The effects of seismic airguns on cetaceans in UK waters

Carolyn J. Stone and Mark L. Tasker

Joint Nature Conservation Committee, Dunnet House, 7 Thistle Place, Aberdeen, AB10 1UZ, UK

Contact e-mail: cjsbarton@barnacle1.fsnet.co.uk

ABSTRACT

Observations undertaken during 201 seismic surveys in UK and adjacent waters were analysed to examine effects on cetaceans. Sighting rates, distance from the airguns and orientation were compared for periods when airguns were active and when they were silent, both for surveys with airgun arrays of large volume and surveys with smaller volume arrays. The results demonstrate that cetaceans can be disturbed by seismic exploration. Small odontocetes showed the strongest lateral spatial avoidance (extending at least as far as the limit of visual observation) in response to active airguns, while mysticetes and killer whales showed more localised spatial avoidance. Long-finned pilot whales showed only a change in orientation and sperm whales showed no statistically significant effects. Responses to active airguns were greater during those seismic surveys with large volume airgun arrays than those with smaller volumes of airguns. It is suggested that the different taxonomic groups of cetaceans may adopt different strategies for responding to acoustic disturbance from seismic surveys; some small odontocetes move out of the immediate area, while the slower moving mysticetes orient away from the vessel and increase their distance from the source but do not move away from the area completely.

KEYWORDS: NOISE; EUROPE; CONSERVATION; SURVEY-VESSEL; SHORT-TERM CHANGE; MONITORING

INTRODUCTION

Cetaceans use sound to communicate and, in some cases, to echolocate. Their ability to detect calls from conspecifics, echolocation signals and other natural sounds is likely to be of paramount importance. Man-made sounds have the potential to interfere with their natural functions, such as feeding, social interactions and navigation, as well as the potential to cause physical harm. Seismic surveys use airguns to generate sound for the purpose of exploration of geological features beneath the seabed; seismic surveys are commonplace in the world's oceans, with noise from seismic airguns being recorded frequently over large distances (Nieukirk *et al.*, 2004). The airguns used produce sound at low frequencies that overlap with those used by mysticetes; these species are therefore considered to be vulnerable to disturbance from seismic surveys. Seismic operations also emit incidental high frequency sounds (Goold and Fish, 1998) that could potentially disturb odontocetes which communicate and echolocate using high frequencies. Several reports have called for more research into the effects of anthropogenic noise on marine mammals (Cox *et al.*, 2006; National Research Council, 2000; 2003; 2005). More specifically, Richardson *et al*. (1995) concluded that information is needed about reactions of odontocetes to underwater noise from airgun arrays used for seismic exploration. Kastelein and Wartzok (2004) also highlighted the need for information on the behavioural responses of marine mammals to current mitigation measures.

To address conservation concerns that have arisen in relation to seismic surveys, in 1995 the UK government and the Joint Nature Conservation Committee (JNCC) issued guidelines for seismic operations (latest version: JNCC, 2004). The guidelines have requirements for operators at the planning stage and during the operation of a seismic survey. For example, for at least 30 minutes prior to using airguns, onboard observers should check for the presence of marine mammals within 500m of the airgun array; if any are detected then use of the airguns must be delayed until at least 20 minutes after the last sighting. Whether marine mammals are detected or not, a 'soft start' procedure should be employed, where airgun array power is gradually built up over at least 20min from a low energy starting level. Seismic operators should submit a report to JNCC, using standard recording forms that are used to assess the implementation of the guidelines and the effects of seismic airguns on marine mammals. Previous analyses of annual data sets (Stone, 1997; 1998b; 2000; 2001; 2003) have been limited by small sample sizes. This paper uses data combined over four years (1997-2000) to investigate further the effects of seismic airgun activity on cetaceans.

METHODS

Visual monitoring for marine mammals was conducted during daylight on seismic survey vessels operating in UK and some adjacent waters, to ensure implementation of the JNCC guidelines. Observers ranged from biologists experienced in marine mammal surveys, to non-scientific personnel who had usually received training that included the implementation of the guidelines, data recording and marine mammal identification. Data from 201 seismic surveys during which weather conditions were recorded were used, enabling the influence of weather on the detection of cetaceans to be controlled when analysing the data. The surveys covered 152 quadrants (1° × 1° rectangles), including those passed in transit (Fig. 1). All except two surveys (in 1997) took place between 1998 and 2000. Survey effort was not evenly distributed spatially or temporally, peaking during summer and in the northern North Sea and to the west of Shetland. The proportion of time when the seismic sources were active (shooting) also varied spatially and temporally.

A total of 110 surveys used large airgun arrays with volumes in excess of 1,300 cubic inches (cu.in.), with most (79%) using volumes of at least 3,000cu.in. The noise characteristics of these large volume airgun arrays varied between surveys, but typically frequencies used were 3-218Hz, with a peak energy output from the source of around 65-70 bar metres, equating to a peak source level of around 250dB re. 1μPa @ 1m in the dominant bandwidth. A total of 39,168hr 06min was spent watching for cetaceans during these 110 surveys with large volumes of airguns, with the airguns being active for 38% of this time. The remaining 91 surveys, hereafter collectively termed site surveys, used low

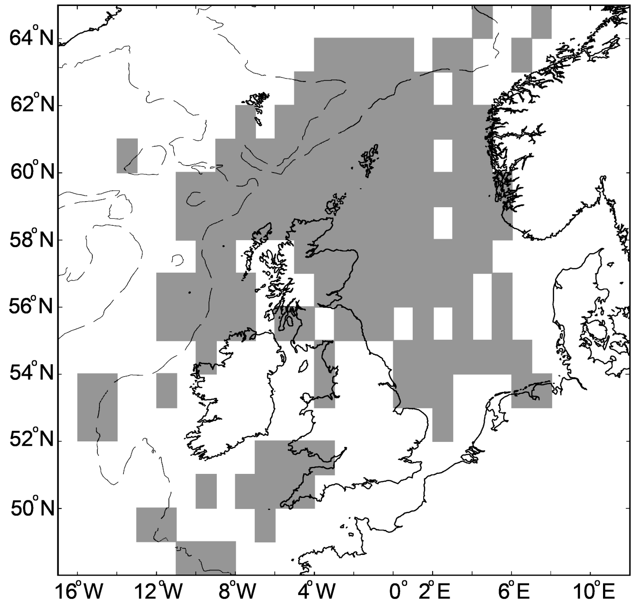

Fig. 1. Quadrants surveyed for cetaceans from seismic surveys, with 1,000m isobath.

power output to survey small areas to shallow depth (e.g. for rig site, pipeline, cable route, debris or anchor search surveys). On most (87%) site surveys the total array volume was 180cu.in. or less; the maximum array volume for these surveys was 820cu.in. The frequencies used during site surveys were typically 3-250Hz, with a peak energy output of around 10 bar metres, equating to a peak source level of around 235dB re. 1μPa @ 1m. Data from site surveys were analysed separately from surveys with large volume airgun arrays. Most site surveys were of short duration; observations during site surveys totalled 5,383hr 44min, with the airguns active for 17% of this time.

