NOSC TR 847

Technical Report 847

AURAL DISCRIMINATION OF TARGETS BY HUMAN SUBJECTS USING BROADBAND SONAR PULSES

DW Martin and WWL Au
Code 511

October 1982

Approved for public release; distribution unlimited

NOSC
NAVAL OCEAN SYSTEMS CENTER
San Diego, California 92152

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
NOSC Technical Report 847 (TR 847)

2. GOVT ACCESSION NO.
A123 466

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
AURAL DISCRIMINATION OF TARGETS BY HUMAN SUBJECTS USING BROADBAND SONAR PULSES

5. TYPE OF REPORT & PERIOD COVERED
FINAL: FY 1981

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
DW Martin
WWL Au

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Naval Ocean Systems Center, Hawaii Laboratory
PO Box 997
Kailua, Hawaii 96744

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
611512N; ZR00001; ZR0110824; 512-ZS64

11. CONTROLLING OFFICE NAME AND ADDRESS
Code 013
Naval Ocean Systems Center
San Diego, CA 92152

12. REPORT DATE
October 1982

13. NUMBER OF PAGES
16

14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Aural discrimination
Echo recognition
Echolocation
Human hearing
Sonar

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Sonar echo discrimination experiments were conducted with human subjects, using targets employed in a dolphin echo-recognition study. Digital recordings of the target echoes were obtained using a dolphin-like echolocation signal with a peak-frequency of 122 kHz, and were played back to the subject at 1/50 of the original sample rate. Targets included hollow cylinders of aluminum, bronze, steel and glass having diameters of 3.81 and 7.62 cm, and a solid 7.62-cm aluminum cylinder. All targets were 17.78 cm in length. Echo amplitudes were adjusted so that stimulus intensity was not a cue. The subjects discriminated between echoes from (1) solid and hollow, and (2) small and

(Continued on reverse side)

DD FORM 1473 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-LF-014-6601

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. Continued.

large aluminum cylinders with correct responses of 98% and 92%, respectively, after one session per task. Correct responses for the aluminum-bronze and the aluminum-steel discriminations were 98% and 95%, respectively. Correct responses for the aluminum-glass discriminations varied between 72% and 98%. Differences in time-separation-pitch associated with correlated echo highlights and differences in echo duration were the predominant discrimination cues.

CONTENTS

ILLUSTRATIONS

TABLES

OBJECTIVES

1. Identify echo features which allow discrimination between targets.

2. Determine the ability of human subjects to make target discriminations similar to those of dolphins.

3. Compare the performance of the human with that of the dolphin on similar tasks.

RESULTS

1. Human subjects can make fine discriminations of target structure, size and material composition using cylindrical targets after the original echoes are stretched in time by a factor of 50.

2. Differences in time-separation-pitch associated with correlated echo highlights and differences in echo duration were the predominant discrimination cues in all of the tasks except that involving the truncated aluminum and glass echoes.

3. For the truncated aluminum and glass echoes, differences in "click pitch" not attributed to time-separation-pitch seemed to be the dominant cue.

4. Human subjects performed as well as or better than the dolphin in similar target discrimination experiments.

RECOMMENDATION

1. Further experiments should be conducted to measure target discriminability in the presence of noise as a function of target shape and of target aspect.

INTRODUCTION

The ability of an echolocating dolphin to discriminate target size, wall thickness, internal structure (solid or hollow) and material composition of cylindrical targets was studied by Au and Hammer (ref 1,2). The purpose of the study reported here was to identify echo features which allow discrimination between targets, to determine the ability of human subjects to make similar target discriminations using broadband simulated dolphin sonar pulses to ensonify the same targets, and to compare the performance of the human subjects with that of the dolphin on similar tasks. Broadband echoes were recorded for the same targets used by Au and Hammer (ref 1), and these echoes were transformed into the human hearing range by digitally time expanding them when presented to human subjects in a manner similar to that of Fish et al (ref 3).

Hammer and Au (ref 2) used a baseline-probe technique with cylinders of two different diameters (3.81 and 7.62 cm) for the baseline targets; all cylinders were 17.78 cm in length. In the preliminary experiment to test general discrimination capabilities, they found that the dolphin could easily discriminate targets of different sizes, structure (solid or hollow), and material composition (aluminum, rock, polyvinyl chloride). Using aluminum cylinders, they found that the dolphin could discriminate wall thickness differences of 0.16 cm for the small (3.81-cm OD) cylinders and 0.32 cm for the large (7.62-cm OD) cylinders. For cylinders of different material composition but with the same structure and dimensions, the dolphin could discriminate between aluminum and bronze and between aluminum and steel. However, the animal could not discriminate between aluminum and glass. Schusterman et al (ref 4) extended the work of Hammer and Au (ref 2) by employing a forced-choice technique between the aluminum and glass cylinders, using the same animal. They found that the dolphin could be trained to discriminate between the small aluminum and glass cylinders but could not be trained to discriminate between the large aluminum and glass cylinders.

An analysis of the target echoes (ref 1,2) indicated that the time difference between the initial echo component reflected off the front face of the cylinders and the echo components due to internal reflections within the targets seemed to provide the primary discrimination cues to the animal. The results of a matched-filter analysis which indicated the times of arrival of the echo components corresponded well with the behavioral results. It was suggested that the time-separation-pitch (TSP) generated by the highly correlated first and second echo components was used in making fine discriminations. In this study, we attempted to identify discrimination cues by interrogating the subjects and by manipulating the recorded echoes.

