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Canada

June 2010

Correct citation for this report is:

Moulton , V.D., M. Holst. 2010
Effects of Seismic Survey Sound on Cetaceans in the Northwest Atlantic.
Environmental Studies Research Funds Report No. 182. St. John's. 28p.

The Environmental Studies Research Funds are financed from special levies on the oil and gas industry and administered by Natural Resources Canada for the Minister of Natural Resources Canada and the Minister of Indian Affairs and Northern Development.

Published under the auspices of the
Environmental Studies Research Funds
NE22-4/182E-PDF

Environmental Research Studies Funds
Report No. 182

June 2010

Effects of Seismic Survey Sound on Cetaceans in the Northwest Atlantic

by

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Abstract

Numbers, sighting distances, and behaviour of cetaceans were observed during eight seismic programs off eastern Canada during 2003–2008. Observers watched for 9180 h from seismic vessels including all daylight periods when airguns operated and many periods without airguns. During the monitored seismic surveys, mysticetes in particular showed localized avoidance of the active airgun array. Sighting rates were significantly lower during operations with the full airgun array compared with non-seismic periods; reduced sighting rates during seismic suggest that some baleen whales avoided the source vessel by several kilometres. Mysticetes were also seen significantly farther away from the source vessel during seismic compared to non-seismic periods; on average, baleen whales were seen ~200 m farther from the vessel during seismic operations. Mysticetes were also noted to swim away from the vessel more often during seismic compared with non-seismic periods. Delphinids were initially detected significantly farther away during airgun activity (by ~200 m) compared with non-seismic periods, but there was no significant difference between sighting rates. For large toothed whales (sperm whales, *Physeter macrocephalus*, and beaked whales), sighting rates and distances were similar during periods when airguns were active vs. silent. Although there were few beaked whale sightings during the study (*n* = 15), there was little evidence, based on behavioural observations, to indicate that these whales responded overtly to airgun sounds. An examination of vessel-based observations during periods when the airgun arrays were being ramped up suggests that the effectiveness of this mitigation measure at alerting cetaceans to the ensuing seismic operations with the full airgun array varies with species.

Key Words: cetacean, seismic, airgun array, underwater noise, northwest Atlantic, behaviour, disturbance

Résumé

Les nombres, les distances de repérage et le comportement des cétacés ont été observés lors de huit programmes sismiques au large de la côte Est du Canada entre 2003 et 2008. Les observateurs ont œuvré pendant 9 180 h à bord de navires sismologiques y compris toutes les périodes du jour où les canons à air fonctionnaient et bon nombre de périodes sans les canons à air. Lors des levés sismiques analysés, ce sont les mysticètes qui ont démontré un évitement localisé du réseau actif de canons à air. Les taux de repérage étaient plus bas et ce, de façon significative, lors des opérations avec le plein réseau de canons à air comparativement aux périodes non sismiques; les taux de repérage plus bas observés lors des périodes sismiques laissent supposer que certains cétacés à fanons ont évité le navire source de plusieurs kilomètres. Les mysticètes ont également été aperçus beaucoup plus loin du navire source lors des périodes sismiques comparativement aux périodes non sismiques; en moyenne, les cétacés à fanons ont été observés ~200 m plus loin du navire lors des opérations sismiques. On a également noté que les mysticètes s'éloignaient plus souvent du navire lors des périodes sismiques comparativement aux périodes non sismiques. Des delphinidés ont été détectés beaucoup plus loin lors des activités de canons à air (~200 m) comparativement aux périodes non sismiques mais aucune différence significative n'a été notée entre les taux de repérage. Pour ce qui est des cétacés à grandes dents (grands cachalots, *Physeter macrocephalus* et baleines à bec), les taux et distances de repérage étaient similaires lors des périodes où les canons à air étaient actifs comparativement à silencieux. Bien que peu des baleines à bec aient été repérées lors de l'étude (n = 15), peu de preuves, fondées sur les observations comportementales, ont permis d'indiquer que ces baleines répondaient ouvertement aux sons des canons à air. Un examen des observations faites à bord des navires au cours des périodes où les réseaux de canons à air avaient été augmentés laisse supposer que l'efficacité de cette mesure d'atténuation à alerter les cétacés des opérations sismiques consécutives à l'aide du plein réseau de canons à air varie selon l'espèce.

Mots clés : cétacés, sismique, réseau de canons à air, bruit sous l'eau, nord-ouest des côtes de l'Atlantique, comportement, perturbation

Introduction

The effect of seismic survey sound on marine mammals is a controversial topic that has received much attention in the regulatory, scientific, and industry communities. Seismic surveys involve the use of airguns that emit strong pulsed sound into the water column typically every 8-15 sec. It is theorized that if marine mammals are exposed to these sounds at close range there is a risk of hearing impairment or injury; at farther distances, behavioural and distributional changes have been documented for certain species (e.g., Southall et al., 2007).

Mysticetes are thought to be more likely to respond to airguns than odontocetes because they use low frequencies at which most of the energy from airguns is emitted (Richardson et al., 1995). In general, mysticetes tend to avoid operating airguns, but avoidance radii are variable (e.g., Stone & Tasker, 2006; Weir, 2008). At distances beyond a few kilometres, mysticetes often show no overt reactions to airgun pulses even though the sounds remain well above ambient noise levels out to much longer distances. However, some mysticetes exposed to strong noise pulses from airguns react by deviating from their normal migration heading and/or interrupting their feeding and moving away (e.g., Richardson et al., 1999).

There is an increasing amount of information about responses of various odontocetes to seismic surveys based on monitoring studies (e.g., Moulton & Miller, 2005; Bain & Williams, 2006; Stone and Tasker, 2006; Potter et al., 2007; Weir, 2008). Dolphins and porpoises are often seen by observers on active seismic vessels, occasionally at close range (e.g., bow riding; Moulton & Miller, 2005). However, localized avoidance by delphinids has also been reported, but in most cases, avoidance radii appear to be small (e.g., Goold, 1996b; Gordon et al., 2004; Stone & Tasker, 2006; Weir, 2008; Richardson et al., 2009). In contrast, belugas (*Delphinapterus leucas*) summering in the Canadian Beaufort Sea showed larger-scale displacement, tending to avoid operating seismic vessels by 10–20 km (e.g., Miller et al., 2005). Recent studies show little evidence of conspicuous reactions by sperm whales (*Physeter macrocephalus*) to airgun pulses, contrary to earlier indications (e.g., Gordon et al., 2006; Stone & Tasker, 2006; Winsor & Mate, 2006; Jochens et al., 2008; Weir, 2008; Miller et al., 2009). There are few data on the behavioural reactions of beaked whales to seismic surveys. Concern has been expressed that this group of cetaceans may be at increased risk to noise exposure because of evidence that beaked whales stranded after exposure to strong noise from mid-frequency sonar (e.g., Simmonds & Lopez-Jurado, 1991; Frantzis, 1998; Jepson et al., 2003; Barlow & Gisiner, 2006). As airgun sounds are quite different from high-power sonars, it is unknown whether beaked whales would ever react similarly to seismic surveys; one beaked whale stranding event has been associated with a seismic survey (Malakoff, 2002; Cox et al., 2006), but no cause and effect relationship between this stranding and the seismic survey was established.

Monitoring and mitigating the potential effects of seismic survey sounds on marine mammals has become standard practice in many international jurisdictions, including Canada. Fisheries and Oceans Canada has published the “Statement of Canadian Practice with respect to the Mitigation of Seismic Sound in the Marine Environment” and these regulatory guidelines have been adopted by the oil and gas industry in Atlantic Canada (C-NLOPB, 2008; C-NSOPB, 2008). The guidelines require that dedicated marine mammal observers (MMOs) monitor for marine mammals (and sea turtles) during daylight periods when airguns are active and during the 30-min period before ramp up or soft start. Ramp up is the standard practice of gradually increasing the number of airguns in an array over time (i.e., ~30 min in this study). Seismic operators have the option of activating a single airgun during turns between seismic survey lines. The MMOs implement mitigation measures as required, including the delay of ramp up and the shutdown of airgun(s) when a designated marine mammal (or sea turtle) is detected within a defined safety zone. As a minimum requirement, marine mammals listed on Schedule 1 of Canada's federal *Species at Risk Act* (*SARA*) as endangered or threatened require that the airgun(s) be shut down when the animal is detected within a 500-m safety zone. Cetaceans that occur in the northwest Atlantic that are listed on Schedule 1 as endangered (currently no cetaceans are listed as threatened) include the blue whale (*Balaenoptera musculus)*, North Atlantic right whale (*Eubalaena glacialis*), and northern bottlenose whale (*Hyperoodon ampullatus,* Scotian Shelf population).

Besides allowing for mitigation measures to be implemented, visual monitoring also allows for the collection of data that can be used to assess potential differences in sighting rates, behaviour, and distribution of marine mammals around the seismic vessel during periods when airguns are inactive vs. active. However, off the east coast of Canada, visual observations are often impeded by prevailing fog during the summer. Observations from seismic vessels are limited to those in relative close proximity (i.e., within several kilometres) but nonetheless offer valuable insight into marine mammal response to seismic survey sound.

Despite the attention and the large number of marine mammal monitoring programs that have taken place worldwide, results of these programs have seldom found their way into scientific literature (e.g., Gordon et al., 2004; Miller et al., 2005; Stone & Tasker, 2006; Gailey et al., 2007; Yazvenko et al. 2007a,b; Weir, 2008). Here we present the findings of eight vessel-based monitoring programs in four locations in Atlantic Canada during 2003–2008 — three off the coast of Newfoundland and one off the coast of Nova Scotia. Observational protocols were consistent across seismic monitoring programs, and experienced biologists conducted the majority of observations.

This study focuses on cetacean sightings and behaviour during seismic programs and does not consider the potential effects of these operations on cetacean hearing or physiology. Based on the known reactions of cetaceans to seismic survey sound, it was hypothesized that sighting distances would be greater and sighting rates lower during seismic vs. non-seismic periods, and that cetaceans would be more likely to swim away from the seismic vessel during seismic vs. non-seismic periods. If the standard practice of ramping up the airgun array was effective at achieving its objective to deter cetaceans from close approach to the array, we expected that fewer cetaceans would be observed close to the vessel during ramp up than during periods when the airguns were silent.

Materials and Methods

Study Areas

Monitoring data were collected in three areas offshore Newfoundland and one area offshore Nova Scotia during 2003–2008. Areas offshore Newfoundland included Orphan Basin and the Laurentian Sub-basin where water depths typically exceeded 1500 m, and the Jeanne d'Arc Basin where water depth was < 200 m. The monitoring program offshore Nova Scotia primarily occurred in water deeper than 2000 m on the Scotian Slope but also included a portion of the Scotian Shelf (Figure 1). Transit routes to the seismic survey sites were not included in the study areas. The Jeanne d'Arc Basin study area was unique in that existing offshore oil production installations occurred in very close proximity to the three seismic programs (Figure 1D) that took place there in 2005, 2006, and 2008. Offshore installations were located northwest of the seismic area on the Scotian Slope (Figure 1A). No such installations occurred in or near the seismic programs in the Orphan Basin and Laurentian Sub-basin.

