10 August 1962, Volume 137, Number 3528 **SCIENCE**

Sonar System of the Blind

New research measures their accuracy in detecting the texture, size, and distance of objects "by ear."

Winthrop N. Kellogg

One of the most remarkable discoveries of modern times has been the development of long-range scanning devices like radar and sonar. The Air Force and the Navy, as constituted today, could not exist without them. By electronically analyzing the echoes which are bounced off of objects in the sky (radar) or from objects in the ocean ("active" sonar), the location, movement, and characteristics of these objects can be determined. Although the basic principle of reflected echoes is the same for both, radar makes use of radio echoes and sonar of sonic or ultrasonic echoes. The development of sonar (*so*und *na*vigation *r*anging) was necessitated by the fact that radar (*ra*dio *d*etecting *a*nd *r*anging) will not work beneath the surface of the water.

Today, all large vessels and many smaller ones are equipped with echo sounders or fathometers which beam sonar pulses downward to measure the depth of the water beneath the hull. The echo sounder thus takes the place of the sounding lead. Commercial fishermen locate schools of fishes by the ultrasonic vibrations which are reflected from the fishes' bodies. A submarine navigating beneath the polar ice cap determines by sonar not only (i) the distance and contour of the bottom but also (ii) the amount of free water between the top of the vessel and the ice above it and (iii) the presence of reefs, submerged mountains, or other obstacles in a horizontal plane.

Echo Ranging in Animals

But these electronic marvels of radar and sonar are matched or even surpassed by the echo ranging or sonic perception of such animals as the bat and the bottlenose dolphin or porpoise. Bats catch night-flying insects on the wing by listening to the echoes of their own rapidly repeated cries (*1*). This unique method of distance perception in the bat was originally discovered by Spallanzani as far back as 1793 (*2*). Within the last decade or so it has also been determined that the bottlenose dolphin—and probably the larger-toothed whales as well—navigate in the ocean by emitting trains or series of underwater sonic pulses (*3*). Dolphins may be able to distinguish one food fish from another by this method (*3*). Some nocturnal birds (*4*), and even blinded laboratory rats (*5*), employ echo ranging to some degree for orientation in space. Thomas C. Poulter of the Stanford Research Institute has recently found that the California sea lion emits trains of echo-ranging signals like those of the bottlenose dolphin (*6*).

In the light of all this it seems surprising that human beings, with their superior neural and sensory equipment, make so little use of sonic echoes in daily life. In fact, echoes are usually considered to be a hindrance rather than an asset in auditory perception, and when they are noted at all, they are often the cause of special comment. In acoustical engineering great emphasis is placed on designing rooms and wall surfaces which are "anechoic"—that is to say, which reflect few if any echoes. A blind man tapping with a cane—and hence producing a regular sequence of sound pulses—is probably the closest human analogue to the remarkable sonar systems of the porpoise and the bat. With some embarrassment, I quote here a recent statement of my own on this subject (*3*, p. 48): "the avoidance of objects by the blind appears to be very crude when compared to the precise auditory perception of which bats are capable." The present article gives newly obtained data in partial refutation of this statement. It shows just how accurate the echo ranging of experienced blind people can be.

Observations of Blind People

Of course, the avoidance of obstacles by the blind is by no means a recently observed phenomenon. The "amazing ability" of an unusual blind person to detect objects was described by Diderot in 1779 (*7*). A number of other outstanding cases have been studied since that time. Current tests of this "obstacle sense" of the blind have demonstrated how much the skill can vary from one person to the next. A few blind people seem to lack it altogether (*8*). Research has shown, however, that it is not a special endowment and that blindfolded normal (or seeing) subjects can *learn* with practice to detect objects in a manner similar to that of the genuinely blind (*9*).

The precise mechanism by which this is accomplished when vision is eliminated was not altogether clear prior to the work of Dallenbach and his associates (*10*). The skin of the face was presumed by some to be particularly sensitive, and it was supposed that the blind detected objects by changes in air currents or in air pressure. Blind observers had reported, in fact, that cover-

The author is professor of experimental psychology at Florida State University, Tallahassee.

