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Determining recorder distances from multicopters to avoid bat disturbance

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Introduction: This study examines the impact of two multicopters, differing in size and weight (ConVecDro hexacopter, DJI Mavic 2 Pro quadcopter), on the activity of bats assigned to three distinct echolocation groups. The objective was to define thresholds (in decibels) below which bat echolocation groups show weak or no impact on activity. Using the known noise profile of the multicopter and a model of sound attenuation in air, these thresholds were then used to determine optimal recording device placement distances by estimating frequency-specific sound levels at increasing recording distances. Directional properties of the recording device were also considered.

Methods: Bat activity was recorded at distances 10.0 m, 12.2 m, 14.8 m, 17.4 m and 20 m, with the recording device oriented towards and away from the multicopter. We analyzed the effects of noise emissions from the multicopters in relation to the distance between the recording device and the multicopter to identify their influence on the recorded bat activity.

Results: The study shows the differences in recorded bat activity between two multicopters with different noise profiles. The larger and heavier ConVecDro produced louder, and potentially more deterrent noise emissions, for Pipistrelloid and particularly for *Nyctaloid* groups. In contrast, the DJI Mavic 2 Pro had a weaker deterrent effect on bat activity, and only the *Nyctaloid* groups were affected. Based on our observations of both multicopters, the threshold value below which no echolocation group showed any detectable impact was 4.5 dB at 23 kHz. In our setup, where the recording device was oriented towards the multicopter, it should be placed at 20 m for the DJI Mavic 2 Pro and at 36.0 m for the ConVecDro.

Discussion: The findings indicate that multicopter noise exerts a significant influence on bat activity, with the magnitude of the impact varying depending on the echolocation group and the specific characteristics of the multicopter noise profile. The ability to define noise threshold values for the different echolocation groups suggests that beyond a certain point, multicopter noise has no discernible effect on bat activity levels compared to a control group.

KEYWORDS

bat recording, mobile detection, monitoring, multicopter, noise, recording distance, sound pressure level (SPL) thresholds

1 Introduction

Wind energy is a key driver in the shift toward renewable energy, but it poses a green-green dilemma by conflicting with species conservation (Voigt et al., 2024). Onshore turbines primarily impact migrating bats (Chiroptera), especially *Pipistrelloid* and *Nyctaloid* species, whereas other species tend to fly at lower altitudes (below 60 m) (Merlet et al., 2025). The conservation of bats in the vicinity of wind turbines is therefore an increasingly important aspect of wildlife protection (Salguero et al., 2023). Several studies have shown increasing bat mortality at wind turbines due to their growing number and expanding risk area. Mean fatality rates have been estimated at approximately 12 bats per turbine per year in North America and 14 in Europe (Sánchez-Navarro et al., 2023; Thompson et al., 2017; Voigt et al., 2024). Bats are important components of ecosystems and are strictly protected in several countries, while the expansion of renewable energy remains a global priority (Tuneu-Corral et al., 2023). To balance renewable energy production with wildlife protection, evidence-based mitigation measures are essential. Currently, wind turbines are often curtailed during periods of expected bat activity, which can substantially reduce energy production. However, bats may also be at risk during turbine operation outside these expected activity periods. Detailed information on bat activity is therefore crucial to refine and optimize curtailment strategies.

Several approaches are commonly used to monitor the presence and activity of bats. Prior to wind turbine construction, bat presence is typically assessed using one or a combination of the following methods: mist netting to capture individuals, radio telemetry to track movements, stationary acoustic monitoring at fixed ground locations, and mobile acoustic transect surveys (Figure 1) (Hurst et al., 2020). However, due to the limited range of ultrasonic sounds (Voigt et al., 2021), acoustic methods do not assess bat activity in the later risk area of a wind turbine close to the rotors, typically between 60 and 250 m, depending on turbine dimensions (Schaub et al., 2024). Acoustic data on bat activity within the risk area of a wind turbine can therefore usually only be obtained through nacelle- or tower-based monitoring after construction (Figure 1).

However, these two methods at wind turbines also cover only a limited part of the risk area. Nacelle-based monitoring mainly samples the space in front of and below the nacelle, while tower-based monitoring only partly extends coverage downward (Figure 1). With increasing rotor diameters, these fixed-position methods capture a progressively smaller fraction of the risk area, and coverage is further reduced by acoustic shadowing from the tower and nacelle, which attenuate sound from one side (Bach et al., 2020; Voigt et al., 2021). Furthermore, both methods can only be applied after turbine construction and cannot be used to predict bat mortality risk during the planning process. Therefore, a new mobile method is needed that can reliably cover the wind turbine's risk area both prior to construction and during active operation.

A novel approach for acquiring acoustic bat data and assessing collision risk at wind turbines is the use of unmanned aerial systems (UAS). UAS can be deployed before and after the installation of a wind turbine and can cover the complete risk area due to their high mobility. Several studies have shown that UAS can be effective in detecting bats (August and Moore, 2019; Ednie et al., 2021; Fu et al., 2018; Kuhlmann et al., 2022; Michez et al., 2021). A complete UAS-based recording system consists of a drone and a recording device with an integrated ultrasonic microphone for recording and

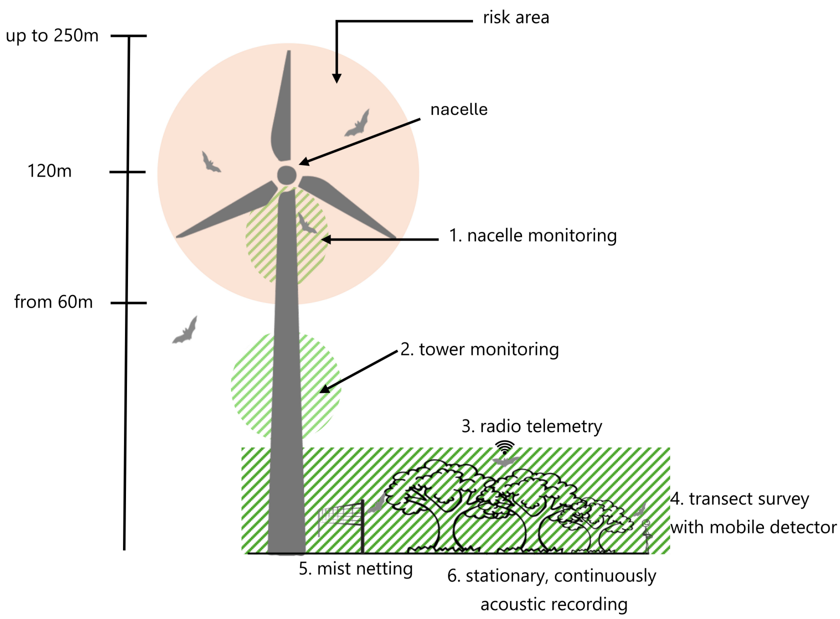

FIGURE 1
Common methods to sample bat activity data at wind turbines and in the countryside: (1) Nacelle monitoring, (2) tower monitoring, (3) radio telemetry, (4) transect surveys with a mobile detector, (5) mist-netting, and (6) stationary continuous acoustic recording. The green hatched area is a simplified representation of the range within which bats can be detected acoustically, and the orange area is a simplified representation of the risk area for bats within the rotor-swept zone. The scale on the left, from 60 m to over 250 m, indicates the possible extent of the rotor-swept zone, from the lower to the upper rotor tip, according to current wind turbine standards.

processing acoustic data. Various types of UAS have been tested, with multicopter systems proving to be the most effective platform for mobile bat-call recording (August and Moore, 2019; Jokisch et al., 2019; Roswag et al., 2025). However, multicopters generate noise during flight, which may affect the results in two ways. First, acoustically, the noise can interfere with the identification of bat calls, particularly when automated call-analysis software is used (Roswag et al., 2025). Second, the noise may disturb bat behavior and activity, as some species are known to be sensitive to sound disturbance (Schaub et al., 2008; Weaver et al., 2020). To reduce multicopter noise during recording, different recording device positions have been tested in previous studies (August and Moore, 2019; Ednie et al., 2021; Kloepper and Kinniry, 2018). The optimal configuration was found to be mounting the recording device below the multicopter, particularly when it is suspended at some distance from the aircraft.