A previous experiment was performed by Fish et al (ref 3), using human divers instrumented with a broadband sonar that projected dolphin-like signals. They replicated the

---

1. Au, WWL and CE Hammer, Jr. Target Recognition via Echolocation by *Tursiops truncatus*, in: Animal Sonar Systems, RG Busnell and JF Fish, ed, p 855-858, Plenum Press, New York, 1980.
2. Hammer, CE, Jr and WWL Au, Porpoise Echo-Recognition: An Analysis of Controlling Target Characteristics, J Acoust Soc Amer, 68, p 1285-1293, 1980.
3. Fish, JF, CS Johnson and DK Ljungblad, Sonar Target Discrimination by Instrumented Human Divers, J Acoust Soc Amer, 59, p 602-606, 1976.
4. Schusterman, RJ, D Kersting and WWL Au, Response Bias and Attention in Discriminative Echolocation by *Tursiops truncatus*, in: Animal Sonar Systems, RG Busnell and JF Fish, ed, p 983-986, Plenum Press, New York, 1980.

dolphin experiment of Evans and Powell (ref 5) in discriminating the thickness and material composition of metallic plates. They also performed experiments which discriminated size and shape of planar targets. It was found that in all cases the human subjects performed as well as or better than the Atlantic bottlenose dolphin. However, the cues used by the subjects in the material composition and thickness discriminations were not discussed and there were no indications as to how the various discriminations were being made.

MATERIALS AND METHODS

Target echoes were collected using an HP-2100 minicomputer-controlled monostatic echo measurement system which transmitted a broadband, porpoise-like echolocation signal. A description of the backscatter measurement system, including a block diagram, was presented by Au and Snyder (ref 6). The incident signal was generated by driving a specially designed 10.5-cm-square planar transducer with an exponential decaying four-cycle sine wave pulse causing the transducer to ring in the desired manner. The incident signal, along with its frequency spectrum plotted on a logarithmic scale, is shown in figure 1. The 50-μs

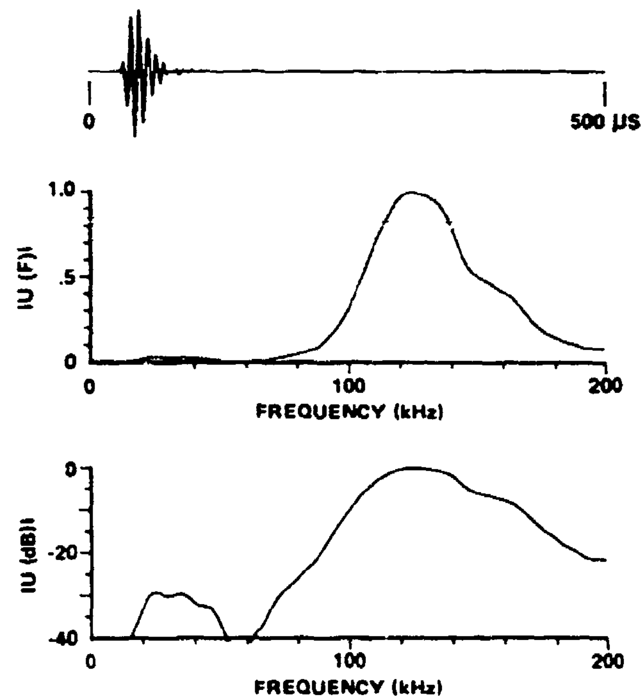

Figure 1. Simulated dolphin echolocation signal used as the incident signal.

---

5. Evans WE and BA Powell, Discrimination of Different Metallic Plates by an Echolocating Delphinid, in: Animal Sonar Systems: Biology and Bionics, RE Busnell, ed, Laboratoire de Physiologie, Jouy-en-Josas 78, France, 1967.
6. Au, WW and KJ Snyder, Long-Range Target Detection in Open Waters by an Echolocating Atlantic Bottlenose Dolphin *(Tursiops truncatus)*, J Acoust Soc Amer, 68, p 1077-1084, 1980.

duration, 122-kHz peak frequency, and 39-kHz bandwidth (3 dB) of this simulated porpoise click are similar to those reported by Au (ref 7) for *T. truncatus* in Kaneohe Bay.

The target echoes were measured in a 33- by 30-m saltwater pool with a maximum depth of 4.7 m. The targets were suspended at a range of 2.4 m from the transducer at a depth of 1.8 m. The echoes were digitized at a 1-MHz sample rate and stored on a digital magnetic tape. Ten echo samples were collected for each target.

The digitally recorded echoes were transferred to disk files and presented to human subjects, using a PDP-11 minicomputer. The subjects listened to the signals in a sound isolation booth via Koss ESP-9B electrostatic headphones. Preliminary experiments with a limited set of echoes indicated that a stretch factor of 50 and a repetition rate of 4 pulses/second provided optimal discrimination performance. Therefore, these values were used in subsequent experiments. The stretch factor is defined as the recording sample rate divided by the playback sample rate. With a stretch factor of 50, the original peak frequency of 122 kHz was transformed to approximately 2.4 kHz, and the echo duration was increased by a factor of 50.

