Effects of Underwater Sound on Marine Fish and Mammals

John A. Lewis

Aeronautical and Maritime Research Laboratory
Defence Science and Technology Organisation
G.P.O. Box 4331
Melbourne, Vic. 3001
Australia

DSTO Unpublished Report

1990

Abstract

Literature on the effects of underwater sound on marine fish and mammals is reviewed. Characteristics of hearing are discussed, as are published accounts on the effects of sound on these animals. For fish, aspects reviewed include the effect of sound in attracting or repulsing fish, and the debilatory potential of intense sound. For marine mammals, the zone of influence of a noise source, acoustical deterrents, and the effects of sonar and more general industrial and maritime noise are discussed.

Contents

Effects of Underwater Sound on Marine Fish and Mammals

1. *Introduction*

Recognition of the need to better conserve and protect many marine animals and their habitats often necessitates an improved understanding on how human activities can impact on these communities. The effects of underwater noise is one such area. Noise can be generated during seismic exploration, in the construction and maintenance of offshore industries, by general shipping and boating activity, and during military exercises. Increasingly, the question is being posed as to whether this noise effects marine animals, particularly the larger marine mammals, and what physical or behavioural responses are likely.

In this report, the available literature on the effects of underwater noise on marine life is reviewed, with emphasis on the effects on marine fish and mammals.

2. *Hearing in Marine Fish and Mammals*

The sensitivity of an animal to sound can be conveniently represented by an audiogram: a curve which shows the thresholds or minimum sound levels to which an animal will respond over a range of frequencies. The audiograms for some representative fish, marine mammals and man are presented in Figure 1.

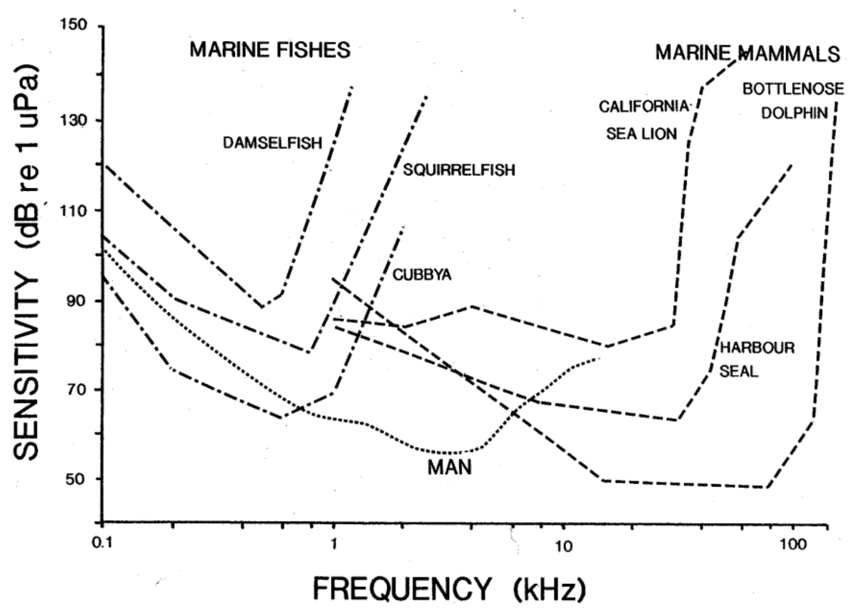

Figure 1. A comparison of hearing curves for selected marine fishes, marine mammals and man (after Myrberg, 1980).

In general, fish are sensitive to a rather restricted range of frequencies and even the best fish are relatively insensitive to sound at frequencies above 2 or 3 kHz (Hawkins 1986). Within their restricted frequency range, however, many fish are acutely sensitive to sound. Fish respond either to sound pressure or particle velocity, and it is the former which leads to greatest sensitivity. A linkage between the swimbladder and the ear is characteristic of those fish which are sensitive to sound pressure, and the absolute sensitivity of fish and their frequency range appears to depend on the degree of association between the swimbladder and the ear (Hawkins 1986). For example, cypriniform or ostariophysan fish (e.g. the catfish *Ictalurus nebulosus*), which have a close connection between the two, show a very acute sensitivity to sounds and an extended frequency range, whereas the cod *Gadus morhua*, in which the swimbladder is simply placed close to the ear, is less sensitive and has a more restricted frequency range (Figure 2). Inherently less sensitive fish species, such as the salmon *Salmo salar* and the dab *Limanda limanda* (Figure 2), have been shown to be sensitive to particle velocity.

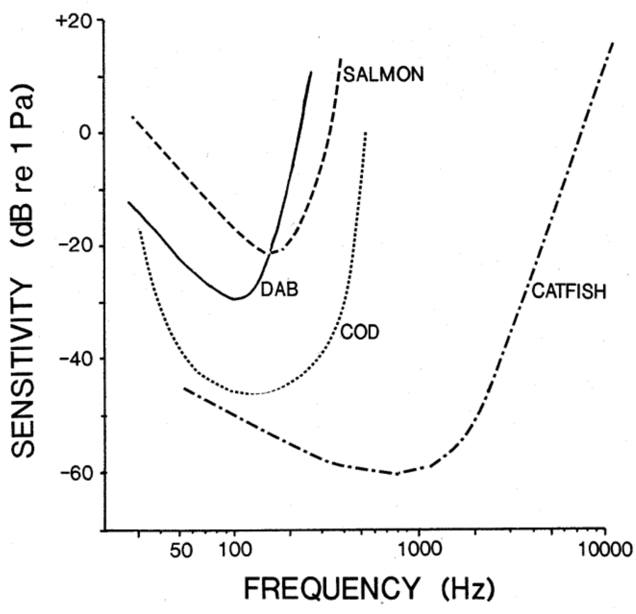

Figure 2. Audiograms for four species of teleost fish (after Hawkins 1980).

Sharks appear to have excellent hearing within the frequency range 10- 800 Hz but seem unable to hear frequencies above 1 kHz (Myrberg 1976).

The use of sound by whales for communication and echolocation has evoked considerable interest in the hearing and sound production capacities of these animals (Kellogg 1961, Dudok van Heel 1962, Tavolga 1964, 1967, Busnel and Fish 1980, Wood 1987). Baleen (mysticete) whales are not known to echolocate but this ability has been found in about a dozen toothed (odontocete) whales, including dolphins (Evans 1987). Although characteristics of the sounds produced by whales have been reported for ten species of baleen and nineteen species of toothed whale (Evans 1987), with some exceptions (Figure 3) little quantitative information is available on the auditory sensitivity of these animals (Myrberg 1980). Sound-detection thresholds have been obtained over a wide range of frequencies for only six toothed whale species: the bottlenose dolphin *Tursiops truncatus* (Johnson 1966, 1967), the common dolphin *Delphinus delphis* (Bel'kovich and Solntseva 1970), the harbor porpoise *Phocoena phocoena* (Anderson 1970), the beluga (white) whale *Delphinapterus leucas* (White *et al*. 1978), the killer whale *Orcinus orca* (Hall and Johnson 1971) and the freshwater Amazon River dolphin *Inia geoffrensis* (Jacobs and Hall 1972). Characteristics of the sound production and hearing of these species are summarized in Table 1, and audiograms for the bottlenose dolphin, beluga whale, harbour porpoise and killer whale presented in Figure 3. Electrophysiological audiograms for the striped dolphin *Stenella coeruleoalba*, the spotted dolphin *Stenella attenuata*, and the rough-toothed dolphin *Steno bredanensis* resembled the behavioural audiogram for *Tursiops truncatus* (Bullock *et al*. 1968).