The results of previous studies also indicated that most multicopters tested had a negative impact on recorded bat activity in close proximity to the aircraft, and, to our knowledge, no study has so far reported an attraction effect. All observed effects were deterrent, particularly for *Myotis* and *Nyctaloid* species (Ednie et al., 2021; Kuhlmann et al., 2022; Roswag et al., 2025). Very lightweight UAS (such as the DJI Mini 2 and lighter-than-air UAS) had no detectable influence on recorded bat activity. However, they were unsuitable for carrying a recording device, especially at higher wind speeds (>6 m/s), because of their low weight and instability. According to (Kuhlmann et al., 2022), the best available alternative among multicopters capable of withstanding stronger winds while carrying a suitable recording device is the DJI Mavic 2 Pro. Additionally, the hexacopter tested by (Jespersen et al., 2022) demonstrated good performance at a recording distance of up to 30 m, although no systematic assessment of its effect on bat activity was conducted. These studies showed that noise emitted by multicopters can lead to species-specific deterrent effects in bats. It is therefore crucial to determine the optimal placement of the recording device on multicopters in order to minimize noise in the recordings and to ensure that bat activity within the recording area is not affected. The emitted noise profile of the multicopter characterizes the sound pressure levels (SPLs) across frequencies during flight, usually during hovering (Schäffer et al., 2021).

The primary aim of this study was to optimize acoustic bat monitoring using UAS. Therefore, we focused on the following research questions:

1. Is it possible to determine the optimal position of the recording device for bat detection based on the noise profile of a multicopter? We hypothesized that (i) the optimal distance of the recording device below the multicopter can be predicted by the noise profile of a multicopter, on the basis of a critical threshold value per bat echolocation group (groups of species that share echolocation characteristics reflecting similarities in foraging strategies and habitat use, Schnitzler and Kalko, 2001), below which no effect of the multicopter on bat activity can be detected.
2. Does the reduction of the bat activity depend on the recording distance from the multicopter? Assuming that the multicopter has a deterrent effect, we hypothesized that (ii) the number of identified files containing bat calls, as a proxy for bat activity, increases with the distance between the multicopter and the recording device as long as the multicopter has a deterrent effect. This hypothesis is based on the fact that with increasing source–receiver distance due to geometric spreading and atmospheric absorption in air, the SPL (and thus acoustic energy) decreases, which reduces the noise intensity generated by the multicopter at larger distances (Kapoor et al., 2018).
3. How does the orientation of the recording device (facing toward vs. away from the multicopter) influence the number of recorded and identified bat calls? We hypothesized that (iii) the orientation of the recording device influences the acoustic sampling area and thereby affects the number of recorded and identified bat calls. Specifically, when the recording device faces towards the multicopter, its sampling area is expected to be more strongly masked by multicopter noise than when it faces away from it. Consequently, we expected a recording device oriented away from the multicopter to yield a higher number of recorded and identified bat calls than one oriented towards the multicopter.

2 Materials and methods

To address the three research questions, we conducted field and laboratory work (Figure 2). First, laboratory noise measurements were performed for two different multicopters, as both multicopters meet the required flight-stability criteria and have been used in previous studies. Moreover, their differing sizes yield markedly different noise profiles, enabling a more robust basis for threshold determination. We used the ConVecDro (Third Element Aviation GmbH merged with HHLA Sky company, Bielefeld, Germany) and the DJI Mavic 2 Pro (DJI, Shenzhen, China) to record their noise profiles. Second, field tests were conducted to quantify (j) how multicopter flights affect the activity of different bat echolocation groups and (jj) how recorded bat activity varies with recording device distance and orientation. The results obtained were utilized to delineate threshold values below which a deterrent effect on bats is significantly diminished (t_1) and becomes undetectable (t_2).

2.1 Study sites

Field tests were conducted in Southern Germany at three study sites nearby waterbodies with known and comparably high bat activity (Roswag et al., 2025): Aileswasensee (48°36'N, 9°15'E), Beutwangsee (48°36'N, 9°18'E), and Neckar (48°35'N, 9°13'E).

2.2 Investigated multicopters

This study employs two multicopters with different noise emissions. First, the ConVecDro (Third Element Aviation GmbH, 2023),

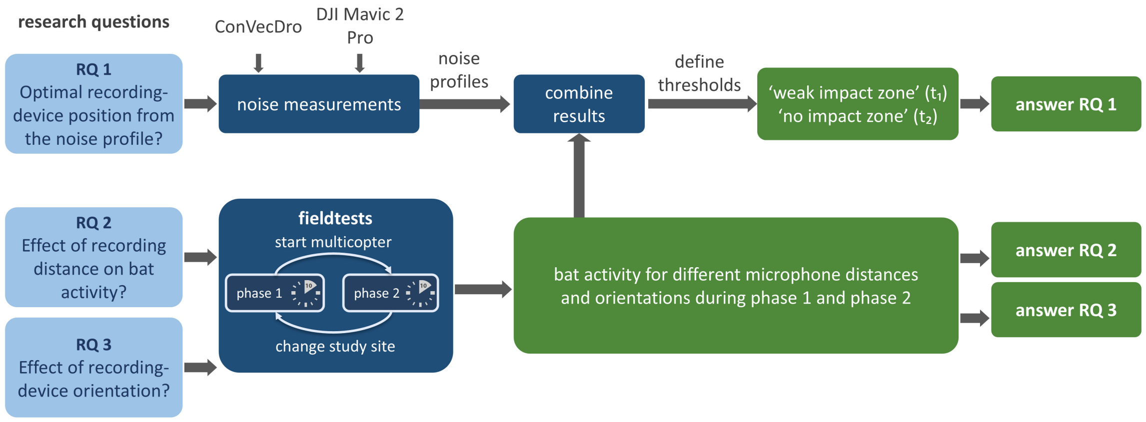

FIGURE 2
Schematic overview of the study design. The workflow is read from left to right, linking each research question (light blue) to the methods (dark blue) and the corresponding results (green) used to answer it. t_1 marks the threshold between the 'strong impact' and 'weak impact' zones, and t_2 the threshold between the 'weak impact' and 'no impact' zones.

which was modified to reduce its light and noise emissions. The ConVecDro is equipped with lighting in accordance with EN 4709-004 standard, comprising a green beacon light instead of cold white light (compare Roswag et al., 2025) and two position lights, one green and one red. To reduce noise emissions, we added teardrop-shaped structures underneath each of the six arms to optimize airflow and to minimize turbulence. This modification resulted in a frequency-dependent noise reduction of 3 to 5 dB. The DJI Mavic 2 Pro was used as a second multicopter. The DJI Mavic 2 Pro is equipped with integrated red and green navigation lights similar to the ConVecDro, as well as a cold-white auxiliary light that enhances visibility and positioning when the drone is within 10 m of the ground. More technical information is listed in Table 1. During the field test, the multicopter was flown by a licensed pilot (license identification number: DEU-RP-wn105I189zp6).