Discrimination performances were measured using 64-trial sessions, with one repeated signal per trial. The signal was a pre-recorded echo from either one of two or one of four targets. The subjects classified targets into one of two categories by pressing either of two pushbutton switches, one of which was labeled A, and the other, B. The stimulus was repeated at four pulses per second for 15 seconds or until the subject responded, whichever occurred first. Failure to respond on any trial was considered an abort. Correct response feedback was provided at the end of each trial by lights labeled A and B, corresponding to the two pushbutton switches. Prior to the beginning of each session, the subjects were provided with a warmup period during which they could listen to signals from either of the two categories by pressing either of switches labeled A and B. The length of the warmup period was determined by the subjects and a session began when a subject pressed both switches simultaneously.

The investigation was divided into four experimental phases. In each phase, the signal presentation was randomized during warmup and testing, with equal *a priori* probabilities of occurrence for each signal. A pseudo-random signal presentation schedule was used in which a specific signal could not be presented on more than three consecutive trials.

PHASE I

The same targets used by Hammer and Au (ref 2) in their experiment I were used in this phase to measure the discrimination performance of a human subject. The target pairs are described in table 1, with the 3.81-cm and 7.62-cm OD aluminum cylinders used as the reference pair (signal A). For any given session, two pairs of target echoes were used: the reference pair and another pair. On any given trial, one of four possible target echoes would be presented. An exception was made when the PVC cylinder was tested. In this case, only the large aluminum reference cylinder was used for the A signal. During this phase, only one echo per target was used, and only one subject (DM) was tested.

7. Au, WWL, Echolocation Signals of the Atlantic Bottlenose Dolphin *(Tursiops truncatus)* in Open Waters, in: Animal Sonar Systems, RG Busnell and JF Fish, ed, p 251-282, Plenum Press, New York, 1980.

Target Pairs	1		2		3		4		5		
Composition	Al	Al	Crk	Crk	Al	Al	Al	Al	Cpn	Cpn	PVC
Wall Th (cm)	0.64	0.95	Solid	Solid	0.48	0.64	Solid	Solid	Solid	Solid	0.79
Out Dia (cm)	3.81	7.62	3.81	7.62	6.35	11.4	3.81	7.62	4.06	6.35	7.62

Table 1. Targets used in phase I to measure general discrimination performance. The reference target pair (signal A) was always target pair 1. Crk denotes coral rock encapsulated in a degassed epoxy mix. Cpn denotes corprene. For tests with the PVC, only the 7.62-cm aluminum target of target pair 1 was used as the reference.

PHASE II

In this phase, the capability of the subjects to discriminate target internal structure was determined. Two experiments were conducted, one involving the discrimination between hollow and solid aluminum cylinders, and the other involving the discrimination between large and small hollow aluminum cylinders. The large aluminum cylinder (7.62-cm OD) had a wall thickness of 0.40 cm and the small aluminum cylinder (3.81-cm OD) had a wall thickness of 0.32 cm. In both experiments, the hollow, 7.62-cm OD aluminum target was used as the reference, or signal A. In the first experiment, signal B was the set of echoes from a 7.62-cm OD solid aluminum cylinder. In the second experiment, signal B was the set of echoes from the 3.81-cm OD aluminum cylinder. In both cases, the signal peak amplitudes were adjusted to be the same so that target strength would not be a discrimination cue. Because these signals had similar shapes and durations, peak amplitude normalization was virtually equivalent to energy normalization. None of the subjects reported any loudness difference. In any given trial, one of ten randomly chosen echoes from a target was used,* and four subjects were tested. The use of ten echoes per target will be referred to as the MP (multiple ping) condition. The SP condition refers to the use of a single ping per target.

PHASE III

This phase involved the discrimination of material composition. Targets composed of aluminum, steel, bronze and glass, with the same dimensions and structure, were used. These were the same targets used in experiment III of the Hammer and Au study (ref 2). The aluminum target echoes were always used as the reference echoes (signal A). Both SP and MP data were collected with three to five subjects.

PHASE IV

In this phase, the duration of the echoes from the large aluminum and glass cylinders was manipulated to determine its relevance to the discrimination cues. The aluminum target echo was always used as the reference echo. Each target was represented by ten echoes, and two subjects were used.

*Slight variations existed between echoes from a given target, due primarily to target motion.

RESULTS AND DISCUSSION

PHASE I

Only one subject was tested because the task was found to be trivial. The subject performed better than 95 percent correct for all of the discriminations. No prior training was required, and two sessions, representing 128 trials, were conducted for each discrimination. Multiple cues were available, since the echo clicks were dissimilar in both the frequency and time domains. Using the same targets, the dolphin in the experiment of Hammer and Au (ref 2) discriminated the reference aluminum targets from the others 100 percent of the time after training.

PHASE II

The average performance of four subjects in the hollow versus solid aluminum cylinder discrimination task was 98 percent correct, with no prior learning and one session per subject. The use of multiple echoes introduces some variance between similar signals which would force the subject to use cues that are associated with a target type rather than cues associated with a specific echo. The predominant cue reported by the subjects was the longer duration of the hollow cylinder echoes. This difference was described as "click and hiss" for the hollow cylinder and "click only" for the solid cylinder. Time-separation-pitch cues also were reported, but they were not as obvious as the duration cues.

