Chapter 16

Cetaceans and Humans: Influences of Noise

[1]BERND WÜRSIG and [2]PETER G.H. EVANS
[1]Marine Mammal Research Program, Texas A&M University, 4700 Ave. U, Galveston, TX, 77551, USA. E-mail: wursigb@tamug.tamu.edu; [2]Department of Zoology, University of Oxford, South Parks Road, Oxford, OX1 3PS, UK. E-mail: peter.evans@zoo.ox.ac.uk

1. INTRODUCTION

Whales, dolphins and porpoises face a multitude of problems at the hands of humans. These include incidental kills in fishing nets and lines, direct kills for food or bait, debilitation (and death) due to pollution or other forms of habitat degradation (see Chapters 12-15 in this volume), and the mainly unknown potential effects of larger-scale ecological changes such as human-induced global climate change (Brownell *et al.*, 1989; Tynan and DeMaster, 1997). But besides these problems, there is another often difficult to measure cause of decline in health of habitat for marine mammals. This is human-induced noise, and its potential effects were not investigated until relatively recently, in the past thirty years or so. A rather thorough discussion of noise impacts on marine mammals is provided by Richardson *et al.* (1995); we here summarise the situation for cetaceans, and provide several examples and possible mitigation efforts.

2. CETACEAN USE OF SOUND AND THE MODERN UNDERWATER NOISE ENVIRONMENT

Cetaceans are all acoustic animals par excellence, and we therefore expect that underwater anthropogenic noises might be particularly disruptive to their lives (see Chapters 4 and 8). However, cetaceans are also large-brained, generally adaptive creatures, and while considering influences of habitat change we would be amiss not to take this adaptability into account. Despite all that has been written on sound influences, we still do not know very much about how sounds can affect long-term behaviour, well-being, reproduction, and - overall - the fitness of individuals and the health of populations.

As a general rule, the larger the mammal, the more probable it is to have sensitive low frequency hearing, usually at the expense of acute high frequency hearing. We humans hear reasonably well from about 20 Hz (cycles per second) up to as high as 15,000 - 20,000 Hz (or 15-20 kHz). The lowest frequency that we can hear is called the upper limit of infrasound; and the highest frequency is the lower limit of ultrasound. In general, human females have higher frequency hearing capability than males. Everybody loses some high frequency hearing with age, and men tend to do so more rapidly and drastically than women. The first author of this paper is fifty years old, and can hear to only about 10 kHz. Elephants and rhinoceroses have low frequency hearing, stretching into infrasound. Large whales, especially blue and fin whales, produce such sounds and are probably sensitive to them as well; we have no evidence for infrasound production or hearing in any toothed whale species (review by Richardson *et al.*, 1995). On the other hand, toothed whales have sensitive hearing at mid and very high frequencies but not at low frequencies. They make and receive clicks that reach far into ultrasound and that are used largely for echolocation. We have no good evidence that any baleen whales can make ultrasounds or can echolocate (for a more detailed description, see Chapter 4).

The higher the frequency, the more sound attenuates with distance. In other words, a sound of a particular intensity at 100 Hz might reach to a distance of one kilometre, while a sound of the same intensity but at 10 kHz might only reach for 150 metres (for a more thorough review, see Malme, 1995). So, we expect to find low frequency sounds being used as long-distance communication or contact calls, and higher frequency sounds being used for short-range communication and echolocation. This is exactly what happens, with blue and fin whales emitting moans that reach into infrasound and that can be heard for up to several hundred kilometres in some situations in deep water (Payne and McVay, 1971); and with dolphins whistling to each other and echolocating at relatively close distances within generally one kilometre (Au, 1993, Norris *et al.*, 1994). Large toothed whales, such as pilot whales, appear to have lower frequencies of sound projection and optimum hearing than do the smaller dolphins and porpoises, but there is much variability in this among species.

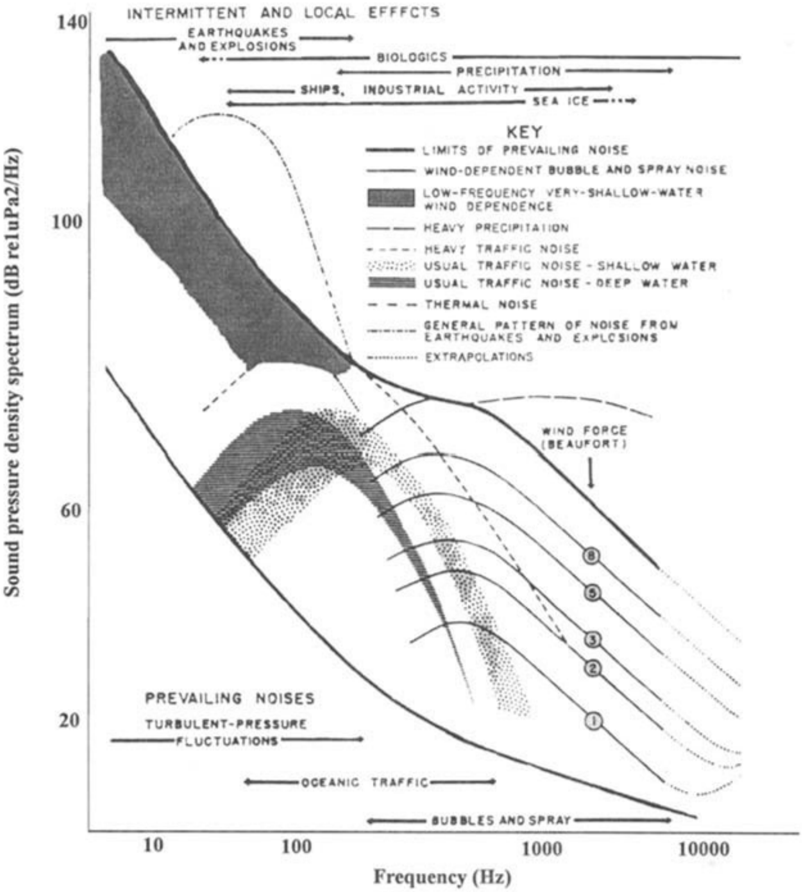

Figure 1. Generalised ambient noise spectra from a variety of sources: geophysical, weather-related, biological, and human-caused. This was originally compiled by Wenz (1962) and has been re-plotted to presently used units of sound intensity on the ordinate.

