Proceedings of the Institute of Acoustics

ARE LOW FREQUENCY SOUNDS A MARINE HEARING HAZARD: A CASE STUDY IN THE CANARY ISLANDS

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1. INTRODUCTION

The Canary Islands are exposed continuously to heavy maritime traffic (fig.1), with an average of over 100 ships entering and leaving the two main ports of the Archipelago, Santa Cruz de Tenerife and Las Palmas de Gran Canaria.

Cetaceans, and specially sperm whales (*Physeter macrocephalus*), are present throughout the year in these waters (André, 1997).

Collisions with whales and small cetaceans in this area have frequently been reported over the last five years, including some well documented accidents. In addition, animals have stranded in this area with severe injuries and evidence of violent impacts. In other regions, collisions between toothed whales and dolphins, and boats are considered to be uncommon (Reynolds, 1985, Fertl, 1994), However, Slijper (1968) reported that sperm whales were struck and killed by ships.

Many of the 27 cetacean species encountered in the Archipelago (André and Martín, 1996), do not actually threaten the security of the ferry passengers, because of their small size and their avoidance of ships (see Richardson *et al.*, 1995 for a review). However, because of their abundance on the ferry routes (André , 1997) and their great size and unusual diving behaviour, sperm whales may represent a navigational risk.

Several previous workers have used sound playbacks to keep cetaceans away from specific areas (Fish and Vania, 1971, Akamatsu *et al.*, 1993), to alert them to possible dangers, such as fishing gear (Lien *et al.*, 1990, 1992, Todd *et al.*, 1992, Goodson *et al.*, 1994, Jefferson and Curry, 1994) and to study their responses to the vocalisations of other whales (Clark and Clark, 1980, Tyack, 1983) or their reactions to man made sounds (Ames, 1978, Tyack *et al.*, 1993).

Therefore series of experiments, including the playback of natural and artificial sounds, were conducted to test the feasibility of using an underwater speaker system to repel sperm whales and other cetaceans from ferry routes. The main purpose of these tests was to observe the behavioural responses of sperm whales and assess the efficiency of this method for keeping them away from the speed ferries cruising routes.

In addition, during the study period, ears were obtained from two whales involved in a collision. Preliminary assessment of the inner ears of these whales were obtained with computerized tomography (CT scanner) in order to determine whether the acoustic budget in the area may be influencing the collision rates between ships and resident cetaceans.

2. UNDERWATER SPEAKER EXPERIMENTS

2.1. Materials

2.1.1. *Recording equipment.* The recording equipment installed permanently aboard the research vessel "Monachus", a thirteen meter diesel powered boat, includes of a recording system and an independent directional hydrophone (Gordon, 1987). The recording system consists of a towed hydrophone with a streamlined body on the end of a 100m cable. Two AQ-4 Benthos elements (frequency response 1 Hz to 15 kHz), and two preamplifiers (Benthos AQ-501, flat frequency response: 3.2Hz to 100 kHz, gain 32 dB +/- 0.2 dB) are mounted inside the streamlined housing. Output from the hydrophone is routed to a Sony TCD II Pro DAT recorder (frequency response 20 Hz to 22 kHz, ± 1,0 dB). The directional hydrophone is composed of ten Benthos AQ-1 elements (frequency response 1 Hz - 10 kHz) connected in series to form a short line array. These are connected to a single AQ-501 preamplifier. The directivity of the unit for a 3kHz signal is 5 degrees (± 3 dB) perpendicular to the line of elements.

