feature article

Human-generated sound and marine mammals

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Loud anthropogenic noises can alter the behavior of whales and other marine mammals, sometimes with fatal consequences.

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Most species of large whales are endangered because for centuries whaling fleets have decimated their populations. In the late 1960s, marine-mammal biologists discovered that fishermen setting nets for tuna in the Pacific Ocean were killing more than 100 000 dolphins a year. The cause of marine-mammal conservation became so popular at the dawn of the environmental movement that one of the first environmental accomplishments of the US Congress was to enact the Marine Mammal Protection Act of 1972, which prohibits the killing or injuring of marine mammals.

Today, small remnant populations of whales, such as the North Atlantic right whale, are threatened by entanglement in fishing gear and collisions by ships. Indeed, marine biologists have estimated that hundreds of thousands of marine mammals are killed each year in fishing gear.[1] Inadvertent effects of human activities can pose a serious risk to coastal populations, as evidenced by the recent extinction of the Chinese river dolphin due to fishing, pollution, and overdevelopment of the Yangtze River. A few decades ago, conservation efforts focused on reducing the intentional hunting of marine mammals. Nowadays, when hunts for marine mammals are better controlled, the slow degradation of habitat from a combination of sources may have a bigger impact. For example, biologists have documented cases in which the effects of coastal development—including noise, pollution, and dredging—have caused marine mammals to abandon critical breeding habitat.[2] Noise in particular is at issue in legal actions that have been brought against the US Navy for sonar exercises that may have caused whales to strand and die (see PHYSICS TODAY, February 2008, page 23).

Behavior modification

Biologist Roger Payne and ocean engineer Douglas Webb were the first to raise the alarm about the effect of sound on marine mammals.[3] In 1971 they considered the then recently discovered low-frequency calls associated with the reproduction of baleen whales. Payne and Webb noted that in the preindustrial ocean those calls could have been heard about 280 km away, but the low-frequency propulsion noise of modern commercial ships had so elevated ambient noise in the sea that the detection range for whale calls could be as low as 90 km. In addition to that decrease, whale populations had been greatly reduced by whaling. Thus the average separation between vocalizing males and females may have increased at the same time as their range of communication was reduced. If noise interferes with breeding behavior, it could inhibit the recovery of depleted populations.

Despite reason for concern, decades passed with little work on how shipping noise affects whale communication. One problem was methodological. How could one study whether shipping noise was the reason that a whale did not detect a call emanating from 200 km away? It has taken marine biologists decades to develop methods to study effects of sounds from sources only a few kilometers away.

We still do not know how often shipping noise prevents a whale from detecting important signals. Recent work, however, has shown that marine mammals can compensate for noise, at least to a point, by increasing the level of their own calls, shifting their signals out of the noise band, making their signals longer or more redundant, or waiting to signal until noise is reduced. Many of those compensation mechanisms involve increased energy expenditure or other costs to the signaler. For the signaler to modify its behavior and accept that cost suggests a problem with the reduced range of communication caused by shipping noise.

Since Payne and Webb's paper was published, researchers have increasingly developed and applied methods to study whether exposure to sound disrupts the normal behavior of marine mammals. Some early experiments, motivated by concerns about the impact of offshore oil-industry activities, tracked migrating gray whales as they passed a sound source moored in the migration corridor off California. The whales, which were exposed to experimental playback of continuous industrial sounds such as those from ships or drill rigs, avoided sound pressure levels (SPLs) of 120 dB relative to 1 μPa. (Henceforth, I'll drop explicit mention of the 1 μPa reference pressure; see the box on page 41 for a review of definitions and notations of sound levels.) Aerial observations of bowhead whales migrating past a seismic survey vessel showed that those whales also avoided exposures greater than about 120 dB. The air guns used for the seismic surveys were so intense that the whales rarely came within 20 km of a survey vessel.

