Agenda Item 4.4: **Disturbance to cetaceans by shipping**

Ship Collisions with Whales

Submitted by: **Germany**

ASCOBANS

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Secretariat's Note

The attached report was prepared by Sven Koschinski at the request of the Gesellschaft zum Schutz der Meeressäugetiere (GSM), as a contribution to the work of the CMS Scientific Council in its consideration of threats to migratory species, including barriers to migration. It was previously circulated as an information document to the 7th COP of CMS in September 2002 at the request of Dr. Rainer Blanke, Scientific Councillor for Germany.

Ship collisions with whales

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In recent years the problem of collisions between vessels and whales has come to the attention of both the scientific community and the general public, since ship strikes with whales occur world-wide and with all types of vessels. Laist *et al*. (2001) reported an evident increase in collisions since 1950. Since vessel traffic is increasing in most parts of the world and some fast ferries reach speeds of over 35 knots there is a potential for a further increase of collisions. Therefore it is important to improve our knowledge about the occurrence and reasons for collisions. Also there is an urgent need for political action to protect the most critically endangered cetacean species or populations affected by collisions.

Occurrence of ship strikes, affected species

Collisions between ships and whales often result in the death of the whales struck or in serious injury (e. g., Kraus 1990). In some cases also heavy damage to the ships are reported (André *et al*. 1997, Capoulade 2002). Recent information collected by Laist *et al*. (2001) suggests that ship strikes of whales are more common today than previously suspected: e. g., 9 % (85 out of 589) of analysed stranding records from the US, France and South Africa indicated vessel collision.

In the reviewed literature, evidence of ship collisions was found for at least 17 cetacean species. The most comprehensive study on ship strikes involving great whales (i. e. baleen whales and sperm whales, *Physeter macrocephalus*) was prepared by Laist *et al.* (2001) who examined historical and recent records of 74 collisions as well as stranding records of 98 whales apparently struck by ships. A review of strandings extracted from different data bases[1] revealed that fin whales (*Balaenoptera physalus*) were struck most frequently (30% of reviewed collision victims). Other species involved were southern right whales (*Eubalaena australis*, 13%), northern right whales (*Eubalaena glacialis*, 12%), humpback whales (*Megaptera novaeangliae*, 12%), minke whales (*Balaenoptera acutorostrata*, 6%), sperm whales (3%) and sei whales (*Balaenoptera borealis*, 2%). Ship collisions were also reported for grey whales (*Eschrichtius robustus*), blue whales (*Balaenoptera musculus*), Bryde's whales (*Balaenoptera edeni*) and bowhead whales (*Balaena mysticetus*). Honma *et al*. (1999) investigated the death of a Stejneger's beaked whale (*Mesoplodon stejnegeri*) after a collision with a high speed ferry in the Sea of Japan. Kiszka & Jauniaux (2002) necropsied a Sowerby's beaked whale (*Mesoplodon bidens*) found in France and considered a ship strike the cause of death. Strandings data from France and Italy add pilot whales (*Globicephala melas*), bottlenose dolphins (*Tursiops truncatus*) and Striped dolphins (*Stenella coeruleoalba*) to the list of affected species (Pesante *et al*. 2002). However, numbers of dolphins hit by ships may be low compared to their population size (Pesante *et al*. 2002). The

[1] *U.S. Atlantic Coast 1975-1996, Italy 1986-1997, France 1972-1998, South Africa 1963-1998 (southern right whales only)*

same might be true for harbour porpoises (*Phocoena phocoena*) which are occasionally hit by speed boats (Jim Darling, pers. comm.)[2].

In some areas ship strikes are likely to endanger regional populations of whales. In the case of the critically endangered northern right whale (of which a remnant population of only about 300 whales inhabit areas near or even within important shipping lanes!) vessel collisions constitute to at least 34,7 % of their deaths and therefore are a major conservation issue (Clapham 2002). Also fin whales in the Mediterranean Sea appear to be in critical danger since the animals off Corsica and Sardinia belong to a small genetically isolated subpopulation, estimated around 3500 individuals (Panigada 2002, Pesante *et al*. 2002) and 22 % of the reviewed stranding records for fin whales (24 out of 111) are attributed to ship collisions (Laist *et al*. 2001).

Collisions with sailing vessels were excluded form analysis by Laist *et al*. (2001) due to data limitations and assumption that such collisions only cause minor injuries. However, there are anecdotal data which suggest that significant injuries like large bleeding wounds are also caused by collisions with sailing vessels (e. g., Anonymous 1997; Tim Kröger[3], pers. comm.). Also for racing yachts which can reach a speed of about 30 knots a number of collisions or dangerous interactions are reported (e. g. in 6 out of 9 yachts participating in the *Whitbread round the world race* in 1997/98; Tim Kröger, pers. comm.).

The occurrence of ship strikes might be underestimated since some collisions only inflict internal injuries which might be overlooked in stranded carcasses. Also some whales struck by ships might sink to the bottom and therefore undoubtedly go unrecognised by scientists or official authorities (e. g., Kraus 1990).

