Echo Ranging in the Porpoise

Perception of objects by reflected sound is demonstrated for the first time in marine animals.

W. N. Kellogg

It has long been known that bats orient themselves in flight by the process of echo ranging or echolocation. That is, they emit a series of short high-frequency sound pulses, the echoes of which, upon their return to the bat's ears, are the means by which it avoids colliding with objects while in flight. An analysis of echo ranging in the bat undertaken by Griffin (*1*) indicates that bats may even find the flying insects which they eat in this manner. The basic principle behind the process is the same as that of Navy sonar and of the marine Fathometer or echo sounder.

That animals of the sea, especially the great whales and the porpoises, may employ a similar method to avoid colliding with objects in their pathway—as well as with the ocean bottom—has often been suggested but has never been conclusively demonstrated. Yet it is known that some of the dolphins and certain of the larger whales make many underwater noises (*2*). To date, these sounds have perhaps been most successfully studied in the case of the shallow-water porpoise, or bottlenose dolphin, *Tursiops truncatus* (Montagu). This animal, it should be noted, belongs to the order of Cetacea, suborder Odontoceti. It is one of the smaller of the toothed whales, of which the giant sperm whale is the largest representative. Kellogg, Kohler, and Morris (*3*) have made acoustical analyses of some of the submarine noises produced by *Tursiops* and have published a preliminary, although incomplete, frequency spectrum describing one class of sounds emitted.

Such facts as are at present available indicate the following:

1) The underwater noises made by the bottlenose dolphin satisfy fully the necessary acoustical and temporal requirements for echo ranging in water. Those of the short-pulse variety occur in trains or series, the individual pulses of which have a duration as short as 1 millisecond (*3*). These trains of repeated sound signals, like the cries of the bat, are particularly well suited to the production of a continuous series of echoes. In general, the pulses are complex in frequency pattern and contain many ultrasonic vibrations (*3*, *4*). Although high frequencies are by no means essential for echo ranging, such frequencies would be particularly useful under certain conditions—for example, when there is a residual background of water and wave noise.

2) The acoustic receptor of the Odontoceti is remarkably well adapated for responding to sound vibrations in water. Its structure alone suggests a kind of supersensitivity to sound (*5*). Moreover, observations of the reactions to water-borne noises made by wild or noncaptive porpoises, such as the reactions reported by Fraser (*6*) and by Howell (*7*), imply that the sense of hearing in these animals is very acute indeed. So far as is known, however, the only extensive tests of hearing on these cetaceans are those attempted by Kellogg and Kohler (*8*) and by Schevill and Lawrence (*9*). The results show that *Tursiops truncatus* is capable of reacting to sound vibrations, in water, at least as high in frequency as 80 kilocycles per second—or two full octaves above the upper frequency threshold for hearing in man.

There seems little reason to doubt, therefore, that *T. truncatus* both emits and can receive sound vibrations in water which possess the necessary characteristics for echolocation. It may consequently be said to possess an echo-ranging or a sonar system.

3) But even though this animal appears to have a kind of sonar system, there is as yet no direct evidence that he actually uses it as such. To investigate this matter further, it now becomes necessary to test captive porpoises for the avoidance and location of objects in water, after vision has been experimentally eliminated. This is, in fact, the object or purpose of the present research program. This article summarizes a series of investigations on underwater echo ranging conducted at the Marine Laboratories of Florida State University, 43 miles south of Tallahassee on the Gulf of Mexico (*10*).

Subjects and Equipment

The subjects were two bottlenose dolphins donated by the Marine Studios of Marineland, Florida, and transported 260 miles by truck to the university's laboratories. They were between seven and eight feet in length, and each was estimated to have a weight of around 300 pounds.

Although these animals are known to be both playful and intelligent (*11*), there are nevertheless marked variations in the behavior of different individuals. In the case of our own two subjects, for example, the male, a young adolescent, appeared to be quite dependent upon the more mature female and swam immediately to her side in times of stress or excitement. The female, in turn, displayed a certain reserve or sophistication by withdrawing, of her own choice, from active participation in two of the studies to be reported. As a consequence, the tests in two of the echo-ranging situations were confined to the behavior of one animal alone. In the remaining situations, both individuals took part. The animals were given the names of Albert and Betty.

The observations were made in a specially dredged pool or enclosure where the porpoises were maintained (*12*). The surface dimensions of the pool were 55 by 70 feet, and the depth was 5½ feet at low tide and 7 feet at high tide. The sides and bottom of the excavation were of soft marl or muck, which produced a poor reflecting surface for underwater sound signals. This material served, therefore, as a kind of natural baffle; its damping effect upon audio vibrations was excellent for studies of echo ranging. The pool was connected to the nearby waters of Alligator Harbor through large concrete pipes which permitted a free tidal flow both into and out of the enclosure. A 30-inch boardwalk was built around the bank at the water level, and the land area nearby was fenced off some distance back from the excavation.