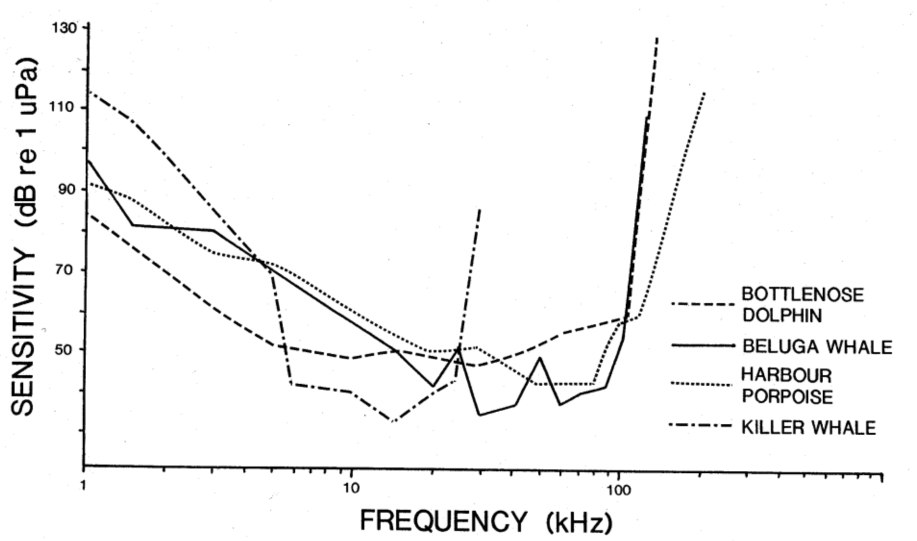

Figure 3. Audiograms for four species of odontocete whale (after Turl 1972).

All the toothed whales tested show extremely high sensitivity to a wide range of high frequency sounds. The most characteristic sounds produced by these animals are the echolocation clicks which peak in frequencies from 14 to 150 kHz, a range reflected in the high frequency sensitivity of their hearing. The region of peak sensitivity generally correlates with the animals' own signal characteristics, a correlation also found in fishes and other animal groups where similar data are available (Myrberg 1980). If this relationship also held for the baleen whales, an indication of hearing sensitivity could be gained from characteristics of their signals. Most baleen whale calls are of comparatively low frequencies with their maximum energy less than 1000 Hz, although high frequency clicks have been recorded for blue, fin, sei, minke and humpback whales (Table 2). Turl (1982) concluded that if the sounds produced by large whales are indications of sounds they could receive, then the whales' hearing bandwidth extends from 12 Hz to 30 kHz. Anatomical evidence supports specialization in baleen whales for hearing low frequency sounds (Fleischer 1976). Low frequency sounds (<3 kHz) carry over great distances and it has been speculated that the great whales may be in sound contact over distances of tens or even hundreds of kilometres (Evans 1987).

Table 1. Characteristics of sound production and hearing in toothed whales (data from Wood and Evans 1980).

	Signal		Hearing	
Species	Peak Frequency kHz	Source Levels dB re 1 μPa	Range kHz	Maximum Sensitivity kHz
Bottlenose dolphin	15-130	155-204	0.075-150	20-80
Common dolphin	20-100	140	0.1-280	60-100
Killer whale	14	178	0.5-31	15
Harbor porpoise	20-150	112	1-150	8,32,64
Beluga whale	40,80,120	160-180	1-123	60-65
Amazon River dolphin	60-65	146	1-105	30-50

Hearing characteristics have been studied in the Californian sea lion *Zalophus californianus* (Schusterman *et al*. 1972, Schusterman 1974), the harp seal *Pagophilus groenlandicus* (Terhune and Ronald 1971, 1972), the harbor seal *Phoca vitulina* (Mohl 1968, Terhune 1988), the ringed seal *Pusa hispida* (Terhune and Ronald 1975), and the grey seal *Halichoerus grypus* (Ridgway and Joyce 1975). The four latter species, all phocids, have been found to have very similar hearing (Figure 4), with no difference in sensitivity greater than 20 dB at any frequency. Their hearing can therefore by characterized by a single audiogram (Myrberg 1980). Both the phocids and the otariid (the Californian sea lion) show a broad range of sensitivity to high frequencies with loss of sensitivity above 50 kHz and 28 kHz respectively (Figure 4).

Table 2. Characteristics of sounds produced by whales (Evans 1987).

Species	Sound Type	Frequency Range Hz	Maximum Energy Hz
Baleen whales			
Blue whale	moan	12.5-200	20-32
	click	21,000-31,000	25,000
Fin whale	moan	?6-95	18-75
	click	16,000-28,000	
Sei whale	click		3000
Bryde's whale	moan	70-245	
Minke whale	grunt	80-140	
	thump train	<100-800+	100-200
	click	3300-12,000	4000-7500
	ratchet pulse		850
Humpback whale	moan/groan	<4000	
	grunt	120-250	
	chirp/whistle	500-1650	1600
	click	2000-7000	
Gray whale	knock	90-2000	300-1000
	grunt	250-300	250-300
	moan	125-1250	170-430
	belch	150-1570	225-600
Bowhead whale	moan	50-500	50-300
	tonal purr	100-800	
	tonal call	150-375	
	complex call	100-3500	
Southern right whale	up call		50-200
	down call		100-200
	constant call		50-500
	high call		200-500
	hybrid call		50-500
	pulsed call		50-200
Toothed whales			
Sperm whale	clicks	<100-30,000	10,000-16,000
Narwhal	whistle	300-18,000	
	pulsed tones		500-5000
	clicks	500-24,000	500-24,000
Beluga whale	clicks		1200-120,000
Killer whale	clicks	100-80,000	250-40,000
	whistle	1500-18,000	6000-12,000

	pulsed call	1000-25,000	1000-6000

Table 2. (cont.)

Species	Sound Type	Frequency Range Hz	Maximum Energy Hz
Long-finned pilot whale	whistle	2800-4700	3400-4700
Rough-toothed dolphin	whistle		3000-10,000
	clicks	100-200,000	
Indo-Pacific hump-backed dolphin	whistle		3000-20,000
	scream		3000-30,000
	clicks		10,000-30,000
Atlantic white-sided dolphin	whistle	8200-12,000	
Pacific white-sided dolphin	whistle	1000-12,000	
	clicks	60-80,000	
Common dolphin	whistle	4000-16,000	
	clicks	200-150,000	4000-60,000
Bottlenose dolphin	bark	200-16,000	
	whistle	2000-20,000	
	clicks	200-300,000+	15,000-130,000
Spotted dolphin	whistle	6500-13,300	
	pulses	-150,000	
Spinner dolphin	whistle	8700-14,300	
Commerson's dolphin	pulsed cry	1000-6000	
	clicks	-100,000+	
Heaviside's dolphin	clicks	-5000	800-1000
	tonal cry	-5000	800-1000
Harbour porpoise	pulses	41,000-160,000	2000 110,000-150,000
Indus susu	clicks	25,000-200,000	100,000
Amazon River dolphin	pulses		60,000-65,000

