Received: 22 February 2021 | Accepted: 9 July 2021

DOI: 10.1111/2041-210X.13691

RESEARCH ARTICLE

Methods in Ecology and Evolution BRITISH ECOLOGICAL SOCIETY

Determination of optimal flight altitude to minimise acoustic drone disturbance to wildlife using species audiograms

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Funding information
Natural Environment Research Council

Handling Editor: Lian Pin Koh

Abstract

1. Unmanned aerial vehicles (UAVs) are increasingly important in wildlife data collection but concern over wildlife disturbance has led several countries to ban their use in National Parks. Disturbance is an animal welfare concern and impedes scientific data collection through provoking aberrant behaviour. Dealing with the issue of disturbance will enable wildlife researchers to use UAV technology more effectively and ethically.
2. Here we present a novel method to determine optimal flight altitude for minimising drone disturbance for wildlife using species audiograms. We recorded sound profiles of seven common UAV systems in the horizontal and vertical planes at 5-m increments up to 120 m. To understand how mammals perceive UAV sound, we used audiograms of 20 species to calculate the loudness of each UAV for each species across the measured distances. These calculations filter the UAV noise based on the sensitivity of species' hearing over the relevant frequency spectrum.
3. We have devised a method to optimise the trade-off between image spatial resolution and flight altitude. We calculated the lowest point at which either the UAV sound level decreases below an acceptable threshold, here chosen as 40 dB, weighted according to species' hearing sensitivity, or disturbance cannot be significantly further minimised by flying higher. The latter is quantified as the point above which each additional 5 m of flight altitude causes on average less than 0.05 dB decrease in sound pressure level.
4. Reliable data on appropriate flight altitudes can guide policy regulations on flying UAVs over wildlife, thus enabling increased use of this technology for scientific data collection and for wildlife conservation purposes. The methodology is readily applicable to other species and UAV systems for which sound recordings and audiograms are available.

Isla Duporge and Marcus P. Spiegel contributed equally to this work.

KEYWORDS
aerial survey, anthrophony, audiogram, audiometry, conservation, remote sensing, sound pressure level, unmanned aerial vehicle (UAV)

1 | INTRODUCTION

The introduction of unmanned aerial vehicles (UAVs) is revolutionising the study of wildlife. Recent applications include gathering biological samples (e.g. blow samples from whales Acevedo-Whitehouse et al., 2010; Dominguez-Sanchez et al., 2018; Geoghegan et al., 2018; Pirotta et al., 2017), monitoring morphometric attributes (Burnett et al., 2019) and collecting behavioural data (Fiori et al., 2020; Graving et al., 2019). In addition UAVs have been used for census surveys (He et al., 2020; Linchant et al., 2018; Vermeulen et al., 2013; Ratcliffe et al., 2015), for anti-poaching surveillance (Marks, 2014; Mulero-Pazmany et al., 2014), for mapping species habitat use and distribution (Goebel et al., 2015; Koh & Wich, 2012; Perryman et al., 2014; Szantoi et al., 2017; van Andel et al., 2015), for locating radio-tagged animals (Muller et al., 2019), for assessing species body mass and condition (Christiansen et al., 2019; Krause et al., 2017), for relocating animals to mitigate human–wildlife conflict (Hahn et al., 2017; Schiffman, 2014) and for kinematic analysis (i.e. recording running giraffes; Basu et al., 2019). This technology also enables behavioural ecologists to study fine-scale wildlife movements that are undetectable from the ground (Fiori et al., 2020). Flying UAVs is less disruptive than collecting data using existing techniques (e.g. manned aircraft Colefax et al., 2019; Yang et al., 2019) or vessels (Pirotta et al., 2017), and can be used to access species in locations that are impractical or unsafe to visit on foot. It is now possible to use automated analysis techniques to speed up detection of species in resulting imagery (Gray et al., 2019). The applications of UAVs to wildlife studies are numerous and continue to grow (Duffy et al., 2020; Hodgson & Koh, 2016). However, there is significant scope for misuse: alarming media coverage has portrayed UAVs as a new source of disturbance in natural habitats (Keane, 2018; Sawer, 2016). Social media videos showing wildlife being harassed have been widely circulated (e.g. a video showing a bear cub highly distressed by a UAV has gathered more than 8.5 million views Bittel, 2018; Youtube, 2018). Although alarmist news articles and social anxiety are common when new technologies become widely available (Bauer, 1995), disturbance should be taken seriously as the noise emitted from UAV systems can distress wildlife in several ways. Disturbance effects include obscuring auditory detection and communication, and eliciting behaviours that displace time and energy from primary survival functions (e.g. feeding, mating and breeding; Mulero-Pazmany et al., 2017). Additionally, disturbance impedes collection of scientific data as unnatural movement is triggered.

Using UAVs for wildlife monitoring and surveying is hampered by a lack of research and clarity on disturbance issues (Jeanneret & Rambaldi, 2016; Rambaldi, 2019). Concerns over the possible adverse effects of UAV use on wildlife have caused several countries to ban UAVs in National Parks, including in the United States (Baltrus, 2014) and South Africa (Drone Laws in South Africa, 2021).

There is a growing body of literature discussing the impact of UAV-generated disturbance on large mammals based primarily on visual observation of aberrant behaviour (Arona et al., 2018; Hodgson & Koh, 2016). Guidelines on advised flight altitudes based on visual observations are presented in several studies, for example, 25–40 m above water level (AWL) for bottlenose dolphins (Fettermann et al., 2019) and 80–100 m above-ground level (AGL) for snub-nosed monkeys (He et al., 2020). All guidelines require nuance as different UAV designs generate different sound profiles, and sound propagation loss (sound wave dissemination) is affected by numerous environmental and situational factors (e.g. vegetation) and atmospheric conditions (e.g. wind speed and direction; Bennitt et al., 2019).

