education. If the program has the endorsement of the government, they will be ready to try it out with very little feeling of hesitancy because the teaching methods are new and different. Moreover, there is reason to hope that the interest in better science teaching which has resulted from the American experimental curricula in secondary school science will result in changes and improvements in Asia, and perhaps in Nepal, affecting the teaching of science at the secondary level. These American courses, as well as other studies (*13*), emphasize observation and experiment. We hope that a program such as the one we propose for Nepal at the elementary levels will provide a useful preparation for more formal course changes patterned on the American model. In fact, we believe that some such preparation will be found necessary if science courses based on the American experimental courses are to maintain their spirit and emphasis as they are adapted for use in Asia.

In concluding, we must emphasize that much of what has been said is tentative, based as it is on a limited pilot study. Yet the study does indicate that research of this nature can provide needed perspective for the improvement of science teaching in non-Western countries. We hope it will lead to more study and discussion, with regard both to Nepal and to other developing countries.

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Human Echo Perception

Behavioral measurements are being made of human ability to detect objects by use of echoes.

Charles E. Rice

Some bats and porpoises are known to navigate and find food through the use of echolocation, a sonar technique in which they systematically emit sounds and interpret the echoes from objects in their surroundings (*1*). It is only in the last 20 years that the auditory nature of this unusual form of environmental sensing has been firmly established. Previously, the sensory process involved had been the subject of years of heated philosophic and scientific debate. This was particularly true in the case of bats and the similar case of sightless humans. The "obstacle sense of the blind" and "facial vision" were terms often used to describe the skill with which blind persons avoided collision with objects in their paths. In 1749, Diderot (*2*), for example, published a comment about a blind man who could judge the proximity of objects by the action of air on his face. Hayes (*3*) has written a very interesting history of early scientific inquiry into the sensory basis of this phenomenon.

Measurement of the extent to which organisms can rely on sonar required controlled experiments. Griffin (*1*) and others have measured the skill of bats, and Kellogg (*4*) has brought the porpois *Tursiops truncatus* to the laboratory for the same purpose. Both of these animals have shown exceptional perceptual abilities involving the use of echolocation sonar, and certain physiological adaptations of their auditory anatomy lead us to expect that humans will be found to be much less skillful with a similar technique (*5*). Measurements of human echo perception are now being made, and a report on some findings from our laboratory at Stanford Research Institute follows.

Important Earlier Studies

It was not till the early 1940's that a group of scientists at Cornell University—Michael Supa, Milton Cotzin, and Karl Dallenbach (*6*)—began a series of laboratory experiments in which all sensory channels except for the auditory channel were found to be irrevelant to "facial vision." They concluded that the perception of echoes reflected from objects approached provides sufficient information for detection and avoidance of many of these objects.

Kohler (*7*) demonstrated individual differences in ability to use echoes in this way and attempted to relate echo perception to human psychoacoustics. His was also the initial attempt to stimulate development of sonar-type mobility aids for the blind.

More recently, Kellogg (*8*), after conducting many experiments to define the echolocation ability of the Atlantic bottlenose dolphin, became interested in the similar sonar of blind persons. A major contribution of Kellogg's work was the demonstration that traditional psychophysical techniques can be used to obtain quantitative measures of this normally ignored ability. Making use of these psychophysical methods, my associates and I have conducted experiments designed to specify some of the characteristics of the human sonar

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system and to show the influence of certain variables on echolocation. In the simplest analysis, these variables can be divided into variables of the acoustic signal, of the physical environment modifying that signal, and of the receptor system receiving the echo.

Signal Variables

Although several investigators (*7, 9*) have demonstrated that ambient noises are sufficient to yield some echo cues, Kohler found that echo information is greatly enhanced if the subject intentionally emits a signal which will echo from objects.

Various signals have been used in earlier studies of human echolocation abilities (*7, 8, 10*). These signals have varied with respect to site of origin, duration, frequency components, intensity, method of emission, and repetition rate. In many cases, characteristics of bat sonar or of electronic radar systems have led investigators to use repeated frequency-modulated signals of short duration. In some cases, as in signals developed by Kay (*11*), the signals are ultrasonic, aspects of the echoes being brought into the audible frequency range electronically. Kohler made some preliminary empirical studies of electrically generated signals with his test subjects, but many investigators have designed what they feel is an ideal signal without prior empirical study of the extent of human ability to use the echoes produced.

An alternative approach is that of allowing the subject to develop his own vocal and oral sounds in order to explore nearly unlimited variety of possible signals. Thus, subjects can efficiently "try out" a number of emissions until the one is found that returns an empirically effective echo. This approach takes advantage of the possibility that some people may be able to use one type of signal better than another, and also of the fact that blind subjects, in particular, may have developed and used signals of their own over the years.

The first approach allows one to equate the signal variables for all subjects. The alternative method allows subjects to choose what they consider an effective signal but prevents the experimenter from determining whether differences in skill are due to differences in signal or to subject variables.

Consequently both methods of signal selection have been used, and the results compared.

In our first studies, therefore, subjects were instructed to make any oral sound they wished until they found a signal which brought them good echo information. Once the subject had decided upon a signal (usually after a few half-hour sessions), he was required to use this same signal in all tests unless otherwise instructed.

A detailed description of the subjects, apparatus, and procedures used in the original study in which subject-emitted signals were used has appeared elsewhere (*12*). Figure 1 shows subject D.B. in position for making a "yes" or "no" judgment as to the presence or absence of a target in this echo-detection task. This experiment established a measure of the minimum size target detectable by each of five blind subjects at several distances. Targets were presented 100 times in random order with an equal number of no-target trials. Retests on this same task were made to verify the results and to determine whether manipulation of certain variables affected performance. These retests indicated, for example, that no improvement in performance occurred over a 2-year period.

The subjects used a variety of signals, and there were individual differences in performance. This is illustrated in Fig. 2, which shows the percentage of "yes" responses for a series of targets of different areas and presented at several distances (the areas of the targets were increased by equal steps). It is interesting to note that each subject tended to maintain his position in the group throughout the experiment.

