Classification of electronically generated phantom targets by an Atlantic bottlenose dolphin (*Tursiops truncatus*)

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Animal behavior experiments require not only stimulus control of the animal's behavior, but also precise control of the stimulus itself. In discrimination experiments with real target presentation, the complex interdependence between the physical dimensions and the backscattering process of an object make it difficult to extract and control relevant echo parameters separately. In other phantom-echo experiments, the echoes were relatively simple and could only simulate certain properties of targets. The echo-simulation method utilized in this paper can be used to transform any animal echolocation sound into phantom echoes of high fidelity and complexity. The developed phantom-echo system is implemented on a digital signal-processing board and gives an experimenter fully programmable control over the echo-generating process and the echo structure itself. In this experiment, the capability of a dolphin to discriminate between acoustically simulated phantom replicas of targets and their real equivalents was tested. Phantom replicas were presented in a probe technique during a materials discrimination experiment. The animal accepted the phantom echoes and classified them in the same manner as it classified real targets. © *2000 Acoustical Society of America.* [S0001-4966(00)01205-4]

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INTRODUCTION

The biological sonar of bats and dolphins is characterized by outstanding discrimination and classification capabilities, even under difficult conditions such as high noise and cluttered environments (Nachtigall and Moore, 1988; Au, 1993). In order to investigate the echolocation system of these mammals, behavioral experiments are valuable to measure perceptional thresholds and to examine the classification of certain target features.

Echo stimuli used in behavioral experiments to study discrimination and classification capabilities of echolocating animals have been from either real targets (mainly in dolphin experiments) or simplified electronically generated echoes (mainly in bat experiments). Both types of stimuli present their own disadvantages. The complex interdependence between the physical dimension and the backscattering characteristics of a target make it difficult to independently control echo parameters such as amplitude, highlight number, duration, and phase relationships. The inability to precisely and independently control echo parameters can severely limit what can be learned from real-target experiments. Past experiments with electronically generated echoes often lacked proximity to reality. The echoes were often ''canned'' and could not change according to the animal's echolocation signal or consisted only of a few wavefronts and could not simulate reality (Roverud, 1989; Mogdans *et al.*, 1993). This project utilizes an echo-simulation method that combines the advantages of both approaches to echo stimuli presentation (this method was first described in Aubauer and Au, 1998).

I. ACOUSTIC SIMULATION OF UNDERWATER TARGETS

The target impulse response $h(t)$ can be used to describe the acoustic backscattering process of targets (Aubauer and Au, 1998). The backscattered target echo $e(t)$ is the convolution of the incident signal $s(t)$ with the target impulse response and can be expressed in both the time and the frequency domain

$$e(t)=h(t)*s(t)=\int_{-\infty}^{\infty} h(\tau)\cdot s(t-\tau)\,d\tau, \tag{1}$$

$$E(\omega)=H(\omega)\cdot S(\omega). \tag{2}$$

With these equations, it is possible to determine either the impulse response of a real target or, if the impulse response is known, to simulate an echo of a real target for any incident signal. For the echo simulation, the incident signal has to be measured with a hydrophone and transformed via convolution or Fourier and inverse Fourier transformation into the ''phantom echo,'' which is played back to the echolocating animal with a projector hydrophone. Since a hydrophone placement at the same position where the phantom target appears would cause an unwanted echo overlap of the hydrophone and the phantom target, both receiver and projector hydrophones have to be positioned separate from the phantom target location. Consequently, the signal transmission path, which causes propagation time delay and attenuation, has to be considered in the target impulse response. Moreover, the inverse hydrophone transfer function can be included, to equalize the hydrophone characteristic and achieve a flat frequency response. The phantom-echo generation can be done either in the time or frequency domain and can be executed by digital signal processing. In

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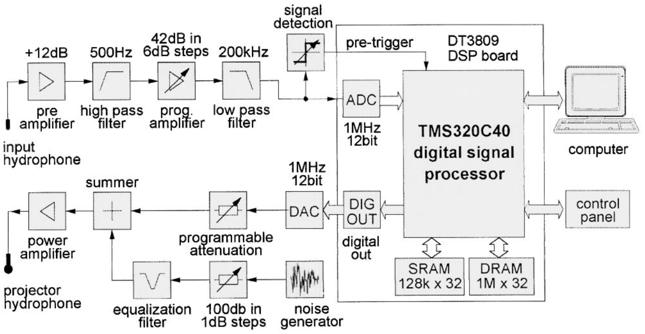

FIG. 1. Block diagram of the phantom-echo generator.

general, the introduced target impulse response represents a target only from one aspect and is dependent on the orientation of the target relative to the sound transmitting and receiving location.

