The effects of seismic operations in UK waters: analysis of Marine Mammal Observer data

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ABSTRACT

Sixteen years of information from observers on board seismic survey vessels in UK and adjacent waters have demonstrated the varied responses of marine mammals to seismic surveys. Most species showed some response to firing with 'large arrays' (airgun volume 500 cubic inches or more), but responses were less evident when 'small arrays' (less than 500 cubic inches) were active. Several species/species groups responded proactively to the soft start procedure (where the level of firing is increased gradually) indicating that this can be an effective mitigation measure in reducing the risk of physiological damage. Despite the challenge in assigning ecological significance to the varied observed effects, the analyses in this study confirm that marine mammals are sensitive to noise from seismic surveys and therefore mitigation measures should continue to be applied to all seismic operations and such measures should cover all species.

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

INTRODUCTION

Over the past few decades, concern has developed over the potentially negative impact of anthropogenic noise on marine mammals, including that from marine seismic surveys used to explore oil and gas reserves. Sound produced by airguns is directed at the seabed with the resultant reflections being analysed to map the geological structures below the sea floor. The airguns produce high levels of impulsive low frequency sound with an inherent risk of disturbance and possibly acoustic trauma (e.g. auditory injury) to marine mammals and other marine organisms. Although no direct evidence exists for a causal link between airgun sound and injury to marine mammals, data on auditory sensitivities and comparisons with human and other terrestrial mammal data (Southall *et al.,* 2007), together with propagation modelling, suggest that hearing could be damaged by the sound levels emitted by airguns if the animals are very close to the guns. There is also evidence for short-term behavioural responses of marine mammals to seismic surveys such as avoidance of the area shown by some species of mysticete (e.g. McCauley *et al.,* 1998; 2000; Richardson *et al.,* 1986; 1999) and some small odontocetes (Barkaszi *et al.,* 2012; Stone and Tasker 2006; Thompson *et al.,* 2013; Weir, 2008a). However, investigating biologically significant effects at the population level has proven very challenging (e.g. Gordon *et al.,* 2004; NRC, 2005; Thomsen *et al.*, 2011).

To address conservation concerns in relation to seismic surveys, in 1995 the UK government and the Joint Nature Conservation Committee (JNCC) issued guidelines for seismic operations taking place on the UK continental shelf (latest version: JNCC, 2017). The guidelines aim to reduce the risk of causing injury, and may assist with reducing potential disturbance to marine European Protected Species as part of measures related to Article 12 of the EC Habitats Directive (92/43/EEC) and the Directive's transposition into UK legislation. All applications to conduct seismic surveys for oil and gas exploration within the UK continental shelf require consent from the Department for Business, Energy

and Industrial Strategy (BEIS, formerly known as the Department of Energy and Climate Change), with the JNCC guidelines informing the consent conditions for such surveys. Amongst the provisions of the guidelines is a requirement for having marine mammal observers (MMOs) on board to monitor for the presence of marine mammals prior to commencing firing the airguns, with the commencement of firing being delayed if marine mammals are detected within a defined mitigation zone. For some surveys, there are also provisions for passive acoustic monitoring (PAM) to be employed during conditions that are not conducive to visual observations (e.g. darkness). The primary role of the MMO or PAM operator, therefore, is to provide advice to enable the crew to comply with the guidelines and hence mitigate potential negative impacts of seismic operations on marine mammals. In the course of this work, MMOs and PAM operators collect data on the seismic operations, the watches and any marine mammals detected. In addition to monitoring for the presence of marine mammals and delaying the commencement of airgun firing if marine mammals are detected within the defined mitigation zone, the guidelines also require that when airguns do commence firing, the level of firing must increase gradually by using a soft start/ramp up procedure. The assumption is that animals will show an avoidance response to lower levels of sound enabling them to leave the area where they could potentially be injured before sound levels reach certain thresholds. However, there is a need for evidence on the effectiveness of this method (Barlow and Gisiner, 2006).

All data from seismic surveys in UK waters are returned to JNCC where, after quality checks, they are included in a database; over the years a large amount of data has accrued. This paper presents the results of analyses of MMO data from UK and adjacent waters, including all data from 1994, just prior to the introduction of the JNCC guidelines, until the end of 2010. Previous analyses have used subsets (up to four years) of these data (e.g. Stone and Tasker, 2006). Analysis of this longer dataset with increased sample sizes

has permitted further statistical testing of a larger number of species. The aim of the analyses was to examine whether there were any detectable effects of seismic operations on marine mammals, with a focus on the responses of marine mammals to the soft start procedure to provide some insight as to its effectiveness.

METHODS

Data collection and quality control

MMOs working on seismic surveys operating in UK and sometimes adjacent waters (Norway, Ireland, Faroes, the Netherlands, Denmark, Germany and France) between 1994 and 2010 submitted records of their monitoring effort and the marine mammals observed during daylight hours using standardised recording forms. Observers ranged from biologists experienced in marine mammal surveys to non-scientific personnel, most of whom had undergone basic JNCC-recognised MMO training. In addition, PAM was utilised on some surveys during night-time operations and sometimes also during the day. Information on the watch/acoustic monitoring period included the time, location, source activity and weather conditions. Sea state was categorised as 'glassy' (equivalent to Beaufort sea states of 0–1), 'slight' (Beaufort sea states 2–3), 'choppy' (Beaufort sea states 4–5) and 'rough' (Beaufort sea states $> = 6$); swell was categorised as 0–2m, 2–4m or > 4m; visibility was categorised as < 1km, 1–5km or > 5km; sun glare was categorised as 'none', 'weak', 'strong' or 'variable'. Information on marine mammal sightings/acoustic detections included species, number of animals, behaviour, closest surface distance of approach to the airguns and the airgun activity at the time of the encounter. Observers most commonly used a rangefinder stick (Heinemann, 1981) to estimate the range to animals but other methods were also used (e.g. reticle binoculars or by relating to an object at a known distance).

All data extracted from MMO reports were subjected to rigorous quality checks (including checks on species identification, source activity corresponding between the different recording forms and consecutive positions being credible given the time interval and speed of the vessel) and only those considered to be of acceptable quality were used in the analysis. Where species descriptions were missing or inadequate or did not correspond with the identification given, identifications were usually down-graded from a single species to a group of similar-looking species, based on the description given. Photographs, where available, were used to confirm identification. Some sighting records did not have associated effort data; approximately 15% of surveys had effort or operational data (the latter were not required for this analysis) that were either missing or discarded due to errors. Sightings without associated effort records were not used when calculating detection rates but were used for other aspects of the analysis. Data of acceptable quality that were used in the analysis corresponded to 1,196 seismic surveys, 91% of which were entirely in UK waters.

Size of airgun arrays

Airgun array volume ranged from 6 cubic inches (in^3) to 10,170 in^3 (only nine surveys used volumes exceeding 5,500 in^3), although precise airgun volumes were not always recorded. Where airgun volume was known, 'small arrays' (total airgun volume less than 500 in^3, e.g. site surveys) were used on 678 surveys (15.9% of monitoring effort) and 'large arrays' (total volume 500 in^3 or more) were used on 500 surveys (84.1% of monitoring effort). Reports from 18 surveys did not provide sufficient information to assign them to either category.

Data analysis

It was considered that if the operation of airguns during seismic surveys had no effect on marine mammals (the null hypothesis) then there would be no difference in the occurrence or behaviour of animals regardless of source activity. Occurrence might be reflected by detection rates per hour (although detection rates may also be influenced by behaviour, e.g. dive duration). Behavioural response was examined by considering clearly defined behaviours and analysing the closest distance of surface approach to the source. The null hypothesis (i.e. airgun operation had no effect) would be rejected if a statistically significant difference in response was found.

As the characteristics of airgun arrays may influence the degree of any response of marine mammals to the sound produced, surveys with 'small arrays' were analysed separately from those with 'large arrays' where possible. Results are presented for individual species where sample size permitted. When this was not possible, groups of combined species were used (e.g. all mysticetes) comprising all identified and unidentified animals within that taxonomic grouping. Combined species groups were more often used for surveys with 'small arrays' than those with 'large arrays', as surveys with 'small arrays' tended to be of short duration so sample sizes were lower. Non-parametric statistical tests were used throughout. In some analyses only small sample sizes were available but, despite this, significant results were still able to be detected with the non-parametric analysis techniques used (Siegel and Castellan, 1988).