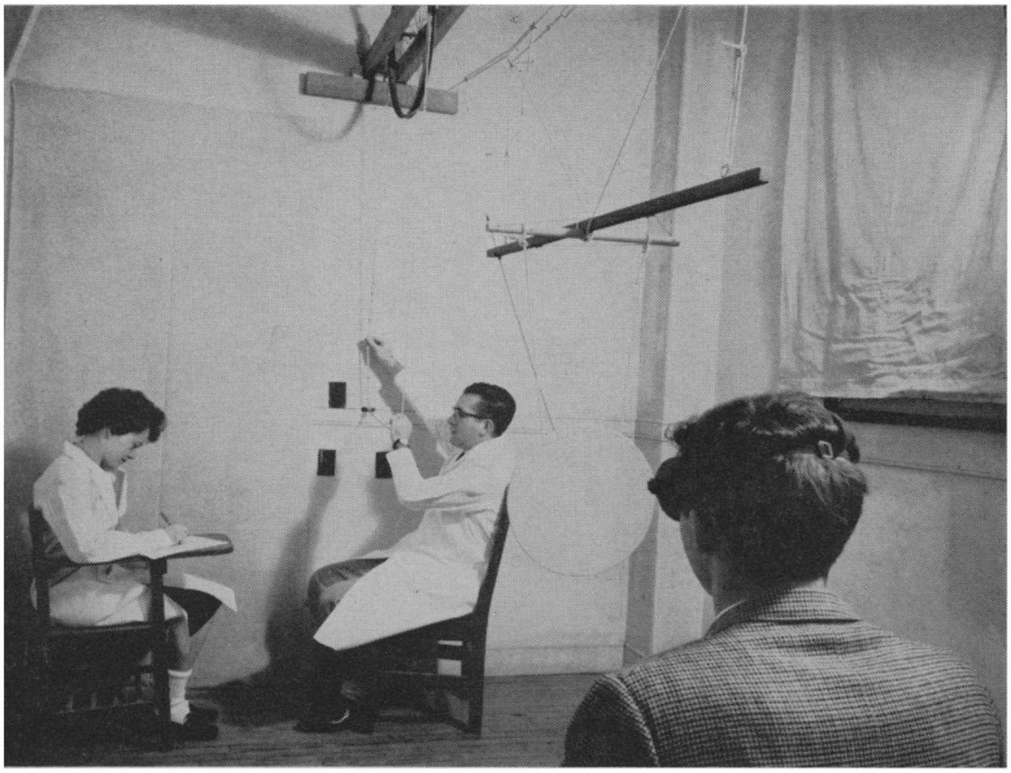


Fig. 1. The arrangement for presenting the stimuli in the distance-discrimination or depth-perception experiment. The disc used as a target is silently moved to one of seven fixed positions.

ing the face seriously affected their ability to avoid obstacles. The term *facial vision* was applied to this apparent perception through the skin.

Through a systematic study of the matter, however, it was demonstrated that the crucial cues were actually received via the acoustic receptor, and that the subjects were probably responding to echoes. McCarty and Worchel (*11*) found a blind boy who could avoid obstacles when riding a bicycle. The boy made "clicking sounds" with his mouth while navigating and listened to the echoes of his own noises.

Electronic echo-ranging devices based both upon the reflection of ultrasonic echoes and on the reflection of light beams have been constructed to assist the less-skilled blind in moving about (*12*). The operator aims the apparatus as he walks, and it sounds a buzzer or otherwise signals when he is close to an obstacle. Such devices have generally not proved popular with the blind, probably because (i) the equipment has to be carried and (ii) it has to be overtly manipulated in order to produce satisfactory results.

It is worthy of note that previous studies of the navigational talents of blinded human beings have, for the most part, been qualitative or descriptive in nature. They have been concerned, in other words, with investigating the obstacle sense—with finding out how well blind people could avoid certain barriers or obstructions, and with the mechanism of this avoidance. Since it had been shown (*3, 13*) that porpoises can distinguish between objects of different size by echo ranging, the question arose as to whether the blind could accomplish the same thing. If the answer was "Yes," would it then be possible to obtain quantitative or numerical measurements of this ability? Could threshold fractions for echo ranging be calculated in the same way that $\Delta I/I$ is computed for visual distance and for size perception? What would the psychophysical function look like? Would Weber's law hold in such a case? Last but not least, do we have here a procedure for comparing quantitatively the sonar of human beings with that of the bat and the porpoise?

Taking off from a group of questions like these, we set up a series of experiments to measure the sensitivity of blind and seeing observers to changes in the distance, size, and texture of various stimulus objects. The results have by no means answered all of the questions, but they do seem to offer considerable promise for the application of psychophysical techniques to the sonar system of the blind (*14*).