On the other hand some deaths may have been attributed falsely to ships due to collisions with whales floating on the surface being already dead (Laist *et al*. 2001). Experienced observers, however, can easily distinguish whales killed by vessels from whales already dead when struck by a ship. In the first case whales have massive haematoms that sometimes lack external expression (Laist *et al*. 2001).

Types of injuries

Ship strike injuries to whales take two forms: (1) propeller wounds (i. e., long parallel deep slashes or cuts into the blubber on the back or severed tails) and (2) blunt trauma injuries with fractured skulls, jaws or vertebrae in conjunction with large hematoms (Laist *et al.* 2001).

A number of whales do survive ship strikes, although healing of wounds can be a problem (Pesante *et al*. 2002). For example, 3,7 % (14 out of 379) of identified fin whales and 6,6 % (4 out of 61) known individual sperm whales in the Mediterranean Sea showed signs of possible collisions (healed-over lesions, non cicatrised wounds or propeller scars). Over 7 % (12 out of 168) individually known right whales show major wounds from large ships' propellers on the back (Kraus 1990).

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Types of vessels involved

A wide range of vessel types of all sizes were reported to be involved into collisions with whales: whale-watching vessels, cargo ships, ferries, high speed ferries (e. g. hydrofoils), Navy ships, passenger vessels, patrol boats, recreational boats, research vessels and even a hopper dredge. High speed vessels were involved in 15 % of 40 accounts reported since 1975 by Laist *et al.* (2001). Although all types of vessels may hit whales, most lethal and serious injuries are caused by large ships (e. g., 80 m or longer) and vessels travelling at speeds faster than 14 knots (Laist *et al.* 2001). For example, the French ferry line SNCM which operates high speed car-ferries between the mainland and Corsica (France) and Sardinia (Italy) at a travel speed of 35 knots, assessed the collision risk for their three vessels close to one collision per year (Capoulade 2002). This is worrisome in the light that in most coastal areas the number of high-speed vessels is constantly increasing (e. g., Pesante *et al*. 2002). Small and slower vessels tend to hit whales less often.

Most collisions occur on the continental shelf. This reflects aggregation of both, vessels and whales (Laist *et al.* 2001). Regular reports of collisions by local vessel traffic, for example recurring reports of ferries hitting fin whales off Corsica and Sardinia or sperm whales near the Canary Islands, suggest high risk areas (Laist *et al.* 2001). Especially calving and nursing areas of whales must be considered high risk areas due to the high proportion of calves and juveniles hit by vessels (cf. Laist *et al.* 2001).

Vessel underwater sound vs. whale hearing abilities

Vessel underwater sound

Vessels ranging from the smallest boat to the largest supertanker produce underwater sound (Table 1). Richardson *et al*. (1995) give an overview about sound generated by different types of vessels. Sound levels generally increase with ship size and speed. Whereas frequency spectra from small ships contain strong tones at frequencies up to several hundred Hertz and broadband source levels are between approximately 170 and 180 dB (re 1µPa-m), large vessels tend to create stronger and lower frequency sounds. Broadband source levels of supertanker noise can exceed 205 dB, with the highest energy below 150 Hz. These ships can be audible to some cetaceans for about 80 km (cf. Erbe & Farmer 2000). Infrasound components of propeller noise of a supertanker could be measured at a distance of up to 463 km. Due to the large numbers of vessels, their wide distribution, and mobility, shipping noise is a major contributor to the overall background noise in the sea (Richardson *et al*. 1995).

The noise of a large ocean-going vessel is a combination of narrowband sounds at specific frequencies and broadband sounds with energy spread over a range of frequencies. Narrowband sounds include tonal components from propeller blade rate (up to 100 Hz) or resonant characteristics such as 'propeller singing' (between 100 and 1000 Hz). Broadband sounds are caused by propeller cavitation and water flow along the hull and may extend to 100.000 Hz, peaking at 50 to 150 Hz (Richardson *et al*. 1995). Virtually no information was found about sound generated by sailing ships. It is assumed that their sound is comparably faint and may mainly contain frequency components of up to several kHz from water flow along the hull. Table 1 gives some examples of underwater vessel sound characteristics.

Table 1: Estimated source levels (at 1 m) of some noise components of different vessels (from Richardson et al. 1995)

vessel	frequency [Hz]	source level (1/3 octave band) [dB re 1µPa-m]
5 m Zodiac (25 hp outboard)	6300	152
7 m outboard (2 x 80 hp)	400-800	156
trawler	100-250	158
25 m tug	1000	170
25 m tug	5000	161
		source level of dominant tone [dB re 1µPa-m]
25 m tug	37	166
135 m freighter	41	172
135 m tanker	428	169
340 m supertanker	6,8	190
340 m supertanker	40-70	190
274 m container ship	7,7	181
274 m container ship	23	198
274 m container ship	38	186