A natural advantage of this testing environment was the turbidity or opacity of the water. Shoal water in this part of

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the Gulf is generally brownish during the warmer months but clears somewhat during the winter. In addition, the mud in the pool itself was continually stirred by the swimming of the porpoises, and this reduced even further the penetration of light. Regular tests of the degree of light penetration were made with a Secchi disc, and the findings were confirmed by transparency measurements with a photoelectric colorimeter. The results showed the light penetration to be as low as 10 inches in some instances, although the average penetration was closer to 20 inches. Harmless dyes were available to reduce the underwater visibility even further should this become necessary, but these were never used except in an exploratory way. The possibility that the porpoises could locate objects in the water by vision was minimized, therefore, by this turbidity.

To facilitate the lowering of underwater gear into the water, a network of horizontal wires and cables, supported by rows of small telephone poles on the bank, was stretched across the entire area of the pool about 15 feet above the water. This network was a permanent installation and was used for supporting various sorts of running tackle, which could be manipulated by assistants from the shore. With suitable rigging of this kind, one or more objects could be lowered into the water or removed from it at any desired place or places. A heavy crane mounted on a short dock protruding into one end of the pool took care of unusually heavy equipment.

The electronic accessories used in this work included several varieties of hydrophones (or underwater microphones), a heavy underwater transducer (or speaker), preamplifiers, amplifiers, oscilloscopes and oscilloscope camera, tape recorders, and air speakers. These devices were used (i) for listening to the submarine noises made by the animals while they were being tested, (ii) for recording and photographing some of these sounds, and (iii) for projecting back into the water to the porpoises the recordings of their own noises made while they were performing at echo-ranging problems.

Reactions to Submerged Targets

In the wild or natural state, *T. truncatus* catches and eats live fishes, but in captivity it must learn to eat dead (although fresh) fish. With practice it can be trained to eat from the hand. Suppose that a test or "target" food fish is thrown into the pool in such a way as to strike the water 30 feet or so from the porpoises' positions. If the test is to be critical, the animals should not be able to see either the fish in the air or the motions of the thrower. The instant the bait enters the water, both animals immediately turn and race toward it at maximum speed, although before they can arrive at the spot, the fish, if fresh, will have sunk beneath the surface. The bait is by then not visible to human observers on the bank or to the animals, yet one or the other of the porpoises never fails to retrieve it and usually surfaces almost immediately with the fish in its mouth. The whole procedure takes but a few seconds. There is no exploratory or searching behavior whatever.

What, then, is the sensory mechanism for accomplishing this trick? Obviously it cannot be a visual mechanism in such turbid water. It cannot be an olfactory mechanism, for the sense of smell does not exist in these animals (*13*). The olfactory bulbs are missing altogether, and the nostrils or blowhole is closed during submersion. Gustatory reception seems highly improbable, since the chase and seizure are much too fast for any tasting to take place. The response is like that of a dog picking up a stick on the run. There remain the tactual and temperature senses, and audition. We are forced to infer by the process of elimination that the acoustic receptor must be the sensory channel which is employed.

A deduction of this kind is confirmed by underwater listening to the animals' sounds as the chase takes place. Although porpoise sound signals may be entirely absent before the target fish strikes the water, the noise of its splash produces a torrent of sputtering sound pulses as both animals dash toward the target. When the seizure is complete, the sounds again subside.

To investigate this phenomenon in a more systematic way, the following tests were conducted:

1) Objects of various sorts were thrown or lowered into the water so as to make a splash upon entering. These included BB shot, pebbles, fishes, and 4-foot poles. Such objects also served as echo-ranging targets after submersion.

2) Streamlined or "teardrop" objects were silently lowered into the water without surface noise, yet they served, upon submersion, as targets for reflected sound waves.

3) Surface splashes alone were produced, but no underwater target was furnished. This was accomplished in several ways, although most effectively by dropping water in measured quantities upon the surface of the pool.

The major results obtained from these tests are enumerated below:

1) If the pool was perfectly quiet, even a single BB shot tossed into the water would elicit an underwater beaming response on the part of the porpoises.

2) Water dropped upon the surface which created a splashing noise sufficiently different from the background noise to be perceived was also followed by bursts of exploratory sound pulses, although these were likely to be of only momentary duration. A single drop of water from a medicine dropper did not cause enough surface noise to elicit this reaction. Under favorable conditions, however, a half-teaspoonful of water dropped from a height of 5 or 6 feet would elicit exploratory sound pulses. The splashing of a stream of water from a hose did the same thing. But since no echoes were returned after the porpoises' original sound bursts, the pattern of pulse signals in these cases was no more than exploratory and ended after a single burst.