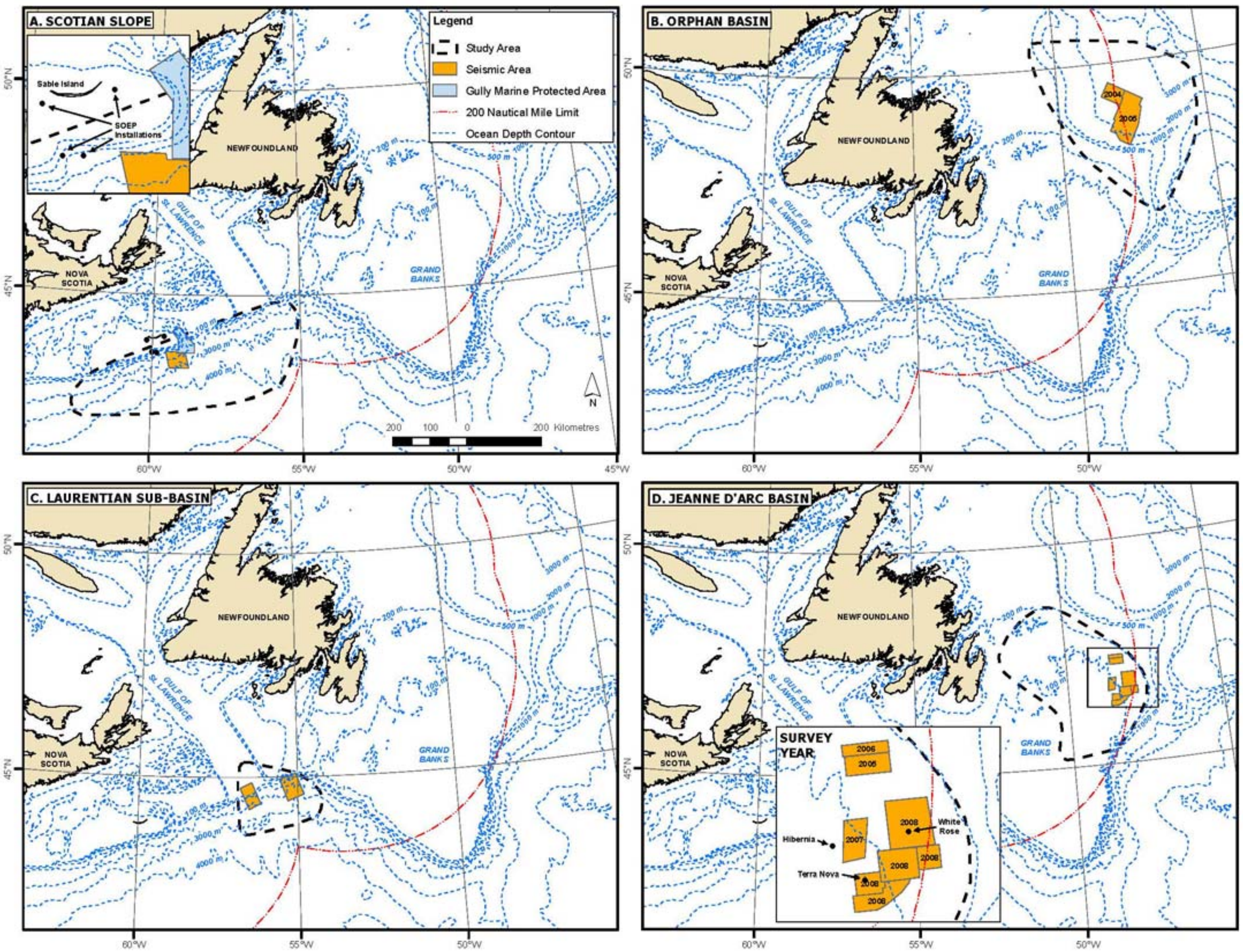

Figure 1. Locations where seismic survey data were acquired (seismic areas) and the broader areas where cetacean data were collected (study areas) in A. Scotian Slope (2003), B. Orphan Basin (2004–2005), C. Laurentian Sub-basin (2005), and D. Jeanne d'Arc Basin (2005–2008). [SOEP = Sable Offshore Energy Project]

Seismic Programs

All seismic programs involved the acquisition of 3-D seismic data with airgun arrays consisting of 24–32 airguns and a total discharge volume of 3000–5085 in^3 (Table 1). For the seven programs off the coast of Newfoundland, the source level of the arrays according to operator specifications ranged from 256–261.3 dB re 1 μPa (peak to peak); the array used on the Scotian Slope had an estimated source level of 228 dB re 1 μPa (rms) (Austin & Carr, 2005). The airgun arrays were activated (i.e., shotpoint interval) every 9–11 s (depending on vessel speed), towed at a depth of 6–8 m, and 134–520 m astern of the bridge. Depending on the program, eight or 10 streamers, each 6 km in length, were towed behind the seismic source vessel at a depth of 8–9 m. Streamers were separated by 100 m resulting in a total spread of 700 or 900 m. A guard boat (or picket vessel) accompanied each seismic source vessel and typically sailed ahead of it.

Monitoring Platforms, Procedures, and Data Recording

Survey Platforms—All observations were conducted from the bridge and bridge wings of the seismic source vessels. The height of the bridges above sea level ranged from 10.3–19 m and vessels ranged in length from 80.6–93 m. The bridges generally afforded good visibility around the vessels, including the bow and stern. Other survey vessel and program details are summarized in Table 1.

Monitoring Procedures—Two biologists (i.e., MMOs) and one Fisheries Liaison Officer (FLO) were stationed aboard most vessels. The biologists had considerable prior vessel-based experience with marine mammal observations and the FLOs were experienced fish harvesters who participated in a marine mammal training session prior to duty on the ship. Observers normally conducted 2–3 hour (h) watches for cetaceans followed by a 2–3 h break; this was repeated three times per day. Typically, only one observer was on watch at a time but occasionally two observers conducted watches simultaneously.

Observers scanned the waters around the vessel using 7×50 Fujinon binoculars equipped with reticles to measure depression angle relative to the horizon. The distance estimates derived from the binoculars were corrected for earth curvature as outlined in Lerczak and Hobbs (1998). Observational effort was typically focused ahead of the vessel to detect cetaceans as the vessel approached. The safety zone was 500 m for all seismic programs with the exception of the Scotian Slope program, in which a 700-m safety zone was used (Austin & Carr, 2005). Observers recorded operational information and meteorological conditions at regular intervals, typically at the start and end of each seismic survey line, whenever conditions changed markedly, or every 30 min. These written records were supplemented with accounts of the cetaceans that were sighted.

Data Recording—For all records, the date, time, and observer on duty were recorded. Latitude, longitude, and information about seismic activity were available from the computer monitors located on the bridge. Operational activities that were recorded included the survey line number being shot and the type of seismic activity — ramping up, line shooting (i.e., array), seismic testing, shutdowns, and other. Environmental conditions that were recorded included wind force (Beaufort wind force), visibility (km), and obstructions to visibility (e.g., rain, fog, glare, darkness). Water depth and water temperature were also recorded when the data were available from the ship's computers.

The position of the survey vessel was logged automatically by the ship's navigation system each time the airguns were activated. When available, "shotpoint" data files (with positions for every time the airguns were activated) were used to validate the cetacean sighting data for monitoring programs. For cruises where shotpoint data files were unavailable, a GPS was used to log the position of the ship during both non-seismic and seismic periods.

Table 1. Summary of seismic survey programs on the Scotian Slope, Laurentian Sub-basin, Orphan Basin, and Jeanne d'Arc Basin.

	Scotian Slope	Laurentian Sub-basin	Orphan Basin [a]			Jeanne d'Arc Basin			
Operation Dates									
Start	22-May-03	14-Jun-05	26-Jun-04	23-Jun-05	12-May-05	3-Oct-05	10-Jul-06	18-Jun-07	7-May-08
End	16-Oct-03	29-Sep-05	18-Sep-04	10-Oct-05	24-Sep-05	8-Nov-05	16-Aug-06	14-Jul-07	29-Sep-08
Water Depth									
Minimum (m)	100	250	500	500	500	50	50	50	50
Maximum (m)	3850	3000	3300	3300	3300	200	200	200	200
Average (m)	2036	1465	2348	2252	2252	147	120	137	114
Vessel (M/V)	*Ramform Viking*	*Western Neptune*	*Veritas Vantage*	*Western Patriot*	*Geco Diamond*	*Western Neptune*	*Western Regent*	*Western Patriot*	*Veritas Vantage*
Length (m)	86.2	93	93	78	80.6	93	93	78	93
Width (m)	39.6	23	22	17	14.8	23	23	17	22
Bridge height asl (m)	15	17	19	10.3	15	17	14.5	10.3	19
Airgun Array									
Total volume (in^3)	3090	5085	4450	3000	5085	5085	5085	5085	4430
Number of airguns	28	24	24	32	24	24	24	24	24
Source level (dB re 1 uPa)	228 rms [b]	260.5 p-p	256 p-p	259.4 p-p	260.5 p-p	260.5 p-p	260.5 p-p	260.5 p-p	261.3 p-p
Distance behind bridge (m)	300	485	221	450	295	485	520	520	134
Deployment depth (m)	6	7	7	7	7	7	7	6	8

Note: asl = above sea level

[a] In 2005, seismic data collected from the *Western Patriot* and *Geco Diamond* were part of the same seismic program.

[b] Based on field measurements (broadband: 1–512 Hz; Austin & Carr, 2005).

For each cetacean sighting, the following was recorded: species, number of individuals seen, behaviour when first sighted, behaviour after initial sighting, heading, bearing, distance (initial and closest point of approach relative to the bridge), identification reliability, and seismic status.

Survey Effort

MMOs watched for cetaceans during most daylight periods and alternated their watches throughout the day at regular intervals. To account for the influences of sighting conditions on cetacean sighting rates and distances, different subsets of the data were excluded depending on the particular analysis. For analyses of sighting rates, data were standardized to exclude periods when winds exceeded Beaufort wind force 4, visibility was less than 1 km, and more than one MMO was on watch. This resulted in the exclusion of ~60% of the monitoring effort, which was mostly (28.9%) attributable to poor visibility. For analyses of sighting distances, data were excluded when winds exceeded Beaufort wind force 4 and visibility was less than 5 km; this resulted in the exclusion of 70% of the monitoring effort.

Analysis Approach

Sightings and observational effort were divided into the following general categories based on airgun activity: No Airguns, Single Airgun, Ramp Up, Array, Testing, and All Seismic. No Airguns encompassed periods when no airguns were active. Single Airgun included periods when one airgun, typically the smallest in volume, was operated when the seismic vessel was turning between seismic survey lines. Ramp Up consisted of periods when the number of operating airguns was gradually increased over a duration of ~30 min after the array had been inactive. Array was defined as those times when the full seismic array was active (excluding Ramp Up, Single Airgun, and Testing). Testing consisted of periods when the seismic operator was checking the status of various airguns. The All Seismic category was defined as all times when any airguns were active; this included periods of Single Airgun, Ramp Up, Array, and Testing.

