Auditory and behavioral responses of California sea lions (*Zalophus californianus*) to single underwater impulses from an arc-gap transducer [a]

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ABSTRACT

A behavioral response paradigm was used to measure underwater hearing thresholds in two California sea lions (*Zalophus californianus*) before and after exposure to underwater impulses from an arc-gap transducer. Preexposure and postexposure hearing thresholds were compared to determine if the subjects experienced temporary shifts in their masked hearing thresholds (MTTS). Hearing thresholds were measured at 1 and 10 kHz. Exposures consisted of single underwater impulses produced by an arc-gap transducer referred to as a “pulsed power device” (PPD). The electrical charge of the PPD was varied from 1.32 to 2.77 kJ; the distance between the subject and the PPD was varied over the range 3.4 to 25 m. No MTTS was observed in either subject at the highest received levels: peak pressures of approximately 6.8 and 14 kPa, rms pressures of approximately 178 and 183 dB re 1 μPa, and total energy fluxes of 161 and 163 dB re 1 $\mu Pa^2 s$ for the two subjects. Behavioral reactions to the tests were observed in both subjects. These reactions primarily consisted of temporary avoidance of the site where exposure to the PPD impulse had previously occurred.

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I. INTRODUCTION

Pinnipeds are known to negatively impact the commercial passenger fishing vessel (CPFV) industry in southern California through depredation of gear and catch. A number of measures have been used to non-lethally prevent sea lion interaction with CPFVs, including gunshots, small explosive charges (“seal bombs”), and electronic sound generators (e.g., acoustic harassment devices, or AHDs) (Richardson *et al*., 1995; Reeves *et al*., 1996; NMFS, 1997). Unfortunately, none of the available non-lethal deterrent methods have been completely effective. Many acoustic deterrents are initially effective but become less so over time as the sea lions become habituated to the sound, learn to ignore or avoid the sound, or actually become less sensitive to the sound (e.g., through permanent hearing damage). In some cases acoustic deterrents may have actually alerted the sea lions to the presence of the CPFV (and its associated fish)—the so called “dinner bell” effect (Richardson *et al*., 1995).

In a variation of the AHD concept, Shaughnessy *et al*. (1981) used an arc-gap transducer to generate underwater shock waves in an effort to deter Cape fur seals (*Arctocephalus pusillus*) from fishing nets. The arc-gap transducer, or sparker, produces an electric spark which vaporizes the water between two submerged electrodes. This causes gas bubbles to form and then quickly collapse, producing an underwater shock wave. At a stored electrical energy setting of 520 J, the device was capable of producing a shock wave with a peak pressure of 132 dB re 1 μPa (~ 4 Pa) at 1 m. The device appeared effective at close range (2–10 m) but was ineffective at larger distances. In 1997, NOAA Fisheries contracted the Pacific States Marine Fisheries Commission (PSMFC) to develop, build, and test an arc-gap transducer capable of producing larger peak pressures than the device used by Shaughnessy *et al*., which would presumably give the device a larger effective range. The resulting transducer, known as a pulsed power device (PPD), operates similarly to an arc-gap transducer but is capable of storing up to 3 kJ of electrical energy, compared to the 0.52 kJ of the Shaughnessy *et al*. device.

This paper presents the results of a study designed to investigate the potential auditory effects of exposure to impulses produced by the PPD on California sea lions (*Zalophus californianus*). Marine mammals exposed to sufficiently intense underwater impulses may suffer hearing loss, called a noise induced (hearing) threshold shift (NITS) or simply a threshold shift (TS). A TS may be a temporary threshold shift (TTS) or a permanent threshold shift (PTS). TTS is associated with a temporary hearing loss; PTS indicates permanent hearing loss. There have been two studies of TTS in pinnipeds: Kastak and Shusterman (1996) reported TTS in a harbor seal (*Phoca vitulina*) exposed to airborne noise from nearby construction. Kastak *et al*. (1999) reported TTS in a California sea lion, harbor seal, and Northern elephant seal (*Mirounga angustirostris*) exposed to underwater octave band noise.

The auditory effects of the PPD were assessed by using a behavioral response paradigm to measure underwater hearing thresholds in trained sea lions before and after exposure to single underwater impulses produced by the PPD. The preexposure and postexposure hearing thresholds were then compared to see if a TTS had occurred. Tests were conducted at several combinations of PPD electrical charge and distance from the sea lion.

II. METHODS

A. Experimental subjects

Experimental subjects consisted of two male California sea lions: NRT (age 19 years, approximate weight 120 kg) and LIB (23 years, 150 kg). Neither subject had participated in any previous hearing studies. Subjects were housed in a floating netted enclosure (3.7 × 7.4 m) with an adjacent haul-out area [Fig. 1(a)], located in San Diego Bay. The study followed a protocol approved by the Institutional Animal Care and Use Committee at SPAWAR Systems Center, San Diego and followed all applicable U.S. Department of Defense guidelines. Both subjects were healthy during the course of the study.

B. Experimental apparatus

1. Underwater stations

The test apparatus consisted of two underwater listening stations, designated as the “S1 station” and the “S2 station”. The S1 station was the site for the presentation of a “start” signal to begin the hearing test and the underwater impulse produced by the PPD. The hearing tests were conducted at the S2 station. Two stations were used to spatially separate the location of the hearing test (the S2 station) from the site of exposure to the PPD impulsive sound (the S1 station). A similar approach was used with dolphins and white whales by Schlundt *et al*. (2000) and Finneran *et al*.(2000, 2002b). Each station consisted of a polyvinylchloride (PVC) frame with a plastic biteplate on which the subjects were trained to position. The S1 and S2 biteplates were located at depths of approximately 1.7 and 2 m, respectively. Each station contained an underwater video camera.

The S1 station [Fig. 1(b)] contained a single sound projector (ITC 1032) that was used to emit a 1-s tone as the start signal for the subject to begin hearing tests. These start tones, or “S1 tones”, were at a frequency of 6 kHz and SPL of 120 and 130 dB re 1 μPa for NRT and LIB, respectively (LIB responded better to the higher level). The S1 start tones were produced using a personal computer (PC) with a National Instruments PCI-MIO-16E-1 multifunction board, then amplified (BGW PS2) and input to the ITC 1032.

The S2 station [Fig. 1(c)] contained two sound projectors: one (ITC 1001) used to project hearing test tones, or “S2 tones”, and one (USRD J9) used to project masking noise. Hearing tests were performed at 1 and 10 kHz. The inclusion of additional test frequencies, while desirable, was not practical because of time constraints. The specific frequencies were selected to strike a balance between the range of frequencies present in the PPD waveform (see section III.B.2), and the audible frequency range of *Zalophus* (see Schusterman *et al*., 1972; Kastak and Schusterman, 1998). The order in which the S2 frequencies were tested was varied from day to day. The S2 tones were 250 ms in duration including 50-ms rise and fall times. S2 tones were generated using the PCI-MIO-16E-1, attenuated (HP 350D), filtered (Wavetek 452), and amplified (BGW PS4) before being input to the ITC 1001 sound projector.

