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Observations on the Behavioral Responses of Bowhead Whales (*Balaena mysticetus*) to Active Geophysical Vessels in the Alaskan Beaufort Sea

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ABSTRACT. The responses of bowhead whales to controlled approaches by geophysical vessels producing airgun blasts were observed during the course of four field experiments conducted in the Alaskan Beaufort Sea in September 1984. Behavioral responses included shorter surfacing and dive times, fewer blows per surfacing, longer blow intervals and subtle to overt changes in surface behaviors. Subtle behavioral responses occurred at 3.5 and 8.2 km with received airgun noise levels of 142 and 157 dB respectively (all levels in dB re 1μPa). Partial avoidance (i.e., some whales leaving the observation area while others remained) occurred at ranges of 3.5 and 7.6 km, with sound levels of 142 and 158 dB respectively. Total avoidance (i.e., all whales leaving the observation area) occurred at 1.3, 7.2, 3.5 and 2.9 km, with corresponding sound levels of 152, 165, 178 and 165 dB. The similarities among experiments reported here support the conclusion that short-term behavioral changes occur when bowhead whales are exposed to airgun blasts from approaching geophysical vessels at ranges <10 km. These disturbance effects wane within one hour after a disturbance; long-term effects on social, behavioral or physiologic parameters are not known at this time.

Key words: bowhead whale, *Balaena mysticetus*, geophysical vessel, bioacoustics, airguns

RÉSUMÉ. Au cours de quatre expériences sur le terrain, menées dans la mer de Beaufort de l'Alaska en septembre 1984, on a étudié le comportement des baleines franches en réponse à l'approche contrôlée de navires de prospection géophysique qui émettaient des ondes de choc à l'aide de canons à air. Parmi les comportements provoqués, on a remarqué une diminution du temps à la surface et du temps en plongée, une diminution du nombre de souffles par remontée à la surface, une augmentation de l'intervalle entre les souffles ainsi que des changements dans le comportement à la surface, allant de peu visibles à nettement visibles. Les modifications peu visibles du comportement ont été observées à 3,5 et 8,2 km, alors que le niveau de bruit des canons à air atteignait respectivement 142 et 157 dB (Les niveaux en dB ont tous une pression de référence de 1 μPa). Une fuite partielle (c.-à-d. que quelques baleines ont quitté la zone d'observation alors que d'autres y sont restées) a été observée à des distances de 3,5 et 7,6 km avec des niveaux de bruit respectifs de 142 et 158 dB. Une fuite totale (c.-à-d. que toutes les baleines ont quitté la zone d'observation) a été observée à 1,3, 7,2, 3,5 et 2,9 km, avec des niveaux de bruit correspondants de 152, 165, 178 et 165 dB. Les ressemblances entre les expériences rapportées ici soutiennent la conclusion que des changements dans le comportement à court terme se produisent quand les baleines sont exposées aux ondes de choc du canon à air des navires de prospection géophysique, à des distances inférieures à 10 km. Ces effets dus à la perturbation disparaissent dans l'heure qui la suit, mais on ne connaît pas encore les effets à long terme sur les paramètres sociaux et physiologiques ainsi que sur ceux du comportement.

Mots clés: baleine franche, *Balaena mysticetus*, navire de prospection géophysique, bioacoustique, canons à air

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INTRODUCTION

The bowhead whale, *Balaena mysticetus*, is a large baleen whale that resides in or near icy polar waters. Of the four stocks recognized, the largest is the Western Arctic Stock (ca. 7200; International Whaling Commission, 1988), which migrates annually from wintering areas in the western Bering Sea to summer feeding areas in the eastern Canadian Beaufort Sea (Ljungblad *et al.*, 1986). In the fall (September, October), bowheads migrate west through the Alaskan Beaufort Sea and pass through regions being explored or developed for oil resources. The fall migration coincides with the only ice-free period of the year. These open water conditions are of particular importance to geophysical companies that conduct marine seismic surveys to detect optimal drilling sites for oil companies. During a typical seismic survey, noise pulses produced by airguns (hereafter, airgun blasts) with source levels of 245-252 dB are emitted every 10-15 s from an airgun array towed by a geophysical vessel (Barger and Hamblen, 1980). Geophysical vessels cannot operate unless sea ice is absent from the area to be explored. The shortness of the ice-free season, and the need to complete seismic explorations in such a brief period (generally less than six weeks), forces numerous vessels to operate simultaneously within the bowhead migration corridor as the whales pass through the Beaufort Sea.

The potential effects of geophysical seismic survey activities on westward migrating bowheads in the Alaskan Beaufort Sea have been a concern of the U.S. Minerals Management Service (MMS) and the U.S. National Marine Fisheries Service (NMFS). In response to this concern the MMS, with advice and assistance from the NMFS, implemented a program to obtain behavioral observations of whales in the presence of airgun blasts and to monitor and regulate seismic exploration in the Alaskan Beaufort Sea each fall, 1981-84. In 1981, behavioral data were collected on whales located at varying distances from operating geophysical vessels (Fraker *et al.*, 1985). In 1982 and 1983, systematic grid surveys were flown in the Alaskan Beaufort Sea near actively "shooting" geophysical vessels (Reeves *et al.*, 1983; Ljungblad *et al.*, 1984). Visual observations of whales in the presence of seismic sounds were supplemented with acoustic sonobuoys to listen to and record underwater sounds made by the vessels, their airguns and bowheads. In addition, observations of whales that were not near operating geophysical vessels were made on an opportunistic basis.

The results of these studies and similar work conducted in the Canadian Beaufort Sea (Richardson *et al.*, 1984) supported the contention that bowheads seldom reacted to working geophysical vessels when they were over 10 km away. Because few additional conclusions could be drawn, a dedicated aircraft and scientific team was assigned to conduct controlled field experiments designed to collect data on the responses of bowheads to the direct approach of active geophysical vessels operating in the Alaskan Beaufort Sea in 1983 and 1984. Due to the severe ice conditions that prevailed in the fall of 1983, no experiments were undertaken. In fall 1984, four experiments were success-

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fully completed by the Naval Ocean Systems Center (NOSC), with support provided by the MMS. The experiments were conducted under the provisions of a scientific research permit issued to MMS by NMFS and with the cooperation of geophysical vessels operating in the Alaskan Beaufort Sea. The findings of the experiments and comparisons with similar studies are presented in this paper.

METHODS

The principal objectives of the direct approach geophysical vessel response experiments were to gauge bowhead behavioral response to airgun blasts and to determine at what distance from an active vessel subtle, partial and total avoidance behaviors or other manifestations of disturbance were likely to be displayed. Such information is vital in defining a "zone of influence" that potentially exists around an active geophysical vessel emitting low-frequency, high-energy airgun blasts.

The general approach in conducting the experiments was to use an aircraft and scientific team to locate bowheads and observe and measure the behavior of the whales while recording waterborne noise and environmental variables, and at the same time control by radio communication the approach and operation of the participating geophysical vessel.

Aircraft Operation

The survey aircraft was a deHavilland Series 300 Twin Otter, capable of 9 h of continuous flight and equipped with bubble windows to enhance viewing, a radar altimeter for precise altitude determination, and a Global Navigation System (GNS) 500A Series VLF computer to provide position updates accurate to ±0.6 km (0.37 nm)·h^{-1} of flying. Observations from the aircraft were conducted at an altitude of 457 m (1500 ft) or greater to minimize possible disturbance to the whales under observation (Richardson *et al.*, 1984). An airspeed of approximately 100 knots (204 km·h^{-1}) was maintained while searching and circling. When ice floes were present in an observation area, they were used as reference points while the whales were submerged. When suitable natural reference points were not available, Fluorescein dye markers or smoke flares were dropped from the aircraft.

Flight data were stored on a portable computer interfaced to the aircraft's GNS. The computer was programmed to automatically input the following variables at 4 min intervals: entry number, time (local and GMT), latitude, longitude and altitude. Specific comments, such as number of whales, behaviors, change in environmental conditions, etc., could be entered at any time during a flight. The computer was accessed to a serial plotter/printer to provide a hard copy of all data stored in the computer's memory. In addition, crew members were linked to a common communication system and recorder to insure that all comments were heard and recorded. Additional onboard equipment included 35 mm single-lens reflex cameras with 70-210 mm zoom lenses, ASA-200 color slide film, binoculars, clinometers, stopwatches and a video recorder with 75 mm lens (6:1 zoom ratio).

Sonobuoys

Sonobuoys are expendable underwater sound measurement devices that can be reliably deployed from an aircraft. In this study, the sonobuoys were used to obtain calibrated airgun blast levels from geophysical vessels, as well as for recording bowhead whale sounds. Three types of sonobuoys were used: the AN/SSQ-57A and 41B for whale sounds and airgun detection, and the AN/SSQ-41A (modified) for recording airgun blasts. Sonobuoy signals were received via a FM link by a modified USQ-42 receiver and recorded on a Nagra IV-SJ analog tape recorder.

