Auditory Weighting Functions and Frequency-Dependent Effects of Sound in Bottlenose Dolphins (*Tursiops Truncatus*)

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LONG-TERM GOALS

The long term goal of this effort is to develop meaningful auditory weighting functions for marine mammals. These weighting functions would improve assessments of the effects of anthropogenic sound by emphasizing frequencies to which animals are most sensitive and de-emphasizing those to which they are not.

OBJECTIVES

The objective of this effort is to develop auditory weighting functions for bottlenose dolphins with normal hearing and high-frequency hearing loss. The weighting functions would be defined by measuring subjective loudness and temporary threshold shift (TTS) as functions of the sound frequency.

The specific objectives for FY08 were to (1) define TTS onset/growth at 3 kHz in a bottlenose dolphin with good high-frequency hearing, (2) train the same dolphin to participate in equal loudness tests, and (3) define TTS-onset at 20 kHz in a second bottlenose dolphin.

APPROACH

TTS is defined as the difference between hearing thresholds measured before and after an intense (fatiguing) sound exposure. Hearing thresholds are estimated using either a behavioral response paradigm, where the subject is trained to perform a specific action when it hears a test tone, or an electrophysiological method, where auditory evoked potentials (AEPs) are measured in response to test tones.

Behavioral methods developed at the Navy Marine Mammal Program (MMP) allow thresholds to be obtained within four minutes of intense sound exposures. This is accomplished using computer-controlled stimulus presentations, recording acoustic responses emitted by the subject in response to those stimuli, and presenting multiple trials before subject reinforcement. Dolphins typically produce an acoustic response (a whistle) within a few hundred milliseconds of tone onset, allowing a rapid pace of stimulus presentation and fast threshold estimates. A modified up/down descending staircase technique is used to adjust the stimulus level in an adaptive fashion from one trial to the next and bracket the threshold.

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Electrophysiological thresholds are estimated by measuring a type of AEP called an auditory steady state response (ASSR). Hearing tests are conducted underwater using a stimulus projected in the direct field stimulus (not via a "jawphone"). A statistical test (magnitude-squared coherence) is used to objectively determine the presence or absence of AEPs in response to stimuli at different levels. Thresholds are based on the lowest detectable response with a 1% probability of false detection.

Subjects are trained to wear suction cup-mounted hydrophones during the fatiguing sound exposures to allow estimates of the received sound levels regardless of subject location. Pure-tone exposures are characterized by the average sound pressure level (SPL), sound exposure level (SEL), and exposure duration. Tests are conducted in a quiet, above ground test pool.