3) A solid object immersed with complete quietness, on the other hand, produced no echo ranging until the animals happened to make sporadic exploratory ranging signals. A delay of 10 or 15 seconds might therefore result after a streamlined target had been lowered in this manner. Yet if the same target was dropped with a splash, this was at once followed by a continuous sound pattern. The splash appeared to serve as a cue for the production of the sound signals, and if echoes were returned from the original burst, the beaming continued.

The behavior of Albert, who learned to take fish from the hand (Betty would never consistently do this), was particularly significant in this connection. It was never necessary to signal or call the porpoise when a fish was inserted into the water—even from behind a screen which concealed all movement from the air. During feeding he would make occasional exploratory bursts of sound pulses which might be compared to "glancing" or "looking" in terms of vision. These bursts were usually from 1 to 2 seconds long and occurred every 10 seconds or so. He appeared to be "searching" for the fish. As soon as the fish was submerged (or as soon as the beaming signals produced echoes), the pattern of sounds would change. Discrete bursts of sound pulses would now be separated by intervals no longer than a second or two. As the porpoise moved toward the tar-

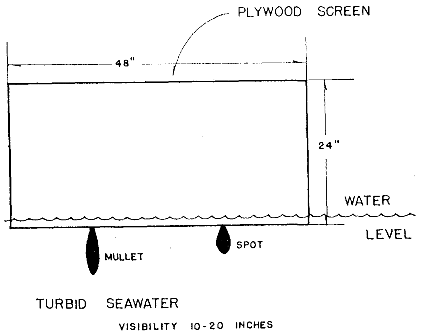

Fig. 1. Arrangement for presenting the stimuli in the fish-discrimination experiment. On any given trial, a spot (the preferred fish) and a mullet (the nonpreferred fish) were lowered simultaneously into the water from behind the plywood screen. The spot projected approximately 6 inches below the screen, the mullet 12 inches. A trial began when the fishes were submerged and ended when the porpoise took or touched either fish. The positions of the "positive" and "negative" fishes were randomly rotated from trial to trial.

get, the intervals between bursts were eliminated altogether.

While making these sounds and approaching the target, the animal would continually oscillate its head or reorient its body from right to left through an arc of perhaps 10 degrees, as a human being might when employing binaural localization. If the target fish was moved laterally under the water as Albert approached, the porpoise immediately turned so as to keep the stimulus in his sagittal plane, continually making small head oscillations at the same time.

Avoidance of Obstacles

The ability to avoid submerged objects while swimming was examined in these animals by immersing a series of obstructions which completely bracketed the swimming area. The obstacles used in these tests were light poles or posts 52 inches long. They therefore subtended most of the vertical distance between the surface and the bottom. The poles were made of galvanized sheet metal and were triangular in cross section, each side being 2 inches wide. Thirty-six of these poles were suspended over the water by rigging attached to the overhanging cables and lowered simultaneously by assistants at a predetermined signal. The poles were arranged in a regular geometrical pattern, the rows and columns of which were 8 feet (about one porpoise length) apart.

Since these obstructions were of metal and were suspended freely from above, they were extremely sensitive to contact stimuli. If touched or struck lightly either in air or in water, they gave off a metallic, bell-like ring or ping. Metallic noises of this sort made under the water could be heard by means of the hydrophone and regular underwater acoustical gear. They could also be recorded on magnetic tape along with porpoise sound signals. The metallic sounds served therefore as a means of automatically recording the collisions which the porpoises made with any of the submerged obstacles.

In the first 20-minute session of this sort there was a total of four collisions for both animals. So far as we could tell, these were made after the body of a porpoise had actually passed an obstruction. It appeared that the horizontal tail flukes of one of these small whales must have touched an obstacle as the animal was in the process of turning into a new alley. The second session was better than the first, and all subsequent trials were perfect, showing no collisions whatever. It looked as though the subjects had rapidly *learned* to navigate through the maze of obstructions in the limited swimming space allowed them. In one series of observations made during the dark phase of the moon, in nearly total darkness at night, there were also no errors.

As a final test we broadcast back to the animals, while they were swimming through the field of obstacles, tape recordings of their own noises which had been made during an earlier session in the same situation. The sounds were projected by a heavy Navy transducer, type 1-K. But the projected noises seemed not to affect the accuracy or the speed of their swimming in any way. And there were no collisions.

The most reasonable interpretation of this result appears to be that the porpoises were able to distinguish their own sound signals from the artificially produced interference. This interpretation finds support in the recent observations of Griffin (*14*) and of Griffin and Grinnell (*15*) that distracting or jamming sounds do not seriously disturb the echo-ranging ability of the bat.

