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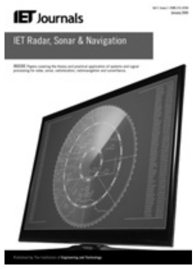

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# Why dolphin biosonar performs so well in spite of mediocre 'equipment'

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**Abstract:** Dolphins have been found to have an excellent sonar system that is able to detect and recognise targets in noisy and highly reverberant environments. However, their 'equipment' has only mediocre characteristics from a technological sonar perspective. How dolphins perform the biosonar task so well is addressed in this manuscript. Echolocating dolphins have the capability to make fine discrimination of target properties such as wall thickness difference of water-filled cylinders and material differences in metallic plates, and to discriminate and recognise species of fish food. The high temporal resolution of the biosonar signals along with the high dynamic range of its auditory system are critical factors for target discrimination. An experiment in metallic plate composition discrimination suggests that dolphins attended to echoes 20–30 dB below the maximum level. Some of the properties of the dolphin sonar system are fairly mediocre, yet the total performance of the system is often outstanding. When compared to some technological sonar, the energy content of the dolphin sonar signal is not very high, the transmission and receiving beamwidths are fairly large, and the auditory filters are not very narrow. Yet the dolphin sonar has demonstrated excellent capabilities in spite of some mediocre features of its 'hardware.'

## 1 Introduction

Echolocation experiments with captive dolphins began about five decades ago with Schevill and Lawrence [1] and Kellog [2] attempting to obtain evidence that bottlenose dolphins (*Tursiops truncates*) echolocate. Norris *et al.* [3] provided unequivocal evidence to demonstrate echolocation in dolphins by using suction cup blindfolds to cover a dolphin's eyes while the animal was required to swim and avoid obstacles, and retrieve fish rewards that were thrown into the animal's tank. Busnel and Dziedzic [4] also trained a blindfolded harbour porpoise (*Phocoena phocoena*) to swim through a maze of vertically hanging wire. Following these initial studies, various types of echolocation experiments have been performed to study the biosonar process and determine the capabilities of odontocetes to detect, discriminate, localise and recognise targets.

The biosonar capabilities of dolphins to perform complex target discrimination tasks have been conducted mainly with objects that are foreign to these animals but familiar to humans. Review articles on the target discrimination experiments have been written by Nachtigall [5], Au [6] and Au and Hastings [7]. Some of these experiments included material and wall thickness discrimination of metallic plates [8], material composition of cylinders at arbitrary aspects [9], material composition discrimination of spheres [10], shape discrimination of planar targets [11], shape discrimination between spheres and cylinders [12], shape matching of polyvinyl chloride (PVC) objects across vision and echolocation [13] and wall thickness of metallic cylinders [14]. These and other experiments have clearly shown that dolphins possess a very sophisticated biosonar system that has certain capabilities beyond the most modern and sophisticated technological sonar. From these experiments, we have gained much knowledge about the target discrimination and recognition capabilities of the dolphin biosonar system, but we have yet to design a technological sonar that can rival that of the dolphins' in detecting, discriminating and recognising targets in noisy and reverberant environments.

A simple internet search on dolphin mine hunting systems will bring up several descriptions of the US Navy Mk 4, Mk 7, and Mk 8 dolphin mine hunting systems. The Mk 4 system is used to detect mines tethered off the sea floor. In the Mk 7 system dolphins are used to detect and mark mines that are laying proud on the bottom of the ocean or buried in the sediment. Dolphins have been used in mine hunting, sweep and interdiction operations to detect and mark Iraqi mines. The Mk 8 system is a joint team with both dolphin and human components that are used in shallow waters.

As we proceed through this manuscript it will be obvious that some of the characteristics of the dolphin sonar are not very sophisticated (its biosonar 'equipment' is rather mediocre with respect to certain features of great importance in manmade systems), yet dolphins can perform biosonar tasks that the most sophisticated technological sonar cannot. In this article, we will describe some of the general properties of the dolphin biosonar system, discuss some of the prior sonar discrimination experiments, the use of the biosonar in nature and in mine hunting, and attempt to elucidate how dolphins can perform such amazing tasks and perhaps introduce some different aspects of sonar system design that may be helpful in making progress in sonar development.

## 2 Biosonar system

### 2.1 Hearing and auditory filters

The first audiogram of a dolphin was obtained by Johnson [15] who found that the Atlantic bottlenose dolphin would hear over an approximately 12 octave range of frequency with a maximum sensitivity of about 40 dB at 1 μPa. The auditory system is similar to most mammalian auditory systems and can be modelled as bank of constant-$Q$ filters. The auditory filter shape of a mammalian subject can be determined by performing a notched noise masking experiment where the tone signal is directly in the middle of the notch. Such a study was performed by Lemonds *et al.* [16] and their results are shown in Fig. 1 for frequencies of 40, 60, 80 and 100 kHz centre frequency. Note that the filters are not very narrow. The shapes are similar to that of humans if we normalised the frequency by dividing by $f_o$ for any given filter. If the 3 dB bandwidth is plotted as a function of frequency, a line representing a $Q$ of 7.2 would fit the bandwidth data very well with a $r^2$ value of 0.95. Mathematically, much narrower overlapping filters can be created and used to analyse sonar echoes.

### 2.2 Biosonar signal and beam patterns

The bottlenose dolphin emits brief broadband biosonar signals that have peak-to-peak amplitudes that vary between 190 and 228 dB [6], depending on the circumstances. The biggest influence on the source level is the target range followed by the amount of noise. An example of a biosonar signal used by an Atlantic bottlenose dolphin is shown in Fig. 2. The signal is short, between 50 and 70 μs, in duration and resembles a tonal signal that is amplitude modulated by either a $\cos^2$ or a Gaussian envelope. Owing to the short duration, the spectrum is necessarily broad with a $Q$ of approximately 2.4–3. It should be noted that the biosonar signal in Fig. 2 is only representative; there can be large variations in the peak frequency, bandwidth and spectral shape in some sonar searches and rather consistent stereotypical patterns in other sonar searches [6, 17]. The peak frequency varies from about 90 to 130 kHz with bandwidths between 35 and 50 kHz. The peak-to-peak source level for dolphins in open waters varies between 190 and 228 dB at 1 μPa.

