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EFFECTS OF VARIOUS RUNWAY LIGHTING PARAMETERS UPON THE RELATION BETWEEN RUNWAY VISUAL RANGE AND VISUAL RANGE OF CENTERLINE AND EDGE LIGHTS IN FOG

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16. Abstract

Thirty six students and 54 commercial airline pilots were tested in the NASA/FAA Fog Chamber, Richmond, California to determine the effect of runway edge and centerline light intensity and spacing, fog density (cat.-I, II, IIIA, IIIB), ambient luminance level, and lateral and vertical offset distance of the subject from the runway's centerline upon horizontal visual range. These data were obtained to evaluate the adequacy of the "Balanced Lighting System" to provide maximum visual range in fog viewing both centerline and runway edge lights. The daytime "Balanced Lighting System" was compared against two other candidate lighting systems with centerline lights 1 and 5 percent as intense as the edge lights; the nighttime "Balanced Lighting System" was compared against other candidate lighting systems with centerline lights 0.05, 25, 125, and 625 percent as intense as the edge lights. The second objective was to determine if visual range is affected by the presence of runway centerline lights lying between the subject and the farthestmost light visible through the fog. The third objective was to determine if college student subjects differ from commercial airline pilots in their horizontal visual range through fog. Two studies were conducted.

Results of Study I indicated statistically significant differences between the various fog densities and cockpit lateral offset conditions as well as several interactions. The results of Study II indicated that visual range determined by counting either centerline or edge lights that possess characteristics of the "Balanced Lighting System" is not statistically different than when viewing runway lights possessing any of the other candidate intensity-spacing characteristics. Relatively large differences were found between the day and nighttime mean visual range, however. Eye height above the runway also played an important role in determining visual range, particularly in category I fog conditions. These findings are compared with those from previous studies and topics related to the "Balanced Lighting System" are discussed.

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PREFACE

The observations reported here indicate that the visual range of the centerline lights is considerably less than the RVR, particularly under category I conditions, and indicate that the visual range of the centerline lights in clear weather would be of the order of 2500 feet by day and by night. These observations are not consistent with the observations reported in references 30 and 33 cited in this report, or with popular opinion.

These differences have not been resolved because of the scheduled closing of the fog chamber in June 1974.

FOREWORD

The present investigations were performed as a result of an interagency agreement (DOT–FA73WAI–346) between the National Aeronautics and Space Administration and the Federal Aviation Administration. The NASA program manager was Dr. Edward M. Huff, Chief, Man-Machine Integration Branch, Ames Research Center. The FAA program manager was Mr. Walter C. Fisher, Chief, Visual Aids Section, Washington, D. C. The project was finalized on April 13, 1973 after detailed research protocols were prepared and negotiated with the FAA. The project was completed on June 28, 1973.

ACKNOWLEDGEMENTS

Without the continued and dedicated assistance of the following individuals this report would not have been completed within the relatively short period of time it has. I am indebted to Richard Willens for his work reducing and analyzing portions of these data, to Terye Galvan and Dr. Madeleine Gross for help in text preparation and editing, and to David Nylen, L. Markham Dawson, and Kirby Gilliland for their aid in preparing tables and illustrations. The outstanding assistance of the Ames' Graphics and Photographic Branches is also acknowledged with gratitude. Finally, I want to thank the staff at the NASA/FAA Fog Chamber located at Richmond, California, for their strenuous efforts to complete the data collection on schedule and with so few testing problems.

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INTRODUCTION

At the fourth meeting of the All Weather Operations Panel of the International Civil Aviation Organization (ICAO) (26), the member states were urged to conduct further investigations having to do with low visibility landing. Those states having airports with "Balanced Lighting Systems" were invited to "study further the effect upon the assessment of runway visual range of the relationship between runway edge and centre line lights in a balanced lighting system. . . ." These studies were to investigate the procedures to be used to assess runway visual range (RVR) with particular regard to the "relative guidance obtained by the pilot from the different sets of runway lights during take-off and landing" and "the need to take account of the cumulative effect of lights in a row, as the viewing angle approaches that at which they appear to merge, with particular reference to the influence of the spacing of centre line lights in different visibility conditions." (26, Appendix B, Recommendation 3/2) No precise definition of what is meant by relative guidance is available, however.[1] Presumably such guidance includes all those visual cues that a pilot relies upon to perform takeoff and landing safely. A great deal more work is needed to define what these cues are, particularly in low visibility conditions, and how they may interact with each other. A detailed discussion of this subject is beyond the scope of the present report.

The primary objective of the two investigations conducted here was to define the relationship(s) between the "Balanced Lighting System" currently used in the United States (26) and horizontal visual range (VR)[2] through fog for a number of viewing conditions. Figure 1 graphically illustrates the "Balanced Lighting System" runway light spacing and intensity characteristics. According to ICAO usage, a runway lighting system is said to be balanced if a linear relationship exists between the runway centerline (CL) light spacing and the ratio of intensities of the runway's CL and edge lights (26). Hereafter, the term "edge" (E) lights will be used to stand for High Intensity Runway Lights (HIRL) specified in current FAA regulatory circulars (4,5).

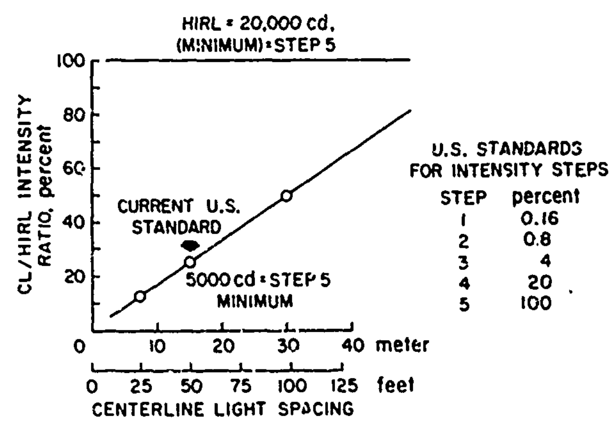

Figure 1. Balanced Lighting System.

Since the specification of a "Balanced Lighting System" provided by the ICAO (26) does not specify a particular runway edge light intensity or CL light intensity or spacing, it is important to ask whether a particular combination of these variables might be found that is better than those now in use in terms of providing for maximum VR under the full range of anticipated visibility conditions. In the present investigation several candidate runway lighting systems were compared with the current U. S. standard precision instrument approach lighting system that uses 5,000 cd CL lights spaced 50 feet apart and edge lights of 20,000 cd maximum intensity spaced 200 feet apart on step 5.[3]

An attempt was made in the two present investigations to determine whether the pilot's VR of centerline and edge lights through fog corresponds more closely to equivalent RVR when the current U. S. standard (50 feet CL spacing) for the "Balanced Lighting System" is used or when another candidate lighting system is used. Two daytime and nine nighttime candidate lighting systems were evaluated against the "Balanced Lighting System." During the formulation of the present experimental design, the FAA requested that CL spacing be investigated only in 50-foot multiples and also that runway light intensities be studied that could be achieved by present step setting controls. The two daytime candidate systems consisted of 20,000 cd edge lights spaced 200 feet apart with the CL lights reduced to 1,000 and 200 cd, respectively, at 50- and 100-foot spacings, i.e., CL light intensities 5 and 1 percent as intense as the edge lights. The intensity of both the edge and CL lights was varied for the nine nighttime lighting systems investigated. The maximum intensity of each CL light investigated here was 5,000 cd. Centerline light intensities were 5, 25, 125, and 625 percent that of the edge lights for the nighttime tests.

The second objective of the present investigations was to determine if visual range is affected by the presence of runway centerline lights lying between the subject and the farthestmost light visible through the fog. This matter has to do with a possible cumulative visual effect of viewing more than one runway light at a time.

The third objective of the present investigations was to determine if college student subjects differed from commercial airline pilots in their horizontal VR through fog.

The fourth objective was to evaluate a number of alternative candidate runway lighting systems to determine whether they would yield greater VR than the "Balanced Lighting System."

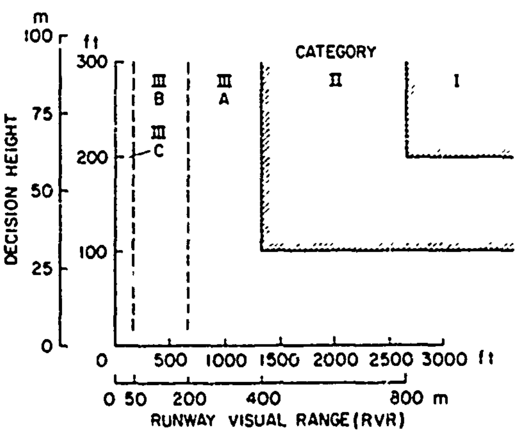

Figure 2. Standard I.C.A.O. landing approach limitations.

The Low Visibility Environment

Figure 2 gives the currently established relationships between RVR and operational categories. At present, only airports having approved lighting, navigation, and other ILS equipment will allow category II, IIIA, and IIIB landings. Pilots must also receive special training for these low visibility conditions.

If RVR can be determined accurately so that it represents the pilot's visual range along the glide slope, it is possible to set meaningful standards for allowing or prohibiting landings and takeoffs. Such a capability is "...not only a significant factor in air-traffic safety, it can also contribute to an improvement in the traffic regularity at an airport" (35, p. 68). The original intent of the RVR measurement system was, "...to increase airport utilization by improving and augmenting terminal weather observing techniques" (30, p. 6).

The subject of the optical properties of fog is too complex to be treated in depth here. The reader is referred elsewhere for further information on this subject (2, 12, 13, 17, 18, 20, 31). Nevertheless, it is important to point out that RVR is significantly affected by the type of fog that exists at an airport. One writer (14, pp. 24–28) has listed six basic types of fog showing for each how slant visual range varies as a function of aircraft altitude. Figure 3 presents three "visibility curves" from reference 14 that illustrate the large and sometimes unexpected influence fog can have upon VR.

These drawings indicate that eye height and type of fog interact to affect slant visual range. As the pilot descends through various types of fog, VR may decrease, remain constant, or may increase! Horonjeff (25, p. 14) has pointed out that in category II conditions, the pilot will make visual contact with standard U. S. approach lights shortly before he reaches the 100-foot decision height or at about 1500 feet from the runway's threshold. As Horonjeff has correctly pointed out however, "... just making contact with the lights is not enough for adequate guidance. He must see a sufficient number of lights in the pattern, and he must see them clearly." Horonjeff has suggested that the pilot will have to see at least a 450-foot-long segment of the runway at 90 knots airspeed or at least a 700-foot-long segment at 140 knots airspeed to control his aircraft adequately during letdown. There is a wide divergence of opinion on how long this visual ground segment should be under given landing conditions. There is little disagreement, however, with the statement that the farther the pilot can see through the fog the better in terms of executing a safe landing.

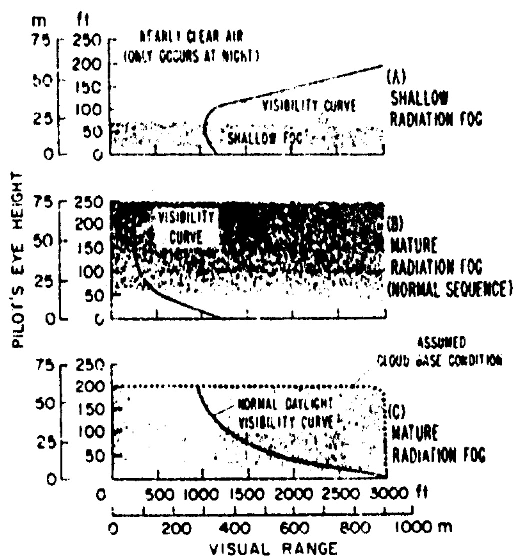

Figure 3. Visual range as a function of eye height and type of fog (adapted from 14).

Review of Previous Research

A limited number of horizontal VR determinations were made at the FAA/University of California fog chamber (now the NASA/FAA fog chamber) early in their research program (22, 33). They determined the farthest discernible CL light through category I (2600 ft RVR) and category II (1200 ft RVR) fog during the day and nighttime using various CL light intensities and spacings. The subject was positioned at three distances from the runway's threshold to assess the possible interfering effect of the approach lights. These researchers found that for 1,000 cp CL lights spaced 100 feet apart during nighttime runs, subjects positioned on the threshold perceived CL lights 1,200 feet and 2,600 feet away in 1,200- and 2,600-foot RVR fog conditions, respectively. Thus, VR was found to be equivalent to RVR. The same equivalency was also found for 1,000 cp CL lights spaced 50 feet apart during both the day and nighttime runs, which suggests that the 50 foot CL spacing aided daytime VR. The other VR data presented are not applicable to the present investigation or review due to the low CL light intensities and differences in spacings used. "The density of the fog was measured by the same type of transmissometer that is now installed at many airports in the United States" (33, p. 1). No details were given regarding the light source used in the transmissometer.

In the introduction to their own investigation of VR through fog, Lefkowitz and Schlatter (30, pp. 5–22) review the literature on this subject from 1948 to 1966. Data concerning the distributions of day and nighttime visual illuminance thresholds (E_t) were presented graphically. Four of these previous VR studies were oriented toward engineering evaluation of weather forecasting equipment or aircraft landing aids (7, 9, 10, 19). Another study compared pilots' slant range visibility with horizontal VR through fog (29), while another analyzed the probability of seeing various numbers of runway lights through fog during a landing (15).

In their summary of previous research, Lefkowitz and Schlatter (30, p. 23) comment, "It is evident from the previous section that the data on which the RVR system is based would not pass without challenge as to scientific and statistical adequacy. Despite this reservation, 96 percent of the pilots polled in an opinion survey described RVR as fairly or extremely helpful in giving them a more accurate picture of terminal weather conditions (38). The practical constraints on the RVR system can be characterized as human factor and instrument limitations."

Lefkowitz and Schlatter rightly suggest that the pilot's visual contrast and illuminance thresholds are the two most "intangible" variables in the solution of the RVR equations. They remark that there is a complete lack of pilot's environmental flight data. This is particularly critical in light of the extremely wide range of pilot visual illuminance threshold values found under actual low visibility sighting conditions. Their review of previous VR research makes this last point abundantly clear. They found that median values for the visual illuminance threshold cited ranged from 0.8 mi-c to 3,200 mi-c or a range of 3.6 $\log_{10}$ units for the nighttime test runs and from 15 mi-c to 7,900 mi-c (for a range of 2.7 $\log_{10}$ units) for the daytime test runs.[4] If maximum values are used, these E_t ranges are even larger, by as many as 5 orders of magnitude!

When one considers the importance placed upon the visual threshold constant used in both Allard's (11) and Koschmieder's Law (27), in light of the extremely large variation in this parameter discussed above, and the fact that current practice in calculating RVR uses a fixed E_t value, which takes one of two values, it is clear that further research is needed on this and the other parameters related to the RVR concept. It is also easy to appreciate the large differences in calculated RVR that result from small changes in the viewing environment.

Another important cause for the large variations in visual threshold that can occur during flight through fog and clouds is the fact that both of these atmospheric conditions exhibit widely varying spatial inhomogeneity. Because the pilot is traveling through the medium, this variation is translated into a temporal variation in ambient luminance. Unfortunately, the effect that repeated exposure to widely fluctuating ambient luminance has upon visual threshold has only been investigated in rather limited laboratory situations. Nevertheless, it is known that the human eye adapts to the light about twice as fast as it adapts to the dark. Also, Wald and Clark (36) have shown that there is a nonlinear regular relationship between the luminance of a scene and the duration of subsequent dark adaptation. They reported that a 3.6-mL scene viewed for five seconds requires about 60 seconds for the eye to regain its initial level of dark adaptation, a 245-mL scene viewed for five seconds requires almost ten minutes, and an 1,890-mL scene viewed for five seconds requires about 13 minutes. The two brightest viewing conditions produced approximately a 2 $\log_{10}$ unit loss of sensitivity.

These investigators also determined how long it took for the eye to regain its initial level of dark adaptation after exposure to a 333-mL scene for exposure durations that ranged from 10 seconds to 20 minutes. A nonlinear regular relationship was found to exist between these two variables. In general, the longer the exposure duration the slower the rate of subsequent dark adaptation during the first five minutes in the dark. Approximately the same findings have been reported by Mote and Riopelle (32). Since the pilot can encounter such a wide range of ambient luminances during daytime flight through clouds and fog it is extremely difficult to estimate from laboratory data such as is cited above how large a shift in visual threshold might be expected. Again, much more work is needed on this particular aspect of vision in flight.

Lefkowitz and Schlatter (30) tested 30 subjects in groups of three standing outdoors atop a specially equipped mobile laboratory vehicle parked on the runway centerline at NAFEC airport, runway 13-31. Only four of these subjects were pilots. They were tested only when the atmospheric transmittance had deteriorated to less than 80 percent for daytime and to 50 percent for nighttime runs as measured by a 500-foot-long baseline transmissometer. Both CL and edge lights were counted. Twelve CL/edge light intensity combinations were studied with the CL lights 25 feet apart and nine CL/edge light intensity combinations with the CL lights spaced 50 feet apart. Both sets of edge lights possessed maximum output intensities of 10,000, 2,000, and 400 cd at step settings 5, 4, and 3, respectively. The CL lights were type L-845 (improved) flush mounted, bidirectional, and possessed a luminous output of 10,000, 2,000, and 400 cd at step settings 5, 4, and 3, respectively. The summary findings of this investigation are presented in the form of cumulative relative frequencies of the subjects' illuminance threshold (E_t) for day and nighttime viewing conditions averaged across all of the CL/edge light intensity combinations. They have been reproduced by permission in Figure 4.

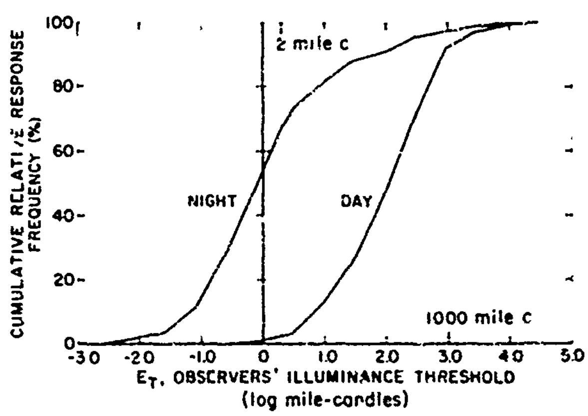

Figure 4. Distribution of subjects' illumination threshold for day and nighttime conditions (adapted from 30).

The 1,000 mi-c marker on the X axis indicates the daytime E_t value, and the 2 mi-c marker (top of graph) indicates the nighttime E_t value currently used to calculate RVR. It is apparent that 20 of the 30 subjects (67 percent) could see farther at night and 27 of the 30 (92 percent) could see farther during the day than predicted by the RVR determinations. Lefkowitz and Schlatter also presented graphs showing the distribution of their subjects' mean VR for three step settings, day and nighttime runs, and three RVR intervals. These results have been reproduced by permission in Figures 5 through 7. Zero differences on the X axis indicates that VR equals the calculated RVR interval shown. A positive difference indicates that VR exceeds and a negative difference indicates that VR is less than the RVR interval by the amount shown.

Several comments can be made about these VR data: (1) Regarding day versus nighttime viewing conditions within RVR intervals, the nighttime VR results tend to cluster together more

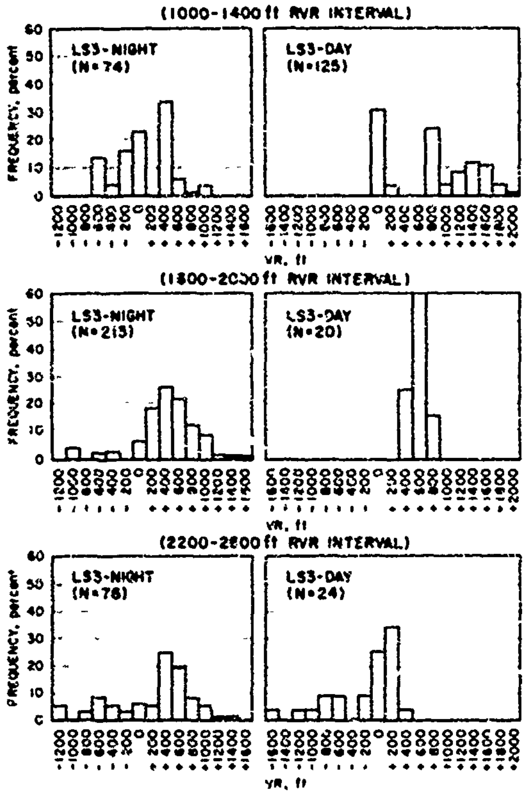

Figure 5. Distribution of visual range data for three RVR intervals, light step 3, and day and nighttime conditions (adapted from 30).

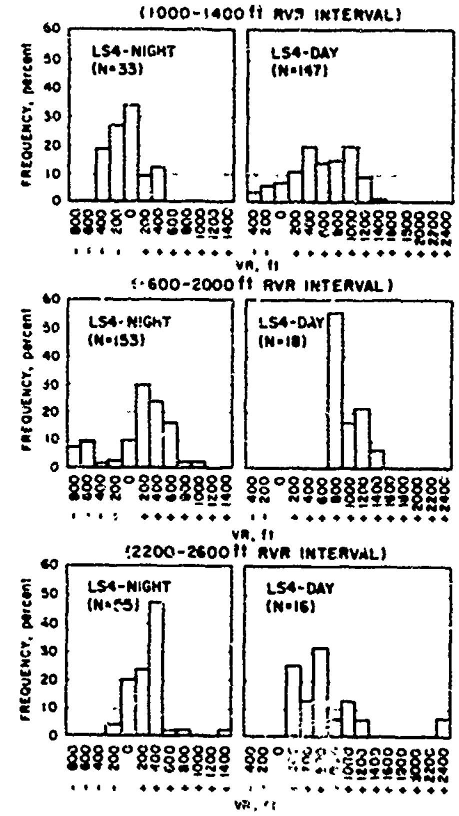

Figure 6. Distribution of visual range data for three RVR intervals, light step 4, and day and nighttime conditions (adapted from 30).

symmetrically and closer to the calculated RVR than do the daytime VR results; this is true for all three step settings and for all three RVR ranges. (2) Regarding the day versus nighttime viewing conditions for the 1,000- to 1,400-foot RVR range, the daytime VR results tend to yield VR that are greater than what would be expected on the basis of calculated RVR than does the nighttime viewing condition. This trend is not nearly as clear-cut for the 1,600- to 2,000- and the 2,200- to 2,600-foot RVR ranges, however. The subjects in the Lefkowitz and Schlatter study were stationary during their sightings, which makes their data more applicable to the decision of whether or not to takeoff than to land. Nevertheless, such data are useful in defining a limiting VR.

In a paper titled "Decision height and RVR minima," Blanchard (15) presents the results of VR calculations for several visual environments. He points out that "visual contact has been taken as the height at which a 300-ft segment of approach lights is in view ahead of aircraft and this is probably the minimum number which should be seen by the pilot to ensure that the lights have been correctly identified" (15, p. 192). He presents graphs showing the probability-of-visual-contact in fog and the probability of cloud break (15, Fig. 7) and a family of probability-of-visual-contact curves for a 3° glide slope and 14° cockpit cutoff angle. Horizontal VR is plotted against wheel height. For the 95 percent probability curve, for instance, the relationship is linear from (zero wheel height/100 m VR) to (135-ft wheel height/650 m VR). He also presents a graph that illustrates the

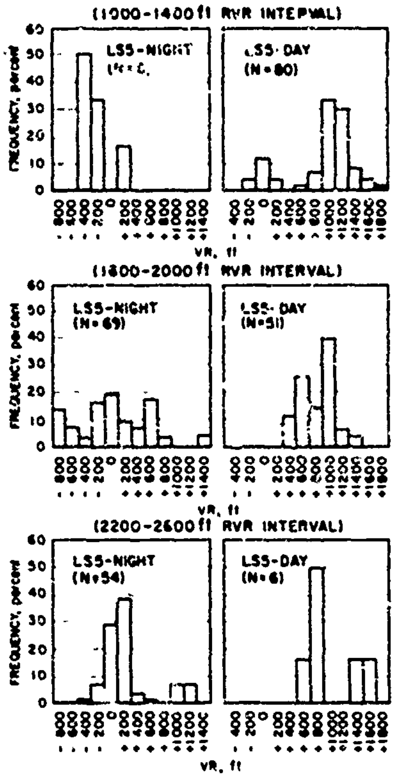

Figure 7. Distribution of visual range data for three RVR intervals, light step 5, and day and nighttime conditions (adapted from 30).

relationship between horizontal VR (ordinate) and RVR (abscissa) for four different approach light/HIRL intensities. This graph has been modified and included here as Figure 8.