Each of the five subjects (and subsequent blind and sighted subjects) has selected either a form of "hiss" or a tongue "click" as his signal. In this initial study, the five were permitted to continue or repeat their signal as often as they wished, but were required to respond within 10 seconds of the "ready" signal. In order to evaluate the relationship of the preferred signal to ability at the task, an experiment was then performed with two pairs of subjects, one pair using a hiss-type signal and the other using

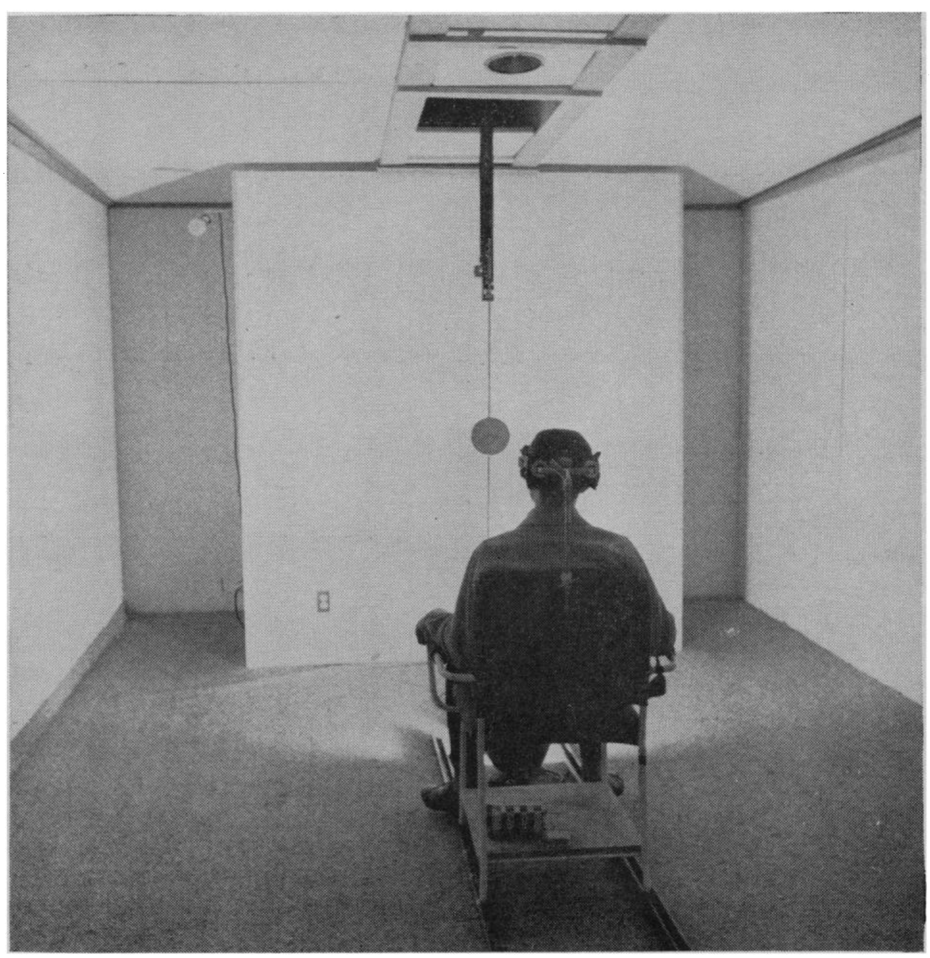


Fig. 1. Subject, apparatus, and target in position for the size-threshold experiment.

tongue clicks. In each pair, one member was superior to the other in his ability to detect small targets. Members of the "hiss" pair were asked to change their signal to a tongue click, and members of the "click" pair were asked to change to a hiss signal. It was hypothesized that, if one signal were superior to the other, significant change in performance would be revealed by the comparison. As Fig. 3 reveals, there is no convincing evidence of such superiority. It also appears that the signal chosen by the subject suits his needs as well as, or better than, the alternative signal. After initial training with the nonpreferred signal, the time from initial sound to response varied from 3 to 10 seconds and was correlated with target size. Practice effects could not be equalized precisely, but when the subjects had achieved what was believed to be asymptotic performance with the nonpreferred signal, the final measurement series was commenced. It appears that some decrement in performance is the rule when the signal type is changed, but the subject can still perform reasonably well. Significant and usable information can, therefore, be obtained by subjects using signals of either type.

To carry the comparison of these basic signal types a step farther, and also to assess differences in echolocation ability among individuals in the group, two experiments were conducted in which the performances of all subjects were compared, the signal being uniform throughout. In the first experiment an electrical circuit was developed by means of which a click signal could be produced from a speaker 7 centimeters in diameter. This speaker was installed in a cylinder 12 centimeters long and mounted in front of the subject at mouth level. It was aimed at the fixed target position. The electronic clicker, which emitted a signal four times per second, produced energy throughout the audible spectrum, and was relatively uniform from click to click. The procedure described above for detecting minimum target size was used, with the target at a distance of 91 centimeters. The subject could initiate and terminate the clicking by means of a hand-held push-button switch.

In the second experiment the subjects, apparatus, and procedure were the same as in the first except for the fact that the speaker emitted a continuous white noise.

In Fig. 4 the results of these experiments are compared with results of the original experiment in which the subjects used preferred signals with a target distance of 91 centimeters. It does not appear that the use of the artificial sound source had an enhancing effect on performance. If a generalization can be made, it is that the subjects tended to do as well with the artificial sound which mimicked their preferred sound as they had done with the preferred oral signal. Subjects S.B., S.K., and J.W. were the least able to use artificially produced sound of the nonpreferred type. The others performed about equally well with arti-