Sonobuoys are designed to detect and amplify extremely low levels of underwater sound and therefore become overloaded when exposed to the high levels generated by the seismic air guns. To reduce the overloading problem, modifications were performed on the AN/SSQ-41A to allow it to operate in a normal manner in the presence of signals up to 165 dB; levels in excess of 165 dB were calculated and plotted from undistorted measurements. The 41A was chosen because the buoy could be disassembled, modified and resealed without significantly affecting its overall reliability.

The bulk of the modification effort was centered on the desensitization of the sonobuoy main amplifier circuitry, because it was determined that the hydrophone array and its associated preamplifier were capable of passing a 250-Hz sine wave equivalent to 190 dB without significant distortion. The main amplifier board distorted the same signal at approximately 140 dB. With a design goal of 165 dB operation in mind, the preamplifier gain was reduced by 16 dB and an attenuating resistor was inserted in the signal path to further reduce the amplitude of the incoming pulse. In addition, the automatic gain control circuit was disabled and the buoy's frequency response was flattened to ±0.5 dB from 25 to 1000 Hz.

To insure that the data quality was consistent regardless of the buoy used, a calibration was performed on each buoy prior to use in the field. The calibration effort was approached on three levels: electronic, water tank and open ocean. The electronic calibration, performed on each unit, consisted of injecting a calibrated sine wave into the hydrophone preamplifier and stepping the frequency from 20 to 1000 Hz. This allowed precise adjustment of the system gain as well as confirmation of the electronic frequency response. Random buoys were then chosen to undergo a complete system calibration, performed in a water tank using a variable sound source and calibrated hydrophones. Sonobuoy hydrophone characteristics were also confirmed at NOSC's TRANSDEC transducer calibration facility. Finally, several of the modified sonobuoys were tested in the open ocean, again using a variable sound source and calibrated hydrophones.

Analysis of Airgun Blasts

The analog tape recordings were analyzed in the laboratory in both the time and frequency domains, using the transient-capture mode of a Spectral Dynamics Model 375 spectrum analyzer. With an analysis band width set to 500 Hz, the SD375 digitized the input signal at a rate of 1280 samples·s^{-1}. The memory period, or time width of the time-domain signal, was 0.8 s, which allowed for a total of 1024 samples for each seismic pulse analyzed. To examine the signal frequency components, the SD375 performed a Fast Fourier Transform on the time data. The transformed data, combined with a weighting function (which limits spurious frequency components) was presented as a spectrum of 400 cells, with a cell band width of 1.25 Hz.

The analysis of the data collected from the experiments had to be approached carefully due to the configuration of the modified 41A's transducers. Frequency-dependent vertical directionality is introduced into the system when a linear array of hydrophones is used, which results in a rejection of spurious noise due to reflections from the ocean floor and surface. This is a distinct advantage for the buoy's intended naval mission, but potentially causes difficulties in interpretation of the data in our application. However, the hydrophone is specified to operate omnidirectionally in the vertical plane to ±3 dB between 10 and 300 Hz and undergoes a "soft" transition to full directionality between 300 and 1540 Hz, so data collected to 300 Hz can be considered valid for this analysis.

The airgun wave form was stored and plotted in the time domain with linear scaling appropriate to the size of the signal. In keeping with the analysis procedure adopted by Greene (1984), the root-mean-square (rms) level of the signal in dB re 1 volt was determined by measuring and squaring the peak value of the highest amplitude component of the blast, dividing by 2, and computing 10 times the logarithm of the result. The sound pressure level in dB was then determined by comparing the signal to a calibration standard.

In interpreting the results of this analysis, it is important to consider several key points. To describe the characteristics of a pulse-type signal using the procedure adopted by Greene (1984) it is necessary to make the assumption that the largest peak in the wave form is sinusoidal in nature, which is generally the case with seismic-like signals. In addition, the sound pressure levels reported are rms values and are directly related to the instantaneous peak level of the seismic signal. This peak value did not persist for the entire duration of the airgun discharge cycle, and thus does not provide information as to the overall energy contained in the pulse (as reported by Malme *et al.*, 1983). Finally, the peak value of the signal tended to be quite variable from one pulse to the next, undoubtedly due to transmission anomalies between the source and the receiver. In an effort to smooth out some of this variability, the peak levels represent an average of 5 successive seismic pulses, chosen such that they bracketed the pulse at the reported range.

Coordination with Geophysical Vessels

Arrangements were made in advance of the field season for the research team on board the aircraft to establish direct marine-band communications with the seismic vessels operating in the Beaufort Sea. In addition, the research team communicated daily with the geophysical base camps of Western Geophysical Co. and Geophysical Service Inc. in Deadhorse. This close coordination between the aerial research team and the cooperating geophysical companies was designed to provide reasonable notice to vessel operators of when and where a seismic response experiment might occur. Both parties agreed to the following experimental protocol. Whenever the necessary minimum field conditions for an experiment were met, the operator of the vessel nearest the whales under observation was notified and requested to operate the vessel as required to conduct an experiment under the conditions of the scientific research permit.

Experimental Design

Certain conditions were required for the successful completion of a direct approach experiment. The fall bowhead migration and concomitant whale behaviors (preferably feeding or milling) needed to occur in an area of open water with acceptable environmental conditions and the presence of cooperating geophysical vessel(s). Adequate visibility (little or no fog or precipitation and high cloud ceiling(s), low sea state (Beaufort 03 or less) and little or no wind were necessary to ensure the completion of an experiment from start to finish.

The experimental procedure was to guide a participating geophysical vessel, operating as if conducting a full-scale geophysical survey, directly toward bowheads under observation by the aerial survey crew. Pre-experiment, experiment and post-experiment scenarios were desirable. Pre-experiment observations began once a group of whales (3-20 individuals) was located. During the initial 1-3 h of pre-experiment observations, vessels in the area were contacted and, if possible, one was selected to participate in the experiment. The experimental observations commenced as the participating vessel began its approach. If the whales under observation remained in the same general region in which they were first located and continued with their first-observed behaviors until after the participating vessel began its active approach, it was assumed that there was negligible disturbance from other sources. Based on earlier studies (Fraker *et al.*, 1982; Reeves *et al.*, 1983; Richardson *et al.*, 1984; Ljungblad *et al.*, 1984), it was assumed that overt behavioral responses would not occur until the vessel had closed to approximately 10 km. Therefore 10 km was selected as the range beyond which behavioral responses would be negligible, and observed behaviors were classified as pre-experiment. Post-experiment observations, following each "active" approach, were dependent upon fuel reserves and remaining daylight. Whenever possible, observations were made in half-hour increments after the discontinuation of the participating vessel's airgun blasts.

When the vessel had approached to within 1 km of the whales or, in the judgment of the investigators, when all the whales were responding adversely to the vessel, the operator of the vessel was asked to shut down its airguns. One condition of the scientific research permit stipulated that seismic vessels were not to approach whales closer than 1 km during the experiments. Therefore, mid-course changes in vessel direction were made to ensure an approach of 1 km or greater. Additional changes in the vessel's course and its operational status were made only to avoid collisions with ice or other potential hazards.

Analysis of Behavioral Data

Whale positions and aircraft altitude were taken from the computerized flight data, while behavioral observations were transcribed from audiotape onto data recording sheets in the laboratory. Measures of surfacing, respiration and dive characteristics were used to identify behavior changes associated with the presence or absence of airgun blasts. We adopted the five major quantitative behavioral characteristics used by Reeves *et al.* (1983), Richardson *et al.* (1984) and Würsig *et al.* (1984a) to describe the surface/dive profiles of bowhead whales. These are: 1) interval between blows (respiration), 2) number of blows per surfacing, 3) length of time at the surface (surface interval), 4) length of time below the surface (dive time), and 5) blow rate (the number of blows divided by the combined length of the surface interval and subsequent dive).

The first three of these behavioral characteristics can be ascertained while watching individual whales that cannot be re-identified. Dive time, however, requires that a whale be recognized by some distinguishing feature or features, i.e., distinctive white chin patches, scars or other reliable marks on the head, back or flukes. Since dive times required the identification of individuals at the initiation of a dive and at the subsequent moment of surfacing, they were gathered less frequently. Blow rate, calculated from a complete surface and subsequent dive cycle, was also infrequently obtained. Interval between blows, on the other hand, was the only characteristic that did not require observation of a full surfacing, and consequently was the most frequently collected datum.

Observations during each experiment were sorted into categories for comparison: pre-experiment (no airgun sounds or a source greater than 10 km away), experiment (sound source 10-5 km away), close-experiment (sound source less than 5 km away) and post-experiment (0-30 and 30-60 min following the vessel departure). In some instances sample sizes for individual categories obtained during an experiment were too small for meaningful statistical analysis. In these cases, the data from similar categories were pooled to obtain sample sizes adequate for analysis. Subsequently, the data for all adult whales were pooled and sorted into either pre-experiment (no airgun sounds present or with the source at a distance of greater than 10 km) or experiment (exposed to airgun blasts whose source was at a range of 10 km or less) categories. These data were then analyzed for differences between pre-experiment and experimental conditions.

