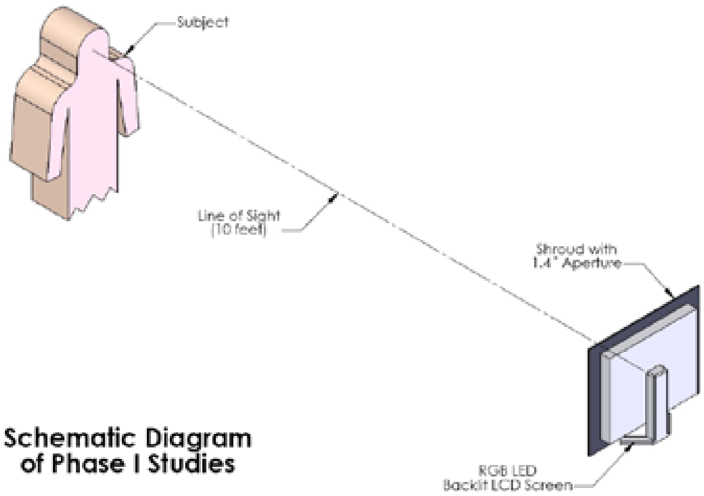


Figure 7. Schematic Representation of the Phase I Experimental Setup

Figure 8. Experimental Setup Used for Phase I of the Study (Subjects faced a luminous aperture and used a keyboard to respond to the light stimulus.)

PHASE I: EXPERIMENTAL PROCEDURE. Phase I was conducted in two different sessions using the following procedures. In Session 1, the test subjects sat in a totally darkened environment with the test stimulus providing the only light source. In Session 2, the subjects sat behind a simulated control console with a low CCT backlight (approximately 2300 K), which was adjusted to provide approximately 15 lux. A low CCT was chosen to simulate dimmed incandescent instrument backlighting. Light from the simulated console and test stimulus were the only sources that the subjects experienced.

The subjects were instructed to observe the color on the screen and to categorize the sample as one of five colors: white, yellow, red, green, or blue. The subjects used the computer's keyboard to indicate whether they believed it to be "white" (by pressing the up arrow "↑" key) or "yellow," "red," "blue," or "green" (by pressing the down arrow "↓" key). If the subject felt that he/she made a mistake, a condition could be repeated by pressing the left arrow "←" key. Each chromaticity test point was displayed a total of five times.

PHASE I: SUBJECTS. Ten subjects (5 male and 5 female) ranging in age from 25 to 62 years (average age: 38 years) participated in Session 1 of Phase I. Eight subjects (5 male and 3 female) of ages 26-62 years (average age: 38 years) participated in Session 2. All subjects were tested for color deficiency and all were color-normal.

PHASE II: APPARATUS. Phase II was intended to investigate the subjects' perception of several chromaticities when presented in an airport runway context. Accordingly, the apparatus used in this phase was constructed to be as geometrically true as possible, yet scaled in size to be viewed within the laboratory. For the purposes of this experiment, a decision height of 200 ft and an approach angle of 3° were used. The largest possible scale that would fit in the space available was 1:255. The full-size dimensions on which the scale model was constructed are shown in figure 9.

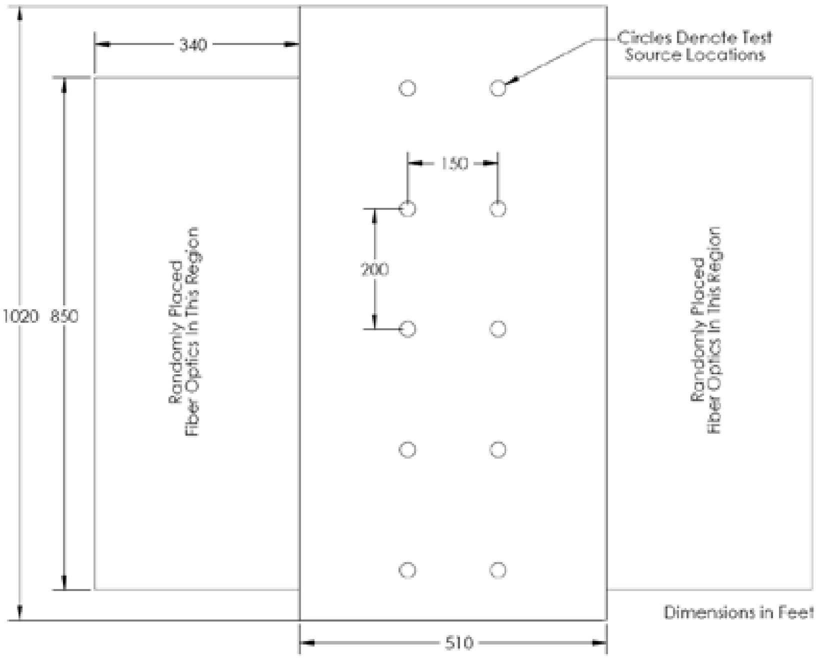


Figure 9. Plan View of the Experimental Apparatus Used for Study 1, Phase II (The full-size dimensions provided are those on which the scale model was constructed.)

The center portion, which constituted the runway lighting, was dark until the test sources were energized. To the sides of the runway, end-emitting fiber optics were placed in random locations, creating side fields resembling parking lot and residential property lighting that often surround an airfield. Two low-intensity sources (filtered to resemble metal halide and high-pressure sodium sources) fed these optical fibers. The entire model was painted black so that it would blend into the background of the black-painted room (figure 10).

Figure 10. Subject Observing the Experimental Apparatus in Phase II

A total of ten, phosphor-converted white LEDs (two rows of five each) were used as the sample light sources. The arrangement was designed to be nondescript so that it would resemble either taxiway lights or runway edge lights without providing subjects with nonchromatic cues as to what the color should be (e.g., an approach array configuration may elicit a response of “white” because of its specific layout, when subjects may have otherwise answered differently). The LEDs were equipped with an aperture to limit the source size to less than 5 minutes of arc as seen from the viewing location, so that they would be seen as point sources by the subjects (just as airfield lighting would appear to pilots).

The primary LED sources were chosen from four different chromaticity bins: Cree WC, 5A, 6C, and 7C. Theatrical filters or “gels” (Roscolux #62, #65, #316, and #321) were used to shift the chromaticity of the primary light sources to provide additional sample chromaticities. A total of 16 chromaticities were investigated in Phase II. They are shown plotted on the 1931 CIE chromaticity diagram in figure 11 and detailed in table 1. Points with an asterisk next to them were only viewed by the first seven subjects because their responses were enough to determine that those samples would only rarely be identified as white; therefore, no further investigation was warranted. Accordingly, their use was discontinued for subjects 8 through 21 to shorten trial times and to avoid unnecessary fatigue for the remaining subjects.

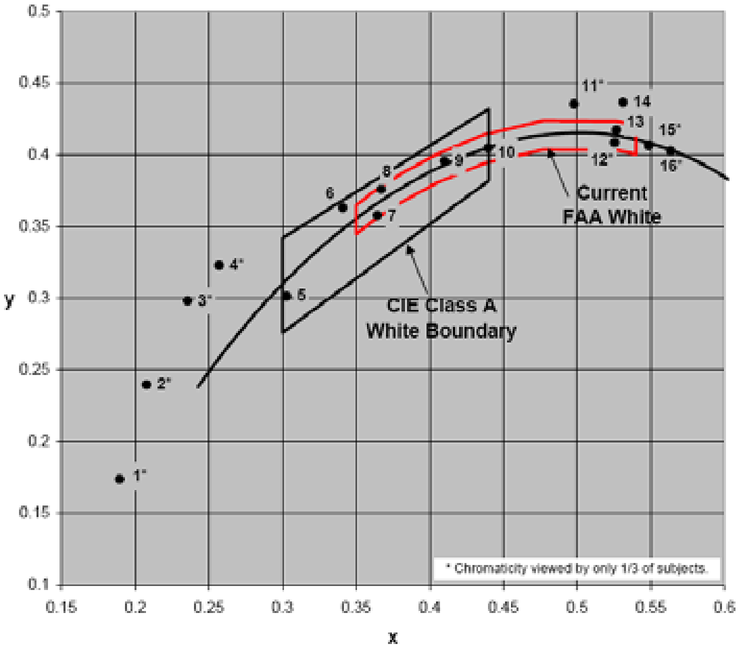


Figure 11. Phase II Test Points Shown on CIE 1931 Color Space

Table 1. Summary of the Chromaticity and Illuminance at the Subject's Eye of the Test Stimuli Used for Phase II

Roscolux Number	Point	LED	x	y	Illuminance (lux)
No filter	10	1	0.440	0.405	0.068
	9	2	0.410	0.396	0.088
	7	3	0.365	0.358	0.066
	5	4	0.303	0.301	0.067
#65* (Daylight Blue)	4*	1	0.257	0.323	0.068
	3*	2	0.236	0.298	0.077
	2*	3	0.208	0.240	0.079
	1*	4	0.189	0.174	0.071
#321* (Soft Golden Amber)	16*	1	0.563	0.403	0.073
	15*	2	0.549	0.407	0.089
	12*	3	0.525	0.409	0.082
	11*	4	0.498	0.435	0.082
#62 (Booster Blue)	8	1	0.367	0.376	0.073
	6	2	0.341	0.363	0.078
#316 (Gallo Gold)	14	1	0.531	0.437	0.080
	13	2	0.527	0.417	0.080

(Roscolux filters are products of Rosco Laboratories, Inc. Point numbers correspond to figure 11. Points with asterisks were viewed by the first seven subjects and discontinued for the remainder of subjects due to their low acceptability.)

The LED sources were driven with constant current, which was adjusted to provide between 0.059 and 0.089 lux at the subject's eye. This illuminance was higher than the Phase I illuminance due to the presence of multiple light sources, each with an intensity similar to Phase I. This level corresponded to ten light sources operated between the minimum and maximum intensity requirements of a Medium-Intensity Approach Light System (MALS) at 100% output, as defined by FAA-E-2980 [13] (page 12): 8,000≤ Intensity (I) ≤12,000 cd , scaled for this experiment to 0.12≤ I ≤0.19 cd. The illuminance was measured using a Gigahertz-Optik $X9_1$ photometer, and the chromaticity was measured using a Photo Research, Inc. PR-705 SpectraScan® System spectroradiometer.

PHASE II: EXPERIMENTAL PROCEDURE. The subjects were divided into four groups, each with a unique sample randomization. Each chromaticity test point was presented to the subjects a total of four times. The gels used to shift the lights' chromaticity were manually changed by the tester. The subjects were asked to turn away during filter changes so they were unable to observe the changes being made.

The subjects were tested individually. Prior to the tests, the subjects waited in a dimly lit room so that the time needed for them to adapt to the darkness in the test room was reduced. When a subject was ready to participate, the tester led them into position in the darkened laboratory. They were allowed to adapt to the dark for an additional 5 minutes before the test was started.

When the subject was ready, the tester started a computer program, which turned the LED light sources on and off in a randomized order. A chromaticity sample was presented to the subject and the tester asked the subject if the color of the light was white. If the answer was not "white," then the subject was required to respond with the color (red, yellow, green, or blue) he or she perceived it to be. No other color names were permitted. The tester recorded the responses for every condition in the software.

PHASE II: SUBJECTS. A total of 21 subjects (11 male and 10 female) participated in this phase. The age range of the subjects was 18 to 64 years (mean age = 39 years). All were tested for color deficiency and all were color-normal. Three subjects currently hold or have held a pilot's license. One subject was a retired military aviator.

RESULTS AND DISCUSSION.

PHASE I. As the subjects participated in Sessions 1 and 2, the computer program recorded whether the subject called each chromaticity displayed "white" or "red," or "yellow," "green," or "blue" and created a file for each subject's results. A MATLAB (The MathWorks, Inc.) script was written that combined the subjects' results files from a session, tallied the number of identifications as "white" for each chromaticity point tested, and divided that number by the number of presentations of that chromaticity point to generate the percentage acceptance as white. The MATLAB script then used the percentage acceptance values to create acceptance contours, which are plotted on the CIE 1931 chromaticity diagram. The plots for Sessions 1 and 2 are shown figures 12 and 13, respectively.

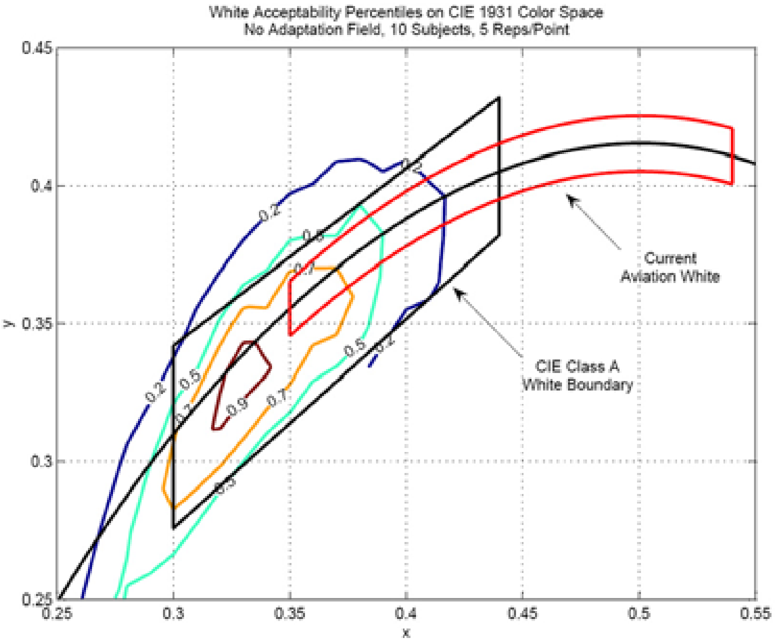


Figure 12. White Acceptability Profiles for Phase I–Session 1 (no adaptation field) Plotted on CIE 1931 Color Space in Relation to the Current Aviation White Boundary and the CIE Class A White Boundary

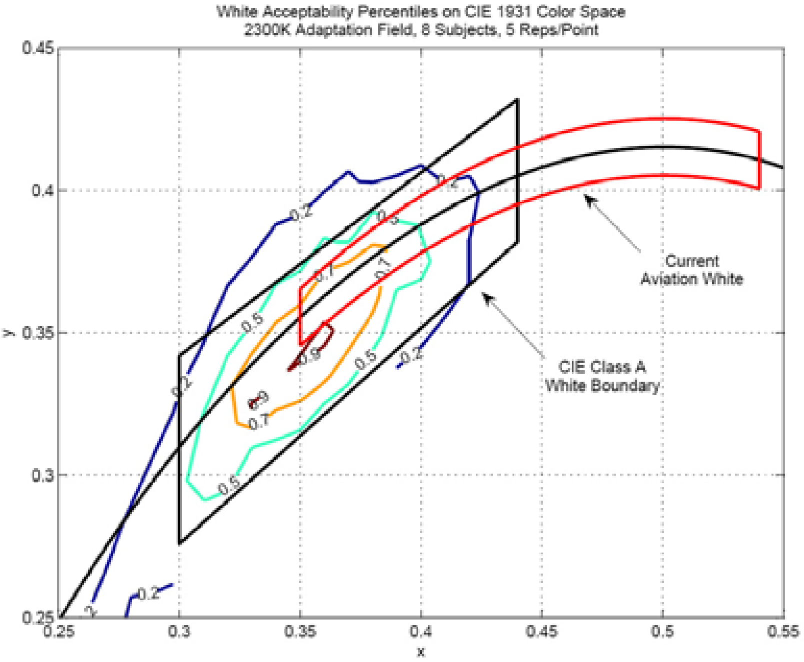


Figure 13. White Acceptability Profiles for Phase I–Session 2 (2300-K adaptation field) Plotted on CIE 1931 Color Space in Relation to the Current Aviation White Boundary and the CIE Class A White Boundary

The data in figure 12 were collected during Session 1 from ten subjects with a total of five repetitions per point. The white acceptance intervals seem to correlate to the CIE Class A White boundary in terms of shape but not with respect to size or centroid position [8].

Figure 13 shows Session 2 data collected from eight subjects with a total of five repetitions per point. In terms of shape and orientation, Session 2 acceptance intervals match the CIE Class A White region better than the Session 1 data shown in figure 12. Note that the sizes of the various acceptance intervals are still inconsistent with the Class A White boundary.

The addition of the 2300-K adaptation field in Session 2 resulted in a shift of the acceptance intervals toward higher values of x when compared to the results of Session 1. The adaptation field also resulted in a reduction in the size of the 50%, 70%, and 90% regions.

PHASE II. The software interface for Phase II also created a file for each subject containing their responses. These files were combined and processed with Microsoft® Excel®. Again, the total number of "white" responses was divided by the total number of presentations for each chromaticity value to obtain a percentage acceptance as white. These values are shown in figure 14. The data from which figure 14 was generated were gathered from a total of 21 subjects, with each point displayed four times. The values marked with an asterisk were displayed only to the first seven subjects. They were discontinued from further presentation due to their relatively low level of acceptance as white. The results are shown by test point and chromaticity in table 2.

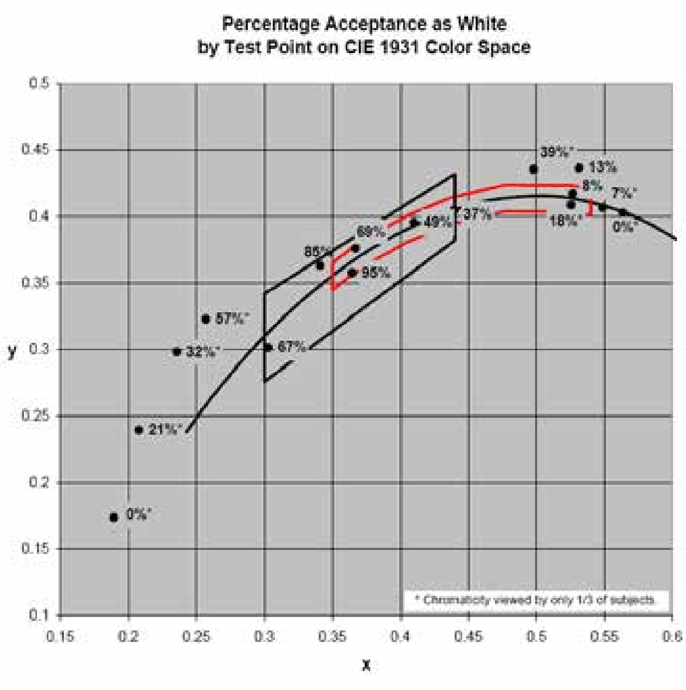


Figure 14. Percentage Acceptance as White for Phase II (in-context) Test Points (The black body locus, current aviation white boundary, and CIE Class A white boundary are shown for reference. Points marked with an asterisk (*) were shown to one-third of the subjects.)

Table 2. Percentage Acceptance as "White" by Test Point Chromaticity

Test Point	x	y	Acceptance as White (%)
1*	0.189	0.174	0
2*	0.208	0.240	21
3*	0.236	0.298	32
4*	0.257	0.323	57
5	0.303	0.301	67
6	0.341	0.363	85
7	0.365	0.358	95
8	0.367	0.376	69
9	0.410	0.396	49
10	0.440	0.405	37
11*	0.498	0.435	39
12*	0.525	0.409	18
13	0.527	0.417	8
14	0.531	0.437	13
15*	0.549	0.407	7
16*	0.563	0.403	0

(Note: Points with asterisks were viewed by the first seven subjects and discontinued for the remaining subjects due to their low acceptability.)

Note that test points 9 and 10 (which are very similar in chromaticity to an incandescent source) had acceptances as white of 49% and 37%, respectively (see table 2).

The Phase II results are consistent with the confidence intervals for dark-adapted viewing conditions constructed for and presented in CIE 107 [8]. This comparison is shown in figure 15.

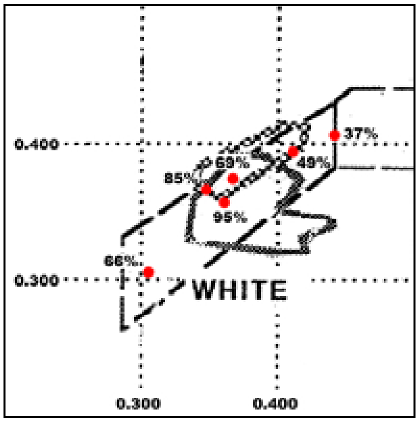


Figure 15. Phase II Acceptance Levels (marked with red dots) Superimposed on a Confidence Interval Plot Presented in CIE 107 [8]

Figures 16 and 17 show comparisons of the results of Phases I and II. Figure 16 compares the data from Phase I–Session 1 to Phase II. Fairly close agreement between the two experiments can be observed, particularly the 70% and 80% acceptance intervals. The 90% acceptance interval seems to be centered further to the left than the Phase II data suggest it should be, however.

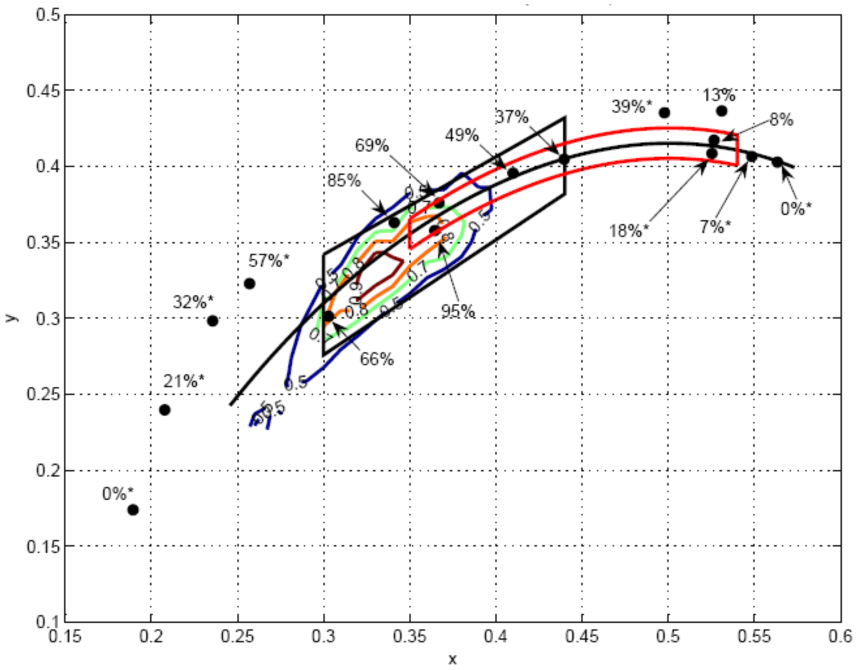


Figure 16. Phase II Results Superimposed on the White Acceptance Profiles Constructed From the Results of Phase I–Session 1 (no adaptation field)

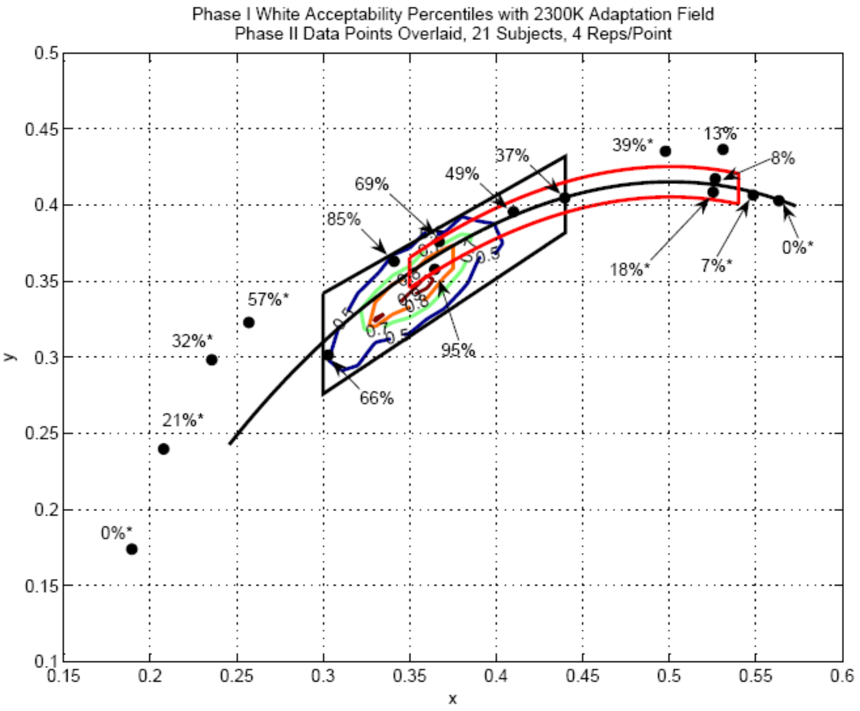


Figure 17. Phase II Results Superimposed on the White Acceptance Profiles Constructed From the Results of Phase I–Session 2 (with 2300-K adaptation field)

Figure 17 is a comparison of Phase I–Session 2 results to the Phase II results. The centroid of the acceptance regions plotted from Phase I is more consistent with the location of the 95% Phase II test point. The acceptance regions are smaller in size than the Phase II test points suggest they should be, but overall, the data from both experiments show reasonable agreement.