Ambient noise levels at the test site (in San Diego Bay) were variable, thus band-limited white noise (masking noise) was introduced to keep thresholds consistent despite ambient noise fluctuations. Masking noise was generated on a second computer running custom software (see Finneran *et al*., 2002a). This system continuously generated masking noise with a frequency spectrum that was compensated to eliminate the effects of projector frequency-dependent transmission characteristics and acoustic multipaths. Masking noise was generated using a PCI-MIO-16E-1, attenuated (HP 355D), filtered (Ithaco 4302), and amplified (BGW PS2) before being input to the USRD J9 sound projector. The projected masking noise was centered at the appropriate S2 frequency and had a frequency bandwidth equal to the test frequency; e.g., for hearing thresholds measured at 10 kHz, the noise frequency bandwidth extended from 5 to 15 kHz. The noise spectral density was 90 and 80 dB re 1 $\mu Pa^2/Hz$ for S2 frequencies of 1 and 10 kHz, respectively. The noise spectral density was flat within ±3 dB over these ranges. Noise was generated during the entire test period (i.e., throughout the time that the subject was in the test enclosure).

The acoustic pressure during each S2 tone presentation was measured using a B&K 8103 hydrophone (mounted to the S2 PVC frame), amplified (B&K 2635), filtered (SRS 560), digitized using the PCI-MIO-16E-1 multifunction board, and stored on the PC. The pressure during the S1 start tone presentation was measured using a Reson TC4013 hydrophone (mounted to the S1 PVC frame), amplified and filtered (B&K 2635, SRS 560), and digitized (PCI-MIO-16E-1). The PC was also used to record the time each S1 and S2 tone was produced.

2. *Pulsed power device (PPD)*

The PPD was developed and built by Pulse Power Technologies, Inc. In this device, a large electrical voltage is generated between two oppositely charged electrodes immersed in the water column. The terminals are then brought incrementally closer until an electrical arc bridges the small gap between them. The electrical arc momentarily vaporizes the water between the terminals, producing gas bubbles which quickly collapse. The expansion and collapse of the gas bubbles produces an impulsive pressure waveform in the water. The PPD featured several discrete settings for the amount of electrical energy to be discharged through the arc-gap, ranging from 1.32 to 2.77 kJ.

Each exposure condition was assigned a nominal level, from N1 to N5 for NRT and L1 to L4 for LIB, in the order in which they were tested. Testing with NRT was complete before the first exposures were conducted with LIB. After preliminary examination of the results for NRT, we concluded that the exposure level N1, which featured a neoprene sheath to reduce the sparker output, was substantially below TTS-inducing levels and therefore LIB was tested at only four exposure conditions. The particular PPD charge setting and distance to the subject were chosen in an attempt to match the exposures L1–L4 with N2–N5. Unfortunately, we were not able to achieve the same pressures and energy flux levels at L4 as we obtained at level N5. The PPD had a tendency to misfire (for an electrical arc to bridge the gap before intended) at the higher charge settings; for this reason level L4 was tested with 2.44 kJ charge instead of 2.77 kJ.

The acoustic pressure produced by the PPD was measured during each subject exposure using a hydrophone (Reson TC4013) mounted to the S1 PVC frame between the subject and the PPD; the hydrophone was located 0.6 m from the subject’s ears. The hydrophone output was amplified and filtered from 2 Hz–100 kHz (B&K 2635 and SRS 560), then digitized at 200 kHz using the PCI-MIO-16E-1. The maximum pressure (p_{max}), minimum pressure (p_{min}), peak-to-peak SPL ($SPL_{\mathrm{p\text{-}p}}$), rms SPL ($SPL_{\mathrm{rms}}$), total energy flux ($E_{\mathrm{T}}$), and effective duration (τ) were calculated from the digitized waveforms. A distance correction based on daily calibration measurements using a second hydrophone (B&K 8105 with a B&K 2635 amplifier) located at the location of the subjects’ ears was used to correct the sound levels measured during exposure (0.6 m from the subjects’ ears) to the actual received sound levels at the ear position.

The maximum and minimum pressures were defined as the maximum positive or negative peak, respectively, in the measured waveform. The effective duration of each impulse was defined as the difference between the times at which the cumulative integral of the instantaneous pressure squared [$p^2(t)$] reached 5% and 95% of its final value (see Clark *et al.*, 1999). The energy flux spectral density $E(m)$ was calculated as

$$E(m) = |P(m)|^2, \qquad m = 0, 1, ..., N\text{-}1, \tag{1}$$

where

$$P(m) = \Delta t \sum_{n=0}^{N-1} p(n) e^{-j2\pi mn/N}, \qquad m = 0, 1, ..., N\text{-}1, \tag{2}$$

$p(n)$ is the digitized pressure waveform, $P(m)$ is the discrete Fourier transform of $p(n)$, N is the number of samples in $p(n)$, Δt is the sampling interval, and $j = (-1)^{1/2}$. Fourier analysis of each signal was based on an 82 ms time window (to produce the desired frequency resolution). Note that the medium characteristic impedance ρc has been eliminated from the definition of $E(m)$ described by Fricke *et al.* (1985) and Johnston *et al.* (1988); this was done to emphasize that the energy flux spectral density was based on individual pressure measurements (rather than actual acoustic intensity measurements). The energy flux spectral density thus has units of μPa^2·s/Hz, rather than J·m^{-2}·Hz^{-1} (0 dB re 1 J·m^{-2}·Hz^{-1} would be equivalent to 182 dB re 1 μPa^2·s/Hz, for seawater with nominal values of density $\rho = 1026$ kg/m^3 and sound speed $c = 1500$ m/s). The energy flux density E_T was calculated from

$$E_{\mathrm{T}} = \Delta t \sum_{n=0}^{N-1} p^2(n), \tag{3}$$

where ρc was again removed from the equation. The energy flux density has units of μPa^2·s (0 dB re 1 J/m^2 would be equivalent to 182 dB re 1 μPa^2·s, for seawater with $\rho = 1026$ kg/m^3 and $c = 1500$ m/s).

Table I shows the mean values for p_{max}, p_{min}, $SPL_{\text{p-p}}$, SPL_{rms}, E_T, and τ at each exposure condition for NRT and LIB. The values following the ± symbols in Table I indicate the standard deviations for linear quantities and the maximum ± excursions for decibel quantities. Figures 2 and 3 show representative pressure waveforms and energy flux spectral densities measured for each of the exposure conditions for NRT and LIB, respectively. Note that the ordinate and abscissa scales are not uniform throughout the panels. Pressure waveforms in Figs. 2 and 3 show the effects of multipath propagation caused by reflections from the surface and bottom. Many of the recorded waveforms show two positive pressure peaks separated by several milliseconds, presumably caused by bottom reflection. This second pressure peak resulted in higher total energy fluxes than one would have encountered in open water without the bottom-reflected component.

C. Procedure

1. Overview

Figure 4 illustrates the test procedure and hearing threshold calculation technique. The test procedure was similar to that used by Finneran *et al*. (2000, 2002b). Each subject participated in one test session each day. Each test session was either an exposure session, where the subject was exposed to a single underwater impulse produced by the PPD, or a control session, where the PPD firing sequence was simulated but no impulse was produced (a “mock” exposure). During each test session, three hearing tests were performed [Fig. 4(a)]. Two hearing tests were conducted before the exposure (or mock exposure); these tests produced preexposure hearing thresholds at the two S2 frequencies (1 and 10 kHz). One hearing test was performed after the exposure (postexposure). Preexposure thresholds were measured at both 1 and 10 kHz to verify that the subject’s hearing was within normal baseline values at each frequency. The order in which the preexposure frequencies were tested was varied from day to day. The postexposure hearing test was performed at the last S2 frequency tested preexposure. Table I lists the individual exposure conditions for NRT and LIB. Each exposure condition was repeated over two days to conduct hearing tests at each S2 frequency immediately before and after exposure. Eight control sessions were conducted for each subject: four control sessions with 1 kHz tested postexposure and four control sessions with 10 kHz tested postexposure. The control sessions were randomly interspersed within the exposure sequence.