Subjects and General Procedure

The subjects were four male college students, three of them juniors and the fourth a postgraduate student. Two were completely blind and had been so for 5 and 10 years, respectively. The other two served as normal controls and were blindfolded by means of opaque goggles during all of the tests. Each of the blind individuals was very skillful in navigating and used a collapsible cane only occasionally, or in a noisy environment. Even then it was not used for "tapping" but rather as a protective probe.

The research work was conducted in a sound-insulated experimental chamber approximately 12 by 9 feet in area, with a ceiling height of 11 feet 4 inches. The noise level in the room was down about 10 decibels from that in adjacent rooms. Preliminary tests in research cubicles which were more completely soundproofed appeared to disturb one of the blinded subjects and to reduce his accuracy. Some degree of extraneous noise was therefore deemed to be better than none at all. This may well mean that blind people, depending as they do so heavily upon hearing, are "lost" and anxious in acoustically pure surroundings which fail to return familiar reverberations.

The echo-ranging targets or stimuli to be observed were flat discs made of quarter-inch plywood and of other materials. They were presented to the subject individually but in rapid succession. Judgments were always made between two successive stimuli of a pair. This permitted the use of the method of constant stimuli (the method of constants), and the method of paired comparisons. All discs were presented on a level with the subject's face when he was seated, and at measured distances from his face.

By a system of small ropes and bicycle wheels (used as pulleys), the distance of a given disc from the observer could be quickly changed. With additional equipment, two separate discs, each differing from the other, could be presented successively. The observer began sending echo-ranging sounds upon a signal from the experimenter. As soon as a judgment had been made, the apparatus was reset, and the subject was told to start on the next target. In making a judgment, the subject simply stated: (i) whether a single disc was nearer or farther away than it had been during the previous presentation, a moment before; (ii) whether one of two successively presented discs was larger or smaller than the other member of the pair; and (iii) whether or not a disc was of the same material as the disc with which it was compared.

Auditory Scanning

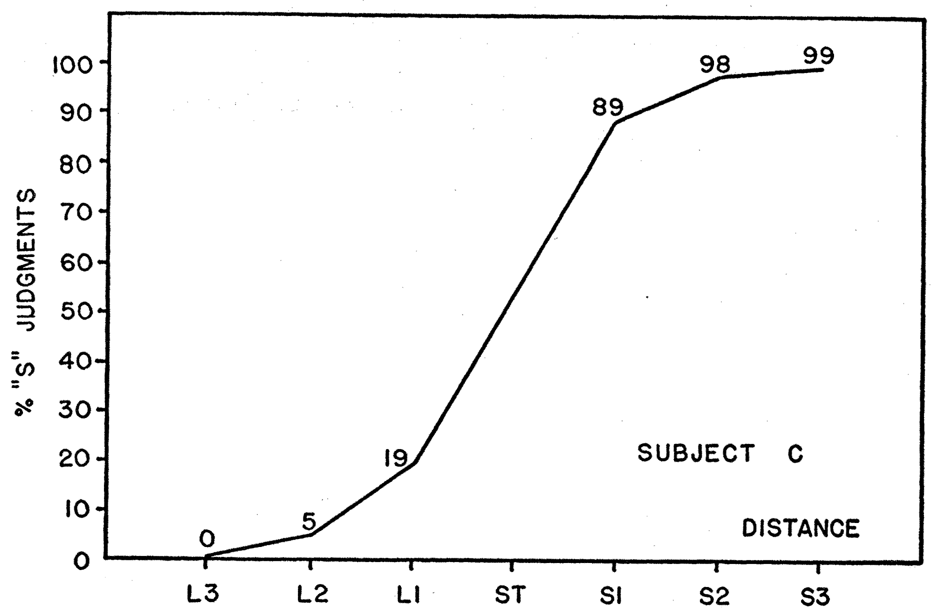
The subjects were not restricted in any way with respect to the noises they made. They were told to make "any sounds they wanted." The object was not to study the effectiveness of different sorts of acoustic signals but rather to find out what blind people could do by using any or all signals at their command. Both of the blind subjects in these experiments employed tongue-clicking to some extent—a sound reminiscent of the sonar "pings" of the porpoise. Sometimes they snapped their fingers a few times. They also resorted to hissing and, on rare occasions, to whistling.