Typical echo waveforms and frequency spectra for the hollow and solid cylinders are shown in figure 2. The time and frequency values are shown in terms of both the transformed and the real-time values (in parentheses). The transformed values represent a time expansion of the original data by a factor of 50. The solid line in the spectrum plot represents the referenced aluminum cylinder and the dotted spectrum is for the solid target. A comparison of the echo waveforms indicates that the hollow cylinder echo has a longer duration than that from the solid cylinder, and the secondary internal scattering components are spaced further apart for the hollow cylinder. The backscattering process associated with hollow and solid cylinders involves a variety of internal and circumferential scattering paths. Detailed discussions of backscattering of acoustic waves from hollow and solid cylinders can be found in Barnard and McKinney (ref 8), Shirley and Diercks (ref 9), Neubauer and Dragonette (ref 10) and Welton et al (ref 11). The frequency spectra were very dissimilar; however, frequency cues were not reported by any of the subjects, probably because the duration cues were so apparent.

With the subjects reporting no loudness differences between the echoes, four subjects could discriminate the small versus the large aluminum cylinders with a 92-percent correct response accuracy and with no prior learning. Typical echo waveforms, frequency spectra and matched filter responses for the large and small aluminum cylinders are shown in figure 3. The waveform and spectrum associated with the 7.62-cm OD cylinder are the same as in figure 2, and are presented again for easy comparison with the 3.81-cm OD cylinder.

---

8. Barnard, GR and CM McKinney, Scattering of Acoustic Energy by Solid and Air-Filled Cylinders in Water, J Acoust Soc Amer, 33, p 226-238, 1961.
9. Shirley, DJ and KJ Diercks, Analysis of the Frequency Response of Simple Geometric Targets, J Acoust Soc Amer, 48, p 1275-1282, 1970.
10. Neubauer, WG and LR Dragonette, Observation of Waves Radiated from Circular Cylinders Caused by an Incident Pulse, J Acoust Soc Amer, 48, p 1135-1149, 1970.
11. Welton, PJ, M de Billy, A Hayman and G Quentin, Backscattering of Short Ultrasonic Pulses by Solid Elastic Cylinders at Large *ka*, J Acoust Soc Amer, 67, 470-476, 1980.

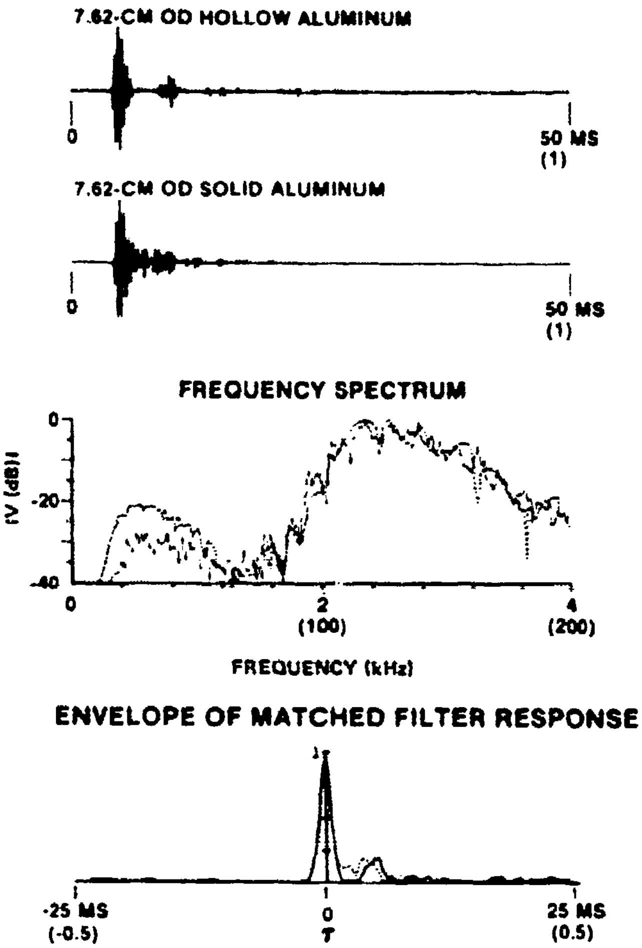

Figure 2. Typical echo waveforms, frequency spectra and matched filter responses for the 7.62-cm hollow and solid aluminum cylinders. The numbers in parentheses refer to the original echoes and the other values refer to the stretched echoes presented to the human subjects. The solid spectrum is for the hollow target and the dotted spectrum is for the solid target.

