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The primary emphasis in this paper is on possible cues used by dolphins in performing different sonar discrimination tasks.

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TARGET SONAR DISCRIMINATION CUES

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One of the outstanding characteristics of the dolphin sonar system which distinguishes it from any man-made sonar is the ability to make fine distinctions in the features or properties of targets. Sonar experiments have shown that dolphins can discriminate between objects differing in size, structure, shape and material composition. This discrimination capability has amazed and sparked the interest of many involved in the development and use of active sonar systems.

The ability to perform fine target discrimination, recognition, or classification are often considered synonymous however, there are subtle differences in each function. Target discrimination means the ability to discern some feature or features in the sonar returns that would allow a signal processing unit to decide that target A and B are different targets. Target recognition means the ability to recognize features or qualities of the sonar returns associated with specific targets compared with returns from any other targets. Target recognition involves a discrimination capability, an ability to recall from memory the features of sonar returns from specific targets and the ability to compare present sonar returns with those stored in memory. Target classification means the ability to separate targets into different classes such as metal versus non-metal, organic versus inorganic, eatable versus non-eatable, smooth surface versus rough surface etc. Most of the experiments that will be discussed in this chapter will involve target discrimination; a few will involve target recognition. Target classification experiments involving many different classes of targets are generally difficult to construct and train with animals.

The primary emphasis in this paper will be on possible cues used by dolphins in performing different sonar discrimination tasks. Most of the dolphin sonar discrimination research has been performed in the Soviet Union (Ayrapet'yants and Konstantinov, 1974; Bel'kovich and Dubrovskiy, 1976) and in the United States of America. An extensive review of these experiments has been performed by Nachtigall (1980).

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J. Thomas *et al.*, Plenum Press, New York, 1992

In sonar discrimination experiments dolphins are generally required to choose between at least two targets presented either simultaneously or successively. The targets will usually differ along a single physical dimension and the animal's discrimination threshold is determined by progressively making the difference smaller. Although differences in targets may exist in a single physical dimension (e.g. diameter, wall thickness, length, etc.), several acoustic features may be affected as this single dimension is varied. Therefore, the important consideration in sonar discrimination experiments is to determine what acoustic features are being tested and how these features change with changes to the physical characteristics of the targets. Unfortunately, this is easier said than done since the backscattering process is often quite complex even with simple geometrically shaped targets.

SIZE DISCRIMINATION

Cylinder Length and Diameter

Ayrapet'yants et al. (1969) found that a Black Sea bottlenose dolphin (*Tursiops truncatus*) could discriminate a 30 mm long cylinder from the 25 mm long standard at the 70% correct response level. Zaslavskiy et al. (1969) also found that a harbor porpoise (*Phocoena phocoena*) could discriminate cylinders that were 75 mm versus 95 mm in length at the 80% correct response level. Evans (1973) also studied cylinder size discrimination capability of an echolocating Atlantic Bottlenose dolphin (*Tursiops truncatus*) and an Amazon River dolphin (*Inia geofrensis*). Solid chloroprene cylinders were presented simultaneously and the blindfolded dolphins were required to discriminate the standard from the non standard cylinder. The diameter of the non-standard cylinders was varied in 1 dB target strength increments. The results indicated that both species could discriminate target strength differences of 1 dB at performance levels above 70% correct.

The experiments of Ayrapet'yants et al. (1969) and Zaslavskiy et al. (1969) were actually target strength discrimination experiments. Highlights or echo components were probably present in the echoes from the sonar signal penetrating and propagating along different acoustic paths within the targets and from circumferential waves (Neubauer, 1986). However, for a signal that is incident normal to the longitudinal axis of a cylinder, the echo structure is affected by the diameter and material composition and not length. Since the diameter and material composition were fixed and only length varied, only the amplitude of the target echoes was affected by different lengths. The target strength of an acoustically rigid or soft cylinder of finite length can be expressed as (Urick, 1983)

$$TS = 10 \text{ Log } (aL^2/2\lambda) \qquad (1)$$

where a is the radius, L is the length of the cylinder and λ is the wavelength of the signal. The differences in target strength were approximately 1.6 and 2.1 dB for the targets used by Ayrapet'yants et al. (1969) and Zaslavskiy et al. (1969), respectively. These values compare well with the

1 dB difference observed in the experiment of Evans (1973). However, since the diameter of the cylinders was varied in Evans experiment, additional cues from circumferential waves (Barnard and McKinney, 1961; Diercks et al., 1963) may have been present.

Sphere Diameter

There has been an abundance of sphere size discrimination experiments performed with metallic targets using *Tursiops*. A summation of these experiments are given in Table 1. The 4th column of Table 1 is the difference in the target strength calculated for a standard and comparison sphere at the animal's threshold. The target strength of a large, rigid or soft sphere can be expressed as (Urick, 1983)

$$TS = 20 \text{ Log } (a/2) \tag{2}$$

where a is the radius of the sphere.

Two cues associated with sphere size discrimination are the differences in target strength and the highlight structure of the echoes. The incident signal penetrating and propagating along different paths within a sphere will result in the presence of many highlights or echo components (Shirley and Diercks, 1970). Circumferential wave components will also contribute to the echo structure (Wille, 1965; Uberall et al., 1966). Examples of the echo structure and

Table 1. Results of biosonar size discrimination experiments with spherical targets. Stand. Diam. is the diameter of the standard sphere. Increm. Diam. is the incremental diameter of the comparison sphere at the dolphin's discrimination threshold. T.S. Diff. is the difference in target strength between the standard and comparison target (calculated).