Low frequency hearing abilities of large whales

Anatomical evidence suggests that baleen whales are adapted to hear low frequencies (Darlene Ketten[4], Michel André[5], pers. comm.). Unfortunately no psychoacoustical or electrophysiological work on the auditory sensitivity of baleen or large toothed whales has been reported. However, various species react behaviourally to calls from conspecifics (e. g. Frankel *et al*. 1995; Watkins 1981 - cited in Richardson *et al*. 1995). For each species, the frequency range of reasonably acute hearing presumably includes the frequency range of their calls. Several species of baleen whales are reported to produce moans and grunts in the frequency range of below 2000 Hz. Some components can be as low as 10 Hz (e. g., fin whale) to 60 Hz (e. g., minke whale). Sperm whales produce sounds in the range of 100 Hz to 30 kHz (with dominant frequencies at 2-4 and 10-16 kHz) (Richardson *et al*. 1995). This matches well with some of the frequency components of underwater sound

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generated by ships. Therefore it can be assumed that cetacean hearing acuity in the frequency range of large vessels' noise is reasonably sensitive.

Behavioural evidence suggests that baleen whales are capable of directional hearing (Richardson *et al*. 1995). The precision of localisation depends on species, frequency, and other characteristics of the sound. The relatively large distance between both ears in large whales may enhance their ability to localise sound cues (Gourevich 1980 - cited in Richardson *et al*. 1995). For the perception of low-frequency sound (long wavelength) components time-phase differences between both ears are most important. For high frequencies, intensity differences and differences in arrival time are the characteristics used to localise a sound source.

Different studies were able to show reactions of sperm whales to various kinds of boats (from whale watching boats to chasing catcher boats; see Richardson *et al*., 1995). One indication that whales react to the sound of ships is that in the 19th century when commercial whaling vessels were equipped with steam engines, whalers found that bowhead whales were more easily approached under sail (Lubbock 1937 - cited in Richardson *et al*. 1995). After switching to even noisier diesel engines in catcher boats, whales were even more frightened (Tønnesen & Johnsen 1982 - cited in Richardson *et al*. 1995). Richardson & Greene (1993 - cited in Richardson *et al*. 1995) were able to show that bowhead whales fled from a distant boat approaching them, when the broadband received noise level was as low as 90 dB (re 1µPa-m).

Whale reactions to ships

Most whales show a distinct avoidance behaviour to vessels. Changes in surfacing patterns and duration of underwater travel or swimming speed as well as horizontal and vertical changes in swimming direction are among the observed responses (cf. Richardson *et al*. 1995). For example, in Southeast Alaska humpback whales seem to have two avoidance strategies from vessels, horizontal avoidance at distances over 2 km and vertical avoidance closer than 2 km to ships (Baker *et al*. 1982, 1983 - cited in Richardson *et al*. 1995). Different studies suggest that bowhead whales in the Beaufort Sea start avoiding diesel powered vessels at distances of 4 km or more. However, some bowhead whales are seen within a few hundred meters to ships, possibly depending on the approach angle (cf. Richardson *et al*. 1995). Migrating grey whales were observed changing their course at distances of 200 to 300 m to move around vessels in their path (Wyrick 1954 - cited in Richardson *et al*. 1995). However, grey whales often collide with vessels or come very close (15 to 30 m) to ships before they react (Schulberg *et al*. 1989- cited in Richardson *et al*. 1995).

Avoidance reactions like these are obviously not always effective in preventing collisions, injury and mortality.

Possible reasons for collisions

In most interactions between ships and whales, avoidance strategies of whales or ships seem to be successful. However, as in traffic accidents of humans with cars there could be several reasons for fatal interactions. These are on the side of the whales: (1) a high probability of encounters, (2) a reduced perception, (3) distraction by other activities, (4) impaired hearing, (5) lack of recognition of the threat posed by ships, and (6) habituation to noise. On the side of the vessels (7) bad sighting conditions and (8) high speed account for a number of collisions. So far the reasons for collisions are a matter of speculation. However, there are a few hints that a combination of many factors play a role and that there are interspecific and individual differences.

1. High probability of encounters

If whales spend a high proportion of their time at the surface the probability of a ship strike is increased. As Tregenza (2002) points out, the time spent at or near the surface is an important factor in assessing the probability of a whale being struck by a ship. Therefore it is most likely that juvenile or sick individuals, or slow swimming species or species which spend a high proportion of their time at the surface for activities such as resting, feeding and courtship (e. g., northern right whales) are affected to a larger extent than others (Terhune & Verboom 1999; Laist *et al*. 2001, Clapham 2002).

Laist *et al*. (2001) were able to show that a high proportion of struck northern right whales (75 %; n=8), southern right whales (55 %; n=11) and humpback whales (80 %; n=10) were calves or juveniles (juveniles spend more time at the surface than adults). However, Panigada[6] (pers. comm.) did not find a particular accumulation of juvenile deaths of fin whales struck by ships.

André *et al*. (1997) stress that due to their unusual diving behaviour with long resting and socialising periods at the surface sperm whales are especially at risk.

