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Effectiveness of Linear Elements for Taxiway and Runway Delineation

June 2017

DOT/FAA/TC-TN17/38

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16. Abstract

Runway and taxiway edge lighting systems provide delineation using point sources of light. Centerline lighting systems also use points of light provided by airfield lighting fixtures. Published evidence from roadway delineation applications suggests that the continuous delineation provided by linear elements may be superior at presenting visual information for guidance than intermittent delineation provided by arrays of point sources. A series of studies were conducted to identify whether linear light source elements could provide benefits over conventional airfield lighting practices. The results identified relationships between linear element length, spacing, and visual acquisition times were developed. Such relationships can be useful in assessing whether, and to what extent, linear delineation elements provide similar (or improved) levels of visual performance compared to conventional delineation practices.

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LIST OF SYMBOLS AND ACRONYMS

p	Probability level (in statistical analyses)
r^2	Coefficient of determination (in correlation analysis)
AC	Advisory Circular
ANOVA	Analysis of variance
FAA	Federal Aviation Administration
KOSU	Ohio State University Airport
LED	Light-emitting diode
LRC	Lighting Research Center
PEGASAS	Partnership to Enhance General Aviation Safety, Accessibility and Sustainability
RPI	Rensselaer Polytechnic Institute
RT	Response time
RWY	Runway

EXECUTIVE SUMMARY

Runway and taxiway edge lighting systems provide delineation using point sources of light. Centerline lighting systems also uses points of light provided by airfield lighting fixtures. Published evidence from roadway delineation applications suggests that the continuous delineation provided by linear elements may be superior at presenting visual information for guidance than intermittent delineation provided by arrays of point sources.

Three studies were conducted to identify whether linear light source elements could provide benefits over conventional airfield lighting practices. The results identified relationships between linear element length, spacing, and visual acquisition times. The linear element fixture has not completed the Federal Aviation Administration approval process, and this technical note does not address the suitability of the fixture for its intended use in airport pavements. Overall, the results of the three studies consistently suggested that there can be visual benefits to using linear light sources in special applications, such as the high-speed exits tested in this study, or for runway status lights.

INTRODUCTION

PURPOSE.

Previous studies of linear delineation elements in roadway applications have suggested that these systems are beneficial to provide information to drivers about the geometric configuration of roadway facilities. These types of systems have not been widely investigated for aviation lighting applications.

This technical note summarizes the series of studies that were conducted to evaluate the potential benefits of linear runway, taxiway edge, and centerline delineation relative to conventional lighting practices that use discrete light fixtures to provide a point source appearance.

SCOPE.

This technical note consists of research from three studies.

1. Study 1—Laboratory: Initial laboratory experiments were conducted to ascertain whether, and how much, linear elements could provide superior visual information to observers in comparison to conventional runway and taxiway lighting configurations that use fixed images and simple animations. Also, a mathematical model was developed, relating visual identification times to factors such as the length and spacing of linear elements.

2. Study 2—Simulation: Simulations of linear delineation were performed in a flight simulator to present the linear sources in a more realistic, airport setting to validate results of the laboratory study.

3. Study 3—Field: Full-scale field installations were conducted to verify whether the model had utility for assessing the potential benefits of linear lighting.

A linear element fixture has not completed the Federal Aviation Administration (FAA) approval process. As such, this technical note cannot accurately address any conclusive cost results.

OBJECTIVE.

The objectives of the three studies were as follows:

1. Identify whether linear light source elements could provide benefits over conventional airfield lighting practices.

2. Confirm whether results from static, image-based studies would be consistent with those from more realistic conditions in simulator-based and real-world field installations.

BACKGROUND

Published research and observations by operational staff at airports suggest that more continuous delineation of airfield taxiways and runways could provide superior visual guidance over conventional lighting practices. This section briefly describes existing lighting practices and summarizes published research on delineation from both aviation and roadway contexts.

AIRFIELD LIGHTING PRACTICES.

Table 1 summarizes several typical spacing practices for runway and taxiway edge and centerline lighting [1]. The use of light fixtures to delineate the airfield can produce a sensation of a "sea of blue" where taxiways intersect with runways [2].

Table 1. Representative Edge and Centerline Practices for Airfield Lighting

Application	Condition	Minimum Spacing (ft)*
Runway edge lighting	General	200
Runway centerline lighting	General	50
Taxiway edge lighting	Short section	50
	Intermediate section	100
	Long section	200
Taxiway centerline lighting†	Very tight curved section	25
	Tight curved section	50
	Wide curved section	100
	Straight section	200

*Special situations (e.g., very complex geometries) may require shorter spacing.
†Spacing should be halved when airfield is used under low-visibility conditions.

Several research studies have been undertaken to identify proper geometric configurations (e.g., dimensions, length, spacing), or to assess the use of linear elements, for adequate visual guidance in an aviation lighting context. Evaluating lighting technology options for heliport lighting, Kimberlin et al. [3] discussed the potential use of light pipes to provide linear information that "may provide a clearer indication of location, glideslope, and outline than can be provided by the point source" and could also be more readily distinguished from background sources of light more likely to have a point-source appearance. More recently, Gallagher [4] investigated the potential for using light-emitting diode (LED) light source arrays in linear configurations to assist with delineation of airfield locations. Increased visual acquisition distances were found in operational field tests of such systems, but Gallagher [4] noted several potential shortcomings with the particular systems that were evaluated regarding their robustness for installation and the potential for suboptimally installed systems to provide a noncontinuous appearance. Parmalee [5] describes, in the context of pilot satisfaction, that linear elements can reinforce the orientation of a target, which can provide information that increases a pilot's confidence when approaching an airfield. Earlier studies [6 and 7]) of taxiway exit lighting design found that spacing centerline light fixtures more than 40 feet apart resulted in a noncontinuous appearance.

ROADWAY DELINEATION STUDIES.

Although aviation lighting differs from roadway marking and delineation in many important ways, both types of systems are meant to provide information to pilots or drivers regarding the geometric configurations of the road, taxiway, or runway ahead; the locations of potentially hazardous areas, such as sharp curves; and the locations of possible conflict points, such as intersections. Kao [8] postulated that because intermittent roadway markings and delineation (i.e., dashed markings) contained gaps regarding the location of roadway edges, such delineation was probably inferior to continuous markings, particularly under nighttime viewing conditions or during adverse weather. A few investigations of roadway delineation exhibit Kao's [8] hypothesis. Steyvers and De Waard [9] measured driving speeds along rural roadways with various edge and centerline configurations and found differences in average driving speeds between roads with continuous and dashed edge line markings (higher speeds with continuous markings), but these differences were only found during daytime driving. In comparison, Van Driel et al. [10] reviewed several studies of roadway edge line characteristics and found no reliable differences on vehicle speeds overall between roads with continuous and intermittent (dashed) edge lines. Zwahlen and Schnell [11] reported that visibility distances of centerlines consisting of continuous or dashed lines were longer for continuous lines.

The Oregon Department of Transportation evaluated two systems that provided linear forms of roadway delineation. One was a lighted guidance tube, consisting of light-guiding film around a tubular shape illuminated by halogen lamps at each end [12]. These systems were mounted atop concrete Jersey barriers along a roadway curve edge. Not only did drivers navigating the curve report that they felt the tube system was helpful and increased their comfort level, but driving speeds of vehicles entering the curve were sometimes reduced, attributed to the increased visual information, which increased drivers' awareness of the extent and sharpness of the curve. The second system evaluated was a retroreflective linear delineation system [13] mounted to the side edges of concrete barriers. This system reflected light from vehicle headlamps at night to form a linear pattern along the outer edge of the curve. Speeds for vehicles entering and exiting the curves were lower than without the linear system installed. These studies demonstrate the complexity of understanding the purpose and impacts of visual delineation along roadways because in some cases, more continuous delineation resulted in higher speeds, while in others it resulted in lower speeds.

It seems logical to assume that linear (in contrast to intermittent) delineation information could be beneficial in terms of providing more complete visual information to a pilot or driver. In the context of visual dot-matrix displays, it has been found that displays with higher amounts of white space between dot elements that comprise characters could reduce the legibility of symbols, and the effect was more pronounced at lower light levels and when the symbols had lower contrast [14 and 15]. Similarly, dot-matrix characters were more difficult to read when overprinted against other characters, compared to stroke-written symbols consisting of line segments rather than arrays of dots [16 and15].

To understand the possible impacts of linear delineation methods on visual acquisition times in an airfield lighting context, a series of laboratory human factors studies was conducted. These studies were conducted among several research organizations and are described accordingly in the following sections of this technical note.

Currently, pilots rely on various point-source light applications spread out at specified spacing on runways and taxiways to delineate the edge of taxiways and runways. Point sources also are used to create a centerline on runways and taxiways and, with added colors, identify special use surfaces such as high-speed turnoffs. The intent of using a series of lights is to create a line of points in the direction of the runway, taxiway, or high-speed turnoff. At airports having a complex system of taxiways, a pilot may become confused or disorientated. As noted above, the transportation industry has evaluated linear delineation applications as a way to enhance visual cues along roadways. Results from these evaluations suggested benefits to using continuous delineations versus intermittent cues.

STUDY 1—LABORATORY

STUDY 1: INTRODUCTION.

This section describes the experimental apparatus and procedures of the experimental investigations conducted at the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute (RPI).

STUDY 1: OBJECTIVES.

The objectives of these experiments were as follows:

- Identify whether linear light source elements could provide benefits over conventional airfield lighting practices.
- Provide a quantitative model for assessing the tradeoffs between linear element length and spacing in terms of visual acquisition times.

STUDY 1: METHODS.

EXPERIMENT 1. In each experiment, the primary display was a laptop computer screen, which served to display the experimental stimuli and record subjects' responses. Specifically, Experiment 1 was conducted to gauge the feasibility of using computer-generated images as the stimuli in the study.

Taxiway edge delineation was provided by simulating elevated light fixtures spaced 25, 50, 100, or 200 ft apart throughout all visible taxiways, or by using a continuous line to delineate all visible taxiway edges. Figure 1 shows examples of the visual stimulus conditions.

In Experiment 1, simulated views of taxiway intersections were developed having one of four geometric configurations, as shown in figure 1.

- Cross: A 90° intersection in which both intersecting taxiways continue beyond the intersection point
- Tee: A 90° intersection in which the taxiway from which the observer is viewing ends, with only perpendicular right and left turns possible at the intersection point

- Skew left: A tee-like intersection in which the taxiway from which the observer is viewing ends, with a 30° (nonsharp) left turn or a 150° (sharp) right turn possible at the intersection point (traveling at high speeds, only a left turn would be possible)

- Skew right: A tee-like intersection in which the taxiway from which the observer is viewing ends, with a 150° (sharp) left turn or a 30° (nonsharp) right turn possible at the intersection point (traveling at high speeds, only a right turn would be possible)

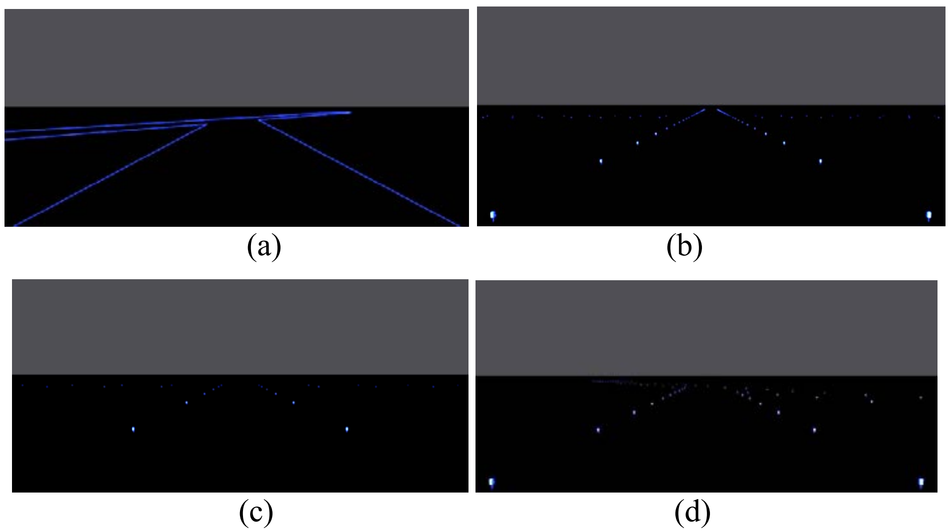


Figure 1. Visual Stimuli Used in Experiment 1: (a) Continuous Delineation on a Skew Right Intersection; (b) 50-ft Spacing on a Cross Intersection; (c) 100-ft Spacing on a Tee Intersection; and (d) 50-ft Spacing on a Skew Left Intersection

All images in Experiment 1 consisted of blue delineation elements (having a luminance of about 7 cd/m²) presented on a black background (luminance of 1 cd/m²). A horizon line was made visible in the images using a dark gray background above the apparent horizon. The view simulated the appearance observable 500 ft away from the intersection at a height of 15 ft. No other elements were visible in each scene.

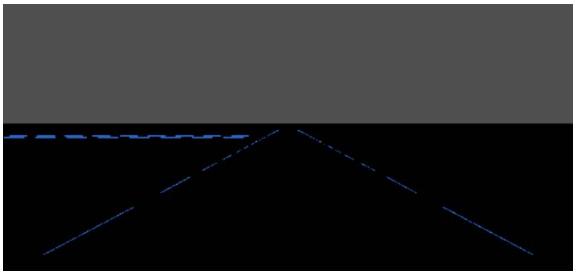
The experimental procedure was as follows: Eight subjects (4 male and 4 female, aged 24 to 66 years) entered the laboratory and, upon signing an informed consent form approved by the RPI Institutional Review Board (IRB), viewed in random order each of the 20 configurations (5 spacings: 0 [continuous], 25, 50, 100 and 200 ft, and 4 intersection types: cross, tee, skew left, skew right). The images were displayed using customized software (National Instruments LabVIEW™) that displayed each image for up to 10 seconds. Subjects were instructed to press any button on the computer keyboard once they could determine the type of intersection, and to do so as quickly as possible. As soon as they did, the image was removed from the display, and a legend linking each arrow key on the computer keyboard to an intersection type was displayed. Subjects had as much time as needed to press the appropriate arrow key signifying the type of intersection they saw. The time between displaying each image and the initial key press was recorded, as well as the response given for the type of intersection. In this way, response times and accuracy could be measured.

EXPERIMENT 2. In Experiment 2, the same basic methodology of Experiment 1 was used, but the delineation conditions were changed. The intersection types used in the images consisted of left or right turnoffs from a taxiway on which the observer would be traveling. The geometry of the turns could be either perpendicular (90°) or skewed at an angle of 30° to simulate a possible high-speed exit that could be navigated at higher speeds than a perpendicular intersection. Viewing distance and height remained the same as in Experiment 1. Linear elements (4 inches wide) were used in all stimuli in which the length of the elements and their spacing (from leading edge to leading edge, not the distance between adjacent edges of the delineator elements) were changed empirically as follows:

- Element length: 2, 8, or 32 ft
- Element spacing: 50, 100, or 200 ft

As in Experiment 1, no elements other than the delineation were visible in each image. Ten subjects (7 male and 3 female, aged 22 to 58 years) participated in Experiment 2. Figure 2 shows examples of the experimental stimuli used in this experiment.

(a)

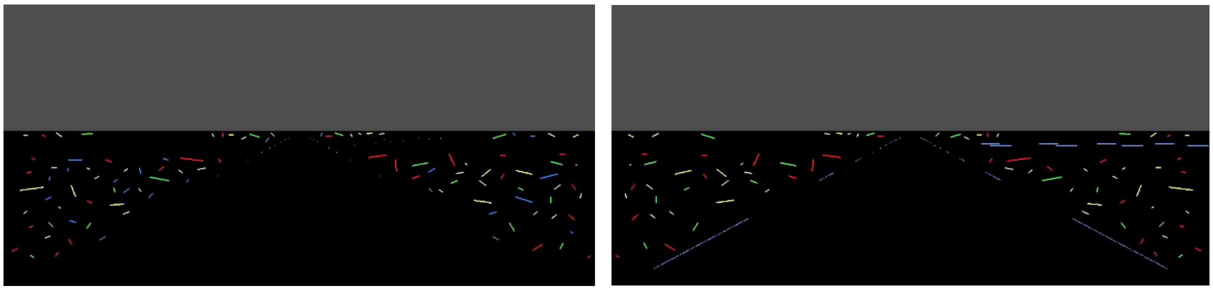


(b)

(c)

Figure 2. Visual Stimuli Used in Experiment 2: (a) 2-ft Elements Spaced 100 ft Apart on a Skew Left Intersection; (b) 32-ft Elements Spaced 50 ft Apart on a Perpendicular Left Intersection; and (c) 8-ft Elements Spaced 50 ft Apart on a Skew Right Intersection

EXPERIMENT 3. Experiment 3 used identical stimuli and procedures as Experiment 2, but all conditions were presented against a visual field of background noise produced by randomly oriented and colored line segments distributed along the nontaxiway areas of the scene. Ten subjects (6 male and 4 female, aged 22 to 56 years) participated in Experiment 3. Figure 3 illustrates examples of the visual stimuli used in this experiment.



(a) (b)

Figure 3. Visual Stimuli Used in Experiment 3: (a) 2-ft Elements Spaced 100 ft Apart on a Skew Right Intersection and (b) 32-ft Elements Spaced 50 ft Apart on a Perpendicular Right Intersection

EXPERIMENT 4. Each stimulus in Experiments 1 through 3 used only edge lines to provide delineation of the taxiway/geometries, and these were always blue in color. Also, the images were static, displaying a nonmoving scene. To assess the role of centerline linear characteristics (having locations and colors different than the elements displayed in Experiments 1 through 3) on visual perception, and to assess whether effects of element length and spacing differed under dynamic viewing conditions, Experiments 4 and 5 used animated simulations of the view while traversing down a runway toward an intersection with a taxiway, using colors representative of the lighting found on these facilities.

The created scenario consisted of a view along a runway, containing white edge lights (4 in. by 4 in., with a luminance of 120 cd/m²) spaced 200 ft apart on each side of the runway. Centerline lights along the runway were also 4 in. by 4 in. and spaced every 50 ft. The starting location for the animation was from a distance 2000 ft away from the taxiway intersection, with a viewing height of 10 ft and a simulated driving speed of 50 mph (73 ft/s). Within 500 ft of the intersection point between the runway and taxiway, the runway centerline lights changed to have a combination of the following length and spacing characteristics (remaining white in color, and having a width of 4 in.):

- Length: 2, 8, or 32 ft
- Spacing: 50, 100, or 200 ft

The taxiway centerline lights had the same width, length, and spacing characteristics as the runway centerline lights in a given scenario, but were green in color (luminance: 70 cd/m²). Taxiway edge lights were blue (luminance: 7 cd/m²), were 4 in. by 4 in. in size, and were spaced 100 ft apart. The background was black (luminance: 1 cd/m²). The taxiway could be located on either the left or right side of the runway and was angled at either a perpendicular (90°, representing a low-speed taxiway exit) or skew (30°, representing a high-speed taxiway exit) angle.

Similar to previous experiments, subjects (9 subjects: 6 male and 3 female, aged 24 to 52 years) were instructed to watch the animation on a laptop computer screen and were instructed to press a key on the laptop computer keyboard as soon as they could clearly identify the side and angular geometry of the taxiway intersections. The time taken to press the key was recorded. All conditions were presented in random order for each subject.

EXPERIMENT 5. Experiment 5 was conducted in an identical manner to Experiment 4, except a neutral density filter (transmission 25%) was placed over the computer screen. The result was to reduce the luminance of the background and colored elements in the scenes from those in Experiment 4 by a factor of four, to the following values:

- Black background: 0.25 cd/m²
- White runway edge and centerline lights: 30 cd/m²
- Green taxiway centerline lights: 18 cd/m²
- Blue taxiway edge lights: 1.8 cd/m²

The same subjects who participated in Experiment 4 also participated in Experiment 5.