Baiji	whistle		6,000
	clicks	8000-120,000	

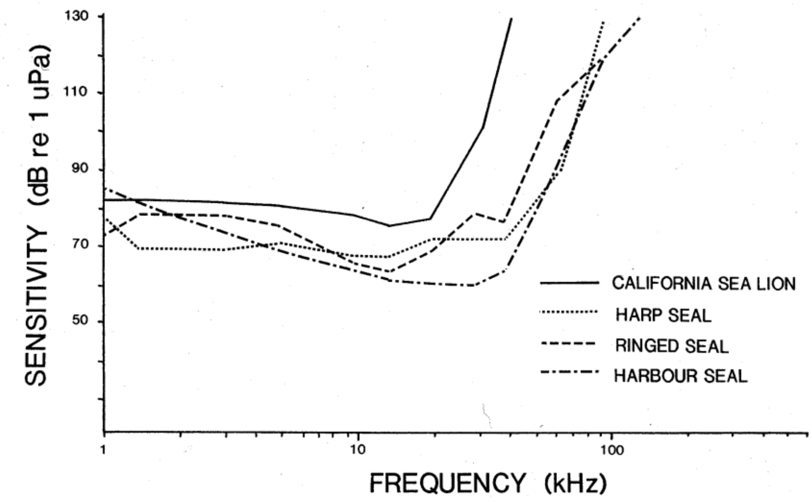

Figure 4. Audiograms for four pinniped species (after Turl 1972)

3. *Effects of Sound on Fish*

3.1 Attraction and Repulsion

Sound has been traditionally used to attract fish in many primitive fisheries (Hashimoto and Maniwa 1967, Hawkins 1973). Many of the artificial sounds used appear to imitate natural sounds, though the biological significance of these is not always known (Hawkins 1973). The sounds of struggling fish have been shown to be effective in attracting predatory species (Nelson and Gruber 1963) and the replayed sound of fish swimming and eating can attract the same species (Hashimoto and Maniwa 1967). Richard (1968) showed that low frequency pulsed noise signals were effective in attracting fish but pulsed pure tones or continuous noise signals were not. He concluded that the impulsive character of a sound was the primary attracting component, probably because impulsive sounds simulate the noise bursts produced by feeding fish and the struggling movements of prey animals.

The struggles of a disabled fish are known to bring sharks from considerable distances (Cousteau and Cousteau 1970). Experiments have shown that the effectiveness of such sounds in eliciting approach responses from sharks increases with pulse irregularity, increasing pulse rate and lowering of the frequency spectrum (Myrberg *et al.* 1972). Although sounds having frequencies in the range 10 to 800 Hz have been found to be highly attractive to numerous species of sharks (Myrberg 1976), sounds appears to be most attractive at extremely low frequencies, ie. 10 to 40 Hz (Myrberg *et al.* 1976). The characteristics of the attractive sounds reflect those in the erratic hydrodynamic sounds made by fish when they are actively feeding, fleeing or fighting (Myrberg 1976).

Various attempts have been made to elicit avoidance responses from fish, or to guide their movements, with sound but few attempts have been successful (VanDerwalker 1967, Hawkins 1973). The usual response of a fish to sounds is one of quickened movement, or a startle response (Moulton 1964), but these reactions are often brief in duration and the fish appear to adjust quickly, even to very high sound levels (Burner and Moore 1953, Chapman and Hawkins 1968). Recorded sounds of dolphins have been found to cause fish to flee. The sounds of Risso's dolphin *Grampus griseus*, recorded in the range 0.5 to 7 kHz, have been found to cause shoals of yellowtail to rapidly descend and disperse, and fish have also been observed to flee from recorded bottlenose dolphin sounds (Hashimoto and Maniwa 1967).

3.2 Injury

Norris and Mohl (1983) raised the hypothesis that some toothed whales may emit sounds so intense that their prey is debilitated and capture made easier. The basis for this hypothesis was the observations that a small dolphin may be able to generate sound intensities capable of stunning prey (Bel'kovich and Yablokov 1963), that the teeth and jaws of sperm whales (*Physeter catodon*) did not appear to be essential for food getting (Berzin 1972), and that captive bottlenose dolphins are able to disorient schooling fish by use of click trains (Hult 1982). Norris and Mohl (1983) found little information on the sound intensities required to stun potential prey. Studies on the effects of explosives on fish suggested lethal thresholds of 229 to 234 dB re 1 μPa for short rise time explosives and 5 to 10 dB higher for explosives with slow rise times, whilst their own studies found that the squid *Loligo vulgaris* was fatally injured by peak pressures of 246 to 252 dB re 1 μPa.

Available information suggested that bottlenose dolphins are able to produce peak sound levels equal to established lethal thresholds for fish (Norris and Mohl 1983). Although most odontocetes produce sounds in the 140 to 180 dB re 1 μPa range in captivity (Diercks 1972), and recordings in nature have been of similar levels (Fish and Turl 1976, Watkins 1980), average source levels as high as 228.6 dB re 1 μPa at 1 yard have been measured for dolphins (Au *et al*. 1978). Circumstantial observations of dolphins in captivity producing very loud impulsive sounds, sometimes so intense they could be heard through tank walls or to cause ringing in the ears of earphone-equipped listeners, have also been reported (Tavolga and Essapian 1957, Caldwell *et al*. 1962, Lilly 1962, Norris and Mohl 1983).

Some observations have been made which indicate prey debilitation by odontocetes (Norris and Mohl 1983). Fish have been seen to become disorientated in the presence of esonifying dolphins and wild fish schools being fed upon by dolphins were found to be so lethargic they could be removed from the water by hand. Pistol or snapping shrimps (Alpheidae) appear able to debilitate prey by the intense sound produced when the snapping claw is snapped shut. *Alphaeus californiensis* has been observed to stalk small fish, stun them by a snap of the claw, then retrieve and eat them (MacGinitie and MacGinitie 1968).

Zagaeski (1987) conducted a laboratory study on the effects of high intensity sound pulses on fish to further assess the feasibility of Norris and Mohl's prey stunning hypothesis. In their experiments, guppies (*Lebistes reticulatus*) were subjected to sound pulses produced by a high voltage sound source, with the subsequent ability of the fish to orient itself closely monitored. The 50% affected threshold was found to be 236 $\pm$ 6 dB re 1 μPa. Some fish were affected at 225 dB re 1 μPa.

Another aspect of the hypothesis that odontocetes stun their prey by pulses of intense sound was investigated by Mackay and Pegg (1988). They were especially interested in the case of squid, not only because they are "the agile prey of ponderous sperm whales", but because they also have no swim bladder. In their experiment an octopus was exposed to pulses of intense sound with no significant effect. They concluded that, as the sound level used was greater than expected from animal vocal activity, the negative result suggested that acoustic stunning of water-like prey may not be a completely reliable hunting method.

4. Effects of Sound on Marine Mammals

4.1 The Zone of Influence.

To enable the prediction of the effects of noise from offshore oil and gas operations on marine mammals, Miles *et al.* (1987) attempted to define the zone of influence of a noise source. The "zone of auditory damage" was considered to represent one extreme, where the noise level would cause discomfort or possibly permanent damage to the auditory system, while the other extreme was the "zone of audibility", where behaviour may be affected at any distance where the noise is audible. Alternative definitions of the zone of influence were the "zone of responsiveness", defined as the area in which animals respond overtly by avoidance or some other alteration in behaviour, and the "zone of masking", the area in which the ability of an animal to hear important environmental sounds (calls from members of its own species, echolocation signals etc.) would be impaired by the masking effect of the noise signal.