Collisions with sleeping whales are also reported frequently. Slijper (1979 - cited in Laist *et al*. 2001) refers to "many stories of ships colliding with sleeping sperm whales" and reports similar events with bowhead whales, humpback whales and right whales. However, the expression "sleeping" in anecdotal reports might only emphasise that at times whales seem to be oblivious to vessel sound for whatever reason.

Likewise diseases, abnormally high infestations with parasites and entanglements may cause whales to spend more time at the surface (Laist *et al*. 2001). Kiszka & Jauniaux (2002) note that debilitated cetaceans probably rest at the water surface more often than when they are healthy.

2. Reduced perception

If sound were the main stimulus for behavioural reactions of cetaceans to vessels, one would expect a response to strong or rapidly changing vessel noise. However, under certain oceanographic conditions it is possible that cetaceans are confused with the acoustic information they receive from an approaching ship, or have difficulties to locate an approaching vessel. In these cases, specific acoustic effects

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would be responsible for impeded perception. These are a downward refracting sound profile, near field effects such as the Lloyd mirror effect and shallow water effects. It is also likely that shielding by the hull impedes the perception of sound.

- Downward refracting sound profile (afternoon effect)

Terhune and Verboom (1999) and Bondaryk (2002) describe a downward refracting sound profile in temperate or warm stratified waters (such as the Mediterranean Sea or the Bay of Fundy in summer) caused by a thermal gradient. In the warm surface water sound travels faster than in the colder layers further down. This sound velocity gradient causes the path of the sound to bend away from the surface. This would mean that a whale will not be able to hear an approaching ship until it is within 500 m distance. Cetaceans on collision course might therefore be unable to hear the vessel in time to avoid being struck.

- Absorption from the ship's hull and bubbles in the wake

The ability of a large ship's hull or minute air bubbles surrounding it to shield engine and propeller noise in front of the vessel can be assumed an important factor for collisions (Terhune & Verboom 1999). Submariners have reported that they found themselves immediately in front of a supertanker because the massive hull of the tanker blocked its propeller sound (Stepputat[7], pers. comm.). Sound directionality around ships depends largely on the type of ship and propulsion it uses and is frequency dependent. Ships radiate a lot of energy from their flanks. To the front, the hull absorbs a large part of the acoustic energy from propeller cavitation noise (especially at lower frequencies) (John Potter[8], Christine Erbe[9], pers. comm.). Injected air bubbles behind the ship absorb part of the energy from higher frequencies such as cavitation noise > 1 kHz (cf. Urick 1967).

- Lloyd mirror effect and other near-field effects

Terhune and Verboom (1999) note that it requires some distance before sound levels radiated by ships are built up. In the "near-field" of a ship where a whale would be in imminent danger of a collision, the sound perceived by the whale's ears might be low compared to other ships some distance away (i. e. in the far-field; cf. Urick 1967; Richardson *et al*. 1995). The maximum distance of near-field effects can be estimated as

$$d = a^2 / ë$$

with a = longest active dimension of the source radiating the same amount of energy and $ë$ = wavelength (Richardson *et al*. 1995).

This means that the range within which a near-field effect can occur strongly depends on the size of the sound source. However, since sound radiation from ships is not fully understood the results from this equation are not sufficient for a precise calculation of the near-field zone: For a 300 m supertanker at a frequency of 100 Hz this equation results in a maximum range of 6 km (if the length of the hull is taken as the dimension of the sound source), if only the size of the propeller (e. g., 8 m) is used for the calculation the same equation results in 4 m! It can be assumed that a larger part of the hull radiates sound with maximum energy. Therefore we can assume that the effects might occur somewhere within these limits.

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A certain acoustic effect which also occurs in the near-field (without normal sound propagation conditions) is the *Lloyd mirror effect*. Immediately prior to a collision, the sound source (ship) and the receiver (whales' ears) are very close to the surface and close together. Under these conditions the reflection of the ship's sound from the surface strongly interacts with direct sound radiation. Hence, the reflected sound is out of phase with the direct sound. If the source has strong tonal or narrow bandwidth components (as in ships' noise), this phenomenon produces an interference pattern in these frequencies. It may be observed as range-dependent fluctuations in sound level at received locations along a horizontal radial line from the source. This phenomenon, called the *Lloyd mirror effect* or *image interference effect*, is strongest with low frequency components and only occurs in calm sea conditions. However, the interference pattern created by this effect will be distorted by a downward refracting sound profile (Urick 1967).

Theoretically, with a pure tone source and a smooth surface, constructive and destructive interference could lead to pressure doubling at the maxima and total cancellation at the minima. Although, because of wave roughness and finite bandwidth effects, variations in received level are more commonly < 6 dB from maxima to minima for narrow band components (Urick 1967, Richardson *et al*. 1995). Broad band components of ships' noise will probably not be affected by the Lloyd mirror effect alike. Unfortunately, no information on interference of broad band noise is available so far.