INTERPRETING PHASE II RESULTS. The CIE 1976 color space was created to uniformly describe the relationship between the change in the perception of color and the distance traveled across the diagram. The results of Phases I and II were converted into this color space to better understand the relationship between vector length (in chromaticity space) and the percentage of acceptability for the test points. A plot of Phase I–Session 2 (2300-K adaptation field) and Phase II test points is shown in figure 18.

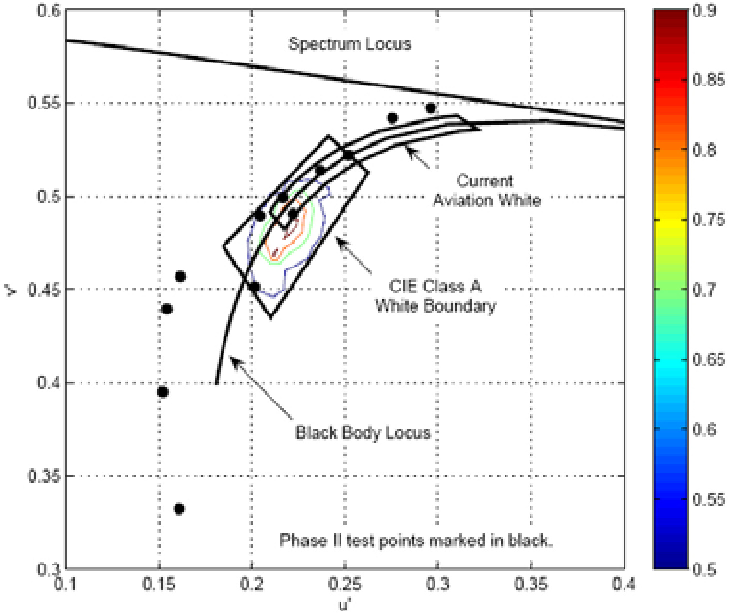


Figure 18. Phase I–Session 2 (with 2300-K adaptation field) and Phase II Test Points Plotted on CIE 1976 Color Space

Once converted into the CIE 1976 color space, the vector length from the 95% acceptance point to each of the other test points was calculated and plotted against percentage acceptance for travel toward bluer and more yellow chromaticity values. Functions were then fit to these data points, as shown in figure 19.

Based on the analysis shown in figure 19, the percentage acceptance as "white" diminishes more slowly for shifts toward bluer chromaticity values than for shifts toward more yellow chromaticity values. This indicates that for a given vector distance from the 95% point, blue is less likely to be confused with white than yellow.

Predictions of white acceptance for chromaticity values along the Planckian locus in the blue direction are shown in figure 20. These predictions are based on the function for travel toward bluer chromaticity, as shown in figure 19.

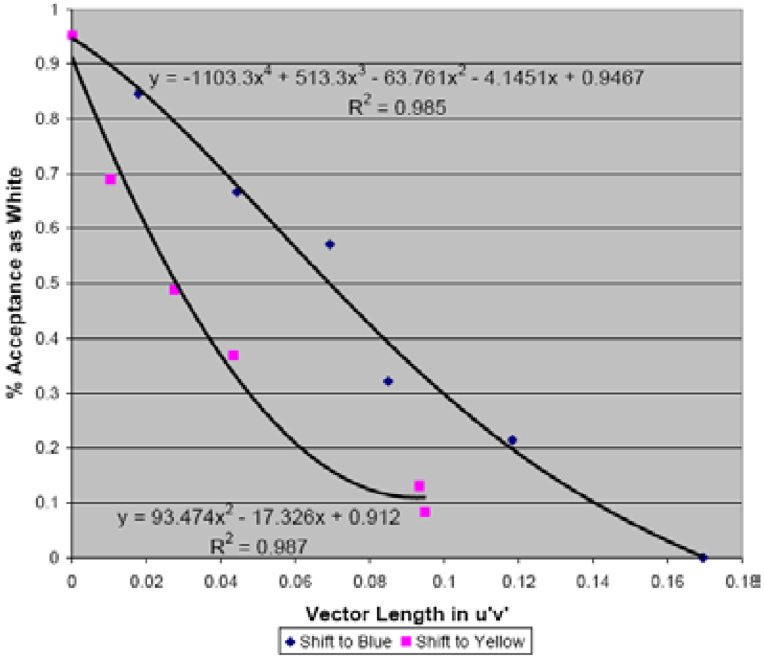


Figure 19. Percentage Acceptance as White as a Function of Vector Length From the 95% Acceptance Point in CIE 1976 Chromaticity Space

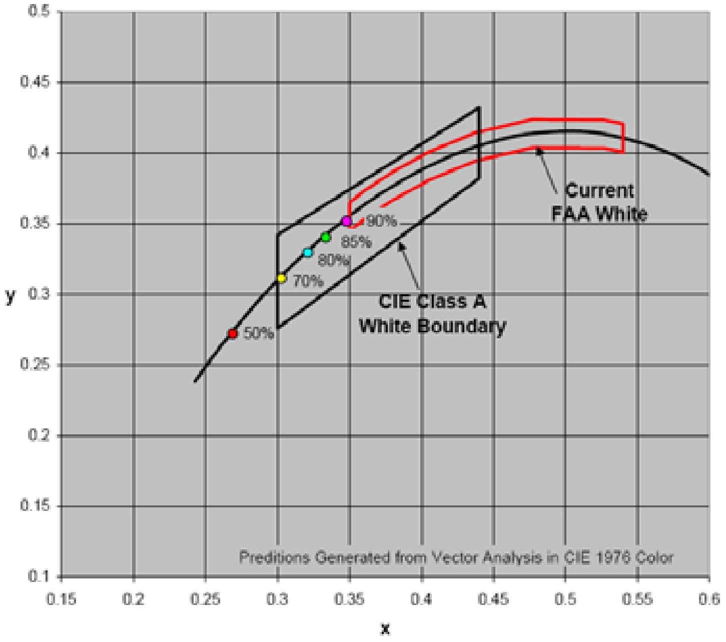


Figure 20. Percentage Acceptance as White for Various Locations Along the Planckian Locus Based on Vector Length Analysis

ANECDOTAL REMARKS. After the experiment, the subjects with piloting experience offered their remarks and opinions on white airport lighting. They noted that white signal lights are easily confused with yellow. One pilot mentioned that white signals often shift to a yellow appearance when the atmosphere is hazy or foggy. This observation is consistent with the increased scattering of the shorter visible wavelengths of light under these conditions. All the pilots agreed that bluer whites would make the identification of white easier.

RECOMMENDATIONS.

When incandescent filament sources were the only practical light sources for signal lights, a chromaticity specification for white that accommodated such sources was logical. Based on the findings of this research, a chromaticity boundary for white representing a 90% identification rate would be very small relative to the existing white boundaries. These small areas are shown in figures 5, 12, and 13. Such a small area would make it difficult to find a suitable source. Lower-naming accuracy boundaries for white (such as 70% or 80%) would severely bring in the boundary on the yellow side, yet extend it out to the present CIE S 004 [2] boundary on the blue side.

This research indicates that the current color boundary of aviation white extends too far toward the yellow region. The naming accuracy for all experimental conditions for which x is greater than 0.440 (i.e., the current aviation white boundary), is less than 40%. Anecdotal remarks by pilots involved in this study corroborate this claim.

Alternatively, the blue boundary of aviation white may be too conservative. The point with the highest-naming accuracy as “white” (95%) in Phase II was at x = 0.365, which is toward the blue boundary of the currently defined aviation white. Vector analysis performed on the Phase II data indicates that the lower percent of color-naming accuracy occurs more gradually on the blue side than on the yellow side. Consequently, the blue boundary can be moved to a higher CCT along the black body without sacrificing as much accuracy as is lost when the yellow boundary is not moved to an area of higher white identification and remains at an area obtainable with unfiltered incandescent lamps. For example, for white, a blue boundary of x = 0.330 (~5500 K) corresponds to an 85% naming accuracy; a boundary of x = 0.320 (~6000 K) corresponds to an 80% naming accuracy; and a boundary of x = 0.300 (~7500 K) corresponds to a 70% naming accuracy.

In addition to establishing x-chromaticity boundaries, the allowed tolerance in the vertical y-chromaticity direction should be considered as well. In terms of color identification accuracy, the y-dimension of SAE AS25050 [1] is not consistent with the allowable change in the x-direction. CIE S 004 [2] is more consistent in this regard, with its specified chromaticity boundaries approximately the same x,y proportions as the contours of equal identification accuracy, as shown in figures 16 through 18. The current vertical allowances are also more restrictive than the American National Standards Institute (ANSI) white LED binning system [14] currently used by LED manufacturers to set manufacturing tolerances and stocking bins. An aviation white specification with such a narrow bin size would make LED selection difficult and would increase the cost with little or no demonstrated performance increase. ANSI C78.377 [14] white LED bins are shown in figure 21 plotted with the SAE AS25050 and CIE S 004 white boundaries.

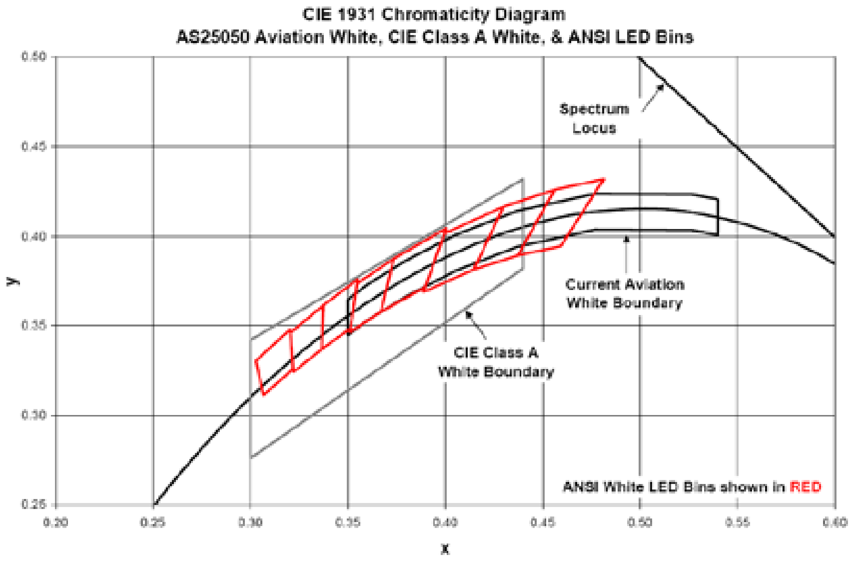


Figure 21. ANSI C78.377 [13] White LED Bins Shown in the CIE 1931 Chromaticity Diagram and the White Boundaries of SAE AS25050 [1] and CIE S 004 Class A [2]

Based on the results of this study, the CIE recommendations, and the available literature, the following recommendations are made.

- The yellow boundary of aviation white should be moved to x = 0.440 (from x = 0.540). This would allow for limited use of unfiltered incandescent sources, although incandescent lamps operated under dimmed conditions may fall outside this boundary. This change would help to limit confusion between white and yellow signal colors.

- The blue boundary of aviation white should be moved to x = 0.320 (from x = 0.350). This would allow some relatively high CCT LED sources to be used (up to roughly 6000 K) while still obtaining a color identification accuracy of 80%—considerably higher than on the yellow boundary. This blue boundary is more conservative than the present CIE S 004 blue boundary of aviation white, further guarding against confusion with blue signals and restricting the range of allowable white chromaticity values that could be presented to a pilot.

- The boundaries in the y-direction should be expanded to fully cover the white LED chromaticity bins specified by ANSI C78.377 [14]. CIE S 004 [2] boundaries currently do this.

Before implementing any changes based on the following recommendations, the FAA should consider a field validation study and consider other restrictions regarding the mixing of light source technologies on a single runway.

STUDY 2: COLOR IDENTIFICATION OF AVIATION SIGNAL LIGHTS USING LEDs BY COLOR-NORMAL AND COLOR-DEFICIENT OBSERVERS

INTRODUCTION.

As the use of LEDs increase for airfield (runway and taxiway) signaling applications, it is important to ensure that they can be adequately identified by pilots, including those with color vision deficiencies. Color specifications for signal lights in aviation applications used by the FAA [15 and 16] have been unchanged for several decades. Filtered incandescent lamps, which have been the dominant source of signal light, have provided consistent chromaticities within the allowable color boundaries. Additionally, the relative transmittance of the colored-glass filters create luminous intensity differences among incandescent signal lights of different colors, which could provide additional cues, thereby allowing some color-deficient pilots to distinguish among them.

Commercially available LED sources used in aviation signal lights have chromaticities within the permissible color boundaries [16] but can look perceptibly different than aviation signal lights using incandescent sources. In addition, the luminous efficacies of LEDs of several different colors (red, yellow, green, and white) are very similar, which could lead to confusion in the field from signal lights that have similar luminous intensities while still meeting the luminous intensity specifications [15]. If such signals are used, a color-deficient pilot's ability to discriminate among colored signal lights could be reduced.

The following sections describe Study 2, conducted by the LRC at RPI, in collaboration with the FAA Civil Aerospace Medical Institute (CAMI), which assessed the ability of color-normal and color-deficient observers to identify the colors of incandescent and LED signal lights, presented alone and in the presence of signal lights of different colors. The results of this study will assist the FAA in evaluating the impact of using LED sources for signal applications.

BACKGROUND.

COLOR VISION ABILITIES OF PILOTS. The certification process for private and commercial pilots' licenses includes a color vision test. The FAA permits one of a number of approved tests to be used for this purpose, and if a person does not pass the color vision test, a pilot can be given an opportunity to pass a second, specific color vision test, known as the signal light gun (SLG) test.

The SLG is a hand-held, battery-operated, portable light source that projects a narrow, high-intensity beam of light in one of three colors: white, green, or red. The test is conducted outdoors during the daytime and observers complete two sets of color judgment trials from distances of 1000 and 1500 ft away from the signal light gun. At each distance, each light source color is shown and identified to the observer. Then, a randomly ordered sequence of six presentations, at least one of each color, is presented, and the observer must correctly identify them at both distances to pass [17]. If the SLG test is passed, a color-deficient observer could be eligible for an unrestricted pilot's license.

CHROMATICITY REQUIREMENTS FOR AVIATION SIGNAL LIGHTS. Figure 22 shows the chromaticity boundaries currently specified by the FAA for aviation signal lights. (Figure 22 comes from the 1963 standard MIL-C-25050A [4], but the chromaticity requirements are the same as those in the present standard, which is currently maintained by the SAE.) Any chromaticities within the boundaries specified in figure 22 are considered acceptable signal light colors, but incandescent and LED signal lights can differ substantially in terms of their chromaticity coordinates within a particular color boundary. Colored LEDs tend to have chromaticity coordinates closer to the spectrum locus of the diagram, implying that they have a more saturated color appearance.

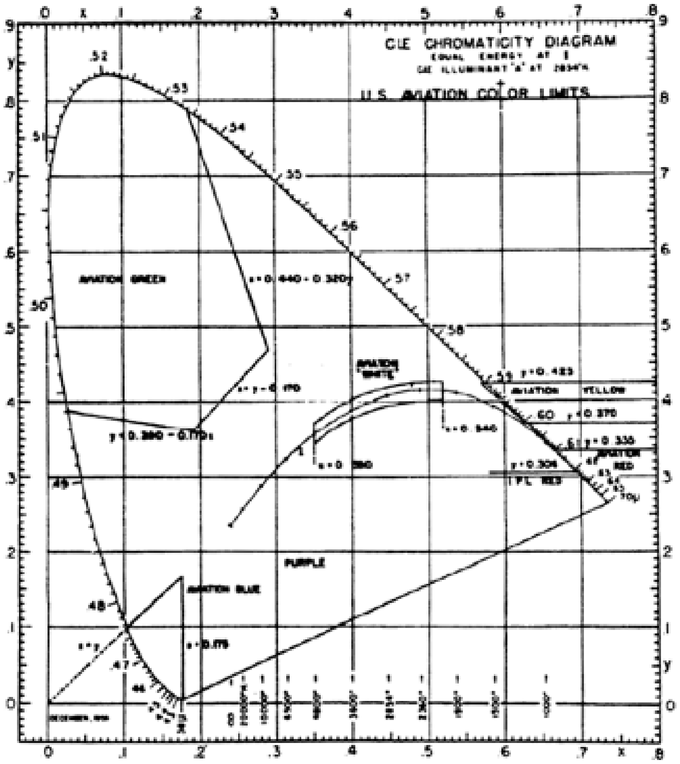


Figure 22. Current Aviation Signal Light Color Boundaries [16]

The CIE [2] reviewed a number of research studies on chromaticity boundaries for white, yellow, green, red, and blue signal lights for color identification. In general, the CIE recommendations for colors (in terms of x,y chromaticity coordinates) used in aviation signal lights are summarized below (see appendix B).

- White—The CIE 107 [8] recommended restricting the white boundary's x value to be no greater than 0.42 to avoid confusion with yellow. The x value was also recommended to be no less than 0.3. In general, this results in a boundary that is shifted to the left of the current white color boundary used by the FAA.

- Yellow—The CIE 107 [8] recommended that the yellow boundary's y value be between 0.4 and 0.425, and the horizontal width of the boundary be 0.2 units along the x-axis.

This results in a boundary region that is generally shifted up and to the left and is wider than the current yellow boundary used by the FAA.

- Green—The CIE 107 [8] recommended using only roughly the leftmost half of the region (yellow boundary y = 0.726, white boundary x = 0.625y – 0.041, blue boundary y = 0.400) corresponding to the current boundary used by the FAA when persons with red-green deficiencies are required to identify the signals.

- Red—The CIE 107 [8] recommended restricting the red boundary y value to a minimum of 0.29 and a maximum of 0.32, with a horizontal width of 0.2 units along the x-axis, when persons with red-green color deficiencies are required to identify the signals. In comparison, the current red color boundary used by the FAA is narrower and has no minimum y value.

- Blue—The CIE 107 [8] recommended a chromaticity boundary that is not very different from the current blue color boundary used by the FAA. However, spectral wavelengths shorter than about 460 nanometers (nm) are excluded by the CIE recommendation but are allowable by the FAA.

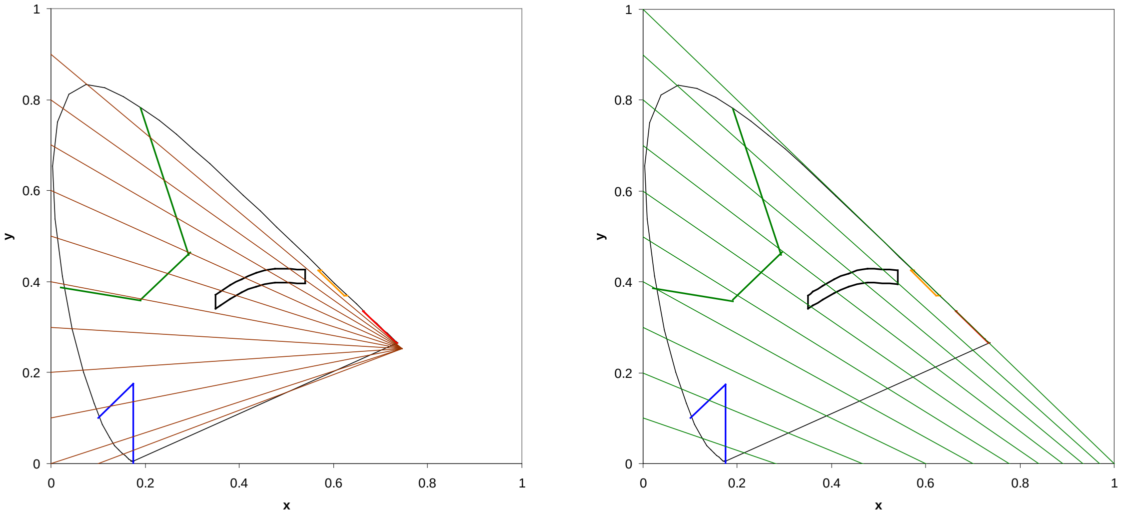
Generally, LEDs produce chromaticities that are within the current FAA color boundaries, with some exceptions. Many white LEDs can have CCTs high enough to be outside the current FAA boundary for white signals. The results of Study 1 confirmed that the current FAA white boundary excludes a chromaticity region with a high probability of being identified as white, and includes regions that can be misidentified as yellow, in agreement with the CIE recommendations.

Notably, there are two general color categories of LEDs that produce chromaticities within the current FAA green boundary. These are often marketed as “green” and “cyan” LEDs. Green LEDs typically have peak wavelengths near 525 nm, and cyan LEDs typically have peak wavelengths near 500 nm. The chromaticity coordinates of green LEDs tend to be near the (x,y) point (0.2,0.7), and cyan LEDs will be closer to the (x,y) point (0.1,0.6). Although both are within the current FAA green color boundary (figure 22), only the cyan LED falls within the CIE 107 [8] recommendation for green when persons with red-green color deficiencies need to identify the color. Nonetheless, all colorimetric data (from measured samples or from data supplied by the FAA) for green LED aviation lighting products and prototypes appear to represent green, not cyan, LEDs. This could be because the color name “cyan” implies a blue-green, rather than a green, appearance, but this is only speculation.

