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THE RELATIVE IMPORTANCE OF CONTRAST AND MOTION IN VISUAL TARGET DETECTION

H. E. Petersen and D. J. Dugas

A Report prepared for

UNITED STATES AIR FORCE PROJECT RAND

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PREFACE

This study investigates a fundamental question concerning the visual process--the relative importance of contrast and motion in the detection of moving targets--that arose during a previous experiment by the authors in visual detection of moving targets (see *An Experimental Investigation of the Effect of Target Motion on Visual Detection,* R-614-PR). The results of this study may be used for further modification of an exponential detection model developed by H. H. Bailey of The Rand Corporation, allowing it to be applied to targets having variable speed and contrast. It will have military application in problems of camouflage, reconnaissance, and remote displays, with particular relevance to problems of airborne search for both low-flying aircraft and moving surface vehicles.

The authors are consultants to The Rand Corporation.

SUMMARY

An experimental test is described in which the relative roles of contrast and motion in the detection of targets were investigated. Results of a previous study had suggested that the effect of motion on detectability might be caused entirely by contrast changes as the target moved over a complex background. The present test employed a television display and an artificial background designed to investigate contrast and motion effects separately. Both search experiments and single-fixation experiments were conducted.

The tests showed independent effects of both contrast and motion on the detectability of targets located in a complex background. In the range of contrast and speed investigated here, the effects can be accounted for by modifying the exponent in the detection probability function with a linear contrast term and a second-power velocity term:

$$P = 1 - e^{-\left(\frac{f}{A_s}\right) A_{d_o} C(1+0.45v^2)t}$$

where f = glimpse rate, generally assumed to be three per second

A_s = area to be searched in time t

A_{d_o} = normalized detection aperture; an empirical constant that varies with target size and background complexity

C = contrast of target with respect to background

v = target velocity in deg/sec subtended at the observer's eye

t = search time

The combined term $A_{d_o}C(1 + 0.45v^2)$ is defined as the detection aperture, that is, the single-glimpse area in which a target could be detected under the given conditions of contrast and motion. Detection aperture is thus a direct measure of the rate at which an area can be searched. Values determined in this study ranged up to a maximum of about 500 deg^2 (or 100 sq in., which is almost half of the display area) at a target speed of 5 deg/sec. At greater target speeds, the aperture did not increase much more, probably due to interference of the boundaries of the display.

Single-fixation experiments confirmed the increase in aperture size for moving targets, but also demonstrated a gradual increase in the fixation time required to detect a target as a function of its distance from the fixation point.

Search patterns used by observers in this test were found to be more nearly random than systematic, with a consequent loss of efficiency ranging up to a factor of 2.5. With prior knowledge of detection aperture, it should be possible to devise a search strategy that would approach systematic, thus improving the detection performance considerably.

CONTENTS

I. INTRODUCTION

The purpose of this study is to investigate the relative roles of contrast and motion in the detection of targets. The results of a previous study,(1) involving search of a television display, suggested that the increased probability of detection for a moving target compared to a stationary one was due primarily, or perhaps entirely, to changes in contrast as the target moved over a complex background. Because all target paths used in that study involved contrast changes, it could not be determined whether any of the enhancement in detectability was due to motion itself. The present test used displays that were designed so that target paths had no contrast changes, thus the effect of target speed could be investigated separately.

Some additional tests were conducted to get an idea of the effect of motion on detection aperture. When an observer is searching a display, an *effective* detection aperture can be calculated from the initial search rate, the total search area, and the glimpse rate. However, this is not the true area of a glimpse in which the target can be detected. Therefore, the second group of tests did not involve searching the display, but required the subject to fixate on a central spot while targets were displayed at various locations in the periphery.

II. EXPERIMENTS

SEARCH

Target and Background

Essentially the same equipment was used in this study as was used in Ref. 1; a complete description is given in the Appendix. The background used throughout the present test is illustrated in Fig. 1. It consisted of an electronically generated pattern of bright dots in a rectangular array of 38 rows and 34 columns on a uniform background. Spacing between dots was about 0.6 in. horizontally and 0.4 in. vertically. Average brightness of the background was 12 milliLamberts, and contrast of the dots in relation to the background was 1.5.

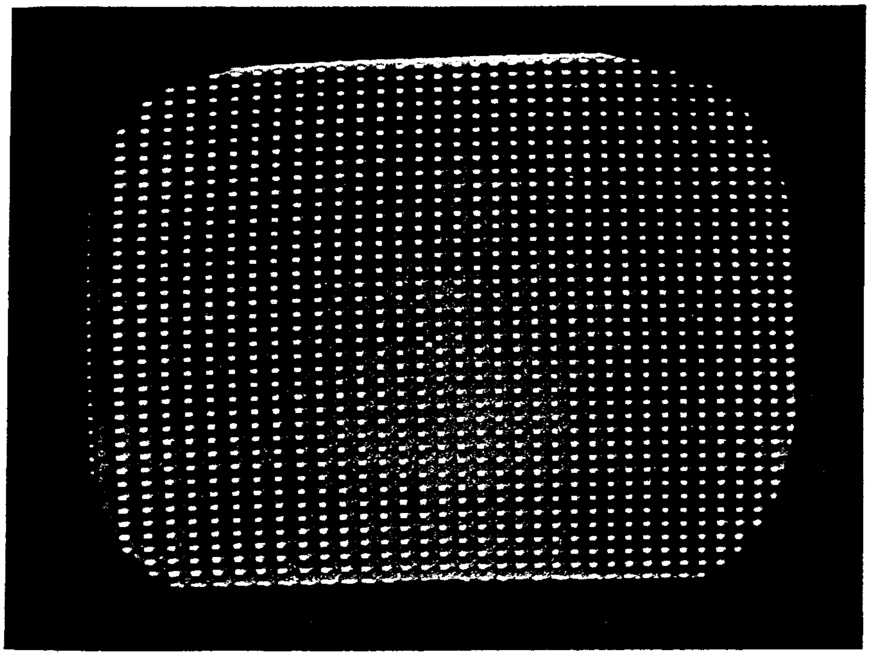
The target was a solid square, the same size as the dots in the background pattern (0.1 by 0.1 in.) and was always brighter than the background. The target was inserted electronically in the display and was controlled by a stylus on the Rand Tablet. The target was always presented half-way between rows of dots in the pattern, never overlaying a dot nor passing over dots in the moving tests. Thus the contrast remained constant throughout a given test run. Two contrasts were used during the test: 0.3 and 0.5 as measured at the video signal input.

"Contrast" as used in this report was calculated from the video signal inputs measured with an oscilloscope, not from luminance measurements at the tube face. The values of C used here were obtained from the relation

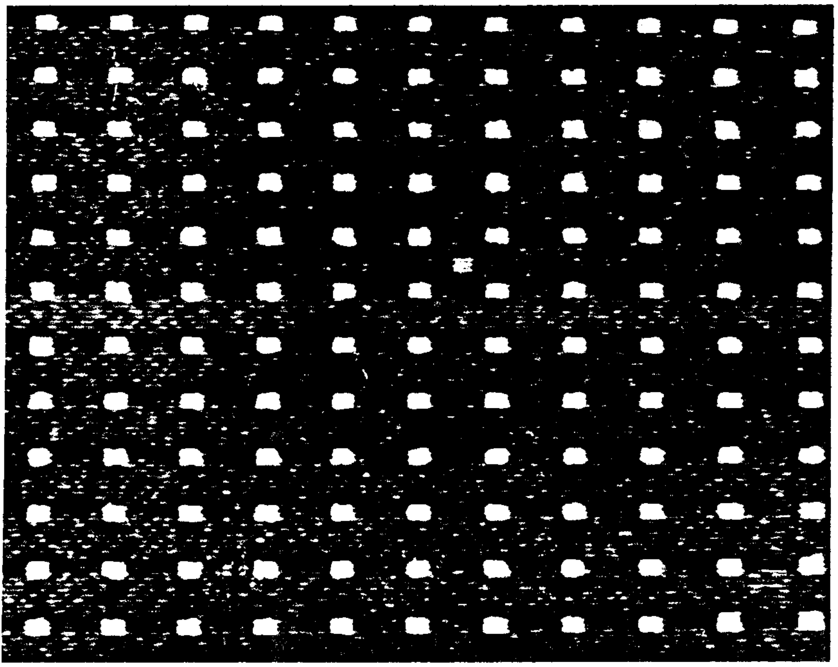
$$C = \frac{S_T - S_B}{S_B - S_o} \qquad (1)$$

where S_T = target signal voltage, S_B = background signal, and S_o = black level.