A small industry has sprung from the observation that marine mammals may avoid loud sounds. Acoustic harassment devices are typically electronic sound sources designed to deter seals from catching farmed fish or to keep marine mammals away from such dangers as nets. The devices do

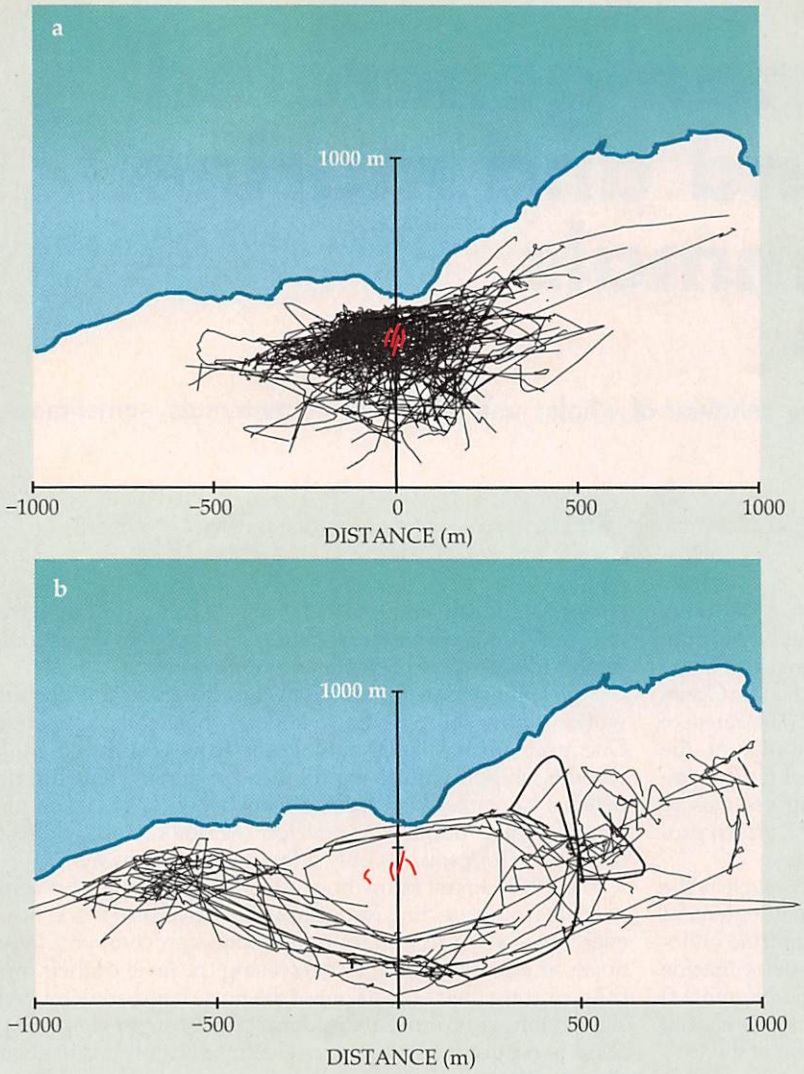

Figure 1. Harbor porpoises avoid loud noises. In these plots, the white area is a part of the Clayoquot Sound in British Columbia, Canada; black lines indicate porpoise tracks; and the red bits indicate float lines from which an electric pinger was suspended. **(a)** In this control run, the pingers are off. **(b)** When the pingers are on, they emit short noises with a sound pressure level of 145 dB relative to 1 μPa. The gap in tracks shows that porpoises avoid coming within a few hundred meters of the pingers. (Adapted from ref. 4.)

not always deter seals, which may even interpret their loud sound as a dinner bell. The noises may be more likely to repel more sensitive animals such as the harbor porpoise. Many studies of porpoises in the wild and in the lab show that the animals avoid low levels of sound exposure at much greater distances than do seals. Figure 1, for example, shows tracks of harbor porpoises in British Columbia, Canada, observed in control conditions and when they were exposed to short, 145-dB sounds.[4] The porpoises avoided coming within a few hundred meters of the pinger; that is, they shied away from SPLs greater than about 100 dB. For fisheries where porpoises entangle in nets and die, pingers can be attached to the nets to reduce the number of animals killed. On the other hand, loud acoustic harassment devices may prevent porpoises, whales, and other cetaceans from using large swatches of their preferred habitat.