Parametric and nonparametric statistical tests were employed as appropriate and are referred to in the sections in which they appear. All statistical tests used may be found in Sokal and Rohlf (1981) and Zar (1984). Sample sizes of behavioral characteristics for cow-calf pairs were too low for statistical analysis but are presented for pre-experiment through post-experiment conditions for subjective comparison.

RESULTS

Experimental Results

Experiment No. 1: On 18 September, the first direct approach experiment, toward a group of eight whales, was undertaken approximately 20 km north of Barter Island, with cooperation from the geophysical vessel *Western Beaufort* (Fig. 1:1). The *Western Beaufort* is a "high resolution" geophysical vessel equipped with a single 11 311 cm^3 (80 in^3) airgun, which fired once every 4 s. The calculated source level for the seismic blasts produced by this airgun is approximately 220 dB at 1 m (Barger and Hamblen, 1980). Sonobuoys dropped in 46 m water near the whales provided data on airgun blast levels, vessel noise and ambient levels throughout the 5.5 h experimental period. During the vessel approach, airgun blast levels ranged from 132 dB at 9.7 km to 152 dB at 1.3 km, when the airguns were shut down (Fig. 2).

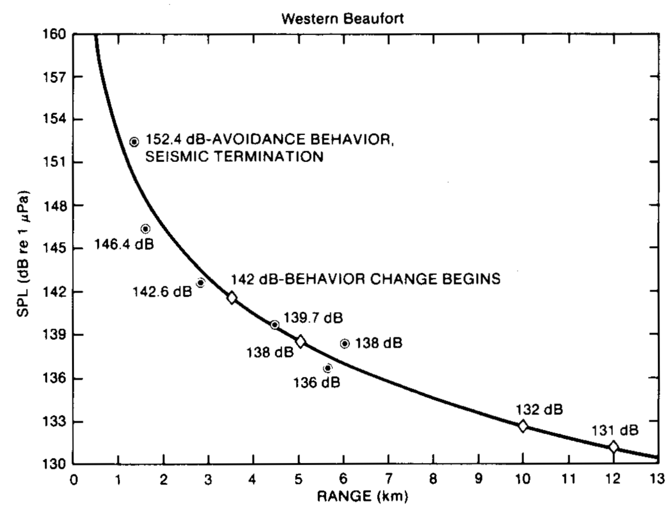

FIG. 2. Received airgun blast noise levels vs. range for the *Western Beaufort*. Line is a least squares regression line fit to the measured sound levels. ♦ = estimated sound level; + = measured sound level.

Thirty-one surfacings were observed during the initial 2.6 h of observations, with the vessel more than 12 km away. The general behavior of the whales included milling, socializing and traveling at slow to medium speeds (Table 1). Thirty-two surfac-

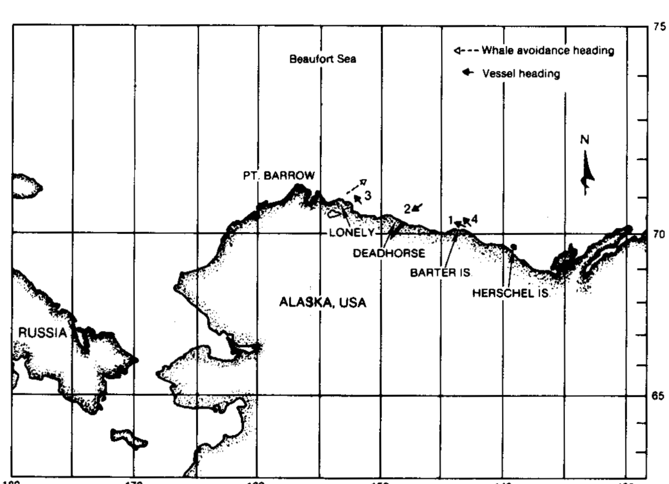

FIG. 1. Study area in the Alaskan Beaufort Sea showing the locations of seismic response experiments: No. 1, 18 September, *Western Beaufort*; No. 2, 20 September, *Western Aleutian*; No. 3, 23 September, *Arctic Star*; and No. 4, 26 September, *Western Polaris*.

TABLE 1. General bowhead whale surface behavior during four seismic vessel approach experiments

		Behavior as % of whales		
Experiment no: *vessel*	Number of surfacings	Milling	Socializing	Traveling
No. 1: *Western Beaufort*				
Pre-experiment >10 km	31	13	19	68
Experiment 10-5 km	32	17	22	61
Close-experiment <5 km	16	0	0	100
No. 2: *Western Aleutian*				
Pre-experiment >10 km	9	22	56	22
Experiment 10-5 km	8	0	0	100
Post-experiment <30 min	9	0	0	100
Post-experiment >30 min	7	12	2	86
No. 3: *Arctic Star*				
Pre-experiment >10 km	43	18	13	69
Pre-experiment >10 km	13	14	0	86
Experiment 10-5 km	15	2	0	98
Close-experiment <5 km	15	0	0	100
No. 4: *Western Polaris*				
Pre-experiment >10 km	84	37	56	7
Experiment 10-5 km	18	0	0	100
Close-experiment <5 km	25	0	0	100
Post-experiment <30 min	18	28	0	72
Post-experiment >30 min	21	28	20	52

ings were observed as the vessel approached from approximately 10 to 5 km. Milling and socializing behaviors increased and traveling decreased during this period.

Overt changes in the whales' behavior began to occur as the vessel approached to within 3.5 km of the whales. Individual whales that had previously been widely separated surfaced synchronously within a few whale lengths of each other. Others huddled tightly together for a short time before traveling away from the approaching vessel at medium to fast speeds. The vessel discontinued its approach at 1.3 km, when all whales were dispersing at medium to fast speed.

The principal surfacing, respiration and dive variables for adult whales changed significantly as the vessel approached to within 5 km (Table 2; Fig. 3). Mean blow interval, which was relatively unchanged at ranges greater than 5 km, increased significantly when the vessel was <5 km away. Concomitantly, the mean number of blows per surfacing declined significantly when the vessel closed to within less than 5 km. Mean length of surfacing declined as the vessel approached from 10 to 5 km and continued to decline as the vessel closed to within 1.3 km. Mean length of dive showed a pronounced and significant decrease at all ranges as the vessel approached (Table 2).

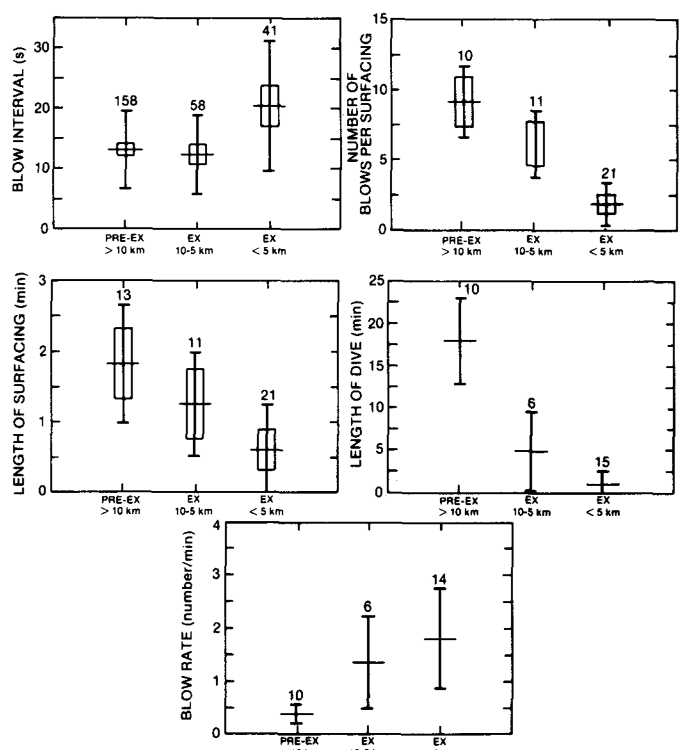

FIG. 3. Surfacing, respiration and dive characteristics for bowhead whales during different categories of exposure to airgun blasts from the *Western Beaufort*. Horizontal bars are means, vertical lines are 1 standard deviation from the mean, closed bars are 95% confidence limits to the mean and numbers at the top of bars are sample sizes. ex = experiment.

Experiment No. 2: On 20 September, a second direct approach experiment, toward a group of three whales, was undertaken approximately 66 km northeast of Deadhorse, with cooperation from the geophysical vessel *Western Aleutian* (Fig. 1:2). The *Western Aleutian* is equipped with a multiple airgun array, of which 20 guns are activated and fire synchronously every 12-14 s. The estimated source level of sound produced by this airgun array is between 230 and 240 dB at 1 m (Western Geophysical, pers. comm.). Sonobuoys dropped in 36 m of water near the whales provided data on airgun blast levels, vessel noise and ambient levels throughout the 5.0 h experimental period. During the vessel's approach, airgun blast levels ranged from 165 dB at startup (7.2 km) to an estimated 170 dB at shutdown (3.5 km) (Fig. 4).