Figure 8 shows that for nighttime viewing conditions, approach lights twice as intense as the HIRL lights (curve A) yield a lower VR than approach lights five times as intense as the HIRL lights (curve B). Likewise, for the daytime viewing conditions, having the approach lights six times as intense as the HIRL lights (curve C) yields a lower VR than having the approach lights 15 times as intense as the HIRL lights (curve D).

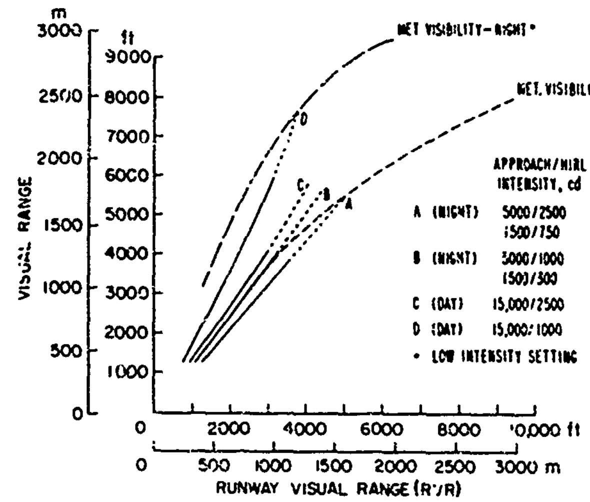

Figure 8. Horizontal VR as a function of RVR for selected viewing conditions (adapted from 15).

New insights into the relative importance of such visual variables as ambient illumination level, runway light intensity and spacing, and fog density, upon VR in the low visibility environment have been gained from the various studies cited above. Nevertheless, these previous field studies have had to contend with ever-changing fog transmission, ambient illumination levels, and other factors that make interpretation of the results difficult at best and application of the conclusions hazardous. Such is the nature of field research; it is to the credit of those who performed this kind of work that some useful data were obtained. The present investigations were initiated because the FAA felt that further work in relatively controlled low visibility conditions was needed.

The approach used in the present investigations involved determining VR by counting the number of centerline and edge lights that were discernible through fog under relatively repeatable and quantified conditions in a fog chamber. These visual ranges were then plotted against equivalent RVR for each viewing condition.

EXPERIMENTAL HYPOTHESES TESTED

The following experimental hypotheses were tested in the present investigations and can be directly related to tasks b and c, respectively, of Task II of the interagency agreement under which this project was performed. These hypotheses are worded in their null form to make them amenable to testing by statistical criteria. The first hypothesis tested had to do with whether or not VR is influenced by viewing more than one CL light through the fog. It was reasoned that since VR is partially a function of the eye's level of light adaptation (35) at the time the sighting is made, the presence of many CL lights would very likely raise the eye's threshold compared to the situation where only a single CL light was visible, and that VR would be influenced accordingly. Also of concern was the determination of the precise nature of any such influence. These data could be useful in refining further the methodology used to determine RVR.

Hypothesis 1 No difference in horizontal VR will be found when viewing a single runway CL light through the fog than when viewing more than one.

The second hypothesis concerned the relationship between VR based upon viewing runway CL lights through fog and equivalent RVR based upon the runway edge lights when both the intensity and spacing of the CL lights are changed from those conforming to the U. S. standard for a "Balanced Lighting System."

Hypothesis 2 No difference in horizontal VR will be found for the "Balanced Lighting System" runway conditions when viewing CL lights through the fog than when viewing edge lights.

In response to a request from the FAA program manager after this effort had begun, a third hypothesis was developed and tested. It had to do with whether college student observers could perceive runway lights any farther through the fog than commercial airline pilot observers.

Hypothesis 3 The horizontal VR of college students will not differ from the horizontal VR of commercial airline pilots when viewing the same runway lights through the fog.

All three hypotheses were tested in Study I of the present research efforts; the second hypothesis was tested in Studies I and II.

A fourth experimental objective was to investigate a number of alternative candidate lighting systems to determine whether they would yield greater VR than the "Balanced Lighting System." This investigation was made in Study II.

METHOD

Testing Facility

All testing was done in the NASA/FAA fog chamber located at Richmond, California. This facility is described in detail elsewhere (21, 22). Briefly, it consists of a building 820 feet long, 30 feet wide, and from 30 to 10 feet high. The present investigations were conducted at the low end of the building. The roof and upper portion of the walls are covered with translucent corrugated fiberglass panels. The floor is surfaced with asphalt concrete. A full set of 1/10-scale approach, threshold, touchdown zone, runway centerline (CL), and High Intensity Runway Lights (HIRL) have been installed on this surface as have all standard white runway markings in conformance with current U. S. National Standard specifications (but without strobe flashing approach lights).

Scale Reduction Details: All linear dimensions on the floor of the fog chamber are 1/10 full scale. Since fog is generated for 800 feet of building length, this is equivalent to 8,000 feet for testing purposes. To ensure that the visual scene within the fog chamber presented to the subject(s) is fully representative of the full-scale visual scene, the illumination and apparent intensities of the runway lights must be maintained as well. This is accomplished by reducing the intensity of all light sources by an appropriate factor. Since illumination at the eye varies as the inverse square of the distance between the eye and the source of light, and the linear scale reduction factor is 1/10, the effective light source intensity is therefore reduced by $(1/10)^2$ or 1/100. Because brightness is the effective intensity divided by the projected area of the light source, the linear dimensions of all optical components of all runway light sources is also reduced by 1/10 their full-scale dimensions. This results in a reduction of the light output *area* of each fixture to 1/100 of the full-scale area.

Since all of the linear dimensions and light intensities in the fog chamber are reduced as they would be if the subject were in the real environment at ten times the viewing distance, the visual scene appears very nearly as it should except for several factors discussed in a previous report from the fog chamber (22). Hereafter, all linear dimensions cited represent their full-scale equivalents.

Fog Generation and Control: Water droplet fog can be fed into 800 feet of the facility. It is produced by feeding water and compressed air through some 100 nozzles. The light scattering and absorption properties of this fog are comparable to natural fog. Other details of the fog generating system are given elsewhere (22, Appendix 6).

The method used to determine fog density for establishing the day and nighttime testing conditions in the fog chamber was the same as used in previous fog chamber studies (cf. 22, p. 12). Observers were stationed at opposite ends of the runway. Between them extended a row of HIRL (edge) lights spaced 200 feet apart set at 20,000 cd (step 5) intensity. When both observers saw the same specified number of lights, the visibility conditions were considered at proper test conditions. This procedure was used only once at the beginning of these investigations; thereafter, the chamber's transmissometers automatically controlled fog density.

It must be pointed out that no RVR measurement equipment was available in the fog chamber, nor has such equipment been present for the numerous investigations conducted there for several years. Since no RVR transmissometer equipment was present or readily available for use in the present investigation, the above procedure was considered the next best procedure to use. However, caution must be exercised in attempting to relate the present VR data to other VR data related to RVR determined automatically. Hereafter, the term *equivalent RVR* will be used to refer to data obtained by this technique.

Fog density within the fog chamber was controlled automatically throughout the entire investigation by means of several transmissometer units each having 63 foot-long baselines. Each transmissometer controlled a set of solenoid-operated fog nozzles discussed above. The transmission factors measured for each fog density condition are given below (in percent transmission). A spectral filter was used in the transmissometer that possessed a maximum transmission at 800 nm, which is just beyond the visible range. Therefore, the present fog chamber transmission values may not fully represent visual transmission through fog.

Category	Day	Night
I	14.28	5.00
II	3.33	1.00
IIIA	.10	.001
IIIB	.005	.0003

Fog Particle Characteristics: In terms of its optical properties, the fog produced within the fog chamber is considered to be fairly representative of real fog. The size of the fog particles produced in the chamber and their relative distribution by size are also approximately the same as found in real fog. To maintain the same degree of light attenuation, however, there have to be more particles present per unit volume. Airport fog-density measurement systems typically use either a 250- or 500-foot-long baseline over which light transmission is measured periodically. This full-scale distance is equivalent to 25- or 50-feet in the fog chamber. Therefore, if, say 10 percent of the projected light reaches the opposite end of the baseline and enters the receiver unit 50 scale feet away in the fog chamber, this would represent the same attenuation as a transmission of 10 percent along a baseline of 500 feet at an actual airport site.

Photometric Measurements: Photometric measurements of CL and edge light luminances and selected markings were made periodically during testing using a United Detector Technology, Model 11A Photometer/Radiometer with telephotometer head. Correlative measurements were also made using a Pritchard Spectra photometer with 2 min arc aperture. All values cited are traceable to a new Gamma 100 ft-L standard source. Table 1 presents these data.

Figure 9. Photograph of runway centerline light fixture and light shutter modification.

During the night runs of Study I, with all building lights and runway lights off, the luminance at the reference eye position[5] (looking horizontally down the runway) in 2,400-foot RVR fog was 3.72×10^{-4} lux. This value increased to 5.11×10^{-2} lux when the CL and edge lights were turned on to step 5. The first value is representative of the amount of outdoor ambient illuminance that enters the fog chamber's translucent fiberglass panels at night and scatters within the fog.

Runway Centerline Light Modification: The 1/10 scale flush runway CL (type L-850) fixtures (6) existing in the fog chamber and described elsewhere (22), were modified for the present investigations. In order to be able to turn each CL light on and off in a sequential manner, a solenoid-actuated metal shutter (Fig. 9) was installed in front of each fixture within the last 3000 feet of runway. Special control circuitry was also developed to open and close each shutter sequentially in either direction in 50- or 100-foot multiples, i.e., every fixture or every other fixture.

The 54.1- and 55.2-(scale) foot eye heights represent the lowest eye positions that were achievable using a full-scale cockpit. A 15-foot eye height is assumed in the definition of RVR, and the reader should keep this unavoidable discrepancy in mind when interpreting these findings.

Other Test Equipment Used: Each subject sat within a full-scale Convair C-122 cockpit section (Fig. 10). The reference eye position for Study I was 55.2 (scale) feet above the runway. For Study II, the reference eye position for the *low* cockpit condition was 54.1 (scale) feet and 65.4 (scale) feet above the runway for the *high* cockpit condition. A stream of cold air from a compressed air line was directed upon the outside of the pilot and the co-pilot windows to remove fog condensate.

The interior of the pilot's side of the cockpit is shown in Figure 11 and included the following features. A small button was located on the right-hand side of each yoke. When depressed, this button locked a number into the response readout display (the rectangular control unit between the two subjects in Fig. 11). This number corresponded to a particular CL light.

The small response box held by each subject (Fig. 11) contained a silent rotary switch with which he could select a number from one to 22 without influencing the other subject. These numbers were displayed silently on a display screen located directly above the rectangular control unit mentioned previously. The experimenter, who sat behind and between the subjects, recorded the data by hand.

Figure 10. Photograph of Convair cockpit used in the present investigations.

Figure 11. Photograph of pilot's side of cockpit interior showing response and display equipment used.

The right- and left-hand side cockpit windows were sandblasted, light diffusing plastic. The four remaining forward windows were clear plastic. During maximum sunlight luminance conditions outside the fog chamber, both side windows possessed a luminance of from 19.5 to 22.3 lux over their surfaces.

In order to ensure a 15° arc lower window-frame cutoff angle, the cockpit was located at a distance from the first (reference) CL light such that, when the subject adjusted his seat to the appropriate height, he could just see this runway light above the lower frame of the forward window. Measurements indicated that this head position adjustment procedure placed the eyes within plus or minus 0.75 in. of the reference eye position.

Visual Range Determination Techniques

Visual range[2] was determined using five different methods. The first two methods were used to test hypothesis 1 and the last three to test hypothesis 2. These methods included:

1. Detection task that indicated the VR at which the subject first noticed that a CL light had been extinguished. The CL lights were extinguished sequentially beginning with the farthestmost light.

2. Detection task that indicated the VR at which the subject first noticed that a CL light had been extinguished. The CL lights were extinguished sequentially beginning with the nearest light.

3. Sequential CL light count beginning with the nearest light with all runway lights on.

4. Sequential left-edge light count with all runway lights on.

5. Sequential right-edge light count with all runway lights on.

Each method was discussed in detail and demonstrated to each pair of subjects to ensure that they understood these tasks.

The nearest visible[6] CL light was identified as number 1; a green filter was placed in front of it to aid each subject in determining its location. Likewise, red glass filters were located in front of the left- and right-hand number 1 edge lights.

The constantly changing patches of fog that are common in real-life situations were also present to some degree during these tests. These patches could be seen during the daytime runs particularly. They tended to move across the field of view horizontally rather than diagonally or up and down.

The first VR determination method involved automatically turning off the CL lights one by one, beginning with the farthestmost light at a constant rate of 1 light per 0.65 second. When a subject noted that a CL light had disappeared he depressed the thumb button on his yoke which "locked" a number, corresponding to that CL light position, into a digital readout. Occasionally, temporal variations in fog density led to premature responses. For, although the CL light had indeed disappeared, it was due to the intervening fog and not because the experimental apparatus had extinguished the light. The duration from the start of this type of measurement trial to the moment when the subject responded was relatively long even for the least dense fog condition (i.e., about 35 sec). This relatively long duration, nevertheless, helped control for temporal estimation cues. If either or both subjects responded prematurely, that trial was repeated later.

The second VR determination method was similar to the first except that the CL lights were extinguished sequentially starting with the nearest (No. 1, green) light. These trials took only about 15 seconds to complete.

An observational problem common to the last three VR determination methods was that of standardizing viewing time. It was found that one could see somewhat farther through the fog if allowed to wait until patches of fog drifted out of the line of sight. Therefore, it was necessary to limit the viewing-counting time each trial to 20 seconds for the last three types of VR measurement methods described above. Only occasionally did a subject request more time than this. When this occurred, he was urged to respond within the next several seconds. If a subject lost his count and had to start over again, enough time was allowed for him to do this.

Other Data Collected

In addition to the VR judgments described above, each subject was asked a series of multiple choice questions immediately after they had completed their observations. The primary intent of these questions, which are found in Appendices A and B, was to assess the subjects' opinions regarding the relationship between their prior experiences in fog environments, and various experimental parameters (e.g., estimates of the adequacy of this low visibility simulation).

The test instructions given to each subject are given in Appendix C.

Experimental Design I

Study I By mutual agreement with the FAA Program Manager, the experimental conditions shown in Figure 12 were investigated first. This design can be characterized as a 4 X 3 X 2 factorial

Ambient luminance and pilot offset		Fog density equivalency: Cat. I (2400 ft RVR)	Cat. II (1200 ft RVR)	Cat IIIA (700 ft RVR)	Cat. IIIB (300 ft RVR)
Day (2.78×10^{1} lux)	Zero				
	5.04 m				
	10.12 m				
Night (9.29×10^{4} lux)	Zero				
	5.04 m				
	10.12 m				

Figure 12. Experimental design for Study I.

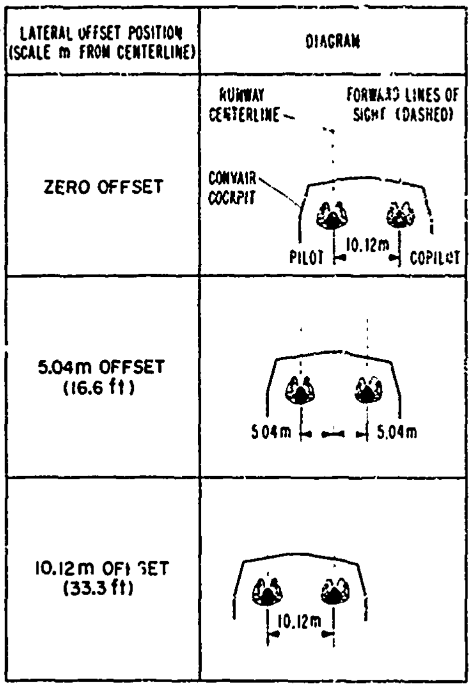

Figure 13. Diagram of the three lateral offset viewing positions tested in Study I.

design with partial replication. This design was selected so as to determine the influence these environmental variables have upon detecting the extinction of CL lights through fog and thereby test the first experimental hypothesis. Subjects were tested in pilot–co-pilot pairs. Each subject sat in the same seat during the entire test period. Each pair of subjects was tested under a different RVR condition and all three lateral offset conditions during either the day or the night. Several subjects participated in both day and night runs as indicated by asterisks in Table 2. As discussed below, the fact that both students and commercial airline pilots were tested in Study I made it possible to test the third experimental hypothesis regarding whether the horizontal VR of one group will differ from that of the other. A total of 990 responses were obtained in this investigation.

Figure 13 illustrates schematically the three cockpit lateral offset positions that were investigated. The cockpit's interseat distance of 1.01 m (3.33 ft) established the zero and 10.12-(scale) m offset conditions. Hereafter, the lateral offset value cited refers to the *scale* distance from the pilot's seat to the left of the runway's CL.

Experimental Design II

Study II The experimental design used in Study II is given in Figure 14. These variables were selected by mutual agreement with the FAA Program Manager to test the second experimental hypothesis. A total of 13 experimental conditions were tested in each of four equivalent fog densities. These included the experimental conditions to test the (second) hypothesis that pilots will not be able to see any farther down the runway through fog when looking at CL than at runway edge lights for the "Balanced Lighting System."

To obtain data on the question of whether another candidate lighting system might be found that would yield greater VR than that afforded by the currently used U. S. standard "Balanced Lighting System," a number of other CL/Edge (E) light intensity combinations were also investigated in Study II. Two other candidate CL/E light combinations were investigated during *daytime* lighting conditions. For the "Balanced Lighting System" the CL lights were 25 percent as intense as the edge lights. For the other two candidate systems the CL lights were 5 and 1 percent as intense as the edge lights. The effect of 50- and 100-foot CL spacing was also investigated. A total of four CL/E intensity ratios were investigated during *nighttime* runs as indicated; 5, 25, 125, and 625 percent.

These experimental conditions may be more clearly related to the question of the adequacy of the present "Balanced Lighting System" to provide for maximum VR in fog by reference to

Ambient Luminance and Runway Light Step Setting		CL/E Ratio (%)	Fog density equivalency								Experimental Condition
			Cat. I (2400 ft RVR)		Cat. II (1200 ft RVR)		Cat. IIIA (700 ft RVR)		Cat. IIIB (300 ft RVR)		
			50'	100'	50'	100'	50'	100'	50'	100'	
Daytime	CL = 5 (5000 cd) E = 5 (20000 cd)	25									1
	CL = 4 (1000 cd) E = 5 (20000 cd)	5									2
	CL = 3 (200 cd) E = 5 (20000 cd)	1									3
Nighttime	CL = 5 (5000 cd) E = 5 (20000 cd)	25									4
	CL = 4 (1000 cd) E = 4 (4000 cd)	25									5
	CL = 3 (200 cd) E = 3 (800 cd)	25									6
	CL = 4 (1000 cd) E = 3 (800 cd)	125									[illegible]
	CL = 5 (5000 cd) E = 4 (4000 cd)	125									8
	CL = 5 (5000 cd) E = 3 (800 cd)	625									9
	CL = 3 (200 cd) E = 4 (4000 cd)	5	This cell not tested.								10
	CL =5 (5000 cd) E = off	—									11
	CL = 4 (1000 cd) E = off	—									12
	CL = 3 (200 cd) E = off	—									13

Figure 14. Experimental design for Study II.

CURVE	HIRL INTENSITY (cd)	DAY	NIGHT	EXPERIMENTAL CONDITIONS*
1	800		X	9
2	4 000		X	8
	800		X	7
3	20 000	X	X	14
	4 000		X	5
	800		X	6
4	20 000	X		2
5	20 000	X		1

NOTES *THESE NUMBERS REFER TO THE NUMBERED CONDITIONS GIVEN IN THE TEXT

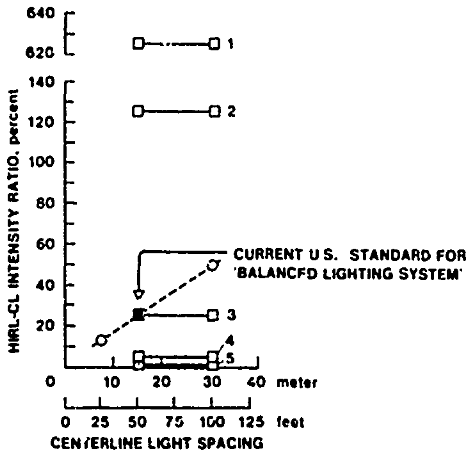

Figure 15. Relationship of the runway lighting variables tested in Study II to the "Balanced Lighting System."

Figure 15, which shows the relationship between CL light spacing and the CL to HIRL intensity ratio. Numbers given in the experimental condition column of Figure 14 correspond to the numbered experimental conditions given in the upper right-hand portion of Figure 15. The current U.S. standard for the "Balanced Lighting System" is shown by the filled square at the intersection of the dashed diagonal line and the horizontal line labeled 3.

A total of 9,824 responses were obtained in Study II.

To obtain data on the influence of pilot eye height above the runway upon VR, two heights were investigated in Study II. The cockpit was positioned so that the reference eye position was 54.1 (scale) feet above the runway (hereafter called the *low* position). Every cell in Figure 14 was studied at this eye height. Because of the severe time restrictions, a limited amount of data was obtained for each cell noted in Figure 14 with the cockpit raised to an eye position of 65.4 (scale) feet above the runway (hereafter called the *high* position).

Test Subjects for Study I

A total of 38 male volunteers took part in the first study, 30 were college students and 8 were commercial airline pilots. Table 2 provides age, distance acuity (black letters on white background; Snellen notation) and student/pilot category information for each subject. All were paid for their services.

Test Subjects for Study II

Fifty-two male volunteers took part in Study II. All but six were commercial airline pilots. All pilots possessed valid CAB licenses. All students possessed 20:20 or better near and distant acuity. All subjects were paid for their services. The mean age of the day pilots was 33.9 years and the day student 20 years. The mean age of the night pilots was 34.6 years and the night students 18.5 years. The day and night pilots had a mean of 5317 and 5793 flight hours, respectively.

The average testing time for Study I was 40 minutes, and for Study II about 60 and 90 minutes for the daytime and nighttime runs, respectively. Approximately 15 minutes was required to change from one fog density to another. Only about 1 minute was required to move the cockpit into the proper lateral offset position during Study I.

RESULTS

The most distant CL or edge light perceived by each subject through the fog was converted into visual range (feet) from the subject's eye position for both studies. All of the following data represent these converted VRs.

Hypothesis One

The first experimental hypothesis tested was that no difference in horizontal VR will be found when viewing a single runway CL light through the fog than when viewing more than one CL light. This hypothesis bears upon the matter of whether VR is influenced by the presence of runway CL or edge lights located nearer to the subject than the light at the limit of his visual range.

The first VR determination method was used to test this hypothesis. This technique required the subject to respond when he first detected that a CL light had been extinguished from view. By extinguishing the CL lights sequentially beginning with the most distant light, the eye had to make this detection under the (light-adapting) influence of all of the visible foreground CL and edge lights. The mean detection VR data averaged across the pilot and co-pilot seats are presented in Tables 3 and 4 for Studies I and II, respectively. The agreement between these two sets of data for comparable viewing conditions, is good. Results of a t-test (37) indicated that the mean CL light detection VRs found in Study I are not significantly different from those found in Study II, for comparable viewing conditions, except for one case (cat. I, day; $p < 0.01$).