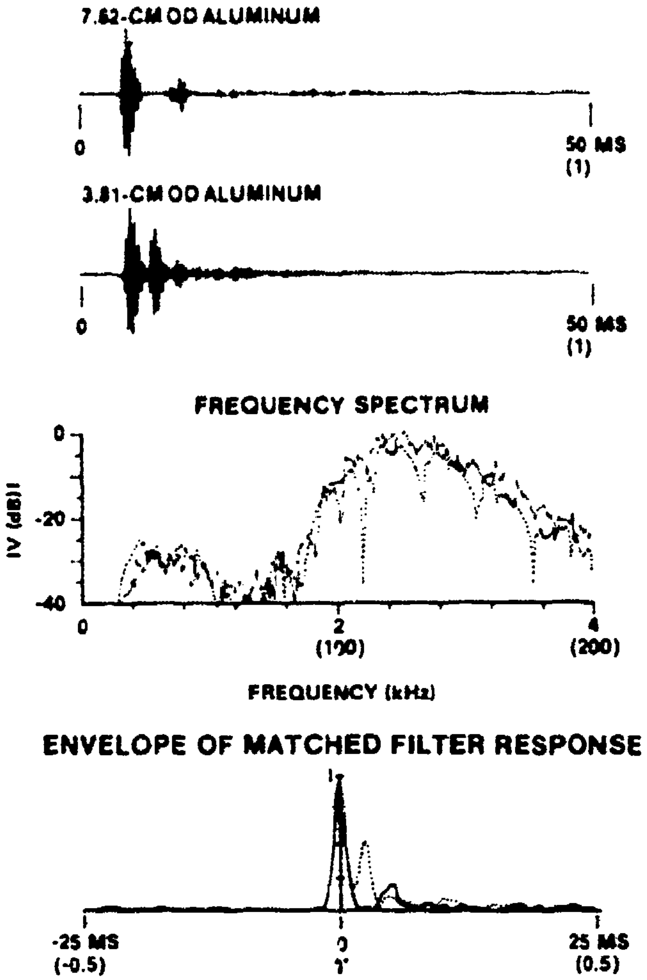

Figure 3. Typical echo waveforms, frequency spectra and matched filter responses for the 7.62-cm and 3.81-cm aluminum cylinders. The solid spectrum is for the 7.62-cm cylinder and the dotted spectrum is for the 3.81-cm cylinder.

The subjects reported two dominant cues, the longer duration of the large cylinder echo and the higher pitch associated with the small cylinder echo. The subjects also reported that some of the ten echoes from each target were identified using the duration cue, and the others using the frequency cue. From figure 3 it can be seen that the delay between the first and second echo components is shorter for the small cylinder, as would be expected since the internal acoustic paths are shorter for the small cylinder. In addition, the second echo component of the small target has a higher amplitude than the corresponding echo component of the large target. The appearances of the echo waveforms suggest a higher correlation between the first and second echo components for the small cylinder than for the large cylinder. Arrival time differences between highly correlated echo components can result in the presence of time-separation-pitch (ref 12,13). This TSP will be perceived at a frequency equal to the reciprocal of the time delay between echo components. We attribute the higher pitch reported by subjects for the small cylinder to TSP. The frequency spectra indicate that TSP should be perceived since the spectra show periodic ripples (ref 14). The ripples are more widely separated for the small cylinder and should result in a higher frequency TSP.

PHASE III

The aluminum-steel and the aluminum-bronze discriminations each were performed with two pairs of targets, the reference pair consisting of echoes from the 3.81-cm and 7.62-cm aluminum cylinders (signal A) and the other consisting of echoes from steel or bronze cylinders of the same diameters. Single-ping data were used so that one of four echoes occurred on each trial. The average performance of three subjects in the aluminum-bronze discrimination was 98 percent correct and 95 percent correct for the aluminum-steel discrimination. Each subject participated in two sessions, or 128 trials, for each discrimination task without any prior training.

In both discrimination tasks, the subjects first determined whether an echo originated from a large or small cylinder based on a duration cue. Echoes from the large cylinders had longer durations. Subjects reported that discrimination between the small aluminum and bronze cylinders was based on the presence of a lower TSP in the bronze than in the aluminum. From figure 6 of Hammer and Au (ref 2), we can see that the time separation between the first and second echo components was 52 μs for the small bronze cylinder and 45 μs for the small aluminum cylinder. After stretching the signals by a factor of 50, the resulting TSP should be 385 Hz for the bronze and 444 Hz for the aluminum. Discrimination between the large aluminum and bronze cylinders was based on the presence of TSP with the aluminum cylinder and the absence of TSP with the bronze cylinder. Figure 7 of Hammer and Au (ref 2) shows that there is interference between the second and third echo components in the bronze target, which may have affected the perception of TSP.

The aluminum-steel discrimination was made on the basis of clearly perceptible TSP with both the small and large aluminum cylinder echoes. The presence of TSP was not as definite for the steel cylinders. The envelope of the matched filter responses in figures 6 and 7 of Hammer and Au (ref 2) suggests that the aluminum targets should result in the presence of clearer TSPs.

The aluminum-glass discrimination task was performed using three different conditions: (a) single ping with one of two possible targets presented on each trial, (b) single ping with one of four targets, (c) multiple pings with one of two targets. The results of this discrimination task are shown in table 2, which includes the results for small and large cylinders. These results represent data obtained after the subject's performances stabilized. Large differences between subjects in the ability to discriminate the target echoes are apparent from the results. The data indicate that all of the subjects could discriminate between aluminum and glass with performance accuracy varying between 72.3 and 97.9 percent correct. Subjects' performances were not degraded by transferring from a one-of-two-targets to a one-of-four-targets task using single-ping information. However, the transfer

---

12. Small, AM and ME McClellan, Pitch Associated with Time Delay between Two Pulse Trains. J Acoust Soc Amer, 35, p 1246–1255, 1963.
13. McClellan, ME and AM Small, Time-Separation Pitch Associated with Correlated Noise Burst. J Acoust Soc Amer, 38, p 142–143, 1965.
14. Bilsen, FA, Repetition Pitch: Monaural Interaction of a Sound with the Same but Phase-Shifted Sound, Acustica, 17, p 295–300, 1966.