Observers routinely recorded information including the duration of the watch for marine mammals and the duration of airgun activity during the watch. Weather conditions, including sea state, swell and visibility, were recorded. When marine mammals were encountered, the information recorded included date, time, airgun activity, location, depth, species, number, direction of travel (relative to the vessel and in compass points), behaviour and the closest distance of approach to the airguns. Observers were asked to provide descriptions of marine mammals to support their identification. Where descriptions were not sufficient to confirm the identification, the taxonomic level of the identification was downgraded (e.g. from common bottlenose dolphin (*Tursiops truncatus*) to dolphin sp.). Videos or photographs, where available, were used to verify identification. Sometimes sightings that could not be identified to the species level could nevertheless be identified as being one of a group of morphologically similar species, e.g. fin/sei whale (*Balaenoptera physalus/ B. borealis*), white-beaked dolphin/Atlantic white-sided dolphin (*Lagenorhynchus albirostris/L. acutus*). At times, particularly with distant or brief sightings, it was impossible to identify animals beyond the level of small odontocete (i.e. excluding sperm whale (*Physeter macrocephalus*), killer whale (*Orcinus orca*), long-finned pilot whale (*Globicephala melas*) and beaked whales) or a mysticete. For some groups of morphologically similar species there were considerable numbers of sightings and in order to gain as much information from the data as possible these species groups were included in the analyses.

Weather conditions varied considerably and influenced the ability of observers to detect cetaceans, with sighting rates increasing as sea state and swell decreased and as visibility increased. As the proportion of time spent shooting also varied in relation to weather conditions, periods of poor weather were discarded when comparing sighting rates or distance of animals from the source in relation to airgun activity. In these cases only periods with sea states of 'slight' (equivalent to sea state 3) or less, swell of less than 2m and visibility of more than 5km were used.

RESULTS

Sighting rate of cetaceans

There were 1,625 sightings of cetaceans (Table 1). Sighting rates were calculated per unit effort (1,000 hours of observations), and were compared between periods of shooting and periods when the airguns were silent. Variations in sighting rate due to location, season or observer ability were controlled by using matched pairs within each day of each survey. Only periods of good weather conditions were used, as defined above.

Sighting rates of all cetaceans combined, all small odontocetes combined, and the *Lagenorhynchus* species (both individual species and a group comprising all *Lagenorhynchus* species combined) were significantly reduced during periods of shooting on surveys with large volume airgun arrays (Fig. 2; Table 2). For site surveys, a significant reduction in sighting rate during periods of shooting was found for all small odontocetes combined (z =2.116, n=14, p=0.0170; Fig. 3).

Sighting rates through the course of surveys were examined for evidence of exclusion from survey areas due to the continued use of seismic airguns, using only periods of good weather conditions. The influence of location and season was controlled by using only data from known areas and months of peak abundance, established using various sources (e.g. Bloor *et al.*, 1996; Clark and Charif, 1998; JNCC, 1995; NERC, 1998; Northridge *et al.*, 1995; Pollock *et al.*, 2000; Pollock *et al.*, 1997; Reid *et al.*, 2003; Skov *et al.*, 1995). Kruskal-Wallis analysis of variance showed that variations in sighting rate (over a maximum of 18 weeks) during surveys with large volume airgun arrays were non-significant for all species. For site surveys the results (over a maximum of four weeks) were also non-significant.

Distance of cetaceans from the airguns

The median closest distance of approach to the airguns was compared between periods of shooting and periods when the airguns were not firing, using only periods of good weather conditions (as defined above). Only species where the sample size equalled or exceeded 10 sightings were used.

All small odontocetes tested, killer whales and all mysticetes combined remained significantly further from the source during periods of shooting on surveys with large volume airgun arrays (Fig. 4; Table 3). The only species found to approach closer to the airguns during periods of shooting was the sperm whale, but this result was not statistically significant. During site surveys no significant differences in the closest distance of approach of animals to the source were found (Fig. 5).

The proportion of sightings of small odontocetes within a given range of large volume airgun arrays was significantly reduced during periods of shooting (Fig. 6; Kolmogorov-Smirnov test χ^2 approximation = 21.021, df=1, p<0.001), while for other cetaceans no significant differences were found (χ^2 approximation = 3.056, df=1). During site surveys

Table 1

Summary of cetacean sightings from seismic survey vessels.

Species		Number of sightings	Number of individuals
Unidentified cetacean sp.		41	358
Unidentified whale sp.		59[1]	163
Unidentified large whale sp.		54[1]	129
Northern right whale (probable)	*Eubalaena glacialis*	1	1
Humpback whale	*Megaptera novaeangliae*	8	10
Blue whale	*Balaenoptera musculus*	4[1]	4
Fin whale	*Balaenoptera physalus*	116[1]	244
Sei whale	*Balaenoptera borealis*	13	16
Unidentified fin/blue whale		10	18
Unidentified fin/sei whale		56[1]	97
Unidentified fin/sei/blue whale		6	9
Unidentified fin/sei/humpback whale		27	40
Unidentified fin/sei/blue/humpback whale		17	36
Common minke whale	*Balaenoptera acutorostrata*	79[1]	103
Sperm whale	*Physeter macrocephalus*	123[1]	191
Unidentified humpback/sperm whale		12	17
Unidentified medium whale sp.		8	13
Unidentified beaked whale sp.	*Mesoplodon/Ziphius/Hyperoodon* spp.	3	3
Northern bottlenose whale	*Hyperoodon ampullatus*	2	11
Sowerby's beaked whale	*Mesoplodon bidens*	1	1
Long-finned pilot whale	*Globicephala melas*	172[1]	3,384
Killer whale	*Orcinus orca*	61	357
Unidentified dolphin sp.		226[1]	6,203
Unidentified dolphin sp. not porpoise		34	432
Risso's dolphin	*Grampus griseus*	10	28
Common bottlenose dolphin	*Tursiops truncatus*	34[1]	321
Unidentified unpatterned dolphin sp.[2]		2	12
White-beaked dolphin	*Lagenorhynchus albirostris*	172[1]	1,365
Atlantic white-sided dolphin	*Lagenorhynchus acutus*	198[1]	12,879
Unidentified *Lagenorhynchus* sp.[3]		44[1]	815
Common dolphin	*Delphinus delphis*	24[1]	246
Striped dolphin	*Stenella coeruleoalba*	5[1]	255
Unid. common/Atlantic white-sided dolphin		4	143
Unidentified common/striped dolphin		5	39
Unidentified common/Atlantic white-sided/striped dolphin		1	65
Unidentified patterned dolphin sp.[4]		5	18
Harbour porpoise	*Phocoena phocoena*	37	111
Total		**1,625**	**28,137**

[1]Includes mixed species sightings; [2]unpatterned dolphin = Risso's/common bottlenose dolphin; [3]*Lagenorhynchus* sp. = white-beaked/Atlantic white-sided dolphin; [4]patterned dolphin = white-beaked/ Atlantic white-sided/common/striped dolphin.