In order to determine the eye's ability to detect CL light offset *without* the light adapting influence of the various foreground lights, the second VR determination method was used, i.e., the CL lights were extinguished sequentially beginning with the nearest CL light. The mean results of these tests are presented in Tables 5 and 6 averaged across the pilot and co-pilot seats for Studies I and II, respectively.

Again, the agreement between the mean VR data from both studies for comparable viewing conditions was very good. The only significant difference between these two sets of data was for the category I, day data (37, t-test, $p < 0.05$). The fog density main effect was also found to be highly significant in Studies I and II. Study I results were ($F(3,12) = 214$; $p < 0.001$) and Study II ($F(1,8) = 74.8$; $p < 0.001$). The other significant findings are presented in Tables 9 through 11.

In order to illustrate these mean data graphically, the data from Tables 3 and 5 are presented in Figure 16 (for Study I; day) and from Tables 4 and 6 in Figure 17 (for Study I; nighttime). The effect of each of the three lateral cockpit offset positions is also shown and was found to be a significant main effect by analysis of variance ($F(2,24) = 4.3$; $p < 0.05$). Equivalent RVR is shown on the X axis in both ft and m and mean visual range is plotted upon the Y axis in both ft and m. The solid diagonal line in each graph indicates where the data should lie if equivalent RVR accurately predicts VR for the conditions noted.

It was reasoned that if the foreground lights played a role in altering the visual threshold for perceiving more distant runway CL lights, then the VR for the "away" extinction technique should

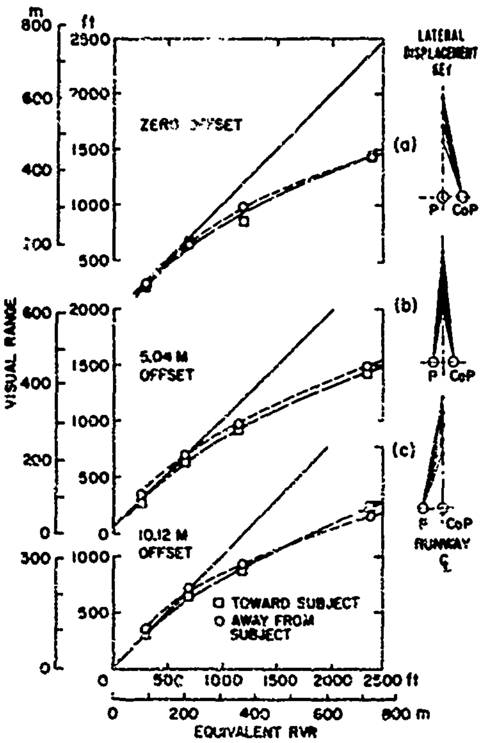

Figure 16. Sequential centerline light extinction-detection range mean daytime results (Study I).

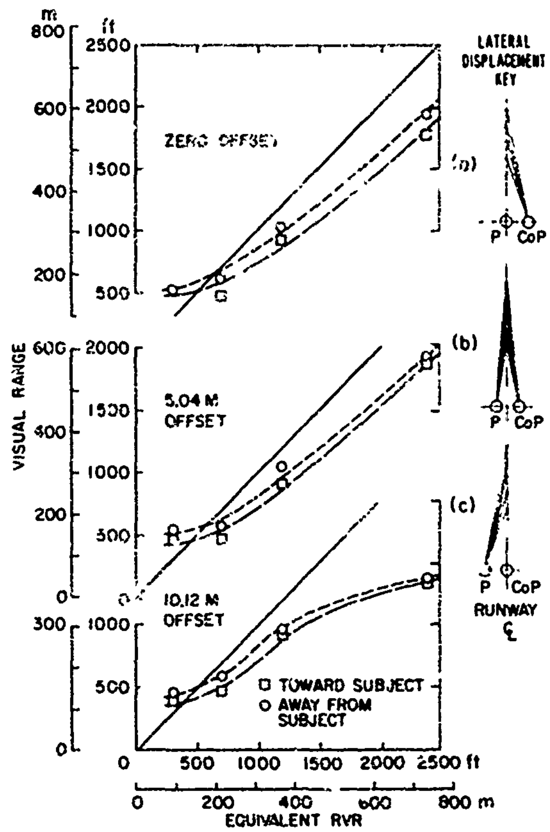

Figure 17. Sequential centerline light extinction-detection range mean nighttime results (Study I).

be significantly greater than for the "toward" extinction technique. An analysis of variance indicated that the mean "away" data did not differ significantly from the mean "toward" data within each cockpit offset condition shown in Figures 16 or 17. Other comparisons were made from the data obtained, however, before either accepting or rejecting hypothesis I.

Mean detection VR data were also obtained in Study II for the cockpit in the high position, and the 50-foot CL spacing. Both CL and edge lights were at step setting 5. Mean sequential extinction data in the "toward" direction are presented in Table 7 and in Table 8 for the "away" direction. These mean day and nighttime data have been plotted in Figures 18 and 19, respectively. Again, statistical tests showed that the mean "toward" CL light sequential extinction VR was not significantly different from the mean "away" CL light sequential extinction under these viewing conditions. Therefore, it is possible to say that this higher viewing position (eye height = 65.4 ft above runway) did not influence mean VR through these fog conditions using these sequential extinction testing methods.

An analysis of variance was performed on the mean VR data from both studies where the VR resulting from counting CL lights that remained on continuously was compared to the VR resulting

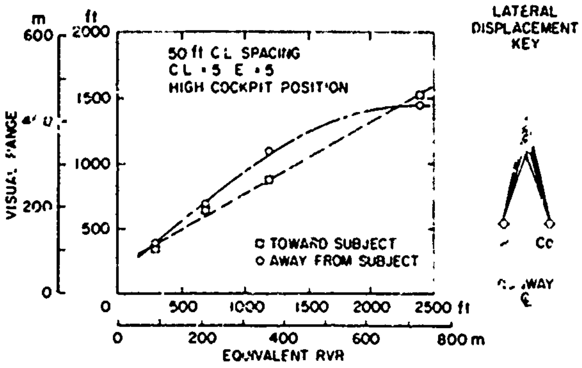

Figure 18. Sequential centerline light extinction-detection range mean daytime results (Study II).

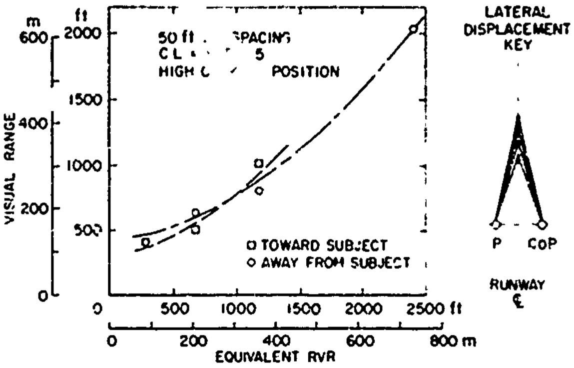

Figure 19. Sequential centerline light extinction-detection range mean nighttime results (Study II).

from detecting the furthestmost CL light that had been extinguished in the "away" direction. The difference between these measures of VR through the fog was highly significant ($F(1,36) = 336$; $p < 0.001$), ($F(1,56) = 58.5$; $p < 0.001$), for Studies I and II, respectively.

Although it is not possible to make a strict experimental comparison between these two sets of VR data because of differences in the measurement techniques used, the fact that a relatively greater VR was achieved using the sequential CL light extinction technique (mean = 1460 ft Study I; mean = 1165 ft Study II) versus a continuous CL light count (mean = 1003 ft Study I; mean = 829 ft Study II) may have some important implications regarding the possible use of flashed CL lights in low visibility conditions. This possibility deserves further study.

In view of the finding that the foreground CL lights did not significantly influence VR viewing CL lights raised the question of whether the runway edge lights may have affected VR through the fog of viewing the CL lights. To assess this possibility each subject in Study II counted CL lights that remained on continuously (i.e., VR determination method 3) for each of the four fog density, two CL-spacing, and three CL step setting conditions with the edge lights turned off during the daytime runs. These mean data are presented in Table 9. These edge-light-off mean VR data have been plotted with their comparable edge light on data in Figures 20 and 21 for the 50- and 100-foot CL spacings, respectively. The edge lights were kept on step 5 for the data shown here.

Keeping in mind the relatively small number of sightings made for the edge-lights-off data, no definite trend is seen as to which experimental condition yields a greater VR for CL lights spaced 50 feet apart; however, for the CL lights spaced 100 feet apart, mean VR of the CL lights is greater with the edge lights on in every case. Also, a small, insignificant reduction in VR was found when the CL lights were turned to a lower step setting than 5. It may well be that these findings are partially a result of the high background brightness of the daytime viewing conditions so that the 100-foot CL spacing produced more angular separation between each visible CL light viewed from the pilot's eye position than would be produced by the 50-foot CL spacing. The larger angular separation would act to increase the magnitude of the luminance difference between each CL light's glow field[7] and the glow field's immediate background. If this is the case, one would expect greater VR while viewing the CL lights spaced 100 feet apart due to greater effective contrast for each. /.

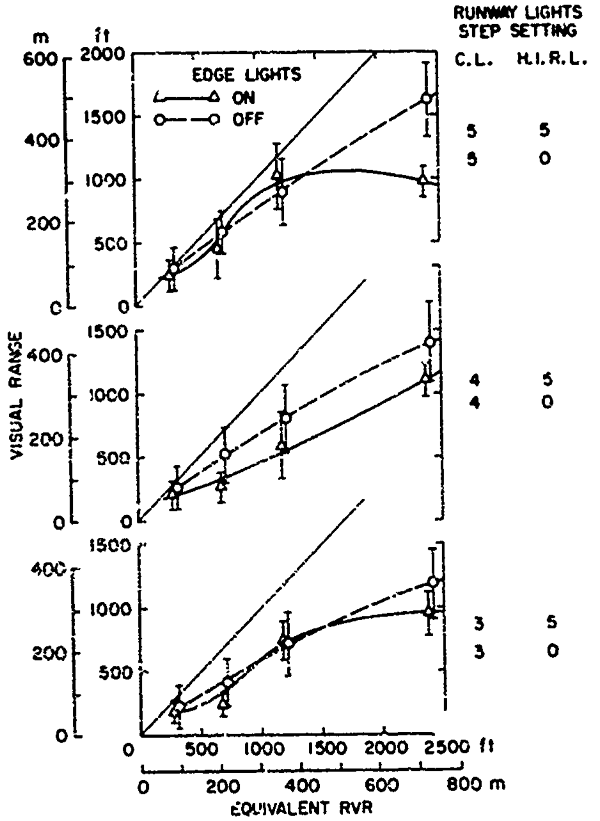

Figure 20. Effect of runway edge lights upon VR viewing centerline lights spaced 50 feet apart (Study II).

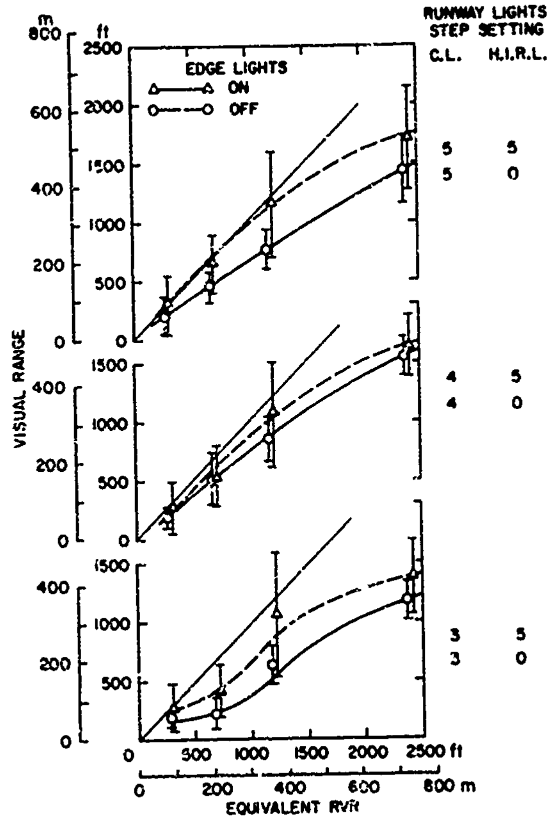

Figure 21. Effect of runway edge lights upon VR viewing centerline lights spaced 100 feet apart (Study II).

analysis of variance indicated that the CL light spacing main effect was significant both for the day, low cockpit condition ($F(1,56) = 8.1$; $p < 0.005$) and for the nighttime, low cockpit condition ($F(1,56) = 12$; $p < 0.001$). Compared to the 50-foot spacing, the 100-foot CL light spacing is likely to improve the pilot's perception of altitude and range.

From all of the mean VR data presented to this point it is not possible to reject the first experimental hypothesis. Nevertheless, the present subjects did tend to see CL lights farther through these fog conditions with the foreground CL lights off.

Hypothesis Two

The second hypothesis tested was that no difference in horizontal VR will be found for runway lighting conditions that conform to the current U. S. standard "Balanced Lighting System" configuration when viewing CL lights than when viewing edge lights through the fog. Visual range data bearing upon this hypothesis were obtained in both Studies I and II.

Centerline Light Count Results: Mean VR data from Study I for counting CL lights through these fog conditions are presented in Table 10. It should be remembered that all runway lights remained on throughout all of these tests and the subjects were stationary. The significance of difference between these variables was tested by analysis of variance, the results of which are presented in Tables 11 through 13. Three separate analyses were required because of the use of a factorial design program and the fact that experimental difficulties led to some of the design cells not being completely filled with data. These three analysis of variance summary tables are complete factorial designs, however.

These mean VR data from Study I have been plotted in Figure 22. They indicate that: (1) In general, the farther the subject is offset laterally from the runway's centerline, the shorter will his VR likely be by using CL lights as targets ($F(2,24) = 4.3$; $p < 0.05$); this is more likely to be true during daytime runs than during nighttime runs. (2) At any given lateral offset position, the difference between the equivalent RVR and mean VR increases with a decrease in fog density ($F(2,12) = 214.2$; $p < 0.001$).

Mean VR data from Study II for counting CL lights are presented in Tables 14 and 15 for the cockpit in the low and high position, respectively.

The data from these two tables have been plotted in Figures 23 through 25 for each fog density, CL spacing, and selected CL and edge light intensity settings. The 5.04 m offset curves

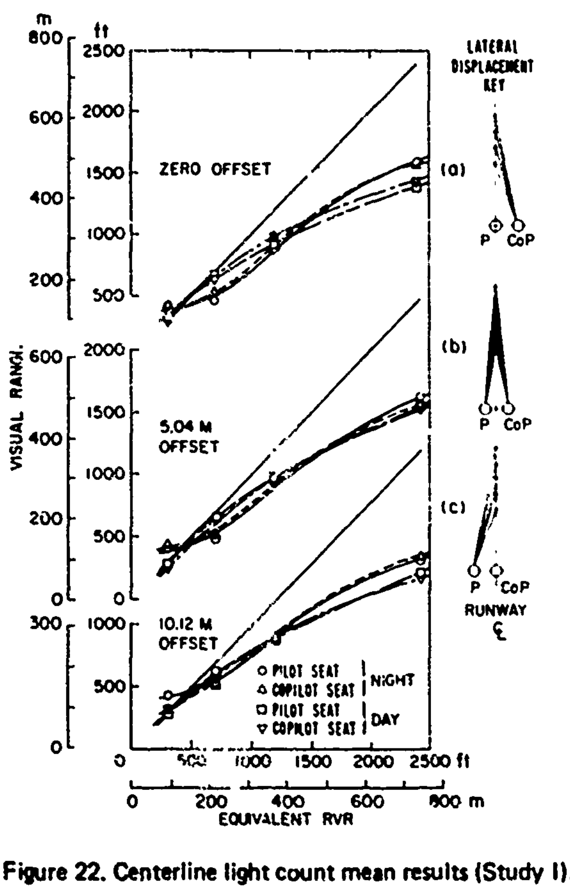

Figure 22. Centerline light count mean results (Study I).

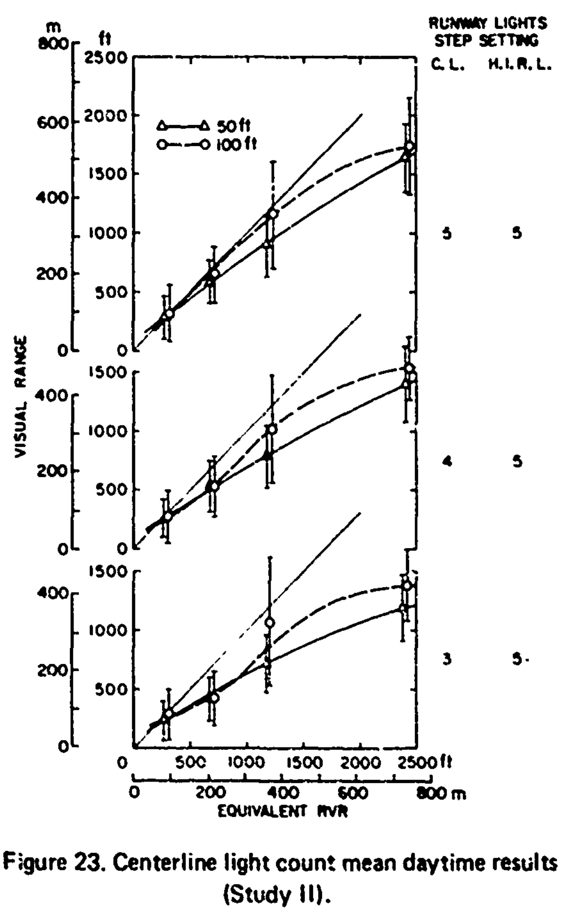

Figure 23. Centerline light count mean daytime results (Study II).

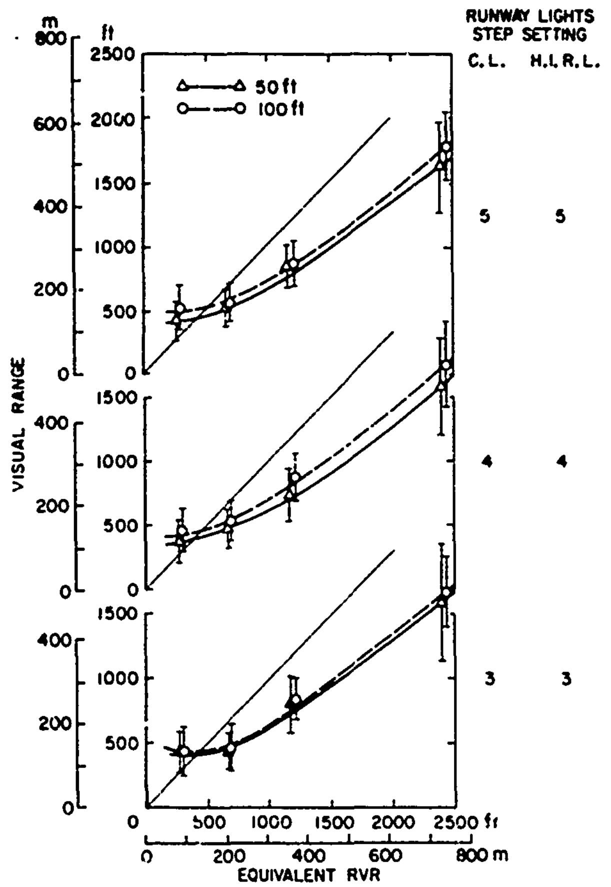

Figure 24. Centerline light count mean nighttime results (Study II).

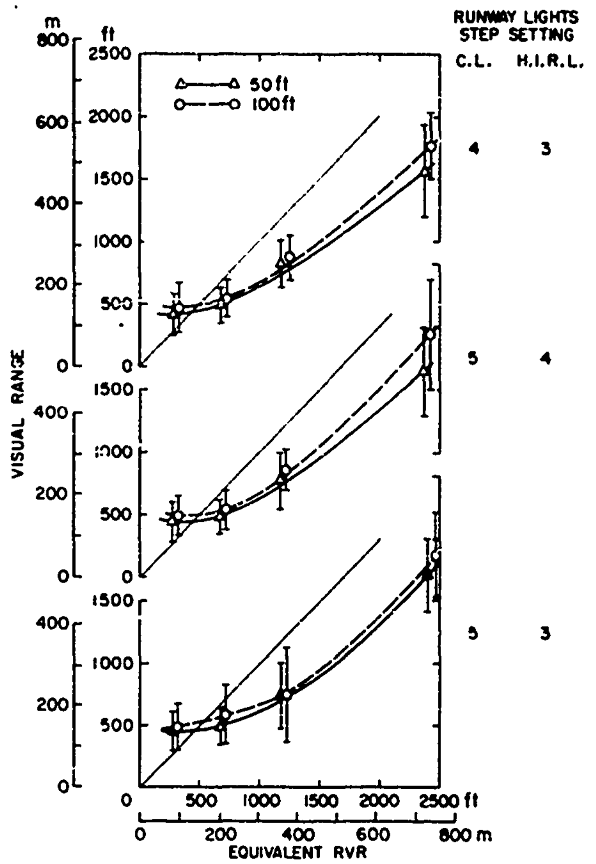

Figure 25. Centerline light count mean nighttime results (Study II).

given in Figure 16 for Study I may be compared against the corresponding daytime data curves in Figure 23 (viz. CL = 5, E = 5, 50-ft CL spacing) and also with the corresponding nighttime curves presented in Figure 24 (viz. CL = 5, E = 5, 50-ft CL spacing) for Study II. The two sets of mean VR data agree extremely well for all comparable experimental conditions.

The fact that most of the data presented in Figures 22 through 25 lie below the diagonal line indicates that equivalent RVR tends to overestimate both day and nighttime VR viewing CL lights in fog conditions equivalent to categories I and II.

Edge Light Count Results (Right Side of Runway): The mean VR results obtained in Study I by counting right-hand runway edge lights through these fog conditions are presented in Table 16. The same type of data obtained in Study II are presented in Tables 17 and 18.

To determine the repeatability of the mean VR data obtained in Study I with those obtained in Study II for the findings presented in Tables 16 and 17, respectively, a number of t-tests (37) were performed. In all eight (four day; four nighttime) comparisons made, not one mean VR differed significantly from the first study to the second, indicating the good repeatability that was achieved between the two studies.

The mean VR data given in Table 16 have been plotted in Figures 26 and 27 to illustrate the effect of day and nighttime illumination and pilot and co-pilot seat viewing position upon mean VR counting right-hand runway edge lights, respectively. Schematic plan view drawings on the right-hand side of each figure show the relative spatial relationship of the pilot and co-pilot seat to the runway's centerline for each set of data.

Mean VR data obtained in Study II are plotted in Figures 28 through 31 for each of the experimental conditions noted. As before, the mean VR data obtained from Study I agree well with comparable mean VR data obtained from Study II.

The present CL light count (VR determination method 3) mean VR data for the CL = 5, E = 5 step setting were replotted as frequency distributions of the difference (ft) between mean VR and equivalent RVR for both the 50-foot and the 100-foot CL spacing. These data are plotted in Figure 32. The zero point on the abscissa indicates no difference between VR and calculated RVR for the conditions noted. A positive difference indicates that VR is greater than calculated RVR.