2.3 Recording of noise profiles of the multicopters

We recorded the noise profiles (SPLs over frequency) of the multicopters in an anechoic room to exclude external sources of interference. We focused specifically on ultrasonic emissions in the frequency ranges employed by bat species occurring in Germany. These echolocation calls range from the minimum end-frequency of 16 kHz (*Nyctalus noctula*) to maximum start-frequency of 150 kHz (*Myotis nattereri*) (Skiba, 2014; Supplementary Table 1). Since multicopter noise exhibits directional characteristics and depends on rotor geometry, electronic speed controllers (ESCs), operating-condition-dependent rotational speed, and the specific motor–propeller configuration, the noise profile cannot be generalized across UAS platforms. Therefore, both multicopters were tested separately under identical measurement conditions. We recorded the noise emissions of each multicopter while hovering for one minute at a distance of 65 cm at the top of the multicopter. Although this upper measurement position does not provide a complete acoustic directivity map, previous studies indicate that multicopter noise can vary substantially depending on the position of the recording device. Kloet et al. (2017) found that the highest sound pressure levels occurred at approximately 45° and that measurements taken from the underside of the multirotor, with motors and propellers running, were approximately 5 dB(A) higher than measurements taken from above. However, measurements below the rotor plane may also be affected by rotor downwash and flow-induced turbulence, which can influence the recorded sound levels. The potential influence of such turbulence below the multicopter, together with the comparatively moderate difference between upper and lower measurements reported in previous studies, was the main reason why we selected an upper measurement position in our setup. Recordings were conducted using an HBK4939 ¼″ free-field microphone together with an HBK3052 input module (Hottinger Brüel & Kjær A/S Teknikerbyen 28, DK-2830 Virum, Denmark), enabling measurements up to 100 kHz (Möller et al., 2024). After completing the recordings of noise profiles, we used a spherical sound propagation model and an atmospheric model (ISO 9613-1) to calculate noise emissions under various conditions, including humidity and ambient temperature, at distances of 12.2 m, 14.8 m, 17.4 m, and 20 m.

TABLE 1 **Technical specifications of the selected multicopters, including model, take-off weight, dimensions (including propellers), maximum flight time, and maximum wind resistance.**

Multicopter model	Take-off weight [g]	Dimensions (incl. propeller) [mm]	Max flight time [min]	Max wind resistance [m/s]
DJI Mavic 2 Pro	907	322 × 232 × 84	24	8–10.5
ConVecDro	5,000	1,430 × 1,430 × 530	30	15

2.4 Data collection of bat activities in the field

From May to September 2023 and from April to May 2024, we conducted recordings during nights with suitable weather conditions (wind speed ≤ 6 m/s, no precipitation, temperature > 10 °C), starting 30 min after sunset and continuing for up to 4 h. To quantify the effect of recording distance on the bat activity, four upward-facing recording devices (Song Meter SM4BAT FS, Wildlife Acoustics, Inc., Maynard, USA) were mounted on a 2 to 4 cm thick and 12 m long rod at different heights (Figure 3A). To stabilize the rod, we used three nylon ropes that were anchored laterally to the ground. In a real-life scenario, a recording device lighter than the Song Meter SM4BAT FS would be suspended below the multicopter on a cord or winch, pointing downward. In pre-tests we could show that save flight conditions with the multicopters can be achieved when a payload of approximately 300 g is suspended below the multicopter on a 10 m cord. The Song Meter SM4BAT FS weighs approximately 1.3 kg with batteries (Wildlife Acoustics, Inc., 2019) and thus far exceeds this payload, so it is too heavy to be suspended below the multicopter and cannot be deployed on the drone in practice. Therefore, we replicated this scenario by attaching a recording device consisting of a lightweight smartphone with an ultrasonic microphone (Echo Meter Touch 2 Pro, Wildlife Acoustics, Inc., Maynard, USA) to the top of the rod at 12 m height facing downwards and hovering the multicopter 10 m above the rod. The other recording devices (Song Meter SM4BAT FS) were mounted at 2.6 m intervals at 2 m, 4.6 m, 7.2 m, and 9.8 m, respectively. We used the more sensitive Song Meter SM4BAT FS for the distance analysis because its larger recording area is better suited to detect whether bats remained present or were deterred, whereas the lighter Echo Meter Touch 2 Pro represented the recording device that would realistically be carried by the multicopter. This configuration led to recording distances of 10.0 m, 12.2 m, 14.8 m, 17.4 m and 20.0 m between the multicopter and the recording devices (Figure 3A). The maximum length of the rod and the lateral rope anchoring required to keep the setup stable limited the positions at which the recording devices could be mounted. For this reason, the downward-facing recording device at the top of the rod (10.0 m) and the nearest upward-facing recording device (12.2 m) could not be placed at an identical distance from the multicopter, which constrained the comparison of the two orientations. The parameters used for the recording were a sample rate of 500 kHz, a gain of 12 dB, a minimum duration of 1.5 ms, a trigger window of 3 s, and a trigger level of 12 dB.

Each measurement sequence consisted of two 10-minute phases: a control phase (phase 1) in which bat calls were recorded without the presence of a multicopter and an experimental phase (phase 2) during which the respective multicopter hovered at 22 m above ground level while recording bat calls (Figure 3B). The pilot started the multicopter 20 m away from the rod and ascended to an altitude of 22 m. Once the correct altitude was reached, the multicopter was navigated directly above the rod and phase 2 recordings started. After each measurement sequence, the study site was relocated, enabling tests to be conducted at all three locations in a rotating sequence over the course of a single night. The ConVecDro measurement sequences were conducted between May and August 2023, while the DJI Mavic 2 Pro was tested between August and September 2023 and between April and May 2024. Prior to the measurement sequences, ambient temperature

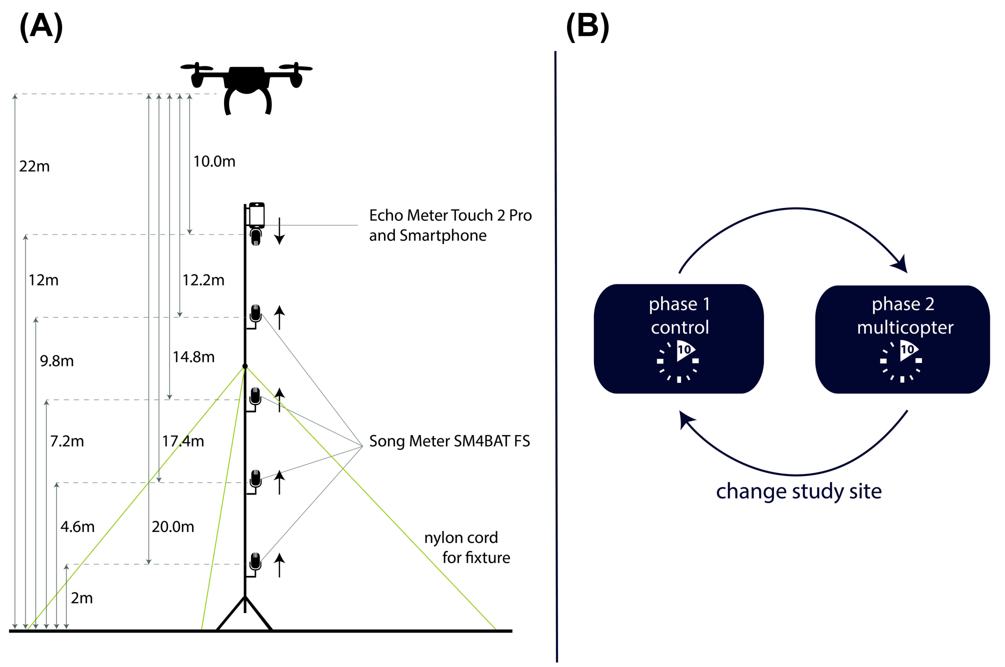

FIGURE 3
(A) Test setup. Five recording devices (four Song Meter SM4BAT FS and one Echo Meter Touch 2 Pro) were mounted at different heights. The arrows, to the right of the recording devices, show the recording orientations for each device. **(B)** Measurement sequence consisting of two 10-minute phases: a control phase (phase 1) in which bat calls were recorded without the presence of a multicopter and an experimental phase (phase 2) during which the multicopter hovered above the rod while recording bat calls, followed by a relocation of the study site.

