NASA CONTRACTOR REPORT

NASA CR-1220

DISCRIMINATION OF INCREASES IN THE BRIGHTNESS OF A FLASHING BEACON

by R. S. Lincoln, S. Seidenstein, and C. V. Juliano

Prepared by
LOCKHEED MISSILES & SPACE COMPANY
Sunnyvale, Calif.
for Langley Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • OCTOBER 1968

NASA CR-1220

DISCRIMINATION OF INCREASES IN THE BRIGHTNESS OF A FLASHING BEACON

By R. S. Lincoln, S. Seidenstein, and C. V. Juliano

Prepared under Contract No. NAS 1-6801 by
LOCKHEED MISSILES & SPACE COMPANY
Sunnyvale, Calif.

for Langley Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – CFSTI price $3.00

CONTENTS

ILLUSTRATIONS

TABLES

SUMMARY

If electronic devices should fail, the pilot of a rendezvousing spacecraft would have to depend upon direct visual sensing of important parameters, such as range and range rate, in order to complete his mission. A cue for judgments of changes in range might be derived from associated changes in the brightness of a beacon light located on the vehicle with which the pilot was attempting to rendezvous. This report describes a study of the effects, on such judgments, of four variables: beacon flash rate, beacon "on" time, beacon intensity, and rate of vehicle closure.

Twenty-five subjects viewed a "point" source beacon, represented by a xenon arc lamp, through a lens that provided a virtual image of the beacon at a point near infinity. Flash rate and "on" time were controlled by motor driven cams, while rate of closure was controlled with a servo motor that rotated a circular neutral filter, the density of which increased linearly. Initial brightness was varied with a second circular filter. In a counterbalanced experimental design each subject was exposed to combinations of all four variables, each at five levels. On certain trials, a "steady" rather than a flashing beacon was employed.

The principal measure of performance was the amount of time required to discriminate a change in beacon brightness, measured from the initiation of a trial to its termination by the subject when he was "absolutely sure" that the brightness of the beacon had increased.

The results indicated that the thresholds for brightness increase were positively related to the rate at which the brightness of the beacon increased. A less prominent, but statistically significant relationship was also found between initial level of beacon illuminance and discrimination thresholds. The higher the initial illuminance, the shorter the discrimination time.

Within the range investigated in this experiment, flash rate and "on" time had no significant effect on the time required for brightness discrimination.

The observed results were compared with those obtained in other relevant studies, and recommendations both for beacon design and future research were made.

INTRODUCTION

The completion of a rendezvous maneuver without the assistance of electronic sensors places heavy demands upon the sensory capabilities of the astronaut who must perform the maneuver. Of critical importance is his ability to directly sense angles, angular rates, range, and range rates relative to the spacecraft with which he is attempting to rendezvous. The position in space of this target spacecraft may be identified, particularly at extreme ranges, by means of a flashing beacon. Cues derived from the characteristics of the beacon may provide the information necessary to the astronaut as a basis for his perceptual judgments.

With regard to judging the relative rate of closure between the chaser and target spacecraft, the beacon will provide a consistent cue; the brightness of the beacon will increase, according to the inverse square law, as the distance separating the two vehicles decreases. The purpose of the present experiment was to determine the ability of human observers to discriminate changes in the brightness of a simulated beacon as a function of certain characteristics of the beacon. More specifically, thresholds for the perception of increases in beacon brightness were determined for various initial levels of beacon brightness, the rate of brightness increase, the beacon flash rate, and the duration of the flashes. The obtained thresholds differ from typical psychophysical thresholds as a result of the manner in which they were determined. Rather than being stimulus values detected 50 percent of the time, the thresholds obtained in the present study are considerably more conservative since they are intended to represent stimulus changes that would be detected very nearly 100 percent of the time.

Examination of related studies reveals two relevant classes of experiments. One class of studies concerns the identification of stimulus variables affecting the initial detection of flashing lights, while the other class of studies concerns the perception of changes in lights that, in effect, have already been detected.

Detection studies are relevant because the beacon that might be used in judging rate of closure is likely to be the same beacon that must first be detected before rate can be perceived. Consequently, an examination of beacon characteristics optimal for detection may help to define the range of characteristics that should be investigated in a study of the perception of brightness change. At the least, it would be desirable to determine the degree of correspondence between optimal characteristics for the two different tasks.

The effects of variation in beacon brightness, flash rate, and flash duration have typically received attention in studies of the detection of flashing lights. Other variables, such as rate of lateral beacon motion, which do not concern characteristics inherent in the beacon itself, have also been investigated. Thus, Shea and Summers (ref. 1) examined the effects of velocity, intensity, and starfield background upon the detectability of point source targets. They appear to have found that target velocity was by far the most important variable, while the differences between background star densities and target intensities (equivalent to third and fifth magnitude stars) were not great. The validity of these conclusions is weakened, however, by an inappropriate statistical analysis which actually made use of only a portion of the number of degrees of freedom available.

Johnson (ref. 2) studied the effect of flash rate and pattern upon the time required to detect a stroboscopic beacon. Although his results suggested an optimal rate of one flash per second, detection times for flash rates of one flash in two and three seconds did not differ significantly from the presumed optimum, nor did flash pattern have a significant effect.

The detectability of low luminance flashing lights has been investigated by Wienke (ref. 3) who projected his lights against a star background provided by a planetarium. He found that, at each of two luminance levels, the probability of detection was relatively independent of the two flash rates employed.

In an earlier study, Crumley and Atkinson (ref. 4) worked on problems concerned with the exterior lighting of Naval aircraft. As part of this effort, they studied the factorial combinations of five flash rates (.67, 1.00, 1.25, 1.67, and 2.00 per second) and five flash durations (33%, 50%, 66%, 75%, 80% "on" time). Flash rate had no significant effect on detection time, while "on" times of 66% and below were significantly better than longer durations. Once more these results must be interpreted with caution because only four subjects were used and the effects of practice were not accounted for in the analysis.

In summary, it would appear that physical rather than psychological constraints may be more important in determining the characteristics of beacons used for detecting objects. Of the variables pertinent to the present study, only "on" time seems to have significantly affected detection time (as long as the intensity of the light was well above threshold). Although similar negative results may not be obtained when the task is to report changes in the brightness of a beacon, the detection studies appear to be of only limited value in selecting parametric values for that type of task.

In actuality, the available literature on thresholds for brightness discrimination is also of little value in establishing either the specific values or even the range of values for parameters to be investigated. This situation results, in part, from the common concern with relatively large fields rather than with a point source as used in the present beacon simulation. As Geldard (ref. 5) has reported, the effect of field size is critical since differential thresholds for small sources are considerably greater than comparable thresholds for extended sources. Furthermore, many studies have employed simultaneous rather than successive presentation of test and comparison fields. As a consequence, generalizations from typical studies are inappropriate for the present purpose.

The effect of rate of brightness change has been investigated by Drew (ref. 6) whose conclusion that differential thresholds increase with decreasing rates of change is in direct contrast with results reported by Connors (ref. 7).

In Connor's experiment the discrimination of brightness differences was studied in relation to the rate of brightness change and the initial level of brightness of a point source. A constant rate of one flash per second and an "on" time of 10 percent were employed. As previously suggested, results showed that the slower rates of change in fact produced lower thresholds.

Clearly Connor's study is most directly applicable to the present experiment, yet even in that work there is very little suggestion of the appropriate range of parameters which should be systematically investigated. The rationale for those values selected for study has been, therefore, to choose rates of brightness change and initial levels of brightness that fall within a range that might conceivably be encountered in a realistic operation. The levels for the remaining two experimental variables (flash rate and "on" time) have been somewhat arbitrarily selected so as to cover a range broad enough to enhance the chances of encompassing values that are optimal for detecting increases in beacon brightness.

EQUIPMENT

The general features of the experimental facility are shown in Figure 1. The experimenter and the subject were separated by a partition through which projected a light tight tunnel joining the point light source and the lens. The interior of the tunnel was painted with low reflectance (.1%), almost perfectly diffusing, black paint to minimize reflections.

The subject was seated in an adjustable chair and was requested to position his head against a head rest during each experimental trial. A bite board was not used in the study because the experimental conditions were specifically intended to approximate an operational situation in which the additional control provided by a bite board would not be available.

The lens, through which the subject viewed the point source light, was included in the equipment to further enhance the realism of the subject's task. In effect the lens provided a virtual image of the simulated beacon at near optical infinity by producing parallel light rays at the subject's eye. In this manner cues of convergence and accommodation, not present in the "real world", were eliminated. A schematic diagram of the lens and its properties is shown in Figure 2, and a detailed description of its use in a similar application is presented in reference 8.