The mean VR data shown in Figure 32 for the CL light count results indicates a rather marked change in the distribution of VR responses between category I and category II viewing conditions. The category I condition yielded VR estimates that were from 300 to 1,200 feet under the

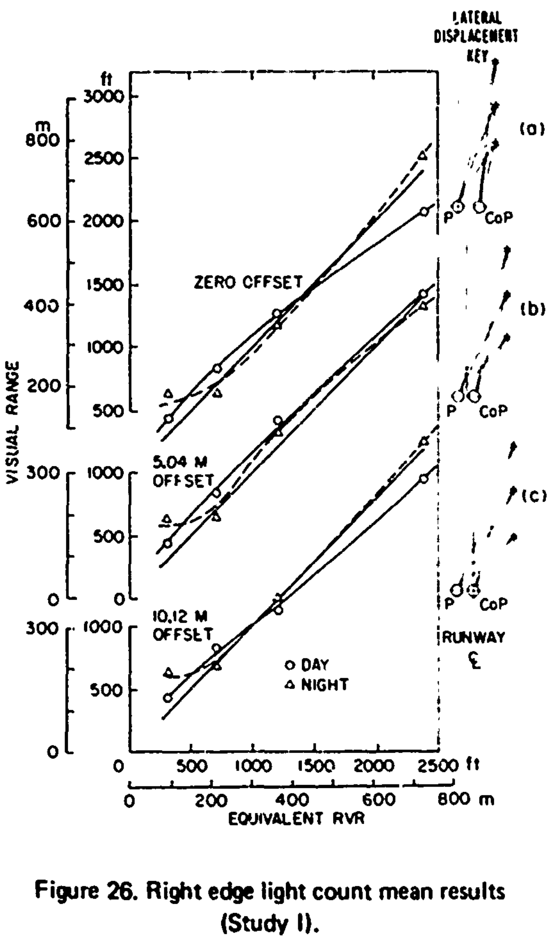

Figure 26. Right edge light count mean results (Study I).

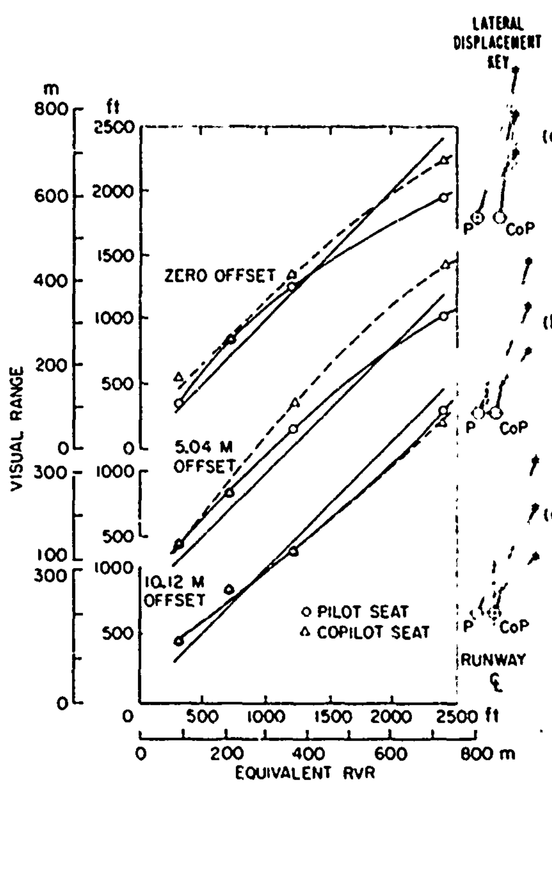

Figure 27. Right edge light count mean results (Study I).

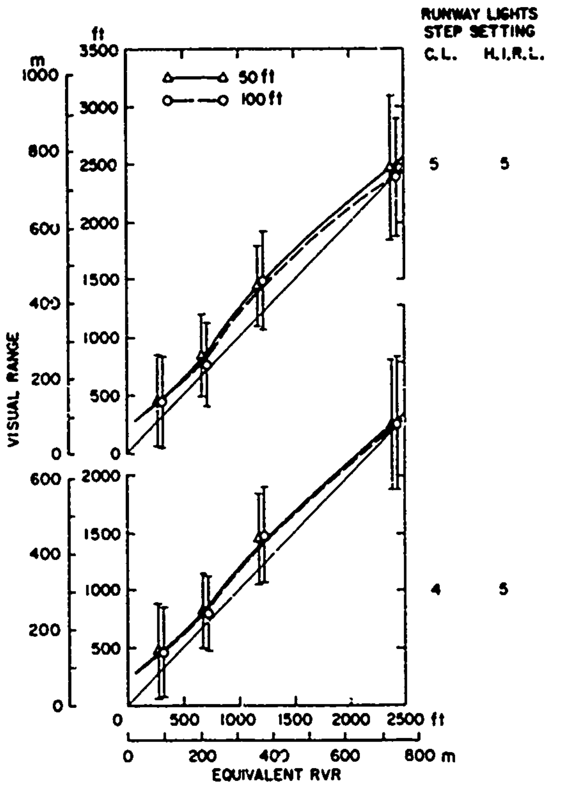

Figure 28. Right edge light count mean daytime results (Study II).

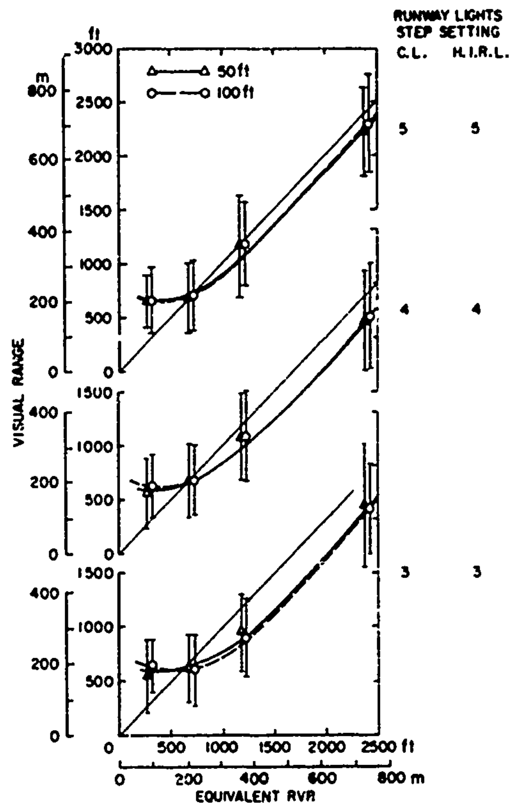

Figure 29. Right edge light count mean nighttime results (Study II).

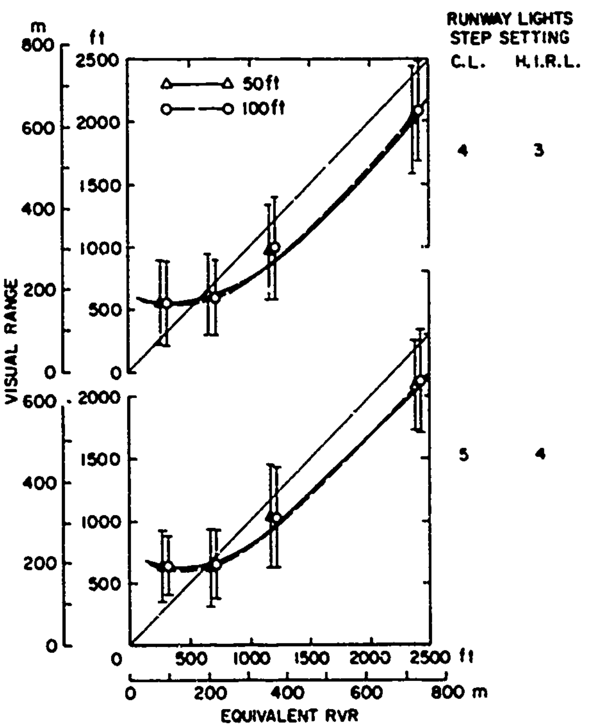

Figure 30. Right edge light count mean nighttime results (Study II).

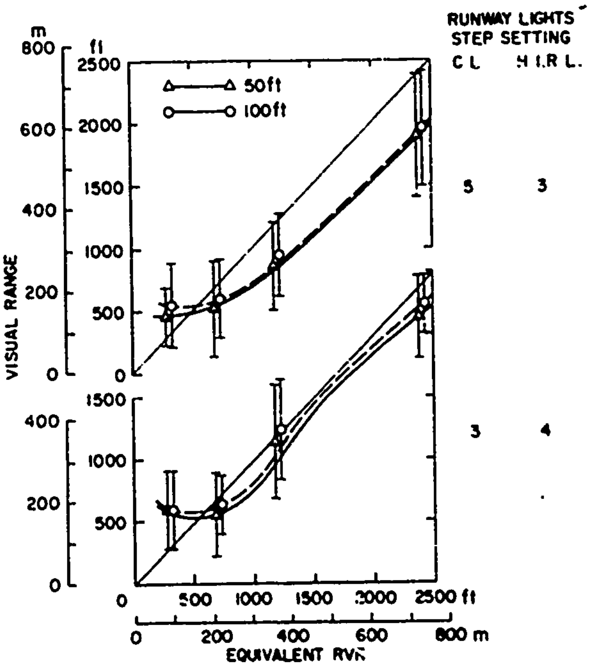

Figure 31. Right edge light count mean nighttime results (Study II).

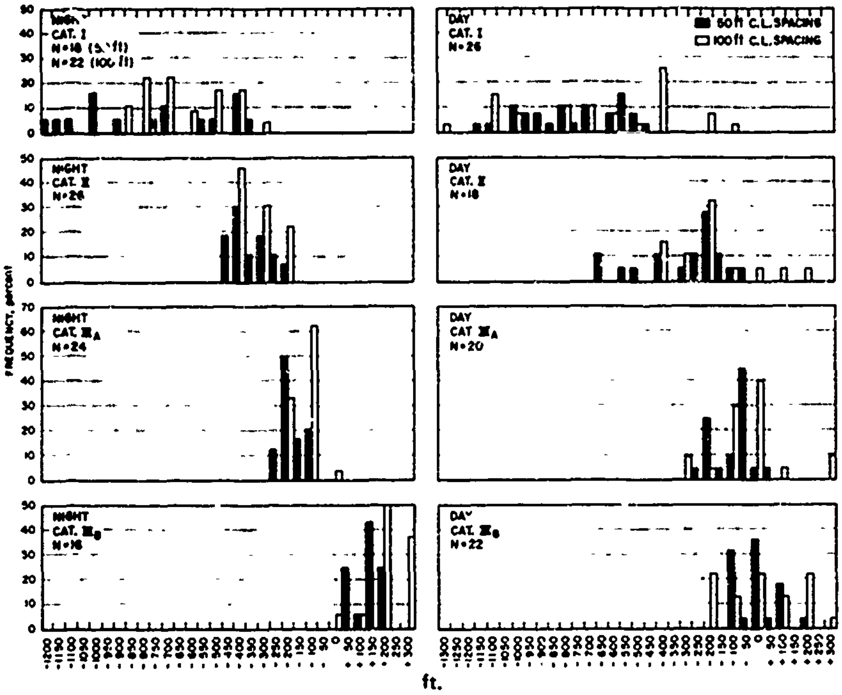

Figure 32. Frequency distribution of difference between VR and calculated RVR for CL = 5, E = 5, centerline light count results (Study II).

equivalent RVR at night and from 100 to 1,300 feet under the equivalent RVR during the day. On the other hand, the category II viewing condition yielded VR estimates that were far closer: The mean VR extends from 200 to 450 feet under the equivalent RVR at night and from 650 feet under to 200 feet beyond the equivalent RVR during the day.

Similar left-hand and right-hand runway edge light count VR data (VR determination methods 4 and 5) are plotted in Figures 33 and 34, respectively. A progressive shift of the frequency distributions in the positive direction with increasing fog density is apparent, indicating that for the nighttime data, VR tends to be estimated more and more accurately by the equivalent RVR for category I, II, and IIIA viewing conditions. Under category IIIB viewing conditions, however, equivalent RVR underestimates VR by from zero to 300 feet. Much the same trend is found for the daytime data.

Edge Light Count Results (Left Side of Runway): The mean results obtained in Study I by counting left-hand runway edge lights through these fog conditions are presented in Table 19; the findings from Study II are presented in Tables 20 and 21, for the cockpit in the low and high positions, respectively.

A number of t-tests were performed on comparable mean VR data from Studies I and II. Mean VR from Study I was not significantly different from that of Study II except for one case (viz. cat. II, day; $p < 0.05$).

The mean VR data from Study I (Table 19) have been plotted in Figures 35 and 36 to illustrate the effect of day and nighttime illumination and pilot and co-pilot seat viewing position upon

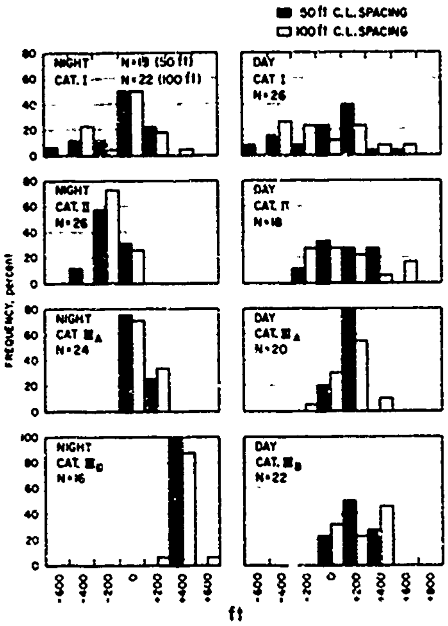

Figure 33. Frequency distribution of difference between VR and calculated RVR for CL = 5, E = 5, left edge light count mean results (Study II).

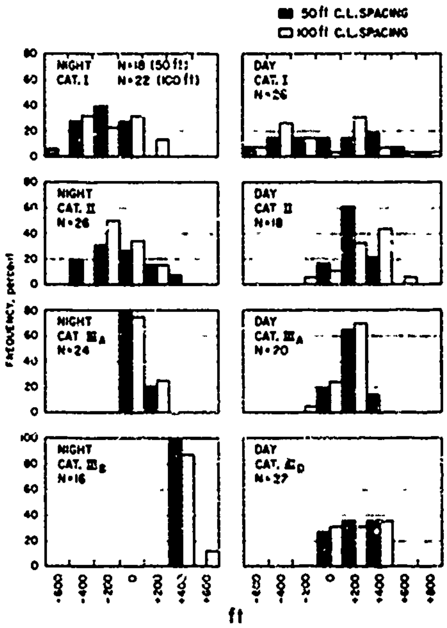

Figure 34. Frequency distribution of difference between VR and calculated RVR for CL = 5, E = 5, right edge light count mean results (Study II).

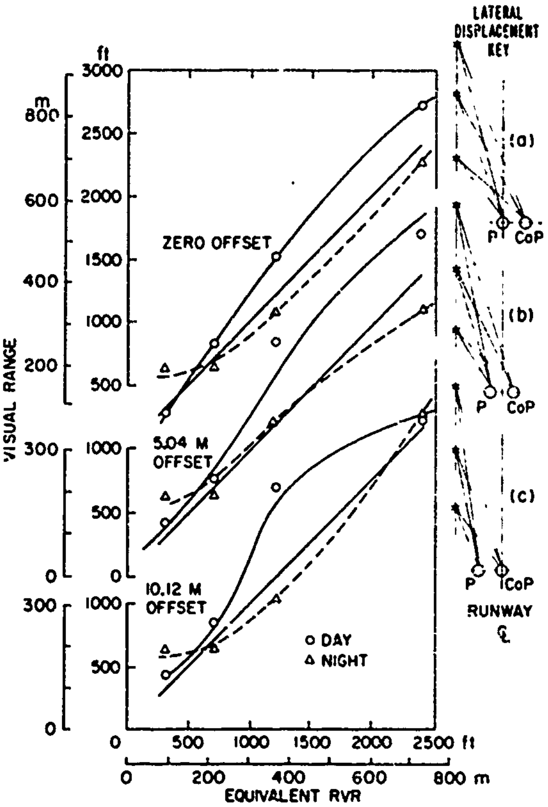

Figure 35. Left edge light count mean results (Study I).

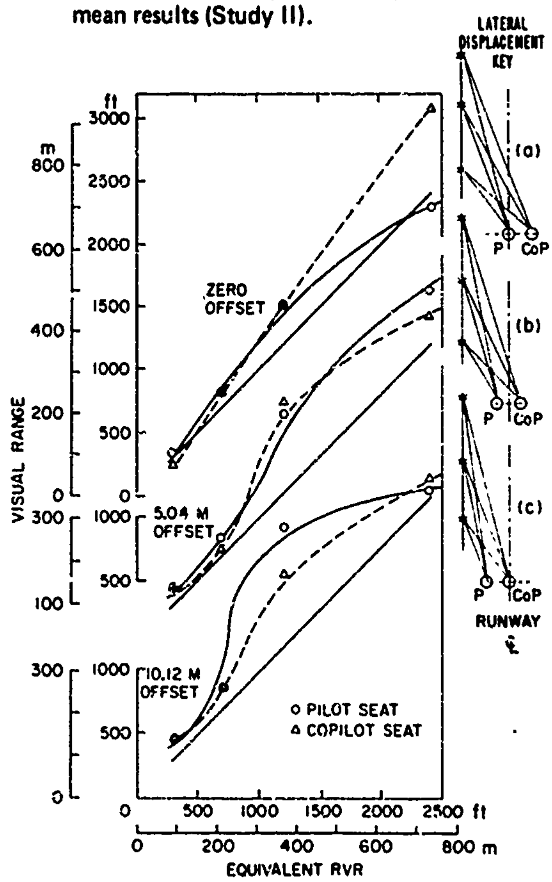

Figure 36. Left edge light count mean results (Study I).

mean VR counting left-hand runway edge lights; mean VR data obtained in Study II have been plotted in Figures 37 through 40 for each experimental condition tested.

Having presented the mean CL and edge light count data, it is possible to address the second experimental hypothesis: that VR through fog will be no greater when viewing CL lights than when viewing edge lights. Since it was found that mean VR was always greater when viewing edge lights, regardless of which side of the runway they were on, the present data have been plotted in a manner that illustrates how much farther these subjects could see the right-hand runway edge lights. Figure 41 resents the mean VR obtained by counting edge lights minus the mean VR obtained by counting CL lights for each experimental condition tested in Study I.

Neither the lateral cockpit offset or day/night illumination variables played any significant role in affecting mean VR under these viewing conditions. Visual range was greater viewing the edge lights than viewing the CL lights by an amount that ranged from under 150 feet (cat. IIIB) to more than 750 feet (cat. I), depending upon the subject's lateral offset distance and the illumination conditions.

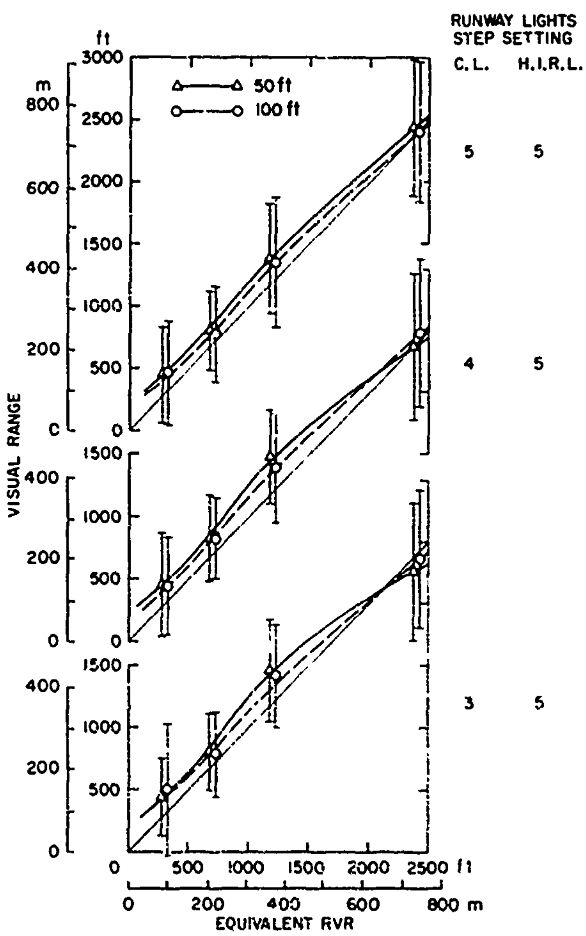

Figure 37. Left edge light count mean daytime results (Study II).

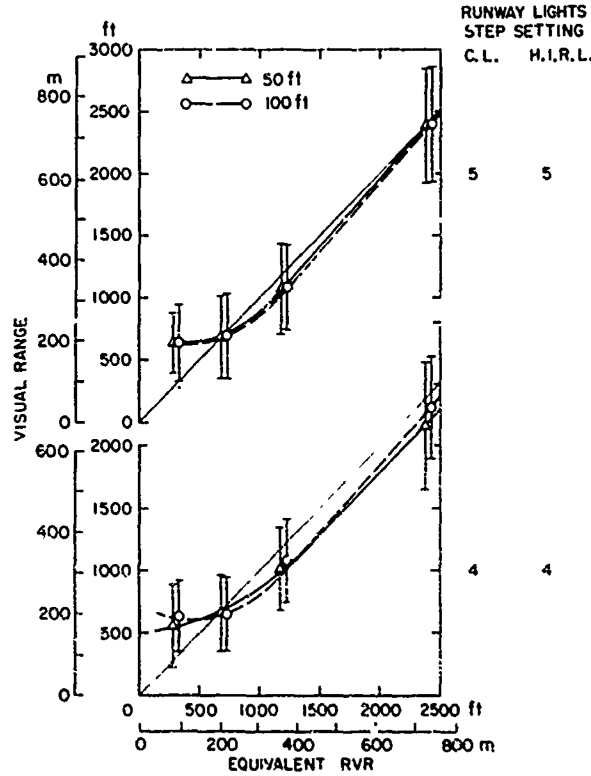

Figure 38. Left edge light count mean nighttime results (Study II).

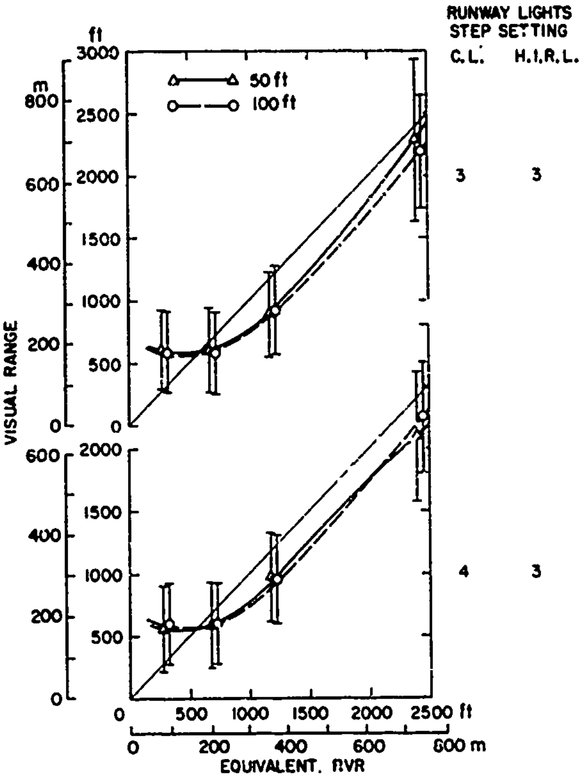

Figure 39. Left edge light count mean nighttime results (Study II).

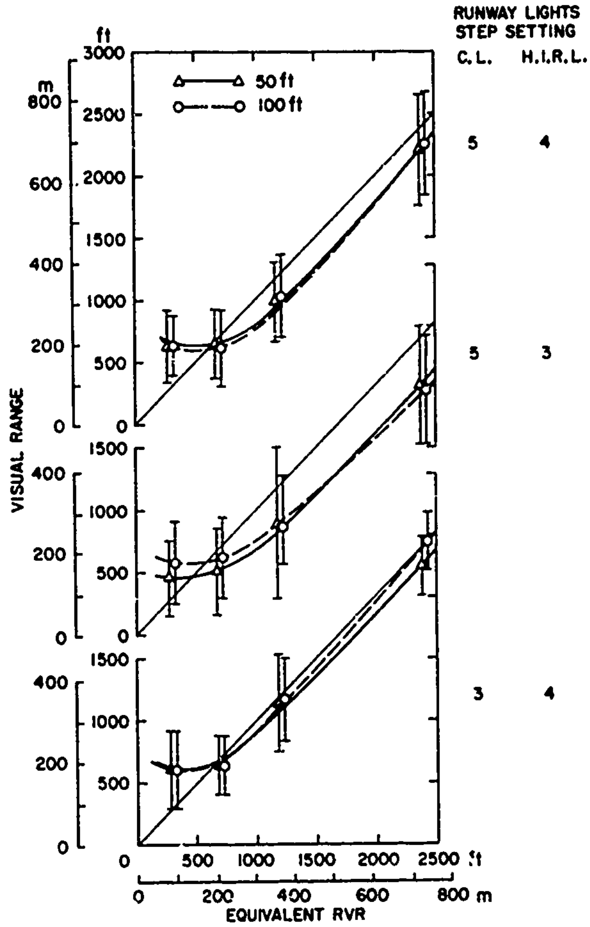

Figure 40. Left edge light count mean nighttime results (Study II).