First, do no harm

The use of intense deterrent sound sources highlights the need to define what exposures to underwater sound might harm a marine mammal. By the early 1970s, scientists had collected some data on effects of explosives on terrestrial mammals—for example, sheep submerged in a pond—that could help define levels that ruptured eardrums or caused injury to the lungs or other organs. Let alone the gruesomeness of the experiments, which I doubt would pass today's animal welfare standards, submerged terrestrial mammals are not good proxies for marine mammals. In any event, as concern about the effects of sound on marine mammals increased in the early 1990s, it became clear that not enough data were available to define safe-exposure criteria for marine mammals.

During the 1990s the US Office of Naval Research supported the development of new methods to define levels of sound exposure that affect hearing in captive marine mammals. Those approaches take their cue from studies on humans. Extensive research in the workplace suggests that a useful standard is to limit noise exposure to below levels that affect our hearing. Although peak sound level can be an important indicator for risk of injury, particularly for impulse noise, sound exposure in the workplace is typically integrated over an eight-hour workday. That integrated sound exposure level (SEL) is a better overall predictor of risk than the SPL.

The basic concept is to measure the faintest sound an animal can hear, then expose the animal to a noise stimulus and retest hearing. Measuring the noise just loud enough to cause a temporary reduction in hearing sensitivity gives a conservative estimate of the exposure that could pose a risk of injury if sustained or increased. In the mid-1990s, studies began to report exposures leading to temporary threshold shift (the term of art for temporary hearing loss) in captive seals and dolphins. By 2007 Brandon Southall and colleagues had gathered enough data from TTS experiments with marine mammals and from studies of other species to establish criteria for acoustic injury.[5] For whales and dolphins, the criteria set a maximum 0-to-peak pressure level of 230 dB, a maximum SEL of 198 dB for pulsed sounds, and a maximum SEL of 215 dB for nonpulsed sounds. Data from seals suggest that their auditory systems may be affected by lower levels of sound; criteria for them are a maximum 0-to-peak pressure level of 218 dB and maximum SELs of 186 dB for pulsed sounds and 203 dB for nonpulsed sounds.

According to current US regulations, SPLs above 180 dB pose a risk of injury to whales and dolphins. Despite seals' apparently greater sensitivity to noise exposure, regulations set 190 dB as the threshold for risk of injury to them. US regulations also establish criteria for disrupting behavior. They set the disruption threshold at 160 dB for whales and dolphins. The threshold for porpoises is lower—120 dB—because of evidence that they respond to sounds at lower levels than many other cetacean species. Note that the US regulations are in terms of SPL, a different measure from the 0-to-peak pressure and SEL used for the criteria suggested by Southall and company.

The sound produced by air-gun arrays, explosives, and some sonars is so intense that it could directly injure animals in the immediate vicinity. US regulations require that such sound sources be shut down if a marine mammal might enter the zone of potential injury. The standard oil-industry practice for reducing unintentional exposure during seismic surveys is to start firing just one air gun and slowly increase the number of guns until the full array is firing. Once the array is operating, regulators assume, whales will swim out of the danger zone. So the survey ships are allowed to operate at night and in fog when it is impossible to sight animals.

Dtag, you're it

The assumptions behind noise regulations have a Goldilocks feel to them—whales will respond to air guns strongly enough to stay out of danger but not so strongly as to significantly disrupt their behavior. And as discussed above, evidence exists that baleen whales, such as the bowhead and gray, reliably avoid air guns. But by 2000 it was clear that empirical evidence could not justify the assumption that toothed whales—related to but distinct from the baleens—moved out of a danger zone as a seismic survey vessel either ramped up an air-gun array or approached with a full array firing. Indeed, sperm whales tend to be sighted closer to seismic vessels when air guns are active.[6] The lack of definitive data for toothed whales was not lost on the US Minerals Management Service (MMS), which is responsible for assessing the impacts of its leases of offshore tracts for oil development. As the oil industry moved into the deep-water habitat of sperm whales, which the US lists as endangered, the MMS was stimulated to support research on how sperm whales in the Gulf of Mexico respond to air guns.

