Underwater sound of three unoccupied aerial vehicles at varying altitudes and horizontal distances

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ABSTRACT:
Unoccupied aerial vehicles (UAVs), or “drones,” are increasingly used as a tool for cetacean research, but knowledge about how these tools contribute to underwater sound is lacking. In this study, underwater sound levels of three commonly used UAV models (Mavic Pro Platinum, Phantom 4 Pro v2.0, Inspire 1 Pro) were recorded. For each model, three replicate flights were conducted at 36 positions at standardized horizontal (0–30 m) and vertical (2–40 m) distances from a hydrophone (1 m depth). Median broadband received levels of the Inspire were highest at 96.5 dB_{rms} 141–17 783 Hz re 1 \mu Pa^2, followed by the Phantom (92.4 dB_{rms} 141–17 783 Hz re 1 \mu Pa^2) and Mavic, which was quietest (85.9 dB_{rms} 141–17 783 Hz re 1 \mu Pa^2). Median ambient sound levels in the absence of an UAV were 82.7 dB_{rms} 141–17 783 Hz re 1 \mu Pa^2. Significant increases in ambient sound levels associated with UAV flights occurred at higher altitudes than previously reported, and received levels decreased more with increasing horizontal distance of the UAV than with altitude. To minimize potential noise impacts on sensitive marine animal subjects, we recommend increasing horizontal distance to the animal, rather than altitude, and choosing the quietest UAV feasible.

I. INTRODUCTION

Unoccupied aerial vehicles (UAVs), or “drones,” are increasingly used as a cost-effective tool in marine research (Yang et al., 2022). Various studies of marine animals, particularly marine mammals, benefit from UAVs, including abundance, behavior, photo-identification, entanglement rates, health assessments, behavioral responses to stressors, kinematics, bioenergetics, and morphometrics (Christiansen et al., 2016a; Christiansen et al., 2018; Christiansen et al., 2019; Torres et al., 2020; Orbach et al., 2020; Ramp et al., 2021; Landeo-Yauri et al., 2021; Azizéh et al., 2021; Arranz et al., 2021). Despite the increasing use of UAVs in ecological research, the impacts of UAV noise on the marine environment remain largely unknown. To our knowledge, few studies have measured the underwater sound level associated with UAVs (Christiansen et al., 2016b; Erbe et al., 2017; Lloyd et al., 2017). These studies demonstrated that UAVs are relatively quiet compared to other platforms of marine observation, such as research vessels, and that their noise impact decreases with increasing altitude (Christiansen et al., 2016b; Erbe et al., 2017).

However, these studies were conducted exclusively in a shallow water environment or tanks (<10 m) and did not test the effect of horizontal distance. Flying at the maximum practicable altitude for research purposes is currently the predominant method of mitigating potential noise impacts (Raoult et al., 2020; Duporge et al., 2021). However, the physical properties of sound waves encountering an air-water surface suggest that the level of sound received underwater from a source above water should decrease faster with horizontal distance to the receiver than with altitude (Lurton and Jackson, 2004). Assuming calm surface conditions, sound is entirely reflected when hitting the water surface at angles above the critical angle of 13°, such that sound waves that enter the water at sub-critical angles can only be received if they are reflected by the seabed (Lurton and Jackson, 2004). To our knowledge, the effect of horizontal distance versus vertical altitude on the underwater received sound level of UAV has not previously been tested.

Beyond distance, other factors influence the sounds that UAVs produce. For example, noise varies by model, due to differences in mass, relative power, payload, and design (Christiansen et al., 2016b; Erbe et al., 2017; Duporge et al., 2021). It is, therefore, important to choose the most appropriate model depending on the target species and study requirements (Hodgson and Koh, 2016). To date, underwater sound levels have only been measured for a limited range of UAVs,
excluding models commonly used for marine mammal research such as the DJI Mavic and Phantom series.