Sighting data were grouped separately for mysticetes, delphinids, and large toothed whales (sperm and beaked whales). Data were not pooled across all cetacean species given the variable hearing capabilities of different species (Au et al., 2000) and thus, expected differences in potential reactions to seismic survey sounds. Where sample size permitted, analyses were conducted on a species basis. Results and statistical tests are based on cetacean sightings (total number of singletons (sightings of one individual) or groups seen) instead of the number of individual cetaceans to avoid pseudoreplication[1] problems. Results were considered statistically significant if alpha was < 0.05.

Sighting Rates—Wilcoxon's matched-pairs signed-rank tests were performed to examine the effects of seismic survey sound on cetacean sighting rates. For all analyses, the data were standardized to number of cetacean sightings observed per hour of survey effort to allow meaningful comparisons of the numbers of cetaceans encountered during different seismic categories. Because the seismic vessels travelled at speeds of 4–5 knots (during surveying and any time when the streamers were deployed), the distance travelled each hour was generally consistent for each seismic category. Data were organized into bi-weekly periods for each of the eight seismic programs. This minimized the influences of seasonality (periods of natural occurrence and absence of cetaceans in the study areas), location, vessel type (e.g.,

[1] Pseudoreplication occurs when replicates are somehow dependent on one another. Marine mammals within a closely spaced group are not independent as the behaviour of an individual is likely dependent on the behaviour of others in the group. Pseudoreplication can result in the underestimation of true variance and *p*-values in significance tests. There is also an increased risk of committing a Type I error (rejecting a null hypothesis when it is true).

height of bridge asl), and operational parameters on cetacean sighting rates, to allow reliable comparisons of sighting rates during periods with and without airgun activity. Tests were performed for each cetacean group and rate comparisons were made between periods of No Airguns and Array and periods of No Airguns and All Seismic. In addition, sighting rates during periods of Ramp Up were compared with No Airguns when sample sizes allowed. Rate comparisons were also made for humpback whales (*Megaptera novaeangliae*) and long-finned pilot whales (*Globicephala melas*).

Both sighting and effort data were excluded when visibility was < 1 km, Beaufort wind force was > 4, and when more than one observer was on watch. This resulted in the exclusion of 5378 h of effort. To verify that visibility conditions (i.e., when visibility was ≥ 1 km) and hence, the likelihood of detecting a cetacean did not significantly differ during periods with and without airgun activity, χ^2 tests were performed to examine the proportions of effort during No Airguns vs. Array in different visibility ranges for each of the eight monitoring programs. No significant differences were found ($p > 0.25$ in all eight χ^2 tests).

Sighting Distances—MMOs recorded the radial distances at which cetaceans were initially observed as well as the Closest Point of Approach (CPA) of the animals relative to observer location on the bridge. CPAs were not systematically recorded during the Scotian Slope monitoring program. Mann-Whitney *U* tests were performed to compare sighting distances during periods of No Airguns and periods of Single Airgun, Ramp Up, Array, and All Seismic. Data were excluded if Beaufort wind force was > 4 and visibility was < 5 km. This resulted in the exclusion of 217, 231, and 22 sightings of mysticetes, delphinids, and large toothed whales, respectively.

Behaviour—For each sighting, observers recorded the initial behaviour observed and, when possible, the subsequent behaviour. Observers also noted the movement type of cetaceans relative to the vessel including the following categories: swim towards, swim parallel, swim away, flee, mill, none, and unknown. MMOs also recorded a written statement describing a cetacean's behaviour. Given the nature of seismic surveys, i.e., travelling along straight seismic lines with no option to change course or slow down to extend the observation duration of a cetacean sighting, information on behaviour was often limited. The proportions of cetaceans exhibiting various movement types during periods of No Airguns and periods of Array, Ramp Up, and Single Airgun operations were examined via χ^2 analyses.

Results

Summary of Sighting Effort

Observers conducted 9179.7 h of watches during the eight seismic monitoring programs (Table 2). Of this effort, 3046.6 h and 6133.1 h occurred during periods of No Airguns and All Seismic, respectively. Periods of Array totalled 4147.4 h and Ramp Up, Single Airgun, and Testing totalled 530.4 h, 1328.2 h, and 127.0 h, respectively. The entire safety zone was not visible due to fog ~30% of the time that MMOs were on watch. Most sighting effort occurred in Orphan Basin (~40%) followed by Jeanne d'Arc Basin (~30%).

Table 2. Monitoring effort during various seismic categories in the Scotian Slope, Laurentian Sub-basin, Orphan Basin, and Jeanne d'Arc Basin study areas.

	Visual Effort (h)						
Study Area / Year	No Airguns	Single Airgun	Ramp Up	Array	Testing	All Seismic	Total
Scotian Slope	880.3		67.4	459.7	1.2	528.3	1408.6
Laurentian Sub-basin	202.4	440.1	115.4	609.3	24.5	1189.3	1391.7
Orphan Basin 2004	591.3	10.2	60.6	524.6	6.5	602.0	1193.3
Orphan Basin 2005	629.5	304.1	127.1	1332.9	56.3	1820.4	2449.9
Jeanne d'Arc Basin 2005	146.5	48.8	17.6	91.9	4.4	162.7	309.3
Jeanne d'Arc Basin 2006	191.4		38.9	242.3	15.7	296.9	488.3
Jeanne d'Arc Basin 2007	63.6	64.5	22.5	151.0	13.9	251.9	315.5
Jeanne d'Arc Basin 2008	341.6	460.6	80.8	735.8	4.5	1281.7	1623.3
Total	3046.6	1328.2	530.4	4147.4	127.0	6133.1	9179.7

Note: excludes periods when vessels were transiting to the study area.

Summary of Sightings

Overall, 1901 cetacean sightings were recorded. Of these sightings, 654 and 1247 were made during periods of No Airguns and All Seismic, respectively (Table 3). Mysticetes, delphinids, and large toothed whales accounted for 48.4%, 46.3%, and 5.3% of total sightings. The species composition varied depending on the location of the survey, with deepwater species like sperm whales, beaked whales, and long-finned pilot whales more prevalent in the Laurentian Sub-basin, Orphan Basin, and Scotian Slope whereas these species were mostly absent from the Jeanne d'Arc Basin (only two unidentified beaked whales, one unidentified toothed whale, and three long-finned pilot whales were recorded) where water depth was < 200 m. No North Atlantic right whales were seen during any of the seismic programs.

Mysticetes—Humpback whales accounted for almost half (47.0%) of the 920 mysticete sightings, followed by fin (14.8%; *B. physalus*), minke (7.2%; *B. acutorostrata*), and blue (6.6%) whales (Table 3). Other species or groups (sei whale, *B. borealis*, blue/fin, fin/sei, and unidentified mysticetes) accounted for the remaining 24.4% of mysticete sightings.

Delphinids—Long-finned pilot whales (43.8%) and unidentified delphinids (29.7%) accounted for the majority of the 880 delphinid sightings (Table 3). There were 104 and 82 sightings of Atlantic white-sided (*Lagenorhynchus acutus*) and common dolphins (*Delphinus delphis*), respectively. Small numbers of white-beaked (*L. albirostris*), striped (*Stenella coeruleoalba*), Risso's (*Grampus griseus*), bottlenose (*Tursiops truncates*), and Atlantic spotted dolphins (*S. frontalis*) and killer whales (*Orcinus orca*) were also recorded.

Large Toothed Whales—Of the 101 large toothed whale sightings, there were 77 sightings (76.2%) of sperm whales (Table 3). Other species included northern bottlenose whales (12 sightings) and Sowerby's beaked whale (one sighting; *Mesoplodon bidens*). MMOs also made two and nine sightings of unidentified beaked whales and unidentified large toothed whales, respectively.

Table 3. Numbers of mysticete, delphinid, and large toothed whale sightings observed during various seismic categories.

Cetacean Group / Species	Number of Sightings						
	No Airguns	Single Airgun	Ramp Up	Array	Testing	All Seismic	Total
Mysticetes							
Blue Whale	16	20	6	18	1	45	61
Blue/Fin Whale	1						1
Fin Whale	47	28	6	54	1	89	136
Fin/Sei Whale	17	4	1	10		15	32
Sei Whale	12	4		7		11	23
Humpback Whale	190	41	28	166	7	242	432
Minke Whale	24	10	3	28	1	42	66
Unident. Mysticete	55	42	15	53	4	114	169
Total	362	149	59	336	14	558	920
Delphinids							
Long-finned Pilot Whale	108	51	24	198	4	277	385
Atl. White-sided Dolphin	25	41	13	25		79	104
Common Dolphin	28	12	4	38		54	82
White-beaked Dolphin	5	7	1	2	1	11	16
Striped Dolphin	3	2		3	1	6	9
Risso's Dolphin	2	2	2	4		8	10
Bottlenose Dolphin	1	5		2		7	8
Atlantic Spotted Dolphin	2						2
Killer Whale	1	1		1		2	3
Unident. Delphinid	71	57	24	106	3	190	261
Total	246	178	68	379	9	634	880
Large Toothed Whales							
Sperm Whale	34	11	6	26		43	77
Northern Bottlenose Whale	8		2	2		4	12
Sowerby's Beaked Whale				1		1	1
Unident. Beaked Whale				2		2	2
Unident. Toothed Whale	4	1		4		5	9
Total	46	12	8	35	0	55	101

Note: unident. = unidentified

Sighting Rates

Overall, mysticetes and delphinids were observed at similar rates, considering data from all eight seismic monitoring programs (Figure 2). During periods when the airguns were inactive, mysticetes were observed at nearly twice the rate of delphinids. Toothed whales were seen much less frequently.

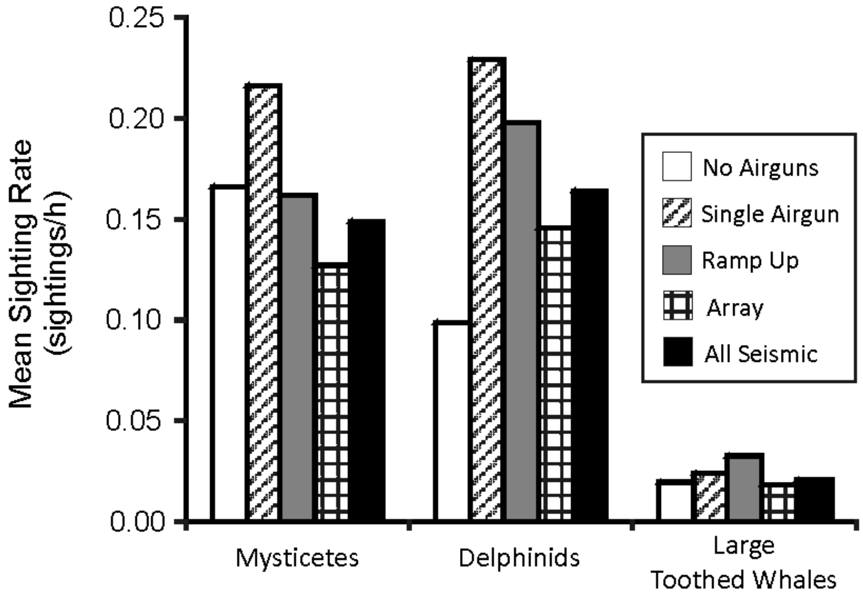

Figure 2. Mean sighting rates of mysticetes, delphinids, and large toothed whales during seismic categories considering all sighting distances.