The phantom-echo generator (PEG) was implemented on the DT3809 digital signal-processing (DSP) system from Data Translation plugged into a PC (Aubauer and Au, 1998). The signal input and output and a hand-held control panel was realized externally and connected through diverse analog and digital interfaces to the DSP system. A block diagram of the PEG is shown in Fig. 1.

The input signal received with the Brüel & Kjær 8103 hydrophone was amplified and filtered with a 500-Hz high-pass and a 200-kHz low-pass filter before going to the analog input of the DSP system. A pretrigger signal was generated when the analog input signal exceeded the user-set input threshold. The DSP system was able to collect pre- and post-triggered data before and after the trigger event, so even the beginning of a signal, before it exceeded the trigger level, was acquired. The input signal was digitized with a sampling rate of 1 MHz and 12-bit resolution. The signal transformation based on the fast convolution method was programed on the digital signal processor, which allowed the generation of a phantom echo of 512 digital samples in less than 3 ms. After a certain time delay, which determined the distance of the phantom target from the echolocating animal, the phantom echo was put out with the same sampling rate and resolution as the input signal was acquired. The system was calibrated prior to the experiment so that phantom echoes returning to the animal had the same amplitude as echoes from a real target (Aubauer and Au, 1998). The spherical ITO1042 hydrophone from International Transducer Corporation served as projector hydrophone; its transmit sensitivity curve is shown in Fig. 2. To compensate for the hydrophone frequency characteristics, the phantom echo was digitally pre-equalized on the DSP system for an overall frequency response of 20 to 250 kHz within ±1 dB. The system was controlled from the PC and a hand-held control panel (Aubauer and Au, 1998).

II. TARGET IMPULSE RESPONSES

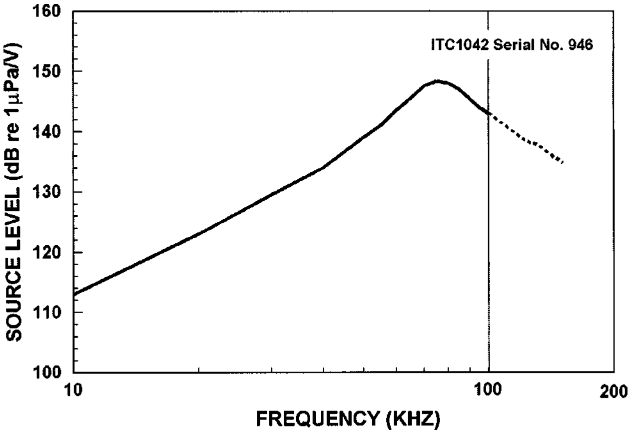

FIG. 2. Transmit calibration curve for the ITC1042. The instrument's curve was plotted out to 100 kHz (solid line). Values up to 150 kHz (dashed line) were obtained from manufacturer's standard curve.

The theoretical evaluation of the acoustical impulse response of real targets is difficult, because of the propagation capability of both longitudinal and transversal waves in solids, and is only possible under simplifying assumptions (Neubauer, 1986; Shirley and Diercks, 1970). The impulse responses of certain, especially useful targets were therefore determined experimentally. Spheres of 7.62-cm diameter were selected for the experiment because of their aspect-independent but diverse impulse responses and echoes. The impulse responses were measured in a tank filled with seawater. Two different hydrophones were used for signal projection and echo measurement. The piezoceramic multielement transducer WAU1 (custom-made hydrophone) was used for projection of a delta pulse that was bandlimited between 40 and 260 kHz. The incident signal and the target echo were received with the Brüel & Kjær 8103 measuring hydrophone. The measured echo signals were averaged 2000 times and background clutter was subtracted, in order to improve the signal-to-noise ratio to about 52 dB.