<u>PRACTICAL IMPLICATIONS OF COLOR VISION DEFICIENCY</u>. About 8% of males have some form of color vision deficiency [18]. Deficiencies are much rarer in females because they are caused by recessive genes on the X chromosome; since males only have one X chromosome, the probability of color deficiency is much higher in males. The two most common color deficiencies are dichromatic conditions in which the long-wavelength (L) (protan) or medium-wavelength (M) (deutan) cone pigments are missing or anomalous. Of the male population, about 2% have some form of protan deficiency, which is almost equally divided between those with a missing L cone pigment (protanopes) and those with an anomalous L cone pigment

(protanomalous). Those with a protan deficiency have a peak absorption that sufficiently differs from the usual peak near 565 nm, which means these individuals can make different color matches from the general population. About 6% of males have a deutan deficiency, of which 1% are missing the M cone pigment (deuteranopes) and about 5% have an anomalous M cone pigment (deuteranomalous) with a peak absorption different from the usual peak near 535 nm [18]. Tritan deficiencies (missing or anomalous short-wavelength cone pigment) are extremely rare.

Protanopes and deuteranopes lack trichromatic vision, which means certain chromaticities that would be readily distinguished by most people are confused. These confusion lines [19] are systematic and are shown in figure 23(a) and (b). Some protanomalous and deuteranomalous individuals, although trichromatic, may have similar difficulties distinguishing among some colors along these confusion lines [18].



(a)

(b)

Figure 23. Color Confusion Lines for (a) Protanopes and (b) Deuteranopes

<u>THE LED TECHNOLOGY</u>. Unlike incandescent signals, which are created by placing a colored glass filter in front of the incandescent source, LEDs of different types produce narrowband spectral output that does not require filtering. In addition, except for blue LEDs, most LED colors (e.g., white, yellow, green, and red) have similar luminous efficacies. LEDs of the same nominal wattage (e.g., 1 watt (W)) will produce approximately equal amounts of lux (in lumens (lm)) when operated under normal conditions (blue LEDs will produce about one-third the lux as other colors for the same wattage).

This difference can have practical implications. If a red incandescent signal and a white incandescent signal are seen in the same field of view and use the same wattage incandescent lamp (as in a Precision Approach Path Indicator (PAPI) system), the white signal is likely to have a higher luminous intensity than the red signal. That is because the transmission of clear glass is likely to be substantially higher than that of red glass; and this phenomenon is likely the reason that the FAA's luminous intensity requirements for colored signal lights in Advisory Circular 150/5345-46B [15] are generally highest for white signals (with clear glass lenses) and increasingly lower for yellow, green, red, and blue signals in the same rank order as the transmission of colored glass of these colors.

An experienced pilot with a protan or deutan deficiency viewing a signal with side-by-side white and red lights may differentiate between the colors by comparing their relative intensities. If an aviation signal light using LEDs is designed using equal nominal input current to the LED sources, a red and white signal will have similar luminous intensities and the large difference in relative intensity will not be available to differentiate them. This could be important because the luminous intensity requirements for most signal lights specified by reference 15 are simply minimum values with no restriction on maximum values.

Study 2 was conducted to address whether the use of LED aviation signals had any effect on color identification by both color-normal and color-deficient observers and to discern the extent to which observers might use intensity differences in combination with color differences to identify correct colors. Color identification performance was measured for individuals with normal color vision and with color vision deficiencies (who could otherwise pass the SLG test and serve as pilots without restricted licenses) to signal lights constructed using LED and filtered incandescent sources. The LEDs were operated either with similar input current values (thus producing similar luminous intensities for white, yellow, red, and green signals) or with the LEDs operated at different input currents to mimic the relative intensity of incandescent signals.

METHODS: SESSION 1.

Session 1 was conducted during February and March 2010 in conjunction with another study conducted by CAMI to evaluate different color vision tests including the SLG test. The study was conducted at the Watervliet Facility of RPI in Watervliet, NY. Color vision tests were set up in a large laboratory and an adjacent small room. The apparatus for the color identification study was set up in another adjacent small room.

SUBJECTS. Test subjects with normal and deficient color vision were recruited and diagnosed in terms of color vision status by CAMI. A total of 30 subjects in each group were targeted. Not all color-deficient subjects were included in the final experimental sample because not all passed the SLG test (as described below).

The test subjects were divided into three groups, with demographic characteristics.

- Color-normal—29 subjects, mean age 27 years, median age 25 years, standard deviation 8 years, 4 females
- Protan—8 subjects, mean age 31 years, median age 28 years, standard deviation 11 years, no females
- Deutan—13 subjects, mean age 34 years, median age 33 years, standard deviation 11 years, 1 female

COLOR VISION ASSESSMENT. Color vision assessments were made by CAMI investigators based on the results of the Colour Assessment and Diagnosis (CAD) test [20]. The CAD test is a computerized color vision test that screens for normal color vision, quantifies loss of chromatic sensitivity and classifies by type of color vision and degree of color deficiency. The full, definitive CAD test takes about 15 minutes to complete; however, unlike the Nagel anomaloscope, which is the traditional benchmark, diagnosis with the CAD test does not require an expert examiner to administer. Early versions of the test required considerable computer expertise to administer, but the current version is more user-friendly and can be operated via familiar drop-down menus. The subject observes the movement of a colored target on a dynamic checkerboard background. The subject then has to indicate the direction of the target movement via a response pad that employs a forced-choice procedure with four buttons corresponding to the four diagonal directions of movement. In earlier test versions, the subject could repeat a trial by pressing the center button on the response pad (the direction of movement changed if repeated); however, in the most current version, repeating trials is only possible through the test administrator's keyboard. The very large number of trials prevents the subjects from learning responses, which is possible on pseudoisochromatic plate tests, known as PIPs. The CAD test plots the individual's chromatic discrimination sensitivity in the CIE 1931 color space and provides both red/green and yellow/blue thresholds relative to the standard normal observer. No color naming is involved. The viewing distance from the 17-inch ViewSonic® E70fSB cathode ray tube monitor is 140 cm (~55 inches). Red/green and yellow/blue threshold values were recorded and CAD diagnoses were used to classify subjects.

All subjects also completed the SLG test using an ATI Avionics, Inc. Model 901 SLG provided by the FAA. The SLG test was administered outdoors from a distance of 1000 ft. To simulate a viewing distance of 1500 ft, a neutral density filter with an approximate transmittance of 30% was used in conjunction with the SLG.

Table 3 lists the luminous intensities for the 1000-ft and simulated 1500-ft distance conditions. Figure 24 shows the measured chromaticity coordinates of the SLG for each color. Note that the green SLG condition falls just outside the current green FAA boundary; this was also found in a survey of SLGs in Canada performed by Hovis, et al. [21]. The neutral filter had little effect on the chromaticity of each color.

Table 3. Luminous Intensities From the SLG for Each Color and Viewing Condition

Viewing Distance (ft)	Color	Luminous Intensity (cd)
1000	White	108,000
1000	Green	21,000
1000	Red	12,000
1500 (simulated with filter)	White	36,000
1500 (simulated with filter)	Green	6,500
1500 (simulated with filter)	Red	3,100

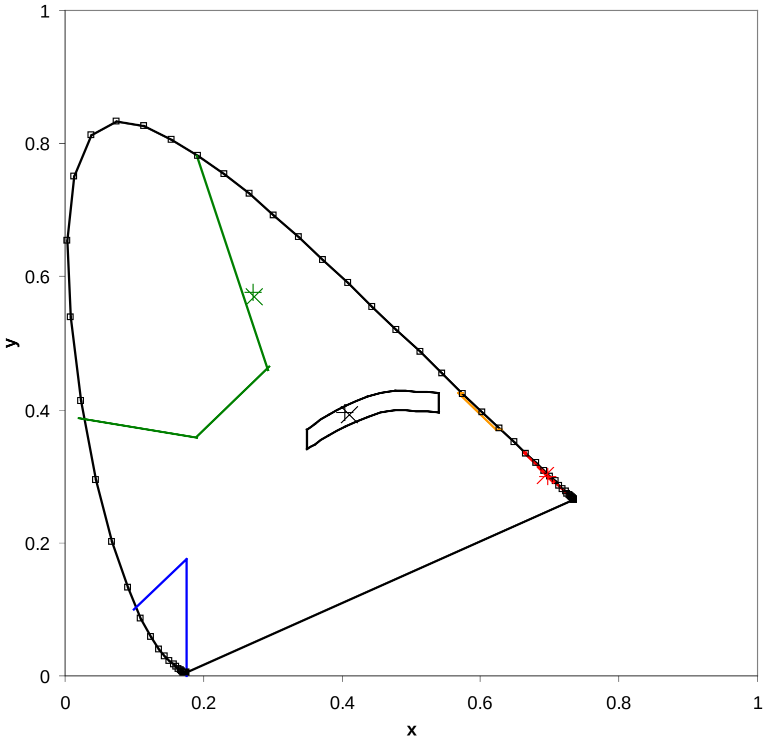


Figure 24. Chromaticity Coordinates for the Green, White, and Red Functions of the SLG Used

At each simulated viewing distance, subjects viewed each SLG color twice, presented in random order (the simulated distances were also presented in counterbalanced order among all groups of subjects). To pass the SLG test, they had to name all the colors correctly.

EXPERIMENTAL APPARATUS. Subjects arrived at the laboratory in groups of four. After signing informed consent forms approved by RPI's and FAA's Institutional Review Boards, the subjects in each group rotated through several stations, three of which consisted of several color vision tests and one of which was the color identification experiment. Figure 25 shows the room containing the color identification experimental apparatus. During the tests, the lights in the room were extinguished and the door was closed.

The signal light display was located at one end of a long table (8 ft), and subjects sat at the opposite end next to a laptop computer. The signal light display consisted of two rows of five, metal electrical enclosures. The bottom row contained 35-W incandescent lamps mounted behind 0.6-mm-diameter pinhole apertures. The aperture size was selected so that at the subjects' minimum viewing distance (2 m), the simulated signal lights would subtend a visual angle of 1 minute of arc and, therefore, would appear like a point source of light. The apertures were covered from inside by different combinations of theatrical gel filters (Roscolux) to obtain chromaticities matching those of typical aviation incandescent signal lights, within the current FAA color boundaries.

Figure 25. Photograph of Experimental Test Room (showing the laptop computer near the subjects' seating position (not shown) in the foreground, and the simulated signal display in the background)

The following filters were used to generate the different signal colors:

- White: none
- Yellow: #13, #14, and #312
- Green: #73 and #388
- Red: #124
- Blue: #80 and #4230

The five incandescent color positions were randomly located.

The top row of enclosures was also outfitted with 0.6-mm-diameter pinhole apertures, with a 1-W LED (Luxeon® with a lambertian distribution) behind each pinhole. White, amber (yellow), green, red, and blue LEDs were used and positioned in random order across the row.

The measured chromaticity coordinates of the incandescent and LED signals are shown in figure 26. The illuminances produced by each signal light at the eyes of subjects when seated in front of the apparatus (from 2 m) are listed in table 4. The incandescent signals had different light levels that corresponded to the transmittance of the colored filters used. The LED signals were operated in two different modes. In one mode, the LEDs were operated under the same nominal input power conditions so that the white, yellow, green, and red signals all produced similar illuminances (and the blue LED signal produced about one-third the illuminance of the other colors). In the other mode, the LEDs were operated so that they produced illuminances proportional to the corresponding incandescent signal of the same nominal color. Also listed in table 4 is the equivalent luminous intensity for two different viewing distances, 100 m and 1 km, which would produce the same illuminance at an observer's eyes as the simulated signal lights in the experimental apparatus.

Table 4. Illuminances Produced at Subjects' Eyes by Each Signal Light Condition for (a) Incandescent, (b) LED Incandescent-Mimicking, and (c) LED Equal Nominal Power (Also shown is the luminous intensity of a signal viewed from 100 m and 1 km that would produce the same illuminance at a subject's eyes.)

(a.) Incandescent

Color	Illuminance at 2 m (mlx)	Equivalent Luminous Intensity at 100 m (cd)	Equivalent Luminous Intensity at 1 km (cd)
White	13.4	134	13,400
Yellow	5.8	58	5,800
Red	1.8	18	1,800
Blue	0.2	2	200
Green	2.8	28	2,800

(b) LED: Incandescent-Mimicking

Color	Illuminance at 2 m (mlx)	Equivalent Luminous Intensity at 100 m (cd)	Equivalent Luminous Intensity at 1 km (cd)
White	13.9	139	13,900
Yellow	5.6	56	5,600
Red	1.9	19	1,900
Blue	0.2	2	200
Green	2.8	28	2,800

(c) LED: Equal Nominal Input Power

Color	Illuminance at 2 m (mlx)	Equivalent Luminous Intensity at 100 m (cd)	Equivalent Luminous Intensity at 1 km (cd)
White	8.3	83	8,300
Yellow	7.5	75	7,500
Red	8.3	83	8,300
Blue	2.8	28	2,800
Green	8.3	83	8,300

mlx = Millilux

Figure 26 shows the measured chromaticity coordinates for the incandescent and LED sources used in Session 1. All the chromaticities were within the FAA's color boundaries for each nominal color, with the exception of the white LED signal. Since the results of Study 1 and the CIE 107 [8] recommended a white boundary that was extended beyond the leftmost boundary of the FAA's recommendation (x = 0.35), an LED with a lower x value (x = 0.32) was selected for the study.

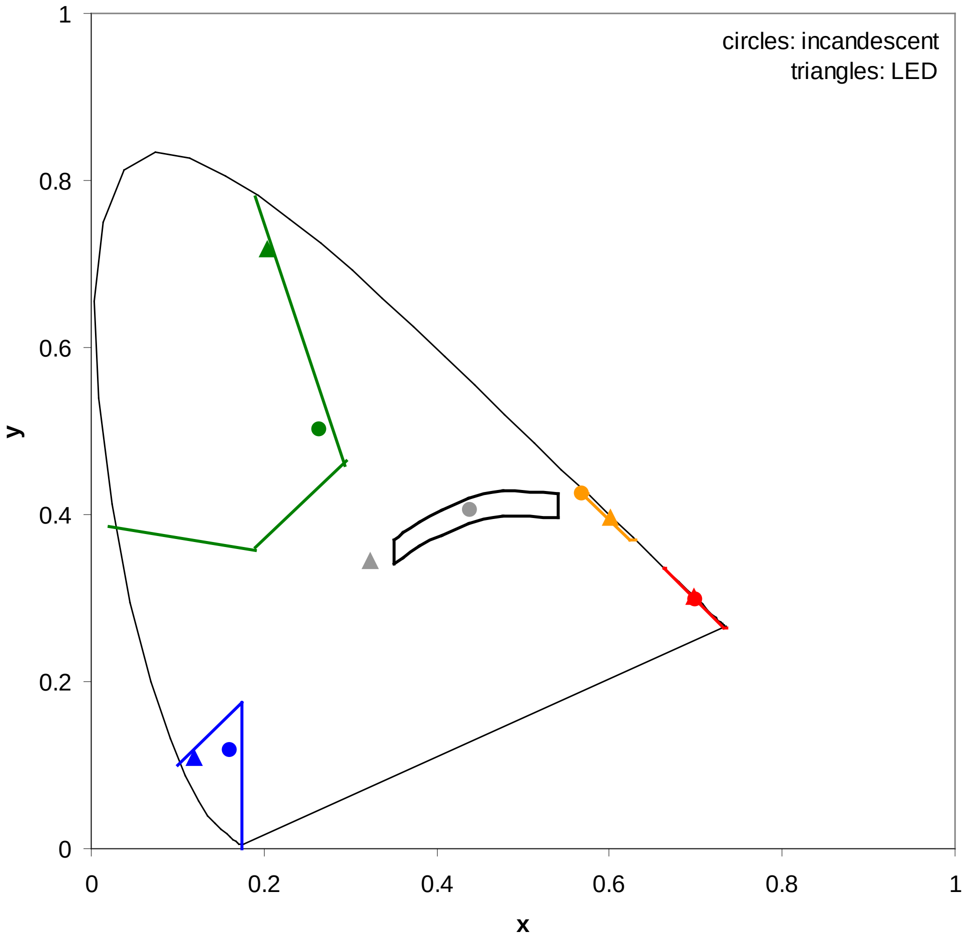


Figure 26. Chromaticity Coordinates of the Stimuli Used

<u>EXPERIMENTAL PROCEDURE</u>. For each test Session of the color identification experiment, the subjects entered the room and the lights were extinguished; the tester explained the procedure to them and answered any questions they had about the procedure. The laptop computer ran a LabVIEW (National Instruments Corp.) system design software program that interfaced with power supplies connected to the LEDs and incandescent lamps. The brightness of the laptop screen was adjusted so that it produced a luminance of about 3 cd/m² (candelas per square meter).

In each Session, either a single signal light or a pair of signal lights was displayed for 5 seconds. The signal or pair of signals would be either incandescent, LED with equivalent nominal input power, or LED with incandescent-mimicking intensities. For each of these three sources, there were 15 possible stimuli: each of the five individual colored signals, and ten possible pairs consisting of all possible combinations of the five signal colors. Thus, there were 45 possible stimulus presentations. Each stimulus presentation was displayed four times to each subject, in randomized order, for a total of 180 stimulus presentations per subject.

The stimulus presentation was displayed for 5 seconds and then was switched off. The laptop screen, which was equipped with a touch screen interface, displayed two sets of five buttons labeled with the five possible colors (white, yellow, green, blue, and red). Upon the start of each stimulus presentation, subjects could select which colors were visible in the display using a stylus pointer. Subjects were instructed to use the response buttons on the left side of the display if only a single signal light was displayed, and to use the buttons on both the left and right of the display sides to indicate the colors of the signal lights when a pair of signal lights was displayed. (Only pairs of signals of matching source type were displayed, so the pairs always differed in color.)

After the subjects entered their color responses, they could press a “submit answer” button on the laptop display to continue with the next stimulus presentation. After the 5-second display duration, subjects had an additional 5 seconds in which to enter their responses. If they did not press the submit button by this time, the program recorded any responses entered or “no response” if none was given, and then displayed the next stimulus presentation. After each subject had completed all 180 experimental trials, the program saved the results into a file for subsequent analysis. Occasionally, supply malfunctions resulted in some stimulus presentations in which one or more of the signals were not presented.

RESULTS: SESSION 1.

Tables 5 through 7 show the color identification data for the color-normal subjects for each source configuration (incandescent, LED with nominally equal input power, and LED with incandescent-mimicking intensity) and each matrix in the tables is organized accordingly. The cell in the upper left of each matrix refers to a different signal color (white, yellow, green, blue, or red). Below that cell, the six bottom rows of each matrix refer to the possible responses that each signal could have received (no response, white, yellow, green, blue, or red), indicated by the left-hand cell in each row. The row that corresponds to correct identification is in italics. The central columns segregate the data by whether the signal was presented alone, or if it was presented as one of a pair of signal lights with another color. Because colors were never presented with the same color in a pair, the column corresponding to the same color as the upper left cell of each matrix are blank. The value “n” given in the heading of each column corresponds to the total number of trials presented for each configuration. For example, in table 5, the color-normal subjects performed a total of 98 trials with the white incandescent signal presented alone, and 98 trials with the white incandescent signal displayed with another signal of each of the four other colors (yellow, green, blue, and red). The sum of the n values in table 5 is 490, meaning the color-normal subjects experienced a total of 490 trials where a white incandescent signal was presented, either alone or with another color. The right-hand column in each matrix contains the overall data for each color, collapsed across the accompanying color (if any).

The percentage values in each of the columns are the percentage of times each signal (presented alone, in a pair with another color, or overall) was identified as the color in the left-hand cell of the corresponding row. For example, in table 5, when the white incandescent signal was presented to the color-normal subjects alone, it was identified as white (correctly) 94.9% of the time and yellow (incorrectly) 5.1% of the time.

Tables 8 through 10 show the same type of data for the protan subjects, and tables 11 through 13 show the response data for the deutan subjects. (Again, only data for subjects who passed the SLG test are included in tables 8 through 13.)