Until relatively recently, we who study how sound affects marine mammals have been hampered by primitive methods of measuring an animal's behavioral responses and acoustic exposure. I have worked with engineer Mark Johnson to develop a tool to solve the problem—a tag that can be placed on the animal to record sound and movement. Our Dtag (digital tag), shown in figure 2 and on this month's cover, uses three-axis magnetometers and accelerometers to measure the orientation and movement of a whale, a pressure sensor to measure depth of dive, and calibrated hydrophones to measure sound at the whale. The tag is attached to a whale with suction cups and records behavioral data at a high rate to flash memory. It is programmed to detach from the whale after up to 18 hours, during which time it collects up to about 10 gigabytes of data. After detachment, a radio beacon guides scientists to the tag, so that they can download the data. Not only can the Dtag record subtle details of behavioral responses, but it also acts as an acoustic dosimeter, recording sounds—including anthropogenic sounds—as heard by the whale.

Deep-diving toothed whales can remain out of sight for more than an hour and have been among the most difficult animals to observe in the wild. In particular, beaked whales, a family of toothed whales, are one of the least studied marine mammals. Even though they live in deep water, beaked whales are known primarily from strandings. Beaked and sperm whales make their living by using echolocation to forage in an ecosystem that thrives hundreds of meters below the sea surface, seldom seen or exploited by humans. The ability to record sound and movements of a toothed whale continuously as it dives provides a powerful capability to learn about the echolocation-based foraging behavior of those poorly known animals.

Biologists have used estimates of the population size and metabolic rate of sperm whales to calculate that those whales alone probably take about as much biomass out of the ocean as do all human fisheries.[7] One reason for the ecological success of deep-diving toothed whales is that they use biosonar to find, select, and capture prey (see the article by Whit Au

Acoustic measurements

Underwater sound is typically measured by sensing acoustic pressure—that is, the deviation from the average hydrostatic pressure. Typically, acoustic measures are given in units of decibels (dB) with respect to some reference. If p is a measured acoustic pressure and p_{ref} a reference pressure, then the sound pressure level (SPL) in decibels with respect to the reference pressure is

$$\mathrm{SPL} = 20\log_{10}\left(\frac{p}{p_{\mathrm{ref}}}\right).$$

So, for example, beaked whales have been observed to avoid SPLs of 136–140 dB re 1 μPa or greater. The reference pressure of 1 μPa is standard for underwater sound pressure measurements. With that understanding, I'll assume pressures are measured in μPa and will drop the explicit accounting of the reference pressure.

Short transient sounds are often described in terms of a peak pressure, while longer transients and continuous sounds are more typically expressed in terms of a root mean square (rms) pressure,

$$p_{\mathrm{rms}} = \sqrt{\frac{1}{T}\int_0^T p^2(t)\,dt},$$

where T is the averaging time. For a time-varying pressure, $p(t)$, the 0-to-peak SPL in decibels is $20\log_{10}\{\max[|p(t)|]\}$, and the peak-to-peak SPL is $20\log_{10}\{\max[p(t)] - \min[p(t)]\}$.

When working with the rms pressure, the appropriate SPL is

$$\mathrm{SPL}_{\mathrm{rms}} = 10\log_{10}\left(\frac{1}{T}\int_0^T p^2(t)\,dt\right).$$

The rms value of the pressure can vary considerably with T, and so T should be specified along with $\mathrm{SPL}_{\mathrm{rms}}$.

The sound exposure level (SEL) is a measure used when energy is a more appropriate variable than the instantaneous or mean pressure. By definition,

$$\mathrm{SEL} = 10\log_{10}\left(\frac{1}{T_{\mathrm{ref}}}\int_0^T \frac{p^2}{p_{\mathrm{ref}}^2}\,dt\right).$$

With the understanding first that time is measured in seconds, the reference time value T_{ref} is 1 s, and second that pressures are handled as above, $\mathrm{SEL} = \mathrm{SPL}_{\mathrm{rms}} + 10\log_{10}T$. In precise notation, SEL may be expressed in units of dB re 1μPa^2·s.

and Jim Simmons, Physics Today, September 2007, page 40). The biosonar produces high-frequency clicks in a narrow, forward-directed beam. When searching for prey, beaked whales make several clicks per second as they scan the water in front of them. Once they have selected their prey, usually a squid or deepwater fish, and have approached to within a body length or so, they suddenly accelerate the click rate, producing what sounds to humans like a buzz.[8] The more rapid clicks allow the whales to update the location of the prey more often, which helps them to capture it. Figure 3a shows the outgoing clicks as recorded by the Dtag on a beaked whale and clearly exhibits the switch from search clicks to buzz. My colleagues and I were pleasantly surprised to learn that the Dtag could also record echoes from prey. Figure 3b plots those echoes as a beaked whale searches for prey, selects a target, and closes in on it; again, one can clearly see the transition to buzzing. Figure 3c plots the whale's dynamic acceleration—that is, the acceleration that is derived from body movement.