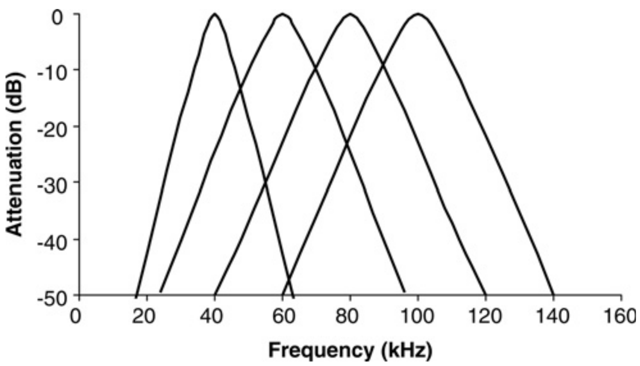


**Fig. 1** *Auditory filter shape for a bottlenose dolphin (from Lemonds et al. [16])*

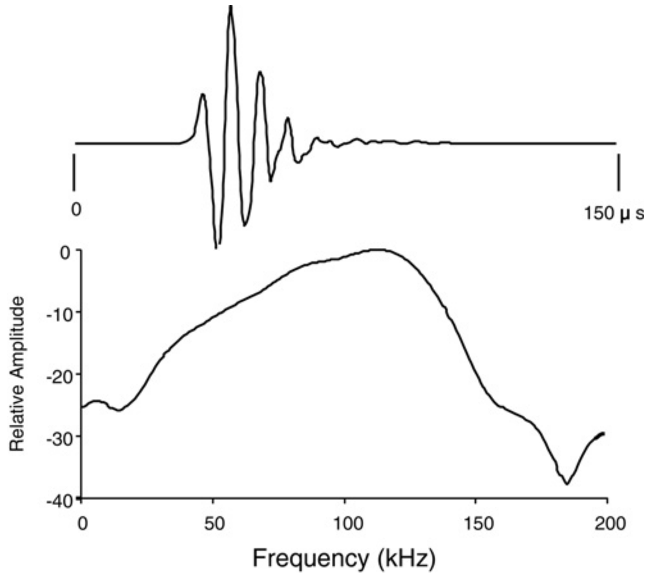


**Fig. 2** *Waveform and frequency spectrum of a typical biosonar signal emitted from a bottlenose dolphin (from Au [6])*

The broadband nature of the dolphin's biosonar signal is perhaps the singly most important factor in explaining the animal's capability to make fine discrimination and recognition of targets. The broadband property of the signal allows for fine temporal resolution on the order of 20 μs. Therefore echoes from most objects will have several 'highlights' caused by specular reflections from different parts of an object or from echoes propagating along different pathways within a target or a combination of both processes. These extended echoes can provide a sense of 'texture' when presented to an auditory system and may provide important cues to a dolphin.

Although the peak-to-peak amplitude can be very high, the amount of energy in the click is not very high when compared with technological sonars. We can compare the energy flux density of a typical sonar tone burst and that of a dolphin biosonar signal by first defining the dolphin sonar signal as $p(t) = As(i)$, where $A$ is the peak amplitude and $s(t)$ is the normalised waveform. The energy flux density of the dolphin signal can be expressed as

$$E_{\text{dolphin}} = \text{SPL}_{\text{pp}} - 6 + 10\log\left(\int_0^T s^2(t)\,\mathrm{d}t\right) \quad (1)$$

The energy flux density of a tone burst is

$$E_{\text{TB}} = \text{SPL}_{\text{pp}} - 9 + 10\log(T) \quad (2)$$

where $T$ is the duration of the tone burst. The integral of the normalised dolphin biosonar signal squared in (1) is about −52 dB [6] so that we can express the difference in energy between the dolphin click and a tone burst as

$$\Delta E = E_{\text{TB}} = E_{\text{dolphin}} = 49 + 10\log(T) \quad (3)$$

A graph of the amount of energy a tone burst would have over a biosonar signal of the same peak-to-peak amplitude is shown in Fig. 3. A very short tone burst of 100 μs will have about 9 dB more energy than the high-frequency dolphin sonar signal of the same peak-to-peak amplitude. The excess energy increases logarithmically with the duration of a tone burst. A 1 ms tone would have 19 dB more energy than a dolphin emitting the same peak-to-peak level biosonar signal. Therefore most technological sonar will project much more power into the water than a dolphin.

Dolphins project their biosonar signal in a beam and receive echoes via a broader beam. The beam patterns of the transmitting and receiving beams are shown in Fig. 4 in both the horizontal and vertical planes. The half-power beamwidth of the transmitting beam in the horizontal plane is approximately 10° in both planes. The receive beam has a half-power beam width of approximately 14° in the horizontal plane and 17° in the vertical plane. The major axis in the vertical plane is pointed between 5 and 10° above the horizontal plane and is pointed directly ahead of the animal in the horizontal plane. These beam patterns are very wide in comparison to many technological sonars. For example, the Echoscope 3D Sonar from CodaOctopus has 128 beams in both the horizontal and vertical planes, each beam being 0.39° wide so that a swath of 50° × 50° is covered in one ping. For a relatively small target such as a mine, the beam of the dolphin will likely encompass the whole target at ranges greater than about 10 m so that the echoes will be a

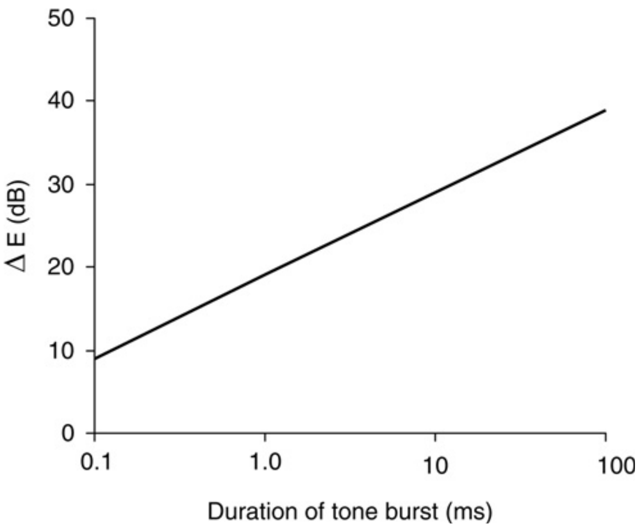


**Fig. 3** *Amount of energy in dB that a tone burst would have over a dolphin echolocation signal*

composite or summation of reflections from different parts of the target. The integration of multiple highlights by an auditory system may be to the advantage of a dolphin but not to a man-made sonar system.

