Temporary threshold shift in a harbor seal (*Phoca vitulina*)

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During in-air auditory threshold testing, a harbor seal was inadvertently exposed to broadband construction noise for 6 days, averaging 6 to 7 h of intermittent exposure per day. When tested immediately upon cessation of the noise, a temporary threshold shift (TTS) of 8 dB at 100 Hz was evident. In addition, the animal's false alarm rate increased from 7% in the pre-exposure session to 30% in the post-exposure test session. Following 1 week of recovery, the subject's threshold was within 2 dB of its original level, and the false alarm rate was less than 10%. The data suggest that TTS can be induced in seals, and that our subject may have suffered from tinnitus, resulting in a reduced ability to distinguish signal-present from signal-absent trials. © *1996 Acoustical Society of America.*

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INTRODUCTION

Much interest in the hearing capabilities of marine mammals stems from our need to avoid exposing these animals to potentially harmful amounts of anthropogenic noise. Evidence of this recent concern is reflected in the increasing number of investigations into noise and its effects on marine mammals, despite the lack of data on the hearing abilities of the vast majority of these animals (National Research Council, 1994). An increased awareness of the importance of acoustic orientation in marine mammals has led the U.S. National Marine Fisheries Service to propose a "120 decibel" rule, regarding the maximum sound level to which any marine mammal can be exposed. The 120-dB rule is based primarily on a series of studies regarding avoidance responses of baleen whales to a low-frequency underwater sound source (Malme *et al.*, 1983, 1984, 1988). The estimated received sound level causing 50% avoidance was on the order of 120 dB *re*: 1 μPa. Unfortunately, the 120-dB criterion has been promulgated without regard to such critical variables as the species in question or the characteristics of the noise. In order to make more informed decisions regarding exposure limits and to effectively make assessments regarding the environmental impacts of man-made noise in the ocean, data on the hearing sensitivity and the effects of noise on the animals exposed to such stimuli is necessary. In addition, it is important to identify and characterize the sound sources in question. The prevalent man-made sounds in the ocean come from shipping and industrial activities, and in a frequency band from about 20 to 300 Hz, ambient noise is dominated by such sounds (Richardson *et al.*, 1991). This type of noise has potentially adverse effects on marine organisms. Possible deleterious effects of noise include the following: masking of relevant bioacoustic signals; escape from and avoidance of noise contaminated areas; startle responses; orienting and defense responses; general annoyance and helplessness from being denied a safe escape route; and temporary and permanent threshold shifts (TTS and PTS).

Experimental studies of TTS have been performed on relatively few nonhuman animals (Clark, 1991). While TTS has been experimentally induced in several species of primates, rodents, birds, and reptiles, each of these studies was attempting to find animal models of TTS in order to predict the factors involved in noise-induced permanent threshold shift (NIPTS) in humans. Nothing is currently known about the possible damaging effects of noise on the hearing of marine mammals, despite the increasing literature regarding the hearing abilities of certain species such as the beluga, bottlenose dolphin, and harbor seal (see reviews in Fobes and Smock, 1981; Richardson *et al.*, 1991; Schusterman, 1981). Because of public sentiment and difficulty in procuring the proper permits, it is not possible to perform controlled experiments that address the issue of NIPTS in marine mammals. However, extrapolations from controlled, low-noise-level TTS experiments can be used to assess the potential risk for PTS in real world situations.

Although the parameters involved in TTS in marine mammals are presently unknown, some general trends have emerged from the study of TTS in other animals. The magnitude of TTS depends on several factors, including the intensity, duration and frequency characteristics of the fatiguing noise, the frequency of the test stimulus, and the duration of the recovery period (Clark, 1991; Elliot and Fraser, 1970). In typical animal models of noise-induced hearing loss, an exposure time of less than 1 h to noise of moderate to high intensity (80–120 dB SPL) is sufficient to induce some degree of TTS. There can be, however, strong variability both within and between taxa. Clark *et al.* (1974), for example, exposed chinchillas to noise levels of 123 dB SPL for 15 min, after which TTS on the order of 70 dB and PTS on the order of 50 dB were found. Primates, however, appear to be less susceptible than chinchillas to TTS and PTS. Moody *et al.* (1976) exposed rhesus macaques to sound-pressure levels of 90 and 120 dB SPL, and found that a TTS plateau was not reached until 8 to 12 h of exposure for both levels.