UAV noise transmitted underwater with received levels that exceed ambient sound levels is a potential source of disturbance for marine animals (Schad and Fischer, 2022). Whether an animal is able to perceive the sound depends on the received frequencies and sound pressure levels of the UAV sound, the ambient sound level, and the animals’ hearing threshold and sensitivities (Erbe et al., 2016b). Previous studies have shown a variety of reactions depending on the species of interest, ranging from no sign of disturbance to behavioral changes (Raoult et al., 2020; Palomino-González et al., 2021). Behavioral responses of large whales have rarely been documented [but see Atkinson et al. (2021)]. Small cetaceans regularly alter their behavior in response to UAVs (Ramos et al., 2018; Fettermann et al., 2019; Castro et al., 2021; Giles et al., 2021; Palomino-González et al., 2021). Manatees were observed to respond to UAV noise with increased activity levels, decreased respiration rates, and behavioral reactions (Ramos et al., 2018; Landeo-Yauri et al., 2021). Behavioral responses can be a sign of disturbance as well as bias the results of ecological studies. Therefore, it is important to understand the model-specific influence of an UAV and its underwater sound on target animals to minimize potential disturbance and to understand the possible observer bias when using UAVs for applications such as behavioral observation or stress assessment studies (Schad and Fischer, 2022).

In this study, we measured the underwater received levels of three Da-Jiang Innovations Science and Technology Co., Ltd. (DJI) UAV models in water deeper than 35 m with ambient sound levels around 82.7 dB rms 141–17 783 Hz re 1 µPa². Each model was measured at varying altitudes and horizontal distances to quantify how these UAVs contribute to ambient sound conditions.

II. MATERIALS AND METHODS

A. Experimental setup

Data were collected between August 22 and September 3, 2021, in southeastern Skjálfandi Bay, Iceland (66.017–66.045°N, 17.610–17.644°W; depth > 35 m) between 04:50 am and 10:16 am. A SoundTrap ST300 (Ocean Instruments, New Zealand) was attached to a drifting buoy at 1 m below the surface. The instrument had a sensitivity of −175.2 dB re 1 V/µPa. It recorded continuously at a sampling rate of 72 kHz and saved sound data as 16-bit encoded wav files. To mark the different horizontal distances from the hydrophone, a straight rope with smaller buoys attached to it was tied to the buoy of the hydrophone and laid on the water surface. The straightness of the rope was ensured by attaching a large fast-drifting buoy to the end of the rope and a drift anchor to the buoy of the hydrophone.

Research was conducted from a 5 m inflatable research vessel. The engine was turned off during experiments, and a minimum distance of 100 m to the hydrophone was maintained at all times. Experiments were conducted by three researchers: (1) an UAV operator; (2) an UAV observer; and (3) an observer who monitored the surrounding area for wildlife or vessels, using a drop-down hydrophone. Before each flight, a 1-min control was recorded to enable the calculation of ambient sound level in the absence of an UAV.

Three models of DJI UAVs were tested: a Mavic Pro Platinum, a Phantom 4 Pro v2.0, and an Inspire 1 Pro (hereafter, for simplicity, the UAV models will be referred to as Mavic, Phantom, and Inspire). Each UAV was flown at 36 positions: six different altitudes (2, 5, 10, 20, 30, and 40 m), covering the range mostly used for marine mammal research, including blow sampling and photogrammetry, and six different horizontal distances (0, 2, 5, 10, 20, and 30 m). Horizontal distance to the hydrophone was maintained by hovering over the corresponding marking buoys on the rope. During flight, altitude was estimated according to the altitude reading on the operating panel of the UAV remote controller; additionally, a light detection and ranging (LiDAR) system weighing 145.5 g (Dawson et al., 2017), which recorded the laser height every second, was attached to the UAVs to retrospectively calculate accurate altitude. At each position, the UAV hovered for 20 s, and each position was replicated three times. All UAVs were tested
Beaufort sea state 1. Sea state was visually assessed. Voice recordings were used to synchronize the hydrophone and LiDAR by GPS time and to record the exact timing of each flight and position.