Armed with a tag that could measure behavioral responses to measured dosages of sound at a whale, my colleagues and I were ready to study the effects of air guns on deep-diving sperm whales. One component of the Sperm Whale Seismic Study (SWSS), sponsored by a number of governmental and industrial agencies, used small boats to tag sperm whales and then directed a seismic survey vessel to ramp up its air-gun array and conduct a controlled approach to the tagged whales.[9] In the course of five experiments, we obtained tracking information for seven whales. We found no evidence of avoidance behavior as the seismic vessel advanced toward the whales; indeed, the whale that was approached most closely rested near the surface for an unusually long time. Immediately after the air guns stopped, that whale started a foraging dive—apparently, it had waited to start foraging. The other six whales did conduct deep foraging dives during exposure to air guns. However, they reduced their swimming effort significantly and, judging from their diminished buzz rate, may have reduced their attempts to capture prey. As figure 4 shows, the reduction in buzz rate became more pronounced as the seismic vessel got closer to a whale. The data raise concern that the Goldilocks assumptions do not apply to toothed whales. No evidence suggests that the whales move away from approaching air guns, but there is evidence that the air guns disrupt their foraging behavior.

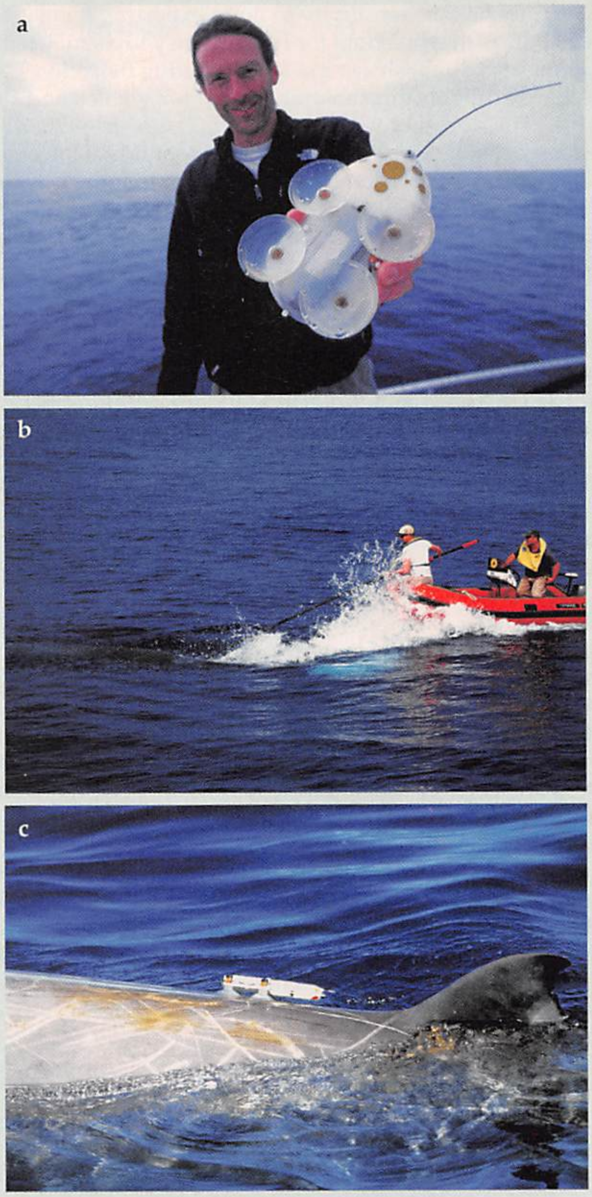

Figure 2. A whale gets fitted with a digital tag. **(a)** Mark Johnson, design engineer of the Dtag, holds a tag in its housing. Pointing toward the viewer are the suction cups used to attach the tag to the whale. Extending to the upper right is the antenna for the radio beacon used to find the tag once it releases from the whale. **(b)** Marine biologists use a carbon fiber pole to attach a tag to a pilot whale. **(c)** A beaked whale displays a Dtag. (Photographs are by Todd Pusser, under a National Marine Fisheries Service research permit.)