EXPERIMENT 6. Following the laboratory studies a field experiment was conducted in a dark, enclosed building ("Watervliet Dome"), which formerly had been used as a skating rink and has a painted concrete floor. Eight-foot-long LED fixtures were constructed with blue and green LEDs in the bottom of a cut polyvinyl chloride (PVC) pipe and covered with a diffuser. The LEDs were wired so that the central 2 ft, the central 4 ft, or all 8 ft of the light source could be switched on. In this experiment, only the green LEDs were used. Configurations with either 2 or 8 ft length, and either 25 or 100 ft spacing between fixtures, were arranged in random order, either simulating centerlines for a left or right, perpendicular or skew intersection. Subjects sat in an adjacent room with a window open to the space and, after looking up from a laptop computer screen, were instructed to indicate the form of the simulated intersection as quickly as possible. Software on the laptop computers recorded and stored the response times.

STUDY 1: RESULTS.

EXPERIMENT 1. Figure 4 shows the response time results for Experiment 1 under each delineation condition, collapsed across all intersection types. A repeated measures analysis of variance (ANOVA) revealed a statistically significant ($p<0.05$) effect of the delineation spacing condition on response times. Assuming the continuous delineation condition corresponds to a spacing of 0 feet, the response times increase monotonically as a function of spacing.

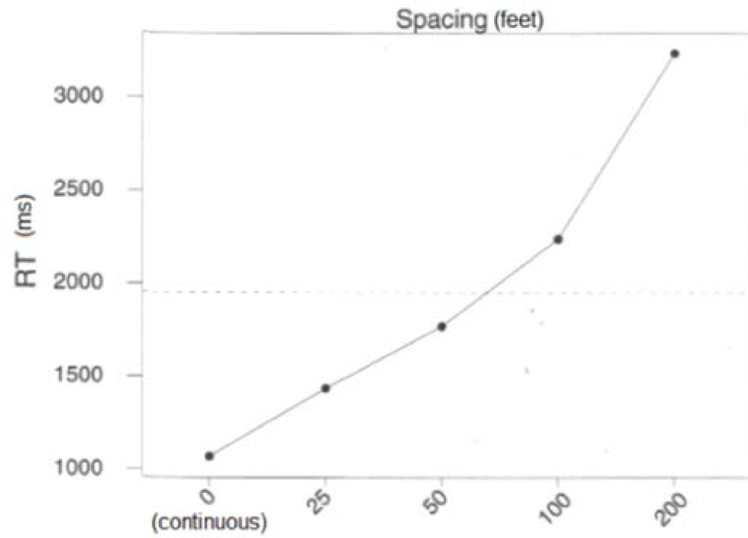


Figure 4. Mean Response Times for Delineation Spacing Conditions Tested in Experiment 1

There was also a statistically significant ($p<0.05$) effect of intersection type on response times, with the tee intersection eliciting substantially longer response times than the other three types (mean time 2492 ms for tee, 1825 ms for cross, 1804 ms for skew left, and 1699 ms for skew right). The tee intersections were most commonly confused with cross intersections.

The proportion of correct identification for each spacing condition is shown in figure 5. As in figure 4, the data show the best identification occurring for the continuous delineation and the worst for the longest spacing of 200 ft. A repeated measures ANOVA revealed a statistically significant ($p<0.05$) effect on identification accuracy, but differences among 25, 50, and 100 ft were negligible.

The results of Experiment 1 suggested that the image display technique used in the present study was a feasible way to compare different delineation conditions. They also suggested that under the conditions used in Experiment 1, there were advantages to spacing edge lights closer than 200 ft apart, but little advantage (under these conditions) to spacing them 25 or 50 ft apart relative to 100 ft. However, even with a spacing of 25 ft, the edge delineator lights did not perform as well as the continuous linear delineation.

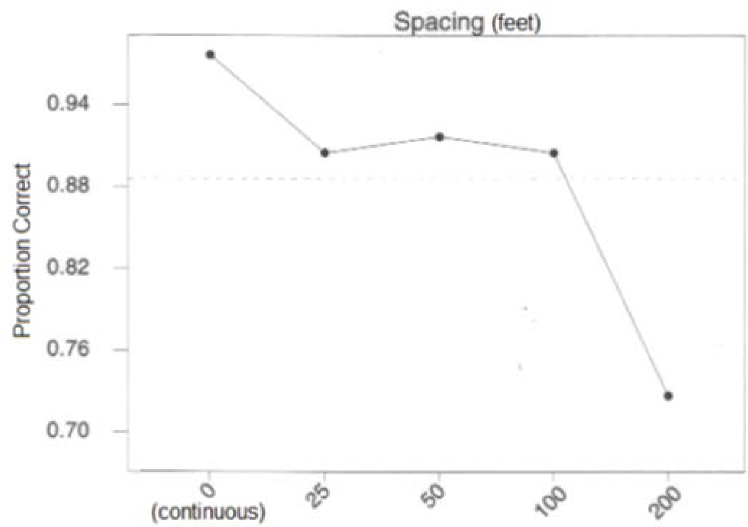


Figure 5. Proportion of Correct Responses for Delineation Spacing Conditions Tested in Experiment 1

EXPERIMENT 2. Since Experiment 1 used mainly discrete edge light delineation (except for completely continuous delineation), it was not clear if using delineation elements with distinct length rather than the discrete point sources of light would have any advantage. However, there were differences found in Experiment 1 between completely continuous delineation and discrete lights spaced 25 ft apart. The conditions used in Experiment 2 were selected to begin to understand how these factors interact in terms of response times and accuracy.

Figure 6 shows the mean response times plotted as a function of the delineation element length and the spacing of delineation elements.

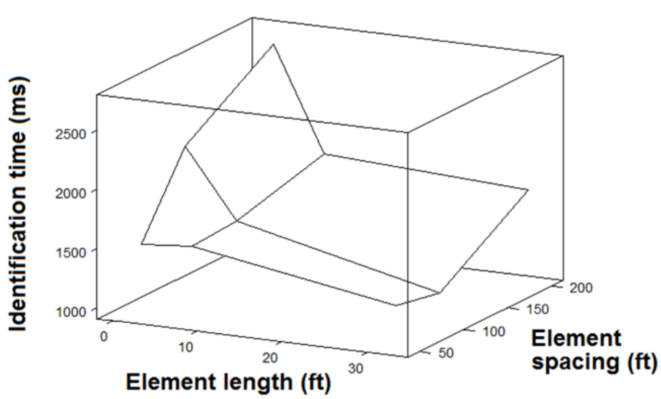


Figure 6. Mean Response Times as a Function of Linear Element Length and Spacing in Experiment 2

As expected, the longest response times occurred when the length was smallest (2 ft) and the spacing was greatest (200 ft), and the shortest response times occurred when the length was greatest (32 ft) and the spacing was smallest (50 ft). The response times (*RT*, in ms) could be predicted closely with a high goodness of fit (r^2=0.81) using a multiple linear regression model based on the logarithms of the length (L, in ft) and spacing (S, in ft):

$$RT = 286 - 607 \log L + 989 \log S \quad (1)$$

Figure 7 shows the agreement between the measured and predicted response times using equation 1.

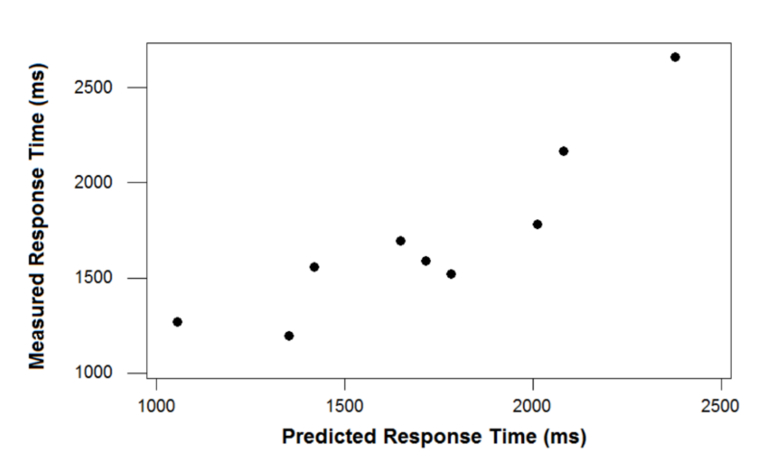


Figure 7. Correspondence Between Measured (Vertical Axis) and Predicted (Horizontal Axis) Response Times in Experiment 2

The response times also suggest an interaction between the length and spacing, although this interaction only approached but did not reach statistical significance (p<0.07). As an illustration, for the response times with a spacing of 50 ft, there was little difference among delineation element lengths; but larger differences were evident for longer spacings of 100 ft and 200 ft.

The proportion of correct identifications in Experiment 2 always exceeded 0.9, and no statistically significant effects of length nor spacing were found (p>0.05).

To facilitate comparisons between the results of Experiments 1 and 2, the conditions of 50-, 100-, and 200-ft spacing using discrete delineators were compared to the same spacing conditions using the delineator length of 2 ft. This is because the images from Experiment 2 using 2-ft delineator lengths looked very similar in appearance to those from Experiment 1 using discrete delineation elements. Figure 8 shows the correlation between the response times for these corresponding conditions. There was a strong (r^2=0.90) correlation, and on average, the corresponding response times differed by about 13%. A two-way ANOVA conducted on the data from Experiments 1 and 2 for their common spacing values of 50, 100, and 200 ft confirmed that the response times to the point source and 2-ft elements were not statistically significantly different (p>0.05). This correspondence suggests that the 2-ft-long delineator elements used in Experiment 2 may be effectively considered as point sources under the conditions underlying this study.

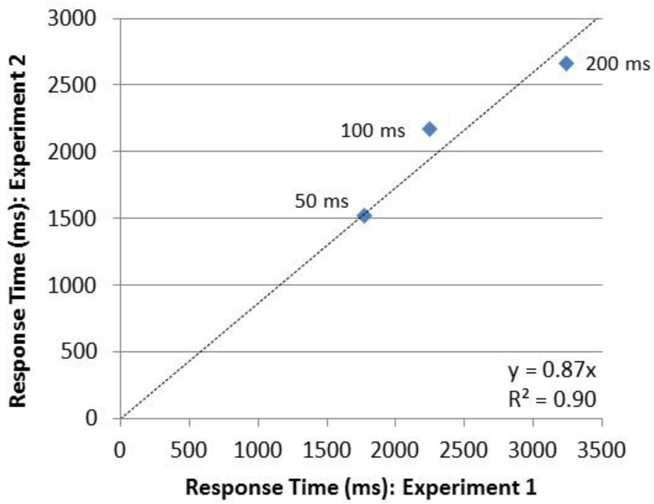


Figure 8. Comparison of Mean Response Times for 50-, 100-, and 200-ft Spacing of Discrete Delineator Elements in Experiment 1 to Mean Response Times for the Same Spacing for the 2-ft Elements in Experiment 2

EXPERIMENT 3. As described above, Experiment 2 was conducted using images of scenes that were uncluttered in appearance, with no competing visual elements that might produce visual noise. To assess whether and how the presence of visual noise might confound the relationships among identification, delineation element length, and delineation element spacing, the present experiment (Experiment 3) was conducted using a high level of visual noise as illustrated in figure 3.

Plotted in the same manner as in figure 6, the surface plot in figure 9 shows the mean response times plotted as a function of the delineation element length and the spacing of delineation elements. Visually, this figure is very similar to figure 6. The main difference between figure 6 and figure 9 is the scale of the vertical axes. The longest mean response time in Experiment 2 was 2663 ms (for the 2-ft length and 200-ft spacing conditions), whereas it was 5768 ms for the same condition in Experiment 3. A repeated measures ANOVA revealed statistically significant ($p<0.05$) effects of both spacing and length, and a statistically significant ($p<0.05$) interaction between these factors, on response times.

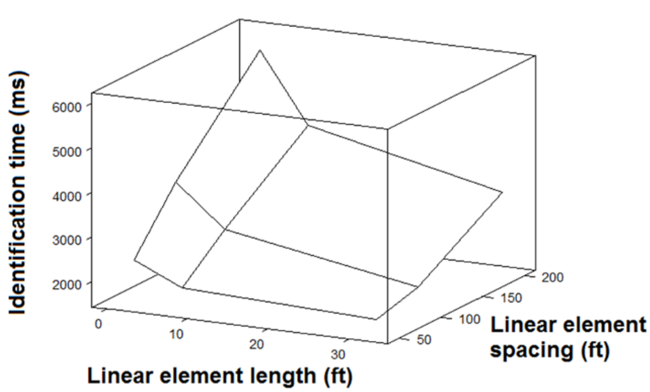


Figure 9. Mean Response Times as a Function of Linear Element Length and Spacing in Experiment 3

When the response times for the corresponding conditions were compared between Experiments 2 and 3 (figure 10), there was a strong correlation (r^2=0.86) between them. On average, the response times in Experiment 3 were about 1.8 times longer than for the corresponding conditions in Experiment 2. These results suggest that the presence of visual noise resulted in longer identification response times for delineation; but that the presence of visual noise, at least under the conditions in the present study, did not interact with either element length or spacing to influence response times.

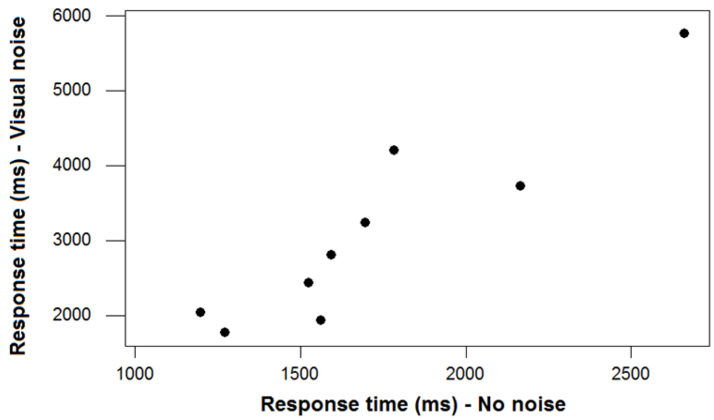


Figure 10. Correlation Between Mean Response Times in Experiment 2 (Without Visual Noise) and Experiment 3 (With Visual Noise)

The proportion of accurate identification averaged above 0.9 overall in Experiment 3. The proportion of correct identification decreased below 0.9 only for 2-ft elements spaced 100 ft or more apart and for 8-ft elements spaced 200 ft apart. Even for the worst condition (2-ft length, 200-ft spacing), the proportion of correct identification was 0.78.

EXPERIMENT 4. As described in the Methods section of this report, Experiment 4 differed from previous experiments in two significant ways.

- Stimuli were presented dynamically through animations simulating the appearance of runway and taxiway delineation while traveling along a runway.
- Different stimuli were presented along centerlines rather than edge lines, while edge line conditions remained constant (and consisted of discrete point-source elements) for all stimuli.

However, because the dimensions of the independent variables (delineation element length and delineation element spacing) remained the same, the results from Experiment 4 can be plotted in the same manner as in Experiments 2 and 3. Figure 11 shows the mean response times in Experiment 4 as a function of element length and spacing.

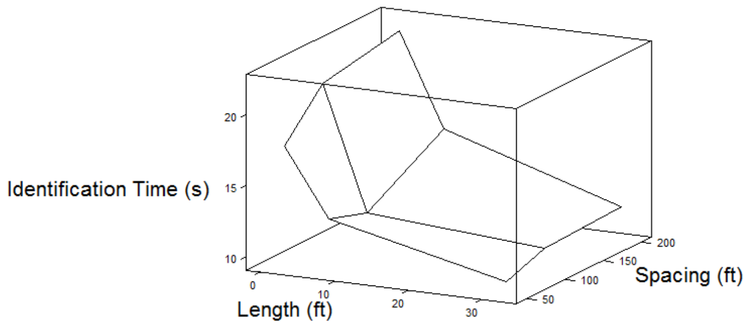


Figure 11. Mean Response Times as a Function of Linear Element Length and Spacing in Experiment 4

Again, the visual appearance of figure 11 is very similar to figure 6, but with very different values on the vertical axis. Note that the identification times in figure 11 are in seconds, whereas they are in milliseconds for earlier experiments. A repeated measures ANOVA revealed statistically significant ($p<0.05$) effects of length and spacing, as well as a statistically significant ($p<0.05$) interaction between length and spacing, on mean response times.

Figure 12 shows the correlation between the corresponding response times in Experiments 2 and 4. There is a reasonably high correlation ($r^2=0.73$) between the results from the two experiments, despite the large difference in the absolute magnitudes of the measured response times (response times in Experiment 4 averaged about 8.6 times longer than in Experiment 2). This finding suggests that the predictive model relating relative response times in equation 1 can be applied to the conditions underlying Experiment 4, even though this experiment used dynamic animations that were based on centerline delineation characteristics. Accuracy of identification was not measured in Experiment 4 so no analyses of this response are available.

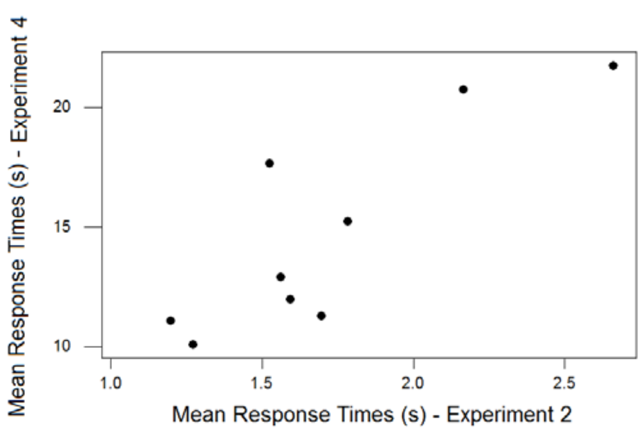


Figure 12. Correlation Between Mean Response Times in Experiments 2 and 4

EXPERIMENT 5. The conditions in Experiment 5 were identical to those in Experiment 4 except that the luminances of the animated displays were reduced by a factor of four. The mean response times in Experiment 5 are plotted in figure 13 as a function of delineation element length and spacing. The visual appearance of figure 13 is very similar to the graphs displaying the results of the previous experiments. In addition, the absolute values of the response times are similar to those of Experiment 4 (figure 11), despite the reduced luminances.

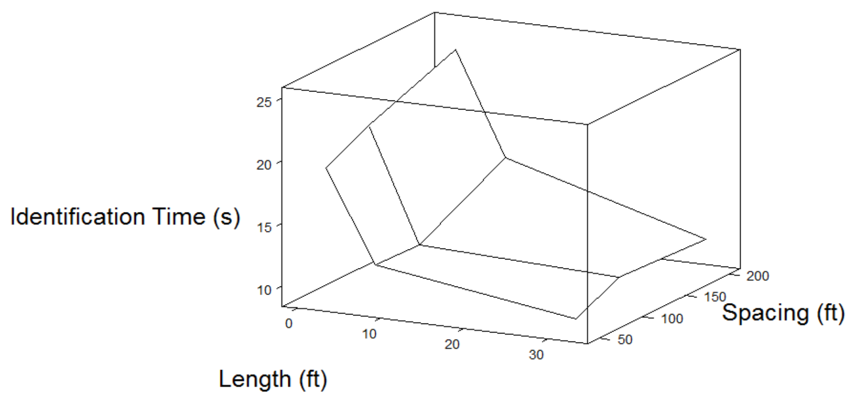


Figure 13. Mean Response Times as a Function of Linear Element Length and Spacing in Experiment 5

The correlation between the results of Experiments 5 and 2 for corresponding conditions of delineation element length and spacing is shown in figure 14, with a moderately high goodness of fit (r^2=0.69). Response times in Experiment 5 were about 8.8 times longer than in Experiment 2.

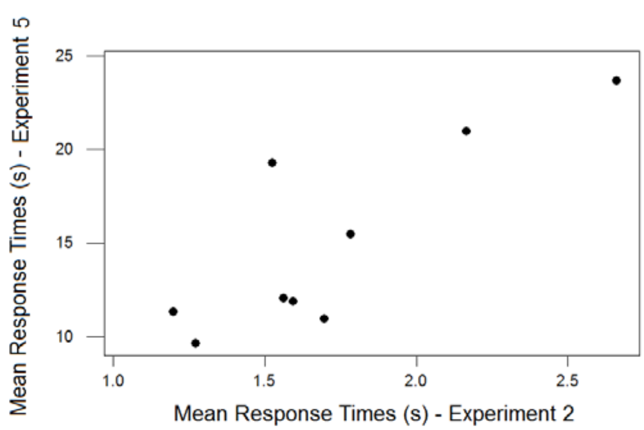


Figure 14. Correlation Between Mean Response Times in Experiments 2 and 5

The close correspondence in the response time results from Experiments 4 and 5 suggest that the contrast between the luminance of the delineation elements and the background (pavement) influences their effectiveness, since the contrast of the elements in each of these experiments was the same.

