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# Auditory masking of tonal and conspecific signals by continuous active sonar, amplitude modulated noise, and Gaussian noise in killer whales (*Orcinus orca*)

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## ABSTRACT:

Continuous active sonar is thought to mitigate severe acoustic impacts due to its lower sound pressure level compared to pulsed active sonar typically used by world navies. However, due to its almost continuous duty cycle, continuous active sonar could have a higher potential for auditory masking. Here, we evaluate the auditory masking potential of several noise types including a recording of continuous active sonar, amplitude modulated noise, and Gaussian noise, on signal detection in two killer whales. Signals were either a 1.5 kHz pure tone or a recording of a broadband burst-pulse killer whale call. For the 1.5 kHz tone, all noise types resulted in statistically significant masking, however, there was a release from masking of approximately 13 dB for the amplitude-modulated noise. When the killer whale call was the signal, the whales employed an off-frequency listening strategy where the whales were able to detect frequency components of the signal that did not directly overlap with the noise. However, this strategy was less useful for the continuous active sonar noise due to its broadband harmonic structure. Continuous active sonar has spectral features that considerably overlap with those of killer whale calls, making this type of noise an effective auditory masker. © 2024 Acoustical Society of America. <https://doi.org/10.1121/10.0028626>

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## I. INTRODUCTION

Killer whales (*Orcinus orca*) are the largest delphinid odontocetes and are found throughout the world's oceans, with highest concentrations in higher latitudes and colder regions (Heyning and Dahlheim, 1988). These animals often live in life-long matrilineal groups (Baird, 2000), where sound is paramount for coordinating group behavior, identifying group membership, conveying individual identity, and facilitating navigation and predation (Ford, 1989). As cooperative hunters, killer whales have been observed coordinating group behavior while employing a wide range of hunting strategies (Hoelzel, 1991; Jefferson *et al.*, 1991). This coordination is based not only on visual cues, but also on acoustic communication. Vocal signals of killer whales include clicks, whistles, and burst-pulse sounds (Ford, 1989). Whistles and burst-pulse sounds do not always have a clear acoustic distinction (Murray *et al.*, 1998) and thus, the term “call” herein will be used to refer to any vocalization that is not a biosonar click. Killer whale calls typically have fundamental frequencies between 500 Hz and 15 kHz

often with multiple harmonics that can extend above 40 kHz (Holt *et al.*, 2011). Source levels of call types are on average between 140 and 155 dB re 1  $\mu$ Pa, but can exceed 175 dB re 1  $\mu$ Pa and can vary depending on ambient noise levels (Holt *et al.*, 2011; Miller, 2006).

Anthropogenic noise has been identified as a major threat to killer whales including the endangered southern resident population, whose home range extends along the west coast of North America between British Columbia and northern California (NOAA Fisheries, 2022). Sources of anthropogenic noise include, but are not limited to shipping, recreational boating, marine construction, seismic exploration, and naval operations (Hildebrand, 2009; Richardson *et al.*, 1995). Negative impacts from anthropogenic noise include changes in behavior leading to a decrease in individual fitness (Southall *et al.*, 2011), auditory masking of biologically relevant sounds (Branstetter and Sills, 2022; Erbe *et al.*, 2016), temporary and permanent changes in hearing sensitivity (Finneran and Branstetter, 2013; Kastak *et al.*, 2008), stress, pain, and death (Parsons, 2017). Navy sonar has been implicated in well-documented mass strandings of Cuvier's beaked whales (*Ziphius cavirostris*), Blainsville's beaked whales (*Mesoplodon densirostris*), and northern

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minke whales (*Balaenoptera acutorostrata*) (Parsons, 2017). Conventional pulsed active sonar (PAS) operates on a low duty cycle with relatively high source levels (Curé *et al.*, 2021). This is the type of sonar thought to be responsible for the documented mass strandings. Continuous active sonar (CAS) has a much higher duty cycle that approaches a continuous source but with lower source levels compared to PAS. Thus, the application of CAS is thought to mitigate the more severe acoustic impacts associated with PAS operations. However, due to the almost continuous nature of CAS, negative impacts from auditory masking may be more likely to occur (von Benda-Beckmann *et al.*, 2021).

Auditory masking occurs when one sound or aggregates of multiple sounds, often called noise, interfere with the detection, discrimination, or recognition of another sound, typically called a signal. Auditory masking has been studied under controlled laboratory conditions, most frequently with pure tone signals and white noise (Fletcher, 1940). For example, the detection of pure tones in broadband noise have been measured to estimate critical ratios in at least five odontocete and ten pinniped species (Branstetter and Sills, 2022; Jones *et al.*, 2023). The critical ratio (CR) can be defined as

$$CR = S_m - N, \quad (1)$$

where  $S_m$  is the level of a masked tonal signal at threshold expressed in dB re 1  $\mu$ Pa, and  $N$  is the spectral density of the noise centered on the signal expressed in dB re 1  $\mu$ Pa<sup>2</sup>/Hz. Critical ratios have been used to predict auditory masking in a variety of scenarios with some degree of success, especially if the noise type is broadband, steady-state, and with few amplitude fluctuations. However, for more complex noise and signal types, more complicated models of masking are required (Branstetter *et al.*, 2013b; Branstetter and Sills, 2022; Cunningham *et al.*, 2014; Kastelein *et al.*, 2021; Sills *et al.*, 2017).

Most auditory masking studies have investigated tone detection masked by Gaussian noise of varying bandwidths [e.g., Au and Moore (1990) and Branstetter *et al.* (2017b)]. Continuous active sonar is a tonal sound so typical masking patterns associated with Gaussian noise maskers (e.g., critical ratio or critical bands) may not accurately predict the masking effects of CAS. Tone-on-tone masking experiments with bottlenose dolphins (*Tursiops truncatus*) demonstrate that more masking occurs when the tone signal is similar in frequency to the tone masker (Johnson, 1971). Masking has also been studied with natural tonal noise such as ice squeak noise produced by pressure changes in oceanic ice (Branstetter *et al.*, 2013c; Branstetter *et al.*, 2016). In a study with bottlenose dolphins (Branstetter *et al.*, 2013c) auditory masking was more severe in ice squeak noise than any other masking noise tested, which included Gaussian, snapping shrimp, and comodulated noise. Subsequent experiments revealed that the elevated thresholds were likely due to the random frequency modulation pattern of ice squeak noise, in which the dolphin could hear the signal but misidentified

the signal as part of the background noise. In contrast, when frequency-modulated maskers were more predictable, detection thresholds were not elevated and were consistent with critical ratio predictions. The authors suggested that the elevated detection thresholds were a form of informational masking rather than energetic masking since the dolphin could likely hear the tonal signal but wrongfully classified it as part of the masking noise (Branstetter *et al.*, 2016).