Table 5. Color Identification Data for the Color-Normal Subjects to the Incandescent Signal Stimuli

Response to White Incandescent	**When Paired With**						
	None (n=98)	**White (n=0)**	**Yellow (n=98)**	**Green (n=98)**	**Blue (n=98)**	**Red (n=98)**	**Overall (n=490)**
No response	0.0%	- -	0.9%	3.1%	5.1%	0.0%	1.6%
White	*94.9%*	- -	*93.9%*	*92.9%*	*90.8%*	*94.9%*	*93.5%*
Yellow	5.1%	- -	6.1%	4.1%	4.1%	5.1%	4.9%
Green	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%
Blue	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%
Red	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%

Response to Yellow Incandescent	**When Paired With**						
	None (n=98)	**White (n=98)**	**Yellow (n=0)**	**Green (n=98)**	**Blue (n=98)**	**Red (n=98)**	**Overall (n=490)**
No response	0.0%	0.0%	- -	0.0%	1.0%	0.0%	0.2%
White	0.0%	3.1%	- -	2.0%	0.0%	1.0%	1.2%
Yellow	*99.0%*	*95.9%*	- -	*95.9%*	*98.0%*	*98.0%*	*97.4%*
Green	0.0%	0.0%	- -	1.0%	0.0%	0.0%	0.2%
Blue	0.0%	0.0%	- -	0.0%	1.0%	0.0%	0.2%
Red	1.0%	1.0%	- -	1.0%	0.0%	1.0%	0.8%

Response to Green Incandescent	**When Paired With**						
	None (n=98)	**White (n=98)**	**Yellow (n=98)**	**Green (n=0)**	**Blue (n=98)**	**Red (n=98)**	**Overall (n=490)**
No response	0.0%	1.0%	1.0%	- -	0.0%	0.0%	0.4%
White	10.0%	6.1%	10.2%	- -	5.1%	9.2%	8.2%
Yellow	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
Green	*87.8%*	*90.8%*	*88.8%*	- -	*92.9%*	*89.8%*	*90.0%*
Blue	2.0%	2.0%	0.0%	- -	2.0%	1.0%	1.4%
Red	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%

Response to Blue Incandescent	**When Paired With**						
	None (n=98)	**White (n=98)**	**Yellow (n=98)**	**Green (n=98)**	**Blue (n=0)**	**Red (n=98)**	**Overall (n=490)**
No response	2.0%	0.0%	0.0%	0.0%	- -	0.0%	0.4%
White	1.0%	5.1%	0.0%	0.0%	- -	0.0%	1.2%
Yellow	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
Green	0.0%	0.0%	0.0%	0.0%	- -	1.0%	0.2%
Blue	*96.9%*	*94.9%*	*100.0%*	*100.0%*	- -	*99.0%*	*98.2%*
Red	0.0%	1.0%	0.0%	0.0%	- -	0.0%	0.0%

Response to Red Incandescent	**When Paired With**						
	None (n=98)	**White (n=98)**	**Yellow (n=98)**	**Green (n=98)**	**Blue (n=98)**	**Red (n=0)**	**Overall (n=490)**
No response	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
White	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Yellow	0.0%	0.0%	0.0%	1.0%	0.0%	- -	0.2%
Green	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Blue	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Red	*100.0%*	*100.0%*	*100.0%*	*99.0%*	*100.0%*	- -	*99.8%*

Table 6. Color Identification Data for the Color-Normal Subjects to the LED (Nominally Equal Input Power) Stimuli

Response to White LED (equal input)	**When Paired With**						
	None (n=114)	**White (n=0)**	**Yellow (n=114)**	**Green (n=114)**	**Blue (n=114)**	**Red (n=114)**	**Overall (n=570)**
No response	0.0%	- -	0.9%	0.0%	0.9%	0.9%	0.5%
White	*98.2%*	- -	*96.5%*	*99.1%*	*97.4%*	*98.2%*	*97.9%*
Yellow	1.8%	- -	2.6%	0.9%	0.9%	0.9%	1.4%
Green	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%
Blue	0.0%	- -	0.0%	0.0%	0.9%	0.0%	0.2%
Red	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%

Response to Yellow LED (equal input)	**When Paired With**						
	None (n=114)	**White (n=114)**	**Yellow (n=0)**	**Green (n=114)**	**Blue (n=114)**	**Red (n=114)**	**Overall (n=570)**
No response	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
White	0.0%	0.9%	- -	0.0%	0.9%	0.9%	0.5%
Yellow	*100.0%*	*98.2%*	- -	*100.0%*	*98.2%*	*98.2%*	*99.0%*
Green	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
Blue	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
Red	0.0%	0.9%	- -	0.0%	0.9%	0.9%	0.5%

Response to Green LED (equal input)	**When Paired With**						
	None (n=114)	**White (n=114)**	**Yellow (n=114)**	**Green (n=0)**	**Blue (n=114)**	**Red (n=114)**	**Overall (n=570)**
No response	0.0%	0.0%	0.0%	- -	0.0%	1.8%	0.4%
White	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
Yellow	0.9%	0.0%	0.0%	- -	0.0%	0.0%	0.2%
Green	*99.1%*	*100.0%*	*98.2%*	- -	*100.0%*	*98.2%*	*99.1%*
Blue	0.0%	0.0%	1.8%	- -	0.0%	0.0%	0.4%
Red	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%

Response to Blue LED (equal input)	**When Paired With**						
	None (n=114)	**White (n=114)**	**Yellow (n=114)**	**Green (n=114)**	**Blue (n=0)**	**Red (n=114)**	**Overall (n=570)**
No response	0.0%	0.9%	0.0%	1.8%	- -	0.0%	0.5%
White	0.0%	0.9%	0.0%	0.9%	- -	0.0%	0.4%
Yellow	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
Green	1.8%	0.9%	0.9%	0.9%	- -	0.9%	1.0%
Blue	*98.2%*	*97.4%*	*99.1%*	*96.5%*	- -	*99.1%*	*98.1%*
Red	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%

Response to Red LED (equal input)	**When Paired With**						
	None (n=114)	**White (n=114)**	**Yellow (n=114)**	**Green (n=114)**	**Blue (n=114)**	**Red (n=0)**	**Overall (n=570)**
No response	1.8%	0.0%	0.0%	0.0%	0.0%	- -	0.4%
White	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Yellow	0.0%	0.0%	0.9%	0.0%	0.0%	- -	0.2%
Green	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Blue	0.0%	0.0%	0.9%	0.0%	0.0%	- -	0.2%
Red	*98.2%*	*100.0%*	*98.2%*	*100.0%*	*100.0%*	- -	*99.3%*

Table 7. Color Identification Data for the Color-Normal Subjects to the LED (Incandescent-Mimicking Intensity) Stimuli

Response to White LED (unequal input)	**When Paired With**						
	None (n=114)	**White (n=0)**	**Yellow (n=114)**	**Green (n=114)**	**Blue (n=114)**	**Red (n=114)**	**Overall (n=570)**
No Response	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.5%
White	*100.0%*	- -	*98.2%*	*100.0%*	*97.4%*	*98.2%*	*98.8%*
Yellow	0.0%	- -	1.8%	0.0%	2.6%	0.9%	1.0%
Green	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%
Blue	0.0%	- -	0.0%	0.0%	0.9%	0.9%	0.2%
Red	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%

Response to Yellow LED (unequal input)	**When Paired With**						
	None (n=114)	**White (n=114)**	**Yellow (n=0)**	**Green (n=114)**	**Blue (n=114)**	**Red (n=114)**	**Overall (n=570)**
No Response	0.0%	0.0%	- -	0.9%	0.0%	0.9%	0.4%
White	0.0%	0.0%	- -	0.9%	0.0%	0.0%	0.2%
Yellow	*98.2%*	*99.1%*	- -	*96.5%*	*99.1%*	*95.6%*	*97.8%*
Green	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
Blue	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
Red	1.8%	0.9%	- -	1.8%	0.9%	3.5%	1.8%

Response to Green LED (unequal input)	**When Paired With**						
	None (n=114)	**White (n=114)**	**Yellow (n=114)**	**Green (n=0)**	**Blue (n=114)**	**Red (n=114)**	**Overall (n=570)**
No Response	0.0%	0.0%	0.0%	- -	0.9%	0.0%	0.2%
White	0.0%	0.0%	0.9%	- -	0.0%	0.0%	0.2%
Yellow	0.0%	0.0%	0.0%	- -	0.9%	0.9%	0.4%
Green	*100.0%*	*100.0%*	*99.1%*	- -	*98.2%*	*98.2%*	*99.1%*
Blue	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
Red	0.0%	0.0%	0.0%	- -	0.0%	0.9%	0.2%

Response to Blue LED (unequal input)	**When Paired With**						
	None (n=114)	**White (n=114)**	**Yellow (n=114)**	**Green (n=114)**	**Blue (n=0)**	**Red (n=114)**	**Overall (n=570)**
No Response	0.9%	0.0%	0.0%	0.9%	- -	0.0%	0.4%
White	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
Yellow	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
Green	0.0%	1.8%	0.0%	0.0%	- -	1.8%	0.7%
Blue	*99.1%*	*98.2%*	*100.0%*	*99.1%*	- -	*98.2%*	*99.0%*
Red	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%

Response to Red LED (unequal input)	**When Paired With**						
	None (n=114)	**White (n=114)**	**Yellow (n=114)**	**Green (n=114)**	**Blue (n=114)**	**Red (n=0)**	**Overall (n=570)**
No response	0.0%	0.0%	0.9%	0.0%	0.0%	- -	0.2%
White	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Yellow	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Green	0.0%	0.0%	0.0%	0.9%	0.0%	- -	0.2%
Blue	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Red	*100.0%*	*100.0%*	*99.1%*	*99.1%*	*100.0%*	- -	*99.7%*

Table 8. Color Identification Data for the Protan Subjects to the Incandescent Signal Stimuli

Response to White Incandescent	**When Paired With**						
	None (n=32)	**White (n=0)**	**Yellow (n=32)**	**Green (n=32)**	**Blue (n=32)**	**Red (n=32)**	**Overall (n=160)**
No response	0.0%	- -	0.0%	3.1%	6.2%	0.0%	1.9%
White	*96.9%*	- -	*96.9%*	*87.5%*	*87.5%*	*90.6%*	*91.9%*
Yellow	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%
Green	3.1%	- -	3.1%	9.4%	6.2%	9.4%	6.2%
Blue	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%
Red	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%

Response to Yellow Incandescent	**When Paired With**						
	None (n=32)	**White (n=32)**	**Yellow (n=0)**	**Green (n=32)**	**Blue (n=32)**	**Red (n=32)**	**Overall (n=160)**
No response	0.0%	0.0%	- -	3.1%	0.0%	0.0%	0.6%
White	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
Yellow	*59.4%*	*59.4%*	- -	*56.2%*	*68.8%*	*59.4%*	*60.6%*
Green	28.1%	15.6%	- -	9.4%	9.4%	40.6%	20.6%
Blue	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
Red	12.5%	25.0%	- -	31.2%	21.9%	0.0%	18.1%

Response to Green Incandescent	**When Paired With**						
	None (n=32)	**White (n=32)**	**Yellow (n=32)**	**Green (n=0)**	**Blue (n=32)**	**Red (n=32)**	**Overall (n=160)**
No response	0.0%	0.0%	3.1%	- -	0.0%	0.0%	0.6%
White	53.1%	43.8%	43.8%	- -	34.4%	40.6%	43.1%
Yellow	0.0%	0.0%	0.0%	- -	3.1%	0.0%	0.6%
Green	*46.9%*	*56.2%*	*53.1%*	- -	*62.5%*	*59.4%*	*55.6%*
Blue	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
Red	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%

Response to Blue Incandescent	**When Paired With**						
	None (n=32)	**White (n=32)**	**Yellow (n=32)**	**Green (n=32)**	**Blue (n=0)**	**Red (n=32)**	**Overall (n=160)**
No response	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
White	0.0%	3.1%	0.0%	0.0%	- -	0.0%	0.6%
Yellow	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
Green	0.0%	3.1%	0.0%	0.0%	- -	0.0%	0.6%
Blue	*100.0%*	*93.8%*	*96.9%*	*96.9%*	- -	*100.0%*	*97.5%*
Red	0.0%	0.0%	3.1%	3.1%	- -	0.0%	1.2%

Response to Red Incandescent	**When Paired With**						
	None (n=32)	**White (n=32)**	**Yellow (n=32)**	**Green (n=32)**	**Blue (n=32)**	**Red (n=0)**	**Overall (n=160)**
No response	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
White	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Yellow	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Green	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Blue	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Red	*100.0%*	*100.0%*	*100.0%*	*100.0%*	*100.0%*	- -	*100.0%*

Table 9. Color Identification Data for the Protan Subjects to the LED (Nominally Equal Input Power) Stimuli

Response to White LED (equal input)	**When Paired With**						
	None (n=32)	**White (n=0)**	**Yellow (n=32)**	**Green (n=32)**	**Blue (n=32)**	**Red (n=32)**	**Overall (n=160)**
No response	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%
White	*100.0%*	- -	*87.5%*	*93.8%*	*90.6%*	*90.6%*	*92.5%*
Yellow	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%
Green	0.0%	- -	0.0%	0.0%	3.1%	0.0%	0.6%
Blue	0.0%	- -	12.5%	6.2%	6.2%	9.4%	6.9%
Red	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%

Response to Yellow LED (equal input)	**When Paired With**						
	None (n=32)	**White (n=32)**	**Yellow (n=0)**	**Green (n=32)**	**Blue (n=32)**	**Red (n=32)**	**Overall (n=160)**
No response	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
White	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
Yellow	*53.1%*	*34.4%*	- -	*25.0%*	*31.2%*	*43.8%*	*37.5%*
Green	12.5%	3.1%	- -	12.5%	12.5%	9.4%	10.0%
Blue	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
Red	34.4%	62.5%	- -	62.5%	56.2%	46.9%	52.5%

Response to Green LED (equal input)	**When Paired With**						
	None (n=32)	**White (n=32)**	**Yellow (n=32)**	**Green (n=0)**	**Blue (n=32)**	**Red (n=32)**	**Overall (n=160)**
No response	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
White	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
Yellow	34.4%	28.1%	28.1%	- -	25.0%	28.1%	28.8%
Green	*65.6%*	*71.9%*	*71.9%*	- -	*75.0%*	*71.9%*	*71.2%*
Blue	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
Red	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%

Response to Blue LED (equal input)	**When Paired With**						
	None (n=32)	**White (n=32)**	**Yellow (n=32)**	**Green (n=32)**	**Blue (n=0)**	**Red (n=32)**	**Overall (n=160)**
No response	3.1%	0.0%	0.0%	0.0%	- -	0.0%	0.6%
White	25.0%	25.0%	21.9%	18.8%	- -	18.8%	21.9%
Yellow	0.0%	0.0%	0.0%	3.1%	- -	0.0%	0.6%
Green	0.0%	3.1%	0.0%	0.0%	- -	6.2%	1.9%
Blue	*71.9%*	*71.9%*	*78.1%*	*78.1%*	- -	*75.0%*	*75.0%*
Red	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%

Response to Red LED (equal input)	**When Paired With**						
	None (n=32)	**White (n=32)**	**Yellow (n=32)**	**Green (n=32)**	**Blue (n=32)**	**Red (n=0)**	**Overall (n=160)**
No response	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
White	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Yellow	9.4%	9.4%	9.4%	9.4%	6.2%	- -	8.8%
Green	6.2%	6.2%	3.1%	0.0%	0.0%	- -	3.1%
Blue	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Red	*84.4%*	*84.4%*	*87.5%*	*90.6%*	*93.8%*	- -	*88.1%*

Table 10. Color Identification Data for the Protan Subjects to the LED (Incandescent-Mimicking Intensity) Stimuli

Response to White LED (unequal input)	**When Paired With**						
	None (n=32)	**White (n=0)**	**Yellow (n=32)**	**Green (n=32)**	**Blue (n=32)**	**Red (n=32)**	**Overall (n=160)**
No response	0.0%	- -	0.0%	0.0%	0.0%	3.1%	0.6%
White	*100.0%*	- -	*90.6%*	*93.8%*	*100.0%*	*93.8%*	*95.6%*
Yellow	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%
Green	0.0%	- -	0.0%	3.1%	0.0%	0.0%	0.6%
Blue	0.0%	- -	9.4%	3.1%	0.0%	3.1%	3.1%
Red	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%

Response to Yellow LED (unequal input)	**When Paired With**						
	None (n=32)	**White (n=32)**	**Yellow (n=0)**	**Green (n=32)**	**Blue (n=32)**	**Red (n=32)**	**Overall (n=160)**
No response	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
White	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.4%
Yellow	*43.8%*	*40.6%*	- -	*31.2%*	*31.2%*	*46.9%*	*38.8%*
Green	12.5%	15.6%	- -	3.1%	9.4%	15.6%	11.2%
Blue	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
Red	43.8%	43.8%	- -	65.6%	59.4%	37.5%	50.0%

Response to Green LED (unequal input)	**When Paired With**						
	None (n=32)	**White (n=32)**	**Yellow (n=32)**	**Green (n=0)**	**Blue (n=32)**	**Red (n=32)**	**Overall (n=160)**
No Response	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
White	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
Yellow	15.6%	25.0%	15.6%	- -	6.2%	15.6%	15.6%
Green	*84.4%*	*68.8%*	*84.4%*	- -	*90.6%*	*84.4%*	*82.5%*
Blue	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
Red	0.0%	6.2%	0.0%	- -	3.1%	0.0%	1.9%

Response to Blue LED (unequal input)	**When Paired With**						
	None (n=32)	**White (n=32)**	**Yellow (n=32)**	**Green (n=32)**	**Blue (n=0)**	**Red (n=32)**	**Overall (n=160)**
No response	3.1%	0.0%	0.0%	3.1%	- -	3.1%	1.9%
White	12.5%	25.0%	15.6%	15.6%	- -	12.5%	16.2%
Yellow	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
Green	0.0%	3.1%	0.0%	0.0%	- -	3.1%	1.2%
Blue	*84.4%*	*71.9%*	*84.4%*	*81.2%*	- -	*81.2%*	*80.6%*
Red	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%

Response to Red LED (unequal input)	**When Paired With**						
	None (n=32)	**White (n=32)**	**Yellow (n=32)**	**Green (n=32)**	**Blue (n=32)**	**Red (n=0)**	**Overall (n=160)**
No response	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
White	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Yellow	9.4%	12.5%	9.4%	9.4%	9.4%	- -	10.0%
Green	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Blue	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Red	*90.6%*	*87.5%*	*90.6%*	*90.6%*	*90.6%*	- -	*90.0%*

Table 11. Color Identification Data for the Deutan Subjects to the Incandescent Signal Stimuli

Response to White Incandescent	**When Paired With**						
	None (n=46)	**White (n=0)**	**Yellow (n=46)**	**Green (n=46)**	**Blue (n=46)**	**Red (n=46)**	**Overall (n=230)**
No response	2.2%	- -	0.0%	0.0%	4.4%	0.0%	1.3%
White	*95.6%*	- -	*91.3%*	*93.5%*	*89.1%*	*95.6%*	*93.0%*
Yellow	2.2%	- -	6.5%	6.5%	4.4%	4.4%	4.8%
Green	0.0%	- -	2.2%	0.0%	2.2%	0.0%	0.9%
Blue	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%
Red	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%

Response to Yellow Incandescent	**When Paired With**						
	None (n=46)	**White (n=46)**	**Yellow (n=0)**	**Green (n=46)**	**Blue (n=46)**	**Red (n=46)**	**Overall (n=230)**
No response	0.0%	4.4%	- -	2.2%	0.0%	0.0%	1.3%
White	0.0%	2.2%	- -	0.0%	0.0%	0.0%	0.4%
Yellow	*87.0%*	*67.4%*	- -	*87.0%*	*82.6%*	*89.1%*	*82.6%*
Green	0.0%	2.2%	- -	4.4%	2.2%	10.9%	3.9%
Blue	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
Red	13.0%	23.9%	- -	6.5%	15.2%	0.0%	11.7%

Response to Green Incandescent	**When Paired With**						
	None (n=46)	**White (n=46)**	**Yellow (n=46)**	**Green (n=0)**	**Blue (n=46)**	**Red (n=46)**	**Overall (n=230)**
No response	0.0%	0.0%	2.2%	- -	0.0%	0.0%	0.4%
White	41.3%	26.1%	32.6%	- -	23.9%	30.4%	30.9%
Yellow	0.0%	0.0%	0.0%	- -	2.2%	2.2%	0.9%
Green	*56.5%*	*69.6%*	*63.0%*	- -	*73.9%*	*65.2%*	*65.6%*
Blue	0.0%	4.4%	2.2%	- -	0.0%	2.2%	1.7%
Red	2.2%	0.0%	0.0%	- -	0.0%	0.0%	0.4%

Response to Blue Incandescent	**When Paired With**						
	None (n=46)	**White (n=46)**	**Yellow (n=46)**	**Green (n=46)**	**Blue (n=0)**	**Red (n=46)**	**Overall (n=230)**
No response	0.0%	0.0%	0.0%	0.0%	- -	2.2%	0.4%
White	0.0%	4.4%	0.0%	0.0%	- -	0.0%	0.9%
Yellow	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
Green	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
Blue	*100.0%*	*95.6%*	*100.0%*	*100.0%*	- -	*97.8%*	*98.7%*
Red	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%

Response to Red Incandescent	**When Paired With**						
	None (n=46)	**White (n=46)**	**Yellow (n=46)**	**Green (n=46)**	**Blue (n=46)**	**Red (n=0)**	**Overall (n=230)**
No response	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
White	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Yellow	0.0%	0.0%	0.0%	2.2%	0.0%	- -	0.4%
Green	2.2%	0.0%	4.4%	2.2%	4.4%	- -	2.6%
Blue	0.0%	0.0%	0.0%	0.0%	2.2%	- -	0.4%
Red	*97.8%*	*100.0%*	*95.6%*	*95.6%*	*93.5%*	- -	*96.5%*

Table 12. Color Identification Data for the Deutan Subjects to the LED (Nominally Equal Input Power) Stimuli

Response to White LED (equal input)	**When Paired With**						
	None (n=50)	**White (n=0)**	**Yellow (n=50)**	**Green (n=50)**	**Blue (n=50)**	**Red (n=50)**	**Overall (n=250)**
No response	0.0%	- -	2.0%	0.0%	4.0%	0.0%	1.2%
White	*96.0%*	- -	*96.0%*	*96.0%*	*90.0%*	*90.0%*	*93.6%*
Yellow	0.0%	- -	2.0%	0.0%	2.0%	2.0%	1.2%
Green	4.0%	- -	0.0%	2.0%	4.0%	8.0%	3.6%
Blue	0.0%	- -	0.0%	2.0%	0.0%	0.0%	0.4%
Red	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%

Response to Yellow LED (equal input)	**When Paired With**						
	None (n=50)	**White (n=50)**	**Yellow (n=0)**	**Green (n=50)**	**Blue (n=50)**	**Red (n=50)**	**Overall (n=250)**
No response	0.0%	2.0%	- -	0.0%	2.0%	0.0%	0.8%
White	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
Yellow	*78.0%*	*62.0%*	- -	*62.0%*	*66.0%*	*72.0%*	*68.0%*
Green	6.0%	2.0%	- -	0.0%	4.0%	16.0%	5.6%
Blue	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
Red	16.0%	34.0%	- -	38.0%	28.0%	12.0%	25.6%

Response to Green LED (equal input)	**When Paired With**						
	None (n=50)	**White (n=50)**	**Yellow (n=50)**	**Green (n=0)**	**Blue (n=50)**	**Red (n=50)**	**Overall (n=250)**
No response	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
White	0.0%	0.0%	2.0%	- -	0.0%	0.0%	0.4%
Yellow	20.0%	20.0%	20.0%	- -	16.0%	4.0%	16.0%
Green	*80.0%*	*80.0%*	*78.0%*	- -	*82.0%*	*94.0%*	*82.8%*
Blue	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
Red	0.0%	0.0%	0.0%	- -	2.0%	2.0%	0.8%

Response to Blue LED (equal input)	**When Paired With**						
	None (n=50)	**White (n=50)**	**Yellow (n=50)**	**Green (n=50)**	**Blue (n=0)**	**Red (n=50)**	**Overall (n=250)**
No response	0.0%	0.0%	2.0%	0.0%	- -	0.0%	0.4%
White	4.0%	12.0%	4.0%	10.0%	- -	0.0%	6.0%
Yellow	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
Green	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
Blue	*96.0%*	*88.0%*	*94.0%*	*90.0%*	- -	*100.0%*	*93.6%*
Red	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%

Response to Red LED (equal input)	**When Paired With**						
	None (n=50)	**White (n=50)**	**Yellow (n=50)**	**Green (n=50)**	**Blue (n=50)**	**Red (n=0)**	**Overall (n=250)**
No response	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
White	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Yellow	0.0%	0.0%	2.0%	0.0%	0.0%	- -	0.4%
Green	0.0%	0.0%	2.0%	2.0%	0.0%	- -	0.8%
Blue	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Red	*100.0%*	*100.0%*	*96.0%*	*98.0%*	*100.0%*	- -	*98.8%*

Table 13. Color Identification Data for the Deutan Subjects to the LED (Incandescent-Mimicking Intensity) Stimuli

Response to White LED (unequal input)	**When Paired With**						
	None (n=50)	**White (n=0)**	**Yellow (n=50)**	**Green (n=50)**	**Blue (n=50)**	**Red (n=50)**	**Overall (n=250)**
No response	0.0%	- -	0.0%	0.0%	4.0%	0.0%	0.8%
White	*96.0%*	- -	*94.0%*	*98.0%*	*96.0%*	*98.0%*	*96.4%*
Yellow	0.0%	- -	6.0%	0.0%	0.0%	0.0%	1.2%
Green	2.0%	- -	0.0%	0.0%	0.0%	0.0%	0.4%
Blue	2.0%	- -	0.0%	2.0%	0.0%	2.0%	1.2%
Red	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%

Response to Yellow LED (unequal input)	**When Paired With**						
	None (n=50)	**White (n=50)**	**Yellow (n=0)**	**Green (n=50)**	**Blue (n=50)**	**Red (n=50)**	**Overall (n=250)**
No response	0.0%	2.0%	- -	2.0%	0.0%	0.0%	0.8%
White	0.0%	2.0%	- -	6.0%	0.0%	0.0%	1.6%
Yellow	*70.0%*	*58.0%*	- -	*50.0%*	*66.0%*	*74.0%*	*63.6%*
Green	2.0%	2.0%	- -	0.0%	2.0%	6.0%	2.8%
Blue	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
Red	28.0%	34.0%	- -	42.0%	32.0%	20.0%	31.2%

Response to Green LED (unequal input)	**When Paired With**						
	None (n=50)	**White (n=50)**	**Yellow (n=50)**	**Green (n=0)**	**Blue (n=50)**	**Red (n=50)**	**Overall (n=250)**
No response	2.0%	0.0%	2.0%	- -	0.0%	0.0%	0.8%
White	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
Yellow	12.0%	18.0%	4.0%	- -	16.0%	10.0%	12.0%
Green	*84.0%*	*80.0%*	*94.0%*	- -	*84.0%*	*90.0%*	*86.4%*
Blue	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
Red	2.0%	2.0%	0.0%	- -	0.0%	0.0%	0.8%

Response to Blue LED (unequal input)	**When Paired With**						
	None (n=50)	**White (n=50)**	**Yellow (n=50)**	**Green (n=50)**	**Blue (n=0)**	**Red (n=50)**	**Overall (n=250)**
No response	0.0%	0.0%	2.0%	0.0%	- -	0.0%	0.4%
White	0.0%	6.0%	0.0%	0.0%	- -	0.0%	1.2%
Yellow	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
Green	2.0%	2.0%	2.0%	0.0%	- -	0.0%	1.2%
Blue	*98.0%*	*92.0%*	*94.0%*	*100.0%*	- -	*100.0%*	*96.8%*
Red	0.0%	0.0%	2.0%	0.0%	- -	0.0%	0.4%

Response to Red LED (unequal input)	**When Paired With**						
	None (n=50)	**White (n=50)**	**Yellow (n=50)**	**Green (n=50)**	**Blue (n=50)**	**Red (n=0)**	**Overall (n=250)**
No response	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
White	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Yellow	0.0%	2.0%	4.0%	0.0%	4.0%	- -	2.0%
Green	2.0%	0.0%	8.0%	0.0%	4.0%	- -	2.8%
Blue	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Red	*98.0%*	*98.0%*	*88.0%*	*100.0%*	*92.0%*	- -	*95.2%*

Figure 27 shows the overall color identification percentages (including when the signal was presented alone and as part of a pair) for each color-vision group to each signal color for the incandescent signals. Figure 28 shows the same data for the LED signals with nominally equal input power, and figure 29 for the LED with incandescent-mimicking intensity signals. These figures demonstrate the generally superior color identification performance for the color-normal subject in the study relative to the protan and deutan subjects, as expected.

