Effects of sonic booms on breeding gray seals and harbor seals on Sable Island, Canada

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The Concorde produces audible sonic booms as it passes 15 km north of Sable Island, Nova Scotia, where gray and harbor seals occur year round. The purpose of this research was to assess how sonic booms affect these seals. The intensity of the booms was measured and three types of data (beach counts, frequency of behavior, and heart rate) were collected before and after booms during the breeding seasons of the two species. In addition to the data taken during breeding, beach counts were made before and after booms during the gray seal moult. The greatest range in overpressure within a single boom was 2.70 psf during gray seal breeding and 2.07 psf during harbor seal breeding. No significant differences were found in the behavior or beach counts of gray seals following sonic booms, regardless of the season. Beach counts and most behaviors of harbor seals also did not differ significantly following booms, however, harbor seals became more vigilant. The heart rates of four gray seal mothers and three pups showed no clear change as a result of booms, but six male harbor seals showed a nonsignificant tendency toward elevated heart rates during the 15-s interval of the boom. These results suggest sonic booms produced by the Concorde, in level flight at altitude and producing on average a sonic boom of 0.9 psf, do not substantially affect the breeding behavior of gray or harbor seals.
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I. INTRODUCTION

Marine mammal reaction to anthropogenic disturbance, such as boats, aircraft, seismic exploration, and human presence alone, is usually difficult to measure and much of the available information is anecdotal. Most of the data on disturbance responses come from short-term behavioral reactions such as termination of feeding or social interactions, and increase in vigilance (alertness) and/or avoidance responses (Richardson, 1995). There are a few studies of seals' reactions to aircraft overflights, but they rarely include measurements of sound levels (reviewed in Richardson, 1995).

The degree to which seals react to aircraft varies with characteristics of the flyover (Johnson, 1977; Kelly *et al.*, 1986). Variables such as the type, speed, flight path, and altitude of the craft affect disturbance responses in seals. For example, studies in which fixed wing aircraft were used for aerial surveys have reported altitude levels at which seals become disturbed and leave their haulout locations (e.g., Brueggeman *et al.*, 1990 as cited in Richardson, 1995; Osborn, 1985). Some species, such as bearded seals (*Erignathus barbatus*), appear to react more strongly to helicopters than fixed wing aircraft (Burns and Frost, 1979), although there are reports of walrus (*Odobenus rosmarus*) calf mortality caused by larger animals stampeding to the water when small aircraft approached (see Johnson *et al.*, 1989).

Characteristics of the seals and the season also play roles in the severity of a disturbance response. The number of animals and sex and age compositions of haulout groups appear to be important factors of how strongly the animals react to aircraft. Small groups of seals, groups composed primarily of young animals, and groups with mothers and pups tend to react most strongly (e.g., Salter, 1979). Male elephant seals showed a longer-lasting response to simulated sonic booms than females, while the response of California sea lions to the same stimulus varied with season (Stewart, 1982). During the breeding season females were more alert and males did not respond, but outside the breeding season more than half of the animals moved to the water. Some authors have speculated that dramatic disturbances can lead to increased pup mortality (e.g., Bowles and Stewart, 1980), as has been documented in walruses but not in Northern elephant seals or California sea lions (Stewart, 1982).

Generally, it is difficult to determine if seal reactions are to the sound stimulus and/or visual stimulus associated with the aircraft. Sonic booms generated by supersonic aircraft and rocket launches have caused California sea lions (*Zalophus californianus*) to stampede to the water, but not Northern elephant seals (*Mirounga angustirostris*) (Stewart *et al.*, 1993). In these cases the aircraft were not visible so the seals must have been responding to auditory stimuli alone.

With the potential for an increase in the use of supersonic commercial transport, it is important to assess how widespread and extensive the effects of sonic booms might be on marine mammals. The greatest impacts are likely to occur on breeding grounds that are within a few km of the flight paths of supersonic jets. There are presently few opportunities where such studies can be conducted, but one location is at Sable Island, Nova Scotia, Canada. Breeding

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gray seals and harbor seals haul out on Sable Island and are exposed to sonic boom generated by the Concorde on its daily trans-Atlantic flights. Their reaction to these booms has never been documented although the Concorde has been passing the island since the 1970s.

Gray seals and harbor seals use Sable Island throughout the year. Gray seals give birth to their young from late December through January and females remain on the pupping grounds throughout lactation. Adult males maintain positions near females and compete for the opportunity to mate with them, on land, at the end of lactation (Boness and James, 1979). Female harbor seals give birth to and nurse a single pup on land during their breeding season in May and June. Unlike gray seals, harbor seal females forage at sea during lactation, most often leaving their pups behind on shore (Boness *et al.*, 1994) and mating occurs in the water (Allen, 1985; Coltman *et al.*, 1998) at the end of lactation.

Sonic booms could substantially affect gray and harbor seals in several ways. The booms could cause movement and activity that would interrupt normal maternal care, leading to a decrease in pup growth rate and weaning weight, which could affect future survival of young (e.g., Boness *et al.*, 1995). Booms could cause an increase in the direct mortality of pups through trampling or causing them to flee the beach and be exposed to shark predation or by becoming separated from their mothers prematurely and starving to death.

The purpose of this study was to assess the impact of sonic booms on gray and harbor seals on Sable Island during breeding. It also examined whether gray seals tended to leave the beaches in response to booms during their moult. Both of these species have been repeatedly exposed to the Concorde's sonic booms on Sable Island, and thus may show decreased responses due to habituation. If habituation has occurred, adult seals are likely to respond less than pups, which would not have previously experienced sonic booms.

II. METHODS

A. Study site

Data for this study were collected on Sable Island, Canada (44 °N, 60 °W), from 2–27 January 1997 during the gray seal breeding season and 26 May–17 June 1998 during the harbor seal breeding and gray seal moulting seasons. Sable Island is a 40-km long crescent-shaped sandbar in the Northwest Atlantic, 163 km from land.

