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Abstract

The objective of the study is to determine the acceptable level of maximum luminous intensity of LED-lighted X signs used at airport runways that maintains clear visibility of the lighted X sign to show that the runway is closed. A theoretical study with literature review was first made (Part 1), then vision experiments were conducted using pilots as subjects (Part 2). The methods and results of these studies are reported.

Key words

Airport; signaling; lighted X sign; luminous intensity; glare; visibility.

1. Introduction

This study was performed with support of U.S. Department of Transportation (DOT) - Federal Aviation Administration (FAA) under the Inter-agency agreement 693KA9-18-N-00023 "Maximum Luminous Intensity for LED Signaling in an Airport Environment" between the FAA and National Institute of Standards and Technology (NIST). So-called "lighted X sign" is a fixture of multiple light sources forming the shape of character X and is used at airport runways to visually inform incoming airplanes that the runway is temporarily closed. Only the minimum luminous intensity is currently specified. The objective of this study is to investigate any adverse effects of too high luminous intensity and to determine appropriate maximum luminous intensity levels of light-emitting diode (LED)-lighted X sign that maintains clear visibility of the lighted X sign. A theoretical study with literature review was first conducted (Part 1). Then vision experiments were conducted using pilots as subjects (Part 2). The methods and results of these studies are reported.

1.1 Description of the Object (Lighted X)

The Temporary Runway Closure Lighted Visual Aid is identified as L-893, heretofore referred to as *Lighted X*–a lighted visual aid placed at the front end of a runway in airports to inform incoming airplanes that the runway is temporarily closed for landing. It eliminates the likelihood of unintended landings on closed runways especially at night and at times of low visibility.

The specifications for the part are published in the US DOT-FAA Advisory Circular 150/5345-55A [1]. Its use and application are covered under related Advisory Circular 150/5340-1 [2] and 150/5370-2 [3]. The specification for the part is based on a prototype described in a DOT Technical Report published by the FAA Technical Center [4]. The development of the lighted visual aid was originally developed in response to the recommendation of Task Group 3-1.6 of the National Airspace Review of 1982. After several prototypes were constructed and evaluated, the resulting design was that of a multi-light source in the configuration of the letter X which any pilot will recognize as an indication of a closed runway when marked on the pavement. The criteria for the design was provided by the FAA Office of Airport Safety and Standards and the Airport Safety R&D Section at the FAA William J Hughes Technical Center.

The lighted X is designed so that the light can be detected at 5 nautical miles (≈ 9.26 km) and the character X can be recognized at 1.5 nautical miles (2778 m ≈2.78 km) from the runway. The color of light is Aviation White. The lighted X is portable, typically carried on a trailer, with 4.3 m (14 ft)[*] arms forming the X as this was the longest part that could be made that still meet portability requirements. It is presented at an angle of 5° off normal in order to be visible to the approaching aircraft. Originally it was equipped with nine 150 W incandescent lamps, two on each segment of the X and one at the center such that the bulbs were equally spaced at 1.07 m apart with total intensity of 70000 cd for daytime and 2000 cd for nighttime. Currently, 9 to 17 lamps are used to form the X character, in a size of about 3 m x 4.3 m. Lighted X is available in both incandescent lamp and LED lamp versions.

[*] Non-SI units (with corresponding SI units) are used in this document, as these units are used in the FAA regulations and by the U.S. aviation community, to which this document is intended to provide information.

In addition to the FAA specifications for Lighted Runway Closure Markers, the LED lighted X also adheres to the specifications of the FAA Engineering Brief 67, "Light Sources Other Than Incandescent and Xenon For Airport and Obstruction Lighting Fixtures" [5] for the design including photometric testing and the part is referred to as the L-893X. There is a beam diameter requirement for day and night intensities and a minimum of nine light sources equally spaced on the entire X similar to the original prototype.

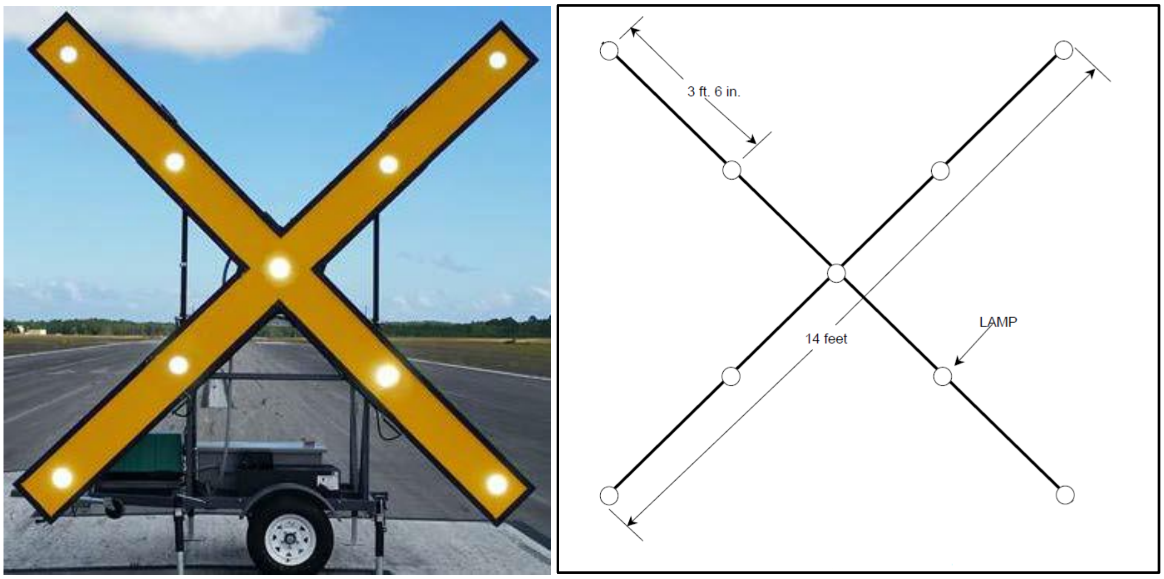

Fig. 1. Lighted X sign and specifications

1.2 Description of the Problem

The current manufactured L-893X is made according to the luminous intensity specifications for L-893 and in addition, to FAA EB-67, "Light Sources Other Than Incandescent and Xenon For Airport and Obstruction Lighting Fixtures". The existing performance specification for Lighted Runway Closure Markers only specifies the minimum luminous intensity.

Measurements of LED lamps used for the lighted X signs show that their luminous intensity tend to be much higher than the defined minimum luminous intensity requirement.

The objective of this study is to determine the adverse effects of the high luminous intensity of the lamps forming the lighted X and to quantify the acceptable range of the luminous intensity to determine the upper limit of luminous intensity that may help FAA to update the performance specification of the lighted X sign. The effect of color of light was also studied by using two different correlated color temperatures (CCT) of light; 2900 K representing incandescent lamps and 5700 K representing LED lamps.

2. Approach

This study was conducted in two parts:
Part I Theoretical Study– Study of Related Literature: to evaluate characteristics of the lighted X using fundamental vision science theory and literature, to understand the problem reported and determine which characteristic may be sub-optimal.

Part II Experimental Study– Vision Experiment using Lighted X Sign model: to conduct vision experiments using subjects and a model lighted X source to determine the acceptable maximum luminous intensity of lighted X signs that avoids glare and provides sufficient visibility for the X sign.

The detailed methods and results of Part I and Part II studies are reported in sections 3 and 4. Appendix A provides further details on vision fundamentals and calculations presented in Part I study.

3. Part I Theoretical Study– Study of Related Literature

3.1 Lighted X Physical Characteristics and Visual Tasks

The lighted X visual aid needs to 1) provide sufficient luminance so that it can be acquired (detected) at a distance of 5 nautical miles (9.26 km) and 2) provide luminance with sufficient spatial and temporal contrast such that the X shape is conspicuous and recognizable from 1.5 nautical miles (2.78 km).There was no problem reported with the temporal contrast (blinking) and so this was not a focus in this review.

The visual task by the aircraft pilot is to *detect* and then *recognize* the lighted X. There are two distances involved in the specification of the lighted X: the Acquisition Distance, specified to be no closer than 5 nautical miles (9.26 km), at which the aircraft pilot needs to spatially detect the lighted X; and the Recognition Distance at 1.5 nautical miles (2.78 km) at which the lighted X must be recognizable as the letter X.

The human visual system has many functions, so we limit the background material to ***spatial visual acuity*** which is the relevant topic to help evaluate if the lighted X specifications of size, luminance and spatial configuration of luminaires are appropriate for the assigned visual tasks. Details about the background material can be found in the Appendix A.

3.2 Detection of Lighted X

There is no minimum threshold size to detect a point source of light. It only needs to have luminance above the threshold for detectability at the given background luminance. Faraway stars that subtend only fractions of arc-seconds of visual angle are still seen by the unaided eye, but only when its luminance is higher than the background, such as on a clear night in areas with low background luminance. However, there is a size threshold for an object, not a light source, to be visible to the eye.

The lighted X appears as a point source from a distance of 5 nautical miles (9.26 km). While size is not important in detecting a point source, there is a size threshold for an object to be visible. Size in the visual sense is expressed as visual angular extent and the widely accepted value for an object to be visible is 1′ (minute; unit of plane angle[1]). This is dictated by geometric and physical optics (Rayleigh criterion) and the anatomical spacing of the photoreceptors in the retina. Two point sources have to be separated by a minimum distance in order to be resolved by the eye.

The lighted X per current specification subtends 1.1′ of visual angle at 5 nautical miles (9.26 km), which is just slightly above the generally accepted threshold of 1′. Given the 14 ft arms (4.3 m diagonal) of the X, the sources at the ends of the diagonal arms are 9.9 ft (3.017 m) apart in the horizontal and vertical direction. This is only slightly less than the 3.1 m separation of two point sources that the eye optics can theoretically resolve, given perfect background conditions. At 5 nautical miles (9.26 km), the X should be visible, and the furthermost corner lights may not be resolved, and the entire object will appear as one blinking light source.

3.3 Recognition of the Lighted X as letter X

3.3.1 Size

The second visual task of recognizing the lighted X as the letter X requires that its retinal projection at 1.5 nautical miles (2.78 km) distance be above the minimum threshold for size, and that there is adequate luminance and spatial contrast relative to the local background.

Pilots have a required 20/20 visual acuity, which correlates to a minimum angular resolution of 1′ of visual angle. The lighted X at 1.5 nautical miles (2.78 km) subtends 3.7′ visual angle in the horizontal and vertical. This is just slightly smaller than the size of a Row 8 (20/20) letter on a (US) Snellen chart as viewed from 20 ft (6.1 m) distance in visual acuity testing.

In related literature [6] on signage, the recognizability of a letter sign such as the lighted X depends on various factors such as viewing distance, angle, dwell time, and familiarity. The letter sign needs to first be legible before it can be recognized and understood. The Legibility Index (LI) [7] is used in land traffic control signage to determine the appropriate size of letters at the speeds and threshold distances that a sign needs to be legible. LI is the ratio of the threshold legibility distance in feet, to the height of the letter in inches. Current LI for traffic signage is 30. The visual angle subtended by a letter is smaller if the LI value is larger.

Using 1.5 nautical miles (2.78 km) as the threshold legibility distance, the current specification of 3.0 m sign height equates to a Legibility Index (LI) of 76, far greater than the LI of 30 used for highway signs, meaning that the visual angle of the X sign at 1.5 nautical miles is less than half of that used for traffic signs.

