Echolocation: high-frequency component in the click of the Harbour Porpoise (*Phocoena ph. L.*)

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Besides the already known low-frequency components of the Phocoena echolocation pulse, a narrow-band pulse of 0.1-msec duration, with the main energy between 110 and 150 kHz and a source level of 40 dB *re* 1 μbar at 1 m has been found. The properties of this pulse can explain how wires below 1-mm diam can be detected by echolocation. The results are consistent with the hypothesis that the emission is restricted to a narrow beam.

Subject Classification: 16.6.

INTRODUCTION

The ability of a blindfolded Harbour porpoise to avoid thin wires in a maze has been investigated by Busnel, Dziedzic, and Andersen (1965), and Busnel and Dziedzic (1967). They found that avoidance was near perfect for wires above 0.5 mm, while performance deteriorated rapidly for smaller wires. Detection of the wires was assumed to be by echolocation. The low-frequency sound emission of *Phocoena* however, appears to be unsuitable for the wire-detection problem, as well as for the more natural problems of detecting fish, etc. The sound emission ("clicks") as described by Busnel, Dziedzic, and Andersen (1963); Busnel, Dziedzic, and Escudie (1969); and Schevill, Watkins, and Ray (1969), appear to be narrow-band sounds with the main energy in the 2-kHz region. The intensity is given as 1 μbar at 1 m. A calculation (for details see discussion) of the intensity of the echo of such a sound from wires of 0.5 mm in diameter at 0.5 m distance indicates a return level in the order of −100 dB//1 μbar. This is 65 dB below the absolute threshold at 2 kHz for *Phocoena* (Andersen, 1970). As the duration of the click is only 2 msec, and the threshold estimates were obtained with long duration tones, it is appropriate to raise the threshold figure by 40 dB, as per experimental results of Johnson (1968a), obtained from the Bottlenosed porpoise (*Tursiops truncatus*). Although many approximations and assumptions are involved in the estimation of the intensity of the echo, it is evident that an intensity, that is more than 10 orders of magnitude below the estimate of the threshold makes echolocation by means of the described clicks unlikely as an explanation of the maze performance.

The main reason for the low echo return is due to the large ratio between the wavelength of the sound (75 cm) and the diameter of the wire (0.05 cm), in which case Rayleigh's fourth power law of scattering applies. Consequently it was decided to record the click of *Phocoena* with instrumentation sensitive to higher frequencies in order to test the possibility of the presence of very high-frequency components. The previous investigations had been restricted to 50 and 10 kHz, respectively.

I. MATERIAL AND METHODS

The recordings were made in a 9×5×1 m tank (for details see Andersen, 1970). The experimental subject was a male subadult porpoise about $1\frac{1}{2}$ to $2\frac{1}{2}$ years old. He had been in captivity for nine months prior to this investigation and was considered a healthy animal. The animal had previously been subjected to operant conditioning and was for the present purpose trained to swim between three hydrophones in a setup explained later on. When passing the hydrophones the animal emitted click series as always when new objects are placed within the tank. Another subadult male was present in the tank during some of the recordings but was not engaged in the experiment.

Since the measurements took place over the period of a year, the instrumentation varied from time to time. Basically, recordings were made on Lyrec TR47 four-track instrumentation recorders with a dynamic range of 35 dB (unweighted) at 0.7% 3rd harmonic distortion and upper 3 dB limits at 125 and 250 kHz, respectively. Hydrophones were Brüel & Kjær 8100, Atlantic Research LC 32 and Dyna Empire TR 147. Preamplifiers were Brüel & Kjær 2606 and 2607 measuring amplifiers, plus a specially made battery operated preamplifier. The LC 32 and 8100 hydrophone were calibrated individually by Brüel & Kjær. The hydrophone calibration procedure is described by

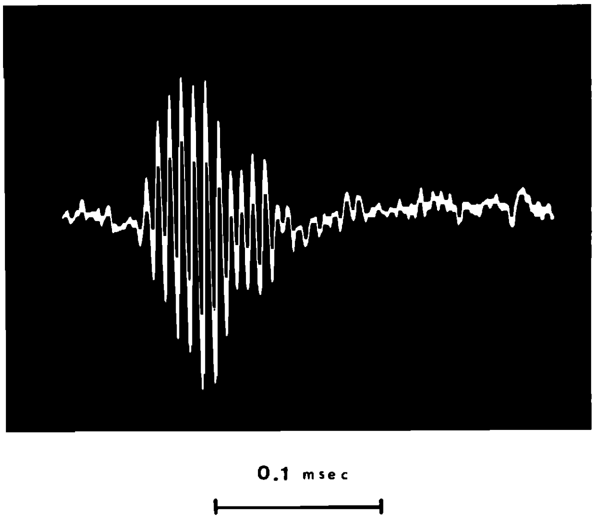

FIG. 1. Oscillogram of the high-frequency component of a *Phocoena* click. Hydrophone: Brüel & Kjær 8100.