B. Data processing

Due to noise artifacts from the surface buoy throughout the majority of each recording, one second out of the 20 s per position and per control minute was manually chosen for analysis using Raven Pro 2.0.1 (Center for Conservation Bioacoustics, 2016). Mean LiDAR altitudes were calculated for each position. A DC offset was removed in Audacity (Audacity Team, 2018). For the first replicate of each UAV model at the position 0 m horizontal distance and 2 m altitude, band level plots were created for the entire frequency range (50–36 000 Hz, excluding 0–50 Hz due to high ambient sound levels) with a 10 Hz resolution, Welch-averaged over 1 s, Hann window, and 0% overlap. Decade sound pressure levels were calculated in R 3.6.1 (R Core Team, 2019) and visualized in the same figure (Fig. 2).

The band level plots indicated that the majority of energy of all UAVs was below 17 783 Hz (upper boundary of the 16 000 Hz decade band, according to ISO 2017; Ainslie et al., 2022). Since the UAV noise did not exceed environmental ambient sounds below 141 Hz (lower boundary of the 160 Hz decade band), the range between 141 and 17 783 Hz (160–16 000 Hz decade bands) was chosen for broadband analysis. Additionally, the UAVs...
were compared in a low-frequency range (141–1122 Hz; 160–1000 Hz deci-decade bands), a mid-frequency range (1123–17783 Hz; 1250–16000 Hz deci-decade bands), and a high-frequency band (28184–35481 Hz; 32000 Hz deci-decade band). In the low-frequency range, the deci-decade bands were grouped due to oscillations, creating signals of high and low energy in the single bands that did not represent the data well (Fig. 2). In the mid-frequency range, the deci-decade bands were also grouped. This analysis is supposed to provide background information for any research on marine animals; therefore, no single deci-decade band can be selected as a maximum hearing sensitivity for a specific species. Results would vary depending on the band randomly chosen, and a broader frequency band is, therefore, more comparable. The high-frequency range was chosen due to the high intensity in this deci-decade band from the Inspire (Fig. 3).

For each position and each control minute, received sound pressure levels at the hydrophone (hereafter, “received levels”) were calculated in PAMguide (Merchant et al., 2015) using a 1 Hz, 1-s resolution, no averaging, and a Hann window with 0% overlap. Root-mean-square (rms) sound pressure levels were calculated for a broadband (141–17783 Hz), low-frequency (141–1122 Hz), mid-frequency (1123–17783 Hz), and high-frequency (28184–35481 Hz) range in R, by taking the square root of the sum of squares of the linear sound pressure levels. To put the received levels of the UAVs into context, the received level of a rigid hull inflatable boat (RHIB) passing at 1.38 km distance was calculated using the same parameters.

C. Data analysis

To compare the three different UAVs, median, minimum, and maximum received levels were calculated in the broadband, low-, mid-, and high-frequency range, including all replicates of all positions with a maximum horizontal distance of 2 m and a maximum LiDAR altitude of 5 m for each UAV. Median, minimum, and maximum received levels of the control minutes were calculated for comparison. Given that the Inspire has been measured in previous studies (Christiansen et al., 2016b; Erbe et al., 2017), we calculated additional median, minimum, and maximum received levels for comparability in the range used in this study (141–17783 Hz), in the study by Christiansen et al. (2016b) (160–1500 Hz), and in the study by Erbe et al. (2017) (100–3000 Hz). In accordance with the previous studies, we included all flights with altitudes between 5 and 10 m and 0 m horizontal distance.

Due to normal data distribution with unequal variances, Welch tests were used to assess the difference in received levels between the UAVs and between each UAV and the control (\(z = 0.03\), adjusted due to repeated comparisons). All statistical analyses were conducted in R.