The limits of the zone of audibility would generally be where the ratio of industrial to ambient noise (the signal-to-noise ratio, S:N) equals 0 dB. However, if the absolute detection threshold of hearing for an animal is above the ambient noise level, then the zone of audibility is limited by the detection threshold, and not by ambient noise (Miles *et al.* 1987). In evaluating the zone of audibility, the 1/3 octave wide band around a particular frequency which affects an animals ability to detect a signal at that frequency must also be considered. Some behavioural evidence for baleen whales suggests that the zone of influence may approach the zone of audibility at some frequencies, as they are able to detect and respond to calls from conspecifics many kilometres away (Watkins 1981b, Tyack and Whitehead 1983). Malme *et al*. (1983) also found that gray whales responded to killer whale sounds when S:N equaled 0 dB. Payne and Webb (1971) found that, in deepwater, 20 Hz calls, with a source level of 180 dB re 1 μPa at 1 m, were possibly heard by fin whales 100's to 1000's of kilometres away. In shallow water however the zone of audibility is expected to be restricted by the greater rate of sound attenuation. At high frequencies, dolphins gain increased auditory sensitivity through their ability to discriminate between the directions of signal and noise sources, but baleen whales do not appear to have this ability (Gales 1982, Miles *et al*. 1987).

Gales (1982) stressed that the zone of influence should be based on the noise levels which caused whales to react overtly, ie. the zone of responsiveness. However, so little information was available on noises which would and would not elicit responses that only the zone of potential audibility could be calculated. Although, in theory, whales might react to underwater industrial noise at any range where it is audible, bowhead and gray whales have been observed within areas esonified by industrial activities (Miles *et al*. 1987). However, reactions are variable, and while some bowhead whales showed no detectable reaction to broadband noise up to at least 20 dB above ambient, others showed an avoidance reaction to broadband noise levels as low as 10 dB above ambient. Generally, the zone of responsiveness would be considerably smaller than the zone of audibility, but the extent of the zone for a given whale at any given time would appear to depend on the whale's activity (eg. resting, feeding, socializing, migrating), its situation (deep or shallow water) and the nature of the sound source (Miles *et al*. 1987). For migrating whales off California, the 0.1 and 0.5 probability of avoidance for received broadband industrial noise was estimated to be 110 and 120 dB re 1 μPa respectively. This corresponded to S:N ratios of 20 to 30 dB (Miles *et al*. 1987).

Responsiveness may depend on the nature of the noise and not just its level. Whales are generally more responsive to variable sounds than continuous sounds (Miles *et al*. 1987). Bowhead whales have been found to react strongly and consistently to vessels that are heading directly toward the whales and, as a result, boats have been identified as the industrial activity that most consistently affects this species (Richardson 1985, Richardson *et al*. 1985).

The importance of masking to whales, particularly baleen whales, is largely unknown (Miles *et al*. 1987). However, certain toothed whales are known to be able to adapt to increased background noise levels by altering the frequency of their calls or increasing intensity (Au 1980, Au *et al*. 1985).

Gales (1982) attempted to predict the effects of high sound pressure levels on marine mammals. He considered that, for a mammal adapted to life in the sea, levels below 200 dB re 1 μPa would be unlikely to cause auditory damage. By analogy with humans , in which sounds tend to become uncomfortably loud at levels 100 to 120 dB above threshold, corresponding levels would be approximately 143 to 180 dB for dolphins and seals.

4.2 Acoustical Deterrents

Interactions between marine mammals and fishing operations frequently occur and can result in incidental mortality, injury, or disruption to the marine mammals, and/or damage or loss of fishing gear and catch (Mate and Harvey 1987). Major conflicts include the incidental mortality of dolphins, porpoises, sea lions and fur seals during purse seine, gill net and trawl fisheries, and the damage to gear and fish by pinnipeds (seals and sea lions) during troll and gill net fisheries. The production of underwater sounds, as warnings or irritants has often been considered a promising method for repelling marine mammals from fishing operations. In Scotland, a series of trials were undertaken to investigate the effectiveness of sound as a deterrent to marauding grey (*Halichoerus grypus*) and common (*Phoca vitulina*) seals at salmon netting stations (Anderson and Hawkins 1978). Hearing in salmonid fish is restricted to low frequencies, with greatest sensitivity at 160 Hz and a steep loss of sensitivity above 200 Hz, whilst the hearing range in seals extends to high frequencies. Sounds could therefore be produced which would scare seals but not fish. In the trials a wide variety of sounds were transmitted, including electronically generated pure and pulsed tones at frequencies from 1 to 100 kHz, and recorded signals of killer whale calls and assorted loud noises such as banging, shouting and metallic scraping. None of the sounds was found to be consistently effective in scaring seals although the taped sounds tended to produce more reaction than synthesized sounds. A captive seal showed a positive avoidance reaction only to taped killer whale calls but showed rapid habituation to these sounds when replayed.

The reaction of marine mammals to killer whale vocalizations appears quite variable. Gray whales (*Eschrichtius robustus*) and beluga whales (*Delphinapterus leucas*) have both shown positive avoidance reactions to killer whale vocalizations (Cummings and Thompson 1971, Fish and Vania 1971), but, when played to southern right whales (*Eubalaena australis*), they produced either investigative behaviour or no response (Cummings *et al*. 1972, 1974). Pryor and Norris (1978) report that broadcasting killer whale sounds to open ocean porpoises (*Stenella* sp.) enclosed in purse seine nets caused many to panic and blunder into the net which they normally would have avoided.

Acoustic deterrents to keep Cape fur seals (*Arctocephalus pusillus*) from fishing nets off southern Africa have also been investigated (Shaughnessy *et al*. 1981). Weighted firecrackers, taped killer whale sounds and sweep frequency pulses (0.5 to 0.6 kHz, 0.6 to 3 kHz, 0.6 to 10 kHz) and an underwater shockwave generator were tested but none of these was concluded to be effective in reducing seal disturbances. Firecrackers, rifle bullets fired into the water and the shock wave generator caused seals to dive, and often move away from the nets, but not flee, and animals soon returned to feeding. Seals showed an initial alarm reaction to killer whale vocalizations and, to a lesser extent, to sweep pulse frequencies, but did not avoid them. The authors concluded that Cape fur seals are likely to habituate to any deterrent which merely frightens them without causing pain.

Mate *et al*. (1987) developed an acoustical harassment device (AHD) to produce loud and highly variable noises in an effort to scare harbor seals (*Phoca vitulina*), and perhaps cause auditory pain at close range. Frequencies of 12 and 17 kHz were chosen because, among other reasons, seals showed good sensitivity to these frequencies whilst they were beyond the hearing range of fish. Source levels in trials were in the range 158 to 200 dB re 1 μPa. Effects of the AHD were variable. In hatchery and gill net operations, the device kept most seals at least 150 m away, but some were seen to pass within a few metres of the AHD by choice. This suggested that the AHD caused psychological irritation for most seals, rather than physical pain.

Other studies also found the AHD to not be completely successful. Geiger and Jeffries (1987) observed that, although initially seals were kept 100 m from active AHDs, subsequently some seals were observed between 10 and 50 m of the device. With continued use over several weeks the method seemed to lose all effectiveness and even to increase the incidence of fish damage, perhaps by attracting seals to the fishing operation. Maximum effect seemed to result from the startle effect and the device could remain useful if used prudently by continually moving the sound source and increasing the interval between pulses, thus postponing the habituation/learning process by the seals. Some short term success was achieved in driving Californian sea lions (*Zalophus californianus*) away from fishing operations when an AHD was used in combination with cracker shells (Hanan and Scholl 1987a, Scholl 1987) and in herding harbor seals downstream from a river seining site (Hanan and Scholl 1987b). AHD's were found partially effective when used to create an acoustic barrier to prevent harbor seals entering Netarts Bay, Oregon (Harvey *et al*. 1987), and in keeping seals and sea lions away from fish ladders (Rivinus 1987).