The preexposure and postexposure hearing test procedures were very similar. The preexposure hearing test procedure is presented in detail, followed by a discussion of the postexposure hearing test procedure.

2. *Preexposure hearing tests*

The hearing test procedure was based on the Method of Free Response, or MFR (Egan *et al.*, 1961). The hearing tests were divided into a number of relatively long observation periods, called “dives”. Each dive began with the trainer directing the subject (with a hand signal and spoken command) to the S1 station. The subject was trained to remain on the S1 station until presented with the S1 start tone. Upon hearing the S1 start tone, the subject proceeded to the S2 station. Once the subject was positioned at the S2 station, a block of hearing test trials was presented. The trial block was ended when the trainer sounded an underwater buzzer to signal the subject to return to the surface and receive fish reward. The process was then repeated as necessary.

Each trial block contained a variable number of trials. Each trial was 2.0 s in duration. The time interval between trials (the interstimulus interval, or ISI) was randomized between 5 and 12 s. Neither the subject nor the trainer knew when the next trial would occur. Eighty-percent of the trials contained a 250 ms S2 tone beginning 50 ms before the trial start. The remaining 20% of the trials were no-tone or catch trials. Since the subject did not know when the next trial would occur, the catch trial periods functioned as “equipment catch trials” and were primarily used to confirm that the sound system was not producing artifacts coinciding with the stimulus.

Subjects were trained to produce a vocal response if they heard a tone and to remain quiet otherwise. Each tone trial had two possible outcomes: Vocal responses occurring within a tone trial were recorded as “hits”. No vocal response during a tone trial was a “miss”. The amplitudes of the S2 tones were adjusted using a modified up/down staircase procedure (e.g., Cornsweet, 1962): the amplitude was decreased 2 dB following each hit and increased 2 dB following each miss.

The trainer and computer operator monitored the sound in the water (using the Reson TC4013 hydrophone mounted on the S2 frame) for any vocal responses by the subject. The computer operator and trainer were aware of the session type (control or exposure), the type of trial (catch or tone), the S2 tone amplitude during each tone trial, and were notified as each trial began. The point at which reinforcement was delivered (i.e., the number of trials per trial block) was determined by the computer operator. The number of trials per trial block was randomly varied within the following guidelines: Only correct responses were reinforced. An attempt was made to reinforce responses to low-level tones (i.e., at a lower level than any previously responded to). If the subject missed several tones in a row, the first subsequent hit was generally not reinforced. The dive times were normally kept under 2 min. The amount of reinforcement was scaled to the performance of the subject during the dive (e.g., more reinforcement was given for longer dives and/or responding to low-level tones).

After reinforcement, the next dive was begun and the procedure repeated until the hearing test was complete. Preexposure hearing tests were conducted until at least 10 “reversals”, defined as a transition from a hit to a miss or from a miss to a hit, were obtained. The first S2 tone at each frequency was presented approximately 10 dB above the expected threshold. Each preexposure threshold could usually be estimated after 20 to 30 trials.

Figures 4(b)–(e) illustrate the threshold calculation method. The preexposure hearing test resulted in a record of the subject’s performance (hit or miss) to each tone trial [Fig. 4(b)]. The performance data were then converted to a series of reversals, shown in Fig. 4(d). The time and amplitude for each reversal were defined as the mean time and mean pressure, respectively, of the hit/miss pair. Time values in Fig. 4(d) are referenced to the time of the exposure (or mock exposure), thus the preexposure reversals occurred at negative times. Finally, preexposure hearing thresholds were calculated as the mean pressure of the first 10 hit-miss/miss-hit reversal points [Fig. 4(e)]. The time at which the threshold occurred was defined as the mean time of the 10 reversals.

3. Postexposure hearing tests

The postexposure hearing test procedure was identical to the preexposure procedure with two exceptions: (1) During exposure sessions, a single impulse was produced by the PPD approximately 0.5 s before the start of the first S1 start tone of the postexposure hearing test. During control sessions, a switch was used to disable the PPD triggering signal, preventing the PPD from firing. (2) The postexposure hearing tests were conducted for at least 10 min to enable any TS and recovery to be tracked.

Figures 4(c)–(e) illustrate the postexposure threshold calculation. As with the preexposure tests, the postexposure hearing test resulted in a record of the subject’s performance (hit or miss) to each tone [Fig. 4(c)], which was converted to a series of reversals, shown in Fig. 4(d). The time and amplitude for each reversal were defined as the mean time and mean pressure, respectively, of the hit/miss pair. Since the time values in Fig. 4(d) are referenced to the time of the exposure (or mock exposure), the postexposure reversals occurred at positive times. Postexposure hearing thresholds were calculated by applying a 10-point moving average to the postexposure reversals [Fig. 4(d)–(e)]. Each output of the moving average consisted of two values: the mean pressure over the 10 reversals and the mean time over which the 10 reversals occurred. The postexposure threshold as a function of time thus represented the mean time and mean pressure of each group of 10 postexposure reversals. Thresholds at specific postexposure times (e.g., 5 min, 10 min) were obtained by interpolating within the collection of thresholds from the moving average.

The TS was calculated by subtracting the preexposure threshold from the postexposure threshold. An MTTS was defined as a 6-dB or larger TS. This 6-dB criterion was based on other marine mammal TTS studies using similar test paradigms (e.g., Schlundt *et al*., 2000; Finneran *et al*., 2000) and was considered to be the minimum shift that was larger than any day-to-day or session-to-session variations in the subjects' masked hearing thresholds.

By definition a TTS will recover after some amount of time (i.e., the postexposure threshold will return to the preexposure level). Meaningful comparisons of TSs resulting from different exposure conditions thus require the TSs to be measured at the same time postexposure. The first postexposure threshold was often obtained (i.e., the mean time of the first 10 postexposure reversals was) about 3–5 min after the exposure. Thresholds were obtained within 5 min post exposure in nearly all (33/34; the exception was 5.6 min postexposure) cases, thus the threshold shifts at approximately 5 min (TS_5) and 10 min (TS_{10}) postexposure were convenient metrics to compare the effects of different exposures.

4. *False alarm rate*

Any vocal response during a catch trial was recorded as a false alarm. Any vocal response by a subject not occurring within a trial was also recorded as a false alarm. The ISI (defined from the start of one tone to the start of the next tone) was randomly varied between 5–12 s, thus the majority of time spent on the S2 station was outside any trials and functioned as an additional "catch trial" period.

The false alarm rate R_{FA} was defined as

$$R_{FA} = \frac{N_{FA}}{T - N_{S2} T_1} T_1, \tag{4}$$

where N_{FA} is the number of false alarms, T is the total amount of time the subject spent on the S2 station, N_{S2} is the number of S2 tone trials presented, and T_1 is the trial duration. For the MFR,

R_{FA} values calculated using Eq. (4) are analogous to false alarm rates obtained from a single interval experiment (Miller, 1969); however, this study employed a modified version of the MFR: the ISI was not open-ended but randomized between 5 and 12 s. The R_{FA} values calculated here are therefore not identical to those obtained with the MFR or to false alarm rates obtained from a single interval experiment; however, they do reliably assess a subject's response bias from session to session. The denominator of Eq. (4) is the total amount of time during which the subject was on the S2 station without a tone trial present, therefore R_{FA} is a way of normalizing the number of false alarms with respect to the amount of time that the subject had an opportunity to commit a false alarm (see Finneran *et al*., 2002a; Finneran *et al*., 2002b).

