



Drones and marine mammals in Svalbard, Norway

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Abstract

The impact of remotely piloted aircraft systems (RPAS) on marine mammals remains poorly documented despite their increasing use. In the high-Arctic Archipelago of Svalbard, where marine mammals face increasing pressure from climate change and expanding tourism, the use of RPAS remains largely unregulated. In this study we assessed the impacts of RPAS across a range of species to provide science-based management advice, using a variety of aircraft sizes and approach strategies. We explored RPAS sound levels and animal behavior prior to and after flights. Preexperimental alertness influenced sensitivity to disturbance notably. Harbor seals were more sensitive during prebreeding than during molting, reacting at distances of 80 m, whereas walrus responded at distances <50 m. Polar bears reacted to the sound of RPAS during take-off at 300 m, although response levels were relatively low. White whales reacted to the sight of RPAS when flown ahead of the pod, below 15 m. Variations in sound levels typical in overhead descents and manual flights increased disturbance potential more than RPAS size; preprogrammed flight paths are advised. Our study highlights factors that can influence sensitivity to RPAS including tidal state and swell, the presence of young individuals, ambient noise levels, and RPAS approach strategies.

KEYWORDS

arctic marine mammals, behavior, distance threshold, disturbance, drone, haul-out, remotely piloted aircraft system (RPAS)

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1 | INTRODUCTION

Recent developments of remotely piloted aerial systems (RPAS, or drones) have led to a rapid increase in their use with marine mammals by naturalists, nature documentary film teams, and the scientific community. For researchers, these aircraft provide unprecedented capabilities to film animals and landscapes (Shahbazi et al., 2014). RPAS are especially useful in intermediate-scale applications (hundreds of meters to a few kilometers), when surveying sensitive or aggressive species, or obtaining observations of places that would otherwise be hard to reach (Chabot & Bird, 2015). Given the rapid increase in the use of RPAS and the limited knowledge of their potential impacts on wildlife (Ditmer et al., 2015; Goebel et al., 2015; Mulero-Pázmány et al., 2017; Rümmler et al., 2016; Vas et al., 2015), Hodgson and Koh (2016) developed a series of precautionary guidelines. These authors also encouraged researchers to report disturbance observations in their studies as well as quantifying disturbance through experimental designs as a means for providing science-based management of these new technologies (Christie et al., 2016; Hodgson & Koh, 2016).

RPAS technology already has benefited marine mammal research programs in a wide variety of ways. In particular, these inexpensive aircraft improve observation capacities and make intermediate-scale surveys more affordable (Koski et al., 2009; Raoult et al., 2020; Sorrell et al., 2019). Studies using RPAS on marine mammals report few responses from cetaceans (Domínguez-Sánchez et al., 2018; Fettermann et al., 2019) and pinnipeds (see Arona et al. 2018; Krause et al. 2017; Moreland et al. 2015; Sweeney et al. 2016). Smith et al. (2016) concluded that potential impacts on marine mammals could arise from both acoustic or visual stimuli, although experiments specifically assessing RPAS disturbance thresholds are still scarce (Fettermann et al., 2019; Pomeroy et al., 2015).

Few studies assessing RPAS disturbance on wildlife have considered their potential acoustic impacts (Arona et al., 2018; Christiansen et al., 2016, 2020; Erbe et al., 2017; Goebel et al., 2015; Scobie & Hugenholtz, 2016), and only a small fraction of studies have reported sound levels measured during flight missions as opposed to measuring sound levels received from RPAS hovering at fixed positions (Arona et al., 2018; Erbe et al., 2017). However, the scientific use of RPAS generally involves following different flight trajectories, rather than hovering in fixed positions; thus, variations in the sound emitted by moving RPAS represent both a potential source of disturbance and a key knowledge gap (Erbe et al., 2017; Raoult et al., 2020). In the high-Arctic Archipelago of Svalbard, Norway, RPAS usage has surged as a consequence of increases in tourism (Viken, 2011; Viken & Jørgensen, 1998) as well as increased scientific research usage (Aksnes & Rørstad, 2015; Misund et al., 2017). This raises the question as to how strictly regulated RPAS use should be given the concerns for nature conservation laid out in the Svalbard Treaty (Svalbard Treaty - Article 2, in Miljøverndepartementet 1994–1995: 29). To date, RPAS are not subject to the same restrictions as manned aircraft, which are not allowed to fly closer than one nautical mile from large concentrations of mammals or birds (Svalbard Environmental Protection Act - Act of 15 June 2001 No. 79). For recreational use, this “gray zone” has generally been resolved via a ban on the use of RPAS by some tour companies, though their usage by private tourists and others remains unregulated (outside a corridor near the airport). Scientific use requires a permit issued by the Governor of Svalbard and the national animal care authority. Similarly, other countries within the Arctic, including Canada and the United States, have regulated the use of RPAS near people, in cities, airports, and National Parks, but no clear guidelines pertaining to flights over wildlife are in place beyond general restrictions on potentially disturbing activities within protected areas. In this study, we tested the effects of RPAS on several marine mammal species in Svalbard, defining “disturbance” as an increase in the level of agitation or alertness above pre-flight levels (see Pomeroy et al. 2015). Our aim was to provide science-based advice for the development of regulations on the use of RPAS regionally by characterizing disturbance induced by several commercially available vertical take-off and landing (VTOL) RPAS of different sizes. We tested different approach strategies and considered a variety of factors that might influence animal responses. In addition, we characterized the acoustic outputs of the RPAS used in our disturbance experiments in order to account for variations in sound emissions that were likely to occur when flying in the field. Colonially living marine mammals such as harbor seals (*Phoca vitulina vitulina*) and walrus (*Odobenus rosmarus rosmarus*) occur at predictable haul-out sites along the western coastline of Svalbard and, for this

study, these species provided the opportunity to perform structured, repeated experiments. Understanding how RPAS impact solitary species such as polar bears (*Ursus maritimus*) or highly mobile, spatially unpredictable social species such as white whales (*Delphinapterus leucas*) was more challenging given their less predictable encounter rates. Thus, our investigations with these latter species were of a more opportunistic nature.

2 | MATERIALS AND METHODS

We conducted fieldwork and data collection on harbor seals and walrus over two seasons. Harbor seal studies were conducted at Midtøya, in Forlandsøyane (78.34°N, 11.57°E), a small island located west of Prins Karls Forland and walrus studies were conducted at Sarstangen (78.73°N, 11.46°E), a natural sand spit extending off the coast of Spitsbergen into Forlandsundet (Figure 1). Data collection on polar bears and white whales were conducted within Isfjorden (Figure 1) on an opportunistic basis.