Similar mean VR data obtained in Study II are presented in Figures 42 through 45. Once again, these subjects could see farther through these fog conditions when viewing runway edge lights than they could when viewing the CL lights. The CL = 5, E = 5 curve in Figure 42 (50-ft CL spacing) agrees very closely with the corresponding data given in Figure 41 (cf. 5.04 m offset, day) from Study I.

It is apparent that for the 50-foot CL spacing condition, only under categories I and II conditions is daytime mean VR greater than nighttime mean VR. For the 100-foot CL spacing condition, daytime mean VR is greater than nighttime mean VR only under category I conditions.

Based upon the present VR data, it appears to be reasonable to reject hypothesis 2.

The mean VR data presented in Figures 43 through 45 also allow one to make comparative statements about the effect that changes in the step settings of both CL and edge lights have upon VR through fog at night with the cockpit in the low position (i.e., eye height 54.1 ft above the

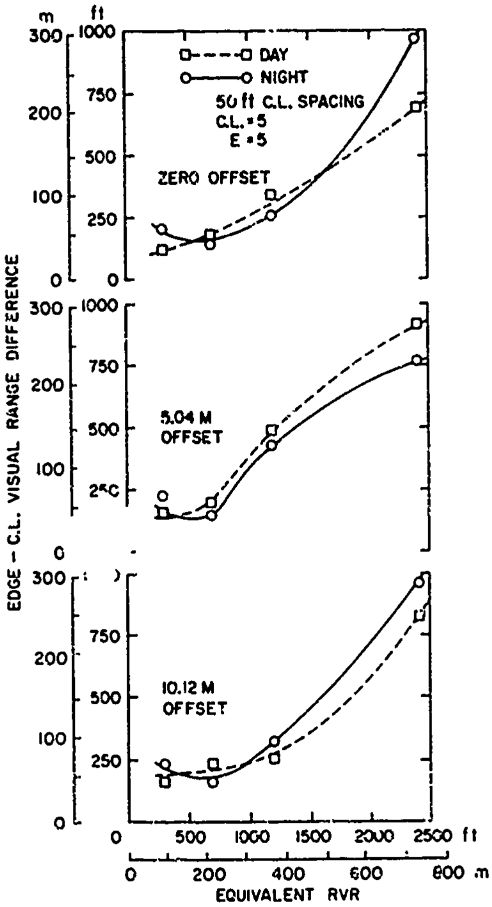

Figure 41. Visual range counting edge lights minus VR counting centerline lights (Study I).

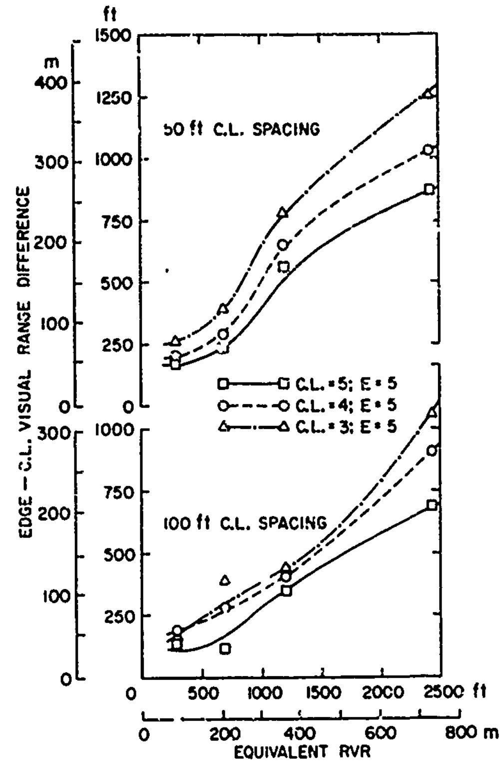

Figure 42. Visual range counting edge lights minus VR counting centerline lights, daytime, low cockpit (Study II).

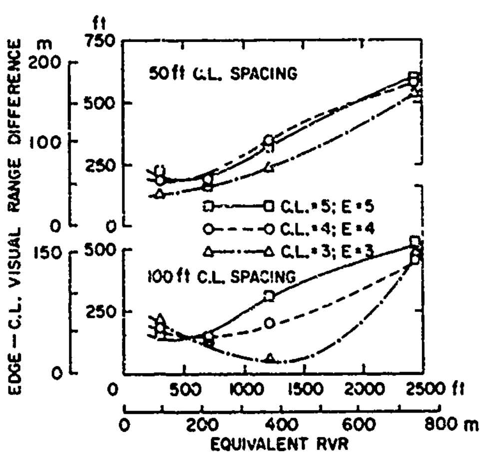

Figure 43. Visual range counting edge lights minus VR counting centerline lights, nighttime, low cockpit (Study II).

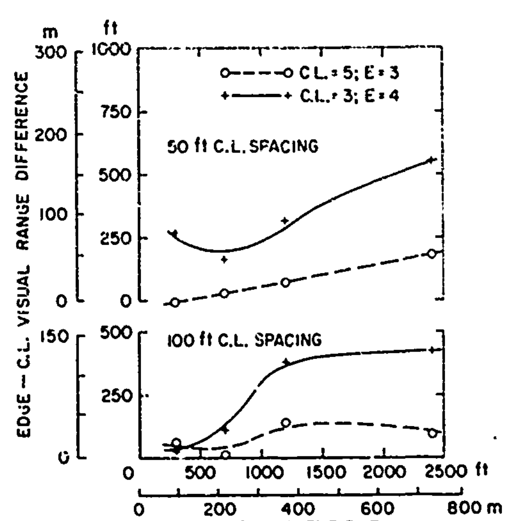

Figure 44. Visual range counting edge lights minus VR counting centerline lights, nighttime, low cockpit (Study II).

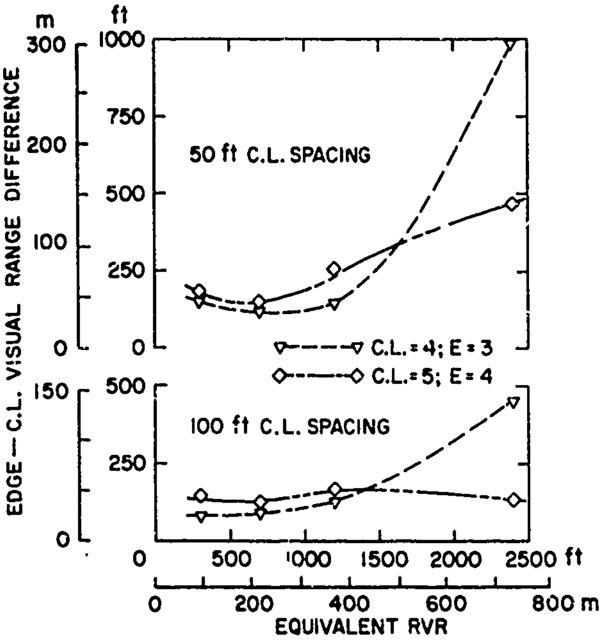

Figure 45. Visual range counting edge lights minus VR counting centerline lights, nighttime, low cockpit (Study II).

runway). It is of interest to note that mean VR, viewing CL lights spaced 100 feet apart through fog, tends to be more equivalent to mean VR viewing the edge lights than when the CL lights are spaced 50 feet apart.

For either of the two CL spacings shown in Figures 43 through 45, the CL = 5, E = 3 step setting condition yielded the closest correspondence of mean VR between viewing CL and edge lights, almost regardless of fog density. This finding is not unexpected since this particular combination of runway light intensities produces the greatest visual contrast (in favor of sighting the CL lights) but without producing as large an amount of (glare) luminance within the field of view.

Results from analyses of variance performed on the mean data from Study II are presented in Tables 22 through 24 for the continuous CL light count method. The fog density and CL-edge light step setting main effects were highly significant in all three analyses as were their mutual interaction.

Tables 25 through 27 present the results of analyses of variance performed on the mean VR data obtained by counting the number of visible right-hand runway edge lights through the fog from Study II. Here, fog density was the only significant main effect found for the daytime testing. The CL-edge light intensity step setting main effect was significant in both nighttime analyses. Fog density was a significant main effect in the nighttime, low cockpit condition as well.

The last analyses of variance performed on the mean VR data from Study II are presented in Tables 28 through 30 for the left-hand runway edge light count mean data. Again, fog density was the only significant main effect found for the daytime testing. Both the CL spacing and intensity step setting main effect were significant in both nighttime analyses.

Hypothesis Three

The third experimental hypothesis was that the horizontal VR of college student subjects will not differ from the horizontal VR of commercial airline pilots. Data from Studies I and II were available for testing this hypothesis; results are presented in Table 31. The significance of difference of the mean VR data for each group of subjects was determined by t-test. In only one of the eight comparisons did the mean VR differ between the two groups of subjects (viz. cat. I, day; $p < 0.005$). Clearly, there were no marked differences in the ability of one group over the other in making VR judgments under the present viewing conditions. Indeed, there was no particular reason for believing there would be. The present data did not lead to the rejection of the third hypothesis.

DISCUSSION

This discussion will be confined to two subjects: the effect on VR of viewing more than one runway light at a time through fog, and observations in regard to visual range through fog while viewing runway light intensities other than the current U. S. standard known as the "Balanced Lighting System."

Visual Range Viewing More Than One Runway Light

A question with both theoretical and applied implications was raised in the early stages of planning for the present investigation. It had to do with the influence that viewing more than one runway light through the fog would have upon horizontal VR using the runway light(s) as the target. Theoretical interest in this question stems from knowledge gained in several psychophysical studies that the presence of more than one light source in the visual field produces additive visual sensitivity changes (1, 16, 23, 24). Only one of these investigations was concerned with visibility through fog (1) and it did not consider the VR of a row of receding lights. The possibility that there might be cumulative effect upon the pilot's VR in fog while viewing receding runway lights led to the practical interest in this matter.

When a VR determination technique was used that required the subject to detect the farthest CL light extinguished with and without the presence of light from foreground CL lights, there was no evidence found for a cumulative visual sensitivity effect *during daytime sightings*. This is reasonable in light of the fact that the relatively high luminance of the background fog greatly reduces the relative brightness of the glow field (1). The limited amount of nighttime data obtained in Study I (cf. Fig. 17), which shows a trend in the direction of a cumulative effect, was not statistically significant. The more extensive data obtained in Study II showed no decided trend in this direction.

It may be that these findings are the result of the testing method used since the human eye is known to be more sensitive to a rapid change in intensity (as was involved in the offset methods used here) than it is to a more gradual intensity change (such as would be produced by viewing a light through constantly changing fog density conditions).

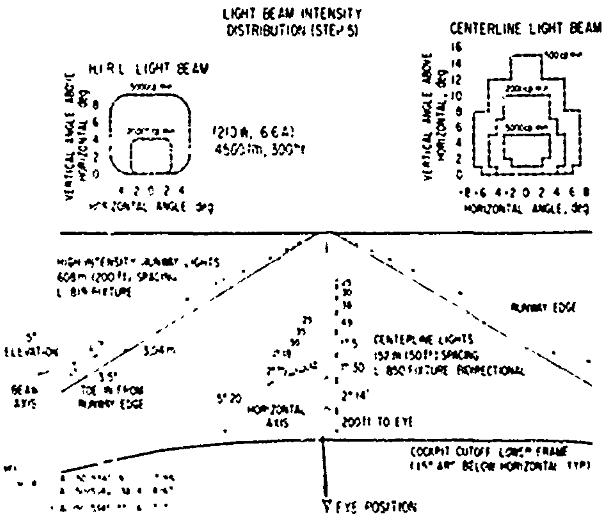

Figure 46. Schematic diagram of runway light angular separations viewed from pilot seat position.

The schematic diagram presented in Figure 46 illustrates how the CL and edge lights appear from about a 25-foot eye height. This diagram also shows the angular separation between the first 550 feet of runway CL lights and about the first 1,500 feet of runway edge lights. The angular separation between two adjacent CL lights spaced 50 feet apart and located beyond about

500 feet from the pilot will be less than one-half degree arc. Reference to the CL light beam intensity distribution diagram in the upper right-hand corner of Figure 46 for a type L-850 fixture (6) shows that when viewed from within ±2 deg arc of the vertical plane passing through the 0 deg horizontal angle position, the intensity will be maximum (i.e., 5,000 cp at step 5) from 1 to 5 deg arc above the horizontal and will be 2,000 cp intensity at step 5 when viewed from 5 deg arc to 10 deg arc above the horizontal. Even though each more distant CL light will yield a progressively lower illumination level at the pilot's eyes, approximately as the inverse square of the separation distance (in clear air), progressively more lights will appear within a progressively smaller frontal plane region to produce the resultant glow field from the CL lights. The exact tradeoff between these two factors is not yet known.

In regard to the pilot's perception of the various runway lights through the fog, it is necessary to consider two separate components of the light emitted by a given light source: a "direct" component that leaves the fixture and travels directly to the eye without any line of sight deviations, and a "glow field" component that is made up of all the other light that is emitted from the light source and which reaches the eye. The glow field component often appears as an enlarged, diffuse area of light extending some angular distance from the light source. As has been pointed out elsewhere, one can perceive the presence of a glow field at a much greater VR than one can reliably perceive the direct component which typically appears as a tiny "hot spot" within the glow field (1).

Depending upon such factors as fog density, ambient fog luminance level, the angle between the pilot to runway to sun line for daytime viewing, eye height and distance from the runway, approach velocity, and others, the pilot must make his decision to land or go around on the basis of a constantly and rapidly changing visual scene comprising many overlapping glow fields, which may or may not be sharply defined enough to provide runway centerline guidance cues to him. As aircraft altitude above and range from the runway decreases, these glow fields can merge into a single area of relatively high luminance which, for all practical purposes, is almost useless in providing landing cues to the pilot. If the glow field and direct component of each runway light is seen distinctly, however, then the pilot can perceive runway alignment information by visually extrapolating through the row of CL lights toward his aircraft. He can also obtain altitude and approach velocity information by perceiving the rate at which the runway lights are moving through his visual field. Yaw, pitch, and roll information is also available under these viewing conditions.

Pilots are faced with a demanding visual organization and decision-making task in real time because they must constantly seek an acceptable compromise between the sometimes marginal information content of hazy glow fields while at the same time try to maximize their VR through the fog. And, because of the great amount of variability from one landing to the next and between the individual experiences each pilot has had during low visibility landings, it is almost impossible to predict beforehand what a pilot will do under even the most general set of conditions. Nevertheless, it is still important to continue to quantify both the visual properties of the landing environment as well as to try to expand the range of the pilot's perceptual capabilities under specified viewing conditions. Without such data it will certainly be impossible to derive sufficiently valid and reliable estimates of landing success in low visibility conditions.

Figure 47 is a photograph taken in the NASA/FAA Fog Chamber at night under approximately 2,600 foot RVR fog conditions from an eye height of 54.1 feet just to the left of the runway's centerline. This photograph illustrates the general appearance to the pilot of the merged glow fields from the receding CL lights. The runway edge lights appear as individual sources of light, presumably because they were photographed from a position well outside of the region of each fixture's light output envelope of maximum intensity (cf. the HIRL light beam intensity distribution in the upper left-hand corner of Fig. 46 for type L-819 fixture) (4,5). This region of maximal intensity extends only 5 deg to each side of the beam's centerline. The light that is visible from these edge lights in Figure 47 is no doubt due to light that is refracted from the fog particles in the direction of the camera.

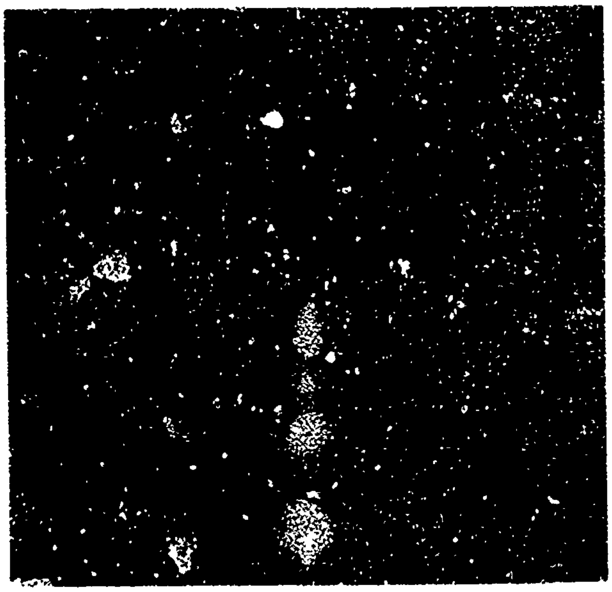

Figure 47. Photograph of fog chamber runway lighting at night in category I conditions.

Preliminary work on quantifying the extent of these glow fields was conducted recently by personnel at the Visibility Laboratory, Scripps Institution of Oceanography using 35-mm color transparency film taken in the NASA/FAA Fog Chamber at night under various combinations of fog densities and runway light settings. Figure 48 illustrates one of these relative luminance arrays, which was made by scanning a transparency optically and then digitizing it as a 128-by-128 relative luminance array. This array was then scanned microphotometrically along the two horizontal rows and one vertical column shown by the dotted lines in Figure 49. Figure 50 gives the maximum and minimum relative (gray scale range) intensity relatable to the scans shown in Figures 51 through 53. Figures 51, 52, and 53 present the results of the scan of row 1, row 2, and column 1, respectively. It is clear that the glow field extends a significant angular distance horizontally from the line that represents the row of receding CL lights. Due to limitations in the dynamic range inherent in the photographic process and microphotometric scanning procedures used, these scans are only relative, i.e., they are not usable for accurate, absolute

Figure 48. Microphotometric relative luminance array for nighttime runway fog scene in approximately category I conditions.

Figure 49. Diagram of microphotometric scan locations of Figure 48 scene.

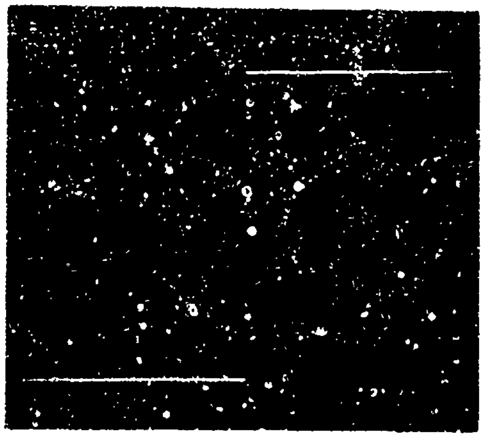

Figure 50. Relative luminance range calibration used in microphotometric scans.

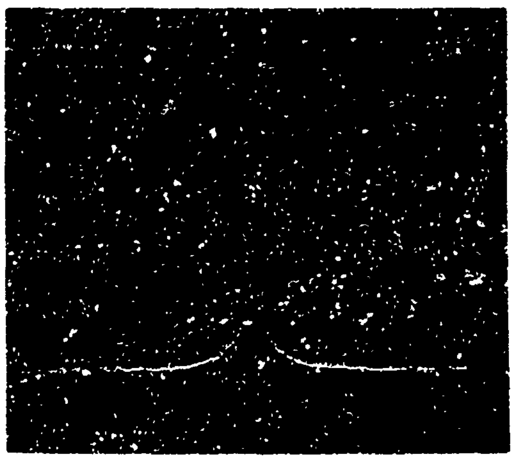

Figure 51. Microphotometric scan results for horizontal row 1 of Figure 49.

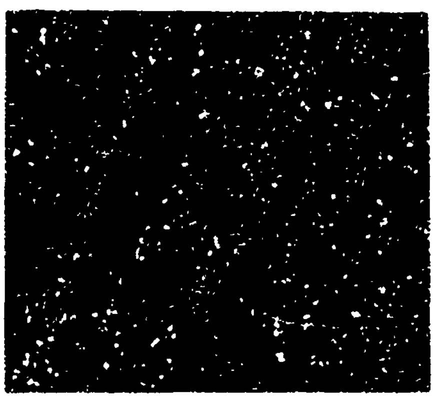

Figure 52. Microphotometric scan results for horizontal row 2 of Figure 49.

Figure 53. Microphotometric scan results for vertical column 1 of Figure 49

quantification purposes. Nevertheless, the angular width of the most distant CL light shown in Figure 51 (assumed for initial calculation purposes to be at a distance of 2,600 ft and 10 in. in diameter (6)) calculated trigonometrically is 0° 1′ 6″ arc, yet the width of the glow field (cf. Fig. 51) at the 50 percent of maximum (peak) intensity position is at least 30′ arc and at the 10 percent of peak intensity position is at least 2° 45′ arc. The peak intensity of the distribution shown in Figure 51 is approximately 0.42 of the full intensity range (cf. Fig. 50).

Considering the estimated angular width of the glow field shown in Figure 52 for the CL light located about 300 feet from the camera, the trigonometrically determined angular width of this source is 0° 9′ 32″ arc. Yet the angular width at the 50 percent of maximum (peak) intensity position is at least 5° arc and at the 10 percent of maximum intensity position is at least 13° arc. The peak intensity of Figure 52 is approximately 0.98 of maximum.

Figure 53 illustrates the significant fact that, beyond the nearest CL light, the glow fields of each fixture merge together in the radial direction into a single large luminous area with only four relatively distinguishable intensity peaks, each of which is separated by "background" luminance of no more than one-half of peak luminance. The maximum (peak) intensity shown in Figure 53 for the peak distribution shown on the right side (i.e., the same CL light as was measured in the row 2 horizontal scan and approximately 300 ft distance) is 0.97 of maximum.

When the pilot is confronted by this kind of scene at night it is apparent that it is the glow field that forms the visual background for most of the visible CL lights. Therefore, the task of distinguishing individual runway lights at night in fog becomes a matter of making a relatively rapid *contrast* threshold (E_c) determination, *not* an illuminance threshold (E_t) determination as is currently required in the use of Allard's Law (11), i.e., in those viewing conditions where the pilot can see farther viewing light sources than reflecting surface contrast markings.

Returning to the present VR data for the 50- and 100-foot CL spacing conditions shown in Figures 23 through 25, a small increase in VR was found for the 100-foot CL spacing regardless of the step setting at which the CL and edge lights were set. This is an interesting finding since the amount of luminous flux should be about one-half as great at the eyes for the 100-foot CL spacing condition as for the 50-foot spacing. In a report on visibility research conducted by the National Bureau of Standards (1), the authors remark that the glow field component, ". . . is primarily a function of the intensity of the source in directions other than the direction toward the observer, while the visual range of the light (the distance at which regularly transmitted light can be perceived) is determined by the intensity in the direction of the observer. If it were possible to block off the line of sight between the observer and the lights so that only the direct light would be obscured, the distance at which the glow could be detected would be substantially unchanged, although the visual range of the light would then be zero. The background brightness has a much greater effect on the detection range of the glow than on the visual range of the regularly transmitted light." This is to say that at night pilots are far more likely to perceive and respond to the glow field produced by the runway lights than they are to the direct component from the fixture.

If the above statement by the National Bureau of Standards concerning the importance of the intensity of the glow field and direct component upon an observer's VR using them as targets is correct, then it is difficult to explain the present 50- versus 100-foot CL light spacing data. The author believes that another visual sensitivity factor must be taken into account in addition to (and perhaps more importantly than) the intensity dimension discussed above. That is the factor of the effective visual contrast of the glow field seen against its own surrounding background. Thus, the rate at which the luminance diminishes with increasing angular distance from the point of maximum intensity of the glow field is likely to determine whether or not a glow field originating from a row of receding CL lights in fog will be acceptable to a pilot in terms of providing him with necessary and sufficient visual guidance cues to land his aircraft. Now let us try to integrate this concept with the present VR data.