An AHD used in Alaska near beluga whales seemingly drove them from the area and the effects lasted for several days, whilst in other areas cetaceans appeared to be unaffected (Mate and Harvey 1987).

The average underwater sound level of an AHD has been measured at 135-140 dB at about 100 m (Awbrey and Thomas 1987). Attenuation rates were about 6 dB per doubling of distance in shallow water and about 9 dB in deep water. These authors (1984) theorized that physical discomfort in pinnipeds would occur 25 to 50 m from the sound source. They cautioned that exposure to higher intensities could cause hearing loss (to this frequency band) which would be impossible to distinguish from acclimation. Greenlaw (1987) estimated the sound levels to cause pain to be 185 dB re 1 μPa for seals, 192 dB re 1 μPa for humans and 200 dB re 1 μPa for sea lions. Seal bombs, which explode at 2 to 3 m depths, produce a source sound exposure level of nearly 190 dB with most of the sound energy below 1 kHz (Awbrey and Thomas 1987).

4.3 Effects of Sonar on Dolphins

A number of authors (McBride and Hebb 1948, Kellogg and Kohler 1952, Kellogg 1961, Nicol 1967), in discussing the acute acoustic sense of dolphins, comment that supersonic depth finders will drive away schools of these animals. Such comments appear to be based on the circumstantial observations of Fraser (1947) who reported:

> "On December 30, 1945, a school of about a hundred *Delphinus delphis* was near the ship in calm water, splashing, diving and leaping vertically out of the water. The dolphins suddenly dashed away at great speed and their disappearance coincided with the switching on of the ship's supersonic echo-sounding machine. This sensitiveness to supersonic emissions was confirmed on a later occasion."

Evans (1987) reported suggestions that sidescan sonar and echo-sounders, which transmit in the frequency range 5 to 250 kHz depending on the equipment type and its use, could disrupt the echolocation behaviour of small cetaceans as most have hearing ranges of 1 to 150 kHz. He considered that if the sounds were not very loud the animals may be able to ignore them.

4.4 Other Noise

Many cetaceans have been found to show a negative response to boat traffic. Among the smaller cetaceans, negative response have been observed in the harbour porpoise in northwest Scotland, Denmark and Washington State (Evans 1987). In Alaska, beluga whales responded more to outboard motors than to inboard-powered vessels or playbacks of oil drilling sounds, and outboard motor noise seemed to cause aversion even from a considerable distance (Stewart *et al*. 1982). In several areas of Alaska, beluga numbers have declined and this has been attributed to increased use of outboard-powered boats (Hazard 1988). Belugas are also considered to be easily frightened by low-flying aircraft. In Australia, bottlenose dolphins in Jervis Bay have been observed to flee from an outboard powered runabout unless it was idling, yet stay and even approach a slow-moving diesel-powered trawler (Anonymous 1988). Speed boats operating at speeds greater than 25 knots generate significant sound in the frequency range 1 to 50 kHz, well within the hearing range of the toothed whales (Evans 1987). Evans (1987) has tested the effects of different engine sounds on the white-beaked and Risso's dolphins in Scotland and found a marked negative response at frequencies above 10 kHz.

The ambient noise levels in areas of high marine traffic can rise by up to 10 dB but these levels are predominantly in the range 10 to 100 Hz with very little above 1 kHz (Ross 1976, Evans 1987). Such noise is considered unlikely to effect dolphins and porpoises, but may effect baleen whales whose hearing range extends down to 12 Hz (Evans 1987). Bowhead whales react strongly to close approach by boats (Richardson *et al*. 1985). Subtle behavioural changes in response to an idling boat 3 to 4 km away were noted in one instance, and the flight reaction began when an oncoming boat was 2 to 4 km away. Other baleen whales have been found to show considerable tolerance of boats, but often avoid rapidly or erratically moving vessels (Swartz and Cummings 1978, Ray *et al.* 1978, Watkins 1981a).

Marine seismic survey vessels typically use an array of airguns to produce noise pulses with source levels of 245 to 252 dB re 1 μPa at 1 m (Evans 1987). The underwater noise level exceeds 150 dB at horizontal distances out to several kilometres, and weaker noise is often detectable as far as 25 to 90 km away (Richardson *et al*. 1985). Within a few kilometres of the source frequencies <100 Hz dominate but in shallow water these attenuate rapidly and further away most energy is in the range 75 to 500 Hz. Migrating gray whales off California have been observed to show avoidance behaviour when the sound exceeded 160 dB re 1 μPa, corresponding to ranges less than 5 km for a full-scale array of airguns or less than 1 km for a single airgun (Malme *et al.* 1983, 1984).

Richardson *et al*. (1985) found no clear evidence of bowhead whales moving away from seismic vessels 6 km or more away, although there was sometimes evidence of subtle changes in surfacing, diving and respiration behaviour. Avoidance reactions were exhibited when they received seismic pulses stronger than about 160 dB re 1 μPa (Richardson *et al.* 1986). However, bowhead whales 33 km from a seismic vessel have been observed to show mild reactions to the presence of seismic sounds, eg. huddling or spending longer at the surface (Reeves *et al*. 1984). Ljungblad *et al*. (1988) observed the behavioural responses of bowhead whales to controlled approaches by geophysical vessels producing airgun blasts. Short term behavioural changes occurred when whales were exposed to airgun blasts from vessels at ranges < 10 km, with avoidance reactions commencing at received noise levels of 142 dB re 1 μPa. Disturbance effects were observed to wane within one hour after a disturbance.

McBride and Hebb (1948) observed that at Marineland, Florida, a single .22-calibre rifle shot would make all porpoises (presumably *Tursiops truncatus*) within a mile or so swim rapidly seaward.

Bowheads have been observed to often occur in areas where low frequency underwater noise from drillships and dredges was readily detectable by hydrophones and, presumably, by the whales (Richardson *et al*. 1985). From these observations, and observations that bowheads reacted strongly to approaching boats and low altitude aircraft, it was suggested that these whales tend to react to transient or recently-begun industrial activities, but often tolerate considerable noise from operations that continue with little change for hours or days.

5. Conclusions

Sound can be effective in attracting fish when the character of the sound simulates the noise of feeding fish or the struggling of prey animals. However, even high sound levels rarely elicit an avoidance response and the reactions of quickened movement or a startle response are only of brief duration. Intense sound levels of 225 dB re 1 μPa and higher can disorient or kill fish, but the magnitude of such an effect would depend on the abundance of fish in the vicinity of the sound source and the sound attenuation.

The group of marine animals most likely to be adversely affected by sound are the whales. Toothed whales are known to be extremely sensitive to a wide range of high frequency sounds; the hearing range of bottlenose dolphins extending from 75 Hz to 150 kHz, with maximum sensitivity in the range 20 to 80 kHz. This hearing range has evolved as part of their echolocation ability in which echolocation signals are produced with peak frequencies in the range 15 to 130 kHz. Several species of dolphin and the related beluga whale have been observed to flee from high frequency sounds, including sonar depth-sounders and the noise of outboard motors, but to tolerate low frequency noise. The reasons for this reaction can only be speculated but such sounds are likely to interfere with, or mask, the animals echolocation ability. Although dolphins are known to be able to increase the intensity of their echolocation signals in response to increased background noise, this capacity would be limited.

Baleen whales do not possess the same high frequency sensitivity as the toothed whales, but appear highly sensitive to low frequency sounds. They have been observed to show avoidance reactions to noises at distances of several kilometres. Gray whales off California showed an avoidance response when sound levels exceeded 160 dB re 1 uPa. The implications of the avoidance response to migrating whales is difficult to determine without detailed study, but it is unlikely to seriously disrupt migration routes.