Fish Discrimination Experiment

At first our two subjects were fed on mullet, *Mugil cephalus* (Linnaeus), but they soon began to refuse this fish. It therefore became necessary to supply them with a fish called spot, *Leiostomus xanthurus* (Lacépède), which they ate readily. Mullet thrown into the water would be chased but rejected. If held in the hand, a mullet would be approached but not taken.

As a consequence of this behavior, the question arose whether the animals could discriminate between preferred fish (the spot) and nonpreferred fish (the mullet) without seeing either fish. The fish-discrimination experiment was planned to examine this possibility. The discrimination cues were differences in the sizes of the preferred and the nonpreferred stimuli. To this end, mullet were selected for the experiment which were about twice as large in over-all length as the spot.

The general arrangement of the experiment is shown in Fig. 1. A rectangular screen of marine plywood was mounted solidly at the end of a 15-foot dock which projected into the pool. The screen was placed in such a way that its bottom edge was 1 to 2 inches below the surface of the water. From behind the screen, which concealed visible movement in the air, a spot and a mullet were silently lowered into the water at the same time. The tail of the spot was held by the experimenter so that the body of the fish projected approximately 6 inches below the bottom of the plywood screen. The mullet was held so as to project 12 inches below the screen. Every effort was made to eliminate all water noises as the fishes were inserted. That this was successfully accomplished was periodically checked by underwater listening. As in any discrimination experiment, the positions of the positive and negative stimuli were randomly rotated from trial to trial, although the absolute point of insertion of each fish was held constant with reference to the edges of the plywood screen.

Since the subject (Albert) was by this time well practiced in taking foodfish from the hand, he would approach the end of the dock whenever human beings came near it and wait there to be fed. Generally he lay at the top of the water, 3 to 10 feet from the plywood screen, where he would ogle the experimenters first with one eye and then with the other, submerging for a few inches between breaths, which occurred rather rapidly in such instances. A regularly timed trial began with the immersion of the two stimuli and ended when the porpoise took or touched either fish. If

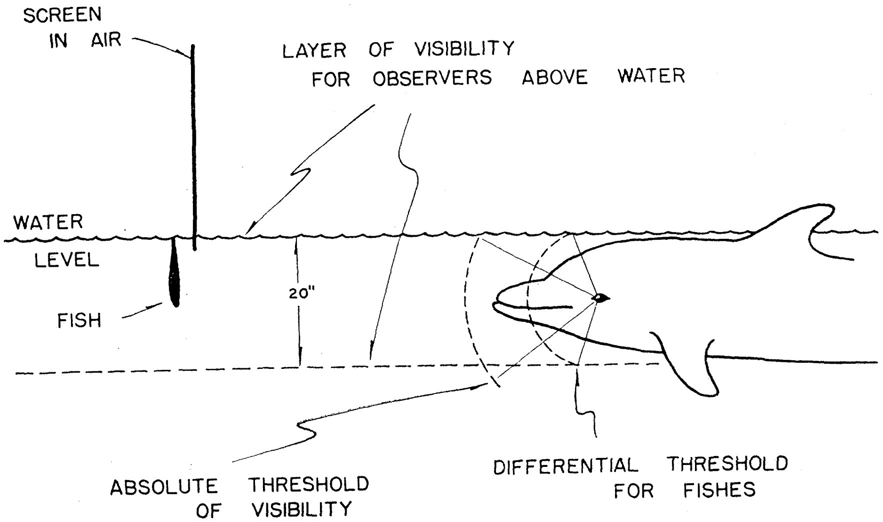

Fig. 2. The turbidity of the water acted somewhat like a one-way-vision screen. The experimenters above the water level could see sufficiently far beneath the surface to observe the porpoise's head and mouth, but the animal could not detect the target fishes in a horizontal direction. The difference between the absolute threshold for distance and the differential threshold—or the threshold of discrimination between the target fishes—is also illustrated in this figure.