To compare the difference in broadband received levels between UAV positions, a generalized linear model (GLM) with a \(\gamma\) distribution was constructed for each UAV separately. Explanatory variables were LiDAR altitude, horizontal distance, and an interaction of LiDAR altitude and horizontal distance. Model assumptions were visually assessed in R; models were built using the nlme package (Pinheiro et al., 2021). Additionally, the increase in broadband received levels due to UAV noise compared to ambient sound levels was tested for significance for each position with increasing altitude (standardizing horizontal distance at 0 m) and increasing horizontal distance (standardizing altitude at 2 m) using Wilcoxon tests (\(z = 0.03\), adjusted due to repeated comparison with the same control).

III. RESULTS

A. UAV model comparison

Band level plots of all three UAVs reveal most energy to be between 141 and 17783 Hz (160–16000 Hz deci-decade bands) and decreasing energy with increasing frequency (Fig. 2). All three UAVs had a peaked spectrum in the low-frequency range (141–1122 Hz; 160–1000 Hz deci-decade bands). The frequency and amplitude of peaks and troughs were inconsistent between replicates (see supplementary material) and were, therefore, not quantified. The Inspire had additional oscillating energy between 29700 Hz and 35400 Hz with a peak at 32400 Hz (Fig. 3). The intensity at this frequency was 51.6 (49.0–53.8, minimum and

![FIG. 3. (Color online) Band level plot of the first replicate of the Inspire in the high-frequency band (28184–35481 Hz). Values were calculated in PAMguide with a 7200 sample resolution, Welch-averaged over 1 s, Hann window, and 0% overlap.](https://doi.org/10.1121/10.0019805)
maximum values of the three replicates) dB re 1 μPa. This is 16.1 dB above the ambient sound level of 35.5 (34.7–36.4) dB re 1 μPa².

At a maximum horizontal distance of 2 m and a maximum LiDAR altitude of 5 m, the Mavic was the quietest of the three UAV models in all frequency ranges measured, the Phantom was the second loudest, and the Inspire was the loudest UAV (for detailed intensity values in all ranges, see Table I). All UAVs significantly increased the received level compared to the control in all frequency ranges measured, except for the Mavic in the high-frequency range (for test statistics, see supplementary material).

The difference in received levels between the UAVs was also significant in all frequency ranges measured, except for the difference between the Phantom and the Inspire in the broadband and low-frequency ranges (supplementary material).

For context, the received level of a RHIB boat passing at 1.38 km distance from the hydrophone was 121.6 dB rms 141–17 783 Hz re 1 μPa².

For comparability with previous studies, the received levels of the Inspire were measured to be 92.9 dB rms 141–17 783 Hz re 1 μPa² (minimum 92.5 to maximum 98.2 dB rms 141–17 783 Hz re 1 μPa²; n = 5) in the frequency range used in this study (141–17 783 Hz) when flown at altitudes between 5 and 10 m and 0 m horizontal distance. In the frequency range 160–1500 Hz, the received levels were 91.8 dB rms 160–1500 Hz re 1 μPa (minimum 91.0 to maximum 96.8 dB rms 160–1500 Hz re 1 μPa; n = 5), while Christiansen et al. (2016b) measured 101 dB rms 160–1500 Hz re 1 μPa (minimum 98 to maximum 102 dB rms 160–1500 Hz re 1 μPa; n = 5). In the frequency range 100–3000 Hz, the received levels were 91.9 dB rms 100–3000 Hz re 1 μPa (minimum 91.1 to maximum 96.8 dB rms 100–3000 Hz re 1 μPa; n = 5), while Erbe et al. (2017) measured 88.0 dB rms 100–3000 Hz re 1 μPa (no min/max available) when flown at 5 m altitude and 88.6 dB rms 100–3000 Hz re 1 μPa when flown at 10 m altitude.