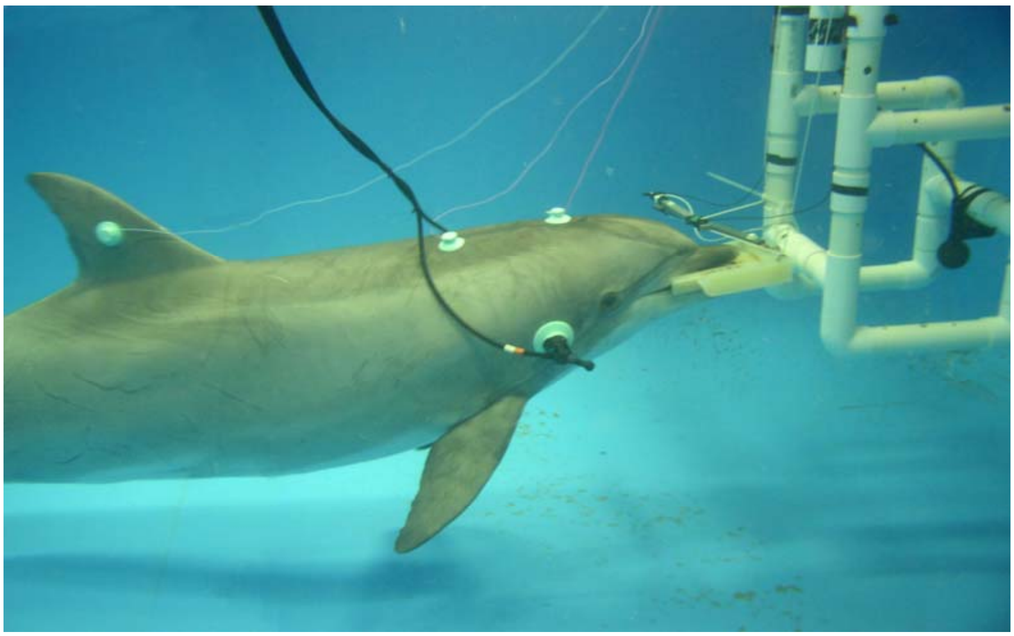

Figure 1. A dolphin subject in the pool during a TTS experiment. Suction cup-mounted hydrophones placed near the ears were used to record the sound levels during the fatiguing sound exposure. Surface electrodes embedded in small suction cups placed on the head and back are used to measure AEPs.

Equal loudness tests use a loudness comparison method where the subject is presented two sequential tonal stimuli. The subject is trained to whistle if the first tone is louder than the second and to produce a "buzz" response if the second tone is louder than the first. The majority of trials feature stimulus pairs for which the loudness relationship between the two tone pairs is known, for example two tones at the same frequency but with different SPLs. The subject's performance on the "known" trials allows its performance to be tracked within each session. Approximately 17% of the trials are probe trials, consisting of a standard tone, whose frequency and SPL are fixed, and comparison tone, whose frequency is fixed within a session but whose SPL varies. The subject's responses to the probe trials are analyzed to determine the transition point between responses, which indicates the SPL of the comparison tone that is equally loud to the standard tone.

James Finneran served as the PI and project manager, developed the hardware and software for AEP and behavioral hearing tests and the loudness comparison tests, analyzed the acoustic and threshold data, and performed the TTS mathematical modeling. Carolyn Melka served as the technical coordinator for the threshold, TTS, and equal loudness tests conducted in the pool, conducted the daily experiments, calibrated the sound system, and analyzed/archived the resulting data. Brian Branstetter and Laura Yeates assisted with data collection and analysis.

WORK COMPLETED

We finished TTS measurements at 3 kHz in a bottlenose dolphin with good high-frequency hearing. The same dolphin has been trained in the loudness comparison test; preliminary data are now being collected. We also obtained TTS data at 20 kHz from a second dolphin subject for whom data at 3 kHz already existed.

RESULTS

The 3-kHz TTS data were the first TTS data acquired from our new test subject; 3 kHz was chosen for its relevance to Navy mid-frequency tactical sonars and to allow comparison with existing data from other subjects. These new data now give us TTS data at 3 kHz (from the quiet test pool) for three individual dolphins. The onset of TTS at an SEL of 195 dB re 1 μPa^2·s for tones with durations < ~16 s is well-supprted by these data.