The sea has always been a noisy place, but is even more so today (Wenz, 1962; Fig. 1). In the pre-industrial ocean, there were wave noises; the din of rain on the surface; sounds of earthquakes and sea ice; and biological sounds of croaker fishes, pistol shrimps, and marine mammals. The general ambient, or background, noise due to these multiple sources usually would have been about 50-70 dB at 100Hz on a standardised measurement scale, but louder near the surface during rainstorms. However, now in many regions, there is the constant din of major shipping lanes, explosions and pile driving near shore, oil and gas exploration activities, and fishing and pleasure craft (Fig. 2). There is also an ever-greater reliance on acoustics for naval operations (sonar) and the gathering of some oceanographic data, such as synoptic basin-wide temperature measurements (Munk *et al.*, 1994).

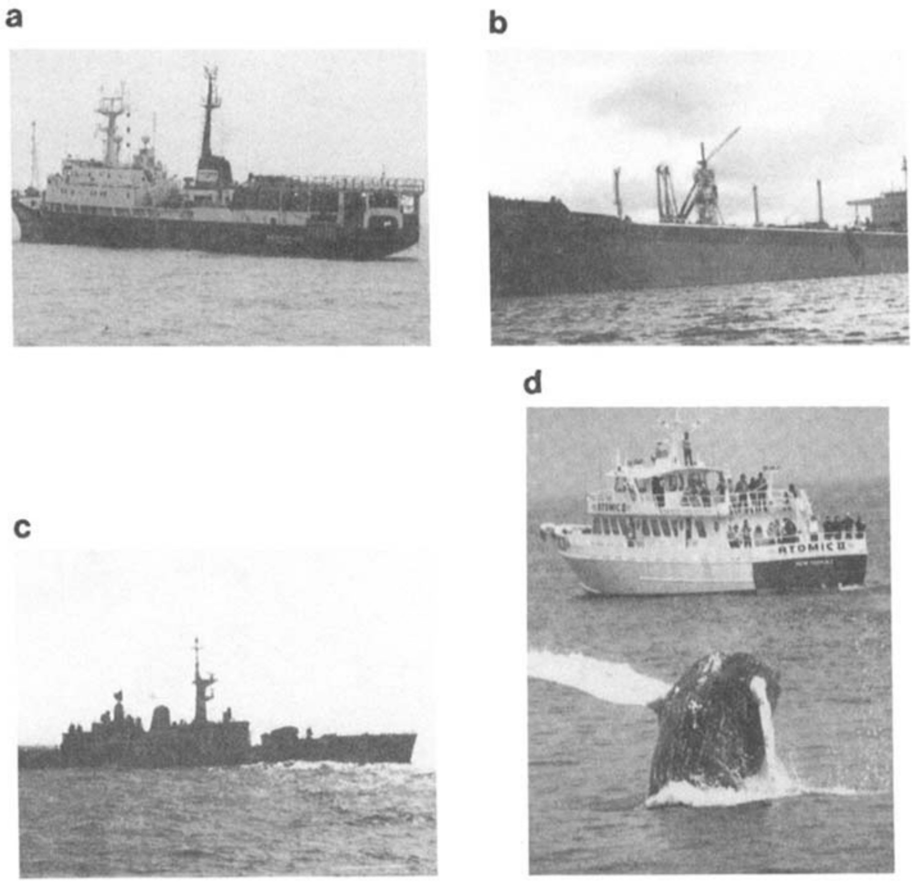

Figure 2. Examples of vessels which can disturb cetaceans through the sounds they produce: a) Seismic vessel; b) Supertanker; c) Warship on NATO exercise; and d) Whale watching vessel. (Photos: a, b, c: P.G.H. Evans; d: W. Rossiter)

All in all, the ocean is tremendously noisy especially in the northern hemisphere, where most shipping lanes occur. Indeed, Ross (1976) estimated that between 1950 and 1975, ambient noise had risen by 10 dB in areas where shipping noise dominates, and he predicted it would rise a further 5 dB by the end of the twentieth century as shipping traffic increased. Of course, there is more noise near large harbours and generally more noise in surface waters than in ocean depths. However, in deep water, there tends to be a mid-water depth where water temperature and pressure interact to create a sound speed minimum, about 1 km below the surface in the tropics but only 100 m or so below the surface in cold waters. This area of sound speed minimum channels sounds (by bending waves of sound into it), and therefore this is an especially noisy place for low frequency sounds that travel for great distances (Malme, 1995). It has been speculated that blue and fin whales might increase their communication distances by calling and listening while in this channel, utilising "cylindrical sound spreading" instead of the general "spherical sound spreading" of the deep ocean (Payne and McVay, 1971), but this assertion remains untested. Conversely, such species may also move out of these sound channels to avoid loud noises.