Table 2

Difference in sighting rate of cetaceans in relation to the use of large volume seismic airgun arrays (Wilcoxon signed ranks test).

Species	*z*	*n*	*P*
All cetaceans combined	2.005	193	0.0222
All mysticetes combined	0.585	65	n.s.
Humpback whale	-1.604	3	n.s.
Fin whale	0.082	30	n.s.
Fin/sei whale[1]	0.228	36	n.s.
Common minke whale	0.547	23	n.s.
Sperm whale	0.578	23	n.s.
Long-finned pilot whale	0.735	31	n.s.
Killer whale	1.244	9	n.s.
All small odontocetes combined	2.290	128	0.0110
Common bottlenose dolphin	-0.908	9	n.s.
Lagenorhynchus spp.[2]	3.685	85	0.0001
White-beaked dolphin	1.916	35	0.0274
Atlantic white-sided dolphin	2.806	49	0.0025
Harbour porpoise	0.345	14	n.s.

[1]Includes fin whales, sei whales and unidentified fin/sei whales; [2]includes white-beaked dolphins, Atlantic white-sided dolphins and unidentified *Lagenorhynchus* sp; n.s.= not significant.

there were no significant differences in the proportion of sightings within a given range of the airguns in relation to airgun activity for any cetaceans (small odontocetes: χ^2 approximation = 0.097, df=1; other cetaceans: χ^2 approximation=1.214, df=1).

Orientation of cetaceans

The orientation of some species or species groups (all cetaceans combined, all mysticetes combined, all small odontocetes combined, long-finned pilot whale, *Lagenorhynchus* spp., white-beaked dolphin and harbour porpoise (*Phocoena phocoena*)) varied significantly with airgun activity (Table 4); partitioning showed that significantly fewer animals were travelling towards the vessel and/or more were travelling away from the vessel during periods of shooting. Orientation during site surveys differed with airgun activity for all species or species groups tested (Table 5), with significantly fewer animals travelling towards the vessel and/or more travelling away from the vessel during periods of shooting.

Although precise data on other aspects of behaviour were not collected, observers' records suggested that fewer cetaceans were feeding, fewer were interacting with the vessel or its equipment (e.g. bow-riding) and more were altering course when airguns were active. Observers also gained the impression that small odontocetes tended to swim faster when airguns were active and some mysticetes remained submerged more when airguns were silent.

Sightings during the soft start

Sightings occurring only during the soft start were compared with those only occurring at other times during surveys with large volume airgun arrays (no

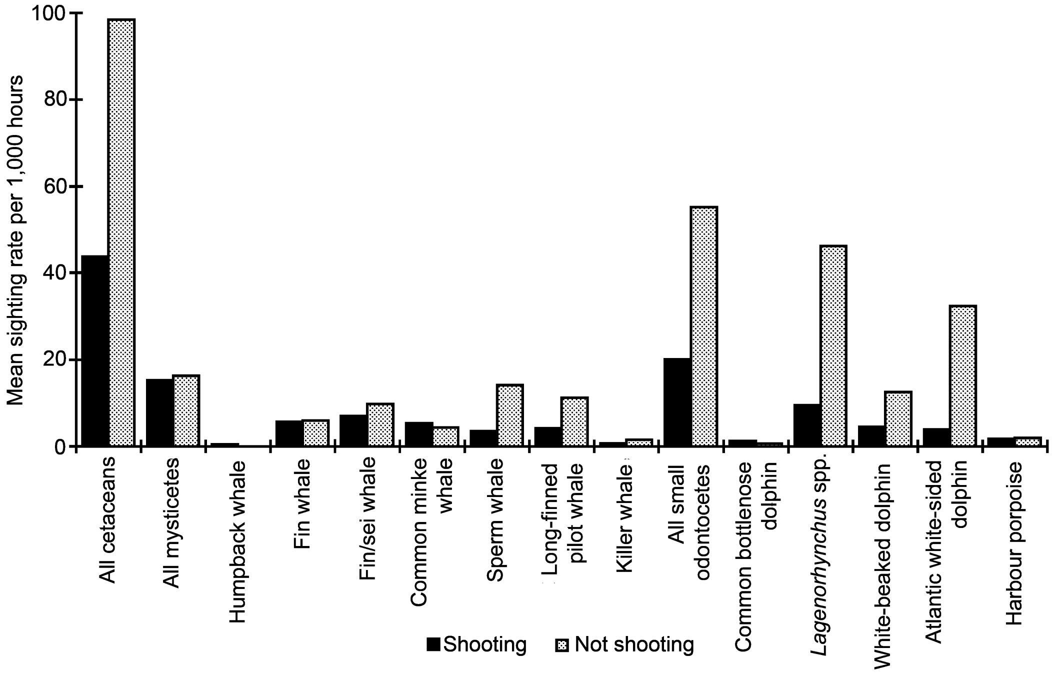

Fig. 2. Sighting rates of cetaceans in relation to the use of large volume airgun arrays.

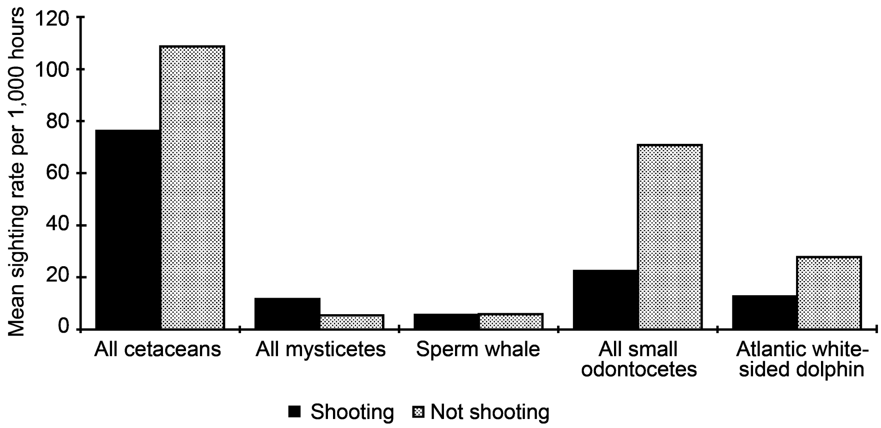

Fig. 3. Sighting rates of cetaceans in relation to the use of airguns during site surveys.