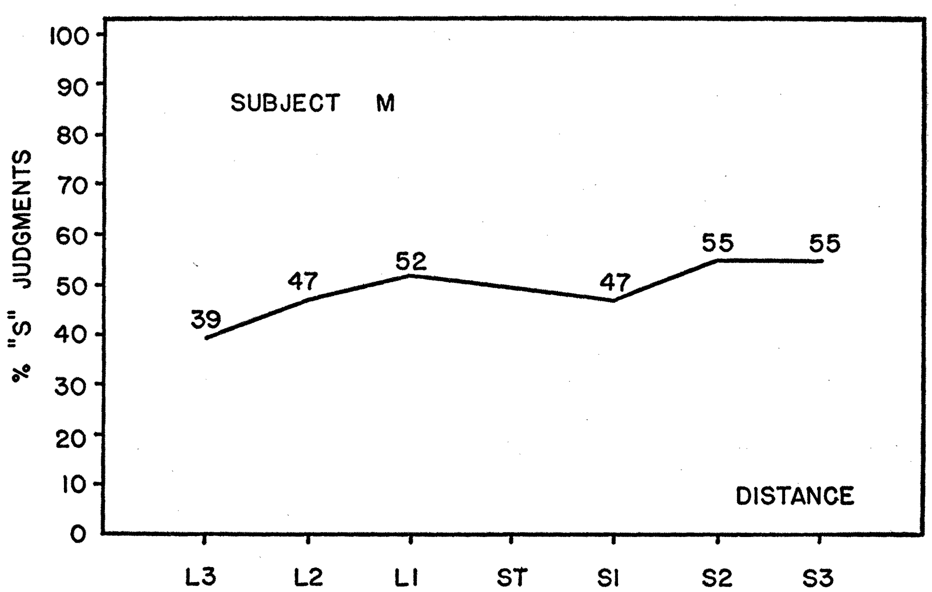
By far the preferred source of auditory signals, however, was the human voice, which was used in a repetitive and sometimes in a sing-song fashion. One of the subjects actually sang the diatonic scale, or part of the scale. He would also repeat the word *now* by saying, "Now, now, now, now, now . . ." varying the pitch of his voice as he did so. The other subject fell into a speech pattern somewhat like the following:

"Now, this is the . . . this is the . . . uh . . . let me see . . . now, this, I think, is the smaller (or larger) disc."

The blindfolded normal subjects also used vocal signals, for the most part. One of them, who was studying Russian, chose continuously to repeat the Russian word *"dva."*

While the sounds were being emitted and the judgment was being formulated, each of the blind observers oscillated





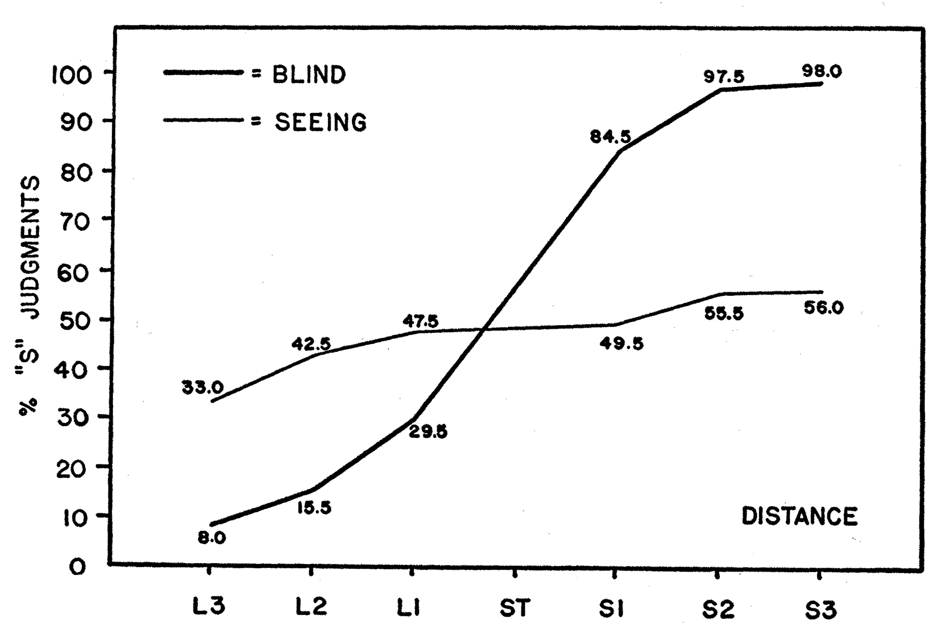


Fig. 2 (top). Psychophysical curve for one of the blind observers in the distance-discrimination experiment. The stimuli are given on the abscissa. The numbers above each point on the curve represent the percentage of "smaller" judgments for that point. This graph is similar to those obtained in measuring sensitivity in vision and in other sense modalities.