Additionally, the critical print size, defined as the smallest letter height necessary for maximum reading speed is typically accepted to be between two to three times the size threshold [8].

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[1] 1 minute (of plane angle) is equal to (1/60)° or ≈ 0.017°. This unit is equal to a non-SI unit, arc-minute, used in aviation and optometry.

Using 10′ visual angle as a critical print size for maximum reading speed, which is double the angular extent for 20/20 visual acuity corresponds to a X sign height of 8.1 m. This is 2.5 times the height of the lighted X current specification of 3.0 m.

3.3.2 *Luminance Contrast*

The specified minimum luminous intensity of the L-893X is 70000 cd during the day and 2000 cd at night. The luminance from the background comes from all other sources in the visual field being viewed. The Weber fraction ($\Delta L/L$) for a 'just noticeable difference' in perceived change is a constant proportion for the background-adapted eye for a wide range of luminance levels. For cone photoreceptors, this is generally accepted to be about 1 % over a wide luminance range and for rods, it is 14 %. [9]

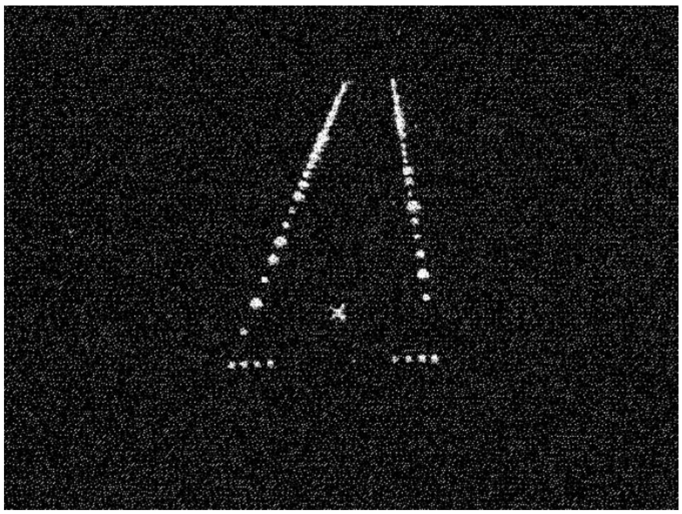

Fig. 2. Lighted X at night (Ref.3).

Assuming ground luminance values for an overcast day, the L893 and L893X are 360 and 520 times above the threshold for luminance contrast respectively. However, the nighttime specification of 2000 cd will be a million times in luminance contrast. This high contrast will pose visual performance problems for the dark-adapted eye. [10]

3.3.3 *Spatial Contrast*

A feature, shape or form, becomes recognizable because it has 'edges' that define its form. Edges are spatial points where there is luminance change – *i.e.*, light/dark transitions in the visual field. These could occur over large visual angles (low spatial frequencies) or small angles (high spatial frequencies. We experience luminance and spatial contrast all times.[11] Our ability to recognize objects due to luminance contrast within the viewing field is called spatial contrast sensitivity.

The smallest detail becomes the critical detail for recognition. For the letter X, the edge transitions around the center are critical to its recognizability. The optimal spatial frequency varies with luminance level as well as contrast levels. The spacing of the lamp and beam size of each lamp will affect the spatial frequency as well as the luminance contrast level. The contrast can be degraded further by atmospheric conditions which will blur the edge definition.

At the current specification, the four lamps forming a square surrounding the middle of the X are 1.51 m apart (horizontal and vertical) from each other, and 1.07 m from the center lamp of the X. Using a spatial frequency 30 cycles per degree (/°) which is on the upper limit for human spatial contrast sensitivity, two lamps need to be 2.42 m apart in order to be perceived as separate. Therefore, the five lamps near the center, viewed from 1.5 nautical miles (2.78 km) will not have any edge contrast between them and likely to be perceived as one bright spot. The lamps at the farthest ends of the X are 3.02 m apart (horizontally), which is more than the 2.42 m and should be perceptible as separate. They will, however, be dimmer relative to the group of five lamps that become visually merged as one.

3.4 Summary of Preliminary Study of Possible Problems with Current Lighted X Specifications

1. The lighted X intensity specification for daytime is about 500 times the background luminance but the nighttime intensity is a million times the background luminance which will cause problems for the dark-adapted eye. This minimum specification is likely too high.
2. The size of the lighted X subtends about 3.7′ of visual angle at 1.5 nautical miles (2.78 km). As a reference, a letter on the Snellen chart that a subject with 20/20 visual acuity views, subtends 5′ of visual angle. The current size specification of 3.0 m high is smaller than what is recommended for similar land traffic symbols which leads it to not be readily recognizable at the required distance of 1.5 nautical miles (2.78 km).
3. At the current specification, the four lamps surrounding the middle one are spaced too close together to be resolved and will be visually perceived as one large beam at 1.5 nautical miles (2.78 km), thereby losing the critical detail of light to dark edge transitions around the center that makes the letter X recognizable. The lamps at the ends of the arms should be resolvable but will be faint in comparison to the group of five lamps that will be visually merged as one large beam. This would create difficulty in recognition of the letter X. As the number of lamps increase, e.g. 17, the spacing is even smaller, which will only exacerbate the problem.
4. The combination of small size, lamps too close together and high intensity all contribute to its poor recognizability at the required distance of 1.5 nautical miles (2.78 km).

4. Part II Experimental Study– Vision Experiment using a lighted X sign model

The vision experiments were conducted at NIST during four weeks in July to August 2019, using a scale model of lighted X sign (6.5 cm x 6.5 cm) viewed at 60 m (and 30 m) distances, simulating the geometry of an airport and incoming aircraft at distance of 1.5 nautical miles (≈ 2.8 km). 20 pilots were used as subjects for this experiment. Under several different conditions of lighted X, eight levels of luminous intensity were presented to each subject, who evaluated the visibility of the X sign.

4.1 Experimental set up

The experiments were conducted using a model of lighted X source in a scale of 1/46. The real size of the light X source is 4.3 m (14 ft) diagonal square, 3.02 m (9.9 ft) high square shape (Ref 1). The lighted X model has 9.2 cm diagonal length, thus 6.51 cm x 6.51 cm square shape. The experiment simulated a pilot viewing the real lighted X at 1.5 nautical miles (2.78 km), at which distance the real lighted X must be clearly visible by the FAA specification. Thus, the viewing distance of the model was set to 59.9 m (≈ 60 m), which is 1/46.4 of 1.5 nautical miles (2778 m). The experimental geometry is illustrated in Fig. 3.

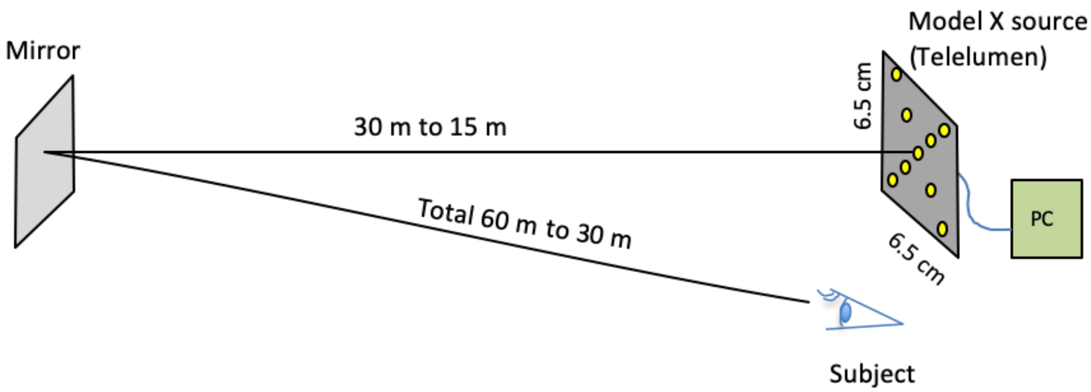

Fig. 3. Experimental geometry of Lighted X

In addition, two times the current size of lighted X (called "2X" in this paper) was simulated because the visibility of the current size (called "1X" in this paper) was deemed not sufficient from our theoretical study (Part I) and from our preliminary experiment; a need for enlarging the size was considered. To simulate the two times size, the viewing distance was set to 1/2 (30 m total) by moving the mirror but using the same lighted X model source. This simulates two times the size of lighted X at 1.5 nautical miles (2.78 km).

This set up was assembled at the NIST photometric tunnel laboratory, which is a 40 m long dark room, and the scale (1/46) of the model was chosen to fit to this lab space and available light source to fabricate a lighted X model. Figure 4 shows the layout of the laboratory, which has a 35 m long rail system, on which a five-axis goniophotometer stage is installed. The goniophotometer stage can be moved on the rail at any distances from the light source, which is measured with a linear encoder and displayed digitally. A scientific quality surface-mirror (70 cm x 50 cm) was mounted on the goniophotometer stage and its angle was aligned so that the subject could view the model lighted X at 60 m or 30 m distance. A maximum of two subjects could participate in the experiment at a time, although in most cases only one subject at a time participated.

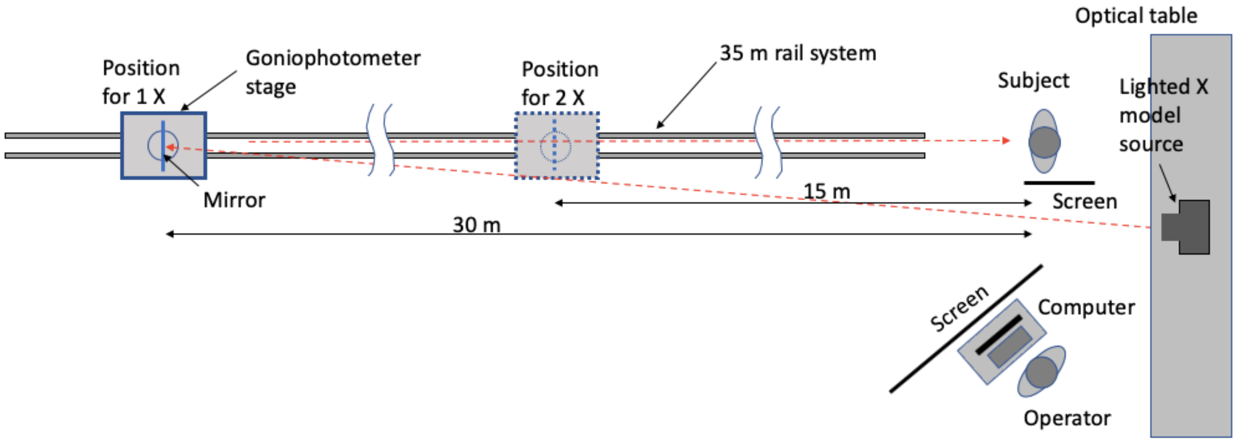

Fig. 4. Experimental layout of the NIST photometric tunnel laboratory

To investigate the effect of different spacing between lamps, we developed a lighted X model simulating lighted X with 9 lamps, 13 lamps, and 17 lamps. The lighted X model was built using a commercially available spectrally tunable lighting source with 16 channel LED sources having a light emitting area of 10 cm diameter. Three apertures with 9, 13, and 17 holes were fabricated, and placed over the top of the source's light emitting area. The dimensions of the model lighted X (an example of 17 holes) are shown in Fig. 5.