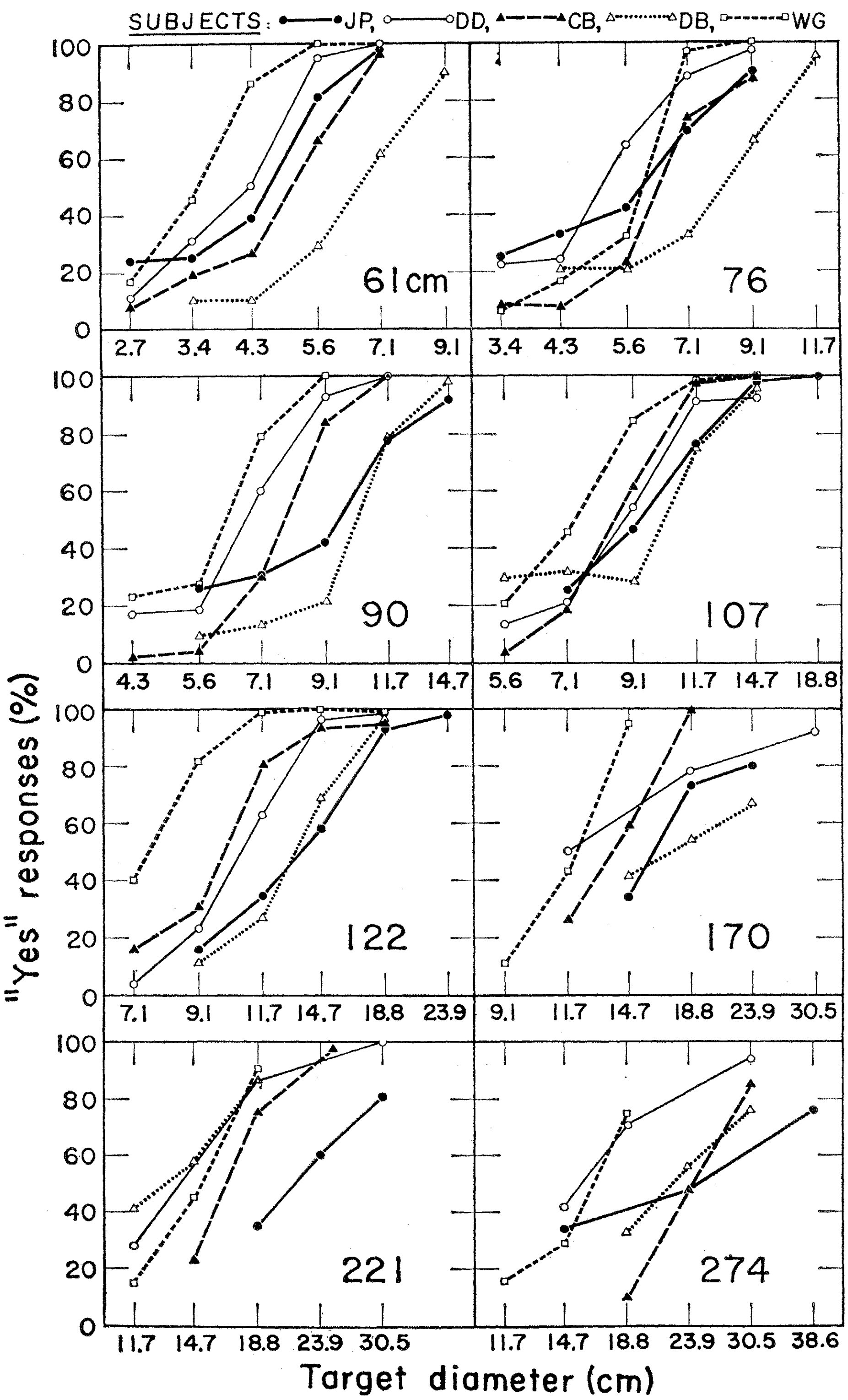


Fig. 2. Percentage of "yes" responses for each subject at each distance in the size-threshold experiment.

ficial and natural signals. No dramatic changes in performance resulted from standardization of the signals, and it seems logical to conclude that, since signal and target variables were held constant, the differences in performance were due to differences in echo perception among individuals.

Usable Signals

The physical characteristics of the signals used by the subjects must be described if signal variables are to be related to behavioral data. These physical properties, when related to the psychoacoustic limitations of the human auditory system, define certain limits for echo-detection ability.

The sensitivity of the human ear, for example, is bounded by a sound pressure level of about 0.0002 dyne per square centimeter and a sound intensity 130 decibels above that reference level.

We know, too, that the intensity of a sound decreases as a function of distance from the source. In echolocation, any signal which is emitted must travel to the echoing surface and return; hence, the intensity of the echo to be detected will be considerably less than the intensity of the outgoing signal. If the sound is radiating uniformly in all directions, its intensity will vary inversely as the square of the distance from the source. Hence, the subject's ability to detect the echo of a constant signal will decrease as distance from the echoing surface increases.

The velocity of sound may be assumed to be approximately 344 meters per second. The duration of the emitted signal and the distance of the echoing surface therefore determine whether, or how much, the outgoing pulse overlaps the returning echo. This is an important factor in determining whether the signal-to-noise ratio will favor detection, and whether the human auditory system will be sufficiently sensitive to detect the echo.

Another acoustic characteristic which limits the echo information received is the spectrum of the signal. The higher the frequency of the signal, the shorter the wavelength, and the shorter the wavelength, the better the reflection of sound energy from the echoing surface.

Assuming that the human ear is capable of hearing sound of frequency as high as 15 to 20 kilohertz and that an object must have a diameter equivalent to at least a single wavelength in order to reflect a usable echo, we can hypothesize a minimum size for a target detectable by a human subject. This minimum target diameter would be 17 to 23 millimeters; subjects with superior skill do detect a target of 27-millimeter diameter at a distance of 61 centimeters. No formal

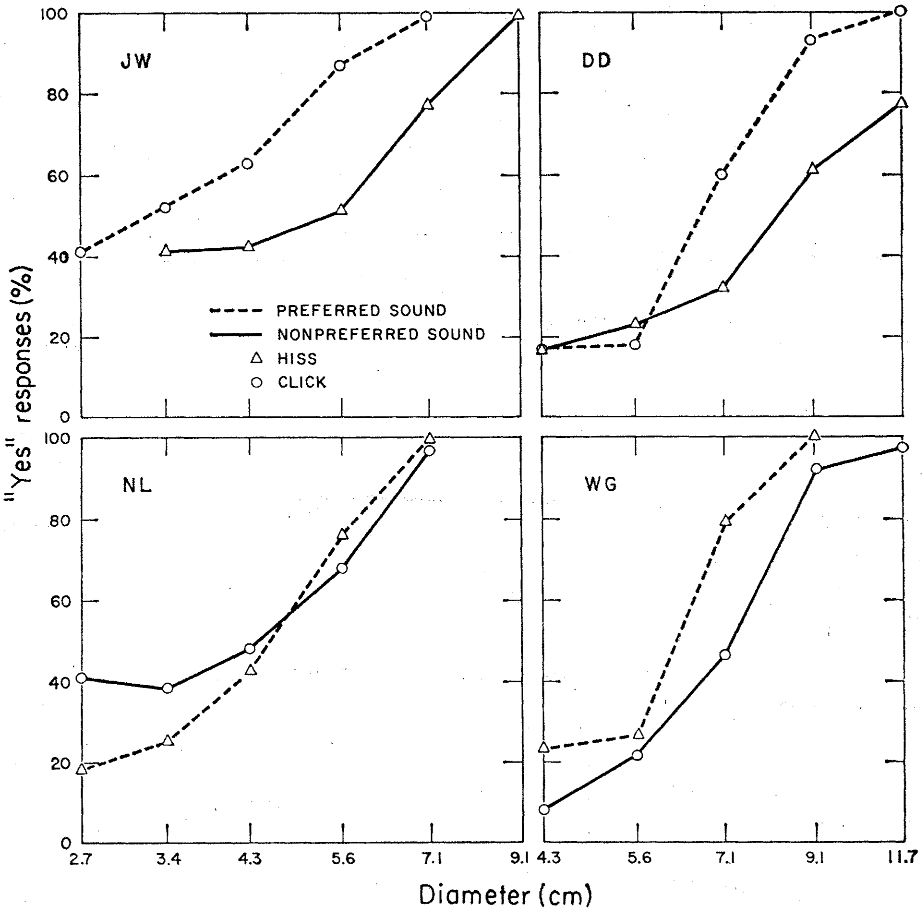


Fig. 3. Performances of four subjects (J.W., D.D., N.L., and W.G.) using the preferred and nonpreferred oral signals.