3. SOUND DISTURBANCE

Anthropogenic noises can disrupt the lives of animals in several ways, and cetaceans are no exception: sounds can 1) frighten them or make them curious, but in either way change their behaviour; 2) compete with communication signals or echolocation, by sound masking, and thus decrease the efficiency of finding food, mating, caring for young, or avoiding predators; cause 3a) physical effects such as stress leading to changes in hormone levels and perhaps lowered immunity from diseases, 3b) a temporary loss of hearing (or temporary threshold shift) or permanent damage to hearing, or 3c) - in the worst of cases with explosions or other loud noises that also send shock waves - possible death (Richardson and Würsig, 1997). We have tentative information about No. 1 above, at least for changes in behaviour in the short term. We know even less about long-term behavioural changes, such as threshold of sound intensity that might cause abandonment of an area. Almost nothing is known about noise-induced stress in marine mammals. Information about hearing losses, and more debilitating chronic or catastrophic effects is limited but some relevant studies are underway. Let us begin with several examples of industrial sounds changing behaviour.

One of the most dramatic sound-induced behavioural changes of cetaceans occurs in springtime near ice, when beluga whales and narwhals hear icebreakers in the distance. One such study, which relied on thousands of animals of both species being censused from the air during a three-year research project, found that the animals reacted to ships passing by at distances as great as about 90 km (LGL and Greeneridge, 1986; Finley *et al.*, 1990; Cosens and Dueck, 1993). They moved away from the ships, and were almost totally absent within about 20 km of the ships' tracks. Belugas and narwhals are generally less sensitive in summer, but it is unclear whether this is due to less confining ice in the area or perhaps because by summer they have habituated to vessel noises. One of us (BW) has repeatedly seen bowhead whales in summer being "more skittish" of industrial noises when near a confining shoreline than when in open water, and perhaps the ice at least in part enhances such a nervousness factor for the belugas and narwhals.

Bowhead whales have been studied intensively relative to oil exploration and development activities, with many of these data reviewed in a book on bowheads by Burns *et al.* (1993), and with a summary in Richardson *et al.* (1995). Behavioural reactions can vary dramatically depending on whether the animals are migrating, feeding, socialising, resting; or with no obvious relationship to general patterns of behaviour. However, one rather consistent finding stands out: bowhead whales tend to have shorter surfacings, shorter dives, fewer respirations per surfacing, and, overall, somewhat higher respiration rates when there is strong industrial noise in close proximity. This is particularly dramatic for loud pulsive "seismic" sounds made to explore the ocean bottom for oil and gas. These short duration intense sounds (usually about 242-252 dB re 1μPa @ 1 m in the case of multiple airgun arrays, and 226 dB re 1μPa @ 1 m for single airguns), projecting from behind a medium-sized moving vessel, strongly affect respiration and dive-related behaviour at distances of at least 10 km, and become particularly strong when the seismic vessel is closer than 5 km (Ljungblad *et al.*, 1988). Recent (1996-98) studies show near-total avoidance out to longer ranges of 20 km for migrating bowheads passing a localised area of seismic work (W. John Richardson, LGL Ltd., Toronto, Canada, *pers. comm.*, March 1999). When a fast-moving vessel rapidly converges on a group, bowheads tend to scatter in "all directions", and the resultant social disruption can last for at least several hours.

Gray whale responses to disturbance have also been measured during migration and while they are feeding, and these are broadly similar to the findings in bowheads. A particularly instructive experiment was conducted off the California coast, with a vessel anchored near the path of northward-migrating gray whales while observers on shore tracked movements of whales and whale pods with the help of surveyor's transits, or theodolites (Malme and Miles, 1985). On the vessel, researchers projected scaleddown sounds of seismic airguns to approaching whales. Observers on shore did not know when the experiment was "on" or "off", and therefore could not have been biased in their descriptions of whale movements. Analyses found a dramatic shift in movement patterns beginning at a distance of about 1km from the single airgun. In terms of sound level, this corresponds to a distance of about 5km with a full array of airguns used during normal seismic exploration. Gray whales tended to slow when they heard the noises, and some reversed or shifted directions for a time before passing by the vessel several hundred metres to the side of their original track. The intervals between respirations tended to decrease, and there was some evidence of whales apparently purposefully entering near-shore sound shadows created by underwater topography. The majority of whales avoided the area where the received sound level was greater than 170 dB (re. 1μPa @ 1 m); less consistent but still measurable effects were obtained at about 140-160 dB, which would correspond to distances of about 5 to 10 km from a full seismic source (Malme and Miles, 1985). Recent studies of U.S. Navy low frequency active sonar hums (LFA) at 100-500 Hz indicate that migrating gray whales react in similar fashion as to the seismic noises, at about the same received sound levels (Tyack and Clark, 1998). However, there was little indication of disturbance when feeding blue and fin whales were exposed to the same sounds, although blue whales may have made slightly fewer of their own low-frequency calls when the LFA was on (Clark *et al.*, 1998).

Sperm whales, the largest odontocetes, appear to react to both seismic (Bowles *et al.*, 1994) and pulsed sounds of sonar (Watkins *et al.*, 1993), by moving away and by limiting or altogether stopping their own pulsed calls (or "clicks"). In one case in the southern Indian Ocean, sperm whales ceased calling in apparent response to a seismic airgun array greater than 300 km from the whales, with a received sound level only about 10-15 dB above ambient sound intensity (Bowles *et al.*, 1994). As well, sperm whales and pilot whales of the same study ceased calling within at least 10 km range while experimental low frequency (57 Hz) hums were projected from a research vessel, but hourglass dolphins (as well as Antarctic fur seals) may have been attracted to the hums, as they approached the ship during playbacks, and the dolphins rode the bow. Other reactions to noises by changing vocalisations are known. Lesage *et al.* (1999) reported that for beluga whales in the presence of ferries in the St. Lawrence River, calling rate declined overall from that of boat absence (but, with redundancy of some calls, see Mitigation section, below) and frequencies of calls shifted upwards. Narwhals have been known to become totally silent and leave an area ensonified by ice-breaking or other vessels (Finley *et al.*, 1990). An excellent summary of other examples, including shifts in vocalisations in response to noises or other stimuli in captivity, is found in Lesage *et al.* (1999).