Luminance measurements at the display surface were made with a Honeywell 1°/21° photometer which had previously been calibrated by Kocher et al.(2) These measurements indicated that there was a linear



a. Photo of entire display including a target



b. Actual size segment of the display including a target

Fig. 1 Background pattern used throughout the tests relationship between brightness on the display and the corresponding video signal input. The conversion factor for the particular monitor settings that were used in the test is given by

$$L = 57(S - S_o) \tag{2}$$

where L is the luminance in milliLamberts and S is the video signal in volts. The average brightness of the display including the dot pattern was 13 mL.

The dot pattern itself served only as a clutter factor, which was found to be necessary to assure that target detection times would be long enough to measure accurately. With a completely structureless background, the target was almost always detectable in one glimpse.

Target motion was controlled by a device that mechanically guided the stylus over the Tablet. Motion was always in the horizontal direction at speeds up to 2 in./sec.* The maximum excursion from its starting point on the display was 0.7 in., and it was moved back and forth over the same short path until detected. Thus the change in location of the target in relation to the detection aperture was negligible.

The static targets could be located in any one of 20 selected points on the display. The same 20 points were used as initial points for moving targets.

Procedure

The subject was seated in front of a television monitor so that his eyes were about 24 in. from the screen and his line of sight was approximately perpendicular to the center of the screen. The display subtended an angle of 31 deg vertically by 40 deg horizontally at the observer's eye. The target subtended 0.25 by 0.25 deg. The ambient light level was maintained in the photopic range, but care was taken to prevent reflections of overhead lights in the screen.

During the tests, the experimenter operated the equipment that controlled the target location and movement. The subject timed his own detections with a stop watch.

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*One inch on screen is 2.3 deg at the observer's eye.

Rather than use a large number of naive observers in this test, it was decided to use only two subjects who had acquired considerable experience in searching for targets on this type of display and exhibited consistent performance from trial to trial. In some preliminary tests using less experienced observers, it was found that the results were inconsistent from one run to the next, and that learning effects often masked the effects of motion or contrast.

The following procedure was used in determining detection times at the various speeds:

1. Two or three sample detections were tried so that the subject would know what contrast and motion to expect, and could familiarize himself with the operation of the watch.
2. A display was switched on with a static target located at one of the 20 preselected points. The subject started the watch as soon as the display appeared and began his search. When he found the target, he stopped the watch and recorded the elapsed time on a data sheet.
3. The display was then switched off while the experimenter repositioned the target. Contrast was not changed.
4. The display was switched on again with the target in a new location, and the subject searched and recorded the detection time as before.
5. The same procedure continued until the static target had appeared in all 20 locations.
6. Similar sequences of 20 target locations were run for moving targets at each of the speeds: 1.1, 2.1, 3.1, and 4.8 deg/sec.* A final sequence of static targets was run after the moving target tests to check for learning effects and repeatability.
7. The target-to-background contrast was changed to a new value and the entire procedure repeated once more.

SINGLE FIXATION

The test equipment, display, and procedure for the second experiment were essentially the same as for the first, except for the following items:

1. Only one subject was tested.

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*Only one subject was tested at the highest speed.

2. The subject was instructed not to search, but to maintain a fixed gaze on a marked spot in the center of the display.
3. Only a high contrast target was used (C = 0.5).

The subject timed his own detections with the stop watch as before and was allowed as much time as he desired as long as he did not shift his fixation point.

One series of detections was run in which the target was moved back and forth at a rate of 13 deg/sec in each of the 20 target locations used previously. Another series was run in which a static target was first placed near the central fixation point, then was placed progressively farther from center on one of eight azimuths in each succeeding picture. When the static target could no longer be detected in this manner, the subject could turn the target off and on manually at any rate that he found aided detection. The series continued, with the target placed farther and farther from the fixation point, until it could no longer be detected even when flashed at a rapid rate.

III. RESULTS

Detection data for the search experiment were converted to cumulative percentage of targets found as a function of elapsed time. The resulting curves for high and low contrast are presented in Figs. 2 and 3. Increasing the speed at constant contrast clearly decreases the target detection times, and the magnitude of the effect for a given speed seems to be similar at the two contrasts tested. We note also that increasing the contrast from 0.3 to 0.5 had about the same effect on detectability as increasing the speed from 1 deg/sec to 2 deg/sec or from 2 deg/sec to 3 deg/sec.

Results of the fixation experiment for static targets are plotted as time-to-detect as a function of distance from the fixation point in Figs. 4 and 5. Data for the near periphery are plotted on an expanded time scale in the lower portion of each figure. Performance was slightly better on horizontal azimuths than for vertical or diagonal azimuths. In both figures detection times begin at slightly less than one-half second, remaining nearly constant out to a peripheral angle of about 6 to 7 deg (2½ to 3 in.) from the fixation point. Beyond this there appears a steep rise in detection times, until at about 9 deg from center, no targets are detected.

It is interesting to note that in many cases extra time did help in detection. For example, some targets were found after more than a minute of fixation, although there was no "searching" in this time period. Figure 6 shows the detection times for a target moving rapidly back and forth (at 13 deg/sec) over a short distance in the periphery. In this case there is a gradual increase in detection time with peripheral angle amounting to 0.044 sec/deg which extends out to the limits of the display (20 deg). In the case of the flashing target, one or two slow flashes were usually sufficient to detect the target out to a peripheral distance of about 4 in. (9.5 deg) for the vertical and about 6 in. (14 deg) for the horizontal azimuth. Beyond this, more flashes or faster flashing resulted in detections out to the limits of the display.