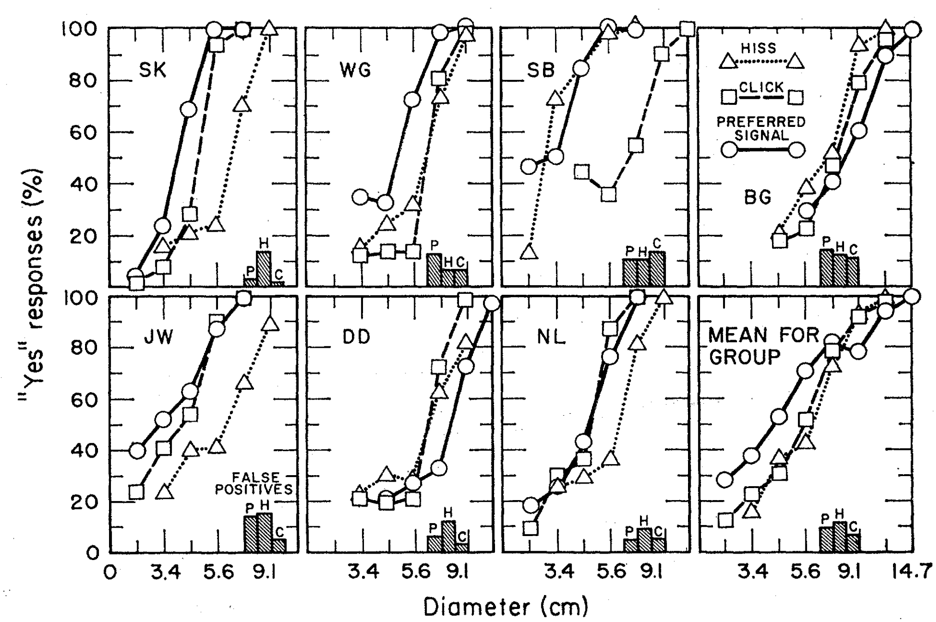


Fig. 4. Comparison of six subjects' performances with preferred oral signal, electronic hiss, and electronic click signals.

test of this hypothesis has been made, but our results seem to indicate that the performance of human subjects is limited by the diameter-to-wavelength relationship. The 27-millimeter wavelength would be associated with a signal frequency of about 12,500 hertz —within normal hearing range for those subjects who detected a target of 27-millimeter diameter.

It may be of interest to look at some of the physical characteristics of the signals developed and used by the subjects of our experiments. Spectrograms representative of the two types —an elongated hiss and a tongue click—appear in Fig. 5.

The spectrogram is a graphic representation of the spectrum and duration of an acoustic signal. The horizontal dimension represents time, and the vertical dimension shows the frequencies. Intensity appears as relative density or darkness of the record. The frequency range of the spectrograms shown was from 170 hertz to 16 kilohertz, and, as may be seen, the signals covered this full range. The duration of a tongue click is about 0.025 second, hence, in most instances represented in Fig. 5, the echo returns before the click is finished.

However, the data showed no difference between performance when considerable signal-echo overlap occurred and performance when there was no overlap. It appears, therefore, that the subject is capable of using the echo from the click signal whether or not it overlaps the signal.

The hiss signal, it may be observed, has the essential characteristics of a white noise, with frequency components covering almost the entire audible spectrum. Since the echolocating technique with this signal involves emission of the signal for as long as 5 seconds at a time, the overlap of echo and signal is virtually continuous. Performances of click-using and hiss-using subjects (for example, the performances of W.G. and D.D. in Fig. 2) are comparable. Apparently either signal is sufficient to provide information on the presence or absence of an object, under the conditions of this experiment.

Although these physical principles governing sound waves determine to some extent the requirements for an efficient echo-detection signal, it is the entire auditory system of the organism which plays the primary role. This system sets the limits on how well the echo information arriving at the ear can be used.

Environmental Variables

When sound energy strikes a physical object, there is some change in the characteristics of the sound. It is absorbed or reflected, or both, in varying degrees. The amplitude, frequency, and direction of the sound are modified by the collision, and these factors determine what echo information the auditory receptor will receive. In addition, an infinitely varying world of sound surrounds the receptor. These environmental factors which influence human echo perception determine the usefulness of this means of sensing objects at a distance; as has been pointed out elsewhere (*13*), a laboratory demonstration of echo-locating ability in humans is quite different from the practical use of such ability in the cacophony of the real environment.

In our experiments we have attempted in most instances to hold the environmental variables constant while exploring the emitted signal or the subject variables. In one study, however, the effect of a variation in an echoing surface was measured (*14*). In this study, interest was focused on the relationship of target-surface geometry to detection ability. While holding the area constant at approximately 31 square centimeters, we varied the shape and the dimensions of the target. A circular target, a square target, and two oblong targets were used, at a distance of 122 centimeters. The oblongs had side-dimension ratios of 4 to 1 and 16 to 1, respectively, and were presented in both vertical and horizontal orientation. Each target was