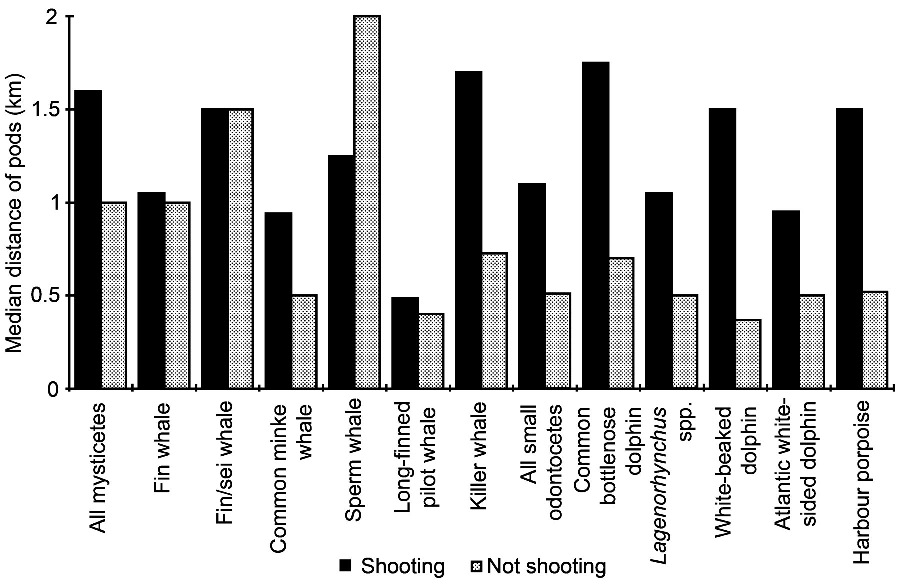

Fig. 4. Median closest distance of approach of cetaceans to large volume airgun arrays in relation to airgun activity.

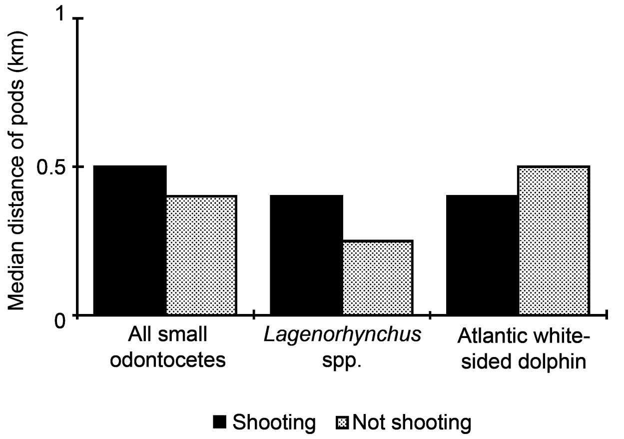

Fig. 5. Median closest distance of approach of cetaceans to airguns in relation to airgun activity during site surveys.

Table 3

Difference in closest distance of approach of cetaceans to the airguns in relation to the use of large volume seismic airgun arrays (Wilcoxon test).

Species	*z*	*n*	*P*
All mysticetes combined	2.529	148	0.0057
Fin whale	1.546	57	n.s.
Fin/sei whale	1.226	78	n.s.
Common minke whale	1.206	42	n.s.
Sperm whale	-0.445	51	n.s.
Long-finned pilot whale	-0.243	59	n.s.
Killer whale	1.843	14	0.0329
All small odontocetes combined	4.707	292	<0.0001
Common bottlenose dolphin	-1.701	14	0.0446
Lagenorhynchus spp.	4.464	164	<0.0001
White-beaked dolphin	3.702	71	0.00011
Atlantic white-sided dolphin	2.428	80	0.0075
Harbour porpoise	2.503	21	0.0062

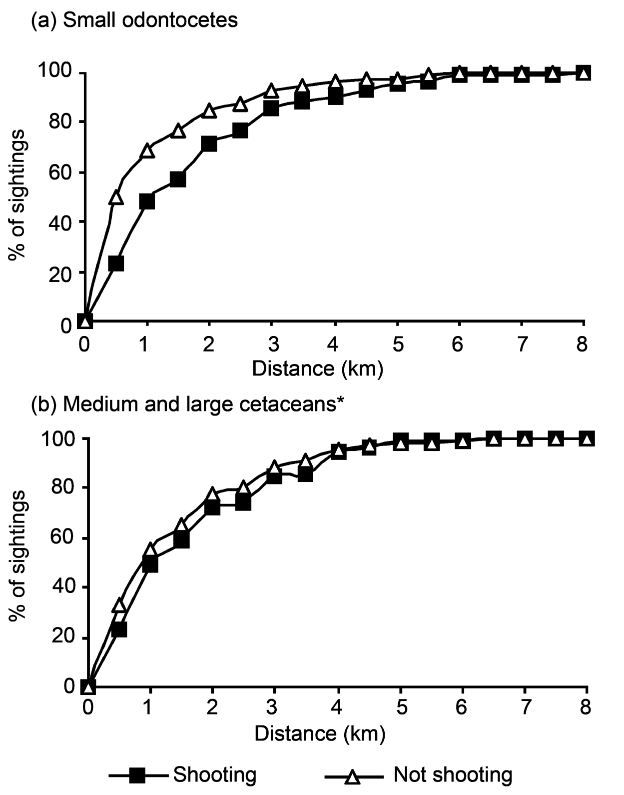

Fig. 6. Proportion of cetacean sightings occurring within specified distances of large volume airgun arrays, in relation to airgun activity. * Medium and large cetaceans = long-finned pilot whale, killer whale, beaked whales, sperm whale and mysticetes.

sightings occurred during the soft start on site surveys). As sample sizes were small, all cetaceans were combined.

The median closest distance of approach of cetaceans observed during periods of good weather varied according to the activity of the airguns (median distance when shooting at full power=1.1km, during soft start=900m, when not shooting=700m; Kruskal-Wallis statistic=18.970, n=569, df=2, p<0.001). Multiple comparisons revealed significant differences between the distance of cetaceans when the airguns were not firing and during shooting at full power levels, but the distance of cetaceans during the soft start did not differ significantly from either shooting at full power or not shooting.

Although sample sizes were too small to test differences in orientation of cetaceans during the soft start, more small odontocetes were seen heading away from the vessel (29%) during the soft start than in any other direction, although it was also noted that there were occasional instances of white-beaked dolphins bow-riding. Mysticetes were also more often seen heading away from the vessel (22%) than towards it (11%) during the soft start, while the few long-finned pilot whales seen during the soft start tended to head towards the vessel (67%).

Of 12 sightings that were present at the onset of a soft start, two exhibited startle responses. A pod of long-finned pilot whales 290m from the airguns altered course and swam away from the vessel as the soft start commenced. In another case, a sperm whale at 2km from the airguns had previously been swimming slowly and had dived; it resurfaced as the soft start began and swam rapidly at the surface.

DISCUSSION

The responses observed here indicate that there is some level of disturbance of cetaceans by seismic airguns. The observations suggest that small odontocetes show the strongest lateral spatial avoidance of active airguns, with mysticetes and killer whales showing some localised spatial avoidance, long-finned pilot whales showing only a change in orientation and sperm whales showing no statistically significant effects from these data.