Experimental control was concentrated on a single panel where, by means of appropriate switch operations, the experimenter could select the

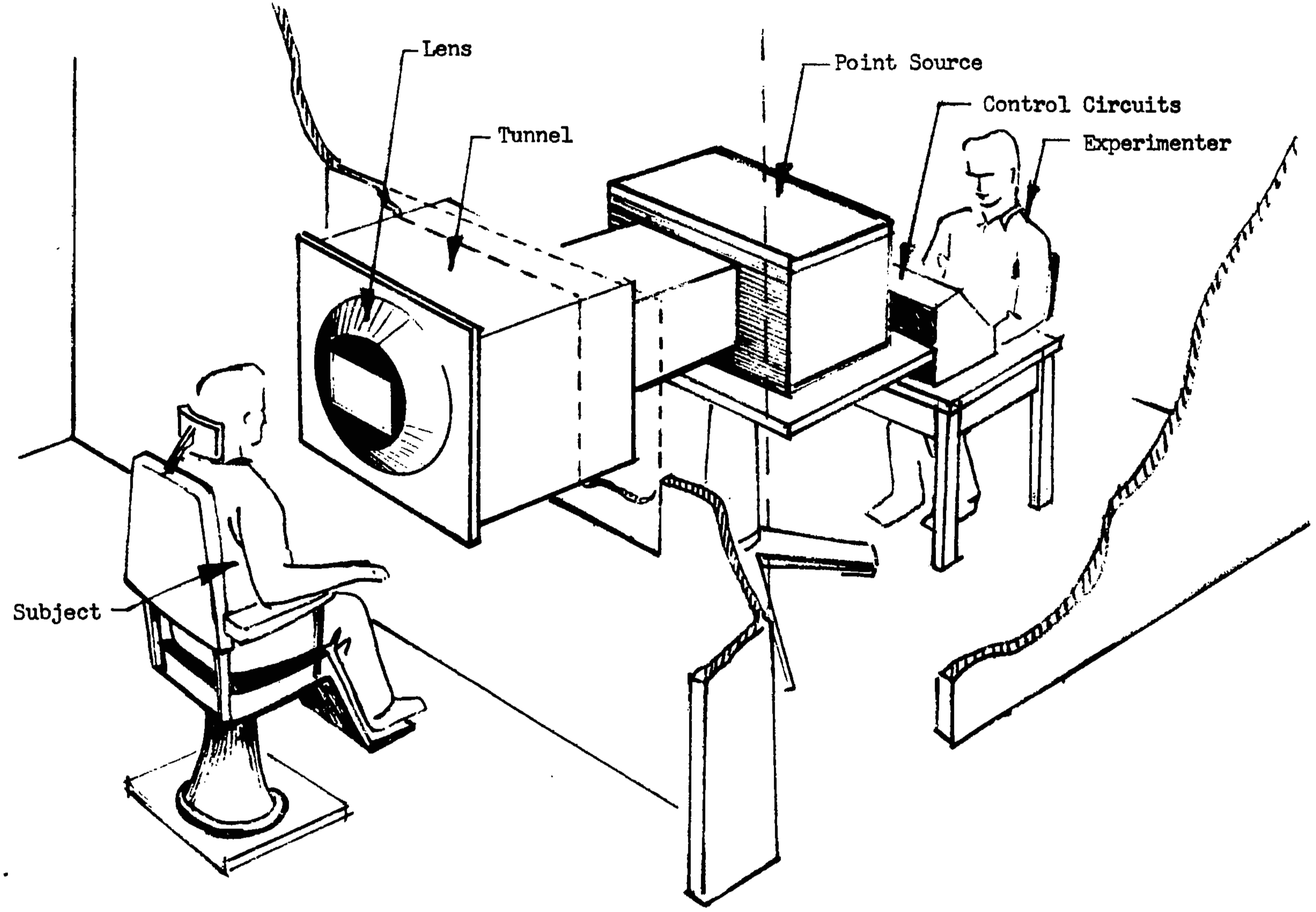

Fig. 1. Experimental Facility

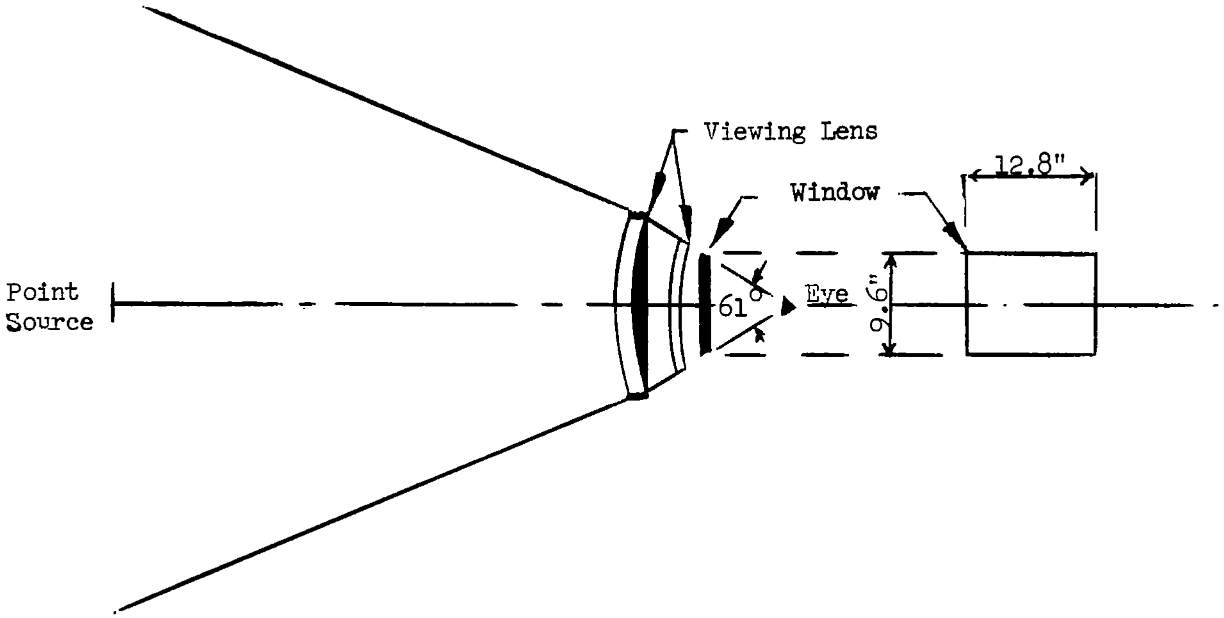

Fig. 2 Lens Schematic

flash, rate, flash duration, and rate of brightness change for each trial.

A schematic diagram of the mechanism for controlling the experimental variables is pictured in Figure 3. A 75 watt xenon arc lamp served as the point light source. To improve stability, the power supply normally provided with this lamp was replaced by a highly regulated supply. After passing through an infrared filter and a collimating lens, the light passed through a pair of circular neutral variable density filters. Since the density of the filters was proportional to their angle of rotation, the logarithm of their transmission was also proportional to angular position. Each of the filters covered two log units in 270 degrees.

The first filter (the balance) served two functions; because of its reversed direction it compensated for the intensity gradient across the width of the collimated light beam, that would be produced by a single filter, and it served as a means of establishing the initial level of beacon brightness required for each trial. For this latter function, the angular position of the filter was altered by turning a knob geared to the filter. A scale associated with the knob provided a direct indication of the filter position.

Rotation of the second filter (the wedge) accomplished the change in stimulus brightness which the subjects attempted to detect. A servo motor drove the wedge, and a ten-turn potentiometer connected to a digital voltmeter was used to monitor wedge position. Selection of wedge rate was controlled by switching to calibrated resistors in the servo speed control circuit.