2.1 | Harbor seals and walrus

At the harbor seal haul out on Midtøya, we conducted four flight sessions during the annual molt (August 18 and 19) in 2017 and five sessions during the prebreeding period (May 25–29) in 2018. Our walrus studies were conducted on August 21 and 22, 2017, when we performed two flight sessions at Sarstangen. Each flight session included a

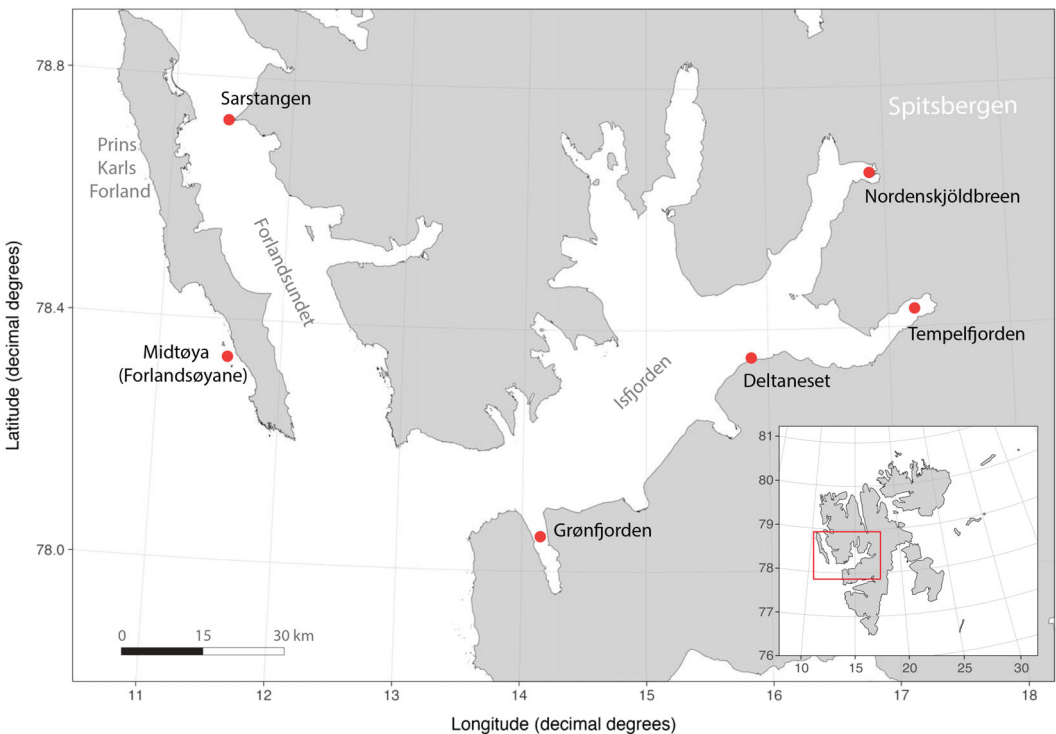


FIGURE 1 Sampling locations in Svalbard. We performed disturbance experiments on Atlantic walrus at Sarstangen and harbor seals at Midtøya. Opportunistic sampling included RPAS flight tests on a female polar bear at Nordenskjöldbreen and Deltanaset, and pods of white whales at Tempelfjorden and Grønfjorden.

preexperimental control period, the flight experiments and a postexperimental period, entire sessions lasted between 1.5 and 2.5 h (Figure S1). For all flights we launched the RPAS from an observation position 120 m away from the main haul-out groups and we used a Sony Handycam 4K video camera (Sony Electronics Inc., San Diego, CA) to record the behavior of the animals from ground level. We recorded ambient noise with a Song Meter SM4 (Wildlife Acoustics, Inc., Maynard, MA), that we placed 50 m from the subject animals.

We started and ended acoustic and video recordings 30 min before and after our flight operations, respectively, providing behavioral observations of the aggregations before, during, and after flights. Flights took place only under low wind conditions (<6 m/s), with no precipitation. We categorized ocean swell into three categories following Demarchi (2012): none, low, and medium-high. Tidal state was determined using mean sea level (MSL), as corrected values from the nearest meteorological station operated by the Norwegian Hydrographic Service, in Ny-Ålesund (78.92°N, 11.90°E), with a vertical resolution of 10 cm and a temporal resolution of 10 min (Figure S2).

Each flight comprised the period between a take-off and a landing operation, and generally included a single flight profile. Individual flight profiles ranged in altitude from 120 to 20 m (Table S1), using the center of the animal aggregation as a reference point (in the case of the pinniped experiments). We kept a constant speed of 40 km/hr throughout the horizontal flights, and a descent rate of 2 m/s in vertical flights. The RPAS collect video data with sufficient resolution at those speeds, that still images of suitable analytical quality were retrieved.

We followed four flight strategies, reflecting different ways animals could potentially be approached in “real world” situations (Table S1). The flight strategies were: (1) wide orbits around the animals, maintaining a minimum horizontal distance of 50 m; (2) close orbits, maintaining a minimum horizontal distance of 20 m; (3) straight-line paths from the operator crossing directly over the animals and ending approximately 50 m behind them; and (4) overhead descents from a maximum altitude of 120 m, ending as soon as any disturbance response was elicited at the haul-out. Whereas straight-line and overhead descent profiles aimed to test the disturbance potential on animals over which the RPAS is purposely flown, we chose orbit profiles to systematically recreate a situation similar to that which unobserved or nontargeted animals could experience when a RPAS flies in an area near them.

The different RPAS models used were the DJI Inspire 2, the DJI Phantom 4 and the DJI Mavic Air (DJI, Shenzhen, Guangdong, China; Table 1; see specifications in Table S2). Most wide-orbit and close-orbit profiles were preprogrammed using the Autopilot Hangar application on an Ipad Pro (9.7-inch) (Apple, Inc., Cupertino, CA) and flown in auto-pilot mode in Visual Line of Sight (VLOS) in order to ensure repeatability across sessions. Preprogrammed flight profiles were set to maintain a constant altitude and speed and thus minimize the occurrence of abrupt movements that increase the noise signal of the aircraft (only wind gusts and occasional losses of GPS signal can cause disruptions in the trajectory). Straight-line profiles were either preprogrammed or flown manually, particularly at low altitudes, and all overhead descents were flown manually.

We used the video recordings from ground level to score the behavior of seals, adopting a scan sampling strategy (Altmann, 1974) to capture potential variation in behavior over the course of each flight session. Throughout each video, we registered behaviors every 10 s, scoring 10 individuals across the haul-out or as many as were visible when fewer individuals remained on shore. We chose focal individuals based on visibility; if they were not visible at a given moment, we replaced them with a different individual nearby. We kept walruses as focal individuals even when hidden within the haul-out, if it was clear that all the individuals were still and resting.

