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DISTANCE DISCRIMINATION IN A SIMULATED SPACE ENVIRONMENT

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## SUMMARY

The just noticeable difference (JND) for distance was investigated by a paired-comparisons method using successive comparisons. The research utilized an optically simulated large target located in a textureless environment at distances along the saggital plane out to 12,800 ft. The value of $\Delta D/D$ varied from less than 3% at 200 ft. to about 7% at 12,800 ft. The results confirm the power function relationship between distance threshold and observation distance.

## INTRODUCTION

There have been several investigations of depth discrimination under experimental conditions in which judgments could be influenced both by binocular retinal disparity and by monocular cues to depth localization (Beebe-Center, Carmichael, and Mead, 1944; Holway, Jameson, Zegler, Hurvich, Warren and Cook, 1945; Teichner, Kobrich and Dusek, 1955a; Teichner, Kobrick and Wehrkamp, 1955b; Jameson and Hurvich, 1959). A summary by Teichner et al. (1955a) concluded that the just-perceptible-difference in distance ($\Delta D$) grows as the 1.35 power of observation distance,

$$\Delta D = KD^{1.35}. \qquad (1)$$

All of these studies shared several experimental characteristics which limited generalization of the results. Monocular cues are frequently peculiar to a particular stimulus situation, and even when a terrain effect was ruled out statistically (Teichner et al., 1955a; 1955b) or, to some extent, experimentally (Beebe-Center et al., 1944), texture cues from the surround may nevertheless have been present. Moreover, the physical target sizes and the maximum viewing distances were typically rather small. The targets were usually rectangles with a maximum dimension of about 5 ft. and were located no more than and most often considerably less than 300 ft. distant. Jameson and Hurvich (1959), citing results from the Holway et al. (1945) paper, emphasized the importance of distance range by considering the curvature of the wave front of the light-bundle incident to the eye, since it is related to changes in image clarity and ocular accommodation. Finally, the experiments discussed above were concerned only with the accuracy of equality settings. A literature search failed to locate a study which established the proximal and distal linear thresholds of distance.

This paper reports the results of a depth discrimination study which utilized an optically simulated large target (simulated size approximately 24 ft. high and 13 ft. in diameter) located in a textureless environment at simulated distances along the saggital plane out to 12,800 ft. Unlike the previously cited studies, the standard and comparison targets were viewed sequentially rather than simultaneously.

## METHOD

_Subjects_.--Three male _Os_, ranging in age from 20 to 24 years, were paid to participate in this experiment. They were selected from a list of volunteers on the basis of possessing at least 20/20 visual acuity and high depth discrimination as judged by an optometrist.

Apparatus.--Judgments were made of targets produced by an opto-mechanical simulator offering a high-fidelity, three-dimensional presentation of a 30 ft. x 13 ft. space vehicle (Apollo Command and Service Module) illuminated by a "sun" source in a star-free, outer space environment. Since the light source was maintained at a constant distance from the target, apparent brightness also varied appropriately with apparent distance. A special feature of the apparatus is that the simulated distance is achieved by having the apparent source of the light rays appropriate to the distance being presented. Thus, all the visual target cues which would be present in the real situation are provided in the simulation. The distance range available was 200 ft. to 20,000 ft. During all sessions, the target was tilted 37° toward the O, so that the maximum simulated vertical dimension was approximately 24 ft.

Procedure.--Each O observed the target from a station in a room adjoining the simulator. He was seated in a fully-enclosed "capsule" and viewed the display through a 9 in. dia. "porthole" situated 18 in. in front of him. His head was enclosed in a soft helmet which located his eyes in the optical axis. An intercommunication system provided verbal contact between the experimenter and observer. Between the "porthole" and the final ocular lens there was a remotely controlled shutter used to occlude the scene between stimulus presentations.

The Method of Constant Stimuli was employed to establish the proximal and distal JNDs of distance for each of seven Standard Distances selected to form a geometric series. It should be understood that the term "distance" when used in the context of the present experiment stands for "apparent" distance, in deference to the fact that the visual display was simulated.