## 3 Examples of biosonar performance

Many experiments have been performed that highlight the capabilities of the dolphin's biosonar to perform complex target discrimination and recognition tasks. Only four experiments will be discussed here, one on target detection in reverberation, one on material composition and wall thickness discrimination, one on fish discrimination and recognition and finally, one on an instrumented dolphin hunting for a dummy mine placed on the ocean bottom. Readers who would like to read more on dolphin sonar discrimination experiments should consider Au [6].

### 3.1 Target detection in reverberation

A sonar system is usually limited by noise or reverberation. Reverberation differs from noise in several aspects. It is caused by the sonar itself and is the total contribution of unwanted echoes scattered back from objects and inhomogeneities in the medium. Murchison [18] studied the effects of bottom reverberation on the target detection capabilities of two bottlenose dolphins in Kaneohe Bay. A 6.35 cm diameter solid steel sphere was used and eventually placed on the bottom. The animals' 50% correct detection threshold ranges for different target depth are shown in Fig. 5. The threshold range for the target on the bottom was approximately 70 m.

Au [19] used a simulated dolphin sonar signal to measure the scattering strength of the bottom where Murchison performed his experiment. Taking the target strength into consideration and the difference in the transmit and receive beam patterns of the transducer and the dolphin, the reverberation form of the sonar equation was used to estimate an echo energy-to-reverberation ($E/R$) of approximately 4 dB. An integration time of 264 μs, which seems typical for the bottlenose dolphins receiving short broadband signals [6], was used in the estimation of $E/R$. An example of an $E/R$ ratio of 4 dB is shown in Fig. 6 [19]. The highest highlight of the target echo is clearly detectable; however, the secondary highlights are masked

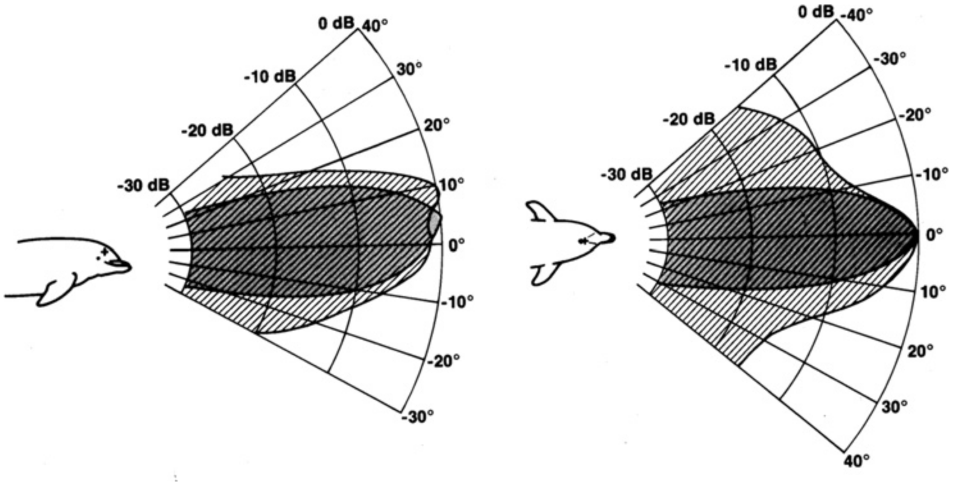


**Fig. 4** *Transmit and receive biosonar beam pattern of an Atlantic bottlenose dolphin in the vertical and horizontal planes*

Inner (narrower) beam is the transmit beam pattern and the outer (wider) beam is the receive beam pattern (from Au [6])




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by the reverberation so that the acoustic quality of the echo was altered. The dolphin probably could hear the largest highlight but the echo probably did not 'sound' like the sphere they were trained to detect and consequently reported the target as not present. Therefore it seems that a target detection experiment probably is not purely one of detecting signal in reverberation, but also involves discriminating the features of the echoes from a target. If the lower amplitude highlights are masked by reverberation or noise, the dolphins might hear the larger highlight components of the echo but the echo probably would not 'sound' like the target they were trained to detect. Therefore target detection in noise and reverberation, also involves target recognition. In another experiment in which a clutter screen of forty eight 5.1 cm diameter cork spheres evenly spaced 15.2 cm apart in a 6 × 8 array were used with metallic cylinders placed at different distances in front of the screen [21]. The dolphin's detection threshold when the smallest cylinder (3.81 cm diameter, 10 cm long) was placed in the plane of the clutter screen occurred at the signal-to-reverberation ratio of 3 dB.

### 3.2 Discrimination of material composition and thickness of metallic plates

Evans and Powell [22] demonstrated that a blindfolded, echolocating bottlenose dolphin could discriminate between metallic plates of different thickness and material composition. The dolphin was trained to recognise a 30 cm diameter circular copper disc of 0.22 cm thickness from comparison targets of the same diameter. A schematic of the dolphin performing a typical search and the various comparison materials and plate thicknesses are shown in Fig. 7. The dolphins could perform the discrimination task well above chance levels.

Au and Martin [23] examined the plates used in the experiment of Evans and Powell [22] with an echo ranging system that projected simulated dolphin echolocation signals. Backscatter results at normal incidence indicated that virtually no cues for discrimination were present in the echoes. However, when the plates were examined at angles away from the normal, the different plates began to display unique highlight structures. Examples of backscatter at normal incidence and at 14° incidence are shown in Fig. 8. The echoes from the 14° incidence angle are about 20 dB below that of the normal incidence, yet the discrimination cues were present for the off-axis backscatter. This implies that dolphins are able to use cues that are at least 20 dB below the maximum amplitude of the echoes at normal incidence in order to discriminate targets. In the example of

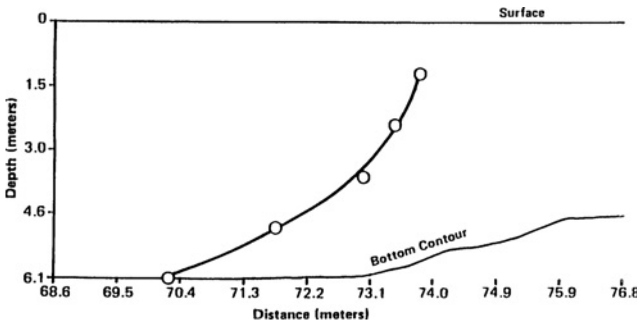


**Fig. 5** *Target detection threshold as a function of target depth*

Detection range when the 6.35 cm diameter sphere lay on the bottom was approximately 70 m (from Murchison [18])