The SOCRATES CAS signal is a frequency modulated (FM) hyperbolic upsweep, with start and stop frequencies of 1 and 2 kHz, respectively (von Benda-Beckmann *et al.*, 2021; Curé *et al.*, 2021). This particular CAS signal has a duration of 19s with a 1s off interval before repeating. There are also noticeable harmonics that extend above 15 kHz (Fig. 1). The spectral components of the CAS signal overlap in frequency with killer whale vocalizations to the extent that it has apparently elicited an anti-predator response in marine mammals exposed to the sound (Isojunno *et al.*, 2020). The frequency overlap also makes CAS a highly plausible candidate for auditory masking of killer whale communication signals.

The goal of the current study was to measure masked detection thresholds of a tone signal and a killer whale call (KWC) in the presence of CAS noise. Because propagated CAS can become an amplitude modulated (AM) complex masker (see Fig. 1), detection thresholds were also measured in the presence of AM noise, Gaussian noise, as well as when no noise was projected into the pool for comparison.

## II. METHODS

### A. Subjects

Two adult-male killer whales participated in this study, and both had extensive experience participating in hearing tests. Both had good species-representative hearing, with their audiograms and demographic data available in a previous publication (Branstetter *et al.*, 2017a). At the time of the current study, the two males' estimated ages were 26 years (whale C) and 17 years (whale E). The whales were housed in a 21 000 m<sup>3</sup> complex of interconnected pools at SeaWorld San Diego. The study followed a protocol approved by the Animal Care Review Committee at Sea World, as well as an Institutional Animal Care and Use Committee at the National Marine Mammal Foundation.

### B. Signal and noise generation

#### 1. Signals

The signal was either a pure tone or a recorded KWC. The pure-tone signal was a 1.5 kHz, 500 ms sinusoid with 10 ms linear onset and offset ramps to reduce spectral splatter. The frequency of the tone was set to the center frequency of the CAS noise so that the tone would be symmetrically embedded with respect to the frequency band of the CAS noise (see below). The playback rate for the pure tone was 50 kS/s. The KWC was recorded in northern Puget Sound (Washington State, U.S.A) from an individual

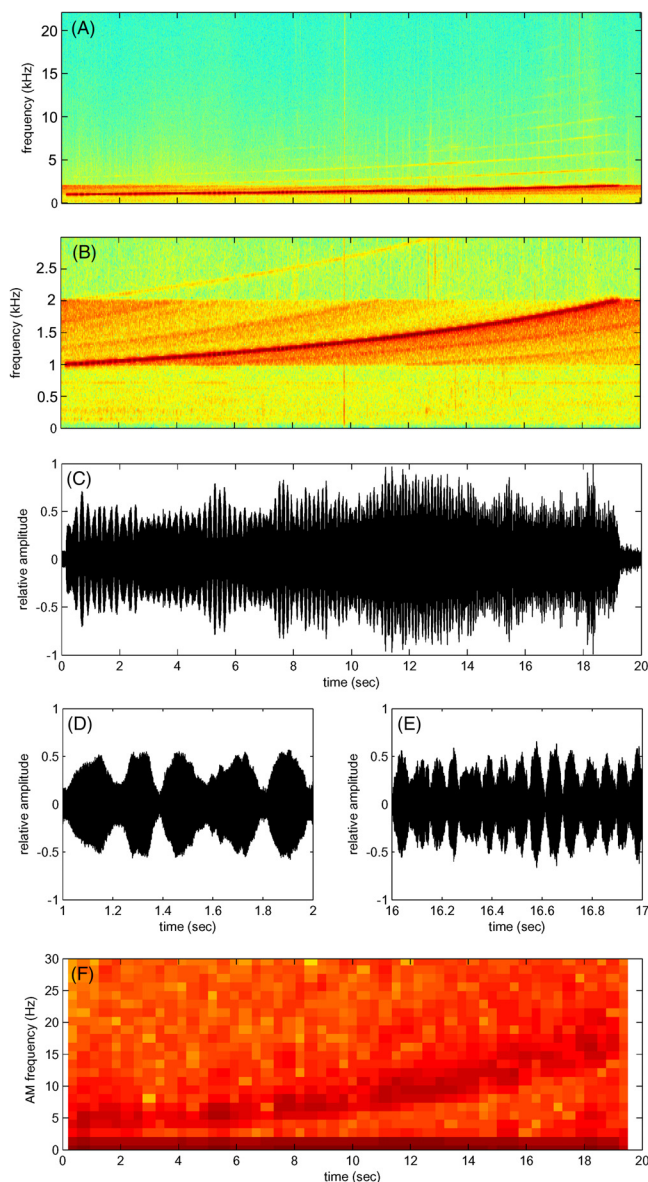


FIG. 1. (Color online) Spectrograms and waveforms of the SOCRATES continuous active sonar recorded in the field (Isojunno *et al.*, 2020). All panels display different aspects of the same 20-s recording. Panels (A) and (B) display spectrograms with different frequency ranges. Panel (C) is the time-amplitude waveform. Panels (D) and (E) display amplitude modulation for 1-s clips towards the beginning and end of the signal. Panel (F) displays a spectrogram of the CAS Hilbert envelope to illustrate how the AM rate increases from approximately 5 to 20 Hz.

of the Southern Resident population and is an exemplar of the “S1” call, a predominant call type of J-pod members (Ford, 1989); details about recording location, hardware and methodology can be found in Holt *et al.* (2011). The KWC was a 1295 ms, frequency-modulated burst-pulse with a fundamental frequency of approximately 1040 Hz and harmonics extending up to approximately 10 kHz. Figure 2 displays the KWC signal projected into the hearing test pool. The recording used for the KWC playback was sampled at 96 kHz, which was also the playback update rate. Onset-offset ramps of 10 ms were applied to the KWC recording to reduce spectral splatter.