III. RESULTS AND DISCUSSION

A. PPD waveforms

The shallow test site depth affected the pressure waveforms produced at the location of the subject. The most striking feature was the presence of a second positive peak in the pressure waveform, presumably caused by the bottom-reflected wave from the PPD. The presence of the bottom reflected wave resulted in higher energy flux densities than would exist in PPD waveforms in open water. The differences between the pressure waveforms measured in the current study and those expected from the PPD in open water illustrate the importance of basing impact criteria for particular effects (such as TTS) on the actual received levels that produced the effect, rather than, for the case of the PPD, electrical charge and distance combinations that produced the effects.

B. Preexposure thresholds and false alarm rates

Table II shows the preexposure masked hearing thresholds and false alarm rates measured for NRT and LIB. In this table, data from both control and exposure sessions are pooled. Masked thresholds and false alarm rates for NRT at 1 and 10 kHz were 118 and 115 dB re 1 µPa and 5.3

and 5.5%, respectively. Masked thresholds and false alarm rates for LIB at 1 and 10 kHz were 122 and 114 dB re 1 µPa and 3.3 and 3.4%, respectively. False alarm rates for both subjects had large variances (standard deviations were of the same order of magnitude as the mean values). Thresholds were generally within ± 4 dB from day-to-day. The variability in the preexposure hearing thresholds was similar to that observed in behavioral hearing tests with human and animal subjects (e.g., Johnson, 1967; NIOSH, 1998).

The critical ratio (CR) is defined as the ratio of the masked threshold to the noise power spectral density (Fletcher, 1940). CRs are a measure of the auditory system's ability to detect a signal in noise and may be used to compare masked hearing thresholds measured with different noise levels. CRs for the present study were 28 and 32 dB re 1 Hz and 35 and 34 dB re 1 Hz at 1 and 10 kHz, respectively. Masked thresholds and CRs at 1 kHz were similar to those measured in *Zalophus* by Southall *et al*. (2000). Southall *et al*. reported thresholds of 122 and 119 dB re 1 µPa and CRs of 28 and 22 dB re 1 Hz at 800 and 1200 Hz, respectively. Southall *et al*. used octave-band masking noise spectral density levels of 94 and 97 dB re 1 µPa^2/Hz at 800 and 1200 Hz, respectively (at 1 kHz, an octave band would extend from approximately 700–1400 Hz, which is smaller than the bandwidth employed in the present study). There are no existing data for CRs above 2.5 kHz in *Zalophus*. CRs have been measured near 10 kHz in the harbor seal (20 dB re 1 Hz at 8 kHz; Terhune, 1991; Turnbull and Terhune, 1990), northern fur seal, *Callorhinus ursinus*, (21 dB re 1 Hz at 8 kHz; Moore and Schusterman, 1987), ringed seal, *Phoca hispida*, (32 dB re 1 Hz at 8 kHz; Terhune and Ronald, 1975), and harp seal, *Phoca groenlandica*, (35 dB re 1 Hz at 8.6 kHz; Terhune and Ronald, 1971). The current data are at the high end of this range. Unfortunately, there are insufficient data to identify whether the measured CRs are within the normal range of variability for *Zalophus*, or if they indicate a loss of hearing sensitivity at 10 kHz. Any pre-existing hearing loss at 10 kHz would have resulted in less observed TS than one would measure from an un-impaired listener.

Table III compares the postexposure false alarm rates measured during control and exposure sessions. As with the preexposure data, variances in the false alarm rates were relatively high. There were no significant differences between the control and exposure session mean false alarm rates for either NRT [$t(5) = 0.398$, $p = 0.707$ at 1 kHz and $t(6) = -0.952$, $p = 0.380$ at 10 kHz] or LIB [$t(5) = 0.421$, $p = 0.692$ at 1 kHz and $t(3) = -0.952$, $p = 0.411$ at 10 kHz].

C. Direct effects of the exposures

Neither subject showed any signs of physical injury as a result of exposure to the impulsive sounds produced by the PPD. There were no 6 dB or larger threshold shifts observed (i.e., no MTTS according to the 6-dB criterion) in any of the exposure or control sessions. At the conclusion of the study both subjects' hearing thresholds were within normal baseline ranges; there were no permanent auditory, appetite, or health effects of the exposures.

Figure 5 shows the threshold shifts measured at 5 min (TS_5) and 10 min (TS_{10}) postexposure plotted versus the exposure condition for NRT [Fig. 5(a)] and LIB [Fig. 5(b)]. The upper and lower panels in each figure show the results obtained at 1 kHz and 10 kHz, respectively. Filled symbols show the amount of TS_5; open symbols show the measured TS_{10}. The data points for TS_5 and TS_{10} are offset for clarity. The control session results are grouped together. Figure 5 provides of way of comparing the amounts of TS obtained after exposures to the amount of TS observed during control sessions. There are no obvious relationships between the exposure condition and the resulting TS in the data of Fig. 5; for these two subjects the particular exposure conditions used were below those necessary to cause a significant MTTS. Most (31/36 for NRT, 30/32 for LIB) of the measured TSs were within ±4 dB. All of the control sessions and most of the exposure sessions resulted in negative amounts of TS for NRT at 10 kHz. Since this occurred in all of the control sessions, it seems likely that this is an artifact peculiar to this subject at 10 kHz with the test paradigm employed. The TS results for NRT at 1 kHz and for LIB were distributed more evenly about zero. The values of TS_5 and TS_{10} were normally within ±2 dB of each other for a particular test. In summary, the TSs observed and differences between TS_5 and TS_{10} were within the normal variability associated with behavioral hearing tests and should not be interpreted as significant.

D. Indirect (behavioral) effects of the exposures

Previous marine mammal TTS studies have reported “behavioral reactions” in the test subjects after exposure to high levels of underwater sound (Kastak *et al*., 1999; Schlundt *et al*., 2000). These reactions mainly consisted of alterations in the subjects’ trained behaviors apparently designed to allow the subject to avoid the sound exposure itself (for long duration exposures) or to avoid the spatial location of the exposure during subsequent tests. More severe reactions such as aggression toward the test apparatus have also been observed (e.g., Schlundt *et al*., 2000). In the current study, alterations in the trained behaviors of NRT and LIB began to occur as the exposure levels increased.

The reaction of NRT was mild: At level N3 NRT did not leave the S1 station after exposure to the PPD impulse and the S1 start signal and required a second S1 start signal to be presented before he proceeded to the S2 station. At levels N4 and N5, the subject returned to the trainer after exposure to the impulsive sound. Following this, the trainer directed NRT to the S1 station, another S1 start signal was presented, and the subject proceeded to the S2 station for the hearing test. It is unknown why NRT returned to the trainer after exposure to the impulse. It is possible that he initially confused the impulsive sound with a commonly used “recall” sound produced by the trainer slapping the water surface.

The reactions of LIB were more substantial. At levels L2, L3, and L4 LIB was reluctant to return to the S1 station after exposure to the PPD impulse. The severity of this behavior (i.e., the amount of time required for him to resume stationing on the S1 biteplate) increased as the test sequence progressed. As the testing progressed over a number of days, LIB became reluctant to station on the S1 biteplate *before* the exposure. Other reactions included looking around with his head out of the water (level L3) and hauling out (level L4).

It is important to distinguish these deviations in the subjects' trained behaviors from reactions that may occur in wild and/or naive animals. The exposure paradigm, with exposure levels increasing over a number of days, likely had an impact on the subjects' behaviors (i.e., the subjects knew that the exposure levels were increasing from day to day). [This particular exposure sequence was a conservative approach used because the PPD was a novel stimulus. If significant amounts of TTS had been observed after an exposure, testing would not have continued to higher levels.] The fact that one subject (LIB) was reluctant to station on the S1 biteplate before the exposure indicates that the subjects' prior experiences with the test apparatus also affected their reactions. Although the subjects both showed clear behavioral reactions to the impulsive sounds, no changes in general health or appetite were detected.