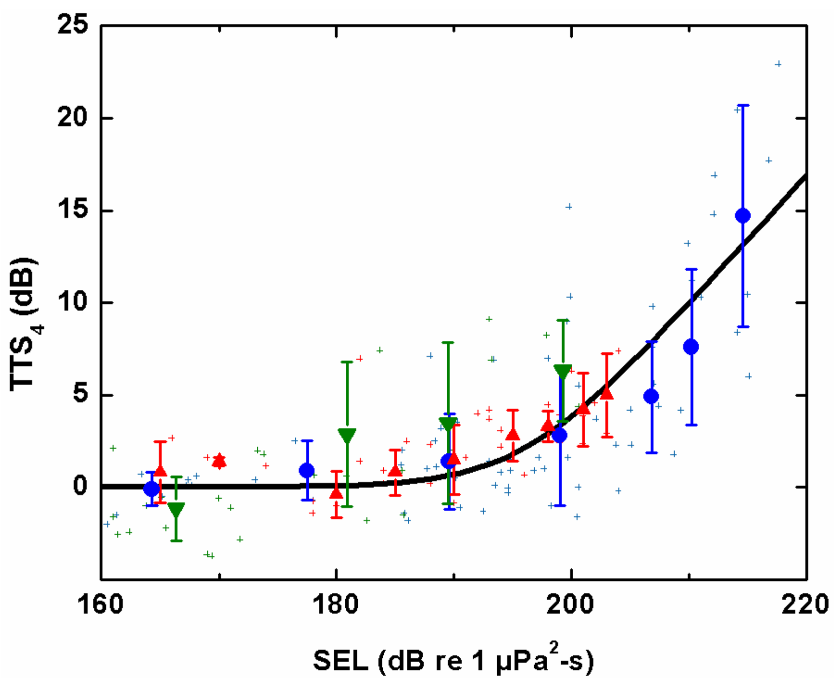

Figure 2. TTS as a function of SEL after 3-kHz exposures in three bottlenose dolphins. Hearing was tested at 4.5 kHz, about 1/2-octave above the exposure frequency. The amount of TTS grows exponentially with the exposure SEL at low levels; at higher levels the growth is approximately linear. The onset point is near 195 dB re 1 μPa^2·s.

A previous study of TTS at 20 kHz suggested that the onset of TTS at 20 kHz may occur at significantly lower exposure levels than at 3 kHz [Finneran et al. (2007). "Assessing temporary threshold shift in a bottlenose dolphin (*Tursiops truncatus*) using multiple simultaneous auditory evoked potentials," J. Acoust. Soc. Am. 122, 1249–1264.]. TTS measurements conducted with the same subject as the 2007 paper, but at lower exposure levels, allowed us to define the onset of TTS in this subject for 20-kHz exposures. A comparison of these data to existing data for 3-kHz exposures in this subject reveal substantial differences between onset-TTS levels (Fig. 3). This means TTS will occur after lower exposure levels at 20 kHz compared to 3 kHz. Consequently, acoustic impact thresholds based on 3-kHz data would not be appropriate for 20-kHz exposures – they will underestimate the effects. It is also important to note that in Fig. 3, the difference between the onset of TTS at 3 and 20 kHz is not simply the difference in thresholds – the thresholds at 3 and 20 kHz are ~10 dB apart, not the ~20 dB difference observed in the exposures sufficient to cause TTS.

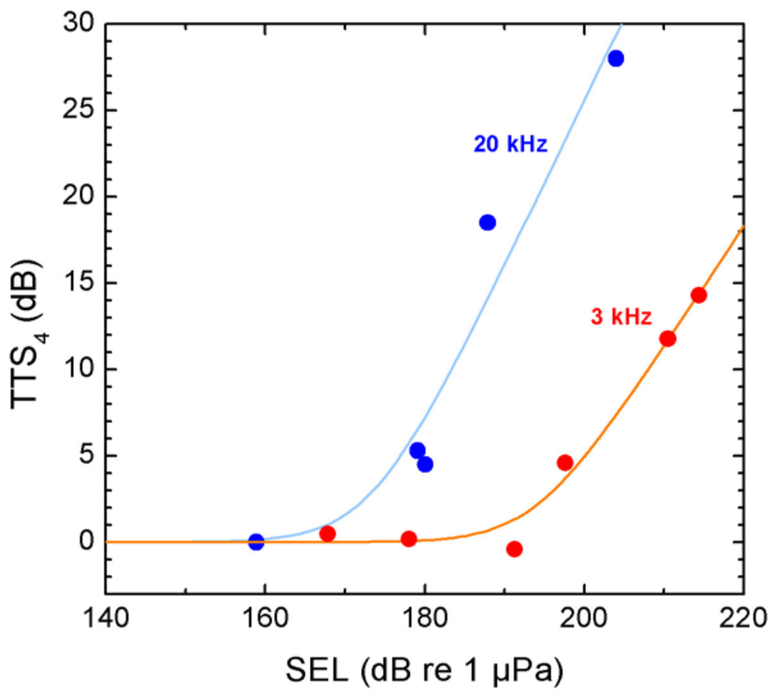

Figure 3. TTS as a function of SEL for 64-s exposures at 3 kHz and 20 kHz. Hearing was tested at 4.5 kHz and 30 kHz, respectively, using behavioral methods. The onset of TTS after 20-kHz exposures was significantly lower than the onset of TTS for 3-kHz exposures.

