DO LEDS INCREASE THE ACCURACY OF LED AVIATION SIGNAL LIGHT COLOR IDENTIFICATION BY PILOTS WITH AND WITHOUT COLOR-DEFICIENT VISION?

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INTRODUCTION

Light-emitting diodes (LEDs) are being used for many airfield signal lighting applications, and it is important to ensure that they can be correctly identified by pilots, including those with deficient color vision. Until recently, color specifications for aviation signal lights used by the Federal Aviation Administration (FAA) [1] and maintained by the Society of Automotive Engineers (SAE) [2] have been unchanged for several decades. Filtered incandescent lamps used in most signal lights have largely consistent and predictable chromaticities within the allowable aviation color boundaries. Additionally, colored glass filters produce luminous intensity differences among incandescent signal lights of different colors, and these differences might assist color-deficient pilots (e.g., protans and deutans [3]) in distinguishing among them.

Many commercially available LEDs have chromaticities within the SAE color boundaries [2] but look perceptibly different than incandescent sources of the same nominal color. In addition, because the luminous efficacies (in lm/W) of red, yellow, green and white LEDs are similar, LED signal lights with these colors could have similar luminous intensities while still meeting FAA [1] requirements. If such signals were used, a color deficient pilot's ability to discriminate among their colors might be reduced because the redundant information of intensity differences would not be present. It is therefore important to understand the practical implications of these differences between LED and incandescent light sources.

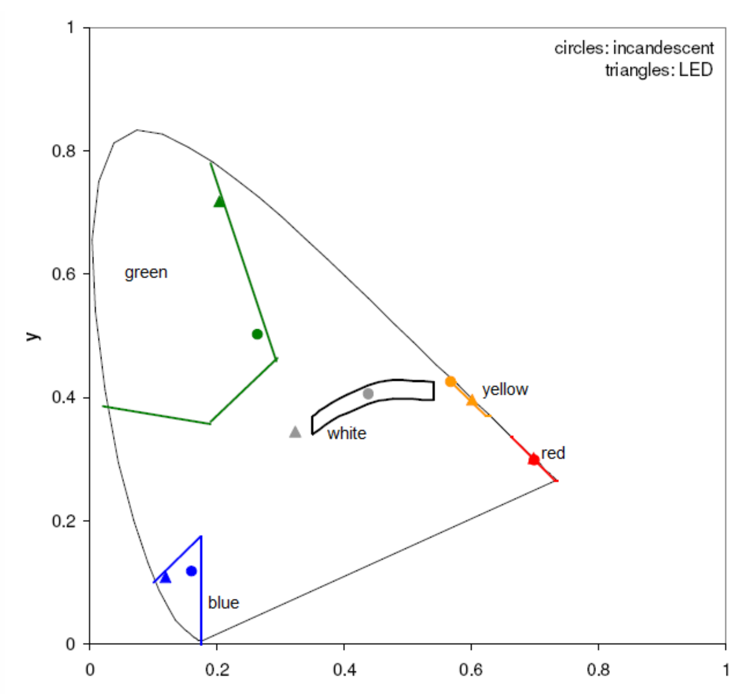

Figure 1. Chromaticity regions specified by the SAE [2] for each aviation signal light color, and chromaticities of the incandescent and LED stimuli used in the present study.

BACKGROUND

The SAE specifies chromaticity requirements for aviation signal lights of several colors: white, yellow, green, red and blue [2]. These chromaticity regions are shown in Figure 1. The regions were selected to try to maximize pilots' abilities to differentiate and properly identify each signal color. Although the FAA requires pilots to pass an approved color vision test in order to be licensed, a prospective pilot who does not pass the test can be provided an opportunity to pass a second color test based on the aviation signal light gun (SLG). The SLG is a handheld, portable light source that can project a narrow beam of white, red or green light as a backup signal light, such as during a power outage when conventional airfield lighting would not be available. Color-deficient observers who can correctly identify white, red and green light from the SLG could be eligible for an unrestricted license. Nonetheless, color-deficient pilots may have more difficulty distinguishing between certain colors than color-normal observers, particularly along the axis overlapping the red, yellow and green chromaticity regions.

In general, LED colored sources produce narrow-bandwidth spectra that appear highly saturated in color appearance relative to incandescent counterparts of the same nominal colors. In theory, this saturation will help with color identification because a saturated color will be less likely to be identified as white.