Beach strandings

In 1998, just when the scientific and regulatory communities felt they were getting a handle on what exposures to sound pose a risk of injury to marine mammals, a letter in the journal *Nature* linked an atypical mass stranding of beaked whales to a naval sonar exercise.[10] In most mass strandings, a group of whales comes ashore together. The stranding reported in *Nature* occurred over a 30-hour period during which 12 beaked whales beached in several different locations along 38 km of coastline; the average separation of stranded whales was 3.5 km. As the letter's author Alexandros Frantzis noted, "This suggests that the cause has a large synchronous spatial extent and a sudden onset. Such characteristics are shown by sound in the ocean."

The strandings began within a few hours of the first sonar transmissions of a four-day naval exercise. The intensity of the sonar was less than the 0-to-peak sound level thought to pose a risk of injury. Moreover, the duration of the pings and the speed of the ship make it unlikely that a whale farther than tens of meters from the ship would have been exposed to an SEL sufficient to cause TTS. Nonetheless, in 2000 a similarly atypical stranding of beaked whales coincided with a naval sonar exercise in the Bahamas.[11] Scientists now know of one or two dozen atypical mass strandings of beaked whales that have occurred in the presence of naval ships that might have been using sonar. The number of individual whales involved in some of those mass strandings is greater than the group size typical for the species, which suggests that several groups were impacted. And it seems unlikely that warships in all cases would have passed close