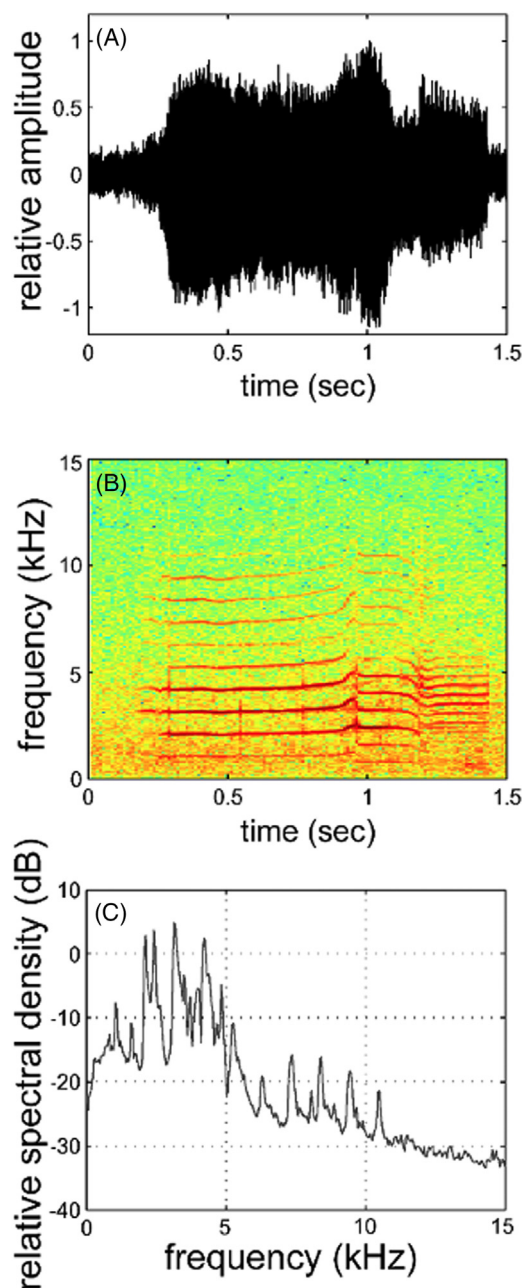


FIG. 2. (Color online) Waveform, spectrogram and spectral density of the playback of the killer whale S1 call recorded in the hearing test pool.

## 2. Noise types

Continuous active sonar, Gaussian, AM, and ambient pool noise (herein “no noise”) were used to mask the signals (see Table I). The CAS noise was an in-field recording of the SOCRATES CAS source used during a controlled exposure study (Isojunno *et al.*, 2020), recorded with a sampling rate of 44.1 kHz. The CAS noise was a hyperbolic FM upswEEP with a start and stop frequency of 1 and 2 kHz, respectively, with multiple harmonics that decrease in amplitude and extend above 15 kHz. The duration of the CAS was 19 s followed by a 1-s “off” interval. Onset-offset ramps of 10 ms were applied to CAS noise to reduce spectral splatter. The CAS noise is then repeated both in the

TABLE I. Parameters of signal and noise types. Signal levels (dB RMS re 1  $\mu$ Pa) varied to estimate detection thresholds. Noise types were Gaussian, continuous active sonar (CAS), and amplitude modulated (AM). The pressure spectral densities (PSD) for all noise types were presented at 90 dB re 1  $\mu$ Pa<sup>2</sup>/Hz. The CAS noise had an AM rate that swept upwards from approximately 5 to 20 Hz over the 19 s duration of the noise. The fundamental frequency of CAS also swept upwards from 1 to 2 kHz over the 19 s duration.

Signal	Frequency (kHz)	Duration (ms)	dB RMS	
Pure tone	1.5	500	variable	
Killer whale call	1.04–10	1295	variable	
Noise	AM rate (Hz)	Duration (s)	dB PSD	Bandwidth
Gaussian	none	continuous	90	1–2 kHz
CAS	5–20	19 on/1 off	90	1–2 kHz
AM5	5	continuous	90	1–2 kHz
AM20	20	continuous	90	1–2 kHz

recording and during playback. Although there is a 1-s off interval every 19 s, the off interval in the recording was full of reverberation and echoes. Figure 3 displays the CAS noise projected into the killer whale testing pool. The FM and AM features of the field recorded CAS are well preserved in the pool-playback version with some variations in overall amplitude. Because the CAS noise in the field recording overlapped with delayed and attenuated versions of itself (i.e., echoes), amplitude modulation occurs (see Figs. 1 and 3). The change in AM rates were inspected by spectrogram analysis (FFT length = 128, no overlap) of the Hilbert envelope of the CAS waveform. The Hilbert envelope  $E(t)$  of the time-domain waveform  $f(t)$  was calculated by

$$E(t) = \sqrt{h(t)^2 + f(t)^2}, \quad (2)$$

where  $h(t)$  is the imaginary part of the Hilbert transform of  $f(t)$ . The Hilbert envelope was then low-pass filtered (fifth order Butterworth with a cutoff frequency of 100 Hz) and resampled at 200 S/s (Cool Edit Pro 2.0, Syntrillium Software Corp., Phoenix, AZ). Amplitude modulation rates had a start frequency of roughly 5 Hz and gradually increased to approximately 20 Hz at the end of the signal [Figs. 1(F) and 3(F)]. Because CAS is amplitude modulated and AM noise can result in a release from masking (Buus, 1985; Kastelein *et al.*, 2021), sinusoidal AM noise, as well as Gaussian noise, were created for comparison purposes. Amplitude modulated noise was generated by multiplying an offset cosine function by broadband Gaussian noise ( $n(t)$ )

$$n_{am}(t) = \frac{[1 - \cos(2\pi f_m t)]}{2} * n(t),$$

where  $f_m$  is the modulation frequency,  $t$  is time, and  $n_{am}(t)$  is the amplitude modulated noise. Two AM frequencies were chosen: 5 Hz (AM5) and 20 Hz (AM20). Both AM noise types and the Gaussian noise were then bandpass filtered with a 32nd order Butterworth filter with start and stop frequencies of 1 and 2 kHz, respectively (Cool Edit Pro 2.0,