Most of the time, aviation signal light color is only one cue regarding the configuration and orientation of lighted elements on the airfield. Usually, the spatial configuration provides enough information to a pilot, so that the specific type of airfield facility (e.g., runway, taxiway) can be deduced. For limited applications such as a precision approach path indicator (PAPI) system, in which an array of four signal lights can appear as a mixture of white or red lights with the number of white and red lights indicating the approach angle, the color of the light is the essential cue to a pilot. Even if the colors might be confused by a color-deficient pilot, the luminous intensity of a red incandescent light is likely to be substantially lower than that of a white incandescent light, because of the difference in transmission between red and clear lenses. The intensity difference serves as redundant information to the color. Since LED signal lights do not depend upon a lens to filter the source for color, the luminous intensities of red and white lights in an LED PAPI system might be very similar, removing the redundant cue. Of course, the red LED signal could be designed to produce a much lower intensity than the white signal, but this is not necessarily required by FAA [1] specifications.

In order to understand these issues, a laboratory study was conducted to assess the impact of the differing chromaticities of LED compared to incandescent signals, and of relative luminous intensities of different colors on color identification by both color-normal and color-deficient observers.

METHODS

Apparatus

A scale model signal display box was developed containing filtered incandescent and LED sources of each of the five aviation signal light colors. Each row of the box contained five 0.6-

mm-diameter circular pinhole apertures behind which the light sources (and filters, for the incandescent lights) were placed. The bottom row contained 35 W incandescent lamps with the apertures covered by different combinations of theatrical gel filters to create chromaticities matching those of typical aviation incandescent signal lights within the SAE color boundaries [2]. The top row contained five 1-W LEDs behind each pinhole aperture. In each row, the location of each of the colors was randomized. The scale model box was placed at the end of an 8-ft table so that the viewing distance between the box and the eyes of a typical observer was slightly over 6 ft. This distance ensured that the 0.6-mm apertures subtended no more than 1 minute of arc, effectively making them point sources when switched on.

Table 1.
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 an Observer's Eyes.

a. Incandescent

Color	Illuminance @ 2 m (mlx)	Equivalent Luminous Intensity @ 100 m (cd)	Equivalent Luminous Intensity @ 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 @ 2 m (mlx)	Equivalent Luminous Intensity @ 100 m (cd)	Equivalent Luminous Intensity @ 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 @ 2 m (mlx)	Equivalent Luminous Intensity @ 100 m (cd)	Equivalent Luminous Intensity @ 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

Figure 1 shows the chromaticities of the incandescent and LED signal lights used in the study, and Table 1 lists the illuminance produced by each condition. As shown in Table 1, the luminous intensities of the LED signal lights were scaled in two different ways – one in which their outputs were adjusted to produce similar intensities as the incandescent signals, and one in which the outputs of the white, yellow, red and green LEDs were adjusted to produce approximately equal intensities (the exception being the blue LED, which was adjusted to a luminous intensity of about one-third that of the other colors, in proportion to its relative luminous efficacy. It can also be seen in Figure 1 that the chromaticity of the white LED signal used in the study did not conform to SAE requirements for aviation white [2]; this was intentional as FAA [4,5] had adjusted the chromaticity boundary of white LED aviation signal lights based on human factors research [5,6] demonstrating that this change helped increase correct identification as white. The present experiment was in part, a validation test of this newer criterion for white LED signal lights.

Subjects

A total of 50 subjects participated in the study. Subjects were recruited through a temporary employment agency; subjects self-reporting as color-normal and color-deficient were recruited. All subjects were tested and categorized for color vision status (normal, protan or deutan) by researchers from the FAA Civil Aerospace Medical Institute (CAMI) as part of a separate study conducted by CAMI. The breakdown of color vision status, age and sex for the subjects is as follows:

- Color-normal: 29 subjects (25 male/5 female), mean age 27 years, median 25 years, s.d. 8 years
- Protan: 8 subjects (all male), mean age 31 years, median 28 years, s.d. 11 years
- Deutan: 13 subjects (12 male/1 female), mean age 34 years, median 33 years, s.d. 11 years

All prospective subjects who tested as protans or deutans were also given the SLG test, and only subjects who passed this latter test were included in the study. This likely resulted in excluding color deficient subjects whose deficiencies were greatest, but ensured that the color-deficient subject population was representative of those who could be issued unrestricted pilots' licenses.