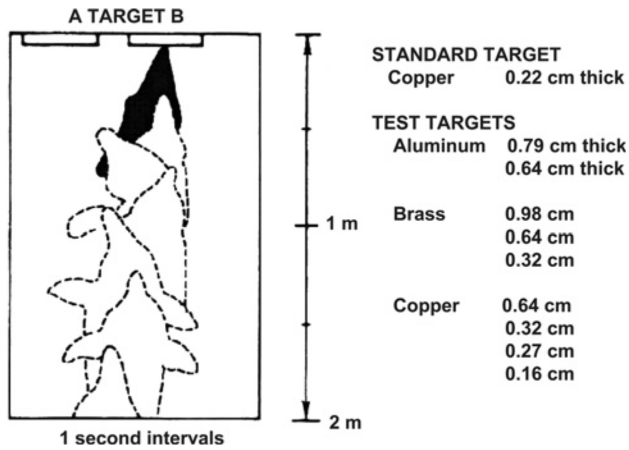


**Fig. 7** *Typical sonar search by the blindfolded bottlenose dolphin and the various comparison targets comparison target used by Evans and Powell [22]*

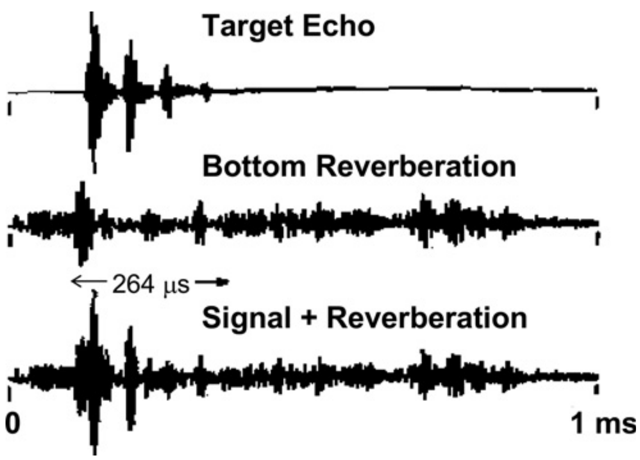


**Fig. 6** *Target echo in reverberation at the dolphin's threshold of detection (from Au [19])*

264 μs in the bottom panel is the integration time of the dolphin measured by Au *et al.* [20]

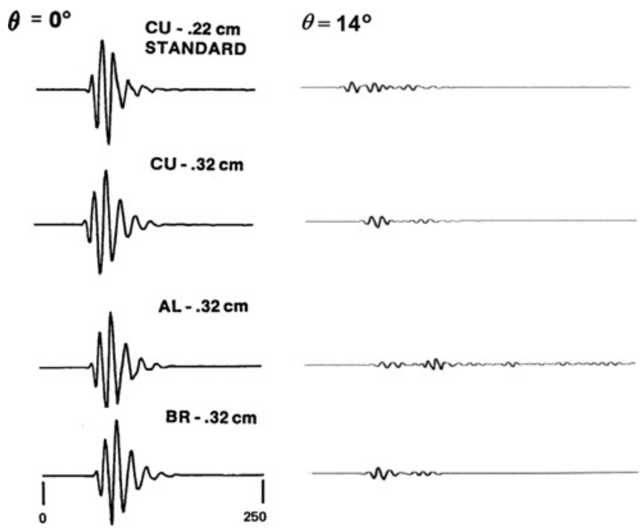


**Fig. 8** *Examples of backscatter from the standard disk and some of the comparison disks used by Evans and Powell [22]*

Fig. 7, the dolphin examined target A at an angle away from the normal at the 1 m mark and probably made its decision at that point with a reconfirming slant at the $\frac{1}{2}$ m mark.

### 3.3 Discrimination of fish species

Au *et al.* [24] performed a study to determine what acoustic cues would be available for echolocating dolphins to discriminate fish prey. They measured the broadband acoustic backscatter from four different species of fish, Atlantic cod, mullet, seabass and pollack, using simulated dolphin and porpoise echolocation signals as the fish were rotated. Data were collected from three fish per species except for the pollack since only one fish was available. Examples of the echoes from the four species of fish are shown in Fig. 9 for different aspect angles. The 90° aspect refers to the case when the fish is oriented with its side facing the transducer and 180° refer to the tail aspect. It is obvious from the echoes that there multiple high lights present as the signal reflected off various surfaces of the swimbladder as well as some other internal structures. Since different species of fish have swimbladders that are different in shape, volume and size, it is not surprising that the echoes were different for the different species and that there was an aspect dependency in the structure within a species. It is not farfetched to imagine dolphins learning the features of the echoes from different species. In the waters of British Columbia and the state of Washington, killer whales have a strong preference to Chinook salmon even during times when the Chinook salmon population is down to about 15% of the total salmon population [25].