E. Effects of masking noise

There have been few studies of the effects of masking noise on the amount of observed TS in mammals. Parker *et al*. (1976) and Humes (1980) showed that the presence of masking noise resulted in elevated hearing thresholds (simulating a preexposure loss in hearing sensitivity) and decreased the amount of TTS measured in humans. Ades *et al*. (1974) also measured smaller amounts of PTS in chinchillas when thresholds were obtained in the presence of masking noise compared to the amount of PTS measured when thresholds were determined in quiet. Unfortunately, there are no conclusive data for the relationship between masking noise and TTS in marine mammals (see Schlundt *et al*., 2000); it is possible that larger TSs may have been observed in the present study if the masking noise was not used. Masking noise was employed because the test site had a variable ambient noise level. The masking noise level was the lowest at which uniform frequency content and stable hearing thresholds could be maintained. Preexposure hearing thresholds (Table II) were approximately 30–35 dB above published thresholds for *Zalophus* (Schusterman *et al*., 1972; Kastak and Schusterman, 1998); however, subjects' thresholds measured in San Diego Bay without masking noise (ambient noise levels in

San Diego Bay at the test site were approximately 78 and 69 dB re 1 µPa^2/Hz at 1 and 10 kHz, respectively) were only approximately 7–14 dB below the masked thresholds.

F. Comparison to existing data

Kastak *et al*. (1999) measured 2.9–6.7 dB of TTS in a California sea lion exposed to 20 min of octave band noise (1 and 2 kHz noise center frequencies). Figure 6 compares the TTS-inducing stimuli used by Kastak *et al*. to the exposure conditions used in the current study. Figures 6(a) and 6(b) show the peak pressure and rms pressure of each exposure, respectively, versus the exposure duration; Fig. 6(c) plots the exposure energy flux versus the duration. The open circles represent the data from the current study (no MTTS) and the solid rectangles show the range of exposures used by Kastak *et al*. (1999). Peak pressures for the Kastak *et al*. data were approximated as the rms pressure + 3 dB.

Figures 6(a) and 6(b) illustrate the importance of considering both amplitude and duration when estimating the impact of sounds on marine mammals: Although some of the PPD impulses had relatively high peak and rms pressures (higher than those causing TTS in the Kastak *et al*. study), the duration of these impulses was relatively short, thus the total energy was much lower than the energy in the noise exposures used by Kastak *et al*. [Fig. 6(c)]. Thus, it is not surprising that the single impulses from the PPD (at the charge levels and distances employed) did not cause a TTS in the subjects studied.

The solid line in Fig. 6(b) is a line with a slope of -3 dB per doubling of time fit to the mean value of the Kastak *et al*. data set. This is sometimes called a “-3 dB exchange rate” or an “equal-energy criterion”, since any two continuous-type sounds whose rms pressures and durations fall on the line will have the same total energy flux. For single, continuous exposures, exposures of equal energy lead to approximately equal effects on mammalian auditory systems (Ward, 1997). The limited amount of odontocete onset-TTS data from single impulsive, tonal, and noise exposures are also fit reasonably well by the –3 dB exchange rate (Finneran *et al*., 2002b). It therefore seems reasonable that an equal energy rule would apply to pinnipeds as well (and thus the Kastak *et al*. data could be extrapolated to other durations on an equal energy basis); however, this has yet to be experimentally verified (see Southall *et al*., 2001).

IV. CONCLUSIONS

(1) Auditory and behavioral effects of the PPD were assessed by measuring hearing thresholds in two trained California sea lions before and after exposure to single underwater impulses produced by the PPD.

(2) The pressure waveforms produced by the PPD were strongly influenced by the shallow depth at the test site. Most received pressure waveforms featured a second positive pressure peak produced from the bottom reflection. This condition resulted in larger total energy fluxes than one would have in open water without a bottom reflected wave.

(3) No MTTS was observed in either subject at the highest received levels: peak pressures of approximately 6.8 and 14 kPa, rms pressures of approximately 178 and 183 dB re 1 μPa, and total energy fluxes of 161 and 163 dB re 1 $\mu Pa^2 s$ for the two subjects. The total energy fluxes in the exposures were at least 25 dB lower than the mean energy flux level employed by Kastak *et al*. (1999), who observed small amounts of TTS in a California sea lion exposed to 20 min of octave band noise.

(4) Behavioral reactions to the tests were observed in both subjects. These reactions primarily consisted of attempts to avoid the site where exposure to the PPD impulse had previously occurred.

V. ACKNOWLEDGMENTS

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Table I. Exposure conditions for NRT and LIB. Mean values are listed. The ± values indicate the standard deviation for linear units (e.g., kPa) and the maximum ± excursion for values in dBs.

Subject	Level	Charge (kJ)	Distance (m)	$p_{\max}$ (kPa)	$p_{\min}$ (kPa)	$SPL_{\text{p-p}}$ (dB re 1 µPa)	SPL_{rms} (dB re 1 µPa)	E_{T} (dB *re*:1 $\mu Pa^2 \cdot s$)	τ (ms)
NRT	N1	1.32[a]	15	0.065 ± 0.015	-0.041 ± 0.016	160 ± 2	143 ± 1	128 ± 1	28.3 ± 8.0
NRT	N2	1.32	25	0.49 ± 0.063	-0.74 ± 0.28	182 ± 1	155 ± 2	137 ± 1	16.2 ± 3.0
NRT	N3	1.32	6.5	1.2 ± 0.086	-2.2 ± 0.029	190 ± 1	169 ± 1	148 ± 1	10.5 ± 0.63
NRT	N4	2.44	6.5	7.0 ± 1.4	-6.3 ± 2.7	202 ± 2	177 ± 2	158 ± 2	13.9 ± 0.49
NRT	N5	2.77	3.4	14 ± 6.0	-4.9 ± 0.12	205 ± 3	183 ± 1	163 ± 1	14.2 ± 0.12
LIB	L1	1.32	25	0.54 ± 0.18	-0.96 ± 0.093	183 ± 1	153 ± 4	139 ± 1	18.7 ± 3.6
LIB	L2	2.19	15	1.7 ± 0.35	-1.4 ± 0.21	190 ± 1	165 ± 1	149 ± 2	18.3 ± 2.3
LIB	L3	2.19	6.5	5.3 ± 0.096	-5.8 ± 0.026	201 ± 1	175 ± 1	156 ± 1	13.8 ± 0.59
LIB	L4	2.44	3.4	6.8 ± 0.64	-3.3 ± 1.2	200 ± 1	178 ± 1	161 ± 4	11.5 ± 0.60

[a] At level N1 a neoprene rubber sheath was placed over the electrode assembly to reduce the sound output.

Table II. Mean values for preexposure masked hearing thresholds and false alarm rates for NRT and LIB. The ± values are standard deviations. Data from exposure and control sessions are pooled.

	NRT			LIB		
Frequency (kHz)	Threshold (dB re 1 µPa)	R_{FA} (%)	n	Threshold (dB re 1 µPa)	R_{FA} (%)	n
1	118 ± 2	5.3 ± 2.4	18	122 ± 2	3.3 ± 3.1	16
10	115 ± 4	5.5 ± 3.2	18	114 ± 2	3.4 ± 2.8	16

Table III. Mean values for postexposure false alarm rates for NRT and LIB. The ± values are standard deviations.