Procedure

For each experimental session, each subject entered the laboratory, signed an approved consent form and had the procedure explained to them and any questions answered. The apparatus was set up in a dark room and subjects sat in front of the laptop computer that controlled the stimuli and recorded the data. The luminance of the screen on the laptop was adjusted to 3 cd/m². Each trial consisted of the presentation of either a single signal light or a pair of signal lights, which was displayed for a total of 5 s. The signal, or pair of signals, was either incandescent (as in Table 1a), LED with incandescent-mimicking intensities (Table 1b), or LED with equivalent nominal input power (Table 1c). For each of these three light source configurations, there were 15 possible stimuli: each of the five individual colors and ten pairs consisting of all possible combinations of the five colors. Each of the 45 possible stimulus presentations (3 light source configurations × 15 stimuli) was shown four times to each subjects in randomized order, for a total of 180 presentations per subject.

After the 5 s presentation time, the light(s) were switched off and subjects used a stylus and touch-screen interface on the laptop screen to indicate the color (white, yellow, green, red or blue) of the signal or pair of signals. If a single light was displayed, only a single color choice was made; if a pair of signals was displayed, subjects were instructed to use the left-side interface to indicate the color of the left-most signal, and the right-side interface to indicate the color of the right-most signal. Subjects had a total of 10 s to enter their responses; if they did not, the software saved a null-response and the next trial presentation was displayed. A forced-choice procedure was used (subjects had to guess one of the five aviation signal light colors; if they thought a signal was orange, they would have to choose either red or yellow as their response). After displaying all 180 stimulus presentations for a given subject, the software saved the data into a file for subsequent analysis.

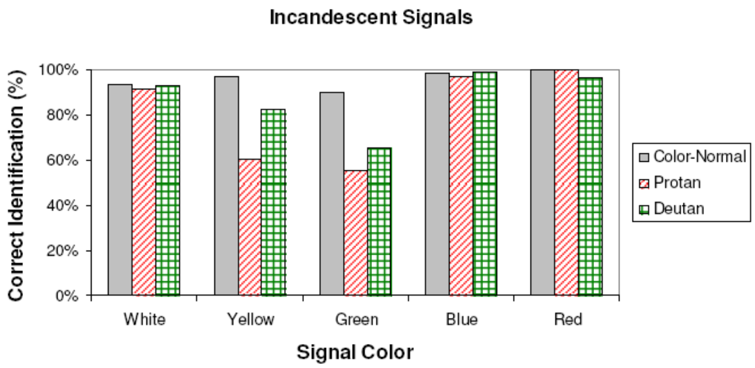

Figure 2. Correct identification percentages for each color-vision group to the incandescent stimuli.

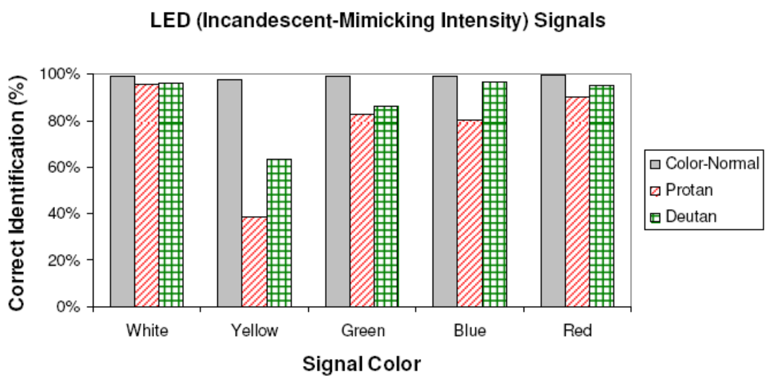

Figure 3. Correct identification percentages for each color-vision group to the LED (incandescent-mimicking) stimuli.