Fig. 3 (middle). Graph of "smaller" judgments for one of the seeing subjects in the discrimination of distance. Compare this with Fig. 2.

Fig. 4 (bottom). The performance of the blind versus the seeing subjects on judging distance. All points on the "seeing" curve, except that at the extreme left, are within the limits of chance expectancy.

Table 1. Characteristics of target stimuli; the same 1-foot disc was used at different distances.

Position	Distance from 0 (ft)*	Approximate projected or perceptual area (sq ft)†	Angle subtended
L3	1.00	0.785	53° 08′
L2	1.26	.489	43° 12′
L1	1.59	.310	34° 52′
St	2.00	.196	28° 04′
S1	2.55	.124	22° 10′
S2	3.19	.078	17° 50′
S3	3.97	.049	14° 22′

* Each distance is about 126 percent of the next smaller distance; therefore, the differences are relative.
† Each projected area is about 158 percent of the next smaller area; therefore, the differences are relative.

his head from side to side at angles varying from 5 to as much as 45 degrees on either side of the median plane. This behavior is particularly significant, we think, since it is precisely the method used by the bottlenose porpoise in locating a target in turbid water. Head oscillations in the porpoise have been noted by Schevill and Lawrence (*15*), by myself (*13*), and by Norris *et al.* (*16*). I have described the phenomenon in detail (*3, 17*) and have given it the name of "auditory scanning." Auditory scanning is a combination of echo ranging and binaural localization. The lateral oscillations of the head continuously modulate the intensity and phase differences of the echoing sound waves reaching each of the ears. By accentuating the difference in the echoes received by the two ears, the oscillations enhance the accuracy of perceiving the target.

On some occasions, surprisingly enough, one of the blind subjects moved his head up and down as he was making the sounds. In spite of the generally vague or poor directionality of the human voice, it appeared as if he were trying to "aim" the sound at the circumference of the disc in order to pinpoint the location of its edge. With vertical oscillations of this sort, the differential binaural effect produced by the echo would of course be low. The normal control subjects did not use any form of oscillation very much, although they tried on occasion to imitate the blind in this respect.

Perception of Distance and Size

For this experiment a single disc 1 foot in diameter was used. It was made of ¼-inch fir plywood and was painted with a sand-texture paint to give a hard, diffuse reflecting surface. The disc was moved silently by the experimenter to one of seven fixed positions at distances from the face of the observer which varied from 1 foot to 3.97 feet. Each position therefore constituted a separate "stimulus" to be judged. The standard position (St) was at 2 feet. Three of the comparison stimuli (L3, L2, and L1) were closer to the observer and consequently appeared larger than the standard. The remaining three (S1, S2, and S3) were farther from the observer and appeared smaller than the standard. A given comparison stimulus was always compared with the standard stimulus and never with another comparison stimulus or with itself; nor was the subject required to compare standard with standard. The subject compared L3, L2, L1, S1, S2, and S3, respectively, with the standard, making 100 judgments in each case. The arrangement for moving the stimuli is shown in Fig. 1.

The observer in the experiment always knew that one of the stimuli of any given pair was closer to him than the other member of that same pair, but the order of presentation (for example, presentation of L3 before St, or of St before L3) was randomized. A person totally unable to perceive any difference in the distance of the two would get a score of 50 percent (chance accuracy). Any percentage greater than 50 would indicate some degree of perceptibility, provided there was no constant error. The characteristics of the stimuli at the seven stimulus positions are shown in Table 1. It may be noted that the angle subtended at the different positions extended from 14°22′ to 53°08′.

A standard psychophysical curve may be plotted from the data by using the percentage of "smaller" (or "larger") judgments made at each stimulus position. Such a plot for one of the blinded subjects is given in Fig. 2. A comparable graph for one of the normal or seeing observers is shown in Fig. 3. In Fig. 4 there is a single combined psychophysical function for the two blind subjects, together with a similar combined curve for the normal blindfolded subjects.