Levin (1973). In the frequency range of interest to this paper, tone bursts of 0.6 msec were used. The remaining equipment was calibrated at the recording site by means of a Brüel & Kjær 2010 heterodyne analyzer and a 2305 level recorder. The response of the entire system for one of the recording channels is given in Fig. 2(a).

Estimates of the transient response for the 8100 hydrophone used to record the clicks in Figs. 1 and 3 were obtained in two ways. (1) From a theoretical Laplace model with two double complex poles and one double, complex zero (Cassel, 1966). The response of this model to a Dirac pulse was found to have a component at about 150 kHz and one at about 60 kHz. The 150-kHz component was negligible after 20 μsec. (2) The frequency response of the hydrophone was simulated with suitable filters at scaled down frequencies. This system was then excited with what corresponds to a 50-nsec duration, 1.5-nsec rise-time pulse. The transient response obtained this way conformed closely with the one obtained mathematically.

The transient response of the remaining equipment was obtained directly and found to be of no significance compared to that of the hydrophone. The 8100 hydrophone at 150 kHz is omnidirectional within 3 dB in the *XY* plane. In the *XZ* plane, the total variation of sensitivity is within 30 dB. The average maximum slope is 0.5 dB per degree.

The three hydrophones were suspended as corners in a triangle with sides of approximately 1 m. They were all located 0.4 m below the water surface. A 35-mm solenoid-operated camera was located approximately 3 m above this array. All three hydrophones were within the field of view of the camera. A digital timer was also in the camera field. The camera was operated remotely and a pulsing unit connected to the shutter recorded the taking of each frame on the fourth channel of the recorder. The digital timer was synchronized with the starting of the tape and it offered an additional means of identifying the photographs. This system enabled the position of the porpoise to be linked to a specific recorded signal.

To obtain recordings from the "instrumented" part of the tank, the animal was trained to enter the recording area and emit pulses. Also, food was thrown into the recording area, and the sound emission preceding food intake was recorded. An observer, with monitoring headphones, triggered the camera whenever he judged the clicking animal to be within the desired area.

Analyses of the clicks have mainly been by oscillography, using a Hewlett Packard 1201 A storage oscilloscope. Spectrograms of the clicks were prepared by transferring at reduced speed to a tape loop on a Revox F 36 recorder a part of the recording. For each revolution of the loop a segment containing the signal was applied to a slowly scanning waveanalyzer (Brüel & Kjær 2010) by means of a gate circuit (Brüel & Kjær 5549). The output of the waveanalyzer was stored in a peakhold circuit, (Brüel & Kjær 2425) while being graphically recorded (Brüel & Kjær 2305), whereupon the peakhold circuit was reset in preparation for the next cycle. Since the spectrograms of Fig. 2 were made with logarithmic frequency scale to facilitate comparison with the audiogram, an automatic bandwidth-changing program was chosen with the output compensated to indicate the power in a 1-Hz-wide band over the entire scale. The changeover frequencies are readily identifiable in Fig. 2 due to unavoidable transients during switching. The effective analyzing bandwidths are given in Fig. 2(a).

II. RESULTS

The results consist of tape recordings of click trains, 18 of which allow for estimations from the photographs of distance from and bearing to the three hydrophones.