Mysticetes—Sighting rates of mysticetes were significantly higher during periods of No Airguns vs. Array considering comparisons of paired bi-weekly periods (T = 179.5, n = 34, $0.01 < p < 0.05$). The average rates were 0.167 sightings/h and 0.128 sightings/h during periods of No Airguns and Array, respectively (Figure 2). Rates were also higher during periods of No Airguns vs. All Seismic (μ = 0.149 sightings/h) but the difference was not significant (T = 339, n = 39, $0.10 < p < 0.25$). Sighting rates of mysticetes were similar during periods of No Airguns and Ramp Up (μ = 0.162 sightings/h; T = 134, n = 25, $0.10 < p < 0.25$). Small sample sizes during periods of Single Airgun did not allow for bi-weekly comparisons.

Like the mysticete group, sighting rates of humpback whales (the most frequently sighted mysticete) were significantly higher during periods of No Airguns (μ = 0.089 sightings/h) vs. Array (μ = 0.053 sightings/h; T = 30, n = 17, $0.01 < p < 0.025$). Rates were, on average, not significantly different during non-seismic periods and All Seismic (μ = 0.057 sightings/h; T = 47, n = 17, $0.05 < p < 0.10$).

Delphinids—Although delphinid sighting rates appeared to be higher during periods when the airguns were active vs. silent (Figure 2), there were no significant differences between bi-weekly sighting rates during No Airguns (μ = 0.099 sightings/h) vs. Array (μ = 0.146 sightings/h; T = 356.5, n = 40, $p > 0.25$) or All Seismic (μ = 0.165 sightings/h; T = 371, n = 44, $0.05 < p < 0.10$). Similarly, long-finned pilot whales were observed more frequently during periods of Array and All Seismic vs. No Airguns, but the differences were not significant when bi-weekly rates were compared ($p > 0.25$ in both tests).

Large Toothed Whales—Sighting rates of large toothed whales were similar (Figure 2) during periods of No Airguns (μ = 0.020 sightings/h) vs. Array (μ = 0.019 sightings/h; T = 70, n = 17, $p > 0.25$) and All Seismic (μ = 0.021 sightings/h; T = 84, n = 21, $0.25 > p > 0.10$). The differences were not significant based on the comparison of rates during paired bi-weekly periods.

Sighting Distances

Based on analyses of initial sighing distances and CPAs of cetaceans, there was little indication that seismic survey sound resulted in large-scale avoidance of the area around the seismic vessels (Figures 3–5). However, results indicate that some cetacean groups and species exhibited localized avoidance of seismic survey sound (Tables 4–6).

Mysticetes—Overall, mysticetes were seen significantly farther away from the seismic ship during periods when airguns were active vs. silent (Figure 3; Table 4). This was observed during periods of Array and All Seismic vs. periods of No Airguns. Also, during periods of Ramp Up and Single Airgun use, mysticetes were, on average, seen farther from the seismic ship than during periods of No Airguns, although the difference in sighting distances was not as large and was not significantly different during periods of No Airguns vs. Single Airgun. Significant differences were found for both initial and CPA distances (Table 4). Considering both initial and CPA distances, mysticetes, on average, were observed ~200 m farther from the seismic ship during periods of Array and All Seismic vs. No Airguns (Figure 3). During Ramp Up, mysticetes were, on average, seen ~650 m farther from the source vessel than during No Airguns (Figure 3).

Blue whales were seen farther from the seismic ship during periods when the airguns were active vs. silent (Figure 3). The average initial sighting distance during periods of No Airguns was 1227 m vs. 1904 m during periods of Array (U = 64.5, n_1= 12, n_2 = 17, p = 0.048). Similarly, blue whales were initially sighted significantly farther from the vessel during periods of Ramp Up (μ = 3611 m), Single Airgun (μ = 1662 m), and All Seismic (μ = 2000 m; Table 4) vs. No Airguns. The mean CPA for blue whales was also closer during periods of No Airguns vs. other seismic categories but was only significantly different during periods of Ramp Up and All Seismic vs. No Airguns (Table 4).

Although fin whales were on average seen farther from the seismic vessel when the airgun(s) were active vs. inactive, the differences were not significant (Table 4). The mean initial sighting distances for fin whales were 1985 m, 2074 m, and 2192 m during periods of No Airguns, Array, and All Seismic, respectively (Figure 3). Based on CPA distances, fin whales were seen significantly farther from the source vessel during Ramp Up compared with No Airguns, but the sample size for ramp-up periods was small (Table 4).

Humpback whales were the most frequently observed mysticete and were, on average, initially observed significantly farther (Table 4) from the seismic vessel during periods of Array (μ = 2827 m) and All Seismic (2604 m) vs. No Airguns (2381 m). Mean initial sighting distances were similar during periods of No Airguns and Single Airgun (Figure 3). On average, humpbacks were initially seen farther from the vessel during periods of Ramp Up (μ = 2600 m) vs. No Airguns but the results were not significantly different. The same statistical trends were observed for CPA distances (Table 4); humpbacks did, on average, stay significantly farther from the seismic vessel during periods of Array (μ = 2505 m) and All Seismic (2445 m) vs. No Airguns (2002 m).

During periods of No Airguns, minke whales were initially observed at an average distance of 564 m form the vessel. Sighting distances during this time were significantly closer to the vessel than during periods of Array (μ = 963 m) and All Seismic (μ = 881 m; Table 4). Distances were not significantly different during periods of No Airguns vs. Single Airgun (Table 4). The same trends were observed for CPA distances.

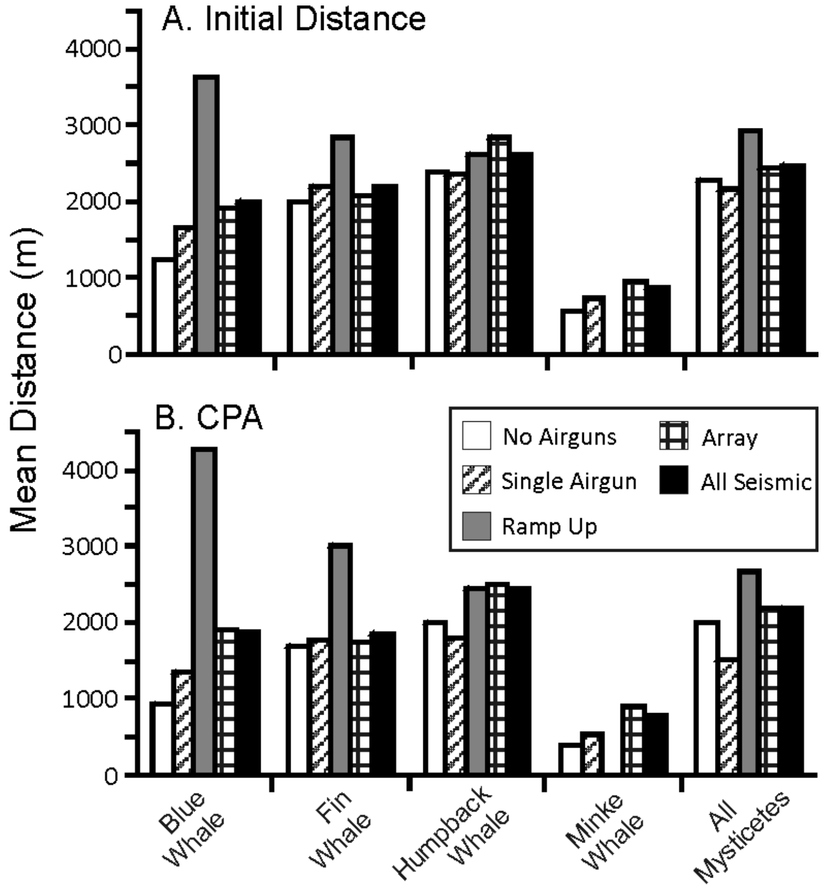

Figure 3. Mean sighting distances (m) of mysticetes for A. Initial Distance and B. CPA to the bridge during various seismic categories for all monitoring programs combined.

Delphinids—Delphinids were initially seen significantly farther away from the seismic ship during periods of Array (μ = 1560 m) and All Seismic (μ = 1455 m) vs. periods of No Airguns (μ = 1227 m; Table 5). Considering initial sighting distances, delphinids, on average, were observed at least 200 m farther from the seismic ship during periods of Array and All Seismic vs. No Airguns (Figure 4). Significant differences in initial sighting distances were not observed during periods of Ramp Up and Single Airgun vs. No Airguns. Significant differences were not found for CPA distances.

Long-finned pilot whales were the most frequently observed delphinid and were initially observed significantly farther (Table 5) from the seismic vessel during periods of Array (μ = 1170 m) and All Seismic (μ = 1137 m) vs. No Airguns (μ = 955 m). Initial sighting distances were larger during periods of Ramp Up and Single Airgun vs. No Airguns but the differences were not significant (Table 5). No significant differences in CPAs of long-finned pilot whales were found and the average CPA during periods of Array (μ = 867 m) and All Seismic (μ = 897 m) were slightly closer to the vessel than during periods of No Airguns (μ = 924 m; Figure 4).

Table 4. Results of Mann-Whitney *U* tests comparing sighting distances (Initial and CPA) of mysticetes during periods of No Airguns vs. Single Airgun, Ramp Up, Array, and All Seismic for all monitoring programs combined; significant results are indicated in bold.

	Blue Whale			Fin Whale			Humpback Whale			Minke Whale			All Mysticetes		
	U	n_1, n_2	*p*	*U*	n_1, n_2	*p*	*U*	n_1, n_2	*p*	*U*	n_1, n_2	*p*	*U*	n_1, n_2	*p*
Initial Distance															
No Airguns vs. Single Airgun	64.0	12,19	**0.021**	321.5	35,22	0.149	2064.5	142,32	0.210	55.0	16,9	0.168	14744.5	268,112	0.394
No Airguns vs. Ramp Up	11.5	12,5	**0.025**	59.0	35,5	0.122	1548.0	142,23	0.345	-	-	-	5115.5	268,47	**0.020**
No Airguns vs. Array	64.5	12,17	**0.048**	639.0	35,40	0.259	11271.5	142,133	**0.003**	135.5	16,25	**0.042**	31476.0	268,257	**0.044**
No Airguns vs. All Seismic	140.0	12,41	**0.012**	1025.5	35,68	0.126	16306.0	142,195	**0.003**	216.0	16,38	**0.048**	52235.0	268,429	**0.021**
CPA Distance															
No Airguns vs. Single Airgun	50.0	8,19	0.083	270.5	25,22	0.462	2206.0	138,32	0.497	52.5	14,9	0.254	13729.0	247,112	0.455
No Airguns vs. Ramp Up	3.0	8,4	**0.013**	17.5	25,4	**0.020**	1311.5	138,22	0.153	-	-	-	4124.0	247,44	**0.006**
No Airguns vs. Array	24.5	8,11	0.052	448.5	25,37	0.421	11228.0	138,133	**0.001**	87.5	14,25	**0.005**	27606.5	247,248	**0.029**
No Airguns vs. All Seismic	77.5	8,34	**0.030**	766.5	25,64	0.380	15926.0	138,194	**0.002**	154.0	14,38	**0.011**	46256.5	247,415	**0.018**

Table 5. Results of Mann-Whitney *U* tests comparing sighting distances (Initial and CPA) of delphinids during periods of No Airguns vs. Single Airgun, Ramp Up, Array, and All Seismic for all monitoring programs combined; significant results are indicated with bold.