The westbound flight track of the Concorde {50° 41′ N, 15° 00′ W; 50° 50′ N, 20° 00′ W; 50° 30′ N, 30° 00′W–49° 16′ N, 40° 00′ W; 47° 03′ N, 50° 00′ W–46° 1′ N, 53° 00′ W; 44° 14′ N, 60° 00′ W–42° 46′N, 65° 00′ W) passes 8.4 nautical miles, or 15.5 km, north of Sable Island. Sonic booms are regularly heard in association with these flights.

B. Sonic booms

Two Boom Event Analyzer Recorders (BEARs) with PCB, Inc., model 106B50 high intensity ICP pressure sensors (frequency response: ±5% between 0.5 and 8000 Hz) with built-in preamplifier and windscreens were provided by the Noise Effects Branch, Armstrong Laboratory, at Wright-Patterson AFB, OH. The BEARs (frequency response set from 0.5 to 2500 Hz; maximum peak overpressure 165 dB *re*: 20 μPa) were designed to capture the full waveform of impulsive acoustic events and store them in digital form (Lee and Downing, 1993). The BEARs were set up at inland locations to digitally record sonic booms during the gray seal breeding season. Maximum sound pressure levels (rms, dB *re*: 20 μPA) were taken from a Brüel & Kjær, model 2236 handheld sound level meter (SLM) positioned at one of four inland locations. Recordings were calibrated daily using a Brüel & Kjær 124-dB Pistonphone Calibrator.

During the harbor seal breeding season in the summer, sonic booms were recorded using a TEAC model RD-135T DAT recorder and PCB 106B50 microphone with power supply, stationed at an inland location. Recordings were calibrated twice daily using a Brüel & Kjær 124-dB Pistonphone Calibrator.

C. Behavior

To assess if animals would respond to sonic booms with a dramatic startle response by fleeing into the water, we counted the number of gray seals and harbor seals on shorelines before and after booms. To detect more subtle behavioral impacts, we used videotaped records. These data involved paired comparisons of behavior during set time intervals before and after booms. Finally, we measured physiological impacts by deploying heart rate transmitters on free-ranging animals and comparing heart rates before, during, and after booms.

The number of gray seals along the shoreline adjacent to the videotaping sites were counted before and after the booms, to record the number of animals that left the beach. The haul-out groups included adults and pups during the breeding season and all age classes during the moulting season. Beach counts of harbor seals were conducted at two locations. One location was along the circumference of Wallace Lake, a small inland lake where there was the highest density of mothers and pups, as well as males. The other was along the North Beach wherever there was a haul-out group. The number of harbor seals using Sable Island during the breeding season has declined and haul-out groups, consisting primarily of adult males, were small and dispersed.

During the gray seal breeding season, remote video stations were established in two inland locations overlooking groups of mothers, their pups, and adult males. The locations were chosen based on having a concentration of mothers and pups; 11 mother–pup pairs at one site and 14 at the other. We also needed a good vantage point for the video camera so that we could see all of the animals in the field of view and access the camera without disturbance to the animals. The animals were videotaped daily, from 0745 to 1130 h and from 1230 to 1600 h, using time-lapse video equipment (Furhman Diversified, Inc., Seabrook, TX). Mothers and their pups were paint-marked for identification and daily maps of individuals' locations were drawn at the beginning of each tape session to assist with identification on videotapes. All animals in the field of view that were identified were included in the analysis. Because the video setup was focused on the same group for the season, we were able to observe the same mother–pup pairs throughout their lactation.

We used two sampling designs to detect possible changes in gray seal behavior in response to the sonic booms. In one analysis we compared the behavior of gray seals during the minute in which the boom was recorded with a randomly selected minute during the afternoon taping session, prior to the afternoon boom. In the second analysis, we compared each animal's behavior during a 10-min period before and after the boom.

In the minute of the boom, when we expected to detect immediate, or startle, responses to the boom, all animals were scored as to whether they were inactive or exhibiting low-level activity (subtle body movements such as raising the head to scan the area, scratching, or stretching) or moving (any activity involving position or location changes). For animals nursing at the time of booms, nursing terminations were also recorded. For a control condition, the behaviors of the same individuals were recorded during a randomly chosen 1-min interval in the afternoon when there were no sonic booms. Comparisons of the proportion of observations in which animals were active, moving, or nursing between boom and control minutes were made using paired *t*-tests Because proportional data violate assumptions of normality, we used 500 randomizations of the data to calculate the probabilities of our test statistics (Manly, 1997).

During the 10-min interval immediately preceding and following boom events we expected to detect more subtle, long-lasting, or cumulative effects. We recorded the frequency of aggressive encounters, number of movements, distance moved in seal lengths, occurrences of nursing (on-teat time), and number of 1-min intervals in which low-level activities occurred.

Harbor seal behavior was recorded on real-time videos, using Sony model TR700 video recorders. As with the gray seals, we observed frequency of aggression, frequency and duration of vigilance (scanning) behavior, movements on the beach, and total distance moved (measured in seal lengths) by the harbor seals. We were uncertain how long the effects of disturbance might last in harbor seals so we used several different time intervals for paired comparisons of behaviors before and after booms. We compared behavior in the 30 s following booms to that by the same individuals in the 30 s prior to the boom, and repeated the process for 1 min, 3 min, and 5 min following and preceding the boom.

Bonferroni adjustments were applied to significance levels of individual behavior variables, to test the overall null hypothesis that sonic booms did not affect the behavior of gray or harbor seals at $\alpha=0.05$ (Manly, 1997). Thus each of the four gray seal behavior variables were tested at a significance level of $\alpha=0.0125$ and the five harbor seal variables were tested at $\alpha=0.01$.

D. Heart rates

Heart rate monitoring units (Wildlife Computers, Inc., Isanti, MN) were deployed on five gray seal mother–offspring pairs and nine adult male harbor seals. Myocardial pacemaker electrodes (Medtronic, Inc.) were used on gray seals and salmon fishing hooks served as electrodes on harbor seals. Upon capture, gray seal females were sedated using Telazol® and harbor seals were given diazepam. Because handling and both drugs were likely to affect the seals' heart rates, we did not include heart rate data from the first 24 h following deployment of the units. The units were programed to store heart rate at 5-s intervals and were left on the animals for 4–13 days.