Seven Comparison Distances for each Standard were selected during an extensive series of exploratory trials employing two Os. The criterion for selecting the range of Comparison Distances was that the most proximal and distal distances should be judged correctly in at least 18 of 20 trials. The remaining Comparison Distances consisted of equally spaced (or occasionally equal logarithmically spaced) distances within this range. The 4th Comparison Distance was identical with the Standard Distance. Once the Comparison Distances were selected, they were used for all Os. The data gathered in the exploratory trials were not included in the final analysis. The third O was given three practice sessions, during which it was determined that his judgment was essentially the same as those of the other Os, so he proceeded directly to the final phase of the research.

The procedure was the same for both the exploratory and final sessions. On a given day each O made judgments at only a single Standard Distance, and each O judged a different Standard that day. The Standard was presented first, and was identified by the experimenter each time it appeared. Following a 3-sec. exposure, the shutter occluded the scene; the target was moved to a randomly selected Comparison Distance, and 3 sec. later the shutter opened for 3 sec., and O responded "nearer" or "farther". No "equal" judgments were permitted. Following a 3-sec. intertrial interval this sequence was repeated until each Standard-Comparison pair had been presented 10 times. The Os judged each of the various Standards in a random fashion on three different days, making a total of 30 responses to each stimulus pair. The Os were not told the simulated distances of the Standard or Comparison stimuli until the termination of the experiment.

## EQUATIONS AND SYMBOLS

(1) $\Delta D = KD^{1.35}$

(2) $\Delta D = KD^{1.0}$

(3) $\Delta D = K(D + \Delta D)^{1.0}$

(4) $\frac{D_1}{D_2} = \frac{D_3}{D_4}$

(5) $\frac{\Delta D_1}{\Delta D_2} = \frac{\Delta D_3}{\Delta D_4}$

(6) $\Delta D_p = 0.011D^{1.19}$

(7) $\Delta D_d = 0.011D^{1.20}$

(8) $\Delta \alpha_p = 0.108\alpha^{0.78}$

(9) $\Delta \alpha_d = 0.112\alpha^{0.79}$

(10) $\Delta \alpha = S(\Delta D)/D^2 + D(\Delta D)$

(11) $\Delta D = 0.002D^{1.35}$

$\Delta D$ = just perceptible difference in distance (in ft.)

$K$ = constant denoting intersection of Y axis

$D$ = observation distance (in ft.)

$\Delta \alpha$ = just perceptible difference in visual angle (in min. of arc)

$\alpha$ = visual angle (in min. of arc)

$\Delta D_p$ = proximal just perceptible difference in distance (in ft.)

$\Delta D_d$ = distal just perceptible difference in visual angle (in min. of arc)

$\Delta \alpha_p$ = proximal just perceptible difference in visual angle (in min. of arc)

$\Delta \alpha_d$ = distal just perceptible difference in visual angle (in min. of arc)

$n$ = slope of power function

$m$ = slope of power function

$S$ = size of target (in ft.)

## RESULTS

The percentage of "nearer" responses for all Os to each Standard Comparison pair were treated as ordinate values on a normal distribution and were converted to standard scores which were plotted against the Comparison stimuli (see Fig. 1). The interpolated Comparison Distance corresponding to -1 SD (standard deviation) defined the proximal threshold ($\Delta D$); that for the +1 SD defined the distal threshold. The procedure follows that discussed by Woodworth and Schlosberg (1954).

An initial analysis was made to test if Weber's law held, such that

$$\Delta D = KD^{1.0}. \tag{2}$$

Figure 2 depicts the results of plotting $\Delta D/D$ against log D. The curve was fitted to the data by eye with no distinction made between proximal and distal thresholds. It is clear that the strict Weber relation was not found. Neither was the generalized Weber function endorsed by Ogle (1952)

$$\Delta D = K(D + \Delta D)^{1.0}. \tag{3}$$

The analysis is not shown here, but the values of $\Delta D/(D + \Delta D)$ ranged from 0.03 at 200 ft. to 0.07 at 12,800 ft., and they were very nearly the same for both the proximal and distal thresholds. In other words, rather than being a constant proportion of observation distance, $\Delta D/D$ and $\Delta D/(D + \Delta D)$ increase progressively with observation distance.