The psychophysical curves for the blinded observers, it is clear, follow the typical pattern of psychophysical graphs obtained in measuring sensitivity in the visual, auditory, kinesthetic, and other sense modalities. By contrast, the graphs for the seeing observers show a sensitivity which at most points is so poor that it is not significantly greater than chance performance (*18*).

Table 2. Thresholds for depth perception.

Subject	Distance (in.)	Area (ft^2)	Area ($in.^2$)	Auditory angle
C	4.3	0.076	11.0	4° 42′
W	7.2	.128	18.4	7° 56′

Table 3. $\Delta I/I$ for depth perception.

Subject	Distance	Perceptual area	Auditory angle
C	1/5.6	1/2.6	1/6.7
W	1/3.3	1/1.5	1/3.6

The threshold values, computed from z-scores, for the two blinded individuals, are given in Table 2. A single example of the significance of these figures may be seen in the distance threshold for subject C—the better of the two blind people at auditory scanning. It appears that this observer could detect, by echoes, a change in the position of a 1-foot disc placed 2 feet away from him when that disc was moved nearer or farther away by a little more than 4 inches. The other blind observer was not so accurate.

The threshold fractions for the blind in terms of distance, projected area, and auditory angle are given in Table 3. They range, it may be seen, from about 1/1.5 to about 1/7, with an average of about 1/4. It is worthy of note that the visual threshold for depth perception, as measured by Howard (*19*), is on the average about 1/2 for monocular vision and about 1/40 for binocular vision.

The average fraction for monocular depth perception, according to these figures, is larger than the average obtained from echo ranging. If direct comparisons are made (their value is somewhat questionable), this means that an experienced blind person can perceive differences in distance better than a person using only one eye. Visual thresholds of this sort are, however, obtained without head movement, and oscillations of the head were extensively used by the subjects of this research.

In the experiment just described we held size constant and placed a single disc at varying distances from the subject. To test for size discrimination, these conditions are reversed. In this case we must hold distance constant and vary the absolute size of the targets used as stimuli. This was accomplished by using seven painted wooden discs, like the disc employed for distance perception. The standard stimulus was 9.4 inches in diameter, and the comparison stimuli ranged from 5.8 to 12.0 inches. The entire experiment was performed three separate times for each individual at distances of 12, 18, and 24 inches. The auditory angles subtended by the discs at a distance of 24 inches, for example, ranged from 13°48′ to 28°04′, with the standard subtending an angle of 22°10′.

In any given series of 100 judgments, the standard and one of the comparison stimuli were fastened to the circumference of a 28-inch bicycle wheel, which was mounted horizontally on a level with the observer's face. The two discs were placed 90° apart on the circumference of the wheel, and perpendicular to it. By rotating the wheel, the experimenter could move either disc so as to bring it directly facing the observer. The disc which was not facing the observer was then edgewise with respect to him. As a result, it offered little or no reflecting surface. Either disc could in this way be moved into position as a target at the same time that the other disc of the pair was moved out of position. Figure 5 is a posed picture, taken outside the sound-insulated room, which illustrates this arrangement for presenting the stimuli in the test for size discrimination.