### B. Position comparison

To test whether broadband received levels varied with horizontal distance and LiDAR altitude, GLMs were created

<table>
<thead>
<tr>
<th>Position</th>
<th>Mavic</th>
<th>Phantom</th>
<th>Inspire</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mavic</td>
<td>85.9</td>
<td>92.4</td>
<td>96.5</td>
<td>82.7</td>
</tr>
<tr>
<td>Phantom</td>
<td>(83.2–87.5)</td>
<td>(89.1–97.9)</td>
<td>(92.9–98.2)</td>
<td>(81.1–85.5)</td>
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<tr>
<td>Inspire</td>
<td>81.6</td>
<td>90.9</td>
<td>92.6</td>
<td>76.1</td>
</tr>
<tr>
<td>Control</td>
<td>(141–17 783 Hz)</td>
<td>(141–1122 Hz)</td>
<td>(86.5–96.7)</td>
<td>(88.9–95.0)</td>
</tr>
<tr>
<td>Low</td>
<td>81.6</td>
<td>90.9</td>
<td>92.6</td>
<td>76.1</td>
</tr>
<tr>
<td>Mid</td>
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<td>73.9</td>
<td>74.2</td>
<td>80.9</td>
<td>74.0</td>
</tr>
</tbody>
</table>

For each UAV individually, horizontal distance (Inspire t = –10.833, p < 0.001; Phantom t = –9.849, p < 0.001; Mavic t = –4.648, p < 0.001), LiDAR altitude (Inspire t = –7.706, p < 0.001; Phantom t = –5.951, p < 0.001; Mavic t = –2.964, p = 0.004), and their interaction (Inspire t = 5.623, p < 0.001; Phantom t = 4.784, p < 0.001; Mavic t = 2.454, p = 0.016) significantly contributed to the GLMs of all three UAVs.

According to the GLMs, the received levels of all three UAV models decreased significantly with horizontal distance and with LiDAR altitude but decreased more rapidly with horizontal distance than with altitude [Figs. 4(a)–4(b)]. Plotting the received levels of each position for each UAV individually confirms this trend [Fig. 4(c)]. Of note, the received levels include the ambient sound level (median in the absence of an UAV: 82.7 dB rms 141–17 783 Hz re 1 μPa²). Figure 4 only displays broadband levels; however, the decrease in received levels is similar in the low-, mid-, and high-frequency bands, as long as the UAV produces sound in these frequencies (supplementary material). A table of the received levels of all replicates of each UAV at each position is available in the supplementary material.

When standardizing horizontal distance at 0 m, the Inspire and Phantom significantly increased ambient sound levels up to 40 and 30 m, respectively (for test statistics, see supplementary material); the Mavic did not significantly contribute to ambient sound levels above 2 m altitude.

IV. DISCUSSION

This study compared the received underwater sound levels of three different DJI UAVs when flown at varying altitudes and horizontal distances to the hydrophone receiver.

A. UAV model comparison

Compared to other studies (Christiansen et al., 2016b; Erbe et al., 2017), here we measured the noise associated with UAVs in deeper water (>35 m), reducing the amount of energy received by bottom reflection. However, the noise measured might still include reverberant effects in addition to the direct refracted noise (Urick, 1972).

The broadband received levels measured varied substantially depending on the UAV model. The Mavic was the quietest UAV, only increasing broadband ambient sound levels at close distances from the hydrophone (2 m altitude, 0 m horizontal distance). The second loudest UAV was the Phantom, while the loudest was the Inspire. The Phantom and the Inspire differed mostly in the mid-frequency range and especially in the high-frequency range, where the Inspire produced a peak in energy between 29.7 and 35.4 kHz, while the other two UAVs did not. Similar tonal peaks in energy, e.g., at 18.7 kHz, have been detected in the UAV SwellproSplashdrone (Lloyd et al., 2017). Currently,
the reason for this sound is not known, and specific research is recommended to understand its source. All three models produced a peaked spectrum in the low-frequency range (141–1122 Hz), which can be explained by the rotation of the blade; the frequencies of the various peaks are presumed to vary with the speed of blade rotation (Intaratep et al., 2016). The differences in received levels between UAV models are likely a result of the respective mass, relative power, payload, and design (Christiansen et al., 2016b; Raoult et al., 2020). Therefore, these specifications should be considered when choosing an UAV for marine wildlife research, in combination with factors that determine the suitability of the UAV for research purposes, such as flight time and camera resolution. The results of this study are unique to the UAV models measured and may vary in other models, especially when the rotor configuration is increased to six or eight rotors. We recommend using the quietest UAV feasible to reduce potential impacts. Due to the peak in energy at higher frequencies, attention should be paid when choosing to use the Inspire compared to the other UAV models.