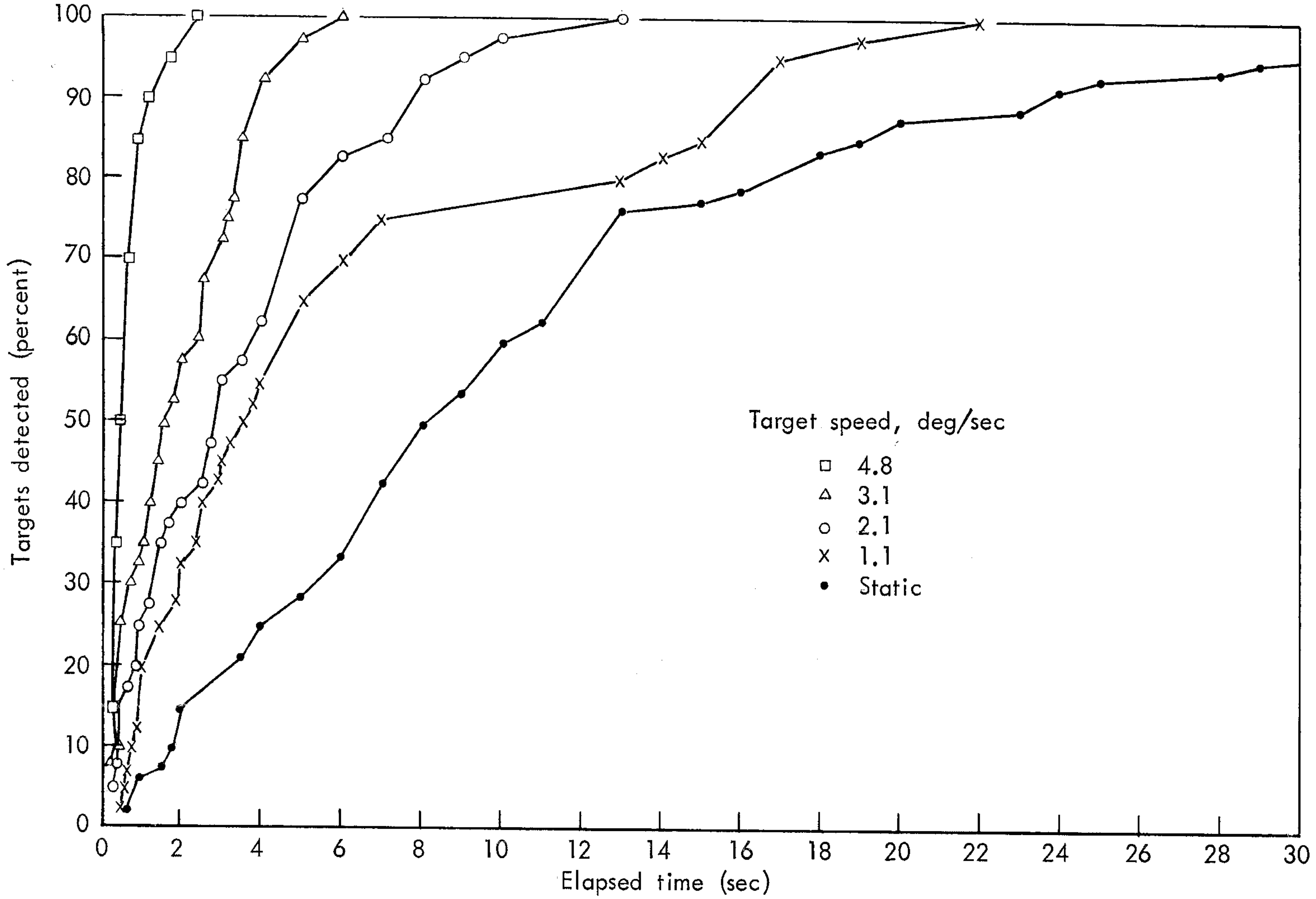

Fig. 2—Targets detected within a given time period for contrast of 0.3

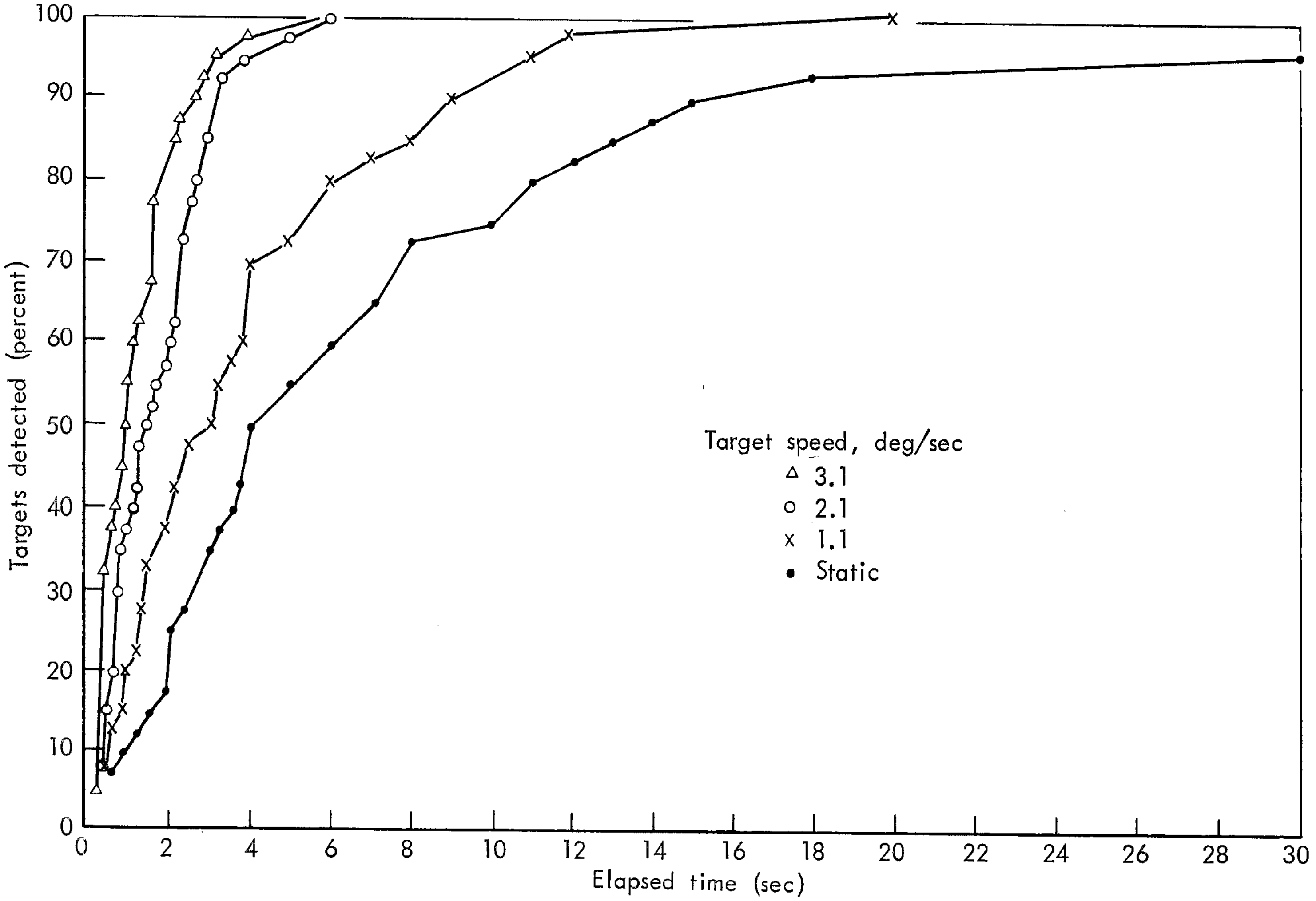

Fig. 3—Targets detected within a given time period for contrast of 0.5

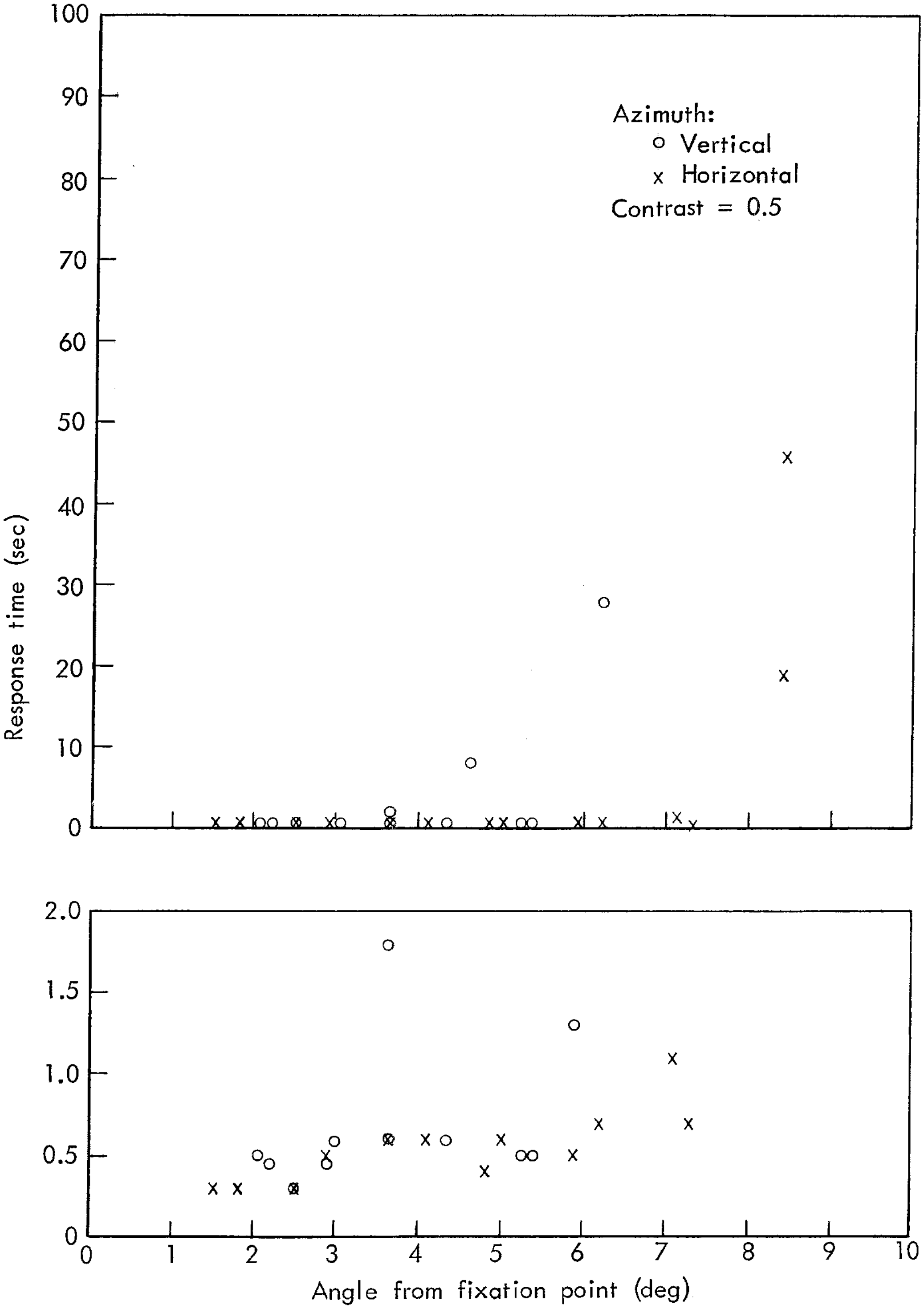

Fig. 4—Detection time as a function of distance from fixation point on vertical and horizontal azimuths, static targets