Marine mammal responses to the soft start

As soft starts are of relatively short duration (recommended minimum 20 minutes), only a minority (2.6%) of encounters occurred during the soft start, therefore the response to the soft start could only be examined for a few species or species groups. Detection of marine mammals that are present may be influenced by weather (e.g. Hammond *et al.,* 2013), location, season, observer ability and monitoring method (visual or acoustic). Matched samples were used to compare detection rates (number of encounters per hour, an encounter being one or more animals occurring together) at three different source activities (not firing, full power or soft start). Each matched sample comprised three detection rates (one for each of the three source activities) where date, survey, monitoring method, sea state, swell, visibility and sun glare were the same, thus controlling to the extent possible for these variables. Comparing detection rates on the same day of the same survey for each matched sample also controlled for location. PAM data were included but each matched sample contained either only PAM data or only visual data and not both (i.e. a matched sample compared either three acoustic detection rates or three sighting rates). Only survey days when there was effort at all three source activities and where

the other variables matched were used; effort during the soft start was only recorded as distinct from effort at full power from July 2009 onwards, therefore only surveys between July 2009 and December 2010 were used to calculate detection rates per hour. As this was a relatively short time period, sample sizes during the soft start were too small to analyse either 'large arrays' or 'small arrays' separately, therefore arrays of both sizes were analysed together. Small sample sizes also precluded any control for inter-observer variation in ability to detect, although comparing within the same day of the same survey for each matched sample limited the influence of inter-observer variation as on 67% of survey days only one observer was used.

The closest surface distance that marine mammals approached the airguns during the soft start was compared to that at other times. Data from all years (1994–2010) were used as all sightings records distinguished between firing at full power and firing during the soft start. 'Large arrays' were analysed separately from 'small arrays'. Range estimation with PAM can be subject to errors due to factors such as the position of the hydrophone array and the angle of the animal with respect to the array (Von Benda-Beckmann *et al.,* 2013); therefore, only sightings were used (although of course it is recognised that there are also errors in visual range detection). As noted above, weather conditions affect the ability of animals to be detected at distance so only sightings during 'good' weather conditions (defined as 'glassy' or 'slight' sea states, equivalent to Beaufort sea state three or less, swell <2m and visibility >5km) were used. Small sample sizes during the soft start meant that there was no allowance for inter-observer variation in ability to detect animals at distance.

Behaviour was compared using sightings (from all years) where source activity did not change during the course of the encounter (i.e. not firing, full power or soft start). PAM data were not used as behaviour cannot be determined from acoustic detections. 'Large arrays' were analysed separately from 'small arrays'. Only clearly defined behaviours were considered; behaviours more prone to individual interpretation by observers (e.g. fast/slow swimming, frequent/infrequent surfacing, etc.) were not included. Similar behaviours (e.g. avoiding the ship or swimming quickly away) were combined to allow for inter-observer variation in terminology. Confirmation of feeding is difficult but during training, MMOs are taught that behaviours indicative of feeding might include cetaceans being observed with a fish, lunge-feeding in rorqual whales and erratic, fast swimming in dolphins with frequent changes of course and birds diving alongside, etc. Behaviour was also compared between encounters where the soft start commenced while the animals were still visible and those where the airguns were not firing throughout or were performing a soft start throughout; the sample size of encounters where the soft start commenced during the course of the encounter was insufficient to analyse 'large arrays' and 'small arrays' separately so arrays of both sizes were analysed together.

Marine mammal responses to airguns in general
When no distinction was made between firing during the soft start and firing at full power, larger sample sizes permitted examination of a wider range of species and for 'large arrays'

and 'small arrays' always to be analysed separately. Larger sample sizes also allowed for control of the influence of inter-observer variation in ability to detect. Matched pairs were used throughout the whole dataset (1994–2010) to compare detection rates per hour at different source activities (airguns firing versus not firing). For each matched pair (detection rate when firing and detection rate when not firing) the date, survey, monitoring method, observer, sea state, swell and visibility were the same, thereby controlling for these variables. PAM data were included but each matched pair contained either only PAM data or only visual data and not both (i.e. a matched pair compared either two acoustic detection rates or two sighting rates).

Changes in detection rates over time were examined using surveys with 'small arrays', as these corresponded mostly to site surveys where firing occurred within a small area (surveys with 'large arrays' often covered a wide area with temporal variation in the precise location of firing throughout the survey). Only sightings were used as PAM was employed less often on surveys with 'small arrays'. Matched pairs were used to compare detection rates at different stages during each survey; a matched pair comprised a detection rate during the first week of a survey and a detection rate throughout later weeks of the same survey. Only surveys lasting three weeks or longer where firing commenced during the first week were used. The influence of weather was controlled by using only periods of good weather conditions (as defined above).

The closest surface distance that marine mammals approached the airguns was compared between periods when the airguns were firing (at any level) and when they were not firing. Only sightings during good weather conditions (as defined above) were used; acoustic detections were not used due to difficulty in range estimation using PAM. Potential inter-observer variation was controlled for by using sightings by observers with a demonstrated ability to detect marine mammals at distance. An initial examination of data from a small subset of known experienced observers found that a minimum of 20% of detections were more than 1km away. This was applied as a criterion for selecting observers with good detection skills throughout the database, selecting from only those observers who had at least 20 sightings.

Recorded behaviours were compared between periods of firing (at any level) and not firing. Only sightings were used and similar behaviours (e.g. logging or resting at the surface) were combined to allow for inter-observer variation in terminology. PAM data were not used as behaviour was not apparent from acoustic detections.

RESULTS

Survey effort
A total of 190,728 hours were recorded as monitoring for marine mammals (95% visual monitoring and 5% acoustic monitoring), with the airguns firing for 38.8% of the total time spent monitoring. Observations covered 199 quadrants (1° rectangles), with survey effort not evenly distributed either spatially or temporally (Fig. 1). Most effort was in the central and northern North Sea, reflecting the location of geology of interest to the oil and gas industry, and between April and September. There were 9,073 sightings or acoustic detections of marine mammals (Table 1).
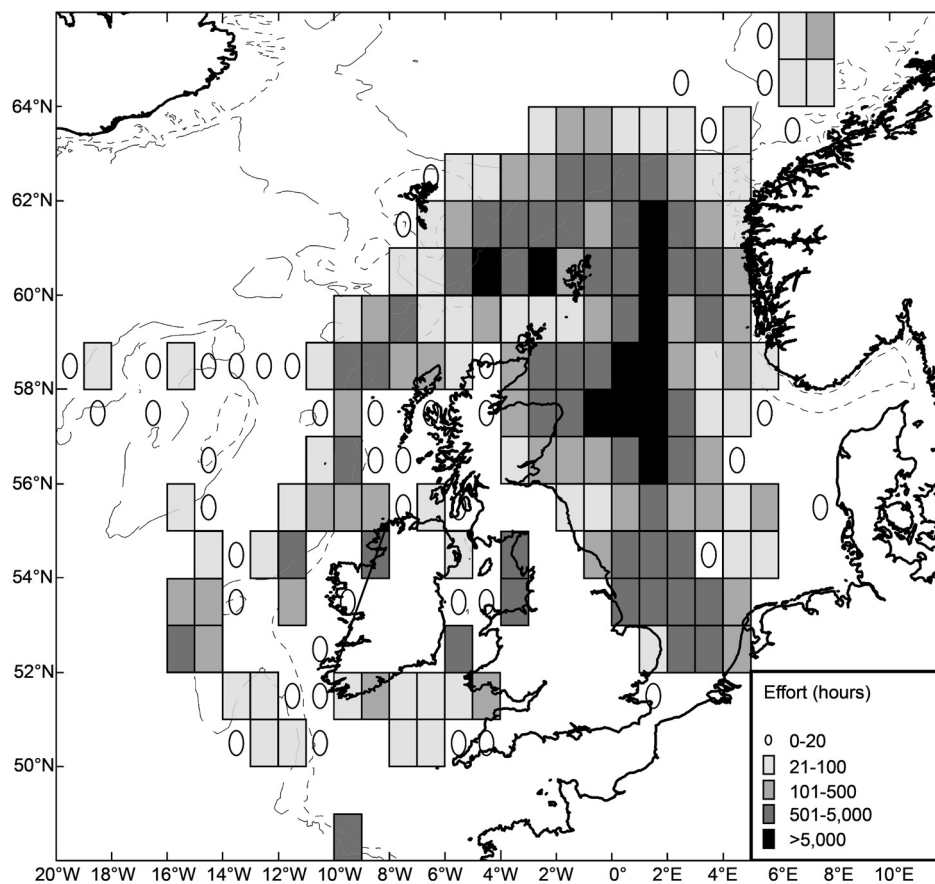
Fig. 1. Effort (hours of visual and acoustic monitoring) during seismic surveys with data available to JNCC between 1994 and 2010 (short dashed line = 200m isobath; long dashed line = 1,000m isobath).