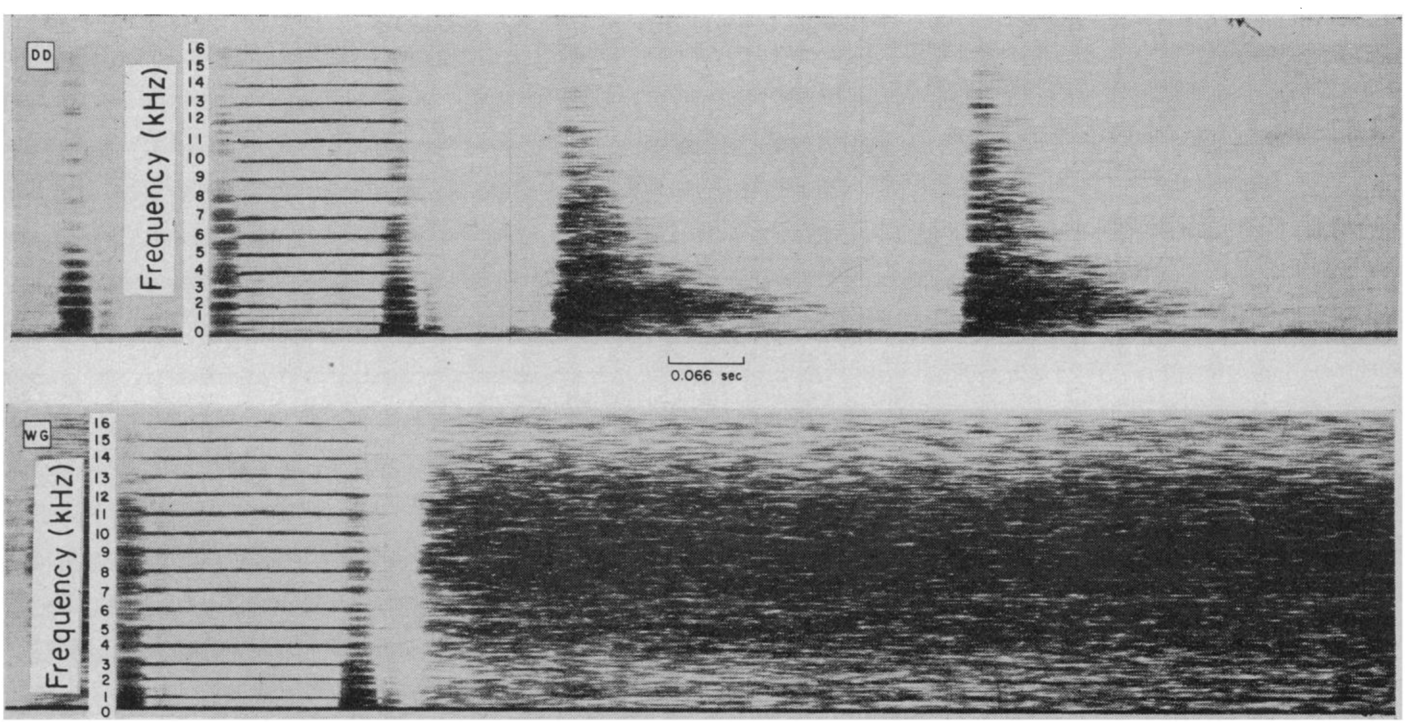
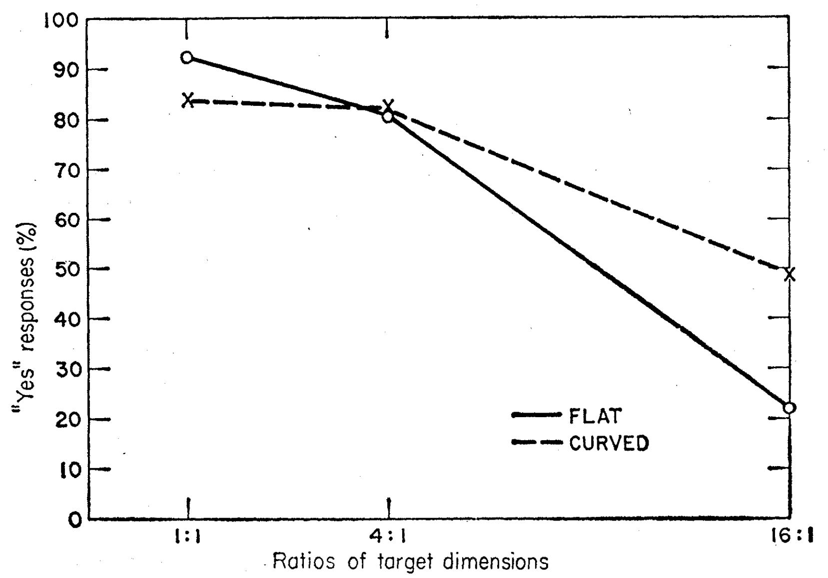


Fig. 5. Sound spectrogram of typical self-generated sonar signals used by subjects in these experiments.



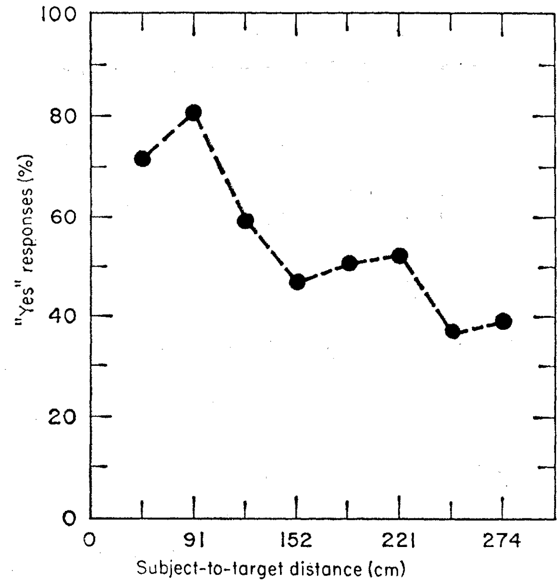


Fig. 6 (left). Effect of target dimensions on detection. Fig. 7 (right). Effect of changes in subject-to-target distance on discrimination of circle, square, and triangle. Each point represents 75 trials with each of the three targets.

made of flat sheet aluminum 1.3 millimeters thick and was presented 100 times in random order, along with 100 no-target trials, to each of the four subjects. The subjects were asked to respond merely "yes" or "no," indicating auditory detection or nondetection of a target. The same presentation procedures were used as in the experiments described above. It was found that, even though the target area was constant, the shorter of the two oblongs (4:1) was detected less often than the square or circle, and the longer oblong (16:1) was detected less often than any of the other targets. Horizontal or vertical orientation made no difference in the percentage of "yes" responses. It was hypothesized that this decrease in number of detections was due to a loss of echo intensity. There is a specular reflection of energy away from the subject's ears as the angle at which the signal strikes the target increases. In order to test this hypothesis, the oblong targets were bent to a radius extending from the center of the subject's head to the face of the target, and the tests were made once more. Bending the target so as to focus the echo back toward the ear resulted in an increase in the number of detections of the longer of the two oblong targets by a statistically significant amount ($p<0.01$). Figure 6 illustrates this effect. This study, therefore, demonstrates the importance of the geometry of the echoing surface in the recovery of echo information.