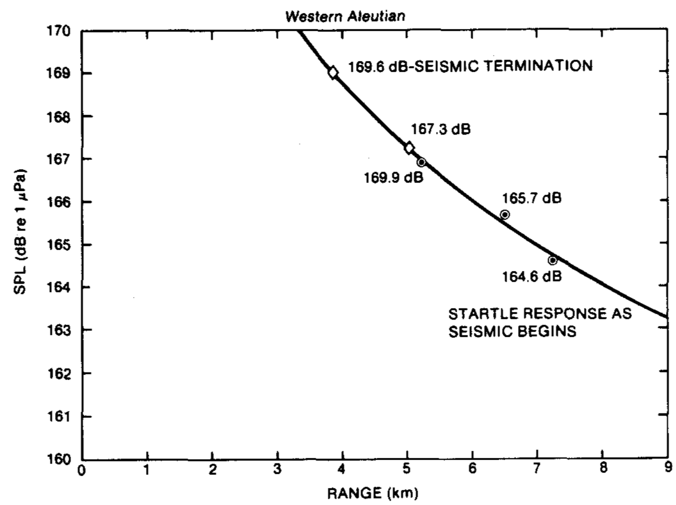

FIG. 4. Received airgun blast noise levels vs. range for the *Western Aleutian*. Line is a least squares regression line fit to the measured sound levels. ♦ = estimated sound level; + = measured sound level.

Nine surfacings were observed while the vessel's airguns were inactive. The general behavior for the whales during these surfacings included milling, socializing and slow traveling (Table 1). Three whales were at the surface as the vessel approached to a range of 7.2 km; two were within one whale length of each other, and the third was 3-5 whale lengths from the pair. The whales' behavior changed abruptly with the commencement of the airgun blasts at 7.2 km. They exhibited a "startle" response, which included considerable water disturbance, tail slaps and sudden travel at moderate to fast speed away from the approaching vessel. The vessel continued its approach toward the whales until it was within 3.5 km, when the airguns were shut down.

After the airgun blasts ceased, the number of whales under observation increased from three to ten, including two cow/calf pairs. Nine surfacings were recorded during the first 30 min of post-experiment observations. All whales were traveling at slow to medium speed away from the inactive vessel (Table 1). Seven surfacings were recorded during the second 30 min post-experiment period, and observed behaviors included milling, social behaviors that included cow/calf nursing bouts and play, and traveling at slow to medium speeds to the west (Table 1).

All respiration parameters changed significantly as the whales were approached by the seismic vessel and throughout the first 30 min of post-experiment observations but returned toward pre-experiment levels during the second 30 min post-experiment period (Table 2; Fig. 5). Mean blow interval increased significantly during exposure to the airgun blasts and continued to increase during the first 30 min of post-experiment observa-

TABLE 2. Summary statistics of the principal surfacing, respiration and dive characteristics during four seismic experiments; all categories are for non-calves

	Blow Interval (s)				No. Blows/Surfacing				Length of Surfacing (min)				Length of Dive (min)				Blow Rate (No./min)			
Seismic Experiment	$\bar{x}$	Rank[a]	S.D.	n	$\bar{x}$	Rank	S.D.	n	$\bar{x}$	Rank	S.D.	n	$\bar{x}$	Rank	S.D.	n	$\bar{x}$	Rank	S.D.	n
Western Beaufort, Sept 18																				
Pre-Experiment > 10 km	13.1	2	6.49	158	9.2	3	2.53	10	1.82	3	0.829	13	17.93	3	5.044	10	0.38	1	0.180	1
Experiment 10-5 km	12.3	1	6.54	58	6.3	2	2.37	11	1.25	2	0.737	11	4.93	2	4.639	6	1.36	2	0.868	6
Experiment < 5 km	20.3	3	10.81	41	2.0	1	1.53	21	0.59	1	0.643	21	1.12	1	1.548	15	1.81	3	0.937	14
	$F = 18.087$ $p < 0.001$ $df_e = 254$ MRT[b] 1 2 3				$F = 45.665$ $p < 0.001$ $df_e = 39$ MRT 1 2 3				$F = 11.774$ $p < 0.001$ $df_e = 42$ MRT 1 2 3				$H(c)$[d] $= 21.077$ $p < 0.001$ $df = 2$ MRT 1 2 3				$H(c)$[d] $= 15.323$ $p < 0.001$ $df = 2$ MRT 1 2 3			
Western Aleutian, Sept 20																				
Pre-Experiment > 10 km	13.0	1	3.78	49	8.5	4	2.33	8	1.81	4	0.593	8	17.80	4	11.703	4	1.46		1.788	5
Experiment 10-5 km	16.6	2	6.51	25	3.0	2	2.52	7	0.73	1	0.823	7	3.11	1	2.103	6	0.78		0.899	4
Post-Experiment ≤ 30 min	22.2	4	10.11	13	2.0	1	0.00	2	0.87	2	0.174	3	7.15	2	2.257	4	0.43		0.230	3
Post-Experiment > 30 min	17.4	3	4.56	27	5.5	3	2.65	4	1.77	3	0.354	2	15.64	3	9.683	3	0.46		—	1
	$F = 10.342$ $p < 0.001$ $df_e = 110$ MRT 1 2 3 4				$t = 4.217$[c] $p < 0.001$ $df = 20$ 1 2 3 4				$t = 3.761$[c] $p = 0.001$ $df = 18$ 1 2 3 4				U[e] $= 59.5$[c] $0.01 < p < 0.02$ MRT 1 2 3 4				No Tests			
Arctic Star, Sept 23																				
Pre-Experiment > 10 km	15.3	1	6.14	132	3.8		1.98	19	1.07		0.578	21	14.15		10.520	6	—		—	—
Pre-Experiment > 10 km	15.9	2	6.10	22	4.5		1.73	4	1.35		0.225	4	—		—	—	—		—	—
Experiment 10-5 km	17.2	3	4.24	17	3.3		2.08	3	1.18		0.436	2	24.27		2.334	2	—		—	—
Experiment < 5 km	19.4	4	3.97	30	3.8		2.99	6	1.19		0.773	6	16.13		13.289	3	—		—	—
	$F = 4.428$ $p < 0.001$ $df_e = 197$ MRT 1 2 3 4				No Tests				No Tests				No Tests				No Tests			
Western Polaris, Sept 26																				
Pre-Experiment > 10 km	14.8	2	7.10	246	8.0	4	2.05	24	1.97	4	0.638	25	16.17	5	11.471	4	0.78	1	0.933	4
Experiment 10-5 km	16.8	5	8.64	182	4.6	3	3.95	29	1.26	3	0.984	31	1.91	2	4.255	9	1.81	2	0.981	8
Experiment < 5 km	15.3	3	9.05	23	3.8	2	2.82	8	0.78	1	0.643	8	0.56	1	0.365	2	2.84	5	0.623	2
Post-Experiment ≤ 30 min	16.2	4	5.08	30	3.6	1	2.30	7	0.93	2	0.442	7	8.44	3	16.353	4	2.01	3	1.127	4
Post-Experiment > 30 min	14.3	1	6.38	160	8.1	5	4.25	16	2.09	5	1.164	18	12.56	4	14.053	4	2.06	4	1.987	4
	$F = 3.039$ $p < 0.05$ $df_e = 636$ MRT 1 2 3 4 5				$F = 6.806$ $p < 0.001$ $df_e = 79$ MRT 1 2 3 4 5				$F = 6.275$ $p < 0.001$ $df_e = 84$ MRT 1 2 3 4 5				U[e] $= 96.0$[c] $p = 0.02$ 1 2 3 4 5				$H(c)$[d] $= 5.122$ $p = 0.27$ $df = 4$ 1 2 3 4 5			

a Rank = rank of means from smallest to largest b MRT = multiple rank test c Groups pooled to give adequate sample sizes d Kruskal-Wallace test e Mann-Whitney test

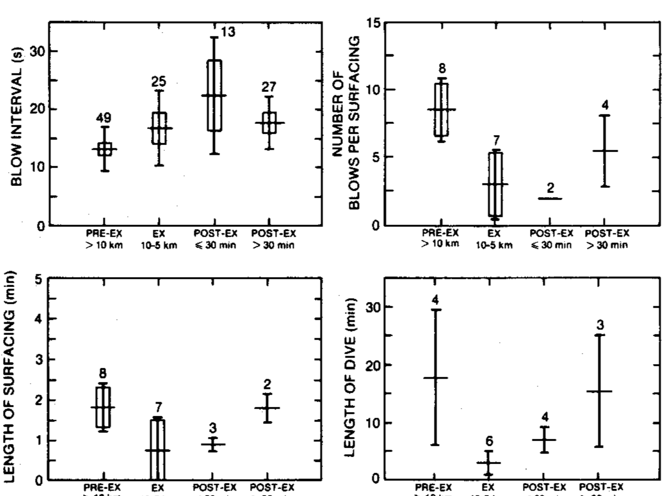

FIG. 5. Surfacing, respiration and dive characteristics for bowhead whales during different categories of exposure to airgun blasts from the *Western Aleutian*. Horizontal bars are means, vertical lines are 1 standard deviation from the mean, closed bars are 95% confidence limits to the mean and numbers at top of bars are sample sizes. ex = experiment.

tions. By the second 30 min period, blow intervals had declined to pre-experiment values. The mean number of blows per surfacing also declined significantly during the first 30 min of the post-experiment period, but as with blow intervals, the number of blows per surfacing began to recover during the second 30 min period. Number of blows per surfacing during the pre-experiment and second post-experiment periods combined were significantly higher than during the period of active seismic sounds and the first post-experiment period combined (Table 2).