Table 1

Marine mammal encounters during seismic surveys in UK and adjacent waters from 1994–2010 and estimated number of individuals (where number of individuals could not be determined with PAM a minimum number of one was assigned). Encounters with mixed species groups are listed under each species but are only counted once in the totals for each column (though may be included in more than one column if the different species were detected by different means).

Species	No. sightings (and no. of individuals)		No. acoustic detections (and no. of individuals)		No. detections both visual and acoustic (and no. of individuals)	
Seal sp.	92	(122)				
Grey seal (*Halichoerus grypus*)	108	(113)				
Harbour seal (*Phoca vitulina*)	23	(24)				
Cetacean sp.	496	(4,107)	40	(40)	5	(34)
Whale sp.	610	(1,265)			1	(1)
Mysticete sp.	410	(843)			1	(1)
North Atlantic right whale (probable) (*Eubalaena glacialis*)	1	(1)				
Humpback whale (*Megaptera novaeangliae*)	22	(48)				
Blue whale (*Balaenoptera musculus*)	13	(14)				
Fin whale (*Balaenoptera physalus*)	342	(789)				
Sei whale (*Balaenoptera borealis*)	23	(34)				
Minke whale (*Balaenoptera acutorostrata*)	724	(854)				
Sperm whale (*Physeter macrocephalus*)	392	(588)	136	(137)	19	(33)
Beaked whale sp. (*Hyperoodon/Mesoplodon/Ziphius*)	9	(21)				
Northern bottlenose whale (*Hyperoodon ampullatus*)	10	(44)				
Sowerby's beaked whale (*Mesoplodon bidens*)	6	(14)				
Long-finned pilot whale (*Globicephala melas*)	471	(9,104)			14	(217)
Killer whale (*Orcinus orca*)	331	(2,227)			1	(2)
False killer whale (*Pseudorca crassidens*)	1	(7)				
Delphinid sp.	376	(7,210)	9	(9)	6	(1,755)
Dolphin sp. or porpoise	1,305	(19,109)	276	(579)	33	(763)
Risso's dolphin (*Grampus griseus*)	77	(661)			4	(55)
Bottlenose dolphin (*Tursiops truncatus*)	100	(1,329)			1	(20)
White-beaked dolphin (*Lagenorhynchus albirostris*)	1,146	(15,847)			20	(322)
Atlantic white-sided dolphin (*Lagenorhynchus acutus*)	670	(39,801)	4	(4)	53	(6,121)
Common dolphin (*Delphinus delphis*)	304	(7,635)			11	(570)
Striped dolphin (*Stenella coeruleoalba*)	10	(427)				
Harbour porpoise (*Phocoena phocoena*)	396	(969)	138	(144)	5	(10)
Total	**8,302**	**(113,207)**	**603**	**(913)**	**169**	**(9,904)**

Table 2

Marine mammal detection rates in relation to airgun activity (not firing or soft start or full power) for the period July 2009 to December 2010 for all array types. Differences in detection rates were tested using the Friedman two-way analysis of variance by ranks (F_r = Friedman statistic; n = number of three-way matched samples for detection rates at the different source activities where other conditions were the same). The null hypothesis is that there is no difference in detection rates at different source activities. Significant differences are shown in bold.

Species	Median detection rate per hour (+ 1st and 3rd quartiles)									F_r	n	p-value
	Not firing			Soft start			Full power					
All cetaceans combined	0.00	0.22	0.39	0.00	0.00	0.00	0.00	0.00	0.28	36.873	723	**< 0.001**
All mysticetes combined	0.00	0.26	0.61	0.00	0.00	0.00	0.00	0.07	0.52	11.438	723	**< 0.01**
Minke whale	0.00	0.37	0.71	0.00	0.00	0.00	0.00	0.20	0.42	6.077	723	**< 0.05**
All delphinids combined	0.00	0.20	0.31	0.00	0.00	0.00	0.00	0.00	0.25	18.919	723	**< 0.001**
White-beaked dolphin	0.13	0.21	0.43	0.00	0.00	0.00	0.00	0.00	0.00	20.000	723	**< 0.001**
Atlantic white-sided dolphin	0.07	0.22	0.26	0.00	0.00	0.00	0.00	0.00	0.12	10.500	723	**< 0.01**

Table 3

Multiple comparisons of treatments comparing marine mammal detection rates during the soft start with those at other times for the period July 2009 to December 2010 for all array types. Differences in detection rates were tested using the Wilcoxon signed ranks test (T^+ = sum of ranks of matched pairs where detection rate when not firing/at full power exceeded detection rate during the soft start [T^+ increases as detection rates when not firing/at full power exceed detection rates during the soft start more often and/or by a greater amount]; z = statistic for large samples; n = number of matched pairs of detection rates at different source activities when other conditions were the same). The null hypothesis is that there is no difference in detection rates at different source activities. Significant differences are shown in bold.

Species	Median detection rate per hour (+ 1st and 3rd quartiles)									
Not firing *vs* soft start	Not firing			Soft start			T^+	z	n	p-value
All cetaceans combined	0.19	0.27	0.49	0.00	0.00	0.00	1,289	3.675	57	**< 0.001**
All mysticetes combined	0.26	0.57	0.85	0.00	0.00	0.00	55	–	10	**0.001**
Minke whale	0.37	0.58	1.22	0.00	0.00	0.00	15	–	5	**0.031**
All delphinids combined	0.16	0.24	0.35	0.00	0.00	0.00	635	2.651	41	**0.004**
White-beaked dolphin	0.13	0.21	0.43	0.00	0.00	0.00	55	–	10	**0.001**
Atlantic white-sided dolphin	0.20	0.24	0.27	0.00	0.00	0.00	45	–	9	**0.002**
Full power *vs* soft start	Full power			Soft start						
All cetaceans combined	0.13	0.32	0.57	0.00	0.00	0.00	373.5	−1.301	34	0.097
All mysticetes combined	0.20	0.42	0.56	0.00	0.00	0.00	36	–	8	**0.004**
Minke whale	0.20	0.32	0.57	0.00	0.00	0.00	15	–	5	**0.031**
All delphinids combined	0.06	0.33	0.57	0.00	0.00	0.56	168.5	−0.530	24	0.298
White-beaked dolphin		–			–		–	–	0	–
Atlantic white-sided dolphin	0.23	0.57	0.64	0.00	0.00	0.00	6	–	3	0.125

Marine mammal responses to the soft start

All species/species groups able to be tested showed that detection rates differed significantly with source activity (Table 2). Subsequent multiple comparisons of treatments showed that for all species/species groups, detection rates were significantly lower during the soft start than when the airguns were not firing (Table 3). Detection rates were also significantly lower during the soft start than when the airguns were firing at full power for all mysticetes combined and the common minke whale (*Balaenoptera acutorostrata*) (Table 3).

The closest surface distance that marine mammals approached the airguns differed significantly with source activity on surveys with 'large arrays' for the majority of species or species groups tested with the exception of the common minke whale (Table 4; Fig. 2). Multiple comparisons of treatments showed that for all species or species groups where there was a significant difference, animals were significantly further from the airguns when they were firing at full power than when they were not firing but the closest surface distance during the soft start did not differ significantly from the closest surface distance at other times. There was no significant difference in the closest surface distance of approach of cetaceans (all species combined) with source activity for 'small arrays' (Table 4; Fig. 2).