After passing through the wedge and balance, the light beam passed through Wratten neutral density filters and entered a telescope and microscope objective that focused the light on an aperture, 0.007 of an inch in diameter, which produced the final point of light observed by the subjects. A shutter, mounted on a rotary solenoid, permitted independent control of both the flash rate and the flash duration. This control was accomplished by means of a set of cams driven by a second motor. The speed of motor rotation determined the flash rate while the extent of the indentations in the cams determined flash duration. A selector switch permitted the experimenter to select the output of the cam required for each trial. As with the wedge drive, cam motor speed could be selected by switching to the appropriate

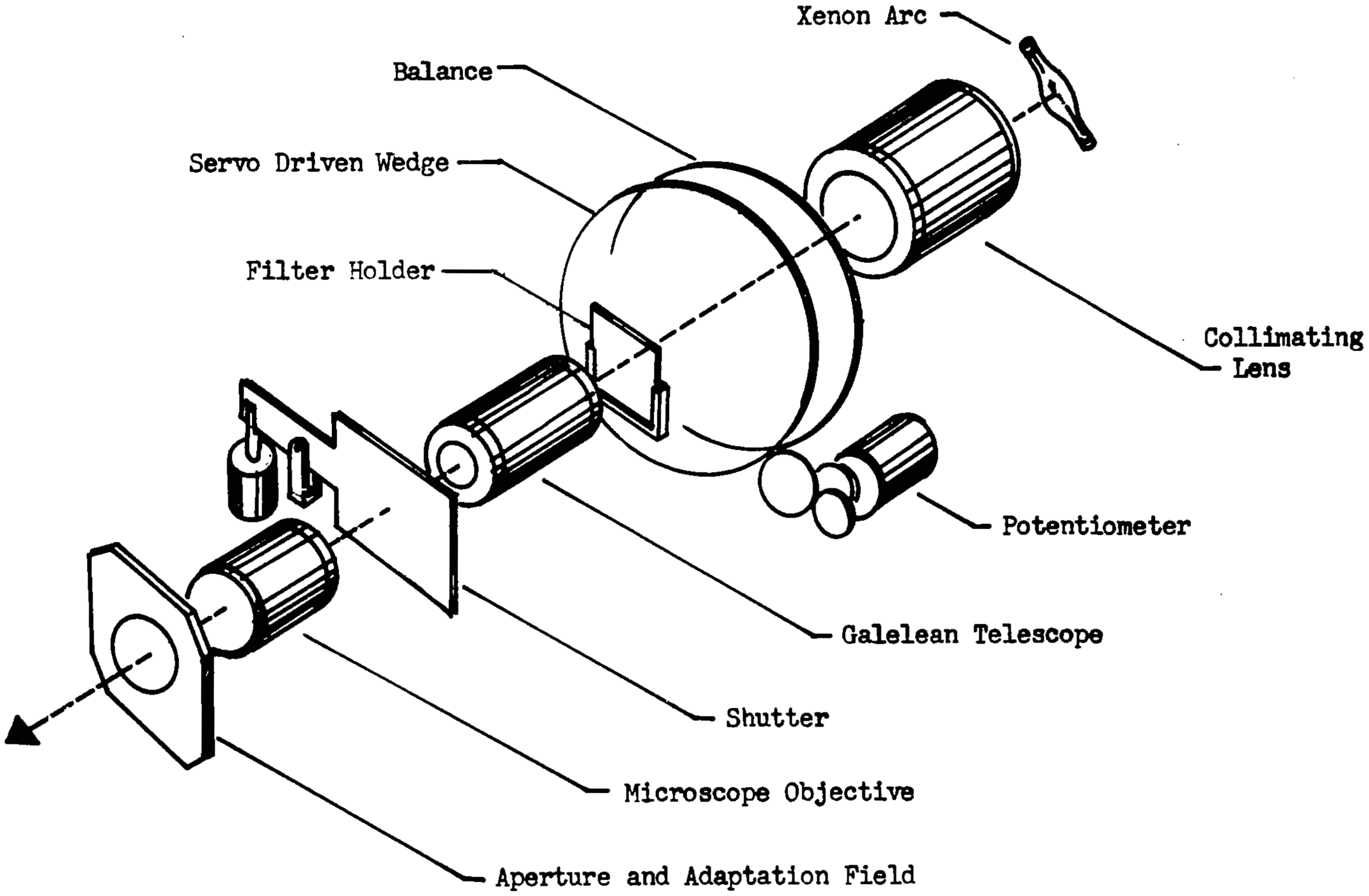

Fig. 3. Apparatus Schematic

calibrated resistor. An additional cam on the camshaft prevented the operation of the shutter before the start of a flash cycle, regardless of the rate or flash duration selected.

An adaptation field, consisting of eight equally spaced points of light against a black surround, was positioned approximately one inch in front of the aperture plate. The points were produced by back lighting eight pinholes (.02 of an inch in diameter) which formed a circle covering approximately two degrees of visual angle around the beacon. The brightness of the adaptation field was controlled from a regulated power supply. The illuminance of the eight points ranged from the equivalent of +3 to +1 magnitude stars.

Two functions were served by the adaptation field. Before the start of each trial the subject's report that he could see the circle of lights indicated that a minimum level of dark adaptation had been maintained. Furthermore, during a trial the circle served as a positional reference intended to reduce the autokinetic movement of the beacon, particularly at low levels of brightness.

Subjects were provided with two push button switches. Operation of the first switch initiated a trial by activating the motors that controlled the wedge and the shutter, and, at the same time, starting a timer. Operation of the second button stopped the timer and the motors. At the end of each trial the experimenter recorded the duration of the trial and the position that the wedge had reached when the subject pushed the "stop" button.

In order to eliminate the sound of the shutter solenoid as a potential (but undesirable) cue to shutter operation, the subjects wore a headset through which they listened to a continuous recording of the solenoid operating at a variety of frequencies. The recording thus masked the sound made by the actual solenoid in operation.

THE EXPERIMENT

Experimental Variables

Table I lists the four experimental variables studied in the experi-

TABLE I

EXPERIMENTAL VARIABLES

	Initial Illuminance		Wedge Rate			
Level	log ft-c.	Star Magnitude	Mean Time For One Log Change(sec.)	S.D. (sec.)	Mean Rate (Log units per sec.)	Simulated Range Rate (ft./sec.)*
1	-7.2441	+1.4	1585	194.6	.00063	80
2	-7.0809	+1.0	590	32.6	.00170	210
3	-6.8894	+0.5	311	10.6	.00320	400
4	-6.6289	-0.1	170	5.5	.00590	735
5	-6.2882	-1.0	85	2.2	.01180	1465

	Flash Rate			Flash Duration
Level	Mean Time (sec.) for 24 flashes	S.D. (sec.)	Mean Flashes per sec.	(% time "on")
1	39.7	2.7	.60	10%
2	31.3	2.0	.76	25%
3	23.0	1.4	1.04	40%
4	16.7	1.1	1.43	55%
5	8.6	0.6	2.80	70%

*Since the simulated approach rate was not constant, these values have a maximum error of 10.5%; an initial range of 30 n.mi. was assumed.

ment, as well as the values assigned to each level of each variable. Since variation in two of these variables was observed during calibration operations, performed both before and after each test run, standard deviations of the mean values for each level are also given for those variables.

Daily calibration of the xenon source indicated considerable variation in intensity, particularly during the early life of the lamp. Consequently, compensating changes were made, before each test run, in the density of the Wratten filters that were employed to reduce the illuminance of the lamp to the desired level.

The illuminance of the dimmest experimental beacon was measured with a telescopic photometer that was calibrated against a special point source mask applied to a standard calibration lamp. This measurement was accomplished without the normal 2.9 log unit neutral density filter in the optical path. The measured illuminance was then reduced by the value of the filter, and the illuminance for each of the other four levels was calculated from that base point, in accordance with the changes in filter density that were established with the balance filter.

For the purposes of the experimental analysis, the levels of initial illuminance were considered to represent beacons of different intensity, all initially viewed from a simulated distance of 30 n.mi. These initial levels may also be considered to represent a beacon of 1900 beam candle/power seen at different initial ranges of 30, 25, 20, 15, and 10 n.mi. Because of the manner in which the increase in beacon brightness (representing decreasing range) was produced, however, range rate does not remain constant for different assumed initial ranges, even for a given rate of wedge rotation. Examination of the method used to simulate changes in beacon range and range rate will help to clarify this point.

As previously indicated, the initial levels of beacon illuminance were selected by manually rotating the circular balance filter to predetermined angular positions. Increases in beacon brightness were then produced by moving the wedge filter through a maximum rotation of one log unit. According to the inverse square law, the resulting ten fold increase in beacon brightness would represent a reduction of the initial simulated range from 30 n.mi. to approximately 9.5 n.mi. Although the two end points can in this way be made to coincide, the logarithmic transmission function of the wedge only approximated the inverse square law. As shown in Figure 4, simulated range rate first increased and then decreased as compared with the inverse square curve. Consequently, the range rates shown in Table I are only approximate. This condition is not unrelated to the "real" world, however, since the range rate between two approaching spacecraft is continuously changing.

From Figure 4 it can be seen that, if an initial range of 30 n.mi. is assumed, variation in the beacon illuminance merely shifts the entire curve either up or down on an absolute scale of illuminance. Furthermore, since the maximum number of degrees traversed by the wedge is constant, changes in range rate retain the same relationship throughout the entire extent of wedge travel, regardless of wedge rate.