	Long-finned Pilot Whale			Atl. White-sided Dolphin			Common Dolphin			All Delphinids		
	U	n_1, n_2	*p*	*U*	n_1, n_2	*p*	*U*	n_1, n_2	*p*	*U*	n_1, n_2	*p*
Initial Distance												
No Airguns vs. Single Airgun	1283.5	68,40	0.313	235.0	18,30	0.228	49.0	20,5	0.487	10377.5	163,133	0.528
No Airguns vs. Ramp Up	413.5	68,16	0.069	51.0	18,8	0.131	-	-	-	3562.0	163,49	0.252
No Airguns vs. Array	5792.0	68,147	**0.031**	175.5	18,22	0.273	182.0	20,23	0.121	20034.5	163,289	**0.004**
No Airguns vs. All Seismic	7966.5	68,205	**0.039**	506.5	18,60	0.346	257.0	20,30	0.197	34539.0	163,477	**0.017**
CPA												
No Airguns vs. Single Airgun	896.5	47,40	0.356	211.5	18,30	0.107	17.0	11,5	0.136	7282.5	115,133	0.517
No Airguns vs. Ramp Up	255.5	47,15	0.056	58.0	18,8	0.231	-	-	-	2345.0	115,43	0.618
No Airguns vs. Array	2891.0	47,124	0.469	164.0	18,20	0.327	61.5	11,15	0.141	13684.5	115,240	0.449
No Airguns vs. All Seismic	4373.0	47,181	0.384	465.5	18,58	0.245	84.5	11,22	0.083	24093.5	115,422	0.454

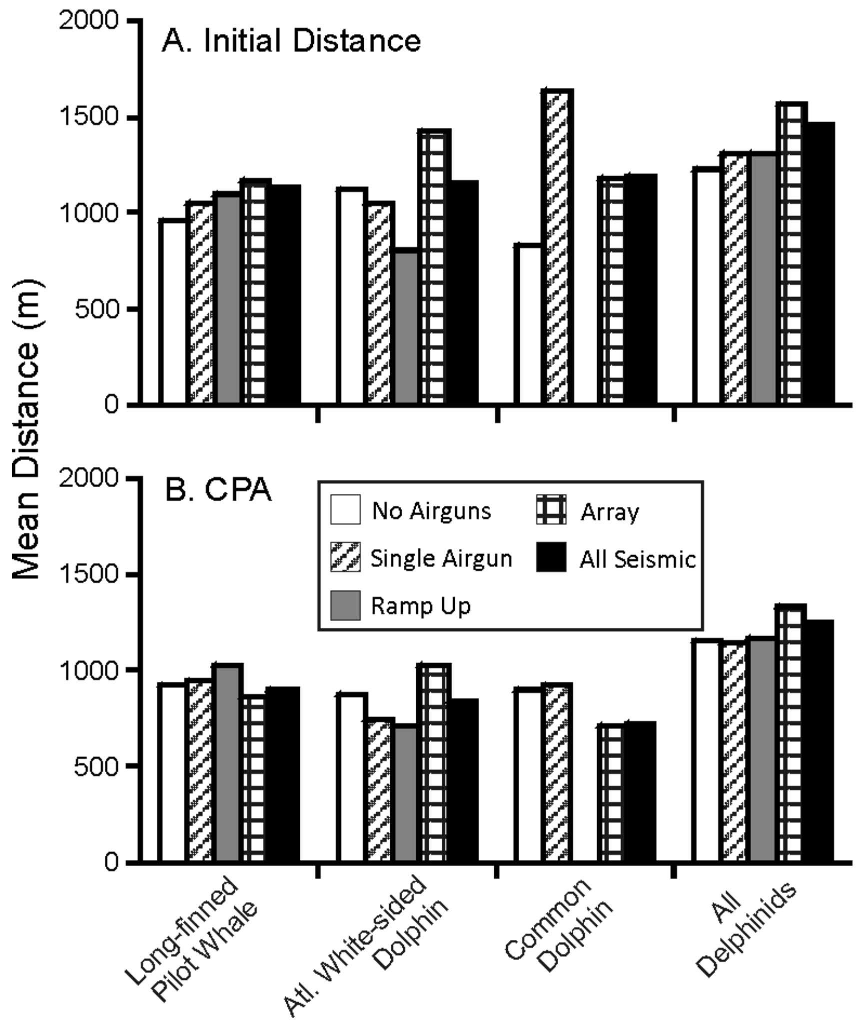

Figure 4. Mean sighting distances (m) of delphinids for A. Initial Distance and B. CPA to the bridge, during various seismic categories for all monitoring programs combined.

Atlantic white-sided dolphins were, on average, initially seen farther from the seismic vessel during periods of Array (μ = 1427 m) vs. No Airguns (μ = 1116 m), but the difference was not significant (Table 5). Similarly, there were no significant differences in CPA distances during periods of No Airguns vs. all other seismic categories.

Although common dolphins were on average seen farther from the seismic vessel during periods when the airgun(s) were active vs. inactive, the differences were not statistically significant (Table 5). Similarly, there were no significant differences in CPA distances during periods of No Airguns vs. all other seismic categories.

Large Toothed Whales—As a group, there were no significant differences in the initial or CPA sighting distances of large toothed whales (sperm, northern bottlenose, Sowerby's beaked, and unidentified toothed whale species) during periods of No Airguns vs. all other seismic categories (Table 6).

Table 6. Results of Mann-Whitney *U* tests comparing sighting distances (Initial and CPA) of large toothed whales during periods of No Airguns vs. Single Airgun, Ramp Up, Array, and All Seismic for all monitoring programs combined; there were no significant results.

	Sperm Whale			All Large Toothed Whales		
	U	n_1, n_2	*p*	*U*	n_1, n_2	*p*
Initial Distance						
No Airguns vs. Single Airgun	91.5	25,9	0.210	98.0	34,9	0.100
No Airguns vs. Ramp Up	69.0	25,6	0.395	122.5	34,8	0.665
No Airguns vs. Array	273.5	25,22	0.487	398.5	34,28	0.136
No Airguns vs. All Seismic	446.0	25,37	0.407	619.0	34,45	0.074
CPA						
No Airguns vs. Single Airgun	77.0	21,9	0.225	82.0	30,9	0.077
No Airguns vs. Ramp Up	40.5	21,4	0.456	76.0	30,6	0.552
No Airguns vs. Array	170.0	21,20	0.148	366.5	30,26	0.350
No Airguns vs. All Seismic	325.5	21,33	0.355	524.5	30,41	0.146

Sperm whales did not exhibit obvious avoidance of the seismic vessel when airguns were active (Figure 5). Sighting distances (initial and CPA) did not differ significantly between periods of No Airguns and all other categories of seismic activity (Table 6). Initial sighting distances were similar during periods of No Airguns (μ = 1852 m) and periods of Array (μ = 1859 m) and All Seismic (μ = 2000 m).

Behaviour

If cetaceans were negatively influenced by seismic activity, it was anticipated that they would tend to swim away from the vessel. Conversely, it was anticipated that fewer cetaceans would be observed milling, swimming towards, and exhibiting no movement relative to the ship during seismic vs. non-seismic periods.

Mysticetes—The behavioural data suggest that mysticetes as a group exhibited avoidance of the seismic vessel during periods of Array, All Seismic, and Single Airgun operations. The proportions of movement types exhibited by mysticetes differed significantly during periods of No Airguns vs. Array (χ^2 = 15.06, *df* = 4, *p* = 0.005) and No Airguns vs. All Seismic (χ^2 = 19.17, *df* = 4, *p* = 0.001). A higher percentage of mysticetes swam away from the vessel during periods of Array (42.6% of 188) than during periods of No Airguns (29.1% of 237). Also, higher percentages of mysticetes were observed milling and swimming towards the seismic vessel during periods of No Airguns vs. Array (Figure 6A). The same trends were observed during periods of No Airguns vs. All Seismic. Similarly, a higher than expected proportion of mysticetes swam away from the seismic vessel and lower than expected proportions exhibited milling and no movement during periods when a Single Airgun was operational (χ^2 = 16.86, *df* = 4, *p* = 0.002; Figure 7A). Mysticete movements during Ramp Up did not differ significantly from those observed during periods of No Airguns (χ^2 = 6.59, *df* = 4, *p* = 0.159; Figure 7A).

Humpback and minke whales exhibited similar patterns in movement during various seismic categories (Figure 6B,D). Both species were significantly more likely to swim away and less likely to swim towards and mill during periods of Array vs. No Airguns (humpbacks: χ^2 = 17.81, *df* = 4, *p* = 0.001;

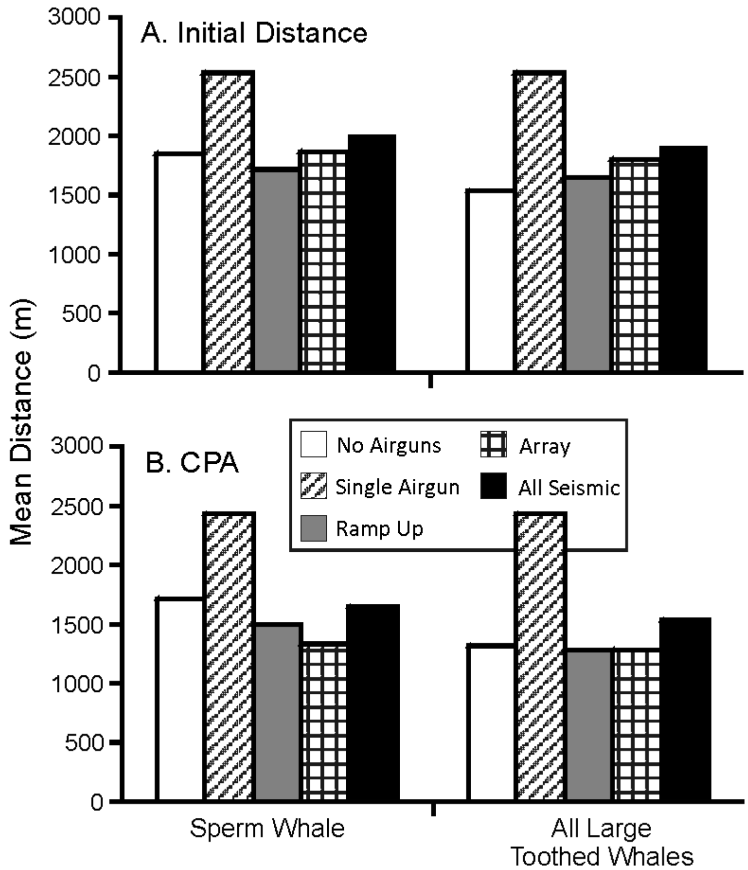

Figure 5. Mean sighting distances (m) of large toothed whales for A. Initial Distance and B. CPA to the bridge, during various seismic categories for all monitoring programs combined.

minkes: $\chi^2 = 11.02$, $df = 3$, $p = 0.026$) and during periods of All Seismic vs. No Airguns (humpbacks: $\chi^2 = 13.80$, $df = 4$, $p = 0.008$; minkes: $\chi^2 = 10.15$, $df = 3$, $p = 0.038$). Fin and blue whale movement types did not differ significantly during periods of Array vs. No Airguns and periods of All Seismic vs. No Airguns ($p > 0.10$ for all χ^2 tests). Proportionally more blue whales swam towards the vessel and proportionally less swam away during periods of Array and All Seismic vs. No Airguns (Figure 6E). Sample size of mysticete species during periods of Single Airgun operations was only large enough to support an analysis of humpback whale movements; the results were not significant ($\chi^2 = 6.21$, $df = 4$, $p = 0.184$; Figure 7B). There were insufficient numbers of species-specific sightings with known movement types during Ramp Up to allow for analysis.