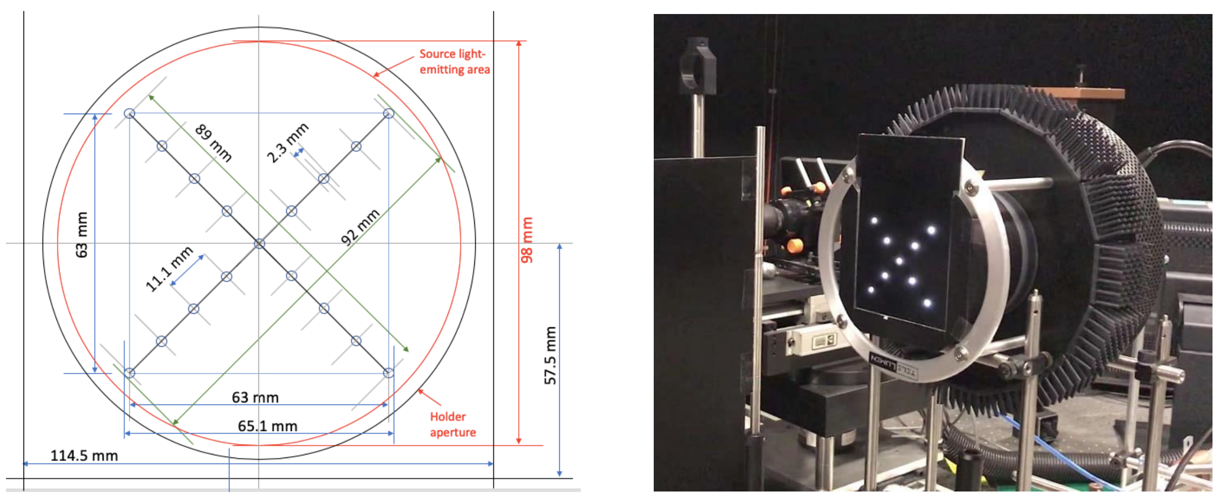

Fig. 5. Dimensions of the lighted X model (example of 17-hole aperture) on the left, and a photograph of the model source on the right (9-hole aperture).

The apertures were made with a thin aluminum plate, on which a number of holes were drilled using three different diameter drill bits to compensate for spatial nonuniformity of luminance over the source area. Then, the luminous intensity of each hole was measured (using a luminance meter) and the size of the holes were further adjusted by enlarging holes or blocking a small part of holes so that the intensity variation is within ± 5 %.

The lighted X model was modulated to flash on and off with a 5 second period with 50 % duty cycle (so, 2.5 s ON, 2.5 s OFF) as the real lighted X is operated. This flashing operation was achieved by the control software of the model light source.

Since the intensity of lighted X sources are specified by the values of effective intensity, the model lighted X was set for effective intensities corresponding to those of the real lighted X from 10 cd to 2000 cd, at 8 different levels: (10, 20, 50, 100, 200, 500, 1000, 2000) cd.

The experiment was also designed to compare LED lights and incandescent lights, so the lighted X model was prepared for two different Correlated Color Temperatures (CCT) of the source, 5700 K (simulating LED lights) and 2950 K (simulating incandescent lamps), used in real lighted X sources.

Therefore, for the experiments, 8 different effective intensity levels of (10, 20, 50, 100, 200, 500, 1000, 2000) cd were set for the following 12 conditions as shown in Table 1. The conditions of model lighted X with 9-hole, 13-hole, and 17-hole apertures, are called 9-lamp, 13-lamp, and 17-lamp configurations, respectively.

Table 1. Conditions for the model Lighted X

Condition	CCT	Size	Aperture configuration
1	5700 K	1 X	9-lamp
2			13-lamp
3			17-lamp
4		2 X	9-lamp
5			13-lamp
6			17-lamp
7	2950 K	1 X	9-lamp
8			13-lamp
9			17-lamp
10		2 X	9-lamp
11			13-lamp
12			17-lamp

In each condition, 8 intensity levels were set, the details of which are described in next section. Therefore, total 12 x 8 = 96 settings were prepared for the Lighted X model source.

4.2 Calibration of lighted X model

The intensity of the lighted X model source was set for each luminous intensity corresponding to the effective intensity values from 10 cd to 2000 cd. Effective intensity (in the FAA specification [1]) is defined by Blondel-Rey equation,

$$I_{\text{eff}} = \frac{\int_{t_1}^{t_2} I(t)\,\mathrm{d}t}{a + (t_2 - t_1)}, \tag{1}$$

where t_1, t_2 are the duration of the flash and a is the visual time constant, for which 2.0 s is normally used [12]. For 2.5 s ON OFF flashing light (see Fig. 6), luminous intensity (steady ON part) of 1 cd produces effective intensity of 0.926 cd.

$$I_e = \frac{\int_t I(t)}{0.2 + \Delta t} \tag{2}$$

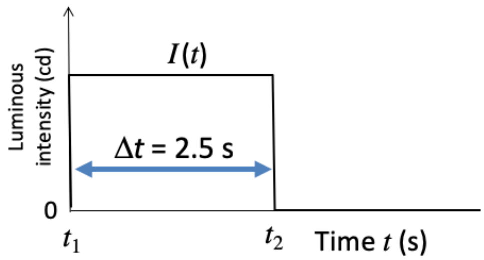

Fig. 6. Waveform data for effective intensity calculation

The luminous intensities (steady light) of the model lighted X with each aperture were set for the 1/46 scale, thus the intensity of lighted X (total of all lamps) must be $(1/46)^2$ of the intensity of the real lighted X (according to Inverse-Square Law). The reflectance of the mirror was measured for this geometry (ρ=0.945) and was included in the calibration. For example, for 2000 cd effective intensity of real lighted X, the luminous intensity (cd) of the lighted X model (ON part) will be 2000/0.926/0.945 x $(1/46.4)^2$ = 1.062 cd. Similarly, luminous intensities at other effective intensity levels were set as in Table 2 below. For 2X condition, the luminous intensity of the model source is ¼ of those of 1X condition.

Table 2. Effective intensity of real lighted X and corresponding (steady-light) luminous intensity of the lighted X model.

Effective Intensity of Real Lighted X (cd)	luminous intensity of Model ON-part (cd)	
	1 X	2 X
2000	1.062	0.265
1000	0.531	0.133
500	0.265	0.066
200	0.106	0.027
100	0.0531	0.0133
50	0.0265	0.0066
20	0.0106	0.0027
10	0.0053	0.00133

Note that these luminous intensity values should be the same for any of the 9-hole, 13-hole, and 17-hole apertures. As the size of the holes in these apertures were about the same, the aperture with fewer number of holes (e.g., 9 holes) needed higher luminance level from the lighted X model source than the aperture with more holes (e.g., 17 holes).

Since the luminous intensity level was very low (as in Table 1), a special high sensitivity photometer was prepared to measure the luminous intensity of the source. The measurements were made at 1 m distance (which was considered long enough, as the light source has near Lambertian distribution). The distance was set for 1 m using a meter stick. Therefore, measured illuminance values in lx are equal to the luminous intensity in cd. The photometer had gain ranges of 10^6, 10^7, 10^8, 10^9, and 10^{10} (V/A). It was calibrated against NIST luminous intensity unit. A hood is added to reduce ambient stray light. The photometer was calibrated against the NIST illuminance unit standard [13]. The expanded uncertainty (k=2) of the illuminance measurements for this experiment was estimated to be 2.0 % for broadband white light at 2950 K and 2.3 % at 5700 K, in addition, absolute uncertainty of ≈ 0.1 mlx due to stray light and signal noise at very low illuminance levels.

The luminous intensities at all intensity levels at all the conditions were measured before starting the vision experiments. During vision experiments, the luminous intensity of the reference setting (effective intensity 2000 cd) at all four conditions were measured at the end of each day of experiment to verify the stability of the source.

4.3 Subjects

20 pilots holding various pilot licenses were recruited by FAA and came to NIST over a period of four weeks. The demographics of the subjects are shown in Fig. 7.

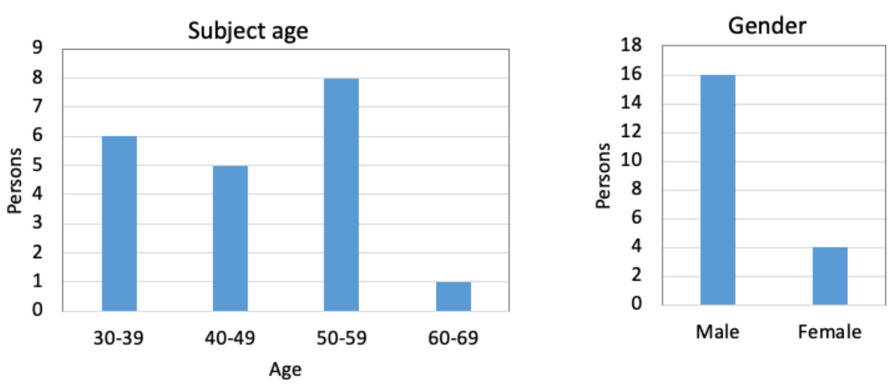

Fig. 7. Demographics of the subjects.

4.4 Vision experiment procedures

The following procedures were taken.

(1) Verify that the subject received Information Sheet from NIST. The operator explained briefly about the document that the subject is protected for privacy and against any risk of hazard or discomfort. He/she can request break at any time.
(2) Ask subject to fill out the demographic form and pilot certification information.

(3) Explain the experiment procedures: Experiment will last about one hour and there will be four sessions, each about 15 min. After each session, we will take a break of one or two minutes, when we turn on lights and subject can relax. During break, we will also change the position of the mirror. During each session, we will present many different intensity levels of lighted X at different conditions.
(4) Explain the subject that we ask him/her to give a rating score in a scale of (1) to (5), which are:

1) don't see X at all
2) see some figure but not X
3) can guess it's an X (but not sure)
4) Sure it's an X though not very clear
5) See X clearly

The subject was instructed to give the answer orally and also make short comments for the reason for his/her rating score - too dim, too bright, blurred, washed out, etc.

(5) Turn off lab room lights. Had subject adapt to dark condition for at least two minutes. In the meantime, the operator let the subject practice two experimental runs.
(6) Start real experiments. There were four sessions. Between sessions, we had two minutes break, when the mirror was moved between 30 m and 15 m.

The order of sessions was: 5700 K (1X, then 2X), then 2950 K (1X then 2X). This order was fixed for all subjects.

In each session, there were three aperture configurations (9-lamp, 13-lamp, 17-lamp), the order of which was randomized for each subject. For each condition, the order of intensity levels shown in Table 3 was used, arranged in a random manner but avoiding presenting very low and very high intensity next to each other, so the first four lights were at lower levels and the last four lights were at higher levels. The same order was used for all subjects.

(7) After finishing each day, we measured the luminous intensity (steady light) at reference setting (2000 cd) for each condition.

Table 3. The order of intensity levels used in the experiment for each subject.

Presentation order	Effective intensity (cd) of real lighted X
1	100
2	10
3	50
4	20
5	200
6	1000
7	500
8	2000

Before and after the entire experiment period, the luminous intensity of all settings in all conditions were measured.

The experiments were conducted for four weeks, from July 16 to August 15, 2020. There were total 20 subjects. Only one time, two subjects did experiments together, in which case, using keypads to give rating scores without knowing the score of the other subject.

An example of experimental scene is shown in Fig. 8. The room was kept completely dark during the experiments.