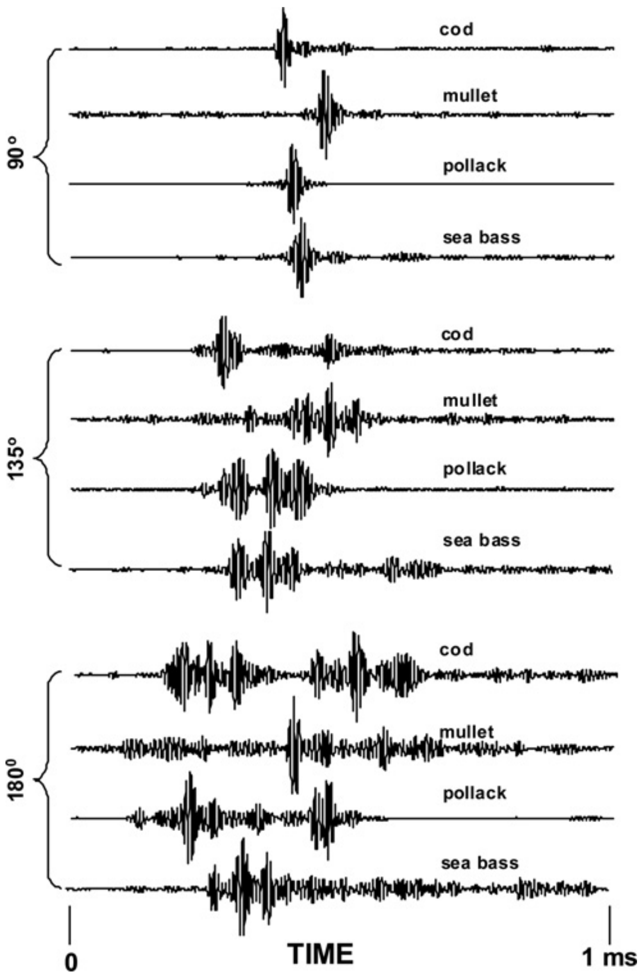


**Fig. 9** *Echoes from four different species of fish using a simulated dolphin biosonar signals (from Au et al. [24])*

Another cue that dolphins could have also used in discriminating fish species is the pattern of change as a fish is examined from different aspects. Certainly, the geometry between a swimming fish and a foraging dolphin will change continuously. In order to get a sense of the pattern, Au *et al.* [24] determined the polargram (frequency spectrum of an echo against fish orientation angle) as a fish was rotated. The four polargrams for the four fish species examined are shown in Fig. 10. Certain patterns are obvious as the aspect angle changed.

Yovel and Au used the fish echoes except for pollack, and extracted six statistics from the envelope of the time series [25]. Muller and Kuc found that a small number of statistical features from the echoes provided sufficient invariance to allow for classification of target echoes [26]. Such features were the characteristic exponent and the dispersion of an alpha-stable model for the amplitude distribution, a crest factor defined as the ratio of maximum squared amplitude and signal energy, the dispersion of the first threshold passage distribution, the structure of the correlation matrix and a non-stationarity in sound channel gain. These features were processed with a support vector machine (SVM) algorithm. The SVM used by Yovel and Au [26] are linear classifiers that seek a decision rule that is based on a linear combination of features extracted from the raw spectrograms of the echoes. Their results are shown in Table 1. The SVM were able to classify the different species very well. Here we are assuming that if a statistical machine can separate the three different species of fish, then the dolphin would also be able to. Yovel and Au [26] also tested the performance of the SVM classifier with noise added to the echoes. The results of this test are given in Table 2. Although performance of the SVM classifier when noise was added to the echoes was worse, the classifier performed much higher than chance (33% correct).

### 3.4 Instrumented dolphins detecting bottom mines

In difficult sonar tasks the freedom of motion allows the dolphin to investigate contacts from multiple aspect angles, which theoretically provides more information than observing objects from a single aspect. However, very little quantitative data have been available for free swimming dolphins conducting open water sonar searches. Martin *et al.* [27] developed two instrumentation packages to monitor the motions and the biosonar process of free-swimming dolphins searching for bottom targets. The biosonar measurement tool (BMT) shown in Fig. 11 is a bite plate device carried by a dolphin and monitors underwater navigational data while simultaneously recording outgoing echolocation clicks and returning echoes through high-gain binaural receivers modelled after the dolphins hearing system. A second package, the instrumented mine simulator (IMS), was placed in simulated mines and monitored the echolocation clicks as received at the target during ensonification. Two dolphin subjects were trained to carry the BMT in detection and identification experiments in which the IMS was also used. Trials, start and stop times, and GPS locations were recorded when the animal was sent on a trial by the trainer from a workboat. This allows full reconstruction in earth coordinates of each trial. The dolphins were also trained to whistle during a trial to report target present. To aid in



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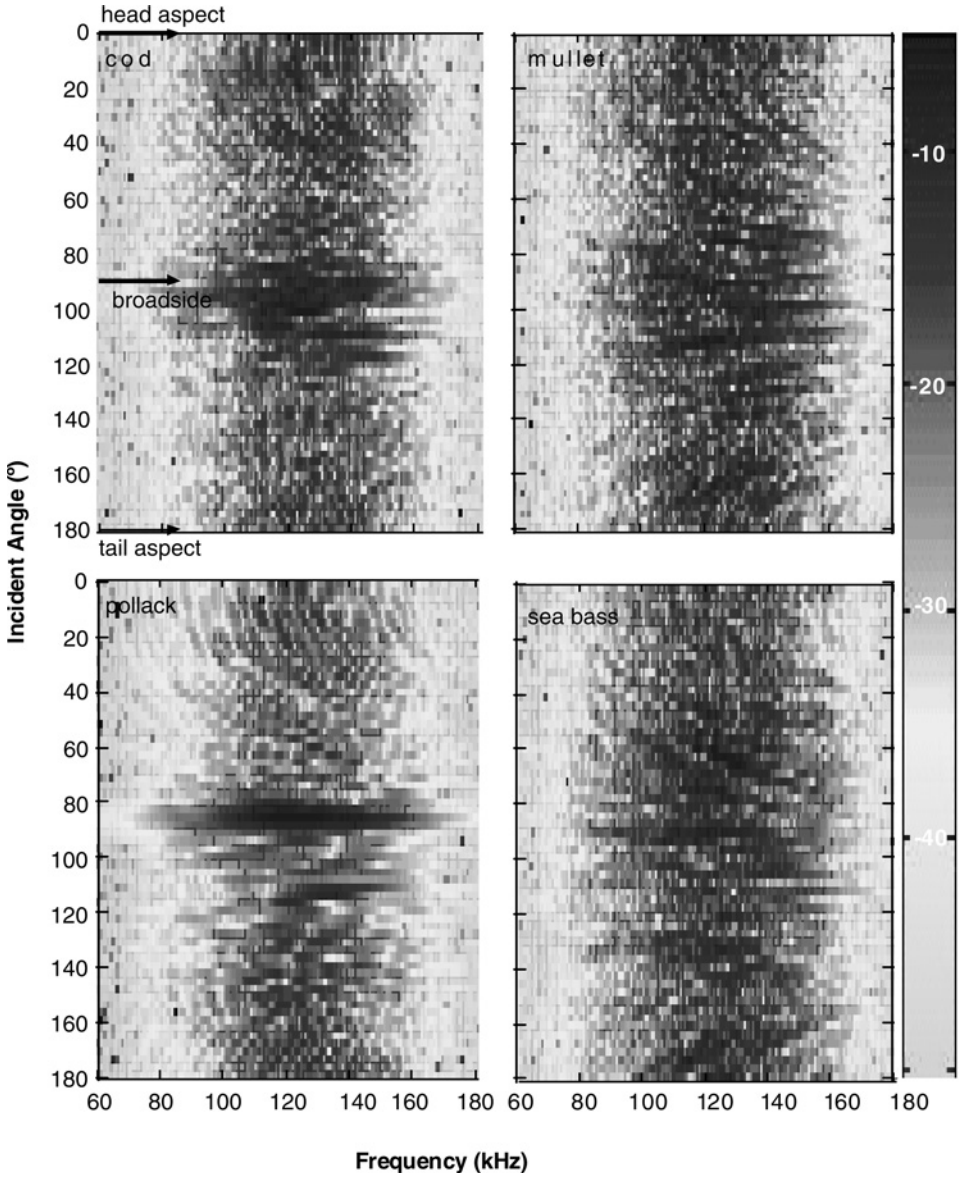