In the area beyond the range of the Lloyd mirror effect, the received level can be reduced quite substantially. This is especially true for shallow radiation angles. Arveson & Vendittis (2000) calculate a reduction of ships' noise by 21 dB for a radiation angle of 5^{o}. They estimate the reduction with the following equation:

$$\textit{received level} = SL + 20 \log(\sin á)$$

with *SL* = source level and *á* = radiation angle.

In conclusion, the Lloyd mirror effect might contribute to a reduction in received levels in a horizontal line from the ship and confusion of the whales about the ship's range and danger level.

- Shallow water effects

At mid-depth, especially in coastal waters with a rocky bottom with good reflecting properties, whales can experience shallow water acoustic effects. Similar to the Lloyd mirror effect, an interference pattern will be created by the echoes from the bottom and surface (Terhune & Verboom 1999). As a consequence, a whale will have difficulties to locate the vessel.

Some of the acoustic effects described above (downward refracting profile, shielding from the hull, near field effect, Lloyd mirror effect) would be strongest just below the surface. While breathing at the surface, a whale's ears are at about 1 m depth. In that case, the quietest location would be directly ahead of the ship (Terhune & Verboom 1999).

3. Distraction by other activities

Whales engaged in certain activities like feeding or courtship behaviour might be distracted from sounds of approaching ships (Laist *et al*. 2001). In this context it is interesting to note that feeding sperm whales reacted strongly to a 10 kHz pulsed sound by diving immediately whereas resting animals completely ignored the sound (after a first response) for the 2,5 remaining hours with repeated stimuli (André *et al*. 1997). Furthermore, humpback, blue, sei whales or fin whales approached by ships were less responsive when engaged in feeding (cf. Richardson *et al.* 1995).

4. Impaired hearing

Erbe & Farmer (2000) report that beluga whales in the St. Lawrence estuary (an area with high shipping activity) approach large ships to much shorter distances than in the comparably quiet Beaufort Sea and assume that either their hearing is impaired because of ongoing noise exposure or high parasitic burdens or the animals from the St. Lawrence estuary are more accustomed to heavy traffic. Therefore, threshold shift or habituation (discussed in paragraph 6) might play a role in ship collisions. Furthermore, the masking of individual ship's noise by ambient shipping noise are discussed as possible reasons for the lack of reaction to vessel sound.

- Temporary or permanent threshold shift

Acoustic overexposure can lead to temporal or permanent hearing loss (Au 1993). In extreme cases, loud continuous noise or sudden blasts of noise can cause physiological damage to the ear or other organs and tissues (Darlene Ketten[10], pers. comm.). Although the impact of shipping noise to disorientation of whales is poorly understood, there is some evidence that acoustic overexposure is responsible for a certain number of ship collisions.

Erbe & Farmer (2000) calculated that a temporary threshold shift (TTS) of 4,8 dB in the hearing sensitivity of beluga whales (*Delphinapterus leucas*) could occur if exposed to cavitation noise of an icebreaker (broadband source level of 205 dB) within a 3-4 km radius for more than 20 min. A TTS of more than 12 dB seems unlikely since this would require a stay of 30 min within a 120 m radius of the sound source. Likewise Erbe (2002) assumes a TTS of 5 dB in killer whales (*Orcinus orca*) after 30 to 50 min of exposure within a radius of 450 m to whale watching boats. Close to major shipping lanes, exposure time to similar sound intensities might even be longer.

Normally, full hearing abilities can be expected to be back 24 hours after exposure (Kastak *et al*. 1999). Unfortunately, it is not fully understood if repeated exposure to TTS, or - in particular - what noise dose causes permanent hearing damage in cetaceans. Superimposed noise levels of a number of whale watching boats following killer whales were close to the critical level assumed to cause permanent hearing loss over prolonged exposure (Erbe 2002). During autopsies of two sperm whales struck by vessels in the Canarian Archipelago changes on the cochlea were found in the region responsible for the detection of low frequencies (Michel André[11], pers. comm.). From the lack of change in behaviour of sperm whales during playback experiments with different low frequency sounds in the same region, André *et al*. (1997) suspect that due to the almost permanently generated engine and propeller noise of the ships in that area, the resident whales in the Canarian Archipelago may have lost sensitivity to these frequencies and thus may not react quickly enough before an imminent collision.

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- High ambient noise can mask ship noise

In general, the range of audibility is limited by sound levels dropping either below an animal's hearing sensitivity (which is unknown in most cetaceans) or below ambient noise (cf. Au 1993): Distant shipping generally dominates ambient noise at frequencies 20 - 300 Hz up to about 80 dB (re 1µPa²/Hz; cf. Richardson *et al.* 1995). It is assumed that in areas with high shipping activities (such as the Ligurian Sea or the Canarian Archipelago), loud distant shipping noise might confuse the whales or mask the sound of individual ships until they are too close to the whale (Terhune & Verboom 1999). However, it seems unlikely that masking is the only factor responsible for a collision, since the noise of individual ships is well above ambient shipping noise (about 190 dB vs. 80 dB) and therefore should be perceived from a distance great enough for an avoidance reaction (cf. Richardson *et al*. 1995).