EXPERIMENT 6. Figure 15 shows the mean response times from Experiment 6 plotted in a similar manner as the data from previous experiments. There was a statistically significant

(p<0.05) effect of spacing and a marginally significant (p=0.08) effect of length on response times, according to a repeated measures ANOVA. For the combinations of length and spacing common to Experiments 2 and 6, there was a moderately high (r^2=0.73) correlation between the mean response times in each experiment.

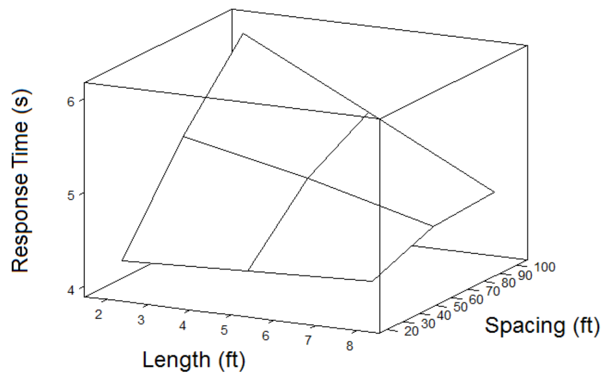


Figure 15. Mean Response Times as a Function of Length and Spacing in Experiment 6

STUDY 1: DISCUSSION.

TRADEOFFS BETWEEN LENGTH AND SPACING. The results of all the experiments described in the Results section are consistent in that they suggest there are tradeoffs between the length and spacing of delineation elements, whether they are used for centerline or edge line delineation. The specific response times depend upon the specific nature of the visual task, the presence of visual noise, and whether the observer is moving or stationary. However, in each case, the relative visual acquisition times appear to be correlated with quantities derived from equation 1. This suggests that equation 1 can be used to assess the relative effectiveness of various combinations of delineation length and spacing compared to point-source delineation, assuming that the 2-ft length elements in Experiments 2 through 5 provided similar visual information as the point-source array elements in Experiment 1, an assumption that is bolstered by the correlation in figure 8.

As an example, Base Case 1 in table 2 shows the predicted response time from equation 1 for a combination of 2-ft (i.e., essentially point-source) element lengths and 50-ft spacing. Assuming desired spacing values of 100, 150, or 200 ft, the minimum element length that gives the same relative response time is shown in table 2. Base Case 2 in table 2 also shows the same comparisons for 2-ft (i.e., essentially point-source) element lengths spaced 100 ft apart. The minimum element lengths needed to produce the same relative response times are listed for spacing values of 150 and 200 ft.

Table 2. Combinations of Delineation Element Length and Spacing to Achieve the Same Relative Response Times Expected From 2-ft-Long Delineation Elements Spaced at 50 and 100 ft

Base Case 1	Element length (ft)	2	6.2	12.0	19.2
	Element spacing (ft)	50	100	150	200
	Relative response time (ms)	1784	1784	1784	1784
Base Case 2	Element length (ft)		2	3.9	6.2
	Element spacing (ft)		100	150	200
	Relative response time (ms)		2081	2081	2081

Thus, under the conditions of the present laboratory experiments, comparisons such as those in table 2 can be used to identify combinations of delineation element length and spacing that would be expected to be equally visually effective as conventional centerline or edge line delineation using discrete point sources of light.

PHOTOMETRIC CONSIDERATIONS. The visual delineation elements investigated in the present study were produced on a computer screen display; and the luminances of variously colored elements were not specifically selected or controlled, except to produce suprathreshold visibility on the display. In Experiments 4 and 5, the luminances of the green taxiway centerline elements were about 70 cd/m^2 and 18 cd/m^2, respectively, viewed against background luminances of 1 cd/m^2 and 0.25 cd/m^2, respectively. Based on the response times in each of these studies, table 3 lists the projected areas (adjusted by the cosine of the viewing angle) and the resulting simulated luminous intensities of the elements toward the direction of the observers in the experiments for the mean distances at which the intersection type was identified. Note that dimensions for identification distances and projected areas in table 3 have been converted to meters to facilitate conversion between luminance and luminous intensity.

Table 3. Identified Luminances, Dimensions, Projected Areas, and Luminous Intensities for the Delineation Elements in Experiments 4 and 5

Luminance (cd/m²)	Length (ft)	Spacing (ft)	Identification Distance (m)	Projected Area (m²)	Luminous Intensity (cd)
18	2	50	178	0.0011	0.02
		100	141	0.0013	0.02
		200	80	0.0023	0.04
	8	50	340	0.0022	0.04
		100	344	0.0022	0.04
		200	263	0.0029	0.05
	32	50	393	0.0077	0.14
		100	356	0.0085	0.15
		200	364	0.0083	0.15
70	2	50	215	0.0009	0.06
		100	145	0.0013	0.09
		200	123	0.0015	0.11
	8	50	321	0.0024	0.16
		100	341	0.0022	0.15
		200	269	0.0028	0.20
	32	50	384	0.0079	0.55
		100	361	0.0084	0.59
		200	357	0.0085	0.59

All luminous intensity values for the elements in these experiments were less than 1 cd. The luminous intensity requirements for green in-pavement taxiway centerline lights [17] require minimum luminous intensities of 20 cd. It is not clear that specifying the photometric performance of linear delineation elements is meaningful, since presumably a large amount of visual information conveyed by these elements is related to the geometry and layout in which they are used. For green centerline elements, luminances of 70 cd/m² against a pavement luminance of 1 cd/m², or 18 cd/m² against a pavement luminance of 0.25 cd/m², appeared to be more than sufficient to convey visual information based on the results from Experiment 5. In earlier experiments, blue delineation elements were used to provide visual guidance in the form of edge lines; the luminances of these elements were even lower (7 cd/m², viewed against a pavement luminance of 1 cd/m²) than the green centerline delineators.

Roadway pavement markings used to provide visual guidance in roadway driving situations use retroreflectivity from vehicle headlights to provide luminance in the general direction of the driver of the vehicle. Typical pavement marking luminances at the threshold distance of visibility (typically about 100 to 150 m away) approach 1 cd/m² [18 and 19], although luminances can often exceed 10 cd/m² at shorter distances. Many visual identification distances listed in table 3 are substantially longer than 150 m. Under such conditions, where the apparent size and visual angle of delineation elements are smaller than at 150 m, luminances somewhat higher than 1 cd/m² may be needed to ensure visual acquisition. As a preliminary estimate that would require substantial field validation, minimum delineation luminances of 7 cd/m² could yield adequate visual guidance under the conditions corresponding to those simulated in the present study.

The 2-ft elements in Experiment 2 performed similarly to the conventional point-source lights in Experiment 1 for the same spacing values. Therefore, another approach that could be taken in the specification of photometric requirements would be to require the luminous intensity of each linear element to be equal to the luminous intensity required for the corresponding point-source element specified by FAA for the intended application (e.g., taxiway edge lights, runway centerline lights, etc.). Thus, for example, a 16-ft in-pavement linear light element used as a taxiway edge light (in place of L-852T) would require a luminous intensity equal to that required by FAA for a single point-source light (e.g., 2 cd). If a 2-ft section of the linear light element were measured according to the same procedure for in-pavement taxiway edge lights outlined in FAA Advisory Circular (AC) 150/5345-46D [17], "Specification for Runway and Taxiway Light Fixtures," the 2-ft section would require a luminous intensity of 0.25 cd. At a typical viewing distance of 300 ft, the luminance of a 2-ft section of the linear light element needed to produce a luminous intensity of 0.25 cd is 49 cd/m², more than the minimum of 7 cd/m² recommended above to ensure sufficient visibility. Further, since the luminous intensity of the linear light element (and the illuminance it would produce at the eyes of a pilot) would not need to exceed that of the point sources presently used for such applications, the linear light element would produce no more disability glare than that produced by a point source light.

<u>CAVEATS AND RECOMMENDATIONS FOR FUTURE STUDY</u>. The present study used a limited range of background luminances (primarily, 1 cd/m² with limited use of 0.25 cd/m² as pavement luminances). In addition, the linear delineation elements used in the simulations for the present study were uniform in appearance. In comparison, the appearance of linear elements consisting of arrays of LED point sources, such as those evaluated by Gallagher [4], could be highly nonuniform—not only because of the optical systems used to distribute light, but also because of installation factors and inadvertent bending or warping of systems during or after installation.

Field studies to measure pilot visibility and satisfaction with various linear delineation elements should be conducted to confirm whether the relationships between linear element length and spacing identified in the present experiments would hold under real-world conditions. In addition, measurements of runway and taxiway pavement luminance should be made to determine whether the contrast between the average luminance of pavement on an airfield and a linear element is related to its visual effectiveness.

Additionally, because it is likely that a linear light element would be composed of several individual light sources, if any individual light sources within a linear element fail, the entire element's luminous intensity would be reduced, but not to zero. The partial indication would likely be an improvement over a completely burned-out point-source light, however. As a preliminary recommendation, a requirement like that from FAA Engineering Brief 67D, "Light Sources Other Than Incandescent and Xenon for Airport and Obstruction Lighting Fixtures," [20] could be adapted so that if more than 25% of the light sources within a single element fixture fail, the entire element would be switched off.

STUDY 1: SUMMARY.

Despite the inherent limitations of the present set of studies, which used static and dynamic simulations presented on a computer screen to represent the various delineation conditions that were investigated, the results presented here were robust and consistent in demonstrating relationships between the length and spacing of linear delineation elements. The results suggest that, when properly defined, linear elements can provide shorter visual acquisition times than conventional point-source based delineation, or the spacing of linear elements could be increased relative to point-source spacing while maintaining visual effectiveness.

STUDY 2—SIMULATION

STUDY 2: INTRODUCTION.

This study summarizes the evaluation of various linear light source configurations for use on taxiway and runway surfaces. The evaluation was conducted by the FAA Airport Safety Research and Development Section from February to June 2015 at the FAA William J. Hughes Technical Center Cockpit Simulation Facility.

STUDY 2: OBJECTIVES.

The objectives of this research effort included the following:

- Evaluate pilot’s reaction and satisfaction to various configurations using an Airbus A320 simulator.
- Summarize collected data to identify optimal lighting configurations that are effective and satisfactory to pilots.
- Validate the relationship between linear source length and spacing developed in Study 1.

STUDY 2: PURPOSE.

The purpose of this evaluation was to conduct simulator evaluations on various linear lighting configurations. This was to be achieved by creating configurations for evaluating both current and revised taxiway light spacing. Since the ultimate goal was to develop application-independent, operational criteria for linear sources, for this study, the application chosen that seemed to lend itself to the uniqueness of a linear source was a high-speed exit. A high-speed exit consists of alternating green and yellow sources along the centerline, indicating the direction of the exit. Currently, alternating green and yellow point-source lights are installed on runways to provide pilots a visual aid to taxiway turnoffs. The alternating green and yellow lead-off lights were installed from the runway centerline beginning with a green light, as depicted in figure 16 [1]. Furthermore, linear lighting configurations were created using standards of current airfield lighting spacing, as referenced in AC 150/5340-30G [1] and shown in table 1.

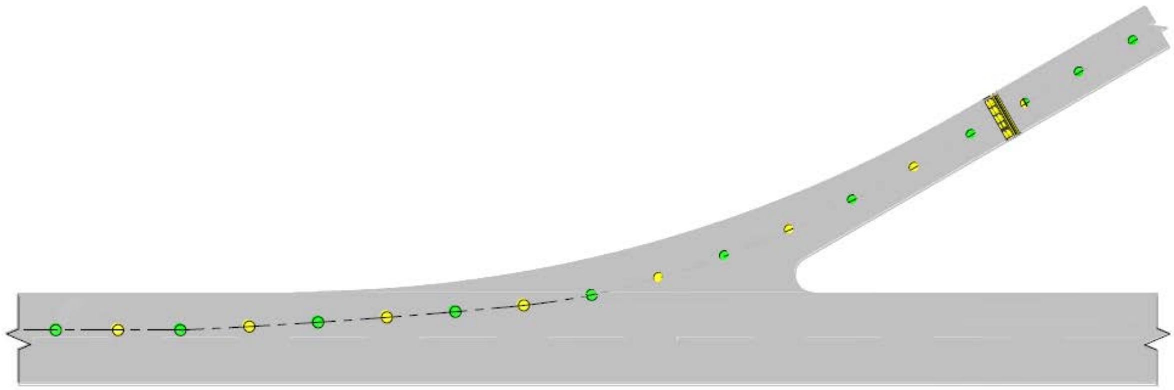


Figure 16. Taxiway Turnoff Diagram

STUDY 2: EVALUATION APPROACH.

The evaluation approach focused on the feedback generated by linear lighting configurations in simulated clear visible nighttime conditions at Chicago O'Hare International Airport (ORD). Subject pilots viewed various configurations in an Airbus A320 cockpit simulator. While taxiing, the aircraft subject pilots were asked to verbally call out configuration setups and provide numerical assessments.

STUDY 2: METHODS.

At the beginning of each run, the researcher announced the script number, which was a unique number to identify each configuration. Each configuration was included in more than one script to prevent memorization. Announcing the script number ensured that the simulator operator cued the correct lighting configuration. A verbal cue was then given for the subject pilot to begin taxiing the aircraft between 20-30 knots. At this point, subject pilots were instructed to scan the runway and taxiway for the lighting configuration. Once the subject pilot identified the lighting configuration, the button on the side stick (figure 17) was pressed to mark this location. The distance of this location to the linear configuration was calculated and stored. Immediately after, the subject pilot reported the configuration setup (e.g., left or right, 30 or 90 degrees), level of difficulty (reporting scale 1-5), and comments assessing the configuration. Lastly, the subject pilot maneuvered the aircraft onto the taxiway following the direction of the lighting configuration.

Figure 17. Side Stick (Distance Measure Button)

STUDY 2: SUBJECT PILOTS.

The evaluation subject pilots consisted of 37 women and men, ranging in age from 21-72 years. Experience level ranged from private pilot certificate holders to Airline Transport Pilot certificate holders. The subjects consisted of current and former military pilots, current and former airline and cargo pilots, and flight instructors. Prior to each evaluation session, subject pilots received a briefing that provided basic information on the background of the research effort and protocol during the evaluation. Following the briefing, each subject pilot was administered a Snellen eye vision test and Ishihara test to test vision acuity and color deficiency. The Snellen and Ishihara eye charts are shown in figures 18 and 19, respectively.

The Snellen eye test was administered to provide a baseline recording on each subject pilot's visual acuity. To complete the test, per test directions, each subject pilot was asked to wear their corrective eyeglasses (if they wore them) and stand approximately 20 feet from the chart. The subject pilots were instructed to cover one eye and begin reading line #8 (20/20). If the subject pilots were unable to read this line, they were instructed to move to the above line until they were able to read each letter of the corresponding line. The same steps were completed covering the opposite eye. The baseline results revealed 29 acuity scores of 20/20, 7 of 20/25, and 1 of 20/30.

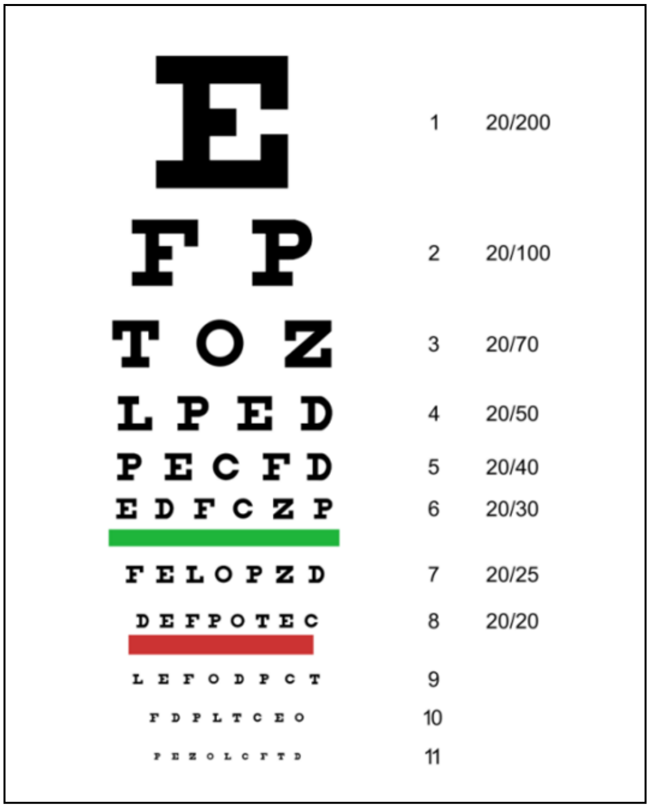


Figure 18. Snellen Chart

The Ishihara Test for Color Deficiency was designed to identify individuals with red-green deficiencies and total color blindness. The purpose of this test was to identify possible outliers in data results of subject pilots with color deficiencies. As directed in the test instructions, subject pilots were instructed to stand approximately 2-1/2 feet in front of the chart and call out the number on a series of cards, as shown in figure 19. Test results were recorded in the Color Vision box of the evaluation sheet. Results revealed only one subject pilot with complete color blindness.

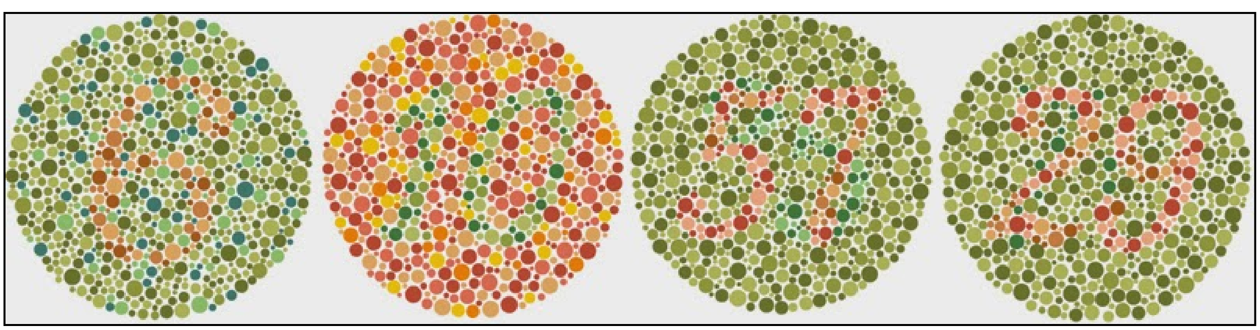


Figure 19. Ishihara Test Cards

STUDY 2: DATA COLLECTION.

The data for this evaluation were compiled from 37 subject pilots. Each subject pilot evaluated 27 of the possible 72 linear lighting configurations. The linear lighting configurations were randomly selected for each subject pilot. However, there was a pre-established list of configurations for each subject pilot. Data were collected in the following three categories:

- Distance
- Correctness of stated configuration
- Assessment value

The distance was a measurement from the point the subject pilot triggered the button signifying positive identification of linear lighting configurations. Subject pilots were asked to state the configuration for recording. Subject pilots were evaluated on the correctness of this response based on configuration. Following the stated configuration, the subject pilots were asked to assess the level of difficulty in identifying the configuration on a scale of 1 to 5, as defined in table 4.

Table 4. Linear Lighting Configuration Rating and Assessment

Difficulty Rating (1 Highest Ranking—5 Lowest)	Assessment
1	Very Easy
2	Somewhat Easy
3	Neither Easy/Difficult"
4	Somewhat Difficult
5	Very Difficult

STUDY 2: RESULTS.

The results of this evaluation were composed of subject pilot responses in the three previously referenced categories of distance, correctness of stated configuration, and assessment value. In total, 72 lighting configurations were evaluated. The combination of possible configurations included 2-, 8-, and 32-ft line length segments, and each of those line segments was evaluated with 50-, 100-, and 200-ft spacing. The results will be discussed accordingly in the following sections. It is worth noting that not all configurations in each category were evaluated in the same intersection. Additionally, different numbers of subject pilots evaluated each configuration.