Stand. Diam. (cm)	Material	Increm. Diam. (cm)	T.S. Diff. (dB)	Range (m)	References
5.71	Ni-steel	0.64	0.9	>.5	Turner and Norris (1967)
10.40	steel	3.90	2.8	2 - 6	[+]Dubrovskiy et al. (1971)
57.10	steel	6.40	0.9	2 - 6	"
5.00	lead	0.50	0.8	8	[+]Dubrovskiy (1972)
1.02	lead	0.15	1.2	3	[*]Fadeyeva (1973)
1.40	lead	0.20	1.2	4.8	[*]Dubrovskiy and Krasnov (1971)
10.20	lead	1.50	1.2	2 - 6	Ayrapet'yant and Konstantinov (1974)

[+] - cited in Ayrapet'yant and Konstantinov (1974)
[*] - cited in Bel'kovich and Dubrovskiy (1976)

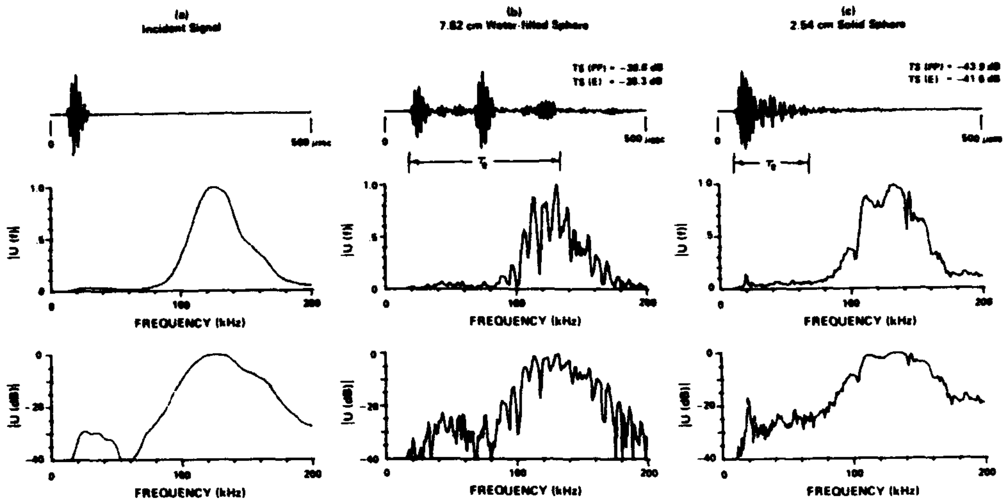

Fig. 1. Example of a simulated dolphin sonar signal and the echo from a 7.62-cm diameter water-filled stainless-steel sphere and 1 2.54-cm diameter solid steel sphere (from Au and Snyder, 1980)

frequency spectrum of echoes from a solid 2.54 cm steel sphere and a 7.62-cm water-filled steel sphere are shown in Fig. 1. A simulated dolphin echolocation signal was used to produce the echoes. The highlight structure (e.g. position and amplitude of the highlights) are determined by the diameter and material composition of the sphere.

Planar Targets

Barta (1969) conducted a size discrimination experiment using circular aluminum disks covered with neoprene. The *Tursiops* was trained to choose the smaller of two simultaneously presented targets. A divider between the targets restricted the minimum range between the dolphin and targets to 0.7 m. The dolphin discriminated a 16.1 cm from a 15.2 cm diameter disk at the 75% correct threshold. Bel'kovich et al. (1969) used plastic foam square targets and trained a common porpoise (*Delphinus delphis*) to choose the larger of two simultaneously presented targets. The dolphin discriminated between a 100 cm^2 and 90.25 cm^2 target at a 77% correct response level.

The main cue available in the planar target size discrimination was differences in target strength. The target strength of a rigid or soft planar target at normal incidence of the signal can be expressed as (Urick, 1983)

$$TS = 20 \text{ Log } (A/\lambda) \tag{3}$$

where A is the area of the target and λ is the wavelength of the signal in water. The target strength differences between the standard and comparison targets at threshold were 1 dB and 0.9 dB for the targets used by Barta (1969) and

Barta (1969), respectively. Backscatter measurements with Barta's targets indicated that threshold size discrimination was performed with a 1 dB difference in target strength.

STRUCTURE DISCRIMINATION

Wall Thickness

Evans and Powell (1967) were first to demonstrate that a blindfolded, echolocating *Tursiops* could discriminate the thickness of metallic plates. The dolphin was trained to discriminate a 30 cm diameter circular copper disc of 0.22 cm thickness from a comparison target. Both targets were presented simultaneously in the same trial. The dolphin did not discriminate the 0.16 and 0.27 thick comparison copper discs from the standard but did discriminate the 0.32 and 0.64 cm thick discs from the standard at a 75% and 90% level, respectively.

The targets used by Evans and Powell (1967) were acoustically examined by Au and Martin (1988) at both normal and 14° from normal incidence angles. An incident angle of 14° corresponded to the incidence angle used by instrumented human divers in the study of Fish et al. (1976) using the same metal plates of Evans and Powell (1967). Au and Martin (1988) found that at normal incidence the backscattered echoes resembled the incident signal and did not seem to contain much useful information for discrimination. However as the incident angle increased to 10°, the echoes began to have multiple highlights which could be used for discrimination. Echoes from four plates at 14° incidence angle are show in Fig. 2. The differences in echo structure between the 22 cm thick copper standard and the 0.32 cm thick copper comparison target are obvious. Two scattering processes were suspected of producing the multiple highlight echoes: "leaky" Lamb waves and edge reflection of internally trapped waves. The two scattering processes are described schematically in Fig. 3. The trapped wave situation is for the longitudinal wave. Transverse waves of lower velocity will also be excited in the plates and converted to longitudinal waves at a boundary upon exiting the plate. The time of arrival of the secondary echo components is a function of the thickness and material composition (velocity of sound in the material) of the plates.

The experiment of Titov (1972) in which a *Tursiops* was trained to discriminate the wall thickness of steel cylinders was briefly described by both Ayrapet'yants and Konstantinov (1974) and Bel'kovich and Dubrovskiy (1976). Presumably, a two-alternative forced choice procedure with simultaneous target presentation was used. The outer diameter and length of the cylinders were 50 mm. The dolphin was trained to choose the thinner of two cylinders presented simultaneously at a range of 5 m. The dolphin was able to discriminate a wall thickness difference of 0.2 mm at the 75% correct response level.