A. The Waveform

Preliminary experiments, using only a hydrophone, amplifier, and a fast sweeping oscilloscope, clearly showed that a powerful high-frequency component was indeed present. Subsequent analyses (Fig. 1) of the tape recordings showed this component to be made up of what appears to be a gated sine wave of seven to more than eleven cycles, with the trailing edge often being hard to define (possibly due to multiple path transmission). The period of the cycles within a pulse range from 7.3 to 9 μsec in LC 32 recordings and 6.4 to 7 μsec in the 8100 hydrophone recordings. The latter result is probably due to "filtration" by hydrophone resonance at 150 kHz. In the LC 32 recordings, the maximum frequency and amplitude usually is found

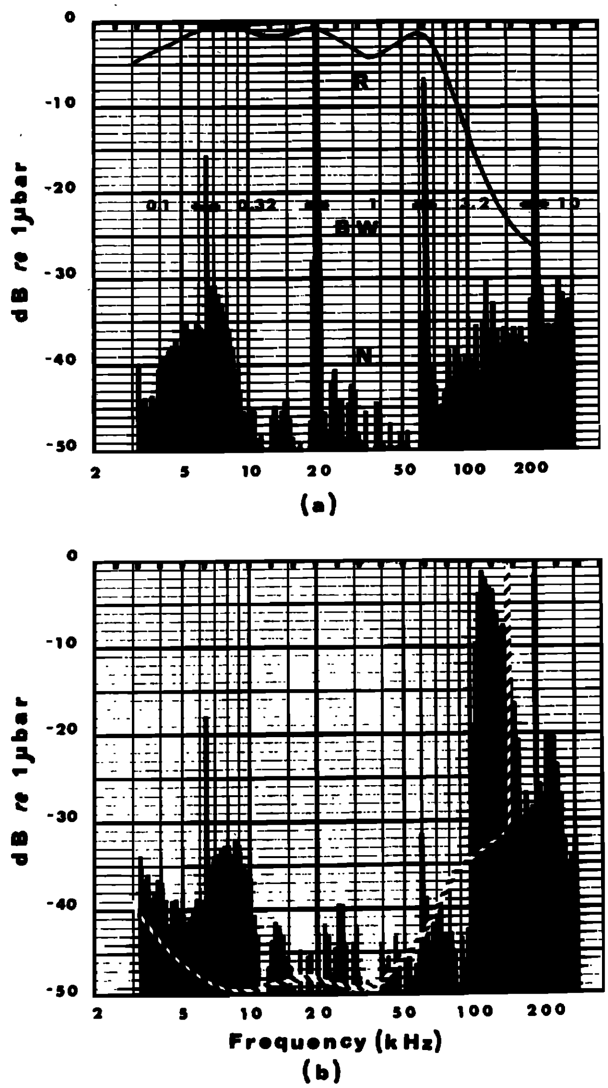

FIG. 2. (a) *R*—Over-all frequency response of recording and analyzing equipment. Hydrophone: LC 32. BW: Analyzing bandwidth, kilohertz. N: Spectrum level of background noise, referred to sensitivity at 120 kHz. Window: 400 μsec. (b) Spectrum level of *Phocoena* click at 0.5 m from the hydrophone [analyzing conditions identical to those in (a)], and *Phocoena* audiogram (redrawn from Andersen, 1970).

within the first two or three cycles of the pulse. Due to the limitation in bandwidth of the recording instrumentation and ambiguity as to start of the pulse the rise time cannot at present be given. Pulse duration has an order of magnitude of 100 μsec, which is more than five times the transient response of the 8100 hydrophone.

The peak pressure for 12 click trains, where distance between animal and hydrophone is known from the photographs and where the hydrophone is seen at an angle of 30° or less, relative to the direction of the head of the porpoise, average 40 dB *re* 1 μbar, referred to 1 m; the range is from 32 to 49 dB.

B. The Spectrum

Figure 2 shows the spectrum of a *Phocoena* click as well as the characteristics of the recording and analyzing system. The "true" spectrum of the click is obtained by subtracting the noise spectrum of Fig. 2(a) from the click spectrum of Fig. 2(b) and weighing the result according to the response curve. The (small) differences between the spectra below 10 kHz have been found to be an instrumental artefact. The remaining differences are real. It thus follows that the bulk of the energy of the click is concentrated between 100 and 160 kHz. Significantly, below 100 kHz where hearing sensitivity is at maximum [Fig. 2(b)] the click is not distinguishable from the noise.

The low-frequency component of the *Phocoena* click has been described in detail [Busnel, Dziedzic, and Andersen (1963); Busnel, Dziedzic, and Escudie (1969); and Schevill, Watkins, and Ray (1969)] and is not covered by the analyses presented here. Due to the low dynamic range of instrumentation recorders and the directional properties of the high-frequency part (see below) the high- and low-frequency components of the click cannot always be identified in the same pulse train. However, whenever a clicking animal is passing the hydrophone arrangement within 1 m and at the same time heading towards one of the hydrophones, both components can readily be identified and separated by filtering. It thus appears that the much shorter high-frequency component is emitted within the first cycle of the relatively long lasting low-frequency component.