The impulse responses of the hollow water-filled steel (HS), the solid steel (SS), and the solid brass sphere (SB) were determined by recasting Eq. (1) and are shown in Fig. 3 on the left side. The outside diameters of all spheres were 76.2 mm (3 in.). The hollow steel sphere had a wall thickness of 1.9 mm and was filled with seawater. The target

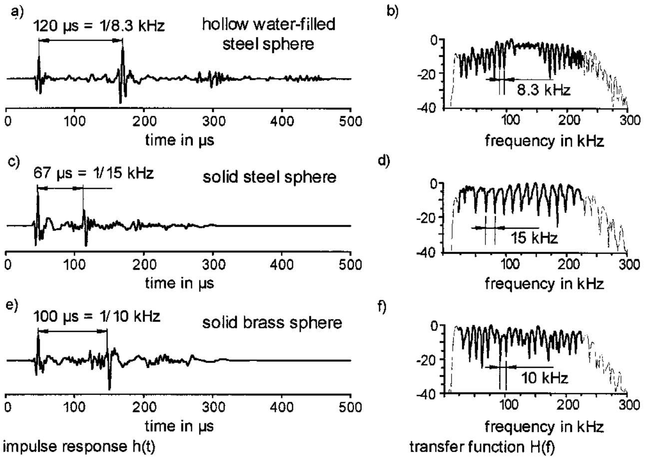

FIG. 3. Target impulse responses of the HS, SS, and SB sphere (a), (c), (e). Target transfer function of the HS, SS, and SB sphere (b), (d), (f). Dashed lines indicates the frequency band limitation of the transfer functions due to the insufficient transmitting characteristic of the measuring system and not of the sphere itself.

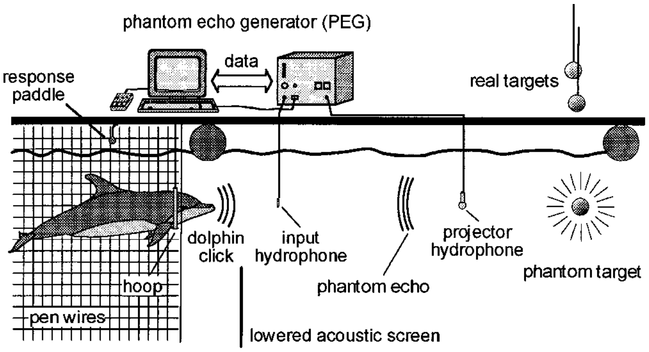

FIG. 4. Experimental configuration showing the dolphin positioned in the hoop, the hydrophone and target placement, and the phantom echo generator.

transfer functions, the Fourier transformations of the impulse responses, are shown on the right side of Fig. 3. Theoretically, the transfer function should not drop off with frequency. Since we used broadband, but nevertheless bandlimited transducers, the drop-off in frequency is a reflection of transducer limitations.

All spheres had a relatively flat and even target transfer function with a distinct periodic ripple structure. The target impulse responses showed clearly separated highlights that corresponded to the wavefronts of the target echoes. The frequency distance between two ripples in the transfer function was about 1 over the time interval between the main peaks of the impulse response. Both solid spheres had relatively similar impulse responses. The impulse response of the stainless-steel sphere was compressed relative to the brass sphere due to the higher sound velocity in steel (Mason, 1958). The hollow water-filled steel sphere was clearly different. The impulse response was significantly longer and the transfer function showed a relatively flat frequency area from 115 to 155 kHz. The target strengths of the SS, SB, and HS spheres were $\mathrm{TS}_{\mathrm{SS}}=-37.5\,\mathrm{dB}$, $\mathrm{TS}_{\mathrm{SP}}=-37.0\,\mathrm{dB}$, and $\mathrm{TS}_{\mathrm{HS}}=-39.8\,\mathrm{dB}$, respectively.