2.1.2. *Underwater Speaker System.* An underwater transducer system (UWS), designed by Kawasaki Heavy Industries, LTD., was also installed aboard "Monachus" for the purpose of the study. The system was composed of four units:
1- an underwater speaker: sound pressure level 189 dB at 9 kHz (re 1μ Pa at 1m) Frequency range 1-30 kHz; non-directional within 15 dB.
2- an amplifier: Output power 800W continuous, frequency range 1-30kHz, input impedance 15 kΩ, manual output level control.
3- a sound generator: Digital Audio Tape Recorder by Pioneer with 2 Hz to 44 kHz playback frequency response.
4- an impedance matching box: input impedance 4Ω / 8Ω, output impedance 50 to ~ 500Ω.
The underwater speaker was designed to be mounted permanently aboard the high speed ferries. The sounds played back to the whales were chosen to be within a broad potential hearing range for the sperm whale as indicated by behavioural audiograms for other toothed whales (see Richardson *et al.*, 1995 for a review). Sounds used were: orca vocalisations (1,5-18 kHz), 1-30 kHz swept sounds, artificial five click codas, engine sounds, 10 kHz pulsed sounds and sounds made by hitting the water surface.

2.2. Methods
2.2.1. *Introductory Comments.* The behaviour of sperm whales encountered during this study generally corresponded with observations made in other locations. Sperm whales are social mammals with most of their behaviour revolving around long dives that are primarily feeding periods with resting intervals. Their travel patterns include both long and short distance transits (Watkins, 1980; Gordon, 1987; Whitehead and Weilgart, 1991).

The behaviour of feeding sperm whales is very predictable. A feeding whale will spend about 10 minutes blowing regularly on the surface before fluking up to make a long feeding dive lasting around 45 mins (Papastravou *et al.*, 1989; Gordon and Steiner, 1992). When whales are disturbed, this regular pattern can be altered. In particular, disturbed whales often dive without fluking up in the normal manner (Busnel and Dziedzic, 1967; Lockyer, 1977). This has been used as an indication of disturbance or behavioural pattern disruption (e.g. Gordon *et al*, 1992).

In this study whales were classified as showing "no reaction" (no behavioural change detected) "slight reaction" (small change in regular rhythm and or shallow dive) and "strong reaction" (dramatic change in behaviour). No attempts were made to measure changes in blow rhythms quantitatively. The poor visibility in many cases avoided to use a statistically reliable method for this estimation.
2.2.1. *Sounds Presentation.* The sounds were played in the following order:

a. 1-30 kHz swept sound 189 dB at 9 kHz (re 1μPa-m)

b. Killer whale vocalisations (172 dB re 1μPa-m)

c. Artificial 5 click codas (180 dB re 1μPa-m) / / /// type. Total duration 2 sec. The "codas" were produced by striking a steel pipe (3m long and 70 mm in diameter) suspended at 1 m depth with a hammer.

d. Engine sound 180 dB at 1 kHz (re 1μPa). The sound was recorded underwater at a distance of 100m from a 15 m ship, 19 gross tons at a speed of 25 knots.

e.10 kHz pulsed sound (180 dB re 1µPa-m). Pulse width 0.3 sec.

f . Water surface strikes (180 dB re 1µPa-m). This sound was generated by the water surface being hit with a bamboo pole of 3 m long and 40 mm in diameter and recorded at 1 meter depth.

The sound pressure of the 180dB source at 100m was 160 dB re 1 µPa. When working with feeding or migrating whales, the boat was always positioned in line behind them. With a resting group, the vessel was perpendicular to the animals' body, in line with it, or facing the animals' head, depending on individuals' behaviour at the moment of the playback.

The total duration of each playback was 10 seconds although on some occasions longer playbacks were performed to investigate whether observed reactions would persist. When no reaction or change in behaviour was observed, the next sound on the list was tested two minutes after the end of the previous playback.

Although sounds were played back in an arbitrary order, whales were exposed first to no particular sound. Instead, the first sound heard was determined by the last sound played in the previous experiment with different. The method described above (a new whale was receiving first the last sound tested during the previous experiment) guaranteed the randomisation of the experiments, avoiding any bias from a consistently ordered playback.

Often an individual whale would be exposed to several sounds until it reacted or started a regular dive (table 2). On 7 occasions we played sounds when the whales were close but not visible. Those experiments are not reflected in the table 2.