Hammer and Au (1980) performed three experiments (general discrimination, wall-thickness and material composition discrimination) to investigate the target recognition and

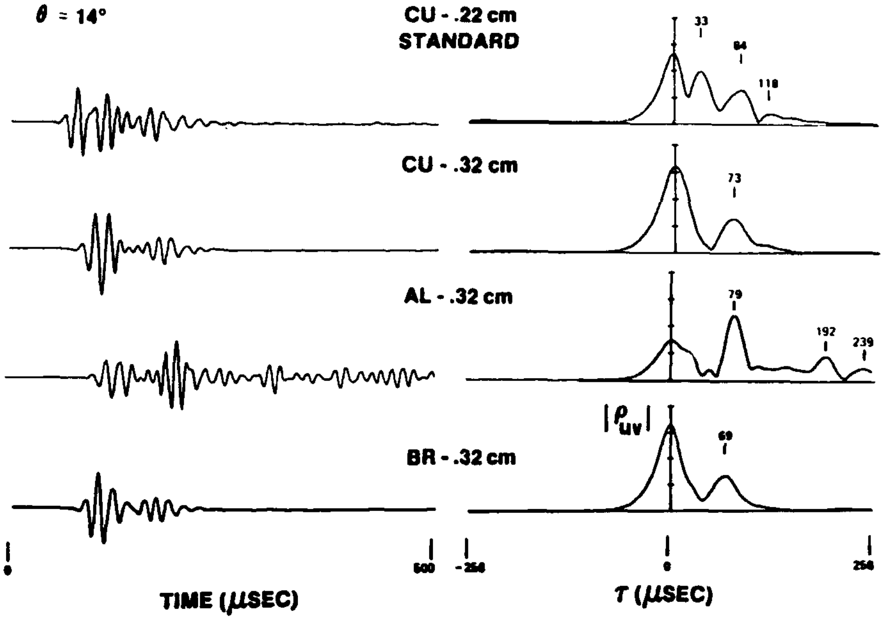

Fig. 2. The echoes and the envelope of the matched filter responses of four plates used in the experiment of Evans and Powell (1967). The relative arrival time of different highlights or echo components are shown in the matched filter responses. The incident angle was 14° from normal incident (from Au and Martin, 1988).

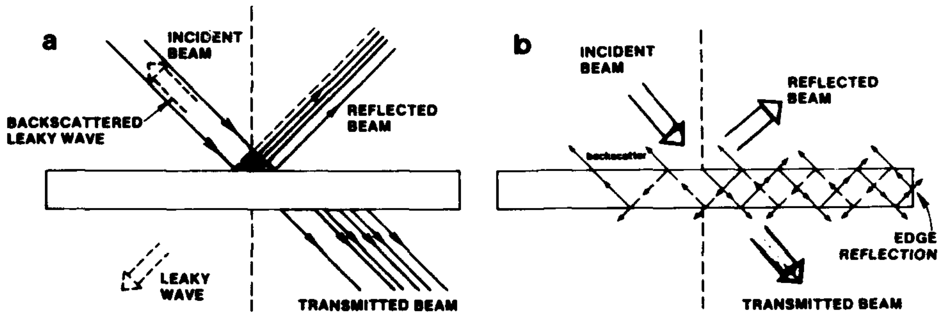

Fig. 3. Schematics describing possible backscattering pro cesses involved with the plates used by Evans and Powell (1967), (a) depicts a leaky wave back-scattering mechanism and (b) depicts a trapped wave and edge reflection mechanism for longitudinal waves. Transverse waves will also be generated at each reflection point in the plate (from Au and Martin, 1988).

discrimination capability of an echolocating *Tursiops*. Two hollow aluminum cylinders, 3.81 cm and 7.62 cm in diameter and two coral rock cylinders of the same diameters, all 17.8 cm long were used as standard targets. The coral rock targets were constructed of coral pebbles encapsulated in degassed epoxy. The targets were presented 6 m and 16 m from the animal's pen. The dolphin was required to echolocate the target and respond to paddle A if it was one of the aluminum standards or paddle B if it was one of the coral rock standards. After baseline performance exceeded 95% correct with the standard targets, probe sessions were conducted to investigate the dolphin's ability to discriminate novel targets varying in structure and composition from the standards. All the probe targets were cylinders, 17.8 cm in length. Two probe targets were used in each probe session and only 8 of 64 trials of the session were used for probe trials, 4 for each probe target.

In the wall thickness experiment, Hammer and Au (1980) investigated the dolphin's ability to discriminate hollow aluminum probe targets with the same outer diameters but different wall thicknesses from the aluminum standards. The results showed that the dolphin could reliably discriminate wall thickness differences of 0.16 cm for the 3.81-cm O.D. cylinders and 0.32 cm for the 7.62-cm O.D. cylinder. A thickness difference threshold was not measured.

The targets used by Hammer and Au (1980) were acoustically examined using simulated dolphin echolocation signals (see also Au and Hammer, 1980). The results for the 3.81 cm cylinders are shown in Fig. 4. The echo structure is shown on the left, the frequency spectrum in the middle and the envelope of the matched filter response on the right. The matched filter results are useful to determine the time of arrival of the various highlights in the echo. The aluminum standard is shown in part a and the comparison or probe targets are shown in parts b-e. From a visual inspection of the echo structures we can see that all of the targets have different arrival times for the secondary echo components, and therefore, different echo structures. Differences in echo structure probably also provided the major cue in the experiment of Titov (1972).

Arrival time differences in the highlights may be perceived as a time-separation pitch (TSP), especially if the echo components are highly correlated. Humans when presented with a correlated pair of sound pulses perceive a pitch that is equal to 1/T, where T is the separation time between pulses (Small and McClellan, 1963; McClellan and Small, 1965). In Fig. 5, the frequency spectrum of the first and second echo components for one of the aluminum targets used by Hammer and Au (1980) are overlaid on the total echo spectrum. Note how well the total spectrum is described by the rippled spectrum for the first two echo components. Such a rippled spectrum is perceived as TSP by humans (Bilsen, 1966).