Phantom echoes determined with the help of these target impulse responses matched the real target echoes for several tested incident signals very well (for a figure showing both real and phantom echoes, see Aubauer and Au, 1998). The cross-correlation coefficient between the phantom and real echo measured in the water tank was between 0.95 and 0.99 for all three spheres and several signals (Aubauer and Au, 1998). This result indicates that the backscattering process of these spheres can be simulated with the target impulse response in high quality.

III. EXPERIMENTAL CONFIGURATION AND PROCEDURE

The phantom-echo classification experiment was conducted in Kaneohe Bay, Oahu, Hawaii with a 12-year-old adult female *Tursiops truncatus* named BJ. During the experiment, the subject was stationed in a floating pen with a hoop window to open water (see Fig. 4). Targets and phantom echoes were presented in front of the hoop window outside of the pen, in order to avoid echo overlap from the target and the pen construction. An echolocation trial began with a single target in the water, an acoustic screen in the raised position, and the dolphin at its intertrial position in front of the trainer with its back to the hoop. When given a hand sign, the dolphin swam 30 ft across the pen and stationed in the hoop approximately up to its pectoral fins, so that its head protruded out of the pen (see Fig. 4). After the animal was properly positioned in the hoop (the animal was monitored with an underwater camera), the acoustic screen was lowered. This cued the animal to start echolocating. The echolocation clicks were recorded with the receiving hydrophone, transmitted to the PEG, and stored for further analysis. During a phantom trial, both targets were out of the water and the echolocation signals were transformed into phantom echoes that were played back to the animal with the projector hydrophone (a target was moved in and out of the water first, so a lack of splashing on the phantom trials would not cue the animal). The PEG setup ensured that the propagation delay and the amplitude of the phantom echoes corresponded to the echoes of the real targets. The depths of the hoop center, both hydrophones, and the targets were at 1.16 m. The *hoop–receiver hydrophone* distance was 2.00 m, the *hoop–projector hydrophone* distance was 6.07 m, and the *hoop–target* distance was 7.60 m. The hydrophones were mounted on 5-mm wooden rods. The spheres were held in a close-fitting nylon net attached to a nylon monofilament line extended with a pulley system back to the trainer's station. An acoustic baffle was placed exactly midway between the dolphin and the targets to eliminate surface reflections.

The dolphin was trained to respond to a target presentation in a go/no-go procedure (Schusterman, 1980). A correct go response corresponded to the presentation of the standard target, which was designated as the solid stainless-steel sphere. A correct no-go response corresponded with the presentation of all other targets. The go responses were limited to a time interval of 6 s starting with lowering the acoustic screen and extending to the time the dolphin's rostrum passed completely out of the hoop station (the dolphin then had to touch the response paddle). A correct no-go response required the dolphin to stay in the hoop for 6 s.

One or two sessions were conducted per day. Each session consisted of 50 trials—25 standard and 25 comparison trials. The order of trials was balanced using modified Gellerman tables (Gellerman, 1933). During the training period only real targets were presented. Blocks of real target discrimination sessions SS versus HS and SS versus SP were conducted. Correct responses were reinforced with a whistle (bridge) and a subsequent fish reward. Incorrect responses were not reinforced and did not delay the next trial. The animal achieved a performance at the SS versus HS task of 99.3%-correct responses. Of the 0.7% incorrect responses, 0.2% were misses and 0.5% were false alarms. At the SS versus SB discrimination task, the dolphin achieved 95.2%-correct responses. Of the 4.8% incorrect responses, 4.2% were misses and 0.6% were false alarms. The total number of trials was 400 and 500, respectively.

The animal was then switched to a partial reinforcement schedule, in which the animal did not receive any reinforcement for a set number of trials (eight trials) per session. These nonreinforced trials produce no reward whether the response was correct or incorrect. Nonreinforced trials were spaced irregularly within the trial sequence of the session (e.g., trials 4, 7, 17, 23, 32, 36, 40, and 47 out of a 50 trial session were nonreinforced). The SS sphere was the standard target and the SB sphere was the comparison target. Four standard and four comparison trials out of 50 trials were designated as nonreinforced trials prior to a session.