Fig. 8. An example of experimental scene (the room was completely dark during experiment)

4.5 Data analysis

All raw results (scores and comments by subjects) were recorded on a spreadsheet. The results were first sorted in the intensity order from 10 cd to 2000 cd for twelve aperture/CCT conditions, with scores and comments given by each subject, then the averages for all subjects were calculated. An example for such analysis is shown in Table 4 and Fig. 9. The effective intensity values in Table 4 are those in real size geometry converted from the measured luminous intensity of the lighted X model source. Note that these cd values could not be set to exact values such as 100 cd, 200 cd, etc., due to limitation of the light source control software.

Table 4. The first step of data analysis

CONDITION	Effective Intensity (cd)	Averge score	Std. dev.
5700K-9 holes-1X	11	1.9	1.3
	17	2.2	1.2
	47	2.9	1.1
	99	3.2	1.1
	209	3.0	1.3
	548	2.6	1.3
	1125	2.6	0.9
	2536	2.2	1.1
	Avereage	2.6	1.2
5700K-13 holes-1X	7	1.4	0.8
	20	2.3	1.2
	48	3.1	1.1
	97	3.0	1.3
	203	3.0	1.3
	528	2.7	1.2
	1092	2.2	1.1
	2231	1.9	1.0
	Avereage	2.4	1.1
5700K-17 holes-1X	7	1.4	0.8
	19	2.1	1.3
	43	2.4	1.2
	96	2.7	1.2
	201	2.9	1.1
	524	2.4	1.1
	1084	2.3	1.1
	2218	1.8	0.8
	Avereage	2.2	1.1

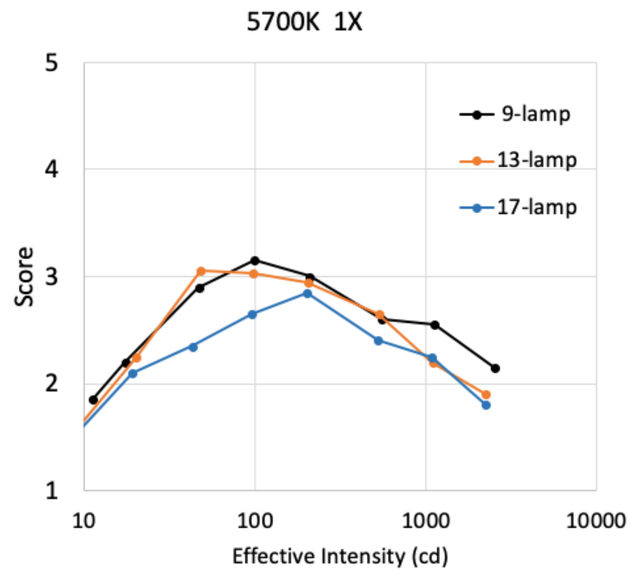

Fig. 9. Plots of average rating scores (5700 K, 1X condition, for all subjects)

The standard deviations for each average rating score in the above are ≈1.1, and an example of a plot with error bars showing the standard deviation is shown in Fig. 10 (left). Since standard deviations are all similar for all conditions, and it is difficult to include these for three curves in one graph as shown in Fig. 9, these error bars are omitted in the subsequent graphs presented. Then, to remove experimental noise in the data, a curve fit was made for each plot of rating scores using a third order polynomial as shown in Fig. 10 (right).

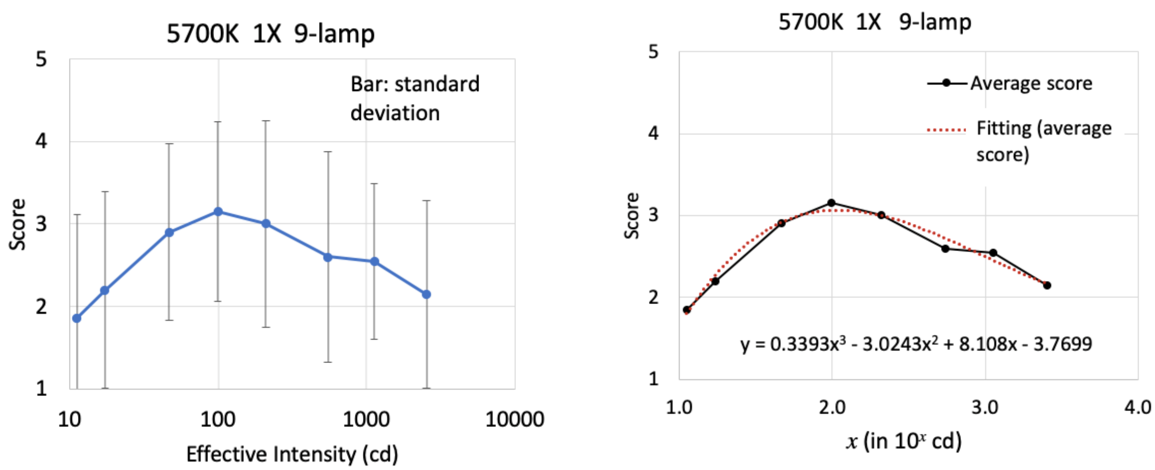

Fig. 10. An example plot of average rating scores with standard deviation (left) and an example of curve fitting (right)

4.6 Results

4.6.1 Average of all subjects

Figures 11 and 12 show the fitting curves of the average rating scores for all subjects for each CCT, size, aperture condition. Dramatic differences between the 1X and 2X conditions are observed. The results for 1X condition indicate that the visual size of 1X condition is not sufficient for clear visibility of the X sign at either CCT conditions. Also, note that, in 1X condition, more lamps make it worse, as the lights at closer spacing tend to merge together at the center as perceived. [see Fig A.15 in Appendix]

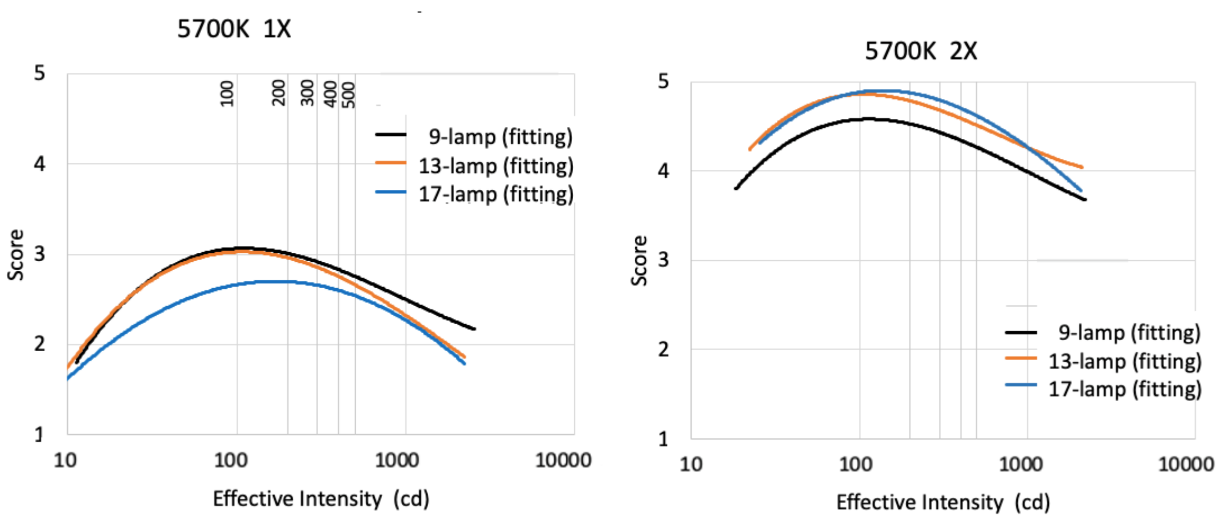

Fig. 11. Fitting curves of the average rating scores for 9-lamp, 13-lamp, and 17-lamp apertures for 5700 K, 1X condition (left) and 2X condition (right).

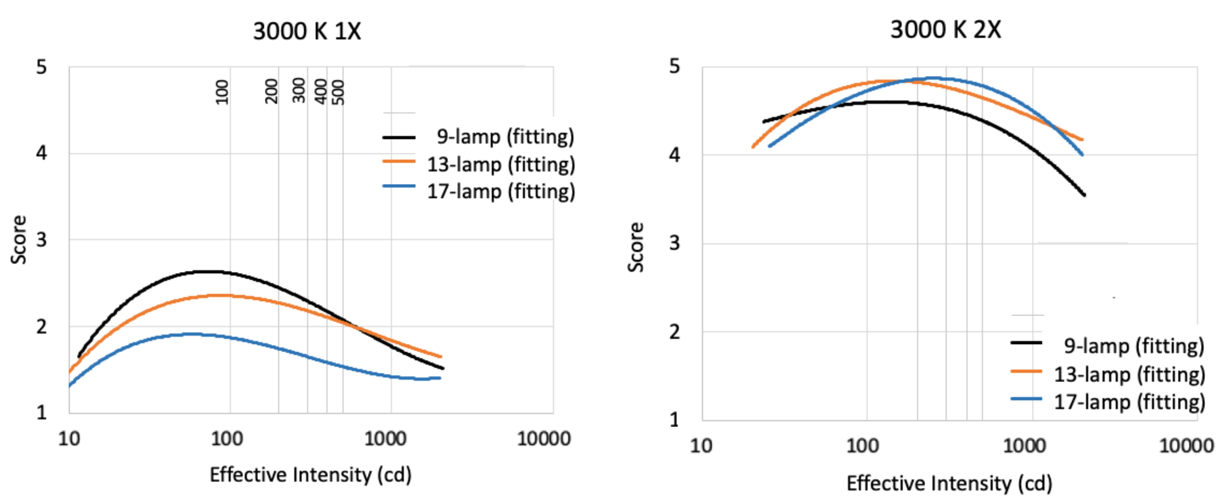

Fig. 12. Fitting curves of the average rating scores for 9-lamp, 13-lamp, and 17-lamp apertures for 3000 K, 1X condition (left) and 2X condition (right).

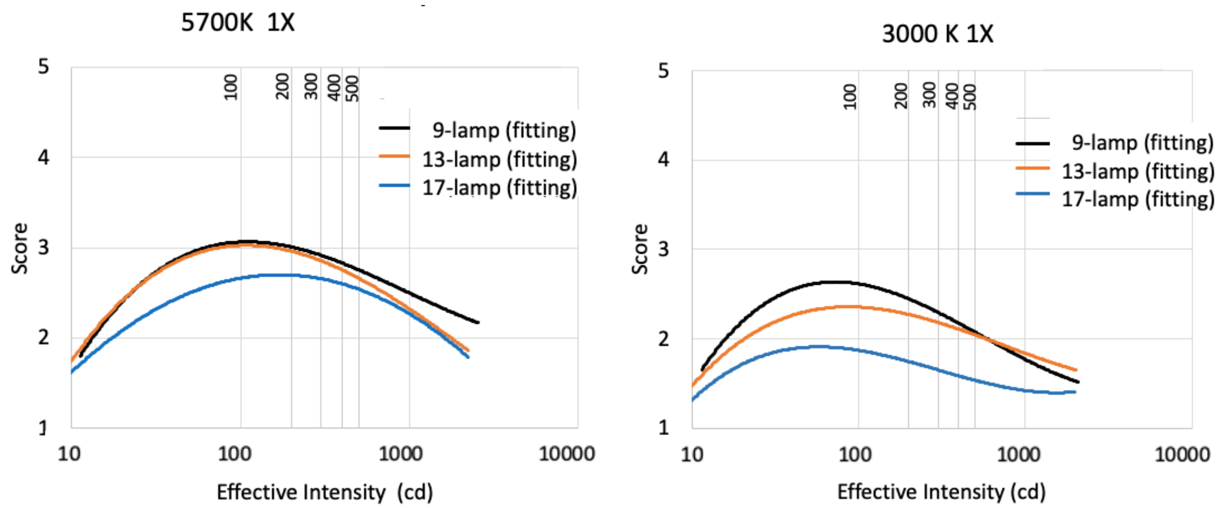

Fig. 13 Results comparing 5700 K (left) and 3000 K (right) for 1X condition.