We based our behavioral categories on those used by Pomeroy et al. (2015), with the addition of a category for comfort movements, as in Kovacs (1987) to cover the whole spectrum of behaviors we observed. In total, we defined seven different behavioral categories:

- (1) Sleeping: individual resting or sleeping, not moving and with its eyes closed.
- (2) Comfort behavior: basically resting but performing low intensity activities such as stretching and scratching.
- (3) Eyes open and/or head-up: an individual with its eyes open, possibly rising the head.
- (4) Side-to-side head moves: a higher degree of alertness, with the animal moving the head sideways (“searching” related or not to RPAS flight operations).

(5) Alert: alert posture while performing changes in position (excluding displacement), or other activities such as shuffling and intense scratching. Agonistic interactions with other individuals were included in this category.

(6) Locomotion: an individual changes location within the group or moves off the haul-out (without fleeing).

(7) Flee: leaves the haul-out with urgency, individually or with the group.

We used Autopilot Hangar to create time-indexed data files of flight telemetry for each preprogrammed profile flown, which contain information about the aircraft and flight trajectory (summarized in Table S3). We calculated horizontal distances between the RPAS and the haul-out with the package *sp* (Pebesma & Bivand, 2013) in R version 3.4.0 (R Core Team, 2017), after converting the coordinates into spatial points. Subsequently, we used horizontal distance and altitude to calculate the real distance between the RPAS and the haul-out using standard trigonometric equations. Because telemetry data are not available on manual flights, we developed an indirect method to estimate the distance from RPAS to the haul-outs (Supplementary Methods 1).

2.2 | Opportunistic sampling: polar bears and white whales

For the less spatially predictable polar bears and white whales, we conducted day trips from Longyearbyen to glacier fronts within Isfjorden, which tend to be areas of aggregation for various marine mammals (Lydersen et al., 2014). We encountered a female polar bear accompanied by two yearling cubs twice, on August 20 and 27, 2018, at Nordenskjöldbreen and Deltanaset (Figure 1), providing us with the opportunity to conduct opportunistic sampling. The trials lasted approximately 5 min each. Upon sighting the bears, we launched a Phantom 4 Pro from the boat and ascended to an altitude of 80 and 110 m, respectively for the two encounters. During the first encounter the female was resting when first sighted, and we performed consecutive straight-line profiles at altitudes of 70, 50, and 20 m, followed by a close approach within a radius of 5 m. During the second encounter, the family unit was walking together upon discovery, and we alternated close-orbit profiles and straight-line overflights along a beach, flying at altitudes of 90, 60, 50, 40, and 20 m. Responses included (1) initiation or interruption of walking and (2) head-lifting.

TABLE 1 Summary of flight sessions. Flights represents the total number of flights per session. The number of manual flights is shown in parentheses. Sea state was pooled into three categories: 1, flat; 2, low; and 3 for medium-high. Tide is expressed relative to the mean sea level, provided by the Norwegian hydrographic service as values corrected from the nearest station at Ny-Ålesund (78.92°N, 11.90°E).

Date	Species	Time	Season	Flights	UAS	Haul-out size	Sea state	Tide
August 18, 2017	<i>P. vitulina</i>	am	molting	6	Phantom 4	45	1	18 to 5
August 18, 2017	<i>P.vitulina</i>	pm	molting	7(1)	Phantom 4	72	1	−33 to −50
August 19, 2017	<i>P.vitulina</i>	am	molting	8	Phantom 4	90	1	−16 to 8
August 19, 2017	<i>P.vitulina</i>	pm	molting	6 (2)	Phantom 4	116	1	26 to 14
August 21, 2017	<i>O.rosmarus</i>	pm	molting	16 (3)	Phantom 4	13	2	41 to 55
August 22, 2017	<i>O.rosmarus</i>	pm	molting	15 (2)	Phantom 4	30	3	−18 to 54
May 25, 2018	<i>P.vitulina</i>	am	prebreeding	15 (1)	Phantom 4	44	3	33 to 24
May 25, 2018	<i>P.vitulina</i>	pm	prebreeding	9 (2)	Inspire 2, Mavic Air	55	1	−42 to −61
May 27, 2018	<i>P.vitulina</i>	am	prebreeding	16 (1)	Phantom 4	14	3	5 to 36
May 28, 2018	<i>P.vitulina</i>	am	prebreeding	8	Inspire 2	13	2	8 to 35
May 29, 2018	<i>P.vitulina</i>	pm	prebreeding	14 (3)	Phantom 4, Mavic Air	47	2	14 to 40

We encountered white whales on June 16, 2017 in Grønfjorden, and on August 26, 2018 in Tempelfjorden. During the 2017 encounter we performed straight-line flights over a pod at an altitude of 1.5 m above sea level. Given the results of the first encounter, in 2018 we approached individuals from an altitude of 90 m and then made incremental descents to altitudes of 40, 30, 25, 20, and 15 m, hovering over the area where the pod was expected to surface. We categorized unchanged swimming trajectories of white whales as no response in contrast to a response which involved the trajectory of the animals deviating, or deeper/ longer diving being initiated.

2.3 | Data analysis

A binomial distribution was the best fit for the harbor seal behavior data (Zuur et al., 2009). Due to the low frequency of high-level responses (4–6), we merged low-level behaviors (0, 1, 2) into a single variable “low-agitation,” and high-level behaviors (3, 4, 5, 6) into a “high-agitation” variable, which we then used as response variables in our models. We did not detect strong temporal autocorrelation in our models' residuals (Figure S6), possibly due to the large 10 s windows between samples and the relatively short RPAS flights. Moreover, models including an autoregressive structure yielded the same results as those that did not. Thus, we selected the latter based on parsimony. All continuous predictors (tide, haul-out size, RPAS distance, flight duration, and flight number) were standardized to overcome scale differences.

Due to large differences in the conditions encountered between the harbor seal molting and prebreeding seasons (Figure S2), as well as the different biological state of the individuals, we analyzed the seasons separately. For each season, we ran a two-step analysis. First, we assessed whether the presence of the RPAS had an impact on behavior through binomial generalized linear mixed models (GLMMs) with seal behavior as a response variable (either low-agitation or high-agitation) and RPAS presence as a main predictor (Equation 1). Sea state was not included due to high correlation with tidal state (Pearson correlation = 0.64). We fitted all possible variable combinations, ranked the models according to AIC values, and selected the most parsimonious model with a $\Delta AIC < 2$:

$$Y = b_0 + b_1 RPAS_{ijk} + b_2 Tide_{ijk} + b_3 Size_{ijk} + (Session_k + Id_{jk} + \varepsilon_{ijk}) \quad (1)$$

where

$$Y = \text{logit}(P_{ijk}) = \log\left(\frac{p}{1-p}\right).$$

The logit link function, p_{ijk} , is the probability that sample i on individual j of session k presents the specified outcome behavior category. $RPAS_{ijk}$ is a categorical variable which divides each flight session in three levels according to RPAS presence: before flights (control period), flight period (including all flights within a session), and after-flight period (including between-flight bouts and postexperimental period), $Tide_{ijk}$ is a continuous predictor, $Size_{ijk}$ is discrete and stands for the size of the hauled-out group. $Session_k$ and ID_{jk} are random intercepts for both session and individual nested within session. These variables were assumed to be normally distributed with mean 0 and variance σ_{S2} and σ_{ID2} , respectively. The residual error ε_{ijk} is the remaining variation within an individual, and it is assumed to be normally distributed with mean 0 and variance σ_e^2 .