The nonreinforced trials served as a preparation to the introduction of nonreinforced probe trials. In the probe technique, which has been used in other target echo recognition tasks (Hammer and Au, 1980), a small number of probes are presented which share some characteristics with the baseline targets, but systematically differ. These probes can be reinforced or nonreinforced. In this experiment, phantom trials were presented as nonreinforced probe trials. Probes were not reinforced because we didn't want to give the animal any feedback, to avoid the possibility of training her to respond in a certain way to the phantoms.

As soon as the discrimination performance of the animal stabilized on a correct-response level higher than 90%, phantom replicas of the standard (PSS) and the comparison sphere (PSB) replaced two of the nonreinforced standard and two of the nonreinforced comparison trials. A session of the first phase of the phantom target classification experiment thus consisted of 21 reinforced standard (SS), 2 nonreinforced standard (SS), and 2 nonreinforced phantom standard presentations (PSS). The same applied to the comparison presentations (21 reinforced real comparison (SB), 2 nonreinforced real comparison (SB), and 2 nonreinforced phantom comparison (PSB) trials).

In the second phase of the phantom target classification experiment, further comparison targets were introduced and no phantom comparison stimuli were presented. This strategy was chosen in order to test the hypothesis that the dolphin was doing a standard versus nonstandard (*A* versus not-*A*) task, not a standard versus a comparison (*A* versus *B*) classification. A session in phase 2 of the experiment consisted of 21 reinforced standard (SS), two nonreinforced standard (SS), and two nonreinforced phantom standard presentations (PSS). The nonstandard trials consisted of 21 reinforced SB and four nonreinforced nonstandard presentations. These four trials consisted of two solid brass (SB), one solid aluminum (SA), and one solid nylon sphere (SN) presentations (all spheres were 76.2 mm in diameter). The nonreinforced trials were selected randomly prior to a session.

IV. RESULTS

The results of the first six sessions of the phantom classification experiment (phase 1) are shown in Fig. 5. The dolphin's performance at the standard trials (SS) is shown in the upper half and the comparison trials (SB) in the lower half of the diagram. The probe trial results of the phantom standard (PSS) and comparison (PSB) stimuli are shown next to the respective real-target performance. On average, the real standard target was identified 92% correct (8% misses) and the real comparison target at 84% (16% false alarms). In comparison, all phantom replicas of the standard sphere (PSS) were classified as standards, where 11 phantoms of the comparison sphere (PSB) were assigned to the comparison class. Only one phantom comparison target was misclassified as the standard.

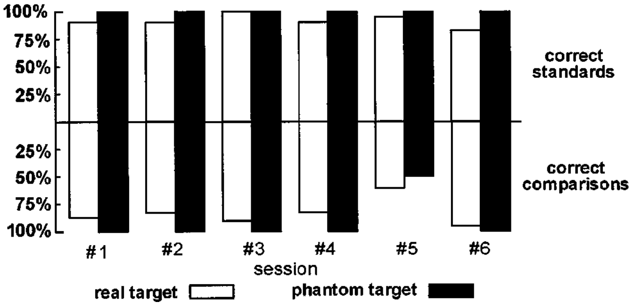

FIG. 5. Dolphin's performance in the first phase of the classification experiment. Standard presentations are shown in the upper half, comparison in the lower half of the diagram. The number *n* denotes the number of trials for each target class per session.

The misclassified phantom trial in session #5 was consistent with a relatively poor performance on real comparison stimuli. After the first half of the session we noticed the camera cable hanging in front of the hoop station, which probably served as a distraction to the animal. The cable was removed and the performance of the animal immediately returned to normal in the second half of session #5.

In addition to the response, the latency time for a go response on a real (SS) and phantom standard trial (PSS) was measured (Fig. 6). The latency time is the time interval between lowering the acoustic screen and starting the trial, and the time when the dolphin leaves the hoop for touching the response paddle (rostrum completely out of the hoop). The mean of the go latency in the first phase of the experiment is clearly below the no-go threshold of 6 s and similar for both real (3.0 s) and phantom standard trials (2.8 s). The standard deviation of the SS trials is under 0.6 s.