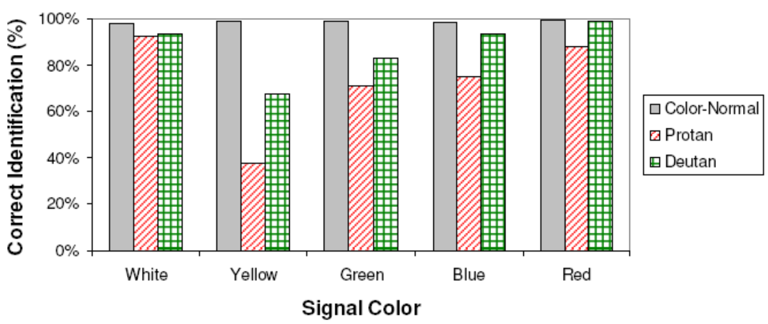

Figure 4. Correct identification percentages for each color-vision group to the LED (equal nominal input power) stimuli.

RESULTS

Collapsing across stimuli consisting of a single light and those consisting of a pair of lights, Figure 2 shows the correct identification percentages for each color and by each color-vision group for the incandescent stimuli. Figure 3 shows the same data for the LED incandescent-mimicking stimuli, and Figure 4 shows the same data for the LED equal nominal input power stimuli.

Table 2.
Statistical Comparison Results for the Color-Normal Subjects at Each Color and Between Each Light Source Configuration; For Each Statistically Significant Effect, the Configuration Resulting in Improved Detection is Listed.

Signal color	Comparison		
	Inc. vs. LED equal nominal input power	**Inc. vs. LED inc.-mimicking**	**LED equal power vs. LED inc.-mimicking**
White	LED equal (p<0.001)	LED inc.-mimic (p<0.001)	n.s.
Yellow	n.s.	n.s.	n.s.
Green	LED equal (p<0.001)	LED inc.-mimic (p<0.001)	n.s.
Blue	n.s.	LED inc.-mimic (p<0.05)	n.s.
Red	n.s.	n.s.	n.s.

Table 3.
Statistical Comparison Results for the Protan Subjects at Each Color and Between Each Light Source Configuration; For Each Statistically Significant Effect, the Configuration Resulting in Improved Detection is Listed.

Signal color	Comparison		
	Inc. vs. LED equal nominal input power	**Inc. vs. LED inc.-mimicking**	**LED equal power vs. LED inc.-mimicking**
White	LED equal (p<0.001)	LED inc.-mimic (p<0.001)	n.s.
Yellow	Inc. (p<0.001)	Inc. (p<0.001)	n.s.
Green	LED equal (p<0.001)	LED inc.-mimic (p<0.001)	LED inc.-mimic (p<0.01)
Blue	Inc. (p<0.001)	Inc. (p<0.001)	n.s.
Red	Inc. (p<0.001)	Inc. (p<0.001)	n.s.

Table 4.
Statistical Comparison Results for the Deutan Subjects at Each Color and Between Each Light Source Configuration; For Each Statistically Significant Effect, the Configuration Resulting in Improved Detection is Listed.

Signal color	Comparison		
	Inc. vs. LED equal nominal input power	**Inc. vs. LED inc.-mimicking**	**LED equal power vs. LED inc.-mimicking**
White	LED equal (p<0.05)	LED inc.-mimic (p<0.05)	n.s.
Yellow	Inc. (p<0.001)	Inc. (p<0.001)	n.s.
Green	LED equal (p<0.001)	LED inc.-mimic (p<0.001)	n.s.
Blue	Inc. (p<0.01)	n.s.	LED inc.-mimic (p<0.01)
Red	n.s.	n.s.	n.s.

Using Fisher's exact tests (and a probability criterion of $p<0.05$) to determine whether the light source configuration impacted color identification, Tables 2, 3 and 4 summarize the statistical comparisons for each color vision group. For the color-normal observers, identification of white, green, and to a lesser extent, blue signals was improved with the LED sources relative to incandescent. There were no reliable differences between the two LED configurations (incandescent-mimicking and equal nominal input power) for the color-normal observers.

For the protans, LED identification was better than incandescent for white and green signals, but the opposite was true for yellow, blue and red. Only for green LED signals were there reliable differences between incandescent-mimicking and equal nominal input power, favoring incandescent-mimicking. For the deutans, LED identification surpassed incandescent for white and green, while incandescent identification was better for yellow, and to a lesser extent, blue signals. No reliable differences between red LED and incandescent signals were found for the protans. Only for blue LED signals were there reliable differences between incandescent-mimicking and equal nominal input power, favoring incandescent-mimicking.