If the selected RPAS presence model included *flight period*, we proceeded to the second step, where we analyzed the effect of RPAS distance. For this, we selected all subsets of the data corresponding to flight periods and applied binomial generalized additive mixed models (GAMM) with RPAS distance as a predictor, as in Equation 2:

$$Y = b_0 + f_1 Dist_{ijk} + b_1 Fnum_{ijk} + b_2 Fdur_{ijk} + b_3 Model_{ijk} + (Session_k + ID_{jk} + \varepsilon_{ijk}) \quad (2)$$

where F_1 is a nonlinear function applied on RPAS distance (Dist_{ijk}). The fixed-effects included flight number, considered as continuous and standardized to test for a cumulative effect (Fnum_{ijk}); flight duration as a continuous variable as well (Fdur_{ijk}); and RPAS model as a categorical variable (Phantom 4, Inspire 2 or Mavic Air, only for the prebreeding season). The random structure was identical to that of the GLMMs. As the GAMM were fitted over the subsets of data corresponding to the flight periods, Tide was not included due to very little variation happening during these time periods. Haul-out size was not included in this analysis as it was not selected in any of the models from the previous step. The selection process began with a global model from which fixed effects were removed one at a time by order of significance of the p -values.

The results from the GAMM for prebreeding season harbor seals suggested that the flights at the end of each session had a stronger influence on the probability that harbor seals presented high-agitation behavior. These flights were generally flown manually, so in order to study the disturbance potential of preprogrammed flights alone, we continued the analyses by removing the time periods corresponding to manual flights and repeating the two-step analysis described earlier.

GLMMs were fitted using package *lme4* version 1.1–21 (Bates et al., 2015) and GAMMs were fitted using package *gamm4* version 0.2–5 (Wood & Scheipl, 2017) in R version 3.4.0 (R Core Team, 2017). We set significance level at $p < .05$.

2.4 | Acoustic characterization and analyses

We carried out acoustic characterizations at a quiet, open area outside Tromsø, Norway (69.57963°N, 19.22076°E) on October 17, 2018 (Supplementary Methods 2). To reproduce sound levels that overflown animals would experience, our experimental setup consisted of a SM4 placed on a platform 0.5 m above the ground, over which we performed a set of flights with each RPAS. The recordings were obtained at 16 bits with a sampling rate of 48 kHz (stereo, a frequency response from 0 to 24 kHz), with a signal-to-noise ratio of 80 dB typical at 1 kHz re 1 Pa.

Tests for each RPAS model comprised two sets of manual flights. The first included straight-line horizontal transects flown at 40 km/hr between the take-off point and the SM4 placed 300 m away, at fixed altitudes of 10, 20, 40, 60, 80, and 100 m. The second set of flights included vertical profiles, with an ascent-descent flown continuously at a speed around 2 m/s (hereafter, V.c. ascent and descent) and an ascent-descent flown intermittently, with quick accelerations from 0 to 2 m/s on each of the altitude levels listed above (hereafter, V.i. ascent and descent). The motivation for testing different vertical profiles was to create a record of the variation in noise levels produced when altitude and speed change, which is common during fieldwork flight missions.

We identified the flight recordings by synchronizing sound meter and screen recordings from an iPad 4 mini (Apple Inc., Cupertino, CA) connected to the remote controller. We performed a preliminary analysis by visual inspection of the spectrograms in Raven Lite 2.0 (Cornell Lab of Ornithology, Ithaca, NY). The spectrograms revealed that RPAS signals were visible at 0.15 kHz, below which it was masked by ambient noise, and up to 24 kHz, the highest frequency recorded. However, the strongest signal decreased steeply above 15 kHz (Figure S7). Thus, during all subsequent analyses, we excluded frequencies below 0.15 kHz. To document the noise produced by the RPAS in a simple way, we computed broadband sound pressure level (SPL) measurements in 1 s time windows (applying half overlapping Hann window, which yields two values per second, and then averaging them) on all horizontal and vertical flights. Because the RPAS sound different when they are flown horizontally versus vertically, we analyzed differences across the frequency spectrum by calculating SPL for all one-third octave level (TOL) bands from 0.15 to 20 kHz for each flight trajectory (horizontal approach, V.c. ascent and descent, V.i. ascent and descent) at 20 m from the SM4, as they were the most stable profiles. Ambient noise arose from a small river in the distance and occasional bird songs; nearby traffic was rare. We calculated ambient SPL for a randomly selected minute before the start of the tests with each RPAS, both as broadband and TOL band SPL. We followed the specifications previously described except for time-averaging, which we did per-min instead of per-s to avoid

short-scale sound variations. We computed both broadband and TOL band analyses using PAMGuide (Merchant et al., 2015) in Matlab.

3 | RESULTS

3.1 | Effect of RPAS on harbor seals

Across the two study years we achieved a total of 89 flights over the harbor seals (Table 1). We obtained 5 and 9.5 hr of ground recording during the molting and prebreeding seasons, respectively. The number of flights in each of the nine sessions flown over harbor seals varied depending on the availability of individuals on shore and their level of responsiveness, and were limited by weather conditions or RPAS battery duration. The flight period—time between the first and the last flight of each session—was 50 ± 15 min (mean $\pm$ SD), ranging from 23 to 70 min (on May 28 and 29, 2018, respectively, Figure S1d, e). During the molting season, we flew an average of 8 profiles per session (8.3 ± 2.6) with a Phantom 4 Pro, and during the prebreeding season we flew 15 ± 6.4 profiles, including also flights with the Inspire 2 and the Mavic Air.

3.1.1 | Effect of RPAS presence

During the prebreeding season, the model for RPAS presence yielded a positive relationship between high-agitation behavior and RPAS flight period as well as tide. The relationship between high-agitation behavior and after-flight periods was negative. During the molting season, high-agitation behavior showed a positive relationship with both RPAS flight and after-flight periods (Table 2). Haul-out group size was not included in any of the models selected.