With both 'large arrays' and 'small arrays', all species and species groups tested showed a reduced tendency to engage in positive interactions with the survey vessel or its equipment (e.g. bow-riding, approaching close to the vessel) or to travel towards the vessel during the soft start compared with when the airguns were not firing; a further reduction was detected when the airguns were firing at full power (Table 5). All species groups that could be tested showed an increased tendency to avoid or travel away from the vessel during the soft start of 'large arrays' than at any other time (Table 5). A reduction in observed feeding in all cetaceans combined was apparent when 'large arrays' were firing at full power but there was little difference in observed feeding between periods when 'large arrays' were not firing and the soft start (Table 5).

There were 84 encounters when marine mammals were present both prior to and during the soft start. On 15 of those encounters (18%), responses were observed concurrent with the soft start commencing that could constitute a startle response (e.g. alteration of course to avoid the vessel, a relative increase in swimming speed, diving, resurfacing, leaping, porpoising, spy-hopping and raising tail flukes). There was only one occasion where animals (*Lagenorhynchus sp.*) that initially moved away at the onset of the soft start subsequently re-approached. There was variation in observed

Table 4

Closest distance of approach of marine mammals to the airguns during the soft start compared to at other times. Differences were tested using the Kruskal-Wallis one-way analysis of variance by ranks (KW = Kruskal-Wallis statistic; degrees of freedom = 2 in all cases; n = number of sightings where closest distance was recorded). The null hypothesis is that there is no difference in how close animals approach the airguns at different source activities. Significant differences are shown in bold.

| Species	Median closest distance (m)			KW	n	p-value
	Not firing	Soft start	Full power			
'Large arrays'						
All cetaceans combined	900	1,000	1,500	82.183	2,927	**< 0.001**
All mysticetes combined	800	800	1,500	20.898	613	**< 0.001**
Minke whale	700	625	1,000	5.965	342	< 0.100
All delphinids combined	800	1,200	1,400	42.615	1,682	**< 0.001**
Lagenorhynchus spp.	500	700	1,000	62.672	721	**< 0.001**
White-beaked dolphin	450	600	1,500	44.825	391	**< 0.001**
Atlantic white-sided dolphin	500	750	800	18.045	263	**< 0.001**
'Small arrays'						
All cetaceans combined	600	1,100	500	4.061	296	< 0.200
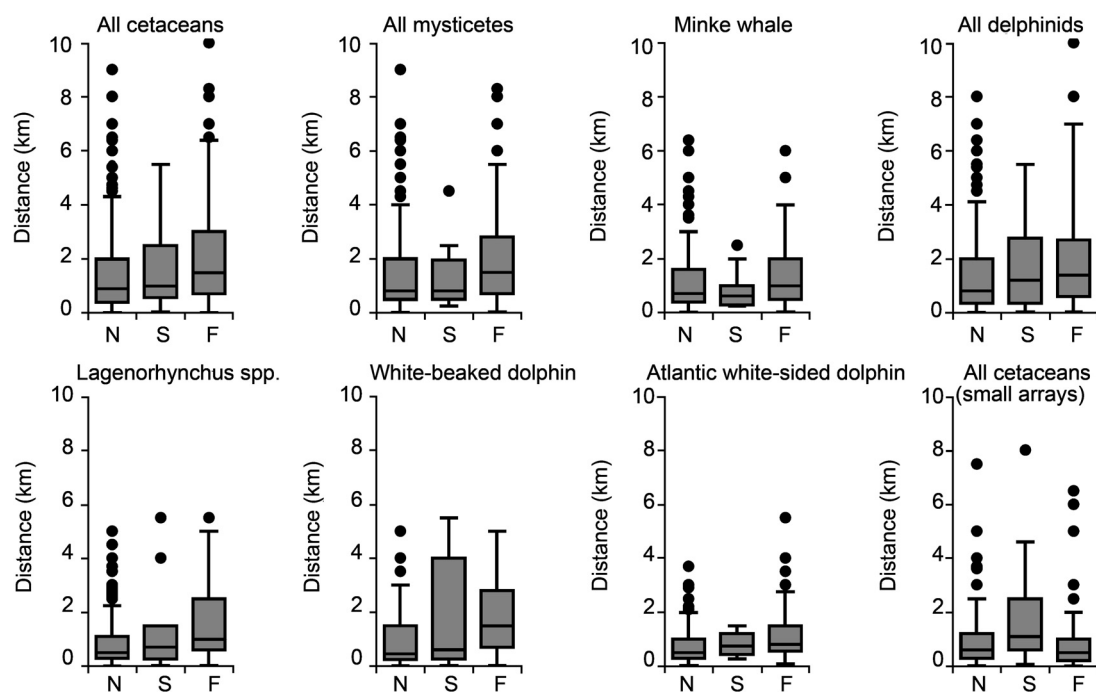
Fig. 2. Box-and-whisker plots of closest distance of approach to the airguns ('large arrays' unless otherwise stated) during the soft start compared to at other times (N = not firing; S = soft start; F = full power). Boxes show median, 1st and 3rd quartiles, whiskers denote range excepting outliers and dots show outliers (> 1.5 × interquartile range outside the 1st or 3rd quartile).

responses between individuals of the same species, e.g. one sperm whale (*Physeter macrocephalus*) dived when the soft start commenced while on another occasion a sperm whale that had recently dived resurfaced and proceeded to swim at speed along the surface. Diving was the only behaviour where sample sizes enabled comparison between encounters where (1) the airguns were not firing throughout (2) were performing a soft start throughout or (3) where the soft start commenced during the course of the encounter. More cetaceans were observed to dive if the soft start commenced during the encounter (Table 6).

Marine mammal responses to airguns in general
A significant reduction in detection rates was evident (Table 7) when 'large arrays' were firing for the grey seal (*Halichoerus grypus*), common minke whale, all beaked whales combined, killer whale (*Orcinus orca*), white-beaked

dolphin (*Lagenorhynchus albirostris*), Atlantic white-sided dolphin (*Lagenorhynchus acutus*) and harbour porpoise (*Phocoena phocoena*). When 'small arrays' were firing detection rates of sperm whales and harbour porpoises were significantly lower (Table 7). Most surveys with 'small arrays' were of short duration, but on those that were prolonged (three weeks or more) detection rates of delphinids decreased significantly after the first week (Table 8).

The approach to 'large arrays' was significantly closer when the airguns were not firing for all mysticetes combined although not for fin (*Balaenoptera physalus*) or common minke whales individually, as well as for killer whales, bottlenose dolphins (*Tursiops truncatus*), white-beaked dolphins, Atlantic white-sided dolphins and the harbour porpoise (Table 9; Fig. 3). The difference in the median closest estimated distance of surface approach between firing

Table 5

Behaviour of marine mammals during the soft start compared to at other times. Differences were tested using the chi-squared test (degrees of freedom = 2 in all cases; *n* = number of sightings where the behaviour was exhibited). The null hypothesis is that there is no difference in behaviour at different source activities. Significant differences are shown in bold.

Behaviour and species	% encounters when behaviour exhibited			χ^2	*n*	p-value
	Not firing	Soft start	Full power			
'Large arrays'						
Avoidance or travel away from vessel						
All cetaceans combined	10.0	20.5	17.9	88.25	975	**< 0.001**
All delphinids combined	8.3	18.5	16.4	61.72	484	**< 0.001**
Lagenorhynchus spp.	7.7	24.5	16.9	35.68	186	**< 0.001**
Dived						
All cetaceans combined	5.3	8.5	6.0	3.82	432	< 0.20
Feeding						
All cetaceans combined	9.4	9.1	7.1	9.89	669	**< 0.01**
All delphinids combined	13.1	11.1	11.1	2.82	555	< 0.30
Lagenorhynchus spp.	14.4	12.2	15.1	0.28	257	< 0.90
Positive interactions or travel towards the vessel						
All cetaceans combined	13.5	10.2	6.7	66.92	873	**< 0.001**
All delphinids combined	18.9	12.0	9.2	54.51	710	**< 0.001**
Lagenorhynchus spp.	27.3	18.4	9.2	39.71	404	**< 0.001**
White-beaked dolphin	36.9	26.9	13.3	32.65	314	**< 0.001**
'Small arrays'						
Positive interactions or travel towards the vessel						
All cetaceans combined	25.4	12.0	9.0	18.93	227	**< 0.001**

Table 6

Behaviour of marine mammals in relation to whether the soft start commenced during the encounter or not (all array types). Differences were tested using the chi-squared test (degrees of freedom = 2; *n* = number of sightings where animals dived). The null hypothesis is that there is no difference in behaviour if the soft start commences during the encounter compared to at other times. Significant differences are shown in bold.