The subjects exposed to 120-dB sound levels, however, showed evidence of PTS after only 8 h of noise exposure. Thus at high noise levels, some amount of permanent damage may occur within the first few hours of exposure (Moody *et al.*, 1976).

If the fatiguing stimulus is intermittent, effects can be harder to interpret. Further, there is not a simple linear relationship between the exposure time and intensity required to produce a given degree of TTS. At short exposure durations, a large increase in intensity is required to increase TTS by a small amount, whereas at longer exposures, a much smaller change in intensity is required (Ward *et al.*, 1959). It is the complex relationship between duration, intensity and duty cycle that makes it nearly impossible to predict the effects of most moderate to intense sounds on animal hearing.

Because of such interactions, sound levels and durations for TTS experiments with marine mammals must be chosen with caution, considering that pathways of sound conduction and mechanisms of inner ear stimulation are unclear for these taxa. Thus any opportunity to gauge a fortuitous TTS in a marine mammal due to uncontrollable noise could provide data needed to run more controlled studies.

We began an audiometric study on a male harbor seal in the summer of 1993. Following initial aerial threshold testing, the subject was inadvertently exposed to noise from a sandblasting operation, generated during pool renovation at our laboratory. Although the levels and durations of the stimulus were not under our control, we had the opportunity to make noise measurements and conduct threshold tests immediately upon cessation of the noise. To our knowledge, this study provides the first documented investigation of TTS in a marine mammal.

I. METHOD

A. Subject

The subject of this experiment was Sprouts, a 4-year-old male harbor seal (*Phoca vitulina*). The seal was housed in free-flow seawater tanks and adjacent haulout space at Long Marine Laboratory in Santa Cruz, California. At the time of exposure, he was involved in aerial, low-frequency audiometric testing (Kastak and Schusterman, 1995), designed in part to compare minimum audible pressure measurements to free-field thresholds obtained from a harbor seal by Terhune (1991).

B. Apparatus

The apparatus for aerial acoustic threshold testing consisted of a PVC frame measuring 45×45×42 cm. An opaque plastic door mounted in the front face of the apparatus separated a chin-stationing device and response paddle. Upon instruction from the experimenter, the door could be opened to expose the paddle using a rope and pulley system. The chin station was mounted to the side of the apparatus approximately 21 cm off the ground, the same height as the response paddle.

Pure tones for audiometric testing were produced by a Stanford Research Systems DS345 function generator. Tones were 500 ms in length with a rise and fall time of 40 ms. The tones were manually triggered by the experimenter, attenuated, and presented to the subject through Telephonics TDH-39 earphones mounted in a specially designed neoprene harness that placed the earpieces into position over the seal's external ear openings. Sound pressure levels of the test tones were measured at the opening of the meatus with an Etymotic Research ER-7C probe microphone system. Ambient noise levels were measured with a Bruel & Kjaer 2203 sound level meter and type 4133 condenser microphone. Noise levels were analyzed with a B&K type 3347 third-octave analyzer.

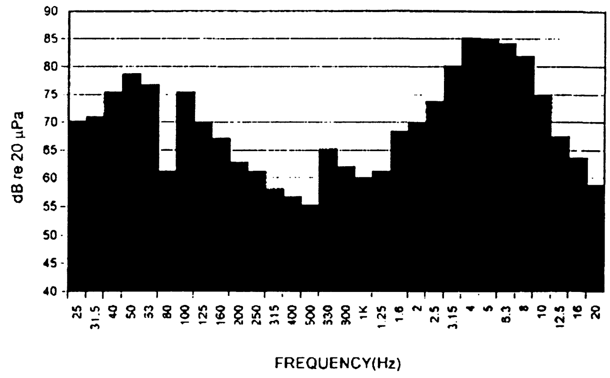

FIG. 1. A typical third octave analysis of the sandblasting noise recorded in the animal enclosure.