3.1.2 | Effect of RPAS distance

RPAS flight distances ranged from 10 to 300 m. The relationship between seal high-agitation behavior and RPAS distance was negative and significant in both seasons (GAMM $\chi^2_{\text{smooth}(\text{distance})} = 90.74$ and 95.93 , $p < .001$ for the prebreeding and molting season, respectively, Table 3). During the prebreeding period the probability of individuals showing high-agitation behavior increased by up to 20% at RPAS distances closer than 80 m, whereas during the molting season it increased up to 40% at flight distances closer than 150 m (Figure 2). During prebreeding, the probability of showing high-agitation behavior was lower when flying Mavic Air (estimate: -0.458 , SE: 0.223) or Inspire 2 (estimate: -0.720 , SE: 0.287) were, compared to Phantom 4 Pro flights. With increasing flight numbers, the probability that harbor seals presented high-agitation behavior also increased (estimate: 0.279, SE: 0.052), suggesting a

	Prebreeding		Molting	
	Estimate	SE	Estimate	SE
Intercept	−2.663	0.460	−1.914	0.187
Flight	0.201	0.071	0.518	0.078
After flight	−0.452	0.074	0.253	0.081
Tide	1.125	0.176	n.s.	n.s.

Note: n.s. = not selected.

TABLE 2 Estimates and standard errors of the explanatory models developed for prebreeding and molting seasons with high-agitation behavior as response variable. The explanatory variable tide was standardized.

greater influence of the later flights, which were generally flown manually. During the molting season, the probability of showing high-agitation behavior increased with flight duration (estimate: 0.132, SE: 0.038); the effect of flight number was highly variable (see SEs Table 3).

3.1.3 | Effect of preprogrammed flights

The RPAS presence models yielded a positive relationship between high-agitation behavior and RPAS preprogrammed flight period for the molting season (as well as tide and after-flight periods, see Table 4), though not for the prebreeding season. The RPAS distance model for the molting season yielded significant negative relationships between the probability of high-agitation behavior and RPAS distance (GAMM $\chi^2_{\text{smooth}(\text{distance})} = 11.83, p < .001$) and flight number (estimate: -0.473 , SE: 0.085). This model predicted a 10% increase in the probability of showing high-

TABLE 3 Best-fit generalized additive mixed models (GAMMs) for high-agitation behavior during the molting and prebreeding seasons for harbor seals at Midtøya, Svalbard, Norway during RPAS test flights. Estimates for fixed effects are followed by SE in parentheses.

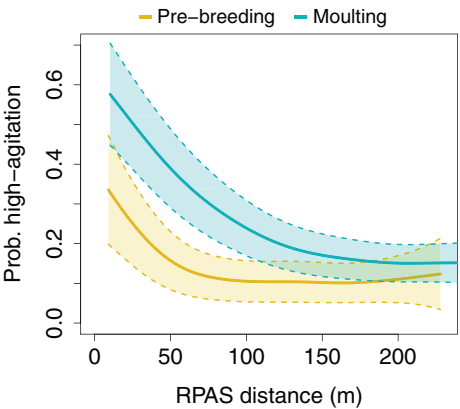
	S(distance)	Inspire 2		Mavic Air		Flight number		Flight duration	
		Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE
Molting	$-(\chi^2 = 95.93, p < .001)$	n.a.	n.a.	n.a.	n.a.	-0.194	0.096	0.132	0.038
Prebreeding	$-(\chi^2 = 90.74, p < .001)$	-0.720	0.287	-0.458	0.223	0.279	0.052	n.s.	n.s.

Note: n.a. = not applicable, only Phantom 4 was used during the molting season; n.s. = not selected. Variables showed different levels of significance: $p < .01$ and $.01 < p < .05$.

TABLE 4 Coefficients of the explanatory models excluding manual flights with high-agitation behavior as a response variable. Explanatory variables tide and haul-out size were standardized.

	Molting		Prebreeding	
	Estimate	SE	Estimate	SE
Intercept	-1.863	0.301	-2.768	0.650
Flight	0.400	0.080	-0.173	0.080
After flight	0.364	0.081	-0.444	0.077
Tide	0.820	0.224	1.573	0.188

FIGURE 2 Effect of RPAS distance on harbor seal behavior by season, as the probability of an individual presenting high-agitation behavior. Fitted estimates from the models (solid lines) are represented along with CIs (polygons) calculated from the fitted models.



agitation behavior when flying at short distances (Figure S7), in contrast to a 20% to 40% increase in the model that included both preprogrammed and manual flights (Figure 2).

3.1.4 | Occurrence of fleeing events

Fleeing was the strongest response we recorded. During the prebreeding season all or part of the haul-out fled during two overhead descents (at 20 m of altitude in a descent from 120 to 10 m, Figure S1a; and at 38 and 20 m of altitude in a descent from 100 to 20 m, Figure S1c). During the molting season harbor seals fled during overhead descents to altitudes of 100 and 60 m (in a descent from 120 to 30 m, Figure S1g). Three additional fleeing incidents occurred during the study, outside RPAS flight experiments, for no apparent reason. In all cases, the seals returned to the haul-out within a few minutes.

3.2 | Effect of RPAS on walruses

We achieved two sessions with a total of 31 flights and 5 hr of ground video and acoustics in association with walruses. We performed 15 and 16 flights in each session, lasting 1:45 and 1:15 hr, respectively. Models failed to converge due to small sample size and very different behavioral states of the walruses between the two sessions, so results are presented in a descriptive manner.

During the first session, 13 walruses were present at the haul-out, including two young individuals based on the size of their bodies and tusks. The preexperimental agitation level was high, but as the session progressed the animals became more settled. In three cases, the walruses fled, moving down the shore to the water line, during a straight-line flight at 60 m of altitude, a close orbit at 50 m, and an overhead descent from 20 to 16 m. In all cases, most individuals remained on shore and moved back to the top of the spit quite quickly, settling down before our flight tests resumed. We identified the same adult individual as being the first to react to the RPAS during all three fleeing events. During the second session, the haul-out had 30 individuals and the preexperimental level of agitation was very low, with most individuals resting in a compact group. Walruses only reacted to the RPAS during an overhead descent, at close distance (20 m altitude), when they began moving their heads side to side or showing Alert behaviors. All individuals went back to resting when the RPAS moved away, though quick accelerations at around 40 m of altitude still caused them to lift their heads. Overall, head-lifting and scratching, without locomotion, were the most common reactions.

3.3 | Opportunistic sampling

During both encounters with polar bears, the female (mother of two cubs) clearly took notice of the RPAS, lifting her head as soon as the RPAS was powered up, at distances of 300 m and 240 m, respectively. The female stood up and started walking slowly towards her cubs during the second transect, when the RPAs reached an altitude of 50 m and she lifted her head again on the following transect at 20 m of altitude. Only when we approached to a 5 m radius did she stop walking to observe the RPAS; she never attempted to flee. Upon retreat of the aircraft, the polar bears continued walking at a slow pace towards the sea. During the second encounter, the female again lifted her head when we overflew the family at 110 m altitude. During subsequent profiles at descending altitudes the bears did not display any overt change in their behavior, walking at the same pace in the same direction. The mother checked her cubs regularly as she walked and lifted her head occasionally, as did one of the cubs; there were no differential reactions to the various types of flight profiles. After the flight trial, we kept the boat at the same distance from the shore and observed the bears, which did not show any signs of distress.