Current evidence indicates substantial inter- and intraspecific variability in the flight altitude at which a disturbance is detected when using the same UAV system (Brisson-Curadeau et al., 2017). For example, sea turtles have been found to be undisturbed by UAVs flown as low as 10 m (AWL; Biserkov & Lukanov, 2017) whereas crocodiles react visibly to UAVs at 50 m (AGL; Bevan et al., 2018). Adélie penguins *Pygoscelis adeliae* are more readily disturbed than gentoo penguins *Pygoscelis papua* during flights over their nest sites conducted at the same altitude (Rummler et al., 2018). One study comparing sound from two UAVs with the hearing thresholds of odontocete and mysticete whales and pinnipeds showed that the noise could only be quantified above ocean ambient sound at 1 m depth when flying at 10 m, therefore, disturbance is only a concern when UAVs are flown very close to the water surface (Christiansen et al., 2016).

However, the concept of disturbance remains ill defined. Species may not immediately change their behaviour when they are disturbed or stressed, yet existing studies have largely focused on assessing animals' responses through visual observation (Fettermann et al., 2019; Ramos et al., 2018; Rümmler et al., 2015; Vas et al., 2015). However, without physiological information or baseline behavioural data from which to understand anomalies, it is difficult to gauge whether disturbance has occurred. For example, the heart rate of black bears increased by 300% when a UAV was flown overhead although no other discernible behavioural response was detected (Ditmer et al., 2015). Sensitivity to noise varies across taxa and within species groups depending on sex, age, life history, breeding season and the level of habituation to noise (Bennitt et al., 2019; Ratcliffe et al., 2015). In a follow-up study on the same black bears, it was found that the elevation of heart rates dropped as the bears became habituated to the sound after 4 weeks of exposure (Ditmer et al., 2019). It is time-, labour-, and cost intensive to gather physiological and behavioural baselines against which to measure disturbance, although these can be revealing.

Planning UAV flights always entails trade-offs between flight altitude and image spatial resolution with the goal of maximising image resolution while minimising disturbance. Image resolution is defined by the ground sampling distance (GSD, distance between pixel centres on the ground), which is linearly related to the height above-ground level for cameras with a fixed focal length. For example, GSD for a survey with the Mavic Pro Platinum over ground is 1.24 cm/pixel, 2.48 cm/pixel and 3.72 cm/pixel for flights at 40, 80 and 120 m respectively. Flight altitude must provide the GSD to meet research aims while the potential for disturbing species is acceptably minimised.

Existing studies assessing UAV disturbance on wildlife often use A-weighted decibels, dB(A), which weight frequency-specific levels according to the sensitivity of human hearing (Ditmer et al., 2015; Hodgson et al., 2013; Wegdell et al., 2019). This method is problematic, as this weighting is based on human perception rather than the hearing sensitivity of the species of interest. Mammalian hearing is very diverse. For example, bats and dolphins hear in the ultrasonic range (>20 kHz), while whales and elephants hear in the infrasonic range (<20 Hz), rendering A-weighted measurements misleading for these species.

Here, we present a new method that calculates advisable flight altitudes based on an interpretation of UAV noise that incorporates species' hearing. We used audiometry—a measurement of the range and sensitivity of hearing generated for different species—and cross-reference these with sound measurements from seven commonly used UAVs. Our method does not rely on longitudinal behavioural datasets to understand disturbance but can be integrated with in-situ behavioural observations. We generated sound profiles for seven commonly used UAVs and applied our method to 20 species for which audiograms were available. The three main research objectives were:

1. Describe the noise profile of seven commonly used UAV systems.
2. Use available audiograms to create species-weighted measurements to demonstrate how different UAVs are heard by various species.
3. Generate advisable flight altitudes for flying each UAV over these species by calculating the lowest altitude at which the loudness is either below an acceptable threshold or no longer decreases significantly with altitude, thus minimising disturbance while maximising image resolution.

2 | MATERIALS AND METHODS

2.1 | UAV audio recording collection

Unmanned aerial vehicles audio recordings were taken for seven commonly used UAV systems from DJI (Shenzhen DJI Sciences and Technologies Ltd.): Inspire 2, Phantom 4, Mavic 2, Mavic Pro, Mavic Pro Platinum, Mavic Mini, and Spark. Recordings were taken 14–25 May 2020 in an open field in Wytham, a research facility belonging to the University of Oxford, UK. Recordings were taken between 23.00 and 03.00 (GMT) on nights when zero wind speed was detected on the anemometer, and ambient background sound levels were low. Flights were conducted by a certified UAV pilot with permission from the UK Civil Aviation Authority.

The sound from each UAV was recorded along a single transect in two principal directions: vertical, with the drone directly overhead, and horizontal, with the drone displaced from the microphone at a fixed height. As we explain later in this section, only the vertical recordings were used to ultimately arrive at advisable flight altitudes. The horizontal recordings were taken to provide a comparison for how UAV noise propagates differently in the horizontal and vertical planes.

Vertical recordings were taken with the microphone at ground level. The internal UAV GPS was used to hover the UAV at the desired altitude during recording. All vertical recordings were taken when there were not any wind gusts or transient noise. For the horizontal recordings, the UAV was fixed to a 1.5 m high speaker stand, and the microphone was held at the same height. The stand provided a consistent setup for our recordings that would not be affected by gusts of wind and enabled us to easily pause measurements when there was transient noise (e.g. owls, aircrafts). Given the flying settings, the recordings are reflective of the UAV hover mode in windless conditions, consistent with the vertical recordings.