Au and Pawloski (1992) performed a wall thickness difference study in the free field and in the presence of masking noise, using aluminum cylinders. Their primary emphasis was to determine the cues used by a bottlenose dolphin in

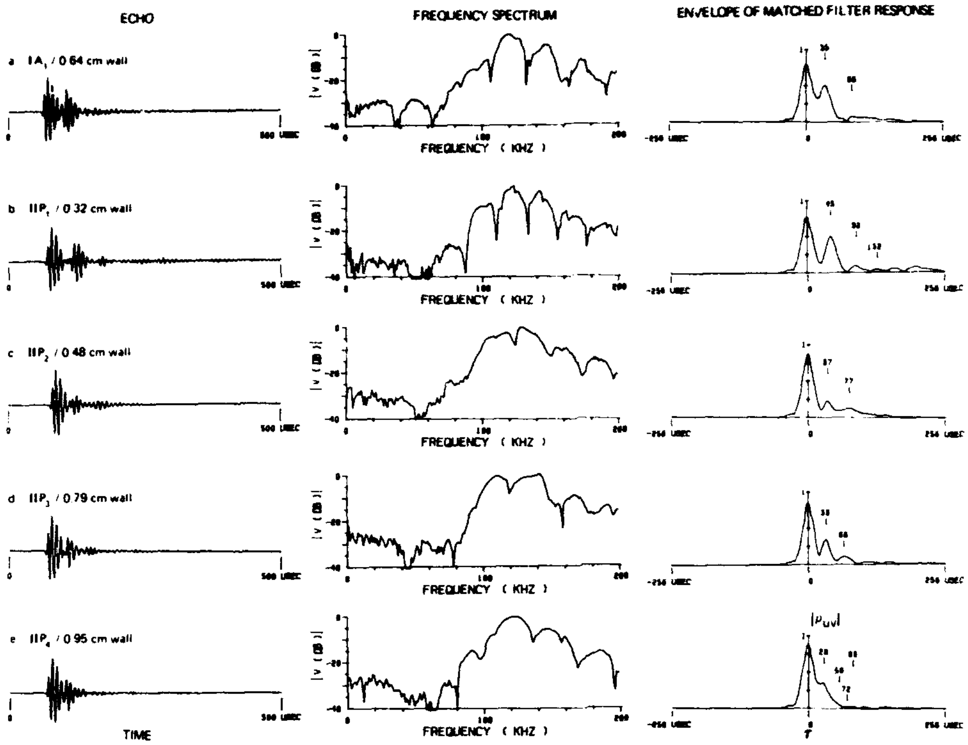

Fig. 4. Results of backscatter measurements of the 3.82-cm O.D. aluminum cylinders used in the wall thickness experiment of Hammer and Au (1980). Target IA_1 was one of the two aluminum standards.

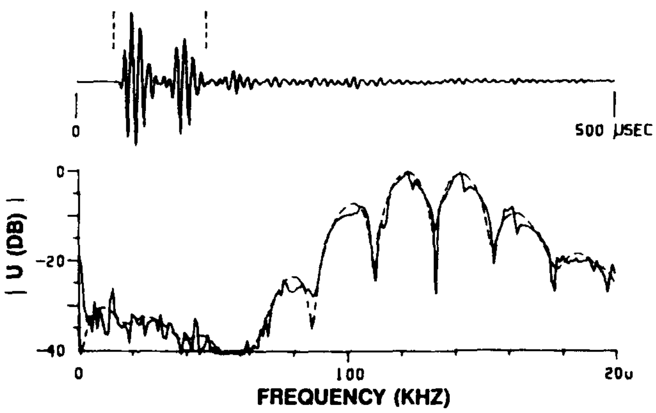

Fig. 5. Example of the ripple spectrum from an echo. The dashed curve is frequency spectrum of the first two echo components or highlights. The target was a 3.82-cm O.D. aluminum cylinder.

performing the discrimination task. A standard cylinder of 6.35 cm wall thickness was compared with cylinders having wall thicknesses that differed from the standard by ± 0.2, ± 0.3, ± 0.4, and ± 0.8 mm. All cylinders had an O.D. of 37.85 mm, and a length of 12.7 cm. The dolphin was required to station in a hoop while the standard and comparison targets, separated by an angle of ± 11° from a center line were simultaneously presented at a range of 8 m. They found that the dolphin 75% correct response threshold occurred at wall thickness differences of -0.23 mm and +0.27 mm. The echoes from the standard and the 0.3 mm thinner comparison target for a typical dolphin echolocation signal are shown in Fig. 6. The animal was able to perform above 75% correct response threshold for this discrimination. The echoes from the standard and the 0.2 mm thinner comparison target are shown in Fig. 7. The animal performed below threshold for this discrimination. Let τ_{s1} be the time between the first and second highlight for the echo from the standard target, and let τ_{c1} be the time between the first and second highlight for the comparison target, then the difference between the two times is $\Delta\tau = \tau_{s1} - \tau_{c1}$. Values for $\Delta\tau$ are given above the

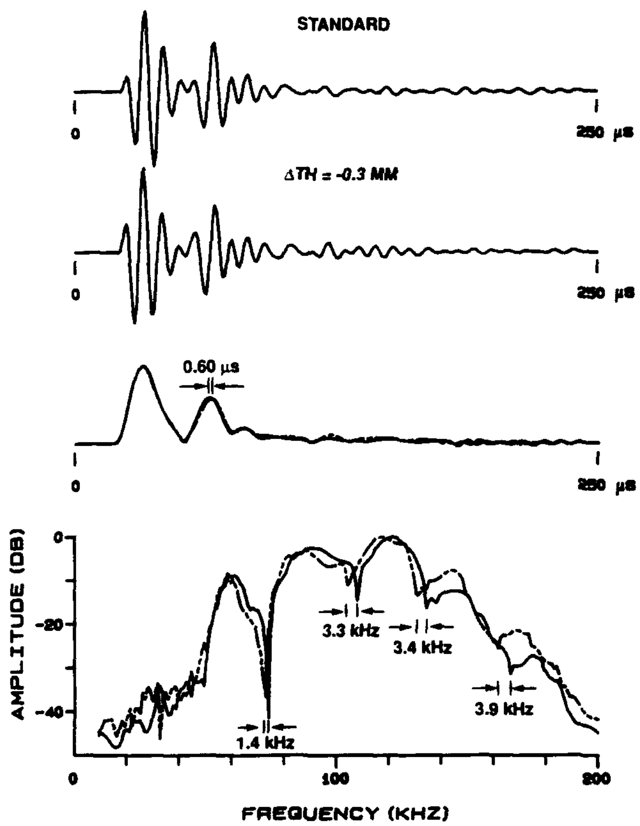

Fig. 6. Echo waveform, envelope and frequency spectrum for the standard and the comparison target having a wall thickness difference of -0.3 mm. The dashed curves for the envelope and the frequency spectrum are for the comparison target (from Au and Pawloski, 1992).