THE 2-FT LINE LENGTH SEGMENTS (50-FT SPACING). The possible combinations for linear lighting configurations with 2-ft line length segments and 50-ft spacing are shown below in table 5. Results showed that subject pilots could not identify a right 90-degree configuration until a distance of 285 ft, while subject pilots identified a right 30-degree turn at the greatest distance of 1181 ft.

Table 5. The 2-ft Line Segment With 50-ft Spacing Configurations

Script Number	Configuration Turn/Angle	Line Length (ft)	Line Spacing (ft)	Average Distance (ft)	Difficulty	Correct Responses
264	Right/90	2	50	285	3	12 of 13
237	Right/30	2	50	439	2	13 of 13
219	Left/90	2	50	511	2	10 of 15
228	Left/90	2	50	575	3	12 of 14
255	Right/90	2	50	662	3	9 of 13
210	Left/30	2	50	770	3	11 of 14
201	Left/30	2	50	909	2	12 of 15
246	Right/30	2	50	1181	2	10 of 13
Average	-	-	-	666	3	-

The configuration in Script 264 (the right 90-degree turn shown in figure 20) was the most difficult for subject pilots to identify, as it was identified only 285 feet away from the intersection. Of the 13 subject pilots, 1 passed the configuration without identification. Subject pilots assessed the configuration as being "Neither Easy/Difficult," and the following were some noteworthy comments:

- "Lights are too small."
- "Can see configuration off centerline, but can't identify angle."
- "Like multiple lights."

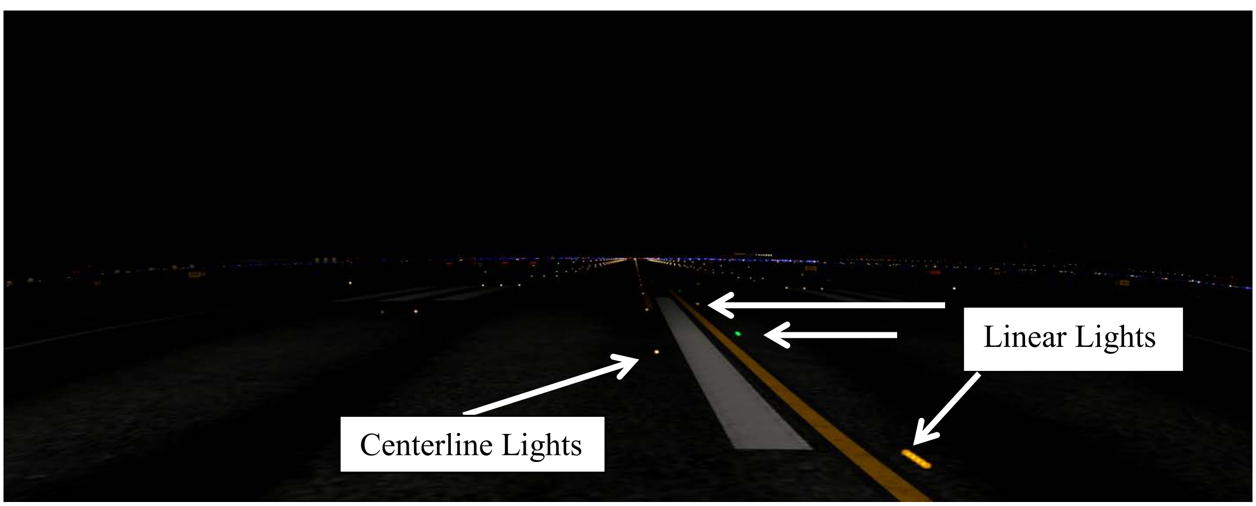


Figure 20. Script 264 Right 90-Degree Turn

The configuration in Script 246(a right 30-degree turn shown in figure 21) was the easiest identifiable, as it was identified at the greatest distance of 1181 ft. Of the 13 responses, 10 were correct. Subject pilots assessed this configuration as being "Somewhat Easy" to identify, and comments provided by the subject pilots included:

- "Configuration was 'somewhat easy' to identify due to the high frequency in lights."
- "Liked that the configuration came from the centerline off."
- "Angle took longer to identify."

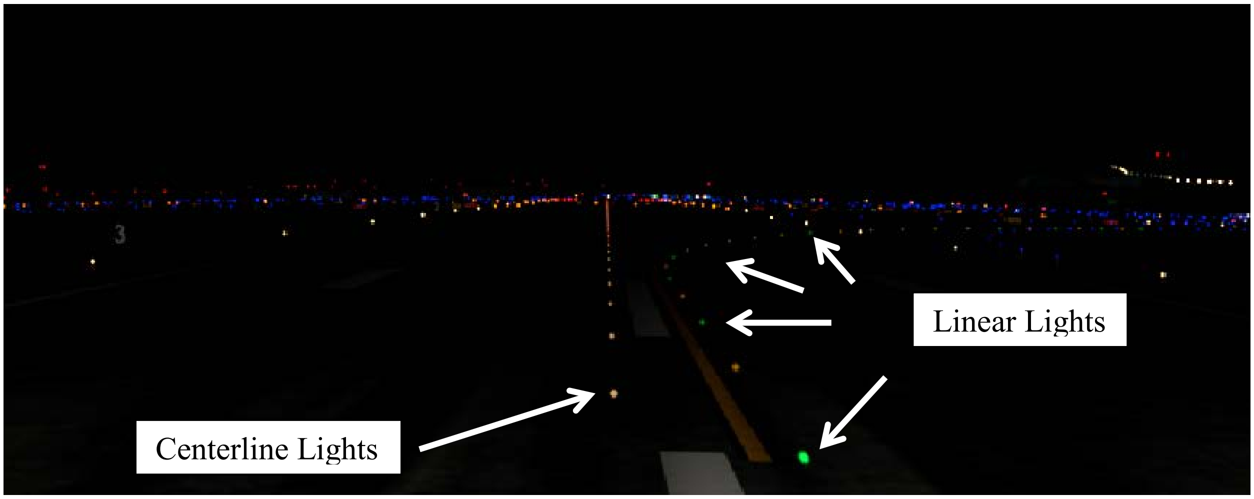


Figure 21. Script 246 Right 30-Degree Turn

Shown in figure 22 are the 8 linear configurations with 2-ft line length segments with 50-ft spacing and their average identifiable distances. Results showed subject pilots identified 30-degree configurations at greater distances, on average 825 ft, while 90-degree turns were identified at shorter distances of only 508 ft.

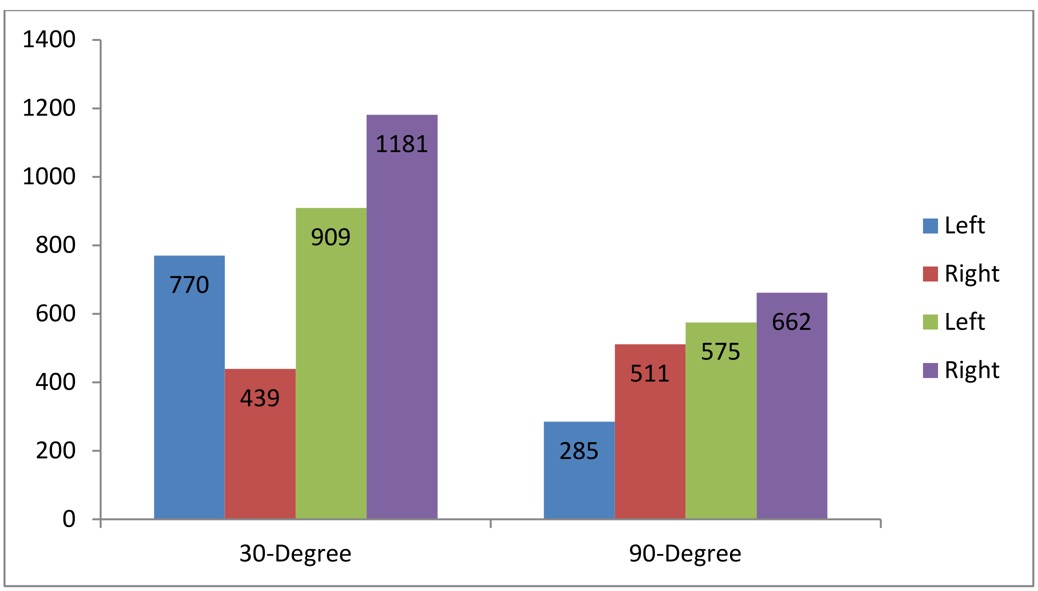


Figure 22. Average Identifiable Distances (Feet) for 2-ft Line Segment With 50-ft Spacing Configurations

<u>THE 2-FT LINE LENGTH SEGMENTS (100-FT SPACING)</u>. Shown in table 6 are all the combinations for the 2-ft line length segment with 100-ft spacing. Results showed subject pilots

required being closer to the intersection at 132 ft to acquire a left 90-degree turn, while they were able to identify a right 30-degree turn at a greater distance of 1053 ft.

Table 6. The 2-ft Line Segment With 100-ft Spacing Configurations

Script Number	Configuration Turn/Angle	Line Length (ft)	Line Spacing (ft)	Average Distance (ft)	Difficulty	Correct Responses
229	Left/90	2	100	132	5	6 of 15
238	Right/30	2	100	279	4	6 of 10
265	Right/90	2	100	297	4	9 of12
211	Left/30	2	100	338	4	10 of 15
256	Right/90	2	100	428	4	12 of 15
220	Left/90	2	100	556	3	9 of 13
202	Left/30	2	100	681	3	9 of 13
247	Right/30	2	100	1053	2	10 of 13
Average	-	-	-	472	4	-

The left 90-degree configuration shown in figure 23 required the longest time to acquire, as it was not identifiable until 132 ft away. It is also worth noting that 9 out of 15 subject pilots passed this configuration without identification. Consequently, subject pilots rated this configuration as being "Very Difficult" to identify. Notable comments from subject pilots are listed below.

- "Brightness is fine but lights too far apart."
- "Too close to centerline lights."
- "Nonexistent."

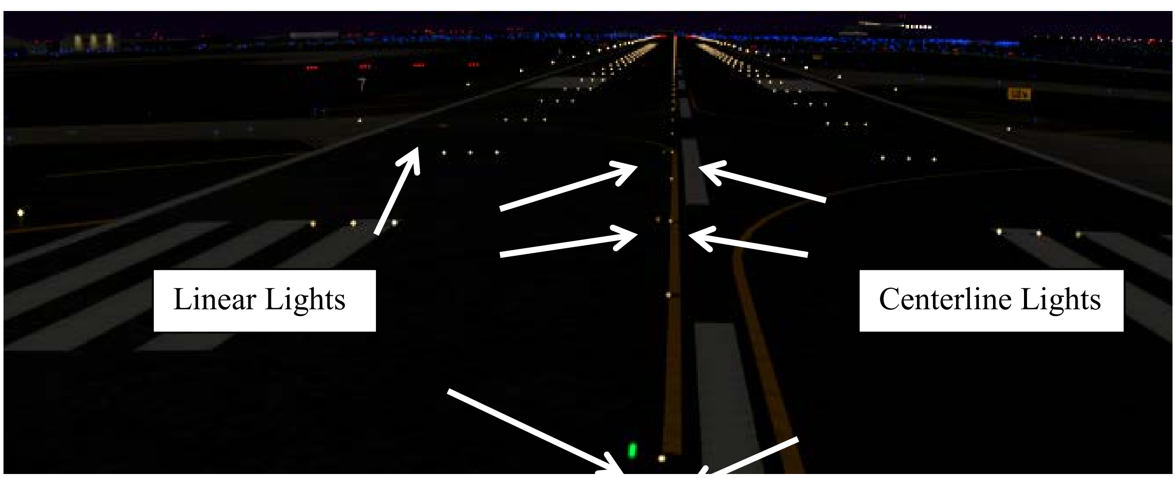


Figure 23. Script 229 Left 90-Degree Turn

The right 30-degree turn shown in figure 24 was identifiable from the greatest distance. Subject pilots identified this configuration 1053 ft away and assessed this configuration as being

"Somewhat Easy" to identify. Of the 13 responses, 2 subject pilots called out the wrong configuration, and 1 passed the configuration. Notable comments included:

- "Liked the spacing."
- "Lights looked brighter."

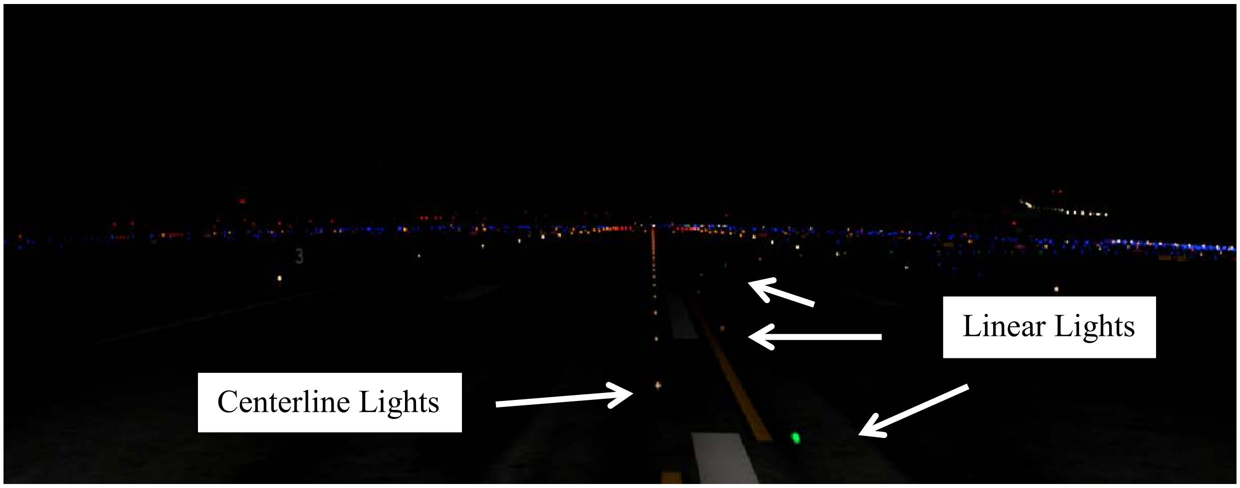


Figure 24. Script 247 Right 30-Degree Turn

Figure 25 shows the 8 configurations having 2-ft line length segments with 100-ft spacing and their average identifiable distances. Results showed subject pilots identified 30-degree configurations at greater distances, 502 ft away, while identifying 90-degree turns 449 ft away.

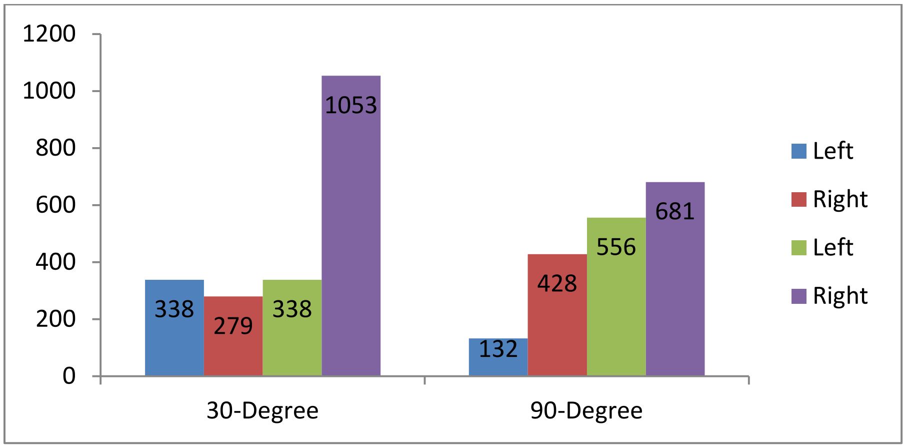


Figure 25. Average Identifiable Distances (Feet) for a 2-ft Line Segment With 100-ft Spacing Configurations

<u>THE 2-FT LINE LENGTH SEGMENTS (200-FT SPACING)</u>. Table 7 shows all the possible configurations with 2-ft line length segments and 200-ft spacing. Left 90-degree turns took the longest time and were closer in distance to the configuration for subject pilots to identify, while right 30-degree configurations were identifiable at greater distances.

Table 7. The 2-ft Line Segment With 200-ft Spacing Configurations

Script Number	Configuration Turn/Angle	Line Length (ft)	Line Spacing (ft)	Average Distance (ft)	Difficulty	Correct Responses
230	Left/90	2	200	89	5	6 of 13
257	Right/90	2	200	100	4	7 of 15
239	Right/30	2	200	145	5	7 of 15
221	Left/90	2	200	224	4	12 of 12
212	Left/30	2	200	309	4	7 of 13
266	Right/90	2	200	358	4	12 of 14
203	Left/30	2	200	547	4	9 of 13
248	Right/30	2	200	835	3	15 of 15
Average	-	-	-	326	4	-

The left 90-degree turn shown in figure 26 required the longest time for subject pilots to identify as it was only identifiable 89 ft away. Subject pilots assessed the configuration as "Very Difficult." Of the 13 subject pilots to evaluate this configuration, 6 passed this configuration without identification. Some of the comments received by the subject pilots included:

- "Don't like small lights with big spacing."
- "No lights between the centerline and taxiway."
- "Lacked sufficient number of lights."

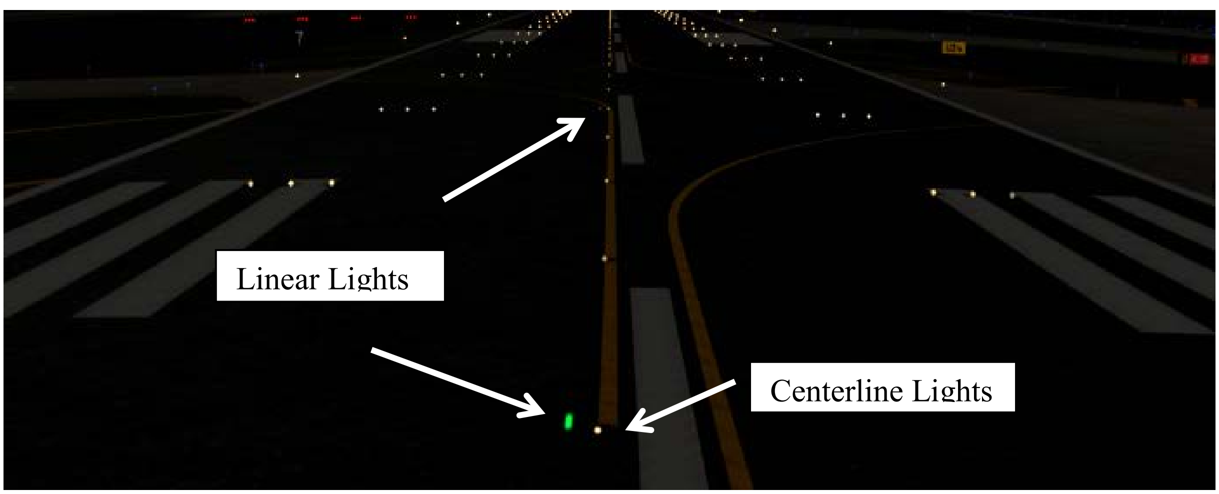


Figure 26. Script 230 Left 90-Degree Turn

The right 30-degree configuration shown below in figure 27 required the least amount of time to acquire. Generally, subject pilots identified the configuration 834 ft away. Of the 15 subject pilots, all 15 correctly identified the configuration. They assessed the configuration as being "Neither Easy/Difficult" to identify, and some comments are listed below.

- "Liked the green."
- "Spotted the green light first."

- “Length of lights are too short.”
- “Liked intensity and size of lights.”
- “Far spacing need more light.”
- “Easy to follow the green.”
- “Spacing was too far lacked lights.”