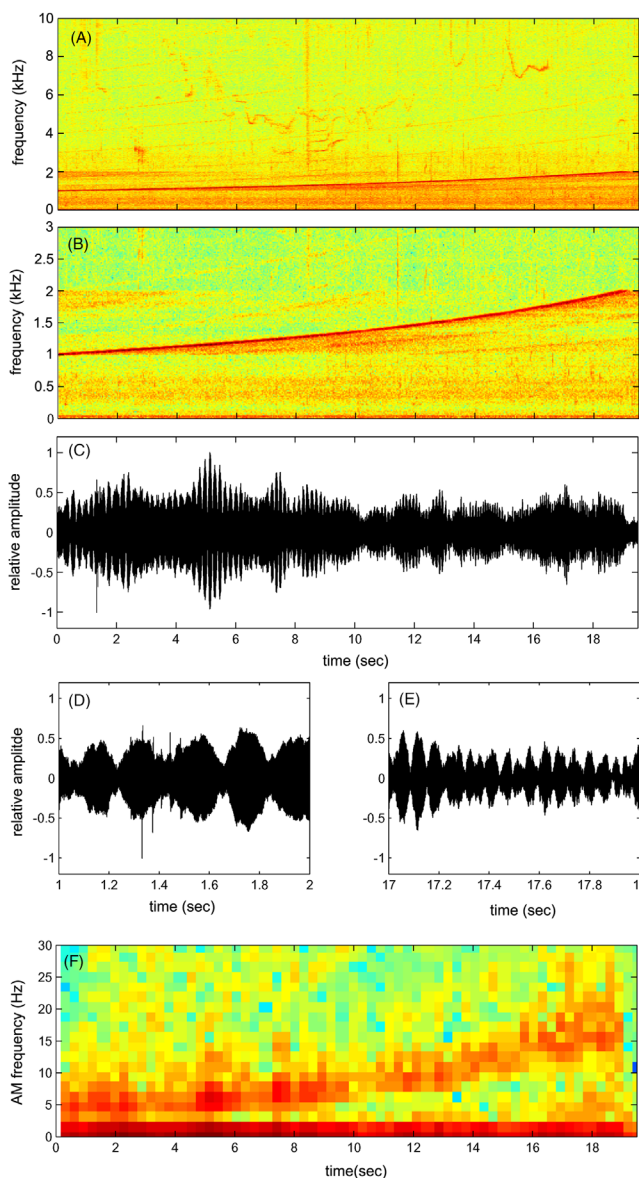


FIG. 3. (Color online) Spectrograms and waveforms of the CAS noise projected into the killer whale testing pool. This is the same sound file from Fig. 1 but recorded at the location of where the killer whale hearing tests occur. The frequency and amplitude modulation of the original recording are preserved well during pool playback. Panels (A) and (B) display spectrograms with different frequency ranges. Vocalizations from the SeaWorld killer whales in the adjacent pools can be seen in the spectrograms. Panel (C) is the time-amplitude waveform. Panels (D) and (E) display amplitude modulation for 1-s clips towards the beginning and end of the signal in panel (C). Panel (F) displays a spectrogram of the CAS Hilbert envelope to illustrate how the AM rate increases from approximately 5 to 20 Hz.

Syntrillium Software Corp., Phoenix, AZ), which were the start and stop frequencies of the CAS noise. Gaussian, AM5, and AM20 were all generated with a 5 s duration and were continuously looped during playback. Each file had a start and stop amplitude of zero to reduce onset-, offset-clicks. All noise types were sampled at 44.1 kHz. For the no-noise condition, noise was not projected from the underwater speaker and was therefore the ambient noise in the testing pool. Example measurements of ambient noise in the testing pool can be found in Branstetter *et al.* (2017a).

### 3. Stimuli presentation and calibrations

Pure tones and KWCs were generated with a 16-bit, National Instruments, USB-6343 multifunction DAQ device. All noise types were generated with the factory soundcard of the Dell Inspiron 15 3000 series. The noise types were manually attenuated (TDT PA5 signal attenuator; Tucker Davis Technologies, Alachua, FL), added to the signal (TDT SM5 Tucker Davis Technologies, Alachua, FL), amplified (Hafler P1000, Tempe, AZ), and projected into the water column with a Lubell LL916 underwater speaker (Lubell Labs Inc, Whitehall, OH). A digital filter was applied to each noise type to compensate for the frequency response of the projector, as well as multipath interference of the pool environment (Branstetter *et al.*, 2021). The Lubell speaker was hung from a gate separating the testing pool from a channel (Fig. 4). The animal's stationing device was constructed from welded aluminum. All points of contact with the metal gate were acoustically insulated with closed-cell neoprene to prevent sound conduction. Furthermore, the disk that the animal stations on was also insulated with closed-cell neoprene to prevent sound conduction and for the animal's comfort.

Signal and noise received levels were calibrated with a Reson TC4033 hydrophone (Teledyne Reson, Slangerup, Denmark) coupled to a Reson VP1000 pre-amp (Teledyne Reson, Slangerup, Denmark). The Reson TC 4033 was positioned at 57 cm from the tip of the stationing device (Fig. 4), which is the approximate midpoint between the whales' auditory meatuses during a hearing test. Signal calibrations

were performed by measuring both the input signal voltage generated by the computer and the resulting received level ( $\text{dB}_{\text{RMS}}$  re  $1 \mu\text{Pa}$ ), for all signal levels tested within a session, and then fitting a linear model to the data to obtain an input-output function (received level as a function of input voltage). For the 1.5 kHz signal,  $\text{dB}_{\text{RMS}}$  was calculated by converting the pressure spectral density ( $\text{dB}$  re  $1 \mu\text{Pa}^2 / \text{Hz}$ ) value at 1.5 kHz to an RMS equivalent value (Finneran, 2003). For the KWC, which is a broadband signal, the  $\text{dB}_{\text{RMS}}$  level was calculated within the frequency band of 500 Hz and 20 kHz. The validity of the linear model was tested before (pre-calibration) and after (post-calibration) a hearing test by measuring the mean difference between the predicted received levels from the model and the actual received level measured in the pool. If the absolute mean difference was greater than 6 dB for either the pre- or post-calibrations, data from that hearing test session were rejected from further analysis. This occurred only once.

The noise spectral density level for all noise conditions (except ambient pool noise) was 90 dB re  $1 \mu\text{Pa}^2/\text{Hz}$ . For noise calibrations, the average spectral density ( $\text{dB}$  re  $1 \mu\text{Pa}^2/\text{Hz}$ ) within the noise band was adjusted by manual attenuation to be within 1 dB of the desired level prior to the hearing test. The average was calculated from 100 ms samples within a 20 s window (the duration of the CAS recording). The noise was measured again after the hearing test and the session's data were rejected if the absolute difference was greater than 4 dB. This occurred only once. No attempt was made to characterize the entire sound field of the testing pool since these measurements would likely be altered in the presence of a large killer whale. The testing pool was a controlled environment with consistent low-ambient noise. Spectral density levels were typically between 60 and 40 dB (re  $1 \mu\text{Pa}^2/\text{Hz}$ ) between 1 kHz and 10 kHz. Noise measurements were recorded weekly and were visually (during signal and noise calibration) and aurally (during each hearing test via the same speaker used to listen to the whale's vocal response) monitored during testing. An example of the spectral density of the ambient noise can be found in Branstetter *et al.* (2017a).