In contrast, Figure 5 shows that if a constant beacon is assumed, while initial range is varied, range rate differs according to the simulated range. This condition results from the fact that the total simulated distance for each of the separate curves is covered in 114 degrees of wedge rotation. Therefore, at any selected wedge rate, the average range rate for the curve starting at 30 miles would be roughly three times the range rate for the curve starting at 10 miles.

Experimental Design

In the experiment it was desired to examine all possible combinations of all five levels of each of the four variables listed in Table I. Four variables, each at five levels, will produce 625 different combinations of experimental treatments. If each combination of treatments were subjected to independent test, a minimum of 625 subjects would be required. Unless the higher order interactions were used as an estimate of error variance, this number would have to be increased to a minimum of 1250 subjects to obtain an estimate of error variance from independent replications. Because a design that would permit the extraction of all interactions of so many variables would be prohibitive in terms of the number of subjects, a design involving repeated measurements on the same subjects and the sacri-

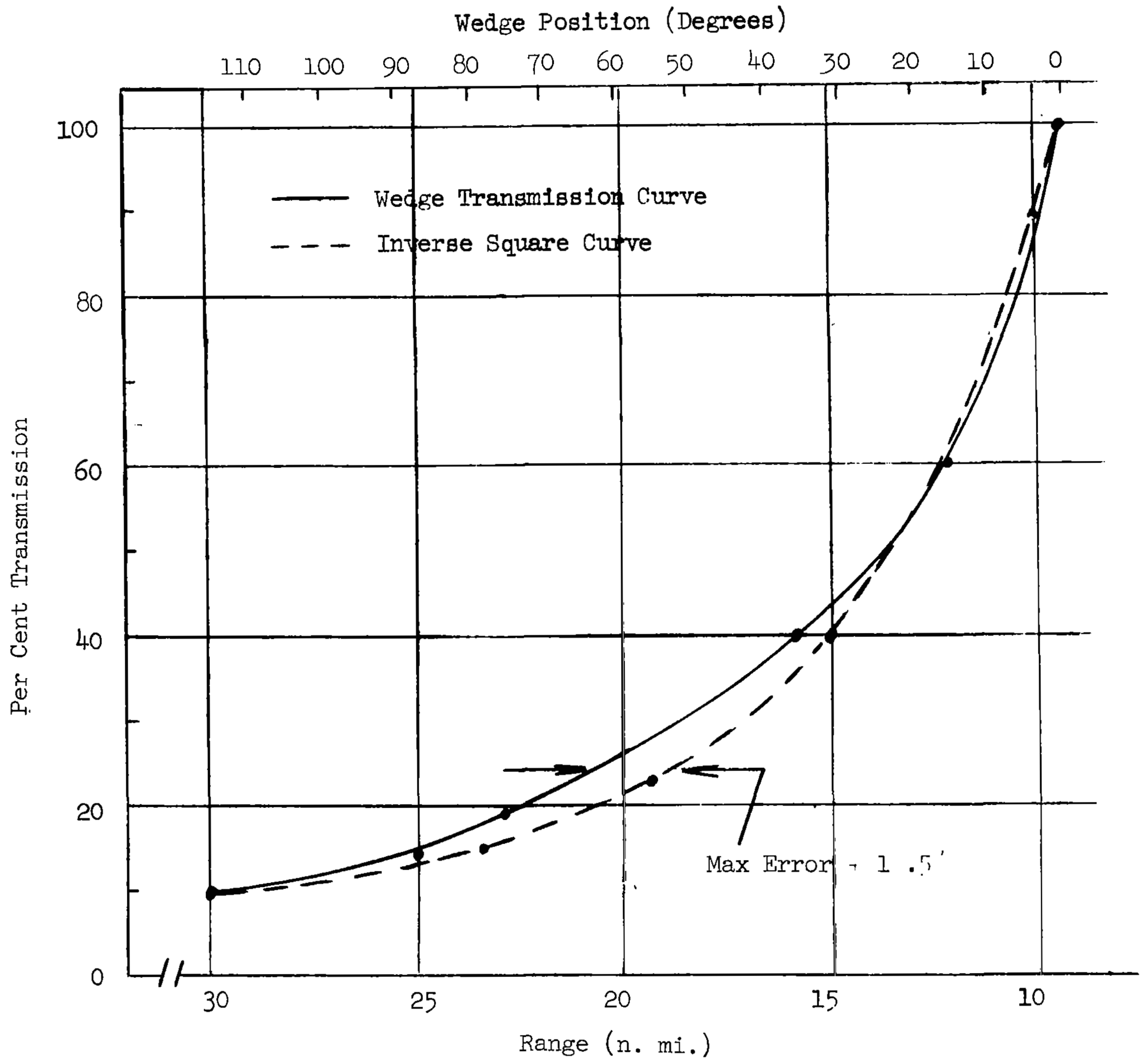

Fig. 4 Transmission of the Wedge Compared with the Inverse Square Relationship

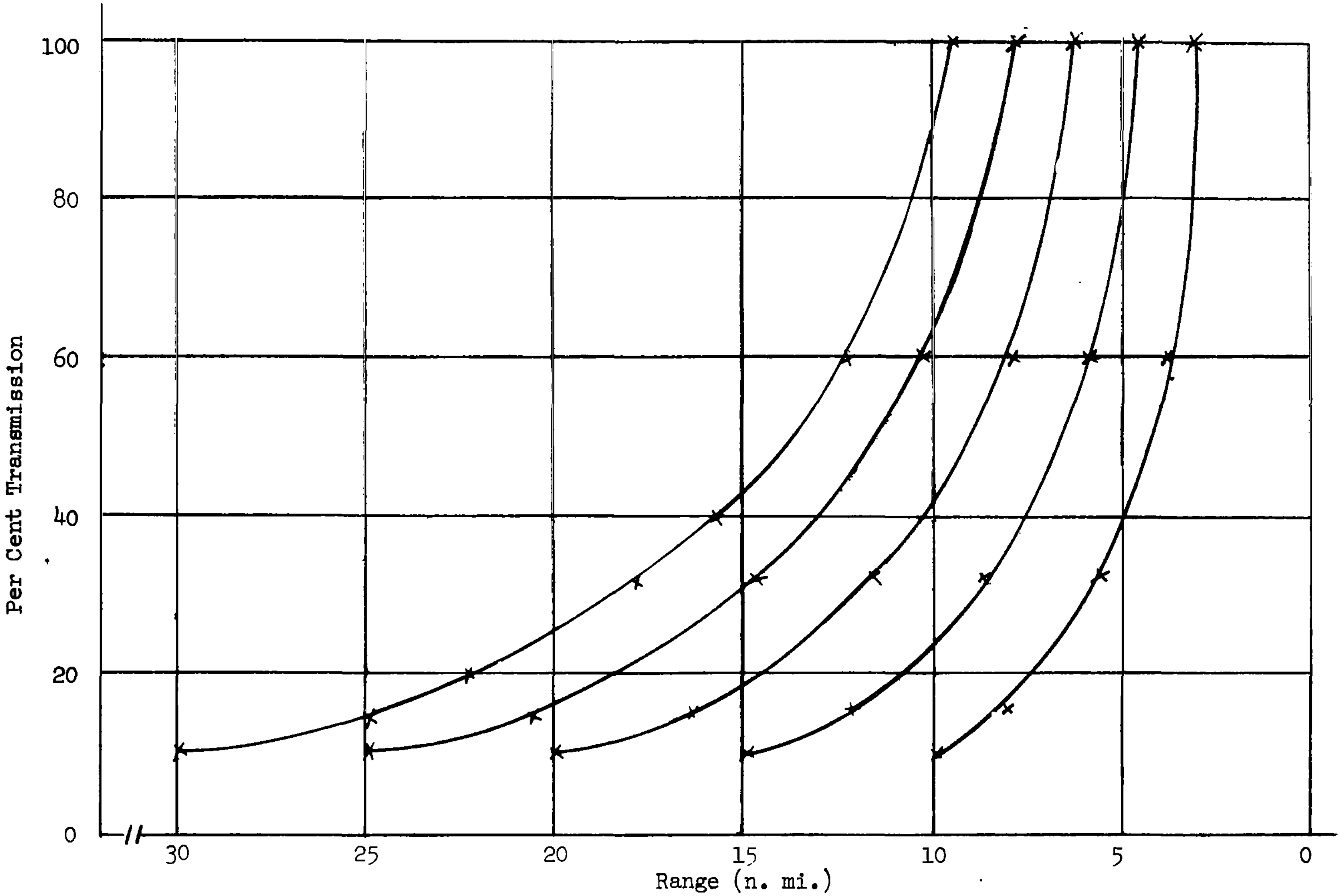

Fig. 5 Transmission as a Function of Different Assumed Initial Ranges

fice of the higher order interactions was indicated.