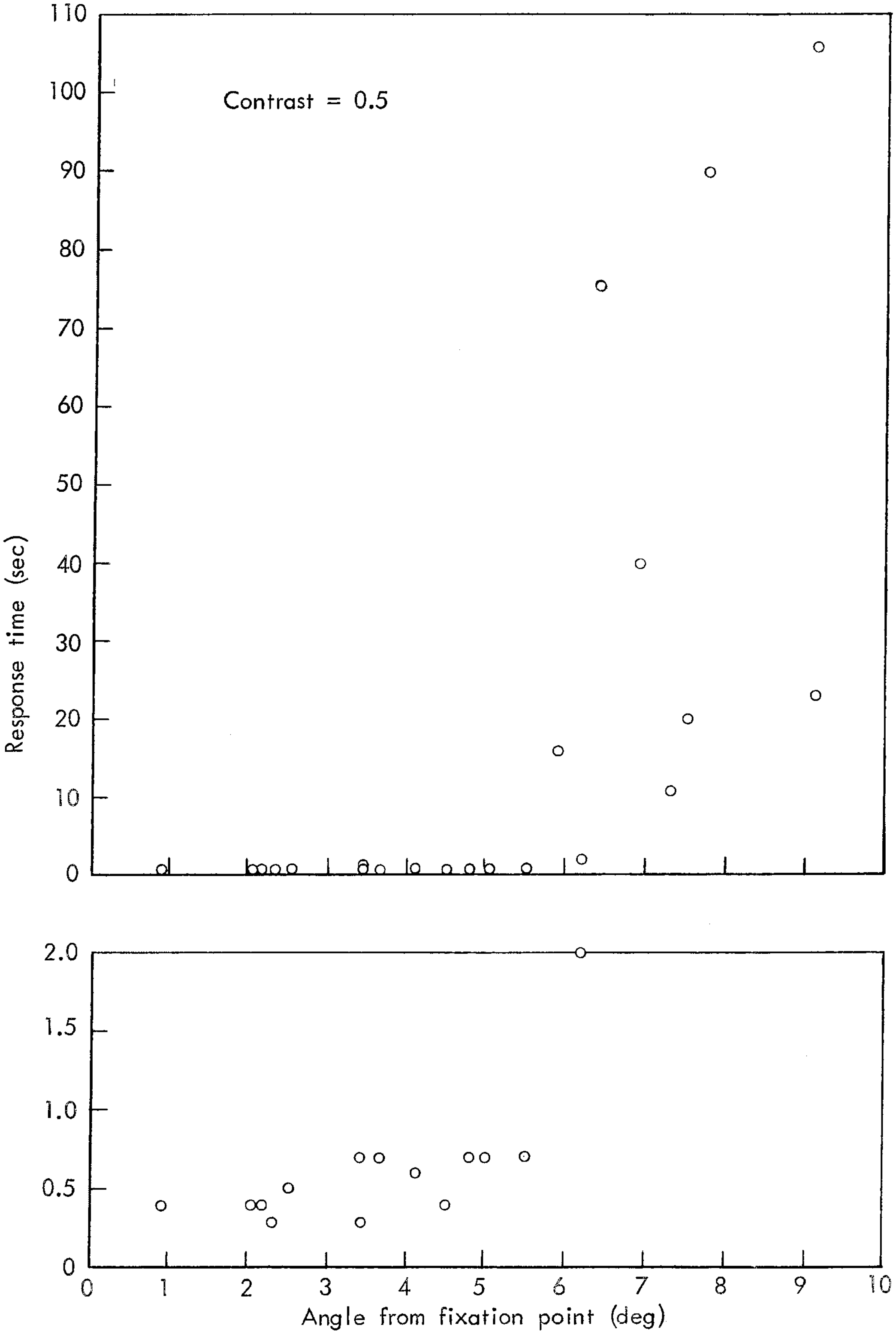

Fig. 5—Detection time as a function of distance from fixation point for diagonal azimuths, static targets

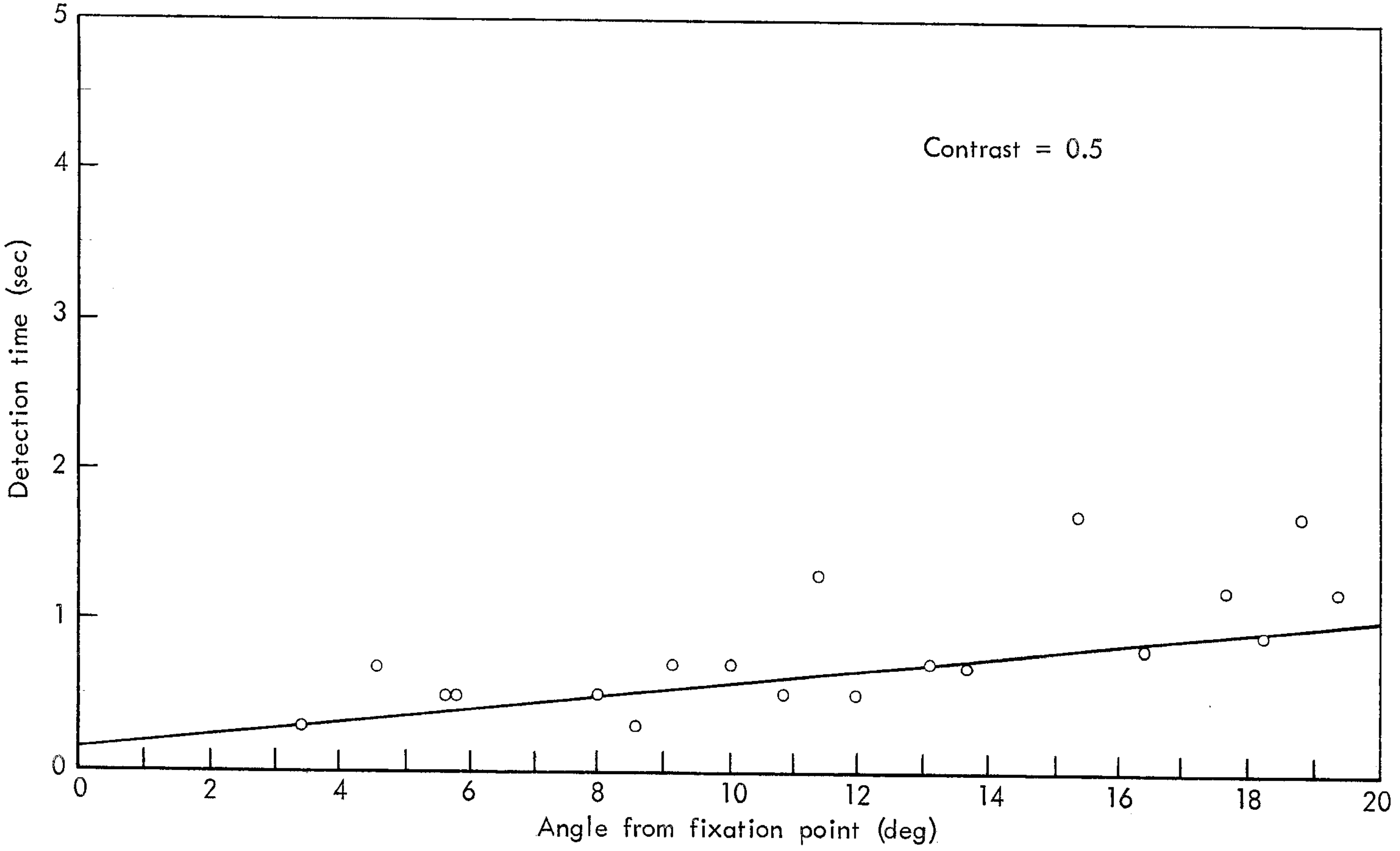

Fig. 6—Detection time as a function of distance from fixation point for targets moving at 13 deg/sec

IV. DATA ANALYSIS

EXPONENTIAL APPROXIMATIONS

Bailey's model(3) for predicting the probability of detecting a static target during random search gives an exponential form for the search term:

$$P = 1 - e^{-Bt} \tag{3}$$

where B includes factors related to glimpse rate, area to be searched, and complexity of the scene. Exponential approximations to the experimental detection data may be obtained by reading the time, t, to reach any desired probability of detection, P, from Figs. 2 and 3, and evaluating B at that point. For the case of $P = 1 - 1/e$, B is simply $1/t_{63}$, where t_{63} is the time required to reach the 63 percent detection level. Table 1 gives the values of t_{63} and B for the various speeds and contrasts tested. The curves obtained with these values of B in the exponents are shown in Figs. 7 and 8 along with the experimental data points for comparison. It can be seen that the data are fairly well approximated by the exponential curves, again validating Bailey's choice of that form for his search term in the static case, and showing that it can also be applied to the moving case with appropriate adjustment in exponent.