The next question is whether qualitative attributes of echoing surfaces can be detected by the human ear. Can the ear tell the difference between smooth and rough, between flat and curved, or between wood and metal surfaces? This type of sonar discrimination ability has been attributed to bats (*15*) and porpoises (*4*). Unlike Dolanski's subjects, Kellogg's subjects could differentiate between materials of different quality. These discriminations in Kellogg's study may well have been based on echo-intensity cues due to different reflectance and absorption characteristics of the targets. Qualitative differences would be recognizable on the basis of a distinctive signature or sound which could be distinguished from nearly all others, much as a familiar word can be recognized whether it is spoken loudly, softly, quickly, or with an accent. Qualitative discrimination involves, then, formation of an auditory concept which is akin to the constancy phenomenon of the visual modality. In an interesting introspective report (*16*), an observer tells of being able to make many qualitative distinctions with the echo information from Kay's mobility aid. Dreher (*17*) has shown that the distinctive spectral characteristics of several target configurations can be graphically described.

Our closest approximation to this task has been a preliminary study of shape discrimination. In this experiment subjects are presented with targets of equal area and of three different shapes—circle, square, and triangle. To date, four subjects have been able to discriminate among the three targets with 80-percent accuracy. Others who have worked at the task have been able to discriminate between two of the targets but not among all three. Subject W.G. has been tested under a number of conditions to determine whether an auditory concept of the shape has been formed; this seems not to be the case. Figure 7 illustrates, as an example, the effect upon shape-discrimination performance of increasing the distance between subject and target.

This, it should be remembered, is a preliminary result, presented here only as an indication of the more qualitative discriminations hypothetically possible.

Individual Differences

Analysis of human echo-perception abilities reveals differences in performance which are related not to differences in signal or environment but to variation among individuals. These may be differences in the auditory portion of the central nervous system—variations of pinna configuration, of ear separation, of attention, of motivation, of intelligence, or of personality. Experience and learning, as determined by the length of time the subject has been blind and the amount of practice he has had at the task, may also contribute to differences in demonstrated ability.

Earlier work (Kohler's, in particular) has indicated that being able to

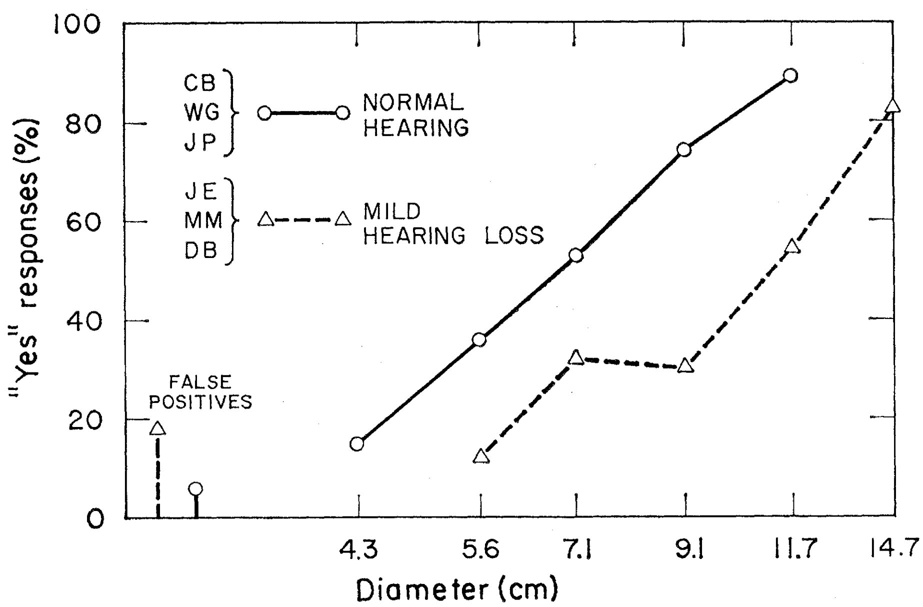
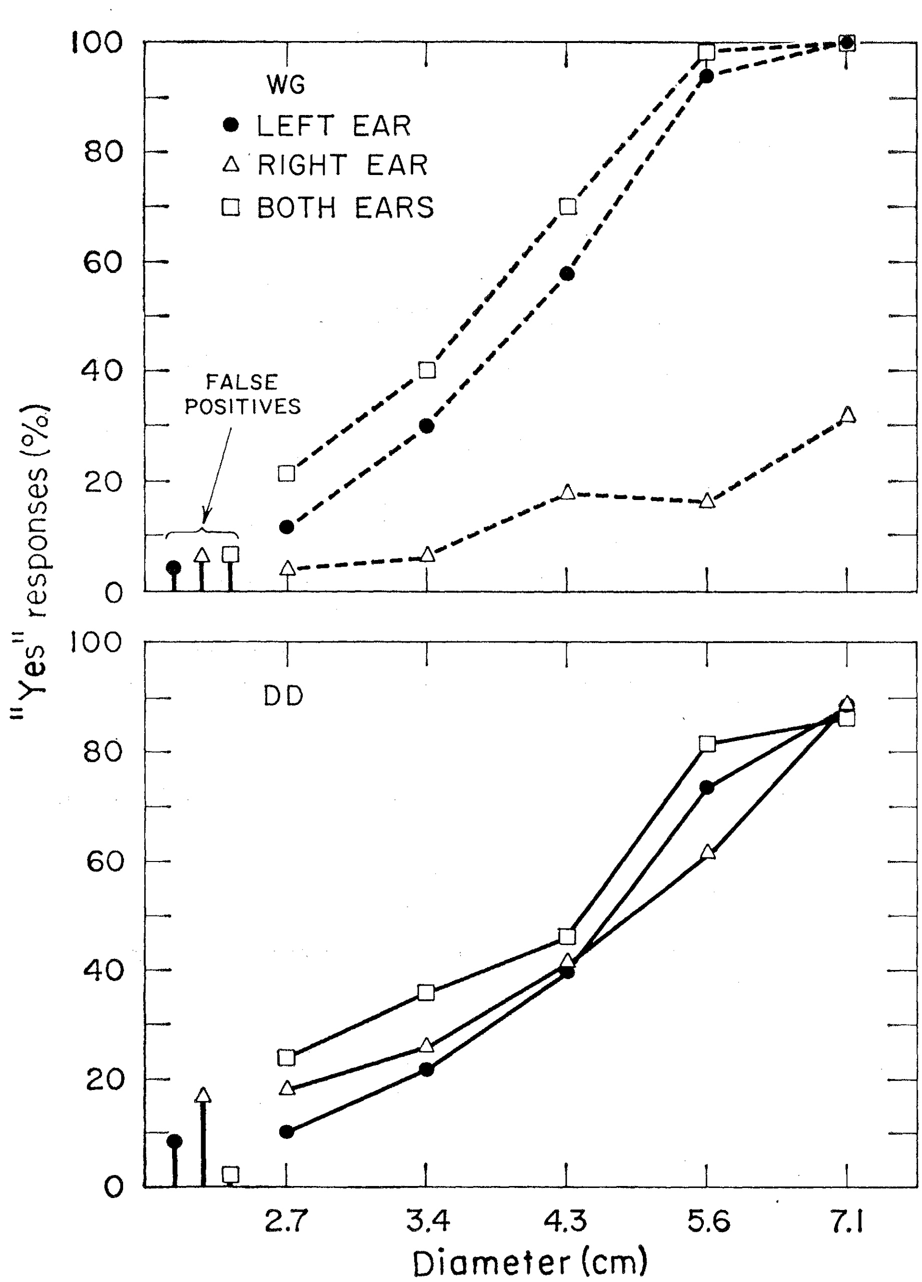