Additional signal and noise recordings were made with a Soundtrap 300 HF (Ocean Instruments, Auckland, New Zealand) that was placed at the same location of the calibration hydrophone. The recordings were made with a sampling rate of 48 kS/s with the device's high-gain setting. The recordings occurred under the same conditions as calibrations and are representative of the acoustic stimuli the whales would receive. These recordings were conducted after the completion of the experiments to provide a comparison between the in-field and in-pool CAS recordings and to provide high-quality waveforms and spectrograms for this publication.

### C. Procedure

Behavioral hearing tests were conducted in an isolated medical pool at SeaWorld San Diego under identical

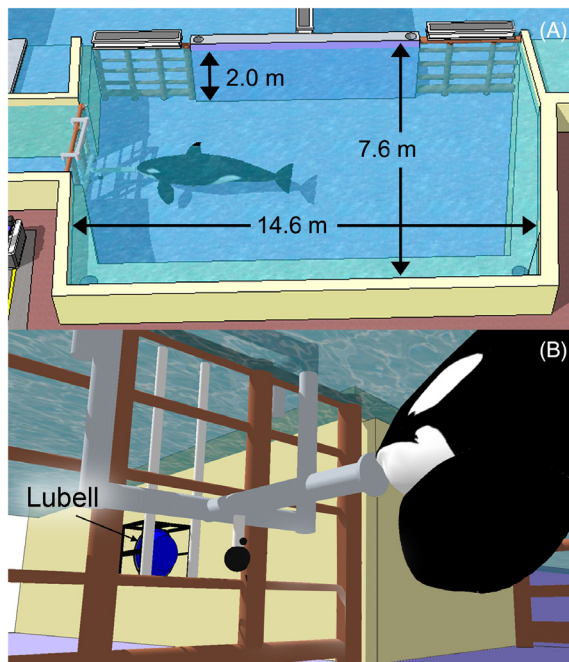


FIG. 4. (Color online) Testing pool and hearing test apparatus. (A) Hearing tests were conducted in an isolated pool 14.6 m long, 7.6 m wide, and 2.0 m deep. (B) The hearing test station was designed to keep the whales at a fixed distance from the sound projector. Adapted with permission from Branstetter *et al.* (2017a), *J. Acoust. Soc. Am.* **141**, 2387–2398. Copyright 2017, Acoustical Society of America.

conditions as [Branstetter et al. \(2021\)](#) using the same apparatus (Fig. 4). For each threshold estimation procedure, masking noise was turned on for the duration of a dive, defined as the interval between two breaths. The noise was turned off after each dive. In response to a hand signal from the trainer, the whale dove and stationed its rostrum on the stationing device, which was kept at a fixed distance of approximately 112 cm from the underwater speaker, and thus provided a constant sound received level with respect to acoustic transmission loss. Once stationed on the device, the whales typically exhaled for buoyancy control, which would signal the experimenter to begin a series of trials for that dive. The number of trials during a single dive was randomly varied between 1 to 10, by the computer software. A go, no-go response procedure was used, where the whale was trained to produce a “raspberry” vocalization if the whale heard a signal during a signal-present trial, or remain silent otherwise ([Branstetter et al., 2017a](#)). The raspberry vocalization was produced by forcing air from the blowhole to produce a low-frequency, embouchure-type sound. Thus, there was both an acoustic and a visual (bubble) indicator of the whale’s response. The acoustic response was monitored by a speaker attached to a listening hydrophone (Reson TC 4033). During each trial, there was a stimulus period (500 ms for the pure tone and 1.5 s for the KWC) followed by a 2-s response interval. There were no explicit trial indicators (i.e., stimulus, such as a light, cuing the whale that a trial was occurring). The fixed time window for behavioral response and the consistent inter-trial interval following the conditioned reinforcer served as the temporal marker for each audiometric trial. The timing of the signal relative to the noise freely varied and was dictated by the animal’s response latency, and the time required for the experimenter to log the animal’s response. Thus, the signal could occur in any portion of the noise with no predetermined probability. During the stimulus period, the whale was randomly presented with a signal-in-noise interval (signal trial), or noise-alone interval (catch trial) chosen at random (50% probability) by the computer software. Trainers had no knowledge of the trial types. If the whale responded correctly to the signal before the end of the response interval, an experimenter who was running the computer software would inform the trainer to produce a conditioned reinforcer (i.e., a whistle bridge) that provided feedback to the whale of its correct response and a “hit” was logged by the computer. If the whale failed to produce a vocal response, no whistle feedback was given, and a “miss” was logged. If a response occurred after the end of the response window (i.e., late response), a miss was logged. During a catch trial, if the whale remained silent, a whistle bridge was given, and a “correct rejection” was logged. If the whale produced a vocal response to a catch trial, no whistle bridge was given, and a “false alarm” was logged. In addition, any vocal response that occurred outside of the response window was logged as a false alarm. There was no inter-trial interval aside from the time required for the experimenter to key in the whale’s response on the computer, which typically was

less than 1 s. After one to ten trials were completed, another conditioned reinforcer was given, which was a sound produced by tapping a bucket lid on the wall (i.e., terminal bridge). This signaled the whale to end the dive and return to the trainer’s station for primary (fish) or secondary (ice cubes, snow, tactile rub down) reinforcement following a variable ratio with reinforcement variety schedule ([Lawrence et al., 2016](#)). This somewhat unconventional reinforcement strategy was sufficient to maintain stimulus control and consistent response bias in this study. Terminal bridges only occurred following a correct response, thus, dives never ended with an incorrect trial. The masking noise was turned off after the terminal bridge, which typically coincided with the animal rising to the surface for a breath of air.

A one-down, one-up, adaptive staircase procedure ([Levitt, 1971](#)) was used to titrate the level of the signal for each threshold measurement [see [Branstetter et al. \(2017a\)](#), Fig. 2]. For each threshold measurement, the level of the signal would typically start 15 to 20 dB above the whale’s estimated threshold. The initial descending step size was 5 dB but switched to 2 dB after the first reversal (miss) and remained 2 dB for all subsequent step sizes. A minimum of 11 reversals were completed during each session. Thresholds (i.e., the dB value where the whale can detect the signal 50% of the time), were calculated by averaging the last ten reversals. Replications for the same signal/noise combinations were performed on different days to reduce the influence of any confounding variables not directly related to the acoustic stimuli (e.g., daily motivation or attention). Data were rejected if (1) the FA rate exceeded 30%, (2) the standard deviation of reversals exceeded 3 dB, or (3) a total of 11 reversals failed to be acquired. False alarm rate was defined as the total number of false alarms divided by the total number of catch trials. The last three replications were used to calculate the average thresholds for each condition. Each killer whale participated in one to three sessions per day where each session was approximately 10 min in duration.