Inspection of Fig. 3 reveals that the JND (just-noticeable-difference) for distance increases exponentially with distance and with visual angle ($\alpha$). In other words, equal stimulus ratios produce equal threshold ratios, that is, if

$$\frac{D_1}{D_2} = \frac{D_3}{D_4} \tag{4}$$

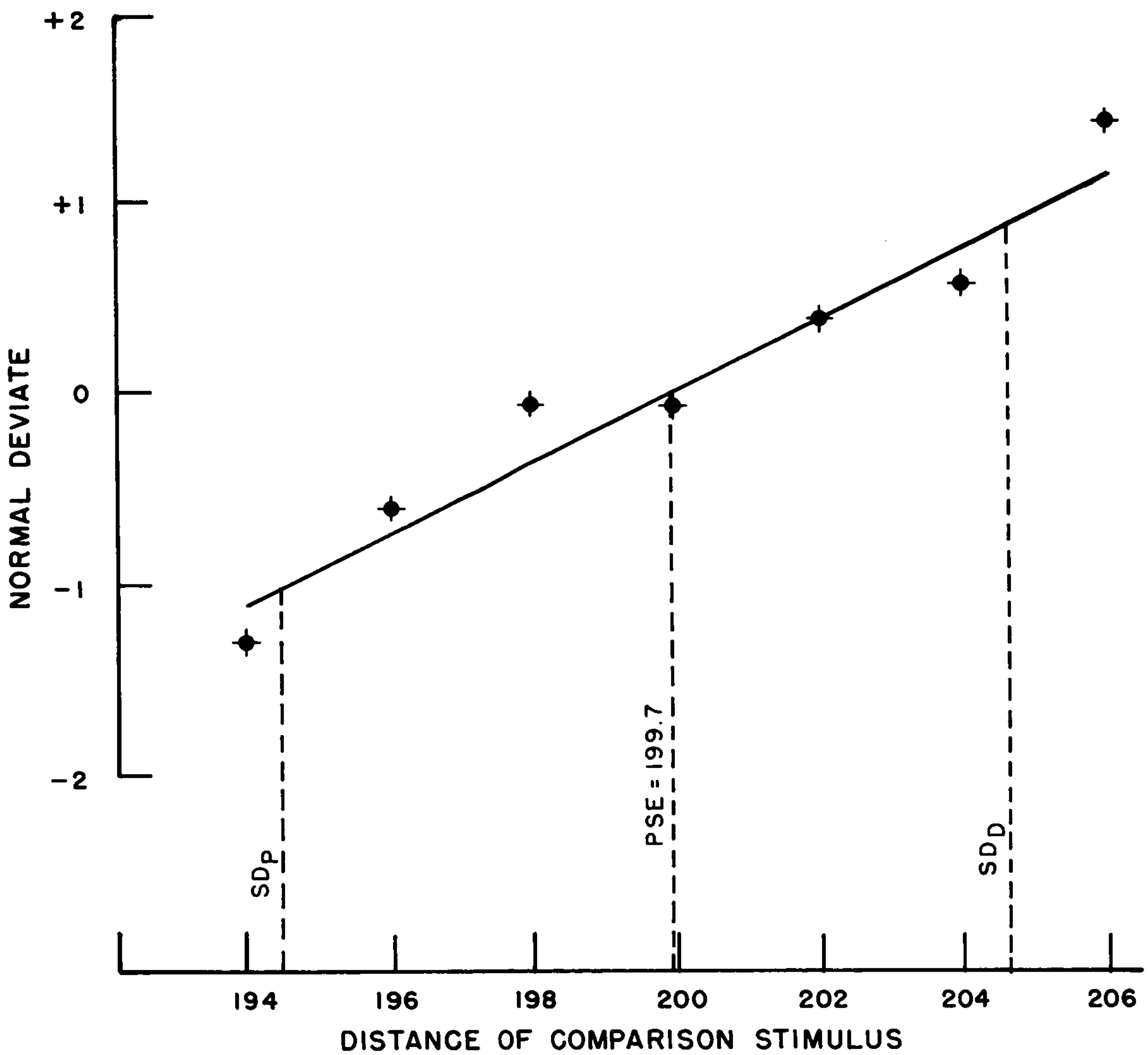


Fig. 1. Computation of proximal and distal thresholds. The points on the best fit (least squares) line corresponding to ±1 z determine the values of the thresholds.