Figure 13 shows a comparison of 5700 K and 3000 K for 1 X condition, which clearly shows much better visibility at 5700 K than 3000 K. The difference for 2 X condition (comparing Figure 11 (right) and Fig. 12 (right) is very small because the rating scores are very high (close to 5) at 2 X condition for both CCT conditions.

4.6.2 Results broken down for age groups

The subjects were divided into two groups – younger (less than 45 years old) and older group (45 years old and higher). The 45 years of age is the approximate average age of all subjects. There were 9 subjects in younger group and 11 in older group. The analysis presented in section 4.6.1 were made for each age group. Two examples for 5700 K (1X and 2X) are shown in Figs. 14 and 15. The results for 3000 K conditions were similar.

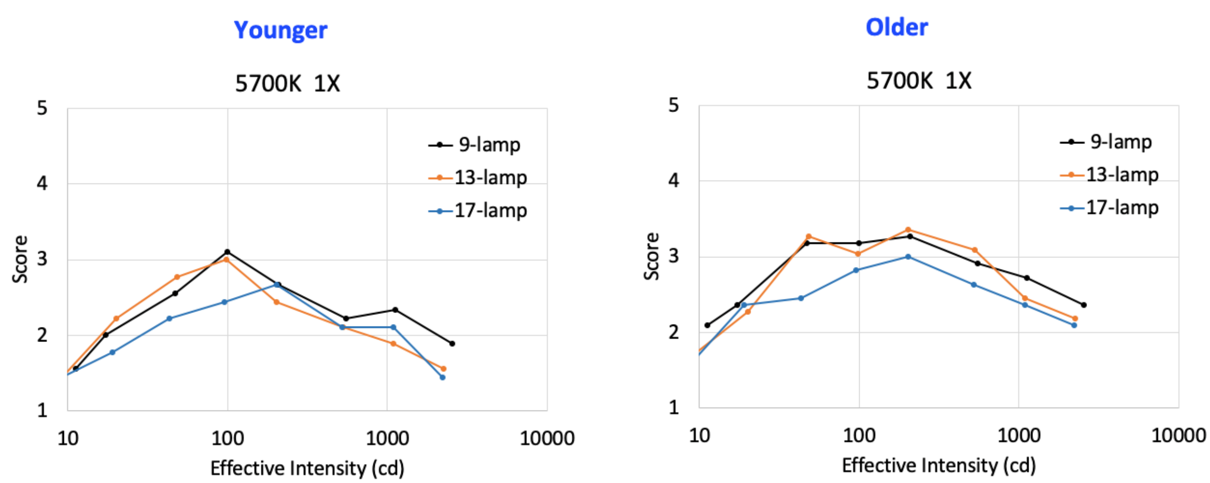

Fig. 14 Average rating scores for 5700 K, 1X condition for younger group (left) and older group (right) of subjects.

Figure 14 shows that the rating scores of older subjects are slightly higher overall. The differences are smaller in Fig. 15, but 9-lamp curves show some difference (older group is slightly higher).

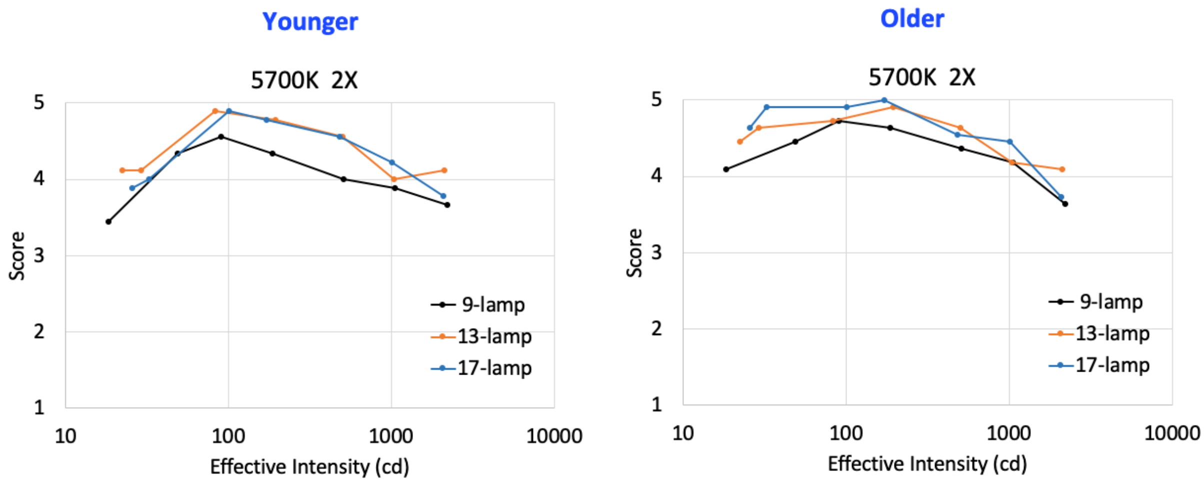

Fig. 15 Average rating scores for 5700 K, 2X condition for younger group (left) and older group (right) of subjects.

4.7 Conclusions

From the results obtained in this experiment, as presented in this report, the following conclusions are made.

- 1X (current 14 ft diagonal size) does not provide sufficient visibility at 1.5 nautical miles (2.78 km) (rating scores only up to ≈3) as predicted by the theoretical study.
- 2X (28 ft diagonal size) made big improvements. (rating scores up to ≈5 at peak).
- In all cases, the peak score lies between 100 cd and 300 cd.
- Current minimum intensity (2000 cd) is clearly too high.
- For 1X size, 9-lamp light performs best.
- For 2X size, 13 or 17 lamp lights perform better than 9-lamp light.
- For 1X size, 3000 K performance is significantly less than 5700 K.
- Older subjects performed better than younger subjects in this subject group (this may not be general tendency).

Acknowledgement

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The authors also thank Yuki Kawashima at Optical Radiation Group, Sensor Science Division, NIST, for his assistance in developing the control program of the spectrally tunable source for the flashing lighted-X model light source.

Appendix A: Estimates of values based on vision fundamentals

A.1 Size of Object (Lighted X) and Minimum Visual Angle

There is a size threshold for an object to be visible. The size or extent of the object as viewed from the eye is expressed in terms of angular extent (in degrees or minutes). At long distances where the angles become very small, this is given as

$$\tan\theta = \frac{dimension\ of\ object}{viewing\ distance} \qquad (A.1)$$

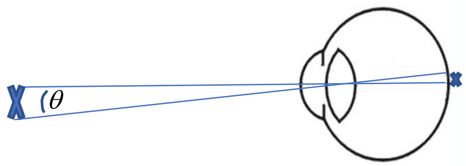

Fig. A.1. The angular extent that an object subtends at the eye is the visual angle. The angle gets larger as the object gets closer.

Visual Angles Subtended by Lighted X at 5 nautical miles (9.26 km) and 1.5 nautical miles (2.78 km) are listed in Table A.1.

Table A.1. Visual Angle and Extent

Object	Height (ft)	Width (ft)	Height (m)	Width (m)	Area (m^2)	θ_{vert} (′)	θ_{horiz}(′)
Distance	5 nautical miles		9260 m				
L893	14 ft 11-1/2 in	12 ft ½ in	4.56	3.67	16.7	1.7	1.4
L893X	11 ft 6 in	11 ft 8 in	3.51	3.56	12.5	1.3	1.3
Distance	1.5 nautical miles (9114 ft)		2778 m				
L893						5.64	4.54
L893X						4.34	4.40

$$\tan\theta = \frac{4.56}{9260'} \qquad \theta = 0.0282° \times \frac{60'}{1°} = 1.7' \text{ vertical} \qquad (A.2)$$

The angular extent that an object subtends generally accepted as visible to the human eye is 1′. This comes from the geometric optical limits of the eye. The human eye in simplified optical terms [14] consist of a lens system which focuses the light to a point close to the lens and forms the image of the scene on the retina, typically 17 mm away from the nodal point. The limiting aperture of the eye is the pupil which contracts and dilates from 2 mm to 9 mm in diameter to control the amount of light. The retina which serves as the projection screen has photoreceptors made up of rods and cones. The rods are sensitive to low levels of light and responsible for scotopic and mesopic vision. The cones are responsible for photopic vision and color sensitivity. The small area in the retina called the fovea is where the cone photoreceptors are at highest density and is where the best-focus image is formed. Aberrations of the eye are corrected to keep the best focus on the fovea. Light captured by the photoreceptors are converted to neural signals such that the scene is interpreted by the brain.

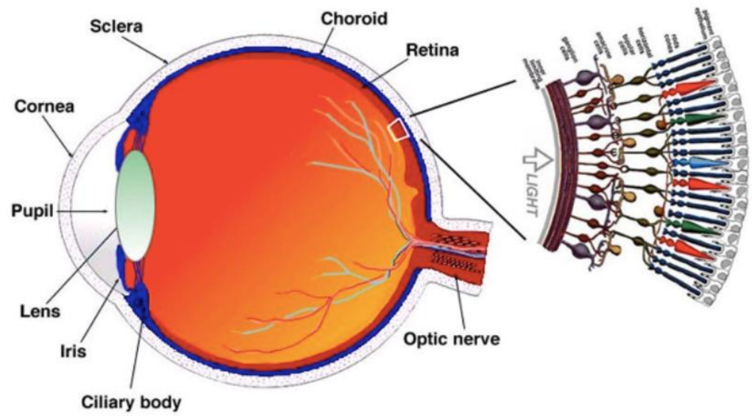

Fig. A.2. Illustration of the human eye with an enlarged illustration of the photoreceptors in the retina. Source https://webvision.med.utah.edu/book/part-i-foundations/simple-anatomy-of-the-retina/*

A.2 Geometric Vision Optics (The Eye as Optic)

Point Spread Function and Airy Disk

The eye as an optic is subject to light diffraction and this limits how well it can resolve two point sources in a scene. If it were a perfect optic with no aberrations, a point source (infinitesimally small) will not be imaged on the retina as a point of light. It gets spread out to form a larger spot of finite size on the retina.

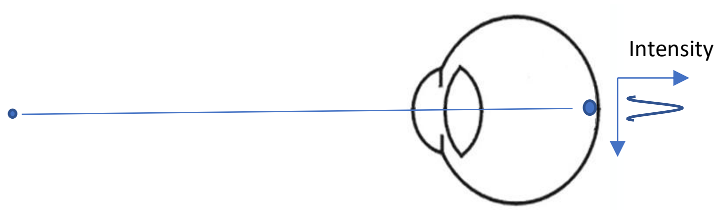

Fig. A.3. A point source is imaged as a larger bright disk of finite dimension, not a point, due to diffraction by the optical elements of the eye.