and relative humidity were measured at 1 m above ground using a multimeter (PeakTech 5035, PeakTech Prüf- und Messtechnik GmbH, Ahrensburg, Germany; humidity accuracy ±5%rH [25 °C, 35–95%rH], temperature accuracy ±3% of reading + 2 °C for −20 to 200 °C using a Type-K probe).

2.5 Preparation of data for statistical analysis

All recording files were split into 1-second segments, which is standard practice for deriving bat activity metrics from acoustic recordings (Meramo et al., 2026; Roswag et al., 2025). In addition, these files were manually classified on species and group level (Kaleidoscope Pro, Wildlife Acoustics Inc., Maynard, USA). For further analyses all identified bat calls were grouped into three echolocation groups: *Pipistrelloid*, *Myotis*, and *Nyctaloid* (Supplementary Table 1).

The three groups were defined based on shared echolocation characteristics that reflect similarities in foraging strategies and habitat use, similar to Roswag et al. (2025). As echolocation traits were linked to acoustic detectability and potential susceptibility to masking by noise, this grouping may also capture differential sensitivity to anthropogenic noise (Schaub et al., 2008). This approach offers two advantages: firstly, it reduces identification errors by clustering species with overlapping call characteristics, and secondly, it increases the sample size for robust analysis. Consequently, the classification accounts for species-specific acoustic adaptations while enabling a comprehensive assessment of noise impact. Therefore, we computed a group-level peak frequency f_{group}, as a weighted mean of species-specific peak frequencies, using the proportion of species-level matches p_s as weights. For each species s, we defined the species peak frequency f_s as the midpoint of the reported peak-frequency range:

$$f_s = \frac{f_{s,min} + f_{s,max}}{2}$$

With the midpoint of each species, we calculated the group peak frequency f_{group} of i individual species as:

$$f_{\mathrm{group}} = \frac{\sum_i p_{s_i} \cdot f_{s_i}}{\sum_i p_{s_i}}$$

2.6 Statistical analysis

For statistical analysis were conducted using RStudio (RStudio Team, 2024) with R version 4.2.1 (R Core Team, 2022). Linear mixed-effects models (LMER), implemented through the lme4 package (version 1.1.31). The unit of analysis was the measurement sequence. For each measurement sequence, bat activity was quantified as the number of one-second files containing identified bat calls per phase, recording position, and echolocation group. Individual bats could not be identified acoustically. Therefore, the number of individual bats was not used as a sample size. Likewise, individual one-second files were used to quantify bat activity within each measurement sequence but were not treated as separate independent observations. Measurement sequences were treated as replicate sampling events, whereas phase- and recording-position-specific observations within the same measurement sequence were treated as paired or repeated measurements.

2.6.1 Effects of the distance between the multicopter and the recording device (model 1)

To address research questions (1) and (2) on how recording device distance from the multicopter affects recorded and identified bat activity, we analyzed only recordings from the four lower devices. We chose these recording devices because they were the same model (Song Meter), faced upward, and were spaced evenly at 2.6 m intervals. We included only complete datasets with no missing values (NA) in the statistical analysis. Consequently, we retained only those test setups that provided data for all distances (12.2 m, 14.8 m, 17.4 m, and 20.0 m).

Prior to analysis, we checked the model assumptions by testing normality of the residuals with the Shapiro–Wilk test and homoscedasticity with the Breusch–Pagan test. If the model assumptions were not met, we performed a sensitivity analysis to assess the robustness of the model, refitting it with log- and square-root-transformed bat activity. When transformations that satisfied the assumptions led to the same conclusions, we considered the model to be robust (Schielzeth et al., 2020). For the model we used the dependent variable as bat activity, quantified as the number of one-second files with identified bat calls per phase. As fixed effects we considered the phase (control or experimental) and the distance between the recording device and the multicopter. To analyze phases 1 and 2 as a pair, we combined location and test day into a single ID for each measurement sequence, which we then included in the model as a grouped random effect. The model was specified with a phase-by-distance interaction as fixed effects and the measurement-sequence identifier as a random intercept, corresponding to the formula

$$\mathrm{bat\_activity} \sim \mathrm{phase} \times \mathrm{distance} + (1|\mathrm{ID})\,.$$

In addition to the model analyses, we compared bat activity between phases 1 and 2 within the same measurement sequence for each distance and recording device orientation, using a Bonferroni-adjusted significance level. Prior to testing, we checked the normality of the differences between pairs. If the differences were not normally distributed, we used the paired Wilcoxon signed-rank test rather than the paired t-test. This enabled us to define threshold values beyond which no effect on bat activity could be detected.

2.6.2 Effect of the orientation of the recording device (model 2)

Regarding research question 3), which concerns the impact of the recording device's orientation on recorded and identified bat activity levels, we used the same parameters as in model 1. However, for this analysis, we only incorporated datasets corresponding to distances of 10.0 m (downwards orientation) and 12.2 m (upwards orientation) into the model.

2.7 Definition of the threshold values for determining the optimum recording device position

To identify threshold values, expressed as SPL per frequency unit, at which the minimum distance for a significant effect on bat activity is reached, we analyzed each echolocation group separately based on its group peak frequency. For this purpose, we defined three impact zones for each group: (k) the strong impact zone, where the multicopter's presence causes a statistically significant reduction in bat activity, (kk) the weak impact zone, where activity is reduced, but the effect is less pronounced and close to the threshold of significance, and (kkk) the no impact zone, where the multicopter has no detectable influence on bat activity.

Threshold 1 (t_1) marks the transition between the strong and the weak impact zone and corresponds to the highest sound pressure level at which the comparison between phases still showed a trend ($0.01 \leq p < 0.05$). Threshold 2 (t_2) marks the transition between the weak and the no-impact zone and corresponds to the highest sound pressure level at which the comparison was neither significant nor showed a trend ($p \geq 0.05$). We obtained the corresponding SPLs (in dB) for both thresholds by extrapolation from the noise profile. The distance from the multicopter at which the emitted noise equaled t_2 was selected as the ideal recording device position. At this distance the recorded and identified bat activity during multicopter flight did not differ significantly from the control.

3 Results

We initially conducted 40 measurement sequences with the ConVecDro and 25 measurement sequences with the DJI Mavic 2 Pro. Nine incomplete ConVecDro sequences were excluded, resulting in 31 ConVecDro sequences for statistical analysis. No DJI Mavic 2 Pro sequences were excluded, so the number of DJI Mavic 2 Pro sequences remained 25. The mean ambient temperature during all runs was: 16.3 ± 4.3 °C and the humidity 83.1 ± 10.9%. We included a total of 105,035 files containing at least one identified bat call in the analyses, of which 3,313 were assigned to the *Myotis* echolocation group, 11,980 to the *Nyctaloid* group and 98,753 to the *Pipistrelloid* group. It should be noted that these numbers represent recordings from five recording devices operating simultaneously. The average bat activity per measurement sequence and recording device was 207 ± 178 1-second files containing at least one bat call.

