Masked tonal hearing thresholds in the beluga whale

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Masked tonal thresholds were measured for a beluga whale at one noise level and 32 frequencies between 40 Hz and 115 kHz. Critical ratios were estimated and compared with those previously measured for the bottlenose dolphin. Beluga whale critical ratios were found to be about 3 dB lower than those of the bottlenose dolphin. Absolute tonal thresholds were extended below previous measurements to 40 Hz.

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INTRODUCTION

The effect of underwater sounds on marine mammals is becoming increasingly important for environmental impact studies (Awbrey *et al.*, 1986), and critical bandwidths are necessary for estimating signal detection in noise. Critical bandwidths have to do with the effect of noise intensity on signal detection. The terms critical band and critical ratio are both used to quantify the effects of noise on detection. In human listners, critical ratios are smaller than critical bands by a factor of about 2.5 over most of the hearing range [see Scharf (1970) for an excellent discussion of critical bands].

Fletcher (1940) suggested the existence of critical bands. He theorized that, when a tonal signal was played in a broad spectrum of white noise, only the noise energy in a relatively narrow band on either side of the tone frequency was effective in masking the noise, the rest of the noise spectrum contributing little or nothing. A useful way to visualize critical bands is through the operation of the basilar membrane. Each tonal signal stimulates a small portion of the basilar membrane, and Fletcher (1940) reasoned that only noise frequencies stimulating the same band of the basilar membrane would mask the tones' reception. Critical ratios are determined by measuring detection thresholds in broadband white noise and dividing the energy of the signal at threshold by the noise energy per hertz in the noise spectrum. This assumes that the filter corresponding to the critical band is flat on top and has vertical sides; i.e., the high-pass and low-pass sides of the filter drop off at infinite dB per octave. Ideally, for measuring critical ratios, a noise spectrum that is perfectly flat should be used. This was not possible in the present case and a more general method of calculating critical ratios was used. In the present experiment, critical ratios are to be calculated by assuming critical ratio filters with vertical sides and calculating their bandwidths by integrating the noise spectral energy on either side of the signal frequency as a function of bandwidth until the integrated noise energy equals the signal energy at threshold.

Masked tonal thresholds have been measured in the bottlenose dolphin (*Tursiops truncatus*) at 15 frequencies between 5 and 100 kHz by Johnson (1968) and at six frequencies between 30 and 120 kHz by Moore and Au (1982). In the present experiment, masked thresholds were measured at 32 frequencies between 40 Hz and 115 kHz. Absolute pure-tone thresholds were extended down in frequency to 40 Hz, which is a lower frequency than those previously measured by White *et al.* (1977) and Awbrey *et al.* (1988).

I. EXPERIMENTAL ARRANGEMENT

The experimental animal was a female *Delphinapterus leucas*, who was about 2 years old when she was captured in 1980. She has been the subject in other experiments and has received training in various experimental procedures.

A block diagram of the electronic apparatus is shown in Fig. 1, and a side view of the experimental pen is shown in Fig. 2. The test pen was located in San Diego Bay at the Naval Ocean Systems Center. The electronic apparatus in Fig. 1 includes an Interstate Electronics Corporation model F-33 function generator, a Hewlett–Packard (H.P.) model 350A attenuator, an H.P. model 465A amplifier (amplifier 1), an H.P. model 467A amplifier (amplifier 2), an NAD Electronics 55 Watt amplifier (amplifier 3), an H.P. model 466A amplifier (amplifier 4), and a General Radio model 1390B noise generator. A Grason-Stadler model 1703 recording audiometer was modified and used to slowly (10 dB/s) turn the test tones on and off, and the recording pen on the audiometer was used to indicate when the animal responded on the standard data cards.

The whale had been trained in previous experiments to station holding a bite plate in her mouth. In the present experiment, the 0.5-cm-thick polyvinyl chloride (PVC) bite plate was suspended from a pivot on the side of the pen with a 6-cm diam, 0.5-cm-thick PVC pipe, which extended 1 m below the water surface. When a tone was played into the water, the whale was trained to push forward until the bite plate touched a 0.2-cm thick × 15-cm-diam disk, suspended 15 cm in front of the bite plate. For frequencies from 40 Hz to 1 kHz, a Cerwin-Vega 188EB speaker was used. It was mounted in a 32-gal (116.5-l) steel garbage can whose bottom had been removed. The speaker was located as shown in Fig. 2. For frequencies between 500 Hz and 110 kHz, a J-9 underwater projector was used, and, between 30 and 115 kHz, a transducer from a boat fathometer, of unknown manufac-