This Point Spread Function (PSF) describes the two-dimensional distribution of light at the imaging plane of the optic (retina) for a point source. For optics with circular elements such as the eye with its circular lens and circular pupil, the 2-D image of a point source spreads to a core bright disk with alternating dark and bright concentric rings with the intensity of the bright rings diminishing as it gets farther away from the core. This is called an Airy pattern and the central bright spot is called the Airy disk. The Airy pattern comes from Fraunhofer diffraction theory and described mathematically using the Bessel function of order 1.[15] The Airy disk spatial extent is expressed as angular radius θ, spanning from the center to the first minimum.

$$\sin\theta = x\frac{\lambda}{d} \qquad \sin\theta \cong \theta = 1.22\frac{\lambda}{d} \tag{A.3}$$

where λ is wavelength of light, d is the pupil diameter and x the location of the dark rings (minima) with respect to the core center. The first dark ring is at radius 1.22 (λ/d) from the Airy disk center. As the pupil gets larger, the Airy disk gets smaller.

The first three dark rings occur at radii 1.22, 2.23, 3.24 λ/d. These dark spots are the 'zeroes' of the Bessel function of order 1. This central spot (Airy disk) contains 86 % of the total light in the image. The second maximum is only 1.75 % relative to the center intensity with other maxima further from the Airy disk diminishing even more.

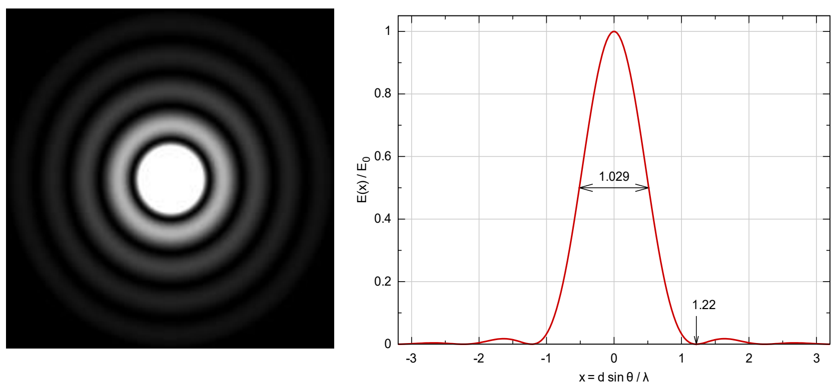

Fig. A.4. On the left is the 2D Airy pattern for the point spread function by circular optical elements. The central spot is the Airy disk, and on the right is the intensity distribution along one axis. [Source: Wikimedia.org]

Rayleigh Criterion:
The accepted criterion for limit to resolution by an optic at this lowest limit, known as the diffraction limit, is based on the Airy disk angular radius (center to first minimum). The Rayleigh criterion [16] states that two images are just resolvable when the center of the diffraction pattern of one is directly over the first minimum of the diffraction pattern of the other and the minimum angular resolution is

$$\theta_{\min} = 1.22\frac{\lambda}{d} \tag{A4}$$

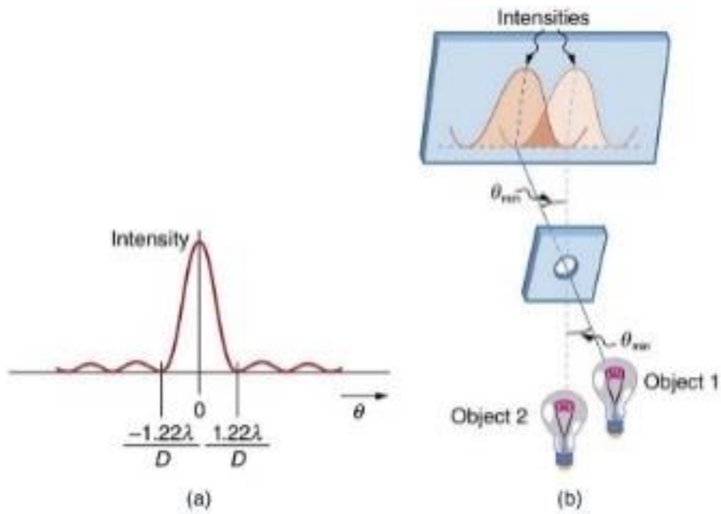

Fig. A.5. The image of two point sources are resolved if the maximum of one point source falls on the first minimum of the other.
[Source: https://openstax.org/books/college-physics/pages/27-6-limits-of-resolution-the-rayleigh-criterion]

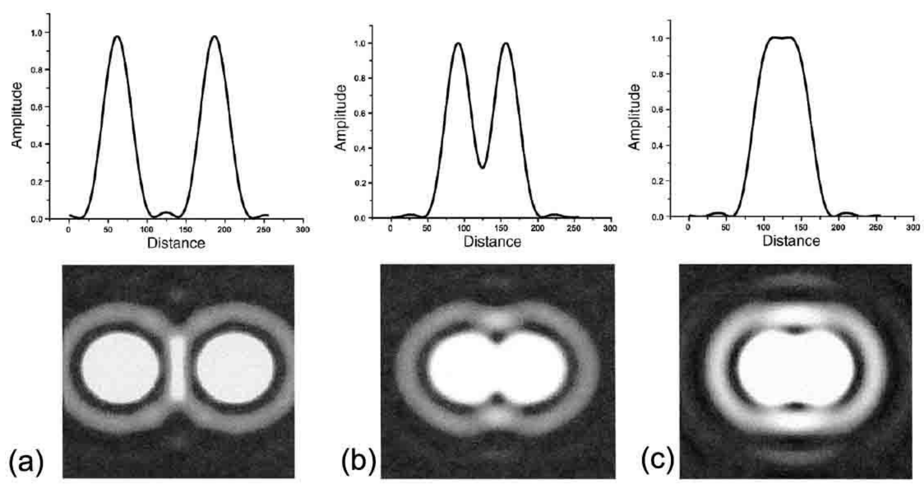

Fig. A.6. (a) Two well-resolved Airy disks (b) Two Airy disks barely resolved and (c) two Airy disks that are unresolved. [Source: https://www.globalsino.com/EM/indexS.html]

A.3 Photoreceptor Density at the Retina

The light collected by the eye optics is then projected to the retina where it interacts with photoreceptors which convert the light stimuli to neural signals that can be processed and interpreted by the brain. The cone photoreceptors responsible for photopic vision are hexagonal cellular structures measuring approximately 2.5 μm in diameter and most concentrated in the foveal region of the retina.[17]

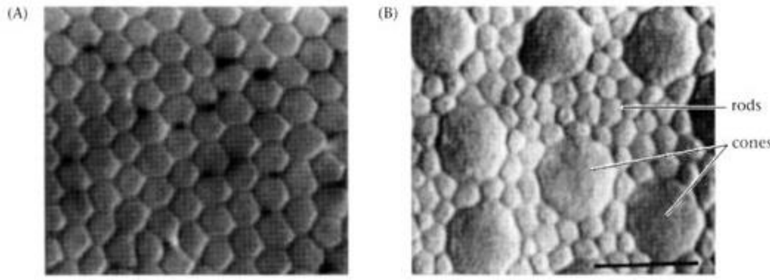

Fig. A.7. (Left) Cones in the foveal area and at right are rods in the rest of the retina. Sizes and densities vary with distance from the center of the fovea. [Source: https://www.cis.rit.edu/people/faculty/montag/vandplite/pages/chap_9/ch9p1.html]

Minimum Angular Resolution (MAR) or Resolving Power of the Eye
If the eye were 'diffraction-limited' the minimum angular resolution would be given by the Rayleigh criterion. The resolution is directly proportional to wavelength and inversely proportional to the pupil diameter. At the retina 17 mm from the nodal point, this corresponds to a spot size of 2.8 μm, which is slightly larger than the center-to-center distance between two cone photoreceptors.

Minimum Angular Resolution of the Eye

$$\theta_{\min} = 1.22\frac{\lambda}{D} = 1.22\frac{550\times10^{-6}}{2} = 3.36\ \times 10^{-4}\ \text{rad} \qquad (A.5)$$

Table A.2. Minimum Angular Resolution

	Value (mm)	$\theta_{\min}$ (rad)	$\theta_{\min}$ ($'$)
Wavelength (green)	550 x10^{-6}		
Pupil Diameter (day)	2	3.36 x10^{-4}	1.16
Pupil Diameter (night)	9	7.46 x10^{-5}	0.26

The minimum separation distance *s* between two points that the eye can theoretically resolve from a distance *L* is

$$s = L \cdot \theta_{\min} \qquad (A.6)$$

L is a distance from the eye to target or the distance from the pupil to fovea in the eye, and *s* is the separation between the two points in either case.

Table A.3. Minimum separation distance between two sources in space (daytime)

Distance (*L*)	Distance [m]	$\theta_{\min}$(rad)	*s* [m]
5 nautical miles	9260	3.36 x10^{-4}	3.1
1.5 nautical miles	2778	3.36 x10^{-4}	0.9

Table A.4. Minimum separation between two points at the retina

		s [mm]
Distance to Fovea	17 mm	
θ_{min}(radians) day	3.36 x10^{-4}	5.7 x10^{-3}
θ_{min}(radians) night	7.46 x10^{-5}	1.3 x10^{-3}

The value 1.3 μm is less than the spacing of the photoreceptors so two points that are theoretically resolvable by the eye optics cannot be detected separately by the retina.

A.4 Psychophysical Vision Measurements and Contrast Thresholds

How we see objects is the study of visual perception which includes the brain's interpretation of the visual stimuli captured by the eye. The human sensory system is sensitive to changes to the physical magnitude of the stimulus. In human vision, that physical stimulus is light, and some of its various characteristics (intensity, wavelength, polarization, etc.) are accessible by the human visual system. We perceive objects in terms of its luminance characteristics spatially and temporally; more specifically, the contrast between an object against the background of the viewed area. Contrast is expressed mathematically in various ways but they all convey magnitude of the light from the object versus the background. There are threshold contrast values below which the visual contrast is imperceptible, and this threshold contrast increases with the background. [18,19]

As the primary sensor of our environment, human vision has been studied extensively and psychophysical metrics have been established. Below are descriptions of contrast measurements relevant to this problem.

A.5 Luminance Contrast

At the specified distance of 5 nautical miles for acquiring the signal from the lighted X, the object is a point source. The specified luminosity of the L-893X is 70000 cd during the day and 2000 cd at night. While the viewing field of the eye is not symmetric, we can use a 60° as the viewing angle for estimating luminance from the Lighted X versus the background area (Fig. A.8).

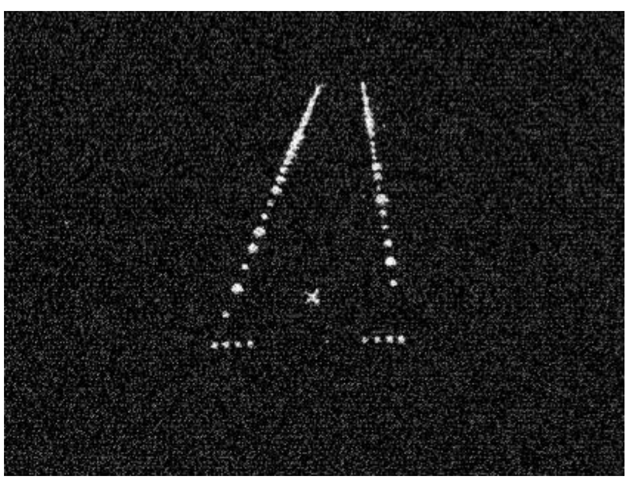

Fig. A. 8. Lighted X at night. Ref.3

Weber's contrast expression is appropriate in this case of an isolated spot against a large background. The luminance contrast from the lighted X against the background using Weber's contrast is given by

$$C = \frac{\Delta L}{L} = \frac{L_x - L_g}{Lg}, \quad \text{(A.7)}$$

where L_x and L_g are the luminance of the lighted X and the ground, respectively. The Weber fraction ($\Delta L/L$) in perceived change is a constant proportion to the background level for the background-adapted eye for a wide range of luminance levels, with an accepted value of 1 % for rods and 14 % for cones.