Seals, like dolphins, have been found to be sensitive to high frequency sound. Such sound is known to, at least initially, cause an avoidance response. However, in the presence of a positive attractant, such as food, seals have shown rapid habituation to the noise source or to return soon after the noise ceases.

6. References

Anderson, S.S. (1970) Auditory sensitivity of the harbour porpoise, *Phocoena phocoena*. In G. Pilleri (Ed.), *Investigations on Cetacea* (Vol. 2, pp. 255-258). Berne: Hirnanat. Inst.

Anderson, S.S. and Hawkins, A.D. (1978) Scaring seals by sound. *Mammal Review,* **8**, 19-24.

Anonymous (1988) *Marine mammals and marine reptiles of Jervis Bay: Stage 1 report*. Report to Department of Defence. The Ecology Lab Pty Ltd and Travers Morgan Pty Ltd.

Au, W.W.L. (1980) Echolocation signals of the Atlantic bottlenose dolphin (*Tursiops truncatus*) in open waters. In R.-G. Busnel and J.F. Fish (Eds.), *Animal Sonar Systems* (pp. 251-282). New York: Plenum Press.

Au, W.W.L., Carder, D.A., Penner, R.H. and Scronce, B.L. (1985) Demonstration of adaptation in Beluga whale echolocation signals. *Journal of the Acoustical Society of America,* **77**, 726-730.

Au, W.W.L., Floyd, R.W. and Haun, J.E. (1978) Propagation of Atlantic bottlenose dolphin echolocation signals. *Journal of the Acoustical Society of America,* **68**, 411-422.

Au, W.W.L., Floyd, R.W., Penner, R.H. and Murchison, A.E. (1974) Measurement of echolocation signals of the Atlantic bottlenose dolphins, *Tursiops truncatus*, in open waters. *Journal of the Acoustical Society of America,* **56**, 1280-1290.

Awbrey, F.T. and Thomas, J.A. (1984) *Measurements of sound propagation from several acoustic harassment devices*. Final report to National Marine Fisheries Service, PO No. 84-JFA-00062. San Diego, CA: Hubbs-Sea World Research Institute. [cited in Geiger and Jeffries 1987]

Awbrey, F.T. and Thomas, J.A. (1987) Measurements of sound propagation from several acoustic harassment devices. In B.R. Mate and J.T. Harvey (Eds.), *Acoustical Deterrents in Marine Mammal Conflicts with Fisheries* (Publication No. ORESU-W-86-001, pp. 85-104). Corvallis, Oregon: Oregon State University.

Bel'kovich, V.M. and Solntseva, G.N. (1970) Anatomy and function of the ear in dolphins. *Zoologichesky Zhurnal,* **2**, 275-282. [cited in Turl and Lindner, 1982]

Bel'kovich, V.M. and Yablokov, A.V. (1963) Marine animals "share experience" with designers. *Nauka Zhiza',* **30** (5), 61-64. [cited in Norris and Mohl 1983]

Berzin, A.A. (1972) *The sperm whale* (Translation No. 600707) . Jerusalem: Israel Program for Scientific Translation. (Original work published 1971) [cited in Norris and Mohl 1983]

Bullock, T.H., Grinnel, A.D., Ikezono, E., Kameda, K., Nomoto, M., Sato, N. and Yanagisawa, K. (1968) Electrophysiological studies on the central auditory mechanisms in cetaceans. *Zeitschrift fuer Vergleichende Physiologie,* **59**, 117-156.

Burner, C.J. and Moore, H.L. (1953) *Attempts to guide small fish with underwater sound* (Special Scientific Report on Fisheries No. 111). U.S. Fisheries and Wildlife Service.

Busnel, R.G. and Fish, J.F. (Eds.) (1980) *Animal Sonar Systems*. Plenum Press.

Caldwell, M.C., Haugen, R.M. and Caldwell, D.K. (1962) High-energy sound associated with fright in the dolphin. *Science,* **138**, 907-908.

Chapman, C.J. and Hawkins, A.D. (1968) In A.B. Tuvia and W. Dickson (Eds.), *Proceedings of a Conference on Fish Behaviour in relation to Fishing Techniques and Tactics* (pp. 717-729). Rome: F.A.O. [cited in Hawkins 1973]

Cousteau, J.-I. and Cousteau, P. (1970) *The Shark*. New York: Doubleday & Co.

Cummings, W.C. and Thompson, P.O. (1971) Gray whales, *Eschrichtius robustus*, avoid the underwater sounds of killer whales, *Orcinus orca*. *Fishery Bulletin, Washington*, **69**, 525-530.

Cummings, W.C., Fish, J.F. and Thompson, P.O. (1972) Sound production and other behaviour of southern right whales, *Eubalaena glacialis*. *Transactions of the San Diego Society of Natural History,* **17**, 1-14.

Cummings, W.C., Thompson, P.O. and Fish, J.F. (1974) Behaviour of southern right whales: R/V *Hero* cruise 72/3. *Antarctic Journal of the United States,* **9**, 33-38.

Diercks, K.J. (1972) *Biological sonar systems: a bionics survey* (Report ARL-TR-34). Applied Research Laboratories, University of Texas. [cited in Norris and Mohl 1983].

Dudok van Heel, W.H. (1962) Sound and cetacea. *Netherlands Journal of Sea Research,* **1**, 407-507.

Evans, P.G.H. (1987) *The Natural History of Whales & Dolphins*. New York: Facts on File Publications.

Fish, J.F. and Turl, C.W. (1976) *Acoustic source levels of four small whales* (Report No. NUC-TP-547). San Diego, CA: Naval Undersea Center.

Fish, J.F. and Vania, J.S. (1971) Killer whale, *Orcinus orca*, sounds repel white whales, *Delphinapterus leucas*. *Fishery Bulletin, Washington,* **69**, 531-535.

Fleischer, G. (1976) Hearing in extinct cetaceans as determined by cochlear structure. *Journal of Paleontology,* **50**, 133-152.

Fraser, F.C. (1947) Sound emitted by dolphins. *Nature,* **160**, 759.

Gales, R.S. (1982) *Effects of noise of offshore oil and gas operations on marine mammals - an introductory assessment* (Technical Report 844, Vols.1 & 2). San Diego, CA: Naval Ocean Systems Center.

Geiger, A.C. and Jeffries, S.J. (1987) Evaluation of seal harassment techniques to protect gill netted salmon. In B.R. Mate and J.T. Harvey (Eds.), *Acoustical Deterrents in Marine Mammal Conflicts with Fisheries* (Publication No. ORESU-W-86-001, pp. 37-55). Corvallis, Oregon: Oregon State University.

Greenlaw, C.F. (1987) Psychoacoustics and pinnipeds. In B.R. Mate and J.T. Harvey (Eds.), *Acoustical Deterrents in Marine Mammal Conflicts with Fisheries* (Publication No. ORESU-W-86-001, pp. 11-15). Corvallis, Oregon: Oregon State University.

Hall, J.D. and Johnson, C.S. (1971) Auditory thresholds of a killer whale Orcinus orca Linnaeus. *Journal of the Acoustical Society of America,* **51**, 515-517.

Hanan, D. and Scholl, J. (1987a) Acoustic harassment testing in the San Francisco Bay Pacific herring, *Clupea harengus*, gill net and purse seine fisheries. In B.R. Mate and J.T. Harvey (Eds.), *Acoustical Deterrents in Marine Mammal Conflicts with Fisheries* (Publication No. ORESU-W-86-001, pp. 56-57). Corvallis, Oregon: Oregon State University.