Few effects on identification accuracy of an accompanying signal color were found relative to when a signal appeared alone, and only for protans. Yellow LED signals were less likely to be identified correctly by protans and more likely to be incorrectly named red when they were accompanied by a green LED signal. In comparison, green LED signals were more likely to be identified correctly by protans and less likely to be misjudged as yellow when they were accompanied by a red LED signal, but only for the equal nominal input power configurations.

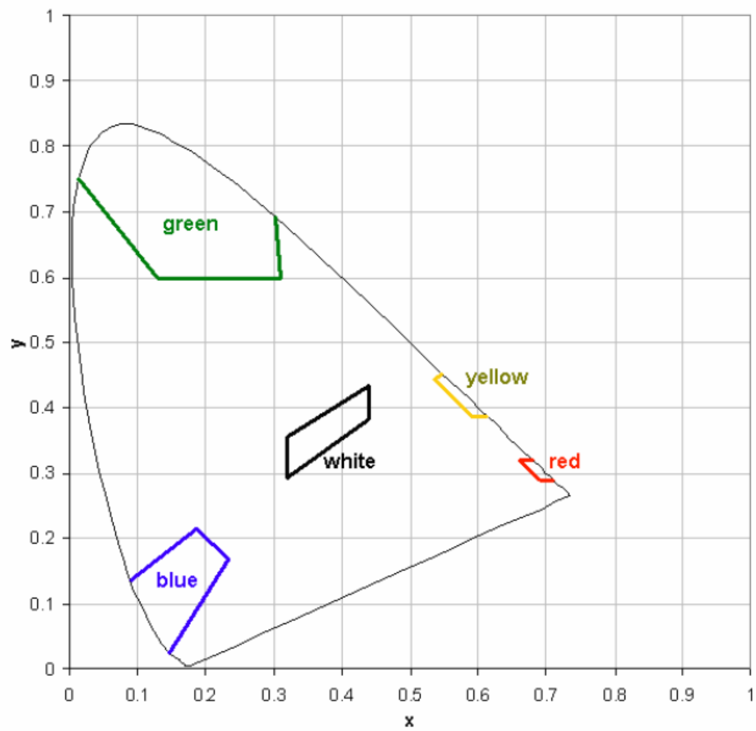

Figure 5. Chromaticity boundaries for LED aviation signal lights proposed by the FAA [4,5].

DISCUSSION

In general, the results summarized here suggest that color identification by color-normal observers is generally improved for the LED signals relative to the incandescent signals in the present study. This is likely because of increased color saturation especially for green. Only 90% of green incandescent signals were identified correctly as green by the color-normal subjects; almost all of the rest of the time they were identified as white. For white signals, the LED chromaticity being blue-shifted relative to the white incandescent chromaticity (see Figure 1) tended to result in the white LED being less likely to be misjudged as yellow, which occurred most of the time the white incandescent signal was not identified as white. The recommendation [4,5] to allow white LED signals with a chromaticity like the one for the white LED in the present study was mirrored in an earlier review by the Commission Internationale de l'Éclairage [7] in its review of signal light color requirements. The data from the present study contributed to the basis for revised chromaticity specifications for LED sources [4,5], which are illustrated in Figure 5.

The effects of the LEDs used in the present study were more mixed for the protan and deutan observers. Although identification of white and green were improved, probably for much the same reasons that identification for color-normal observers was improved, identification of other colors, particularly the yellow signals, was not improved with LED signals. While the yellow LEDs do fall along similar protan and deutan confusion lines as the red LEDs used in the present study, this is also true for the yellow incandescent signals. The chromaticity of the yellow LED signal used in the present study was relatively close to the red boundary. Huang et al. [8] found that protans in particular could misjudge such yellow signals as red, and this appeared to often be the case among the color-deficient subjects in the present study.

To the extent that accurate color identification of aviation signal lights represents a safety benefit, the impact of using LEDs with chromaticities matching those used in the present study would be a net benefit. This is because of the positive impacts of LED chromaticities among the color-normal subjects, and the likely lower proportion of color-deficient observers among pilots with unrestricted licenses compared to the general population (e.g., 2% of males are protans and 6% are deutans, with very few females in either category [3]). Additionally, there appears to be some very small benefit of the intensity differences associated with incandescent signals with colored filters having different transmission for color-deficient individuals. Luminous intensity specifications for signal lights of different colors could include minimum-to-maximum intensity ranges for in-service performance to account for this small effect.

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