(a) Single ping – one of two targets

3.81-cm O.D. cylinder			7.62-cm O.D. cylinder	
Subject	No. trials	% Correct	No. trials	% Correct
DM	192	94.3	256	94.5
KD	192	95.3	191	97.9
PT	318	87.7	256	93.4
DS	384	75.8	382	72.3
GP	384	74.7	382	74.9

(b) Single ping – one of four targets

3.81-cm O.D. cylinder			7.62-cm O.D. cylinder	
Subject	No. trials	% Correct	No. trials	% Correct
DM	210	92.9	210	95.2
KD	139	96.2	125	97.0
PT	191	86.4	193	97.9

(c) Multiple ping – one of two targets

3.81-cm O.D. cylinder			7.62-cm O.D. cylinder	
Subject	No. trials	% Correct	No. trials	% Correct
DM	384	85.2	384	94.3
KD	256	88.3	192	84.4
PT	384	74.0	384	78.4
GP	320	76.6	192	76.6

Table 2. Results of the aluminum-glass discrimination task for three different conditions.

from the use of single-ping to multiple-ping information resulted in a decrease in accuracy for most of the subjects, and the amount of decrease was subject-dependent. The subjects indicated that the echoes from the aluminum and glass targets sounded very similar and that the introduction of variances due to multiple pings made the task more difficult.

The discrimination cue was found to be the difference in echo durations between the aluminum and glass echoes for both the small and large targets. Typical examples of echoes from the small and large targets are shown in figures 4 and 5, respectively. From the figures we can see that the echoes from the glass targets damped out sooner than echoes from the aluminum targets. Visual inspection of the small target echoes indicates that the glass echo damped out approximately 14 ms (0.28 ms before stretching) before the aluminum echo. For the larger targets, the glass echo damped out approximately 5 to 7 ms (0.10 to 0.14 ms before stretching) before the aluminum echo. Schusterman et al (ref 4) trained a dolphin to perform the small aluminum-glass discrimination, but could not train the animal to perform the large target discrimination. The duration difference of 0.10 to 0.14 ms may not have been perceptible to the animal, but could be perceived by humans because the signals were expanded in time by a factor of 50. It may also be possible that the animal could not detect duration cues because these cues are contained in the portion of the signals which are approximately 30 dB below the peak and may have been masked

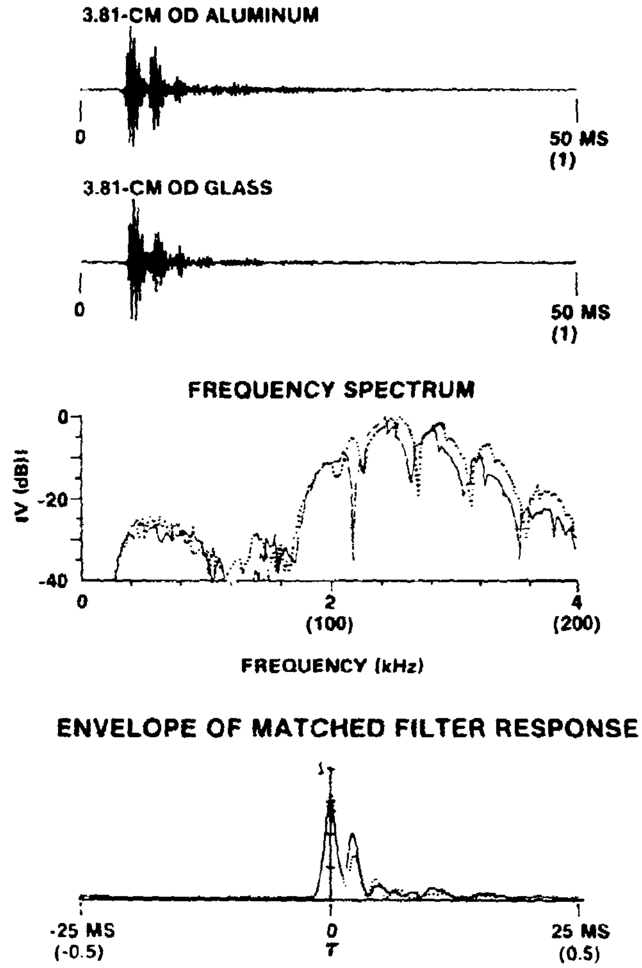

Figure 4. Typical echo waveforms, frequency spectra and matched filter responses for the 3.81-cm aluminum and glass cylinders. The solid spectrum is for the aluminum cylinder and the dotted spectrum is for the glass cylinder.