C. Procedure

Before the beginning of a session, the earphones were fitted over the seal's ears by a trainer. Before a trial began, the subject was required to place his chin on the stationing device. Upon proper orientation, the door was opened to signal the beginning of a trial. There were two trial types. On signal trials, the test tone was presented between 2 to 4 s after the door was opened. On catch trials, no signal was presented. The seal was reinforced with a piece of fish for responding on signal trials and for withholding response on catch trials. Each session consisted of 30 signal trials and 30 catch trials arranged in a quasirandom fashion. Threshold estimates were obtained using a tracking, or staircase procedure (see Moore and Schusterman, 1987, for a description of this technique used with sea lions and fur seals). The test stimulus was initially presented at a suprathreshold level. Following each correct detection, the level of the tone was decreased by 4 dB, until the subject failed to detect it. Following the first miss, the signal level was adjusted in 2-dB increments, down following each detection, and up following each miss. Signal and catch trials were arranged prior to testing in a pseudorandom series with the stipulation that the same trial type could not occur on more than four consecutive trials.

The overall aerial sound-pressure level due to sandblasting noise in the seal's enclosure varied from just under 90 to over 105 dB SPL (unweighted). This variation was caused primarily by changes in orientation of the nozzle of the sandblaster. A typical third-octave analysis of the noise recorded in the seal's enclosure is shown in Fig. 1. Although the overall sound-pressure level varied, the spectral characteristics of the noise remained relatively constant. Subjectively, the sound could be classified into two components, a low frequency "rumble" and a high-frequency "hiss." The loss in the 200- to 2000-Hz range is perhaps explainable by the

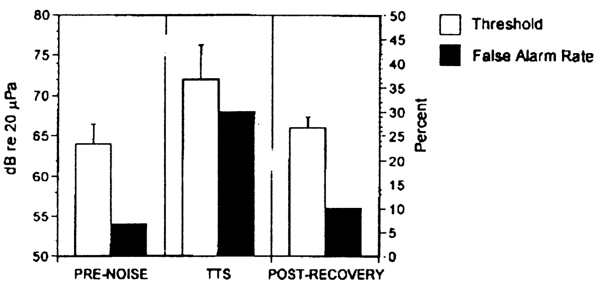

FIG. 2. Thresholds at 100 Hz (in dB *re*: 20 μPa, + 1 s.d.) and false alarm scores (in percent) recorded before noise, immediately following noise, and one week post-recovery.

configuration of the tanks in which the construction was taking place. The third octave band centered at 100 Hz varied from 75 to 90 dB SPL.

Exposure to the noise was sporadic over a 6-day period, occurring between the hours of 9 AM and 4 PM. It is not possible to be sure of the exact exposure times because the seal spent some time underwater during sandblasting. The maximum continuous exposure was approximately 1.5 h. One session was run prior to the first noise exposure, and the TTS session was run on the sixth day of exposure. Immediately preceding TTS testing, the seal was kept out of the water, and received just over 1 h of continuous exposure. Testing commenced immediately upon cessation of noise, and the test session was interrupted once by a 3-min noise exposure.

II. RESULTS

Figure 2 compares calculated threshold and false alarm levels for the session conducted prior to noise exposure, the session immediately following noise exposure, and a recovery session conducted one week following the cessation of noise exposure. Immediately following noise exposure, the 100-Hz threshold was determined to be approximately 72 dB *re*: 20 μPa, an 8 dB increase over pre-exposure levels. In addition, the variability in responding was much higher just following noise exposure, evidenced by the increased standard deviation of the threshold estimate. A one-way ANOVA among the three conditions showed significant differences between the three threshold estimates ($F_{2,44}=31.38$, $p<0.001$). Individual comparisons (Bonferroni method) established significant differences between the noise-exposed threshold and both pre- and post-noise thresholds ($p<0.01$) and found no difference between pre- and post-noise thresholds ($p>0.05$). Prior to noise exposure, false alarm rates had consistently remained below 10%. There were two false alarms in the session conducted prior to exposure (7%) and three false alarms during the post-recovery test (10%). Following exposure, there were significantly more false alarm responses (9 FAs; 30%; Fisher exact test, $p=0.01$) than during pre-noise and post-recovery combined.