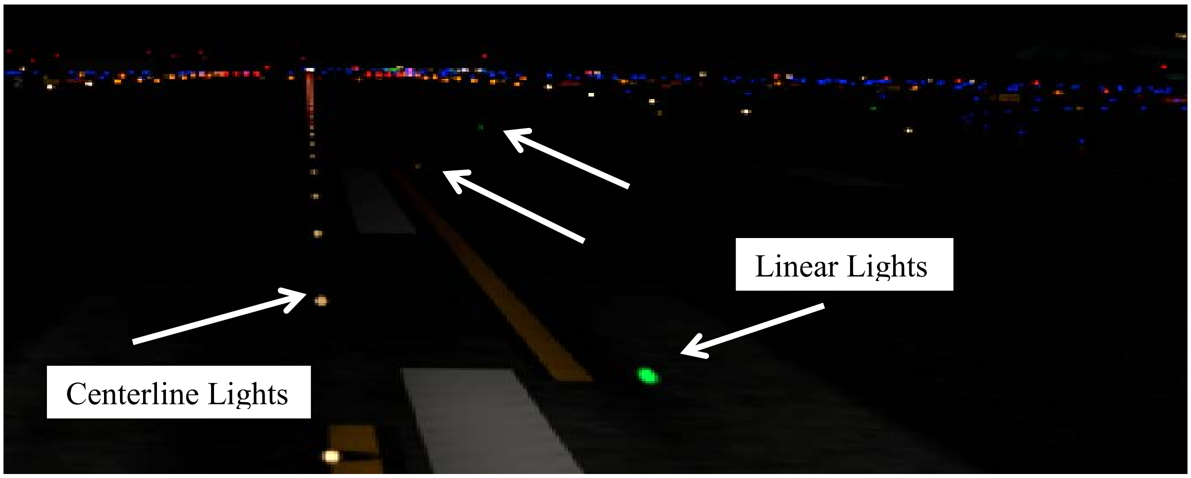


Figure 27. Script 248 Right 30-Degree Turn

Figure 28 shows the 2-ft line length segments with 200-ft spacing configurations and their average identifiable distances. Results showed subject pilots identified the 30-degree configurations in shorter reaction times, which resulted in greater identifiable distances. On average, subject pilots identified 30-degree turns within this category 459 ft away, while identifying 90-degree turns 193 ft away.

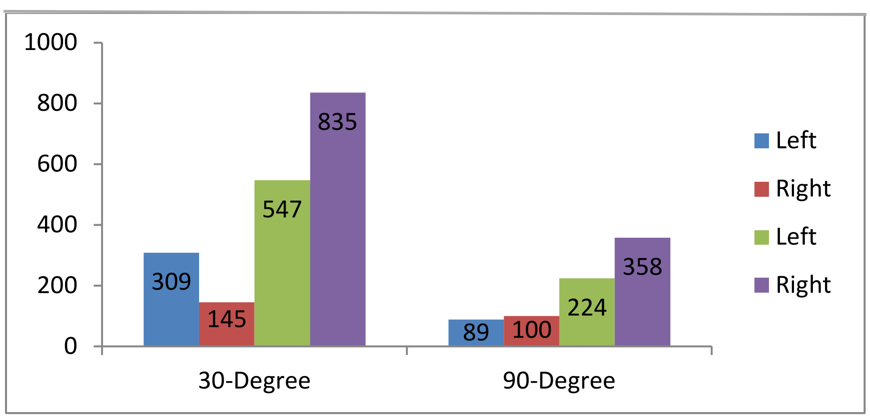


Figure 28. Average Identifiable Distances (ft) for 2-ft Line Segment With 200-ft Spacing Configurations

THE 8-FT LINE LENGTH SEGMENTS (50-FT SPACING). The possible configurations with the 8-ft line length segment and 50-ft spacing are shown in table 8. Results showed that subject pilots required the most amount of time to identify a right 30-degree turn, which was not identified until 468 ft away. Subject pilots required the least amount of time to identify a left 30-degree configuration as it was identifiable 1407 ft away.

Table 8. The 8-ft Line Segment 50-ft Spacing Configurations

Script Number	Configuration Turn/Angle	Line Length (ft)	Line Spacing (ft)	Average Distance	Difficulty	Correct Responses
240	Right/30	8	50	468	2	8 of 13
258	Right/90	8	50	474	3	11 of 13
267	Right/90	8	50	476	2	15 of 15
222	Left/90	8	50	548	2	13 of 15
231	Left/90	8	50	573	2	11 of 13
213	Left/30	8	50	719	2	8 of 13
249	Right/30	8	50	973	2	14 of 15
204	Left/30	8	50	1407	2	10 of 14
Average	-	-	-	705	2	-

The right 30-degree turn shown below in figure 29 required the longest time for subject pilots to identify. Of the 13 responses, 5 subject pilots responded with the incorrect configuration. Some of the comments received included:

- "The angle was harder to identify."
- "Off centerline lights made it easier."
- "Lights between taxiway centerline and taxiway helped."

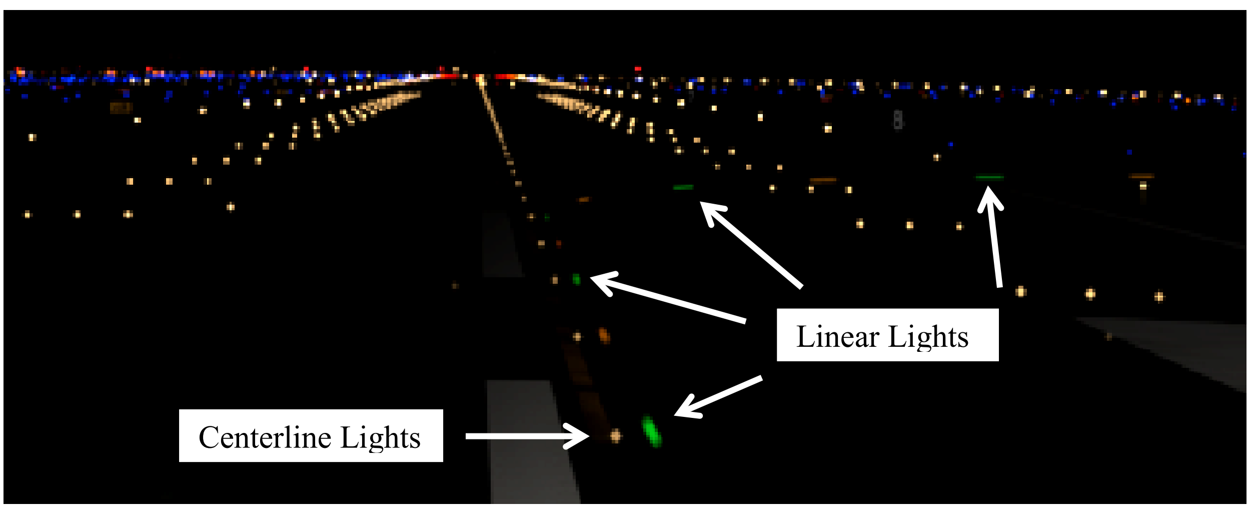


Figure 29. Script 240 Right 30-Degree Turn

The right 30-degree configuration shown in figure 30 was identifiable at the greatest distance. Subject pilots rated the configuration as being "Somewhat Easy" to identify. There were 14 responses to this configuration, and 4 were incorrect. There were no significant comments provided for this configuration.

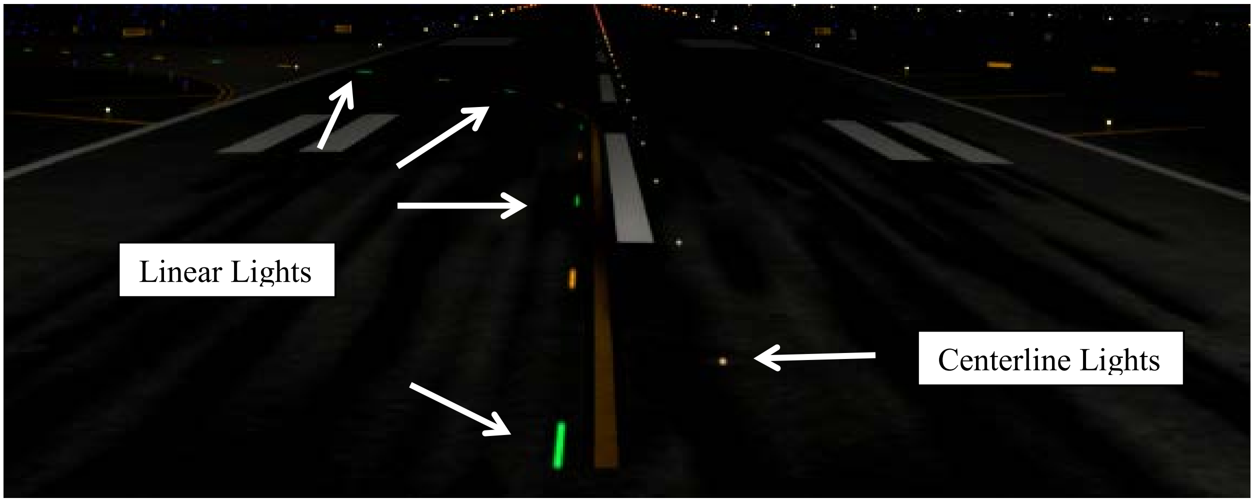


Figure 30. Script 204 Left 30-Degree Turn

Figure 31 shows the 8-ft line length segments with 50-ft spacing configurations and their average identifiable distances. Results showed subject pilots identified 30-degree configurations in shorter reaction times, which resulted in greater identifiable distances. On average, subject pilots identified 30-degree turns within this category 892 ft away, while identifying 90-degree turns 518 ft away.

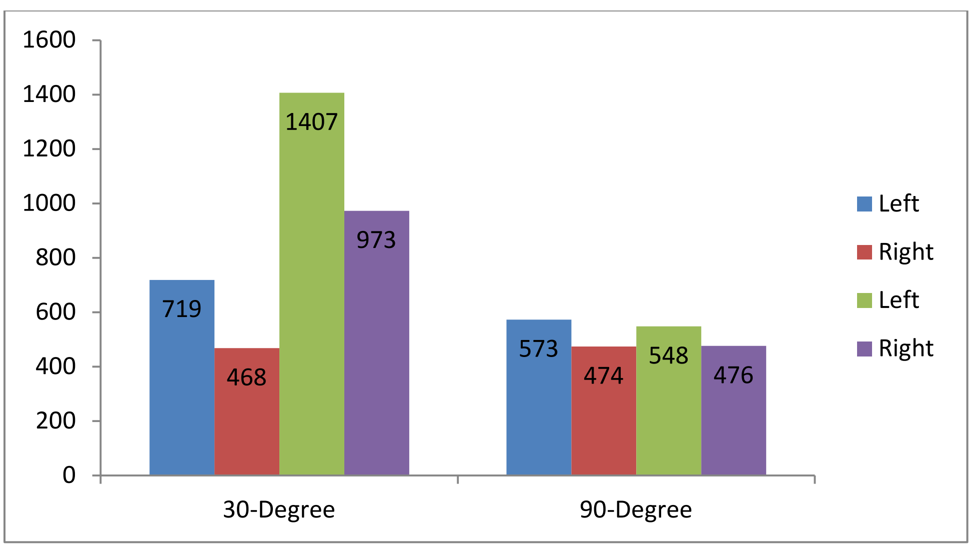


Figure 31. Average Identifiable Distances (ft) for 8-ft Line Segment With 50-ft Spacing Configurations

<u>THE 8-FT LINE LENGTH SEGMENTS (100-FT SPACING)</u>. The possible configurations with the 8-foot line length segment and 100-foot spacing are shown below in table 9. Results showed that subject pilots required the most amount of time to identify a 90-degree turn, which was not identified until 174 ft away. Subject pilots required the least amount of time to identify a right 30-degree configuration as it was identifiable 826 ft away.

Table 9. The 8-ft Line Segment With 100-ft Spacing Configurations

Script Number	Configuration Turn/Angle	Line Length (ft)	Line Spacing (ft)	Average Distance (ft)	Difficulty	Correct Responses
223	Left/90	8	100	174	5	13 of 14
268	Right/90	8	100	320	3	12 of 13
259	Right/90	8	100	349	4	13 of 13
232	Left/90	8	100	363	4	11 of 14
241	Right/30	8	100	472	2	12 of 13
214	Left/30	8	100	496	3	10 of 15
205	Left/30	8	100	763	3	13 of 15
250	Right/30	8	100	826	2	11 of 13
Average	-	-	-	470	3	-

The left 90-degree turn shown in figure 32 required the longest time for subject pilots to acquire. Subject pilots assessed it as being "Very Difficult." There were a total of 14 responses with 1 incorrectly called out configuration. Comments received included:

- "Liked the 2-3 leading off lights."
- "Need more lights."
- "Liked offset from centerline."
- "Could not pick up yellow lights."
- "The longer lights are better."
- "Closer spacing is better."

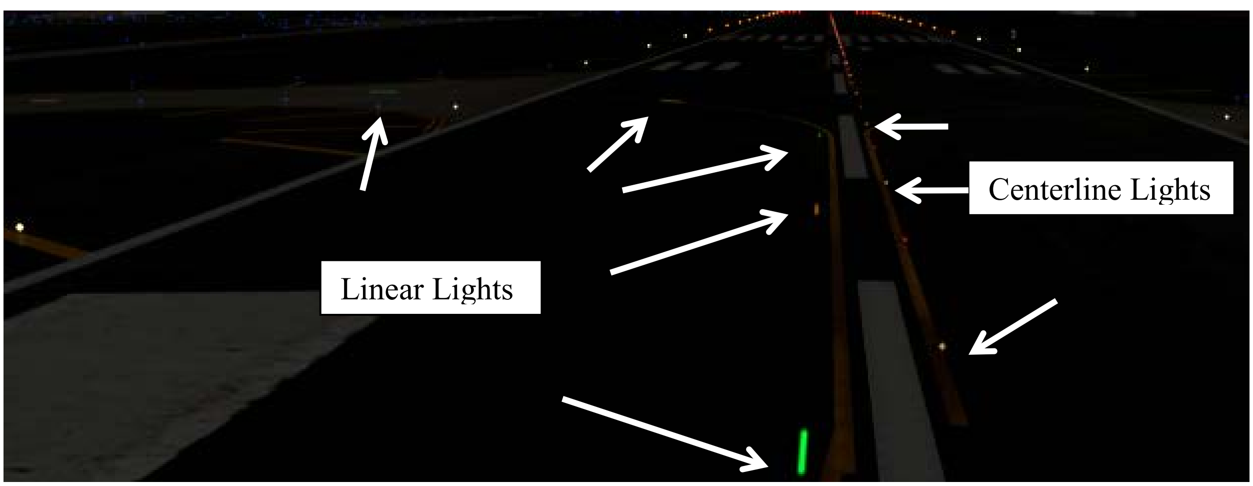


Figure 32. Script 223 Left 90-Degree Turn

The right 30-degree turn configuration shown in figure 33 required the least amount of time to identify. Subject pilots assessed the configuration as being "Somewhat Difficult" to identify. There were a total of 13 responses and only 2 were incorrect. A subject pilot stated, "With this configuration had more indication of the angle."

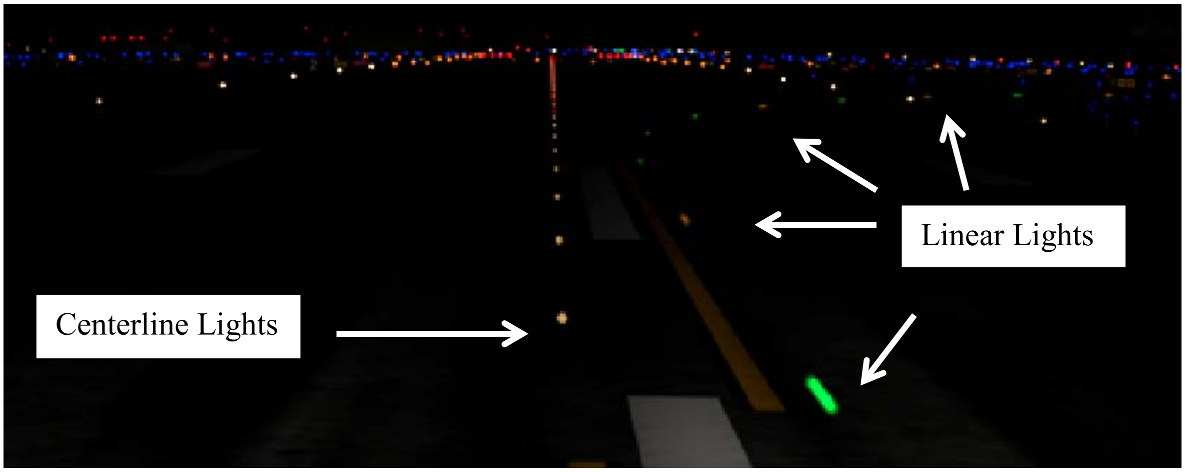


Figure 33. Script 250 Right 30-Degree Turn

Figure 34 shows the 8-ft line length segments with 100-ft spacing configurations and their average identifiable distances. Results showed subject pilots identified 30-degree configurations in shorter reaction times, which resulted in greater identifiable distances. On average, pilots identified 30-degree turns within this category 639 ft away, while identifying 90-degree turns 302 ft away.

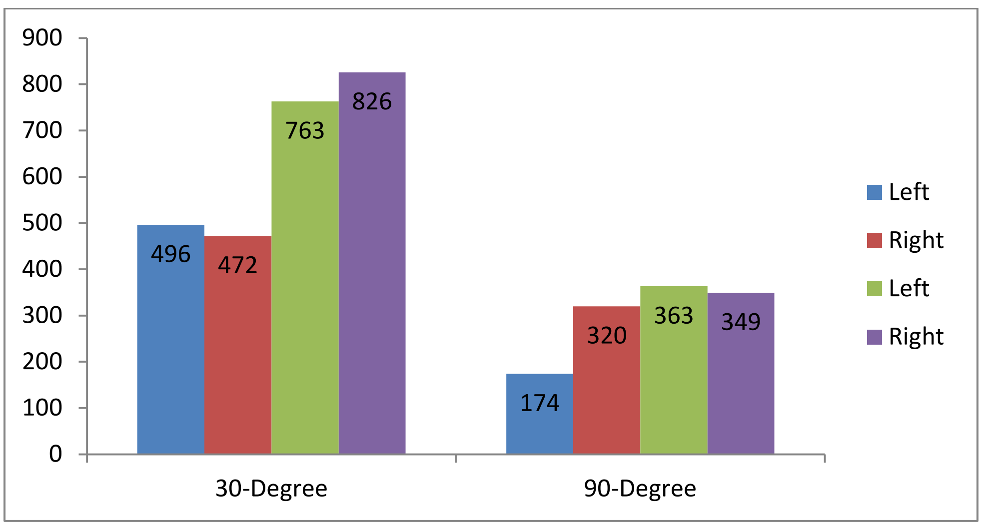


Figure 34. Average Identifiable Distances (ft) for 8-ft Line Segment With 100-ft Spacing Configurations

THE 8-FT LINE LENGTH SEGMENTS (200-FT SPACING). The possible configurations with the 8-ft line length segment and 200-ft spacing are shown in table 10. Results showed that subject pilots required the most amount of time to identify a 90-degree turn, which was not identified until 163 ft away. Subject pilots required the least amount of time to identify a right 30-degree configuration as it was identifiable 708 ft away.

Table 10. The 8-ft Line Segment With 200-ft Spacing Configurations

Script Number	Configuration Turn/Angle	Line Length (ft)	Line Spacing (ft)	Average Distance (ft)	Difficulty	Correct Responses
260	Right/90	8	200	163	5	9 of 15
233	Left/90	8	200	174	5	7 of 16
224	Left/90	8	200	243	4	11 of 13
242	Right/30	8	200	287	4	11 of 14
269	Right/90	8	200	291	3	8 of 13
215	Left/30	8	200	395	4	9 of 15
206	Left/30	8	200	624	3	8 of 13
251	Right/30	8	200	708	2	13 of 13
Average	-	-	-	360	4	

The right 90-degree turn shown in figure 35 required the most amount of time to identify. There were 15 subject pilots to view the configuration; however, 6 of those passed the configuration without identification. Subsequently, the subject pilots assessed the configuration as "Very Difficult" to identify. The comments provided by the subject pilots included:

- "Blended with taxiway centerline lights."
- "Light spacing too far apart."