Recordings were taken vertically and horizontally at 5-m intervals up to a maximum distance of 120 m—the legal limit for UAV flight altitude in the United Kingdom. Three ambient background sound recordings were taken prior to the UAV recording at 5, 50 and 100 m. Each measurement was repeated three times at each distance to ensure consistency. The audio data were recorded using the Signalscope X Pro Advanced Toolset Application (version 10.8.4) from Faber Acoustical (http://faberacoustical.com/) in combination with a calibrated omnidirectional electret condenser microphone micW i437L, Class 2 - sensitivity 7.5 dBFS (94 dB SPL @ 1 kHz) [http://www.micwaudio.com]. The application was run on an Apple iPhone Xs using iOS.13.5.1. We use calibrated recordings from the microphone from 100 Hz to 20 kHz, logging audio spectrograms in 10 Hz bins via the Fast Fourier Transform (FFT) Spectrum Analyser. The total record length was 250 ms, consisting of four exponentially averaged FFT recordings of 100 ms (50% overlap). The noise floor of the measurement system was 32 dB(A).

2.2 | Audiogram data collection

The species audiograms in this paper were taken from an open portal provided by The University of Toledo, Ohio, USA (Heffner, 2020) and a portal on Marine Mammal audiograms created at the Museum für Naturkunde, Berlin, Germany (Animal Audiogram Database, 2021). Each species has a frequency range where its hearing is most sensitive. Audiograms or hearing curves, as shown in this paper, display an individual's hearing range at various frequencies. The audiograms vary in terms of design and the number of individuals measured but should be representative of the species to which the individuals belong. The audiograms were collected under laboratory conditions using either the behavioural psychophysical method or auditory brainstem response (ABR) experiments. The former relies on training animals to react to a sound using either appetitive operant conditioning—recording an animal's response elicited by sound to gain rewards of food or water (Elder, 1934; Hienz et al., 1982; Kastak & Schusterman, 1998; Kojima, 1990; Owren et al., 1988), positive reinforcement training (Schusterman, 1974) or conditioned avoidance (Flydal et al., 2001; Heffner & Heffner, 1990; Heffner et al., 2014). In behavioural psychophysical experiments, species are exposed to sound frequencies of varying amplitude. The hearing threshold is defined as the levels at which the species cease to respond (Jackson et al., 1999). In contrast, ABR does not necessitate training animals but rather measures brain activity (auditory evoked potentials—AEPs) in response to auditory stimuli—electrodes are placed on the skin to record small variations in voltage that are elicited when playing sound of varying frequency and intensity (Sohmer et al., 1991). All the audiograms in this study measured animals' hearing thresholds while varying frequencies in octave intervals.

2.3 | UAV audio processing

Recordings were analysed using the R project for statistical computing (R Core Team, 2020). We used the 10 Hz sound pressure levels (SPLs) generated by the FFT application to calculate third-octave band (TOB) levels and create power spectral density curves (PSDs) representing the frequency profile of each UAV's noise at each distance. We also binned the SPLs into octave bands to match the frequency intervals of the species audiograms, enabling an integrated analysis. Separating the frequency range into octave and TOBs is common in sound analysis to create natural groupings of individual frequencies or narrowband sounds. The bands are unequal in width, such that the upper frequency in an octave band is twice the lower band frequency and the upper frequency in a TOB is the cube root of two times the lower frequency. For example, the 1 kHz centre frequency octave and TOBs range from 710–1,420 Hz and 891–1,122 Hz, respectively, while the 16 Hz octave and TOBs range from 11–22 Hz and 14.1–17.8 Hz respectively.

To calculate the SPL at each band, we added together the 10 Hz SPLs falling within the band's frequency range. Since the sounds at separate frequencies have no correlative relationship, we binned SPLs by adding levels as incoherent sources:

$$\mathrm{SPL}_1 + \mathrm{SPL}_2 + \ldots + \mathrm{SPL}_n = 10\log_{10}\left(10^{\mathrm{SPL}_1/10} + 10^{\mathrm{SPL}_2/10} + \ldots + 10^{\mathrm{SPL}_n/10}\right). \quad (1)$$

For each TOB calculation, we also corrected for the differences between TOB bandwidths and the range of the n assigned 10 Hz SPLs:

$$\text{TOB level} = \sum_{i=1}^{n} (10\ \text{Hz SPL})_i - 10\log_{10}(10n) + 10\log_{10}(\text{TOB Bandwidth}), \quad (2)$$

where the summation is done as in Equation (1). To calculate PSDs, we subtracted $10\log_{10}(\text{TOB Bandwidth})$ from each TOB level, which is equivalent to the computation in Equation (2) without the addition of the final term.

We compiled a single ambient curve for the field site that included the minimum SPL at each 10 Hz bin from all the ambient recordings. We use the lowest magnitude recording to represent persistent ambient noise. Similarly, for each of the three UAV recordings at a given distance, we chose the lowest amplitude sound measurement at each frequency to eliminate spikes caused by transient background noise. The sound curves were trimmed to the 100–20,000 Hz range, as the sensitivity of the microphone at these frequencies below 100 Hz was insufficient. In addition, the majority of species investigated in this study do not hear well below 100 Hz. We compared the ambient and UAV recording PSDs to the sound floor PSD of the microphone, which was provided by the manufacturer, to ensure that the UAV sound was audible above the microphone.

2.4 | Integrating species audiograms with UAV recordings

All UAV recordings were weighted by the species audiograms to provide a measure of how different species perceive the sound level of each UAV based on their hearing sensitivity across the relevant frequency spectrum. The weighting was done by subtracting the species' hearing threshold from the corresponding octave-band level for each octave. Any negative values were set to 0 dB, as these indicate frequencies where the UAV SPL was below the species' hearing threshold. Weighted sound levels for all octave bands were summed to create a single, overall species-weighted sound level. Thus, the loudness of UAV d for species α at a given distance was calculated as:

$$\mathrm{dB}(\alpha)_d = i\text{octavebands} - \sum max\left(\text{recording}_{d,i} - \text{audiogram}_{\alpha,i}, 0\right), \quad (3)$$

where the summation is done logarithmically as in Equation (1).