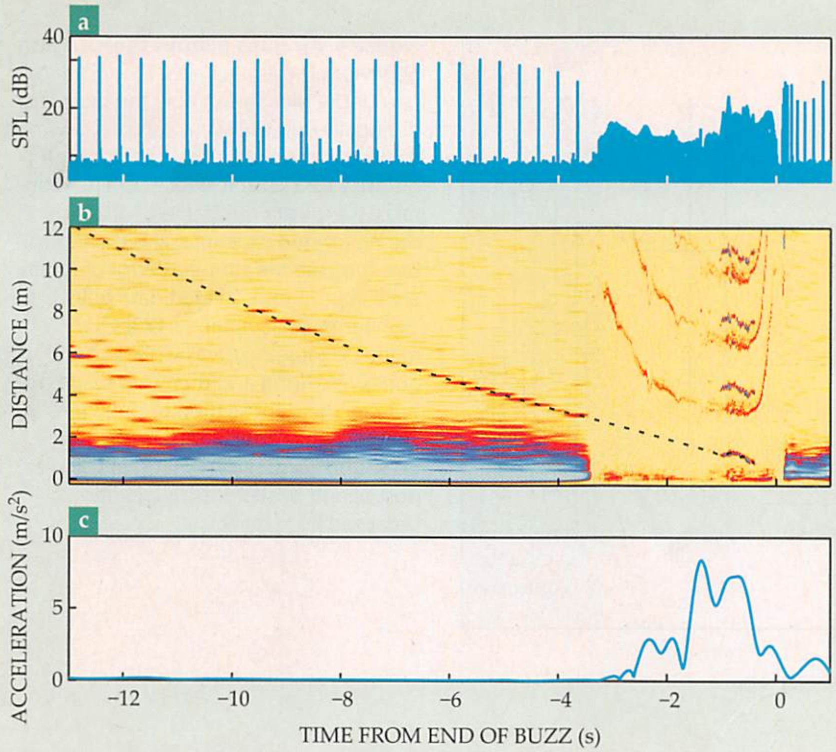

Figure 3. Beaked whales use echolocation to find and catch prey. **(a)** A digital tag attached to a whale reveals strong regular clicks until the whale is close to its prey; the click rate then accelerates. The clicks in the buzz period from −3.4 s to 0 s are so rapid that they appear continuous. The *y*-axis gives the sound pressure level (SPL) relative to an arbitrary reference pressure. **(b)** In this echogram, the *y*-axis indicates the distance to the prey. More precisely, one measures half the time elapsed between an outgoing click and the returning echo, then multiplies by a presumed sound speed of 1500 m/s. The color scale indicates the energy of the signal: blue for an intense signal, yellow for a faint one. The black dashed curve is to guide the eye through relatively strong echoes from the target the whale was approaching. **(c)** Tagging can also indicate the magnitude of a whale's dynamic acceleration. The increased acceleration during the buzz probably indicates movements associated with prey capture. (Adapted from ref. 8.)

enough to each whale to cause TTS. So, criteria based upon TTS may not be sufficient to protect beaked whales from injury or death.

A top research priority identified by most reviews of the sonar–whale problem was to study how beaked whales respond to controlled exposures of sound.[12] One of the biggest concerns about designing appropriate experiments was the difficulty in monitoring the animals. An exceptional opportunity for tracking beaked whales was presented by a sophisticated array of hydrophones covering about 1500 km^2 on a US Navy underwater range in the Tongue of the Ocean in the Bahamas. When a beaked whale makes a foraging dive, the several thousand echolocation clicks it produces can be detected up to 6.5 km away. The hydrophones on the Tongue of the Ocean range are separated by 1–4 km, which allows whales to be reliably detected and located.

In the summers of 2007 and 2008, an international team of biologists, acousticians, and engineers converged on the range to test how beaked and other whales respond to sonar and other sounds. One goal of their experiment, which received government and industry funding, was to determine whether beaked whales are especially sensitive. The sound stimuli selected for the experiment were influenced by a puzzle and a hypothesis. The puzzle was the mismatch between the frequencies used and heard best by beaked whales (above 24 kHz) and the fundamental frequencies of the naval sonars involved in the strandings (below 8 kHz). Most risk analyses would conclude that the large gap between sonar and whale frequencies means there should be little risk of the sonar causing problems for the whales. Several scientists puzzling over the frequency mismatch independently noticed that although the naval sonar signals are very different from the echolocation clicks used by beaked whales, they are quite similar to the calls of killer whales, a dangerous predator of beaked whales. That realization led Walter Zimmer and me to hypothesize that beaked whales might show a strong antipredator response to the sonar signals. The stimuli selected to test our idea were an actual naval sonar signal, calls of marine-mammal-eating killer whales, and a noise stimulus with the same overall frequency band and timing as the sonar signal but with a waveform that sounded very different from either sonar or a killer whale.

The experimental design called for tagging a beaked whale and collecting preexposure data during the whale's first one or two foraging dives. Then, as soon as echolocation clicks were detected in the next foraging dive, a ship was to start playing back one of the stimuli at a level so low that the whale could not hear it, then increase the source level regularly until it reached a maximum intensity (well under that of the sonar) or the whale stopped clicking. In the summer of 2007, the experimental team exposed a tagged whale to sonar during its second dive and to killer-whale calls during its third dive. The following summer a different tagged whale was exposed to the noise stimulus after two preexposure dives.

In all three trials the whale stopped clicking in response to the sound stimulus and in particular produced fewer foraging buzzes than normal. The whale then did an unusually long, slow ascent, moving away from the source of the sound. After exposure to killer-whale calls, the beaked whale swam continuously for 10 hours along an atypically straight course out of the Tongue of the Ocean.

According to our killer-whale hypothesis, given similar exposure levels, beaked whales would show a similar response to sonar and killer-whale calls. That response might differ from the one induced by noise stimulus. In fact, the beaked whales showed similar dive and clicking responses to all three stimuli. But the response to killer-whale calls occurred at a much lower received root mean square SPL, about 100 dB averaged over 0.2 s, and was much stronger and more prolonged than those due to the other stimuli. The anthropogenic stimuli elicited cessation of clicking at received SPLs