To our knowledge, this is the third study to measure the underwater sound levels of the Inspire; however, all studies showed varying results. Comparing the received levels in the frequency range 100–3000 Hz with the study of Erbe et al. (2017), our measurements were only 3.9/3.3 dB_{rms} 100–3000 Hz re 1 \mu Pa higher than the results presented in Erbe et al. (2017). In contrast, in the frequency range 160–1500 Hz, Christiansen et al. (2016b) measured 9.2 dB_{rms} 160–1500 Hz re 1 \mu Pa higher received levels than our results. This is likely an effect of the difference in ambient sound levels at the two different locations. To date, no study has measured the Inspire in a high-frequency band, and therefore, this is the first report of energy in this range. This highlights the importance of measuring a wide range of frequencies relevant to the species under observation. We recommend measuring the received levels of all UAV models used in marine wildlife research, including even higher frequencies than those reported here, to better understand their potential responses of species whose peak hearing includes high frequencies.
Our measurements were conducted during Beaufort sea state 1 with low wind speed. Noise levels might increase in higher sea states as the motors of the UAVs must work harder, and the rotors turn faster, to maintain position. A separate study is recommended to understand the difference in received levels of varying UAVs at different sea states and wind conditions.

B. Position comparison

While the Mavic only contributed significantly to broadband ambient sound levels at the closest distance measured (2 m altitude, 0 m horizontal distance), the Phantom and the Inspire increased broadband received levels at higher altitude ranges (up to 40 m) than previously reported (Christiansen et al., 2016b; Erbe et al., 2017). In contrast, both UAVs only increased broadband ambient sound pressure levels significantly at horizontal distances up to 2 and 5 m, respectively. Therefore, the hypothesis was confirmed that for all UAVs, the received levels decreased faster with horizontal distance than with altitude. The current trend in studies using UAVs is to increase altitude as much as feasible to minimize impacts (Raoul et al., 2020; Duporge et al., 2021). In contrast, we recommend increasing horizontal distance, over vertical distance, to target animals to decrease potential noise impacts when possible. The ability to maintain horizontal distance will depend on the UAV-based sampling methodology and research objectives. For example, when collecting aerial images, the time spent directly above an animal may be reduced whilst still collecting the required image. Similarly, a blow sampling procedure may be altered to only fly directly over the animal as it is about to exhale.

C. Comparison to other platforms of marine observation

Overall, the maximum broadband received levels of all UAVs in close proximity were very low compared to other platforms of marine observation. Small inflatable vessels used for research are tens of dB louder in comparison and, therefore, have a much higher impact on the animals of interest (Jensen et al., 2009; Erbe et al., 2016a). A small RHIB boat passing at 1.38 km distance to the hydrophone was 25.1 dBrms 141–17783 Hz louder than the median received level of the loudest of the three UAVs. Additionally, animals may be able to determine that the sound source is above the water surface, which could alter perceived threat. Therefore, UAVs are a preferable tool for research compared to engine-powered research vessels to minimize noise impacts whenever feasible. It should be noted that the ambient sound level of the study site is relatively low compared to many ocean regions (Fournet et al., 2018; Haver et al., 2019; Laute et al., 2022). The increase in received levels when UAVs were flying in this study may be less ecologically relevant in areas with higher ambient sound levels. Under louder conditions, UAV sounds may be acoustically masked. However, in areas with low ambient sound levels, noise associated with UAVs, while low, significantly increases ambient sound levels and, therefore, needs to be considered when using UAVs as tools for research.