One of us (BW) has observed that Hawaiian spinner dolphins that rest during daytime as a group of about 100 individuals just underneath the flight path of low-flying commercial jetliners at Kaneohe Airport, Kona, Hawaii, dive abruptly in response to the jets. On the other hand, a helicopter flying low over a pod of 12 sperm whales in the Fair Isle Channel, North Scotland, in July 1998 elicited no response at all (N. Thompson *pers. comm.* to PE). Data are badly needed for especially toothed whales, as few detailed studies have been done, and the many anecdotal accounts give often conflicting and certainly inconclusive results. For large whales, attention must be paid to the plethora of low frequency sounds, including those of large ships and ocean acoustic studies; for toothed whales, it seems especially important to investigate how higher frequency clicks and pulses, also used in sonar and other active interrogation of the undersea environment, affect behaviour and health of animals.

Table 1. Estimated threshold values for effects of sound impulses upon fish and cetaceans (assuming spherical spreading of sound; dB values are re. 1μPa @ 1 m)

(a) FISH	PHYSICAL DAMAGE	BEHAVIOURAL AVOIDANCE
Sound Intensity	180 - 220 dB	160 - 180 dB
Dist. from Multiple Seismic Array (248 dB re 1mPa @1m)	0.25 - 2.5 km	2.5 - 25.0 km
Dist. from Single Airgun (226 dB re 1mPa @1m)	0.02 - 0.2 km	0.2 - 2.0 km
(b) BALEEN WHALES		
Sound Intensity	?220 dB	130 - 170 dB
Dist. from Multiple Seismic Array (248 dB re 1mPa @1m)	0.25 km	7.9 - 25.0 km
Dist. from Single Airgun (226 dB re 1mPa @1m)	0.02 km	0.6 - 2.0 km

Source: Evans & Nice (1996), derived from values obtained from various studies detailed therein.

From the various experimental studies conducted on marine mammals and fish, it may be possible to draw some broad generalisations concerning the sound intensities likely to cause either physical damage or at least short term avoidance. Assuming sound transmission loss occurs by spherical spreading (a reasonable approximation for most situations except very shallow waters), one can derive some estimates of the distances at which seismic sound sources within the hearing range of such organisms are likely to have an effect (see Table 1, derived from Evans & Nice, 1996). The interesting implication is that some quite disparate types of marine organism may be affected similarly. However, when the sound intensities are lower at frequencies of high animal sensitivity, then the effects will also be less.

Short term behavioural reactions do not necessarily translate to measurable or important harm to individuals or populations. Such harm may be inferred if communication, food finding, predator avoidance, and - perhaps especially important - care of young are compromised by acoustic masking, by social scattering, or by causing the animals to abandon an area. None of these possibilities, to our knowledge, has been demonstrated with certainty. It is highly likely, however, that gray whales, for example, abandoned the use of San Diego Bay (Reeves, 1977) because of noise; and temporarily abandoned Laguna San Ignacio in Baja California because of traffic, dredging, and noise generated by a salt-production plant. When the plant and associated activities ceased operation, the whales came back (Withrow, 1983, Bryant *et al.*, 1984). A similar scenario of abandonment of area may apply to Indo-Pacific humpbacked dolphins, which are no longer found in the waters immediately adjacent to Victoria Harbour, Kowloon, and north Hong Kong Island (Leatherwood and Jefferson, 1997). However, in that case, both excessive noise and pollution may have been responsible. On the other hand, bottlenose dolphins seem able to handle a prodigious amount of noise, as there are many cases where even if they show short term avoidance, they continue to feed, socialise, and rear calves directly in busy harbours or shipping lanes - a prime example is the Galveston Ship Channel, where the senior author has his base (Fertl, 1994), and another is the Sado Estuary, Portugal (dos Santos *et al.,* 1996).

4. WHALE AND DOLPHIN WATCHING

Whale and dolphin watching has rapidly become a major industry-by-the-sea, with statistics indicating that in the mid-1990's, 5.4 million persons were involved within 65 countries of the world, yielding an annual direct income of $504 million (Hoyt 1996). The financial value may be at least twice as high in 1999 (E. Hoyt, *pers. comm.* to BW). Many former fishing villages, as well as some areas where whale or dolphin hunting used to be the norm, have utilised this new economic resource to great satisfaction. Overall, it is certainly more attractive to have such a sustainable use of our natural resources, and to "love" the animals instead of eating them. However, whale and dolphin watching does need to be controlled, as excessive noise and the mere physical presence of many vessels (and for swim-with-dolphin operations, people in the water) certainly have the potential to change behaviour and perhaps elevate levels of stress (IFAW *et al.*, 1996). There is one major difference between most industrial sounds and the sounds generated by whale watching operations: whereas the former is stationary or tends to "pass by" the animals in some standard or at least partially systematic fashion; in the latter, boats directly orient towards, and stay with, their subjects - the marine mammals themselves. As a result, the animals may not have the chance to habituate as well as with some industrial activities, and may become irritated (or "sensitised") to constant or near-constant day-time approaches. On the other hand, they may become habituated to "constant" human presence. We have few good data on sensitisation or habituation, and find that - overall - whales and dolphins who wish to avoid boats can generally do so in remarkably efficient fashion. Watkins (1986) found that baleen whales in Cape Cod Bay, an area with much industrial as well as commercial tourism activity, have become generally quite habituated to boats around them. They respond by diving or by increased surface activity (such as flipper slapping or leaping) when boats approach rapidly and "head-on", as well as when there are rapid shifts in engine speed and direction.