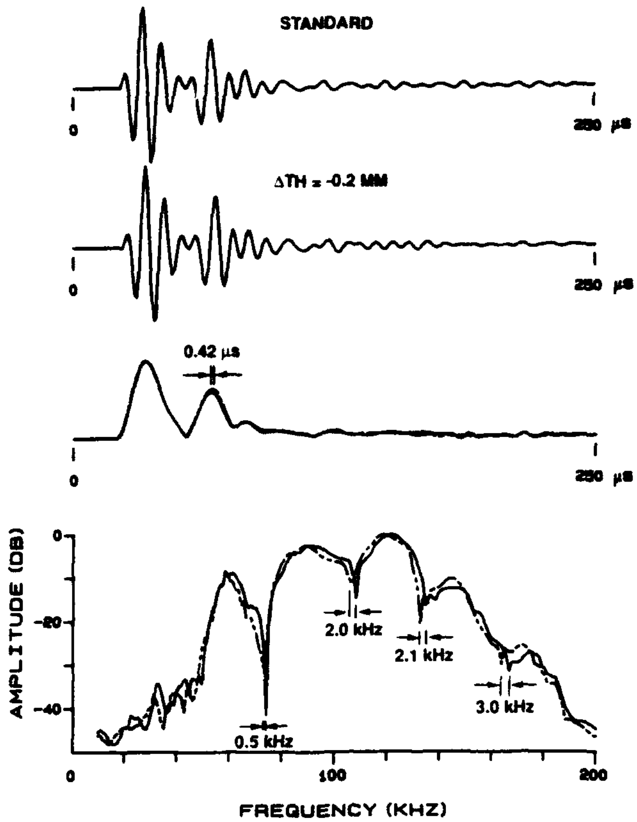

Fig. 7. Echo waveform, waveform envelope and frequency spectrum for the standard and the comparison target having a wall thickness difference of -0.2 mm. The dashed curves for the envelope and the frequency spectrum are for the comparison target (from Au and Pawloski, 1992).

envelopes of the waveforms in Figs. 6 and 7. For the case in which the dolphin performed the task above threshold, $\Delta\tau \approx$ 600 ns and for the case in which the dolphin performed below threshold, $\Delta\tau \approx$ 420 ns. These results imply that if the dolphin processed the echoes in the time domain, the animal can resolve time differences of approximately 500 ns. Differences in the frequency spectra of the echoes from the standard and comparison targets can be seen in Fig. 6 and 7. The frequency spectra for the thinner comparison target resembled the spectrum for the standard target, but was shifted slightly towards lower frequencies. The spectra for the thicker comparison target was shifted toward higher frequencies. If the dolphin used this shift in frequency spectra to discriminate wall thickness difference, then the spectral data suggest that the dolphin could perceive a shift of approximately 3.3 kHz, but not a shift of 2.1 kHz. Splitting the difference in the two cases depicted by Figs. 6 and 7, the dolphin's capability to detect frequency shifts in broadband spectra would be approximately 2.7 kHz. The spectral shifts, also caused the spectral amplitudes at some frequencies to be slightly different by about 3 to 5 dB. However, these amplitude differences were probably not the main cues used by the dolphin since comparable amplitude differences can be seen in the two cases shown in Figs. 6 and 7. Instead of detecting the time interval difference between the first and second highlights in the echoes from the standard and comparison targets or detecting a frequency shift in the spectra of the echoes, the dolphin may have relied on TSP cues. The first two highlights should generate a TSP of approximately 28.30 kHz for the standard, 27.94 kHz for the -.2 mm and 27.77 kHz for the -0.3 mm comparison targets. If the dolphin was using differences in TSP to discriminate the targets, we can infer that the animal could discern a TSP difference of 530 Hz between the standard and the -.3 mm comparison target, but could not discern the 360 Hz difference between the standard and the -0.2 mm comparison target. Therefore, the dolphin's TSP discrimination threshold may be somewhere below 530 Hz and above 360 Hz.

Discrimination tests with the thinner comparison targets were also conducted in the presence of broadband masking noise. For an echo energy-to-noise ratio of 19 dB the dolphin's performance was comparable to its noise-free performance. At an energy-to-noise ratio of 14 dB the dolphin was unable to achieve the 75% correct threshold with any of the comparison targets. An example of an echo from the standard cylinder with the signal-to-noise ratio equal to 23 dB is shown in Fig. 8. All but the first two highlights were masked by the noise, suggesting that the dolphin performed the discrimination task using only the first two highlights during the masking noise portion of the study.

Pyramid Steps

Bel'kovich et al. (1969) trained two Delphinus delphis to discriminate a standard three-stepped pyramid with various comparison targets. The standard pyramid was constructed of foam plastic squares steps, each 12 mm thick. The base step had an area of 100 cm^2, the middle, 49 cm^2 and the top step, 9 cm^2. This standard was compared with the following comparison targets:

a. single layer triangle and square of 100 cm^2 area,
b. a two-stepped pyramid (top step missing),
c. a three-stepped pyramid with the top step smaller than 9 cm^2,
d. three-stepped pyramids with the thickness of the two step varied.