During nighttime viewing of a row of receding CL lights spaced 100-feet apart, one might logically expect each resultant glow field to be better defined due to the larger angular separation between successive lights than is the case for the 50-foot CL spacing condition. In other words, the reduction in VR in fog that is produced by the decrease in the amount of luminance produced by the CL lights spaced 100-feet apart is more than made up for by the enhanced contrast sensitivity of the human visual system. Further research is needed to establish the precise relationship that exists between these two variables. The present investigation should be viewed only as a first step in this direction.

Regarding the matter of the influence that viewing more than one light through the fog has upon VR, the present data showed little if any consistent effect. The author's original expectations were not confirmed; it was expected that a cumulative effect would be found because previous investigators had reported that the visual threshold change and apparent brightness change of a test light is an additive function of the number of lights in the field of view (23, 24). Both of these studies were carried out in non-scattering atmospheres, however. Thus, one would expect most of the glow field perceived by the test subjects in these earlier investigations to have originated within the refractive media of the eyes. In both of these investigations, as well as in an applied study conducted in a fog environment but which did not quantify VR for a row of receding runway lights (1), it was found that the effective intensity of a composite group of light sources is proportional to the number of lights making up the group. Apparently, when the group of light sources are viewed from the vantage of a pilot on final approach, the fog produced glow field does not yield such a cumulative effect.

Observations on the "Balanced Lighting System"

As discussed earlier, the present U. S. standard known as the "Balanced Lighting System" uses runway CL lights spaced 50 feet apart, edge lights spaced 200 feet apart, and a CL light intensity that is 25 percent of the edge light intensity. One design objective of this lighting system is to provide the pilot with approximately equal VR through low visibility conditions whether he is viewing the CL or the edge lights. In the present investigation, the CL light intensity (step 5) was 5,000 cd and the edge light intensity (step 5) was 20,000 cd for both the day and nighttime testing conditions for the "Balanced Lighting System."

Two candidate *daytime* lighting systems were compared against the "Balanced Lighting System"; the first used CL lights of 1,000 cd and edge lights of 20,000 cd or an intensity ratio of 5 percent. The second candidate system used CL lights of 200 cd and edge lights of 20,000 cd or an intensity ratio of 1 percent. Referring to the analyses of variance results for Study II (cf. Tables 22 through 30) the CL-edge light intensity step setting main effect was significant in all but two cases (viz. right-hand edge light count, day, low cockpit; left-hand edge light count, day, low cockpit; cf.

Tables 25 and 28, respectively). Thus, the differences in mean VR shown in Figure 23 for the CL light count results obtained during the day are significantly different at the $p < 0.01$ level of confidence. The "Balanced Lighting System" (top curves in Fig. 23) yielded the largest mean VR for each fog density and CL light spacing investigated.

Considering the *nighttime* mean VR data presented in Figures 24 and 25, the analysis of variance performed (cf. Table 23) indicated a highly significant ($p < 0.001$) CL-edge light intensity step setting main effect. Nevertheless, inspection of the curves for each of these five candidate lighting systems does not reveal any particularly obvious differences in mean VR compared to the "Balanced Lighting System" data (top curves in Fig. 24). This finding is of interest because CL-edge light intensity ratios of 25, 125, and 625 percent were quantified.

One might expect mean VR to decrease for those lighting systems that emit less light toward the pilot. Although this was found, particularly for the category I and II conditions, the effect was very small. It is possible that VR through nighttime fog is more a matter of the eye's contrast threshold sensitivity (E_c), as discussed above, than simply its absolute intensity threshold (E_t).

Comparing mean VR through the fog at night while viewing runway edge lights versus CL lights, each at different intensity settings, it is apparent from the curves of Figures 43 through 45, that pilots can see CL lights about as far away as they can see edge lights when the edge lights are at their *minimum* intensity (step 3; 800 cd) and the CL lights are at their maximum intensity (step 5; 5,000 cd) (cf. Fig. 44). It should be noted that this viewing condition (i.e., CL = 5; E = 3) does lead to the smallest difference in mean VR between viewing CL and edge lights as targets. If one intends a balanced lighting system to yield approximately equal VR through fog when viewing either CL or edge lights and ones does not consider the absolute magnitude of the VR achieved, then setting CL light intensity at 25 percent of the edge light intensity does not lead to the desired result.

Taking the magnitude of the pilot's VR into account, then the present nighttime edge light count data from Study II show that, regardless of the CL light spacing, the CL = 3 (200 cd), E = 4 (4,000 cd) intensity settings yields as great a mean VR under these viewing conditions as does the CL = 5, E = 5 intensity conditions (cf. Figs. 31 and 40), but without the degree of glare associated with the higher runway light step settings. Since the CL = 3, E = 4 setting produces only about 18 percent of the total luminous flux as does the CL = 5, E = 5 settings (all other factors held constant), it is not difficult to understand why commercial airline pilots sometime request that the intensity of the runway lights be reduced during the final stage of their approach in fog at night. The above findings have been evaluated with respect to what is predicted using Allard's Law (11). This subject is discussed next.

Allard's Law has been used to determine the predicted relationship that exists between the extinction coefficient[8] (σ) of fog and RVR (ft), assuming an illuminance threshold (E_t) of $10^{-6.1}$ lux. The results of these calculations for four values of runway edge light intensity (I) are presented in Figure 54. It is apparent that, at any given fog density (i.e., σ), changing the intensity of the runway edge lights produces a relatively small change in calculated RVR; this fact may well be related to the above findings.

Procedures currently used to determine RVR utilize one of several predetermined values for the pilot's contrast threshold (E_c) and light intensity threshold (E_t) (3, 28). Projector and Robinson

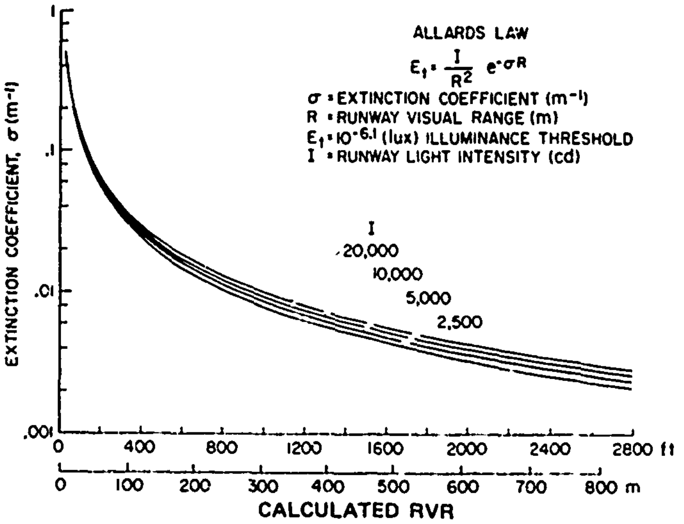

Figure 54. Runway visual range as a function of extinction coefficient for four values of edge light intensity and $E_t = 10^{-6.1}$ using Allard's Law.

(34) have commented in this regard that, "The primary difficulty in the precise application of Allard's Law lies in determining the value of threshold illumination applicable in a given situation. Thresholds vary for different observers, and for any observer at different times, for different visual environments, for different colors with different observers, and for other factors." It can also be pointed out that both E_c and E_t vary with what part of the retina is stimulated. Many investigators have shown that the contrast threshold at the fovea is lower than it is at the periphery. Since the magnitude of this foveal to peripheral E_c difference decreases as retinal illumination level decreases (8), pilots should attempt to keep their eye scans as small as possible during the final phase of landing. This will help keep the retinal image(s) of the various runway lights imaged approximately upon the region of greatest sensitivity.

The visual illuminance threshold is an inverse function of background luminance. Thomas (35, p. 66) has suggested the relationship to be:

$$E_t = -5.7B^{0.64} \tag{1}$$

where: E_t = illuminance threshold of the eye (mi-c), and B = background luminance (cd/m²).

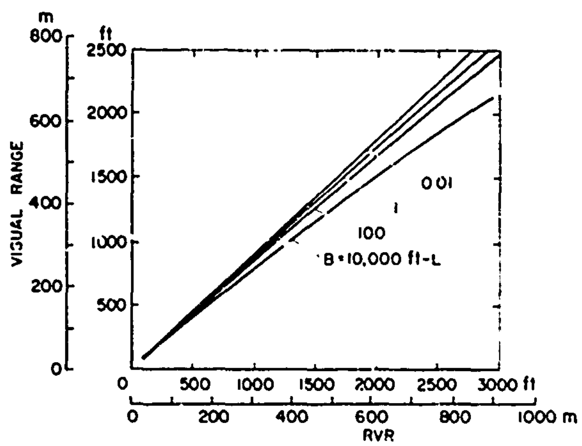

Figure 55. Calculated VR for sighting centerline lights at step 5 as a function of RVR calculated using edge lights at step 5.

Figure 55 illustrates the degree to which VR, using a runway CL light as a target, *decreases* with an increase in background luminance. These curves for four different background luminances were obtained by solving Allard's Law for E_t and a value of σ corresponding to a given RVR and background luminance (B) and letting edge light intensity equal 20,000 cd.

Visual range has also been calculated using equation 1 for the situation in which the CL lights are 5,000 cd and are sighted against background luminances that are different than those presently used to calculate RVR. These families of curves are presented for background luminances of 0.01 and 10 ft-L luminance in Figures 56 and 57, respectively. These two figures

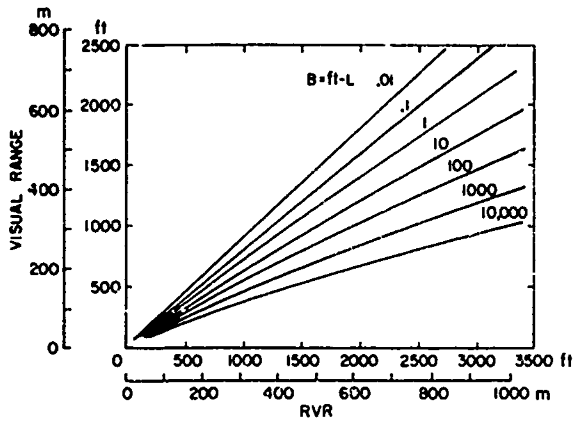

Figure 56. Calculated VR for sighting centerline lights at step 5 as a function of RVR calculated using edge lights at step 5 and background luminance of 0.01 ft-L.

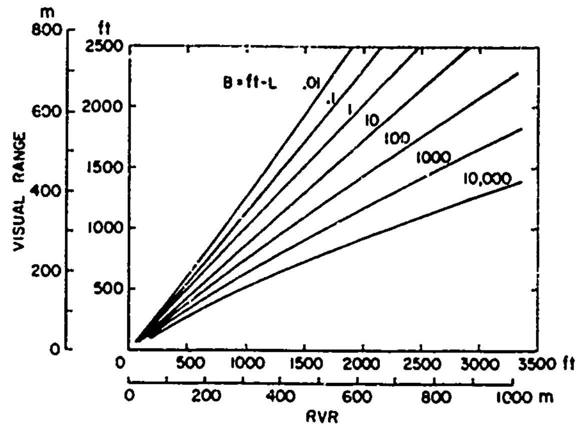

Figure 57. Calculated VR for sighting centerline lights at step 5 as a function of RVR calculated using edge lights at step 5 and background luminance of 10 ft-L.

illustrate the rather dramatic increase in VR that occurs during nighttime viewing conditions. They also demonstrate the important influence that the choice of a background luminance (i.e., visual threshold value) has upon calculated RVR.

CONCLUSIONS

The major conclusions that one may derive from the present investigations are fairly straightforward. There was not found to be any consistent evidence that pointed to a cumulative influence upon mean VR through the fog of viewing a distant runway light in the presence of other runway lights. Nevertheless, more work should be carried out on this particular question in the dynamic situation where the pilot(s) is within a cockpit that is approaching the runway at typical approach velocities. Regarding the matter of whether a runway lighting system other than the present U. S. standard known as the "Balanced Lighting System" might be found that will provide greater VR through fog, one nighttime system was found that provided approximately equivalent VR to the CL lights as to the edge lights. This candidate lighting system was the CL = 5, E = 3 step settings. Although VR was not found to be significantly greater under this candidate nighttime lighting system, compared to the present "Balanced Lighting System," the amount of glare was greatly reduced. Finally, a comparison between the mean VR of college students and commercial airline pilot subjects showed no marked differences.

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APPENDIX A

RESULTS OF MULTIPLE CHOICE QUESTIONNAIRE

FOR STUDY I

The following questions were asked only of certified commercial airline pilot subjects	Frequency score	
	Day $\underline{S}s$	Night $\underline{S}s$
1. About how many category II landings have you made in the past 3 years?		
1 = More than 20	0	0
2 = Between 15 and 20	0	0
3 = Between 10 and 15	0	0
4 = Between 5 and 10	0	0
5 = Five or less	4	4
2. About when was the last time you served as a test subject in this fog chamber?		
1 = Within the past 6 months	0	0
2 = Within the past year	0	0
3 = More than a year ago	0	2
4 = Never	4	2
3. Which runway lights gave you the best overall guidance in terms of providing sufficient runway alignment cues for final taxiing and roll-out?		
1 = Centerline lights only	2	2
2 = Edge lights only (regardless of side)	0	0
3 = Left edge lights only	0	0
4 = Right edge lights only	0	0
5 = All (visible) runway lights	2	2
6 = No lights in particular	0	0
4. What effect, if any, do you think the presence of various building structures had upon your judgments of the farthestmost visible runway light?		
1 = No effect at all	3	3
2 = Perhaps a small effect but not significantly so	1	0
3 = A moderate effect that should be taken into account in interpreting my data	0	1
4 = A great deal of effect, so much so that my data is of little practical value	0	0

	Frequency score	
	Day *Ss*	Night *Ss*
5. About how many hours of training did your airline provide you in making landings in simulated (electronic or otherwise) fog conditions?		
1 = More than 15	2	2
2 = Between 5 and 15	1	0
3 = Less than 5	1	2
6. Do you think that because this test (i.e., of sighting runway lights through fog) was conducted in a non-moving cockpit and required no active VFR control on your part your visual judgments were:		
1 = Just as valid as they would have been in a more realistic simulator	1	1
2 = Reasonably valid but the data must be interpreted with caution	3	3
3 = Totally invalid and the data should not be applied in any real-life situation	0	0
7. Which of the following features would add the most to the realism of this simulation?		
1 = Greater homogeneity of the fog	2	1
2 = Less homogeneity of the fog	0	1
3 = More cockpit realism	2	1
4 = Better cockpit lighting	0	0
5 = Elimination of all objects in the field of view that are out of scale with the runway	0	0
6 = Other	0	1

The following questions were asked of both pilot and college student subjects

	Day *Ss*	Night *Ss*
8. About how would you rate the realism of this fog environment with actual fog conditions you have been in?		
1 = Almost if not totally real	7	11
2 = Reasonably good	8	7
3 = Fair but some features could be improved . . .	0	2
4 = Not realistic at all	1	0

	Frequency score	
9. During today's testing did you ever have the impression that you were in a real aircraft in real fog?	Day Ss	Night Ss
1 = Yes, but only momentarily	10	6
2 = Yes, for relatively long periods of time (say 30 sec)	2	5
3 = Never	4	9

10. If you could control the intensity of the runway centerline and edge lights to give you the best overall visual guidance during landing (for the least dense fog condition you experienced), would you:

	Day Ss	Night Ss
1 = Leave both at their highest intensity (step) setting	9	5
2 = Make the edge lights dimmer than the centerline lights	2	7
3 = Make the centerline lights dimmer than the edge lights	3	4
4 = Turn down the intensity of both	0	2
5 = Other (any other combination)	2	2

11. Regarding the various sideways displacements from the runway centerline, which do you feel gave you the best vantage point for counting accurately the number of centerline lights?

	Day Ss	Night Ss
1 = On centerline (zero offset)	4	7
2 = Pilot offset to left by 1.6 ft	2	4
3 = Pilot offset to left by 3.3 ft	1	6
4 = Doesn't matter particularly	9	3

12. Regarding the various sideways displacements again, which offset gave you the best vantage point for counting accurately the number of edge lights on the left?

	Day Ss	Night Ss
1 = On centerline (zero offset)	2	7
2 = Pilot offset to left by 1.6 ft	1	3
3 = Pilot offset to left by 3.3 ft	5	3
4 = Doesn't matter particularly	8	7

	Frequency score	
13. Regarding the various sideways displacements again, which offset gave you the best vantage point for counting accurately the number of edge lights on the right?	Day <u>S</u>s	Night <u>S</u>s
1 = On centerline (zero offset)	5	3
2 = Pilot offset to left by 1.6 ft	1	3
3 = Pilot offset to left by 3.3 ft	2	4
4 = Doesn't matter particularly	8	10
14. Did the smaller size (1/10th scale) of the simulated runway seem to destroy the realism of the simulation?		
1 = Yes	2	2
2 = No	14	13

APPENDIX B

RESULTS OF MULTIPLE CHOICE QUESTIONNAIRE FOR STUDY II

	Frequency scores					
	Day			Night		
The following questions were asked only of certified commercial airline pilot subjects	Pilot seat	Copilot seat	Total	Pilot seat	Copilot seat	Total
1. About how many category II landings have you made in the past 3 years?						
1 = More than 20						
2 = Between 15 and 20						
3 = Between 10 and 15						
4 = Between 5 and 10				3	1	4
5 = Five or less	3	2	5	4	3	7
2. About when was the last time you served as a test subject in this fog chamber?						
1 = Within the past 6 months . . .	2	1	3	1	1	2
2 = Within the past year						
3 = More than a year ago						
4 = Never	1	1	2	6	3	9
3. Which runway lights gave you the best overall guidance in terms of providing sufficient runway alignment cues for final taxiing and roll-out?						
1 = Centerline lights only	1		1	2	1	3
2 = Edge lights only (regardless of side)						
3 = Left edge lights only						
4 = Right edge lights only						
5 = All visible runway lights . . .	2	2	4	3	2	5
6 = No lights in particular				1		1

	Frequency scores					
	Day			Night		
	Pilot seat	Copilot seat	Total	Pilot seat	Copilot seat	Total
4. What effect, if any, do you think the presence of various building structures (in your field of view) had upon your judgments of the farthestmost visible runway light(s)?						
1 = No effect at all	1	1	2	5	4	9
2 = Perhaps a small effect but not significantly so	1	1	2	2		2
3 = A moderate effect that should be taken into account in interpreting my data	1		1			
4 = A great deal of effect, so much so that my data is of little practical value						
5. About how many hours of training did your airline provide you in making landings in simulated (e.g., electronic or others) fog conditions?						
1 = More than 15	2		2		2	2
2 = Between 5 and 15				2		2
3 = Less than 5	1	2	3	5	2	7
6. Do you think that because this test (i.e., of sighting runway lights through fog) was conducted in a non-moving cockpit and did not require active VFR control by you your visual judgments were:						
1 = Just as valid as they would have been in a more realistic simulator				3		3
2 = Reasonably valid but the data must be interpreted with caution	3	2	5	3	4	7
3 = Totally invalid, these data should not be applied in any real-life situation				1		1

	Frequency scores					
	Day			Night		
	Pilot seat	Copilot seat	Total	Pilot seat	Copilot seat	Total
7. Which of the following features would add the most to the realism of this simulation?						
1 = Greater homogeneity of the fog	1		1	2	1	3
2 = Less homogeneity of the fog .					1	1
3 = More cockpit realism				4		4
4 = Better cockpit lighting				1	1	2
5 = Elimination of all objects in the field of view that are out of scale with the runway . . .	1	1	2		1	1
6 = Other	1	1	2			
The following questions were asked of both pilot and college student subjects						
8. About how would you rate the realism of this fog environment with actual fog conditions you have been in?						
1 = Almost if not totally real . . .	2	2	4	6	4	10
2 = Reasonably good	3	1	4	2	1	3
3 = Fair but some features could be improved		1	1			
4 = Not realistic at all		1	1			
9. During today's testing did you ever have the impression that you were in a real aircraft in real fog?						
1 = Yes, but only momentarily . .	2	2	4	5	1	6
2 = Yes, for relatively long periods of time (e.g., 30 seconds)	1		1	1		1
3 = Never	2	2	4	2	4	6
10. If you could control the intensity of the runway centerline and edge lights to give you the best overall visual guidance during landing (only for the least dense fog you experienced today), would you:						

	Frequency scores					
	Day			Night		
	Pilot seat	Copilot seat	Total	Pilot seat	Copilot seat	Total
1 = Leave both at their highest intensity	3	2	5			
2 = Make the edge lights dimmer than the centerline lights . . .					1	1
3 = Make the centerline lights dimmer than the edge lights .	1	2	3	6	3	9
4 = Make both centerline and edge lights dimmer				2	1	3
5 = Other (any other combination)	1		1			

11. Did the smaller size (1/10th scale) of the simulated runway seem to destroy the realism of the simulation?

	Pilot seat	Copilot seat	Total	Pilot seat	Copilot seat	Total
1 = Yes	1		1			
2 = No	4	4	8	8	5	13

APPENDIX C

TEST INSTRUCTIONS

Each subject wrote his name, age, and number of flight hours in a log book next to a unique subject data coding number. Each pair of subjects then decided whether they wanted to sit in the pilot (left) or co-pilot (right) seat during testing. The viewing seat position was then noted in the log book. Then an experimenter accompanied the pair of subjects to the cockpit which was situated about 500 feet from the high end of the building at a point where there were only centerline and runway edge lights.

As soon as each subject had properly adjusted his chair height he was given the following instructions:

> "The experiment you are about to take part in is designed to find out how far you can see in the fog. We will ask you to merely count the number of centerline lights and runway edge lights you can see. To make this easier for you we have placed a green filter in front of the first centerline light. From now on we will call this light number one. Likewise, in front of the first left-hand and right-hand edge light we have placed a red filter. Please refer to these lights as 'left number one' and 'right number one'."

Each of the five different kinds of visual range measurement methods were then demonstrated to the subjects until they fully understood what was required of them. Some initial difficulty was encountered by the subjects when trying to respond to the sequential extinction of centerline lights beginning with the most distant light. This difficulty stemmed both from the relatively long wait between the start of the trial to the time when a light within the subject's visual range disappeared and from the fact that foreground centerline lights would sometime disappear prematurely due to patches of intervening fog. This difficulty was usually corrected by further explanation and demonstration by the experimenter.

NOTES

1. One reference (30, p. 6), citing a previous United Kingdom report (Ministry of Civil Aviation, Report on landing and takeoff of aircraft in bad weather. H.M.S.O., London, February, 1951), pointed out that "horizontal guidance information" is specified as the "distance at which a pilot would be able to differentiate between the runway and the surrounding terrain."

2. Hereafter, the term "visual range" (VR) is used to denote the most distant discernible runway light rather than the distance beyond which the subject cannot see. Although it may be assumed that the subject could see beyond the presently cited VR, by increasing the intensity or another characteristic of a runway light for instance, exactly how much farther is not known. Nevertheless, maximum VR could not be more than 50 feet for centerline lights and 200 feet for the edge lights since these distances are the inter-light spacing of each type of light.

3. Use of the term "step setting" refers to the intensity of the runway lights consistent with current practice in the U. S. Step 5 = maximum intensity (100 percent luminous output); step 4 = 20 percent of maximum; step 3 = 4 percent of maximum.

4. There is some confusion concerning what illumination level one should use as the "cross over point" from day to nighttime in the choice of the visual illuminance threshold (E_t). Lefkowitz and Schlatter (30, p. 3) cite an *illuminance* value of "... about 2 ft-c as determined by an elementary illuminometer," while Thomas (35, p. 70) cites a *luminance* value of 20 cd/m^2 (5.73 ft-L). Luminance values are only equivalent to illuminance values if the surface that is illuminated is perfecting diffusing.