The heart rate receivers recorded heart rates ranging from 0 to 256 beats per min (bpm). Extreme readings were common and likely instrument artifacts (R. Hill, Wildlife Computers, pers. com.). To remove such artifacts we deleted any rates that were less than 4 bpm—the lowest reported heart rate in a seal (Thompson and Fedak, 1993). We also deleted any rates greater than 207 bpm because a frequency distribution showed a major peak at 207 bpm and individual records periodically showed long strings of 207 bpm, just as strings of zeros occurred.

Using the corrected data sets, gray seal heart rates were averaged over three time periods before booms (3 min, 2 min, and 1 min) and were compared using a repeated measures ANOVA to heart rates during the minute of booms, and to the 3-min, 2-min, and 1-min time period following each boom. Harbor seal heart rates were averaged over 3

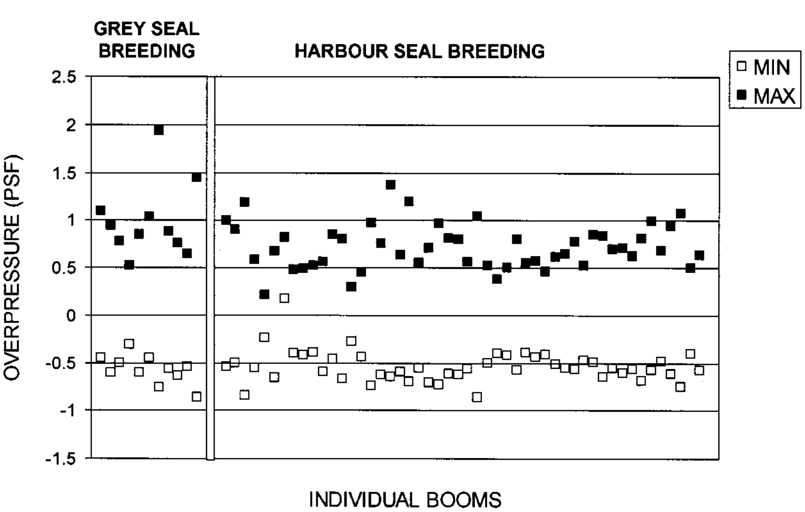

FIG. 1. Minimum and maximum overpressures of *N*-wave sonic booms recorded during the gray and harbor seal breeding seasons and gray seal moulting season on Sable Island, Nova Scotia.

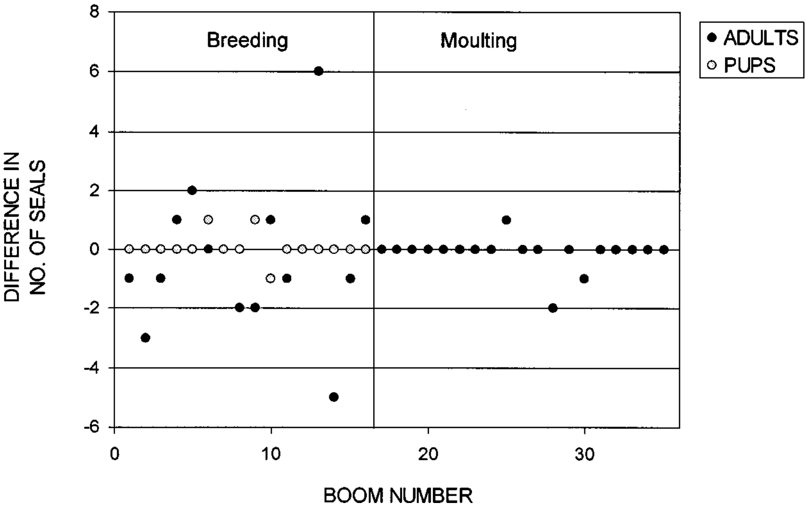

FIG. 2. Difference in number of gray seal adults and pups on beaches before and after sonic boom events during breeding and moulting seasons.

min, 2 min, and 1 min before the booms and compared, using a repeated measures ANOVA, to heart rates in the 15 s that booms occurred and 3-min, 2-min, and 1-min intervals following the booms.

III. RESULTS

A. Sonic booms

There was a range from 0 to 5 sonic booms heard daily during the gray seal and harbor seal breeding seasons. Generally there were three sonic booms each day, two between 0800 and 1000 h and one between 1730 and 1830 h. The times of events varied little between the two field seasons, making them easy to predict to within 15 mins.

During the gray seal breeding season, a total of 66 audible booms were documented, of which 12 were recorded by BEARs (Fig. 1) and 36 were measured by the sound level meter (SLM). There were high correlations between minimum (Pearson correlation, $r=0.997$) and maximum ($r=0.999$) overpressures and the maximum sound level ($r=0.999$) for the four booms that were recorded simultaneously by the two BEARs. There were also high correlations between the maximum sound levels registered by the BEAR units and the SLM (BEAR 17 and SLM: $r=0.938$; BEAR 18 and SLM: $r=0.907$). The mean minimum and maximum overpressure, based on data recorded by the BEARs, were -0.568 psf (s.d.$=0.142$) and 0.935 psf (s.d.$=0.355$), respectively. Sound pressure levels detected by the SLM ranged from 121.68 to 133.33 dB, with a mean of 114.21 dB (s.d.$=6.49$). The greatest range in overpressure within a single sonic boom during gray seal breeding was 2.70 psf.

During the harbor seal breeding season and gray seal moulting season we were able to record 50 (Fig. 1) of 70 noted sonic booms using the DAT recorder. The mean minimum and maximum overpressures were -0.541 (s.d. $=0.166$) and 0.716 psf (s.d.$=0.238$), respectively. The greatest range in overpressure within a single sonic boom in May/June was 2.07 psf.