	NRT				LIB			
Frequency	Control		Exposure		Control		Exposure	
(kHz)	R_{FA} (%)	n	R_{FA} (%)	n	R_{FA} (%)	n	R_{FA} (%)	n
1	5.3 ± 1.3	4	6.2 ± 4.7	5	3.2 ± 3.1	4	4.6 ± 3.2	4
10	6.7 ± 4.5	4	4.1 ± 3.6	5	4.5 ± 4.4	4	2.4 ± 0.4	4

Figure 1. (a) Experimental test site for the sound exposures and the hearing tests. (b) S1 station detail. (c) S2 station detail.

Figure 2. Representative pressure waveforms and energy flux spectral densities measured for exposure conditions N1–N5. Note that the ordinate and abscissa scales are not uniform throughout the panels.

Figure 3. Representative pressure waveforms and energy flux spectral densities measured for exposure conditions L1–L4. Note that the ordinate and abscissa scales are not uniform throughout the panels.

Figure 4. Test sequence and threshold calculation method. (a) A single test session (exposure or control) was conducted each day. During each session, three hearing tests were conducted: two preexposure and one postexposure. (b) Preexposure and (c) postexposure hearing test results consisted of the subjects' performance (hit or miss) as a function of the S2 tone SPL. The filled and open symbols represent hits and misses, respectively. (d) Preexposure thresholds were calculated from the average pressure over the first 10 reversals. Postexposure thresholds were estimated using a 10-pt moving average. (e) The threshold shift was determined by subtracting the preexposure thresholds from the postexposure threshold.

Figure 5. Threshold shifts measured 5 min (TS_5, filled symbols) and 10 min (TS_{10}, open symbols) after exposure for (a) NRT and (b) LIB. The upper panel in each figure shows the results at 1kHz, the lower panel shows the results at 10 kHz. Results from control sessions are grouped. The NRT, 10 kHz, control, TS_5 data point at -7 dB was obtained at 5.6 min postexposure.

Figure 6. Comparison of the PPD exposure conditions to those of Kastak *et al*. (1999). Exposure conditions are displayed as the (a) peak pressure, (b) rms pressure, and (c) total energy flux

versus the exposure duration. The line labeled “-3 dB exchange rate” has a slope of -3 dB per doubling of time and is equivalent to an equal energy criterion for continuous-type sounds.

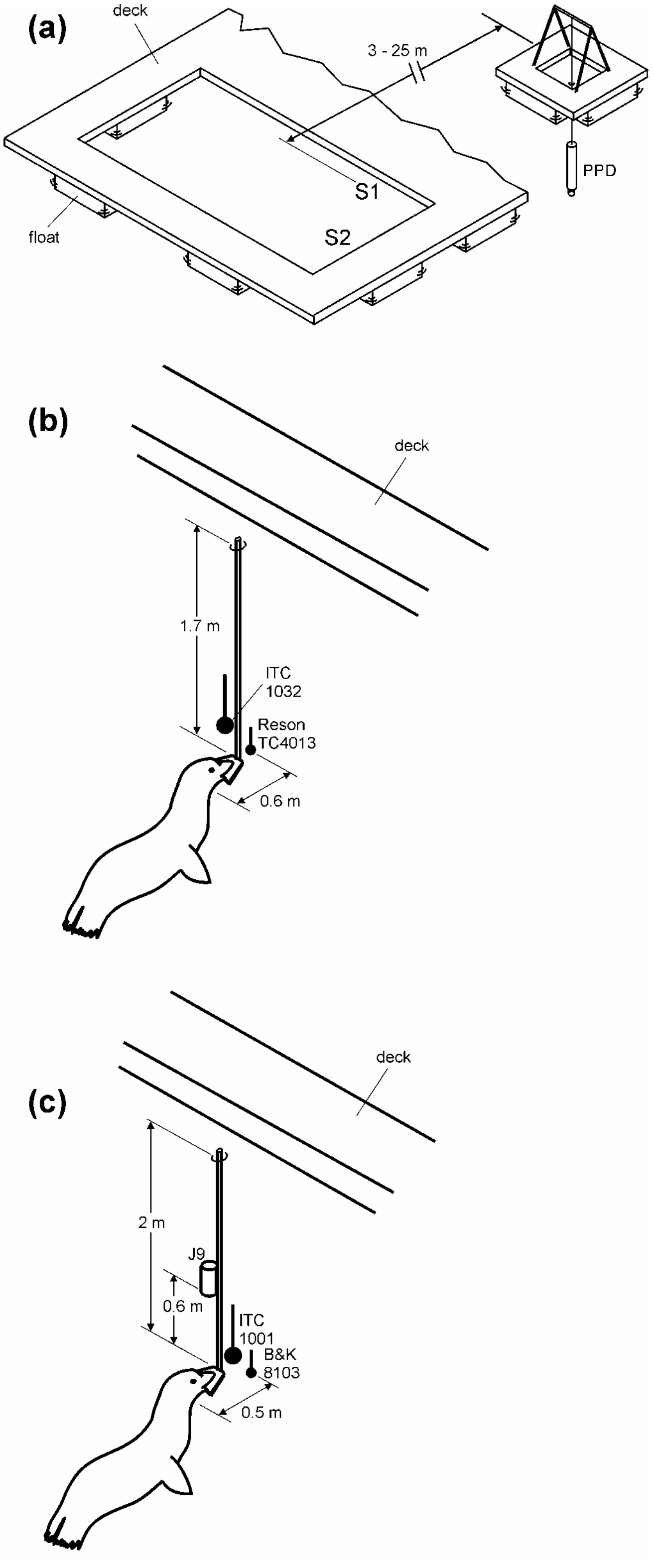
(a)
deck
3 - 25 m
PPD
S1
S2
float
(b)
deck
1.7 m
ITC 1032
Reson TC4013
0.6 m
(c)
deck
2 m
J9
0.6 m
ITC 1001
B&K 8103
0.5 m

FIG. 1

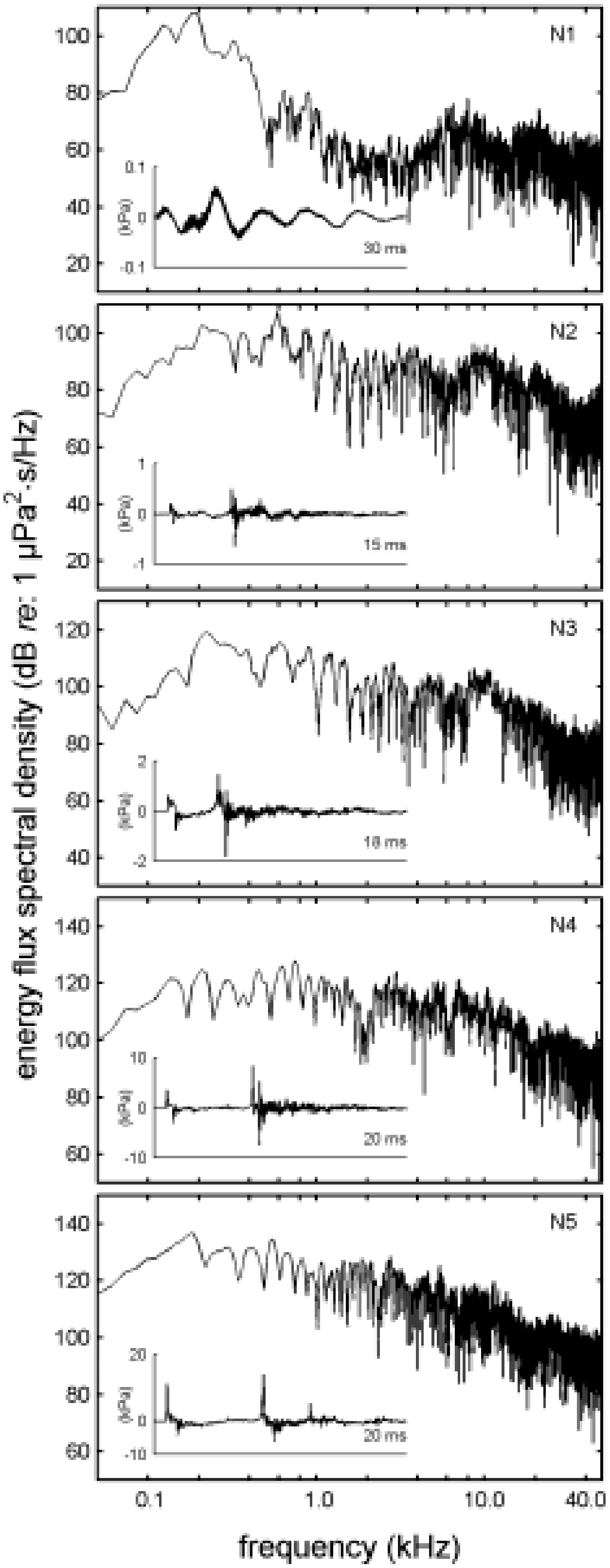
N1
N2
N3
N4
N5
energy flux spectral density (dB re: 1 μPa²·s/Hz)
frequency (kHz)
0.1
1.0
10.0
40.0
100
80
60
40
20
120
140
(kPa)
30 ms
15 ms
18 ms
20 ms
20 ms
0.1
0
-0.1
1
-1
2
-2
10
-10
20