5. The term "reference eye position" refers to the nominal position of the subject's eyes within the cockpit. It was located 1.216 m above the cockpit floor, directly behind the yoke's insertion point into the floor, and approximately 50.4 cm to each side of the cockpit's centerline.

6. The "nearest visible light" refers to that runway light just visible above the lower cutoff angle formed by the lower frame of the forward window.

7. The term "glow field" refers to all light emitted from a runway light fixture which enters the eye except for the direct component which originates at the fixture and travels straight to the eye.

8. The extinction coefficient can be considered to be the proportional loss of light per unit distance along the transmissometer's baseline. Thus,

$$\sigma = \frac{d^L}{L} \times \frac{1}{dR}$$

Thus,

$$\frac{L}{L_o} = e^{-\sigma R}$$

TABLE 1. PHOTOMETRY RESULTS (LUMINANCE VALUES IN FT–L; VALUES IN BRACKETS IN LUX).

Light	Distance to eye, ft (m)	Fog conditions: Clear air	Cat I[a]	Cat II[b]	Cat. IIIA[c]	Cat. IIIB[d]
(a) Centerline light measured						
1. Green	192 (58.52)	1152.6 (107.07)	1315.8 (122.24)		186.5 ±33[e] (17.32 ±3.06)	139 ±11 (12.91 ±1.02)
2. White	242 (73.76)	652.8 (60.64)	40.8 (3.79)		124 ±2 (11.52 ±0.18)	f
3. White	292 (89.00)	3763.2 (349.60)	94.3 ±33 (8.76 ±3.06)		161.5 ±20 (15.00 ±1.86)	
4. White	342 (104.24)	2682.6 (249.21)	15.1 (1.40)		f	
5. White	392 (119.48)	902.7 (83.86)	234.6 (21.79)			
6. White	442 (134.72)	3234 (300.44)	283 ±46 (26.29 ±4.27)			
7. White	492 (149.96)	1274 (118.35)	352 ±68 (32.70 ±6.32)			
8. White	542 (165.20)	f	f			
(b) Right edge light measured						
1. Red	442 (134.72)	168.3 (15.63)	182 (16.91)	170 (15.79)	102 ±6 (9.47 ±0.55)	78.5 ±3 (7.29 ±0.28)
2. White	642 (195.68)	1783.6 (165.70)	225 (20.90)	181 (16.81)	f	f
3. White	842 (256.64)	g	93 (8.64)	64 (5.94)		
(c) Left edge light measured						
1. Red	442 (134.72)	228.5 (21.23)	138 (12.82)	130 (12.08)	126 (11.70)	f
2. White	642 (195.68)	734.4 (68.22)	176 (16.35)	142 (13.19)	f	
3. White	842 (256.64)	622.2 (57.80)	142 (13.19)	66 (6.13)		
4. White	1042 (317.60)	244.8 (22.74)	156 (14.49)	f		
5. White	1242 (378.56)	f	f			

(d) Runway surface location measured[h]

Location	Fog conditions: Clear air	Cat I[a]	Cat II[b]	Cat IIIA[c]	Cat IIIB[d]
(1) White left edge runway stripe	234.6 (21.79)	108 (10.03)	102 (9.47)	117 (10.87)	180 (16.72)
(2) One half degree right of (1)	32.4 (3.01)	64 (5.94)	70 (6.50)	101 ±6[e] (9.38 ±0.56)	170 (15.79)
(3) One half degree left of (4)	41 (3.81)	36 (3.34)	46.5 ±3 (4.32 ±0.28)	68.5 ±4 (6.36 ±0.37)	125 (11.61)
(4) White centerline stripe	387.6 (36.01)	175 ±15 (16.26 ±1.39)	151 ±9 (14.03 ±0.84)	122.5 ±7 (11.38 ±0.65)	120 (11.15)
(5) One half degree right of (4)	33 (3.06)	37 ±9 (3.44 ±0.84)	56.5 ±11 (5.25 ±1.02)	74 ±9 (6.87 ±0.84)	115 (10.66)
(6) One half degree left of (7)	34 (3.16)	41 ±9 (3.81 ±0.84)	36 ±6 (3.34 ±0.56)	46 ±6 (4.27 ±0.56)	84 (7.80)
(7) White right edge runway stripe	320.3 (29.75)	171.5 ±8 (15.93 ±0.74)	128.5 ±9 (11.94 ±0.84)	89.5 ±6 (8.31 ±0.56)	81 (7.52)

Notes All of the above data were obtained during daylight hours with no clouds present and with the sun within 30 deg of zenith. All data were obtained with each light on step setting 5 (maximum) and each reading taken from the pilot's reference eye position.

[a]2400 ft RVR

[b]1200 ft RVR

[c]700 ft RVR

[d]300 ft RVR

[e]Plus minus indicates maximum and minimum luminance readings obtained during 30 sec long measurement period

[f]Runway light not visible through the fog

[g]Data lost due to photometer malfunction

[h]All of these runway surface measurements were obtained at a fixed distance of 342 ft (104.24 m) from the reference eye position

TABLE 2. SUBJECTS TESTED IN STUDY I.

Runs	Name	Age	Distance acuity (Snellen) left	Distance acuity (Snellen) right	Pilot Flt. hrs.	Student
Day	RM*	22				X
	RN*	22	20 17	20·17		X
	PR	22				X
	VP	20	.18	·18		X
	JM*	18	18	20		X
	KF	19	.17	:17		X
	MR*	21	:20	:20		X
	ML	21	.18	:20		X
	AP	20	.17	:17		X
	AB	21	17	:18		X
	BJ	19	:18	:17		X
	BL	20	.18	:17		X
	FM	26	·17	:17		X
	TJ	18	.20	:20		X
	JB	36			5,000	
	BB	45			15,000	
	RC	57			23,000	
	FC	41			7,000	
Night	GR	19	20 18	20:20		X
	PG	18	·17	·17		X
	MR*	21	:20	:20		X
	RM*	22				X
	BB	18	.17	18		X
	RP	19	.18	:20		X
	JS	20	:17	:17		X
	JM*	18	:20	·20		X
	TC	18	:22	:17		X
	SA	21	:18	:22		X
	FG	26	.22	:18		X
	RN*	22	:17	:17		X
	JL	26	:17	:17		X
	SW	22	:17	:17		X
	CG	19	:18	:17		X
	RG	20	:17	:18		X
	DS	30			2,600	
	RP	37			6,100	
	LD	42			14,000	
	TT	40			14,000	

*Indicates that S served in both day and night runs. Mean age of student Ss = 20.6 yrs. Mean age of pilot Ss = 41 yrs.

TABLE 3. MEAN HORIZONTAL VISUAL RANGE OBSERVING RUNWAY CENTERLINE LIGHTS EXTINGUISHED SEQUENTIALLY TOWARD THE SUBJECT WITH COCKPIT IN LOW POSTION (STUDY I).

Ambient luminance	Lateral offset position of pilot	Fog density equivalency Cat. I	Cat. II	Cat. IIIA	Cat. IIIB
Day	Zero	1463 ft SD = 319 n = 12	846 ft SD = 170 n = 12	659 ft SD = 172 n = 12	267 ft SD = 148 n = 12
	5.04 m	1455 ft SD = 242 n = 12	934 ft SD = 214 n = 12	646 ft SD = 215 n = 12	284 ft SD = 145 n = 12
	10.12 m	1480 ft SD = 295 n = 12	896 ft SD = 167 n = 12	663 ft SD = 170 n = 12	313 ft SD = 158 n = 12
Night	Zero	1788 ft SD = 193 n = 12	921 ft SD = 175 n = 12	484 ft SD = 126 n = 12	500 ft SD = 111 n = 6
	5.04 m	1896 ft SD = 237 n = 12	913 ft SD = 148 n = 12	484 ft SD = 156 n = 12	484 ft SD = 159 n = 6
	10.12 m	1855 ft SD = 264 n = 12	930 ft SD = 190 n = 12	488 ft SD = 167 n = 12	400 ft SD = 176 n = 6

Note: All data obtained with CL = 5, E = 5 and 50 foot centerline light spacing.

TABLE 4. MEAN HORIZONTAL VISUAL RANGE DETERMINED BY DETECTING OFFSET OF THE FARTHESTMOST CENTERLINE LIGHT EXTINGUISHED SEQUENTIALLY TOWARD SUBJECT WITH COCKPIT IN LOW POSITION (STUDY II).

Step Setting		Test condition	Fog density equivalency							
			Cat. I		Cat. II		Cat. IIIA		Cat. IIIB	
			50′	100′	50′	100′	50′	100′	50′	100′
Day time	CL 5	$\bar{X}$	1859	1790	931	911	657	539	324	272
		SD	427	498	193	209	306	308	195	248
	E 5	N	26	25	18	18	20	18	22	[illegible]
	CL 4	$\bar{X}$	1648	1494	861	778	548	439	303	219
		SD	420	408	191	192	178	256	172	170
	E 5	N	26	25	18	18	18	18	22	22
	CL 3	$\bar{X}$	1231	1211	881	834	417	356	249	208
		SD	362	382	189	216	188	230	182	177
	E 5	N	26	26	18	18	20	18	22	22
Night time	CL 5	$\bar{X}$	1842	1822	882	863	507	450	445	464
		SD	355	329	248	207	186	169	166	177
	E 5	N	18	22	26	26	24	24	16	16
	CL 4	$\bar{X}$	1814	1724	813	836	475	448	426	445
		SD	386	292	231	217	198	169	166	154
	E 4	N	18	22	26	26	24	24	16	16
	CL 3	$\bar{X}$	1926	1715	804	769	400	375	423	345
		SD	465	318	208	208	185	202	150	194
	E 3	N	22	22	26	26	24	24	16	16
	CL 4	$\bar{X}$	1914	1817	865	817	459	442	442	411
		SD	446	340	202	208	171	175	171	160
	E 3	N	18	22	26	26	24	24	16	16
	CL 5	$\bar{X}$	1936	1783	859	848	530	475	476	430
		SD	394	376	245	212	166	176	160	180
	E 4	N	18	22	26	26	24	24	16	16
	CL 5	$\bar{X}$	2020	1922	825	948	496	480	430	436
		SD	359	336	259	216	151	154	149	205
	E 3	N	18	22	26	24	24	24	16	16
	CL 3	$\bar{X}$	2030	1730	884	925	461	486	334	234
		SD	235	235	240	199	201	138	153	153
	E 4	N	4	4	6	6	8	8	6	6

Note $\bar{X}$ and SD in feet.

TABLE 5. MEAN HORIZONTAL VISUAL RANGE OBSERVING RUNWAY CENTERLINE LIGHTS EXTINGUISHED SEQUENTIALLY AWAY FROM SUBJECT WITH COCKPIT IN LOW POSITION (STUDY I).

Ambient luminance	Lateral offset position of pilot	Fog density equivalency			
		Cat. I	Cat. II	Cat. IIIA	Cat. IIIB
Day	Zero	1463 ft SD = 371 n = 12	996 ft SD = 148 n = 12	655 ft SD = 204 n = 12	296 ft SD = 164 n = 12
	5.04 m	1505 ft SD = 345 n = 12	996 ft SD = 175 n = 12	705 ft SD = 202 n = 12	359 ft SD = 189 n = 12
	10.12 m	1380 ft SD = 335 n = 12	955 ft SD = 184 n = 12	734 ft SD = 200 n = 12	375 ft SD = 186 n = 12
Night	Zero	1950 ft SD = 264 n = 12	1030 ft SD = 143 n = 12	617 ft SD = 130 n = 12	525 ft SD = 147 n = 6
	5.04 m	1950 ft SD = 204 n = 12	1059 ft SD = 201 n = 12	588 ft SD = 144 n = 12	567 ft SD = 130 n = 6
	10.12 m	1892 ft SD = 198 n = 12	984 ft SD = 165 n = 12	600 ft SD = 132 n = 12	484 ft SD = 176 n = 6

Note. All data obtained with CL = 5, E = 5 and 50 foot centerline light spacing.

TABLE 6. MEAN HORIZONTAL VISUAL RANGE DETERMINED BY DETECTING OFFSET OF THE FARTHESTMOST CENTER-LINE LIGHT EXTINGUISHED SEQUENTIALLY AWAY FROM SUBJECT WITH COCKPIT IN LOW POSITION (STUDY II).

	Step Setting	Test condition	Fog density equivalency							
			Cat. I		Cat. II		Cat. IIIA		Cat. IIIB	
			50'	100'	50'	100'	50'	100'	50'	100'
Day time	CL 5	$\bar{X}$	1738	1731	970	986	640	610	374	315
		SD	404	413	342	200	195	246	198	252
	E 5	N	26	26	18	18	20	20	22	22
	CL 4	$\bar{X}$	1613	1513	925	825	600	560	388	288
		SD	295	282	191	327	204	257	161	223
	E 5	N	26	26	18	18	20	20	22	22
	CL 3	$\bar{X}$	1232	1286	825	859	547	465	313	285
		SD	299	334	246	295	234	212	182	225
	E 5	N	26	26	18	18	20	20	22	22
Night time	CL 5	$\bar{X}$	1667	1992	938	957	615	642	564	589
		SD	405	370	203	213	157	153	139	152
	E 5	N	18	22	26	26	24	24	16	16
	CL 4	$\bar{X}$	1859	1928	919	907	586	609	436	570
		SD	412	292	189	296	183	167	130	151
	E 4	N	18	22	26	26	24	24	16	16
	CL 3	$\bar{X}$	2003	1876	819	856	592	577	542	526
		SD	540	419	174	208	144	145	161	164
	E 3	N	22	22	26	26	24	24	16	16
	CL 4	$\bar{X}$	1892	2006	892	934	600	619	542	576
		SD	502	394	218	242	149	166	163	169
	E 3	N	18	22	26	26	24	24	16	16
	CL 5	$\bar{X}$	1981	2031	944	946	632	632	595	576
		SD	448	443	213	251	166	198	120	153
	E 4	N	18	22	26	26	24	24	16	16
	CL 5	$\bar{X}$	2028	2101	894	955	607	665	558	614
		SD	441	378	208	242	169	155	182	177
	E 3	N	18	22	26	24	24	24	16	16
	CL 3	$\bar{X}$	2167	2092	800	859	530	642	475	500
		SD	227	163	145	182	174	142	161	176
	E 4	N	4	4	6	6	8	8	6	6

TABLE 7. MEAN HORIZONTAL VISUAL RANGE DETERMINED BY DETECTING OFFSET OF THE FARTHESTMOST CENTER-LINE LIGHT EXTINGUISHED SEQUENTIALLY TOWARD SUBJECT WITH COCKPIT IN HIGH POSITION (STUDY II).

	Step Setting	Test condition	Fog density equivalency							
			Cat. I		Cat. II		Cat. IIIA		Cat. IIIB	
			50'	100'	50'	100'	50'	100'	50'	100'
Day-time	CL 5	$\bar{X}$	1517	1917	848	736	642	592	342	180
		SD	217	367	253	109	92	92	92	157
	E 5	N	2	2	8	8	2	2	4	4
	CL 4	$\bar{X}$	1042	1342	873	730	542	467	330	205
		SD	192	92	142	152	92	117	114	114
	E 5	N	2	1	8	8	2	2	4	4
	CL 3	$\bar{X}$	692	1267	798	680	417	392	267	180
		SD	142	167	169	200	217	242	117	134
	E 5	N	2	2	8	8	2	2	4	4
Night-time	CL 5	$\bar{X}$	92	2292	1005	930	505	642	405	450
		SD	92	258	152	152	114	142	174	165
	E 5	N	0	4	8	8	4	4	8	6
	CL 4	$\bar{X}$	2192	2317	942	792	480	455	461	367
		SD	92	182	135	215	114	114	171	167
	E 4	N	2	4	8	8	4	4	8	8
	CL 3	$\bar{X}$	2217	1955	823	886	517	442	367	342
		SD	195	188	185	138	117	92	148	171
	E 3	N	4	4	8	8	4	4	8	4
	CL 4	$\bar{X}$	2230	2255	967	855	505	455	448	336
		SD	166	235	148	211	114	114	180	169
	E 3	N	4	4	8	8	4	4	8	8
	CL 5	$\bar{X}$	2330	2455	998	936	517	555	442	436
		SD	134	134	208	150	117	114	195	150
	E 4	N	4	4	8	8	4	4	8	8
	CL 5	$\bar{X}$	2355	2442	911	905	505	517	467	480
		SD	256	242	171	157	114	117	175	152
	E 3	N	4	4	8	8	4	4	8	8

TABLE 8. MEAN HORIZONTAL VISUAL RANGE DETERMINED BY DETECTING OFFSET OF THE FARTHESTMOST CENTERLINE LIGHT EXTINGUISHED SEQUENTIALLY AWAY FROM SUBJECT WITH COCKPIT IN HIGH POSITION (STUDY II).

Step Setting		Test condition	Fog density equivalency							
			Cat I		Cat. II		Cat IIIA		Cat. IIIB	
			50'	100'	50'	100'	50'	100'	50'	100'
Day-time	CL 5	$\bar{X}$	1442	942	1092	923	667	592	367	242
		SD	192	392	198	258	117	242	117	92
	E 5	N	2	2	8	8	2	2	4	4
	CL 4	$\bar{X}$	1067	1242	1017	905	692	592	405	255
		SD	367	342	158	162	92	192	114	134
	E 5	N	2	2	8	8	2	2	4	4
	CL 3	$\bar{X}$	992	1317	836	873	642	517	267	442
		SD	192	267	173	127	142	117	117	292
	E 5	N	2	2	8	8	2	2	4	4
Night time	CL 5	$\bar{X}$	2030	2042	798	755	617	680	405	580
		SD	147	153	109	147	148	114	114	114
	E 5	N	4	4	8	8	4	4	4	4
	CL 4	$\bar{X}$	1892	2130	755	655	655	705	530	380
		SD	92	194	166	188	134	114	114	134
	E 4	N	4	4	8	8	4	4	4	4
	CL 3	$\bar{X}$	1992	1742	780	780	617	692	417	517
		SD	127	301	162	147	117	92	167	167
	E 3	N	4	4	8	8	4	4	4	4
	CL 4	$\bar{X}$	2055	2067	823	692	617	655	417	367
		SD	244	236	135	204	117	114	135	117
	E 3	N	4	4	8	8	4	4	4	4
	CL 5	$\bar{X}$	2105	2117	798	773	655	655	405	467
		SD	147	148	122	135	114	114	114	135
	E 4	N	1	4	8	8	4	4	4	4
	CL 5	$\bar{X}$	2067	2167	798	717	617	705	580	530
		SD	175	271	122	158	135	114	114	114
	E 3	N	4	4	8	8	4	4	4	4

TABLE 9. MEAN HORIZONTAL VISUAL RANGE COUNTING CENTERLINE LIGHTS WITH EDGE LIGHTS OFF AND COCKPIT IN LOW POSITION (STUDY II).

Step setting		Test condition	Fog density equivalency							
			Cat. I		Cat. II		Cat IIIA		Cat IIIB	
			50'	100'	50'	100'	50'	100'	50'	100'
Day	CL 5	$\bar{X}$	967	1442	1017	767	455	467	242	217
		SD	117	298	271	175	239	135	127	175
	E OFF	N	4	4	4	4	4	4	4	4
	CL 4	$\bar{X}$	1105	1542	592	842	267	517	205	192
		SD	134	179	269	204	117	222	114	92
	E OFF	N	4	4	4	4	4	4	4	4
	CL 3	$\bar{X}$	955	1192	755	642	242	217	192	192
		SD	166	163	157	179	92	135	92	92
	E OFF	N	4	4	4	4	4	4	4	4

TABLE 10. MEAN HORIZONTAL VISUAL RANGE COUNTING CENTERLINE LIGHTS FOR THE CL = 5, E = 5 "BALANCED LIGHTING SYSTEM" (STUDY I).

Ambient luminance	Pilot offset	Test condition	Fog density equivalency			
			Cat. I	Cat. II	Cat. IIIB	Cat. IIIA
Day	Zero	$\bar{X}$	1413	946	659	309
		SD	215	222	191	203
		N	12	12	12	12
	5.04 m	$\bar{X}$	1542	971	650	288
		SD	337	245	181	180
		N	12	12	12	12
	10.12 m	$\bar{X}$	1371	888	613	280
		SD	207	182	191	160
		N	12	12	12	12
Night	Zero	$\bar{X}$	1584	934	492	425
		SD	202	176	133	139
		N	12	12	12	6
	5.04 m	$\bar{X}$	1592	917	496	417
		SD	185	155	124	117
		N	12	12	12	6
	10.12 m	$\bar{X}$	1534	917	525	400
		SD	171	148	123	176
		N	12	12	12	6

Note: All data obtained with 50 ft CL spacing

TABLE 11. ANALYSIS OF VARIANCE SUMMARY FOR STUDY I.[a]

Source	df	SS	MS	f
Fog density (D)	3	12778.00	6389.00	214.2[b]
Cockpit offset (O)	2	41.30	20.60	4.3[c]
Day/Night (L)	1	1.00	1.00	.03
Subject seat (S)	1	.56	.56	.02
(D) X (O)	4	32.79	8.19	1.70
(D) X (L)	2	251.00	125.50	4.20[c]
(D) X (S)	2	6.20	3.13	.10
(L) X (S)	1	1.00	1.00	.03
(O) X (S)	2	7.30	3.67	.76
(O) X (L)	2	27.70	13.87	2.87
(D) X (O) X (L)	4	11.10	2.78	.57
(D) X (O) X (S)	4	2.61	.65	.13
(O) X (L) X (S)	2	2.02	1.01	.21
(D) X (L) X (S)	2	6.19	3.09	.10
(D) X (L) X (S) X Subject	12	357.82	29.81	8.66[d]
(D) X (O) X (L) X (S)	4	6.86	1.71	.35
(D) X (L) X (S) X (O X Subj.)	24	115.65	4.81	1.40
(D) X (O) X (L) X (S) X Subj. X Repl.	144	495.52	3.44	---

[a]All of the above statistics are for CL light count mean data only.

[b]$p < 0.001$

[c]$p < 0.05$

[d]$p < 0.01$

TABLE 12. ANALYSIS OF VARIANCE SUMMARY FOR DAYTIME DATA OF STUDY I.

Source	df	SS	MS	f
Fog density (R)	3	10236.4	3412.15	74.78[a]
Cockpit offset (O)	2	54.5	27.25	4.65[b]
Subject seat (S)	1	.27	.27	.0006
(R) × (O)	6	47.10	7.85	1.34
(R) × (S)	3	8.03	2.67	.05
(O) × (S)	2	2.05	1.02	.17
(R) × (O) × (S)	6	8.21	1.36	.23
(R) × (S) × Subject	9	364.99	45.62	10.22[a]
(O) × (S) × Subject × (O)	16	93.66	5.85	1.31
((R) × (O) × (S) × Subject) × Repl	96	428.55	4.46	--

[a] $p < 0.001$
[b] $p < .05$

TABLE 13. ANALYSIS OF VARIANCE SUMMARY FOR NIGHTTIME DATA OF STUDY I.

Source	df	SS	MS	f
Fog density (R)	3	5383.6	1794.5	1068.1[a]
Cockpit offset (O)	2	3.69	1.84	.75
Subject × Repl	4	6.72	1.68	1.17
(R) × (O)	6	8.52	1.42	1.34
(O) × Subject × Repl	8	8.43	1.05	.73
(R) × (O) × Subject × Repl	48	68.13	1.42	---

[a] $p < 0.001$

TABLE 14. MEAN HORIZONTAL VISUAL RANGE COUNTING CENTERLINE LIGHTS WITH COCKPIT IN LOW POSITION (STUDY II).