Figure 4 shows preliminary data collected during loudness comparison tests. For these data, collected over several days, the standard tone (A) had a frequency of 10 kHz and an SPL of 90 dB re 1 µPa. The comparison tone (A) was varied, with the frequency constant on a particular day but the SPL changing according to the values listed in Fig. 4 at the top of each column. Data for comparison frequencies of 5, 7, 10, 14, 20, and 28 kHz are shown. The letters A or B describe the subject's response during a probe trial – A indicates that the subject whistled, thereby selecting the standard tone as the louder; B indicates that the subject buzzed, thereby chosing the comparison tone as the louder. For example, when the comparison tone was at 5 kHz, the subject indicated that tones with SPLs ≥ 110 dB SPL were louder than the standard (10 kHz at 90 dB SPL). The transition point from 105 to 110 dB indicates the region where the standard and comparison tones were equally loud, estimated here as 107.5 dB SPL. That means that a 5-kHz tone at 107.5 dB is as loud as a 90-dB tone at 10 kHz. Similarly, for a 10-kHz comparison tone (the same frequency as the standard), the transition point is between 87 and 92 dB SPL. Since this brackets the actual SPL of the standard tone, it lends confidence that the subject is correctly performing the task.

A = 10k, 90 dB SPL					SPL of B				
		80	85	90	95	100	105	110	115
	B = 5k	A	A	A	A	A	A	B	B
		78	83	88	93	98	103	108	113
	B = 7k	A	A	A	A	A	B	B	B
		72	77	82	87	92	97	102	107
	B = 10k	A	A	A	A	B	B	B	B
		75	80	85	90	95	100	105	110
	B = 14k	A	A	A	B	B	B	B	B
		72	77	82	87	92	97	102	107
	B = 20k	A	A	B	A	B	B	B	B
		77	82	87	92	97	102	107	112
	B = 28k	A	A	A	B	B	B	B	B

Figure 4. Preliminary data for the loudness comparison test. The letter in each box indicates if the subject selected the standard (A) or comparison (B) as the louder tone.

The transition points, or equal-loudness points, from data such as that shown in Fig. 4 can be used to create equal-loudness contours (Fig. 5) by plotting the points at which tones are equally loud compared to the standard. Human weighting schemes were derived from equal-loudness curves such as those in Fig. 5. The data obtained from this study represent the first direct measurement of equal-loudness curves in any animal. The shape of the equal-loudness contour can be used to create a weighting function to properly emphasize frequencies at which auditory sensitivity is highest and lessen the importance of other frequencies, similar to human A- and C-weighting networks.