The ratio of moving to static exponents are compared in Table 1 for the various speeds and contrasts tested. The detection rate increased by about 2 to 5 times for target motion increases from 1 deg/sec to 3 deg/sec, behaving similarly at both contrasts. The variation of this improvement in detection rate as a function of target speed is shown in Fig. 9. An approximate fit to this data in the region illustrated is given by

$$V = 1 + 0.45v^2 \tag{4}$$

where V = ratio of exponents for moving and static curves

v = target speed in deg/sec.

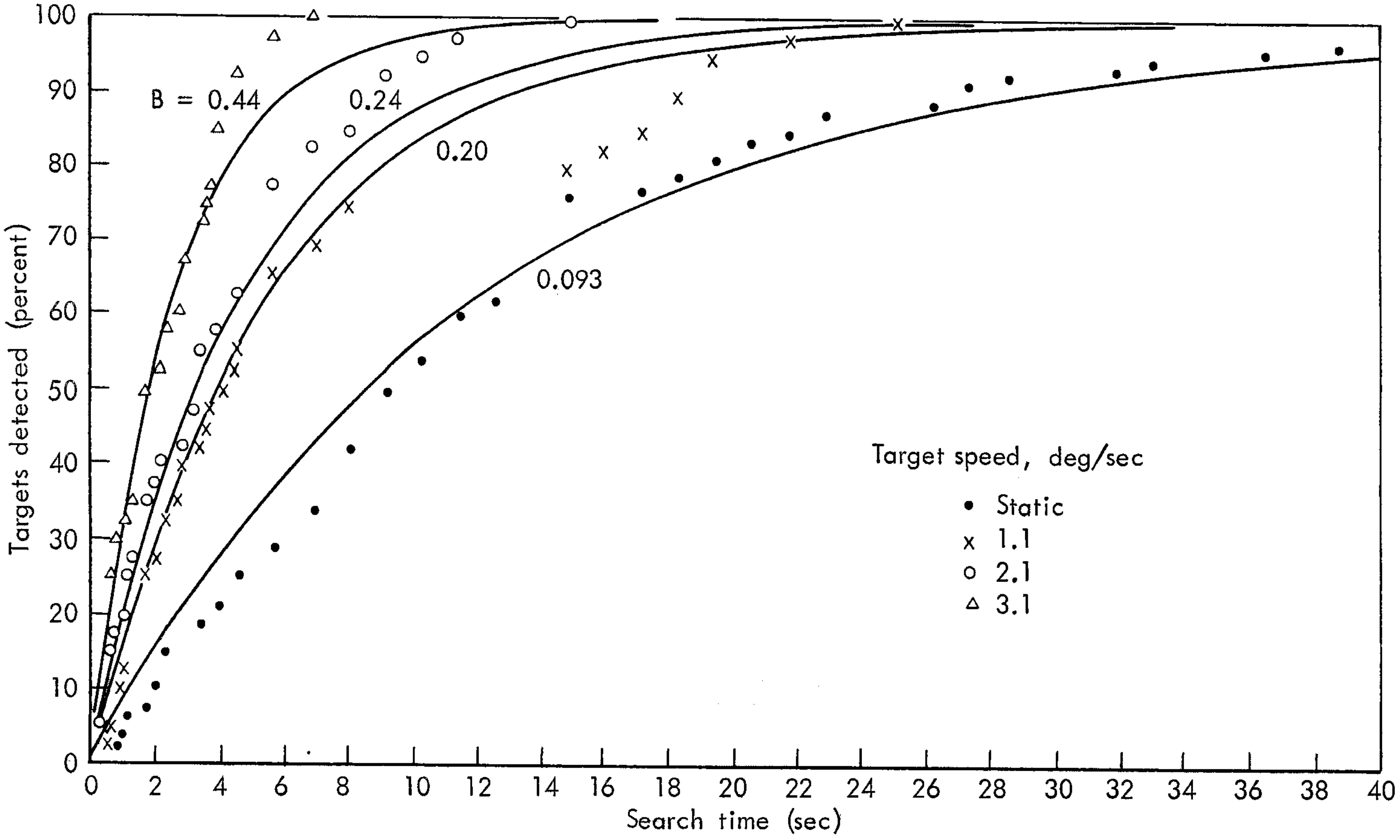

Fig. 7—Exponential approximation to data for contrast of 0.3

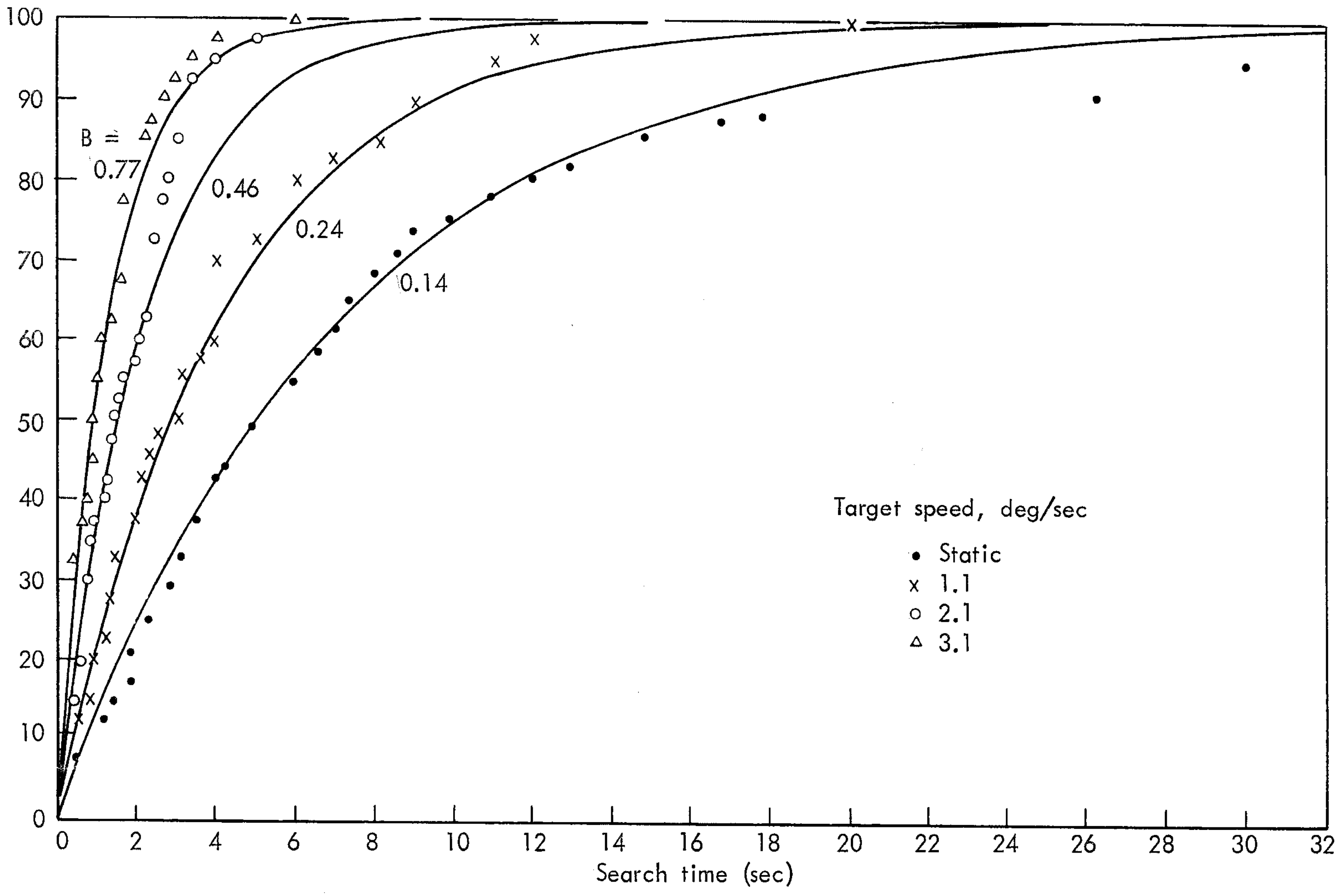

Fig. 8—Exponential approximation to data for contrast of 0.5

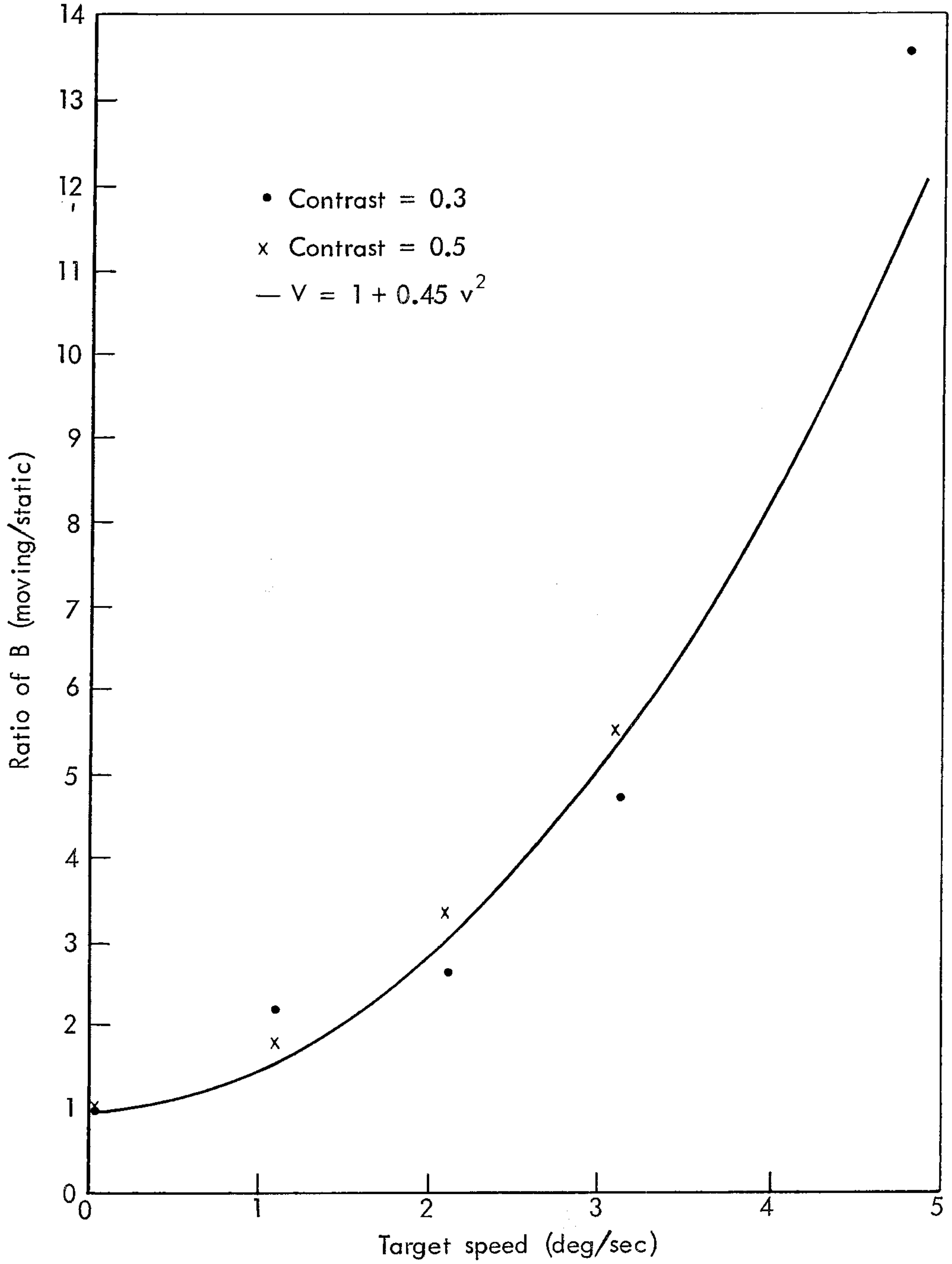

Fig. 9—Motion effects on the time constant, B

Table 1

EXPONENTIAL COEFFICIENTS AND MOVING/STATIC RATIOS

Contrast	Target Speed (deg/sec)	t_{63}	$B = 1/t_{63}$	V
0.3	0	10.5	0.093	1.0
	1.1	4.9	0.20	2.2
	2.1	4.2	0.24	2.6
	3.1	2.3	0.44	4.7
	4.8	0.8	1.25	13.5
0.5	0	7.2	0.14	1.0
	1.1	4.1	0.24	1.8
	2.1	2.2	0.46	3.3
	3.1	1.3	0.77	5.5

The improvement in detection rate with increasing speed obviously cannot continue indefinitely; eventually there must be a decrease in detection rate as motion becomes so fast as to cause blurring. It was not practical with the present equipment to investigate thoroughly the upper bounds of the motion effect. At speeds greater than about 5 deg/sec, the detection times became too short to give accurate data. However, a brief test at higher target speeds and contrast of 0.3 indicated that the curve of performance ratios would begin to flatten somewhere between 5 and 10 deg/sec for this display. A larger display would, of course, require more searching and hence would give a wider spread in detection times.

Increasing contrast also improves the probability of detection as shown by comparing the detection performance in Figs. 2 and 3 or the exponents in Table 1. The ratios of performance at high contrast to those at low contrast are given in Table 2. These ratios varied only from 1.2 to 1.9 for all speeds tested. The average value of 1.6 is very nearly the same as the ratio of the contrasts themselves: $0.5/0.3 = 1.7$, indicating a nearly linear dependence of performance on contrast in the limited region that was investigated. Therefore, the contrast factor, which must also be included in modifying the exponent of the detection probability equation, is simply the absolute value of the target contrast, C, and the total adjustment for variable