Mean length of surfacing and dive duration declined with the onset of airgun blasts. The length of surfacing during exposure to airgun blasts and during the first 30 min of post-experiment observations combined was significantly shorter than lengths of surfacing during the pre-experiment and second 30 min of post-experiment observations combined. The length of dives during the airgun disturbance and immediately following the shutdown of the airguns was also significantly shorter than during the pre-experiment and second post-experiment periods combined (Table 2; Fig. 5). There were insufficient data to determine whether blow rate changed during this experiment.

Experiment No. 3: On 23 September, a third direct approach experiment was undertaken toward a group of seven whales approximately 32 km northeast of Lonely, with cooperation from the geophysical vessel *Arctic Star* (Fig. 1:3). The *Arctic Star* is equipped with a multiple airgun array, of which 18 of 24 guns are fired once every 12-14 s, producing an estimated airgun source level of 246 dB (Ljungblad *et al.*, 1984). Sonobuoys dropped in 17 m of water near the whales provided data on airgun blast levels, vessel noise and ambient levels throughout the 6.0 h experimental period. Airgun blast levels ranged

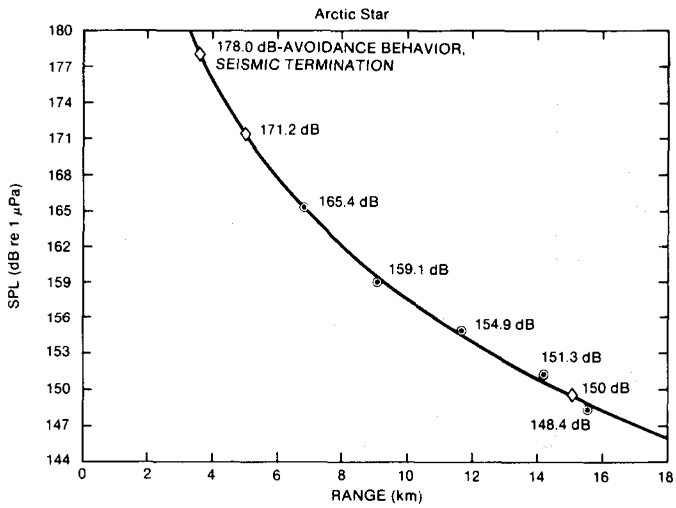

FIG. 6. Received airgun blast noise levels vs. range for the *Arctic Star*. Line is a least square regression line to fit to the measured sound levels. ♦ = estimated sound level; + = measured sound level.

from 148 dB at a distance of >10 km to an estimated 178 dB at 3.5 km when the airguns were shut down (Fig. 6).

The behaviors observed throughout this experiment were somewhat different from those in the earlier experiments, as most of the whales moved slowly through our observation area, stopping for short periods to feed. Forty-three surfacings of at least seven whales were recorded during the initial period of pre-experiment observations when the vessel was active at 15.5 km. General behavior during these surfacings included milling, socializing and traveling at slow to medium speeds (Table 1). During the second pre-experiment period, while the vessel was inactive at a range of 12 km, 13 whale surfacings were recorded. General behavior during these surfacings included milling and traveling at slow to medium speeds (Table 1).

The vessel began its active approach at approximately 11.6 km. During the vessel's approach from 10 to 5 km, the majority of whales were moving at slow to medium speeds (Table 1). When the vessel closed from 5 to within 3.5 km, two whales that had been under constant observation ceased milling and diving and exhibited avoidance behaviors by turning away from the approaching vessel and swimming rapidly to the north. The experiment was terminated at that time.

To analyze the *Arctic Star* experiment the behavioral data were divided into four subsets: a pre-experiment period when the airgun source was *active* at a range of >10 km; a second pre-experiment period when the vessel was *inactive* at a distance of >10 km; an experiment period when the vessel was closing from a range of approximately 12 to 5 km while firing its airguns; and a period of close approach by the vessel when its range to the whales closed from 5 to 3.5 km.

Blow intervals increased as the vessel approached during the pre-experiment period (Table 2; Fig. 7). Blow intervals during the closest approach of the active vessel were significantly greater than at any other point during the experiment. Mean number of blows per surfacing decreased as the vessel approached from 10 to 5 km and then increased slightly during the close (<5 km) approach. The mean length of surfacing increased slightly as the vessel approached to <5 km. No complete dive cycles for individual whales were observed during the pre-experiment period, but mean length of dive decreased during the close approach by the active vessel.

Experiment No. 4: On 26 September, the fourth and final direct approach experiment was undertaken toward a group of 50 whales approximately 42 km northeast of Barter Island, with cooperation from the geophysical vessel *Western Polaris* (Fig. 1:4). The *Western Polaris* is equipped with a multiple airgun array, of which 18 of 24 guns are fired every 12-14 s. The array produces an estimated seismic source level of 250 dB (Ljungblad *et al.*, 1984). Sonobuoys dropped in 46 m of water near the whales again provided data on airgun blast levels, vessel noise and ambient levels throughout the experimental period. During the vessel approach, airgun blast levels ranged from 155 dB at 10.4 km to an estimated 169 dB at 1.8 km (Fig. 8).

Pre-experiment observations on three cow/calf pairs, four single whales, and two groups of 7 and 9 whales were conducted while the inactive vessel approached from 30 km to approximately 12 km. Behaviors during 84 whale sufacings included milling, socializing and traveling at slow to medium speeds (Table 1). Cow-calf interactions and synchronous group diving were also seen during this period.

The airguns were activated at a range of approximately 10.4 km. The whales at the surface gave no obvious response to the airguns' start-up. Eighteen whale surfacings were observed as the vessel closed from approximately 10 to 5 km. All whales were traveling at slow, medium or fast speeds; no whales were milling or socializing (Table 1). When the vessel was 9.5 km from the whales, two calves moved toward each other, within one calf length, then began touching, rolling and flipper slapping. As the vessel approached to 8.2 km, the two calves were joined by three adults, two of which were assumed to be their mothers. The two calves and three adults began socializing on the surface until the vessel was approximately 7.6 km distant, at which time they began moving away from the vessel. A third cow-calf pair, also socializing at the surface, remained in the area of observations until the vessel was 7.0 km away, then began moving slowly to the west, across the course of the approaching vessel. When the vessel was at a range of 6.6 km, another group of seven whales began moving away single file, in a nose to tail formation. In the final phase of the approach (2.9-1.8 km), all whales were traveling west at various rates of speed.

The active approach of the vessel was discontinued when the vessel was at a range of 1.8 km. Within minutes some of the whales ceased traveling and began to mill at the surface. During 18 whale surfacings observed in the first 30 min post-experiment period, whales were milling or continued to travel at slow and medium speeds (Table 1). All fast swimming ceased as the vessel moved away. Twenty-one whale surfacings were observed during the second 30 min post-experiment period. During this period, 48% of the whales were milling and socializing, with some groups surfacing synchronously. The remainder of the whales were traveling at medium to slow speeds (Table 1).

All surfacing, respiration and dive characteristics, except blow rate, changed significantly during the approach of the vessel and the first 30 min post-experiment observation period, but they returned to pre-experiment values during the second 30 min post-experiment observation period (Table 2; Fig. 9). Mean length of surfacing, mean length of dive and mean number of blows per surfacing decreased significantly, and mean blow interval increased significantly, as the vessel approached. Blow rate increased when the vessel was <5 km away and decreased during the post-experiment period, but these changes were not significant (Table 2).