An advisable flight altitude for each UAV over each species was determined using the vertical species-weighted levels depicting how UAV loudness varies with altitude. The advisable altitude is not the point at which the UAV becomes inaudible to a species, as nearly all UAV models are still audible to most species even at 120 m. Rather, we calculated the point at which either the sound level is below 40 dB(species) or flying higher does not yield significant benefits in noise reduction. The 40 dB(species) threshold was chosen because 40 dB(A) LAeq is the sound floor above which sound is considered a disturbance to humans (i.e. World Health Organisation, 1999). There is no similar guideline for animals so we adopt the human threshold dB(A). In some cases, the UAV loudness at a certain altitude may not be below the threshold for a species, but the relationship between sound level and altitude has flattened such that the decrease in loudness achieved by flying higher is minimal. To calculate the altitude above which this relationship flattens, we fit a linear least-squares line through each species-weighted sound curve and iteratively removed the lowest altitude until the slope exceeded (was less negative than) −0.05 dB(species)/5 m, as shown in Figure 1. We designated the

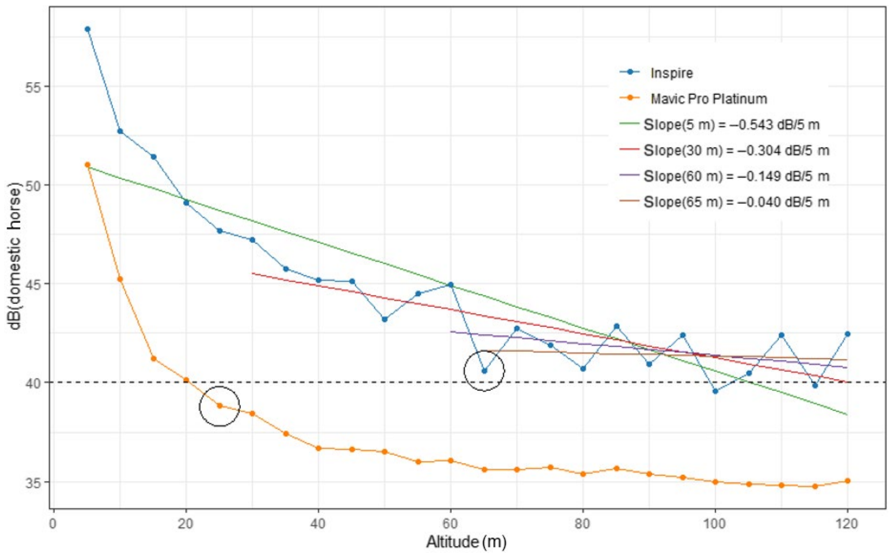

FIGURE 1 Demonstration of calculating the advisable altitudes (circled) for flying the Inspire and Mavic Pro Platinum over the domestic horse. The point where sound level no longer significantly declines with higher altitude (least-squares line slope >−0.05 dB/5 m) before the sound level is below the 40 dB(species) is circled (i.e. Inspire 65 m, Mavic Pro Platinum 25 m). In the latter example the curve has not flattened out, but the sound level (38.8 dB(domestic horse)) is below the threshold

lowest remaining altitude as the advisable altitude for that species and UAV if the UAV sound level was not already below 40 dB(species). We selected 0.05 dB (species)/5 m as the threshold based on our independent visual interpretation of where the sound curves flatten out. A sensitivity analysis confirmed that varying this threshold locally did not significantly change the advisable altitude (Figure S1).

3 | RESULTS

3.1 | The sound profile of UAV systems

Figures 2 and 3 illustrate the different sound profiles of seven commonly used commercial UAV models across the 100–20,000 Hz spectrum. The ambient background sound level was measured at 40.8 dB(A). The UAV sound signal was present above the ambient noise and the microphone noise floor over the entire frequency spectrum. Sound propagation is frequency dependent (i.e. lower frequencies propagate farther than higher frequencies). The variation between UAV systems is not consistent at all frequencies. The difference in amplitude is higher at lower frequencies, and there is more variation at short distances. As the distance increases to >100 m, the sound levels of all the UAVs converge (Figures 2 and 3) and are close to the observed ambient background sound levels. In the horizontal plane (Figure 3), sound does not propagate as far as in the vertical plane (Figure 2). The systems converge with the ambient recording at lower frequencies sooner in the horizontal plane than the vertical. Even at 120 m there is little convergence in the lower frequencies in the vertical plane, while they converge in the horizontal plane after 70 m.

3.2 | Species-weighted measurements of hearing sensitivity based on audiograms

Measurements of four different mammals' sensitivity to sound with distance from its source are shown in Figures 4 and 5. Consistent with an inverse-square law, the UAV loudness generally decreases by a constant weighted decibel value with each doubling of altitude or range. At larger distances, the decrease in noise with distance becomes negligible. In the vertical plane, the same drone is heard approximately 5 dB louder by the reindeer *Rangifer tarandus* as compared with the Indian elephant *Elephas maximus indicus* which hears approximately 10 dB louder than the California sea lion *Zalophus californianus*. Note, an increase of 10 dB is perceived by humans as a doubling in loudness.

There is significant variability in sound propagation between the vertical and horizontal plane. In the horizontal plane the Spark is largely the quietest system, while in the vertical plane, the Mavic 2 Pro or the Mavic Mini is often the quietest. The difference between how loud species hear UAV noise is higher when the UAV is flown at close range, as there is more amplitude variation over the lower frequencies (<1,000 Hz).