Table 2

RATIO OF EXPONENTIAL COEFFICIENTS
AT TWO CONTRASTS

Target Speed (deg/sec)	Ratio of B, High Contrast/Low Contrast
0	1.5
1.1	1.2
2.1	1.9
3.1	1.8

motion and contrast is now:

$$C(1 + 0.45v^2) \tag{5}$$

As originally used by Bailey, the term B included factors related to glimpse rate, area to be searched, glimpse aperture, and performance level:

$$B = f\left(\frac{A_g}{A_s}\right) K \tag{6}$$

Since A_g and K vary in such a way that their product is a constant, we have combined them into a single term A_d, called the detection aperture. Bailey's glimpse aperture, A_g, was the area during each glimpse that had not been examined previously and therefore varied with search time. Making this change, we get:

$$B = f\left(\frac{A_d}{A_s}\right) \tag{7}$$

where f = glimpse rate; assumed to average about three per second

A_s = area to be searched; constant at 236 sq in. for the experimental display used here

A_d = detection aperture, or that area surrounding a fixation point in which the target could be detected at the given conditions of contrast, motion, and background complexity.

Evaluating B for the display used in this test, we have

$$P = 1 - e^{-0.013\ A_d t} \tag{8}$$

Since f and A_s are constants, it is apparently the detection aperture A_d that is being changed by variations in contrast and motion, and indeed it is reasonable to expect that targets can be detected farther out in the peripheral vision when speed or contrast is increased. Then the detection aperture is replaced in the exponent by the function of contrast and motion given in Eq. (5):

$$P = 1 - e^{-0.013\ A_{d_o} C(1+0.45v^2)t} \tag{9}$$

where A_{d_o} = a normalized detection aperture for the particular scene being searched at a reference contrast of 1 and speed of zero.

DETECTION APERTURES

Detection apertures that were used by subjects in the present search test can be calculated from the value of $1/t_{63}$ of the detection curves:

$$A_d = \left(\frac{A_s}{f}\right)\left(\frac{1}{t_{63}}\right) \tag{10}$$

Values of A_d thus obtained are plotted in Fig. 10, along with apertures calculated in a similar manner for the backgrounds used in the previous study.(1) For the dot pattern used in the present test, the aperture size increased steeply with speed up to about 5 deg/sec, where it began leveling off. The limiting aperture is not well defined by the data at the higher contrast, but at a contrast of 0.3 the aperture reached a maximum value of about 100 sq in., which is nearly one-half of the display size. The limiting aperture size is no doubt highly