Most of the energy from seismic airguns is at frequencies below the optimum hearing range of small odontocetes, whose greatest auditory sensitivities lie within the range 10-150kHz; consequently they are sometimes regarded as being relatively insensitive to seismic sounds (Richardson *et al.*, 1995). However, high frequency noise is emitted incidentally during seismic operations. Seismic exploration generally utilises frequencies up to 220Hz, but Goold and Fish (1998) found that noise from seismic airguns also dominated the 200Hz-22kHz bandwidth at ranges of up to 2km from the source and that even at 8km airgun noise exceeded background noise at frequencies of up to 8kHz. They concluded that seismic emissions would be audible to dolphins out to ranges of at least 8km. Furthermore, dolphins may be able to detect low frequency sounds using some mechanism other than conventional hearing. Turl (1993) found that a common bottlenose dolphin responded to sounds of 50-100Hz and suggested that this was due to detection of particle velocity or a combination of pressure and velocity in the near-field.

Those small odontocetes tested showed a greater range of responses to seismic surveys than mysticetes or larger odontocetes. Amongst these responses, significant declines in sighting rates during periods of shooting were observed

Table 4

Direction of travel of cetaceans relative to the survey vessel in relation to airgun activity, during surveys with large volume airgun arrays (χ^2 calculated from frequencies).

Species	Airgun activity	Towards ship	Away from ship	Crossing path of ship	Parallel to ship in same direction	Parallel to ship in opposite direction	Milling or variable	χ^2	*n*	*d.f.*	*P*
All cetaceans combined	Shooting	6.81%	20.43%	22.57%	10.89%	30.74%	8.56%	58.933	1,368	5	<0.001
	Not shooting	19.20%	10.19%	20.49%	11.12%	31.38%	7.61%				
All mysticetes combined	Shooting	4.35%	21.74%	18.84%	10.87%	34.78%	9.42%	12.037	304	5	<0.05
	Not shooting	9.64%	9.64%	21.69%	11.45%	40.96%	6.63%				
Fin whale	Shooting	6.12%	26.53%	16.33%	10.20%	32.65%	8.16%	3.955	108	2	n.s.
	Not shooting	6.78%	11.86%	16.95%	3.39%	54.24%	6.78%				
Fin/ sei whale	Shooting	3.61%	24.10%	13.25%	13.25%	37.35%	8.43%	6.605	174	5	n.s.
	Not shooting	4.40%	13.19%	17.58%	7.69%	50.55%	6.59%				
Common minke whale	Shooting	7.69%	11.54%	34.62%	7.69%	34.62%	3.85%	3.160	73	2	n.s.
	Not shooting	21.28%	6.38%	23.40%	10.64%	31.91%	6.38%				
Sperm whale	Shooting	10.00%	25.00%	7.50%	25.00%	25.00%	7.50%	3.732	104	5	n.s.
	Not shooting	9.38%	21.88%	18.75%	15.63%	23.44%	10.94%				
Long-finned pilot whale	Shooting	7.89%	14.47%	22.37%	10.53%	43.42%	1.32%	12.031	162	5	<0.05
	Not shooting	19.77%	4.65%	13.95%	10.47%	45.35%	5.81%				
All small odontocetes combined	Shooting	8.10%	20.95%	28.57%	7.62%	22.86%	11.90%	45.035	646	5	<0.001
	Not shooting	25.23%	8.49%	22.48%	11.01%	24.77%	8.03%				
Common bottlenose dol.	Shooting	8.33%	33.33%	25.00%	0.00%	25.00%	8.33%	2.556	30	1	n.s.
	Not shooting	22.22%	5.56%	22.22%	11.11%	27.78%	11.11%				
Lagenorhynchus spp.	Shooting	11.11%	18.18%	28.28%	9.09%	21.21%	12.12%	29.676	350	5	<0.001
	Not shooting	32.27%	4.78%	25.50%	9.96%	20.72%	6.77%				
White-beaked dolphin	Shooting	6.12%	26.53%	28.57%	8.16%	16.33%	14.29%	33.081	153	5	<0.001
	Not shooting	48.08%	4.81%	21.15%	6.73%	10.58%	8.65%				
Atlantic white-sided dol.	Shooting	12.50%	12.50%	30.00%	7.50%	27.50%	10.00%	5.211	154	4	n.s.
	Not shooting	21.93%	5.26%	30.70%	8.77%	28.95%	4.39%				
Harbour porpoise	Shooting	0.00%	45.45%	27.27%	0.00%	27.27%	0.00%	4.289	34	1	<0.05
	Not shooting	4.35%	30.43%	4.35%	13.04%	47.83%	0.00%				

Table 5

Direction of travel of cetaceans relative to the survey vessel in relation to airgun activity during site surveys (χ^2 calculated from frequencies).

Species	Airgun activity	Towards ship	Away from ship	Crossing path of ship	Parallel to ship in same direction	Parallel to ship in opposite direction	Milling or variable	χ^2	*n*	*d.f.*	*P*
All cetaceans combined	Shooting	3.29%	14.75%	14.75%	11.48%	45.90%	9.84%	19.380	230	5	< 0.01
	Not shooting	23.08%	7.69%	15.98%	15.98%	25.44%	11.83%				
All small odontocetes combined	Shooting	0.00%	16.67%	10.00%	13.33%	50.00%	10.00%	21.783	124	4	< 0.001
	Not shooting	31.91%	6.38%	20.21%	11.70%	19.15%	10.64%				
Lagenorhynchus spp.	Shooting	0.00%	15.79%	15.79%	10.53%	47.37%	10.53%	10.127	59	1	< 0.01
	Not shooting	37.50%	10.00%	22.50%	7.50%	12.50%	10.00%				
Atlantic white-sided dol.	Shooting	0.00%	17.65%	11.76%	11.76%	47.06%	11.76%	8.410	42	1	< 0.01
	Not shooting	20.00%	12.00%	36.00%	8.00%	16.00%	8.00%				

for the *Lagenorhynchus* species and all small odontocetes combined. This implies that effects persist at least as far as the limit of visual observation. Studies of the effects of seismic airguns on small odontocetes are rare, with most previous work concentrating on mysticetes and sperm whales; one study found that common dolphin (*Delphinus delphis*) populations were apparently temporarily disturbed by seismic surveys (Goold, 1996), while another found a reduction in cetacean diversity, mainly amongst members of the family Delphinidae, during a period of intensification of seismic surveys (Parente and de Araújo, 2005).

Mysticetes have often been considered to be vulnerable to anthropogenic noise (e.g. Ketten, 1998; Richardson *et al.*, 1995), as the frequencies they use overlap with those produced by many industrial sources. Although the auditory sensitivities of mysticetes are not known, there is an assumption that hearing will occupy approximately the same range of frequencies that these animals produce sounds at. Fin whales, for example, produce calls around 20Hz (Watkins, 1981) and would be expected to be sensitive to sounds at these frequencies.