	Step Setting	Test condition	Fog density equivalency							
			Cat. I		Cat II		Cat IIIA		Cat IIIB	
			50′	100′	50′	100′	50′	100′	50′	100′
Day time	CL 5	$\bar{X}$	1627	1731	892	1159	592	657	288	306
		SD	291	416	270	469	173	241	176	250
	E 5	N	26	20	18	18	20	20	22	22
	CL 4	$\bar{X}$	1396	1538	803	1086	527	532	260	283
		SD	318	272	275	468	215	264	167	227
	E 5	N	26	26	18	18	20	20	22	22
	CL 3	$\bar{X}$	1196	1381	720	1064	417	417	222	278
		SD	279	305	250	552	184	279	170	217
	E 5	N	26	26	18	18	20	20	22	22
Night time	CL 5	$\bar{X}$	1625	1778	840	869	515	563	420	511
		SD	365	261	170	172	140	146	158	173
	E 5	N	18	22	26	26	24	24	16	16
	CL 4	$\bar{X}$	1578	1747	732	877	477	525	376	455
		SD	384	325	201	183	154	161	169	170
	E 4	N	18	22	26	26	24	24	16	16
	CL 3	$\bar{X}$	1592	1660	700	831	427	459	420	423
		SD	462	274	224	155	168	186	156	190
	E 3	N	20	22	26	26	24	24	16	16
	CL 4	$\bar{X}$	1567	1760	819	873	480	530	414	467
		SD	375	274	196	164	140	148	171	201
	E 3	N	18	22	26	26	24	24	[illegible]	16
	CL 5	$\bar{X}$	1645	1933	771	857	477	534	445	498
		SD	361	439	229	170	134	141	140	158
	E 4	N	18	22	26	26	24	24	16	16
	CL 5	$\bar{X}$	1711	1856	744	746	494	588	448	480
		SD	300	349	272	367	145	238	150	178
	E 3	N	18	22	26	24	24	24	16	16
	CL 3	$\bar{X}$	1592	1817	800	859	398	530	342	475
		SD	229	201	171	139	150	140	168	287
	E 4	N	4	4	6	6	8	8	6	6

TABLE 15. MEAN HORIZONTAL VISUAL RANGE COUNTING CENTERLINE LIGHTS WITH COCKPIT IN HIGH POSITION (STUDY II).

	Step Setting	Test condition	Fog density equivalency							
			Cat I		Cat. II		Cat IIIA		Cat IIIB	
			50'	100'	50'	100'	50'	100	50'	100'
	CL 5	X	1067	1542	973	955	742	442	292	192
		SD	467	142	182	162	92	142	92	[illegible]
	E 5	N	2	2	8	8	2	2	4	4
Day time	CL 4	X	892	1142	942	892	542	492	292	192
		SD	142	242	224	204	92	92	92	92
	E 5	N	2	2	8	8	2	2	4	4
	CL 3	X	992	1192	792	730	517	392	205	192
		SD	192	392	117	233	117	92	114	92
	E 5	N	2	2	8	8	2	2	4	4
	CL 5	X	2380	2342	811	830	480	[illegible]	386	530
		SD	200	204	135	140	114	92	180	162
	E 5	N	4	4	8	6	4	4	8	8
	CL 4	X	2367	2117	798	730	492	592	448	405
		SD	260	240	138	178	92	92	145	185
	E 4	N	4	4	8	8	4	4	8	3
	CL 3	X	2180	2017	742	830	517	567	[illegible]	517
		SD	157	222	175	140	117	135	157	212
Night time	E 3	N	4	4	8	6	4	4	8	8
	CL 4	X	2405	2167	792	767	480	567	[illegible]	417
		SD	181	135	142	189	114	135	175	175
	E 3	N	4	4	8	8	4	4	8	8
	CL 5	X	2242	2292	830	830	517	592	392	580
		SD	153	92	147	140	117	92	192	275
	E 4	N	4	4	8	8	4	4	8	8
	[illegible]	X	2430	2217	817	817	492	592	461	542
		SD	157	222	135	135	92	92	171	142
	E 3	N	4	4	8	8	4	4	8	8

TABLE 16. MEAN HORIZONTAL VISUAL RANGE COUNTING RIGHT-HAND RUNWAY EDGE LIGHTS FOR THE CL = 5, E = 5 "BALANCED LIGHTING SYSTEM" (STUDY I).[a]

Ambient luminance	Pilot offset	Test condition	Fog density equivalency			
			Cat. I	Cat. II	Cat. IIIA	Cat. IIIB
Day	Zero	$\bar{X}$	2092	1292	842	442
		SD	502	408	242	383
		N	4	4	4	4
	5.04 m	$\bar{X}$	2442	1442	842	442
		SD	711	[illegible]	242	383
		N	4	4	4	4
	10.12 m	$\bar{X}$	2192	1142	842	442
		SD	408	466	242	442
		N	4	4	4	4
Night	Zero	$\bar{X}$	2542	1192	642	642
		SD	342	329	242	0
		N	4	4	4	2
	5.04 m	$\bar{X}$	2342	[illegible]	642	642
		SD	342	342	242	0
		N	4	4	4	2
	10.12 m	$\bar{X}$	2492	1242	692	642
		SD	329	242	329	0
		N	4	4	4	2

[a]All data obtained with 50 ft CL spacing.

TABLE 17. MEAN HORIZONTAL VISUAL RANGE COUNTING RIGHT–HAND RUNWAY EDGE LIGHTS WITH COCKPIT IN LOW POSITION (STUDY II).

	Step Setting	Test condition	Fog density equivalency							
			Cat I		Cat II		Cat IIIA		Cat IIIB	
			50	100	50'	100'	50	100'	50'	100'
	CL 5	X	2488	2404	1453	1509	832	772	460	451
		SD	624	[illegible]	366	431	360	357	401	407
	E 5	N	26	[illegible]	18	18	20	20	22	22
Day time	CL 4	X	2434	2442	1453	1486	822	802	478	478
		SD	568	575	398	413	329	322	409	397
	E 5	N	28	26	18	19	20	20	27	22
	CL 3	X	2442	2442	1498	1498	812	802	478	451
		SD	565	630	403	403	357	322	385	418
	E 5	N	26	26	18	18	20	20	22	22
	CL 5	X	2220	2297	1165	1173	684	692	642	667
		SD	417	453	478	388	323	329	242	308
	E 5	N	18	22	26	26	24	24	16	16
	CL 4	X	2164	2197	1081	1088	675	675	567	630
		SD	454	490	399	411	336	317	339	290
	E 4	N	19	22	26	26	24	24	16	16
	CL 3	X	2122	2115	942	896	617	600	555	642
		SD	573	418	356	360	308	323	341	242
	E 3	N	20	22	26	26	24	24	16	16
Night time	CL 4	X	2020	2088	965	996	600	625	567	555
		SD	429	401	379	411	323	297	339	341
	E 3	N	18	22	26	26	24	24	16	16
	CL 5	X	2075	2106	1027	1019	625	650	630	642
		SD	362	417	417	402	322	282	290	742
	E 4	N	19	22	26	26	24	24	16	16
	CL 5	$\bar{X}$	1898	1951	850	942	517	600	442	542
		SD	499	465	359	342	381	323	242	342
	E 3	N	18	22	26	24	24	24	16	16
	CL 3	X	2142	2242	1142	1242	567	642	609	609
		SD	342	242	466	405	339	242	317	317
	E 4	N	4	4	6	6	8	8	6	6

TABLE 18. MEAN HORIZONTAL VISUAL RANGE COUNTING RIGHT–HAND RUNWAY EDGE LIGHTS WITH COCKPIT IN HIGH POSITION (STUDY II).

	Step Setting	Test condition	Fog density equivalency							
			Cat I		Cat II		Cat IIIA		Cat IIIB	
			50'	100'	50'	100'	50'	100'	50'	100'
	CL 5	$\bar{X}$	2342	2242	1542	1242	842	842	442	392
		SD	342	242	415	442	242	742	242	329
	E 5	N	2	2	8	8	2	2	4	4
Day time	CL 4	$\bar{X}$	2042	2042	1517	1442	742	842	642	442
		SD	242	242	381	242	342	242	242	242
	E 5	N	2	2	8	8	2	2	4	4
	CL 3	$\bar{X}$	2242	2342	1592	1267	842	642	442	442
		SD	442	242	408	453	242	242	242	242
	E 5	N	2	2	8	8	2	2	4	4
	CL 5	$\bar{X}$	2792	2842	1217	1092	642	842	592	642
		SD	408	242	362	329	242	242	374	242
	E 5	N	4	4	8	8	4	4	8	8
	CL 4	X	2742	2892	967	917	642	742	642	617
		SD	342	502	339	339	242	342	242	308
	E 4	N	4	4	8	8	4	4	8	8
	CL 3	$\bar{X}$	2542	2642	892	892	642	642	492	567
		SD	342	383	329	329	242	242	329	339
Night time	E 3	N	4	4	8	8	4	4	8	8
	CL 4	$\bar{X}$	2492	2492	892	817	542	642	542	542
		SD	329	329	329	362	342	242	742	342
	E 3	N	4	4	8	8	4	4	8	8
	CL 5	$\bar{X}$	2592	2642	992	942	642	692	542	617
		SD	329	383	329	342	242	329	342	308
	E 4	N	4	4	6	8	4	[illegible]	8	8
	CL 5	$\bar{X}$	2292	2592	842	942	592	642	517	617
		SD	329	329	242	342	320	242	339	308
	E 3	N	4	4	8	8	4	[illegible]	8	8

TABLE 19. MEAN HORIZONTAL VISUAL RANGE COUNTING LEFT–HAND RUNWAY EDGE LIGHTS FOR THE CL = 5, E = 5 "BALANCED LIGHTING SYSTEM" (STUDY I).[a]

Ambient luminance	Pilot offset	Test condition	Fog density equivalency: Cat. I	Cat. II	Cat. IIIA	Cat. IIIB
Day	Zero	$\bar{X}$	2742	1542	842	292
		SD	997	742	242	329
		N	4	4	4	4
	5.04 m	$\bar{X}$	2742	1892	792	442
		SD	654	408	329	242
		N	4	4	4	4
	10.12 m	$\bar{X}$	2492	1942	842	442
		SD	502	882	242	442
		N	4	4	4	4
Night	Zero	X	2292	1092	642	642
		SD	329	329	242	0
		N	4	4	4	2
	5.04 m	$\bar{X}$	2142	1242	642	642
		SD	342	242	242	0
		N	4	4	4	2
	10.12 m	$\bar{X}$	2542	1042	642	642
		SD	342	329	242	0
		N	4	4	4	2

[a]All data obtained with 50 ft CL spacing.

TABLE 20. MEAN HORIZONTAL VISUAL RANGE COUNTING LEFT–HAND RUNWAY EDGE LIGHTS WITH COCKPIT IN LOW POSITION (STUDY II).

	Step Setting	Test condition	Fog density equivalency: Cat. I 50'	Cat. I 100'	Cat. II 50'	Cat. II 100'	Cat. IIIA 50'	Cat. IIIA 100'	Cat. IIIB 50'	Cat. IIIB 100'
Day time	CL 5	$\bar{X}$	2434	2411	1380	1353	802	782	451	469
		SD	543	559	440	519	322	385	383	416
	E 5	N	26	26	18	18	20	20	22	22
	CL 4	$\bar{X}$	2357	2473	1475	1398	822	822	451	442
		SD	589	592	379	437	350	329	407	390
	E 5	N	26	26	18	18	20	20	22	22
	CL 3	$\bar{X}$	2257	2365	1464	1320	812	782	442	506
		SD	551	551	404	420	313	334	302	527
	E 5	N	26	26	18	18	20	20	22	22
Night time	CL 5	$\bar{X}$	2386	2397	1081	1096	692	700	642	642
		SD	461	467	366	331	329	333	242	313
	E 5	N	18	22	26	26	24	24	16	16
	CL 4	$\bar{X}$	2164	2315	1004	1073	667	659	567	630
		SD	510	418	338	333	308	297	339	290
	E 4	N	18	22	26	26	24	24	16	16
	CL 3	$\bar{X}$	2282	2197	896	927	600	584	605	592
		SD	650	459	331	368	342	333	320	329
	E 3	N	20	22	26	26	24	24	16	16
	CL 4	$\bar{X}$	2098	2242	973	957	584	600	567	605
		SD	515	442	352	355	333	323	339	320
	E 3	N	18	22	26	26	24	24	16	16
	CL 5	$\bar{X}$	2209	2260	996	1027	650	617	630	642
		SD	445	422	326	337	282	308	290	242
	E 4	N	18	22	26	26	24	24	16	16
	CL 5	$\bar{X}$	1998	1969	896	917	509	617	467	580
		SD	478	447	612	369	353	330	308	335
	E 3	N	18	22	26	24	24	24	16	16
	CL 3	$\bar{X}$	2242	2442	1142	1175	642	642	609	609
		SD	242	242	395	336	242	242	317	317
	E 4	N	4	4	6	6	8	8	6	6

TABLE 21. MEAN HORIZONTAL VISUAL RANGE COUNTING LEFT-HAND RUNWAY EDGE LIGHTS WITH COCKPIT IN HIGH POSITION (STUDY II).

	Step Setting	Test condition	Fog density equivalency							
			Cat I		Cat II		Cat IIIA		Cat IIIB	
			50	100'	50'	100'	50'	100'	50'	100'
Day time	CL 5	X	2342	2442	1467	1667	742	942	442	292
		SD	342	442	398	362	342	342	242	329
	E 5	N	2	2	8	8	2	2	4	4
	CL 4	X	2142	2142	1592	1267	842	842	542	442
		SD	342	542	460	427	242	242	342	242
	E 5	N	2	2	8	8	2	2	4	4
	CL 3	X	2242	2242	1442	1292	842	742	442	442
		SD	242	242	442	460	242	342	242	242
	E 5	N	2	2	8	8	2	2	4	4
Night time	CL 5	X	2542	2642	1117	1092	642	842	567	667
		SD	342	242	339	329	242	242	381	308
	E 5	N	4	4	8	8	4	4	8	8
	CL 4	X	2492	2692	942	942	642	742	617	592
		SD	329	329	342	342	[illegible]	342	308	329
	E 4	N	4	4	8	8		4	8	8
	CL 3	X	2442	2292	867	892	642	642	567	592
		SD	242	329	308	329	242	242	381	329
	E 3	N	4	4	8	8	4	4	8	8
	CL 4	X	2242	2342	892	817	642	642	517	542
		SD	242	342	329	308	242	242	339	342
	E 3	N	4	4	8	8	4	4	8	8
	CL 5	X	2392	2492	992	1017	642	642	542	592
		SD	329	408	329	308	242	242	342	329
	E 4	N	4	4	8	8	4	[illegible]	8	8
	CL 5	X	1992	2542	842	817	542	642	517	542
		SD	329	817	242	363	342	242	339	342
	E 3	N	4	4	8	8	4	4	8	8

TABLE 22. ANALYSIS OF VARIANCE SUMMARY FOR CENTER-LINE LIGHT COUNT DAYTIME RESULTS WITH COCKPIT IN LOW POSITION (STUDY II).

Source	df	SS	MS	f
Fog density (D)	3	33382.8	11127.6	123.1[a]
CL spacing (B)	1	731.5	731.5	8.1[b]
CL-edge light intensity step setting (W)	2	904.0	452.0	85.3[a]
(D) × (B)	3	577.9	192.6	2.1
(D) × (W)	6	484.9	80.8	15.2[a]
(B) × (W)	2	9.5	4.8	9
(D) × (B) × (W)	6	39.6	6.6	1.2
Subject × (D × B)	56	5063.5	90.4	14.4[d]
(Subject × W) × (D × B)	112	593.8	5.3	.8
Repl × (D × B × W × Subject)	192	1202.1	6.3	---

$^a p < 0.01$

$^b p < .001$

TABLE 23. ANALYSIS OF VARIANCE SUMMARY FOR CENTER-LINE LIGHT COUNT NIGHTTIME RESULTS WITH COCKPIT IN LOW POSITION (STUDY II).

Source	df	SS	MS	f
Fog density (D)	3	76921.1	25640.4	321.4[a]
CL spacing (B)	1	958.6	958.6	12.0[a]
CL-edge light intensity step setting (W)	5	376.1	75.2	13.9[a]
(D) × (B)	3	327.8	109.3	1.4
(D) × (W)	15	232.2	15.5	2.9[a]
(B) × (W)	5	21.6	4.3	.8
(D) × (B) × (W)	15	95.4	6.4	1.2
Subject × (D × B)	56	4467.1	79.8	48.3[a]
(Subject × W) × (D × B)	280	1516.2	5.4	3.3[a]
Repl. × (D × B × W × Subject)	384	634.9	1.7	---

$^a p < 0.001$

TABLE 24. ANALYSIS OF VARIANCE SUMMARY FOR CENTER-LINE LIGHT COUNT NIGHTTIME RESULTS WITH COCKPIT IN HIGH POSITION (STUDY II)

Source	df	SS	MS	f
Fog density (D)	3	39798.7	13266.2	a
CL spacing (B)	1	1.7	1.7	.3
CL-edge light intensity step setting (W)	5	67.4	13.5	8.9[b]
(D) X (B)	3	165.1	55.0	10.0[c]
(D) X (W)	15	85.5	5.7	3.8[b]
(B) X (W)	5	26.7	5.4	3.5[d]
(D) X (B) X (W)	15	70.1	4.7	3.1[c]
Subject X (D X B)	8	44.1	5.5	2.8[d]
(Subject X W) X (D X B)	40	60.8	1.5	.8
Repl. X (D X B X W X Subject)	96	191.3	2.0	---

[a]Very large value, assume $p < 0.001$

[b]$p < 0.001$

[c]$p < 0.005$

[d]$p < 0.01$

TABLE 25. ANALYSIS OF VARIANCE SUMMARY FOR RIGHT-HAND RUNWAY EDGE LIGHT COUNT DAYTIME RESULTS WITH COCKPIT IN LOW POSITION (STUDY II).

Source	df	SS	MS	f
Fog density (D)	3	5528.1	1842.7	346.5[a]
CL spacing (B)	1	.5	.5	.1
CL-edge light intensity step setting (W)	2	.4	.2	.6
(D) X (B)	3	.9	.3	.1
(D) X (W)	6	1.1	.2	.6
(B) X (W)	2	2	.1	.2
(D) X (B) X (W)	6	2.8	.5	1.5
Subject X (D X B)	56	297.8	5.3	13.8[a]
(Subject X W) X (D X B)	112	35.0	.31	.8
Repl. X (D X B X W X Subject)	192	73.8	.4	---

[a]$p < 0.001$

TABLE 26. ANALYSIS OF VARIANCE SUMMARY FOR RIGHT-HAND RUNWAY EDGE LIGHT COUNT NIGHTTIME RESULTS WITH COCKPIT IN LOW POSITION (STUDY II).

Source	df	SS	MS	f
Fog density (D)	3	7173.1	2391.0	853.2[a]
CL spacing (B)	1	9.6	9.6	3.4
CL-edge light intensity step setting (W)	5	91.5	18.3	38.6[a]
(D) X (B)	3	1.9	.6	.2
(D) X (W)	15	25.6	1.7	3.6[a]
(B) X (W)	5	3.2	.6	1.3
(D) X (B) X (W)	15	4.5	.3	.6
Subject X (D X B)	56	157.0	2.8	14.9[a]
(Subject X W) X (D X B)	280	132.7	.5	2.5[a]
Repl X (D X B X W X Subject)	384	72.1	.2	---

[a]$p < 0.001$

TABLE 27. ANALYSIS OF VARIANCE SUMMARY FOR RIGHT-HAND RUNWAY EDGE LIGHT COUNT NIGHTTIME RESULTS WITH COCKPIT IN HIGH POSITION (STUDY II).

Source	df	SS	MS	f
Fog density (D)	3	3258.3	1086.1	a
CL spacing (B)	1	1.9	1.9	2.4
CL-edge light intensity step setting (W)	5	29.5	6.0	40.2[b]
(D) X (B)	3	4.1	1.4	1.7
(D) X (W)	15	16.2	1.1	7.3[b]
(B) X (W)	5	1.7	.3	2.2
(D) X (B) X (W)	15	3.8	.3	1.7
Subject X (D X B)	8	6.3	.8	3.2[c]
(Subject X W) X (D X B)	40	5.9	.1	.6
Repl. X (D X B X W X Subject)	96	23.6	.3	---

[a]Very large value, assume $p < 0.001$.

[b]$p < 0.001$

[c]$p < 0.005$

TABLE 28. ANALYSIS OF VARIANCE SUMMARY FOR LEFT-HAND RUNWAY EDGE LIGHT COUNT DAYTIME RESULTS WITH COCKPIT IN LOW POSITION (STUDY II).

Source	df	SS	MS	f
Fog density (D)	3	5025.8	1675.3	320.5[a]
CL spacing (B)	1	.5	.5	.1
CL-edge light intensity step setting (W)	2	1.8	.9	2 3
(D) × (B)	3	2.9	1.0	.2
(D) × (W)	6	2.8	.5	1.2
(B) × (W)	2	.5	.3	.6
(D) × (B) × (W)	6	4 7	.8	2.0
Subject × (D × B)	56	292.7	5.2	11.8[a]
(Subject × W) × (D × B)	112	44 0	.4	.9
Repl × (D × B × W × Subject)	192	84.8	4	---

[a]$p < 0.001$

TABLE 29. ANALYSIS OF VARIANCE SUMMARY FOR LEFT-HAND RUNWAY EDGE LIGHT COUNT NIGHTTIME RESULTS WITH COCKPIT IN LOW POSITION (STUDY II).

Source	df	SS	MS	f
Fog density (D)	3	8214.6	2738.2	a
CL spacing (B)	1	14 6	14.6	7.5[b]
CL-edge light intensity step setting (W)	5	79.1	15.8	34.8[c]
(D) × (B)	3	7.8	2.6	1.3
(D) × (W)	15	31.8	2.1	4.7[c]
(B) × (W)	5	3 2	6	1.4
(D) × (B) × (W)	15	14 2	1 0	2.1[b]
Subject × (D × B)	56	108 6	1.9	6.7[c]
(Subject × W) × (D × B)	280	127.2	5	1.6[c]
Repl × (D × B × W × Subject)	384	112 0	.3	--

[a]Very large value, assume $p < 0.001$.
[b]$p < 0.01$
[c]$p < 0.001$

Table 29

TABLE 30. ANALYSIS OF VARIANCE SUMMARY FOR LEFT-HAND RUNWAY EDGE LIGHT COUNT NIGHTTIME RESULTS WITH COCKPIT IN HIGH POSITION (STUDY II).

Source	df	SS	MS	f
Fog density (D)	3	2614.5	871.5	a
CL spacing (B)	1	3.8	3.8	15.5[b]
CL-edge light intensity step setting (W)	5	19.9	4.0	23.5[c]
(D) × (B)	3	4.6	1.5	6.2[d]
(D) × (W)	15	9.7	.6	3.8[c]
(B) × (W)	5	8.7	1.7	[illegible][c]
(D) × (B) × (W)	15	9 3	.6	[illegible][c]
Subject × (D × B)	8	2.0	.2	[illegible]
(Subject × W) × (D × B)	40	6 8	.2	.4
Repl. × (D × B × W × Subject)	96	44.5	.5	---

[a]Very large value, assume $p < 0.001$.
[b]$p < 0.005$
[c]$p < 0.001$
[d]$p < 0.025$

TABLE 31. MEAN DIFFERENCE BETWEEN STUDENT AND PILOT VISUAL RANGE DATA.

Ambient luminance	Test condition	Fog density equivalency							
		Cat. I		Cat II		Cat. IIIA		Cat IIIB	
		Student	Pilot	Student	Pilot	Student	Pilot	Student	Pilot
Day	X̄	1430 0[a]	1650 8[a]	967 5	878 6	642 5	585 4	300 0	288.9
	SD	203 6	277 7	172.9	283 8	196 6	157 6	200.1	164.4
	N	16	24	12	18	18	18	20	14
Night	X̄	1509 2	1597.9	845 6	869 3	492 5	515 4	448.1	420 6
	SD	171 4	338.7	159 7	190 2	133 3	140 3	142 2	158 6
	N	15	28	16	28	12	24	9	16

[a]Denotes significant (t test) difference at $p < 0.005$ level of confidence