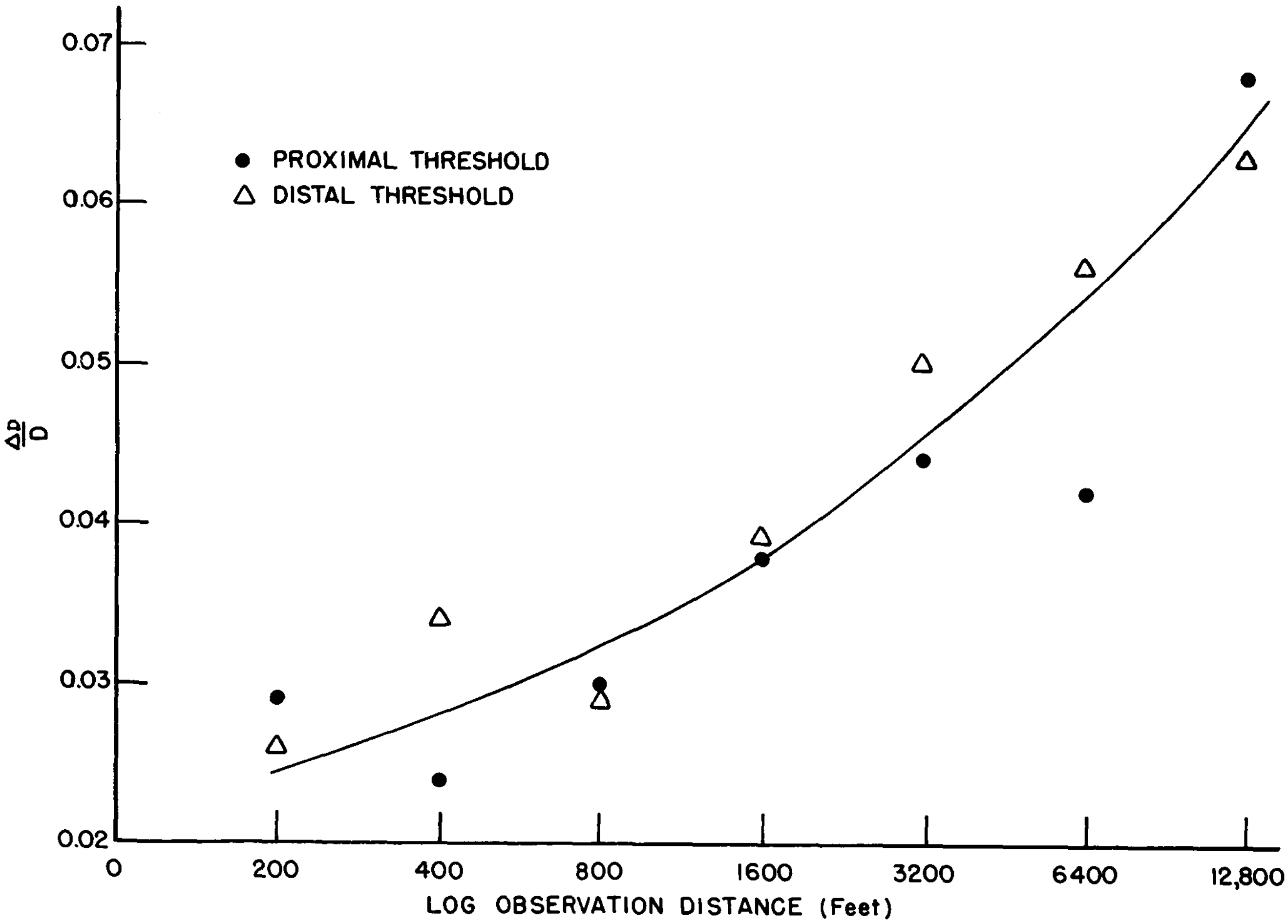


Fig. 2. Proximal and distal differential distance discrimination as a function of observation distance. The curve was fitted by eye with no distinction made between proximal and distal thresholds.