**Fig. 10** *Polargram (frequency against angle of the echoes) for four separate species of fish (from Au et al. [24])*

situational awareness the BMT data were automatically formatted to allow replay of the 4D positional data over time along with acoustic monitoring of the binaural echo data. Fig. 12 provides a screen capture of a replay of one trial illustrating the various features available in virtual replay. The BMT sensor data include: a three-axis attitude heading reference unit, direct measurement of pressure (depth) and velocity for improved positional data, and three channels of passive acoustic data (one low-gain omni-directional hydrophone for monitoring the outgoing echolocation clicks and a biologically inspired high-gain directional binaural receiver modelled after the dolphins binaural auditory system). The low-gain outgoing click monitor allows detailed analysis of the on-axis outgoing signal characteristics. Fig. 13 illustrates the variability observed in one trial's click train spectra, details on the taxonomy applied to the various click types can be found in [28]. The high-gain directional binaural receiver provides echo data similar to what the dolphins received. A low-risk approach to the development of the BMT electronics was employed primarily using Commercial Off The Shelf (COTS) electronics, which made the package considerably

**Table 1** SVM classification performance of fish echoes created with a dolphin-like signal

| | | |
|---|---|---|
| cod against mullet | mullet against sea bass | sea bass against cod |
| 96 ± 1% | 96 ± 1% | 97 ± 1% |
| cod against rest | mullet against rest | see bass against rest |
| 91 ± 1% | 85 ± 2% | 92 ± 1% |

**Table 2** Sensitivity of the SVM to noise

| Ave noise % from max intensity | Cod against rest, % | Mullet against rest, % | Sea bass against rest, % |
|---|---|---|---|
| 10 | 85 ± 3 | 55 ± 10 | 60 ± 3 |
| 20 | 86 ± 3 | 52 ± 8 | 64 ± 7 |
| 30 | 85 ± 3 | 56 ± 15 | 64 ± 5 |
| 40 | 83 ± 4 | 53 ± 11 | 62 ± 8 |
| 50 | 82 ± 3 | 55 ± 11 | 67 ± 6 |

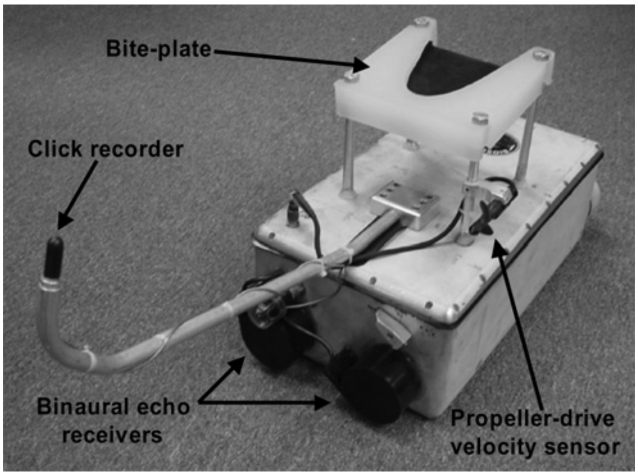


**Fig. 11** *BMT photograph showing external sensors and the bite plate configuration for a dolphin to carry the device*

larger, although significantly less expensive than possible with dedicated circuit designs.

The BMT package along with the IMS provided a detailed and rich data set quantifying the acoustics from transmission, to reception at the object and the reception of binaural echoes from the target, the bottom sediment and clutter targets. After test sessions of multiple target present and target absent trials were conducted, data from the BMT, IMS and search boat computer were uploaded in the laboratory, automatically processed for the four-dimensional replay and subsequent detailed analysis. Overall results of the analysis for the two dolphin subjects (LUT and FLP) show distinctive search strategies for the two animals. One strategy (LUT) was characterised as a rapid search ($<$10 s) with low click production with variable distribution of energy across the echolocation frequency range ($\sim$20 to 120 kHz) and very minimal swim distances. On target-present trials LUT travelled no more than a few metres from the boat swimming in a circle conducting the acoustic search of the area prior to reporting target detection and immediately returning to the workboat. This dolphin appeared to abide by the 'law of least effort' in that energy spent to receive a food reward was minimised. Swimming around the buoy marker, 25–60 m away from the workboat, was only performed when no target was observed in the area and the dolphin had to complete the search pattern circuit around the buoy marker in order to receive a fish reward. LUT echolocated more near the workboat at the start of the

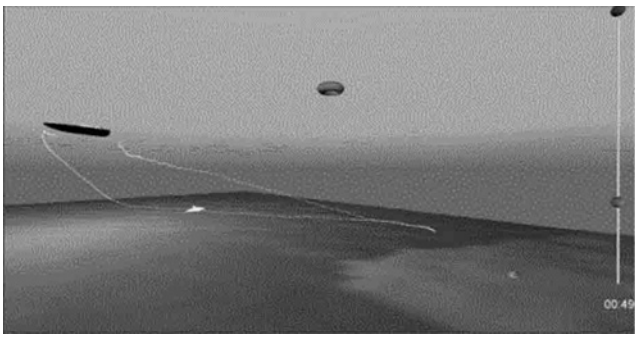

**Fig. 12** *Interactive four-dimensional replay of BMT data for a trial by FLP which is used for situational awareness for researchers*

Major items of this positive trial are the workboat, dolphin, bottom target and surface float