Table A.5. Relevant Photometric Quantities and Units

Photometric Quantity	Unit	Relationship with lumen
Luminous flux	lm (lumen)	
Luminous intensity	cd (candela)	$lm \cdot sr^{-1}$
Illuminance	lx (lux)	$lm \cdot m^{-2}$
Luminance	$cd \cdot m^{-2}$	$lm \cdot sr^{-1} \cdot m^{-2}$

Luminance Contrast Estimate
Eye field of view: 60° = 1.0966 sr
Luminance of lighted X: Intensity/area

$$Luminance = \frac{70000}{16.7} = 4192 \ [\mathrm{cd \cdot m^{-2}}] \quad \text{(A.9)}$$

Converting ground illuminance to luminance:

$$Ground\ luminance = \frac{1000\ \mathrm{lm \cdot m^{-2}}}{1.0966\ sr^{-1}} = 909\ [\mathrm{lm \cdot m^{-2} \cdot sr^{-1}}\ or\ \mathrm{cd \cdot m^{-2}}] \quad \text{(A.10)}$$

Weber's Contrast:

$$C = \frac{\Delta L}{L} = \frac{L_x - L_g}{L_g},\ C = \frac{4192 - 909}{909} = 3.6 \quad \text{(A.11)}$$

Table A.6. Weber contrast estimate between lighted X and ground

Object	Quantity		Luminance	Contrast ΔL/L
Field of view	60°	1.096 sr		
Threshold contrast daytime ΔL/L				0.01
L893 day	70000 cd	$16.7\ m^2$	$4.2 \times 10^3\ cd \cdot m^{-2}$	3.6
L893X day	70000 cd	$12.5\ m^2$	$5.6 \times 10^3\ cd \cdot m^{-2}$	5.2
Ground overcast daytime	$1 \times 10^3\ lm \cdot m^{-2}$		$9.1 \times 10^2\ cd \cdot m^{-2}$	
				Both > 0.01
Threshold contrast night ΔL/L				0.14
L893 night	2000 cd		$1.2 \times 10^2\ cd \cdot m^{-2}$	1.3×10^6
L893X night	2000 cd		$1.6 \times 10^2\ cd \cdot m^{-2}$	1.8×10^6
Ground overcast night	$1 \times 10^{-4}\ lm \cdot m^{-2}$		$9.1 \times 10^{-5}\ cd \cdot m^{-2}$	
				Both >> 0.14
L893 daytime 21 lights	3333 cd/light			
L893X daytime 9 lights	7778 cd/light			

The L893 and L893X both provide more than sufficient luminance contrast from 5 nautical miles away during an overcast day and overcast night. The nighttime contrast is very high, beyond the comfort limit, which could inhibit visibility and recognizability and introduce glare. [10]

A.6 Visual Acuity Test and Minimum Angular Resolution

Visual Acuity is a measure of the smallest visual angle whereby a subject can recognize a letter or number clearly on a Snellen chart (Fig. A.9) (also referred to as Big-E chart) or similar test chart, situated at a standard testing distance from the subject.

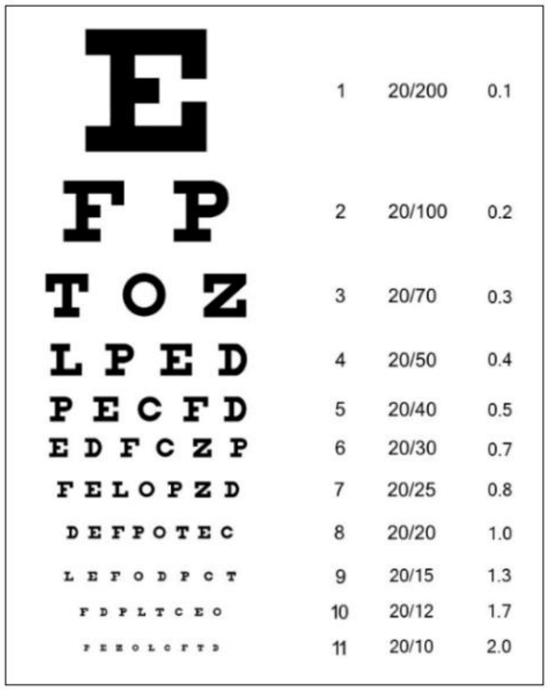

Fig. A.9. Snellen chart for visual acuity testing. Values on the right of the letters are the row numbers, the Snellen fraction, and the decimal equivalent of the fraction

In the US, the standard testing distance is twenty feet, so chosen as this is close enough to ‘optical infinity’ and the eye lens is relaxed. The subject is asked to read rows of optotypes (letters) of successively decreasing size until the subject can no longer identify the letters in the row. The row/size of the smallest letters that the patient can accurately identify corresponds to the patient’s minimum visual angle.

Visual acuity results are expressed as a Snellen fraction relative to the standard observer. The inverse of the Snellen fraction is the Minimum Angular Resolution of the subject. The standard observer is assigned to have visual acuity of 20/20 or minimum angular resolution of 1′ of visual angle. The 20/20 Snellen chart letters are designed such that each feature subtends 1′; the black strokes of the letter E as well as the white spaces between them are each 1′ for the standard observer, for a total of 5′ subtense for the entire letter (Fig. A.10).

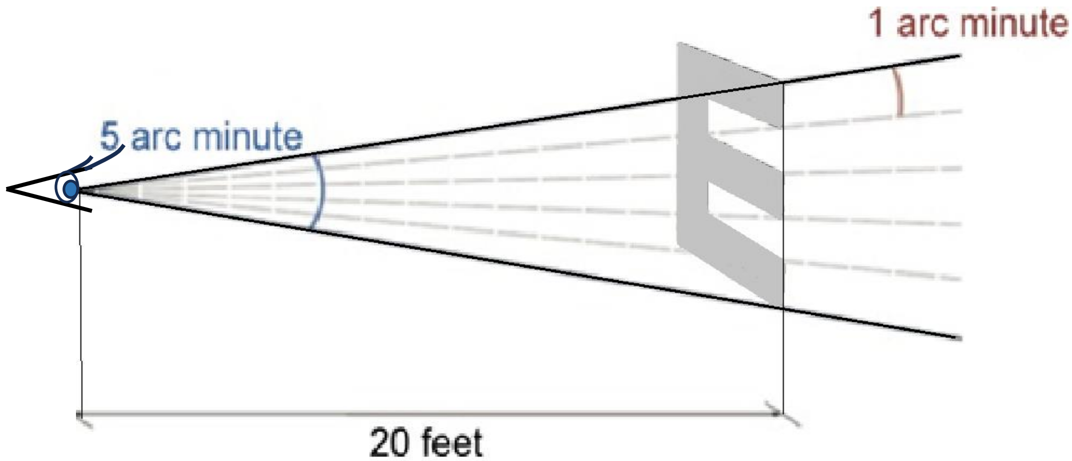

Fig. A.10. Standard observer is assigned a visual acuity of 20/20 or minimum angular resolution of 1′. [Adapted from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6292403]]

A Snellen fraction of 20/50 means that the subject can accurately identify at 20 feet what a standard observer can identify at 50 feet, or a Minimum Angular Resolution of 2.5′ (inverse of 20/50). That is, the letter has to subtend 2.5′ in order to be recognizable to this subject. Snellen ratio is also expressed using 6 meters distance (standard observer is 6/6) or as decimals. Thus, a letter in row 8 for 20/20 visual acuity spans 5′, with each letter thickness and space spanning 1′ . The big E at the top of the chart (20/200) is ten times this size. Chart letter sizes are scaled according to the testing distance.

Visual Angle Subtended by lighted X at 1.5 nautical miles

$$\tan\theta = \frac{3.67\text{ m width}}{2778\text{ m distance}};\ \theta = 0.076\,° \times \frac{60'}{1°} = 4.5\,'\text{ horizontal} \qquad \text{(A.12)}$$

The entire letter X is 4.5′ horizontal and vertical (see Table 1).

A.7 Related Literature on Letter Sign Size

Various factors affect sign recognizability. In this application, the sign is visible head on, perpendicular to the viewer, and is a familiar symbol to the pilot such that legibility and recognizability distance would expectedly be close. Recognition of the letter X requires that it meet the threshold legibility distance; in this case, it has been determined in the specification to be 1.5 nautical miles. The term Legibility Index *LI* is generally used to encompass the variety of distances and letter sizes and speeds at which the sign needs to be legible.

$$LI = \frac{threshold\ legibility\ distance\ \text{(ft)}}{letter\ height\ \text{(in)}} \qquad \text{(A.13)}$$

$$LI\ at\ Current\ Spec\ Size = \frac{threshold\ legibility\ distance\ (\text{ft})}{letter\ height\ (\text{in})} = \frac{9114\ \text{ft}}{119\ \text{in}} = 77 \qquad \text{(A.14)}$$

The Manual on Uniform Traffic Control Devices (MUTCD)[7] is the legal document that governs traffic control device design, placement, and use in the United States, and its guidance is used by all local county and state transportation departments as a minimum standard. According to this document, the letter height is determined using a LI of 30; this LI has been reduced from 50, established from about 50 years ago.[20]

Legibility Index: ratio of threshold legibility distance in ft to height of letter in inches (in). The current highway signage standard LI is 30.

$$Letter\ Height\ for\ LI\ of\ 30 = \frac{threshold\ legibility\ distance\ (\text{ft})}{LI} = \frac{9114\ \text{ft}}{30} = 304\ \text{in} \qquad \text{(A.15)}$$

The critical print size, defined as the smallest letter height necessary for maximum reading speed is typically believed to be between two to three times the size threshold [21]; the latter can be taken to be 20/20 visual acuity or a minimum angular resolution of 1′ per feature. The critical print size therefore that would allow maximum reading speed for the pilot, would be twice this minimum, corresponding to 20/40 or 2′ for each stroke feature or a total of 10′ for the letter.

Critical Print Size:
At visual acuity of 20/20, which is the threshold of the print size that one can read, the letter size subtends 5′ of visual angle. Critical print size needs to be at least two times this threshold, or an angular subtense of 10′. The letter size of the X would then need to be 319 in.

$$\theta = 10 \text{ x } \frac{1^\circ}{60} = 0.167^\circ \text{ horizontal} \qquad \text{(A.16)}$$

$$\tan(0.167) \times 2778\ \text{m} = 8.1\ \text{m}\ \ \text{(319 in)} \qquad \text{(A.17)}$$

Based on these recommendations, the current size specification of the lighted X of 14 ft diagonal arms of the X results in a letter height of 9.9 ft (119 in) is too small, which impedes in its recognizability at 1.5 nautical miles (2.78 km).