3.3 | Optimal flight altitude by UAV system and species

Advisable flight altitudes in Table 1 were calculated for seven UAV systems based on the relationship between noise and altitude (for further exploration see https://tinyurl.com/UAVdisturbance). The method addresses the trade-off between image resolution and minimising disturbance. The advisable altitude is not the point at which the UAV becomes inaudible. Rather, given that a UAV will be flown over a particular species, the method calculates the point at which either the loudness, weighted according to the species' hearing, is below an acceptable threshold or flying any higher will not significantly further minimise disturbance, defined as an average decrease in sound level of equal to or less than 0.05 dB(species) per additional 5 m. Unweighted advisable altitudes for each drone, calculated as if the hearing threshold at all frequencies is 0 dB, have also been included in the table and can be applied cautiously if surveying over any species for which audiograms are not available. The advisable

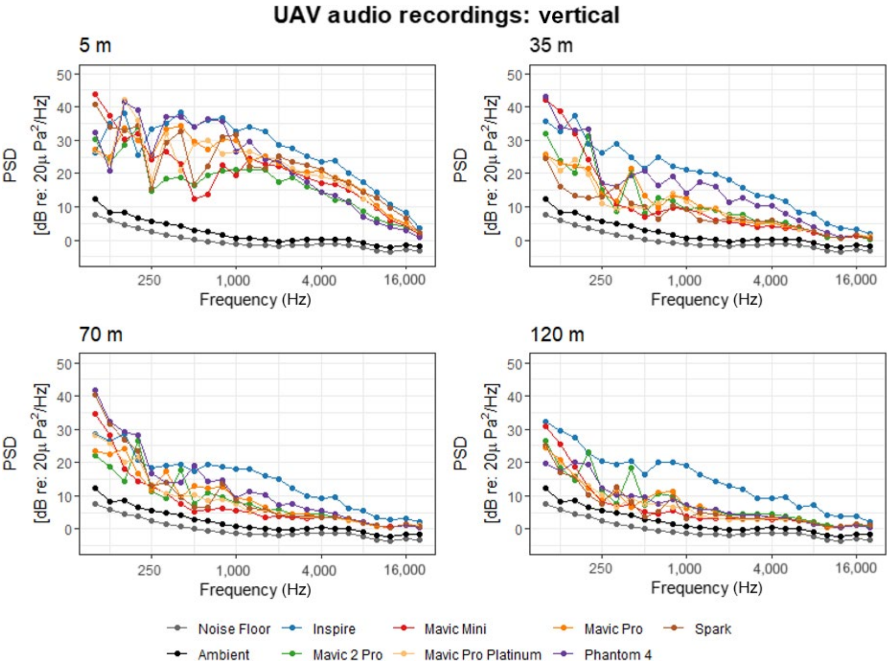

FIGURE 2 Power spectral density (PSD) curves in third-octave bins for seven UAV systems tested at four altitudes. Note the log scale *x*-axis

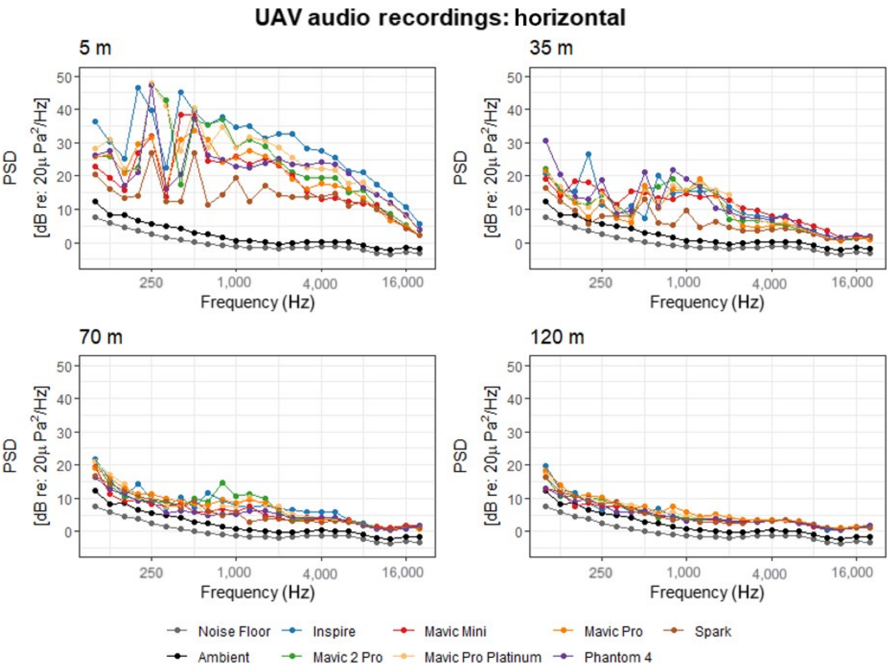

FIGURE 3 Power spectral density (PSD) curves in third-octave bins for seven UAV systems in the horizontal plane. Note the log scale *x*-axis

altitude is generally higher for louder drones, such as the Inspire or Phantom 4, as their sound profiles flatten out only at higher altitudes. For example, to meet the proposed criterion, the Phantom 4 would need to be flown at 120 m above a yellow baboon or De Brazza's monkey while the Mavic Mini could be flown as low as 35 m over these species. The calculation also depends on the hearing sensitivity of the animals. For example, we would advise flying the Inspire at 90 m over a spotted seal, but only 5 m over a harp seal. Table 1 displays the corresponding weighted sound level (dB(species)) at each advisable altitude to facilitate comparisons between different species and UAV systems.