To assess whether there were significant differences for each color-vision group between different sources (incandescent, LED with equal nominal input power, and LED incandescent-mimicking intensity), the distributions of color identification were compared using Fisher's exact test [22] with a statistical significance criterion of p <0.05.

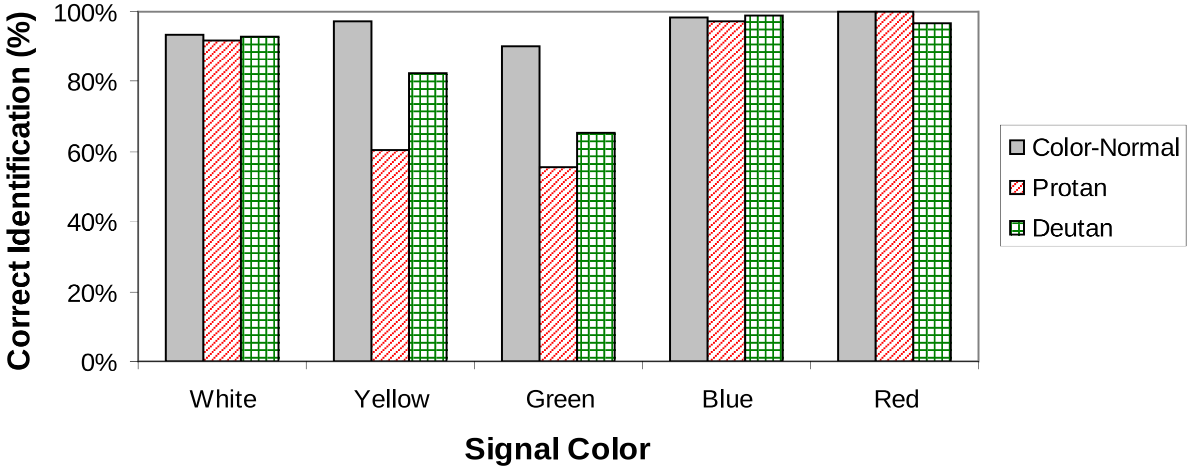


Figure 27. Correct Identification Percentages to Each Color and for Each Color-Vision Group for the Incandescent Signal Lights

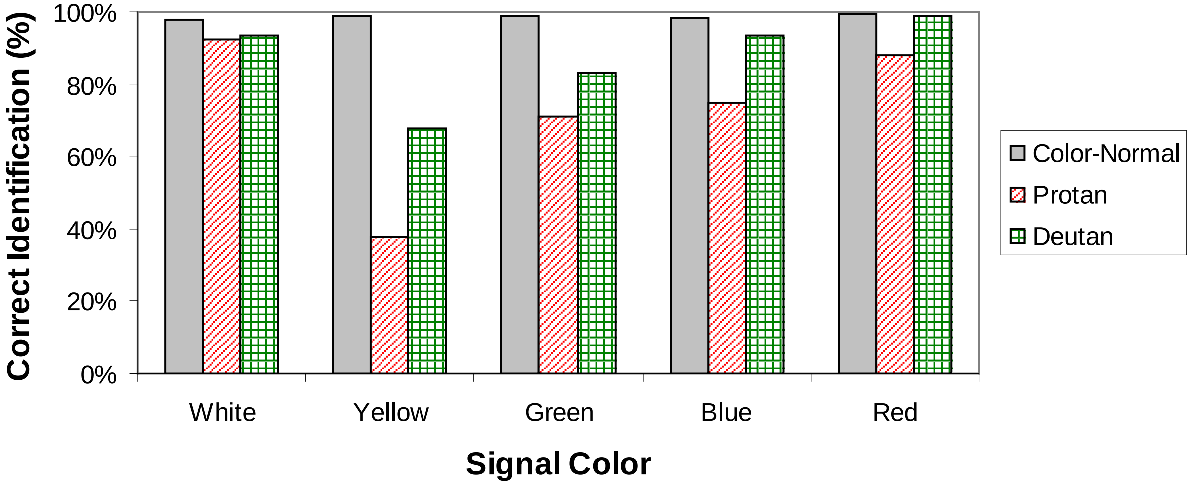


Figure 28. Correct Identification Percentages to Each Color and for Each Color-Vision Group for the LED (Equal Nominal Input Power) Signal Lights

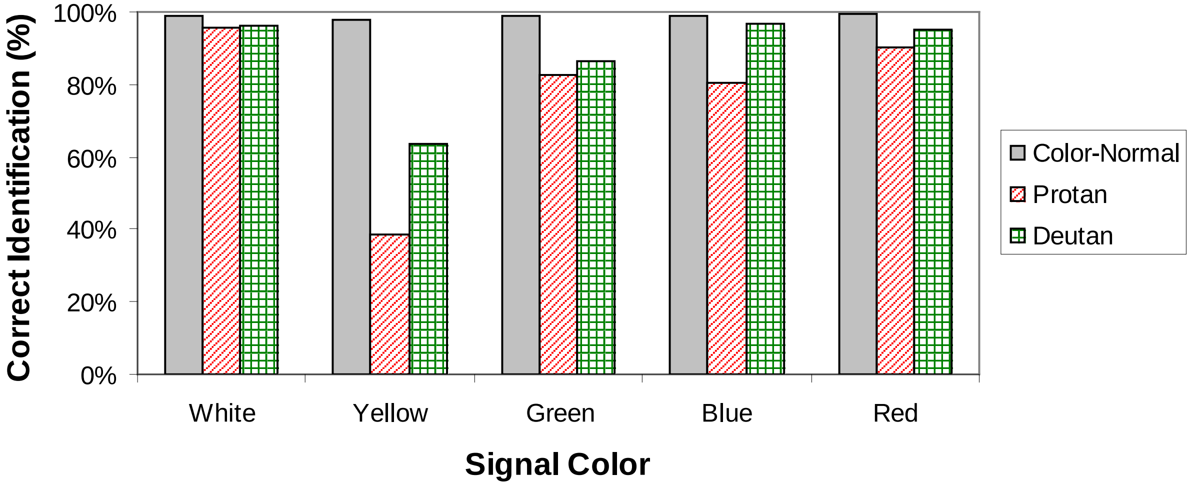


Figure 29. Correct Identification Percentages to Each Color and for Each Color-Vision Group for the LED (Incandescent-Mimicking Intensity) Signal Lights

EFFECTS OF LIGHT SOURCE ON COLOR IDENTIFICATION. Table 14 summarizes the results of the Fisher's exact tests for the color normal subjects, for each color. Table 15 summarizes the statistical tests for the protan subjects, and table 16 summarizes the statistical tests for the deutan subjects.

Table 14. Summary of Statistical Comparisons of the Color Identification Distributions of the Color-Normal Subjects for Each Color, Between Each Light Source Type

	Comparison		
Signal Color	Inc. vs LED-equal	Inc. vs LED-unequal	LED-equal vs LED-unequal
White	LED-equal ($p < 0.001$) More correct (98% vs 94%) Fewer named Yellow	LED-unequal ($p < 0.001$) More correct (99% vs 94%) Fewer named Yellow	n.s.
Yellow	n.s.	n.s.	n.s.
Green	LED-equal ($p < 0.001$) More correct (99% vs 90%) Fewer named White	LED-unequal ($p < 0.001$) More correct (99% vs 90%) Fewer named White	n.s.
Blue	n.s.	LED-unequal ($p < 0.05$) More correct (99% vs 98%) Fewer named White	n.s.
Red	n.s.	n.s.	n.s.

n.s. = Not statistically significant
Inc. = Incandescent
Note: Each cell lists the source resulting in improved detection, and a summary of primary differences between the sources in terms of correct identification or distribution of errors when a significant effect of light source was found.

Table 15. Summary of Statistical Comparisons of the Color Identification Distributions of the Protan Subjects for Each Color Between Each Light Source Type

	Comparison		
Signal Color	Inc. vs LED-equal	Inc. vs LED-unequal	LED-equal vs LED-unequal
White	LED-equal ($p < 0.001$) More correct (93% vs 92%) Fewer named Green More named Blue	LED-unequal ($p < 0.001$) More correct (96% vs 92%) Fewer named Green More named Blue	n.s.
Yellow	Inc. ($p < 0.001$) More correct (61% vs 38%) Fewer named Red More named Yellow	Inc. ($p < 0.001$) More correct (61% vs 39%) Fewer named Red More named Yellow	n.s.
Green	LED-equal ($p < 0.001$) More correct (71% vs 56%) Fewer named White More named Yellow	LED-unequal ($p < 0.001$) More correct (82% vs 56%) Fewer named White More named Yellow	LED-unequal ($p < 0.01$) More correct (82% vs 71%) Fewer named Yellow
Blue	Inc. ($p < 0.001$) More correct (98% vs 75%) Fewer named White	Inc. ($p < 0.001$) More correct (98% vs 81%) Fewer named White	n.s.
Red	Inc. ($p < 0.001$) More correct (100% vs 88%) Fewer named Yellow	Inc. ($p < 0.001$) More correct (100% vs 90%) Fewer named Yellow	n.s.

n.s. = not statistically significant
Inc. = Incandescent
Note: Each cell lists the source resulting in improved detection, and a summary of primary differences between the sources in terms of correct identification or distribution of errors when a significant effect of light source was found.

Table 16. Summary of Statistical Comparisons of the Color Identification Distributions of the Deutan Subjects for Each Color Between Each Light Source Type

Signal Color	Comparison		
	Inc. vs LED-equal	Inc. vs LED-unequal	LED-equal vs LED-unequal
White	LED-equal (p<0.05) More correct (94% v. 93%) Fewer named Yellow More named Green	LED-unequal (p<0.05) More correct (96% v. 93%) Fewer named Yellow	n.s.
Yellow	Inc. (p<0.001) More correct (83% v. 68%) Fewer named Red	Inc. (p<0.001) More correct (83% v. 64%) Fewer named Red	n.s.
Green	LED-equal (p<0.001) More correct (83% v. 66%) Fewer named White More named Yellow	LED-unequal (p<0.001) More correct (86% v. 66%) Fewer named White More named Yellow	n.s.
Blue	Inc. (p<0.01) More correct (99% v. 94%) Fewer named White	n.s.	LED-unequal (p<0.01) More correct (97% v. 94%) Fewer named White
Red	n.s.	n.s.	n.s.

n.s. = Not statistically significant
Inc. = Incandescent
Note: Each cell lists the source resulting in improved detection, and a summary of primary differences between the sources in terms of correct identification or distribution of errors when a significant effect of light source was found.

In general, identification responses for the color-normal subjects were better for both LED conditions than for the incandescent conditions. Identification responses for the protan subjects were generally worse for the yellow, blue, and red LED conditions and generally better for white (only slightly) and green LED conditions. The protan subjects were more likely to correctly identify the green LED conditions when the intensities of the colors were unequal. For the deutan subjects, identification responses were improved with incandescent for yellow, but were improved for the green LED and (slightly) for the white LED conditions. For blue signals, the deutan subjects had slightly better performance when the luminous intensity of the blue signal was lower relative to that of other colors, as in the incandescent and LED-unequal conditions.

EFFECTS OF ACCOMPANYING SIGNAL COLOR. Statistical comparisons of the effects of accompanying signal colors were made by comparing the distributions of color identification when a signal was presented alone to the distributions when it was presented with each other color. All comparisons used Fisher’s exact test [22] with a criterion probability for statistical significance of $p < 0.05$.

No statistically significant effects were found for any of the conditions for both the color-normal and for the deutan subjects. Table 17 summarizes the statistically significant effects found for the protan subjects. When a yellow incandescent signal light was presented, an accompanying red signal did not affect identification accuracy for the protan subjects (but resulted in fewer instances of it being incorrectly called “red”). When a yellow LED signal was presented, an accompanying green signal resulted in poorer identification performance for the protan subjects (with a greater likelihood of the yellow LED signal being incorrectly called “red”). When the green LED-equal signal was presented, an accompanying red signal resulted in improved identification performance for the protan subjects (with fewer instances of it being incorrectly called “yellow”).

Table 17. Summary of Statistically Significant Effects of Accompanying Color on the Distribution of Color Identification for the Protan Subjects

Signal Color	Source	Accompanying Signal Color	Effect Relative to No Other Color Present
Yellow	Incandescent	Red	Equal correct More named Green ($p < 0.01$) Fewer named Red
Yellow	LED-equal	Green	Fewer correct (25% vs 53%, $p < 0.05$) More named Red
Yellow	LED-unequal	Green	Fewer correct (31% vs 44%, $p < 0.05$) More named Red
Green	LED-equal	Red	More correct (72% vs 66%, $p < 0.05$) Fewer named Yellow

METHODS: SESSION 2.

Session 1 used a green LED with a peak wavelength near 525 nm, but cyan LEDs with peak wavelengths closer to 505 nm would also fall within the FAA color boundary for aviation green. Therefore, Session 2 was conducted to provide a preliminary assessment of the impact of green LED signals using cyan LEDs. The primary focus was on subjects with normal color vision. Session 2 occurred in the Levin Photometric Laboratory at the LRC in Troy, NY. A total of thirteen subjects participated in the experiment, eleven with normal color vision (four female, mean age 30 years, median 27 years, standard deviation 10 years), one protan (male, age 60 years) and one deutan (male, age 25 years). All subjects were able to pass the SLG test.

EXPERIMENTAL APPARATUS. Only LED sources (either with equal nominal input power or with incandescent-mimicking intensities) were used in the study. The green LED in the apparatus was replaced with a cyan LED with the chromaticity coordinates shown in figure 30.

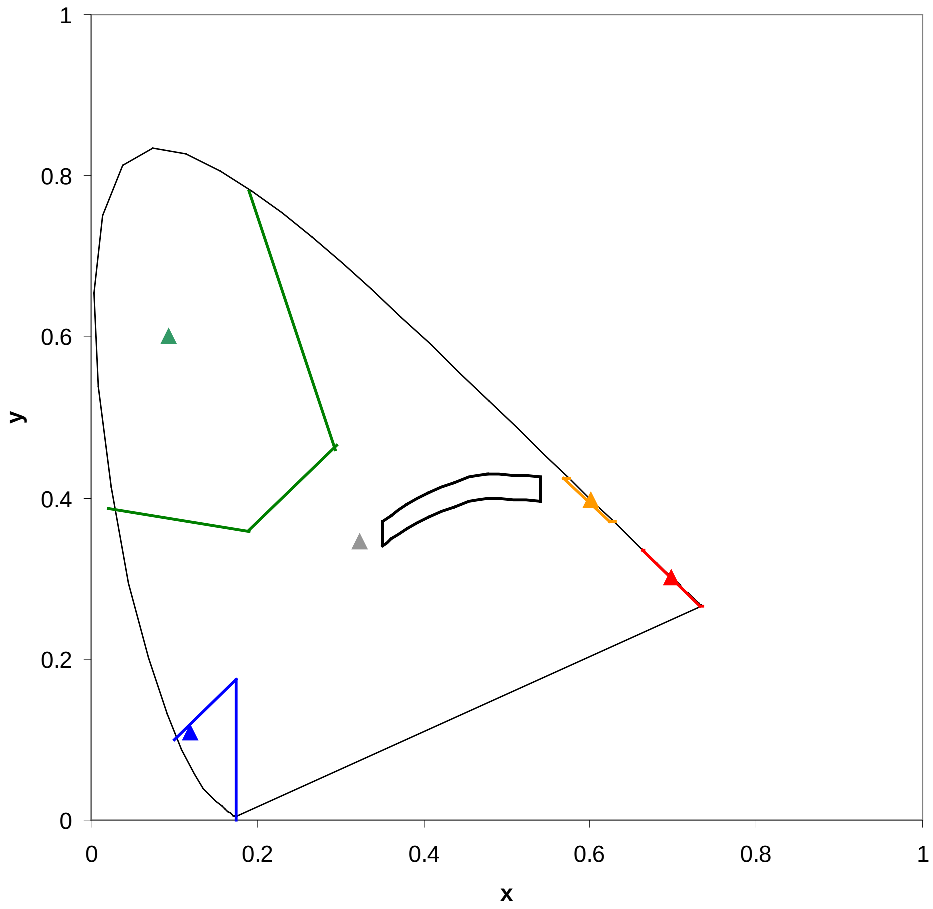


Figure 30. Chromaticity Coordinates of the Stimuli Used in Session 2

Table 18 lists the illuminances from each simulated signal with a 2-m distance in front of the experimental apparatus. Also shown is the luminous intensity of a signal viewed from 100 m and 1 km that would produce the same illuminance at an observer's eyes.

Table 18. Illuminances Produced at Subjects' Eyes by Each Signal Light Condition for (a) LED Incandescent-Mimicking and (b) LED With Equal Nominal Power

(a) LED: Incandescent-Mimicking

Color	Illuminance at 2 m (mlx)	Equivalent Luminous Intensity at 100 m (cd)	Equivalent Luminous Intensity at 1 km (cd)
White	14.2	142	14,200
Yellow	4.4	44	4,400
Red	1.9	19	1,900
Blue	0.2	2	200
Green	2.8	28	2,800

(b) LED: Equal Nominal Input Power

Color	Illuminance at 2 m (mlx)	Equivalent Luminous Intensity at 100 m (cd)	Equivalent Luminous Intensity at 1 km (cd)
White	8.6	86	8,600
Yellow	4.4	44	4,400
Red	8.3	83	8,300
Blue	2.8	28	2,800
Green	8.3	83	8,300

mlx = Millilux

EXPERIMENTAL PROCEDURE. The experimental procedure was identical to Session 1, except the incandescent conditions were omitted. For both LED operating modes (equal nominal power and incandescent-mimicking intensity), each condition was presented alone and with every possible accompanying color a total of four times, in random order. Each subject completed 120 color identification trials.

RESULTS: SESSION 2.

Tables 19 and 20 show the color identification data for the color-normal subjects for each source configuration (LED with nominally equal input power, and LED with incandescent-mimicking intensity). Each table is arranged in the same way as tables 5 through 13. Tables 21 and 22 show the color identification data for the protan subject and tables 23 and 24 show the data for the deutan subject.