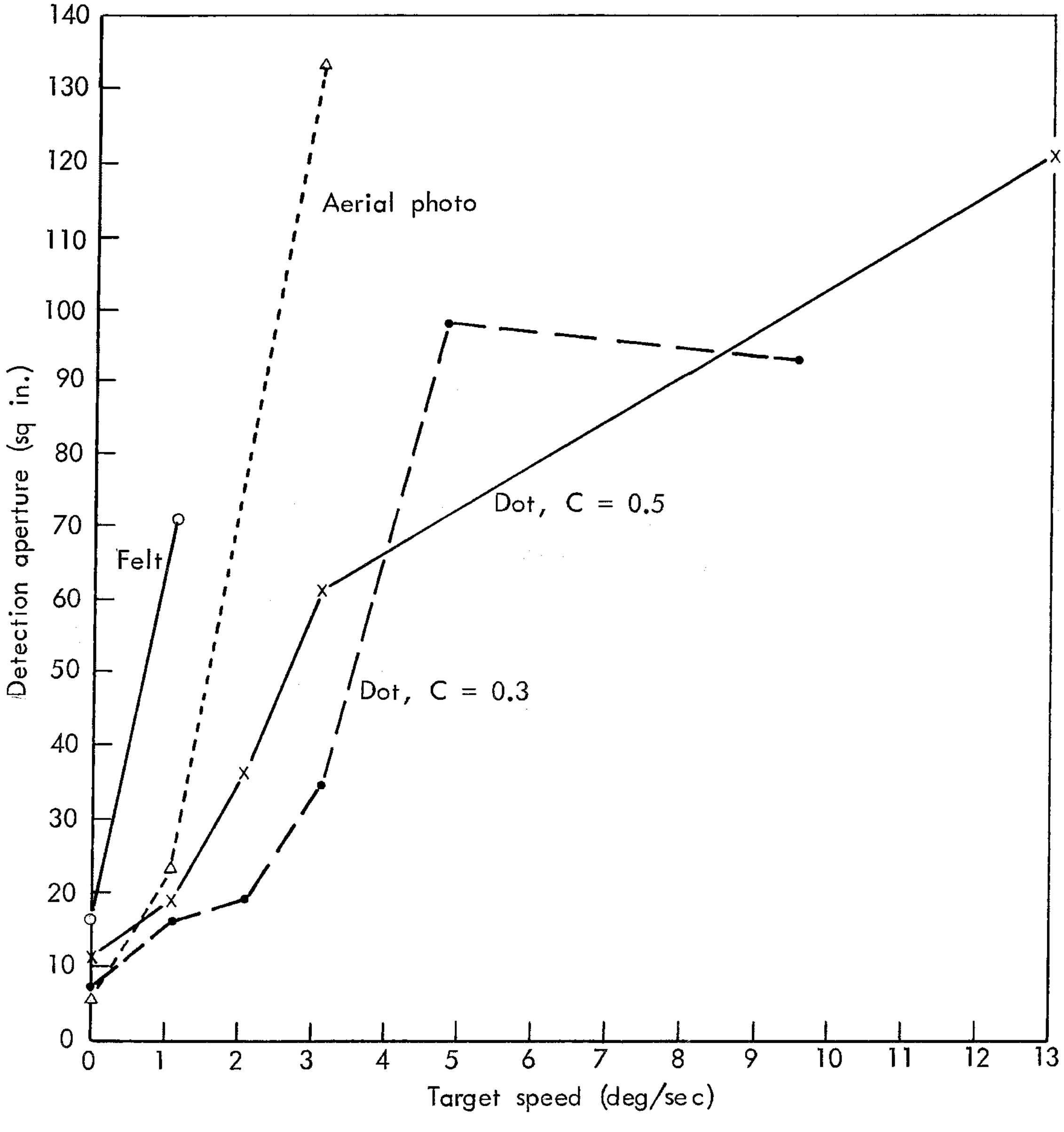

Fig. 10—Variation of detection aperture with speed for felt, aerial photo, and dot backgrounds

dependent on the display size, because as the aperture becomes larger (or the display becomes smaller), the display boundaries interfere more and more with effective positioning of each glimpse.

Apertures for the photo and felt are included on Fig. 10 to illustrate the effect of more complex backgrounds. In these two cases the contrast is variable as the target moves over the background, whereas with the dot pattern, all target paths had constant contrast. Detection apertures in the static case were similar for all the backgrounds; however, they increased more rapidly with motion for the photo and felt. This illustrates the combined effect of motion and variable contrast on detectability as the target changes location.

The normalized detection aperture, A_{d_o}, is an indication of the background complexity, and as such may be used to classify terrain or displays in which a target appears. The A_{d_o} for a particular background can be evaluated by dividing the experimentally determined detection apertures, A_d, at $v = 0$, by the contrast. Such normalized detection apertures are compared in Table 3 for the pattern of dots used in the present test and the three backgrounds used in the previous test.(1) These apertures were also normalized to the target size of the present test since it was half as large as the target used in Ref. 1. Smaller values of A_{d_o} indicate more difficult detection tasks. We note that the values for the grid background are widely different depending on whether the target was centered in a cell or off-center.

Table 3

NORMALIZED DETECTION APERTURES FOR VARIOUS BACKGROUNDS

Background	A_{d_o} (sq in.)
Present test:	
Dot pattern	23
Previous test:[a]	
Grid, centered targets	28
Grid, off-center targets	8
Felt	16
Aerial photo	7

[a] Backgrounds from test described in Ref. 1.

In fact, moving the target just one target diameter away from a grid line made it significantly easier to detect than when it was adjacent to a line. This indicates the sensitivity of A_{d_o} to local contrast characteristics of a scene, particularly when the scene has sharp discontinuities in luminance. The more uniform the background, the more generally applicable A_{d_o} becomes.

The static detection aperture for the dot pattern at a contrast of 0.5 was found to be 11 sq in. (Fig. 10). If circular, this would include a radius of 2 in. or $4\frac{1}{2}$ deg surrounding the fixation point. Comparing this radius to the data from the fixation experiments plotted in Figs. 4 and 5, we find that it falls within the peripheral angle where targets were detected in relatively short times (on the order of one-half second). Beyond about 6 or 7 deg peripheral angle, detection times suddenly increased by an order of magnitude or more. An explanation of these detections after very long fixation times may be a "cerebral search" mode in which the observer selectively brings into his consciousness various parts of his visual field. Areas farther out in the periphery are normally suppressed because searching can be done more effectively by moving the eyes and head so as to take advantage of higher resolution areas of the retina. For the static target and background used in this case, a 6 to 7 deg radius is apparently the maximum aperture that could be used effectively in searching, and glimpses of this size could be made approximately every one-half second. This aperture became much larger for the moving target, extending to the limits of the display. The gradual increase in detection time with peripheral angle that was noted in Fig. 6 suggests that there may be some trade-off between glimpse time and aperture during search. This requires further investigation, but if validated could have application in devising optimum search strategies.

Since the aperture found for the rapidly moving target was at least as great as the display, it might appear that a policy of fixating in the center would provide better detection results in this case than an unrestricted search pattern. Both types of search were tried in a subsequent test and the resultant detection probability curves are shown in Fig. 11. The unrestricted search proved to be

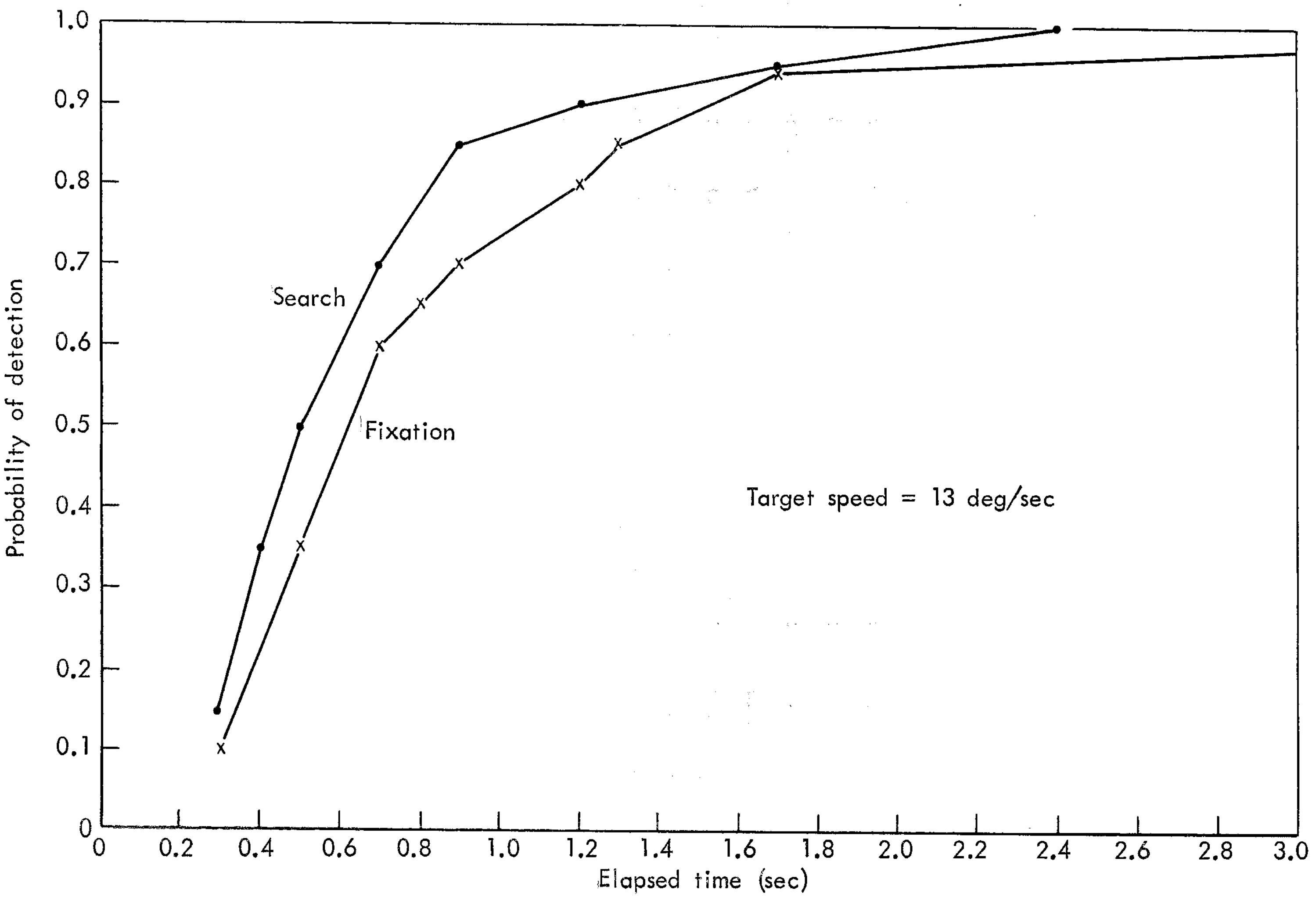

Fig. 11—Comparison of detection performance for unrestricted search and fixation

slightly better than the fixation method for detecting targets. It is interesting to note that even with fixation, an exponential time dependence is obtained.