The same is true for ambient noise from natural sources which is within a similar frequency range as ships' noise (e. g., wave action; at a maximum of 90 dB re 1µPa²/Hz at frequencies between 20 and 300 Hz; Richardson *et al*. 1995). However, masking can assumed to be very efficient only for the faint sound of sailing ships from water flowing along the hull.

5. Lack of recognition of the threat posed by ships

It might be a matter of perception if whales realise a danger and show avoidance behaviour. Richardson *et al.* (1995) conclude from a review of studies that in most behavioural reactions of whales elicited by man-made sound (mostly at frequencies below 1 kHz) the reaction thresholds were rather high - well above the threshold for detection by instruments. For example, from observations of right whales swimming directly into the path of ships without noticeable reaction at assumed received levels of 92 to 105 dB (re 1µPa-m) Terhune & Verboom (1999) conclude that acoustic information may not be the major stimulus to alert right whales to imminent danger. It is assumed that reaction thresholds depend on the perceived relevance or threat.

Whales might not perceive ships as a threat since they have evolved in an environment free of supertankers and fast ferries and the noise of vessels is an ubiquitous phenomenon in their environment. Therefore it is likely that they do not perceive ships as a threat by nature unless they learn that ships can be a deadly threat to them. For example Watkins (1986) observed that young humpback whales in contrast to adults tended to approach a research vessel to investigate its activity. However, a learning process would presuppose that whales can survive collisions. The high proportion of calves and juveniles among collision victims in some whale species and signs of collisions survived by individuals indicate that at least some whales have the chance to learn to avoid vessels as they mature.

However, the acoustic effects described above might adversely affect this learning process. Noise levels received close to the surface will increase immediately after the stern of the ship has passed (cf. acoustic effects in paragraph 2). Thus if a whale survives a strike or is nearly struck, then the loudest sounds of the ship will become evident after the event. This timing will make it difficult for the whale to associate being struck by a ship with the presence of the faint noise just before the accident.

If whales were capable of learning that ships' noise is equivalent to a threat, it might help to scare each new-born calf by chasing it with a boat to enhance the important learning process, at least in small distinct populations like that of the northern right whales at the East Coast of North America (Nick Tregenza[12], pers. comm.).

6. High tolerance to traffic noise and habituation

A number of whale species inhabit areas exposed to heavy maritime traffic. Different observations suggest that habituation to ships' noise occur rapidly and may be a consequence of a long term cumulative effect of many vessels (cf. Watkins 1986). Resident whales in an area with heavy traffic - subjected to a lot of ambient noise - might become habituated faster to disturbing noise than migrating whales from quieter habitats (cf. André *et al*. 1997). From playback experiment with natural and artificial sound in the Canarian Archipelago, André *et al*. (1997) suggest that sperm whales from an area with heavy vessel traffic have a high tolerance to different types of noise, not only to vessel noise. In their experiment neither killer whale sound, nor engine noise or the sound of surface hits with a bamboo stick had any effect on the behaviour of these whales. Sweeps (1-30 kHz), 5-click coda and 10 kHz pulses had an effect initially, but were ignored later. This suggests a rapid habituation after an initial startle response to an unexpected but not inherently disturbing sound in their environment.

Watkins (1986) compared data on behavioural reactions of four baleen whale species to research and whale watching vessels collected over 25 years. He was able to show strong habituation effects in minke whales, fin whales and humpback whales. Only right whales maintained the same variety of reactions to boats over the study period. Over the years of exposure to ships, minke whales changed from initially frequent positive reactions to ships, to uninterested reactions. Fin whales initially showed negative response to boats but changed to uninterested reactions over time. Humpback whales which initially avoided boats, frequently changed their behaviour to often strongly positive reactions. Likewise Jones & Swartz (1984, 1986 - cited in Richardson *et al*. 1995) reported habituation of grey whales to whale watching boats in their breeding lagoons. The proportion of incidents in which whales flee from vessels decreased in the course of the breeding season. Some whales were even attracted to slow moving, quiet or idling boats late in the season.

Possible reasons for lack of reaction of ships officers on duty

7. Bad sighting conditions

In most cases, whales hit by ships were not seen beforehand (40%; n=43) or were seen too late to be avoided (53%; n=43) (Laist *et al*. 2001). In some cases bad sighting conditions were responsible for collisions. For example, out of 37 incidents investigated by Laist *et al*. (2001), 27 collisions (73 %) occurred in daylight, nine (24 %) at night and one at dusk (3 %). However, sea state has a strong influence on sightability of whales (Hammond *et al*. 1995, Scheidat 1996).