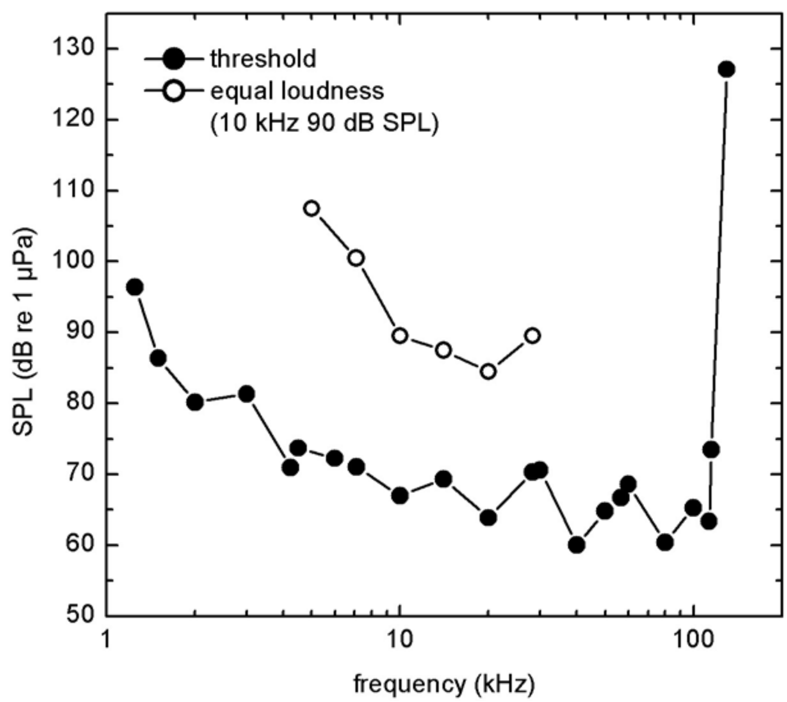

Figure 5. Preliminary equal-loudness contour passing through 10 kHz, 90 dB SPL. The equal-loudness contour tends to parallel the audiogram (the hearing threshold as a function of frequency), but diverges at low frequency.

IMPACT/APPLICATIONS

The observed differences between TTS-onset at 3 kHz and 20 kHz will affect the manner in which Navy predicts auditory effects of high-frequency sonars on wild marine mammals. At present, onset-TTS data from dolphins tested at mid-frequencies (primarily 3 kHz) are used to make predictions at all other frequencies. Data at higher frequencies can be used to create frequency-dependent estimates for onset-TTS (i.e., TTS weighting functions) that are more accurate than current estimates.

Similarly, the equal loudness data show the relationship between the frequency of sound and the subjective loudness of the sound. Weighting functions created from these data may be more appropriate to assessing behavioral effects of sound, under the assumption that the behavioral reactions of animals are more strongly related to the *loudness* of a sound compared to the *SPL* of the sound.

TRANSITIONS

Data resulting from this project have been presented at scientific conferences, briefed to ONR, NMFS, and CNO N45, and published in peer-reviewed scientific journals. We have also briefed a number of visitors this year, including ADM Willard (COMPACFLT), VADM Loose (N4), and RADM Rice (N45). The TTS data are often used in environmental assessments and impact statements that must be prepared for weapons systems development, surveillance systems development, quality assurance tests, oceanographic research, and training exercises. The TTS data that have been collected to date have been used extensively by Navy environmental analysts and have been used to derive acoustic impact criteria for various EAs and EISs, including the SEAWOLF Shock Trial, the WINSTON CHURCHILL Shock Trial, MESA VERDE (LPD 19) Shock Trial, USWTR, HRC, SOCAL, and AFAST EISs. These data have also impacted decision making on naval exercises such as RIMPAC and provided the basis for deconfliction guidelines for US Navy Marine Mammal Systems operating near active acoustic sources. The TTS data are used by not only the US Navy, but also by various NATO allies and the seismic industry for predicting and mitigating effects of sonars and explosives on marine mammals.

The AEP system software developed at the Navy MMP (called EVREST — the Evoked Response Study Tool) has been shared with other researchers conducting AEP measurements, including those at Long Marine Lab at UC Santa Cruz and the Pennsylvania State University Applied Research Lab.

RELATED PROJECTS

"Temporary threshold shift (TTS) in odontocetes in response to multiple airgun impulses," is a related project funded by the International Association of Oil and Gas Producers, Joint Industry Project (JIP). This effort employs techniques and equipment for behavioral and AEP hearing tests developed under previous ONR efforts.

PUBLICATIONS

Finneran, J. J. (2008). "Modified variance ratio for objective detection of transient evoked potentials in bottlenose dolphins (*Tursiops truncatus*)," J. Acoust. Soc. Am. [in press, refereed]

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Finneran, J. J. (2008). “Evoked Response Study Tool (EVREST) User’s Guide,” TD 3226, SSC San Diego, San Diego, CA. [published, non-refereed]

HONORS/AWARDS/PRIZES

James Finneran, SSC San Diego Exemplary Achievement Award, 2008

James Finneran, Department of the Navy Top Scientists and Engineers Award, 2007

James Finneran, SSC San Diego Publication Award, Publication of the Year, Open Literature, 2006

James Finneran, SSC San Diego Publication Award, Honorable Mention, Technical Report, 2006