3.1 Noise profile of two different multicopters

The results show a clear distinction in the noise profile of the multicopters tested, as well as a comparable reduction in noise levels with increasing recording distance (Figure 4). Overall, the SPL at 20 kHz decreases by 35.4 dB from 1 m to 20 m distance from the multirotor and by 8.1 dB between the recording devices facing the multicopter at 12.2 m and 20 m distance. At 45 kHz, the SPL is reduced by 48.7 dB from 1 m to 20 m and by 13.6 dB from 12.2 m to 20 m (Figure 4; Supplementary Table 2). Additionally, the noise profiles indicate that the DJI Mavic 2 Pro (Figure 4A) is 12.5 dB quieter than the ConVecDro (B) at 20 kHz and 13.4 dB quieter at 45 kHz and that the ConVecDro exhibits a notable peak at 16 kHz. Furthermore, all graphs in Figure 4 show SPL variations at higher frequencies caused by ambient temperature and humidity fluctuations during our measurements. These fluctuations predominantly manifest in frequencies exceeding 10 kHz. In addition, the ConVecDro spectrum shows a narrow-band peak near 16 kHz (Figure 4B; Supplementary Table 2), which likely corresponds to the pulse-width modulation (PWM) switching frequency of its Flame ESC (60A 12S V2.0). In contrast, the Mavic 2 Pro exhibits a smoother high-frequency spectrum without such a tonal component.

3.2 Bat activity levels at different distances to multicopter

We observed a significant difference of bat activity only between the control and experimental phase at 12.2 m and 20.0 m for the *Pipistrelloid* group ($P < 0.05$). Here we also observed a trend from 12.2 m to 17.4 m ($0.1 > P < 0.05$). All other comparisons showed no significant effects or statistical trends (Supplementary Table 3).

3.3 Threshold values

Pairwise Wilcoxon signed-rank tests at each recording distance showed that, among the four upward-facing recording devices, the phase comparisons at the recording device closest to the multicopter (12.2 m) consistently yielded lower p-values when they approached significance ($p \approx 0.05$) (Supplementary Table 4). In the *Pipistrelloid* group, only the 12.2 m distance showed clear evidence of phase-related effects (compare effect sizes): ConVecDro exhibited a significant phase difference only at 12.2 m, followed by a decreasing trend that became non-significant at 17.4 m, whereas the DJI Mavic 2 Pro showed only a near-threshold p-value at 12.2 m and clearly non-significant values at all other distances. The *Nyctaloid* group showed the same overall pattern, particularly for the DJI Mavic 2 Pro. For ConVecDro, the phase difference remained significant at all recording distances, although the effect size was smallest at 20 m. No significant differences were observed for the *Myotis* group (Figure 5; Supplementary Table 4).

For the *Myotis* group (42 kHz), we could not define threshold values because no significant differences were detected (Figure 6A; Table 2). For the *Nyctaloid* group (23 kHz), we define t_1 at 9.9 dB and t_2 at 4.5 dB (Figure 6B; Table 2). For the *Pipistrelloid* group (46 kHz), we define t_1 at −2.5 dB and t_2 at −7.8 dB (Figure 6C; Table 2).

3.4 Effect of recording device orientation

The LMER model showed no significant phase × recording-distance interaction between the 10.0 m recording device (Echo Meter Touch 2 Pro, facing away from the multicopter) and the 12.2 m recording device (facing toward the multicopter, Supplementary Table 5; Figure 5). In contrast, distance-specific pairwise Wilcoxon signed-rank tests indicated that phase effects were generally weaker at 10.0 m or similar across both distances

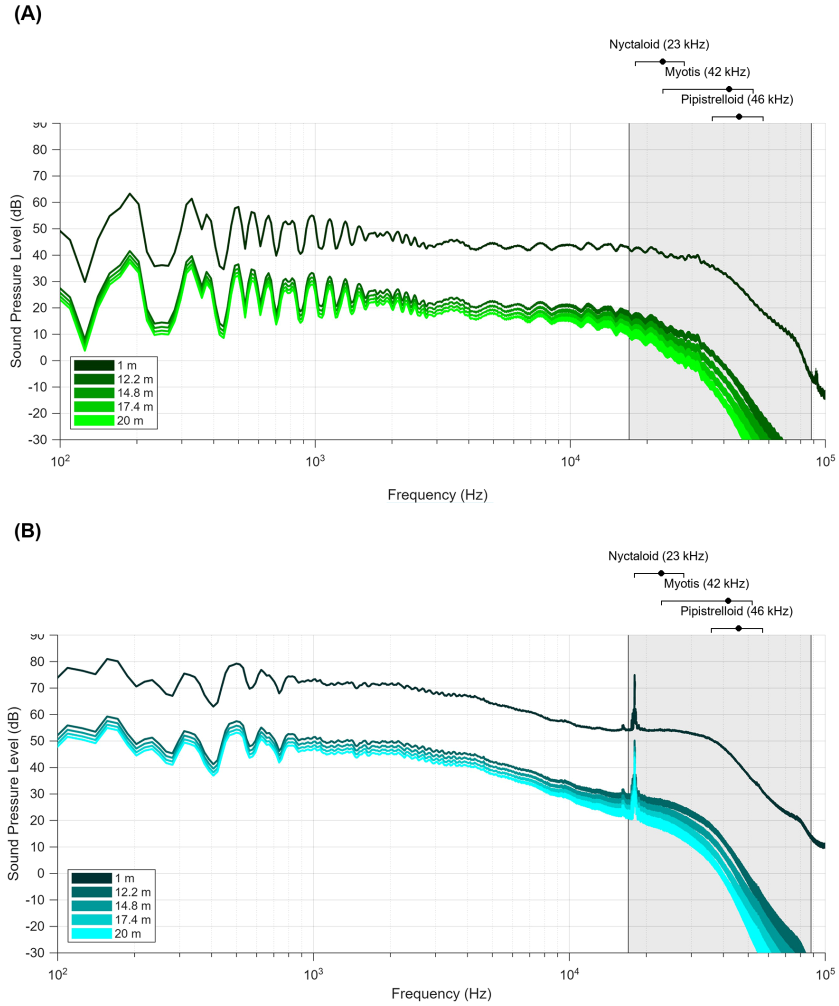

FIGURE 4
Noise profiles for **(A)** DJI Mavic 2 Pro and **(B)** ConVecDro. Each curve represents the calculated noise profile at different distances. From top to bottom, the distances are: 1 m, 12.2 m, 14.8 m, 17.4 m, and 20.0 m. The blue- and green-shaded areas indicate the variation of the sound pressure level (SPL) influenced by ambient temperature of 10 °C and humidity of 75%. The grey-shaded area marks the relevant range in which the echolocation calls of the observed bat species occur. The brackets above the plot mark the peak-frequency span of the three echolocation groups within this range, with the filled circle indicating each group peak frequency (Nyctaloid 23 kHz, Myotis 42 kHz, Pipistrelloid 46 kHz).

(Supplementary Table 4). In the *Nyctaloid* group at phase 2 during the DJI Mavic 2 Pro flights and during the *Pipistrelloid* group during ConVecDro flights, significance at 12.2 m shifted to a trend-level effect at 10.0 m. For the *Pipistrelloid* group at phase 2 during DJI Mavic 2 Pro flights, the 12.2 m comparison was close to the significance threshold, while the 10.0 m comparison was clearly non-significant. No clear distance-related difference was evident in the remaining cases.