2.3. Results

Experiments, i.e. playbacks of sounds, were conducted non-systematically in any of the behaviours described above (when the whales were either feeding or resting after a series of long dives or travelling), depending on the opportunities presented by the activity of the whales (table 1).

	Experiments (playbacks)	Whales observed	Exp./Whale/Day
Total	215	57	3,77
Maximum/day	51	12	4,25
Minimum/day	3	1	3
Average	12,65	4,75	2.66

Table 1. This table shows the number of experiments conducted during the survey as well as the number of sperm whales whose reaction was studied. The last column gives the average number of experiments conducted per whale/day.

2.3.1. *Modifications to Protocol.* The six sounds were played as described in the "Methods" section. It became clear very quickly that the killer whale vocalisations, engine noise and surface strike sounds had no effect on the whales. In order to optimise playback efforts on sounds which were likely to have the greatest effect on whales, sounds were dropped from the playback list. Sounds were dropped in the following order, b, d, f; leaving only c,a and e on the playback list (table 2).

1-30kHz (a)	Orca (b)	5 click coda (c)	Engine (d)	10 kHz pulses (e)	Water surface hit (f)
57	5	39	5	98	11

Table 2. This table shows the number of experiments with each of the sounds tested.

The three remaining sounds to be tested, 1-30 kHz sweep, 5 click coda and 10 kHz pulse, seemed to induce a reaction, either acoustic or behavioural on the whales tested (table 3).

	Feeding Feeding (n= 100)			Resting			Travelling Swimming (n=13)		
		BR	AR		BR	AR		BR	AR
5 click coda	24	0	7	15	0	0			
1-30 kHz	34	11	0	19	0	0	4	0	0
10 kHz	42	31	0	47	2	0	9	0	0

Table 3. Reaction of the whales after the playback of the 5 click coda, 1-30 kHz and 10 kHz sounds. BR, behavioural reaction; AR, acoustic reaction. The whales never reacted when travelling, and showed, when in a feeding process, a significant behavioural reaction at 5% (F of Snedecor) ($p \in [0.19, 0.48]$ and $p \in [0.60, 0.80]$) after the playback of the 1-30 kHz and 10 kHz sounds, and a significant acoustic reaction at 5% (F of Snedecor) ($p \in$ [0.12 , 0.51 after the playback of the 5 click coda sound.

2.4. Discussion

Some groups of sperm whales are known to be long term resident in the central Canary Islands where these experiments took place (André, 1997). Based on monthly acoustic surveys conducted between 1993 and 1994 in this area, the number of sperm whale groups increase during fall and spring, due to migrating groups passing through the area. The experiments with the UWS were conducted during fall, thus testing potentially migrating or resident whales. Whales remaining in the area during the entire year were possibly exposed to more ambient noise from shipping than migrating whales; therefore, one of our hypothesis was that resident whales should have more experience with ship noise, or even habituated to it, than migrating whales. Although it was not possible to systematically identify the whales tested and determine the resident character of the groups they belonged to, the reactions and lack of reactions observed to the experimental sounds have produced some interesting findings.

2.4.1. *Acoustic reaction.* The only change in the regular acoustic behaviour of the whales was observed after the playback of the 5 click codas when the whales stopped clicking. Sperm whales at the surface are usually silent. The whales that were heard clicking, and that ceased clicking after the playback of sounds, were not the focal animals at the surface but diving whales, potentially some distance away. Supposedly, the 5 click coda sound did not actually disturb the whales, but might have induced some curiosity. The acoustic response to an unknown auditory stimulus has been observed with sperm whales in other studies (Watkins and Schevill, 1975). The codas are normally produced by this species in a social context (Watkins and Schevill, 1977, Watkins *et al.*, 1985a, Weilgart and Whitehead, 1993), which suggests that the artificial playback must have had an additional interest to the whales which stopped clicking shortly before resuming their vocalisations. This "break" while vocalising might be accompanied as well by some physical changes in their motion, although previous experiments with pingers (Watkins and Schevill, 1975) showed that the whales continued to swim at the same speed but remained silent until the disturbing sound had vanished. Consequently, the lack of acoustic reaction of the diving whales after the playback of the 10 kHz pulsing might be surprising but possibly understandable with whales habituated to a strong background noise. The lack of change in behaviour of the whales at the surface, suggested that this sound would be of little value in solving the problem of ferry collisions.