Much has recently been written about whale and dolphin watching and potential disturbance, especially for gray, humpback, right, and sperm whales; as well as for dusky, common, Hector's and bottlenose dolphins (for example, see recent reviews by Evans, 1996, Constantine & Baker, 1997, and Constantine, 1999). The general conclusion for the present appears to be that common sense should prevail when approaching marine mammals: do not have more than three boats within 100m of the animals, do not approach rapidly, avoid sudden changes in direction and engine speed, do not cut into a group so as to separate group members. Weinrich (1989) provided a useful figure of distances and boat operation to keep in mind (Fig. 3).

Whales and dolphins may also be in different "moods" relative to their general behavioural mode; and depending on such things as whether they have recently fed, are composed of a nursery unit of mothers and calves, or are sensitised by other human actions or by predators such as killer whales nearby (Würsig 1996). One of us (PE), observing the reactions of harbour porpoise to different vessels, has found marked differences in reaction depending upon the size of boat, its behaviour to the porpoises, and various ecological features of the porpoises (group size, presence of young, season, *etc.*) (Evans *et al.*, 1994). In other words, normally approachable animals can be quite "skittish" at times, and it is up to the experience of the whale watching skipper to recognise these traits (Fig. 4).

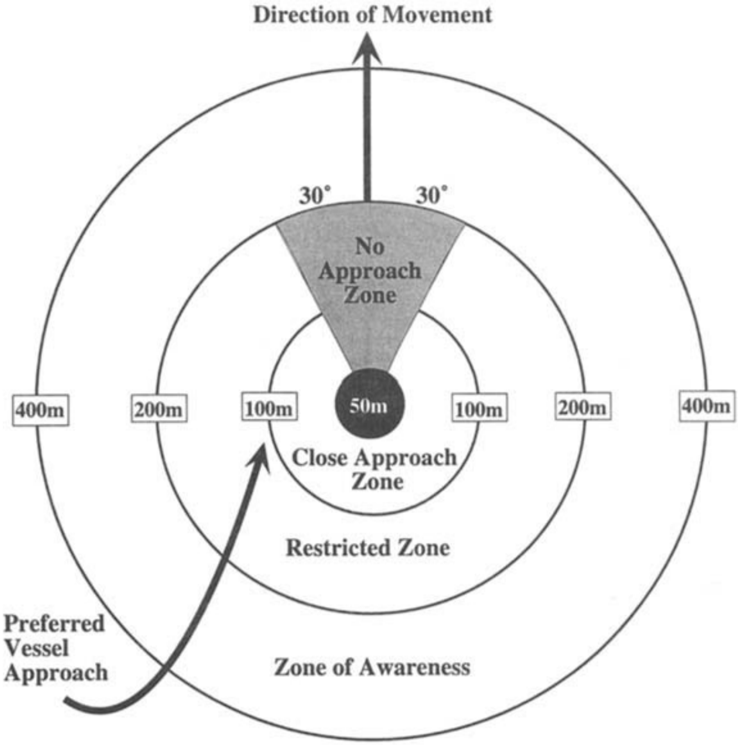

Figure 3. Vessel approach diagram. The 50 m "bull's eye" is a no approach zone. Note that circle diameters are not to scale. (Modified from Beach and Weinrich, 1989)

Constantine (1999) discussed long-term effects of whale and dolphin watching in New Zealand, where five species of dolphins and six of whales are targeted commercially. New Zealand tourism operations are generally quite well regulated and appear to be "sustainable" without chasing animals away from their near-shore haunts. However, Constantine suggested that perhaps too many permits were being issued too rapidly, resulting in the potential to harm individuals and populations in future.

There are certainly opposite extremes of potential disturbance: gray whale mothers and their newborns in Baja California calving lagoons are probably much more easily disturbed than when the same animals (with slightly older calves) are feeding along Vancouver Island, British Columbia. Dusky dolphins that rest and socialise in a bay south of Kaikoura, New Zealand, appear to be much less easily disturbed than are spinner dolphins of Hawaii that spend their daytime in deep rest in small bays (Norris *et al.*, 1994, Würsig, 1996). While tourism has not driven spinner dolphins out of these bays (perhaps because of potentially great importance of the bays to the dolphins), the dolphins are constantly forced by human presence to change their activity levels, from rest to a heightened level of alertness (Forest, 1998). We presently have no information on how this frequent change in behaviour may affect level of stress, and in turn how this might affect survivability.