The results of the second phase of the classification experiment are shown in Fig. 7. Percent-correct responses are drawn for each target class separately. The dolphin got 93% of the standard SS trials ($n=299$) correct and reported 100% of the phantom PSS probes ($n=26$) as standards. The brass comparison sphere SB was reported 89% correct, whereas 77% of the aluminum sphere probes and 100% of the nylon sphere probes (both $n=13$) were classified as comparison stimuli. The mean latency of correct reported SS trials was 3.0 ± 0.7 s and on the PSS trials 2.3 ± 0.5 s.

V. DISCUSSION

Both phases of the experiment clearly show that the dolphin accepted the artificially generated phantom echoes in an

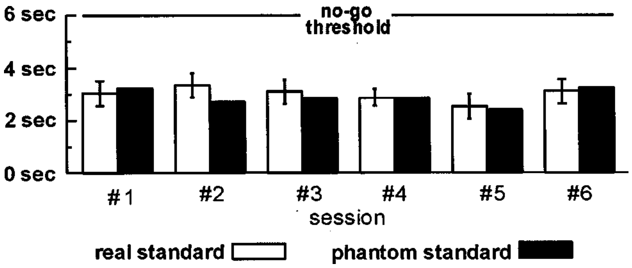

FIG. 6. Go-latency time in the first phase of the classification experiment.

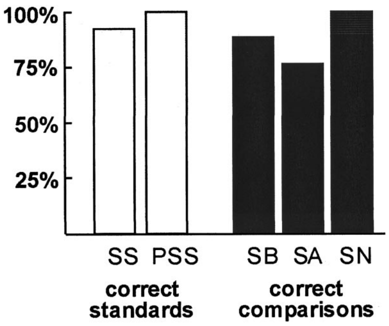

FIG. 7. Correct responses in the second phase of the classification experiment. SS denotes the solid stainless-steel standard sphere, PSS the phantom replica of SS, SB the solid brass sphere, SA the solid aluminum sphere, and SN the solid nylon sphere. The number *n* denotes the number of trials for each target class.

echolocation task. Furthermore, the phantom replicas of the standard and comparison targets were reported in the corresponding real-target class except for one trial, where the animal may have been disturbed. It can be assumed that the dolphin classifies the phantom echoes in the same manner as the echoes of the real-target models. Since further real-target comparison probes (aluminum and nylon) in the second phase of the experiment are reported with high confidence in the comparison class, it can be assumed the dolphin responded in an A/not-A fashion.

It is not clear why the dolphin reported the phantom standard probes PSS with a slightly higher confidence in the real standard class than the real standard targets SS itself. The dynamics of the backscattering process may give a better understanding of these experimental results. Echolocation measurements with artificial dolphin sonar showed that the phantom and the real-target echo behave slightly differently when the target or the projection hydrophone are moving. Because of the mass of the metal spheres, the targets are able to move independently from the surrounding water, whereas the relatively light and small hydrophones move almost perfectly with the water current. Therefore, waves and currents caused by wind and boat traffic caused the real-target echo to fluctuate in amplitude more than the phantom echo, i.e., the phantom echoes were more stable than the real echoes. However, this does not imply that the phantom echo was not perceived as coming from a real target.

There was a slight difference in procedure between phantom echo and real-target trials. On a phantom-echo trial, a real target was lowered into the water and then raised before the target screen was lowered and the dolphin began echolocating the phantom target. On a real-target trial, the real target was lowered into the water and remained there for the dolphin to inspect. Therefore, the only difference was the subsequent removal of the real target just prior to a phantom presentation. However, all targets were introduced and extracted from the water very carefully to minimize any extraneous noise.

From our observations of the animal's performance, it seemed as if the dolphin accepted the phantom echo as coming from a real target. Our experiment was not set up to determine whether the dolphin could distinguish between phantom echoes and real echoes; it was designed to determine how the dolphin would classify phantom stimuli. The results of this experiment indicate that the dolphin classified the echoes from the phantom targets in the same manner as the echoes from real targets.

ACKNOWLEDGMENTS

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