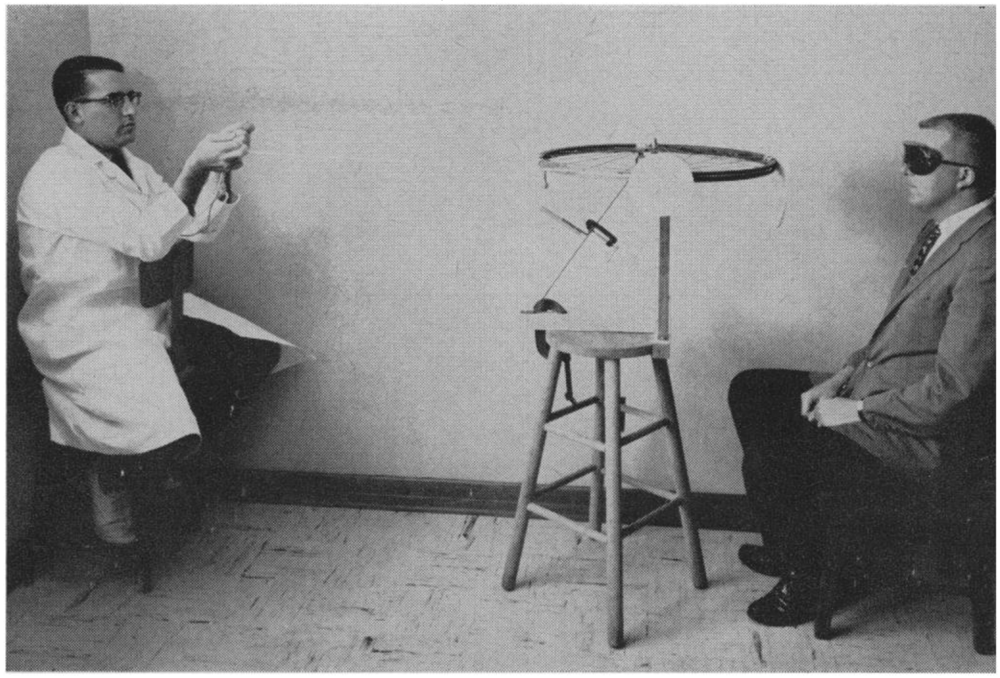


Fig. 5. The arrangement for presenting the stimuli in the size-discrimination experiment.

The general results, while not so striking as those for distance perception, are nevertheless remarkable. As an example, we present in Fig. 6 the data for one of the blind individuals (subject C). The psychophysical function is fairly good at a distance of 12 inches but becomes progressively poorer, particularly with the "L" (the larger) discs, as the distance is increased. The judgments of subject W, on the other hand, did not show this peculiar effect, and his graphs (not shown here) for all three distances were more alike, although not as good as those for subject C at 12 inches (*20*). We consider these aberrations to have been partly due to the apparatus and believe that with better instrumentation they would be less likely to occur.

Perception of Texture and Density

Sonar operators at sea have not infrequently mistaken the echoes returning from a submerged whale for those of a submarine, and Navy lore contains numerous tales of harmless cetaceans which have been depth-charged because of this mistake. Since different materials have different absorption characteristics, for sonic vibrations as well as for light waves, one wonders why the echoes returning from whale blubber should not be easily distinguished from those returning from the steel hull of a ship. The bottlenose dolphin, moreover, seems to have no difficulty in detecting the difference between a water-filled plastic bag and a food fish (*15*), and between the human hand and a food fish of the same size (*3*). Can blinded human beings similarly differentiate between targets of different materials merely by listening to the echoes they reflect?

To investigate this matter, six 1-foot discs, all with different surface characteristics, were presented in pairs to the subjects. The distance of presentation was held constant at 12 inches. The discs were made of the following mate-

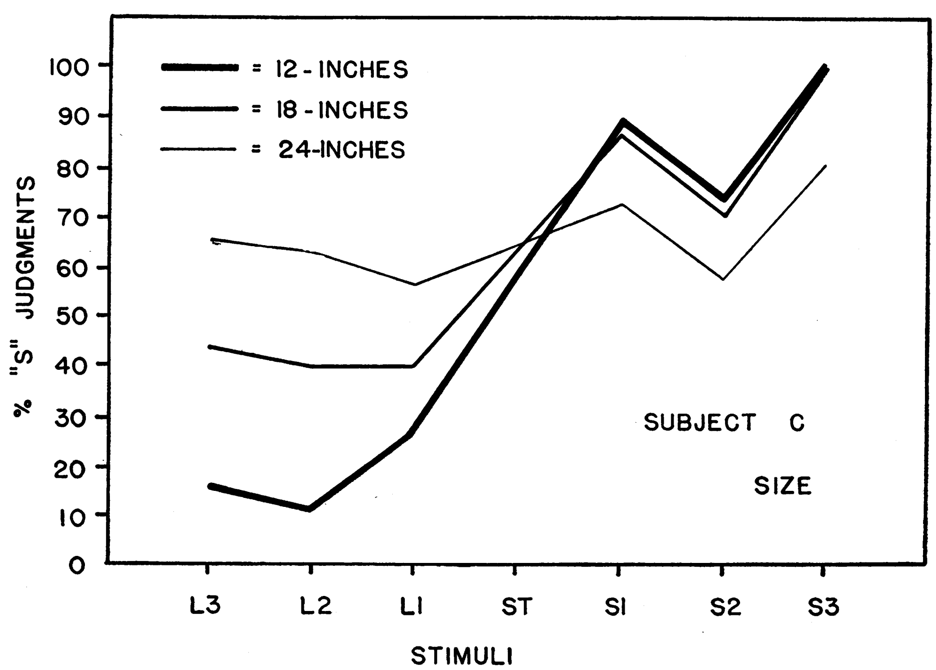


Fig. 6. Size perception for one blind observer at three different distances. The sensitivity seems to break down for this individual as distance is increased (particularly in the case of the larger stimuli), but this rule did apply for the other blind subject.