4 | DISCUSSION

This study provides a method to calculate the minimum advisable altitude by integrating measurements of UAV sounds with species-specific hearing sensitivity. The results demonstrate that noise emitted by different UAV models varies in overall loudness and volume across the frequency spectrum. Sound propagation differs between the horizontal and vertical planes. While sound decays more rapidly with distance in the horizontal for all UAVs, the ordering of UAVs when comparing overall loudness differs between the vertical and horizontal. This is likely due to differences in how the sound

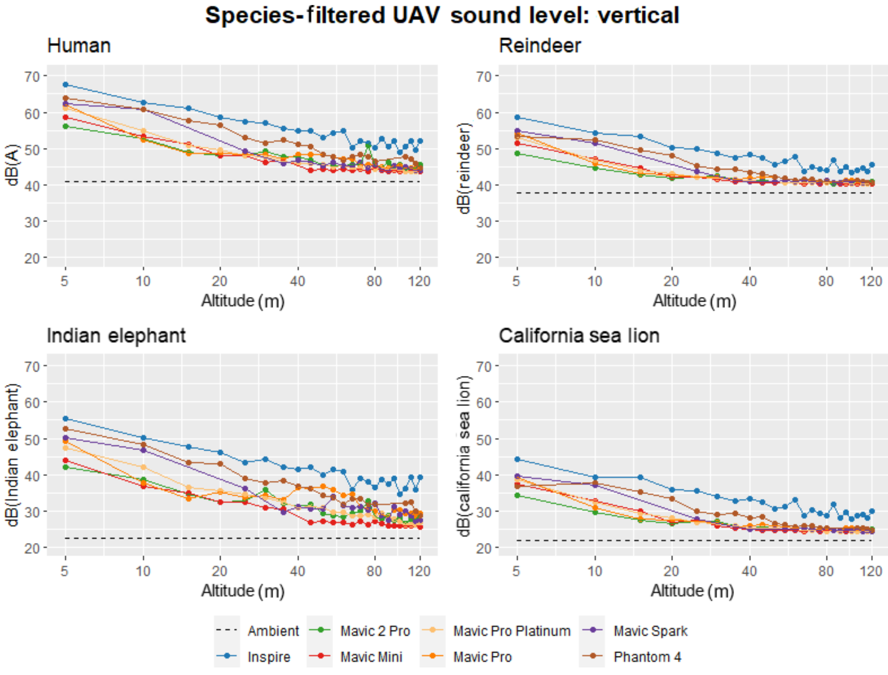

FIGURE 4 Changes with altitude of perceived noise from seven commonly used UAV systems by four mammalian species

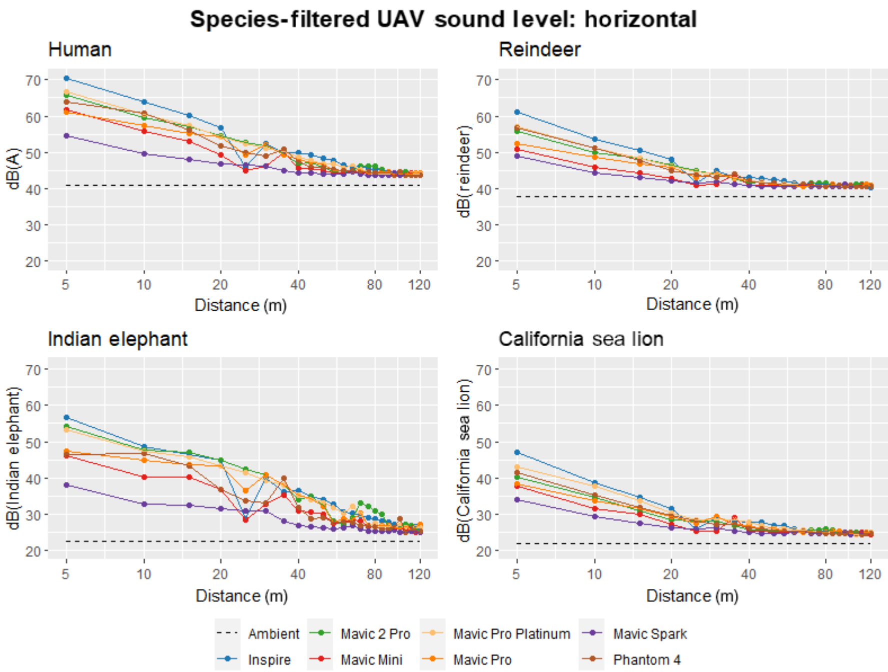

FIGURE 5 Changes with horizontal distance of perceived noise from seven commonly used UAV systems

is directed resulting from variation in propeller design. Some of the variation in sound propagation between the horizontal and vertical planes was likely due to greater attenuation from grass during the horizontal measurements. However, the reduction in noise when standing next to, compared to standing below, a UAV for a given displacement is consistent with previous studies (He et al., 2020). UAVs will be loudest when directly overhead, so we present advisable altitudes derived from only the vertical recordings, which are sufficient even if flying over species with a horizontal offset. Recent improvements in technology have enabled UAVs to operate more quietly, thus leading to a lower advisable altitude, which improves image quality and flight time. For example, the Mavic 2 Pro, despite being heavier than the Mavic Pro (907 g vs. 734 g), is consistently quieter, likely due to its low-noise propellers and newly designed chassis. This translates into substantial differences in the advisable altitudes for the two drones over some of the primates and ungulates.