Repeated measurements, in turn, necessitated a design in which effects associated with successive trials on the same subject could be controlled and extracted in the analysis of the data. Finally, the order in which the various experimental conditions were presented had to be counterbalanced to minimize differential effects associated with the passage of time.

The design selected for the experiment satisfies the requirements outlined in the previous paragraph and is highly efficient with regard to the number of first order interactions that can be evaluated.

Essentially, the scheme represents the combination of a factorial design and a 25 x 25 Greco-Latin square. The 5 x 5 combinations of two of the experimental variables form the Latin component of the square while the 5 x 5 combinations of the other two variables form the Greek component of the square. In the 625 cells of the square appear all possible combinations of the four experimental variables. Each of the 25 rows of the square was assigned to a different experimental subject who, therefore, was exposed to 25 trials representing the columns of the square. As a result of the arrangement of the cells within the square, each subject was exposed to all levels of all variables, and the paired combinations of all variables, an equal number of times. In total, the 25 subjects were exposed to all combinations of the variables at all levels. Furthermore, the order of appearance of each level of each variable and each combination of variables was completely counterbalanced within the total design.

An example indicating the experimental treatments to which one subject might be exposed is shown in Table II.

Procedures

Subjects were selected from a local Junior College according to the following specifications:

1. Male
2. Age between 18 - 35
3. Uncorrected near and far visual acuity at least 20/20 (as measured with an Ortho-Rater). Far vision equal to, or better than near vision.

Each subject appeared at a designated time for two experimental ses-

TABLE II

EXAMPLE OF TRIAL SEQUENCE

Subject	Trial 1	Trial 2	Trial 3	Trial 25
1	A, F 1, 6	D, J 2, 8	C, F 4, 10	B, G 5, 8

A - E = five levels of initial illuminance
F - J = five levels of wedge rate
1 - 5 = five levels of flash rate
6 -10 = five levels of flash duration

sions during a single week; the interval between sessions varied, therefore, between one and three days. The duration of a session averaged about two hours. Subjects were seated in a chair, the height of which was adjusted to position their line of sight on the center of the lens through which they observed the beacon.

At the start of both sessions, a standard set of instructions encouraged the subjects to view a series of beacon flashes, rather than base their judgments on any one particular flash, as a means of improving the consistency of their judgments of increased brightness. Subjects were also requested to be absolutely sure that the brightness of the beacon had increased before terminating a trial. The complete instructions for both days are included in Appendix A.

When the instructions were finished, subjects began a ten minute period of dark adaptation. During this period they were requested to report as soon as they could distinguish the ring of adaptation lights. The same report was also required at the end of each individual trial. Subsequent trials were not started until this report had been made. The interval between trials was approximately 20 seconds in length.

All trials in the first session were intended to provide an opportunity for developing a consistent criterion for judging brightness increases. Three exposures to each of the five levels of all four variables (in various combinations) constituted the main group of 15 practice trials. In addition, two trials were included in which a steady, rather than a flashing beacon was employed. The final practice trials consisted of two sets of three trials each, in which the experimental variables were held constant within the three trial set. By examining the scores achieved within the two sets, the experimenter could obtain a rough notion of the consistency of the subject's judgments. Particularly, when in the experimenter's judgment, responses were highly inconsistent, a final trial was administered with no brightness increase. The readiness of the subject to respond under that condition was taken as an additional index of consistency. When, in the opinion of the experimenter, the subject's responses were too variable, he was apprised of that fact and requested to concentrate on the development of a more reliable criterion.

The second session also started with a short practice session during which subjects were exposed once to each level of each variable in selected combinations. Those trials were followed by two additional trials in which the beacon was steady instead of flashing. The combinations of wedge rate and initial beacon brightness were randomly assigned to the subjects in such a way that all possible combinations of these two variables appeared twice with the steady beacon.

When the practice period was completed, each subject made 25 judgments under conditions presented in sequences prescribed by the experimental design. It was on these judgments that the principal experimental analysis was based.

The final two trials of the second session involved a repetition of the two earlier trials with a steady beacon. Data from these trials were used as a final measure of subject consistency. They also permitted a preliminary check of the relative effect of flashing and steady beacons on the ability to discriminate brightness increases.

Results

The primary experimental data consist of scores reflecting the amount of time required for the subjects to discriminate an increase in beacon brightness under the various experimental conditions. Either in their original form, or in a transformation of it, these data were examined from three different aspects, resulting in three general analyses.

The first analysis concerned the effect, upon discrimination time for brightness increases, of the four experimental variables: (1) initial beacon brightness, (2) rate of brightness increase, (3) beacon flash rate, and (4) flash duration (expressed as a percentage of "on" time per flash). This analysis may be characterized as relative in nature, since the emphasis was on the identification of those variables which significantly affected results, without regard for the actual brightness thresholds.

In contrast, the remaining two major analyses were specifically concerned with the determination of thresholds for the discrimination of brightness increases. For this purpose, the time scores were transformed into corresponding increments in beacon brightness, and the increments were treated as differential thresholds. In the final analysis of these data, the logarithms of the differential thresholds were plotted as a function of the logarithm of the initial brightness level.

Discrimination of brightness increases with a flashing beacon. - The experiment was designed to permit an analysis of variance that would identify significant main experimental effects and certain first order interactions. In actuality there were only 32 degrees of freedom available for evaluating any two of the six possible first order interactions in a single analysis, but an indication of the potential importance of the remaining interactions was obtained by, in effect, performing two additional analyses. In each of these analyses, two more interactions were examined. Because of their expected importance, the principal analysis was performed in such a way that the interactions between rate of brightness increase and flash duration and flash rate were evaluated first. The analysis of variance for the main effects and the two specified interactions is shown in Table III. Actually, fifteen separate analyses could have been performed, testing a different pair of the six first level interactions with a different residual (error) variance in each case. However, these differences in residual variance were negligible with respect to the tests of the main effects.

Examination of Table III clearly indicates the variables that significantly influenced the discrimination time for increases in beacon brightness. The consistent relationships between discrimination time and both initial beacon brightness and rate of brightness increase is obvious in Table IV. This Table also includes mean thresholds, in two different units, for the discrimination of brightness increase as a function of rate of brightness change. The most interesting result exhibited in Table IV is the consistent relationship between rate of increase and the thresholds for discrimination of changes in brightness. Although subjects required more time to discriminate brightness changes when the rate of change was slow, the actual increase in brightness was lower for those slower rates. The thresholds in Table IV are averaged over the five initial levels of illuminance.

Evaluation of the remaining four first order interactions indicated a significant relationship ($p < .05$) between flash rate and initial

TABLE III

ANALYSIS OF VARIANCE OF TIME TO DISCRIMINATE BRIGHTNESS INCREASES
(Flashing Beacon)

Source of Variation	df.	SS	MS	F
Initial Brightness	4	154,172.7	38,543.2	3.15*
Rate of Brightness Increase	4	2,064,428.8	516,107.2	42.24**
Beacon Flash Rate	4	79,363.9	19,841.0	1.62
Flash Duration	4	34,405.9	8,601.5	--
Subjects	24	3,590,544.5	149,606.0	12.24**
Trials	24	188,500.6	7,854.1	--
Rate of Brightness Increase x Flash Rate	16	225,138.1	14,071.1	1.15
Rate of Brightness Increase x Flash Duration	16	126,714.7	7,919.7	--
Residual (Error)	528	6,451,209.0	12,218.2	
Total	624	12,914,478.2		

*$p < .05$

**$p < .01$

TABLE IV

EFFECTS OF INITIAL BRIGHTNESS AND RATE OF INCREASE

Initial Illuminance (log ft-c)	Mean Discrimination Time (sec.)	Rate of Increase (log units/sec.)	Mean Discrimination Time (sec.)	Mean Differential Threshold	
				Log Units	Feet*
-7.2441	129.8	.00063	206.9	.130	16,555
-7.0809	127.6	.00170	139.9	.238	29,380
-6.8894	108.1	.00320	95.7	.306	38,280
-6.6289	102.1	.00590	69.8	.412	51,300
-6.2882	88.3	.01180	43.6	.514	63,875

*Since the simulated approach rate was not constant, these values have a maximum error of 10.5%; an initial range of 30 n.mi. was assumed.

brightness level. Examination of this interaction revealed that it may, for the most part, reflect the difference between results obtained with the brightest beacon as compared with the other four levels of beacon brightness. As Table V shows, discrimination time for the brightest beacon was relatively independent of flash rate while, for the other levels of beacon brightness, the relationship with flash rate varied in an unpredictable manner. However, even this obtained significance could be due to an expected random effect from the five possible tests of this interaction, each using a slightly different estimate for residual (error) variance.