III. DISCUSSION

Although we observed a TTS of approximately 8 dB following intermittent exposure to broadband noise, complete recovery had occurred by approximately one week following exposure. The magnitude of TTS is similar to that observed in other animal subjects following short durations of moderate to intense fatiguing stimuli (Clark, 1991; Kryter, 1994; Moody *et al.*, 1976). However, the effective exposure time in our study must be modified to exclude the amount of time the subject spent underwater. The corresponding reduction in sound energy would have reduced the effective intensity of the noise to levels likely to be much lower than those required to induce TTS. The fatiguing stimulus in this case was intermittent, and significant recovery periods occurred between exposures. The relationship between TTS and intermittent exposure has been investigated (Kryter, 1994; Ward, 1991), and below exposure levels of 115 dB, recovery periods dramatically decrease the effects of exposure. Such results suggest an equal energy concept for exposure in which the effects of sound energy are the same whether they are from sound which is continuous over a specified time period, or exists as the sum of intermittent sounds over a given time period (Kryter, 1994). If this is the case, six days of intermittent exposure equates just under one day of continuous exposure.

While it is plausible that the noise centered around 100 Hz was sufficient to induce an 8 dB TTS, the level of the 100-Hz third octave band varied from only 10 to about 25 dB above the subject's threshold at 100 Hz. It is therefore likely that either the higher-frequency or lower-frequency components (or both) can be implicated in the loss at 100 Hz. Clearly, the relationship between frequency of exposure and frequency of TTS in this species must be investigated further.

Perhaps of even greater concern than the TTS produced was the dramatic increase in false alarm responding during the post-noise session. False alarms for marine mammals in comparable psychophysical tasks are usually low, primarily as a function of training (Schusterman, 1974). In our lab, single session false alarm rates above 10% are extremely rare because we train our animals to adopt a conservative criterion and only respond to the presence of a signal when the animal is confident that the stimulus is present (see Schusterman *et al.*, 1975; Schusterman, 1976). Humans exposed to noise often report tinnitus, with consequences varying from annoyance to interference in interpreting speech (McFadden, 1982). A rise in false alarm responding suggests the inability to discriminate signal from noise, possibly as a consequence of noise-induced tinnitus (Jastreboff, 1990). If this is the case, then studies in the future should focus both on TTS and on changes in response patterns (e.g., increases in false alarm responses) in order to assess the effects of noise on marine mammals.

Although lacking in the controls necessary to thoroughly examine TTS in terms of development, recovery, and frequency-dependent effects, this study provides the first evidence that in air, seals are susceptible to noise-induced hearing loss. We are currently in the process of examining this effect more closely in order to assess TTS occurrence and recovery, as well as to determine whether there are differences in the effects of in-air and underwater susceptibility to noise in pinnipeds. Nevertheless, these data are essential in light of the recent concerns over the possible damaging effects of loud sound sources such as Acoustic Thermometry of Ocean Climate and other oceanographic experiments (National Research Council, 1994); acoustic deterrent devices designed to control predation by pinnipeds; and noise generated by oil drilling, shipping and other industrial activities.

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Bekesy, G. (**1960**). *Experiments in Hearing* (McGraw-Hill, New York).

Clark, W. W. (**1991**). "Recent studies of temporary threshold shift (TTS) and permanent threshold shift (PTS) in animals," J. Acoust. Soc. Am. **90**, 155–163.

Clark, W. W., Clark, C. S., Moody, D. B., and Stebbins, W. C. (**1974**). "Noise-induced hearing loss in the chinchilla, as determined by a positive reinforcement technique," J. Acoust. Soc. Am. **56**, 1202–1209.

Elliot, D. N., and Fraser, W. (**1970**). "Fatigue and adaptation," in *Foundations of Modern Auditory Theory*, edited by J. V. Tobias (Academic, New York), Vol. I, pp. 115–155.

Fobes, J. L., and Smock, C. C. (**1981**). "Sensory capacities of marine mammals," Psychol. Bull. **89**, 288–307.

Jastreboff, P. J. (**1990**). "Phantom auditory perception (tinnitus): mechanisms of generation and perception," Neurosci. Res. **8**, 221–254.