Table 19. Color Identification Data for the Color-Normal Subjects to the LED (Nominally Equal Input Power) Stimuli in Session 2

Response to White LED (equal input)	**When Paired With**						
	None (n=44)	**White (n=0)**	**Yellow (n=44)**	**Cyan (n=44)**	**Blue (n=44)**	**Red (n=44)**	**Overall (n=220)**
No Response	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%
White	*100.0%*	- -	*100.0%*	*100.0%*	*100.0%*	*97.7%*	*99.5%*
Yellow	0.0%	- -	0.0%	0.0%	0.0%	2.3%	0.5%
Green	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%
Blue	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%
Red	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%

Response to Yellow LED (equal input)	**When Paired With**						
	None (n=44)	**White (n=44)**	**Yellow (n=0)**	**Cyan (n=44)**	**Blue (n=44)**	**Red (n=44)**	**Overall (n=220)**
No Response	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
White	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
Yellow	*100.0%*	*100.0%*	- -	*100.0%*	*100.0%*	*100.0%*	*100.0%*
Green	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
Blue	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
Red	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%

Response to Cyan LED (equal input)	**When Paired With**						
	None (n=44)	**White (n=44)**	**Yellow (n=44)**	**Cyan (n=0)**	**Blue (n=44)**	**Red (n=44)**	**Overall (n=220)**
No Response	0.0%	2.3%	0.0%	- -	0.0%	2.3%	0.9%
White	0.0%	0.0%	0.0%	- -	0.0%	2.3%	0.5%
Yellow	0.0%	2.3%	0.0%	- -	0.0%	0.0%	0.5%
Green	*100.0%*	*95.5%*	*100.0%*	- -	*100.0%*	*95.5%*	*98.2%*
Blue	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
Red	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%

Response to Blue LED (equal input)	**When Paired With**						
	None (n=44)	**White (n=44)**	**Yellow (n=44)**	**Cyan (n=44)**	**Blue (n=0)**	**Red (n=44)**	**Overall (n=220)**
No Response	0.0%	0.0%	2.3%	0.0%	- -	2.3%	0.9%
White	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
Yellow	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
Green	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
Blue	*100.0%*	*100.0%*	*97.7%*	*100.0%*	- -	*97.7%*	*99.1%*
Red	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%

Response to Red LED (equal input)	**When Paired With**						
	None (n=44)	**White (n=44)**	**Yellow (n=44)**	**Cyan (n=44)**	**Blue (n=44)**	**Red (n=0)**	**Overall (n=220)**
No Response	0.0%	2.3%	0.0%	0.0%	0.0%	- -	0.5%
White	0.0%	0.0%	0.0%	0.0%	2.3%	- -	0.5%
Yellow	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Green	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Blue	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Red	*100.0%*	*97.7%*	*100.0%*	*100.0%*	*97.7%*	- -	*99.1%*

Table 20. Color Identification Data for the Color-Normal Subjects to the LED (Incandescent-Mimicking Intensity) Stimuli in Session 2

Response to White LED (unequal input)	**When Paired With**						
	None (n=44)	**White (n=0)**	**Yellow (n=44)**	**Cyan (n=44)**	**Blue (n=44)**	**Red (n=44)**	**Overall (n=220)**
No Response	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%
White	*97.7%*	- -	*100.0%*	*97.7%*	*97.7%*	*95.5%*	*97.7%*
Yellow	0.0%	- -	0.0%	2.3%	0.0%	0.0%	0.5%
Green	0.0%	- -	0.0%	0.0%	0.0%	2.3%	0.5%
Blue	0.0%	- -	0.0%	0.0%	2.3%	2.3%	0.9%
Red	2.3%	- -	0.0%	0.0%	0.0%	0.0%	0.5%

Response to Yellow LED (unequal input)	**When Paired With**						
	None (n=44)	**White (n=44)**	**Yellow (n=0)**	**Cyan (n=44)**	**Blue (n=44)**	**Red (n=44)**	**Overall (n=220)**
No Response	0.0%	2.3%	- -	0.0%	2.3%	0.0%	0.9%
White	0.0%	0.0%	- -	0.0%	2.3%	0.0%	0.5%
Yellow	*100.0%*	*97.7%*	- -	*100.0%*	*95.5%*	*100.0%*	*98.6%*
Green	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
Blue	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
Red	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%

Response to Cyan LED (unequal input)	**When Paired With**						
	None (n=44)	**White (n=44)**	**Yellow (n=44)**	**Cyan (n=0)**	**Blue (n=44)**	**Red (n=44)**	**Overall (n=220)**
No Response	0.0%	2.3%	0.0%	- -	0.0%	0.0%	0.5%
White	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
Yellow	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
Green	*100.0%*	*97.7%*	*100.0%*	- -	*100.0%*	*97.7%*	*99.1%*
Blue	0.0%	0.0%	0.0%	- -	0.0%	2.3%	0.5%
Red	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%

Response to Blue LED (unequal input)	**When Paired With**						
	None (n=44)	**White (n=44)**	**Yellow (n=44)**	**Cyan (n=44)**	**Blue (n=0)**	**Red (n=44)**	**Overall (n=220)**
No Response	0.0%	0.0%	0.0%	0.0%	- -	2.3%	0.5%
White	2.3%	0.0%	0.0%	0.0%	- -	0.0%	0.5%
Yellow	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
Green	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
Blue	*97.7%*	*100.0%*	*100.0%*	*100.0%*	- -	*97.7%*	*99.1%*
Red	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%

Response to Red LED (unequal input)	**When Paired With**						
	None (n=44)	**White (n=44)**	**Yellow (n=44)**	**Cyan (n=44)**	**Blue (n=44)**	**Red (n=0)**	**Overall (n=220)**
No Response	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
White	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Yellow	0.0%	0.0%	0.0%	2.3%	0.0%	- -	0.5%
Green	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Blue	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Red	*100.0%*	*100.0%*	*100.0%*	*97.7%*	*100.0%*	- -	*99.5%*

Table 21. Color Identification Data for the Protan Subject to the LED (Nominally Equal Input Power) Stimuli in Session 2

Response to White LED (equal input)	**When Paired With**						
	None (n=4)	**White (n=0)**	**Yellow (n=4)**	**Cyan (n=4)**	**Blue (n=4)**	**Red (n=4)**	**Overall (n=20)**
No Response	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%
White	*75.0%*	- -	*25.0%*	*50.0%*	*25.0%*	*100.0%*	*55.0%*
Yellow	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%
Green	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%
Blue	25.0%	- -	75.0%	50.0%	75.0%		45.0%
Red	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%

Response to Yellow LED (equal input)	**When Paired With**						
	None (n=4)	**White (n=4)**	**Yellow (n=0)**	**Cyan (n=4)**	**Blue (n=4)**	**Red (n=4)**	**Overall (n=20)**
No Response	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
White	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
Yellow	*0.0%*	*25.0%*	- -	*25.0%*	*0.0%*	*25.0%*	*15.0%*
Green	0.0%	0.0%	- -	0.0%	0.0%	50.0%	10.0%
Blue	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
Red	100.0%	75.0%	- -	75.0%	100.0%	25.0%	75.0%

Response to Cyan LED (equal input)	**When Paired With**						
	None (n=4)	**White (n=4)**	**Yellow (n=4)**	**Cyan (n=0)**	**Blue (n=4)**	**Red (n=4)**	**Overall (n=20)**
No Response	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
White	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
Yellow	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
Green	*100.0%*	*100.0%*	*100.0%*	- -	*100.0%*	*100.0%*	*100.0%*
Blue	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
Red	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%

Response to Blue LED (equal input)	**When Paired With**						
	None (n=4)	**White (n=4)**	**Yellow (n=4)**	**Cyan (n=4)**	**Blue (n=0)**	**Red (n=4)**	**Overall (n=20)**
No Response	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
White	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
Yellow	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
Green	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
Blue	*100.0%*	*100.0%*	*100.0%*	*100.0%*	- -	*100.0%*	*100.0%*
Red	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%

Response to Red LED (equal input)	**When Paired With**						
	None (n=4)	**White (n=4)**	**Yellow (n=4)**	**Cyan (n=4)**	**Blue (n=4)**	**Red (n=0)**	**Overall (n=20)**
No Response	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
White	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Yellow	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Green	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Blue	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Red	*100.0%*	*100.0%*	*100.0%*	*100.0%*	*100.0%*	- -	*100.0%*

Table 22. Color Identification Data for the Protan Subject to the LED (Incandescent-Mimicking Intensity) Stimuli in Session 2

Response to White LED (unequal input)	**When Paired With**						
	None (n=4)	**White (n=0)**	**Yellow (n=4)**	**Cyan (n=4)**	**Blue (n=4)**	**Red (n=4)**	**Overall (n=20)**
No Response	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%
White	*50.0%*	- -	*50.0%*	*100.0%*	*75.0%*	*100.0%*	*75.0%*
Yellow	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%
Green	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%
Blue	50.0%	- -	50.0%	0.0%	25.0%	0.0%	25.0%
Red	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%

Response to Yellow LED (unequal input)	**When Paired With**						
	None (n=4)	**White (n=4)**	**Yellow (n=0)**	**Cyan (n=4)**	**Blue (n=4)**	**Red (n=4)**	**Overall (n=20)**
No Response	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
White	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
Yellow	*0.0%*	*0.0%*	- -	*0.0%*	*0.0%*	*0.0%*	*0.0%*
Green	0.0%	0.0%	- -	25.0%	0.0%	25.0%	10.0%
Blue	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
Red	100.0%	100.0%	- -	75.0%	100.0%	70.0%	90.0%

Response to Cyan LED (unequal input)	**When Paired With**						
	None (n=4)	**White (n=4)**	**Yellow (n=4)**	**Cyan (n=0)**	**Blue (n=4)**	**Red (n=4)**	**Overall (n=20)**
No Response	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
White	0.0%	0.0%	25.0%	- -	0.0%	0.0%	5.0%
Yellow	0.0%	25.0%	0.0%	- -	0.0%	0.0%	5.0%
Green	*100.0%*	*75.0%*	*75.0%*	- -	*100.0%*	*100.0%*	*90.0%*
Blue	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
Red	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%

Response to Blue LED (unequal input)	**When Paired With**						
	None (n=4)	**White (n=4)**	**Yellow (n=4)**	**Cyan (n=4)**	**Blue (n=0)**	**Red (n=4)**	**Overall (n=20)**
No Response	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
White	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
Yellow	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
Green	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
Blue	*100.0%*	*100.0%*	*100.0%*	*100.0%*	- -	*100.0%*	*100.0%*
Red	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%

Response to Red LED (unequal input)	**When Paired With**						
	None (n=4)	**White (n=4)**	**Yellow (n=4)**	**Cyan (n=4)**	**Blue (n=4)**	**Red (n=0)**	**Overall (n=20)**
No Response	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
White	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Yellow	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Green	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Blue	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Red	*100.0%*	*100.0%*	*100.0%*	*100.0%*	*100.0%*	- -	*100.0%*

Table 23. Color Identification Data for the Deutan Subject to the LED (Nominally Equal Input Power) Stimuli in Session 2

Response to White LED (equal input)	**When Paired With**						
	None (n=4)	**White (n=0)**	**Yellow (n=4)**	**Cyan (n=4)**	**Blue (n=4)**	**Red (n=4)**	**Overall (n=20)**
No Response	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%
White	*100.0%*	- -	*100.0%*	*100.0%*	*100.0%*	*100.0%*	*100.0%*
Yellow	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%
Green	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%
Blue	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%
Red	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%

Response to Yellow LED (equal input)	**When Paired With**						
	None (n=4)	**White (n=4)**	**Yellow (n=0)**	**Cyan (n=4)**	**Blue (n=4)**	**Red (n=4)**	**Overall (n=20)**
No Response	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
White	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
Yellow	*100.0%*	*100.0%*	- -	*100.0%*	*100.0%*	*100.0%*	*100.0%*
Green	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
Blue	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
Red	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%

Response to Cyan LED (equal input)	**When Paired With**						
	None (n=4)	**White (n=4)**	**Yellow (n=4)**	**Cyan (n=0)**	**Blue (n=4)**	**Red (n=4)**	**Overall (n=20)**
No Response	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
White	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
Yellow	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
Green	*100.0%*	*100.0%*	*100.0%*	- -	*100.0%*	*100.0%*	*100.0%*
Blue	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
Red	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%

Response to Blue LED (equal input)	**When Paired With**						
	None (n=4)	**White (n=4)**	**Yellow (n=4)**	**Cyan (n=4)**	**Blue (n=0)**	**Red (n=4)**	**Overall (n=20)**
No Response	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
White	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
Yellow	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
Green	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
Blue	*100.0%*	*100.0%*	*100.0%*	*100.0%*	- -	*100.0%*	*100.0%*
Red	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%

Response to Red LED (equal input)	**When Paired With**						
	None (n=4)	**White (n=4)**	**Yellow (n=4)**	**Cyan (n=4)**	**Blue (n=4)**	**Red (n=0)**	**Overall (n=20)**
No Response	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
White	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Yellow	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Green	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Blue	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Red	*100.0%*	*100.0%*	*100.0%*	*100.0%*	*100.0%*	- -	*100.0%*

Table 24. Color Identification Data for the Deutan Subject to the LED (Incandescent-Mimicking Intensity) Stimuli in Session 2

Response to White LED (unequal input)	**When Paired With**						
	None (n=4)	**White (n=0)**	**Yellow (n=4)**	**Cyan (n=4)**	**Blue (n=4)**	**Red (n=4)**	**Overall (n=20)**
No Response	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%
White	*100.0%*	- -	*100.0%*	*100.0%*	*100.0%*	*100.0%*	*100.0%*
Yellow	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%
Green	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%
Blue	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%
Red	0.0%	- -	0.0%	0.0%	0.0%	0.0%	0.0%

Response to Yellow LED (unequal input)	**When Paired With**						
	None (n=4)	**White (n=4)**	**Yellow (n=0)**	**Cyan (n=4)**	**Blue (n=4)**	**Red (n=4)**	**Overall (n=20)**
No Response	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
White	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
Yellow	*100.0%*	*100.0%*	- -	*100.0%*	*100.0%*	*100.0%*	*100.0%*
Green	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
Blue	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%
Red	0.0%	0.0%	- -	0.0%	0.0%	0.0%	0.0%

Response to Cyan LED (unequal input)	**When Paired With**						
	None (n=4)	**White (n=4)**	**Yellow (n=4)**	**Cyan (n=0)**	**Blue (n=4)**	**Red (n=4)**	**Overall (n=20)**
No Response	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
White	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
Yellow	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
Green	*100.0%*	*100.0%*	*100.0%*	- -	*100.0%*	*100.0%*	*100.0%*
Blue	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%
Red	0.0%	0.0%	0.0%	- -	0.0%	0.0%	0.0%

Response to Blue LED (unequal input)	**When Paired With**						
	None (n=4)	**White (n=4)**	**Yellow (n=4)**	**Cyan (n=4)**	**Blue (n=0)**	**Red (n=4)**	**Overall (n=20)**
No Response	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
White	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
Yellow	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
Green	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%
Blue	*100.0%*	*100.0%*	*100.0%*	*100.0%*	- -	*100.0%*	*100.0%*
Red	0.0%	0.0%	0.0%	0.0%	- -	0.0%	0.0%

Response to Red LED (unequal input)	**When Paired With**						
	None (n=4)	**White (n=4)**	**Yellow (n=4)**	**Cyan (n=4)**	**Blue (n=4)**	**Red (n=0)**	**Overall (n=20)**
No Response	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
White	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Yellow	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Green	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Blue	0.0%	0.0%	0.0%	0.0%	0.0%	- -	0.0%
Red	*100.0%*	*100.0%*	*100.0%*	*100.0%*	*100.0%*	- -	*100.0%*

Figure 31 shows the percentage of correct identification by subjects in each color-vision group for the LED (nominally equal input power) signals, and figure 32 shows the same data for the incandescent-mimicking LED conditions. Color identification was very high for the color-normal subjects as expected, and the deutan subject did not make any identification errors. The protan subject in Session 2 had particular difficulty identifying either of the yellow LED signals and was more likely to identify it as red than as yellow. Correct color identification of the cyan LED as green for this subject was higher than the mean identification performance of the protan subjects in Session 1 to the green LED conditions in that experiment.

Statistical comparisons of the distribution of color identification were only conducted for the color-normal subjects using Fisher's exact test and a criterion for statistical significance of $p < 0.05$. There were no differences between the LED conditions with equal nominal input power and the incandescent-mimicking LED conditions, nor were there any significant effects of accompanying color on identification.

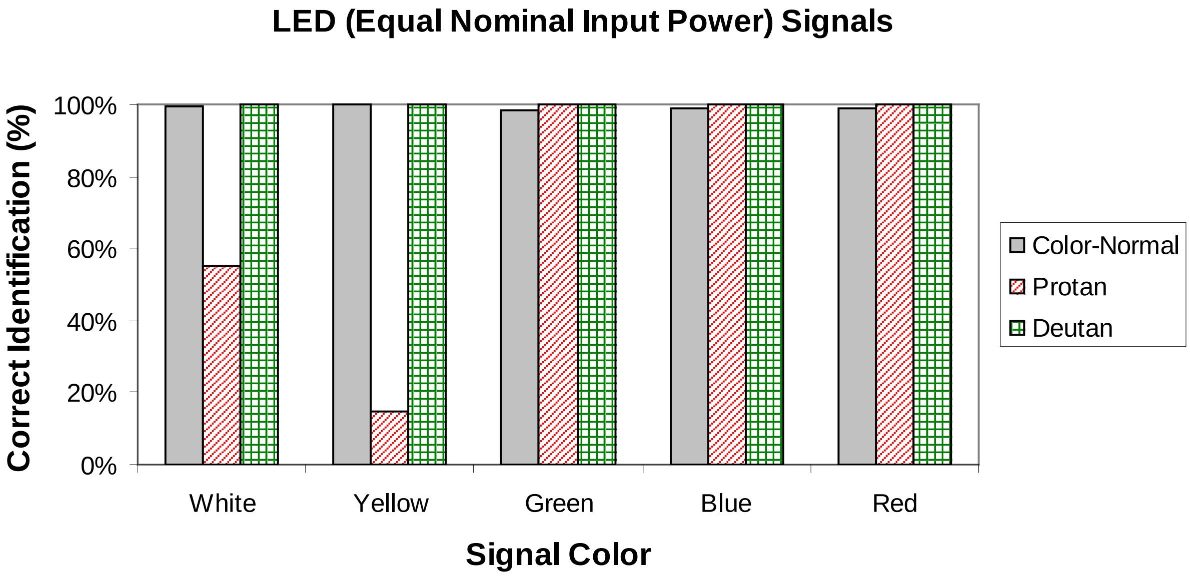


Figure 31. Correct Identification Percentages to Each Color and for Each Color-Vision Group for the LED (Equal Nominal Input Power) Signal Lights in Session 2

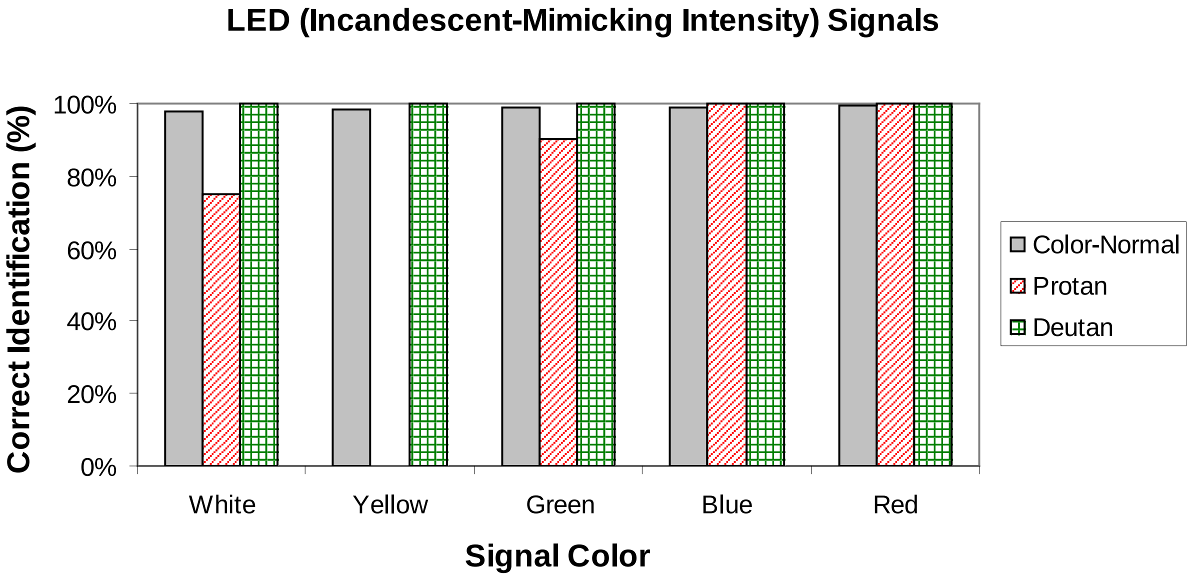


Figure 32. Correct Identification Percentages to Each Color and for Each Color-Vision Group for the LED (Incandescent-Mimicking Intensity) Signal Lights in Session 2

DISCUSSION.

MIXED-COLOR AVIATION LIGHTING SYSTEMS. PAPI systems use red and white signal lights in a single configuration. It is possible to use the data from Sessions 1 and 2 to assess whether significant differences exist in the color identification of red and white signal lights between incandescent signals and LED signals with both of the configurations (equal nominal input power and incandescent-mimicking). Table 25 summarizes the color identification for red and white signals when these two colors were presented alongside each other, for each light source configuration and color-vision group.

Table 25. Correct Identification for White and Red Signal Lights of Each Source Configuration (When Presented Simultaneously) for Each Color-Vision Group

Light Source Configuration	Color-Vision Group	White Signal: Correct Identification (%)	Red Signal: Correct Identification (%)
Incandescent	Color-Normal	94.9	100.0
	Protan	90.6	100.0
	Deutan	95.6	100.0
LED (equal nominal input power)	Color-Normal	98.2	100.0
	Protan	90.6	84.4
	Deutan	90.0	100.0
LED (incandescent-mimicking)	Color-Normal	98.2	100.0
	Protan	93.8	87.5
	Deutan	98.0	98.0

For each signal color and each color-vision group, binominal proportion tests were conducted to determine whether there were statistically significant differences in correct identification between different source configurations. Notably, for the protan subjects identifying the red signal lights, there were significant ($p < 0.05$) differences in correct identification between the incandescent and each LED configuration, with lower identification percentages for the red LED signals than for the red incandescent signals. There were no significant differences in identification between the LED configurations.

A Medium-Intensity Approach Lighting System with Runway Alignment Indicator Lights (MALSR) uses white and green lights within the configuration. Unlike PAPI lights, the spatial configuration of the lights in a MALSR is such that identification by color alone is not essential for the proper interpretation of the system. The data in Session 2 can be used to identify whether the use of LEDs could have implications for the identification of white and green lights when used in the MALSR. Table 26 summarizes the identification for green and white signals when these two colors were presented alongside each other, for each light source configuration and color-vision group.

Table 26. Correct Identification for White and Green Signal Lights of Each Source Configuration (When Presented Simultaneously) for Each Color-Vision Group

Light Source Configuration	Color-Vision Group	White Signal: Correct Identification (%)	Green Signal: Correct Identification (%)
Incandescent	Color-Normal	92.9	90.8
	Protan	87.5	56.2
	Deutan	93.5	69.6
LED (equal nominal input power)	Color-Normal	100.0	100.0
	Protan	93.8	71.9
	Deutan	96.0	80.0
LED (incandescent-mimicking)	Color-Normal	98.2	100.0
	Protan	93.8	68.8
	Deutan	98.0	80.0

The color-normal subjects were the only group for which there were any statistically significant ($p < 0.05$) effects of light source configuration (incandescent, LED with equal nominal input power, and LED with incandescent-mimicking intensity) using binomial proportion tests. Correct identification for the white LED signal (with equal nominal input power) was higher than for the white incandescent signal, and identification was improved for both green LED signals over the green incandescent signal. There were no significant differences between the LED configurations in terms of color identification.

EFFECTS OF LIGHT SOURCE ON COLOR IDENTIFICATION. In general, the data from the main and Session 2 suggest that color identification for color-normal individuals is improved with LED sources having the chromaticities shown in figures 26 and 30 relative to incandescent sources with the chromaticities shown in figure 26. This is likely because of increased color saturation of LED signal lights relative to incandescent signals for the colored signal lights, especially for green. Measurements of green incandescent aviation lighting systems consistently show that their chromaticities are relatively desaturated compared to green (or cyan) LEDs. Even the color-normal subjects in Session 1 misidentified the incandescent green signal as white more than 8% of the time.

For white signal lights, it has been demonstrated previously in Study 1 that adjustment of the current FAA color boundary for white signal lights toward the blue portion of the chromaticity diagram would likely increase the likelihood of correct color identification. This is also implied in the CIE 107 [8] review of signal light colors. The present data are consistent with those findings, for all three color-vision groups addressed in this study.

For individuals with protan and deutan color deficiencies in Session 1, the impact of the LED chromaticities used in figure 26 relative to the incandescent chromaticities was more mixed.

- For the protan subjects, LED color identification was better than incandescent for green signals, and was slightly better for white signals, but was worse with LEDs for yellow, blue, and red signals.
- For the deutan subjects, LED color identification was better than incandescent for green signals, and was slightly better for white signals. Identification was worse for yellow and slightly worse for blue signals. There was no reliable difference in identification between red LED and red incandescent signals.

Overall, accompanying colors had very little effect on the identification of signal lights in the present study. Such effects were only identified for the protan subjects in Session 1. In general, correct identification percentages, when the signals were presented alone, were very close to the overall identification percentages, including conditions presented accompanied by another colored signal. Similarly, there were few differences between the LED conditions having equal nominal input power and those with incandescent-mimicking intensities. Only in rare cases did presenting a light intensity that mimicked an incandescent-like light source appear to be of slight benefit for the color-deficient subjects.