During the first encounter with white whales, we did not observe any reactions while the RPAS remained behind the pod at 1.5 m over the sea; the pod kept swimming straight forward, surfacing regularly. However, when the RPAS hovered in front of the pod, the whales immediately dove and changed direction. During the second encounter, we followed the trajectory of an individual and positioned the RPAS ahead of the whale at 40, 30, 25, 20, and 15 m of altitude. The whale dove deeply after surfacing twice when the RPAS was hovering at 15 m. A second test individual also showed avoidance behavior after surfacing twice when the RPAS was hovering at 10 m over sea level. Soon after that, the whole pod dove and we lost visual contact with all individuals.

3.4 | RPAS acoustic characterization

3.4.1 | Horizontal profiles

Horizontal approaches to the SM4 up to 100 m yielded SPL under 45 dB re 20 μ Pa in all RPAS except Inspire 2, which was louder. Mavic Air yielded lower SPL in general and remained under 50 dB re 20 μ Pa until a distance of 40 m (Figure 3e). We observed a pattern along the range of horizontal distances: flying at distances between 150 to 60 m from the SM4, the RPAS yielded higher SPL at high altitudes; while at distances shorter than 40 m, flights at lower altitudes yielded higher SPL (Figure 3a, c, e).

Profiles flown at altitudes higher than 60 m yielded a slow and constant increase in SPL as the RPAS approached, whereas at lower altitudes the increase in SPL was much steeper, resulting in exponential increases in SPL as distance decreased (Figure 3a, c, e). Approaching at 10 and 20 m of altitude, all aircraft yielded SPL around 60 dB re 20 μ Pa (Figure 3c, e) except Inspire 2, that reached values over 70 dB re 20 μ Pa (Figure 3a).

3.4.2 | Vertical profiles

On vertical flights, ascending profiles yielded lower SPL than descending profiles (Figure 3b, d, f). At 40 m altitude, for example, ascents with all aircraft yielded SPL about 5 dB re 20 μ Pa lower than a horizontal flight at the same altitude. This reduction in SPL is comparable to that between a horizontal flight over the SM4 and at distances of 60–80 m from it (Table S4). In contrast, descending profiles yielded similar SPL to horizontal profiles at the same altitude with all RPAS except Inspire 2, which had higher values (Figure 3b and Table S4).

Mavic Air showed the same pattern at 40 m and below. Phantom 3 Std. and Inspire 2, however, yielded higher SPL when descending below 40 m than during horizontal flights at the same altitudes (Table S4).

3.4.3 | 1/3 Octave band analysis

Inspire 2 yielded the highest SPL values across the spectrum, followed by Phantom 3 Std. and Mavic Air (Figure S9a, b). All flight profiles yielded similar SPL on TOL bands below 0.2 kHz and over 16 kHz, and energy levels decreased steeply over 10 kHz (Figure S9).

Inspire 2 and Mavic Air yielded descending profiles with comparable patterns across the frequency spectrum, with peaks that did not match those of the horizontal profiles (Figure S9). All flight profiles from Phantom 3 Std. showed a similar SPL pattern across the spectrum, but the descending profiles dominated higher frequencies whereas the horizontal profile yielded higher SPLs in the lower frequencies (Figure S9b).

At 20 m of altitude, RPAS yielded TOL SPL that were consistently higher than the ambient noise at the site where the acoustic characterizations took place in Tromsø (calm conditions; see Figure S10). However,