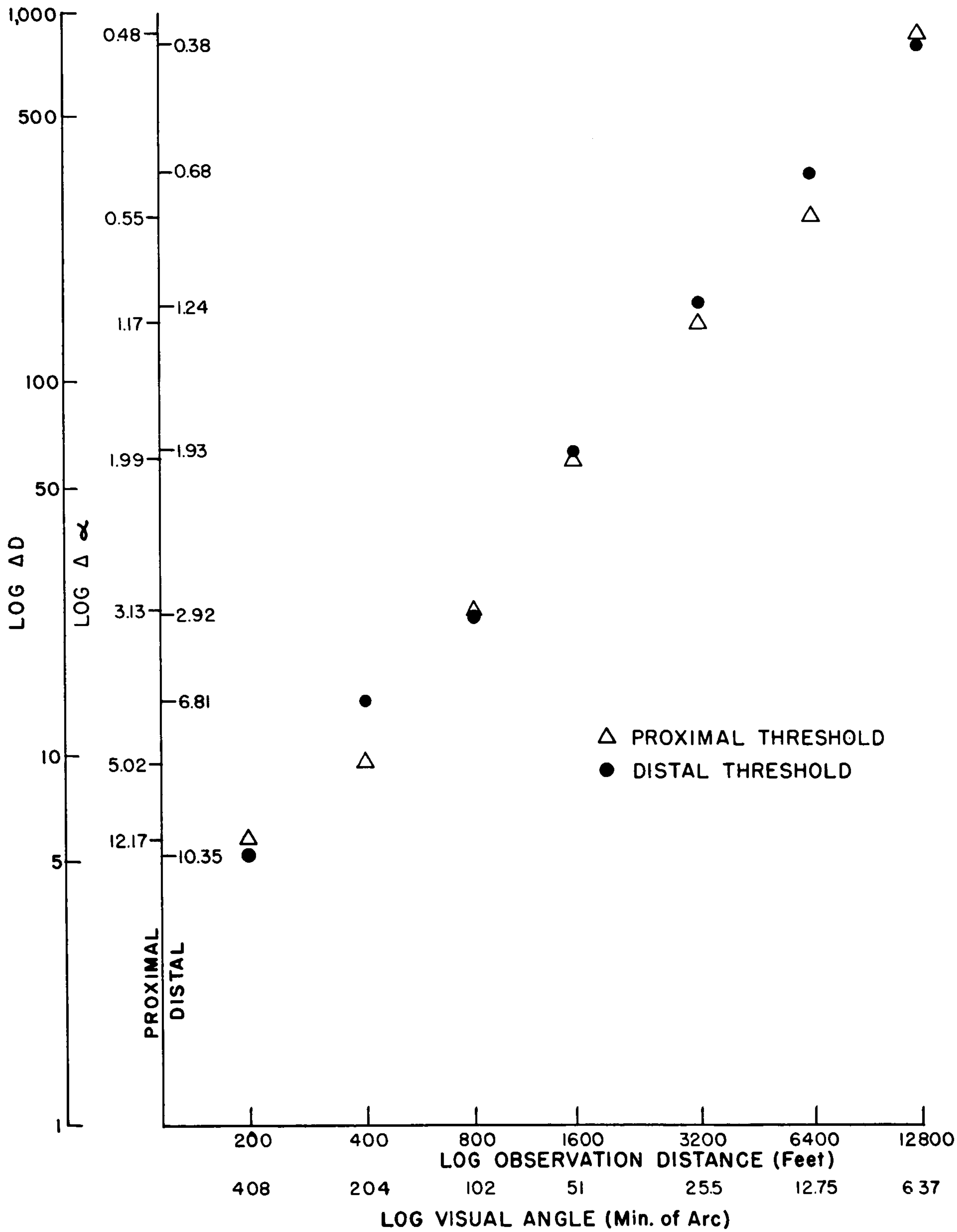


Figure 3. Proximal and distal thresholds for distance and visual angle as a function of observation distance and visual angle.

then

$$\frac{\Delta D_1}{\Delta D_2} = \frac{\Delta D_3}{\Delta D_4} \qquad (5)$$

where $D_1$, $D_2$, $D_3$, and $D_4$ are any four standard distances. These same relationships would hold for distances expressed in visual angle. The proximal and distal thresholds are plotted separately, with each point based upon 90 responses. The smooth lines were fitted by least squares, and the resulting power functions are

$$\Delta D_p = 0.011D^{1.19} \qquad (6)$$

$$\Delta D_d = 0.011D^{1.20}, \qquad (7)$$

where $\Delta D_p$ and $\Delta D_d$ designate the proximal and distal thresholds respectively. There appear to be no consistent differences in the magnitudes of the corresponding thresholds.