FIG. 2

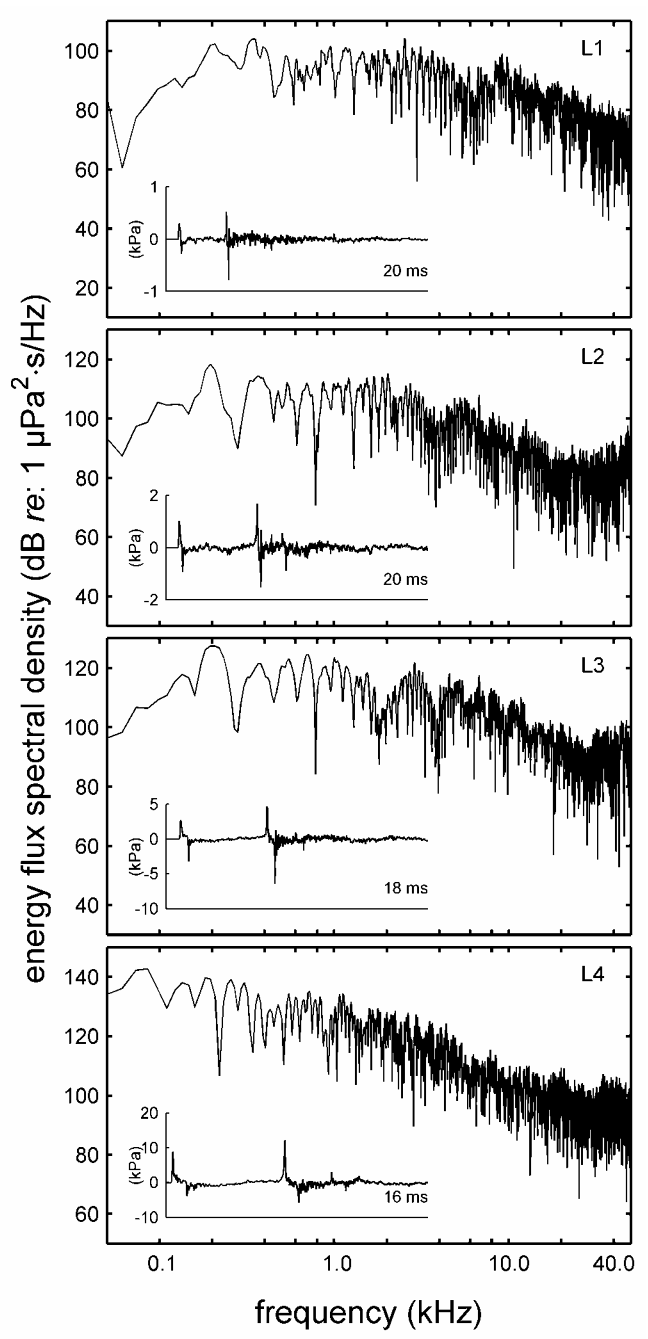
L1
L2
L3
L4
100
80
60
40
20
1
0
-1
(kPa)
20 ms
120
100
80
60
40
2
0
-2
(kPa)
20 ms
120
100
80
60
40
5
0
-5
-10
(kPa)
18 ms
140
120
100
80
60
20
10
0
-10
(kPa)
16 ms
energy flux spectral density (dB re: 1 μPa²·s/Hz)
0.1
1.0
10.0
40.0
frequency (kHz)

FIG. 3

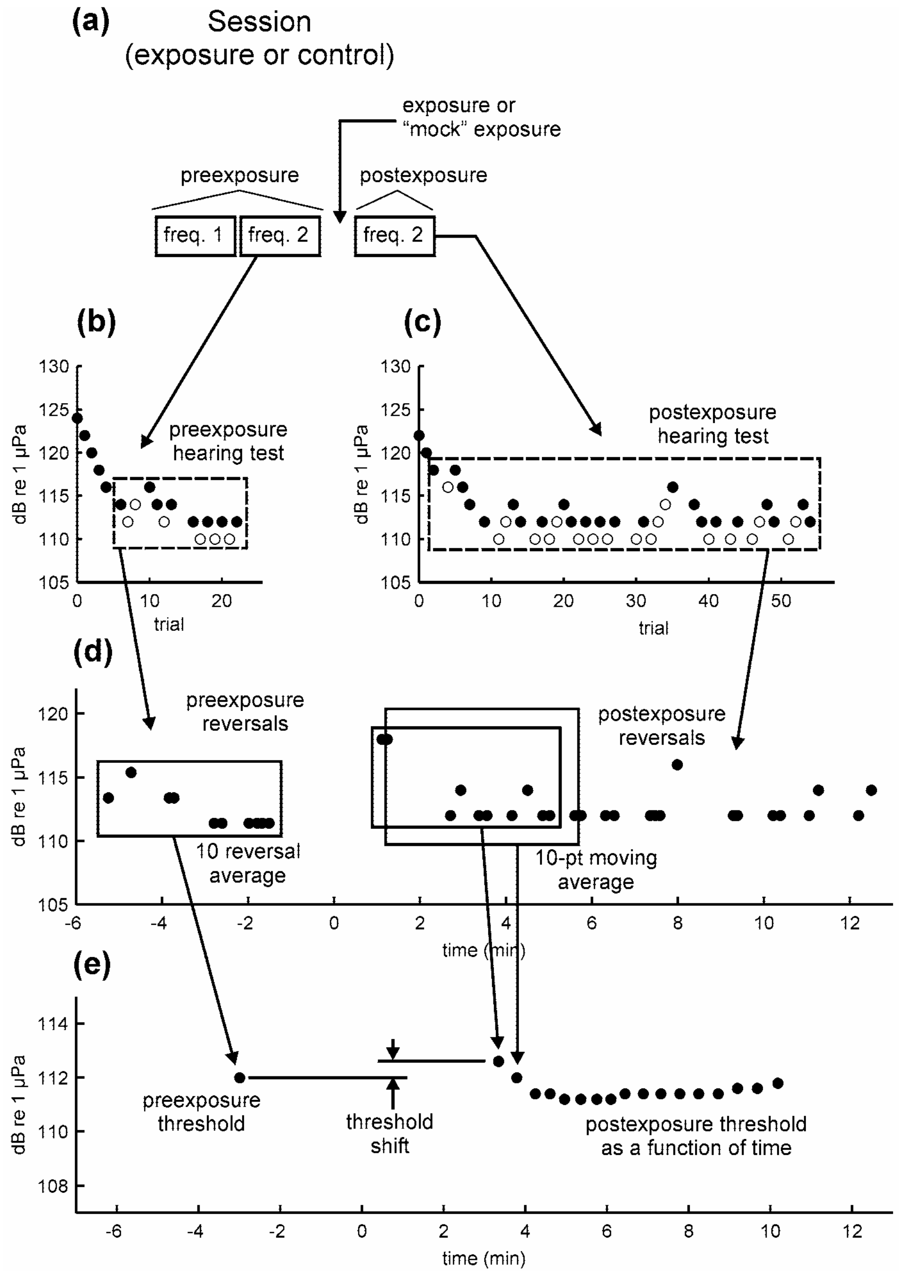
(a)
Session
(exposure or control)
exposure or
"mock" exposure
preexposure
postexposure
freq. 1
freq. 2
freq. 2
(b)
(c)
preexposure
hearing test
postexposure
hearing test
dB re 1 μPa
130
125
120
115
110
105
0
10
20
30
40
50
trial
(d)
preexposure
reversals
postexposure
reversals
10 reversal
average
10-pt moving
average
time (min)
(e)
114
112
110
108
-6
-4
-2
0
2
4
6
8
10
12
preexposure
threshold
threshold
shift
postexposure threshold
as a function of time