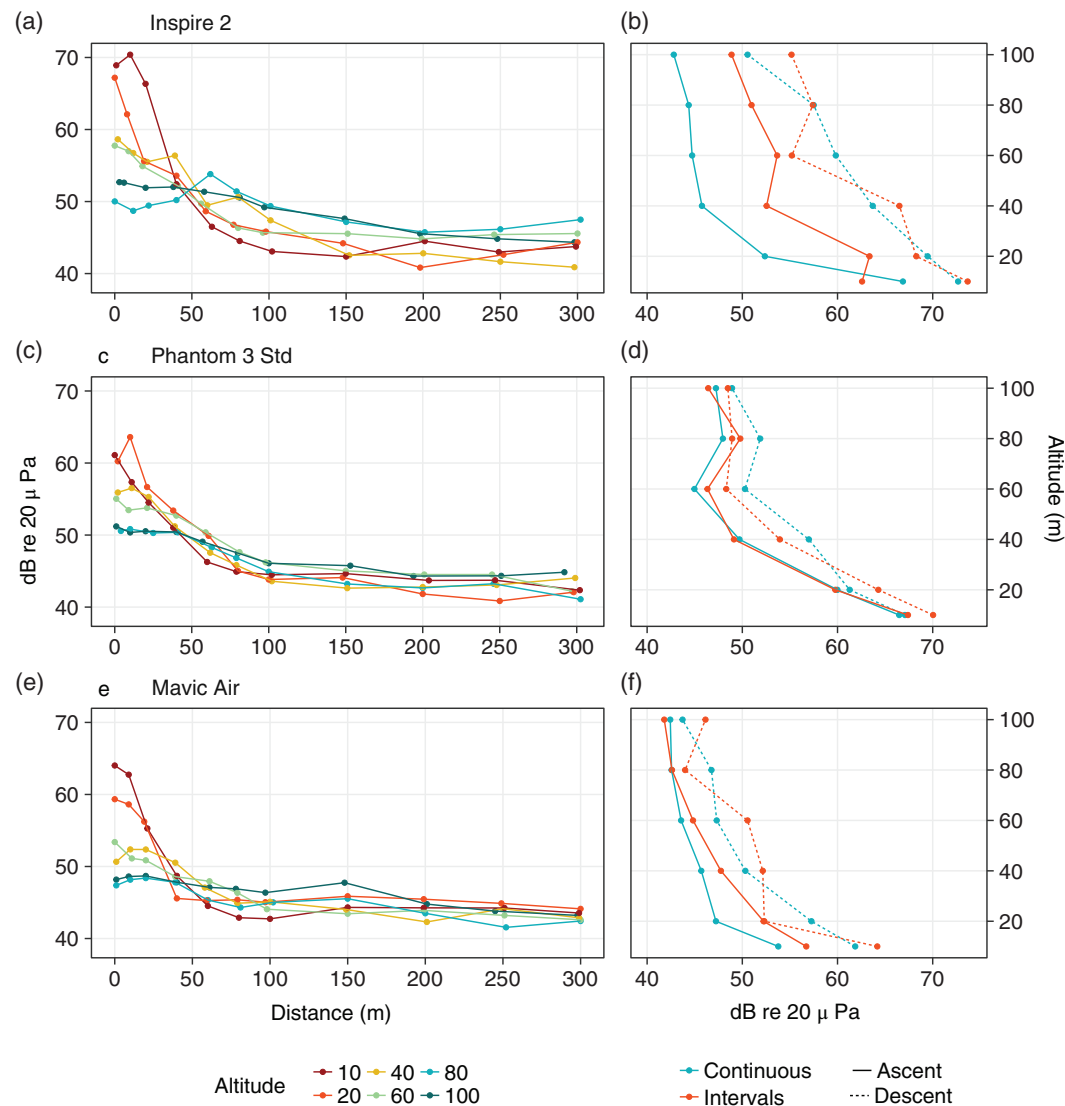


FIGURE 3 Broadband sound pressure level in dB re 20 μ Pa (0.15 to 24 kHz) for profiles flown with Inspire 2 (a and b), Phantom 3 Std. (c and d), Mavic Air (e and f) a, c, e: Horizontal flights, each color corresponds to a flight at a constant altitude and speeds around 40 km/h. b, d, f: Vertical profiles flown over the SM4 at a speed around 2 m/s. Blue lines represent vertical constant ascents (continuous line) and descents (dashed line); orange lines represent vertical intermittent ascents (continuous line) and descents (dashed line).

ambient noise during disturbance experiments in Svalbard was generally much higher (due to wind, wave action and birds, see Figure S10) and likely masked most of the sound produced by the RPAS flying at altitudes over 20 m.

4 | DISCUSSION

In this study, we provide the first overview of the impact that a variety of RPAS and flight profiles can have on the behavior of several Arctic marine mammal species. The acoustic characterizations of the RPAS used during the

disturbance experiments provided a basis for interpretation of our results and those in other studies using similar RPAS. We characterized behavioral tolerance levels for walruses, prebreeding and molting harbor seals and provide descriptive assessments for responses to RPAS for white whales and polar bears, that can be used to design studies using RPAS that avoid disturbance of these and other species.

Our study highlights the complexity of assessing the degree and significance of sensitivity to RPAS disturbance in wildlife. Harbor seal responses were not consistent between seasons, which has also been noted in other marine mammal studies (Pomeroy et al., 2015). During the prebreeding period, harbor seals tended to react from a threshold distance of 80 m, and after flight tests the probability of high agitation state dropped to levels lower than those prior to the experiments. This unexpected result is likely due to a combination of high preexperimental disturbance and tidal conditions, elevating the initial level of alertness in the haul-out group. During the molting season, the model detected an elevated probability of high-agitation behaviors at greater distances, 150 m, and animals maintained higher levels of agitation after the experiments had finished. High preexperimental agitation was likely the cause of the higher sensitivity in this case, as a polar bear visited the haul-out the day prior to the flight experiments. Increased alertness together with a lack of wind and swell, both of which can mask the sound of the RPAS, resulted in a fleeing event during an overhead descent at 100 m altitude. Because our sample sizes are small, this single event might have biased our results for the molting season. The increased level of alertness was likely also why the entire haul-out fled on three occasions when the RPAS was not flying. However, seals at molt seemed to exhibit lower sensitivity to RPAS than in the prebreeding season; the animals did not flee during any other descent or even during low-altitude flights. Physiological state could have influenced the level of responsiveness in harbor seals, but assessments of this would require more complex experimental designs.

Other factors impacting how sensitive animals were to disturbance from RPAS included tidal state, the number of animals hauled out at a given time, the presence of juveniles and ambient noise levels. High tides resulted in increased agitation levels at harbor seal haul-outs, especially during the prebreeding season. Rising tide exposed the seals to increasing swells, forcing individuals to either abandon the haul-out or move to higher elevations (all considered high-agitation behaviors). The lesser influence of tidal state during the molting season is likely due to a combination of individuals at molt wanting to stay dry, and smaller swell during all sessions from this study period, which caused lower stress levels in the group. Our study highlights the importance of accounting for tidal state when assessing disturbance on harbor seal haul-outs.

Unlike harbor seals, walruses were not affected by tidal state because they hauled out well above the high tide mark, on the top of a sand spit. Nevertheless, large swells together with the wind had an indirect influence by masking the sound from RPAS. This likely influenced the results of the second flight session at the walrus haul-out, when the animals did not exhibit any overt reactions.

The effect of haul-out group size on animal reactions to RPAS disturbance was also explored in our analyses. Other studies on harbor seals have shown that larger groups tend to spend more time performing low-energy activities such as sleeping (Kriebler & Barrette, 1984; Terhune & Brillant, 1996). However, our models failed to detect any effect of group size. During the prebreeding season, the haul-outs might have been too small for the seals to benefit from group vigilance and other protective benefits of grouping (see Reder et al., 2003 for more details). During the molting season, higher alertness caused by a polar bear's presence in the area as well as frequent agonistic interactions, might have masked positive effects of haul-out group size (Kriebler & Barrette, 1984). The large differences in haul-out group size between the prebreeding and molting season, however, could help to explain the different level of responsiveness observed between seasons. Walruses also showed the expected pattern, with smaller groups reacting more to RPAS flights than larger groups.

Ditmer et al. (2019) and Barnas et al. (2018) both suggest that polar bears do habituate to RPAS. However, the experimental set-up we tested on harbor seals and walruses likely did not allow for habituation, as flight durations were short, and low numbers of flight sessions were undertaken.

The presence of young individuals within groups of animals has also been reported to influence sensitivity to disturbance (Øren et al., 2018; Pomeroy et al., 2015; Salter, 1979). However, the low numbers of juveniles in harbor seal haul-outs precluded us from testing this in our study. Conversely, young individuals seemed to play a crucial role

in triggering fleeing events at the walrus haul-outs, although they did not seem to react to the RPAS directly, but rather showed an indirect response mediated by a curious adult showing the first signs of alert behavior. In the case of polar bears, the presence of cubs during the RPAS tests likely influenced our results, as females with cubs are more easily disturbed than other age and sex classes (Andersen & Aars, 2008).