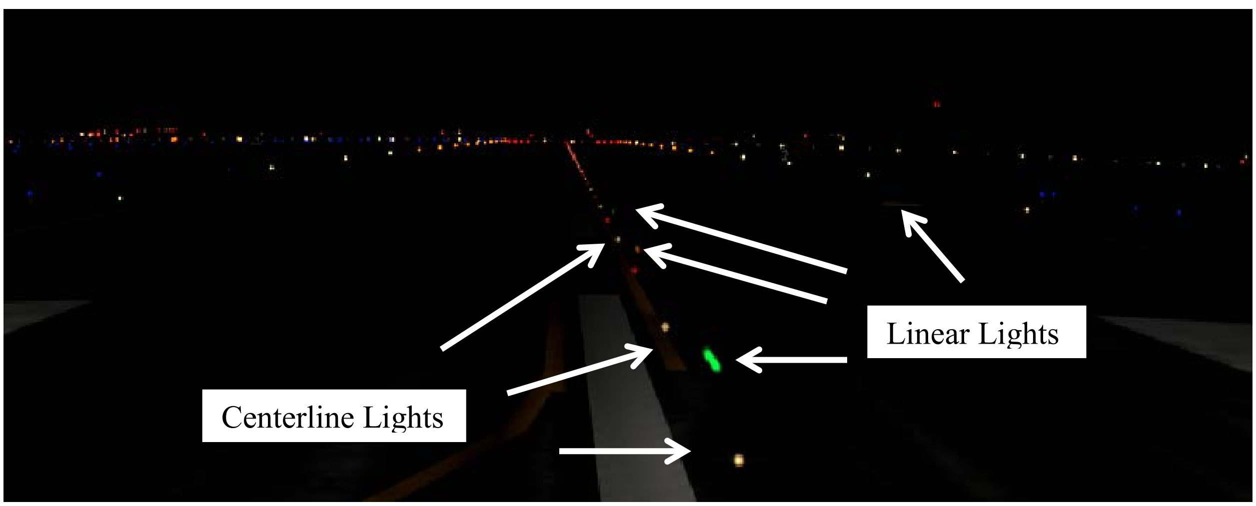


Figure 35. Script 260 Right 90-Degree Turn

The right 30-degree configuration shown below in figure 36 was identifiable at the greatest distance. There were 13 responses, and all 13 called out the configuration correctly. Subject pilots assessed the configuration as "Somewhat Easy" to identify. There were no significant comments received for this configuration.

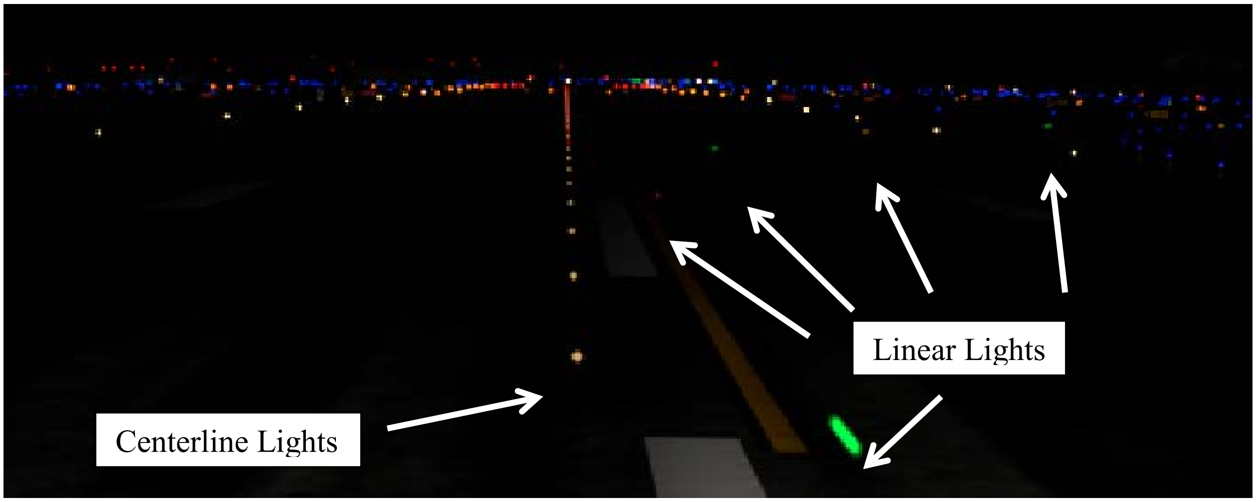


Figure 36. Script 251 Right 30-Degree Turn

Figure 37 shows the 8-ft line length segments with 200-ft spacing configurations and their average identifiable distances. Results showed subject pilots identified 30-degree configurations in shorter reaction times, which resulted in greater identifiable distances. On average, subject pilots identified 30-degree turns within this category 504 ft away, while identifying 90-degree turns 218 ft away.

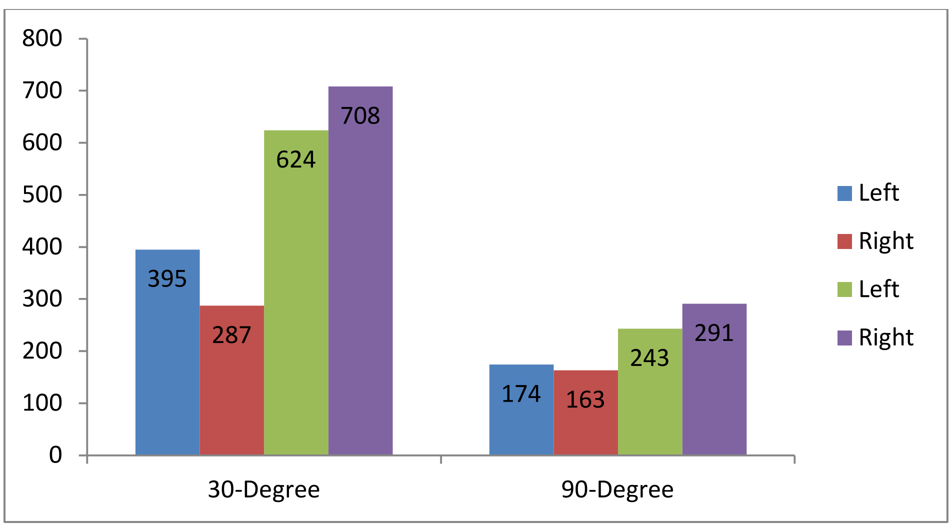


Figure 37. Average Identifiable Distances (ft) for 8-ft Line Segment With 200-ft Spacing Configurations

THE 32-FT LINE LENGTH SEGMENTS (50-FT SPACING). The possible configurations with the 32-ft line length segment and 50-ft spacing are shown below in table 11. Results showed that subject pilots required the most amount of time to identify a right 30-degree turn, which was not identified until 686 ft away. Subject pilots required the least amount of time to identify a left 30-degree configuration as it was identifiable 1277 ft away.

Table 11. The 32-ft Line Segment With 50-ft Spacing Configurations

Script Number	Configuration Turn/Angle	Line Length (ft)	Line Spacing (ft)	Average Distance (ft)	Difficulty	Correct Responses
243	Right/30	32	50	686	2	11 of 13
225	Left/90	32	50	747	2	11 of 13
234	Left/90	32	50	755	2	13 of 13
270	Right/90	32	50	778	2	13 of 14
216	Left/30	32	50	959	2	9 of 13
261	Right/90	32	50	965	2	14 of 15
252	Right/30	32	50	1237	1	14 of 15
207	Left/30	32	50	1277	2	8 of 12
Average	-	-	-	926	2	-

The right 30-degree turn configuration shown in figure 38 required the most amount of time identify. There were 15 subject pilots, and only 2 incorrectly called out the configuration. Subject pilots assessed the configuration as "Somewhat Easy" to identify. Several comments provided by the subject pilots included:

- "Liked the longer lights."
- "Like the number of lights."
- "Longer lights easier to identify."
- "Longer lights stick out more."

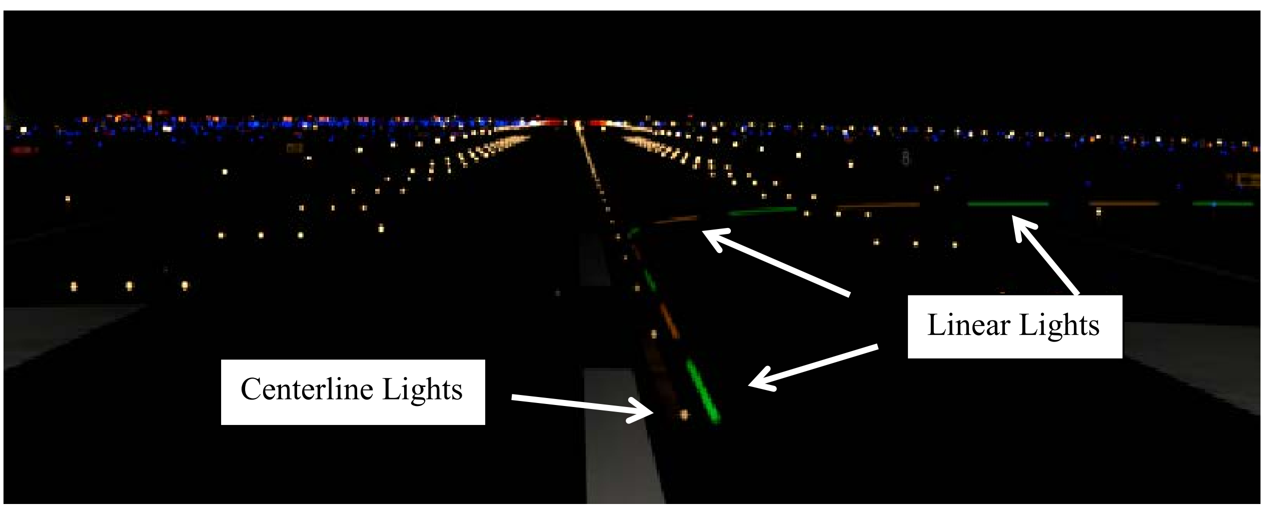


Figure 38. Script 243 Right 30-Degree Turn

The left 30-degree turn shown in figure 39 was identifiable at the greatest distance. There were 12 subject pilots that evaluated this configuration, with 4 incorrect responses. Subject pilots assessed the configuration as being "Somewhat Easy" to identify. Some of the comments received for this configuration included:

- "Like the spacing."
- "Like the number of lights."
- "Could identity from far distance."

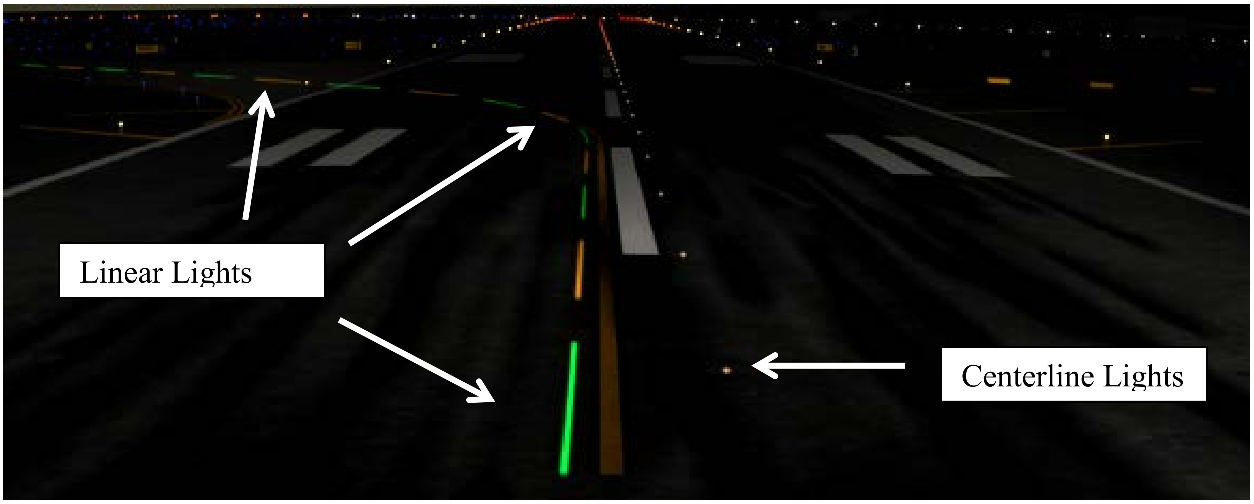


Figure 39. Script 207 Left 30-Degree Turn

Figure 40 shows the 32-ft line length segments with 50-ft spacing configurations and their average identifiable distances. Results showed subject pilots identified 30-degree configurations in shorter reaction times, which resulted in greater identifiable distances. On average, subject pilots identified 30-degree turns within this category 1040 ft away, while identifying 90-degree turns 811 ft away.

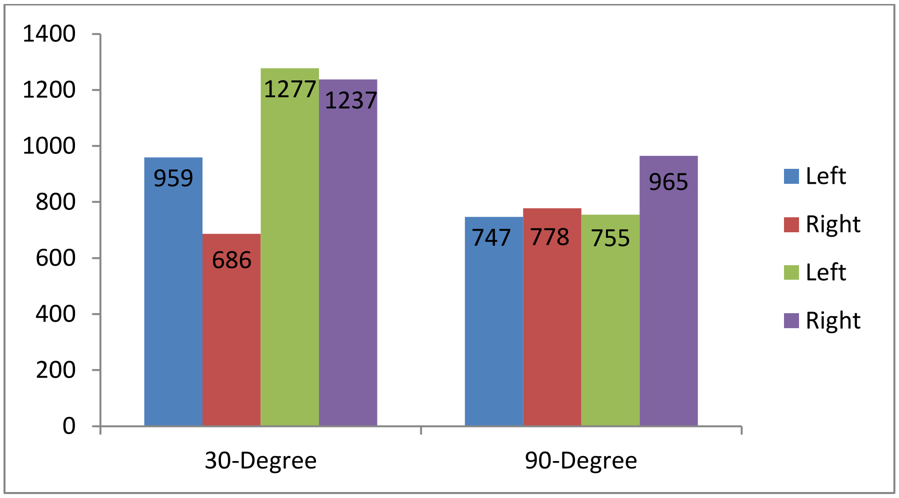


Figure 40. Average Identifiable Distances (ft) for 32-ft Line Segment With 50-ft Spacing Configurations

THE 32-FT LINE LENGTH SEGMENTS (100-FT SPACING). The possible configurations with the 32-ft line length segment and 100-ft spacing are shown in table 12. Results showed that subject pilots required the most amount of time to identify a 90-degree turn, which was not identified until 465 ft away. Subject pilots required the least amount of time to identify a left 30-degree configuration as it was identifiable 1215 ft away.

Table 12. The 32-ft Line Segment With 100-ft Spacing Configurations

Script Number	Configuration Turn/Angle	Line Length (ft)	Line Spacing (ft)	Average Distance (ft)	Difficulty	Correct Responses
226	Left/90	32	100	465	2	14 of 15
235	Left/90	32	100	469	2	13 of 13
244	Right/30	32	100	504	2	7 of 13
271	Right/90	32	100	529	2	14 of 15
262	Right/90	32	100	645	3	12 of 13
217	Left/30	32	100	819	2	7 of 13
253	Right/30	32	100	972	2	12 of 15
208	Left/30	32	100	1215	2	10 of 14
Average	-	-	-	702	2	-

The left 90-degree turn shown below in figure 41 required the most amount of time for subject pilots to identify. There were 15 responses to the configuration and only 1 response was incorrect. Comments provided by the subject pilots included:

- "Perfect configuration between spacing and number of lights."
- "Picked off Green first."
- "Liked the amount of lights on runway to taxiway."
- "Long lights made it easier it easier to identify."
- "Yellow light in turn helped identify angle."

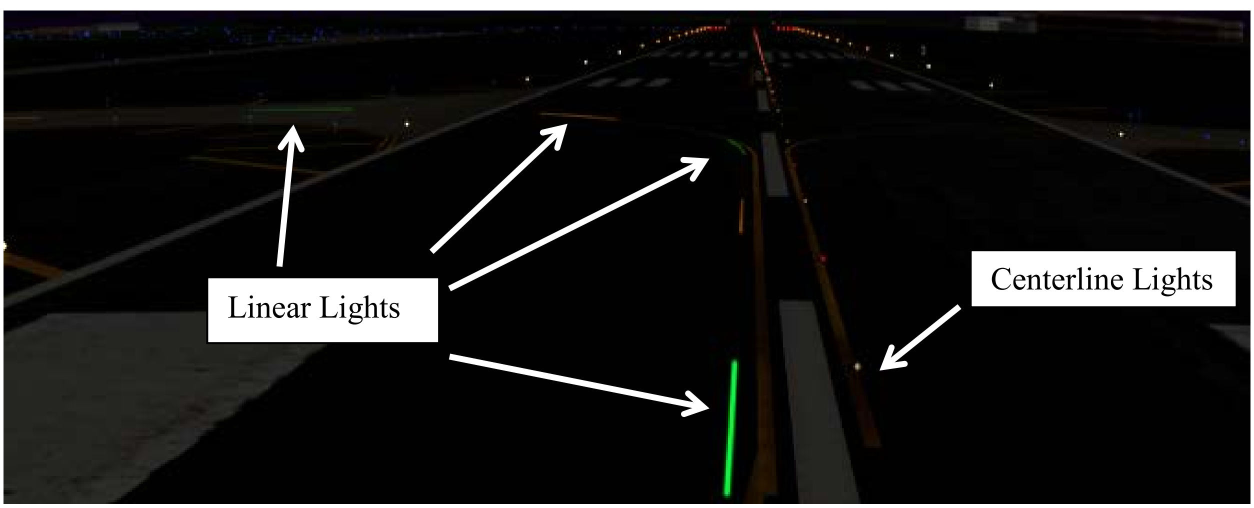


Figure 41. Script 226 Left 90-Degree Turn

The left 30-degree configuration shown in figure 42 required the least amount of time to be identified. There were 14 responses to this configuration and 4 incorrect responses. Comments provided by the subject pilots included:

- "Length of lights made easier to identify."
- "Nice lead in to turn."
- "Angle is harder to identify than direction."

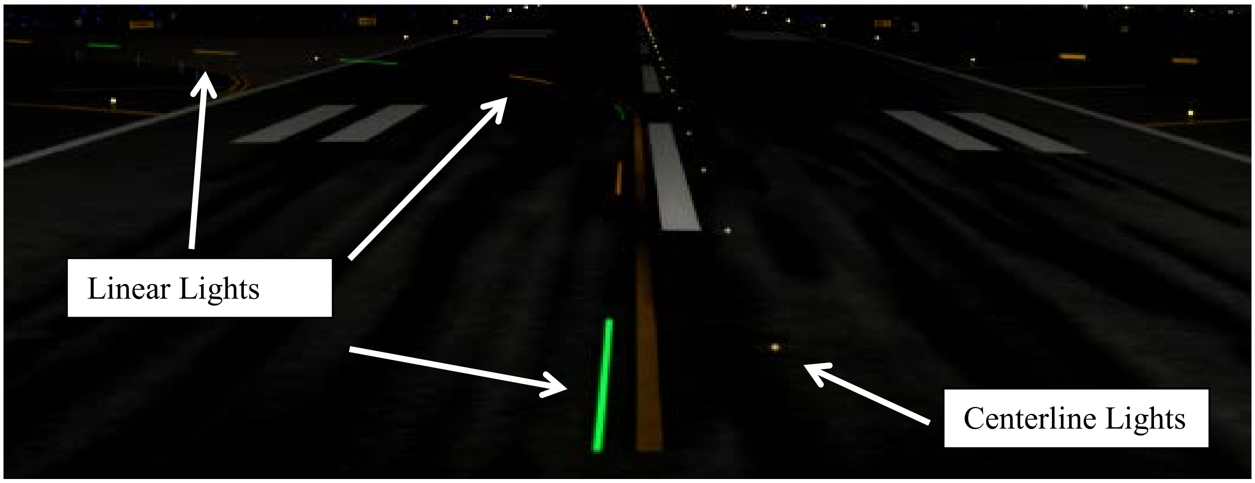


Figure 42. Script 208 Left 30-Degree Turn

Figure 43 shows the 32-ft line length segments with 100-ft spacing configurations and their average identifiable distances. Results showed subject pilots identified 30-degree configurations in shorter reaction times, which resulted in greater identifiable distances. On average, subject pilots identified 30-degree turns within this category 878 ft away, while identifying 90-degree turns 527 ft away.