In spite of their anticipated vulnerability, few responses to airgun activity have been recorded for mysticetes in UK waters. No obvious effects on the occurrence of individual species were found in the present study. However, when all species of mysticetes were combined to permit inclusion of sightings that were not identified to species level, it was found that they occurred further from the airguns during periods of shooting and tended to head away from the vessel at these times. These results indicate that there may be at least some level of localised spatial avoidance of operating airguns by mysticetes. Avoidance of airguns has previously been observed in mysticetes in other regions (e.g. Ljungblad *et al.*, 1988; Richardson *et al.*, 1985; Richardson and Greene, 1993; Richardson *et al.*, 1999; Weller *et al.*, 2002).

The absence of any reduction in sighting rates of mysticetes should not be taken as confirmation that there was no or minimal disturbance. As discussed above, there were other indications of localised spatial avoidance, and in addition there may be effects not able to be detected using these data. For example, effects on vocalisations would not be apparent from visual observations. Changes in call detection rates in response to airgun activity have been found for bowhead whales, *Balaena mysticetus* (Greene *et al.*, 1999; Richardson, 1997). Other studies have also indicated some level of stress, with alterations in surfacing, respiration and dive cycles being observed in mysticetes in response to the use of seismic airguns, sometimes at considerable distances from the source (Ljungblad *et al.*, 1988; Richardson *et al.*, 1985; Richardson *et al.*, 1995; Richardson *et al.*, 1986). Although effects of active airguns on the physiology of the mysticetes found around the UK are largely unknown, in one study, shorter blow intervals indicated an increase in the respiration rate of fin whales within 1km of the airguns during periods of shooting (Stone, 1998a).

No statistically significant effects of airgun activity on sperm whales were found during this study, although a startle response was noted at the onset of shooting on one occasion. Some studies have found that the use of seismic airguns resulted in a decrease in abundance of sperm whales (Mate *et al.*, 1996; Stone, 2006) and negative effects on their communication and orientation (Bowles *et al.*, 1994; Rankin and Evans, 1998), while other studies have shown no response to operating airguns (Madsen *et al.*, 2002; Tyack *et al.*, 2003). Cetaceans hear as well at depth as they do near the surface (Ridgway *et al.*, 1998), so deep-diving species such as sperm whales will be vulnerable to acoustic disturbance throughout the water column. It may be difficult to observe effects on their occurrence or behaviour simply from surface observations due to the relatively small proportion of time they spend at the surface.

Long-finned pilot whales also showed little response to operating airguns. The only observed effect was on their orientation, with more heading away from and fewer towards the vessel during periods of shooting. However, any avoidance appeared to be relatively minor as there was no significant difference in their distance from the airguns in relation to airgun activity. Bowles *et al.* (1994) noted that pilot whales were not vocalising during periods of airgun noise.

For the first time, some effects of airgun activity on killer whales have been assessed. As with the mysticetes, sperm whales and long-finned pilot whales, no reduction in the sighting rate of killer whales was found in response to operating airguns. However, killer whales were found to remain further from the source when it was active, which may indicate some level of spatial avoidance. As with small odontocetes, studies on the effects of airgun activity are rare for medium-sized odontocetes; however, seismic surveys may have been implicated in at least one beaked whale stranding (Peterson, 2003; Taylor *et al.*, 2004).

It is possible that the different cetacean species react to the use of seismic airguns in different ways. It has been suggested that species variation in auditory processing is so important that a distinction should certainly be made between taxonomic groups that have widely different hearing and sensitivity frequencies (National Research Council, 2005). Most of the taxonomic groups examined here have shown at least some response during periods of shooting. The fast moving small odontocetes not only orient away from the source and increase their distance from it, but are able to move out of the immediate area (as indicated by reduced sighting rates during periods of shooting). However, although mysticetes orient away from the survey vessel and increase their distance from the source, they do not move away from the area completely. It is possible that these slower moving species, rather than moving out of the area, have adopted a different strategy in response to anthropogenic noise. Some studies have suggested that cetaceans may remain near the surface during periods of noise – received sound levels near the surface are generally lower than at greater depths (Richardson *et al.*, 1995; Urick, 1983). McCauley *et al.* (1998; 2000) offered this as an explanation for humpback whales spending much of their time at the surface during a period of seismic surveying, and it could also explain an increased tendency for cetaceans to be logging at the water surface during periods of shooting (Stone, 2006). Observations during the present study hinted that some mysticetes may submerge less during periods of shooting; it would be useful to collect precise behavioural data to investigate this further.

The avoidance exhibited by small odontocetes, and to a lesser extent other cetaceans, appears to be temporary. There was no consistent evidence of declining sighting rates throughout the course of seismic surveys. However, it is not known whether animals seen later in a survey are the same individuals that were present earlier, or whether they have left and new animals have arrived. It is also possible that animals may have no choice but to remain in an area, if there is some reason (e.g. food) that they need to be there.

Site surveys had some effects on cetaceans, although less than surveys with large volume airgun arrays. Effects on orientation were evident for all species tested.

Barlow and Gisiner (2006) have stated that marine mammal responses to the soft start are unknown and that since the effectiveness of the method is untested, there is a need for more research. The value of the present study in this respect was limited by small sample sizes – larger sample sizes of sightings during the soft start are needed to assess the effectiveness of this procedure as a mitigation tool. Obtaining larger sample sizes should be feasible by continuing the present programme of data collection from seismic surveys, and would present an economical first step towards evaluating the effectiveness of the soft start.

Although the present study found that more cetaceans were heading away from the vessel than towards it during the soft start (with the exception of long-finned pilot whale), sample sizes were too small to test the significance of this result. Another study found that significantly more cetaceans were heading away from the vessel during the soft start than at any other time, including when airguns were shooting at full power (Stone, 2006). Swimming away from the vessel during the soft start may reduce the potential for disturbance; although in the present study some cetaceans swam away from the vessel during the soft start, conversely some dolphins engaged in bow-riding. Noise levels ahead of the vessel may be less than those abeam of it (McCauley *et al.*, 2000; Richardson *et al.*, 1995), but animals bow-riding during low power shooting may be vulnerable to disturbance if they have insufficient time to move away before full power levels are reached.

As well as minimising disturbance, the aim of the soft start is to reduce the risk of physical injury to undetected animals close to the source, and this risk may increase if shooting were to commence at full power levels with no soft start. Encounters with cetaceans have been noted as occurring at increasing distances from the airguns during the first two-thirds of the soft start, when relative increases in power are greatest, then closer to the airguns again during the latter stages, when relative increases in power are low (Stone, 2006); a secondary peak in the closest distance of approach has been observed at the commencement of the soft start, perhaps due to a startle response. Instances where a startle response was observed during the present study also support the need for a soft start; startle responses would presumably be more severe and/or more frequent if shooting were to commence at full power.

This study concentrated on examining short-term effects of airgun activity on the occurrence and orientation of cetaceans. Other potential effects remain largely unknown, for example long-term effects, effects on vocalisations, behaviour and physiology, consequences of auditory masking and the potential for damage to hearing. The lack of an observed response in some species does not therefore imply that the use of seismic airguns has no effect on those species. Furthermore, although those responses that were observed were short-term effects, it is not known whether these may have been biologically significant: effects that persisted beyond the time of disturbance, responses that affected the ability of animals to engage in essential activities (e.g. breeding, feeding, caring for young, migrating, etc.), or effects that had consequences at the population level. The difficulties of determining the biological significance of observed effects are recognised (National Research Council, 2003; 2005). Until the biological significance of the observed effects can be determined, precautionary guidelines to minimise disturbance should continue to be applied.