In terms of angular subtense of the vertical dimension of the target, the least perceptible difference in retinal size of the stimulus is shown to grow as a power function of target size,

$$\Delta \alpha_p = 0.108\,\alpha^{0.78} \qquad (8)$$

$$\Delta \alpha_d = 0.112\,\alpha^{0.79}. \qquad (9)$$

These functions follow from the geometrical relationships among the differential threshold for visual angle ($\Delta\alpha$), size of target (S), linear threshold for distance ($\Delta D$), and observation distance (D),

$$\Delta\alpha = S(\Delta D)/D^2 + D\,(\Delta D). \qquad (10)$$

Teichner et al. (1955a) averaged the data from several studies concerned with depth discrimination at various observation distances and concluded that $\Delta D$ grows approximately as the 1.35 power of D,

$$\Delta D = 0.002D^{1.35}. \qquad (11)$$

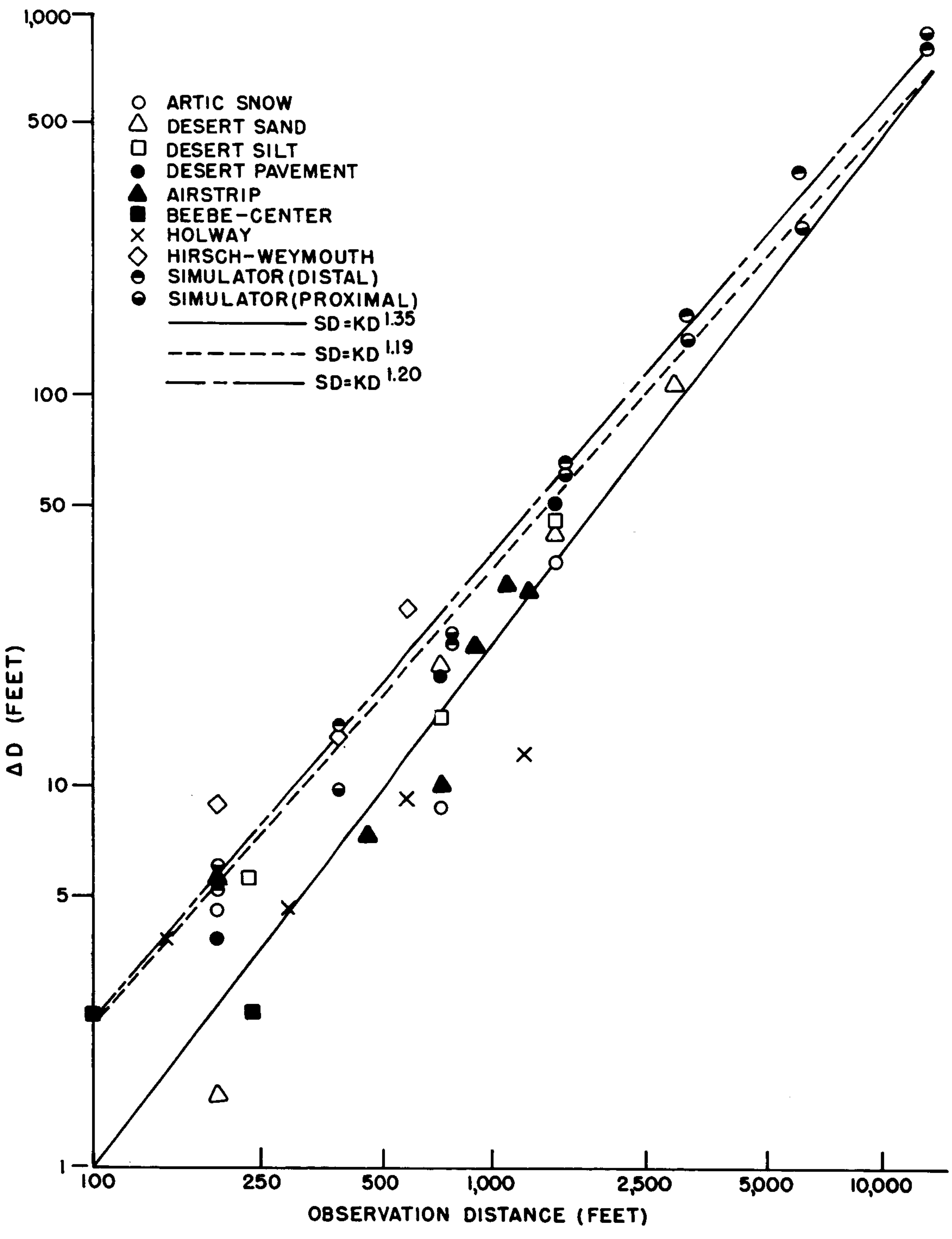


Fig. 4. Data from Fig. 1, Teichner et al. (1955a) and present study (half-filled circles) showing distance discrimination as a function of observation distance. The lowest curve was fitted by the empirical formula $\Delta D = 0.002D^{1.35}$. The proximal curve was fitted by the empirical formula $\Delta D = 0.011D^{1.19}$; the distal curve by $\Delta D = 0.011D^{1.20}$.

Their results are reported in Fig. 4 (adapted from Teichner's, 1955a, Fig. 1). The lowest curve was fitted to the data by formula (11).

Superimposed on Teichner's results are the findings from the present study (half-filled circles). Despite the differences in absolute values of the threshold, the general agreement between the present results and those reported by Teichner et al. (1955a) is impressive, considering the vast differences in the experimental situations.

Assuming adequacy of the distance simulation, the practical meaning of these results is as follows: (a) at a distance of 200 ft. an observer should be able to detect reliably a change in distance of only 5 ft., even under conditions of successive observation; at a range of 12,800 ft. the minimum detectable change is of the order of 800 ft.; (b) in terms of size change of a large target (maximum dimension = 27.34 ft.), at 200 ft. a size change of 11' 16" of visual arc could be detected (target size = 408' of visual arc); at 12,800 ft. a size change of 26" of arc could be detected (target size = 6' 22" of visual arc). It should be noted again that these discriminations were made under conditions such that almost all of the normal terrestrial cues to distance were missing.

## DISCUSSION

In one respect, the results of the present investigation may be interpreted as a test of the adequacy of the simulation of distance. In light of the correspondence between the results reported here and those of previous authors there is no response-based reason for doubting the validity of the display.