Detection of brightness increases with a steady beacon. - The experimental design provided two trials, preceding the main experiment, in which each subject was exposed to a steady (non-flashing) beacon in association with randomly selected initial illuminance and wedge rates. These trials were repeated by each subject, under the same experimental conditions, at the conclusion of the experiment. The combinations of initial illuminance and wedge rates were assigned in such a way that each of the possible 25 combinations of the two variables appeared in both of the pre- and post-experimental trials involving the steady beacon.

A separate analysis of variance was performed on the discrimination times for the pre- and post-administration of each of the two "steady" trials. The analysis for the first trial is presented in Table VI and the analysis for the second trial appears in Table VII. Lacking replication, the three factor interaction was used as an error term in both analyses.

Examination of Tables VI and VII reveals that the same major effects were significant for each of the two "steady" trials. Furthermore, these same effects were also significant for the flashing beacon (Table III). In fact, as Table VIII shows, mean discrimination time, as a function of rate of brightness increase, was, with the exception of the slowest rate, almost identical for both the steady and flashing beacons. In Table VIII, the discrimination times represent the means of the pre- and post-administrations for both trials. As also shown in Table VIII, the effect of initial level of illuminance was much less consistent for the steady beacon, but these means were based upon less than one-sixth as many trials as were available for the flashing beacon.

TABLE V

DISCRIMINATION TIME FOR COMBINATIONS OF FLASH RATE AND INITIAL BEACON BRIGHTNESS

Initial Illuminance (log ft-c)	Flashes Per Second				
	.60	.76	1.04	1.43	2.80
-7.2441	107.9	95.5	123.0	192.3	130.4
-7.0809	165.8	116.3	120.7	111.9	123.0
-6.8894	106.2	73.0	134.4	127.9	99.3
-6.6289	115.1	74.3	65.8	94.6	160.7
-6.2882	83.9	96.3	94.3	90.7	76.1

TABLE VI

ANALYSIS OF VARIANCE OF TIME TO DISCRIMINATE BRIGHTNESS INCREASES ("Steady" Trial 1)

Source of Variation	df	SS	MS	F
Initial Brightness	4	55,460.80	13,865.20	5.05**
Rate of Brightness Increase	4	277,960.22	69,490.05	25.31**
Pre-Post Administration	1	3,487.80	3,487.80	1.27
Initial Brightness x Rate of Increase	16	412,062.48	25,753.90	9.38**
Rate of Increase x Pre-Post Administration	4	36,078.63	9,019.66	3.28*
Initial Brightness x Pre-Post Administration	4	11,017.79	2,754.45	1.00
Initial Brightness x Rate of Increase x Pre-Post Administration	16	43,921.90	2,745.12	
Total	49			

**$p < .01$

*$p < .05$

TABLE VII

ANALYSIS OF VARIANCE OF TIME TO DISCRIMINATE BRIGHTNESS INCREASES

("Steady" Trial 2)

Source of Variation	df	SS	MS	F
Initial Brightness	4	330,228.62	82,557.15	38.13**
Rate of Brightness Increase	4	455,899.38	113,974.85	52.64**
Pre-Post Administration	1	13,389.08	13,389.08	6.18*
Initial Brightness x Rate of Increase	16	1,483,863.34	92,741.46	42.83**
Rate of Increase x Pre-Post Administration	4	23,137.14	5,784.29	2.67
Initial Brightness x Pre-Post Administration	4	3,754.32	938.58	-
Initial Brightness x Rate of Increase x Pre-Post Administration	16	34,642.90	2,165.18	
Total	49			

$^{**}p < .01$
$^{*}p < .05$

TABLE VIII

TIME TO DISCRIMINATE BRIGHTNESS INCREASES WITH STEADY AND FLASHING BEACONS

Wedge Rate (log units/sec.)	Beacon		Initial Illuminance (log ft-c.)	Beacon	
	Steady Sec.	Flashing Sec.		Steady Sec.	Flashing Sec.
.00063	271.1	206.9	-7.2441	229.9	129.8
.00170	143.1	139.9	-7.0809	94.0	127.6
.00320	95.3	95.7	-6.8894	94.1	108.1
.00590	64.7	69.8	-6.6289	72.7	102.1
.01180	38.4	43.6	-6.2882	121.9	88.3

The significant pre-post administration effect evident in Table VII resulted from the fact that subjects were responding more rapidly in the post-experimental version of trial two. Although not significant, the same trend was also apparent in the first "steady" trial. No obvious trend of any sort appeared in the trials involving the flashing beacon.

The significant interaction between initial brightness and rate of increase, (Tables VI and VII) must be interpreted with extreme caution. Since there was no replication of the relevant measurements, this effect is confounded with subjects, and subject differences may, in fact, be responsible for the significant effect.

Thresholds as a function of initial illuminance. - Figure 6 shows the differential thresholds for brightness increase, plotted as a function of initial illuminance, for each rate of increase. Within the range of beacon illuminance examined in the experiment, the differential thresholds exhibited a downward trend as the initial illuminance was increased. The effect of rate of brightness increase is even more obvious. Systematic increases in thresholds were clearly associated with an increase in rate of brightness change, for each initial beacon illuminance.

Discussion

The experimental data have implications regarding both the design of spacecraft beacons and the generality of previously determined thresholds for the discrimination of brightness increases. Each of these two areas of applicability will be considered in relation to the results of other relevant experiments.

Characteristics of spacecraft beacons. - An earlier examination of pertinent reports (refs. 2, 3, 4) suggested that flash rate and flash duration were relatively unimportant with regard to the initial detection of flashing beacons. Over the ranges studied, the results of the present study indicate that these same variables are also unimportant for the discrimination of increases in the brightness of flashing beacons. Neither variable significantly affected discrimination time in the main experiment, and the complete absence of these two variables did not appear greatly to

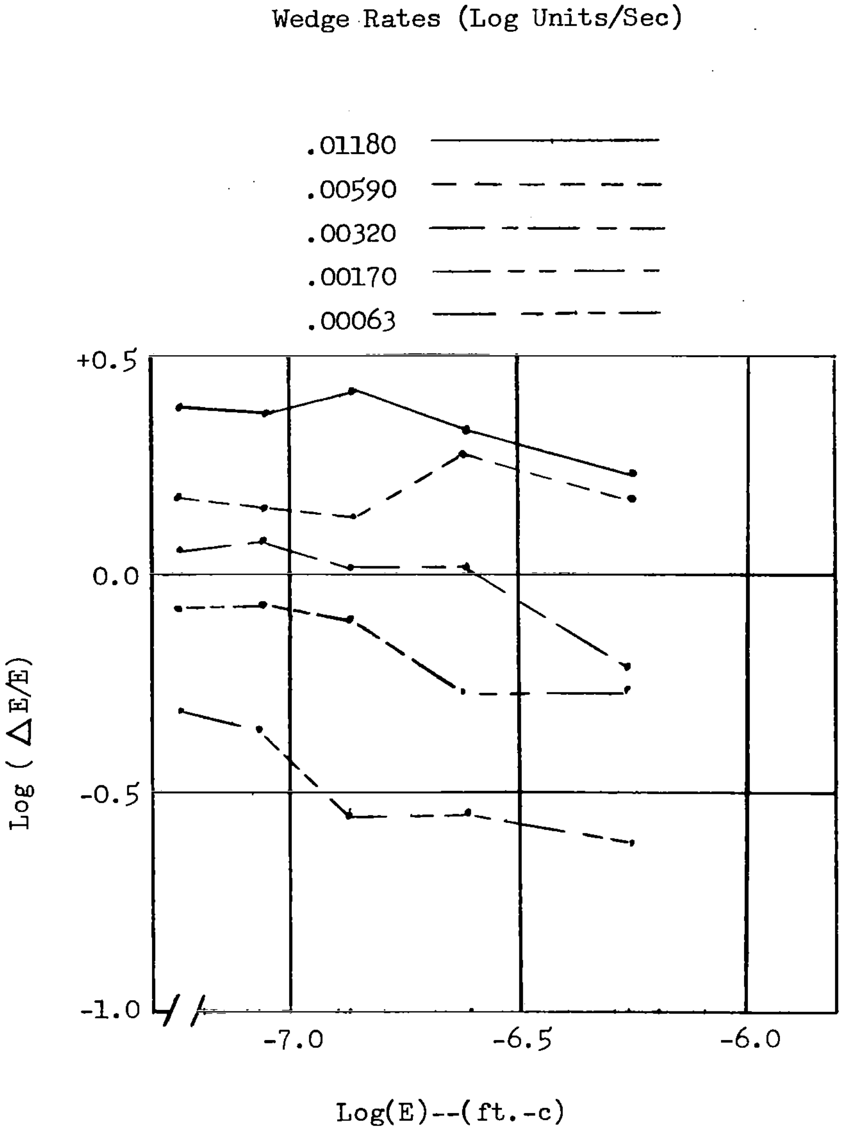

Fig. 6 Log (△ E/E) as a Function of Log (E) for all Wedge Rates

influence that same measure during the trials with the "steady" beacon. Including these latter trials, the flash rates investigated covered a range from 0.0 ("steady" beacon) to 2.8 flashes per second.