The dolphins easily discriminated the standard target from the single-layered targets and the two-stepped pyramid. When the area of the top step of a three-stepped comparison target was reduced to 6.25 and 8.4 cm^2, the dolphins' performance fell to near 70%. The dolphins easily discriminated the comparison three-stepped pyramid when the thickness of the top two steps was reduced from 12 mm to 6 mm. When only the thickness of the middle step was reduced to 6 mm, the dolphins' discrimination performance dropped to 86.7%.

Bel'kovich et al. (1969) concluded that "it is reasonable to assume that the dolphins distinguished between the figures (step thickness differences) by using the change in spectral composition of the reflected echo signals, including change in the relationship between the time of their return and the elements constituting the truncated stepped pyramid". The echoes from stepped pyramids should contain highlights that are associated with each step. The highlights should be highly correlated and could produce TSP in the auditory system of the dolphins. Varying the step size will affect the time of arrival and varying the area will affect the relative amplitude of the highlights.

Solid and Hollow Cylinders

The first experiment of Hammer and Au (1980) involved a general discrimination in which two of the probe targets were solid aluminum that had the same diameters as the two standard aluminum cylinders. The dolphin could easily discriminate the hollow aluminum standards from the solid aluminum probe targets. Backscattered measurements of the targets revealed that the echoes from the solid and hollow cylinders had obviously different echo structures.

MATERIAL COMPOSITION DISCRIMINATION

Metal Plates

Evans and Powell (1967) were the first to demonstrate that an echolocating *Tursiops* could discriminate material composition of metallic plates. Aluminum, copper and brass circular discs of varying wall thickness and a diameter of 30 cm were used as targets. The blindfolded dolphin was required to discriminate the 0.22 cm thick copper standard from a comparison target. The dolphin was able to discriminate aluminum discs of 0.32, 0.64 and 0.79 cm thickness from the copper standard at a performance level greater than 95% correct. Brass discs of 0.64 and 0.98 cm thickness were discriminated from the copper standard with 100% correct performance. However, the dolphin was unable to discriminate the 0.32 cm thick brass from the copper standard. According to Evans (1973) the material composition and thickness experiment was replicated with another *Tursiops* and a *Lagenorhychus obliquidens* with comparable results.

The backscatter results of Au and Martin (1988), previously discussed in the section on thickness discrimination, are also applicable to the material composition discrimination experiment of Evans and Powell (1967). Echoes from the copper standard and aluminum, brass and copper comparison plates at 14° incidence angle are shown in Fig. 2. The differences in echo structure between the 0.22 cm thick copper standard and the comparison plates are obvious. The time of arrival and amplitude of the secondary echo components are functions of the thickness and material composition (velocity of sound in the material) of the plates. These multi-highlight echoes could generate TSP in dolphins.

Solid Spheres and Cylinders

A considerable amount of research has been performed in the Soviet Union on the capability of delphinids to discriminate material composition of spherical and cylindrical targets (Bel'kovich and Dubrovskiy, 1976). Three different dolphin species, Tursiops truncatus, Phocoena phocoena, and Delphinus delphis have been used with targets constructed from a host of different materials. A summary of the Soviet's material composition discrimination experiments with echolocating dolphins is listed in Table 2. The results indicate that dolphins could discriminate most of the materials tested rather easily except for steel versus duraluminum and wax versus rubber. It is interesting to note that three different experiments (Dubrovskiy et al., 1979; Babkin et

Table 2. Summary data of Soviet biosonar material composition discrimination experiments (after Bel'kovich and Dubrovskiy, 1976).

Target	Stand. Target	Comparison Target	% Corr	Range	References/Species
Cyl.	Steel	Wood, Plastic, Glass	75	4-6 m	Zaslavskiy et al.,
d=7.5 cm	Wood	Plastics			1969 (Phocoena)
l=11.5 cm					
Spheres	Steel	Duraluminum	46-67	3-11 m	Dubrovskiy et al.,
d=5.0 cm					1970 (Tursiops)
Spheres	Brass	Alum. Steel, Texolite	>91	-	Abramov et al.,
d=5.0 cm		Ebonite, *Fluoroplastic*	100	-	1971 (Tursiops)
Sphere	Lead	Steel, Duraluminum, Wax	>97	5-11 m	Babkin et al.,
d=5.0 cm		Rubber, Paraffin, Plexigl.	>96	"	1971 (Tursiops)
	Steel	Duraluminum	62	"	
		Wax, Rub., Paraf. Plexigl.	>93	"	
	Dural.	Wax, Rub., Paraf. Plexigl.	>92		
	Wax	Rubber	61	"	
		Paraffin	72	"	
		Plexiglass	100	"	
	Rubber	Paraffin	81	"	
		Plexiglass	86	"	
	Paraf.	Plexiglass	93	"	
Spheres	Steel	Duraluminum	58-65	3-10 m	Titov, 1972
d=5.0 cm	Brass	Duralumin., Ebonite, Steel			(Tursiops)
Spheres	Steel	Duraluminum	70	5-11 m	Titov, 1972
d=5.0 cm		Ebonite, Lead, Plexiglass	>92	"	(Delphinus)
	Ebon.	Plexiglass	78	"	
	Lead	Plexiglass	100	"	
	Brass	Ebonite, Steel, Duralumin.	>93	"	
		Plexiglass, Lead	>90	"	
Spheres					
d=7.0 cm	Alum.	Brass	96	-	Yershova et al.
					1973 and
d=1.0 cm	Alum.	Brass	46	-	Golubkov et al.
					1973 (Tursiops)

al., 1971 and Titov, 1972) comparing steel versus duraluminum resulted in relatively poor performance by the animals.