C. Directionality

The experimental setup does not allow determination of the radiation pattern of the pulse. It was found, however, that whenever the animal viewed a hydrophone at an angle exceeding 30° (estimated from the photographs), the high-frequency component usually was absent. When present, examination of the time relationships between the signal in the three recording channels have shown the signal as being reflected from the walls of the tank, or otherwise inconsistent with the animal as the source and the signal propagated directly to the hydrophone. In no case has it been possible to identify the position of the animal and record the high-frequency component on two hydrophones simultaneously. However, the difference between the signal level at the "illuminated" hydrophone and the noise level at the expected time of arrival of the same signal at one of the other hydrophones at approximately 90° from the rostrum of the porpoise has been established in five cases and found to range from 15 to 27 dB. Besides indicating that the difference between the level straight ahead and at 90° in one specific case was greater than 27 dB, this observation explains why it has not been possible to track the porpoise by simple triangulation, based on time of arrival of the click on the three hydrophones. Also, the low-frequency component is unsuitable for this purpose, possibly due to phase distortions during propagation in the shallow tank. Difference in radiation pattern between the low- and high-frequency component is demonstrated in Fig. 3, in which the two components have been separated by filtering. The oscillogram pattern is interpreted as being the result of scanning head movements, assuming omnidirectional emission of the low-frequency and narrow-beam emission of the high-frequency component.

The possibility remains that the differences observed are due to the hydrophones deviation from omnidirectionality (see p. 1369). However, only rather dramatic, relative motions in the vertical plane could account for results as in Fig. 3, if directionality of the combined porpoise–hydrophone system is assumed to be exclusively that of the hydrophone.

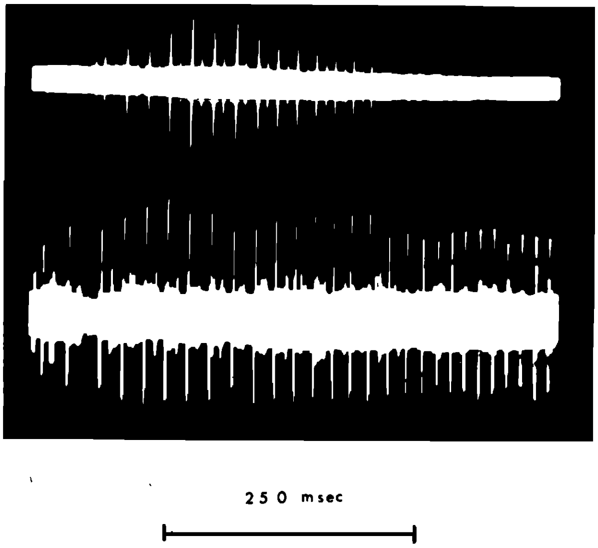

FIG. 3. Oscillogram of a *Phocoena* pulse train. Upper trace filtered through a bandpass filter, centered at 140 kHz, lower trace filtered through a bandpass filter, centered at 2 kHz. Filter slopes: 24 dB/oct. Hydrophone: Brüel & Kjær 8100.

III. DISCUSSION

The limited spectral distribution of the power of the click (Fig. 2) readily explains why the high-frequency component has not been detectable with the instrumentation used by previous investigators of *Phocoena* sounds. The figures obtained for the frequency and source level of the high-frequency component in the *Phocoena* click can be used to estimate the audibility of the backscattered intensity from the metal wires in the maze experiment by Busnel, Dziedzic and Andersen (1965). The backscattering cross section of the wire has been obtained according to an equation given by Bowman *et al.* (1969), p. 109:

$$I_s = I_0 \sigma / 4\pi r^2,$$

where $\sigma = (9\pi^2/4k)(ka)^4$, $k = 2\pi/\lambda$, I_0 is the intensity of the emitted pulse at the wire, I_s is the backscattered intensity at distance r, r is the distance between the porpoise and the wire, a is the diameter of the wire, σ is the backscattering cross section of the wire when $\lambda \gg a$, and λ is the wavelength of the sound pulse.

The threshold of the porpoise is estimated from the audiogram (Andersen, 1970), and the relation between absolute threshold and duration of tone pulses is assumed to be similar to that of the Bottlenosed porpoise (Johnson, 1968a). It turns out that at 0.5 m from a 0.5-mm wire the echo intensity of a 130-kHz pulse of 40 dB *re* 1 μbar at 1 m is −12 dB *re* 1 μbar. The short tone adjusted threshold is −8 dB *re* 1 μbar.