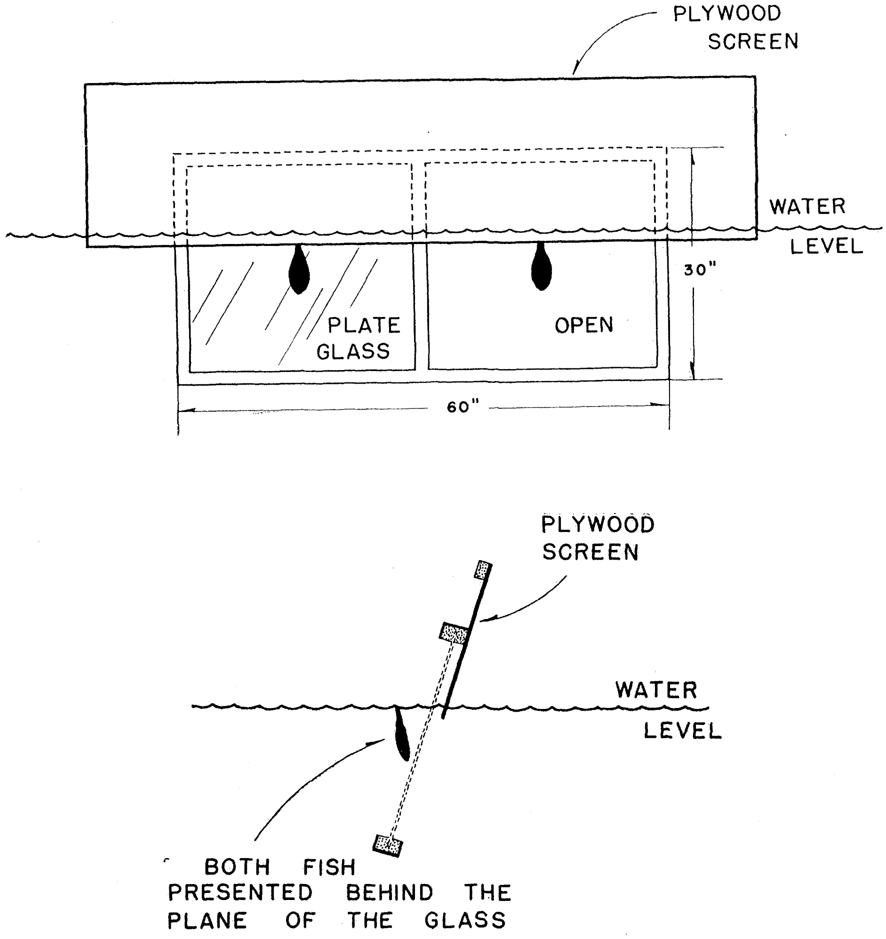

Fig. 3. (Top) Front view and (bottom) side view of the apparatus used in the window experiment. The porpoise was required to distinguish between two fish (spot) which were identical in visual appearance. The fish were presented simultaneously, but one was behind a sheet of plate glass. The glass was randomly shifted between the right and left windows.

the spot was taken, this was counted a successful discrimination. The touching or taking of the mullet was scored as an error.

Because Albert did most of his approaching at or very near the surface, it was not difficult for observers on the dock above him to tell his position with reference to the target fishes, in spite of the turbidity of the water. At the same time, the subject himself could not detect the stimuli by visual means because of this turbidity. The situation in fact possessed some of the characteristics of a *one-way-vision screen*, the advantage being all in favor of the experimenters. The diagram in Fig. 2 should make this clear.

A distinct difference was found to exist between the limits of visibility, as measured by the Secchi disc, and the limits of discriminability between fishes of different size, as tested by human observers under water. The Secchi disc used in these studies was a circular white reflecting surface, 20 centimeters in diameter, which was submerged until it became invisible. The procedure gave an absolute threshold of visibility measured vertically in inches from the surface of the water.

By means of special observations made by skin-diving human beings, horizontal Secchi readings in the pool were compared with vertical readings. Similar tests were made of the maximum horizontal distance, under the water, from which it was possible for a human being to distinguish between a 12-inch mullet and 6-inch spot. The horizontal and vertical Secchi readings were on the whole equal, but the horizontal discrimination threshold was found to be about one-half the absolute Secchi threshold. A Secchi measurement of 20 inches read from the surface could be translated therefore into a horizontal differential threshold between the two fishes of approximately 10 inches. The manner in which this affected the visual capacity of the porpoise is shown schematically in Fig. 2.

Regardless of these limitations, however, it soon became apparent that discrimination of a high order was taking place in the fish-discrimination experiment. In the first daily session of 16 trials, Albert committed four errors. The number of errors decreased irregularly upon successive sessions until none at all occurred. The final 140 trials—some made in near-total darkness at night—gave no errors whatever. The time per trial was not affected—that is, it was not increased—during the night sessions. If vision had played any part in the selection of the preferred fish, a reduction in illumination would certainly have made the task more difficult. It should consequently have increased the response time, and it might also have introduced errors.

Listening and underwater recording which were conducted throughout the experiment showed also that the porpoise reacted to the insertion of the fishes by increasing at once both the intensity and the continuity of his sound signals and by surging forward toward the targets as the signals increased.

Window Experiment

It may still be assumed by some that, in spite of the turbidity of the water, visual discrimination was not really excluded in these studies. Is it possible that Albert was able to distinguish between the fishes of different size by some superhuman ocular ability? To answer this objection, a new experiment was designed in which the use of vision would prove actually to be detrimental and confusing. This experiment is referred to in the present report as the window experiment.