ACKNOWLEDGEMENTS

This work was made possible by the cooperation of the oil and gas industries, seismic exploration companies, and the crews of the seismic survey vessels. Numerous observers, including dedicated marine mammal observers, fishery liaison representatives and members of ships' crews, recorded the data, and their contributions are gratefully acknowledged. The map was plotted using *DMAP* for Windows. Zoë Crutchfield (JNCC) and Tim Barton (University of Aberdeen) are acknowledged for their comments and suggestions during the preparation of the manuscript.

REFERENCES

Barlow, J. and Gisiner, R. 2006. Mitigating, monitoring and assessing the effects of anthropogenic sound on beaked whales. *J. Cetacean Res. Manage.* 7(3):239-49.

Bloor, P.D., Reid, J.B., Webb, A., Begg, G. and Tasker, M.L. 1996. The distribution of seabirds and cetaceans between the Shetland and Faroe Islands. *JNCC Report* 226. 140pp. [Available from the Joint Nature Conservation Committee, Aberdeen].

Bowles, A.E., Smultea, M., Würsig, B., DeMaster, D.P. and Palka, D. 1994. Relative abundance and behaviour of marine mammals exposed to transmissions from the Heard Island Feasibility Test. *J. Acoust. Soc. Am.* 96:2,469-84.

Clark, C.W. and Charif, R.A. 1998. Acoustic monitoring of large whales to the west of Britain and Ireland using bottom-mounted hydrophone arrays, October 1996 – September 1997. *JNCC Report* 281. 25pp. [Available from the Joint Nature Conservation Committee, Aberdeen].

Cox, T.M., Ragen, T.J., Read, A.J., Vos, E., Baird, R.W., Balcomb, K., Barlow, J., Caldwell, J., Cranford, T., Crum, L., D'Amico, A., D'Spain, G., Fernández, A., Finneran, J., Gentry, R., Gerth, W., Gulland, F., Hildebrand, J., Houser, D., Hullar, T., Jepson, P.D., Ketten, D., MacLeod, C.D., Miller, P., Moore, S., Mountain, D., Palka, D., Ponganis, P., Rommel, S., Rowles, T., Taylor, B., Tyack, P., Wartzok, D., Gisiner, R., Mead, J. and Benner, L. 2006. Understanding the impacts of anthropogenic sound on beaked whales. *J. Cetacean Res. Manage.* 7(3):177-87.

Goold, J.C. 1996. Acoustic assessment of populations of common dolphin (*Delphinus delphis*) in conjunction with seismic surveying. *J. Mar. Biol. Assoc. UK* 76:811-20.

Goold, J.C. and Fish, P.J. 1998. Broadband spectra of seismic survey air-gun emissions with reference to dolphin auditory thresholds. *J. Acoust. Soc. Am.* 103(4):2,177-84.

Greene, C.R., Altman, N.S. and Richardson, W.J. 1999. The influence of seismic survey sounds on bowhead whale calling rates. *J. Acoust. Soc. Am.* 106:2,280.

JNCC. 1995. *European seabirds at sea database: seabird and cetacean UKDMAP datasets version 2.1*. JNCC, Peterborough.

JNCC. 2004. Guidelines for minimising acoustic disturbance to marine mammals from seismic surveys. [Available from *http://www.jncc.gov.uk/pdf/Seismic_survey_guidelines_200404.pdf*].

Kastelein, R. and Wartzok, D. 2004. Priroitizing information needs for risk assessment and mitigation strategies. *MMC/JNCC International Policy Workshop on Sound and Marine Mammals*. London, September 28-30 2004.

Ketten, D.R. 1998. Marine mammal auditory systems: a summary of audiometric anatomical data and implications of underwater acoustic impacts. *NOAA Technical Memorandum NMFS SWFSC-256*. 74pp. [Available from the author D.R. Ketten, Department of Biology, Woods Hole Oceanographic Institute].

Ljungblad, D.K., Würsig, B., Swartz, S.L. and Keene, J.M. 1988. Observations on the behavioral responses of bowhead whales (*Balaena mysticetus*) to active geophysical vessels in the Alaskan Beaufort Sea. *Arctic* 41(3):183-94.

Madsen, P.T., Mohl, B., Nielsen, B.K. and Wahlberg, M. 2002. Male sperm whale behaviour during exposures to distant seismic survey pulses. *Aquat. Mamm.* 28:231-40.

Mate, B.R., Stafford, K.M. and Ljungblad, D.K. 1996. A change in sperm whale (*Physeter macrocephalus*) distribution correlated to seismic surveys in the Gulf of Mexico. *J. Acoust. Soc. Am.* 96(5):3,268-69.

McCauley, R.D., Fewtrell, J., Duncan, A.J., Jenner, C., Jenner, M.N., Penrose, J.D., Prince, R.I.T., Adhitya, A., Murdoch, J. and McCabe, K. 2000. Marine seismic surveys – a study of environmental implications. *APPEA Journal* 2000:692-708.

McCauley, R.D., Jenner, M.N., McCabe, K.A. and Murdoch, J. 1998. The response of humpback whales (*Megaptera novaeangliae*) to offshore seismic survey noise: preliminary results of observations about a working seismic vessel and experimental exposures. *APPEA Journal* 1998:692-706.

National Research Council. 2000. *Marine Mammals and Low-Frequency Sound: Progress Since 1994*. The National Academies Press, Washington DC. 160pp.

National Research Council. 2003. *Ocean Noise and Marine Mammals*. The National Academies Press, Washington, DC. 204pp.

National Research Council. 2005. *Marine Mammal Populations and Ocean Noise – Determining when Noise Causes Biologically Significant Effects*. The National Academies Press, Washington DC. 142pp.

NERC. 1998. *United Kingdom Digital Marine Atlas (UKDMAP) – Version 3, July 1998*. National Environment Research Council/British Oceanographic Data Centre, Bidston Observatory, Birkenhead, Merseyside.

Nieukirk, S.L., Stafford, K.M., Mellinger, D.K., Dziak, R.P. and Fox, C.G. 2004. Low-frequency whale and seismic airgun sounds recorded in the mid-Atlantic. *J. Acoust. Soc. Am.* 115(4):1,832-43.

Northridge, S.P., Tasker, M.L., Webb, A. and Williams, J.M. 1995. Distribution and relative abundance of harbour porpoises (*Phocoena phocoena* L.), white-beaked dolphins (*Lagenorynchus albirostris* Gray), and minke whales (*Balaenoptera acutorostrata* Lacépede) around the British Isles. *ICES J. Mar. Sci.* 52:55-66. [With erratum on pp.1,005-12].