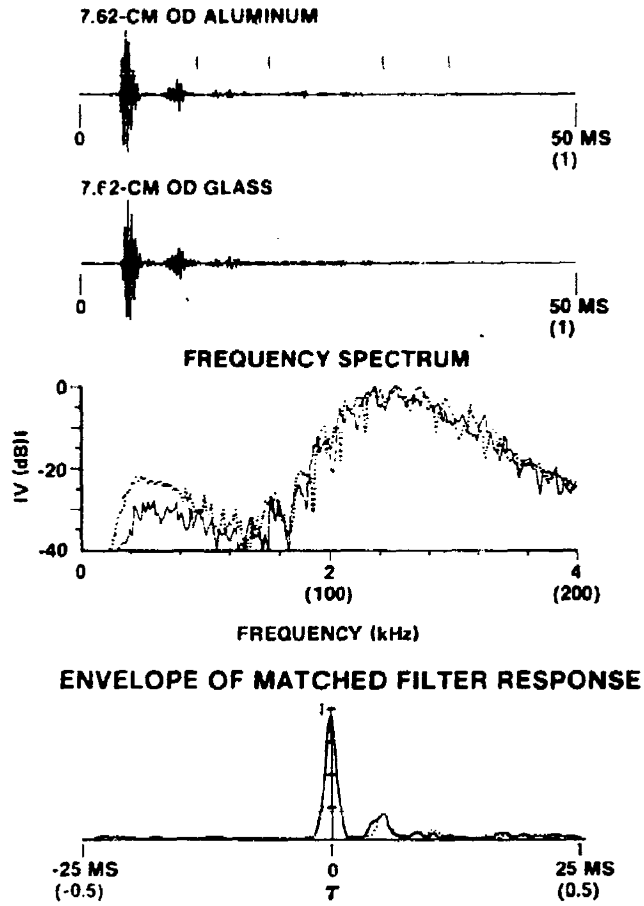

Figure 5. Typical echo waveforms, frequency spectra and matched filter responses for the 7.62-cm aluminum and glass cylinders. The solid spectrum is for the aluminum cylinder and the dotted spectrum is for the glass cylinder. The tic marks shown above the aluminum echo indicate where the signals were truncated during phase III.

by the ambient noise of the bay. A third possibility for the dolphin is that the initial peaks in the echoes could have forward-masked later portions of the echo (ref 15), since the total echo duration is approximately 0.5 to 1.0 ms.

PHASE IV

In order to investigate the aluminum-glass discrimination cues further, the echoes from the large targets were truncated systematically between groups of echo highlights, as shown in figure 5. The truncation caused the signals to be of equal durations. The performance of two subjects was measured again for the total signals. Performance was then measured with progressively shorter signals. In figure 6, the discrimination results of the last three sessions at each duration are shown. It can be seen that the discrimination accuracy decreased.

---

15. Resnick, SB and LL Feth, Discriminability of Time-Reversed Click Pairs: Intensity Effects, J Acoust Soc Amer, 57, p 1493-1499, 1975.

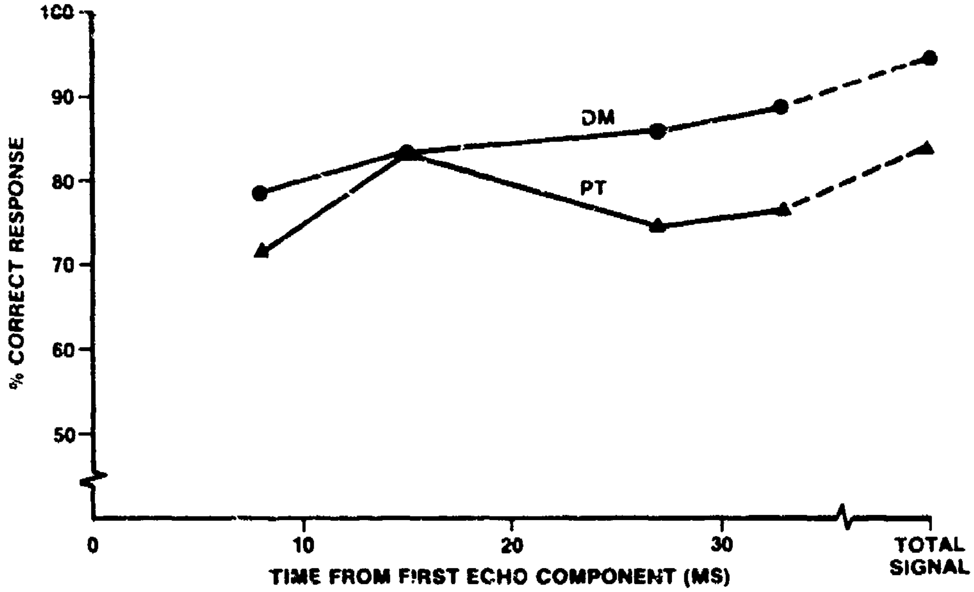

Figure 6. Discrimination performance results with the 7.62-cm aluminum and glass cylinders as a function of the signal duration.

with the exception of one data point for subject PT. The figure also conveys the importance of the duration cue, since performance accuracy decreased when the signal durations were made the same upon the first truncation. From figure 5 we can see that the information in the tail portion of the aluminum echo was approximately 32 dB below the level of the primary echo component. Therefore, the subjects were using information over a 32-dB dynamic range before truncation.

Subjects' performances remained significantly above chance after the duration cue was eliminated upon the first truncation, and remained above chance with further truncations. The final truncation eliminated all but the first two echo components, yet the subjects were able to discriminate the signals above 70 percent correct response. The time between the first and second echo components is virtually the same for both targets; thus, the discrimination probably was based on cues other than difference in TSP. The subjects indicated that the glass target had a slightly higher "click pitch" than the aluminum target when using the truncated signals. Click pitch is defined as the pitch associated with the peak frequency of a broadband transient signal. It was also reported that this cue was difficult to extract and was not always reliable. By examining the frequency spectra of figure 5, we can see that the minima for frequencies above 1.8 kHz for the glass spectrum is approximately 67 Hz higher than that of the aluminum spectrum. Although figure 5 shows the spectra of the total signals, the spectra for the first and second echo components were shown by Hammer and Au (ref 2) to be similar to the total echo spectra.