2.4.2. *Behavioural Reaction.* Five of the six sounds tested (1-30 kHz, Killer whale, 5 click coda, Engine and Water surface) had little effect on the whales. When travelling the whales never reacted to any of the six stimuli. The whales had showed some reaction to the playback of the 1-30 kHz swept sound but it was concluded that this would not help the avoidance of ferries, because the very small number of reactions from the whales may represent a startle response to an unexpected but not inherently disturbing sound in their environment. The whales reacted strongly in response to the 10 kHz pulses, when breathing at the surface after a long dive.

This strong reaction appeared to modify significantly their normal behaviour, specially when the whales were accompanied with calves. When resting at the surface in a compact group, the whales first reacted strongly in response to the 10 kHz pulse sound and then ignored it completely. This latter point, which underlines the habituation or tolerance of this species to disturbing noises in an area already experiencing heavy vessel traffic, suggests that even this sound may have little long term value in avoiding vessel collisions.

None of the low frequency sounds tested were found to have an effect on the whales behaviour. In particular groups of sperm whales resident on the ferry routes (André, 1997), appeared to be unaffected by the noise generated by ships. However, as Blanes (1990) noted with Belugas, 'the continued use of some areas with much boat traffic by feeding and travelling whales may reflect the value of these areas to the whales and should not be interpreted as meaning that the whales are undisturbed'. Our observations during the experiments conducted with the UWS system, suggest the possibility also that resident whale populations may have lost sensitivity in the low frequency band generated by the engines and propellers of the ships and thus may not react in time to prevent collisions.

2.5. Conclusion

Sperm whale reactions to the playbacks, specially to the 10 kHz pulses, ranged from strong sensitivity and avoidance (sudden random fast swims and short dives) to passivity or tolerance, depending on the group activities and experience. The results showed that the whales did not react to low frequency playbacks which suggests sperm whales from an area which has heavy vessel traffic have a high tolerance for low frequency noise specifically.

Due to the purpose of the experiments and the lack of tools available to observe the underwater activities of the sperm whales, the behavioural reactions reported in this study are obviously restricted to the whales at the surface. However, it appeared that the reaction was limited to the focal individual (s) and did not seem to affect the rest of the group, although Watkins *et al.* (1985b, 1993) observed that sperm whales exposed to 3.25-8.4 kHz pulses from submarine sonar not only stopped clicking but also interrupted their activities and left the area. A general avoidance by an entire social group was never observed in this study when the whales were foraging. We found that the heading of the group remained the same and the "surfacing rhythm" of the whales did not appear to change. In addition, the continuous playback of the 10 kHz pulses to a resting group seemed to produce no effect at all after two consecutive strong reaction of all the whales within the group. This interesting observation emphasises that an animal's response to a same signal can change dramatically with time or experience. It appears that the whales rapidly habituated to this sound. During a foraging process, in order to maintain a cohesive structure and favour the efficiency to find preys, a whale belonging to a social group stays in acoustic contact with its group, including between consecutive dives, when resting at the surface. Thus, we could speculate that the 10 kHz pulses had a more disturbing and "uncontrolled" effect on those whales concentrated on their mates vocalisations, than on the same whales gathered at the surface in a compact structure and remaining almost silent.

In our opinion, the solution to the problem of accidental collisions, lies in a better understanding of the hearing sensitivity of the local populations of whales coupled with measures to decrease acoustic exposures of these whales. At this time we do not know how sensitive they are to various acoustic components of the noise from shipping and other human activities. Therefore we do not know what warning sound could be effective to repel whales from the speed ferries yet, at the same time, not create a different auditory hazard or repel them from a valuable resource area.