FIG. 4

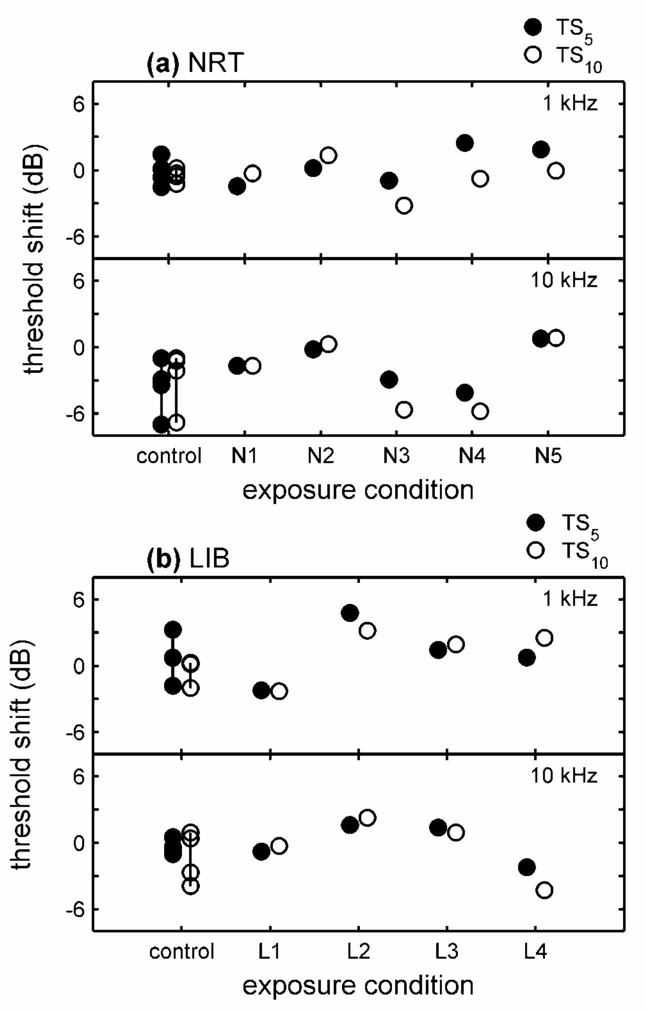
● TS$_5$
○ TS$_{10}$
(a) NRT
1 kHz
10 kHz
threshold shift (dB)
6
0
-6
control
N1
N2
N3
N4
N5
exposure condition
● TS$_5$
○ TS$_{10}$
(b) LIB
1 kHz
10 kHz
threshold shift (dB)
control
L1
L2
L3
L4
exposure condition

FIG. 5

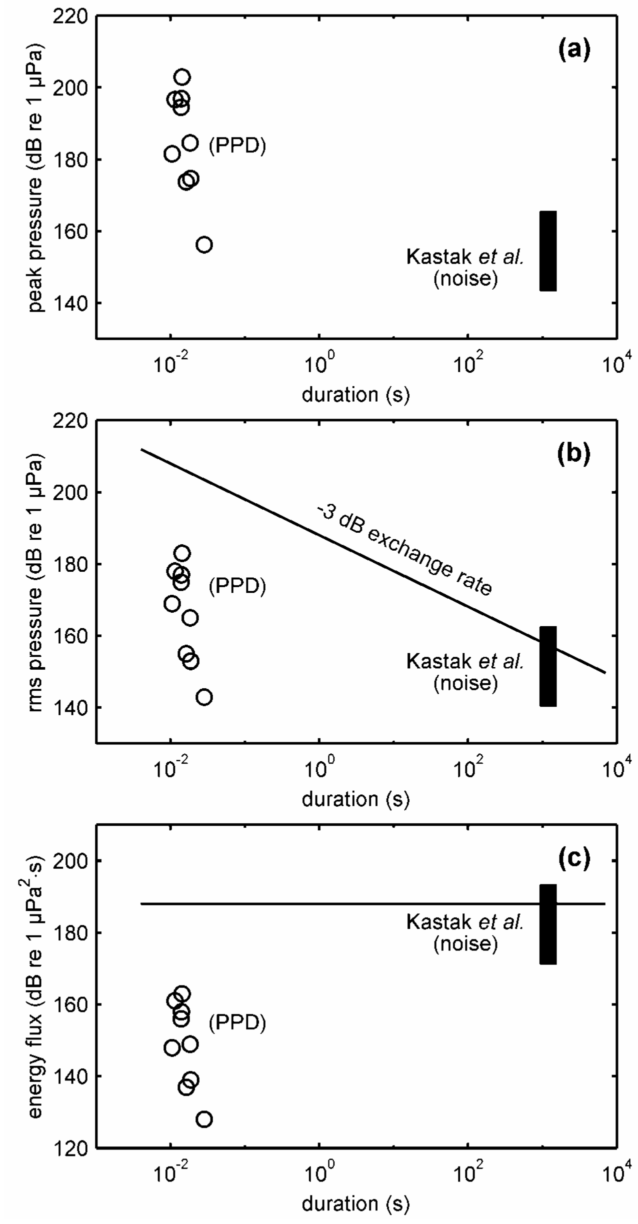
(a)
peak pressure (dB re 1 μPa)
220
200
180
160
140
(PPD)
Kastak *et al.*
(noise)
10^{-2}
10^{0}
10^{2}
10^{4}
duration (s)
(b)
rms pressure (dB re 1 μPa)
220
200
180
160
140
-3 dB exchange rate
(PPD)
Kastak *et al.*
(noise)
10^{-2}
10^{0}
10^{2}
10^{4}
duration (s)
(c)
energy flux (dB re 1 μPa^2·s)
200
180
160
140
120
Kastak *et al.*
(noise)
(PPD)
10^{-2}
10^{0}
10^{2}
10^{4}
duration (s)

FIG. 6