Parente, C.L. and de Araújo, E. 2005. Is the diversity of cetaceans in Brazil reduced by the intensification of the seismic surveys? Paper SC/57/E6 presented to the IWC Scientific Committee, June 2005, Ulsan, Korea. 15pp. [Paper available from the Office of this Journal].

Peterson, G. 2003. Whales beach seismic research. *Geotimes* Jan 2003:8-9. [Available at *www.geotimes.org/jan03/NNwhales.html*].

Pollock, C.M., Mavor, R., Weir, C.R., Reid, A., White, R.W., Tasker, M.L., Webb, A. and Reid, J.B. 2000. *The Distribution of Seabirds and Marine Mammals in the Atlantic Frontier, North and West of Scotland*. Joint Nature Conservation Committee, Aberdeen. 92pp.

Pollock, C.M., Reid, J.B., Webb, A. and Tasker, M.L. 1997. The distribution of seabirds and cetaceans in the waters around Ireland. *JNCC Report* 267. 167pp. [Available from the Joint Nature Conservation Committee, Aberdeen].

Rankin, S. and Evans, W.E. 1998. Effect of low frequency seismic exploration signals on the cetaceans of the Gulf of Mexico. In: The World Marine Mammal Science Conference, Monaco, 20-24 January 1998, Society for Marine Mammalogy and the European Cetacean Society, Centre de Recherche sur les Mammiferes Marins, La Rochelle, France. p110. [Abstract].

Reid, J.B., Evans, P.G.H. and Northridge, S.P. 2003. *Atlas of Cetacean Distribution in North-west European Waters*. Joint Nature Conservation Committee, Peterborough, UK. 76pp.

Richardson, W.J. 1997. Northstar Marine Mammal Monitoring Program, 1996: Marine mammals and acoustical monitoring of a seismic program in the Alaskan Beaufort Sea. Final Report LGL Report TA2121-2. Prepared for BP Exploration (Alaska) Inc. and National Marine Fisheries Service by LGL Ltd and Greenridge Sciences Inc., LGL Ltd., Anchorage.

Richardson, W.J., Fraker, M.A., Würsig, B. and Wells, R.S. 1985. Behavior of bowhead whales *Balaena mysticetus* summering in the Beaufort Sea: reactions to industrial activities. *Biol. Conserv.* 32:195-230.

Richardson, W.J. and Greene, C.R. 1993. Variability in behavioural reaction thresholds of bowhead whales to man-made underwater sounds. *J. Acoust. Soc. Am.* 94:1848.

Richardson, W.J., Greene, C.R., Jr, Malme, C.I. and Thomson, D.H. 1995. *Marine Mammals and Noise*. Academic Press, San Diego. 576pp.

Richardson, W.J., Miller, G.W. and Greene, C.R. 1999. Displacement of migrating bowhead whales by sounds from seismic surveys in shallow waters of the Beaufort Sea. *J. Acoust. Soc. Am.* 106:2281.

Richardson, W.J., Würsig, B. and Greene, C.R. 1986. Reactions of bowhead whales, *Balaena mysticetus*, to seismic exploration in the Canadian Beaufort Sea. *J. Acoust. Soc. Am.* 79:1117-28.

Ridgway, S., Carder, D., Smith, R., Kamolnick, T. and Elsberry, W. 1998. A report on Project Deephear: towards a scientific basis for understanding noise effects on marine mammals. *In*: The World Marine Mammal Science Conference, Monaco, 20-24 January 1998, Society for Marine Mammalogy and the European Cetacean Society, Centre de Recherche sur les Mammiferes Marins, La Rochelle, France. pp.112-13.

Skov, H., Durink, J., Danielsen, F. and Bloch, D. 1995. Co-occurrence of cetaceans and seabirds in the northeast Atlantic. *J. Biogeog.* 22:71-88.

Stone, C.J. 1997. Cetacean observations during seismic surveys in 1996. *JNCC Report* 228. 41pp. [Available from the Joint Nature Conservation Committee, Aberdeen].

Stone, C.J. 1998a. Cetacean and seabird observations in Tranche 52 and Quad 214 during 1998. Unpublished report to Conoco (UK) Limited. 73pp. [Available from the author].

Stone, C.J. 1998b. Cetacean observations during seismic surveys in 1997. *JNCC Report* 278. 57pp. [Available from the Joint Nature Conservation Committee, Aberdeen].

Stone, C.J. 2000. Cetacean observations during seismic surveys in 1998. *JNCC Report* 301. 62pp. [Available from the Joint Nature Conservation Committee, Aberdeen].

Stone, C.J. 2001. Marine mammal observations during seismic surveys in 1999. *JNCC Report* 316. 92pp. [Available from the Joint Nature Conservation Committee, Aberdeen].

Stone, C.J. 2003. Marine mammal observations during seismic surveys in 2000. *JNCC Report* 322. 66pp. [Available from the Joint Nature Conservation Committee, Aberdeen].

Stone, C.J. 2006. Marine mammal observations during seismic surveys in 2001 and 2002. *JNCC Report* 359. 110pp. [Available from the Joint Nature Conservation Committee, Aberdeen].

Taylor, B., Barlow, J., Pitman, R., Ballance, L., Klinger, T., DeMaster, D., Hildebrand, J., Urban, J., Palacios, D. and Mead, J. 2004. A call for research to assess risk of acoustic impact on beaked whale populations. Paper SC/56/E36 presented to the IWC Scientific Committee, July 2004, Sorrento, Italy. 4pp. [Paper available from the Office of this Journal; also available at: *http://www.awionline.org/whales/Noise/Tayloretal2004.pdf*].

Turl, W.C. 1993. Low frequency sound detection by a bottlenose dolphin. *J. Acoust. Soc. Am.* 94(5):3,006-08.

Tyack, P., Johnson, M. and Miller, P. 2003. Tracking responses of sperm whales to experimental exposures of airguns. *In*: Jochens, A.E. and Briggs, D.C. (eds), *Sperm Whale Seismic Study in the Gulf of Mexico: Annual Report: Year 1*. US Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA. 139pp. OCS Study MMS 2003-069.

Urick, R.J. 1983. *Principles of Underwater Sound*. 3rd ed. McGraw Hill, Baskerville, New York. xiv+423pp.

Watkins, W.A. 1981. Activities and underwater sounds of finback whales (*Balaenoptera physalus*). *Sci. Rep. Whales Res. Inst., Tokyo* 33:83-117.

Weller, D.W., Ivashchenko, Y.V., Tsidulko, G.A., Burdin, A.M. and Brownell, R.L., Jr. 2002. Influence of seismic surveys on western gray whales off Sakhalin Island, Russia in 2001. Paper SC/54/BRG14 presented to the IWC Scientific Committee, April 2002, Shimonoseki, Japan (unpublished). 12pp. [Paper available from the Office of this Journal, and at *http://www.livingoceans.org/oilgas/oilandgasreports/Gray%20whales%20and%20seismic.pdf*].

Date received: September 2005
Date accepted: November 2006