SUMMARY AND CONCLUSIONS

The capabilitie of human subjects to perform complex target discrimination using broadband simulated dolphin echolocation signals were determined in a series of four experiments using cylindrical targets. It was found that the human subjects could make fine discriminations of target structure, size and material composition after the original echoes were stretched in time by a factor of 50. Four subjects performed at the 98-percent-correct response level in discriminating between solid and hollow aluminum cylinder echoes after the target strength difference was eliminated. The performance of three subjects in the aluminum-bronze discrimination was 98 percent correct and 95 percent correct for the aluminum-steel discrimination. The aluminum-glass discriminations were more difficult in both the small and large diameter cases. Large individual performance differences were found, with correct responses varying between 72 and 98 percent. For the large aluminum and glass cylinders, the subjects' performance decreased (except for one point) as the echoes were progressively truncated and made to be of the same duration.

Differences in time-separation-pitch associated with correlated echo highlights and differences in echo duration were the predominant discrimination cues in all of the tasks except that involving the truncated aluminum and glass echoes. In that case, differences in "click pitch" not attributed to TSP seemed to be the dominant cue. TSP was useful in the small-large, aluminum-bronze, aluminum-steel discrimination tasks. Echo duration differences were used in the solid-hollow, small-large and the aluminum-glass discrimination tasks.

Human subjects performed as well as or better than the dolphin in the experiments of Hammer and Au (ref 2) and Schusterman et al (ref 4) for the discrimination task of phase I, and for the material composition discrimination task of phase 3. The subjects could discriminate between the large aluminum and glass cylinders, whereas the dolphin could not be trained to perform this discrimination. This performance difference may be attributed to the duration cue being perceived by the human subjects because the signals were stretched by a factor of 50. Additionally, the duration information is approximately 32 dB below the peak level of the primary echo component and may have been masked by the ambient noise of the bay.

REFERENCES

1. Au, WWL and CE Hammer, Jr, Target Recognition via Echolocation by *Tursiops truncatus*, in: Animal Sonar Systems, RG Busnell and JF Fish, ed, p 855–858, Plenum Press, New York, 1980.

2. Hammer, CE, Jr and WWL Au, Porpoise Echo-Recognition: An Analysis of Controlling Target Characteristics, J Acoust Soc Amer, 68, p 1285–1293, 1980.

3. Fish, JF, CS Johnson and DK Ljungblad, Sonar Target Discrimination by Instrumented Human Divers, J Acoust Soc Amer, 59, p 602–606, 1976.

4. Schusterman, RJ, D Kersting and WWL Au, Response Bias and Attention in Discriminative Echolocation by *Tursiops truncatus*, in: Animal Sonar Systems, RG Busnell and JF Fish, ed, p 983–986, Plenum Press, New York, 1980.

5. Evans, WE and BA Powell, Discrimination of Different Metallic Plates by an Echolocating Delphinid, in: Animal Sonar Systems: Biology and Bionics, RE Busnell, ed, Laboratoire de Physiologie, Jouy-en-Josas 78, France, 1967.

6. Au, WW and KJ Snyder, Long-Range Target Detection in Open Waters by an Echolocating Atlantic Bottlenose Dolphin *(Tursiops truncatus)*, J Acoust Soc Amer, 68, p 1077–1084, 1980.

7. Au, WWL, Echolocation Signals of the Atlantic Bottlenose Dolphin *(Tursiops truncatus)* in Open Waters, in: Animal Sonar Systems, RG Busnell and JF Fish, ed, p 251–282, Plenum Press, New York, 1980.

8. Barnard, GR and CM McKinney, Scattering of Acoustic Energy by Solid and Air-Filled Cylinders in Water, J Acoust Soc Amer, 33, p 226–238, 1961.

9. Shirley, DJ and KJ Diercks, Analysis of the Frequency Response of Simple Geometric Targets, J Acoust Soc Amer, 48, p 1275–1282, 1970.

10. Neubauer, WG and LR Dragonette, Observation of Waves Radiated from Circular Cylinders Caused by an Incident Pulse, J Acoust Soc Amer, 48, p 1135–1149, 1970.

11. Welton, PJ, M de Billy, A Hayman and G Quentin, Backscattering of Short Ultrasonic Pulses by Solid Elastic Cylinders at Large *ka*, J Acoust Soc Amer, 67, p 470–476, 1980.

12. Small, AM and ME McClellan, Pitch Associated with Time Delay between Two Pulse Trains, J Acoust Soc Amer, 35, p 1246–1255, 1963.

13. McClellan, ME and AM Small, Time-Separation Pitch Associated with Correlated Noise Burst, J Acoust Soc Amer, 38, p 142–143, 1965.

14. Bilsen, FA, Repetition Pitch: Monaural Interaction of a Sound with the Same but Phase-Shifted Sound, Acustica, 17, p 295–300, 1966.

15. Resnick, SB and LL Feth, Discriminability of Time-Reversed Click Pairs: Intensity Effects, J Acoust Soc Amer, 57, p 1493–1499, 1975.