4 Discussion

4.1 Optimal recording device placement based on the noise profile of a multicopter

Our results demonstrate that it is possible to define sound-level thresholds (dB) above which no significant difference in bat activity levels can be detected between a control group and an experimental phase during which a multicopter is operating. Using such a dB threshold in combination with the multicopter noise profile and applying a model to estimate frequency-specific sound pressure levels at different distances from the multicopter, we showed that an optimal recording device position can be determined (question 1, hypothesis (i)).

We defined the threshold t_2 for each echolocation group as the point beyond which neither a statistically significant difference nor a trend was detectable. Accordingly, the optimal placement of the recording device should be chosen such that no echolocation group shows a significant difference between the control (phase 1) and experimental group (phase 2). In our case, this yielded an optimal distance of 20 m for the DJI Mavic 2 Pro. For the ConVecDro, however, no optimal distance could be defined based on the current results, because no non-significant value was reached for the Nyctaloid group. Extrapolating the ConVecDro noise profile using the predefined threshold t_2 = 4.5 dB suggests that an audio recorder (oriented towards the multirotor) would need to be positioned at approximately 36.0 m.

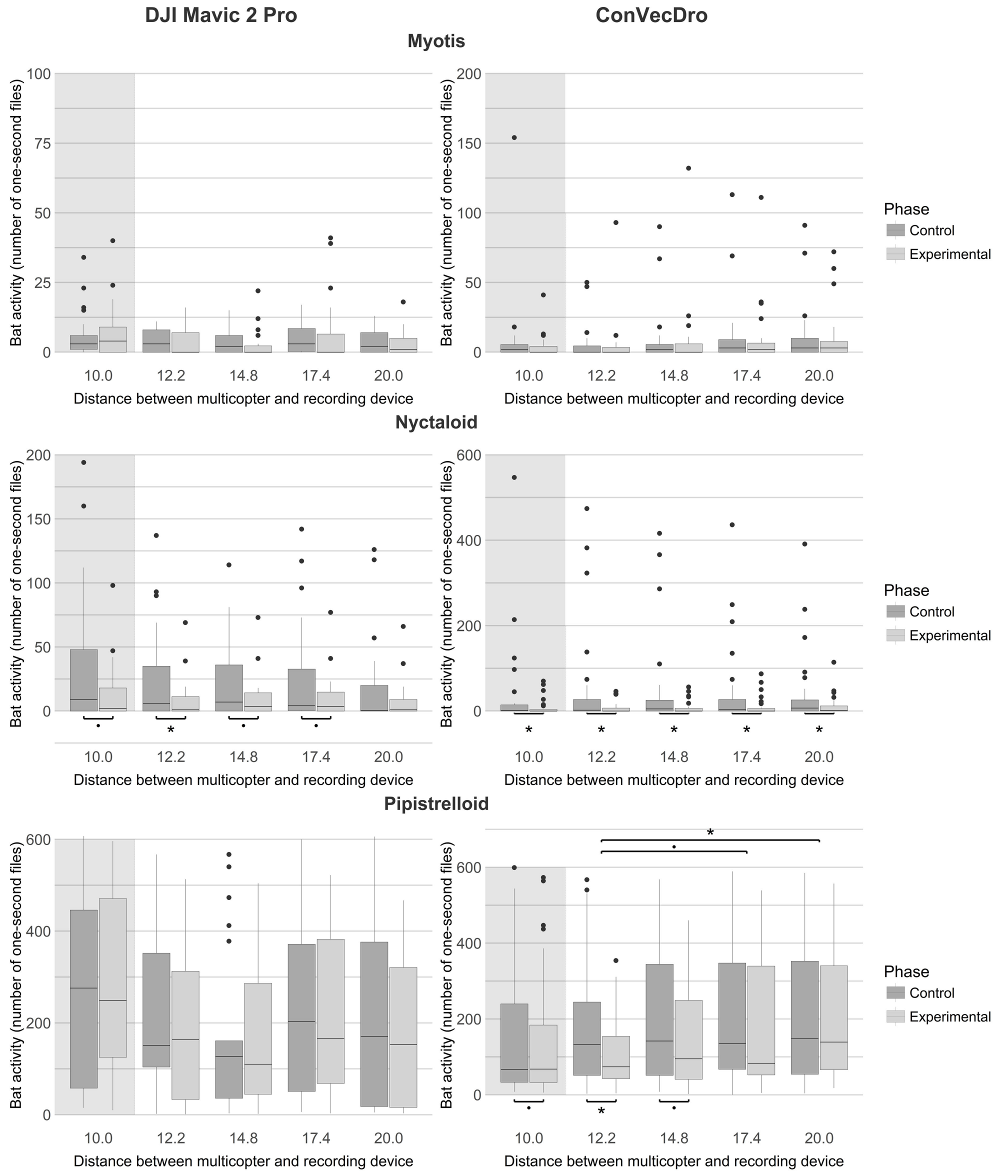

FIGURE 5
Grouped boxplots showing echolocation-group distributions across recording distances for both multicopters (DJI Mavic 2 Pro, left; ConVecDro, right). The grey-shaded background denotes the downward-facing recorder orientation. The brackets below the boxplots refer to the paired Wilcoxon signed-rank tests comparing the control and the experimental phase at each recording distance, where * marks a significant difference at the Bonferroni-adjusted level ($p < 0.01$) and • marks a trend ($0.01 \leq p < 0.05$). The brackets above the boxplots refer to the phase by recording-distance interaction of the linear mixed-effects models between the two distances they span, where * marks a significant difference ($p < 0.05$) and • marks a trend ($0.05 \leq p < 0.1$). Comparisons without a marker were neither significant nor showed a trend.

As the transition between the presence and absence of deterrence is biologically unlikely to represent a hard border, we additionally defined a weak-impact zone using the threshold t_1. For the ConVecDro, considering the Nyctaloid group, the difference between phases remained significant at all tested distances, so that neither threshold could be located within the tested range. The weak-impact zone was therefore derived from the DJI Mavic 2 Pro results, which showed a significant difference at 12.2 m despite lower noise emissions at 23 kHz and only a trend at the larger distances. This indicates that a residual trend between phases still represents a critical zone in which multicopter noise emissions may influence the recorded bat activity.

4.2 Reduction in deterrence with increasing recording distance from the multicopter

When examining the pattern of differences in bat activity between phases (with and without multicopter presence) across recording distances, our results show that these differences decrease as recording distance increases, until they are no longer detectable or become negligible (question 2, hypothesis (ii)).