In contrast, the effect of initial beacon illuminance was a significant factor, and the rate of brightness change was itself of major importance, showing a consistent inverse relationship with discrimination time and a positive relationship with discrimination thresholds.

In this respect the results are in exact agreement with those previously reported by Connors (ref. 7), who concentrated, in her investigation, on higher rates of brightness change extending to approximately 200 times the lower limit of the present experiment. Thus, the same type of relationship between rate of brightness change and discrimination thresholds has been found to hold over a range of rates of brightness increase of some 200 to one.

Since the rate of brightness change is not a characteristic of the beacon itself, information concerning that variable is of greater importance to guidance and control engineers than it is to beacon designers. A positive contribution to beacon design does, however, come from the significant relation between beacon illuminance and discrimination time. Here the implication is straightforward. To reduce the time required to discriminate brightness increases, provide a beacon with as high an illuminance as is consistent with other design constraints. In the present experiment, a nearly ninefold increase in initial beacon illuminance produced a 32% reduction in the mean time required to discriminate an increase in brightness.

At the conclusion of the practice trials subjects were asked to describe the criteria that they had developed for making consistent judgments of increased brightness. Examination of their statements provides some interesting examples of the types of cues relied upon by the subjects. In all, nine different techniques were described. They are listed in Table IX. Only the first two criteria were used frequently. The remaining techniques were each mentioned by only one or two subjects.

In Table IX the subjects' preference for relative judgments is obvious, although this preference was certainly expressed in a variety of ways. Assuming a star background, however, it can be reasonably stated that most

TABLE IX

CRITERIA FOR JUDGING BRIGHTNESS INCREASE

CRITERIA

1. Increase in brightness of beacon relative to brightness of dots in adaptation field.
2. Increase in the length of "rays" emitted by the beacon.[*]
3. Increase in the "size" of beacon relative to size of dots in the adaptation field.
4. Increase in the brightness of beacon relative to initial level of brightness.
5. Increase in the number of "rays" emitted by the beacon.
6. Increase in the "size" of beacon relative to size of the entire ring of dots in the adaptation field.
7. Changes in the "shape" of the beacon from circular to irregular.
8. Increase in beacon glare as observed in alternating foveal and peripheral views.
9. Change in apparent color of the beacon from reddish-orange to white.

---

[*] The apparent "rays" viewed by the subjects presumably are a consequence of retinal irradiation, diffraction and scattering within the ocular media, or diffraction and scattering due to the equipment characteristics.

of the cues used by these subjects would be available in an actual rendezvous.

Since observers are diligent in their efforts to find standards for relative judgments, a comparison of the effectiveness of the various standards employed, and the development of techniques for augmenting their utility should prove to be profitable.

Thresholds for discrimination of brightness increases. - The data displayed in Table IV and Figure 6 clearly indicated that thresholds obtained in the present study were of a magnitude far greater than those typically encountered in the literature on brightness discrimination.

Geldard (ref. 5) reports differential thresholds that run from approximately -2.0 to 0.0 log units, a range within which only the thresholds for the lower rates fall in Figure 6; and even those thresholds are not far from the upper limit of 0.0.

For the rate of brightness increase and initial brightness level most closely resembling those used in the present study, Connors (ref. 7) found a median differential threshold of .279 log units compared with the .451 obtained in this experiment.

Finally, Drew (ref. 6) has described an experiment in which obtained thresholds increased with slower rates of brightness change rather than the reverse relationship reported by Connors and confirmed in the present experiment. For this difference in results there appears to be no ready explanation, particularly since the "steady" trials in this experiment approximated the conditions under which Drew obtained his data. Perhaps the explanation lies in the fact that Drew used a field subtending five degrees of visual angle, rather than a point source.

There are several possible reasons that can be enumerated to account for the elevated thresholds.

1. Geldard (ref. 5) presents results which show that differential thresholds are considerably greater for small fields than for large fields.

2. The low thresholds described by Geldard were obtained from simultaneous comparison of two adjacent fields. Even though some of the subjects in the present experiment attempted to make a similar type of judgment,

by using the dots in the adaptation field as a standard, this arrangement was by no means optimal. Furthermore, certain subjects compared their initial impression of beacon brightness with subsequent impressions, as the brightness slowly increased. Such a procedure might elevate thresholds because of decreased sensitivity of the eye as it adapts to the brighter beacon.

3. No attempt was made to restrict head motion in the present experiment.

4. The instructions given to subjects in this experiment deliberately encouraged them to be "absolutely sure" before judging that an increase in brightness had occurred. In contrast, thresholds, including those from Connor's study, are typically obtained by determining the increment that is discriminable 50% of the time.

The conservative procedure employed in this experiment was chosen as one means of reducing the variability in judgments which was anticipated for this rather ambiguous task. In addition, for practical purposes, it was desired to obtain limiting rather than optimistic estimates of the capability of humans for making the type of judgments involved.

The size of the thresholds observed under these conditions indicate that attention should be given to methods for improving such judgments, if astronauts are ever expected to use them as a basis for flight control actions. The lags in a system dependent upon the sensory capabilities demonstrated in this experiment would be formidable.

Potential applications of discrimination thresholds. - As has been indicated, ΔE, the brightness change required to discriminate an increase in the apparent brightness of a beacon, depends upon the initial brightness of the beacon and the rate of brightness change. Values for ΔE, E_i (initial brightness) and $\log E$ (rate of change of the logarithm of brightness) were plotted as parametric ratios in Figure 6. Although those curves are thought to approximate the relationships between the experimental variables, they are not based upon sufficient data to permit their use as actual design aids. For purposes of illustration, however, four equations have been developed which, together with more extensive empirical data, could be used to determine either ΔR (the increment in range necessary for discriminating a brightness change), given a specific beacon intensity, or the beacon intensity required to assure discrimination of the brightness change associated with a given ΔR. These equations are as follows:

$$(1) \quad E_i = \frac{I}{R_i^{\,2}}$$

$$(2) \quad (\dot{\text{Log}}\ E) = \frac{(.869)\dot{R}_i}{R_i}$$

$$(3) \quad \frac{\Delta E}{E} = \frac{\Delta R(2\,R_i - \Delta R^2)}{(R_i - \Delta R)^2}$$

$$(4) \quad \Delta R = R_i \left[1 - \frac{\left(2\frac{\Delta E}{E} + 1\right)^{\frac{1}{2}}}{\frac{\Delta E}{E} + 1} \right]$$

In these equations, R_i is the initial range in feet, $\dot{R}_i$ is the initial range rate in feet/sec., and I is the intensity of the beacon.

Under the assumption that the relationships pictured in Figure 6 are in fact linear, the combination of empirical data and the four equations would permit the determination of either ΔR or beacon intensity for a variety of initial conditions.

If R_i, $\dot{R}_i$, and I were known for a nighttime beacon sighting, the ΔR required to determine that the beacon was closing could be found by obtaining $\frac{\Delta E}{E}$ with equations (1) and (2) and the proper empirical curve, and entering the resulting value in equation (4). On the other hand, given the allowable ΔR, R_i, and $\dot{R}_i$, the minimum acceptable beacon intensity could be found by obtaining E_i with equations (2) and (3) and the proper empirical curve, and entering the value for E_i in equation (1).

By this means, it would also be possible to examine the tradeoff between power requirements, as represented by beacon intensity, and the maximum acceptable ΔR.

For more precise determinations, the procedures described in the preceding paragraphs should also take into account intervening media such as windows and optical devices that would reduce the level of beacon brightness at the observer's eye. Furthermore, the effect of adaptation field brightness should be examined in order to evaluate its influence upon the empirical curves required for the calculations.