Behaviour and species	% encounters when behaviour exhibited			χ^2	*n*	p-value
	Encounters while not firing	Encounters during which the soft start commenced	Encounters wholly during the soft start			
Dived						
All cetaceans combined	5.7	10.3	9.0	6.67	358	**< 0.05**

and not firing ranged between 300m (Atlantic white-sided dolphin) and 1,500m (bottlenose dolphin). Conversely, mysticetes (all species combined) approached significantly closer to 'small arrays' when they were firing (Table 9; Fig. 3), with the median distance being over 1km further away when the airguns were not firing.

Firing of 'large arrays' affected the movement of cetaceans around the vessel (Table 10). Long-finned pilot whales (*Globicephala melas*), white-beaked dolphins and the combined group of all delphinids engaged in positive interactions with the vessel or its equipment (e.g. bow-riding etc.) or travelled towards the vessel more often when the airguns were silent. On surveys with 'large arrays', significantly more pods of fin whales, common minke whales, long-finned pilot whales, white-beaked dolphins, Atlantic white-sided dolphins and harbour porpoises avoided or travelled away from the vessel during periods when the airguns were firing compared to when they were not firing.

Effects on surfacing/diving behaviours were also apparent, with some cetacean groups remaining close to the water surface when 'large arrays' were active (Table 10). For example, during periods of firing a greater proportion of cetaceans (all species combined) were logging or apparently resting at the surface, whilst milling, where animals continue to surface in the same general vicinity, was more prevalent in mysticetes (all species combined). Delphinids (all species combined) were more often recorded both as diving and logging/ resting at the surface during periods of firing. However, there were no significant differences in surfacing/ diving behaviour for individual species.

Several cetacean species were observed feeding less often when 'large arrays' were firing. Whilst the difference was not statistically significant for individual species, where sample sizes were relatively small, it was significant when all cetaceans were combined (Table 10).

Fewer effects on behaviour were evident with 'small arrays'. When species were combined, it was apparent that positive interactions with the vessel or its equipment or travel towards the vessel occurred more often when the airguns were not firing, while avoidance or travel away was more prevalent when the airguns were firing (Table 10).

DISCUSSION
Use of one of the largest existing datasets of MMO observations of marine mammals during seismic surveys allowed a more thorough examination of the response of marine mammals to seismic surveys in UK waters than has previously been possible (Stone, 2006; Stone and Tasker, 2006). However, it is difficult to infer with certainty the mechanism underlying the observed responses. While

Table 7

Marine mammal detection rates in relation to airgun activity (firing or not firing). Differences in detection rates were tested using the Wilcoxon signed ranks test (T^+ = sum of ranks of matched pairs where detection rate when not firing exceeded detection rate when firing [T^+ increases as detection rates when not firing exceed detection rates when firing more often and/ or by a greater amount]; z = statistic for large samples; n = number of matched pairs of detection rates for active and inactive airguns where other conditions were the same). The null hypothesis is that there is no difference in detection rates whether the source is active or not. Significant differences are shown in bold.

Species	Median detection rate per hour (+ 1st and 3rd quartiles)						T^+	z	n	p-value
	Not firing			Firing						
'Large arrays'										
Grey seal	*0.10*	0.16	*0.34*	*0.00*	0.00	*0.05*	521	2.956	36	**0.002**
Harbour seal	*0.00*	0.07	*0.25*	*0.00*	0.07	*0.10*	25	–	9	0.410
Humpback whale	*0.00*	0.00	*0.22*	*0.00*	0.09	*0.11*	16	–	7	0.406
Fin whale	*0.00*	0.06	*0.19*	*0.00*	0.09	*0.25*	2,543	–0.444	103	0.330
Sei whale	*0.00*	0.03	*0.18*	*0.00*	0.03	*0.17*	39	–	12	0.515
Minke whale	*0.00*	0.13	*0.25*	*0.00*	0.00	*0.19*	24,027.5	3.093	281	**0.001**
Sperm whale	*0.00*	0.11	*0.29*	*0.00*	0.08	*0.18*	3,947.5	1.528	116	0.063
All beaked whales	*0.21*	0.25	*0.28*	*0.00*	0.00	*0.00*	27	–	7	**0.016**
Long-finned pilot whale	*0.00*	0.00	*0.21*	*0.00*	0.08	*0.16*	4,329.5	0.639	127	0.261
Killer whale	*0.00*	0.15	*0.24*	*0.00*	0.00	*0.13*	3,531.5	2.808	103	**0.003**
Risso's dolphin	*0.00*	0.14	*0.36*	*0.00*	0.00	*0.28*	301	1.039	31	0.149
Bottlenose dolphin	*0.00*	0.09	*0.24*	*0.00*	0.08	*0.15*	308	1.176	31	0.119
White-beaked dolphin	*0.00*	0.19	*0.34*	*0.00*	0.00	*0.16*	57,223	7.061	403	**< 0.001**
Atlantic white-sided dolphin	*0.00*	0.13	*0.25*	*0.00*	0.00	*0.20*	26,533.5	3.208	295	**< 0.001**
Common dolphin	*0.00*	0.14	*0.22*	*0.00*	0.00	*0.17*	484	1.312	39	0.152
Harbour porpoise	*0.16*	0.27	*0.43*	*0.00*	0.00	*0.00*	4,278	8.330	92	**< 0.001**
'Small arrays'										
All seals combined	*0.00*	0.00	*0.11*	*0.00*	0.18	*0.37*	5	–	7	0.078
All mysticetes combined	*0.00*	0.00	*0.16*	*0.00*	0.13	*0.24*	196	–1.272	32	0.102
Minke whale	*0.00*	0.00	*0.21*	*0.00*	0.06	*0.19*	103	0.322	19	0.375
Sperm whale	*0.14*	0.17	*0.31*	*0.00*	0.00	*0.00*	114	–	15	**< 0.001**
All delphinids combined	*0.00*	0.15	*0.33*	*0.00*	0.07	*0.23*	3,810	1.419	116	0.078
Long-finned pilot whale	*0.12*	0.26	*0.55*	*0.00*	0.00	*0.31*	29	–	9	0.248
White-beaked dolphin	*0.00*	0.13	*0.28*	*0.00*	0.00	*0.23*	93	0.327	18	0.371
Atlantic white-sided dolphin	*0.00*	0.14	*0.24*	*0.00*	0.00	*0.17*	397	0.687	37	0.245
Common dolphin	*0.00*	0.23	*0.32*	*0.00*	0.21	*0.55*	10	–	6	0.500
Harbour porpoise	*0.18*	0.44	*0.78*	*0.00*	0.00	*0.00*	21	–	6	**0.016**

Table 8

Marine mammal detection rates during the first and later weeks of seismic surveys with 'small arrays'. Differences in detection rates were tested using the Wilcoxon signed ranks test (T^+ = sum of ranks of matched pairs where detection rate during week one exceeded that of later weeks [T^+ increases as detection rates during week one exceed detection rates during later weeks more often and/or by a greater amount]; n = number of matched pairs of detection rates for the first and later weeks of each survey). The null hypothesis is that there is no difference in detection rates as surveys progress. Significant differences are shown in bold.

Species	Median detection rate per hour (+ 1st and 3rd quartiles)						T^+	n	p-value
	Week 1			Later weeks					
All cetaceans combined	*0.02*	0.11	*0.29*	*0.00*	0.02	*0.16*	39	10	0.138
All mysticetes combined	*0.01*	0.02	*0.10*	*0.00*	0.00	*0.03*	11	5	0.219
All delphinids combined	*0.03*	0.10	*0.15*	*0.00*	0.00	*0.05*	31	8	**0.039**
Harbour porpoise	*0.00*	0.01	*0.09*	*0.00*	0.00	*0.00*	11	5	0.219

displacement of animals might be the most likely explanation for reduced detection rates (particularly when combined with increased travel directed away from the vessel), other explanations are also possible. A reduced sighting rate could be a result of longer dive durations, while a reduced acoustic detection rate could result from a reduction in vocalisations. Nevertheless, whatever the underlying mechanism, the results provide clear evidence of responses to the operation of seismic airguns.