Fig. 8 (top left). Comparison of performances of subjects having normal hearing with those suffering mild hearing loss.



hear slight changes in a sound is more important to the perception of echoes than good absolute hearing sensitivity is. All subjects tested in our laboratory have undergone routine audiometric examinations at a speech and hearing clinic under standardized conditions. These examinations covered a frequency range of 250 to 8000 hertz. Sensitivity norms for higher frequencies have not been standardized because of technical problems. The audiograms of all but three of the subjects of our studies showed hearing to be within normal limits up to a frequency of 8000 hertz. In subjects D.B., M.M., and J.E., moderate sensorineural hearing loss was found. In Fig. 8 the mean performance of these three subjects on the minimum-size detection test is compared with that of three subjects with normal hearing. The data seem to indicate that, for this type of task, relatively good hearing is necessary for good performance. This means that, although the basic discriminations may be between two sounds audible to the subject, the relative sensitivity of the ears has a measurable effect on performance. In order to detect small targets, it is necessary to have good high-frequency sensitivity. When the signal and echo are sufficiently audible, the difference threshold factors come into play. We have not yet found either sighted or blind subjects with normal hearing sensitivity who cannot perform satisfactorily in an echo-detection test.

Binaural versus Monaural Echo-Detection Thresholds

In earlier echo-detection studies the subject has, presumably, used both ears. A number of observations of subjects engaged in echo detection, and some subjective reports, indicated to us that monaural echo detection is possible, and that, with some subjects, one ear might serve as the dominant or preferred ear in listening for target echoes. We had, for instance, noticed that J. W. directed her signal as much

Fig. 9 (bottom left). Comparison of subjects' performances with either ear and with both ears.

as 45 degrees to the left of the target in a "presence-absence" experiment. Thus, her right ear was closer to the target, while her left ear was essentially masked to the high frequencies of the target echo by her head. Other subjects reported that they felt one ear or the other played a dominant role in echo detection. To determine whether these observations could be substantiated experimentally, two subjects were tested with the size-threshold experiment at a distance of 61 centimeters. All apparatus and experimental methods were the same as those in the original study except for the fact that one of the subject's ears was effectively masked from ambient sounds by means of a headphone (Sharpe HA-10). Each subject was given 50 trials with each target and 50 trials with no target, in random fashion. The targets used were those of the original tests. Comparison measurements were made with the subject using both ears, then the left ear only, and then the right ear only. Since both of the subjects had had long experience at the task, it was felt that practice effects would not obscure any deficits in performance due to the monaural condition. The data obtained in this experiment are illustrated in Fig. 9, in which each subject's performance under monaural conditions is compared with his binaural performance. This experiment has been conducted with the subject's head (i) unrestricted, so that he could scan freely, and (ii) immobile; results under these two conditions were similar.

These data indicate that W.G. was severely handicapped in his ability to use his right ear. However, the audiogram for W.G. shows normal sensitivity in each ear. It seems, therefore, that the left ear must have been used as the primary source for echo perception. A possible explanation for this one-earedness may be that perception of the targets was based on echo information at frequencies above 8000 hertz and that, although audiograms for W.G. made before and after this test show excellent hearing up to 8000 hertz, his sensitivity to higher frequencies may be less good.

To a sightless person, it is as important to be able to localize the source of an echo cue in space as it is to be able to detect the presence or absence of objects. Recent experiments with four blind subjects indicate that relatively accurate localization information can be

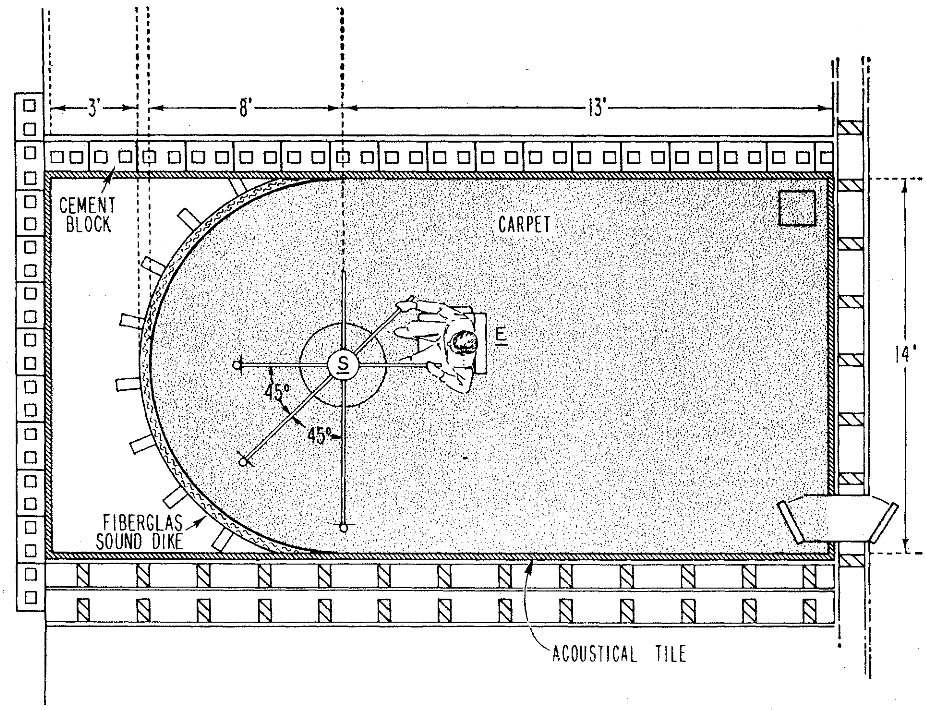


Fig. 10. Schematic drawing of laboratory and apparatus for echolocalization. (*S*) Subject sits beneath the center of the apparatus; (*E*) experimenter is located above and to the rear of the subject, and targets are presented by the arms projecting from the central axis.