RECOMMENDATIONS

1. The intensity of spacecraft beacons should be increased to a maximum consistent with other constraints, if judgments of change in the distance separating rendezvousing vehicles are to be based upon associated increases in beacon brightness.

2. Within the limits investigated in this study, beacon flash rate and "on" time should not be considered as critical factors in the design of beacons intended for use in judging changes in the distance between two rendezvousing spacecraft.

3. Additional research should be performed to extend the implications of this study.

   a) The conclusions of the present study should be extended by verifying the results over a wider range of beacon illuminance, including beacons of both higher and lower intensity than those investigated.

   b) Changes in differential thresholds as a function of the initial starting distance should be determined.

   c) Faster flash rates and shorter "on" times should be investigated in order to determine the points at which these variables become important.

   d) The relative effectiveness of different criteria used in judging brightness increases should be determined, and aids for improving such judgments should be devised and tested.

   e) The ability to utilize optimally aided judgments in the control of a spacecraft should be experimentally evaluated.

APPENDIX A

LANGLEY VISUAL STUDY

Instructions for Day I

(Check to see that shutter is closed). (Check to see 2.9 filter is in place). (Show subject the control room and point out the light source and the control panel. Seat subject in chair and adjust line of sight and headrest. Explain that subject will hear a varying pattern of sounds during the experiment. Maintain light level in room just high enough for reading instructions).

"When two spacecraft must rendezvous, it is necessary, in order to prevent collisions, to provide astronauts with accurate information concerning the rate with which one spacecraft is approaching the other. Normally this information is supplied by radar, but, if the radar should fail, the astronauts might have to depend upon direct visual sightings, without assistance from electronic devices.

Unless the sun were being reflected from the spacecraft, the distance over which the approaching spacecraft could be seen would be limited. To increase this distance, it is likely that a flashing beacon light will be employed.

In addition to helping the astronaut to detect a spacecraft, the beacon may also enable the astronaut to judge the rate with which the spacecraft is approaching, since the brightness of the light will increase as the two spacecraft come closer together.

Our purpose in this study is to determine if such brightness changes might be useful to an astronaut as a means of judging that one spacecraft is approaching another. Your cooperation in making a series of judgments will help us to establish specifications for the design of spacecraft beacons. The beacon that you are to observe will appear straight ahead of you, as a very small point of light, in the center of a ring of small lighted spots that you will see in the window.

During the observation period, this room will be darkened to resemble the conditions under which an astronaut might be looking for a beacon. As you know, your eyes become more sensitive to light when you remain in a darkened room. In order to insure a constant level of sensitivity please tell me when you first see the ring of lighted spots. Use this intercom to tell me when you see the ring. (Explain that subject does not have to operate the switch on the intercom).

During the experiment we will run a series of separate trials. After each trial ends, also tell me as soon as you again see the ring.

Between trials you may relax and move your head away from the head rest, if you wish, while I set up the conditions for the next trial. After you report that you see the ring, and as soon as I complete my set up, I will say the word "start" and you can begin the trial. You will do this by pushing the "start" button.

When you start the trial, the beacon will appear in the center of the ring as a point of light.

Your task will be to observe the beacon and determine when the brightness of the beacon has increased.

In order to produce useful information you must learn to be very consistent in deciding just when an increase in brightness has occurred. Try to develop a standard way of judging which you can apply on each trial. Such a procedure will help you to make consistent judgments.

When you are absolutely sure that the brightness has increased, immediately push the "stop" button. At that time the beacon will go off.

This process, as described, will be repeated over a series of trials. On most of the trials the light will be flashing rather than steady, and from one trial to the next the rate of flashing may be different. Furthermore, the percentage of time that the light is "on" during a flash may be altered, and the rate of brightness change will be varied.

Finally, the initial brightness of the beacon may also be changed from trial to trial. Regardless of the initial level, however, your judgments concerning increases in beacon brightness must be made in comparison to that initial brightness at which the trial started, without regard for conditions on previous trials.

As a result of these different conditions you may find that on some trials you will see a brightness change in a short time, while on other trials it may take a much longer time to notice a change. Do not let this influence your judgments. Regardless of time, push the "stop" button only when you have seen a change in brightness. Because of the low light level of the beacon, you might not see it immediately after a trial begins, or you might not see it on every flash. Consequently you may be able to increase the consistency of your judgments by basing them on a series of successive flashes rather than on the appearance of any one particular flash. Now I shall briefly summarize your actions for each trial:

1. Press the "start" button after I say the word "start" on each trial.
2. Press the "stop" button when you are absolutely sure the brightness has increased.
3. Report that you can see the ring of dots after each trial.
4. Wait for the next trial.

Do you have any questions about the instructions covered so far?

In order to give you a chance to become familiar with procedures, and to help you develop a consistent basis for your judgments, the remainder of today's experimental period will be used exclusively for practice. This practice period is extremely important because the results obtained on the final day will depend upon the consistency with which you learn to make your judgments today. On certain trials, conditions will be identical so that I can determine the consistency of your judgments. If we don't achieve an acceptable level of consistency, we will not be able to run you on the second day of the experiment.

I will be controlling the experiment from the next room. After I shut the door to this room, I shall turn out the lights and we will proceed after a ten minute period that will permit your eyes to become sensitive enough to see the ring of dots. If at any point during the practice trials you wish to communicate with me, just talk into the intercom.

When the ten minute period has elapsed, I will turn on the beacon and show you the range of brightness levels that you will be working with. I will start with the dimmest beacon and gradually increase it to the brightest.

Do you have any questions?"

(Begin timing ten minute interval).
(Turn subject's room lights off. Tell subject when five minutes have passed).
(Reset clock).
(Turn on tape recorder before starting experiment).

LANGLEY VISUAL STUDY

Instructions for Day II

(Adjust seat and head rest).

"Today we will continue with the same procedures upon which you practiced yesterday, and your task will be identical. Please remember to report when you see the ring of dots after each trial.

First, after again viewing the range of beacon brightness, we will run through a short series of practice trials to help you reestablish your basis for judging increases in brightness. Remember to be as consistent as you can from trial to trial and to push the "stop" button only when you are absolutely sure that you have seen a change in brightness.

After the practice period has been completed we will run the final series of trials upon which our experimental results will depend.

Do you have any questions?"

(Adjust headset).

(Turn off lights).

(Give five minute warning).

(Demonstrate brightness range).

REFERENCES

1. Shea, R. A.; and Summers, L. G.: Visual Detection of Point Source Targets. TRW Systems 5408 - 6003 - R0000, April 1966.

2. Johnson, Ivan S. C. Jr.: Human Optical Tracking of Stroboscopic Beacon for Orbital Rendezvous. Report T436, Massachusetts Institute of Technology, September 1965.

3. Wienke, Richard E.: The Effect of Flash Distribution and Illumination Level Upon the Detection of Low Intensity Light Stimuli. Human Factors, vol. 6, 1964, pp. 305-311.

4. Crumley, Lloyd M.; and Atkinson, William: Human Engineering Investigation of the Exterior Lighting of Naval Aircraft: Part I: A Study of the Effect of Flash Rate and On/Off Ratio on the Detectability of Flashing Lights. Report TED NAM EL52003, Dept. of the Navy, Bureau of Aeronautics, September 1954.

5. Geldard, Frank A.: The Human Senses. John Wiley and Sons, 1953, pp. 29-30.

6. Drew, G. C.: The Variation of Sensory Thresholds With the Rate of Application of the Stimulus. Brit. J. Psychol., vol. 27, 1937, p. 297.

7. Connors, Mary M.: The Effect of Rate of Brightness Change on the Discrimination of Brightness Differences. LMSC 9-82-66-1, Biotechnology Orgn. Lockheed Missiles & Space Co., Sunnyvale, Calif., January 1966.

8. Neuberger, T. P.; Myles, W. E.; and Ludwig, U. W.: Virtual Image Display for Space Flight Simulator. AMRL TR 66-58, Wright-Patterson AFB, Ohio, April 1966.

NASA-Langley, 1968 —— 5 CR-1220

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546

OFFICIAL BUSINESS

FIRST CLASS MAIL

POSTAGE AND FEES PAID
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

030 001 30 51 3DS 69255 00903
AIR FORCE WEAPONS LABORATORY/AFWL/
KIRTLAND AIR FORCE BASE, NEW MEXICO 871
ATT E. LOU BOWMAN, ACTING CHIEF TECH. LI

POSTMASTER: If Undeliverable (Section 158 Postal Manual) Do Not Return

> *"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."*
>
> —NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C. 20546