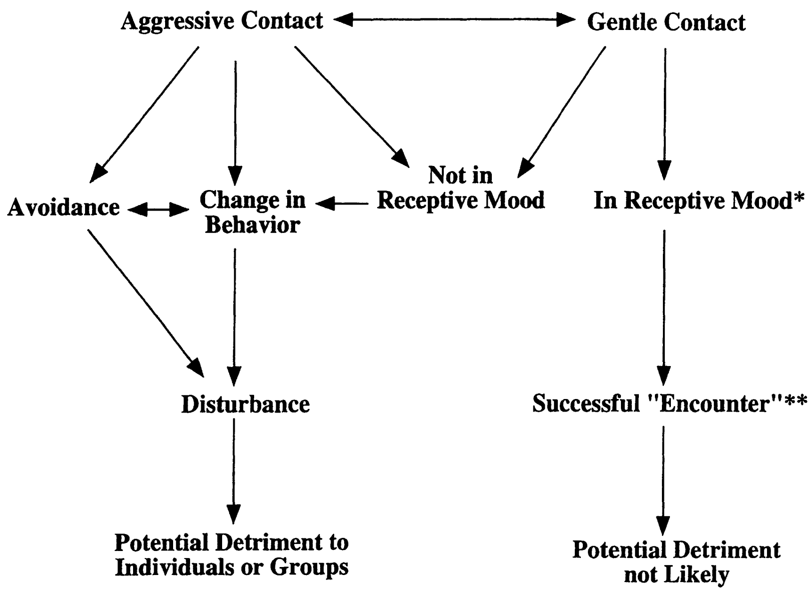

Figure 4. A schematic of how to approach cetaceans for best "whale-watching results. The schematic includes dolphin and porpoise watching, and swimming-with-dolphins. Aggressive contact is defined as rapid approach by the vessel, or rapid changes in speed and direction. Gentle contact means careful appraisal of the animals, their behavioural state, and how best to approach them, usually slowly and not head-on. Note that even gentle contact can result in unacceptable potential detriment if the animals are not in a receptive mood. *Receptive means that the animals are in a behavioural state to likely cause least disturbance (see Fig. 4). **Successful Encounter refers to both the animals not being disturbed, and the humans being happy with the situation.

5. GENERAL CONSIDERATIONS

We know something about short term reactions for whales and dolphins subjected to incidental ("industrial") and directed ("tourism") human activities, and we believe that most of these reactions are due to increased and variable noises. We surmise that auditory masking may be important at times, by decreasing information transfer and efficiency of group functions.

Behavioural and social disruption in the short-term might lead to long-term problems. There are some correlates of behavioural disruption and long-term stress in wild and domesticated terrestrial mammals (Richardson and Würsig, 1995 provide a summary of such studies), and by extrapolation to cetaceans we believe that stress, reproductive dysfunction, and other problems may result. However, requisite physiological studies (in the simplest case, involving hormone analyses from blood) of "stressed" and "unstressed" populations or sub-populations have not been carried out.

One consideration is certainly the importance to dolphins and whales of the area affected by humans, or the area affected versus the habitat available to the animals. Thus, if a particular bay, for example, is the only habitable bay where animals can rest away from deep water dangers, potential abandonment of that bay might be disastrous (in terms of inclusive fitness) to the group of animals that habitually use it. If there are many such bays and they can simply shift their habitat use patterns a bit to avoid humans, then no (or little) harm may take place. On the other hand, places "important" to marine animals are notoriously difficult for humans to define. Our behavioural observations may show little long-term effect in an area simply because dolphins or whales do not leave because they have nowhere else to go. When this is the case, subtle chronic effects may take place that might impact health, reproduction, and ultimately survivability: the animals may become stressed as they tolerate instead of habituate to the human presence.

It was mentioned previously that whales and dolphins may react differently not only by different types and cadences of sounds, but also by other factors of general behaviour, group disposition, *etc*. We expand on this concept in Figure 4, with the understanding that these are generalities gleaned from personal experience. Each statement in Figure 4 is subject to contrary examples; each point is open to argument. In general, however, we find that more gregarious large groups of whales and dolphins tend to be less easily disturbed than small grouped ones or "loners". River dolphins are particularly shy and skittish, as are animals close to shore or surrounded by ice or islands. Pelagic "open ocean" dolphins in general are least disturbed, but here caveats must be made. For example, we have found that striped dolphins are often very shy of vessels from even a large distance, but the congeneric spinner, spotted and clymene dolphins come up to ride the bow of vessels during a majority of encounters (Würsig *et al*., 1998). Likewise, the white-beaked dolphin commonly bow-rides vessels on the European continental shelf but its close relative, the Atlantic white-sided dolphin, rarely does (Evans, 1990). It is also likely, although few data exist on this point, that whales and dolphins are most "skittish" or easily disturbed, when they are not in their usual, or most familiar, surroundings.

Thus, we might find that nearshore Hector's dolphins, for example, may actually become more nervous when they are in deeper oceanic waters than in their usual range. This possibility has, to our knowledge, not been investigated. Dolphins and whales react differently whether they are socialising, looking for food, resting, or taking care of young (Würsig and Würsig, 1980; Fig. 5).

Grouping	**Habitat**
Gregarious, Large Groups ↓	Pelagic ↓
Small, Mixed Groups →	Coastal →
Nursery Groups ↑	Riverine ↑
Temporarily Single Individuals ↑	
Behavior	**Age/Sex Grouping**
Social/Sexual ↓	Mixed ↓
Looking for Food ↑	Juveniles ↓
Feeding →	All Male →
Recently Having Fed ↓	Female/Young ↑
Resting ↑	
Nurturant (Mom with Young Calf) ↑	

Figure 5. Generalised cetacean disturbance variables, with a down-pointing area indicating likely non-disturbance, a right-pointing arrow indicating the possibility of disturbance, and an up-pointing arrow indicating "near-certain" disturbance.

Striking examples of cetaceans that seem oblivious to disturbance while socialising are mating right and bowhead whales, which can be approached easily for photography, biopsy darting, or radio tagging (*e.g.*, Wartzok *et al.*, 1989). Different age and sex groupings also show different amounts of "skittishness". Mixed age and sex groups as well as juvenile groups tend to be least easily disturbed, whereas females and young are often quite shy, and either edge away from approaching activity, or - at times - actively race from it. Interestingly, it is our impression that all-male adult groups are often quite skittish. Males are also known to be especially prone to capture shock when captured for scientific study, tagging, or incidentally in nets (Norris *et al.*, 1994). Perhaps their stress hormone levels are already high, due to social interactions, and an extra dose of human-induced stress is not healthy.