Dubrovskiy et al. (1970, 1971) postulated that dolphins discriminated the material composition of spherical targets by analyzing the period of oscillation, Δ, in the frequency spectrum of the echoes. The parameter Δ is monotonically related to velocity of transverse waves in the target material. Dubrovskiy et al. (1971) and Dubrovskiy and Krasnov (1971) experimentally confirmed this hypothesis. They also argued that size discrimination of spheres could be achieved by the same mechanism associated with Δ. Golubkov et al. (1973); Dubrovskiy and Fadeyeva (1973); Yershova et al. (1973) also considered the time-domain characteristics of echoes from spheres and related the oscillations in the frequency domain to the separation between the primary echo and secondary echo. An example of the echo (measured at the NOSC-Hawaii facility) from a 12.7 cm solid aluminum sphere using simulated dolphin signals is shown in Fig. 8. Note that the echo structure contains many highlights and these highlights may be perceived by a dolphin as TSP. The frequency spectrum of the echo also contains oscillations that are caused by the presence of multiple highlights.

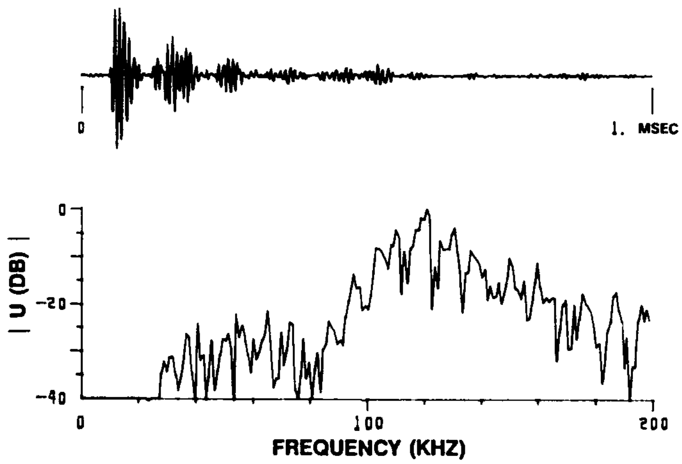

Fig. 8. The echo from a 12.7-cm diameter solid aluminum sphere.

Hollow Water-filled Cylinders

In the third experiment of Hammer and Au (1980), the dolphin's ability to discriminate material composition was tested using *bronze, glass* and stainless steel probe cylinders that had the same dimensions as the aluminum standards. The dolphin could discriminate the bronze and steel cylinders from the aluminum but classified the glass probes with the aluminum standard. In a follow-on study, Schusterman et al. (1980) trained the same dolphin to discriminate between the aluminum and glass cylinders. Using a two-alternative forced-choice response, the dolphin was required to strike paddle A when an aluminum cylinder was presented and paddle B when a glass cylinder was presented. After 30 sessions, the dolphin could perfectly discriminate the 3.61-cm O.D. aluminum and glass cylinders. However, the animal was never able to discriminate between the 7.62-cm O.D. aluminum and glass cylinders.

Echoes from the 3.81-cm O.D. cylinders used by Hammer and Au (1980) are displayed in Fig. 9. The similarities or dissimilarities between the echoes can be more readily determined by studying the envelopes of the matched filter responses rather than the echo waveforms or their frequency spectra. The echo waveforms and their corresponding frequency spectra exhibit many minor variations that tend to hinder comparison of the target echoes. On the other hand, the envelopes of the matched filter responses are fairly simple, yet accentuate details such as time of arrival of highlights, correlation between echo components and transmitted signal, and the relative strength of the various highlights. The matched filter responses of the steel and bronze cylinders are readily discernable from the aluminum standard. The time of arrival of the 2nd highlight for the aluminum standard is considerably different then for the steel and bronze cylinders. However, the time of arrival of the 2nd highlight for the aluminum and glass cylinders is the same, and the overall shape of the two matched filter responses is very similar.

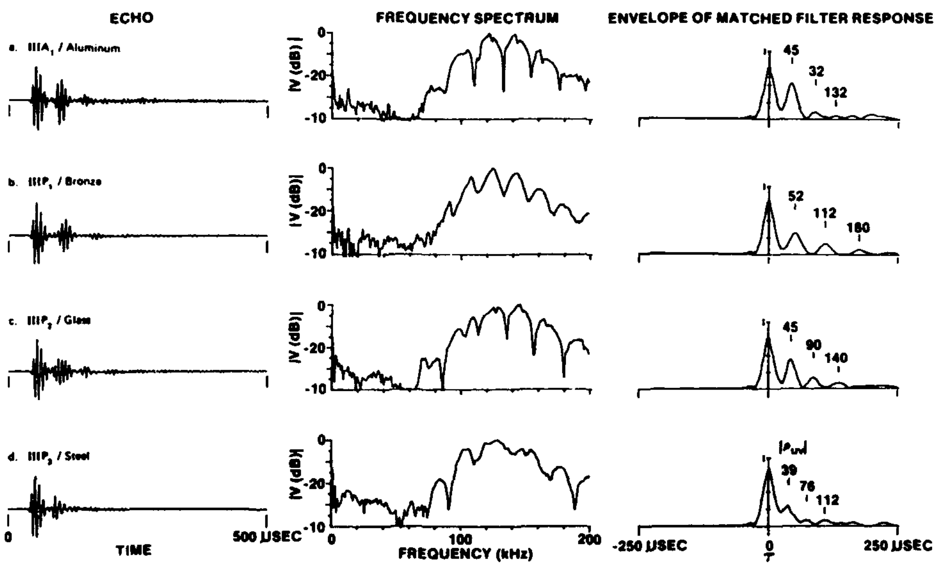

Fig. 9. Results of backscattered measurements of the 3.81-cm O.D. cylinders used by Hammer and Au (1980) in their material composition discrimination experiment.

SHAPE DISCRIMINATION

Planar Targets

Barta (1969) trained a blindfolded dolphin to choose between circular, squares and triangular aluminum disks covered with neoprene as targets. Using the same two alternative forced-choice paradigm as in the size discrimination experiment reported on earlier, the animal reliably discriminated circles from squares and triangles. Bagdonas et al. (1970) used targets made from ebonite (10 mm thick) and trained a Delphinus delphis discriminate a 100^2 cm square from a 50 cm^2 triangle. Bel'kovich and Borisov (1971) trained a Delphinus to differentiate flat squares from similar sized squares with circular holes cut in the center. The animal could differentiate flat squares with 6.5% of the area cut out from whole flat squares.