This pattern was only evident when a difference between phases was detectable for at least one recording distance. For the *Pipistrelloid* group during flights of the DJI Mavic 2 Pro, no

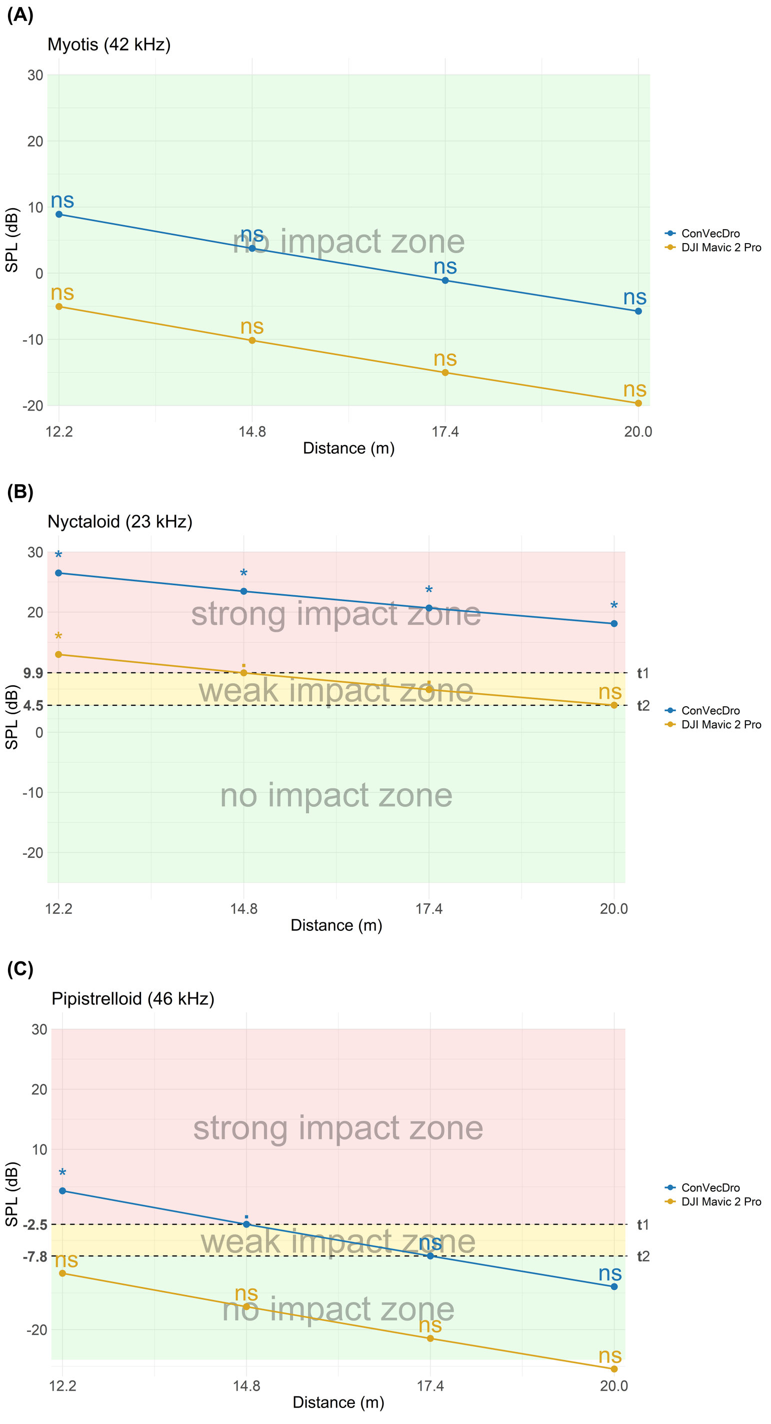

FIGURE 6
Visualization of threshold values t1 and t2 for the echolocation groups for their peak frequency **(A)** *Myotis* (42 kHz) **(B)** *Nyctaloid* (23 kHz) and **(C)** *Pipistrelloid* (46 kHz). Red indicates the strong impact zone, yellow the weak impact zone and green no impact zone. The markers give the result of the paired Wilcoxon signed-rank test at each recording distance, where * marks a significant difference at the Bonferroni-adjusted level ($p < 0.01$), • a trend ($0.01 \leq p < 0.05$) and ns no detectable difference.

significant difference was detected at any of the recording distances included in our test setup. This is consistent with previous studies showing that *Pipistrelloid* species are the least affected group by the presence of multicopters (Ednie et al., 2021; Kuhlmann et al., 2022; Roswag et al., 2025). This also explains why neither the interaction between phase and recording distance, nor the corresponding distance-dependent pattern, was significant. The same applied to the *Myotis* echolocation group for both multicopters. In our case about *Myotis* group, overall activity was low compared to the other echolocation groups and was dominated by *Myotis daubentonii* (85% of species-level detections). This low activity may partly explain why we did not detect any difference between phases in this group, suggesting that any deterrent effect was weak, at least for *M. daubentonii* under our study conditions. This interpretation is

TABLE 2 Defined threshold values t_1, start of the weak impact zone, and t_2, start of the no-impact zone, for each echolocation group and their group peak frequency.

Echolocation group	Threshold t_1 (weak impact zone)	Threshold t_2 (no impact zone)
Myotis (42 kHz)	Not defined	Not defined
Nyctaloid (23 kHz)	9.9 dB	4.5 dB
Pipistrelloid (46 kHz)	−2.5 dB	−7.8 dB

consistent with studies showing that *M. daubentonii* can be relatively robust to broadband noise and may compensate for acoustic interference through a Lombard Effect, that is, by increasing call amplitude in noisy conditions (Foskolos et al., 2022; Pedersen et al., 2022). However, the absence of a deterrent effect in terms of acoustically recorded activity does not necessarily imply the absence of any impact, as noise exposure may still reduce foraging efficiency (Luo et al., 2015). In contrast to our results for the *Myotis* group, Ednie et al. (2021) reported a deterrent effect for *Myotis* species, although their study focused on a different species assemblage, including *M. lucifugus*, *M. septentrionalis*, and *M. leibii*. Species-specific differences in responses to multicopter noise may therefore account, at least in part, for the discrepancy between studies.

For the remaining echolocation groups, a significant difference between phases was detected at least at one recording distance, which allowed us to assess the distance-dependent pattern more clearly. This pattern was most pronounced for the *Pipistrelloid* group during ConVecDro flights. Results from the interaction model indicated that the difference between phases declined with increasing recording distance, changing from a non-significant difference between phases at 12.2 m and 14.8 m to a statistical trend at intermediate distances at 12.2 m and 17.4 m and becoming significant by comparing the phases difference at 12.2 m and 20.0 m. This pattern was supported by distance-specific comparisons, which likewise showed a significant difference at 12.2 m, a trend at 14.8 m, and no significant difference at 17.4 m and 20.0 m. Together, these results clearly indicate that the impact of multicopter noise emissions decreases with increasing recording distance.

For the *Nyctaloid* group, this pattern was less pronounced but still apparent. Although the interaction models including phase and recording distance did not show a significant interaction across the full distance range from 12.2 m to 20.0 m for both multicopter, the phase differences nevertheless declined with increasing distance in both cases. For the ConVecDro, the phase difference was still significant at 20.0 m, whereas for the DJI Mavic 2 Pro it became non-significant at this distance. The less pronounced pattern of a decreasing difference between phases with increasing recording distance in the *Nyctaloid* group may be related to the group's lower peak frequency, which is around 23 kHz, compared with approximately 46 kHz in the *Pipistrelloid* group. In the frequency range from 19 to approximately 30–35 kHz, which is particularly relevant for *Nyctaloid*s, SPL declined more slowly with distance than at higher frequencies. Accordingly, multicopter-related acoustic interference decreased only modestly across the tested distances, which may help to explain why the effect on bat activity changed less strongly over distance in this group. This interpretation aligns with the findings of previous studies, which indicated more pronounced effects on *Nyctaloid* groups compared to other echolocation groups (Ednie et al., 2021; Kuhlmann et al., 2022; Roswag et al., 2025). In addition, multicopters can generate substantial ultrasonic noise within frequency bands relevant to *Nyctaloid*s, including components likely associated with ESCs (Jespersen et al., 2022; Michez et al., 2021). In our study, the ConVecDro likewise showed a pronounced peak at 16 kHz, which may also be related to ESCs and could have contributed to a stronger disturbance effect for *Nyctaloid*s during the ConVecDro flights than for the DJI Mavic 2 Pro.