Hanan, D. and Scholl, J. (1987b) Acoustic harassment testing in the Klamath River salmon fishery. In B.R. Mate and J.T. Harvey (Eds.), *Acoustical Deterrents in Marine Mammal Conflicts with Fisheries* (Publication No. ORESU-W-86-001, pp. 58-64). Corvallis, Oregon: Oregon State University.

Harvey, J.T., Mate, B.R. and Brown, R.F. (1987) The feasibility and effectiveness of using an acoustic barrier to restrict the movements of seals into Netarts Bay, Oregon. In B.R. Mate and J.T. Harvey (Eds.), *Acoustical Deterrents in Marine Mammal Conflicts with Fisheries* (Publication No. ORESU-W-86-001, pp. 75-78). Corvallis, Oregon: Oregon State University.

Hashimoto, T. and Maniwa, Y. (1967) Research on the luring of fish shoals by utilizing underwater acoustical equipment. In W.N. Tavolga (Ed.), *Marine Bio-acoustics* (Vol. 2, pp. 93-104). New York: Pergammon Press.

Hawkins, A.D. (1973) The sensitivity of fish to sounds. *Annual Review of Oceanography and Marine Biology,* **11**, 291-340.

Hawkins, A.D. (1986) Underwater sound and fish behaviour. In T.J. Pitcher (Ed.), *The Behaviour of Teleost Fishes* (pp. 114-151). London: Croom Helm.

Hazard, K. (1988) Beluga whale, *Delphinapterus leucas*. In J.W. Lentfer (Ed.), *Selected Marine Mammals of Alaska: Species Accounts with Research and Management Recommendations* (pp. 195-235). Washington, D.C.: Marine Mammal Commission.

Hult, R. (1982) Another function of echolocation for bottlenose dolphins (*Tursiops truncatus*). *Cetology*, **47**, 1-7.

Jacobs, D.W. and Hall, J.D. (1972) Thresholds of a freshwater dolphin, *Inia geoffrensis* Blainville. *Journal of the Acoustical Society of America*, **51**, 530-533.

Johnson, C.S. (1966) *Auditory thresholds of the bottlenose porpoise (*Tursiops truncatus, *Montagu)* (Report NOTS-TP-4178). U.S. Naval Ordinance Test Station. [cited in Myrberg 1980]

Johnson, C.S. (1967) Sound detection thresholds in marine mammals. In W.N. Tavolga (Ed.), *Marine Bio-acoustics* (Vol. 2, pp. 247-255). New York: Pergammon Press.

Kellogg, W.N. (1961) *Porpoises and Sonar*. Chicago: University of Chicago Press.

Kellogg, W.N. and Kohler, R. (1952) Reactions of the porpoise to ultrasonic frequencies. *Science*, **116**, 250-252.

Lilly, J.C. (1962) Vocal behaviour of the bottlenose dolphin. *Proceedings of the American Philosophical Society,* **106**, 520-529.

Ljungblad, D.K., Würsig, B., Swartz, S.L. and Keene, J.M. (1988) Observations on the behavioural responses of bowhead whales (*Balaena mysticetus*) to active geophysical vessels in the Alaskan Beaufort Sea. *Arctic*, **41**, 183-194.

MacGinitie, G.E. and MacGinitie, N. (1968) *Natural History of Marine Animals.* New York: McGraw-Hill, NY

Mackay, R.S. and Pegg, J. (1988) Debilitation of prey by intense sounds. *Marine Mammal Science*, **4**, 356-359.

Malme, C.I., Miles, P.R., Clark, C.W., Tyack, P. and Bird, J.E. (1983) *Investigations of the potential effects of underwater noise from petroleum industry activities on migrating gray whale behaviour* (Report 5366). Cambridge. MA: BBN Laboratories Inc. (NTIS No. PB86- 174174)

Malme, C.I., Miles, P.R., Clark, C.W., Tyack, P. and Bird, J.E. (1984) *Investigations of the potential effects of underwater noise from petroleum industry activities on migrating gray whale behaviour. Phase 2: January 1984 migration* (Report 5586). Cambridge, MA: BBN Laboratories Inc. (NTIS No. PB86-218377)

Mate, B.R., Brown, R.F., Greenlaw, C.F., Harvey, J.T. and Tempte, J. (1987) An acoustic harassment technique to reduce seal predation on salmon. In B.R. Mate and J.T. Harvey (Eds.), *Acoustical Deterrents in Marine Mammal Conflicts with Fisheries* (Publication No. ORESU-W-86-001, pp. 23-36). Corvallis, Oregon: Oregon State University.

Mate, B.R. and Harvey, J.T. (1987) Introduction and Executive Summary. In B.R. Mate and J.T. Harvey (Eds.), *Acoustical Deterrents in Marine Mammal Conflicts with Fisheries* (Publication No. ORESU-W-86-001, pp. 1-10). Corvallis, Oregon: Oregon State University.

McBride, A.F. and Hebb, D.O. (1948) Behaviour of the captive bottle-nose dolphin, *Tursiops truncatus. Journal of Comparative and Physiological Psychology,* **41**, 111-123.

Miles, P.R., Malme, C.I. and Richardson, W.J. (1987) *Prediction of drilling site-specific interaction of industrial acoustic stimuli and endangered whales in the Alaskan Beaufort Sea* (Report 6509). Cambridge, MA: BBN Laboratories, Inc. (NTIS No. PB88-158498)

Mohl, B. (1968) Auditory sensitivity of the common seal in air and water. *Journal of Auditory Research,* **8**, 27-38.

Moulton, J.M. (1964) Underwater sound: biological perspectives. *Annual Review of Oceanography and Marine Biology*, **2**, 425-454.

Myrberg, A.A., Jr (1976) Behaviour of sharks - a continuing enigma. *Naval Research Reviews*, **29** (7), 1-11.

Myrberg, A.A., Jr (1980) Ocean noise and the behaviour of marine animals: relationships and implications. In F.P. Diemer, F.J. Vernberg and D.Z. Mirkes (Eds.), *Advanced Concepts in Ocean Measurement for Marine Biology* (pp. 461-491). Columbia, S.C.: University of South Carolina Press.

Myrberg, A.A., Jr, Gordon, C.R. and Klimley, A.P. (1976) Attraction of free ranging sharks by low frequency sound, with comments on its biological significance. In A. Schuijf and F.J. Lighter (Eds.), *Sound Reception in Fish* (pp. 205-228). Amsterdam: Elsevier.

Myrberg, A.A., Jr, Ha, S.J., Walewski, S. and Banbury, J.C. (1972) Effectiveness of acoustic signals in attracting epipelagic sharks to an underwater sound source. *Bulletin of Marine Science,* **22**, 926-949.

Nelson, D.R. and Gruber, S.H. (1963) Sharks: attraction by low frequency sounds. *Science*, **142**, 975-977.

Nicol, J.A.C. (1967) Phonoreception. In *Biology of Marine Animals* (2nd edn, pp. 338-344). London: Pitman Paperbacks.

Norris, K.S. and Mohl, B. (1983) Can odontocetes debilitate prey with sound? *American Naturalist*, **122**, 85-104.

Payne, R. and Webb, D. (1971) Orientation by means of long range acoustic signaling in baleen whales. *Annals of the NewYork Acadamy of Sciences*, **188**, 110-141.