Whether the soft start is an effective mitigation measure has been long identified as a key question of interest (e.g. Barton *et al.,* 2008). All species or species groups tested had reduced detection rates during the soft start compared to when the airguns were not firing. All also showed an increased tendency to avoid or travel away from the vessel during soft starts of 'large arrays'. These responses suggest that the soft start can be a useful mitigation tool, causing some marine mammals to move away from the immediate vicinity of airguns before full power is reached, helping to reduce exposure to high levels of sound. Movement directed away from the source can only reduce exposure levels if the avoidance speed of the animal is much greater than the approach speed of the source (Von Benda-Beckmann *et al.,* 2014); seismic survey vessels typically travel at relatively
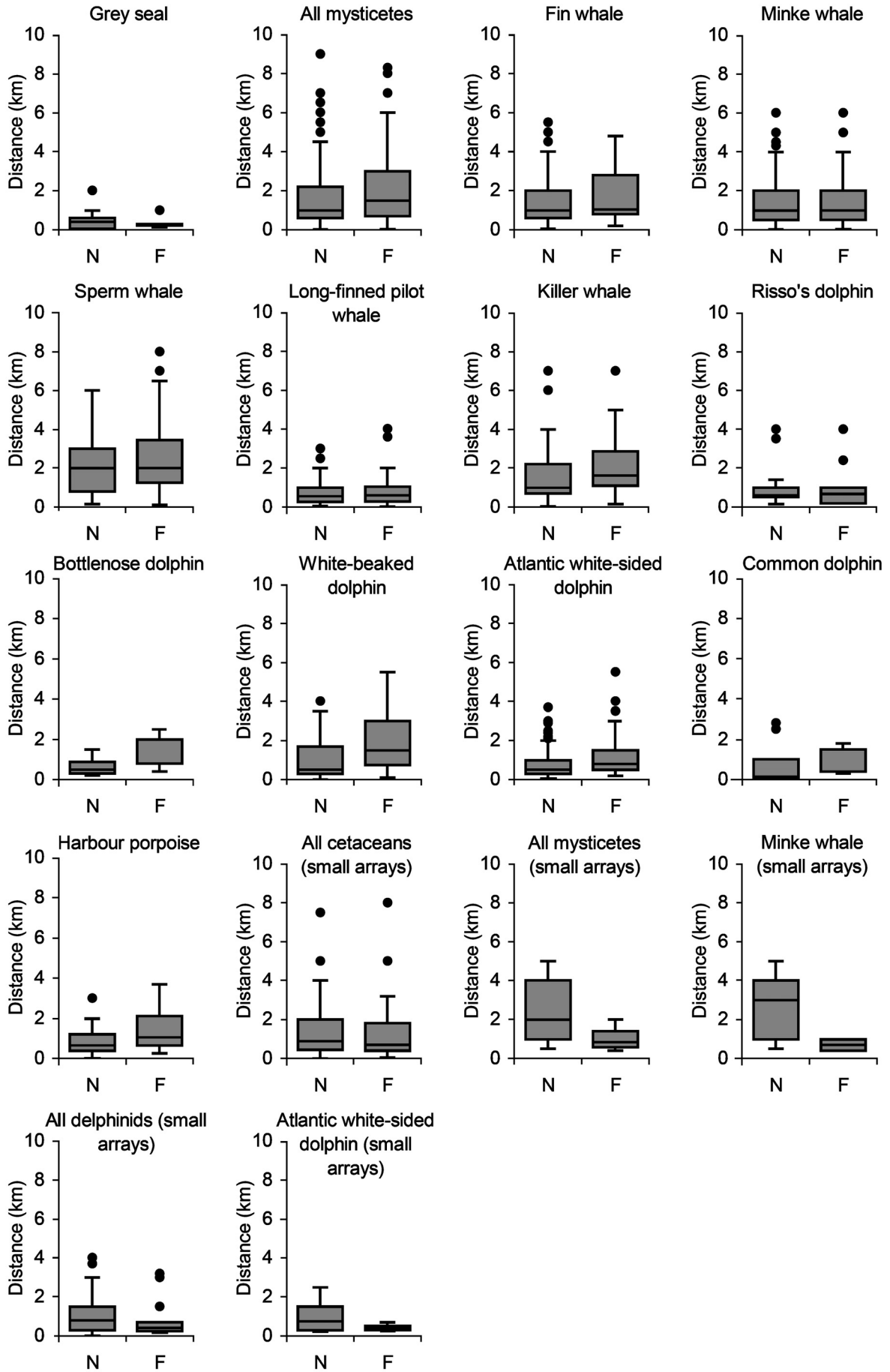
Fig. 3. Box-and-whisker plots of closest distance of approach to the airguns ('large arrays' unless otherwise stated) relative to airgun activity (N = not firing; F = firing). Boxes show median, 1st and 3rd quartiles, whiskers denote range excepting outliers and dots show outliers (> 1.5 × interquartile range outside the 1st or 3rd quartile).

Table 9

Closest distance of approach of marine mammals to the airguns in relation to airgun activity (firing or not firing). Differences were tested using the Wilcoxon-Mann-Whitney test (n = number of sightings where closest distance was recorded). The null hypothesis is that there is no difference in how close animals approach the airguns whether the source is active or not. Significant differences are shown in bold.

Species	Median closest distance (m)		z	n	p-value
	Not firing	Firing			
'Large arrays'					
Grey seal	400	275	0.000	27	0.500
All mysticetes combined	1,000	1,500	9.283	477	**< 0.001**
Fin whale	1,000	1,225	1.382	107	0.084
Minke whale	1,000	1,000	0.813	248	0.209
Sperm whale	2,000	2,000	0.953	111	0.171
Long-finned pilot whale	550	600	0.439	79	0.330
Killer whale	1,000	1,625	2.099	81	**0.018**
Risso's dolphin	600	675	−0.281	23	0.390
Bottlenose dolphin	500	2,000	−1.799	12	**0.036**
White-beaked dolphin	500	1,500	6.075	302	**< 0.001**
Atlantic white-sided dolphin	500	800	3.133	213	**< 0.001**
Common dolphin	150	1,500	1.420	16	0.078
Harbour porpoise	650	1,050	3.065	126	**0.001**
'Small arrays'					
All cetaceans combined	900	700	−0.953	136	0.171
All mysticetes combined	2,000	850	−2.311	25	**0.010**
Minke whale	3,000	700	−0.187	14	0.425
All delphinids combined	700	400	−0.428	66	0.334
Atlantic white-sided dolphin	750	400	−0.147	18	0.440

low speeds (around 4–5 knots) therefore movement away from the source may be effective at reducing exposure to sound from seismic airguns. However, not all individuals travelled away from the vessel during the soft start procedure, highlighting the need to continue to monitor for marine mammals prior to commencing firing airguns, with subsequent delay of firing if marine mammals are detected within the defined mitigation zone. When animals are undetected, the soft start may offer protection to some by causing them to move out of the vicinity of the airguns before full power is reached.

Although the results showed a high level of agreement in the response to the soft start between the species and species groups tested, only a few individual species were tested due to data availability. Caution should thus be exercised as sample sizes were small and another species may respond differently. Nothing is known, for example, about the effectiveness of the soft start for sensitive species such as beaked whales (Barlow and Gisiner, 2006). Moulton and Holst (2010) suggested that the effectiveness of the soft start varies with species and probably circumstances; in the north-west Atlantic they found mysticetes responded to the soft start but, in contrast to the present study, found no response in delphinids or toothed whales. Weir (2008b) observed that a single pod of short-finned pilot whales (*Globicephala macrorhynchus*) initially moved away during a soft start but then changed to milling at the surface, although it was noted that this might represent vertical avoidance. Whilst much can be gained from noise modelling set in the context of assumed response thresholds (Hannay *et al.,* 2011; Von Benda-Beckmann *et al.,* 2014), this needs to be supported by detailed studies on the actual response of marine mammals to the soft start procedure. Von Benda-Beckmann *et al.* (2014) noted that critical research questions that need addressing are documentation of avoidance strategies,

behavioural context and estimates of sound dosage that predicts the onset of an avoidance response for different sound types.