The difference in the acoustic profile of UAVs is of higher relevance when flown close to the target species, and the choice of UAV system is more relevant when flying over species such as elephants, whose hearing sensitivity is higher at very low frequencies (Heffner & Heffner, 1982). UAV sound level converges in the upper frequencies; therefore, the choice of the system has less relevance when flying

TABLE 1 Advisable flight altitude (metres, upper row) and corresponding sound level (dB(species), lower row) based on drone recordings and species audiograms. Bold italics and italics indicate that the curve has levelled off at this altitude, sometimes in addition to the sound level falling below 40 dB. See Table S1 for the altitudes at which the levelling off occurs for all species, including where this point is after the sound level has decreased below 40 dB

Target species		UAV system						
		Inspire	Mavic 2 Pro	Mavic Mini	Mavic Pro	Mavic Pro Platinum	Spark	Phantom 4
Common name and species	**Classification**	**Upper rows: Advisable altitude to fly (metres) Lower rows: dB(*species*) at the advisable altitude**						
Common harbour seal (*Phoca vitulina*)	Carnivora Pinnipedia Phocidae	10	5	5	5	5	5	5
		38.6	33.6	36.4	38.1	37.8	38.7	36.5
California sea lion (*Zalophus californianus*)	Carnivora Pinnipedia Otariidae	**10**	**5**	**5**	**5**	**5**	**5**	**5**
		39.5	34.5	37.5	39.2	38.7	39.8	36.7
Northern fur seal (*Callorhinus ursinus*)	Carnivora Pinnipedia Otariidae	**30**	**5**	**10**	**10**	**10**	**25**	**15**
		38.9	39.3	37.6	35.8	37.4	34.2	39.7
Harp seal (*Pagophilus groenlandicus*)	Carnivora Pinnipedia Phocidae	**5**	**5**	**5**	**5**	**5**	**5**	**5**
		34.2	23.1	25.9	28.9	27.9	29.7	29
Spotted seal (*Phoca largha*)	Carnivora Pinnipedia Phocidae	***90***	***65***	***45***	***105***	***80***	***85***	***120***
		54.2	*50*	*49.4*	*49.3*	*49.2*	*49.6*	*50.4*
Sea Otter (*Enhydra lutris*)	Carnivora Mustelidae	***65***	***35***	***30***	***35***	***35***	***35***	***60***
		45.6	*43.1*	*43.1*	*43.1*	*43.1*	*43.1*	*42.9*
Rhesus macaque (*Macaca mulatta*)	Primates Cercopithecidae	***65***	**35**	***30***	**35**	**35**	***35***	**60**
		42.4	39.8	*39.5*	39.8	39.7	*39.3*	39.5
Japanese macaque (*Macaca fuscata*)	Primates Cercopithecidae	***65***	**80**	***45***	***105***	***100***	***85***	***120***
		47	*42.9*	*42.3*	*42.7*	*42.3*	*42.5*	*43.5*
Vervet monkey (*Chlorocebus pygerythrus*)	Primates Cercopithecidae	***65***	***75***	***60***	***85***	***100***	***115***	***120***
		47.7	*42.4*	*40.6*	*42*	*40.6*	*40.7*	*42.1*
De Brazza's monkey (*Cercopithecus neglectus*)	Primates Cercopithecidae	***65***	***50***	***35***	***70***	**65**	***85***	***120***
		43.7	*40.1*	*40.2*	*40.6*	39.9	*39.8*	*40*
Yellow baboon (*Papio cynocephalus*)	Primates Cercopithecidae	***65***	***50***	***35***	***70***	***95***	***85***	***120***
		47.3	*43.9*	*44.5*	*44*	*43.4*	*43.4*	*43.9*
Chimpanzee (*Pan troglodytes*)	Primates Homininae	***65***	**50**	**30**	***70***	**40**	**35**	**75**
		43.4	39.2	39.9	39.6	39.7	39.5	39.8
Reindeer (*Rangifer tarandus*)	Cetartiodactyla Cervidae	***65***	***35***	***30***	***60***	***35***	***35***	***75***
		43.8	*41.4*	*41.4*	*41.4*	*41.4*	*41.4*	*41*
White-tailed deer (*Odocoileus virginianus*)	Cetartiodactyla Cervidae	***65***	***35***	***30***	***60***	***35***	***35***	***75***
		46.9	*44.5*	*44.6*	*44.2*	*44.4*	*44.5*	*44.1*
Domestic goat (*Capra hircus*)	Cetartiodactyla Bovidae	***90***	***75***	***55***	***105***	***95***	***110***	***120***
		55.6	*50.9*	*49.9*	*49.9*	*49.6*	*49.8*	*50.9*
Domestic cattle (*Bos Taurus*)	Cetartiodactyla Bovidae	***65***	***35***	***30***	***50***	***35***	***35***	***75***
		54.8	*52.3*	*52.4*	*52.2*	*52.2*	*52.4*	*51.9*
Alpaca (*Vicugna pacos*)	Cetartiodactyla Camelidae	***65***	***40***	***30***	***65***	***40***	***35***	***75***
		45.1	*42.7*	*42.6*	*42.4*	*42.1*	*42.6*	*42.3*
Indian elephant (*Elephas maximus*)	Proboscidea Elephantidae	**50**	**10**	**10**	**10**	**15**	**25**	**25**
		39.9	38.8	36.7	37.8	36.5	36.2	39

(Continues)

TABLE 1 (Continued)

Target species		UAV system						
		Inspire	Mavic 2 Pro	Mavic Mini	Mavic Pro	Mavic Pro Platinum	Spark	Phantom 4
Common name and species	Classification	Upper rows: Advisable altitude to fly (metres) Lower rows: dB(*species*) at the advisable altitude						
Domestic horse (*Equus caballus*)	Perissodactyla Equidae	***65***	**15**	**20**	**25**	**25**	**25**	**50**
		40.6	38.7	38.2	38.8	38.8	39.7	38.7
Unweighted		***60***	***105***	***45***	***105***	***80***	***75***	***45***
		57.5	*47.3*	*46.4*	*47.3*	*47.2*	*46.6*	*57.6*

over species with greater high frequency sensitivity (e.g. Felidae and Carnivora species that hunt mainly by sound). The choice of UAV system is especially important for species whose hearing sensitivity is highest between 1.5 and 6 kHz, as UAV sound is concentrated in this bandwidth. As shown in the audiograms, some species hear well across the entire frequency spectrum, while the hearing sensitivity of other species is concentrated at particular frequencies. In addition, some species have an aversion to specific audio frequencies when the sound resembles other noises. For example, elephants are highly sensitive to bee sound, thus UAV sound which is similar to bee sound has been used to move elephants away from cropland (King et al., 2007). To reduce general UAV disturbance to elephants, our results show it would be advisable to use a Mavic Pro, Mavic 2 Pro or Mavic Mini. However, to specifically avoid acoustic similarity to bees, the Mavic Pro Platinum would be optimal. While it is louder overall, it is not as loud at specific bee frequencies (i.e. 200–500 Hz; Islam et al., 2017). Thus, using this method, aversion to specific audio frequencies by certain species can also be factored into UAV study design.