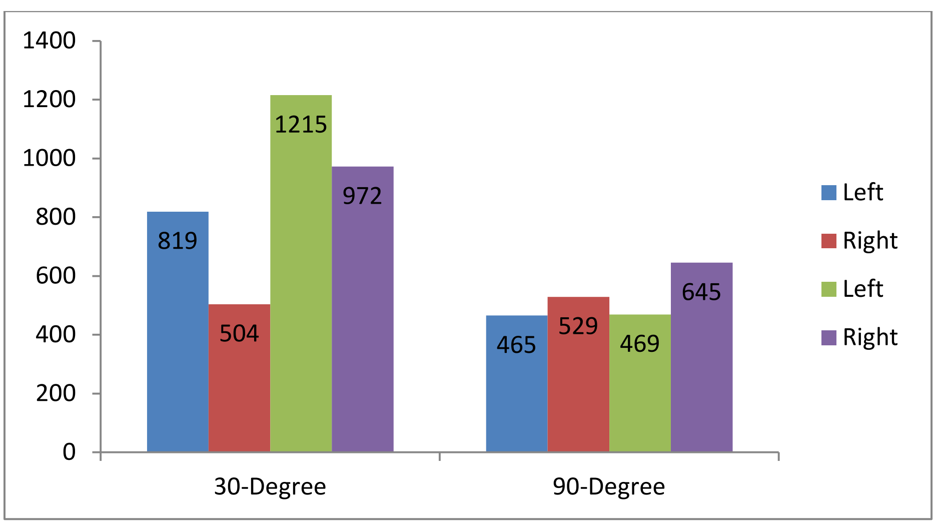


Figure 43. Average Identifiable Distances (ft) for 32-ft Line Segment With 100-ft Spacing Configurations

<u>THE 32-FT LINE LENGTH SEGMENTS (200-FT SPACING)</u>. The possible configurations with the 32-ft line length segment and 200-ft spacing are shown in table 13. Results showed that subject pilots required the most amount of time to identify a 90-degree turn, which was not identified until 264 ft away. Subject pilots required the least amount of time to identify a right 30-degree configuration as it was identifiable 627 ft away.

Table 13. The 32-ft Line Segment With 200-ft Spacing Configurations

Script Number	Configuration Turn/Angle	Line Length (ft)	Line Spacing (ft)	Average Distance (ft)	Difficulty	Correct Responses
227	Left/90	32	200	264	3	15 of 15
272	Right/90	32	200	384	3	13 of 13
245	Right/30	32	200	411	3	7 of 13
209	Left/30	32	200	537	3	13 of 15
236	Left/90	32	200	542	3	13 of 14
263	Right/90	32	200	547	4	12 of 13
218	Left/30	32	200	593	3	8 of 15
254	Right/30	32	200	627	2	13 of 13
Average	-	-	-	488	3	-

The left 90-degree configuration shown in figure 44 required the most amount of time to identify. There were 15 responses to this configuration and all were correct responses. Comments provided by the subject pilots included:

- "Length of light helped identify angle."
- "Difficult to determine angle to far spacing."
- "Angle was hard to spot."
- "Hard to spot because only two lights on taxiway remaining were on taxiway."
- "Interval between lights are bad."

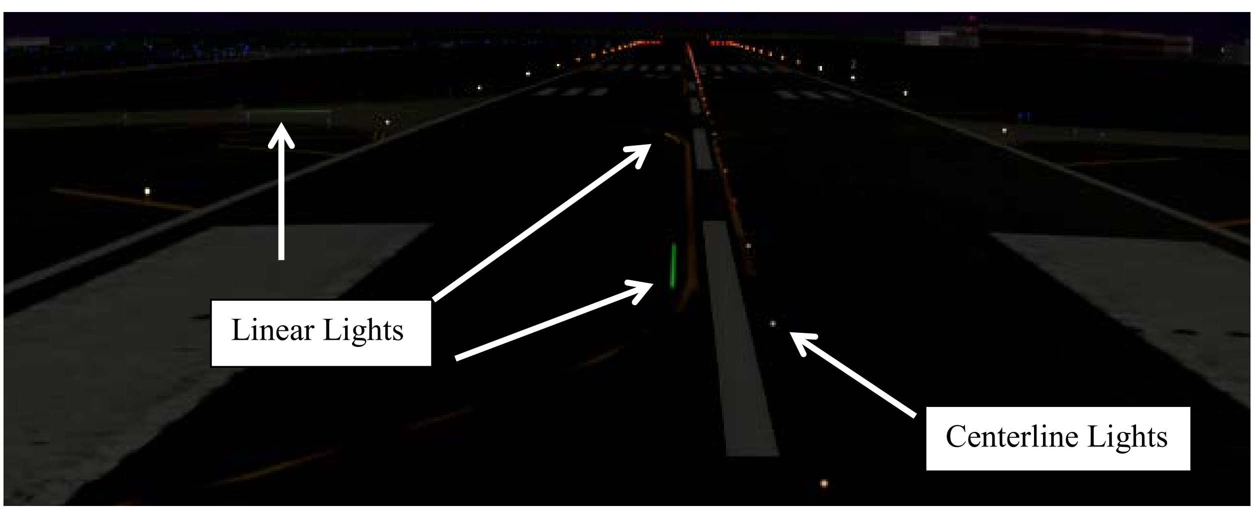


Figure 44. Script 227 Left 90-Degree Turn

The right 30-degree turn is shown in figure 45. There were 13 responses to this configuration and all subject pilots correctly identified the configuration. Subject pilots assessed this configuration as being "Neither Difficult/Easy" to identify. One subject pilot commented, "Spacing made it difficult."

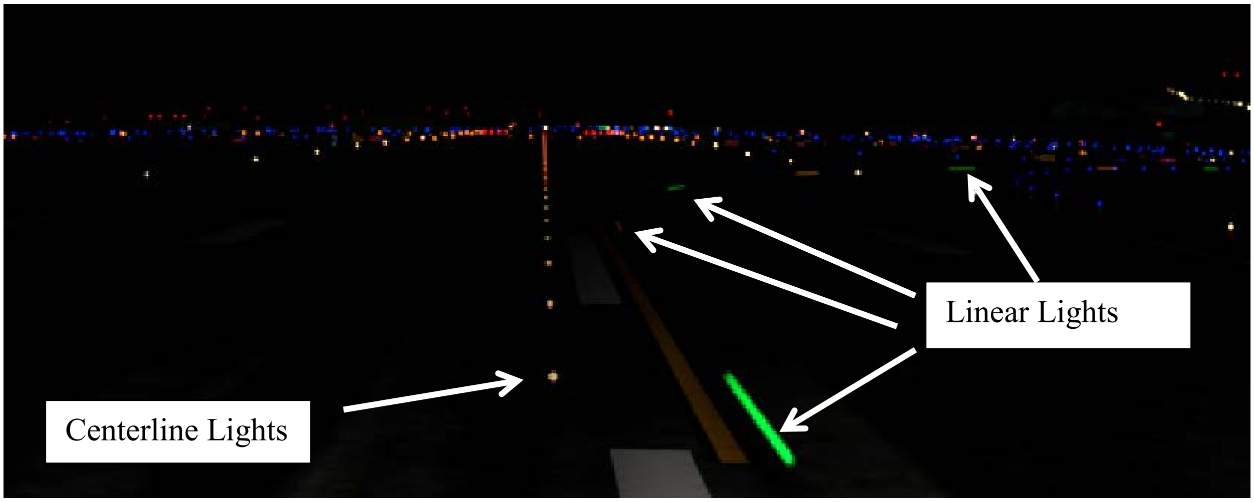


Figure 45. Script 254 Right 30-Degree Turn

Figure 46 shows the 32-ft line length segments with 200-ft spacing configurations and their average identifiable distances. Results showed subject pilots identified 30-degree configurations in shorter reaction times which resulted in greater identifiable distances. On average, subject pilots identified 30-degree turns within this category 542 ft away, while 90-degree turns were identified 434 ft away.

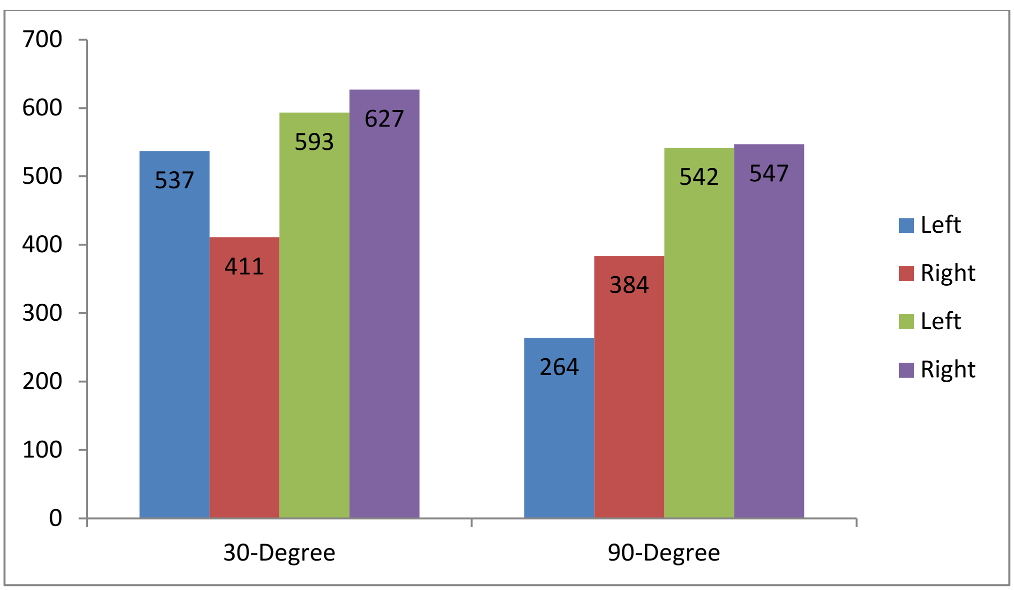


Figure 46. Average Identifiable Distances (ft) for 32-ft Line Segment With 200-ft Spacing Configurations

STUDY 2: SUMMARY.

Results from this simulator evaluation are consistent with results from the LRC studies. As shown in figures 47 and 48, the average results from this simulator study were correlated with predictions generated from the model developed in the previous section of this technical note (r^2=0.82 and r^2=0.88), and show a relationship between linear element length and spacing.

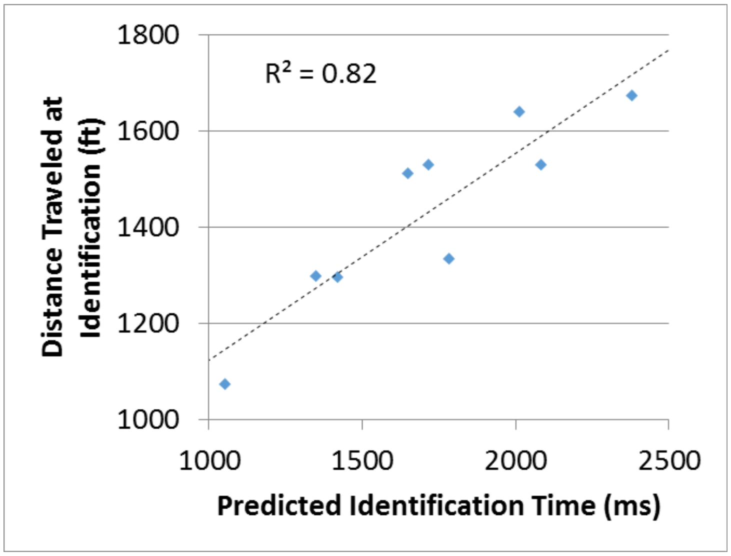


Figure 47. Average Distances Traveled Toward Intersections Upon Identification Versus Predicted Identification Times

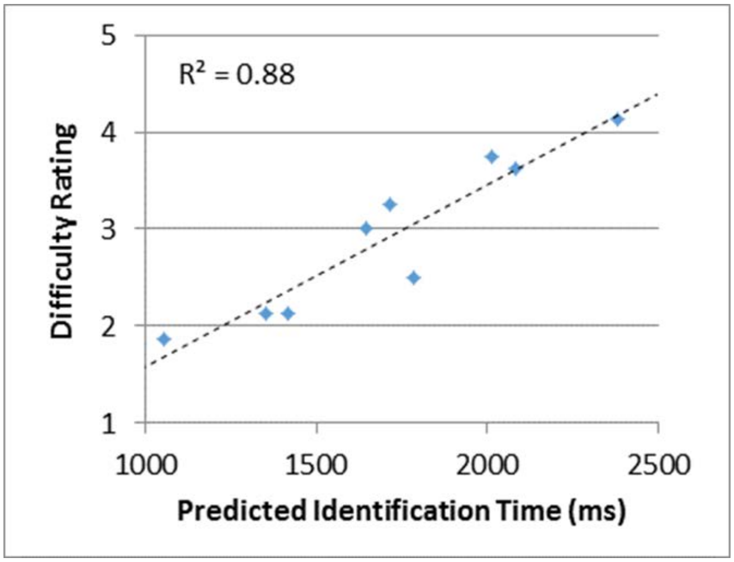


Figure 48. Average Difficulty Ratings Versus Predicted Identification Times

Configurations with 32-ft line length segments produced the greatest acquisition distances, and pilots were very satisfied with the length of line segments. The configurations with the 50-ft spacing proved to be the best configurations for spacing. The 32-ft line length with 50-ft line spacing was the best overall configuration distance. On average, subject pilots were able to view the configuration 926 ft away. Several comments received for these configurations suggested that pilots appreciated the longer light segments as it helped to identify the angle and direction. The configuration featuring the 200-ft spacing proved to be least satisfactory to pilots and produced the lowest acquisition distances. Configurations featuring the 2-ft line length segments proved to be the least satisfactory to pilots and received multiple comments that the line segments were too small. Results also demonstrated that greater acquisition distances were generally found in configurations with 30-degree turns. Those subject pilots who identified the configurations in the shortest time identified the configurations at the greatest distances, thus quicker reaction, while those subject pilots that required longer times identified the configurations at shorter distances and with slower reaction.

STUDY 3—FIELD

STUDY 3: INTRODUCTION.

As described previously, following the completion of the LRC and the Airport Safety Technology Research and Development Section's simulation studies was to conduct a real-world installation of linear airfield lighting elements at an airport in order to assess their visual effectiveness in actual viewing conditions during nighttime operations, compared to point-source elements. The test fixtures (figure 49) were developed by the LRC and contained green LED sources mounted in 8-ft channel sections. The LEDs in each section could be operated to illuminate a 2-, 4-, or 8-ft section. In addition, two 8-ft fixtures could be mounted end-to-end to create the appearance of a 16-ft linear element.

Figure 49. Test Fixtures Located Along the Test Runway

STUDY 3: OBJECTIVE.

The objective of Study 3 was to measure visual acquisition times to various combinations of length (point source, 2 ft, 8 ft, and 16 ft) and spacing (50 ft and 150 ft). The study was conducted by Ohio State University (OSU) at the Ohio State University Airport (KOSU) through the FAA Center of Excellence, Partnership to Enhance General Aviation Safety, Accessibility and Sustainability (PEGASAS). This section of the technical note only briefly describes the initial experimental efforts undertaken through PEGASAS.

STUDY 3: METHODS.

Figure 50 shows an aerial view of the section of KOSU used for the study. The green rectangle denoted LED Configuration indicates the location of the test light fixtures, which were operated from the location identified as Control Center. Fixtures were stored in the location labeled Trailer/storage when not in use. During the experiment, subjects traveled along the airfield in the direction and location of the arrows in figure 50. The solid arrow indicates when the subjects would have the test light fixtures in their field of view.

Figure 50. Aerial View of the Test Section of KOSU Used for the Real-World Field Study

STUDY 3: DATA COLLECTION.

Initial data collection for this project consisted of 45 participants who observed 8 of 32 possible configurations of linear LED lights. The lights were positioned approximately 2500 feet from the threshold of runway (RWY) 27R at KOSU (indicated by the solid arrow in figure 50), with variations in source light length (point source, 2 ft, 8 ft, 16 ft), spacing (50 ft between lights, 150 ft between lights), angle (90^o turns, 30^o turns), and direction of turn (left, right), for a total of 360 observations.

Observations were made uniformly across all array configurations. As shown in table 14, of the 360 observations, the following number of observations was taken for the following conditions.

Table 14. Number of Observations for Each Light Length Configuration

Source Length	Observations	Spacing (ft)	Observations	Angle (degrees)	Observations	Direction	Observations
Point Source	89	50	179	90	177	Right	180
2 ft	89	150	179	30	181	Left	178
8 ft	90	-	-	-	-	-	-
16 ft	90	-	-	-	-	-	-

Note: Two observations were rejected.

The reaction time to determine the configuration was recorded for each participant observation for each combination of light length, spacing, angle, and direction. Participants were asked to determine the given configuration as they were taxiing towards the configuration along RWY 27R, starting from approximately 2500 ft from the beginning of the light configuration.

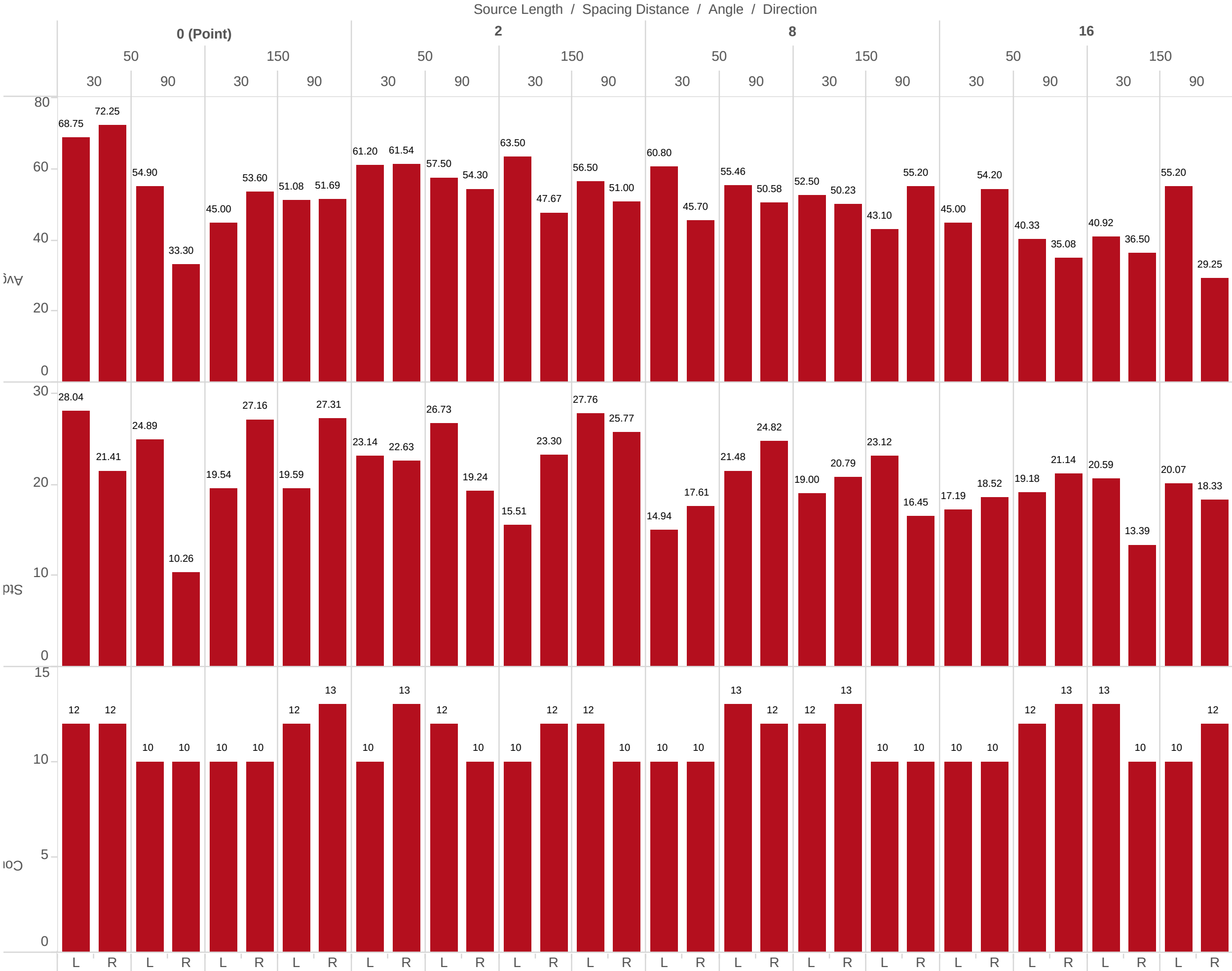
Reaction time was measured in seconds starting from just prior to entering the RWY 27R threshold to the time when the participant verbally noted the lighting configuration. The subject aircraft approached the lights while taxiing along the runway at a typical taxi speed of approximately 15 knots.