The dolphins in the experiments of Barta (1969) and Bagdonas et al. (1970) probably relied on the changes in echo amplitude as they scanned across different shaped targets. The amplitude of the echo from the different targets will vary as a function of the angle of the incident signal, as n shown in Figure 10 for the targets used by Barta (1969). Differences in target strength also provided an additional cue in the targets used by Bagdonas et al. (1970). The cues present in the experiment of Bel'kovich and Borisov (1971) were probably differences in target strength and the presence of secondary highlights caused by reflections off the edges of the circular holes. Bel'kovich and Borisov concluded that differences in reflectivity and in the frequency spectrum of the echo were the primary cues. The presence of secondary highlights for the squares with holes

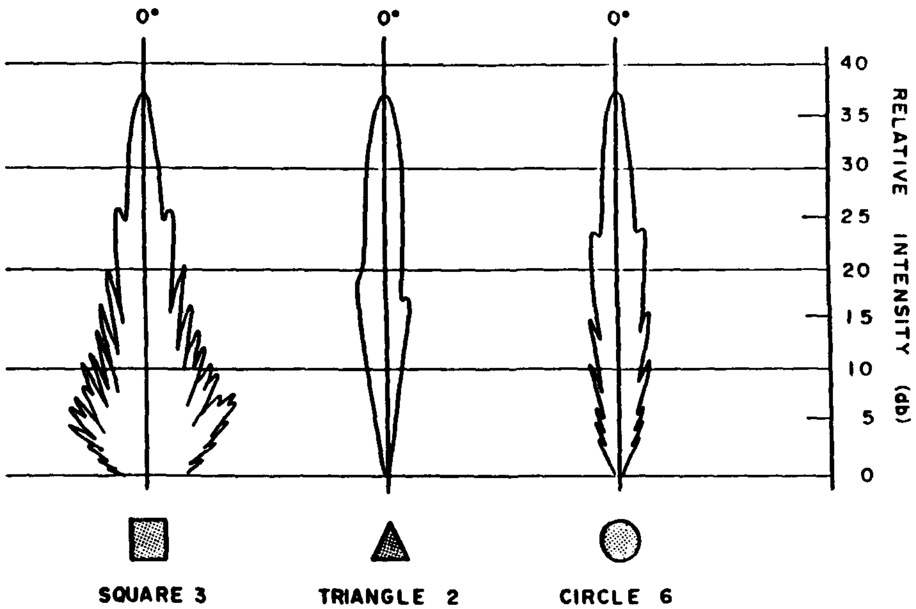

Fig. 10 Polar plots of echo patterns from the targets of Barta (1969) obtained with simulated dolphin signals (from Fish et al., 1976).

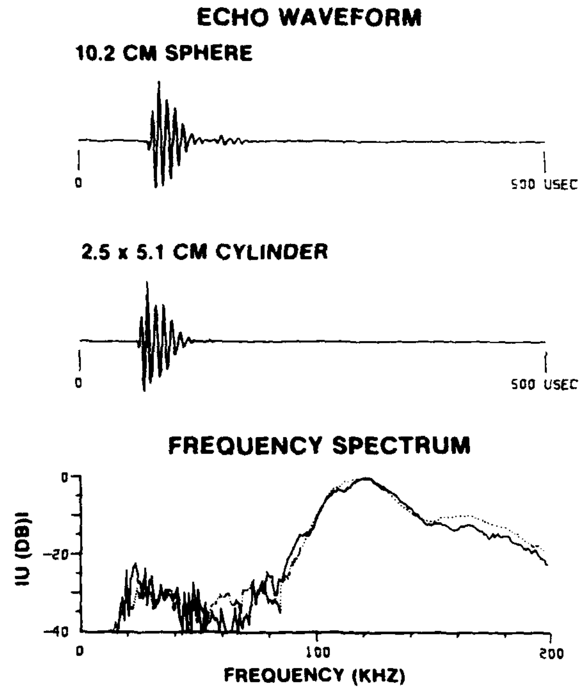

Fig. 11. Results of backscatter measurements of one of the foam spheres and cylinder used in the sphere-cylinder discriminaiton experiment of Au et al. (1980). The dotted frequency spectrum is for the cylinder echo.

when scanning across the flat surfaces of the cubes or the tops of the cylinders and received relatively uniform amplitude echoes when scanning across the curved portion of the cylinders.

SUMMARY AND CONCLUSIONS

Dolphins have a keen capability to discriminate subtle differences in target with their sonar. The categories of various type of discriminations include the following:

a. target size (10 - 20% difference in area)
b. wall thickness of plates and cylinders (0.2 mm - 0.1 cm difference)
c. material composition of plates, spheres and cylinders
d. structure of cylinders and planar targets
e. shapes of planar targets
f. shapes of spheres and cylinders.

The target discrimination capability of echolocating dolphins is in part attributable to the animal being able to recognize 1 dB differences in the amplitude of echoes. The use of broadband short-duration transient-like echolocation signals with good time resolution properties that would allow the signal to encode important target information also play an important role in the dolphins discrimination capabilities.

In the absence of amplitude difference cues, most of the discriminations are probably performed by examining the targets' echo structure. Complex echo structures are the results of specular reflections from the front surface of a target combined with internal reflections that can propagate along different paths, reflections from different parts of a target, and contributions from circumenfertial wave traveling around a target. Dolphin echolocation signals have sufficient bandwidth are short enough in duration so that these highlights are distinct and resolvable. These highlights convey important target information that can be used by the dolphin. The ability to scan across targets and also insonify targets from different angles is another important capability in discriminating targets with reflectivity that is aspect dependent. Plausible answers can be given to explain the basis by which dolphins were able to solve the sonar discrimination task in most if not all of the discrimination experiments discussed. However, in situations where the major cues are derived mainly from the echo structure, we do not know the relative importance of time-domain, frequency domain and TSP cues, assuming that dolphins can perceive TSP. Furthermore, there is insufficient data to quantify the properties of the basic auditory processes associated with discriminating broadband click signals.

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