#### D. Analysis

Masked detection thresholds were transformed into critical ratios [Eq. (1)] and masking levels (ML) using Eq. (3). Although the definition of the critical ratio is often reserved for pure-tone thresholds masked by Gaussian noise, a more expansive operational definition is applied here where the signal is either the tone or the KWC and the noise is Gaussian, CAS, or AM. Masking level can be defined as the difference between the masked signal at threshold ( $S_m$ ) and the absolute detection thresholds (no-noise condition) of the same signal ( $S$ ), where

$$ML = S_m - S. \tag{3}$$

Masking levels normalize the level of a masked signal relative to the absolute detection thresholds of the same signal and are useful for comparing masked threshold for signals that have different absolute thresholds.

Data were analyzed with mixed effects models using the lme4 package (Bates and Maechler, 2009) in R (R Development Core Team, 2012). Signal thresholds were measured for each noise type (categorical variable) with several replications for each whale (repeated measures design). To avoid issues with pseudoreplication, the independent variable *whale* was modeled as a random effect while *signal* (tone or KWC) and *noise* (Gaussian, CAS, AM5, AM20, no noise) were modeled as fixed effects. The dependent variable was *threshold*. Models were fit using maximum likelihood and model comparisons were performed using a likelihood ratio test (LRT) of fixed effects. *Post hoc* Tukey tests were performed with the Estimated Marginal Means (emmeans) package (Lenth et al., 2023) in R.

### III. RESULTS

Data for whale C is presented in Fig. 5, top row [panels (A), (B), and (C)] while data for whale E is presented in the bottom row [panels (D), (E), (F)] (see Table II). Bar plots represent means for masked detection thresholds as a function of both signal and noise types, where black and white bars represent thresholds for pure tones and KWCs, respectively. Error bars in panels (A) and (D) represent standard deviations. Error bars were omitted for the other panels for clarity as noise conditions of the same type have the same standard deviation given that CR and ML are transformations of detection threshold data [e.g., CAS error bars in panel (A) would be the same for CAS in panels (B) and (C)]. Bars with the label CR represent detection thresholds based on critical ratio predictions from Branstetter et al.

(2021). The bar labeled “no noise” represents absolute detection thresholds when no noise is projected into the pool. In the no-noise condition, detection thresholds for the KWC (th = 75 dB, std = 1.53) were significantly lower than for the tonal signal (th = 93, sd = 2.65), [ $\chi^2(1) = 15.481$ ,  $p < 0.001$ ]. Both whales were likely more sensitive to the upper harmonics of the KWCs, resulting in lower detection thresholds compared to the 1.5 kHz pure tone.

Given the difference in sensitivity between the two signals, additional statistical tests were performed with masking levels [Fig. 5, panels (C) and (F)]. Overall, the KWC [Fig. 5, panels (C) and (F), white bars] resulted in lower MLs than the tonal signal [Fig. 5, panels (C) and (F), black bars] in the presence of every noise type tested [ $\chi^2(1) = 27.822$ ,  $p < 0.001$ ]. The main effect of noise type on MLs was significant [ $\chi^2(3) = 8.4774$ ,  $p < 0.037$ ]. *Post hoc* Tukey tests were conducted to compare MLs among all noise conditions with MLs for tones and KWC analyzed separately given the differences in sensitivities. Table III displays the resulting p-values for all *post hoc* tests. Black cells represent p-values that are statistically significant ( $p < 0.05$ ).

For the tone signal, all noise types resulted in a significant increase in MLs compared to unmasked (i.e., no noise) tone, as was expected. There was a significant release from masking for tone MLs in AM5 and AM20 when both MLs are compared to MLs for Gaussian noise. The release from masking for AM5 and AM20 was of 13.5 and 12.5 dB, respectively (Table IV). There was no significant difference between tone MLs masked by Gaussian and CAS even though tone MLs trended lower in the CAS condition for both whales. This insignificant result is questionable

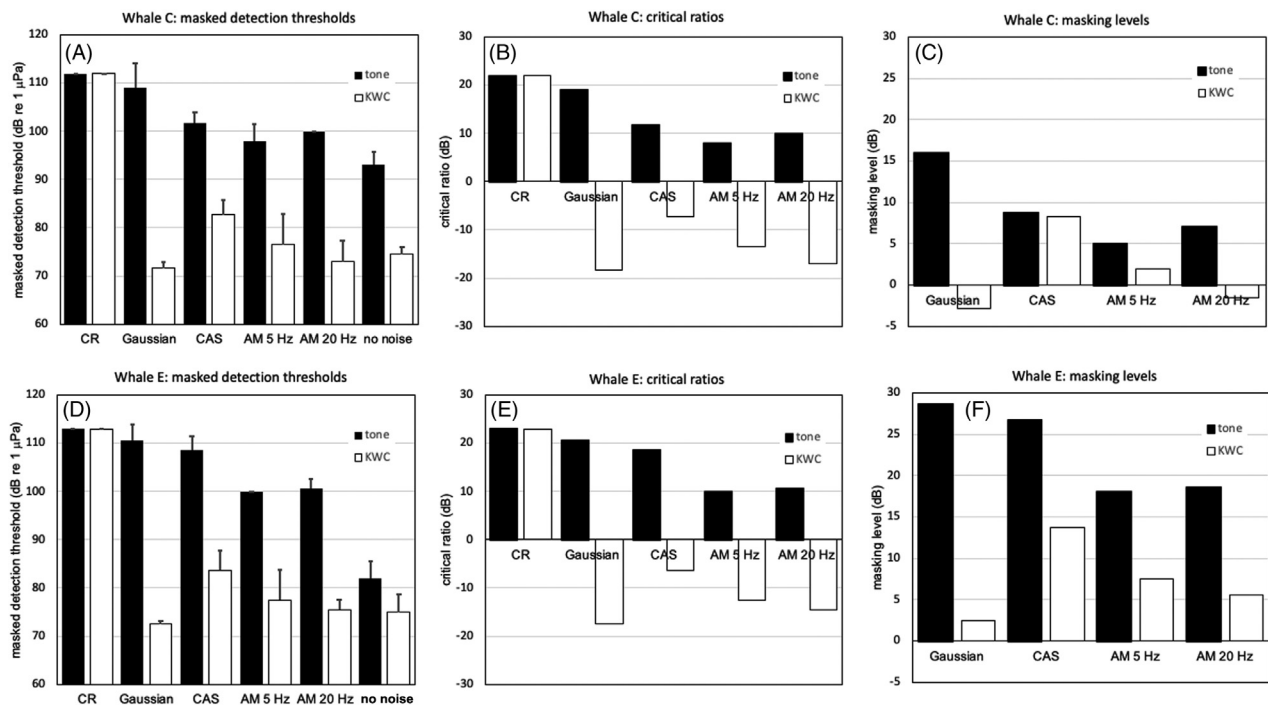


FIG. 5. Masked detection thresholds, critical ratios, and masking levels. Error bars reflect the standard deviation of the average thresholds.