8. High speed of vessels

In many cases, ships are simply too fast for whales to be detected within reaction time of the officers on duty. Laist *et al*. (2001) detected trends in ship strikes related to number of ships and vessel speed. Collisions with motorised vessels appear to

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have begun in the late 1800s and have remained infrequent until the 1950s. Between the 1950s and 1970s they increased to current levels. This increase corresponds with the period when maximum speed of most large ocean-going vessels exceeded 14 to 15 kn. The severity of lesions seems also to be a function of speed. Among collisions with lethal or severe injuries, 89% of the 28 vessels investigated were moving at 14 kn or faster (Laist *et al*. 2001). Collisions with hydrofoils and other fast ferries increased with the number of vessels in operation (cf. Capoulade 2002). The success of "last second" flight responses depends also on the speed of the whale relative to the vessel (cf. Laist *et al.* 2001).

Other factors might include the fact that in most ships, the bridge is situated in the rear part of the vessel. 'Cryptic' behaviour of whales may also play a role: for example, some grey whales disturbed by vessels on their migration route or in their summering grounds tend to exhale underwater and to expose their blowholes only to inhale (e. g., Hubbs & Hubbs 1967 - cited in Richardson *et al*. 1995). This "snorkelling behaviour" makes it difficult to detect them from a ship's bridge in time for avoidance.

Measures adopted by shipping companies

Fast ferries often have two officers on duty during all trips (Capoulade 2002). This seems to be helpful during the day but at night, detection of whales is a matter of chance. Therefore shipping companies have attempted to find technical solutions for the collision problem. The French shipping company SNCM was involved into different research and development actions proposing forward-looking SONAR (**so**und **na**vigation **r**anging), LADAR (**la**ser **d**etection **a**nd **r**anging) and night vision systems (light amplifier or infrared camera) and certain ship protection measures (Capoulade 2002).

Capoulade (2002) reports that for night vision systems a detection distance of at least 600 m is required by European ISO (ratification in progress). The drawback of night vision systems is their bad performance in poor atmospheric conditions (i. e. vapour saturated atmosphere). A detection distance of 600 m allows a maximum of 30 s time for a reaction at a speed of 40 knots. However, only the parts of the whales above the surface can be detected (i. e. back and blow). A whale swimming just below the surface will not be detected by this system.

Therefore sonar and ladar were proposed for submerged obstacles. Bondaryk (2002) calculates that a 20 kHz sonar with a source level of 203 dB (re 1µPa-m) would have a sufficient resolution and power to detect a whale within 2,5 km distance (which would allow a warning time of 2 min). However, active reverberation of the forward projected sound from the water surface and the sea floor may interfere with the echo from the target (the whale) and inhibit detection. Especially in shallow waters, where the water depth is within detection range, a sonar with a broad beamwidth in elevation is useless. Short ranges (e. g., less than 300 m) cannot be covered with most sonars due to multiple reverberation from waves at the surface. Many commercially available sonars can only be operated at low speeds, for example, 12 knots for the *Thomson Petrel* (Capoulade 2002). Another drawback of an active sonar used in warm stratified waters would be the downward refracting sound profile (see above). This effect contributes to additional transmission loss which can partly be overcome with a higher source level of the sonar (Bondaryk 2002). However for loud sound sources the question on animal safety has to be raised.

Ladar tests revealed a detection range of 400 to 800 m[13] for objects 3 to 10 m below the surface (up to 20 m in the Mediterranean Sea) but questions remain regarding the sensitiveness of the eyes of marine animals to the laser (Capoulade[14], pers. comm.).

[13] *depending on the height of the system built by Thomson Marconi for detection of sub-surface mines from a helicopter*

[14] *Frédéric Capoulade, SNCM FERRYTERRANEE, Société maritime Nationale Corse Méditerranée, Marseille / France*

Suggested additional measures

Several mitigation measures have been proposed or implemented in U. S. and Canadian waters to prevent collisions of ships with right whales. Some of these could be also a management option in other regions and for other species. These are a combination of

- aerial surveys with real-time reports of right whale positions to mariners (e. g., Clapham 2002). This is an expensive management tool which might be ineffective if vessel captains refuse to change their route or speed even if informed on whale presence.
- an automated ship identification system (AIS) in combination with a long range radar which enables the coast guard to identify each vessel within critical right whale habitat. Even though expensive, an AIS is an important tool to minimise the risk of any unwanted incident (e. g. oil spills) in coastal waters and may become mandatory in many highly-frequented shipping areas world-wide.
- moving shipping lanes away from critical habitat such as calving and nursing areas. This solution will probably be applied in the Bay of Fundy in the near future (Clapham 2002). This is presumably the most efficient management option although it might not be appropriate for other species or in other regions, especially when not much is known on the use, size and location of their habitat.
- general speed limits for ships in high-collision-risk areas. This could be a very effective measure. Laist *et al*. (2001) suggest a speed limit of 14 kn to vessels operating in high-use whale habitats or in areas inhabited by highly endangered species. However, this measure might be difficult to introduce since it is not popular among shipping companies. Indeed, there is a contrary trend in the shipping industry - to use faster vessels. Especially in passenger transport there is a tendency to establish more ferry lines using high-speed catamarans.

Additional measures are proposed by conservationists and scientists alike. These include:

- introduction of a 'whale anti collision system' - *WACS* (André *et al*. 2002) in combination with ambient noise imaging techniques - *ANI* (André *et al*. 2002, Potter pers. comm.). However, these measures need additional testing (see *research needs*).
- flexible management zones.