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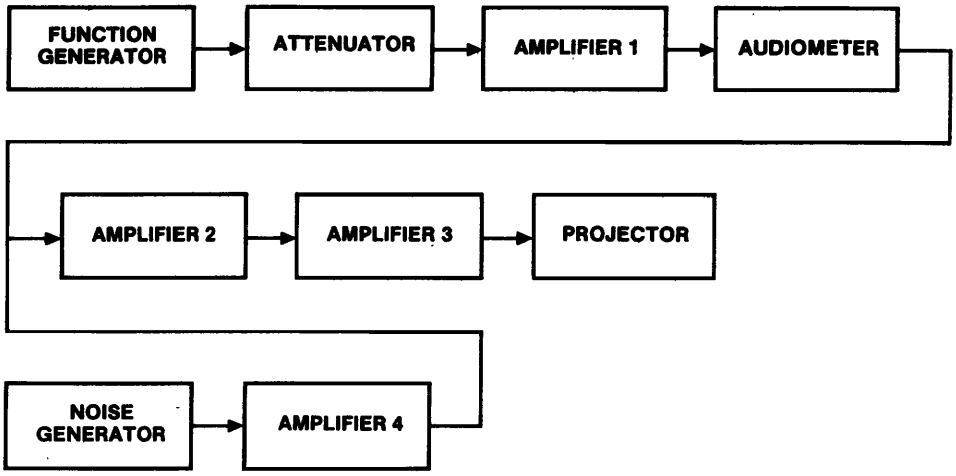

FIG. 1. Block diagram of the electronic apparatus.

ture, but having the typical resonance of such a transducer at 200 kHz, was used. Transducers, speaker, and bite plate were mounted in a line 60 cm from the side of the pen. The spectral levels of the three projectors are shown plotted in Fig. 3.

All calibrations were made using a Bruel & Kjaer (B&K) model 8103 hydrophone mounted on the bite plate during calibrations. The B&K hydrophone fed into a B&K type 2635 charge amplifier, and signals were recorded and analyzed using an H.P. model 356A dynamic signal analyzer. Data were collected using the same psychometric staircase method used by Johnson (1968).

The choice of step size for collecting the data is an important consideration. Johnson (1967) used 1-dB steps and found variations in threshold measurements done on different days to vary by 5 or more dB. White *et al.* (1978) used 5-dB steps and also reported 5- to 10-dB variations not uncommon in thresholds measured days or months apart. Awbrey *et al.* (1988), using a different data collection procedure, reported similar variations. For whatever reasons, these animals do not respond consistently to a given threshold intensity level to better than plus or minus several dB. White *et al.* (1978) measured each threshold from one to seven times. Their data show an average standard deviation of ± 3 dB for thresholds measured more than once. The standard error of the mean, of course, decreases inversely with the square root of the number of measurements, so the number of repetitions of a measurement is at least as important for accurately determining thresholds as step size.

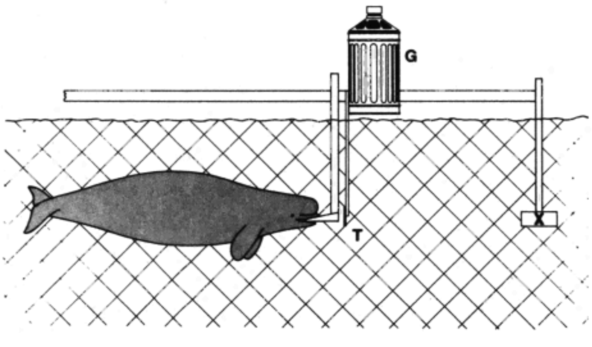

FIG. 2. Physical layout of the experiment: G is the garbage can in which the Cerwin-Vega speaker was mounted, X is the location of the other two transducers used, and T is the target the whale had to touch with the bite plate to respond. The distance from bite plate to projector was 2 m.

In selecting step size, other factors are also important. Working at sound intensities near threshold appears to be stressful to the animal, and there is the problem of maintaining behaviors over extended periods. Interposing random catch trials where the subject is rewarded for not responding when no stimulus is presented, is helpful in maintaining behavior as well as an essential test of the correctness of the animals responses. But, it is important to reduce the stimulus to threshold intensity quickly and keep it there as briefly as possible for the good of the animal's health and for behavior maintenance. In view of all these considerations, a data collection procedure similar to that of White *et al.* (1978) was adapted, i.e., 5-dB steps, at least five up–down reversals at threshold, and four or more repetitions of the measurement with no more than two measurements made in one day with the same stimulus.