TABLE II. Thresholds (th), standard deviation of thresholds (SD), and false alarms rates (FA) for all signal and noise combinations. Data for whale C are above whale E. Noise types include Gaussian, continuous active sonar (CAS), amplitude modulated with a 5 Hz modulation rate (AM5) and a 20 Hz modulation rate (AM20) and ambient noise of the pool (no noise).

	Noise type	Tone signal				no noise	Killer whale call				
		Gaussian	CAS	AM5	AM20		Gaussian	CAS	AM5	AM20	No noise
Whale C	mean th	109	102	98	100	93	72	83	77	73	75
	SD	5.03	2.31	3.54	0.00	2.65	1.34	3.00	6.36	4.24	1.53
	mean FA	2.78	9.17	13.37	5.56	10.56	5.64	3.89	7.78	9.72	4.65
Whale E	mean th	111	109	100	101	82	73	84	78	76	75
	SD	3.21	2.89	0.00	2.12	3.61	0.71	4.04	6.36	2.12	3.74
	mean FA	4.13	7.55	17.27	3.34	2.38	6.57	7.03	3.06	17.69	3.70

considering differences in CAS MLs between the two whales (Fig. 5).

For KWC MLs, there was no significant difference between MLs in the no noise condition and those masked by Gaussian, AM5, or AM20, suggesting the whales likely used an off-frequency listening strategy. However, CAS noise resulted in significantly higher MLs for KWC than any other noise type, suggesting that the off-frequency listening strategy was not available due to the harmonics structure inherent with CAS. There was also a small, but significant difference in KWC thresholds between those masked by Gaussian and AM5.

#### IV. DISCUSSION

##### A. Sensitivity to narrow and broadband signals

In the no noise condition, detection thresholds of the KWC were significantly lower than those of the 1.5 kHz tone. The most parsimonious explanation for the threshold difference is that the KWC is a broadband signal with higher-frequency components extending into the whales' more sensitive hearing range. The KWC had significant

TABLE III. Results from Tukey *post hoc* tests. Black cells represent significant p-values with an alpha level of 0.05. CAS: continuous active sonar, AM5: amplitude modulated noise with a 5 Hz AM rate, AM20: amplitude modulated noise with a 20 Hz AM rate, no noise: no noise was projected.

Signal = tone					
	Gaussian	CAS	AM5	AM20	no noise
Gaussian		0.4283	0.0011	0.0475	<0.0001
CAS	0.4283		0.1138	0.65	<0.0001
AM5	0.0011	0.1138		0.9419	0.0367
AM20	0.0475	0.65	0.9419		0.0061
no noise	<0.0001	<0.0001	0.0367	0.0061	
Signal = KWC					
	Gaussian	CAS	AM5	AM20	no noise
Gaussian		<0.0001	0.0253	0.6627	0.2728
CAS	<0.0001		0.0026	<0.0001	<0.0001
AM5	0.0253	0.0026		0.605	0.6562
AM20	0.6627	<0.0001	0.605		0.9982
no noise	0.2728	<0.0001	0.6562	0.9982	

harmonics up to 5 kHz with additional lower amplitude harmonics extending above 10 kHz (Fig. 2). The killer whale audiogram [Branstetter *et al.* (2017a), Eq. (1)] predicts a detection threshold of 86 dB at 1.5 kHz, which is between the measured detection thresholds 93 and 82 dB for whales (C) and (E), respectively. The model also predicts detection thresholds of 69 and 60 dB for a 5 and 10 kHz tone, respectively. The detection thresholds for KWC were 75 dB for both whales, suggesting that the KWC thresholds were indeed weighted by the frequency sensitivity of this species but limited by the lower amplitude of the higher-frequency harmonics.

##### B. Tone detection in complex noise

Although all noise types were equally calibrated to an average spectral density level of 90 dB re 1  $\mu\text{Pa}^2/\text{Hz}$ , many of the noise types were complex and the instantaneous amplitude and frequency spectrum varied over time. These results represent the average masking levels for each noise type within the testing pool environment. Each threshold was calculated from ten reversals within a single staircase and the standard deviation of the reversals was 3 dB or below. This indicates that despite the potential variability within certain noise types, signal detection within each noise type was fairly consistent.

Because of the difference in sensitivity between the 1.5 kHz tone and the relatively broadband KWC, masked thresholds of these signals were evaluated separately. For the tone signal, each noise type resulted in significant masking. When compared to Gaussian noise, which is the standard used to calculate critical ratios, both AM5 and AM20

TABLE IV. Masking release for tone detection in amplitude modulated noise. Masking release values were calculated by subtracting detection thresholds (dB re 1  $\mu\text{Pa}$ ) masked by AM5 and AM20 noise from detection thresholds masked by Gaussian noise for each killer whale.

Whale	Noise type	
	AM5	AM20
C	14	12
E	13	13
Mean	13.5	12.5

resulted in a release from masking of approximately 13 to 14 dB, respectively. This result is consistent with harbor porpoise (*Phocoena phocoena*) findings from Kastelein *et al.* (2021), where a release from masking of 14.5 dB occurred for AM rates between 1 and 5 Hz. However, for the harbor porpoise, release from masking for an AM rate of 20 Hz was minimal (i.e., <5 dB). The current study only investigates AM rates that were associated with CAS. A more comprehensive investigation of masking release using a broad range of AM rates to generate a full psychometric function is warranted. The release from masking in the current study is likely due to a dip-listening strategy and/or comodulation masking release (CMR). For CMR to occur, the noise stimulus needs to be wider than the auditory filter centered on the signal (Branstetter and Finneran, 2008). Although critical ratios have been measured for killer whales (Branstetter *et al.*, 2021), auditory filter bandwidths have not. Considering that the frequency-dependence patterns of critical ratios for killer whales are very similar to other delphinids (Branstetter *et al.*, 2017b; Branstetter *et al.*, 2021), an assumption can be made that their auditory filter bandwidths and constant-Q ratios may be similar as well. Assuming a constant-Q ratio of 11.3 (Branstetter *et al.*, 2007), the auditory filter centered on a 1.5 kHz tone would be 133 Hz wide, suggesting that several auditory filters that flank the signal band would also process noise, which is a conditional requirement for CMR. Therefore, CMR cannot be ruled out.