Although only one protan and one deutan subject participated in the follow-up study, the data provide no reason to expect the cyan LED to be problematic for either color group. This assumption is also supported by inspection of the color confusion lines [19] for each group, provided in figures 33 and 34. While the green LED lies nearly along the protan and deutan confusion lines that also intersect red and yellow signals, the cyan LED is further removed from these lines. Additionally, the combination of cyan and white LEDs with the chromaticities illustrated in figures 33 and 34 appear to reduce the potential for confusion between these colors for both protans and deutans. However, it is difficult to draw any firm conclusions regarding identification of the cyan LED by protan and deutan individuals from the very limited data in Session 2.

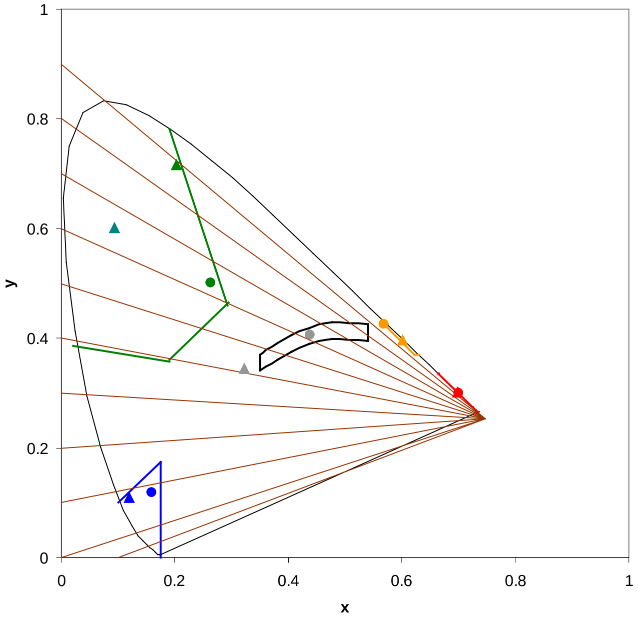


Figure 33. Chromaticity Coordinates of all Stimuli Used in Session 2 Along With Protan Color Confusion Lines (Circles = incandescent, triangles = LED)

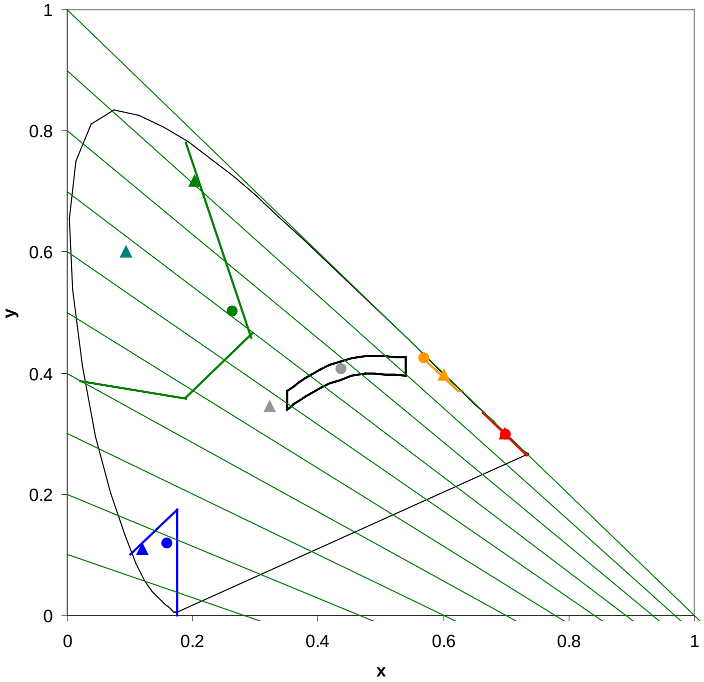


Figure 34. Chromaticity Coordinates of all Stimuli Used in Session 2 Along With Deutan Color Confusion Lines (Circles = incandescent, triangles = LED)

The yellow LED signals used in Session 2 were also problematic for the color-deficient subjects. This was somewhat expected because the chromaticities for the yellow and red LED signals fell almost exactly along the same confusion lines for both protans and deutans; however, this was also true for the incandescent yellow and red signals. The chromaticity for the yellow LED signals is closer to the red portion of the chromaticity diagram, and the yellow LED signals were often misidentified as red. This may be an important finding because the chromaticity of the yellow LED signal is in the central portion of the current FAA yellow color boundary. Presumably, correct identification for yellow LEDs with chromaticities closer to the red boundary could be even lower. This is consistent with the recommendations of the CIE 107 [7], suggesting that the value of the y chromaticity coordinate be no less than about 0.4, rather than being allowed to be as low as 0.37 as specified presently by the FAA. It is also consistent with data from Huang, et al. [23], who found the likelihood of simulated yellow roadway traffic signals being identified as red to increase as the chromaticity approached the red signal color boundary.

In general, the data from the experiments described in this report suggest that the more saturated chromaticities of LED signal lights are a net benefit in terms of color identification. The most consistent benefits of LED sources relative to incandescent signal lamps are for color-normal observers, who are less likely to identify the green signal as white (because of the desaturated appearance of the green incandescent signal) and less likely to identify the white signal as green (because the chromaticity of the incandescent white signal approaches the yellow color boundary). Only subjects who passed the SLG test were included in the data analyses presented here.

The impacts of LEDs on color identification for color-deficient observers are mixed, with some LED sources resulting in better and some in poorer identification than incandescent signals. Although there were few differences between the LED configurations tested in Session 2 (equal nominal input power and incandescent-mimicking intensity), the data suggest, as expected, that there could be a slight benefit to mimicking the relative intensities of the colored incandescent signal lights when using LEDs.

The data and background literature suggest that using cyan LEDs would result in improved color identification for all three color-vision groups evaluated in Session 2, relative to the green LED chromaticity used in Session 1. In addition, limiting the minimum value of the y chromaticity coordinate may improve identification of yellow signals by color-deficient observers. Encouraging green and yellow LED signals to conform to these findings in a manner consistent with the recommendations of the CIE 107 [8] is likely to be beneficial.

Session 2 was conducted under dark, clear conditions. In a perturbed atmospheric environment, such as fog, the apparent colors of signal lights could become desaturated, as light from extraneous sources is superimposed over the signal lights. The impact of this effect has not been investigated in this research, but there is no reason to expect that the appearance of LEDs, which are generally already more saturated than incandescent sources, would maintain a relative increase in saturation.

STUDY 3: COLOR IDENTIFICATION OF YELLOW, RED, AND BLUE AVIATION SIGNAL LIGHTS USING LEDs

INTRODUCTION.

LEDs continue to increase in use for airfield signal lighting applications. LED-based signal lights typically produce light with different color properties than incandescent-based sources, which are presently the dominant light source used for airfield signaling. Direct-emitting colored LEDs produce a relatively narrowband spectral output, resulting in highly saturated color appearance [24]. This is in contrast to incandescent sources, which use filters to remove all but the desired wavelengths from a nominally white light source, generally resulting in a relatively desaturated color.

In addition, most white LEDs are created by using blue LEDs in combination with phosphors, which are excited by the short-wavelength light and produce yellow light. The blue light from the LED chip and yellow light from the phosphor combine to form light that appears white. This generally results in a white source with a higher CCT than more traditional incandescent sources.

Because of these differences, it is important for the FAA to understand whether there can be differences in the way LED signal lights are perceived relative to incandescent-based signal lights.

BACKGROUND.

Previous studies conducted by the LRC at RPI have investigated the ability of color-normal and color-deficient observers to identify the colors of incandescent and LED signals. The results of Study 1 (see above), which evaluated white light sources, confirmed that LEDs with higher CCTs than required by the FAA resulted in high identification as white; these findings are being incorporated into FAA Engineering Brief 67 [25]. In Study 2, white, green, yellow, red, and blue signal lights meeting the present FAA chromaticity requirements were displayed to color-normal, protan, and deutan observers. One type of white, yellow, red, and blue LED of each color and two types of green LEDs (these were nominally called green and cyan, although both were within the current boundary used by the FAA for aviation green signals [16]) were used in the study. Under most conditions, color identification was improved with the LED sources. The primary exception was for the color-deficient (protan and deutan) observers and the yellow LED signals, where correct identification was substantially lower for the LED sources in the following proportions:

- Protans: 61% correct (incandescent), 38% correct (LED)
- Deutans: 83% correct (incandescent), 66% correct (LED)

The current FAA chromaticity boundary for yellow signal lights [16] differs substantially from the recommendation published by CIE 107 [8], as shown in figure 35 along with the FAA and CIE boundaries for the other signal light colors. The CIE recommendation is generally skewed toward shorter wavelengths than the FAA boundary and permits more desaturated colors than the FAA. This is significant because phosphor-based yellow LEDs are becoming available that have slightly less saturated chromaticities than conventional yellow LEDs, but have thermal and electrical properties that could be advantageous for signal lighting [26].

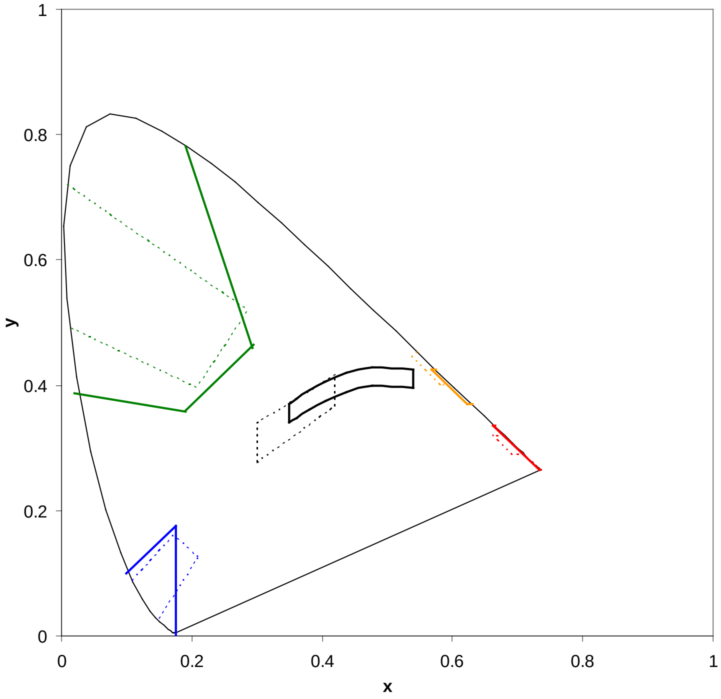


Figure 35. Present FAA Chromaticity Boundaries [16] for Colored Signal Lights (solid lines) and Boundaries for Color-Normal and Color-Deficient Observers Recommended by CIE 107 [8] for the Same Colors (dashed lines).

In addition to this difference in chromaticity boundaries for yellow signal lights, there are presently two different available options for LEDs that would nominally be called red or blue:

- Red: red or red-orange LEDs
- Blue: blue or royal blue LEDs

The red LED typically has a peak wavelength near 630 nm, but the red-orange LED typically has a peak wavelength near 615 nm. The blue LED typically has a peak wavelength near 470 nm, but the royal blue typically has a peak wavelength near 450 nm. The question is whether the shorter-wavelength red and blue LEDs would be reliably identified as red or blue, respectively.

Study 3 was conducted to assess the subjects' ability to identify signal lights with varying chromaticities within and near the FAA and CIE boundaries for yellow, red, and blue signal lights. The results from Study 3 were intended to address the issues regarding the chromaticity region for yellow signal lights to maximize their identification as yellow, and the influence of red or blue LEDs on that identification.

METHOD.

Study 3 used apparatus that consisted of a computer-controlled display with two rows of five rectangular housings, each with a pinhole (0.6-mm diameter) aperture centered on the front panel. An LED or a 35-W incandescent lamp with one or more theatrical gel filters (Roscolux) was placed directly behind each aperture. Subjects were positioned 2 m in front of the display so that when the LED or incandescent lamp was energized, a colored point of light with a chromaticity in or near the FAA or CIE color boundary for yellow, red, or blue was visible. All light sources produced between 9 and 13 millilux (mlx) at the subjects' eyes when viewed from 2 m. Table 27 lists the chromaticities (x,y) and light sources used in the experiment. The experiment was conducted in two sessions; some of the combinations of incandescent lamps and filters were used in both sessions and some in only one session, as identified in table 27.

Table 27. Characteristics of the Light Sources Used in the Study 3 Sessions

Nominal Color	Source	x	y	Session(s)
Yellow	Incandescent	0.524	0.446	1
Yellow	Incandescent	0.524	0.461	1
Yellow	Incandescent	0.531	0.442	2
Yellow	Incandescent	0.575	0.384	2
Yellow	Incandescent	0.588	0.388	2
Yellow	Incandescent	0.620	0.371	1
Yellow	Incandescent	0.533	0.413	1 and 2
Yellow	Incandescent	0.567	0.415	1 and 2
Yellow	LED	0.588	0.410	1 and 2
Yellow	LED	0.604	0.395	1 and 2
Red	LED	0.684	0.313	1 and 2
Red	LED	0.698	0.301	1 and 2
Blue	LED	0.119	0.109	1
Blue	LED	0.158	0.020	2

Eleven color-normal subjects (5 male and 6 female, ages ranging from 26 to 61 years, with a mean age of 45), one protan subject (male, age 60 years) and one deutan subject (male, age 26 years) participated in Session 1. Nine color-normal subjects (3 male and 6 female, ages ranging from 23 to 61 years, with a mean age of 44) participated in Session 2. Color vision was assessed using the Ishihara color plates. All subjects in both sessions, including the deutan subject in Session 1, were able to correctly identify colors from an FAA SLG.

The experiment was conducted in a black-painted room at the Levin Photometry Laboratory at the LRC. Room lights were switched off during each subject's trials. Before starting the experiment, the subjects signed an informed consent form approved by RPI's Institutional Review Board. Once in position, each subject was permitted to adapt to the darkened-room conditions for 5 minutes before the experiment began.

In each trial of each session, one of the ten simulated signal lights, in randomized order was presented on the computer-controlled display for up to 5 seconds. The subjects used a touch screen on a laptop computer to identify whether the signal light appeared to be white, green, yellow, red, or blue; the subjects were instructed to make their best guess if they were unsure about the color of a signal light. The subjects had a total of 10 seconds to record their response before the next trial would begin. The responses were recorded and stored in data files for subsequent analysis. Each condition was repeated six times for a total of 60 trials per subject in each session; the trials took about 10 to 15 minutes for each subject to complete.

RESULTS.

The total percentages of responses from the color-normal subjects for each of the nominally yellow signal lights are shown in figure 36, along with the FAA and CIE chromaticity boundaries for yellow and part of the FAA chromaticity boundary for white signal lights. The letters after each percentage value in figure 36 correspond to the possible responses (y = yellow, w = white, r = red, g = green, b = blue, n/a = no response).

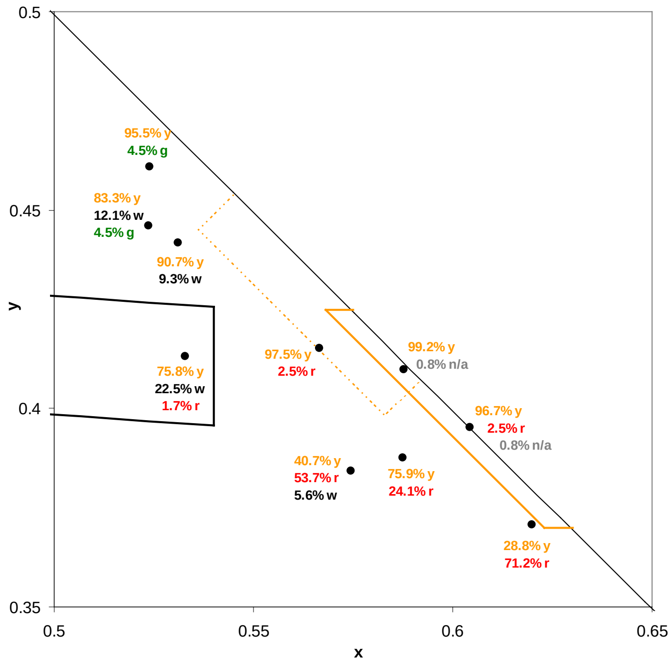


Figure 36. Total Percentage of Color Identification Responses by the Color-Normal Subjects to Each Nominally Yellow Signal Light Presented

Figures 37 and 38 show the responses from the color-normal subjects for the nominally red and blue color signals, respectively.

Figure 39 shows the color identification data for the single protan subject in Session 1 to the nominally yellow signal lights, and figure 40 shows the same values for the single deutan subject. Color identification of the nominally red and blue lights was always 100% for these subjects.

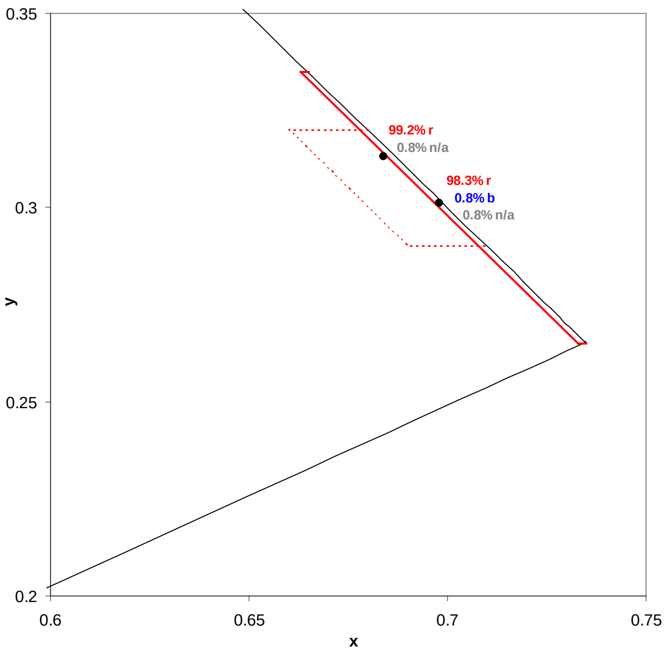


Figure 37. Total Percentage of Color Identification Responses by the Color-Normal Subjects to Each Nominally Red Signal Light Presented

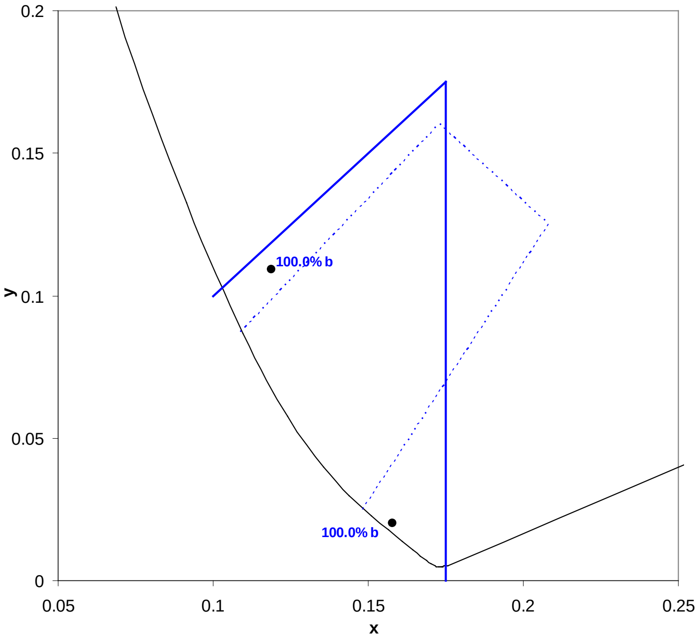


Figure 38. Total Percentage of Color Identification Responses by the Color-Normal Subjects to Each Nominally Blue Signal Light Presented

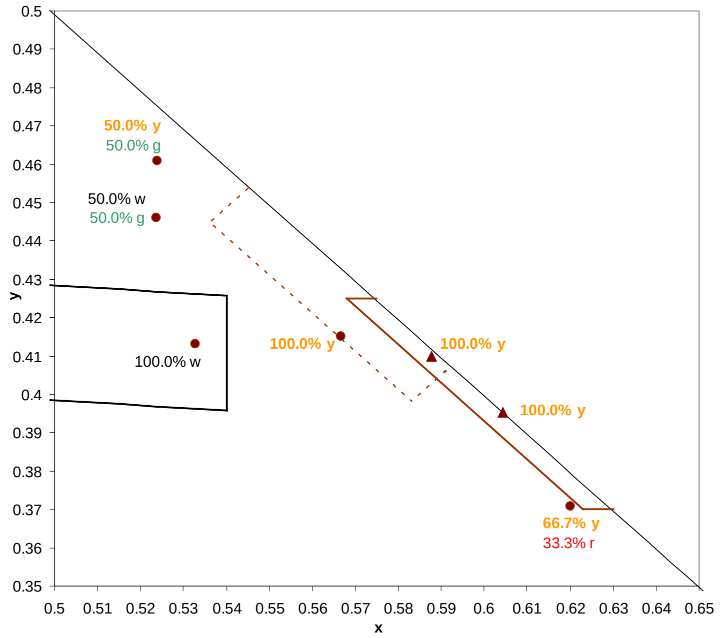


Figure 39. Total Percentage of Color Identification Responses by the Protan Subject to Each Nominally Yellow Signal Light Presented

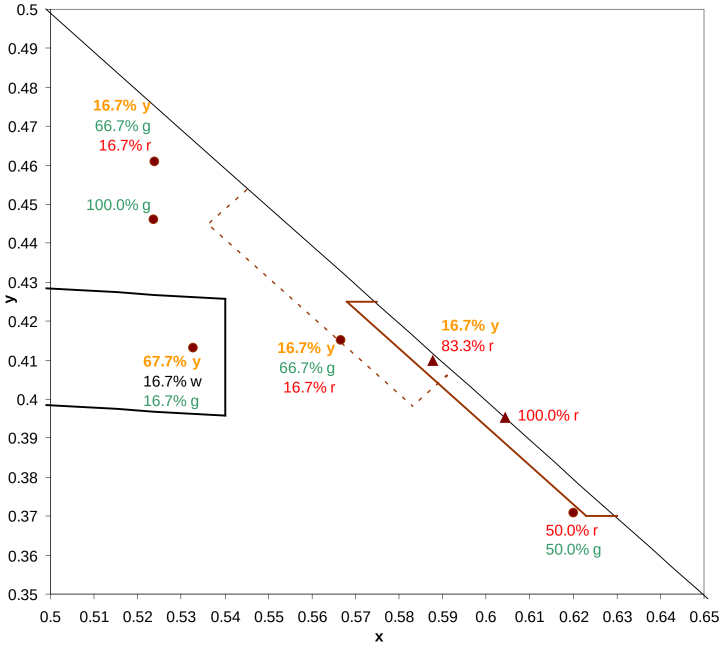


Figure 40. Total Percentage of Color Identification Responses by the Deutan Subject to Each Nominally Yellow Signal Light Presented

DISCUSSION.

YELLOW SIGNAL LIGHTS. The data shown in figure 36 can be used to identify chromaticity regions where identification as yellow is high for color-normal observers, relative to other regions. Figure 41 shows the contours of equal probability for identifying a given chromaticity as yellow, along with the FAA [16] and CIE 107 [8] chromaticity boundaries for yellow. Also shown are the FAA (solid) and CIE (dashed) chromaticity regions for yellow signal lights and the FAA (solid) chromaticity region for white signal lights.