B. Behavior

1. Beach counts

On 16 days of the gray seal breeding season we recorded the number of adults and pups on two portions of the shoreline before and after sonic boom events. Because we could not predict the exact time that a boom event would occur, two of our pre-boom counts were more than 15 min before the boom and, therefore, excluded from the analysis. There was no significant difference between the number of adults

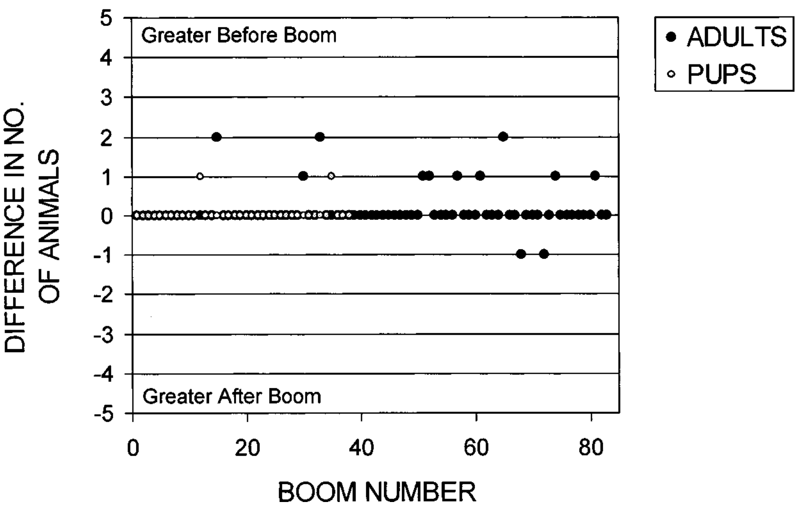

FIG. 3. Difference in number of harbor seal adults and pups on beaches before and after sonic boom events during their breeding season.

TABLE I. Results of the paired t-test comparing the occurrences of low-level activity, movement, and nursing between the minute of booms and control minutes for gray seal pups and adults. Probabilities for paired t-test following 500 randomizations are reported as $p_{\text{randomizations}}$. [Data are proportional and, therefore, violate assumptions of parametric tests. Randomizations of data allow use of parametric tests (Manly, 1997).]

	Behavior	Mean Boom	Mean Control	T	p	$p_{\text{randomization}}$
Pups $N=25$	Low-level activity	0.53	0.59	−0.74	0.464	0.470
	Movement	0.10	0.11	−0.15	0.879	0.858
	Nursing	0.05	0.03	0.75	0.458	0.542
Adults $N=28$	Low-level activity	0.82	0.78	0.95	0.348	0.374
	Movement	0.15	0.18	−0.86	0.396	0.428

on the beach before and after the boom (paired t-test; $t=1.07$, $df=13$, $p=0.304$), with pre-boom group sizes ranging from 14 to 37 adults. Neither was there a difference between the number of pups on beaches before and after booms (paired t-test; $t=0.366$, $df=13$, $p=0.72$; Fig. 2), with pre-boom pup counts ranging from 3 to 29.

We were also able to conduct gray seal beach counts before and after 21 sonic booms during their moulting period. All pre-boom counts were conducted no more than 1 min before the booms and groups were counted less than 1 min after booms. Group sizes before and after booms, which varied from 1 to 15 animals, were compared using nonparametric rank tests because the data were not normally distributed. There was no significant difference between pre- and post-boom counts (Wilcoxin Signed Rank Test; $W=3.00$, $p=0.50$; Fig. 2).

A total of 83 harbor seal counts, 33 at Wallace Lake and 50 on North Beach, were made before and after 55 different boom events (Fig. 3). Counts were made within 1 min prior to booms and within 1 min following booms. Group sizes on North Beach ranged from 1 to 20 adults and on the shoreline of Wallace Lake from 4 to 13 adults and 1 to 10 pups. We found that the number of pups on Wallace Lake shoreline did not change in response to booms (Wilcoxin Signed Rank Test; $W=-3.00$, $p=0.50$). We also found no difference in the number of adults before and after booms at either site (North Beach: $W=-6.00$, $p=0.25$; Wallace Lake: $W=-27.00$, $p=0.13$).

2. Observed behavior

Gray seal video recording sessions commenced on 4 Jan and continued until 27 Jan. At one site recordings provided data on 11 mother–pup pairs and 2 adult males during 30 sonic booms. At the second site, the behavior of 14 mother–pup pairs and 1 adult male was recorded for 24 booms.

Comparing behaviors in the minute of the boom to a randomly selected minute we found no significant differences overall in the occurrence of low-level activity ($t=-0.19$, $df=52$, $p=0.85$) or movement ($t=-0.80$, $df=52$, $p=0.45$) between boom and randomly selected control minutes. When separated by age class, neither pups nor adults differed significantly in the occurrence of low-level activity or movement between the boom minutes and control minutes (Table I).

A total of 27 gray seal nursing bouts were observed during the boom minutes and 15 were observed during the control minute. Of these 11 (41%) were interrupted during the boom and 8 (53%) during the control minute.

Likewise, when behavior data were analyzed using a 10-min period after the boom compared to 10 min before, there were no significant differences in behaviors for either pups or adults (Fig. 4). The mean activity level, measured as the number of 1-min intervals in which animals were active during each 10-min period, did not differ. Nor was there a mean difference in the number of times that animals changed location or the distance moved before and after booms, for either pups or adults (Table II).

As there were only 28 harbor seal pups born on Sable Island during 1998, and they were widely dispersed, only adult and sub-adult males were included in assessments of behavior. Harbor seal males spend about 40% of their time on land during the breeding season and much of this time is spent resting (Coltman *et al.*, 1997). They are rarely aggres-

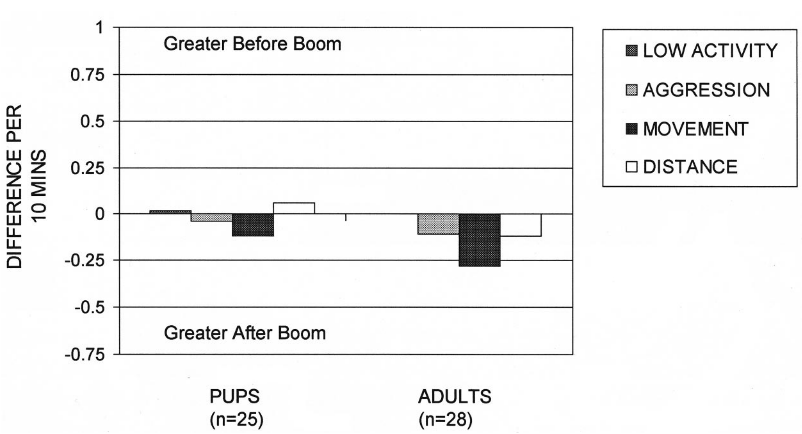

FIG. 4. Differences between gray seal adult and pup behaviors in the 10 min before booms and 10 min following booms.