Detection thresholds for the pure tone in Gaussian or CAS noise were not significantly different from each other. This is a somewhat surprising result considering that the CAS noise and 1.5 kHz tone only overlap (within the 133 Hz filter centered on the signal) for a maximum of 2.2 s of the 20 s noise duration (11%). The remaining 17.8 s of the CAS noise should give the whales the opportunity for off-frequency listening to occur, but the detection thresholds suggest otherwise. Moderate amounts of reverberation occur within the 1 kHz to 2 kHz band during the entire duration of the 20 s CAS noise [Fig. 3(B)], which likely contributed to the relatively high tonal detection thresholds. In addition, the qualitative similarity between the tonal signal and the CAS noise could have resulted in informational masking (Branstetter *et al.*, 2016), in which the whales heard the signal (i.e., it registered in their auditory systems) but the signals were misclassified as noise.

### C. Detection of killer whale calls in complex noise

For KWC detection, absolute thresholds (i.e., no noise condition) were very similar to thresholds masked by Gaussian, AM5, and AM20. These results strongly suggest that the whales were using an off-frequency listening strategy, in which they attentively listened to the upper harmonics of the KWC that were outside the 1–2 kHz band of masking noise (Fig. 6). The off-frequency listening hypothesis is also supported by the negative critical ratios [Figs. 5(B) and 5(E)] for KWC masked by all noise types.

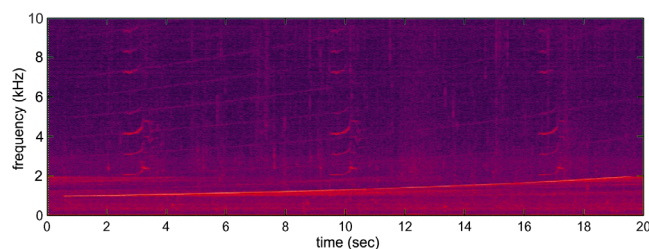


FIG. 6. (Color online) Spectrogram of the killer whale call in CAS noise. The killer whale call is presented at approximately 2.5, 9.5, and 16.5 s in this example. During the study the timing of the signal relative to the CAS noise freely varied. Although the first harmonic is masked well by the CAS, upper harmonics are clearly visible and can provide opportunities for off-frequency listening.

All masked detection thresholds for KWC were lower than the spectral density of the noise, which was 90 dB re  $1 \mu\text{Pa}^2/\text{Hz}$ . In contrast, elevated masked thresholds did occur for the CAS noise, which contained higher frequency harmonics similar to the KWC.

### D. Masking of killer whale calls by continuous active sonar

Currently, noise impacts on marine mammals considered by U.S. federal regulators include behavioral responses, temporary threshold shifts, and physical injury [e.g., permanent threshold shifts (NOAA Fisheries, 2018)]. The use of CAS instead of PAS is thought to mitigate these impacts due to its lower SPLs compared to other types of tactical sonar (e.g., mid-frequency active sonar). However, CAS can have many acoustic properties that make it an effective auditory masker when interacting with the environment, particularly in the case of killer whale communication signals. These features of CAS include its long duration and FM structure that when propagated in the ocean environment, produce significant reverberation. This results in a functionally continuous noise containing multiple harmonics that overlap with the communication frequencies of killer whales (and other marine animals). In the current study, each threshold represents the SPL where a signal can be detected 50% of the time. In their natural habitat, killer whales need to not only detect conspecific calls, but also recognize the pattern of these calls (e.g., frequency contour) that are associated with individuals and group members and are produced under specific behavioral contexts. Recognition requires higher received SPLs because additional cognitive processing is required. For example, bottlenose dolphin hearing experiments demonstrate that recognition thresholds of whistle-like FM tones are approximately 4 dB higher than the detection thresholds of these tones (Branstetter *et al.*, 2016). However, very few laboratory experiments have been conducted with broadband signals similar to natural dolphin whistles or killer whale calls. Although bottlenose dolphins can discriminate between whistles with different broadband spectral profiles (Branstetter *et al.*, 2013a), there is currently no similar discrimination or recognition data for killer whales. However, on an anecdotal note, when the KWC was

first projected into the testing pool for calibrations, almost every killer whale in the adjacent pools approached the testing pool and began extensively vocalizing. This type of behavior was never observed during calibration of pure tones, frequency modulated tones, or any of the noise types. The vocalizing in response to the playback of the KWC was so disruptive that calibrations for the KWC could not be conducted for several days because the vocalizations overlapped with the KWC signal being calibrated. Subsequently, the KWC was played on a continuous loop until vocalizing ceased. This unique observation speculatively suggests that the killer whales recognized the call as being “different” or from a potentially novel conspecific.

Killer whales live in cooperative groups that often coordinate their movements through acoustic communication while hunting and travelling (Jefferson *et al.*, 1991). The broadband harmonic structure of killer whales calls, and other odontocete whistles, have been hypothesized to function as a direction of movement cue (Branstetter *et al.*, 2013a; Lammers and Au, 2003; Miller, 2002), and also a range cue (Mulsow *et al.*, 2018) that likely aid in coordinating group behavior when visual information is limited or non-existent. The CAS recording used in the current experiment had a fundamental frequency and harmonics that significantly overlapped with the KWC tested here and also with KWCs in general. In addition, because CAS is almost continuous and reverberation fills the “off” portion of the signal, killer whales are unlikely or unable to exploit gaps between each source transmission. Findings of the current study demonstrate that auditory masking by CAS has the potential to disrupt killer whale calls used for communication and direction, range, and orientation information, and could potentially have negative impacts on a killer whale’s ability to maintain group cohesion and coordinated movement during foraging and travelling. Killer whales might compensate for CAS masking noise by altering their call amplitude, frequency content, duration, or call rate (i.e., Lombard effect). The Lombard effect in killer whale calling behavior has been observed in the presence of vessel noise (Holt, 2008; Holt *et al.*, 2011). Furthermore, the frequency content of killer whale calls differs among ecotypes that may reduce masking by wind noise typical of their respective habitats (Foote and Nystuen, 2008). Behavioral responses such as changes in group density (i.e., moving closer to one another) could also mitigate CAS masking noise effects, but this has yet to be identified as a behavioral response strategy.

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## AUTHOR DECLARATIONS

### Conflict of Interest

The authors declare no conflicts of interest.

### Ethics Approval

This study adhered to the ethical guidelines of the ASA Ethical Principles, and followed a protocol approved by the Animal Care Review Committee at Sea World, as well as an Institutional Animal Care and Use Committee at the National Marine Mammal Foundation.

### DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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