The present study confirms the power function relationship between distance threshold and observation distance even under severely restricted viewing conditions. Because of the particulars of the experimental design, however, unanswered questions remain concerning the relative importance of the several empirical factors to depth localization listed by Ogle (1958; 1962). Change in retinal image-size is advanced as the most significant cue to depth localization in the present experiment. This conclusion is based upon a process of elimination and is similar to that reached by Holway et al. (1945). The possibility is recognized that changes in binocular disparity and the characteristics of the light-ray bundles were also involved. In fact, Jameson and Hurvich (1959) reanalyzed specific aspects of the earlier Holway et al. (1945) data and reported that retinal image size, binocular disparity, and light-ray configurations work together in an additive fashion to produce depth discrimination, but it was concluded that the last two variables were of minimal importance in the present research for reasons developed below.

It is extremely doubtful that binocular disparity could have played a significant role in the present results. It would be unreasonable to assume that O was making judgments on the basis of binocular parallax angle when the targets were viewed sequentially with a 3-sec. inter-presentation interval. Parenthetically, the mode of presentation tends to weaken the possibility that Os were relying upon vernier alignment of the Standard and Comparison targets, an explanation offered by Teichner et al. (1955a; 1955b) to cover the situation in which the targets are presented simultaneously. Cues from binocular disparity involve differences between the images in the two eyes. In the case of sequential presentation, then, the comparison would have to be between the binocular disparity present on one occasion with a trace of the disparity present in the images recorded 3 sec. earlier. Such a comparison is not impossible, but our present knowledge of the visual system would render it highly unlikely.

By the same token, it should be noted that judgments based solely on size change are likewise based on a comparison of present stimulation with the trace of past stimulation. For this reason the threshold values obtained must be considered remarkably small.

One final possibility that might be considered is that judgments were based on a detection of change in convergence or accommodation from the first presentation to the second. While the shutter was closed O may have maintained his visual fixation and may also have had an after-image of the stimulus. Exposure of the second stimulus would then have produced small changes in convergence and accommodation. If an after-image were present, a small amount of apparent movement of the target might have been detected as well. These possibilities could be investigated by providing a fixation point on the shutter. A change in fixation between presentations should have the effect of increasing the threshold values. Another method of checking the reliability of the results would be to replicate the experiment using a target of different size and shape. Such a replication is currently being planned.

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