The 16-year dataset allowed the response of beaked whales in UK waters to be examined for the first time, although sample size was low (n = 7). For all but one pair of observations, detection rates were lower when 'large arrays' were active, whereas previously there has been little evidence that beaked whales respond overtly to the noise from seismic airguns (Moulton and Holst, 2010). Beaked whales are known to be sensitive to other anthropogenic noise, with cases of mass strandings related to the use of military mid-range frequency sonar (Balcomb and Claridge, 2001; Cox *et al.,* 2006; Evans and England, 2001; Fernández *et al.,* 2005). Southall *et al.* (2007) suggested adopting provisional injury criteria for beaked whales exposed to military sonar at lower levels than for other mid frequency cetaceans. Mid-range frequency sonar uses frequencies of around 3–8kHz (Evans and England, 2001; Tyack *et al.,* 2011), higher than those predominantly produced by airguns (up to about 200Hz: Gausland, 2001; Gulland and Walker, 2001), and has a very long signal duration compared with seismic shots, so it is not necessarily directly comparable. More research is needed to understand the effects of seismic surveys on all species but especially beaked whale species.

Greater responses were observed in mysticetes than had been noted previously in UK waters. Previously, only localised avoidance was evident for all mysticetes combined (Stone and Tasker, 2006), with no significant effects of airgun activity observed for any individual species. The present study revealed responses of common minke whales and fin whales when 'large arrays' were active. The frequency and sound source level of the airguns used on seismic surveys in UK waters were often not recorded, but from available information 'large arrays' produce

Table 10

Behaviour of marine mammals in relation to airgun activity (firing or not firing). Differences were tested using the chi-squared test (n = number of sightings where the behaviour was exhibited). The null hypothesis is that there is no difference in behaviour whether the source is active or not. Significant differences are shown in bold.

Behaviour	% encounters when behaviour exhibited				
Species	Not firing	Firing	χ^2	n	p-value
'Large arrays'					
Avoidance or travel away from vessel/equipment					
Fin whale	14.6	24.3	3.95	61	**< 0.05**
Minke whale	8.2	16.3	8.44	70	**< 0.01**
Sperm whale	18.7	19.7	0.05	68	< 0.90
Long-finned pilot whale	5.1	13.9	9.49	41	**< 0.01**
Killer whale	11.9	18.1	1.70	41	< 0.20
White-beaked dolphin	8.2	19.2	22.24	115	**< 0.001**
Atlantic white-sided dolphin	6.3	12.2	5.80	51	**< 0.05**
Harbour porpoise	20.0	37.5	7.78	82	**< 0.01**
Diving					
Fin whale	11.2	12.5	0.11	38	< 0.80
Minke whale	10.4	7.0	1.77	59	< 0.20
Sperm whale	50.0	43.0	0.90	168	< 0.50
All delphinids combined	1.4	2.2	4.10	75	**< 0.05**
Feeding					
All cetaceans combined	10.3	8.2	7.85	706	**< 0.01**
Fin whale	12.9	9.7	0.71	37	< 0.50
Long-finned pilot whale	8.0	6.3	0.48	32	< 0.50
Killer whale	26.5	16.9	2.34	72	< 0.20
White-beaked dolphin	11.1	12.3	0.28	118	< 0.70
Atlantic white-sided dolphin	23.4	19.9	0.73	139	< 0.50
Logging/resting at surface					
All cetaceans combined	2.6	3.7	6.81	216	**< 0.01**
Sperm whale	29.9	35.9	0.95	115	< 0.50
All delphinids combined	1.3	2.1	4.18	72	**< 0.05**
Long-finned pilot whale	8.9	8.7	0.01	39	< 0.95
Milling					
All mysticetes combined	0.7	3.0	10.16	22	**< 0.001**
Lagenorhynchus spp.	3.1	2.5	0.43	53	< 0.70
White-beaked dolphin	3.2	2.5	0.26	31	< 0.70
Positive interactions or travel towards vessel/equipment					
All mysticetes combined	6.1	3.9	3.22	72	< 0.10
Minke whale	6.8	6.1	0.13	42	< 0.80
All delphinids combined	18.1	9.5	47.60	725	**< 0.001**
Long-finned pilot whale	27.0	15.4	6.93	96	**< 0.01**
White-beaked dolphin	37.1	15.2	31.02	324	**< 0.001**
Atlantic white-sided dolphin	13.1	7.7	3.48	71	< 0.10
Common dolphin	25.7	23.3	0.06	63	< 0.90
'Small arrays'					
Avoidance or travel away from vessel/equipment					
All cetaceans combined	8.7	18.0	12.42	103	**< 0.001**
All delphinids combined	6.7	17.3	11.27	51	**< 0.001**
Diving					
All cetaceans combined	7.2	6.6	0.09	70	< 0.80
Feeding					
All cetaceans combined	9.2	8.2	0.16	89	< 0.70
All delphinids combined	9.4	12.5	0.86	59	< 0.50
Positive interactions or travel towards vessel/equipment					
All cetaceans combined	26.2	11.5	13.84	232	**< 0.001**
All delphinids combined	36.1	11.6	16.35	190	**< 0.001**
Lagenorhynchus spp.	49.5	16.3	8.94	105	**< 0.01**
White-beaked dolphin	67.0	46.7	0.84	84	< 0.50

frequencies predominantly up to around 200Hz with a source level of around 262dBpk–pk re. 1µPa @ 1m and 'small arrays' produce frequencies predominantly up to around 250Hz with a source level of around 241dBpk–pk re. 1µPa @ 1m. Mysticetes are in a low frequency hearing group, estimated to have functional hearing within the range 7Hz to 22kHz (Southall *et al.,* 2007), so airgun sound would be clearly audible to them. The present results correspond more closely to studies elsewhere, where seismic operations have resulted in localised avoidance by common minke whales in the northwest Atlantic (Moulton and Holst, 2010) and a change in vocalisations and some evidence of displacement of fin whales in the western Mediterranean Sea and adjacent waters (Castellote *et al.,* 2012). In the present study, no responses were observed in either humpback whales (*Megaptera novaeangliae*) or sei whales (*Balaenoptera borealis*), although sample sizes were low. Elsewhere avoidance of seismic survey vessels has been demonstrated

for humpback whales (McCauley *et al.,* 1998, 2000; Moulton and Holst, 2010) as well as other mysticetes (e.g. Ljungblad *et al.,* 1988; Richardson and Greene 1993; Richardson *et al.,* 1986, 1999; Yazvenko *et al.,* 2007).

Odontocetes hear best at frequencies above those at which the peak energy from seismic airguns is produced, although seismic airguns also emit higher frequency sounds that would be audible to odontocetes (De Ruiter *et al.,* 2006; Goold and Fish 1998; Madsen *et al.,* 2006; Potter *et al.,* 2007). Most odontocetes belong to a mid-frequency hearing group with functional hearing from about 150Hz to 160kHz, while porpoises belong to a high frequency hearing group with functional hearing between 200Hz and 180kHz (Southall *et al.,* 2007). As most of the energy from seismic airguns is at lower frequencies it is often assumed that mysticetes would be the cetaceans most vulnerable to disturbance from the sound of seismic airguns. Although some odontocetes showed no response, such as the common dolphin (*Delphinus delphis*) and the Risso's dolphin (*Grampus griseus*), in the present study, most mid frequency odontocetes tested and harbour porpoises showed some response to 'large arrays'. In some cases, the response was greater than found previously; killer whales and harbour porpoises had previously been found not to approach so close to airguns when they were active (Stone and Tasker, 2006), but in the present study reduced detection rates were also found. In other cases (white-beaked dolphins, Atlantic white-sided dolphins, bottlenose dolphins and long-finned pilot whales) the present results confirmed previous results (Stone and Tasker, 2006). Similar responses of small or medium-sized odontocetes to noise from seismic airguns have also been observed elsewhere (Barkaszi *et al.,* 2012; Weir 2008a). The present results therefore confirm previous studies showing that the response of cetacean species to noise from seismic airguns does not necessarily correlate with what might be expected based solely on their hearing abilities. It could be that the responses are driven not only by the ability to hear the sound but also by how the sound is perceived; for example, animals may avoid sounds that they might interpret as indicating the presence of predators, to which smaller species may be more vulnerable.