3. ANALYSES OF SPERM WHALE INNER EAR STRUCTURES

The difficulty in determining whether any one whale has auditory damage lies in the rarity of adequate fresh specimens for examination. During this research, one such opportunity did occur. On April 9th, 1996, at 07:30, a ship struck two sperm whales off the North Western coast of Gran Canaria (Fig.1). Weather and sea conditions were good, the wind force was not higher than 3 on the Beaufort scale. The captain of the cargo ship saw the two whales blowing from a distance. He did not change the course of the vessel although it was heading directly towards the whales at full speed (15 knots). From his comments, it appears that the whales were resting at the surface between two successive dives ("feeding behaviour" in the preceding section), and were only moving slowly. Once the vessel reached them, the whales did not attempt any escape manoeuvres. A very loud noise was heard on board, and a few seconds later the two bodies appeared floating at the surface surrounded by blood.

The two whales were towed to land where they arrived 9 hours after the collision and their necropsy was completed less than 24 hours after the accident. The whales were found to be a mature female (total length 10, 6 m) and a male calf (total length 6,1 m). Due to the positions of the animals during the necropsy, only the right ears were accessible in both whales. The ears were fixed in formalin for 5 weeks before further analyses of the ear structures.

CT scans showed that there were no fractures or other overt evidence of impact, or ship strike related injuries; however, ears from both animals had reduced auditory nerve volumes. One animal also had patches of dense tissue in the inner ear.

These findings are consistent with auditory nerve degeneration and fibrous growth in response to inner ear damage. In combination with the results from the playback experiment, these results suggest that low frequency sounds from shipping may be affecting hearing and increasing collision rates.

These findings are however, preliminary, and histologic analyses are underway to determine whether the primary cause of the ear changes seen with CT are disease or noise induced.

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5. FIGURES

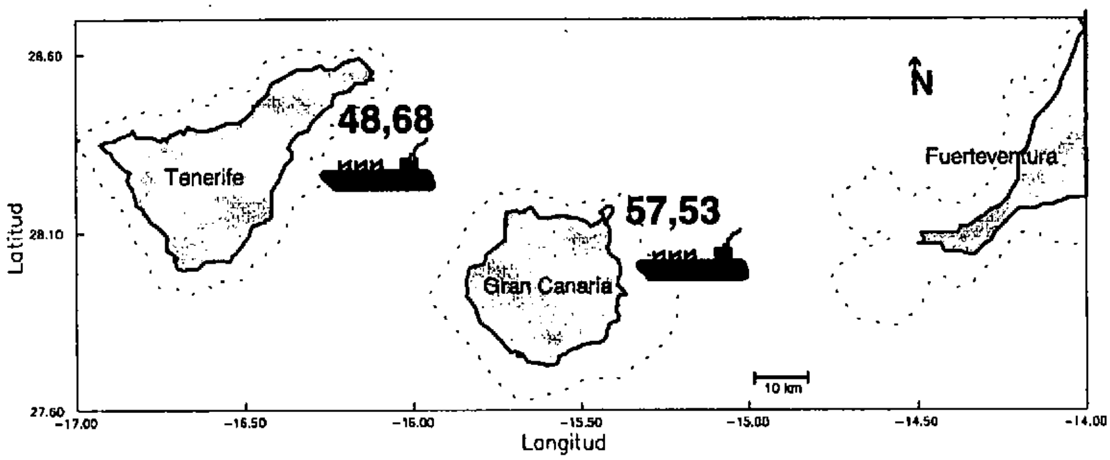

Figure 1. Shipping between the two main ports of the Canary Islands, Santa Cruz de Tenerife and Las Palmas de Gran Canaria (André *et al.*, 1997). Daily averages for ships that enter and leave these two ports are 48,68 and 57, 53 respectively (official data from Las Palmas and Santa Cruz Port Authorities).