Kastak, D., and Schusterman, R. J. (**1995**). "Aerial and underwater hearing thresholds for 100 Hz pure tones in two species of pinnipeds," in *Sensory Systems of Aquatic Mammals*, edited by R. A. Kastelein, J. A. Thomas, and P. E. Nachtigall (De Spil, Woerden, The Netherlands), pp. 71–79.

Kastak, D., and Schusterman, R. J. (**1995**). "Aerial and underwater hearing thresholds for 100 Hz pure tones in two species of pinnipeds," in *Sensory Systems of Aquatic Mammals*, edited by R. A. Kastelein, J. A. Thomas, and P. E. Nachtigall (De Spil, Woerden, The Netherlands), pp. 71–79.

Kryter, K. D. (**1994**). *The Handbook of Hearing and the Effects of Noise* (Academic, San Diego).

Malme, C. I., Miles, P. R., Clark, C. W., Tyack, P., and Bird, J. E. (**1983**). "Investigations of the potential effect of underwater noise from petroleum industry activities on migrating gray whale behavior," BBN Rep. 5366, Bolt Beranek and Newman, Inc., Cambridge, MA.

Malme, C. I., Miles, P. R., Clark, C. W., Tyack, P., and Bird, J. E. (**1984**). "Investigations of the potential effect of underwater noise from petroleum industry activities on migrating gray whale behavior/Phase II: January 1984 migration," BBN Rep. 5586, Bolt Beranek and Newman, Inc., Cambridge, MA.

Malme, C. I., Wursig, B., Bird, J. E., and Tyack, P. (**1988**). "Observations of feeding gray whale responses to controlled industrial noise exposure," in *Port and Ocean Engineering Under Arctic Conditions*, edited by W. M. Sackinger, M. O. Jeffries, J. L. Imm, and S. D. Treacy (Geophysical Institute, University of Alaska, Fairbanks), Vol. II, pp. 55–73.

McFadden, D. (**1982**). *Tinnitus: Facts, Theories, and Treatments* (National Academy Press, Washington, DC).

Melnick, W. (**1991**). "Human temporary threshold shift (TTS) and damage risk," J. Acoust. Soc. Am. **90**, 147–154.

Moody, D. B., Stebbins, W. C., Johnsson, L., and Hawkins, J. E. (**1976**). "Noise-induced hearing loss in the monkey," in *Effects of Noise on Hearing*, edited by D. Henderson, D. S. Hamernik, D. S. Dosanjh, and J. H. Mills (Raven, New York), pp. 309–325.

Moore, P. W. B., and Schusterman, R. J. (**1987**). "Audiometric assessment of northern fur seals *Callorhinus ursinus*," Mar. Mammal Sci. **3**, 31–53.

National Research Council. (**1994**). *Low-frequency Sound and Marine Mammals: Current Knowledge and Research Needs* (National Academy Press, Washington, DC).

Richardson, W. J., Green, C. R. Jr., Malme, C. I., and Thomson, D. H. (**1991**). "Effects of Noise on Marine Mammals," Rep. No. TA834-1 LGL Ecological Research Associates, Bryan, Texas.

Schusterman, R. J. (**1974**). "Low false alarm rates in signal detection by marine mammals," J. Acoust. Soc. Am. **55**, 845–848.

Schusterman, R. J. (**1976**). "California sea lion auditory detection and variation of reinforcement schedules," J. Acoust. Soc. Am. **59**, 997–1000.

Schusterman, R. J. (**1981**). "Behavioral capabilities of seals and sea lions: review of their hearing, visual, learning and diving skills," Psychol. Rec. **31**, 125–143.

Schusterman, R. J., Barrett, B., and Moore, P. (**1975**). "Detection of underwater signals by a California sea lion and a bottlenose porpoise: variation in the payoff matrix," J. Acoust. Soc. Am. **57**, 1526–1532.

Terhune, J. M. (**1991**). "Masked and unmasked pure tone thresholds of a harbor seal listening in air," Can. J. Zool. **69**, 2059–2066.

Ward, W. D. (**1991**). "The role of intermittence in PTS," J. Acoust. Soc. Am. **90**, 164–169.

Ward, W. D., Glorig, A., and Sklar, D. L. (**1959**). "Temporary threshold shift from octave band noise: applications to damage risk criteria," J. Acoust. Soc. Am. **31**, 522–528.