Delphinids—Considering all delphinids combined, there was no clear indication that the likelihood for a delphinid to swim away was higher during periods of Array and All Seismic insofar as could be determined from the seismic vessel. The proportions of delphinids showing each of the five movement types was similar (Figure 8A) during non-seismic vs. Array periods ($\chi^2 = 5.52$, $df = 4$, $p = 0.238$) and non-seismic vs. All Seismic ($\chi^2 = 8.55$, $df = 4$, $p = 0.073$).

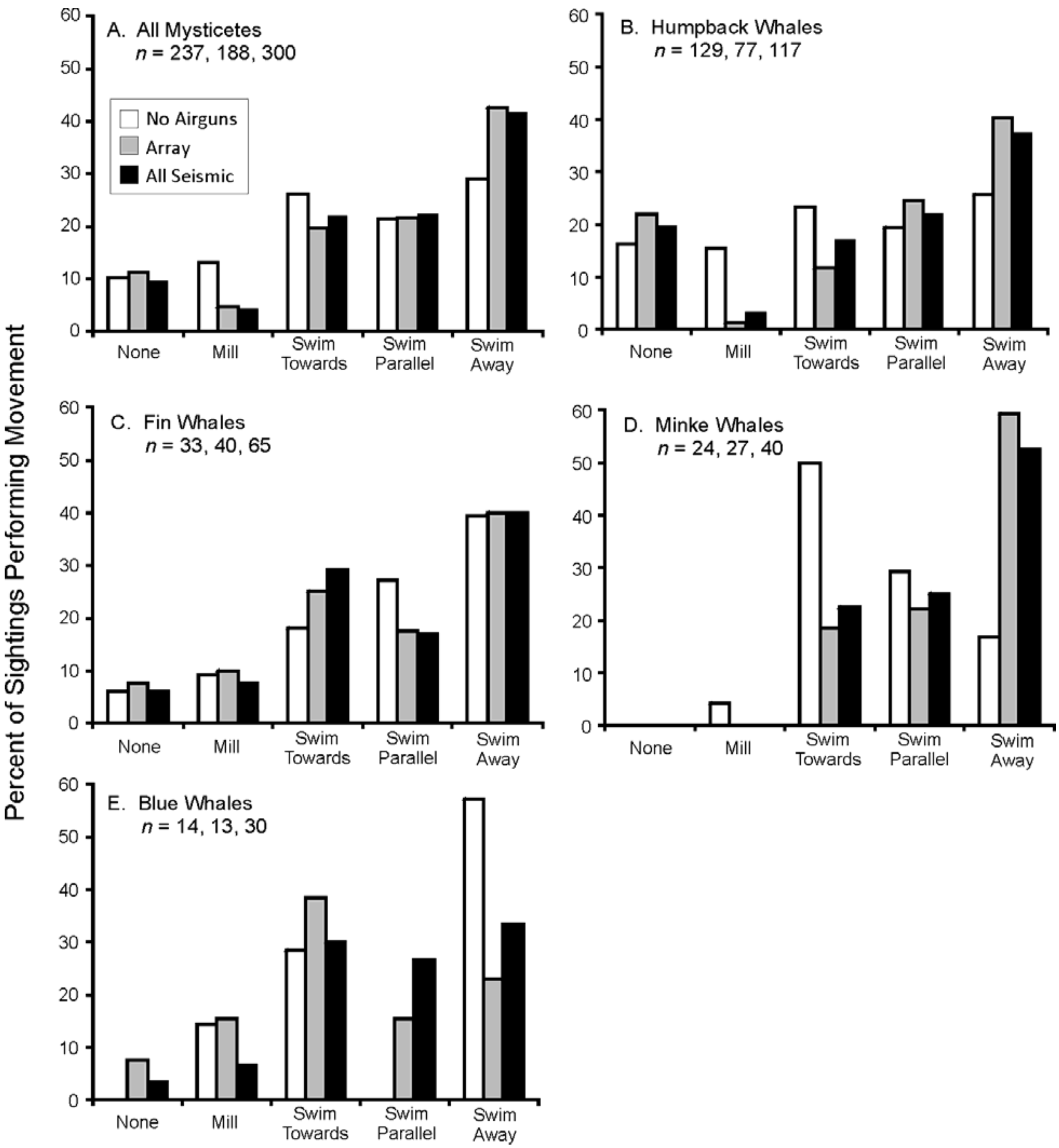

Figure 6. Percentages of mysticetes exhibiting various movement types during periods of No Airguns vs. Array and All Seismic. The three *n* values in each panel are the numbers of sightings observed with known movement types during periods of No Airguns, Array, and All Seismic, respectively.

There was however a tendency for more delphinids to swim away and fewer delphinids to swim towards the seismic vessel during periods of Single Airgun vs. No Airguns (χ^2 = 12.76, *df* = 4, *p* = 0.013). Movement types of delphinids did not differ significantly during Ramp Up vs. No Airguns (χ^2 = 4.10, *df* = 4, *p* = 0.392; Figure 9A).

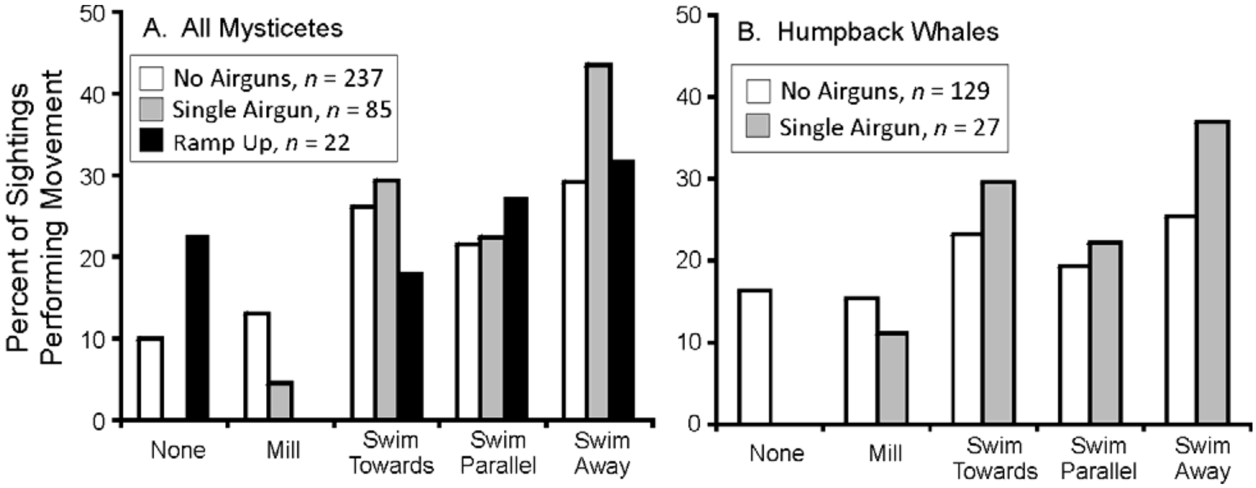

Figure 7. Percentages of A. All Mysticetes and B. Humpback Whales exhibiting various movement types during periods of A. No Airguns vs. Single Airgun and Ramp Up, and B. No Airguns vs. Single Airgun. The *n* values in each panel are the numbers of mysticete sightings observed with known movement types during various seismic categories.

Higher proportions of long-finned pilot whales (Array: 24.5% vs. No Airguns: 19.4%), Atlantic white-sided dolphins (36% vs. 22.7%), and common dolphins (27.8% vs. 23.1%) were observed swimming away during periods of Array vs. No Airguns (Figure 8 B,C, and D). Also, proportionally more Atlantic white-sided and common dolphins swam towards the seismic vessel during periods of No Airguns vs. Array. However, there were no significant differences in the proportions of sightings exhibiting various movement types during non-seismic vs. Array periods (long-finned pilot whales: χ^2 = 2.20, *df* = 4, *p* = 0.700; Atlantic white-sided dolphins: χ^2 = 5.84, *df* = 4, *p* = 0.211; common dolphins: χ^2 = 3.37, *df* = 4, *p* = 0.499). A significant difference was observed in the movement types of Atlantic white-sided dolphins during periods of All Seismic vs. No Airguns (χ^2 = 10.09, *df* = 4, p = 0.039). Long-finned pilot whales showed no obvious avoidance of the seismic vessel during Ramp Up (Figure 9B; χ^2 = 2.71, *df* = 4, p = 0.607) and Single Airgun operations (Figure 9B; χ^2 = 4.10, *df* = 4, *p* = 0.392).

Large Toothed Whales—There was no significant difference in the proportions of large toothed whales exhibiting various movement types during periods of No Airguns vs. Array (χ^2 = 0.70, *df* = 4, *p* = 0.951) and No Airguns vs. All Seismic (χ^2 = 6.47, *df* = 4, *p* = 0.167; Figure 10A). Proportionally more sperm whales milled and swam towards the seismic vessel and proportionally more sperm whales swam away during periods of Array vs. No Airguns (Figure 10B), but the differences were not significant (χ^2 = 4.18, *df* = 4, *p* = 0.382). The same trend was observed during periods of No Airguns vs. All Seismic (χ^2 = 8.83, *df* = 4, *p* = 0.066).