Some of the above mentioned measures could only be implemented in coastal areas (under a country's jurisdiction). The International Maritime Organisation (IMO) (as a central governing authority for ship travel) must implement additional management measures in international waters.

Research needs

In this review, a number of theories for collision reasons are presented. To identify the importance of each theory, and to find solutions to mitigate ship collisions with whales, a lot of effort has to be put into research. In this context, it is important to (1) review the circumstances of all known collision incidents, (2) identify affected whale populations and their critical habitat, (3) develop and test reliable detection systems, and (4) test certain acoustic mitigation measures.

1. Collision research

- It is important to assess the frequency, location, and circumstances of all collisions with whales. This implies a reporting system for all vessel operators, port pilots and port officials (cf. Laist *et al*. 2001).
- Seasonal and diurnal variation in collision frequency should be studied and linked to oceanographic data like sea state or thermal gradients. Acoustic measurements of ships involved into collisions with whales should be conducted.
- Future research should focus on the behaviour of whales close to different types of vessels during different activities, acoustic measurements of shipping noise radiation, assessment of 'zones of impact' around noise sources and identification of possible acoustic reasons for the inability of some whales to react to the ships.

2. Identification of affected whale populations and their critical habitat

- Further research is needed to identify populations affected by ship-strikes.
- It is inevitable to recognise high-risk areas such as calving and nursing areas of these whale populations close to major shipping routes in order to move shipping lanes or establish speed limits as a management option.

3. Detection systems

- Research is needed to develop a reliable automated detection system. This system can be on-board (sonar, ladar, night vision systems) or land-based ('whale anti collision system' - *WACS*, ambient noise imaging - *ANI*) with receivers on all participating ships.
- André *et al*. (2002) propose a *WACS* for the Canarian archipelago. A row of sonobuoys along a shipping corridor equipped with a passive listening system for whale vocalisations could provide real-time information on whale positions. This information could be transferred to all vessels equipped with a *WACS* receiver.
- The system could be combined with ambient noise imaging techniques. *ANI* takes advantage of reflection of ambient noise from any given target, for example a large cetacean. The additional acoustic information could also be visualised to show whale positions. Results of preliminary studies with *ANI* were promising (André *et al*. 2002).
- Forward looking sonar systems and automated infrared viewing systems should also be developed and tested.

4. Acoustic mitigation measures

Some authors reject the idea of mounting pingers on ships' bows because the whales may not be likely to associate such sounds with the danger of a ship (Terhune and Verboom 1999). André *et al*. (1997) suggest that in a high risk area like the Canarian Archipelago the sounds would be of little long-term value in avoiding ship strikes due to possible hearing loss and the rapid habituation in sperm whales in that area (none of the sounds tested in their play-back experiment, although sometimes aversive to the whales initially, seem to be suitable for keeping the whales away from ferries). However, all sounds in their experiment were played back from a stationary source.

- In order to simulate a moving vessel It should be tested whether the effects are stronger when the sound source is moved towards the animals. At least fin whales and humpback whales off Cape Cod were shown to react to the noise of a rapidly approaching ship or to a sudden increase of the intensity of a sound (Watkins 1986).

- Effects of possible acoustic warning devices for whales should be investigated. By adding active sound to fish traps, Lien *et al.* (1992) were able to reduce the probability of humpback whale collisions with the traps by almost 70 %. Pingers used in their study emitted sound with a centre frequency of 4 kHz (SL= 135 dB re 1µPa - m). It should be tested whether this approach is also feasible for moving objects such as ships. High or mid frequency pingers mounted on the lowest point of a ship's bow would counteract near field effects such as the Lloyd mirror effect and shallow water effects (which only occur at low frequencies). Furthermore, there would be no absorption of their sound to the front by the massive hull (see above). Additionally, there would be less masking by natural sounds since these occur at a different frequency range (i. e. at lower frequencies).
- Especially in racing yachts, pingers might have the potential to warn the whales of a danger, since otherwise the faint noise of water flowing along the hull is the only hint to an approaching vessel. Many professional sailors put on their diesel generators when whales are sighted in order to warn the whales of the ship's presence, a measure that might be helpful in some circumstances (Tim Kröger[15], pers. comm.).

Acknowledgements

I would like to thank Petra Deimer and Hans-Jürgen Schütte, who had the idea to this study. Petra Deimer wrote a first draft about whale strikes which was presented to CMS. This review was made possible by a grant from the Gesellschaft zum Schutz der Meeressäugetiere e. V., Hamburg (GSM). I appreciate the comments of Michel Andrè, Frédéric Capoulade, Boris Culik, Christine Erbe, Wolfgang Jans, Christoph Jansen, Darlene Ketten, Tim Kröger, Dave Laist, Simone Panigada, John Potter, Klaus-J. Stepputat and Nick Tregenza. Boris Culik kindly reviewed the manuscript.

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