Like the fish-discrimination experiment, the window experiment was also a discrimination experiment, but in this case the two stimuli to be discriminated were spot (preferred fish) identical in visual appearance. Both of the spot offered on any trial were equally visible, although one of them was unavailable or unattainable since it was presented behind a sheet of plate glass. The unavailable spot was the negative stimulus and the available spot the positive stimulus. A diagram of the apparatus which was used is shown in Fig. 3.

A rectangular frame of angle iron, 30 by 60 inches, contained a square plate-glass window which would slide to the right or left so as to fill one half of the rectangle. The position of the covering glass on any trial was randomly determined. The target fishes were silently inserted from behind a plywood screen so that no movement from the air could be detected by the subject.

Both of the spot were held the same distance behind the plane of the glass, as indicated in Fig. 3 (bottom). In order to reach the available fish, it was necessary for Albert to insert his mouth several inches into the open aperture of the metal framework. An error or failure on any trial would consist of his bumping the plate-glass window or approaching very close to the glass.

To induce the porpoise to place a part of its head inside of the metal frame required a great deal of preliminary training, as might have been expected. All of this training was conducted with the window removed from the framework. Spot were sometimes offered in the right-hand opening and sometimes in the left. In the beginning, it was necessary for the experimenter to hold the fish in front of the plane of the plywood screen, exposing his submerged hand as well as the fish to Albert. By easy stages, the fish were gradually moved backward into and through the framework, as is indicated in Fig. 4.

During the experiment itself the window was adjusted at the beginning of the intertrial interval—that is, immediately after Albert had taken the fish for the preceding trial and while he was submerged and eating the fish (as revealed by underwater listening). In order to control for the sound caused by sliding the window, the movement of the glass was always made in two steps or stages. It was first pushed half way—that is, to the middle of the framework. From this central position it was subsequently moved either the rest of the way, in the same direction, or it was returned to its original position. This two-stage process produced the same sequence of apparatus noise following each trial, but the noise by itself gave no indication of the final location of the glass.

The trials were timed as in the fish-discrimination experiment, and records were made of the approximate starting position on each trial as well as of the direction and speed of swimming during a trial. In 202 trials recorded in this manner, there occurred not a single error, nor even what appeared to be the beginning of an error. No approaches whatever were made toward the fish behind the glass.

On the average it took Albert longer to complete a trial than it had in the fish-discrimination experiment, possibly because of his aversion to putting his nose within the metal frame. Later trials were somewhat faster than earlier trials, showing the effect of practice. Some sessions were conducted in nearly complete darkness at night, but this again caused no change whatever in the accuracy of the performance or in the latency of responding.

The porpoise, in fact, ultimately came up with his own original version of how the problem should be solved. He developed the habit of stationing himself in front of the open window as soon as he had eaten the fish from the preceding trial and before the minimum intertrial interval set by the procedure had elapsed. He got ready, in other words, immediately after the movement of the glass and waited a few feet away for the available or "positive" fish to be submerged. He appeared to have learned through association or conditioning that the positive stimulus would come in the open window, and he distinguished at once the opened from the unopened. All this time the animal sputtered intermittently, as he made what might be termed "auditory glances" in listening for the forthcoming target fish.

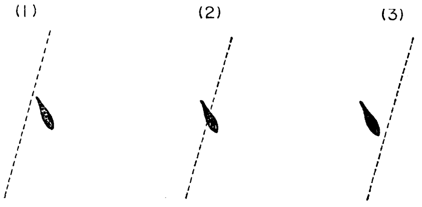

Fig. 4. Preliminary training was necessary in the window experiment in order to get the animal to insert its mouth through the aperture of the metal frame. Fish were first held in front of the frame as in (1), and on successive trials were gradually moved backward through the frame, as in (2) and (3). The glass was removed from the apparatus for these habituating trials.

Plexiglas Experiment

Even though these experiments dispose pretty well of the visual discrimination hypothesis, there remains the possibility that Albert may have been attracted to the target fishes by the chemical stimulus of taste and that his behavior should not, therefore, be accounted for in terms of echo ranging. The responses to submerged nongustatory targets discussed earlier in this article argue strongly against such a possibility. However, as a final check upon the notion that chemical substances in the water may have served as an uncontrolled variable in the window and fish-discrimination studies, an additional experiment was arranged in which food rewards were eliminated altogether. The motivating principle in this instance was avoidance or punishment. The general plan of the experiment, which is here referred to as the Plexiglas experiment, is illustrated in Fig. 5. Both of the porpoises served as subjects in this situation.