Thus according to these estimates (which admittedly are of a very crude nature) hearing threshold and echo intensity for the high-frequency component are of the same order of magnitude at threshold of detection. A similar estimate has been made for echolocating bats by Griffin (1957), who obtained an echo intensity of 46 dB SPL. If the bat audiogram (Dalland, 1967) and the short-tone correction (Johnson, 1968a) are taken into consideration, it appears that also in the bat the estimates of hearing threshold and echo intensity at detection threshold are within the same order of magnitude. While serving the purpose of showing a similarity of the limits of detection performance by echolocating bats and porpoises, the figures are not interpreted as evidence for an exclusive direct relationship between detection, backscattered intensity, and short-tone threshold.

Whether the well known low-frequency component of the *Phocoena* click has a significance of its own or merely is a by-product of the generation process of the more powerful high-frequency component remains to be seen. It appears that the more omnidirectional properties of the low-frequency part could have communicational value as the porpoise is not forced to "face" its audience. On the other hand, the low level and relatively short duration of the 2-kHz pulse makes this signal audible only at very close range.

While it has been argued that in delphinid echolocation there seems to be no overlap between the emitted and the received pulse (Evans, 1967), Dziedzic (1967) makes an exception for *Phocoena* at a distance of less than 90 cm (based on the properties of the 2-kHz pulse). With the evidence for the 130 kHz, 0.1-msec pulse presented here, it is suggested that *Phocoena* in respect to the overlap problem is grouped among the other odontocetes.

The narrow-band 130-kHz pulse appears to be different from any other cetacean pulse reported, notably from the continuous spectrum of the *Steno* click (Norris and Evans, 1967). At present, the only other known odontocete with a monochromatic click is the narwhal (Watkins *et al.*, 1971). However, the frequency within the narwhal pulse is lower than that of *Phocoena* by one order of magnitude and variations of up to one octave within a click series are occasionally found. Such variation has not appeared in the sample of the more than 50 *Phocoena* click series, so far analyzed.

On the possible advantage of the very special pulse of *Phocoena* for echolocation, attention is drawn to the relative ease by which the pulse can be filtered out from noise. In the porpoise a suitable filter could be visualized according to the concept of critical bands, shown by Johnson (1968b) to be present in *Tursiops* up to 100 kHz where the critical bandwidth was in the order of 10 kHz. Thus it appears that *Phocoena* concentrates the main power of its pulse within very few, possibly a single critical band. The significance of this is that sound power has been shown to be integrated separately in each critical band (Feldtkeller and Zwicker, 1956).

A possible disadvantage of the narrow-band nature of the pulse could be the lack of "color" of the echoes by differential reflection at the target. Such color or echo fine structure may provide the cues for the discrimination by echolocation of vespertilionid bats between real and dummy mealworms (Griffin *et al.*, 1965), but the bat pulse covers the range from 100 to 40 kHz, while the *Phocoena* pulse can be considered as monochromatic or at the most covering 20% of an octave. It should be realized that, in the present paper analyses have been made only on pulses recorded in a situation, where the problem of the porpoise presumably have been that of ranging rather than that of identifying. It is conceivable that for identification purposes pulses of different frequencies could be employed, as suggested by the scattered occurrence of such pulses throughout our recordings.

Finally, attention is drawn to the rather remarkable energy distribution of the pulse relative to the audiogram of the species [Fig. 2(b)]: The energy is concentrated just below the upper hearing limit, in a frequency band which is about one octave above best sensitivity. Apart from the effect of pushing the Rayleigh scattering zone to the highest frequencies possible with the available auditory system, we have at present no suggestions for the possible functional significance of this kind of pulse, which appears to be the only item in the repertoire of our experimental animal when homing in on food, etc.

[*Author's Note.* Since the completion of this paper, we have become aware of an article by Dubrovskii, Krasnov, and Titov, "On the Emission of Echolocation Signals by the Azov Sea Harbor Porpoise," Sov. Phys. Acoust. **16**, 444–447 (1971). The paper describes a variety of ultrasonic *Phocoena* clicks and concludes that this porpoise uses echolocation signals in the frequency range up to at least 100 kHz. The present investigation corroborates and in some respects complements the Russian paper, since approach and methodology are different.]

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