A further limitation concerns the position of the bats relative to the recording devices. Acoustic recordings from a single microphone do not allow the exact position of a detected bat to be determined, which would require either a microphone array such as an acoustic camera or a synchronised thermal imaging camera. Each recording device covered a three-dimensional recording area centred at a defined distance from the multicopter. Consequently, in this study bat activity assigned to a given recording distance reflects activity within the recording area around the respective recording device rather than at an exact distance from the multicopter. To characterise these recording areas more precisely and to link the position of individual bats directly to the recorded activity, future studies could combine acoustic recordings with a microphone array or a synchronised thermal imaging camera for an exact correlation between bat activity and distance to the multicopter.

To our knowledge, there is no evidence that bats respond to noise by remaining in an area while calling less frequently, which would cause their activity to be present but under-recorded. European bats have instead been shown to avoid noisy areas (Schaub et al., 2008; Siemers and Schaub, 2011; Finch et al., 2020) or, as described above for *M. daubentonii*, to increase their call amplitude rather than to reduce it. A higher call amplitude increases rather than decreases detectability in noise, so that bats calling under the influence of the multicopter could even be recorded by more distant recording devices. In our setup, the recording device closest to the multicopter could therefore still detect bats located further away. This mechanism would act against, rather than in favour of, detecting a reduction in bat activity, so that the observed deterrent effect is likely conservative.

4.3 Orientation of the recording device

It is well established that acoustic recording devices differ in their directional characteristics (Goodwin et al., 2024; Ratcliffe and Jakobsen, 2018; Wildlife Acoustics, Inc., 2024, 2026) and that higher frequencies, according to their shorter wavelengths, are generally more directional in both propagation and reception than lower frequencies (Cudeiro-Blanco et al., 2022). Consequently, a recording device oriented upwards to the multicopter is more likely to record bats that remain closer to the multicopter than a recording device oriented downwards and away from it. Based on research question 2, we could show that, when a deterrent effect of multicopter noise is present, acoustic recorded bat activity increases with increasing distance from the multicopter. We interpret this pattern primarily as a deterrent effect rather than as reduced detectability due to acoustic masking, because visual inspection of the spectrograms showed only minor multicopter noise in the frequency ranges of the *Pipistrelloid* and *Myotis* echolocation groups. Only for the *Nyctaloid* group, particularly around 20 kHz, minor masking effects cannot be fully excluded (Roswag et al., 2025). Under hypothesis (iii), we predicted that a downwards oriented recording device would record more unaffected bat activity than an upwards oriented recording device. We could partly confirm this hypothesis, because for the echolocation groups, which are affected by the presence of the multicopters, in our study (*Nyctaloid* and *Pipistrelloid*), effect sizes for the phase comparison were consistently larger at the upwards orientated recording device (12.2 m; oriented towards the multicopter) than at the downward oriented device (10.0 m; oriented away from the multicopter). In distance-specific comparisons, the *Pipistrelloid* group during ConVecDro flights and the *Nyctaloid* group during DJI Mavic 2 Pro flights both showed a shift from a significant phase difference at 12.2 m to only a trend at 10.0 m. However, the interaction between phase and recording distances, for these specific positions, was not significant in any case. We therefore interpret the observed differences between orientations as present but too small to be detected robustly by the interaction models.

For the *Nyctaloid* group during ConVecDro flights, no significant phase difference was detected at either position even in the distance-specific comparisons, which we attribute to the group's lower peak frequencies and the weaker atmospheric attenuation at lower frequencies. Finally, because our two orientations were not tested at an identical distance (due to stability constraints of the experimental setup), we expect that a same-distance comparison of an upward versus downward orientated recording devices would likely yield a clearer estimate of the orientation effect.

A limitation of the orientation comparison is that the two recording orientations were not only measured at different distances (10 m to 12.2 m) from the multicopter, but also with different detector types. Thus, detector-specific sensitivity and recording area (Wildlife Acoustics, Inc., 2024, 2026) could have influenced the absolute number of recorded bat calls. However, this potential bias would likely have acted against, rather than in favour of, the observed pattern. The Echo Meter Touch 2 Pro has a smaller recording area than the Song Meter system due to its lower microphone sensitivity and was additionally positioned closer to the multicopter, where a stronger negative effect of multicopter noise would be expected. Under these conditions, the Echo Meter Touch 2 Pro would be expected to record fewer bat calls irrespective of recording device orientation. Nevertheless, it recorded higher bat activity in the relevant comparisons. This indicates that the observed pattern is likely conservative and that differences between a recording device facing the multicopter and a recording device facing away from it would probably be more pronounced if both recording devices were tested at the same distance using identical detector types.

An additional potential limitation of our measurement approach is that ground reflections could bias distance-dependent sound measurements. However, in our setup, ground reflections can be considered negligible because the lowest recording device was mounted 2 m above ground and oriented upwards, and measurements were conducted above a vegetated surface (pasture/grass) that strongly absorbs and scatters ultrasonic waves. Within the frequency range of approximately 20–40 kHz, a significant proportion of the acoustic energy is scattered and absorbed within the grass canopy prior to reaching the soil (Legg and Bradley, 2019, 2020). Consequently, any component that is reflected at the ground level is merely a strongly attenuated residue, given the already short propagation range of high ultrasonic frequencies in air due to atmospheric attenuation (Bond et al., 1992).

5 Conclusion

We could show that it is possible to calculate an optimal distance for placing a recording device beneath a multicopter, provided that the SPL at the peak frequencies of bat echolocation calls is known derived from the multicopter's noise profile. The study also showed that orienting the recording device away from the multicopter allows a shorter mounting distance beneath the multicopter while still reaching an optimal recording position. The deterrent effect of the multicopters differed between echolocation groups. The *Nyctaloid* group was affected by both multicopters, the *Pipistrelloid* group only by the louder ConVecDro, and no deterrent effect was detectable for the *Myotis* group. Although threshold values can be derived for each echolocation group, the optimal recording device placement is governed by the most affected group, because it has to be chosen such that no echolocation group shows a significant difference between the control and experimental phase.

Using the optimal position, at which no influence on bat activity is detectable, provides a solid basis for comparing drone-based acoustic bat detection with conventional methods in further studies. Additionally, further studies should investigate additional distances and multicopter models, using SPLs at the relevant peak frequencies derived from their noise profiles to further optimize this technique.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: HAW Hamburg, https://doi.org/10.48441/41201.3311.2.

Ethics statement

This study was designed to minimize potential disturbance to wildlife. Drone flights were limited to short durations, and all surveys were conducted outside designated nature conservation areas. Prior to the study, the study design was reviewed by the competent nature conservation authority (Nature Conservation Authority of the Esslingen District) and the ethics committee of the Hamburg University of Applied Sciences, which confirmed that no species-protection permit was required for the planned activities. No animals were captured, handled, or otherwise directly manipulated during the study.

Author contributions

MR: Investigation, Visualization, Resources, Funding acquisition, Validation, Data curation, Software, Formal analysis, Writing – review & editing, Supervision, Writing – original draft, Conceptualization, Project administration, Methodology. JF: Methodology, Validation, Conceptualization, Supervision, Formal analysis, Writing – review & editing. AR: Validation, Visualization, Data curation, Conceptualization, Writing – review & editing, Methodology, Supervision. VK: Conceptualization, Writing – review & editing, Validation, Methodology, Visualization, Supervision, Data curation. TT: Supervision, Project administration, Writing – review & editing, Conceptualization, Methodology, Validation.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fetho.2026.1868324/full#supplementary-material

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