Understanding the hearing threshold of wildlife species is critical in attempting to avoid disturbances due to the acoustic impacts of RPAS (Smith et al., 2016). However, the ability of an animal to detect a sound does not necessarily mean that they will react to it, and may only respond when a sound is loud enough that it is perceived to be a threat (Scobie & Hugenholtz, 2016). The RPAS models used in this study produced sound energy in frequencies under 16 kHz, with a steep decline at frequencies over 10 kHz. Comparing animal audiograms with the spectrum of the sound they will be exposed to through RPAS flights could therefore provide insight into the level of disturbance animals may experience (Grubb et al., 2007). Audiograms for our study animals confirm that the sounds produced by the RPAS we used in this study were well within their hearing ranges. Reichmuth et al. (2013, and references therein) found that the lowest hearing threshold of harbor seals was -4 dB re $20 \mu\text{Pa}$ at 3.2 kHz, and their sensitivity remained within 20 dB of this value between 0.5 and 14 kHz. Similarly, polar bears have a low-end hearing threshold of -10 dB re $20 \mu\text{Pa}$ at 14 kHz remaining within 20 dB between at least 4 and 16 kHz (Owen & Bowles, 2011). High hearing sensitivities also have been reported elsewhere for polar bears (Andersen & Aars, 2008), which reacted to snowmobiles at distances greater than 1 km. Given these hearing sensitivities, the detections of RPAS in our study by harbor seals at 100 m altitude and polar bears at a distance of 300 m are reasonable. The sound levels for the RPAS reported in our study can provide important information for people planning to use RPAS with other wildlife, in combination with audiograms of the potential subject species to predict impacts and to avoid them. For example, given that ringed (*Pusa hispida*) and spotted seals (*Phoca largha*) have similar hearing sensitivity to those of harbor seals (Sills et al., 2014, 2015), we would expect them to detect RPAS at similar ranges.

Walruses in our study were able to hear the RPAS descending at 20 m, as they are sensitive to sounds at around 45 to 50 dB re $20 \mu\text{Pa}$ at frequencies between 0.25 and 8 kHz at ambient noise levels of 40 dB re $20 \mu\text{Pa}$ (Kastelein et al., 1993, 1996). However, we suggest that walruses likely have higher hearing sensitivity, since the haul-out group fled during an overflight at 50 m and small flying objects are not likely to be perceived as a visual threat. Thus, greater distances should be used for surveying walruses when possible.

Our results reinforce the relevance of accounting for ambient noise levels when planning RPAS flights with potentially sensitive species. During experiments on polar bears, the lack of wind enabled the female investigated in our study to detect the RPAS at 300 m during the launch. Conversely, a combination of wind, big swells, and large numbers of birds resulted in the RPAS not being noticed until distances were less than 40 m during some of the flight experiments on harbor seals.

Acoustic impacts of RPAS are likely to be modest for species that spend a lot of time underwater, since very little sound penetrates into the water (Christiansen et al., 2016; Erbe et al., 2017). Accordingly, we observed no reactions when RPAS were flown behind white whales, even at low altitudes. Similar results have been reported for other cetacean species (Durban et al., 2015, 2016; Pirodda et al., 2017; Torres et al., 2018). However, RPAS flights under 15 m caused strong visual impacts when flown in front of the whales, which was similar to reactions reported in blue whales and bottlenose dolphins (Domínguez-Sánchez et al., 2018; Fettermann et al., 2019).

Other important factors influencing the level of disturbance included the RPAS model and the approach strategy. Manual flights, including overhead descents and straight-line overflights, caused more agitation than preprogrammed flights both on harbor seals and walruses. Overhead descents present rapid noise onset rates (dB/s) and a sound of higher frequency, and make it harder for the animals to track the RPAS visually. At the same time, the speed and direction in manual flights are often less constant than in preprogrammed flights, and the resulting sudden accelerations cause variations in the pitch of sound produced. By flying orbit profiles, Inspire 2 caused less agitation than Phantom 4 Pro, despite the fact that the former is both larger and noisier. Mavic Air, presumably because of its small size and lower sound levels, also caused less agitation than Phantom 4 Pro, even when flown manually. In addition, flying at low altitudes yields lower noise levels at ranges over 50 m, such as during wide orbit profiles, because

of the acoustic profile of VTOL RPAS (Kloet et al., 2017). Importantly, our study confirms the need to maximize the predictability of the noise source by avoiding descent flights directly above animals and to prioritize preprogrammed flights when these are possible as a way to minimize rapid noise onset rates (Bowles, 1995; Raoult et al., 2020; Sweeney et al., 2016; Vas et al., 2015).

4.1 | Conclusions

Our study provides the first science-based assessment of the impacts of RPAS on marine mammals in Svalbard. We have found that sensitivity to RPAS varies across species and across seasons, but also between consecutive days at the same location. Short-term temporal variations in sensitivity to disturbance can be primarily attributed to factors such as the presence of juveniles in the case of walruses, tidal state, or noise from swell and wind, which can mask sounds from RPAS. Other factors such as physiological state, exemplified in our study by the effects of molt in seals, when they are reluctant to flee to the water at flight distances that would likely stimulate a response at other times of year. However, our experiments suggest that preexperimental levels of agitation might be among the strongest drivers of sensitivity to disturbance by RPAS.

Our study suggests that minimum distances of 50 and 80 m to walruses and harbor seal aggregations should be maintained, respectively. Polar bears showed sensitivity to RPAS as a novel stressor, despite displaying limited behavioral responses, which suggests that caution should be exhibited when flying RPAS near this species. Flight distances should be maximized, and flights should be terminated if fright response is elicited. Given the sensitive hearing of all the species tested in our study, it was not surprising that ambient noise played an important role in masking RPAS sound and therefore influenced the degree of sensitivity they showed in different acoustic environments. Conversely, visual cues caused significant impact on white whales, which highlights the importance of approaching this species only from behind or using altitudes higher than 15 m.

As expected, different RPAS yielded varying levels of sound, mostly in relation to their size, although flying smooth trajectories is likely more important than the particular type of RPAS used. Manual flights, and particularly overhead descents, caused the highest levels of agitation in our study because they produced higher noise levels and variations in sound pitch. Therefore, we suggest preprogramming RPAS flights and following orbit profiles whenever the objective of the study allows for it, as well as avoiding changes in altitude in close proximity to study animals.

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AUTHOR CONTRIBUTIONS

Albert Palomino Gonzalez: Conceptualization; data curation; formal analysis; investigation; methodology; software; validation; visualization; writing-original draft; writing-review & editing. **Kit Kovacs:** Conceptualization; funding acquisition; project administration; resources; supervision; validation; writing-review & editing. **Christian Lydersen:** Conceptualization; funding acquisition; project administration; resources; supervision; validation; writing-review & editing. **Rolf Ims:** Supervision; writing-review & editing. **Andrew Lowther:** Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; writing-review & editing.

ETHICS STATEMENT

This study was approved by the local authorities (Sysselmannen på Svalbard; RIS ID: 10725). We flew RPAS only over small areas and we ceased tests when the study animals showed flight responses, resuming only if they returned quickly and settled into rest.

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SUPPORTING INFORMATION

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