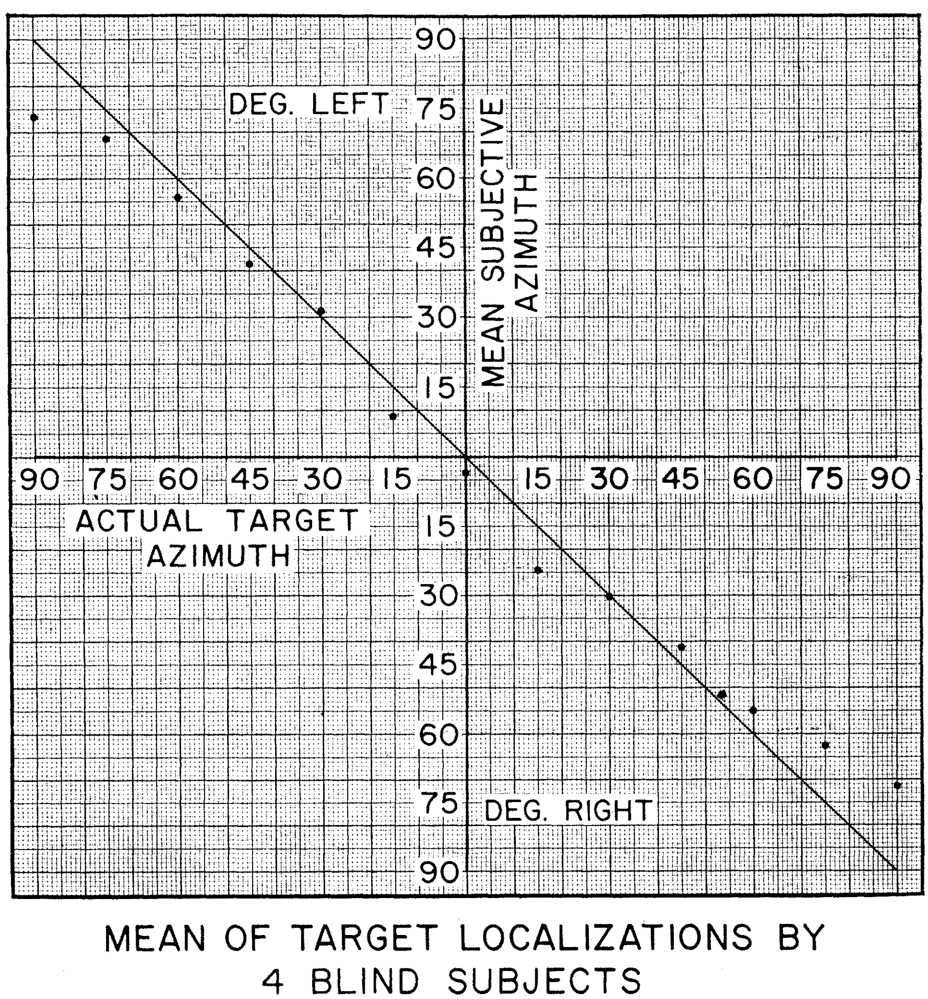


Fig. 11. Echolocalization of target of 16.3-centimeter diameter at a distance of 91 centimeters.

obtained with unaided human sonar. These studies were carried out in a laboratory containing an apparatus which made it possible to present targets at any azimuth position relative to the subject's head (Fig. 10). The subject's head and the circle on whose circumference the target is located have a common vertical axis, and rotation of either on this axis can be measured with accuracy to within a half degree. The targets are held by "arms" extending through the axis, and the subject is seated under the apparatus with his head held firmly beneath the center point. In one study, subjects were given the following instruction: "The target will be presented randomly in various positions on the horizontal plane within the bounds of 90° right and 90° left of the center position. You must hold your head stationary at 0° until you are satisfied you have located the target, then move your head until your nose points directly at where you believe the target to be. On some trials no target will be present, and in this case, simply say *no target*."

The target was then presented at the subject's ear level ten times at each of 13 positions covering the range from 90° left to 90° right in 15-degree steps. Ten no-target trials were also included in the series, and the order of presentation was random. The target, 16.3 centimeters in diameter, was at a distance of 91 centimeters from the subject. The subjects received no information regarding the relative accuracy of their head placements.

The subjects' performances are illustrated by Fig. 11. This figure represents the relationship to the subject's mean subjective judgments of the location of the targets to the actual positions. The true or objective azimuth appears as a solid diagonal line. The subjects' mean judgments for each target azimuth are shown in degrees of deviation from that line. Deviations above the diagonal are to the left of the true position, and deviations below are to the right. The overall standard deviation of judgments for all subjects was 10.1°.

The subjects had little difficulty in detecting the presence or absence of the target within the ±90° horizontal field. There was only one false judgment of "present." Near the 90-degree azimuth positions accuracy decreased and variability of judgment among subjects increased. There was a consistent tendency on the part of all subjects to underestimate the distance of the target from 0°.

The angular width of the target of 16.3-centimeter diameter at a distance of 91 centimeters is 10.2°. This means that, although the subject may not have pointed precisely at the center of the target, his judgment may have fallen somewhere on its surface. It seems fair to conclude from this experiment that, even though their signal is directed forward at 0°, these subjects can detect a target which is as much as 90° to the left or right, and point to its approximate position.

Summary

It has been shown that human test subjects have the ability, under controlled laboratory conditions, to use echoes to detect the presence or absence of targets placed before them. In addition, blind and sighted persons have been able to detect a target monaurally, to make simple shape discriminations, and to locate a target in space. Signal, environmental, and individual variability affect performance in a measurable fashion.

This research is an initial step in measuring the limits of a human being's ability to use echoes as a source of information about his physical surroundings. At this point it seems unlikely that the unaided human ear can rival the bat's auditory system for echo perception. It may be, however, that modern technology can partially bridge the evolutionary gap and bring more useful echoes to man's ear than those it now receives. Such an accomplishment would allow us to examine the extent to which man might benefit from this means of sensing his environment.

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18. I am indebted to S. Y. Bell and B. J. Gilbert for their assistance in gathering the data presented here, and to S. H. Feinstein for his help and participation in every phase of the project. This work was wholly supported by grant NB-04738 from the National Institute of Neurological Diseases and Blindness.