The three projectors used produced noise spectra that were far from flat over much of the frequency range of interest. Because of this, four threshold measurements were made using each projector at each common frequency over frequency bands where there was overlap between projectors. In each case, thresholds were calculated as averages of all the measurements. Probable errors were calculated assuming the measurements to be statistically independent.

II. EXPERIMENTAL RESULTS

Absolute thresholds in the presence of bay noise were measured first to insure that the experimental animal had normal hearing. Thresholds were measured at 32 frequencies between 40 Hz and 125 kHz. Between 5 and 100 kHz, the thresholds were masked by bay noise. Thresholds from 40 Hz to 4 kHz, which were not masked, extend and confirm earlier data (White *et al.*, 1978 and Awbrey *et al.*, 1988) and are shown in Table I. The threshold at 125 kHz was 99 ± 4 dB, which is in good agreement with the previously obtained values for the beluga whale's upper hearing limit. Using the combined data of White *et al.* (1978) and Awbrey *et al.*

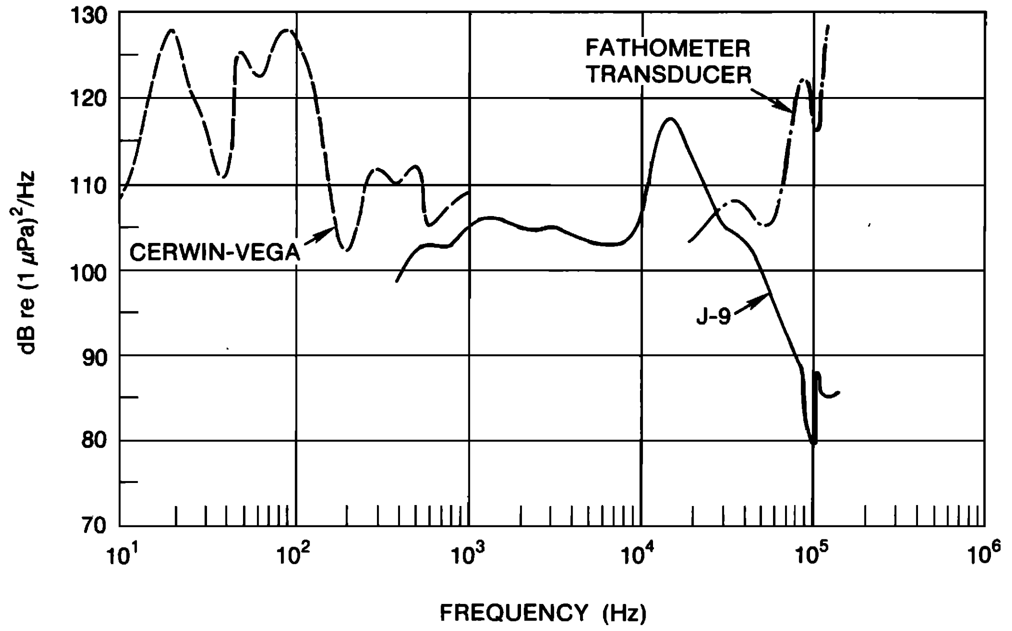

FIG. 3. Noise spectrum levels for the three projectors used.

(1988) and those of the present experiment, we find a least-squares fit to these combined data between 40 Hz and 50 kHz to yield: threshold (dB *re*: 1 μPa) $= 192 \pm 4 - (32 \pm 1) \log (f)$, where f is the frequency in hertz, with a coefficient of coorelation of 0.97.

Masked thresholds were measured at a single noise level for each of the three sound projectors used. In each case, the noise level was set at a magnitude equal to or greater than any absolute threshold level in the frequency band for which the projector was used. Because the projectors did not produce flat noise spectrums in the water, masked thresholds were estimated by integrating the energy in the noise spectra as a function of bandwidth and equating this energy to the tonal energy measured at threshold. This was done using the dynamic frequency analyzer. The estimated critical ratios are shown plotted in Fig. 4. The reason that no measurements are reported for frequencies between 200 and 300 Hz is that the Cerwin-Vega speaker produced harmonics in this band that were high enough in intensity to be detected more readily than the primary frequency.

TABLE I. Absolute tonal thresholds for frequencies from 40 to 4000 Hz in dB *re*: 1 μPa.