A submerged net of wire fencing 5 feet in height was stretched tightly across the width of the pool at the center. It formed a fixed barrier or partition dividing the water area into two approximately equal parts. The wire in the fencing was 1/8 inch in diameter and was woven into squares 5 inches to the side. The net was supported by floats at the surface and was weighted at the botton. Two openings 5 feet wide, located near the middle of the barrier, were the only passages or doorways from one half of the pool to the other. A large curtain of black war-surplus plastic suspended from above could be raised or lowered so as to block or cover both openings.

One of the openings could also be closed by a rigid sheet of clear Plexiglas, as is shown schematically in Fig. 6. Tackle from the shore permitted the Plexiglas to be moved laterally so as to block either hole. With the black curtain raised, the porpoises were therefore confronted with a kind of choice apparatus which required them to distinguish between the doorways in the wire fencing, one of which was blocked by a solid but invisible Plexiglas door.

Two other nets—which might be called "motivating nets"—were placed at the ends of the pool, one at each end, parallel to the barrier net. These motivating nets were movable and were used to induce the animals to pass from one side of the barrier to the other. Since porpoises tend to avoid physical contact and will shy away from any strange or unusual object, they would avoid the motivating net behind them by escaping into the open area of the opposite side. The black curtain was then lowered, and the original motivating net floated back to its starting position. On the next trial the second motivating net, now behind the animals, was used to make them return to the original half of the pool. The subjects were gradually familiarized with the apparatus and conditions in several preliminary sessions with the Plexiglas removed and with both apertures free and unoccupied.

During the regular experimental trials, the Plexiglas door was adjusted in position only when the black curtain was submerged and completely covered both of the openings. As in the case of the window experiment, the lateral movement of the Plexiglas from one side to the other was performed in two stages. The Plexiglas was placed in the center position between the two doorways, and it was then given a final adjustment so as to fill one of the openings. In this way the apparatus noise was a two-stage affair and was always the same, even though the Plexiglas was moved away from an aperture and returned to its original position. The right-left sequence of the open doorway upon successive trials was randomly determined.

The timing of a trial began when the curtain was raised and the choice apparatus was exposed to the animals. The timing ended when the animals came up to blow or exhale on the opposite side of the barrier. Since the two porpoises could be readily identified by the observers, time scores were recorded separately for each. If a collision with the Plexiglas occurred, this could at once be detected by the shaking of the net and the angular displacement of the Plexiglas itself.

Data in this experiment were obtained from 50 trials for each animal, or a total of 100 trials for both. The results showed that only two errors were committed in the entire series of 100 trials. The performance, in other words, was 98 per cent accurate. There was also evidence of learning or adaptation, as indicated by a gradual reduction in the time per trial. Underwater sound signals were again present in this experiment, as in the previous ones.

The conclusion seems inescapable that

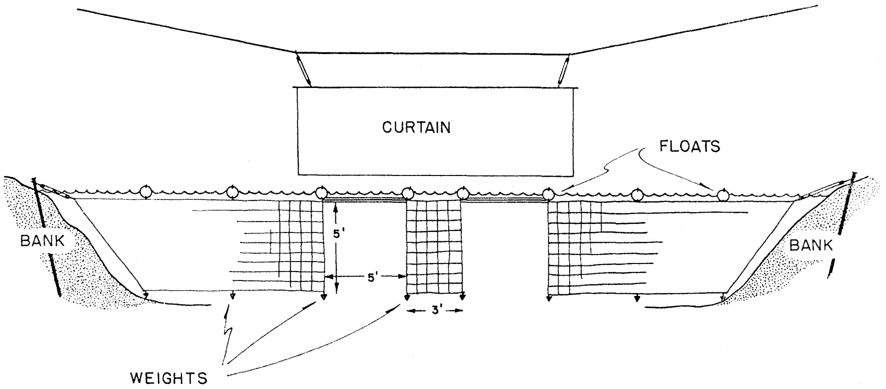

Fig. 5. The plan of the Plexiglas experiment. A steel net or fence was stretched tightly across the porpoise pool beneath the water, dividing it into two sections. The fencing was supported by floats at the surface and was weighted at the bottom. Two openings or doorways (5 feet wide) in the fence permitted the animals to swim from one section of the pool to the other. A heavy sheet of clear Plexiglas was used as a door to block one of the openings. The opaque plastic curtain, manipulated from the bank, could be raised or lowered to cover both openings. When it was raised, exposing the two doorways, this signaled the beginning of a trial. The Plexiglas door was moved from one opening to the other only when the curtain was down, thus concealing the movement.