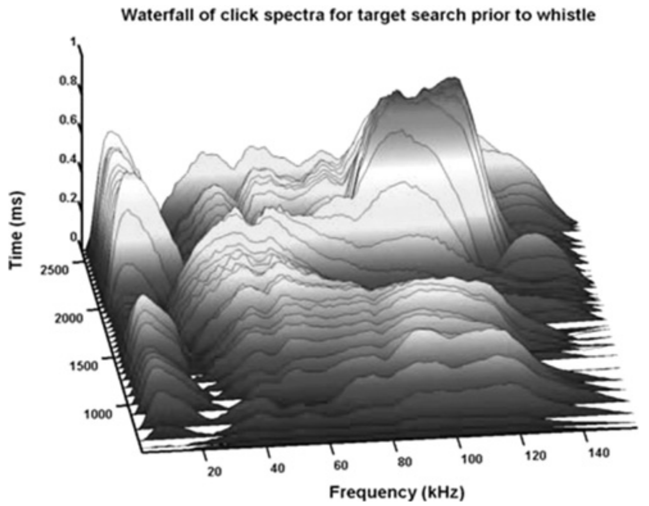


**Fig. 13** *Sample spectra sequence of outgoing clicks from one trial illustrating variability possible in the spectral domain*

negative trials; relatively few clicks were produced in transit to and from the buoy.

Fig. 14 provides an example of one target present trial of data for the subject LUT where the top trace shows outgoing dolphin echolocation clicks superimposed with the calculated heading, pitch and roll of the animal for a period of approximately 3 s of time. The lower trace shows the acoustic data received by the IMS package at the target time aligned with the BMT data also overlaid with the BMT heading, pitch and roll at this time period.

LUT's rapid circular (in heading) search strategy is evident with the azimuthal scan going from an initial value of 150° down to near 50°, a point close to coincidence with maximum target ensonification by the dolphin clicks. At this point the dolphin reversed its heading scan back up to near 100° before scanning back down in heading angle to the 50° region again providing a strong ensonification of the target as observed in the magnitude of the signals received at the IMS package. At this point the animal had made its target present decision and ceased echolocation and provided a target present whistle. This exemplifies the dynamic nature of the biological sonar as compared to most man made sonars which would simply scan past objects without immediate feedback allowing for 'second looks' or finer detail examination. The IMS data provide a direct measurement of the ensonifying signal as received at the target and insights into the search strategies of the animals. The IMS data also help focus analysis times for returning echoes as received in the BMT binaural echo data for detection and identification signal processing.

The biosonar searches of FLP were comparatively slower, on the order of tens of seconds, and could be characterised by copious production of stereotypical echolocation clicks with a bandwidth of 30–60 kHz and extensive swim distances. FLP demonstrated a stereotypical search pattern consisting of a descent to a point immediately above the benthos followed by a methodical search of the region around the search buoy. Click intervals and the number of clicks emitted were comparable between search and acquisition segments, and FLP swam within a few metres of the target prior to reporting it as present (potentially allowing visual confirmation of target ID). The later strategy provided a lower false positive rate (search probability of correct detection $P_d = 0.60$ with probability of false positive




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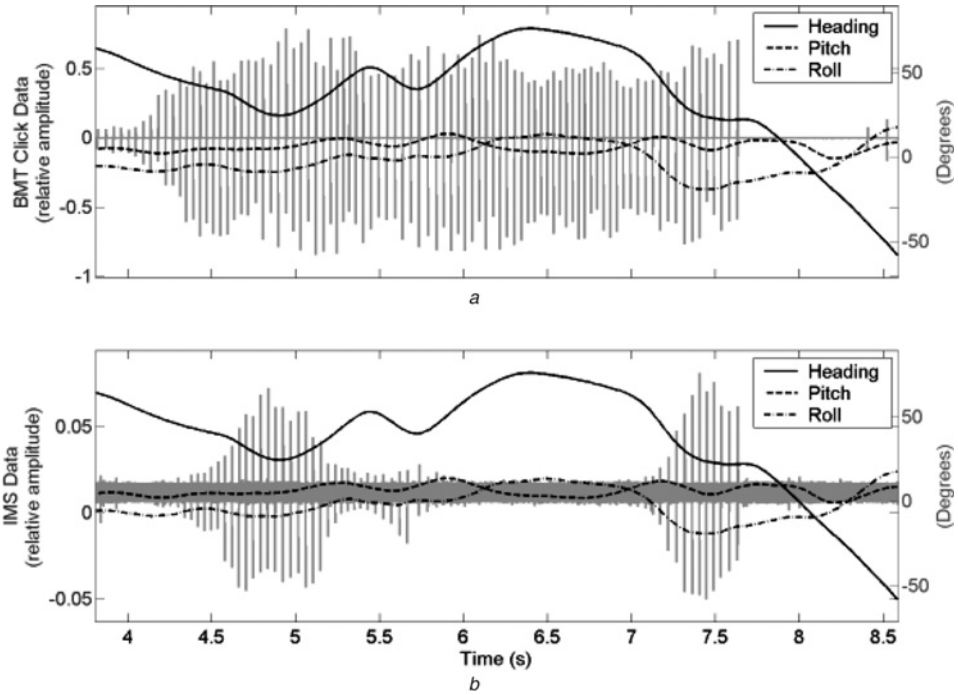


**Fig. 14** *Target present trial of data for the subject LUT*

*a* Shows BMT outgoing click data with the yaw, pitch and roll during a trial
*b* Shows the time synchronised data received at the IMS overlaid with the same BMT yaw, pitch and roll
Times of maximum target ensonification by the dolphin clicks are clearly evident slightly before 8 and $12 \times 10^5$ samples (2.55 and 3.825 s relative to this sample start time). The higher gain setting in the received channels also introduced electronic noise into the system as can be seen in the lower panel

$P_{fa} = 0.0$) than the rapid search strategy of LUT ($P_d = 0.78$ with $P_{fa} = 0.36$) as described in [28].

Differences in the search strategies of the two dolphins are possibly explained by previous training histories and individual hearing ability. FLP was previously trained for open-water target searches in which targets, once detected, were inspected again at a few metres distance for verification prior to marking the identified target. The experiment of Houser *et al.* only required that the dolphins report that a target was present during a positive trial with no requirement for close inspection prior to a positive report [28]. It is quite possible that FLP's previous acquired target marking behaviour training influenced his strategy as observed in this study. In contrast, LUT was a naive animal with little experience in open-water target detection tasks. LUT may have developed a more economical strategy. However, subsequent hearing tests on FLP suggest that FLP has profound hearing loss above 50 kHz [17]. A reduction in hearing sensitivity may explain the reduced search range (shorter interclick intervals), predominant use of wideband clicks with low-frequency peaks, and more abundant click production. Similar characteristics have been observed in dolphins that have known hearing losses performing simpler target detection tasks [29]. The combination of hearing ability and experience may have contributed to FLP developing a conservative search strategy in which no false alarms were committed but with a subsequent reduction in correct detections.