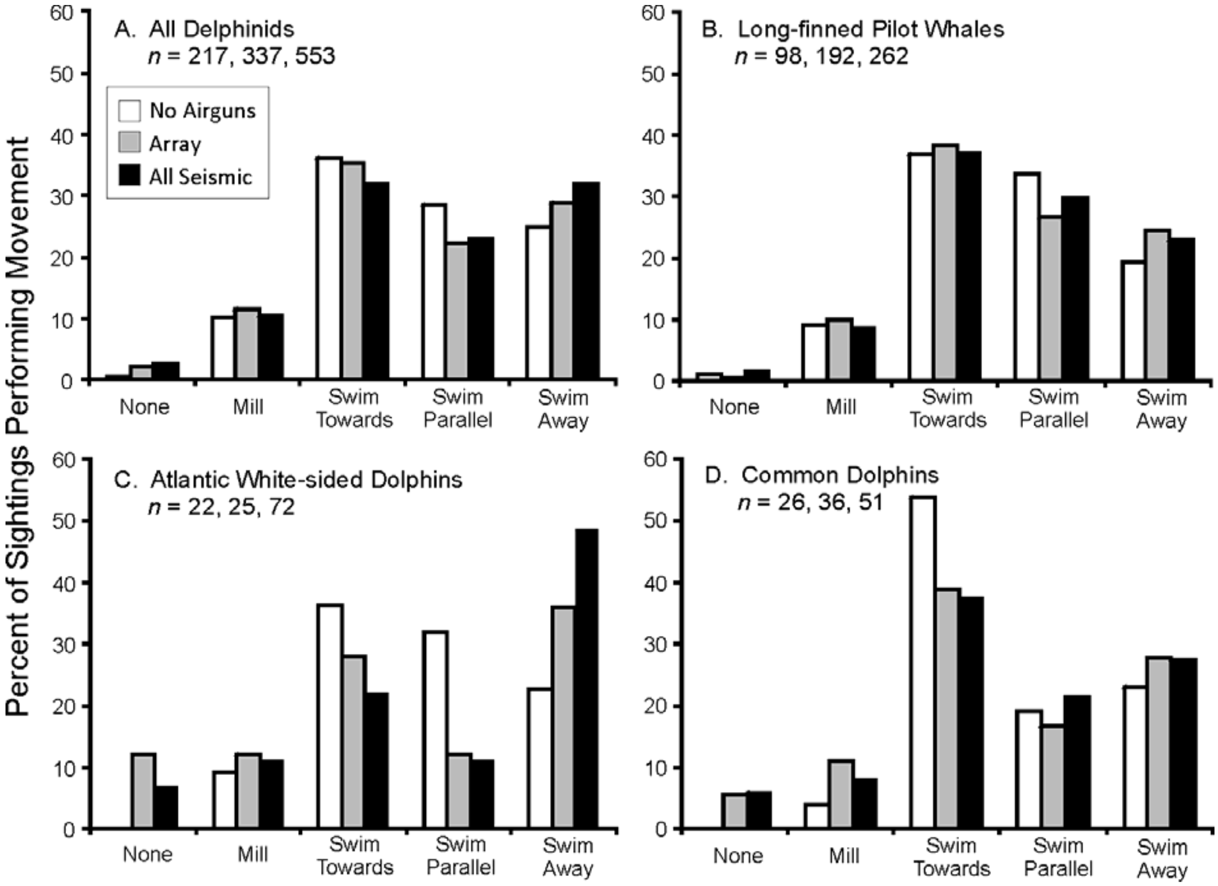

Figure 8. Percentages of delphinids exhibiting various movement types during periods of No Airguns vs. Array and All Seismic. The three *n* values in each panel are the numbers of sightings observed with known movement types during periods of No Airguns, Array, and All Seismic, respectively.

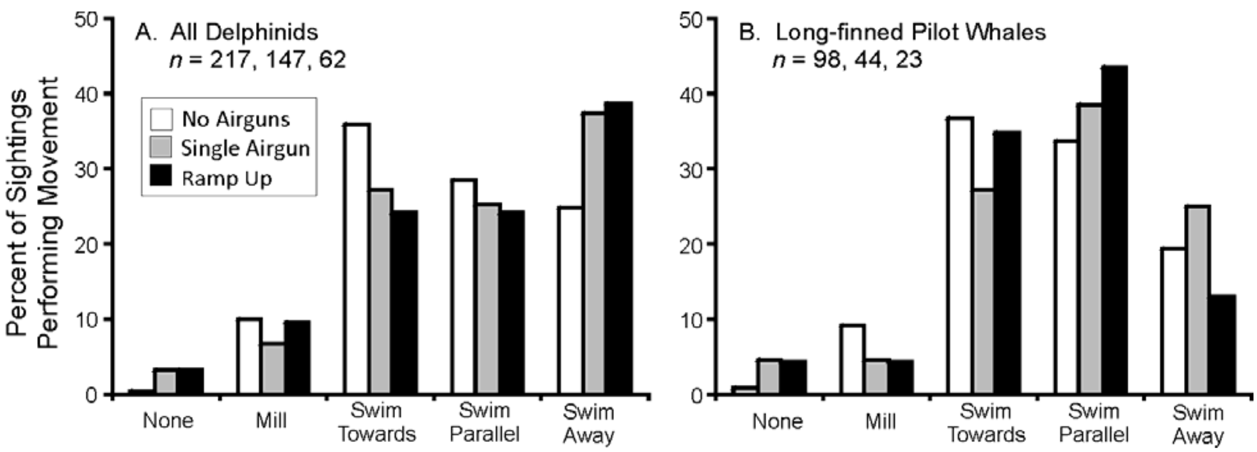

Figure 9. Percentages of delphinids exhibiting various movement types during periods of No Airguns vs. Single Airgun and Ramp Up. The three *n* values in each panel are the numbers of sightings observed with known movement types during periods of No Airguns, Single Airgun, and Ramp Up, respectively.

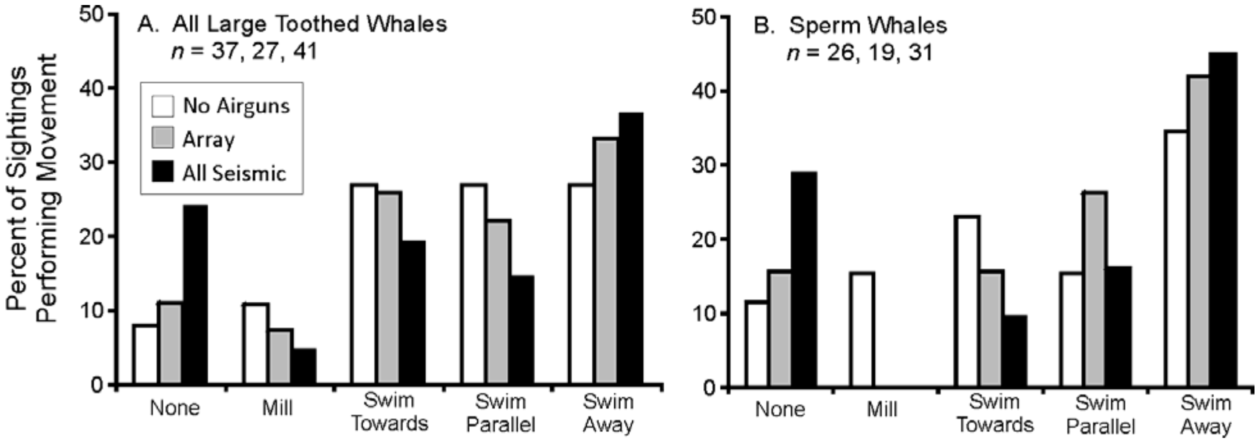

Figure 10. Percentages of large toothed whales exhibiting various movement types during periods of No Airguns vs. Array and All Seismic. The three *n* values in each panel are the numbers of sightings observed with known movement types during periods of No Airguns, Array, and All Seismic, respectively.

Species of Concern—As noted earlier, there is concern that beaked whales may respond more overtly to noise than other cetaceans. Thus, there is merit in examining the behavioural responses of this group of cetaceans more closely. There were 15 sightings of beaked whales within the study areas during the eight monitoring programs; 12 northern bottlenose whales, one Sowerby's beaked whale, and two unidentified beaked whale (identified as potential Sowerby's beaked whales) sightings. There was little evidence to indicate that these beaked whales responded overtly to airgun noise based on visual observations from the seismic vessels (Table 7). Of the seven beaked whale sightings during periods when the airguns were active, five sightings swam towards the vessel (at a medium or fast pace), one exhibited no movement, and one milled in front of the vessel. The CPAs during periods of Ramp Up and Array ranged from 63–1288 m. With the exception of one northern bottlenose whale that swam away slowly during periods of No Airguns, beaked whales generally swam parallel to or towards the vessel. The CPAs during periods of No Airguns ranged from 20–751 m.

There were 61 sightings (totalling 68 individuals) of endangered blue whales recorded in the study areas. Based on behavioural data, there was no obvious evidence that blue whales responded to airgun noise by moving away from the vessel. The proportion of blue whale sightings with known movement type observed swimming away from the vessel was higher during periods of No Airguns (57.1% of 14 sightings) than during Array (21.4% of 14 sightings). When a single airgun was operating, 42.9% of 14 sightings were recorded as moving away from the vessel. Similar proportions of blue whales milled and swam towards the vessel during both non-seismic and seismic periods. There were three blue whale sightings during Ramp Up with known movement type — two were noted as swimming parallel and the other was swimming away from the vessel. Blue whales were most frequently recorded as initially swimming at a slow pace and the subsequent behaviour was most frequently diving — this trend was observed during both non-seismic and seismic periods.

Table 7. Summary of observational data for beaked whale sightings recorded during the eight monitoring programs.

Beaked Whale Sighting	No. of Individuals	Seismic Category	Initial Distance (m)	CPA (m)	Movement Type	Behavioural Description
Northern bottlenose whale	1	No Airguns	838	501	Swim Away	Swam slowly away from vessel while blowing.
	2	No Airguns	300	25	Swim Parallel	Swam slowly near vessel, then dove.
	2	No Airguns	50	50	Swim Parallel	Swam slowly near vessel.
	3	No Airguns	400	400	Swim Parallel	Erratic movements.
	4	No Airguns	800	150	Swim Parallel	
	3	No Airguns	300	50	Swim Towards	Swam rapidly toward bow and were not resighted.
	2	No Airguns	50	20	Swim Parallel	Appeared suddenly near bow and were not resighted.
	1	No Airguns	751	751	Swim Towards	Swam at fast pace towards ship and surfaced three times.
	5	Ramp Up	830	638	Swim Towards	Swimming at medium pace, then dove.
	6	Ramp Up	2000	1000	None	Vessel approached the whales.
	6	Array	700	600	Swim Towards	Blowing repeatedly, porpoising--swimming quickly.
	2	Array	751	200	Swim Towards	Swam fast on a continous course intercepting vessel's trackline, not resighted.
Sowerby's beaked whale	4	Array	1768	1288	Milling	Milling in front of vessel, eventually dove.
Unidentifed beaked whale	1	Array	300	150	Swim Towards	Swam across bow at medium pace.
	1	Array	1669	63	Swim Towards	Swam at fast pace with surfacings.

Summary of Mitigation Measures Implemented

The key mitigation measures MMOs were required to implement were delay of ramp up and shutdown of the airgun(s) when certain species of cetaceans entered a defined safety zone (500 m for all seismic programs with the exception of the Scotian Slope program where a 700-m safety zone was implemented). The crews of the seismic vessels ensured that ramp ups were consistently implemented for the appropriate duration (i.e., 30 min); MMOs monitored the ramp-up duration and timing. During the eight monitoring programs, ramp up was delayed twice because a cetacean (humpback whale and a fin or sei whale) was observed in or was observed approaching the safety zone (500 m).

The airgun arrays were shut down on two occasions because an endangered cetacean (blue whale) was observed within the safety zone; both shutdowns occurred during the Laurentian Sub-basin seismic program. During one occasion, a single blue whale surfaced 100 m in front of the seismic vessel and was observed swimming away from the ship at a medium pace. Prior to the shutdown, the airgun arrays had been operating at full volume for 1.5 h. During the second occasion, a single blue whale approached the seismic ship to a CPA of 396 m before slowly swimming away from the vessel; the whale was initially sighted ~1500 m away. Prior to the shut down, the array had been operating at full volume for at least 1 h.