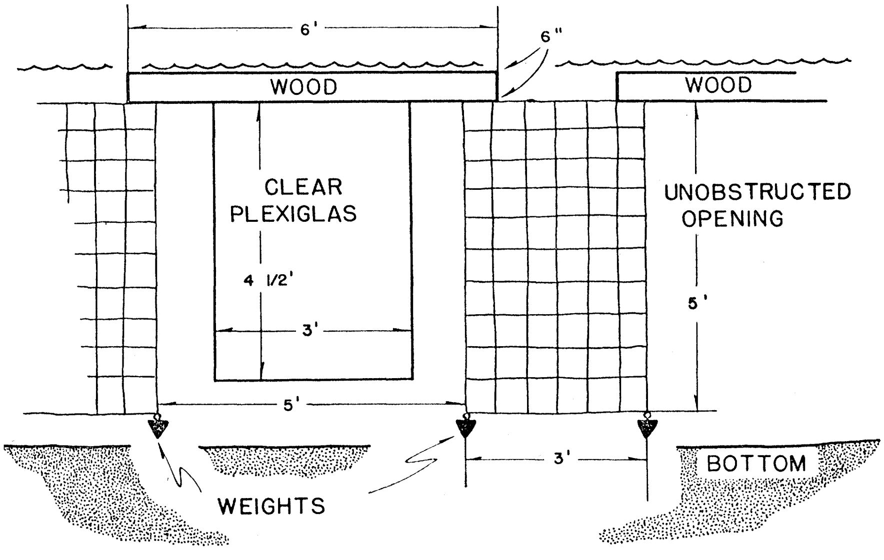

Fig. 6. The Plexiglas door in place in the Plexiglas experiment, whose over-all plan is shown schematically in Fig. 5. The door was moved laterally, by tackle operated from the shore, in such a way as to close or block one opening or the other on any given trial.

the porpoises avoided the solid but invisible Plexiglas door by means of echo ranging. The selection of the open doorway took place, moreover, while the animals were passing through a net of ⅛-inch steel wire, which they also avoided. The location and discrimination of submerged objects by reflected sound signals is without doubt a necessary and a fundamental perceptual avenue for these cetaceans.

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Dosimetry of Radioisotopes

A nomogram permits the estimation of the radiation dose delivered by 30 isotopes of biological interest.

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The statement that radioisotopes are being used with increasing frequency both in biology and in medicine need not be defended here. Indeed the entire problem of irradiation from internally received radioisotopes is assuming increasing importance. Nevertheless, observations are often reported merely in terms of counts per minute or of millicuries without cognizance of whether the isotope provides simply a weak signal or a substantial source of energy. Results so reported are of little quantitative meaning in the evaluation of the degree of change to be anticipated in a biological (or other) system.

A more definitive additional specification, such as the dose rate, is often not reported because of the discouragement caused by the necessary calculations, even when the distortion of a biological system is the primary concern. Therefore, we have developed a simple nomogram (Fig. 1) which permits direct reading of the dose rate for numerous radioisotopes of biological and medical interest (*1*). The use of this device in our center has improved the planning of two types of experiments—namely, tracer as well as radiobiological work. Its use has developed the habit of thinking directly in terms of the forces at work rather than in terms of a partial datum which happens to appear on a luminous dial.

The nomogram permits the reading of beta plus gamma dose rate or either one alone for the center of a cylindrical or of a spherical system. Conversely it aids in choosing isotopes for the delivery of desired dose rates of radiation. The classical dosimetric assumptions (*2*) were employed in constructing it: 1 microcurie is immediately and homogeneously dispersed per kilogram; the system has a density of 1 and behaves like water vis-a-vis irradiation; the entire β-particle energy is absorbed by the system, and the gamma rays have a linear absorption coefficient of 0.03 per centimeter.

The energy due to conversion electrons is included with the β energy; bremstrahlung is neglected, while x-rays due to k capture are not accounted for.

Use of the Nomogram

The formula on which the nomogram is based is the classical one

$$D_{\beta+\gamma} = 51.2\,\bar{E}_{\beta} \cdot n + I_{\gamma} \cdot G \cdot n$$

where $D_{\beta+\gamma}$ is the dose rate in millirad per day at the center of a cylinder or sphere due to β and γ emission; $\bar{E}$ is the average energy in Mev of the beta emission; I_{γ} is the dose rate in rad per microcurie per day at 1 centimeter due to the gamma emission from a point source; G is the geometry factor handling variance in size and shape of the system [its values were calculated from Marinelli, Quimby, and Hine (*3*)]; and n is the concentration of radioactivity in microcuries per kilogram at the onset of the observation.

The beta plus gamma dose rate (per hour or per day) is read as follows.

1) Draw the diagonal corresponding to your isotope on scale A.

2) Choose a cylindrical or spherical model, whichever fits your system best.

3) Draw the vertical from the weight or radius of this model to the diagonal corresponding to your isotope.

4) From the intercept draw a horizontal to scale B.

5) Connect the new intercept on scale

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