TABLE II. Results of repeated measures ANOVA comparing the occurrences of low-level activity, aggression, movement, and distance moved between 10-min intervals immediately before and after booms for gray seal pups and adults. Probabilities for F-values following 500 randomizations are reported as $p_{\text{randomizations}}$. (These data were not normally distributed and, therefore, randomizations were used to calculate true probabilities for each F-value.)

	Behavior	Mean Before	Mean After	F	df	p	$p_{\text{randomization}}$
Pups $N=25$	Low-level activity	0.54	0.55	0.22	1,24	0.6361	0.596
	Aggression	0.01	0.03	2.43	1,24	0.1194	0.442
	Movement	1.07	1.22	0.63	1,24	0.4265	0.312
	Distance moved	0.87	0.87	0.00	1,24	0.9548	0.948
Adults $N=28$	Low-level activity	0.77	0.78	0.29	1,27	0.5887	0.552
	Aggression	0.44	0.52	1.28	1,27	0.2577	0.368
	Movement	1.19	1.40	1.70	1,27	0.1926	0.150
	Distance moved	1.03	1.23	1.15	1,27	0.2831	0.312

sive because mating and competition for mates occur at sea. Consequently, we found low frequencies of aggression in our 10-min samples before the boom and found no increase in incidence of aggression following booms in any of the four time intervals (Fig. 5). We also found little movement by males when they are settled on the beach and there was no increase in movement following booms, regardless of the length of the observation interval (Fig. 5).

Harbor seal males did become significantly more vigilant, both in frequency and duration, following sonic booms (Table III). The effect was most apparent in the 30 s following a boom and least apparent in the 5-min observation period. The difference in frequency of vigilance was still significant when comparing 5-min periods but the difference in duration was not, using the Bonferroni correction (Table III).

C. Heart rates

Of the ten units deployed on gray seals, seven provided useful data, two units were lost, and one unit failed. Heart rate data were obtained from four gray seal females and three pups. The number of booms encompassed in these data varied among individuals, ranging from 3 to 17.

Female gray seals had an average heart rate of 103.0 bpm (s.d.$=36.1$), which was lower than that of pups, 132.6 bpm (s.d.$=30.3$). In none of our three time-interval comparisons did heart rates differ between pre-boom, boom, and post-boom periods for either females or pups (Table IV).

The heart rates of harbor seal males ($n=6$) had a bimodal distribution with one peak below 55 bpm and the second peak above 80 bpm, as illustrated for three males in Fig. 6. In all three time-interval comparisons (1 min, 2 min, and 3 min before and after booms) we found a similar pattern in which heart rates before and after booms were consistently lower than those in the 15-s boom interval (Fig. 7). None of our comparisons were significant, but because of our small sample sizes we had low power to detect significant differences.

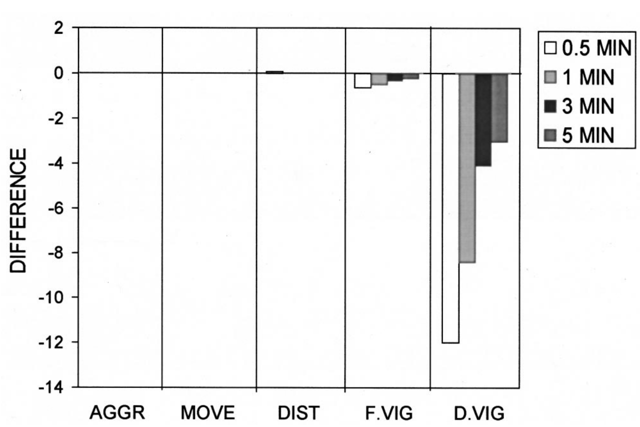

FIG. 5. Differences in five harbor seal behaviors between pre-boom time intervals and post-boom time intervals. Behaviors include aggression (AGGR), movement (MOVE), distance moved (DIST), frequency of vigilance (F.VIG), and duration of vigilance (D.VIG).

IV. DISCUSSION

We studied gray and harbor seals during breeding and gray seals during moulting on Sable Island, Nova Scotia, to assess how sonic booms affect their behavior. We collected three types of data: beach counts, behavior (social, spatial, and vigilance or low activity), and heart rates. Our general design was to collect these data on the same individuals before and after booms and to include all age and sex classes. Pups were expected to be more sensitive than juveniles and adults because the Concorde has been flying past Sable Island since the early 1970s and juvenile and adults may have become habituated to sonic booms. Pups, however, will not

TABLE III. Mean differences[a] in male harbor seal behaviors ($n=41$ sonic booms) within four different observation intervals.

	30 s	1 min	3 min	5 min
Frequency of aggression	0.02	0.01	−0.03	0.01
Frequency of movement	0.02	0.01	−0.03	−0.05
Distance moved	0.06	−0.02	−0.08	−0.11
Frequency of vigilance	−0.29[a] ($p=0.007$)	−0.48[a] ($p=0.006$)	−0.88[a] ($p=0.002$)	−1.09[a] ($p=0.009$)
Duration of vigilance	−6.02[a] ($p=0.0001$)	−8.39[a] ($p=0.001$)	−12.24[a] ($p=0.012$)	−14.95 ($p=0.056$)

[a]Difference=Pre-boom behavior−post-boom behavior.

TABLE IV. Mean heart rates (SEM) for gray seal females and their pups before, during and after sonic boom events. Pre-boom, boom, and post-boom time intervals over which heart rates were averaged are shown in the "Interval Durations" column.