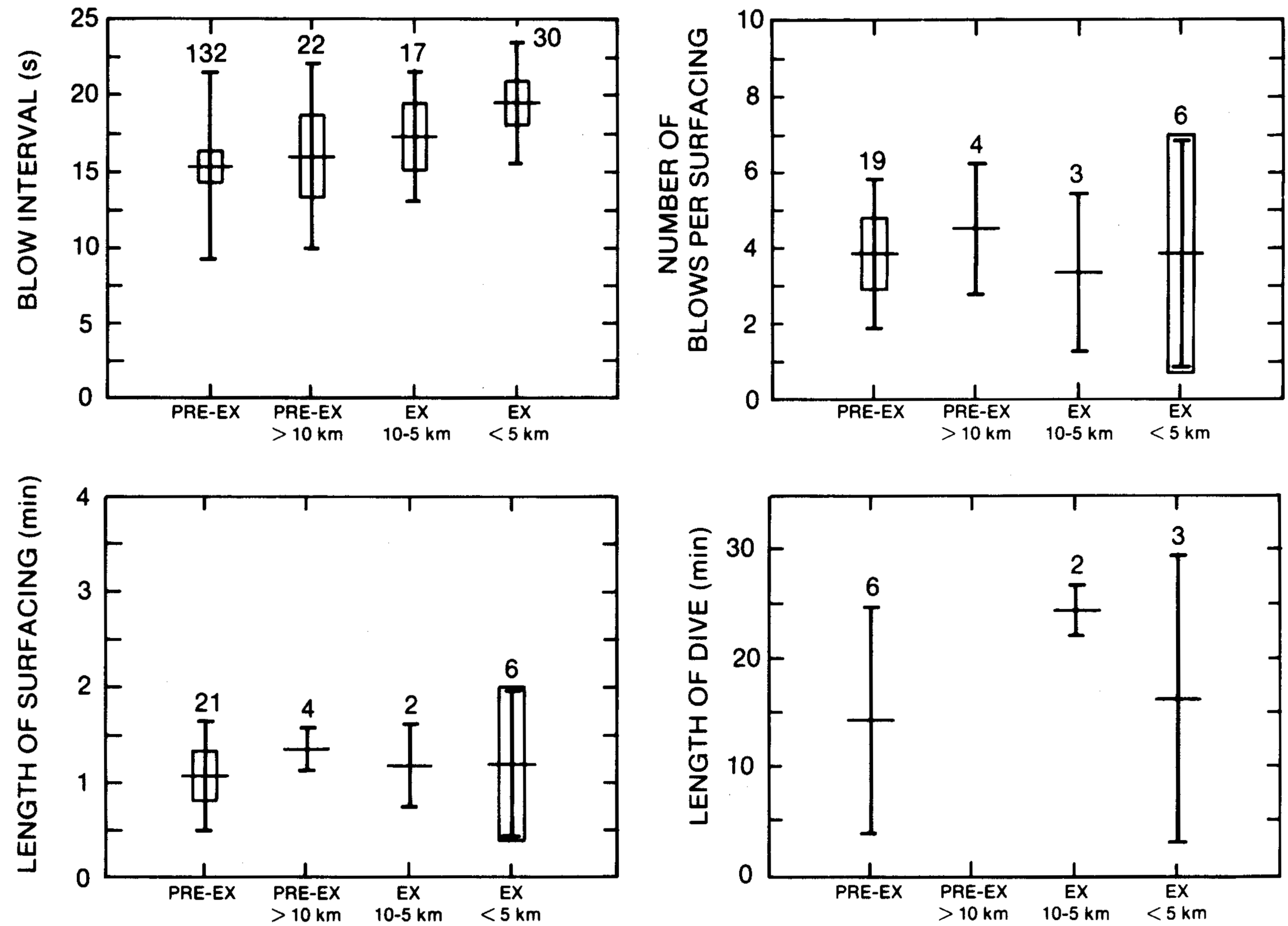

FIG. 7. Surfacing, respiration and dive characteristics for bowhead whales during different categories of exposure to airgun blasts from the *Arctic Star*. Horizontal bars are means, vertical lines are 1 standard deviation from the mean, closed bars are 95% confidence limits to the mean and numbers on top of bars are sample sizes. ex = experiment.

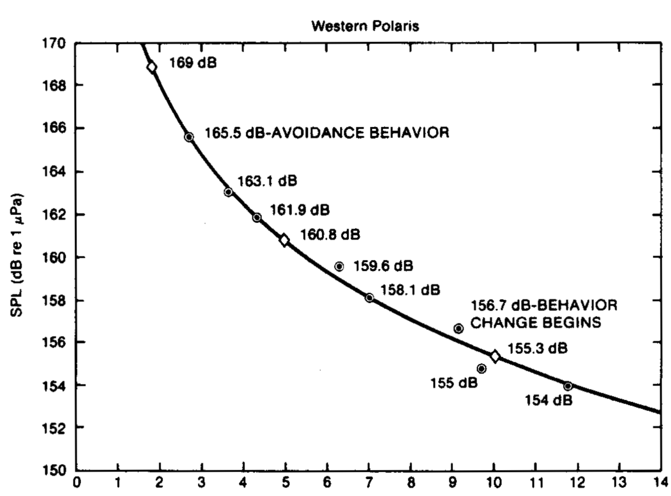

FIG. 8. Received airgun blast noise levels vs. range for the *Western Polaris*. Line is a least squares regression line fit to the measured sound levels. ● = estimated sound level; + = measured sound level.

Combined Experimental Results

The data for all adult whales were pooled into pre-experiment and experiment categories and tested for significant differences (Table 3). Blow interval, number of blows per surfacing and length of surfacing showed distributions approaching normality, but length of dive and blow rate were less normally distributed. Therefore, the first three variables were compared with parametric testing procedures, while the last two variables were treated non-parametrically.

All of the surfacing, respiration and dive characteristics showed changes when whales were exposed to seismic sounds at ranges of < 10 km. Mean blow interval was the only character to increase, from 12.7 to 15.0 s ($t = 7.854, p<0.001$). The remaining characteristics all decreased significantly when whales were exposed to increasing levels of seismic sounds (Table 3, Fig. 10). The number of blows per surfacing decreased from 5.5 to 4.6 blows ($t = 2.221, p<0.02$), duration of surfacing decreased from 1.19 to 1.14 min ($t = 0.501, p<0.50$), duration of dive decreased from 9.61 to 8.15 min ($t = 0.730, p<0.20$), and blow rate declined from 1.43 to 1.25 blows·min^{-1} ($t = 0.641, p<0.50$).

The whale behaviors observed during the four direct approach experiments changed progressively with vessel range. When the airguns were shut down the whales began to exhibit behaviors similar to those seen prior to exposure to airgun blasts. The trend for surfacing, respiration and dive characteristics to first change and then recover became apparent when the data from the experiments were analyzed in the five categories: pre-experiment,

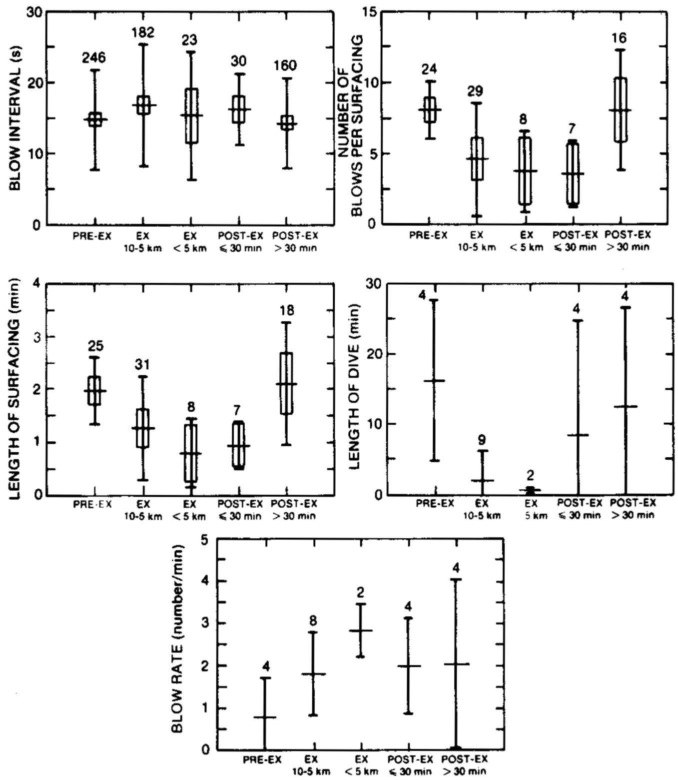

FIG. 9. Surfacing, respiration and dive characteristics for bowhead whales during different categories of exposure to airgun blasts from the *Western Polaris*. Horizontal bars are means, vertical lines are 1 standard deviation from the mean, closed bars are 95% confidence limits to the mean and numbers at top of bars are sample sizes. ex = experiment.