6. MITIGATION

Mitigation of anthropogenic noises can occur both by the animals affected and by the humans producing the noise. Dolphins can at least partially mitigate against masking of their signals by adjusting their echolocation frequencies to overlap minimally with the noise (Au *et al.*, 1974). It has been suggested (Dahlheim, 1987) that gray whales exposed to industrial noises change their frequencies of calling to minimise overlap, but this assertion remains unproved. Lesage *et al.* (1999) found that beluga whales, subjected to vessel noises in the St Lawrence River, repeat certain calls more often, and shift their usual calling range from major energy at about 3.6 kHz without vessel noise to over 5.3 kHz with it. These higher frequencies are above the major energy of ferry noise common in the area. Lesage *et al.* postulate that repetition of signals may create a redundancy of information in order to communicate in the noisy environment, and the frequency shift is intended to overcome masking. Rendell and Gordon (1999) report that long-finned pilot whales in the Mediterranean increased their output of certain whistles during and immediately after military sonar signals centring around 4-5 kHz. It is not known whether this might be due to "nervousness" when the sonar signals were heard or due to an attempt to communicate in spite of the anthropogenic noise. In all of these cases cited above, the human sounds were long-term parts of the animals' environment, and one would expect that they would have habituated to them. Since they did not, we may assume either chronic disturbance, of potential but unknown detriment, an attempt to overcome the noise barrier to communication, or both. It is also possible that whales and dolphins increase their volume, or "talk louder", when other sounds threaten to obscure the message, but no information exists on that point.

At least toothed whales have highly directional hearing. There is some limited evidence of directional hearing in baleen whales as well (Richardson, 1995). It is likely that directional discrimination of noise versus useful biological signals may help in detecting communication and echolocation sounds. This is not unlike the well-known "cocktail effect" that allows humans at a party to converse despite a din of background noise that is, in its entirety, of greater volume than the point-to-point conversation. It is not thoroughly understood how we humans do this, but in our case, eye contact and lip movements as well as directional hearing are likely to be involved.

Habituation to noises with no negative consequences is known to take place throughout the animal kingdom, and cetaceans are no exception (*e.g.*, Watkins, 1986). Thus, a constant hum of activity not correlated with harm will soon be ignored (although it may still increase irritability and therefore at least minor stress); while animals pursued by whaling boat or tuna purse seiner become hypersensitive, or sensitised, to a similar sound. One of us (PE) was particularly struck by how much less approachable pods of spinner dolphins became in a bay in Dominica, West Indies, following the slaughter of a group of animals. This persisted for at least five years.

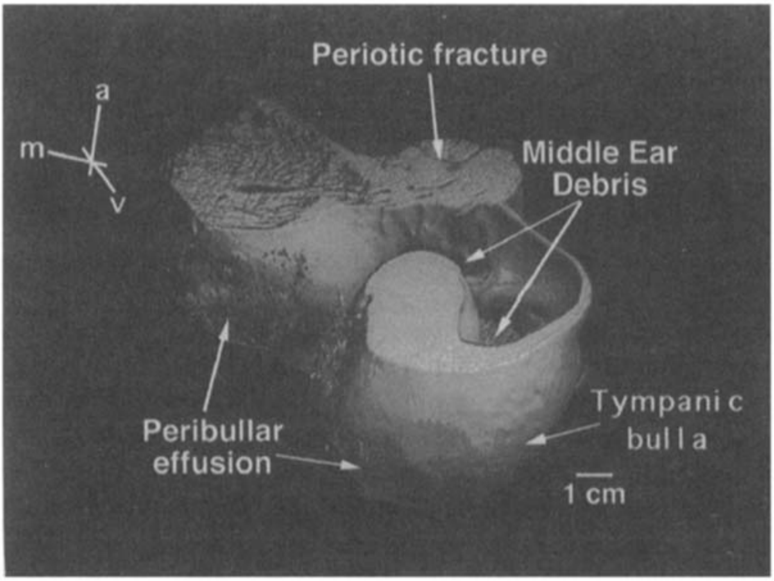

Figure 6. A three-dimensional reconstruction from CT scans of an ear from a humpback whale (*Megaptera novaengliae*) with blast injuries shows multiple fractures throughout the periotoc, which are consistent with intracochlear blood. Blood, serum, and cellular debris of both intra-and extra-cochlear origin filled the middle ear and surrounding peribullar region (Reproduced with permission from D. Ketten; see also Ketten *et al.*, 1993).

Although behavioural habituation seems to be an obviously advantageous trait, it is also possible that it can result indirectly in chronic damage to inner ear hair cells or affect physiology in subtle but long term ways. Lien *et al.* (1995) reported ear damage during humpback whale post-mortem examinations from two individuals found dead in the vicinity of Trinity Bay, NE Newfoundland, where industrial noises of underwater drilling, blasting and dredging occurred at high sound levels, mainly between 20 and 400 Hz. The two humpbacks that had died in fishing gear near blasting both had damaged ears: ruptures of round windows, ossicular chain disruption, and haemorrhages, whilst two autopsied individuals similarly killed in gear from areas where there was no industrial activity, showed no signs of ear damage (Ketten *et al.*, 1993, Fig. 6). Besides the dangers of chronic hearing loss through long term exposure to loud sounds, a habituated whale or dolphin is unlikely to respond appropriately to real danger from a similar sound.

Finally, cetaceans can mitigate against noises by moving, or allowing themselves to be displaced from their traditional habitat. Although this would seem highly negative for the animals, it may not be if other suitable habitat is readily available. In such a case, the displacement may allow the animals to better communicate and be less stressed than staying where they had been. The point here is that habituation may not be totally positive and displacement may not be totally negative, and each case must be evaluated on its own merits.