	Interval durations	Pre-boom	Boom	Post-boom	Repeated measures ANOVA
Females	1 min–1 min–1 min	106.0 (9.7)	105.7 (11.7)	105.6 (12.2)	$F_{2,3}=0.009$, $p=0.99$
	2 min–1 min–2 min	104.4 (10.0)	105.7 (11.7)	105.6 (12.7)	$F_{2,3}=0.095$, $p=0.91$
	3 min–1 min–3 min	104.9 (10.4)	105.7 (11.7)	106.4 (12.3)	$F_{2,3}=0.192$, $p=0.83$
Pups	1 min–1 min–1 min	139.6 (4.2)	142.0 (3.5)	137.7 (2.1)	$F_{2,2}=1.876$, $p=0.27$
	2 min–1 min–2 min	139.8 (3.6)	142.0 (3.5)	138.4 (2.7)	$F_{2,2}=3.738$, $p=0.12$
	3 min–1 min–3 min	140.2 (3.6)	142.0 (3.5)	139.5 (2.4)	$F_{2,2}=1.877$, $p=0.27$

have been directly exposed to the booms prior to being born. Unfortunately, the dramatic decline in harbor seal births over the past few years, combined with their dispersed distribution, made it difficult to collect data on both pups and females of this species.

Disturbance responses such as abandonment of the beach, large-scale movements, or increased aggression may cause separations of mothers and pups and eventual starvation of pups. Likewise, abandonment of the beach, especially by young animals, might increase shark predation. Less direct effects that may be significant are disruptions to maternal care such as reduced suckling, which may lead to lower pup growth rates and weaning weights. Moulting seals have reduced metabolic rates compared to pre-moult periods (Ashwell-Erickson *et al.*, 1986), reducing the need for food. Moulting seals tend to spend more time hauled-out, which allows increased blood flow to the skin and warmer skin correlates with increased hair growth (Feltz and Fay, 1966; Ling, 1974). A frequent disturbance that forces seals into the water could prolong moulting, during which seals fast, by slowing hair growth. In addition, during the moulting fast, seals mobilize lipids stored in the blubber to meet metabolic needs (John *et al.*, 1987) and, therefore, extending the moult and accompanying fast could lead to reduced energy stores and slower recovery of body condition.

During a severe disturbance, animals would be expected to show avoidance behavior by racing to the water, which has been documented in harbor seals and other seal species (Stewart, 1981, 1993; Stewart *et al.*, 1993, 1996). In this study, the number of gray seal and harbor seal adults and pups on beaches during the breeding season did not change following booms, nor did the number of gray seals during the moulting season. Therefore, the seals were not sufficiently startled or disturbed to rush to the water when booms occurred.

Adult gray seals are aggressive on breeding grounds, with aggression occurring between all possible age-sex class comparisons. Some types of aggression occur more frequently toward the end of the breeding season and others earlier in the season (Boness *et al.*, 1982; Boness, 1984; Boness *et al.*, 1995). In addition, the incidence of aggression tends to increase as density on breeding beaches increases (Fogden, 1971), either through crowding or movement. As expected, we found that adult gray seals were more aggressive than pups, however, the incidence of aggression did not increase following booms. Gray seals also did not increase movements on the beaches following booms, which might have been expected if the animals were startled. In contrast to gray seals, harbor seals tend to be less aggressive on land, although male–male aggressive encounters do occur during the breeding season (Thompson, 1988). There was no change in the incidence of harbor seal aggression following sonic booms, nor did the frequency of movement change.

Other studies have shown an increase in vigilance or alertness as a disturbance reaction in seals (Bowles and Stewart, 1980; Stewart, 1981, 1993; Stewart *et al.*, 1996). We measured low-level activity in the gray seals, which would include changes in scanning behavior or vigilance, and found no differences following booms. Harbor seal males did become significantly more vigilant, both in frequency and duration, for up to 5 min following sonic booms. Studies of harbor seal vigilance have found that the frequency of vigilance varies with group size and composition as well as time of year (Renouf and Lawson, 1986; Terhune, 1985). Adult males become more vigilant as the breeding season progresses and when group sizes are small the frequency of individual vigilance increases. In this study, animals were observed during their mating season and group sizes ranged from 1 to 20 animals; therefore, the increased vigilance following sonic booms probably reflects a common tendency for these animals to be alert. The lack of movement to the water by seals suggests that the wariness produced is relatively mild.

A number of studies of birds and mammals have shown that heart rate is a sensitive indicator of arousal and that heart rate can dramatically increase when animals are disturbed or harassed (MacArthur *et al.*, 1979; Moen *et al.*, 1978; Thompson *et al.*, 1968). Few studies have reported seal heart rates, particularly of startled animals. Generally, pinniped heart rates drop when the animals enter periods of apnoea during diving, fright, or sleep and increase above resting heart rate when the animals are breathing following dives (Kooyman, 1989).

Variation in reported heart rates is extreme in seals, ranging from 4 bpm in a free-ranging gray seal during dives (Thompson and Fedak, 1993) to more than 171 bpm in a threatened harp seal pup (Lydersen and Kovacs, 1995). Fedak *et al.* (1988) report that the heart rate of gray seals in a swimming flume was between 110 and 120 bpm and that heart rates did not increase with exercise alone but did increase after multiple dives.

Gray seal pups had higher heart rates than adult females, as has been found in harp seals (Lydersen and Kovacs, 1995). However, neither the heart rates of gray seal mothers