Pryor, K. and Norris, K.S. (1978) The tuna/porpoise problem: behavioural aspects. *Oceanus*, 21, 31-37.

Ray, G.C., Mitchell, E.D., Wartzok, D., Kozicki, V.M. and Maiefski, R. (1978) Radio tracking of a fin whale (*Balaenoptera physalus*). *Science*, **202**, 521-524.

Reeves, R.R., Ljungblad, D.K. and Clarke, J.T. (1984) Bowhead whales and acoustic seismic surveys in the Beaufort Sea. *Polar Record*, **22**, 271-280.

Richard, J.D. (1968) *Journal of the Fisheries Research Board, Canada*, **25**, 1441-1452. [cited in Hawkins 1973]

Richardson, W.J. (1985) *Behaviour, disturbance responses and distribution of bowhead whales Balaena mysticetus in the eastern Beaufort Sea 1980-84* (Report OCS/MMS-85/0034). (PB87-124376/XAB)

Richardson, W.J., Fraker, M.A., Würsig, B. and Wells, R.S. (1985) Behaviour of bowhead whales *Balaena mysticetus* summering in the Beaufort Sea Arctic Ocean and reactions to industrial activities. *Biological Conservation*, **32**, 195-230.

Richardson, W.J., Würsig, B. and Greene, C.R., Jr. (1986) Reactions of bowhead whales, *Balaena mysticetus*, to seismic exploration in the Canadian Beaufort Sea. *Journal of the Acoustical Society of America*, **79**, 1117-1128.

Ridgway, S.H. and Joyce, P.L. (1975) Studies on seal brain by radiotelemetry. *Rapports et Proces-Verbaux des Reunions, Conseil International pour l'Exploration du la Mer*, **169**, 81-91.

Rivinus, A. (1987) Oregon Aquafood's experience with a seal avoidance system. In B.R. Mate and J.T. Harvey (Eds.), *Acoustical Deterrents in Marine Mammal Conflicts with Fisheries* (Publication No. ORESU-W-86-001, pp. 79-80). Corvallis, Oregon: Oregon State University.

Ross, D. (1976) *Mechanics of Underwater Noise.* Oxford: Pergamon Press.

Scholl, J. (1987) Acoustic harassment and cracker shell tests in the Southern California partyboat fishery. In B.R. Mate and J.T. Harvey (Eds.), *Acoustical Deterrents in Marine Mammal Conflicts with Fisheries* (Publication No. ORESU-W-86-001, pp. 66) Corvallis, Oregon: Oregon State University.

Schusterman, R.J. (1974) Auditory sensitivity of a California sea lion to airborne sounds. *Journal of the Acoustical Society of America,* **56**, 1248-1251.

Schusterman, R.J., Balliet, R.F. and Nixon, J. (1972) Underwater audiogram of the California sea lion by the conditioned vocalization technique. *Journal of the Experimental Analysis of Behaviour*, **17**, 339-350.

Shaughnessy, P.D., Semmelink, A., Cooper, J. and Frost, P.G.H. (1981) Attempts to develop acoustic methods of keeping Cape fur seals *Arctocephalus pusillus* from fishing nets. *Biological Conservation,* **21**, 141-158.

Stewart, B.S., Evans, W.E. and Awbrey, F.T. (1982) *Effects of waterborne man-made noise on behaviour of beluhka whales (*Delphinapterus leucas*) in Bristol Bay, Alaska* (Technical Report No. 82-145). San Diego, CA: Hubbs-Sea World Research Institute. [cited in Hazard 1988]

Swartz, S.L. and Cummings, W.C. (1978) Gray whales, *Eschrichtius robustus*, in Laguna San Ignacio, Baja California, Mexico. Prepared by San Diego Natural History Museum for US Marine Mammal Commission, Washington. [cited in Richardson *et al*. 1985].

Tavolga, W.N. (Ed.) (1964) *Marine Bio-acoustics* (Vol. 1). New York: Pergammon Press.

Tavolga, W.N. (Ed.) (1967) *Marine Bio-acoustics* (Vol. 2). New York: Pergammon Press.

Tavolga, M.C. and Essapian, F.S. (1957) The behaviour of the bottlenosed dolphin (*Tursiops truncatus*); mating, pregnancy, paturition, and mother-infant behaviour. *Zoologica*, **42**, 11-31.

Terhune, J.M. (1988) Detection thresholds of a harbour seal to repeated underwater high-frequency, short-duration sinusoidal pulses. *Canadian Journal of Zoology*, **66**, 1578-1582.

Terhune, J.M. and Ronald, K. (1971) The harp seal, *Pagophilus groenlandicus* (Erxleben, 1777). I. The air audiogram. *Canadian Journal of Zoology*, **49**, 385-390.

Terhune, J.M. and Ronald, K. (1972) The harp seal, *Pagophilus groenlandicus* (Erxleben, 1777). III. The underwater audiogram. *Canadian Journal of Zoology*, **50**, 565-569.

Terhune, J.M. and Ronald, K. (1975) Underwater hearing sensitivity of two ringed seals (*Pusa hispida*). *Canadian Journal of Zoology*, **53**, 227-231.

Turl, C.W. (1982) *Possible effects of noise from offshore oil and gas drilling activities on marine mammals - a survey of the literature* (Technical Report 776). San Diego, CA: Naval Oceans Systems Center.

Turl, C.W. and Lindner, E. (1982) Literature review on: I. Underwater noise from offshore oil operations and II. Underwater hearing and sound productions of marine mammals. In R.S. Gales, *Effects of noise of offshore oil and gas operations on marine mammals - an introductory assessment* (Technical Report 844, Vol. 2, Appendix A (A-1 - A-41)). San Diego, CA: Naval Ocean Systems Center.

Tyack, P. and Whitehead, H. (1983) Male competition in large groups of wintering humpback whales. *Behaviour*, **83**, 132-154.

VanDerwalker, J.G. (1967) Response of salmonids to low frequency sound. In W.N. Tavolga (Ed.) *Marine Bio-acoustics* (Vol. 2, pp. 45-58). New York: Pergammon Press.

Watkins, W.A. (1980) Acoustics and behaviour of sperm whales. In R.-G. Busnel and J.F. Fish (Eds.), *Animal Sonar Systems* (pp. 283-290). New York: Plenum Press.

Watkins, W.A. (1981a) Reactions of three species of whales *Balaenoptera physalus*, *Megaptera novaeangliae*, and *Balaenoptera edeni* to implanted radio tags. *Deep-Sea Research*, **28A**, 589-599.

Watkins, W.A. (1981b) Activities and underwater sounds of fin whales. *Scientific Reports of the Whales Research Institute*, **33**, 83-117.

White, M.J., Norris, J.C., Ljungblad, D.K., Baron, K.S. and DeSciara, G.N. (1978) *Auditory thresholds of two beluga whales (*Delphinapterus leucas*)* (Technical Report 78-109). San Diego, CA: Hubbs-Sea World Research Institute. [cited in Turl, 1982]

Wood, F.G. (1987) *Annotated bibliography of publications from the U.S. Navy's marine mammal program* (Report NOSC/TD-627-REV B). San Diego, CA: Naval Ocean Systems Center.

Wood, F.G. and Evans, W.E. (1980) Adaptiveness and ecology of echolocation in toothed whales. In R.-G. Busnel and J.F. Fish (Eds.), *Animal Sonar Systems* (pp. 381-426). New York: Plenum Press.

Zagaeski, M. (1987) Some observations on the prey stunning hypothesis. *Marine Mammal Science*, **3**, 275-279.