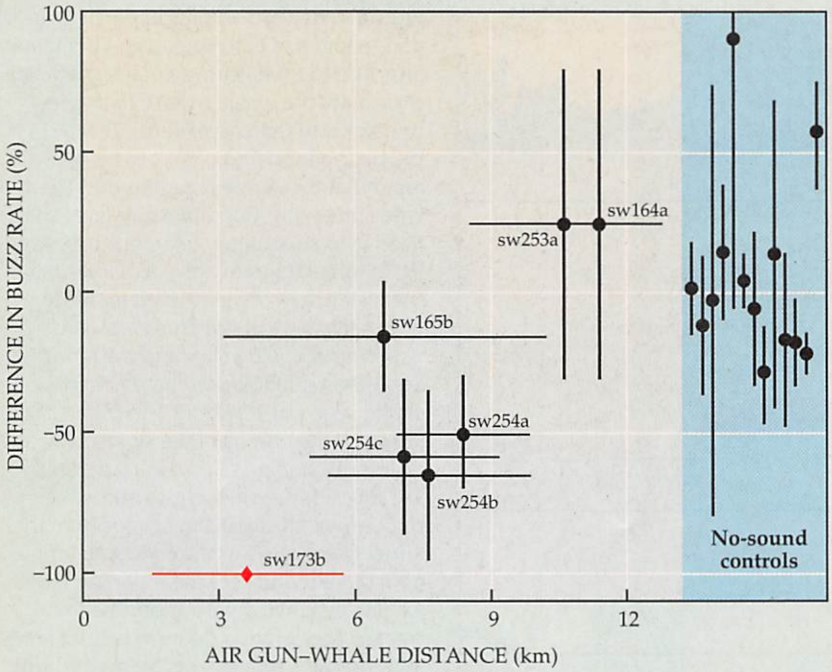

Figure 4. Air guns disrupt the foraging behavior of sperm whales. The left-hand part of the plot shows how the buzz rate during air-gun exposure compares with the postexposure rate as a function of distance to a seismic vessel. The horizontal bars indicate the range of distances during air-gun exposure, and the vertical bars indicate the standard error of difference in buzz rate. The red data point highlights one animal, sw173b, that made no foraging dives while the air guns were firing and therefore made no buzzes. The right section of the figure compares buzz rates during and after no-sound control runs that mimicked exposure and postexposure conditions. (Adapted from ref. 9.)

of about 140 dB, averaged over 0.2 s. That intensity is similar to the 136-dB level of shipping noise that provoked a Cuvier's beaked whale to break off a foraging dive in the Mediterranean Sea.[13] Although the sample size is small, the response of the beaked whales to all the tested anthropogenic stimuli occurs at similar received levels—about 20 dB below the threshold that US regulations consider as predicting onset of behavioral disruption.

Comparable experiments with pilot whales and other similar dolphins led to more varied responses, often at higher exposure levels. Moreover, those species were less likely to show silencing and avoidance behavior. Rather, their more common pattern was to increase vocalizing and to display increased social cohesion during exposure to noise. Although the experiments at the Tongue of the Ocean did not support the killer-whale hypothesis, they do suggest that an antipredator strategy of flight and fright may pose a greater risk for stranding than a social defense against predation. Their findings are consistent with conclusions reported earlier by Southall and colleagues: Beaked whales, like porpoises, may be particularly sensitive to anthropogenic sound, but there is no evidence that they have a special sensitivity to sonar compared with other signals.[5]

Accumulating threats

Dead whales on the beach are the most dramatic effect of anthropogenic sound on marine mammals. However, the cumulative effects of noise and other stressors from human development will likely have more far-reaching impacts on marine-mammal populations. Noise that causes whales to leave an area reduces available habitat. If noise masks communication signals such as whale songs or contact calls, it may disrupt the mating system or parental care and so affect reproduction and survival of the young in endangered populations. If an animal's foraging is disrupted by noise, it may grow more slowly. Not only does fishing gear kill marine mammals directly through entanglement, but fisheries and coastal development change the composition of marine ecosystems in ways that may lower their capacity to support marine mammals and other predators at the top of the food chain. As the effects of human activities accumulate, they may present a serious threat to marine-mammal populations.

Current regulations in the US to protect marine mammals stem from the whaling era and focus on prohibiting individual acts that harm marine mammals. If our society is to protect marine life from today's threats, the regulatory process will need to change to protect the quality of habitats on which marine mammals depend.

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