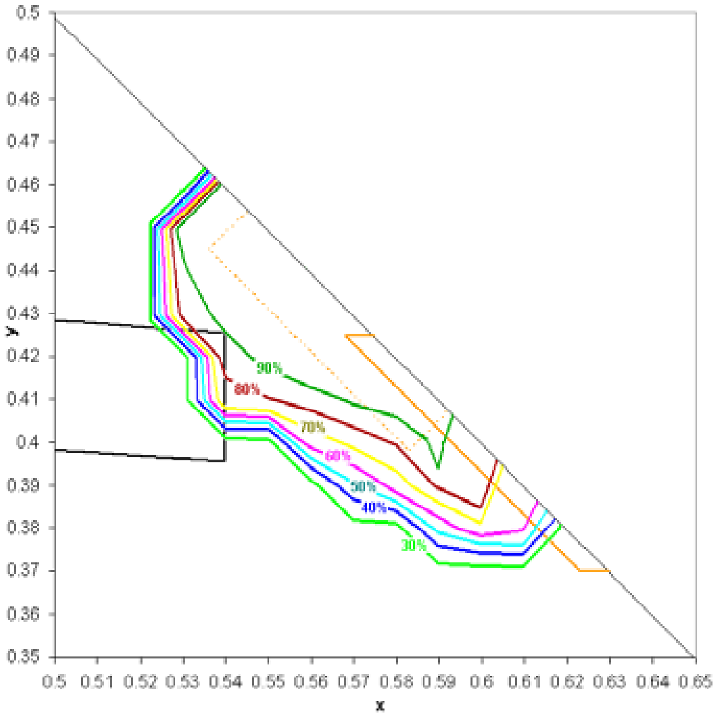


Figure 41. Contours of the Probability of Identifying a Given Chromaticity as Yellow

The region of highest (>90%) identification as yellow in Study 3 appears to be more consistent with the CIE 107 [8] recommendations than with the FAA chromaticity requirements. It appears that there is some tolerance for desaturation before the percentage values shown in figure 41 drop substantially below 90%. In addition, the longer-wavelength portion of the FAA chromaticity boundary (near a chromaticity of x = 0.62, y = 0.38) seems to be associated with a relatively low likelihood of signal lights being identified as yellow.

Regarding the very limited data collected in Session 2 from color-deficient observers (a single protan and a single deutan), figure 39 and, to an even greater extent, figure 40 illustrate that confusion among yellow, red, and green in the chromaticity region identified as yellow using either the FAA or CIE color boundaries are likely to be problematic. The fact that chromaticities of yellow with greater desaturation permitted by the CIE recommendations were never identified as white by these subjects provides some limited confirmation that the CIE recommended boundary for yellow is not likely to result in confusion between yellow and white for color-deficient observers.

One caveat in interpreting the data in Study 3 is that in both sessions, the majority of the colors presented were nominally yellow, with only a small percentage of nominally red or blue signal lights. This could have resulted in finer discrimination among nominally yellow colors (i.e., a slightly greenish-yellow light could have been judged as green; whereas if it had been viewed in comparison with a green light, it could have been identified as yellow).

BLUE AND RED SIGNAL LIGHTS. Only two stimuli for each of the red and blue colors were evaluated in Session 2 (table 27), corresponding to chromaticities for which red and blue LEDs are commercially available. Both the red and blue LEDs tested produced rather highly saturated colors, having fairly narrowband spectral output; therefore, these stimuli were not helpful in identifying the range of desaturation permissible while maintaining high red or blue color identification. The saturated color appearance of the red and blue LEDs used in Session 2 is representative of LEDs that are commercially available not specially produce for this research and thus be LEDs used in aviation lighting fixtures.

Both LEDs of nominal red and nominal blue resulted in very high accurate color identification. Both red LEDs evaluated fell along the FAA chromaticity requirement and the CIE recommendation (figure 37). Both blue LEDs fell within the FAA chromaticity region for blue signal lights; and although they were close, neither was within the CIE recommended boundary (figure 38). However, the two blue chromaticity boundaries have an extensive area of overlap. From a practical point of view, it is unlikely that there is much perceptual difference between them. However, the fact that the chromaticities of the specific LEDs tested both fell outside the CIE 107-recommended [8] boundary suggests that caution should be exercised if this boundary is used in the future, since future LED systems may also fall outside the CIE boundary.

Overall, the results do not suggest that there are any important differences between red and red-orange types of LEDs, or between blue and royal blue types of LEDs, for color identification by color-normal observers. Additionally, the limited data collected for color-deficient observers suggest that red, red-orange, or blue LEDs were not problematic for these individuals. However, the number of subjects with color deficiencies was limited in this study, which prevents generalization of these results.

RECOMMENDATIONS.

Aviation signal lights using LED light sources produce different chromaticities than signal lights using filtered or unfiltered incandescent light sources. The chromaticities of LED signal lights can have advantages in terms of color identification compared to incandescent signal lights. To maximize the likelihood of correct color identification of aviation signal lights using LED sources, a set of chromaticity boundaries for white, green, yellow, red, and blue signal lights using LEDs is recommended based on these studies.

The chromaticity recommendations are given in the following sections for each of the five aviation signal light colors (white, green, yellow, red, and blue) when LED light sources are used. For convenience, the boundaries for each color are represented in terms of equations defining the boundaries and in terms of the chromaticity coordinates for the vertices of each boundary region. All chromaticity coordinates are expressed in terms of the CIE 1931 (x,y) chromaticity space and are rounded to three decimal places.

WHITE: RECOMMENDATION. The proposed chromaticity region for white LED aviation signal lights is as follows:

Boundary Equations
Green boundary: $y = 0.643x + 0.150$
Blue boundary: $x = 0.320$
Purple boundary: $y = 0.757x + 0.050$
Yellow boundary: $x = 0.440$

Boundary Vertex Points
$x = 0.320$, $y = 0.356$
$x = 0.440$, $y = 0.433$
$x = 0.440$, $y = 0.383$
$x = 0.320$, $y = 0.292$

WHITE: RATIONALE. The proposed region for white LED signals was based on the results of Study 1, in which it was found that moving the existing SAE AS25050 [16] blue boundary for white from x = 0.350 to x = 0.320 would result in high identification as white (>80%). The results of Study 1 also indicated that near the SAE AS25050 yellow boundary for white (x = 0.540), there was only about 10% identification as white, but moving the boundary to x = 0.440 would maintain >40% identification as white, a substantial improvement. The x = 0.540 boundary is not essential for LEDs as it is for incandescent lamps when they are dimmed.

GREEN: RECOMMENDATION. The proposed chromaticity region for green LED aviation signal lights is as follows:

Boundary Equations
Blue boundary: $y = 0.768 - 1.306x$
White boundary: $y = 0.600$
Yellow boundary: $y = 3.470 - 9.200x$

Boundary Vertex Points
$x = 0.014$, $y = 0.750$
$x = 0.129$, $y = 0.600$
$x = 0.312$, $y = 0.600$
$x = 0.302$, $y = 0.692$

GREEN: RATIONALE. In Study 2, it was found that individuals had relatively high (~10%) misidentification to nominally green incandescent signals in the desaturated portion of the SAE AS25050 [16] green region, as white. Misidentification as white did not occur when either nominally green (~525 nm) or cyan (~505 nm) LEDs (falling within the SAE AS25050 green region were used), resulting in improved identification. Colorimetric measurements of several LED aviation green signal lighting systems [24] demonstrated that all the systems measured used nominally green LEDs (~525 nm). To avoid differences in the green color appearance that would be possible if nominally green and nominally cyan LED signal lights were mixed, a portion of the existing ICAO Annex 14 [27] green chromaticity region was proposed. Increased saturation is provided by setting the minimum y-coordinate value to y = 0.600. The portion of the region bounded by wavelengths >510 nm on the spectrum locus is used, and the blue boundary is proposed to extend between the 510-nm point on the locus toward the equal-energy point (x = 0.333, y = 0.333). This ensures that the dominant wavelength within the proposed boundary will always be >510 nm and will permit the use of nominally green LEDs (~525 nm).

YELLOW: RECOMMENDATION. The proposed chromaticity region for yellow LED aviation signal lights is as follows:

Boundary Equations
Green boundary: $y = 0.727x + 0.054$
White boundary: $y = 0.980 - x$
Red boundary: $y = 0.387$

Boundary Vertex Points
$x = 0.547, y = 0.452$
$x = 0.536, y = 0.444$
$x = 0.593, y = 0.387$
$x = 0.613, y = 0.387$

YELLOW: RATIONALE. In Study 3, which evaluated color identification near the existing SAE AS25050 [16] region for yellow signal lights, it was shown that near the long-wavelength portion of this region, there was high (>50%) misidentification of yellow as red. In addition, the region encompassing very high (>90%) identification as yellow nearly completely overlapped the region for yellow signals recommended in CIE 107 [8] and CIE S 004/E-2001 [2]. Based on the results of Study 3, it is not necessary for signals to be very close to the spectrum locus to be reliably identified as yellow. The proposed region is also shifted somewhat toward the green relative to the SAE AS25050 region. It is possible that the reason that the SAE AS25050 yellow region shifted toward the red was to increase separation from the SAE AS25050 white region's yellow boundary of x = 0.540, for dimmed incandescent lights that can appear yellowish. A more orange-like yellow would be easier to distinguish from a dimmed white incandescent with a yellowish appearance, but nonincandescent sources, such as LEDs, do not exhibit the same shifts toward yellow when dimmed as incandescent sources. Therefore, adoption of the CIE S 0004/E-2001 [2] yellow region is proposed.

RED: RECOMMENDATION. The proposed chromaticity region for red LED aviation signal lights is as follows:

Boundary Equations
Yellow boundary: $y = 0.320$
White boundary: $y = 0.980 - x$
Purple boundary: $y = 0.290$

Boundary Vertex Points
$x = 0.680$, $y = 0.320$
$x = 0.660$, $y = 0.320$
$x = 0.690$, $y = 0.290$
$x = 0.710$, $y = 0.290$

RED: RATIONALE. The existing SAE AS25050 [16] region for red is very close to the spectrum locus. Studies reviewed in CIE 107 [8] demonstrated that this proximity was not necessary to ensure reliable identification as red. In addition, although very long-wavelength red signal lights could be readily identified as red, the low luminous efficacy at long wavelengths (>650 nm) means very high radiant flux is required to achieve sufficient luminous intensities, which could affect system reliability and efficiency. In Study 3, it was found that both red and red-orange LEDs fit well within the restricted red region recommended by CIE S 004/E-2001 [2], which excludes the long-wavelength chromaticity region. Therefore, this restricted region is proposed for red signals.

BLUE: RECOMMENDATION. The proposed chromaticity region for blue LED aviation signal lights is as follows:

Boundary Equations
Green boundary: $y = 0.805x + 0.065$
White boundary: $y = 0.400 - x$
Purple boundary: $y = 1.668x - 0.222$

Boundary Vertex Points
$x = 0.090$, $y = 0.137$
$x = 0.186$, $y = 0.214$
$x = 0.233$, $y = 0.167$
$x = 0.148$, $y = 0.025$

BLUE: RATIONALE. The existing SAE AS25050 [16] blue region includes very short wavelengths (<450 nm). Although there are nominally royal blue LEDs near 450 nm that are reliably detected as blue, the low luminous efficacy at very short wavelengths means very high radiant flux is required to achieve sufficient luminous intensities, which could affect system reliability and efficiency. Both the CIE S 004/E-2001-[2] and ICAO Annex 14-[27] recommended boundaries for blue eliminate this short-wavelength region. In Study 3, it was found that a blue LED signal light that resulted in 100% identification as blue, fell outside the

CIE S 004/E-2001 [2] region but within the current ICAO Annex 14 region [25]. Additionally, CIE 107 [8] stated, and the results of Study 1 suggest, that signal lights with chromaticities around x = 0.200, y = 0.200 were reliably identified as blue. Therefore, the current ICAO Annex 14 blue region is proposed.

<u>ILLUSTRATION OF PROPOSED CHROMATICITY BOUNDARIES</u>.

Figure 42 shows the proposed chromaticity boundary regions, plotted in the CIE 1931 (x,y) chromaticity region.

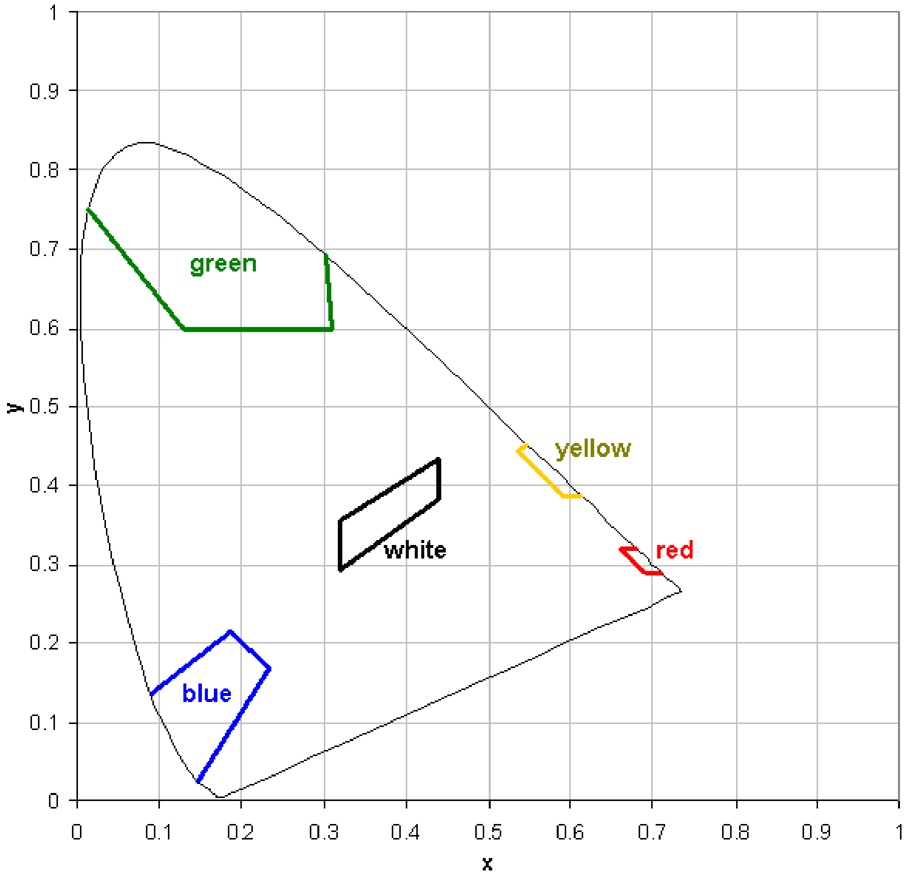


Figure 42. Proposed Chromaticity Boundaries, Plotted in the CIE 1931 (x,y) Chromaticity Diagram

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APPENDIX A—CHROMATICITIES OF TEST POINTS USED FOR STUDY 1, PHASE I TESTS

Point	X	Y
1	0.250	0.204
2	0.250	0.219
3	0.250	0.234
4	0.250	0.249
5	0.250	0.264
6	0.250	0.279
7	0.250	0.294
8	0.260	0.218
9	0.260	0.233
10	0.260	0.248
11	0.260	0.263
12	0.260	0.278
13	0.260	0.293
14	0.260	0.308
15	0.270	0.230
16	0.270	0.245
17	0.270	0.260
18	0.270	0.275
19	0.270	0.290
20	0.270	0.305
21	0.270	0.320
22	0.280	0.243
23	0.280	0.258
24	0.280	0.273
25	0.280	0.288
26	0.280	0.303
27	0.280	0.318
28	0.280	0.333
29	0.290	0.254
30	0.290	0.269
31	0.290	0.284
32	0.290	0.299
33	0.290	0.314
34	0.290	0.329
35	0.290	0.344
36	0.300	0.265
37	0.300	0.280
38	0.300	0.295
39	0.300	0.310
40	0.300	0.325
41	0.300	0.340
42	0.300	0.355
43	0.310	0.275
44	0.310	0.290
45	0.310	0.305
46	0.310	0.320
47	0.310	0.335
48	0.310	0.350
49	0.310	0.365
50	0.320	0.285
51	0.320	0.300
52	0.320	0.315
53	0.320	0.330
54	0.320	0.345
55	0.320	0.360
56	0.320	0.375
57	0.330	0.294
58	0.330	0.309
59	0.330	0.324
60	0.330	0.339
61	0.330	0.354
62	0.330	0.369
63	0.330	0.384
64	0.340	0.303
65	0.340	0.318
66	0.340	0.333
67	0.340	0.348
68	0.340	0.363
69	0.340	0.378
70	0.340	0.393
71	0.350	0.311
72	0.350	0.326
73	0.350	0.341
74	0.350	0.356
75	0.350	0.371
76	0.350	0.386
77	0.350	0.401
78	0.360	0.318
79	0.360	0.333
80	0.360	0.348
81	0.360	0.363
82	0.360	0.378
83	0.360	0.393
84	0.360	0.408
85	0.370	0.325
86	0.370	0.340
87	0.370	0.355
88	0.370	0.370
89	0.370	0.385
90	0.370	0.400
91	0.370	0.415
92	0.380	0.332
93	0.380	0.347
94	0.380	0.362
95	0.380	0.377
96	0.380	0.392
97	0.380	0.407
98	0.380	0.422
99	0.390	0.338
100	0.390	0.353
101	0.390	0.368
102	0.390	0.383
103	0.390	0.398
104	0.390	0.413
105	0.390	0.428
106	0.400	0.343
107	0.400	0.358
108	0.400	0.373
109	0.400	0.388
110	0.400	0.403
111	0.400	0.418
112	0.400	0.433
113	0.410	0.348
114	0.410	0.363
115	0.410	0.378
116	0.410	0.393
117	0.410	0.408
118	0.410	0.423
119	0.410	0.438
120	0.420	0.353
121	0.420	0.368
122	0.420	0.383
123	0.420	0.398
124	0.420	0.413
125	0.420	0.428
126	0.420	0.443
127	0.430	0.357
128	0.430	0.372
129	0.430	0.387
130	0.430	0.402
131	0.430	0.417
132	0.430	0.432
133	0.430	0.447
134	0.440	0.360
135	0.440	0.375
136	0.440	0.390
137	0.440	0.405
138	0.440	0.420
139	0.440	0.435
140	0.440	0.450
141	0.450	0.363
142	0.450	0.378
143	0.450	0.393
144	0.450	0.408
145	0.450	0.423
146	0.450	0.438
147	0.450	0.453

APPENDIX B—COMMISSION INTERNATIONALE DE L'ÉCLAIRAGE RECOMMENDATIONS FOR COLORED SIGNAL LIGHTS

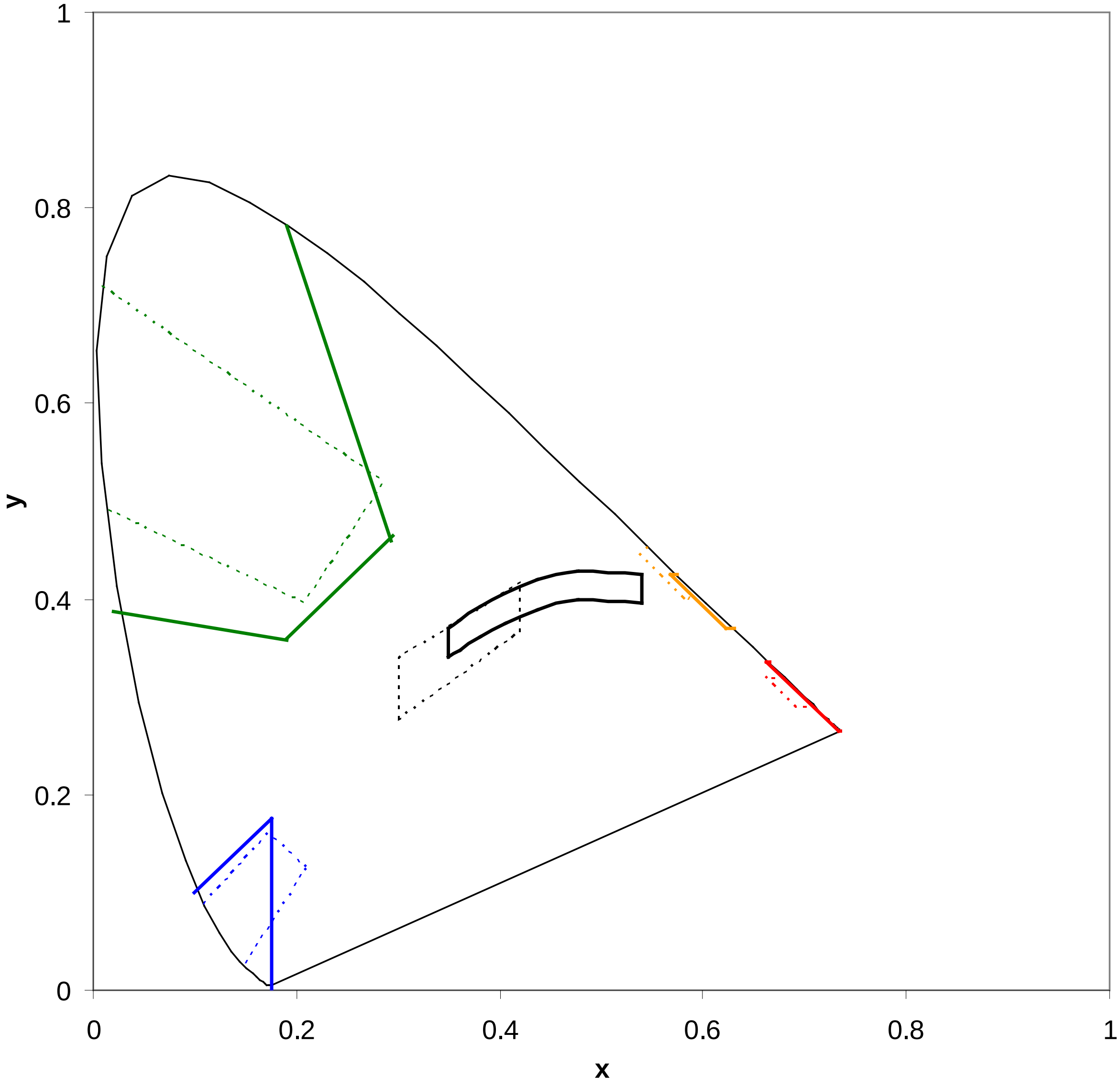

Figure B-1. Present FAA Chromaticity Boundaries [B-1] for Colored Signal Lights (solid lines) and Boundaries for Color-Normal and Color-Deficient Observers Recommended by the CIE [B-2] for the Same Colors (dashed lines)

References.

B-1. Society of Automotive Engineers, "General Requirements for Colors, Aeronautical Equipment," SAE AS25050A, SAE, Warrendale, Pennsylvania, January 6, 2010.

B-2. Commission Internationale de l'Éclairage, "Review of the Official Recommendations of the CIE for the Colours of Signal Lights," Report No. 107, Vienna, Austria, 1994.