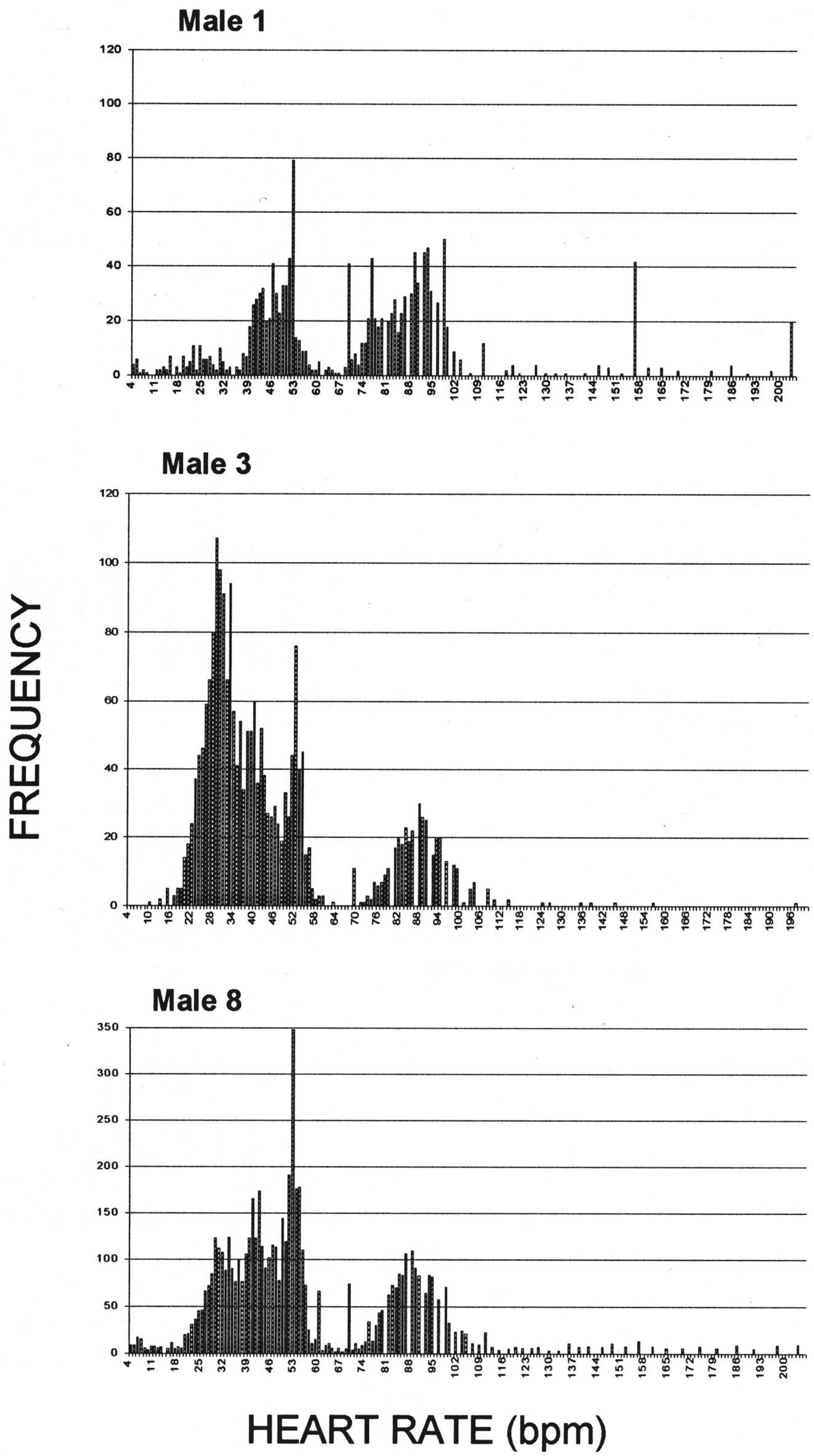

FIG. 6. Frequency distribution of heart rates for three adult males on 5 June 1998, after heart rates below 4 and above 204 bpm have been removed.

or pups differed among pre-boom, boom, and post-boom periods. When harp seal adults and pups are threatened by the approach or touch of a human, they alternate between states of apnoea, when heart rates drop to less than 35 bpm, and hyperventilation, when heart rates increase to over 150 bpm (Lydersen and Kovacs, 1995). Clearly, the gray seals in this study were not similarly stressed by sonic booms.

The heart rates of harbor seal males showed a trend in which their heart rates rose to an average of 66 bpm during the boom and returned to lower pre-boom rates immediately after. The difference in heart rates was not significant probably because the sample sizes were small. The harbor seal heart rates had a bimodal distribution with peaks between 30 and 55 bpm and another between 75 and 100 bpm. It is possible that the lower heart rate occurred while animals were sleeping and the higher heart rate occurred while animals were awake. Thus the increase in heart rates at the time of the boom would reflect that animals awoke from sleep.

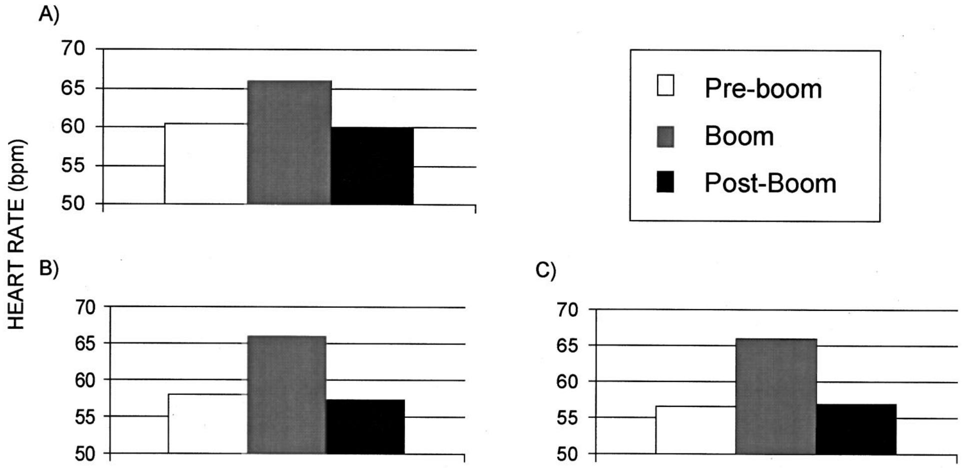

FIG. 7. Mean heart rates of adult male harbor seals ($n=6$) averaged over 15 s in which the boom occurred and (a) 1-min intervals ($F_{2,5}=2.211$, $p=0.160$), (b) 2-min intervals ($F_{2,5}=2.603$, $p=0.123$) and (c) 3-min intervals ($F_{2,5}=3.901$, $p=0.056$) before and after sonic booms.

Unfortunately, we do not have behavior data to confirm this suggestion. Nonetheless, the change in heart rates in response to booms demonstrated that the animals perceived the booms but, because the responses were minor and short-lived, the animals were not severely disturbed.