A.8 Spatial Contrast

Edges, which define shape or form is due to luminance change which may occur over large visual angles, as in Fig. A.11a, or over small angles (Fig. A.11b). The luminance contrast between the dark area and the light area may be high (Fig A.11c) or they may be low (Fig. A.11d). Our sensitivity to luminance contrast within the viewing field is called spatial contrast sensitivity.

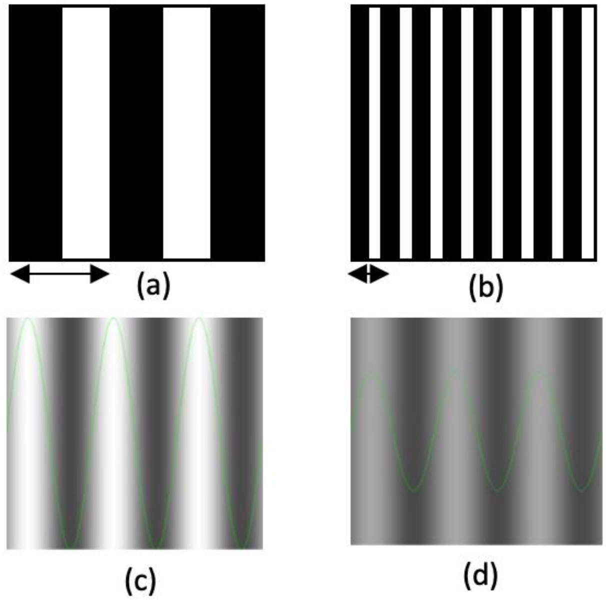

Fig. A. 11. One pair of black and white bands comprise one cycle. The number of cycles that fit in one degree visual angle is the spatial frequency in units of cycles per degree (/°).

Edge transitions in the real world may be sharp, such as those represented by square gratings (Fig A.11a, b) or gradual, such as those represented by the sinusoidal gratings (Fig. A.11c,d). The number of these dark/light band pairs that fit within one degree visual angle is the spatial frequency, expressed in units of cycles per degree (/°). One pair of black and white bands constitutes one cycle. Low spatial frequencies correspond to faint outlines of large or distant objects where the luminance contrast occur over a large visual angle, while high spatial frequencies correspond to fine details that delineate features and the contrast occur over small visual angles.

Physiologically, the bright bands stimulate the photoreceptors in the retina while the dark bands leave them unstimulated. Hence, at least two photoreceptors are involved in determining luminance transition. The upper limit to spatial frequency that we are sensitive to is 60 /°, mainly due to the size of the photoreceptors.

The spatial contrast sensitivity function of the human visual system has been determined to have a bandpass shape, as shown in the Campbell-Robson curve in Fig. A.12.[22] It is presented as a log scale of contrast sensitivity against the spatial frequency of the sine gratings. The luminance contrast changes, from high contrast at the bottom of the chart to low contrast at the top across various spatial frequencies mapped along the *x* axis. For a given spatial frequency range, the gratings gradually become invisible as the contrast decreases. Spatial contrast sensitivity changes with the luminance level and changes with age and vision health.

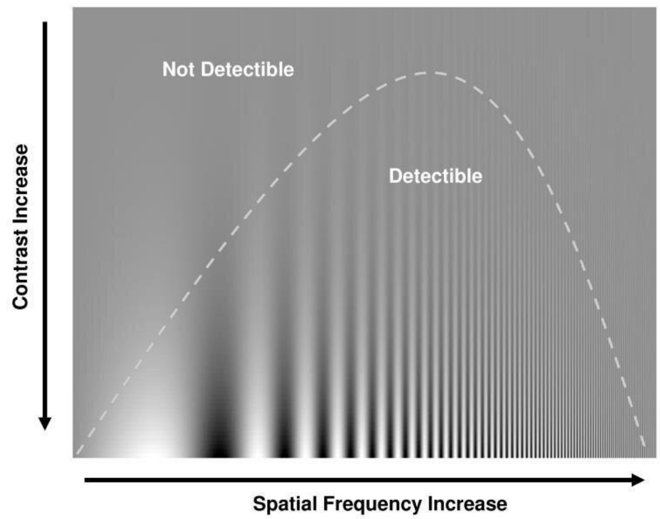

Fig. A.12. The sine gratings of the Campbell Robson spatial contrast sensitivity curve show one's zone of visibility. As you move your eye closer or farther, the zones of visibility will change as you change your visual angle. [Source:Wikimedia.org]

In spatial contrast sensitivity tests,[23] sinusoidal luminance gratings are used, since the sine wave gratings include shades of gray and better represents the real world. A range of spatial frequencies at varying luminance contrast is presented to the subject. The larger the difference between the highest and lowest luminance, the higher the contrast. The lowest contrast at which the subject can detect the grating at a particular spatial frequency is the contrast threshold for that spatial frequency. For instance, if the lowest contrast at which a subject can detect 10 /° is with 10 % luminance contrast, then that 10 % is the contrast threshold at 10 /°. The inverse of the contrast threshold is the contrast sensitivity; so the subject's contrast sensitivity for 10 /° is 1/0.1, or 10. Contrast sensitivity test results are presented as a curve with spatial frequency in the x-axis and contrast sensitivity in the y-axis.

Since testing with sine gratings takes a long time in the clinic, alternatives using letters at various contrast levels are used. The Pelli-Robson letter contrast sensitivity chart tests for low spatial frequencies, 0.5 /° to 2 /° using a single letter size with three letters in a group with the same contrast level. The group at the lowest contrast level that the subject can read is the contrast threshold for the subject. A test score is expressed as log contrast sensitivity, with 2 as the highest score for 100 % contrast sensitivity.[24]

Spatial contrast sensitivity tests have only come into clinical use in the last few decades compared to visual acuity tests which have been around for more than a century. It is used to evaluate quality of vision for general visual function since we experience luminance and spatial contrast at all times. Visual acuity tests only a subset of spatial contrast sensitivity, at approximately 18 to 30 /° and at high luminance contrast.

A.8.1 Effect of Luminance and Spatial Contrast on the Visibility of the Lighted X

There is a range of optimum letter size to stroke-width ratio for letters for signage with an optimum ratio range of 10:1 to 6:1.[25] Snellen letters are designed at 5:1 ratio. The smallest detail becomes the critical detail for recognition. For the letter X, the *edge transitions around the center are critical to its recognizability*. As shown in Fig A.11, the optimal spatial frequency varies with luminance level as well as contrast levels. The spacing of the luminaires and beam size of each luminaire will affect the spatial frequency as well as the luminance contrast level.

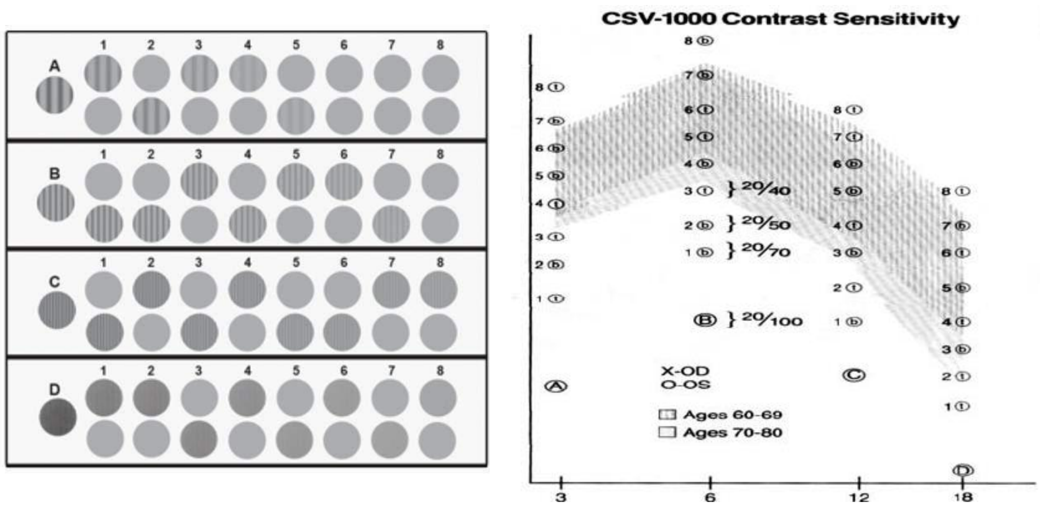

Fig. A. 13. Example of a contrast sensitivity chart used to test for 3, 6, 12 and 18 /° at a testing distance of 2.5 m and a test result. [Source:http://www.vectorvision.com/csv1000-contrast-sensitivity/]

Fig. A. 14. Pelli Robson contrast sensitivity chart using letters instead of sine wave gratings. [Source: Wikimedia.org]

A.8.2 Spatial Frequency

The luminaires provide the letter stroke width (thickness of the letter; in this case, light beam) and needs to cast a beam spanning 1′ of visual angle *at the retina*. Since the luminaire has an angular distribution, the luminosity away from the center needs to be high enough to stimulate the photoreceptors worth 1′.

Beam size *x* for 1′ visual angle (1°/60),

$$x = 2778 \cdot \tan\left(1 \times \frac{1°}{60}\right) = 0.81 \text{ m} \text{ or 2.65 ft beam diameter} \quad \text{(A.18)}$$

Using a spatial frequency value of 30 /° for recognizability (or 0.5 /′), the luminaires closest to the center of the X need a separation of 3′ to provide 1.5 cycles (2 lights and a dark between them).

$$s = \tan\ (3 \times \frac{1°}{60}) \cdot 2778 \text{ m} = 2.42 \text{ m (7.94 ft)} \quad \text{(A.19)}$$

The separation between the luminaires surrounding the center, given the 14 ft arms is 4.95 ft and each is 3.5 ft from the center luminaire. These are less than the separation distance required (7.94 ft) to have an edge transition between them.

$$S = (3.5^2 + 3.5^2)^{1/2} = 4.95 \text{ ft } (< 7.94 \text{ ft}) \quad \text{(A.20)}$$

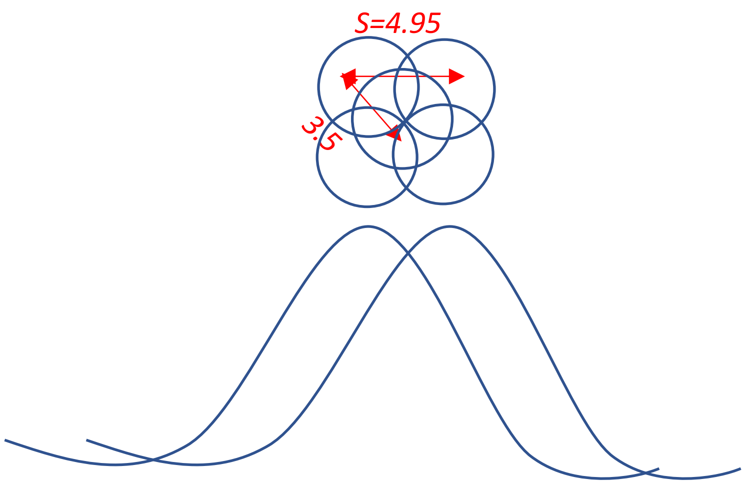

Fig. A.15. Illustration of light beams blending together at the center such that there is no light to dark transition to define the center of the X

A.9 Effect of Atmospheric Conditions on Contrast

Clouds, fog and particulates in the air affect visibility of objects. They attenuate the light from the object of interest as well as scatter the light thereby reducing the luminance contrast and blur the edges between the luminaires.

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