## 4 Discussion and conclusions

We have shown that even with some mediocre properties associated with their biosonar system dolphins have been able to solve perhaps the most difficult sonar problem – that of detecting and recognising a target buried in the ocean bottom surrounded by rocks, coral heads and other debris. Although the transmission and reception beams are relatively wide in comparison to many technological sonars, echolocating dolphins have about a 0.7° angular resolution from its binaural hearing capability ([29]. The shape of the dolphin head apparently causes the individual ear to receive echoes that arrive at a slight angle on either side of the head differentially. So the big question is, with the seemingly poor sonar characteristics how do they do so well? Is it possible to learn from the dolphins in order to build sonars that can have the same capabilities? To say that these animals have millions of years of evolution to perfect their biosonar and therefore are expected to have a more sophisticated system is not a good perspective to have. A better perspective is to learn how they solve difficult sonar problems. We will attempt to provide our perspective on this matter and perhaps contribute to the eventual development of a better way to approach sonar development.

### 4.1 Signal

The role of broadband, transient-like nature of the biosonar signal cannot be overstated in providing the dolphin with its keen target discrimination and recognition capabilities. It is without a doubt one of the most important facets of the biosonar capability since the properties of targets are encoded in the echoes. Without the information carrying capacity of the signal, the dolphin would not be able to achieve any degree of target discrimination and recognition no matter how sophisticated its auditory system may be coupled with the acoustic processing power its brain may have. The time resolution capacity of the biosonar signal is about 20 μs which represent a distance resolution of about 3.0 cm [6]. The 20 μs temporal resolution can be achieved by simply calculating the envelope of the echoes without any match filtering or correlation process. The short signal means that the acoustic power emitted into the water from a single click is limited, which in turn will limit the target detection range. However, this is not an issue for dolphins since in the wild they are probably not interested in prey that is beyond 100–150 m. Unfortunately, the maximum detection range of interest for dolphins in their natural habitat is not known. The limitation on acoustic power is really not a serious limitation in shallow waters filled with false clutter targets, since the more power that is emitted will only increase the intensity of the reverberation, and the echo-to-reverberation ratio will not change.

It might be worthwhile to compare the dolphin's biosonar to a multi-beam sonar. Designers of multi-beam sonars strive to achieve very fine angular resolution with little concern for temporal resolution. A dolphin biosonar has both good temporal and binaural angular resolution. The effectiveness of a multi-beam sonar is often expressed by the quality of the visual image that can be obtained with the unit. With the dolphin, vision may not be a major issue (a dolphin would probably be as effective detecting a mine on the bottom of the ocean blindfolded). This simple comparison might suggest that temporal resolution may be as important as angular resolution when attempting to detect target among clutter such as rocks and coral. Having both good temporal and angular resolution would be ideal.

### 4.2 Training

An important component of the US Navy dolphin mine hunting system is the training that each dolphin must receive in order to properly learn the task. This training can extend for over a year in which the animals are first trained to detect simulated mines in the free field just outside of its home pen. Then eventually the target will be moved progressively further away and finally it will be put on the sea floor. The animal will then be trained to swim along the trainer's boat and trained to detect the simulator laying on the sea floor. Eventually, real mine may be used. After a prolonged period the dolphin eventually learns to generalise and detect man-made objects, be it a mine, a piece of ordnance or even discarded water heaters.

In regards to technological sonar, both the sonar and the operators must be trained to detect mines lying on or even buried in the bottom sediment. The training should go on for long periods of time and computer programming technology must be developed so that an element of training can be incorporated into the algorithms. Training should not be restricted to targets of interest but also to different bottom environments and different types of clutter objects. An important factor to keep in mind is that an animal is constantly learning about its environment. To emulate a dolphin, continuous learning should also be incorporated into the computer algorithms processing the sonar echoes.

### 4.3 Adaptive search pattern

A feature of the dolphin sonar system that is often overlooked is the fact that the sonar is mounted on a very flexible and mobile platform. Dolphins conduct sonar searches in an adaptive manner so that the trajectory of the animal at any given time will be the results of prior echoes. A dolphin is not restricted to running preprogrammed track lines or transects but is free to manoeuvre as the situation dictates. Therefore a dolphin can approach and search on an object at different orientations and obtain whatever information it needs to recognise a target. The multiple highlight structure of echoes will change with different orientation in the dolphin-target geometry and the pattern of change may be an important component of the discrimination and recognition process for the dolphin. The manner in which dolphins conduct sonar searches is an important area of research that should be pursued. For example, chances of detecting a bottom target may improve in some situations by simply changing the grazing angle to reduce bottom reverberation. The most important cues may come from echoes with levels that are considerably lower than the maximum level for many targets. The dolphins in the metal plate experiment of Evans and Powell used cues that came from echoes received at non-normal angles at levels that were 20–30 dB below the level of the echo at normal incidence [20]. A methodology in which the sonar echoes dictate the specific trajectory of a mobile platform at any given time needs to be developed.

### 4.4 Mammalian brain

Finally, the ultimate reason for the keen sonar capability possessed by dolphins has to do with the entire sonar process being controlled by a mammalian brain that allows for versatility and continuous learning. As a contrast, a neural network is trained to recognise features of specific targets, and then the training stops. The 'learned' templates are then used to recognise those targets in the field. This approach implies that only echoes from desired targets are important and echoes from non-target objects are not important. However, knowledge of non-target objects may be very important in order to be successful in detecting and recognising targets of interest and reduce false alarm rates. One important quality of the mammalian brain is the capacity to continuously learn, and in this manner it can adapt to different situations and environments and benefit from previous experiences. Futuristic sonars may need to process signals in a fashion akin to how the brain processes signals and controls the whole sonar process. This may seem to be a daunting proposition but progress can be made in little steps. For example, it would be useful to develop effective ways to process brief broadband sonar signals, making use of the good temporal resolution inherent in these types of signals. It would also be advantageous to develop techniques in which a sonar on a free-roaming vehicle can control and perform adaptive sonar search patterns. Research should also be done on the process of continuous learning in a sonar function. We believe that we can make considerable progress in developing better sonars by following along the path that has been provided by dolphins.

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