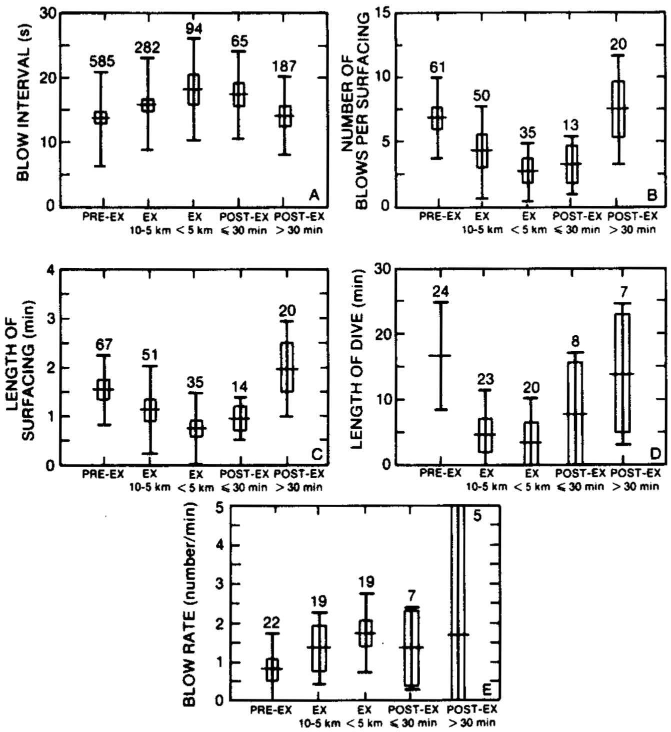

FIG. 11. Overall changes in the behavior characteristics for bowhead whales during different categories of exposure to airgun blasts. Horizontal bars are means, vertical lines are 1 standard deviation from the mean, closed bars are 99% confidence limits to the mean, and numbers at top of bars are sample sizes. ex = experiment.

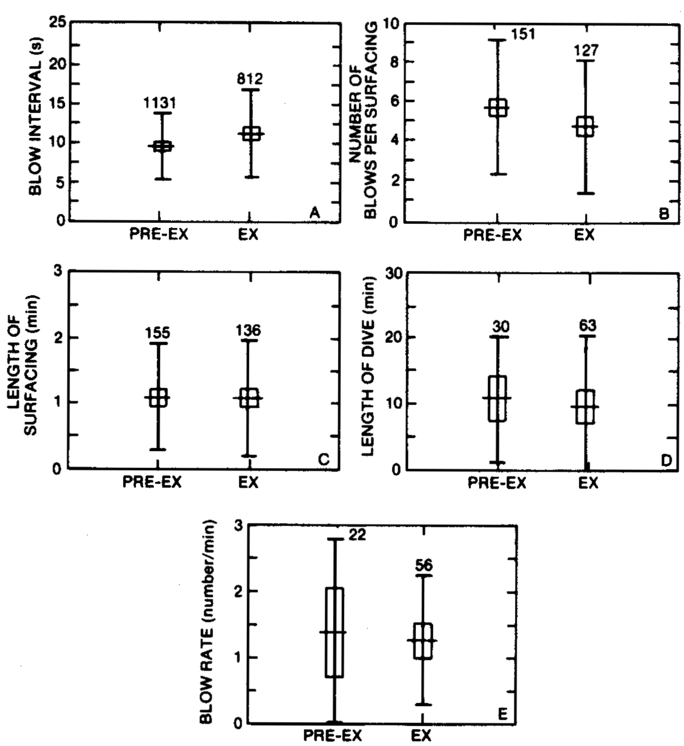

FIG. 10. Pooled mean values for surfacing, respiration and dive characteristics of pre-experiment and experimental whales. Horizontal bars are means, vertical lines are 1 standard deviation from the mean, closed bars are 95% confidence limits to the mean and numbers at top of bars are sample sizes. ex = experiment.

experiment at 5-10 km, experiment at <5 km, 0-30 min post-experiment, and 30-60 min post-experiment (Fig. 11).

Blow interval increased with exposure to seismic sounds at progressively closer ranges and began to decline once seismic sounds ceased. Number of blows per surfacing, length of surfacing and length of dive all decreased with the onset of the experiment, with the lowest values obtained when the sound source was <5 km away. Values for these behaviors continued to decrease during the first 30 min post-experiment period and then began to increase toward values equivalent to those before the experiment began. Values for blow rates followed a similar pattern.

Association between Measured Behavior Characteristics and Swimming Speed

Whale swimming speed was subjectively estimated from the aircraft as stationary, slow, medium or fast. Slow speeds produced no wake, medium speeds produced a slight wake and fast speeds produced a large wake of "white water" behind the swimming whales. To evaluate differences in the behavior characteristics of whales traveling at different speeds, differences among speed categories for pre-experiment and experiment conditions were tested separately. We then tested for differences between pre-experiment and experiment conditions within each speed category (Table 3).

For pre-experiment whales, mean blow intervals did not change appreciably with different swimming speeds, but mean number of blows per surfacing, mean length of surfacing and mean length of dive all decreased as whales moved faster (Table 3).

TABLE 3. Summary of statistics of the principal surfacing, respiration and dive characteristics, fall 1984; all categories except those marked otherwise are for non-calves

	Blow Interval (s)			No. Blows/Surfacing			Length of Surfacing (min)			Length of Dive (min)			Blow Rate (No./min)		
	$\bar{x}$	S.D.	n	$\bar{x}$	S.D.	n	$\bar{x}$	S.D.	n	$\bar{x}$	S.D.	n	$\bar{x}$	S.D.	n
AGE CLASSES															
ALL ADULTS															
Pre-Experiment	12.7^{***}	5.61	1131	5.5^{*}	3.36	151	1.19	0.868	155	9.61	8.140	30	1.43	1.404	22
Experiment	15.0	7.29	812	4.6	3.37	127	1.14	0.828	136	8.15	9.407	63	1.25	0.985	56
ALL ADULTS NON-COW															
Pre-Experiment															
Experiment	14.4	7.01	668	4.4	3.32	106	1.04	0.745	114	7.92	9.395	51	1.30	0.991	45
COWS															
Pre-Experiment															
Experiment	17.8	7.94	144	5.4	3.57	21	1.68	1.026	22	9.14	9.811	12	1.03	0.974	11
CALVES															
Pre-Experiment															
Experiment	18.7	12.65	113	3.1	3.90	21	0.87	1.084	22	8.14	9.470	11	0.68	0.814	10
SPEED OF MOVEMENT															
NONE															
Pre-Experiment	13.1	5.55	274	8.4	2.59	27	1.85	0.740	27	16.17	8.045	4	0.33	0.114	3
Experiment	13.7	7.07	223	6.5	3.62	15	1.64	0.790	20	15.43	5.803	8	0.45	0.189	7
SLOW															
Pre-Experiment	13.4	6.40	348	5.1^{*}	2.63	50	1.12^{*}	0.622	48	10.57	8.169	10	1.11	1.251	7
Experiment	13.9	5.82	179	6.8	3.04	26	1.52	0.755	25	17.00	10.303	11	0.74	0.647	11
MEDIUM															
Pre-Experiment	12.7^{***}	4.94	256	6.9^{***}	3.58	27	1.57^{*}	1.188	28	6.58	6.586	6	1.70	1.798	5
Experiment	16.2	7.94	306	3.9	2.96	58	1.03	0.794	63	5.66	7.750	31	1.28	1.000	25
FAST															
Pre-Experiment	11.6^{**}	2.94	18	3.3	2.75	10	0.57	0.570	10	3.89	6.674	4	1.94	0.297	3
Experiment	16.5	8.16	42	2.5	2.67	15	0.51	0.694	15	0.46	0.268	12	2.20	0.712	12

* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$

This trend was significant for mean number of blows per surfacing ($F = 11.699$, $df = 110$, $p<0.001$) and mean length of surfacing ($F = 8.417$, $df = 109$, $p<0.001$), and not significant for mean length of dive. Mean blow rate increased significantly during faster movement (Mann-Whitney $U = 64.0$, $n = 18$, $p<0.05$).

Under experimental conditions, mean blow intervals increased significantly for faster whales ($F = 6.847$, $df = 746$, $p<0.001$), while mean blow rate also increased greatly as swimming speed increased (Kruskal-Wallace $H_c = 19.673$, $df = 3$, $p<0.001$). The mean number of blows per surfacing, mean length of surfacing and mean length of dive all decreased with increasing speed ($F = 10.017$, $df = 110$, $p<0.001$; $F = 8.428$, $df = 119$, $p<0.001$; and Mann-Whitney $Z = 4.834$, $p<0.001$ respectively). The mean length of dive during experiments was the characteristic most changed at different swimming speeds, with a mean length of 17 min at slow speed and only 0.46 min at fast speed. Whales exposed to seismic sounds at close range generally swam fast and only dove for brief times.

Overall there were differences in the values for the behavior characteristics of whales traveling at different speeds during pre-experiment and experimental conditions. The only significant changes were a lengthening of mean blow interval at medium and fast speeds from 12.7 to 16.2 s ($t = 6.129$, $p<0.001$) and 11.6 to 16.5 s ($t = 2.469$, $p<0.01$) respectively, an increase in the mean number of blows per surfacing of 5.1 to 6.8 for slow-swimming whales ($t = 2.533$, $p<0.05$), a decrease in number of blows per surfacing from 6.9 to 3.9 ($t = 4.065$, $p<0.05$) for medium-swimming whales, a slight but significant increase in the length of surfacing from 1.12 to 1.52 min ($t = 2.421$, $p<0.05$) for slow whales, and a significant decrease in the mean length of surfacing from 1.57 to 1.03 min ($t = 2.553$, $p<0.05$) for whales swimming at medium speeds (Table 3).