Based on our results, we suggest that sonic booms from the Concorde do not have substantial effects on the breeding behavior of gray and harbor seals on Sable Island. The lack of large-scale movements from the beaches to the water in response to the boom precludes the possibility that shark predation or separations of mothers and pups result from these particular sonic booms. Similarly, lack of increased movement on the beaches or increased aggression precludes the possibility of increased mother–pup separation or injury to animals. These behaviors, along with lack of evidence of suckling terminations in response to these booms, suggest that there is no reduction in quality of maternal care. The minor effects of increased vigilance and slight increase in heart rates of harbor seals are unlikely to substantively affect individual animals or the population.

Given the long history of sonic booms from the Concorde's flights near Sable Island and a steady increase of about 13% per year in the gray seal breeding population at Sable (Mohn and Bowen, 1996), it seems unlikely that there are any long-term cumulative effects of these booms on the breeding biology of Sable gray seals. It is more difficult to make such a clear statement about harbor seals since the breeding population at Sable Island is experiencing a major decline at the present time. However, during the twenty-some years of the Concorde flights near Sable Island, the harbor seal population increased substantially from 1987 through 1993 before beginning the substantial decline. It is therefore unlikely that these sonic booms are playing a role in this decline through cumulative effects.

In conclusion, our results show relatively minor or no affects of sonic booms produced by the Concorde on breeding harbor and gray seals. There are several points to consider in interpreting our results. First, the seals breeding on Sable Island have had at least 20 years to habituate to the booms and, therefore, we are not measuring responses at first exposure, with the exception of responses by pups. Second, the carpet booms of the Concorde in level flight over Sable Island produce a relatively minor form of disturbance (approximately 0.9 psf) in comparison to focused booms of greater intensity, such as those produced during low-altitude combat maneuvers. Therefore, it is important to note that the results presented here may not be generalizable to unexposed adult seals or to seals exposed to other types of sonic booms. Finally, we were unable to measure effects of the sonic booms on animals in the water. Sonic booms penetrate water and the impact will vary with oceanic wave conditions and aircraft speed (Sparrow, 1995; Rochat and Sparrow, 1997). Consequently, booms have the potential to affect animals that are in the water foraging or moving between foraging areas and breeding grounds.

V. SUMMARY

We studied gray and harbor seals during breeding and gray seals during moulting on Sable Island, Nova Scotia, to assess how sonic booms affect their behavior. We collected three types of data: beach counts, behavior (social, spatial, and vigilance or low activity), and heart rates. Our general design was to collect these data on the same individuals before and after booms. We deliberately tried to include all age and sex classes in our study since we might have expected different sensitivities for different classes. This would be especially true for pups compared to juvenile and adults because the Concorde has been flying past Sable Island since the early 1970s and juvenile and adults may have become habituated to sonic booms. Pups, however, will not have been directly exposed to the booms prior to being born. Unfortunately, the dramatic decline in harbor seal births over the past few years, combined with their dispersed distribution, made it difficult to collect data on pups especially, but on females as well.

Although the individual data sets may not be specifically biologically significant, taken together, if there were significant effects of booms on these measures or a group of them, it would point to a biologically significant impact on these species. For example, abandonment of the beach, large-scale movements, or increased aggression may cause separations of mothers and pups and eventual starvation of pups. Likewise, abandonment of the beach, especially by young animals, might increase shark predation. Less direct effects that may be significant are disruptions to maternal care such as reduced suckling, which may lead to lower pup growth rates and weaning weights. Moulting is a particularly energetically demanding period following shortly after another demanding period, breeding. Frequent disturbance that forces seals into the water could prolong moulting (during which seals fast) and lead to failures to recover body energy stores or to compromise the immune system, making seals more vulnerable to diseases.

However, our results from gray seals provided no evidence to suggest sonic booms from the Concorde had any effect on this species. No animals of any age or sex class left the beaches in substantial numbers in response to sonic booms, either during the breeding season or the moulting season. There was no indication of increased aggression or increased frequency of movement or distance moved on the breeding grounds by individual animals after booms. Suckling bouts did not appear to be interrupted by booms since the number of times suckling terminated during sampling periods did not differ between the boom periods and control periods. There was not even any apparent effect on low-level activity or vigilance behavior or heart rates for either adults or pups.

Results from the harbor seal study were similar with respect to beach counts and most behavior variables, but small effects were apparent in some behaviors and heart rates. Neither males, females, nor pups left the beaches in response to sonic booms, as evidenced by a lack of change in beach counts before and after booms. Aggression among seals on the beach was very low normally and showed no increase in response to sonic booms. The frequency of movement on land and distances moved before booms did not differ following booms. However, unlike gray seals, the frequency and duration of vigilance, or scanning behavior, did significantly increase following booms and this difference persisted for up to 5 min, although the effect began to diminish. Similar to the effect on vigilance behavior, heart rates increased during booms but diminished rapidly and returned to pre-boom levels.

Based on our results, we suggest that sonic booms from the Concorde do not have substantial effects on the breeding behavior of gray and harbour seals. The lack of large-scale movements from the beaches to the water in response to the boom precludes the possibility that shark predation or separations of mothers and pups result from sonic booms. Similarly, lack of increased movement on the beaches or increased aggression precludes the possibility of increased mother–pup separation or injury to animals. All of these behaviors along with lack of evidence of suckling terminations produced by booms point to no reduction in quality of maternal care. The minor effects of increased vigilance and slight increase in heart rates of harbor seals are unlikely to substantively affect individual animals or the population. Given the long history of sonic booms from the Concorde's flights near Sable Island and a steady increase of about 13% per year in the gray seal breeding population at Sable, it seems unlikely that there are any long-term cumulative effects on the breeding biology of Sable gray seals. It is more difficult to make such a clear statement about harbor seals since the breeding population at Sable Island is experiencing a major decline presently. However, within the twenty-some years of the Concorde flights near Sable Island, the harbor seal population increased substantially from 1987 through 1993 before beginning the substantial decline. It is therefore unlikely that the sonic booms are playing a role in this decline through cumulative effects.

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