Previous analysis of UK MMO data was limited to cetaceans (Stone and Tasker, 2006) but the larger dataset also allowed investigation of the responses of pinnipeds. Detection rates of grey seals were significantly reduced when 'large arrays' were active. In Alaska, pinnipeds such as ringed seals (*Pusa hispida*) have shown minor avoidance during seismic operations (Harris *et al.,* 2001).

The larger dataset also allowed the effects of 'small arrays' to be tested on more species. Previously a change in orientation had been noted for Atlantic white-sided dolphins and reduced detection rates found for all small odontocetes combined (Stone and Tasker, 2006). In the present study, detection rates of sperm whales (n = 15) and harbour porpoises (n = 6) were reduced when 'small arrays' were active, while mysticetes did not show any negative response. Although responses were fewer than with 'large arrays', it is appropriate that some form of mitigation continues to be applied to surveys using 'small arrays'. Sub-bottom profilers (e.g. boomers, pingers and sparkers, with frequencies ranging from 700Hz to 12kHz) are used on some surveys with 'small arrays', but not at the same time as airguns. Any response to the use of sub-bottom profilers during some periods when airguns were not firing could have reduced the statistical significance of any response during periods when the airguns were firing. Detailed records of the operation of sub-bottom profilers were not kept, but they were only used during some of the times when the airguns were not firing. Recording the operation of such equipment would enable future studies to examine any response of marine mammals to their use.

The harbour porpoise was the only species with lower detection rates for both 'large arrays' and 'small arrays', suggesting an increased sensitivity to airgun noise compared to other species. Previous results found only that harbour porpoises tended not to approach so close to 'large arrays' when they were active (Stone and Tasker, 2006). However, the current results are in line with other studies, both field and experimental observations, which all seem to suggest that this species is highly sensitive to underwater noise. For example, a single captive harbour porpoise exposed to noise from a seismic airgun exhibited aversive behavioural responses at received sound pressure levels above 174dBpk–pk re. 1µPa and a masked temporary threshold shift level of 199.7dBpk–pk re. 1µPa, lower than for other odontocetes (Lucke *et al.,* 2009). It seems likely that received levels of sound from the arrays of airguns used in surveys, even 'small' arrays, would be sufficient to elicit a response in harbour porpoises within the vicinity of arrays. Seismic operations within the Moray Firth (UK) using a relatively small array (470in^3) resulted in short-term avoidance by harbour porpoises at received sound pressure levels of 165–172dBpk–pk re. 1µPa, these levels being found at 5–10km from the source, although animals were typically detected again within a few hours and there were indications of possible habituation or tolerance as the survey progressed (Thompson *et al.,* 2013). Nevertheless, those porpoises remaining within the Moray Firth area did reduce their buzzing activity that relates to prey capture or social communication (Pirotta *et al.,* 2014).

On surveys with 'small arrays', where operations were typically concentrated within a small area, detection rates of delphinids decreased significantly after the first week of operations, although sample sizes were low (n = 8). Although the amount of time spent firing in each week of a seismic survey varies hugely, depending on factors such as weather and technical problems, increased habituation or increased sensitisation may occur with repeated exposure to sound (Richardson *et al.,* 1995). An initial tolerance of 'small arrays' by delphinids might give way to increasing sensitisation as surveys progress; alternatively, there could be some other explanation for the later decrease in sighting rates, such as a delayed response due to prey moving out of the area or natural variations in abundance. A reduction in rates of delays in firing (required when marine mammals are within 500m of the airguns) after the initial use of airguns on surveys (Stone, 2015) might point to an adaptive response, with animals 'warned' by previous firing perhaps being less likely to approach close to the vessel.

Although many of the observed responses suggest avoidance, marine mammals may respond to seismic operations in other ways. Some behavioural responses were evident and although not all members of a group may have exhibited the behaviour, in assessing response to noise not all group members need to be observed (Southall *et al., 2007*). Although feeding is not always apparent from surface observations, when all cetaceans were combined significantly fewer animals were recorded as feeding when 'large arrays' were active; a reduction in foraging effort may have significant consequences for individuals and populations. In the Gulf of Mexico, sperm whales did not avoid seismic operations but may have decreased their foraging effort (Jochens *et al., 2008*; Miller *et al., 2009*). Although in the present study there were no observed effects of noise from 'large arrays' on sperm whales, the results are limited to those observations detectable by MMOs; as sperm whales forage at depth, a reduction in foraging would not be readily apparent.

When 'large arrays' were active there were indications that some cetaceans may remain close to the surface (e.g. logging), where noise levels may be lower due to the Lloyd's mirror effect (Richardson *et al., 1995*; Urick, 1983). Other studies have also observed changes in the surfacing behaviour of cetaceans in response to noise from seismic operations, with some reporting a reduction in time at the surface (Gailey *et al., 2007*; Robertson *et al., 2013*) but most reporting an increase in surfacing behaviour (Barkaszi *et al., 2012*; Jochens *et al., 2008*; McCauley *et al., 1998, 2000*; Miller *et al., 2009*). Changes in surfacing, respiration and dive behaviours of cetaceans exposed to seismic operations may have implications for the ability to detect animals (Robertson *et al., 2013*). As most of the effort in the present study was visual, any behaviours which may have influenced sighting rates could potentially mask any changes in numbers of animals in the vicinity. Therefore, a lack of any significant difference in detection rates for some species does not necessarily rule out avoidance. Changes in surfacing, respiration and dive behaviours can be context-dependent, depending on the circumstance and the activity of the animal, with greater responses to noise when animals are travelling than when socialising or feeding (e.g. Robertson *et al., 2013*). The response of marine mammals to airgun activity is likely to be complex, involving many variables that may contribute to results such as those for sperm whales in the present study, where detection rates were reduced when 'small arrays' were active, but no response to 'large arrays' was observed.

MMO observations of cetacean behaviour have the potential to be biased given the difficulty in observing cetaceans and measuring/estimating distances, the subjective nature of interpreting behaviour and the possibility that the MMO may have an expectation, even if subconsciously, that animals will respond differentially between when seismic airguns are firing and when they are not firing. Blind field trials cannot be achieved on board seismic surveys thus the data collected by MMOs currently provide the only data resource with which to test the hypotheses put forward in this paper. Every attempt has been made to limit potential bias where possible, for example by using matched pairs in the statistical analyses. While behavioural response studies with controlled exposures are the best tool to determine whether responses such as reduced detection rates are due to displacement of animals or a change in behaviour, experimental set ups (e.g. Cato *et al., 2013*) are complex and costly and would not be feasible over the same spatial and temporal scales and range of species as this study. MMO data provide the potential for examining behavioural responses with larger sample sizes across a range of species and geographical areas. Continued collation and use of MMO data to address questions such as the effectiveness of the soft start is therefore encouraged.

The National Research Council (NRC, 2005) encouraged the examination of the wealth of marine mammal data collected in compliance with regulatory requirements in order to increase understanding and management. The present study increases our knowledge of the effects of seismic airguns on marine mammal species found in UK waters, demonstrating previously unknown responses in beaked whales, common minke whales, fin whales and grey seals and emphasising the sensitivity of the harbour porpoise. Previously observed effects on some other small and medium sized odontocete species were confirmed. Although effects were more evident for 'large arrays', there were also some effects noted of 'small arrays' on sperm whales, harbour porpoises and all delphinids combined. Despite the variation in effects observed the results thus far confirm that mitigation measures should continue to apply to all types of seismic surveys and cover the risk to all marine mammal species. Despite the difficulties in collecting sufficient data on the effects of seismic surveys on marine mammals to allow for a thorough species by species analysis, some progress has been made with the current study. Understanding the ecological significance of those observable effects to individuals and populations remains however, a much greater challenge.

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