Correlations between Measured Behavior Characteristics

Correlations were found between some behavioral characteristics measured during the vessel approach experiments that were similar to correlations documented for whales in previous studies (Ljungblad *et al.*, 1984; Würsig *et al.*, 1984b). Length of surfacing was correlated with number of blows per surfacing ($r = 0.896$, $p<0.001$, $n = 182$) and with length of previous ($r = 0.566$, $p<0.001$, $n = 37$) and subsequent dives ($r = 0.526$, $p<0.001$, $n = 37$). Length of dive prior to a surfacing was correlated with length of dive subsequent to that surfacing ($r = 0.782$, $p<0.001$, $n = 38$), indicating that particular dive patterns tend to occur in bouts. These data further indicate that the surfacing, respiration and dive characteristics are related, for both physiological and behavioral reasons, and that one variable may be predicted by the changes or pattern of another.

DISCUSSION

Although the ranges at which bowheads responded to approaching seismic vessels varied, general trends between experiments can be summarized (Table 4). These trends clearly indicate that whales responded to the airgun blasts at ranges of less than 10 km, with the strongest responses occurring when the whales were within 5 km of the sound source. Whale behavior began to recover to pre-experiment conditions within 30 min after the airguns were shut down, with definite reversals of the response to airguns and/or vessel seen within one hour of the last airgun activity.

Determining when subtle behavioral changes began to occur was the most difficult part of the experimental observations. Each observer's interpretations were carefully assessed until all agreed that behavioral changes were taking place. Subtle to

TABLE 4. Summary of significant experimental ranges, vessel status, airgun blast levels (dB re 1 μPa) and observed bowhead whale behavioral responses

Range (km)	Vessel status	Behavioral response
Western Beaufort		
>10	Airgun firing, ongoing seismic survey (130 dB)	None
9.6	Airgun firing as vessel approaches (132 dB)	None
3.5	Airgun firing as vessel approaches (142 dB)	Huddling, followed by avoidance responses
1.3	Airgun shut down, vessel departs (152 dB)	All whales exhibiting avoidance responses
Western Aleutian		
>8.0	Airguns shut down, vessel maneuvering for approach	None
7.2	Airguns begin firing as vessel approaches (165 dB)	Startle responses, followed by avoidance responses
3.5	Airguns shut down, vessel departs (170 dB)	All whales exhibiting avoidance responses
Arctic Star		
15.5	Airguns firing, ongoing seismic survey (148 dB)	None
>12	Airguns shut down as vessel maneuvers for approach	None
11.6	Airguns firing as vessel approaches (155 dB)	None
3.5	Airguns shut down, vessel departs (178 dB)	Whales exhibiting avoidance responses
Western Polaris		
12	Airguns shut down, vessel maneuvering for approach	None
10.4	Airguns begin firing as vessel approaches (155 dB)	None
8.2	Airguns firing as vessel approaches (157 dB)	Possible subtle behavior changes
7.6	Airguns firing as vessel approaches (158 dB)	5 whales begin vessel avoidance responses
7.0	Airguns firing as vessel approaches (158 dB)	2 additional whales begin vessel avoidance responses
6.6	Airguns firing as vessel approaches (159 dB)	7 additional whales begin vessel avoidance responses
2.9	Airguns firing as vessel approaches (165 dB)	All whales exhibiting avoidance responses
1.8	Airguns shut down, vessel departs (169 dB)	

obvious changes in behaviors were evident in the *Western Beaufort* experiment in the form of huddling and in the *Western Polaris* experiment in the form of changes in surface behaviors when airgun levels reached intensities of 142 dB and 157 dB at ranges of 3.5 km and 8.2 km respectively. The fact that we waited until all observers were in agreement may have introduced a small degree of error, most likely <0.5 km, in the reported ranges of initial subtle responses.

The interpretations of partial avoidance followed by total avoidance were more straightforward, beginning when the first whale was observed swimming away (partial avoidance) to eventually include all whales moving away (total avoidance) from the approaching vessel. Partial avoidances were obvious in the *Western Beaufort* and *Western Polaris* experiments at ranges of 3.5 km and 7.6 km with airgun intensity levels of 142 dB and 158 dB respectively (Table 4). Total avoidance responses for all experiments occurred at ranges of 1.3 to 7.2 km, with sound intensities of 152 to 165 dB. Although initiation of airgun blasts at 7.2 km (*Western Aleutian* experiment) produced an obvious "startle effect" and elicited immediate avoidance response by three whales, the airgun initiation at 10.4 km (*Western Polaris* experiment) elicited no obvious response, implying that the range of start-up "startle effects" probably occurs somewhere between 7.2 and 10.4 km, assuming intensity levels are similar.

All but one experiment were conducted in water ≥40 m deep. The *Arctic Star* experiment was conducted in water ≤20 m deep, and the sound levels for this experiment at ranges of less than 5 km were approximately 10 dB greater than levels measured at similar ranges for the experiments in deeper water. These differences are thought to be due to sound propagation characteristics that are highly dependent on bottom loss components for shallow water transmission paths (Urick, 1967). Differences in sound propagation properties, combined with variations in site-specific bowhead behaviors, may be responsible for some of the observed responses to approaching geophysical vessels. Bowheads along the shelf break north of Harrison Bay, near where the *Arctic Star* experiment occurred, have been seen feeding less and traveling more than whales seen farther to the east (Ljungblad *et al.*, 1986). Therefore, in this experiment, site-specific behavior (i.e., traveling vs. milling/feeding) may have influenced the whale's response to the approaching seismic vessel.

The tendency for bowhead whales to dive for shorter periods during exposure to close seismic sounds may also be related to the transmission characteristics of the airgun blasts through the water column. Greene (1984) reported that received levels of airgun sounds are reduced near the surface, and if seismic sound is irritating to the whales, one would expect the animals to spend more time where the sound is the least intense. This effect may have been demonstrated during the *Western Polaris* experiment when whales surfaced frequently and their dives were short and shallow as they moved away from the approaching vessel. These whales may have been swimming away near the surface to avoid relatively higher levels of sound in deeper water.

Although conspicuous behavior changes occurred consistently as the geophysical vessels approached to within 5 km, bowhead whales appeared to tolerate continuous full-scale seismic sounds at distances greater than 10 km. Previous studies of bowhead whales also suggest that, in general, little change occurs in behavior when whales are exposed to airgun blasts generated from vessels farther than 10 km away (Reeves *et al.*, 1983; Ljungblad *et al.*, 1984). Richardson (1985) found little evidence that bowhead whales changed their behavior or oriented away from airgun sources at ranges between 6 and 89 km or during three experiments with a single airgun that produced received sound levels of 113-118 dB at ranges of 3-5 km. Richardson *et al.* (1986) did observe bowhead whales orienting away from a single airgun when exposed to sound levels of at least 124-134 dB at ranges of 0.2-4.6 km and during an experiment with a full-scale seismic vessel at ranges of 1.5-7.5 km. Richardson *et al.* (1984) point out that bowheads must routinely experience low-frequency calls from conspecifics that may reach source levels of 189-200 dB (Clark and Johnson, 1984) and that short-duration loud seismic pulses may be equally tolerated. However, whale calls and airgun blasts are *very* different types of sounds, each with different fundamental components and tonal qualities, and responses to each probably vary greatly. Different behavioral responses may also be caused by the approaching ship-noise components that may cue avoidance reactions. It has been demonstrated that bowhead whales react to ship noise alone at distances of up to 4 km (Fraker *et al.*, 1982). Experiments to determine the responses of bowhead whales to approaches by inactive geophysical vessels were not conducted; however, such experiments may contribute valuable information on the significance of airgun blasts in concert with ship noise and their individual and combined effects on bowhead whale behavior.

The observed changes in bowhead behaviors may be comparable to behavior changes of migrating gray whales (*Eschrichtius robustus*) in response to exposure to seismic sounds with average pulse pressure levels of 160 dB (Malme *et al.*, 1983). Malme *et al.* (1983) indicated that some behavior changes occurred at sound pressure levels between 140 and 160 dB but that limited observations precluded definite quantification of the responses. Although behavior responses appear similar, the Malme techniques for deriving dB levels using average pulse pressure vs. rms values directly related to peak result in dB levels that are somewhat lower than those described in this paper. Due to the variations between the data sets and analysis techniques, only a relative comparison of dB levels can be made. The similarities between experiments reported here support the conclusion that short-term behavioral changes occur when bowhead whales are exposed to industrial seismic sounds at ranges <10 km. We also conclude that the disturbance effects wane within one hour after a disturbance; we cannot make further statements about long-term effects on social, behavioral or physiologic parameters.

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