D. Implications for marine wildlife studies and management

The underwater noise of UAVs might be a disturbance to marine animals. The maximum received levels are far below those known to directly damage the auditory systems of marine mammals (Southall et al., 2019). However, the sounds might mask vocalizations. We found that UAVs increased noise levels primarily at low- and mid-frequencies (141–17783 Hz), overlapping, for example, with baleen whale and pinniped vocalizations (Dudzinski et al., 2009). The peak in the high-frequency range (29.7–35.4 kHz) overlaps with vocalizations produced by odontocetes and some pinnipeds (Dudzinski et al., 2009).

Additionally, perception of the sound of an UAV might cause behavioral changes. This is important to consider for welfare implications (Clegg et al., 2021), as well as the possibility that underwater noise might stimulate unwanted behavioral responses in the species under observation, biasing the results of ecological surveys. Whether an animal is able to perceive the UAV noise depends on its frequency hearing range and hearing sensitivity as well as the ambient sound level (Erbe et al., 2016b). While absolute hearing thresholds for baleen whales are unknown, modelled audioograms for baleen whales suggest best hearing abilities in the low- and mid-frequency range where the UAVs produce noise (Cranford and Krysl, 2015; Tubelli et al., 2018). While many odontocetes can also perceive sounds at frequencies lower than 2 kHz, their peak hearing sensitivity is generally higher, making them susceptible to the noise of the Inspire in the high-frequency range between 29.7 and 35.4 kHz [see Erbe et al. (2016b) for marine mammal audioograms]. Choosing the most appropriate UAV model for research should, therefore, depend on the species of interest. In addition to the frequency, the amplitude of the sound needs to be considered. If the signal-to-noise ratio (signal intensity above ambient sound level) of the UAV noise is exceeding the critical threshold (species-specific minimum signal intensity above ambient sound level to be audible), the animal will be able to hear the sound (Richardson et al., 2013). In an environment with high ambient sound levels, an animal is, therefore, less likely to perceive an UAV, while in quiet regions, the sound may be heard.

Beyond hearing ability, behavioral responses to UAVs are likely influenced by numerous factors, including underlying behavioral state, life history stage, habitat, and the size and movement of the sound source, as evidenced by observed responses to other anthropogenic sound sources (Williams et al., 2002; Richardson et al., 2013; Di Clemente et al., 2018; Basran et al., 2020; Koroza and Evans, 2022). However, to date, these complex interactions have not been demonstrated for UAV responses.

Given the lack of understanding around drivers of behavioral responses to UAVs, we encourage systematic...
observations of behavioral responses for all UAV studies. Target species, behavioral state, hearing sensitivity (where available), and vocal range should be included as variables for any response study (Smith et al., 2016). Moreover, existing response studies have been performed with a variety of behavioral classifications and response criteria; future research should use a standard set of criteria to enable comparability across explanatory variables. Combined with the noise data presented here, this can guide appropriate regulations to mitigate the negative impacts of UAVs on marine wildlife and minimize reporting biased results. In particular, adopting a precautionary approach, we recommend maintaining suitable horizontal distance and reducing unnecessary time spent flying directly above the target animal, when adopting a precautionary approach, we recommend main-
ting suitable horizontal distance and reducing unnecessary time spent flying directly above the target animal, when adopting a precautionary approach, we recommend maintaining suitable horizontal distance and reducing unnecessary time spent flying directly above the target animal.

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1See the supplementary material at https://www.scitation.org/doi/suppl/10.1121/10.0019805 for (1) a figure of the received band level of the three replicates of the Inspire, Phantom, and Mavic in the lower frequencies (150–2000 Hz); (2) p-values and test statistics of Welch tests comparing the UAVs with ambient sound pressure levels and between each other in different frequency ranges; (3) a figure of the received level at each position of each UAV in the low-, mid-, and high-frequency bands; (4) a table of the received levels of all replicates of each UAV at each position; and (5) p-values and test statistics of Wilcoxon tests comparing broadband received level of the UAV with ambient sound pressure level for each UAV at varying altitudes (standardized horizontal distance at 0 m) and varying horizontal distances (standardized altitude at 2 m).