While weather conditions, particularly wind, influence sound propagation, testing varying environmental conditions was outside the scope of this study. However, windless conditions, as well as the open field environment, are both favourable for sound propagation. Consequently, our recommendations are conservative and can be applied across different weather conditions and vegetated surfaces. While windy conditions may require the rotor speed to increase as the UAV hovers, the sound of the wind typically obscures the additional sound. Less UAV sound reaches wildlife in highly vegetated areas as compared with open field, as trees and other vegetation impede sound propagation (Tarrero et al., 2008). However, if flying over less porous surfaces, such as ice, additional altitude may be needed to offset the reduction in sound absorbance.

As auditory sensitivity and sound perception has been studied in few wild mammals, it is difficult to extrapolate these findings within taxonomic groups. Certain species have hearing sensitivity concentrated at the extremes, such as ultrasonic sound perception in bats and small rodents and infrasound reception for elephants (Heffner & Heffner, 1982). However, there are not enough data to assess whether there is a natural similarity in auditory sensitivity within taxonomic groups, hence it is not possible to say to which close taxonomic relatives these audiograms can be extrapolated. Future research could use allometry to predict approximate auditory sensitivity from body mass (which applies for some species) or use analysis of the frequency composition and modulation of species' natural calls to inform predictions of noise perception, as vocalisation ranges are similar to ranges of perception. For species not covered in these guidelines and for whom audiograms, allometry or call data cannot be acquired, we have included advisable altitudes in Table 1 based on unweighted calculations of sound levels. These altitudes should be used cautiously, as the unweighted sound level for all UAVs still exceeds 40 dB at the point where the sound decay flattens out. In these situations, we recommend using a quiet drone, such as the Mavic Mini or Spark, when possible.

The method developed in this paper is applicable to assessing other sources of anthrophony. While herd structure, social dominance dynamics and mating strategies that rely on auditory cues have evolved over millennia, anthrophony is comparatively recent and is increasing in both terrestrial and marine habitats. During the last 50 years, low-frequency noise from ships has increased 32-fold along major routes (Miksis-Olds & Nichols, 2016). This is despite the fact that regarding marine operations is more highly regulated than land-based activities. The U.S. Marine Mammal Protection Act categorises marine noise pollution into harassment levels A and B, yet there is little comparable legislation for land-based activities. To put effective anthrophony regulation in place, we need to understand more about the hearing sensitivity of mammals and the impact of noise. This paper presents a method to quantify sources of anthrophony based on individual species' auditory sensitivity and highlights the need for more reliable audiograms for more species.

The method presented here would benefit from additional in-situ behavioural data to assess whether flying at the lowest advisable flight altitude still causes a change in behaviour, due to auditory or visual disturbance. If so, observations from UAVs may not be appropriate. Gathering longitudinal physiological data such as stress hormones or behavioural data to understand responses to UAV flights is useful to comprehensively understand disturbance but it is time intensive and costly to collect. This research is only concerned with auditory disturbance but visual disturbance is also important. Visual disturbance is particularly relevant for species who are aerially predated upon (Barasona et al., 2014; Mesquita et al., 2021). Thus, areas of future recommended research include assessing visual and auditory disturbance from UAVs and comparing disturbance from UAV surveys with other wildlife monitoring methods, such as line transect surveys carried out on foot or by vehicle.

Disturbance caused by UAV is an animal welfare concern and impedes scientific data collection through provoking aberrant behaviour. Information on appropriate altitudes at which to fly over different species will enable UAV technology to be used more reliably and responsibly for both scientific data collection and wildlife conservation purposes.

ACKNOWLEDGEMENTS

We are grateful to Dr Roberto Sal Gomez and Professor Yadvinder Malhi for lending us several UAVs for this experiment and our gratitude goes to Nigel Fisher—the Conservator of Wytham Woods for providing us with a quiet field site in which to collect the data. We are grateful to Dimitri Ponirakis, senior noise analyst at the Cornell Center for Conservation Bioacoustics for his valuable guidance on technical aspects of data processing. We are grateful to Professor Henry Heffner for providing information on the collection of the species audiograms. The authors have no conflict of interest.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTIONS

I.D. conceived and designed the study methodology with guidance from H.K.; Preparation of audiograms carried out by T.C. and I.D.; UAV sound data collection carried out by I.D. with support from ERT and C.L.; Processing the collected data in R Studio carried out by M.P.S.; I.D. led the writing of the manuscript; C.P., D.W.M. and T.W. edited the manuscript and all authors contributed critically to drafts and approved the final manuscript.

PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1111/2041-210X.13691.

DATA AVAILABILITY STATEMENT

All data and code are provided in an open repository https://doi.org/10.5281/zenodo.5119659 and Oxford University Research Archive (https://doi.org/10.5287/bodleian:6gxAJamnj).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Duporge, I., Spiegel, M. P., Thomson, E. R., Chapman, T., Lamberth, C., Pond, C., Macdonald, D. W., Wang, T., & Klinck, H. (2021). Determination of optimal flight altitude to minimise acoustic drone disturbance to wildlife using species audiograms. *Methods in Ecology and Evolution*, 00, 1–12. https://doi.org/10.1111/2041-210X.13691