Frequency (Hz)	Threshold (dB *re*: 1 μPa)
40	140 ± 3
50	139 ± 3
60	131 ± 4
80	133 ± 5
100	127 ± 4
300	108 ± 4
400	107 ± 4
500	105 ± 4
600	100 ± 4
800	103 ± 4
1000	102 ± 4
1500	96 ± 3
2000	95 ± 3
3000	83 ± 6
4000	81 ± 3

III. DISCUSSION

The effects on our results due to the lack of "whiteness" of the noise spectra produced by our projectors are hard to determine. Bilger and Hirsh (1956) used noise bandwidths that were considerably wider than a critical band and with 54-dB/oct cutoffs, and they found that critical ratios can be calculated accurately on the slopes of the noise, providing the masking level was not too high. Greenwood (1961) used noise bands that were narrower than a critical band and with very steep sides. Greenwood's data show the thresholds outside the noise band dropping off at rates somewhat greater than 54 dB/oct, which we assume is the shape of the sides of critical bands. In the present case, the noise spectra sometimes have large variations within a critical band, which does not fit either the Bilger and Hirsh (1956) or the Greenwood (1961) cases. What we have done is interpret the definition of critical ratio in a slightly more general way than is customarily used. We have calculated critical bands by assuming that a critical bandwidth contains an equal amount of energy to that of the just masked tone regardless of the masking noise's spectral shape. This way of calculating critical ratios gives the same results for flat spectra as does dividing the masked tone energy by the energy per hertz of the noise spectra and appears to be reasonable since the critical ratios measured at the same frequencies with projectors projecting very different noise spectra agree to within our experimental accuracy.

Plotted in Fig. 4, along with the critical ratios from the present experiment, are those measured by Johnson (1968) and Moore and Au (1982). Our data do not show an increase in critical ratios at the lower frequencies as do the human data, although the precision of the present measurements may not be great enough to show such an effect. The

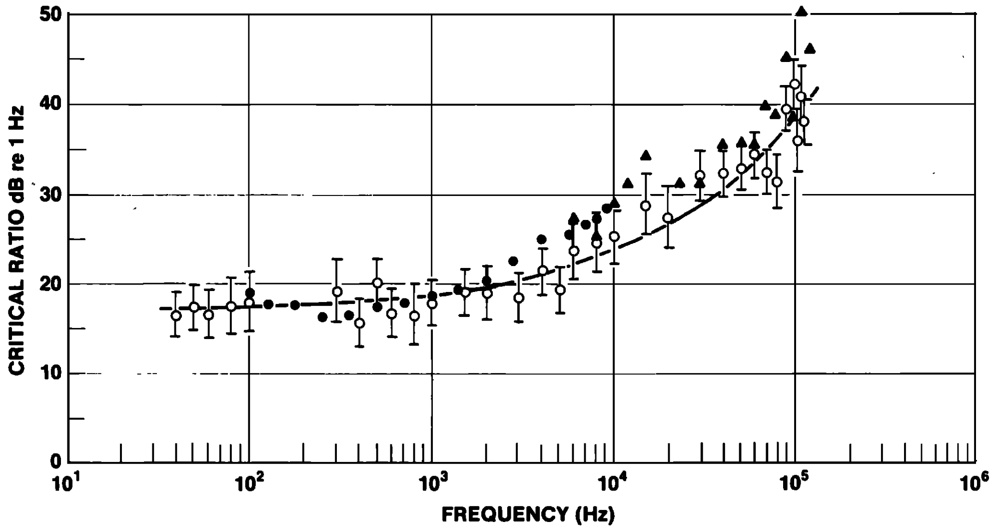

FIG. 4. The open circles give the critical ratio values for the present experiment; the triangles give the averaged data from Johnson *et al.* (1968) and Moore and Au (1982). The solid curve is a plot of the least-squares fit to the beluga's data and is described in the text. The errors indicated are probable errors.

solid line in Fig. 3 represents a least-squares fit to the equation: 10 log (critical ratio) $= a + bf^{1/2}$, where f is the frequency in hertz. This analysis yielded values of 16.7 ± 0.6, 0.070 ± 0.003, and 0.94 for a, b, and r^2. Similar analysis of the combined data taken by Johnson (1968) and Moore and Au (1982) for *Tursiops truncatus* gives volumes for a, b, and r^2, respectively, of 19.8 ± 1.5, 0.075 ± 0.007 and 0.89. Analyzing the human data in the same way, one obtains 15.0 ± 0.5, 0.14 ± 0.01, and 0.94, for a, b, and r^2. This analysis indicates the critical ratios of the beluga to be about 3 dB smaller than those of the bottlenose dolphin. The uncertainty of the critical ratio difference increases with frequency and the difference is not significant at the higher frequencies.

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