SEARCH PATTERNS

Perfectly systematic search would give detection probabilities that are directly proportional to the detection aperture and the time available for search. However, observers cannot search perfectly even if they try because of the difficulty of spacing glimpses so that no overlap occurs.

We may compare the less efficient search patterns with a perfect one by defining the term R as the departure from a linear dependence of detection probability on time. The value of R is equal to the ratio of the time required to reach a given detection probability in the experimental situation and the predicted time to reach the same probability by a perfect search with a detection rate equal to the initial rate found by the experiment. Figure 12 shows the variation of R for both the exponential approximation and also for the data points found in the experimental study described here. The data points more nearly follow the exponential curve in all cases, indicating that the observers were accomplishing a search pattern more nearly random than systematic. The decrease in efficiency of search as a function of performance level is probably due to overlapping of detection apertures and inability to remember exactly where previous glimpses were made.

A more nearly perfect search pattern could improve detection performance at the 90 percent level by two to three times. To achieve this, an observer needs to be able to predict his detection aperture and devise a search pattern that makes optimum use of it. Alternatively, it may be possible to develop a search algorithm that minimizes overlap even when the aperture size is unknown.

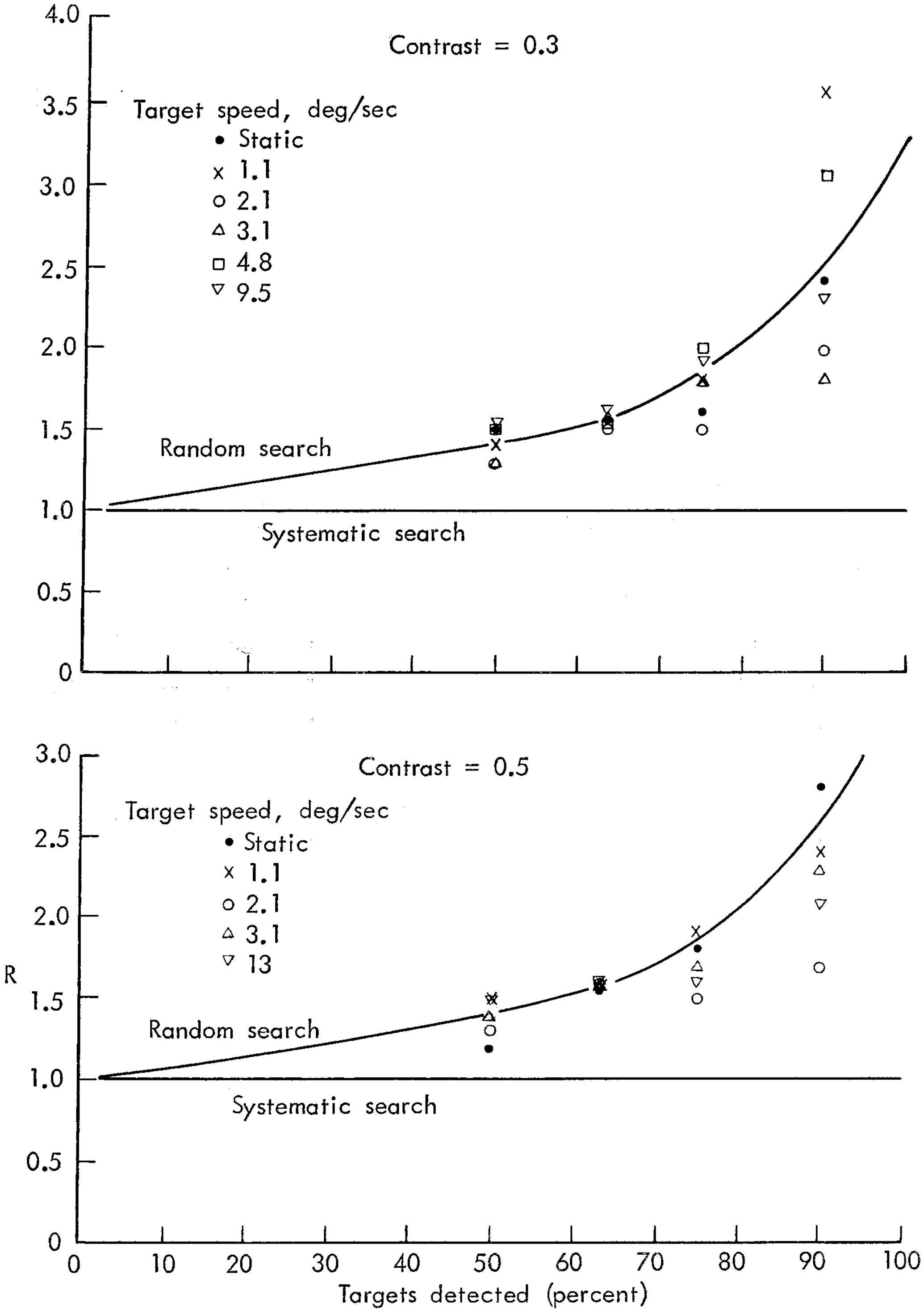

Fig. 12—Efficiency of search as a function of performance level

V. CONCLUSIONS

The experimental tests described in this report have shown independent effects of both contrast and motion on the visual detectability of targets located in a complex background. In the range of contrast and speed investigated here, the effects can be accounted for by modifying the exponent in the detection probability function with a linear contrast term and a squared velocity term:

$$P = 1 - e^{-\left(\frac{f}{A_s}\right) A_{d_o} C(1+0.45v^2)\, t} \tag{11}$$

The combined term, $A_{d_o} C(1 + 0.45v^2)$ is the *detection aperture*, that is, the single-glimpse area in which a target could be detected, given the reference detection aperture, A_{d_o}, target-to-background contrast, C, and target velocity, v. Detection apertures found in these experiments ranged up to a maximum value of about 100 sq in. (almost half the display area) at the highest speeds. While some limit in detection aperture should be expected, those found are believed to be a result of interference with the edge of the display used. The normalized detection aperture, A_{d_o}, is an indicator of the complexity of a particular background/target situation.

Search patterns used by observers in this test were found to be more nearly random than systematic. With prior knowledge of the detection aperture, it should be possible to devise a search strategy that would approach the systematic, and thus could reduce the time to reach the 90 percent detection level by a factor of about 2.

Appendix

EQUIPMENT

The equipment used was part of the IBM-9052 Image Distribution System presently in operation at The Rand Corporation. This system is an 873 television line (nominally 10 MHz bandwidth) video disk recorder that can store up to 32 independent images. The computer-driven picture generator normally used was bypassed, and signals from a COHU model 3204 television camera, viewing the photo to be used, were recorded directly on the disk to assure a constant picture intensity. The pictures were viewed on a Conrac model CQF 21-in. television monitor that had been included as part of the 9052 system. The contrast and brightness settings on the monitor were kept constant throughout.

In each case the backgrounds remained static while the target was electronically inserted in various locations in it. The target consisted of an electronically generated signal of uniform intensity that was positioned in any desired location on the display by means of a stylus on the Rand Tablet.

The Rand Tablet is a 10-by-10-in. matrix of wires imbedded in a flat sheet of plastic. The stylus location is sensed electronically to one part in a thousand in each direction.

The target motion was controlled by a device fabricated especially for this purpose. It consisted of a holder that supported the stylus over the Tablet; a lead screw that moved the stylus holder across the Tablet surface; a motor and associated controller to drive the screw at selected speeds; and microswitches at either end of the lead screw to reverse the stylus motion. The entire device could be placed over the Tablet in various orientations to correspond to the target locations and paths required in the test.

REFERENCES

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