But humans as well can mitigate against impacts of potentially adverse noise. We have already mentioned the obvious tour-operator rules of approaching slowly, changing engine speeds with care, staying at a respectable distance, *etc*. These mitigation techniques may be externally enforced, but are also self-trained since tourism on animals can only be conducted when animals are not scared, skittish, and evasive. However, industry and acoustic ocean science may not always have the same inherent reasons to act responsibly, and education and enforcement are, in our opinion, necessary. Richardson and Würsig (1995) spelled out basic noise mitigation techniques: 1) Design of equipment to be as silent as possible. Propeller shrouding that has been used to silence ships of war is an example; as are also acoustic uncoupling of generators from hulls, engine trains from drive shafts and propellers, and other engineering techniques. 2) Seasonal and hourly timing of activities can help to mitigate effects of industry. For example, if seismic oil exploration needs to be done, it would be advisable not to do it when gray whales migrate through the area in spring and fall; or during the daytime in a bay used by day-resting spinner dolphins. 3) Changes of locations can help to mitigate sounds, so that industrial supply vessels, for example, do not move directly through bowhead whale nearshore feeding grounds, but actually route around the main concentration of animals with only minimal increase in expense of fuel and time. 4) Adjustment of operational procedures can help to mitigate against adverse effects. One way to help is to monitor the area for marine mammals before blasting or projecting other loud sounds. If mammals are present, the activity has to be delayed. Such monitoring has been widely practiced, and is especially well organised for oil rig removal in the Gulf of Mexico (Klima *et al*., 1988). Monitoring presently tends to rely on visual, not acoustic, methods, and may certainly miss animals. It is important to conduct both simultaneously since each has its own advantages and limitations. 5) Other operational changes include keeping vessel speed down, slowly ramping up sounds, staggering sound production so that it does not occur throughout the day, and providing lower-charge warning blasts before projecting intense sounds needed for the job. Except for vessel speed, these latter operational procedures appear to us to be questionable, and may even do more harm than good, if, for example, whales or dolphins are attracted to ramping up sounds, to low-level blasts, or to changes in duty cycles. Even reduced vessel speed may act conversely if animals are less disturbed by a vessel moving rapidly through an area in 20 minutes than if it lingers and takes twice as long.

One technique that has not been thoroughly investigated but which shows promise for the future is a way of shrouding sound once it has been projected into the water. The best method of reduction may be to create an impedance mismatch by a curtain of air bubbles. Air is about 800 times less dense than water, and air bubbles therefore effectively "swallow up" much sound energy moving from water to the bubbles. The technique has recently been investigated in some detail for shrouding around a stationary, very loud percussive hammering ("pile driving") activity for creating a wharf in Hong Kong (Würsig *et al.*, 2000). A curtain of bubbles was created by running air into a perforated rubber hose surrounding the pile driver. Sounds that were bubble-screened were reduced at 250 to 1,000 m distances in the broadband (from 100 Hz to 25.6 kHz) by about 3-5 dB, with greatest reduction at 400-6400 Hz. Indo-Pacific humpbacked dolphins that occurred in the area were therefore subjected to less noise than without the bubble curtain operating. Nevertheless, more experimental studies need to be carried out to ascertain if and how bubble screening can become a commonplace reality both for stationary and moving sources of noise.

There are occasions, however, when reduction of sounds can have detrimental effects. Cetaceans may avoid sound not just because it interferes with their communication or feeding, but because it signifies a potential threat through physical damage; there are a number of recorded instances where a vessel has collided and killed a whale. Propeller damage is another potential threat although it is generally difficult to be sure that wounds on the back or dorsal fin of dolphins are actually caused by this rather than by attacks from sharks or killer whales. For this reason, it is not advisable to suddenly accelerate, slow down or cut one's engine. Most sounds produced by small vessels are in the high frequency range above 1 kHz, particularly when there is cavitation of the propeller (as occurs at high speed or when the propeller is damaged in some way). These sounds do not carry over large distances. Using field trials in Cardigan Bay, West Wales, the second author calculated the distances at which a bottlenose dolphin would hear various small craft, and obtained values of 450 m (jet ski), 800 m (speedboat low speed), 1 km (inflatable high speed), 1.2 km (lobster boat low speed), 1.8 km (speedboat high speed), and 3.2 km (lobster boat high speed) (Evans *et al.*, 1992). Thus, although the area to which a dolphin might be exposed to sound from a jet ski would be small, the often erratic track that a jet ski takes imposes an obvious risk of physical damage particularly to young, "naive" animals that have little time to take avoiding action.

7. CONCLUSIONS

We know that noises can be a problem, and we believe that industrial, military, ocean science, and directed human tourism effects can be quite different. We also know that reactions by animals are likely to be different depending on species, aggregations of groups, age and sex and "mood" variables, and unknown factors. After all, these are large-brained social mammals and - like us - are allowed to be unpredictable just when we believe that we have it all figured out. Noise and high amounts of human activity can hurt cetaceans. Therefore, we need to study the boundaries of such problems and advise operators and legislators of potential mitigation action. However, we do not want "the noise problem" to obscure what we perceive to be generally more evident problems to whales and dolphins. These are directed killing of some declining populations, accidental killing due to indiscriminate fishery practices, and the problems of mortality and lowered fitness due to catastrophic (oil or chemical spills) as well chronic pollution (DDT, PCB, organochlorine, heavy metal leakages) of cetacean prey and therefore the cetaceans themselves. But, we are at the least pleased that humans care enough about our own actions to address "the noise problem", and to attempt to better the well-being - and perhaps simply the quality - of the lives of our mammals of the sea.

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