Table 4. Accuracy (percent) with which different materials were discriminated by subjects C and W.

	Velvet	Denim	Plain wood	Painted wood	Glass	Metal	Nothing
Velvet							
Denim	86.5						
Plain wood	99.5	94.5					
Painted wood	99.5	96.5	47				
Glass	99	86.5	52	54			
Metal	99.5	90.5	69	58.5	47		
Nothing	94.5	97.5	100	100	100	100	

rials: 16-gauge galvanized sheet metal; ⅛-inch glass, mounted on ¼-inch plywood; ¼-inch fir plywood, painted with sand-texture paint; ¼-inch fir plywood, unpainted; denim cloth stretched over a hoop (no backing); and velvet cloth stretched over a hoop (no backing).

Each disc was paired with every other disc by the method of paired comparisons. Each disc was also compared with nothing—that is to say, with no disc at all—to find out if its mere presence or absence was easy or difficult to detect. The discs were presented as in the size discrimination experiment (see Fig. 5), and 100 judgments per pair were made by each subject. The results for the two blind individuals are combined in Table 4.

Table 4 gives the percentages of trials in which the two subjects were correct in their judgments; a score of 50 percent indicates pure guessing or no ability to distinguish. All percentages of 59 or more in this table differ significantly from chance at the 1-percent level of confidence. In a general way, the results point to a distinction between "hard" or good reflecting surfaces and "soft" or poor reflecting surfaces. Thus it may be seen that the echoes from painted wood and glass cannot be separated. Painted wood is also indistinguishable from metal. All of the discs were easy to tell from no disc at all, although the scores are slightly lower for the softer discs than for the harder ones. Surprisingly, denim cloth and velvet can be differentiated 86.5 percent of the time.

We have here clear evidence that the echoes returned from many of these substances are sufficiently distinctive for skilled observers to identify them.

It was not at first recognized that skillful blind people who detected obstacles without a cane or other special aid were actually using the method of echo ranging or sonar, like the porpoise and the bat. For the most part, research on this matter has been qualitative or descriptive in that it sought to discover how well the blind could avoid barriers or obstacles. In the experiments described we have attempted to measure by psychophysical methods the ability of the totally blind to differentiate between stimulus targets which varied from one another in size, in distance from the observer, and in texture or absorption characteristics. The judgments of the subjects were made entirely by listening to echoes which were reflected back from the separate targets. Blindfolded subjects with normal vision acted as experimental controls.

Each observer made his own noises and used whatever natural sounds he considered best. These included talking, singing, whistling, hissing, snapping the fingers, and tongue-clicking. The method of constant stimuli (the method of constants) and the method of paired comparisons were employed to determine sensitivity. Psychophysical curves and threshold values were computed.

The distance or depth perception of one of the blinded individuals was such that he could perceive a movement of 4.3 inches of a 1-foot disc placed 2 feet in front of him. Threshold fractions for this ability averaged about 1/4 and compared favorably with those for monocular depth perception. The discrimination between objects of different sizes, with distance constant, was not so accurate but was nevertheless remarkable. The blinded subjects could also distinguish between targets of the same size which were made of metal, wood, denim cloth, and velvet. Each of these objects simply "sounded different" from the others. Objects of similar density, on the other hand—for example, painted and unpainted wood, or metal and glass—were indistinguishable. The judgments of the normal control subjects were almost never above the level of pure chance.

These unusual performances show that some blind people can observe amazingly well by means of human sonar. Future research on this question may bring to light achievements that compare favorably with those of the porpoise and the bat.

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14. These investigations were supported by a grant from the Research Council of Florida State University and by aid from the psychology department. We are greatly indebted to Mr. Stephen Feinstein and Miss Joan Helmrich for assistance in obtaining and working up the data.

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