Discussion

During the monitored seismic programs, some cetacean groups and species exhibited localized avoidance as evidenced by reduced sighting rates, increased sighting distances, and movements away from the seismic vessel during periods when airgun(s) were operating. Of the three cetacean groups considered here, mysticetes were consistently seen farther away, at lower rates, and moving away from the seismic vessel during airgun operations. This is not surprising given that behavioural and anatomical evidence indicates that baleen whales hear well at frequencies below 1 kHz (Richardson et al., 1995; Ketten, 2000), where most of the energy from airgun pulses is focused. The hearing systems of baleen whales are undoubtedly more sensitive to low-frequency sounds than those of small toothed whales that have been studied directly. Thus, baleen whales are likely to hear airgun pulses farther away than odontocetes; at closer distances, airgun sounds may seem more prominent to baleen than to toothed whales. As mysticete sighting rates during this study were lowest during full-array operations, these whales may exhibit the strongest avoidance of a seismic vessel when received sound levels are relatively higher, i.e., when the maximum number of airguns are operational. The significantly-reduced sighting rates during full-array operations suggest that some baleen whales avoided the seismic vessel by several kilometres, beyond the visual detection range of the observers.

Information available from other studies indicates that mysticetes generally tend to avoid operating airguns, but avoidance radii are quite variable among species, locations, and whale activities (reviewed by Richardson et al., 1995; Gordon et al., 2004). Blue, sei, fin, and minke whales often have been reported in areas ensonified by airgun pulses (e.g., Stone, 2003; MacLean & Haley, 2004; Stone & Tasker, 2006). Sightings by observers on seismic vessels during large-source seismic surveys off the U.K. from 1997 to 2000 suggest that during times of good sightability, sighting rates for mysticetes (mainly fin and sei whales) were similar when large arrays of airguns were active vs. silent (Stone, 2003; Stone & Tasker, 2006). However, these whales tended to exhibit localized avoidance, remaining significantly farther (on average) from the airgun array during seismic operations compared with non-seismic periods (Stone & Tasker, 2006). Stone and Tasker (2006) also noted that baleen whales as a group were more often oriented away from the vessel while a large airgun array was in operation compared with periods when the airguns were silent.

Previous studies seem to indicate that humpbacks show little reaction to seismic operations insofar as visual observations from seismic vessels can detect. McCauley et al. (1998, 2000) found that the overall distribution of humpbacks migrating through their study area off Western Australia was unaffected by the full-scale seismic program (16-airgun, 2678-in^3 array), although localized displacement varied with pod composition, behaviour, and received sound levels. Humpback whales on their summer feeding grounds in southeast Alaska did not exhibit persistent avoidance when exposed to seismic pulses from a 1.64-L (100 in^3) airgun, although some humpbacks seemed "startled" at received levels of 150–169 dB re 1 μPa (Malme et al., 1985). Malme et al. (1985) concluded that there was no clear evidence of avoidance, despite the possibility of subtle effects, at received levels up to 172 dB re 1 μPa on an approximate rms basis. For wintering humpback whales off Angola, there were no significant differences in sighting distances or rates when a 24-airgun array (up to 5085 in^3) was operating vs. silent (Weir, 2008).

During the present study, delphinids were consistently seen within several kilometres of the seismic vessel during periods with and without airgun activity. However, some delphinids appeared to exhibit localized avoidance of the source vessel. Based on initial sighting distances, delphinids were detected 200–300 m farther away from the source vessel during seismic vs. non-seismic periods. However, an examination of the CPA distances did not yield significant differences. These same trends in sighting distances were observed for long-finned pilot whales, which accounted for nearly half (44%) of the delphinid sightings in this study. This suggests that some delphinids either approached the source vessel or allowed the vessel to approach closer during periods when the airguns were active. In fact, proportionally more delphinids were observed swimming toward the seismic vessel than all other movement types during periods with and without airguns. On numerous occasions in the Scotian Slope and Orphan Basin study areas, long-finned pilot whales were observed approaching the bow of the seismic ship, then swimming towards the stern, and subsequently diving just inside the equipment that supports the streamers, and swimming back towards and amongst the streamers. On two occasions when the airguns were active, pilot whales approached the airgun array within ~150 m. These types of observations (i.e., close approaches of delphinids during periods of seismic) have also been noted in other studies (e.g., Stone, 2003; Stone & Tasker, 2006).

Any localized avoidance detected in this study did not lead to a significant decrease in sighting rates of delphinids. Observations of small odontocetes in other areas have yielded variable results but in general there is a tendency for most delphinids to show some avoidance of operating seismic vessels (e.g., Goold, 1996 a,b,c; Calambokidis & Osmek,1998; Stone, 2003; Holst et al., 2006; Stone & Tasker, 2006; Weir, 2008; Richardson et al., 2009). The degree of this avoidance seems to be variable amongst species, and some individuals show no apparent avoidance. However, in most cases, the avoidance radii for delphinids appear to be small, on the order of 1 km or less.

For large toothed whales (sperm and beaked whales) sighted during the current study in the northwest Atlantic, sighting rates and sighting distances were similar during periods when airguns were active vs. silent. Also, there was no tendency for large toothed whales to swim away from the seismic vessel during airgun operations. Although the number of beaked whale sightings was limited, there was no indication based on behavioural observations that these whales responded overtly to airgun sounds. Sperm whales, which accounted for 76% of toothed whale sightings, also exhibited no obvious avoidance of the seismic vessel when airguns were active. Similarly, extensive data from vessel-based monitoring programs in the U.K., Gulf of Mexico, and off Angola suggest that sperm whales in those areas show little evidence of avoidance or behavioural disruption in the presence of operating seismic vessels (e.g., Stone, 2003; Stone & Tasker, 2006; Weir, 2008; Barkaszi et al., 2009). A detailed controlled exposure experiment (i.e., Sperm Whale Seismic Study or SWSS) in the Gulf of Mexico also demonstrated that sperm whales showed no discernable horizontal avoidance of airgun pulses. However, some whales showed changes in diving and foraging behaviour during full-array exposure, possibly indicative of subtle effects on foraging (e.g., Jochens et al., 2008; Miller et al., 2009; Tyack, 2009).

Observational data from the current study was also used to examine the effectiveness of the ramp-up procedure. Ramp up has become a standard mitigation procedure to alert marine mammals in a seismic survey area of increasing sound levels. Use of the ramp-up procedure is based on the assumption that some marine mammals will move away from the airgun sounds before levels are high enough to potentially cause harm. However, some authors (e.g., Pierson et al., 1998; Weilgart, 2007) have suggested that ramping up a high-energy source could actually be harmful if animals habituate to the gradual increase in sound and remain in the area during the initial phases of ramp up until injurious levels are reached. It seems unlikely that baleen whales and other species that tend to avoid industrial sounds would habituate to ramp up.

In the absence of specific evidence of efficacy, ramp up is viewed primarily as a reasonable measure. The effectiveness of the ramp-up procedure has been questioned by many researchers (e.g., Richardson et al., 1995; Pierson et al., 1998; Barlow & Gisiner, 2006) and is currently listed as a research topic of interest by an industry research fund, the E&P Sound and Marine Life Joint Industry Programme (JIP; http://www.soundandmarinelife.org). Results from this study suggest that the effectiveness of ramping up varies with species (and likely circumstances) and may be largely ineffective for some odontocetes. Based on sighting distances, ramp up (over a 30-min period) appeared to be effective at deterring some species from the immediate area around the seismic vessel. Mysticetes were observed significantly farther from the seismic vessel during ramp up compared with periods when the airguns were silent. In particular, significant differences in sighting distances during ramp up were detected for blue whales. However, as the sample size of blue whale sightings during ramp-up periods was small ($n = 5$), the results should be interpreted with caution. Sighting distances of delphinids and toothed whales during periods when the airgun array was ramping up were similar to distances during non-seismic periods.

This study examined the responses of cetaceans to large-source seismic operations in the northwest Atlantic. Although visual observations are most often used as a tool for monitoring cetacean responses, they have numerous limitations. Visual observations are ineffective during periods of poor visibility (e.g., fog, rough seas, darkness), but can also be ineffective for species that are secretive or spend little time at the surface. In Atlantic Canada, visual observations are often impeded by prevailing fog and rough seas. Thus, quite often, only the immediate area around a seismic vessel can be monitored effectively with visual monitoring. In order to examine the full extent of disturbance, visual observations are best complemented by additional monitoring methods, such as aerial surveys or passive acoustic monitoring. Aerial surveys allow for a much greater area to be examined for disturbance of cetaceans by seismic programs. Aerial surveys conducted in the Canadian Beaufort Sea found that sighting rates of belugas were significantly lower at distances of 10–20 km compared with 20–30 km from an operating airgun array (Miller et al., 2005). The low number of beluga sightings by observers on the seismic vessel seemed to confirm that there was a strong avoidance response by these whales, but the extent of avoidance would not have been known without the aerial effort. Passive acoustic monitoring may also be able to provide a more detailed examination of cetacean responses to seismic programs, as the detection range for calling cetaceans is much greater compared with the visual detection range of observers, especially during periods of poor visibility.

Although disturbance effects, such as avoidance, are mostly expected to be relatively short-lived (e.g., occurring during the season of the seismic program but not in subsequent years), it remains unknown whether seismic sounds could have long-term or injurious effects on cetaceans. Some species may be more sensitive to airgun sounds and more rigorous monitoring and mitigation methods may be required for these species. It is essential that we increase our knowledge about the effects of sound exposure, as from airgun arrays, on cetaceans, in order to ensure that the currently used monitoring and mitigation measures are appropriate and effective.

Acknowledgments

Funding for the preparation of this manuscript was provided by the Environmental Studies Research Funds (ESRF). D. Taylor managed the project on behalf of the ESRF and reviewed various drafts of this report, along with J. Lawson (DFO) and M. Thillet (EnCana). Monitoring efforts were funded by Chevron Canada Limited and its Co-venturers: ExxonMobil Canada Ltd., Shell Canada Limited and Imperial Oil Resources Ventures Limited (Orphan Basin); ConocoPhillips Canada Resources Corporation (Laurentian Sub-basin); Marathon Canada Petroleum (Scotian Slope); and Husky Energy Inc., Petro-Canada, and Statoil Hydro Canada Exploration & Production Inc. (Jeanne d'Arc Basin). P. Abgrall, M. Bentley, T. Elliott, M. Force, R. Harris, D. Hauser, M. Holst, C. Jones, T. Lang, B. Mactavish, G. Miller, V. Moulton, H. Patterson and L. Sheppard (all of LGL) were the biologists on the environmental monitoring crews. R. Clarke, E. Jorgensen, G. Sears, R. Strickland, and L. Williams were the fisheries observers on the vessels. The ships' crews were very helpful and supportive of the MMOs on the seismic vessels. We thank R. Buchanan and R. Martin of LGL for logistical support during the field work. M. Fitzgerald and T. Elliott assisted with data analysis and R. Buchanan (all of LGL) reviewed a draft of this report.

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