In addition to reaction time, the accuracy of the participant's observation of the configuration, i.e., whether the participant was able to verbally note the correct angle and direction of the turn that the lighting configuration displayed, was also noted.

STUDY 3: RESULTS.

Figure 51 illustrates the mean, standard deviation, and count of reaction times (i.e., number of subjects who observed a given configuration) for each configuration. Since sample sizes for each configuration were low (about 10 observations per configuration), it was difficult to determine with any statistical significance the difference in reaction time for any given configuration. However, as configurations are grouped by light length, spacing, angle or direction, more meaningful results began to appear.

Length, Angle, Direction

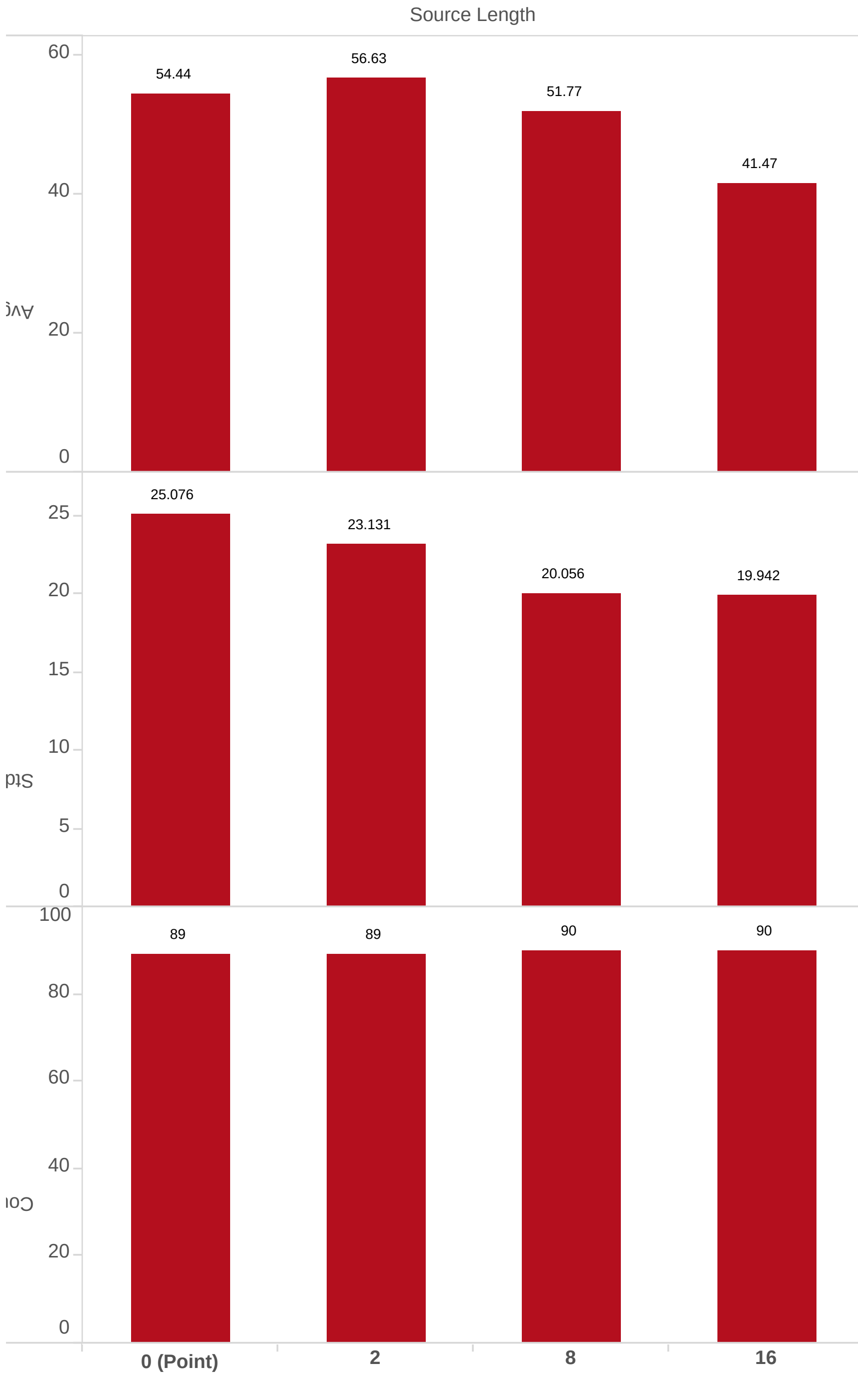


Average of Time in sec, standard deviation of Time in sec and count of Time in sec for each Direction broken down by Source Length, Spacing Distance and Angle.

Figure 51. Raw Data Summary

Figure 52 illustrates the mean, standard deviation, and count of reaction times for each configuration grouped by source light length. This figure clearly shows that there is a decrease in reaction time as light lengths increase. One exception to this pattern is the somewhat increased reaction time between point-source lighting and 2-ft length lights. This could be the result of the point-source lights having a higher, omnidirectional profile than the linear LED lights, which are more directional in design.

Source Length



Average of Time in sec, standard deviation of Time in sec and count of Time in sec for each Source Length.

Figure 52. Data by Light Length

Table 15 reveals the results of two-tailed difference of means t-tests, employed to determine the statistical significance of any differences in reaction times between two light lengths.

Table 15. Reaction Time Statistical Significance by Light Source Length

Source Length (ft)	Sample Size	Mean	Standard Deviation
0 (Point)	89	54.44	25.076
2	89	56.63	23.131
8	90	51.77	20.056
16	90	41.47	19.942

Source Length (ft)	T-Statistics			
	0 (Point)	2 ft	8 ft	16 ft
0 (Point)	-	-0.60561	0.786158	3.82732
2		-	1.50118	4.69406
8			-	3.44527
16				-

Source Length (ft)	P-Values			
	0 (Point)	2 ft	8 ft	16 ft
0 (Point)	-	0.5449	0.4318	1.30E-04
2		-	0.1333	2.67E-06
8			-	5.71E-04
16				-

Source Length (ft)	Significant Difference at 95% Confidence, 5% Significance Level?			
	0 (Point)	2 ft	8 ft	16 ft
0 (Point)	-	No	No	Yes
2		-	No	Yes
8			-	Yes
16				-

Note: Calculated from analyzed data on Tableau®, using Wolfram Alpha® Difference of Means two-tailed T-test.

This analysis revealed that there was a statistically significant decrease in reaction time (i.e., subjects were able to make a determination sooner, and hence farther away from the lights, in the taxiing process) for 16-ft linear lights in comparison to the point, 2-, or 8-ft lights. There was no revealed statistical significance in reaction time among any other light lengths.

Figure 53 illustrates the mean and standard deviation of determination accuracy for each configuration grouped by source light length. Accuracy was scored as 1 = accurate or 0 = inaccurate. The accuracy scores represented in figure 53 are average scores over all observations per light length. As the accuracy score increased, more subjects accurately determined the configuration. As this figure shows it is clear that there was an increase in configuration determination accuracy as light lengths increased.

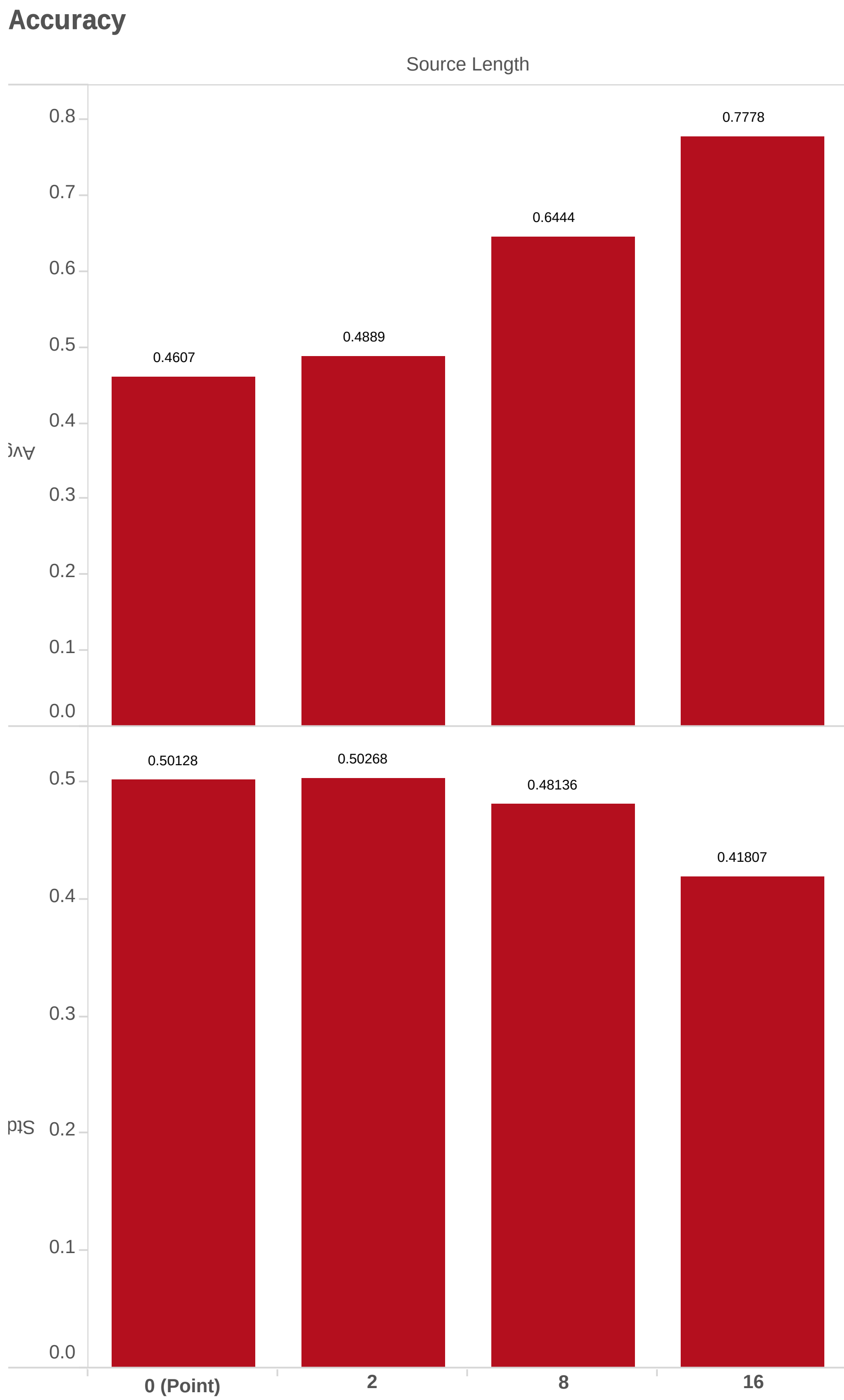


Figure 53. Determination Accuracy by Source Light Length

Table 16 reveals the results of two-tailed difference of means t-tests, employed to determine the statistical significance of any differences in determination accuracy between two light lengths.

Table 16. Determination Accuracy Statistical Significance by Light Source Length

Source Length (ft)	Sample Size	Mean	Standard Deviation	
0 (Point)	89	0.4607	0.50128	
2	89	0.4889	0.50268	
8	90	0.6444	0.48136	
16	90	0.7778	0.41807	
Source Length (ft)	T-Statistics			
	0 (Point)	2 ft	8 ft	16 ft
0 (Point)	-	-0.374751	2.50032	4.59352
2		-	2.11341	4.1781
8			-	1.98496
16				-
Source Length (ft)	P-Values			
	0 (Point)	2 ft	8 ft	16 ft
0 (Point)	-	0.3539	0.01241	4.36E-06
2		-	0.03457	1.47E-05
8			-	4.72E-02
16				-
Source Length (ft)	Significant Difference at 95% Confidence, 5% Significance Level?			
	0 (Point)	2 ft	8 ft	16 ft
0 (Point)	-	No	Yes	Yes
2		-	Yes	Yes
8			-	Yes
16				-

Note: Calculated from analyzed data on Tableau, using Wolfram Alpha Difference of Means two-tailed T-test.

This analysis revealed that there was a statistically significant increase in determination accuracy for 8-ft and 16-ft length lights over point and 2-ft length lighting. Furthermore, there was a statistically significant increase in determination accuracy between 16-ft and 8-ft lengths. There was no statistically significant increase in determination accuracy between point lights and 2-ft length light sources.

These initial analyses of reaction time and determination accuracy reveal that 16-ft linear LED light lengths may present significant benefits over traditional point lights or relatively shorter light lengths.

Figure 54 shows the mean reaction times for each light source spacing (50 and 150 ft). There was a slightly shorter reaction time for the longer spacing value, although this difference was not statistically significant (*p*>0.05), as indicated in table 17.

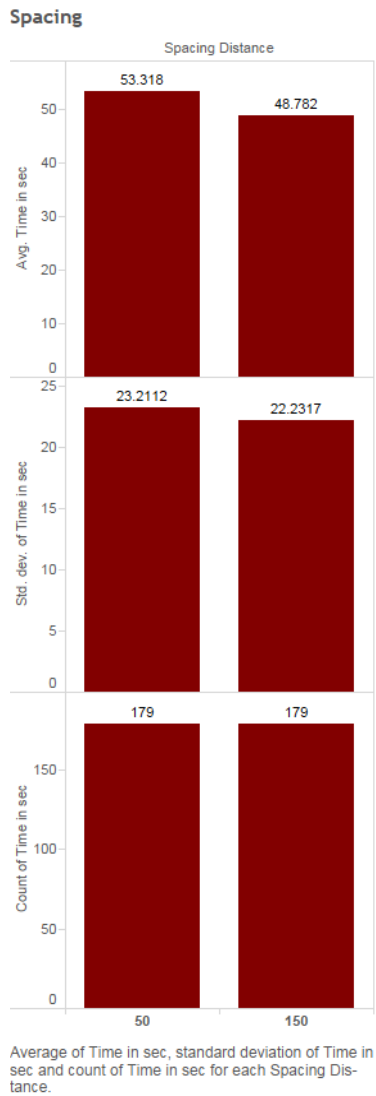


Figure 54. Reaction Time Data by Light Source Spacing

Table 17. Reaction Time Statistical Significance by Light Source Spacing

Spacing	Sample Size	Mean	Standard Deviation
50	179	53.318	23.2112
150	89	48.782	22.2317
T-Statistic for Difference of Mean			1.8882
P-Values			0.059
Significant Difference at 95%			No

Note: Calculated from analyzed data on Tableau®, using Wolfram Alpha® Difference of Means two-tailed T-test.

Figure 55 shows the mean accuracy for each light source spacing condition (50 and 150 ft). Consistent with the reaction time data, there was a slightly higher accuracy for the longer spacing value; this difference was not statistically significant (p>0.05), as indicated in table 18.

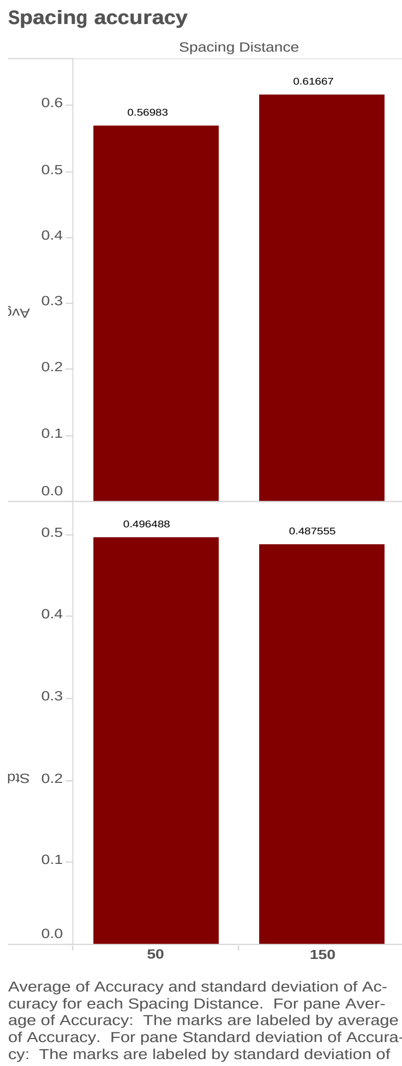


Figure 55. Determination Accuracy Data by Light Source Spacing

Table 18. Determination Accuracy Statistical Significance by Light Source Spacing

Spacing	Sample Size	Mean	Standard Deviation
50	179	0.56983	0.496488
150	179	0.61667	0.487555
T-Statistic for Difference of Mean			0.900589
P-Values			0.3678
Significant Difference at 95%			No

Note: Calculated from analyzed data on Tableau, using Wolfram Alpha Difference of Means two-tailed T-test.

STUDY 3: SUMMARY.

The data in Study 3 were consistent with the predictions of the model developed from the LRC studies, with the exception of the findings for each light source spacing value. In the present results (figures 54 and 55), subjects' responses to the longer spacing were superior (i.e., shorter reaction times and higher determination accuracy) but were predicted to be worse.

This counterintuitive finding may be because when the lights were configured at a 150-ft spacing, the spatial extent of the lights was larger (i.e., they extended farther to the side of the intersection) than at the 50-ft spacing configuration. This greater spatial extent may have provided a stronger cue to subjects about the configuration than the spacing itself, especially when subjects initially view the lights from a distance of about 2500 ft.

To confirm whether the counterintuitive finding with the light source spacing was repeatable, a second field experiment was conducted using only right-side configurations [21]. As in the first experiment, shorter reaction times and improved determination accuracy were elicited for configurations with higher light source length; but slightly improved performance was found for the increased spacing condition. This finding is consistent with the possibility that the peripheral location of the furthest light source element contributed to its being identified sooner.

The possibility that light source spacing and the peripheral location of the furthermost light source in the field studies could be tested by using configurations of lights with the same spatial extent but different spacing. In such a test, the hypothesis would be that the condition with shorter light source spacing would result in higher determination accuracy and in shorter reaction times as predicted by the model described previously in this technical note.

CONCLUSIONS

Overall, the results from the three studies, consisting of (Study 1) laboratory studies using fixed images and simple animations, (Study 2) a full-scale cockpit simulator, and (Study 3) actual runway conditions at an airport, were consistent in suggesting that there can be visual benefits to using linear light elements in special applications. Possible applications include the high-speed exits tested here or runway status lights. Using a linear element to replace runway or taxiway edge lighting could contribute to a possible light pollution issue on airports, such as the "sea of blue" issue that pilots encounter today. The full-scale field study (Study 3) revealed inconsistent results regarding the spacing of linear elements, but may have been confounded by the spatial extent of the different spacing configurations in that study.

In all three studies, under the conditions tested, there did not appear to be any reliable benefits (in terms of identification times or distances) to linear elements as short as 2 ft, relative to the conventional point-source lighting elements presently used for runway and taxiway delineation. This could be because pilots make judgments about the configurations of intersections or other conflict points from distances of hundreds of feet, when the difference in appearance between point-source elements and 2-ft linear elements is negligible from a pilot's viewing location.

The directional guidance provided by a linear element is decreased when viewed parallel to the user's direction of travel as distance from the element increases. The directional benefit is increased when the element is viewed at a distance and at angle different from the direction of travel. This is why the potential for use of a linear element in place of a point source on an airfield is limited. A linear element would be of possible benefit for lighting applications, such as taxiway intersections in which angles of view of the linear element are sufficient to provide a visual cue with a directional component.

The predictive model developed in this technical note will be useful for judging the relative tradeoff between light source spacing and length (treating point sources like 2-ft elements) and could serve as a tool for identifying configurations that are equivalent to existing delineation practices.

Photometric testing methods and failure criteria for individual sections of linear elements to ensure adequate visual performance could follow procedures already specified in Federal Aviation Administration (FAA) Advisory Circular (AC) 150/5345-46D and Engineering Brief 67D.

The sample comparison of installation costs between the legacy point source and a linear element is not conclusive. The linear element fixture has not completed the FAA approval process, and this technical note does not address the suitability of the fixture for its intended use in airport pavements.

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