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Emperor penguin reactions to UAVs: First observations and comparisons with effects of human approach

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ABSTRACT

The use of UAVs has greatly increased in recent years, worldwide and in the Antarctic. Their use has recently increased even in very remote and pristine regions of the Antarctic. There is, however, very little information on the sensitivity of Antarctic species to such disturbance. In particular, there is nothing on the emperor penguin (*Aptenodytes forsteri*), a flagship species of the region. We therefore, during November 2019, tested the responses of emperor penguins at the Atka Bay colony (Queen Maud Land). We video recorded the behaviour of adults and chicks during multirotor UAV activity and human approach. There were, in general, only moderate responses with distinct reactions in fewer than 20% of individuals observed. Chicks increased vigilance behaviour during UAV activity but both adults and chicks did so during human approach. We saw the greatest reaction in chicks during vertical UAV approach. Adults showed intermediate reactions to vertical UAV approach but only very few reactions to horizontal flights.

1. Introduction

The use of UAVs (unmanned aerial vehicles[1]) has increased greatly over the last 10 years and continues to do so. This development even affects the remote and pristine environments of the Antarctic. The users of UAVs in Antarctica are journalists, scientists of diverse fields (Goebel et al., 2015; Lucieer et al., 2012; McGill et al., 2011; Mustafa et al., 2017; Zmarz et al., 2018), recreational users and tourists or private personnel of the stations.

Previous studies on the environmental impact of UAV activities focused on the diverse fauna of the Antarctic Peninsula (Korczak-Abshire et al., 2016; Krause et al., 2021; Mustafa et al., 2018; Rümmler et al, 2016, 2018; Weimerskirch et al., 2018). There is, however, no information on their impact on species of the Antarctic continent such as emperor penguins (*Aptenodytes forsteri*).

Emperor penguin colonies are likely to be targets of UAV use. These penguins are a flagship species for the continental Antarctic. Even though only a small percentage of tourists and journalists visit the continental Antarctic, images of this iconic species and their colonies are often what those coming there demand. In addition, technical advances lead scientists to employ drones increasingly in surveying. For many years, colonies were discovered and monitored mainly from the air by helicopters and airplanes (Giese and Riddle, 1999). More recently, satellite image analysis became an efficient tool for discovering new colonies (Fretwell et al., 2012; Fretwell and Trathan, 2009, 2019, 2020). UAVs provide another promising tool for discovering, investigating and, especially, monitoring penguin colonies. They come in particularly beneficial where satellite image resolution has its limits: identifying singular penguins and differentiating between adults and chicks, the latter being essential for breeding success estimations.

There are few investigations of the vulnerability of emperor penguins to anthropogenic disturbance. Burger and Gochfeld (2007) investigated the impact of tourists approaching emperor penguins on their route to and from the colony and reported changes in behaviour when the penguins were confronted. Kooyman and Mullins (1990) stated that the impact of disturbance depends on the time in the breeding cycle with

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[1] also known as remotely piloted aircraft systems (RPAS) or colloquially drones.

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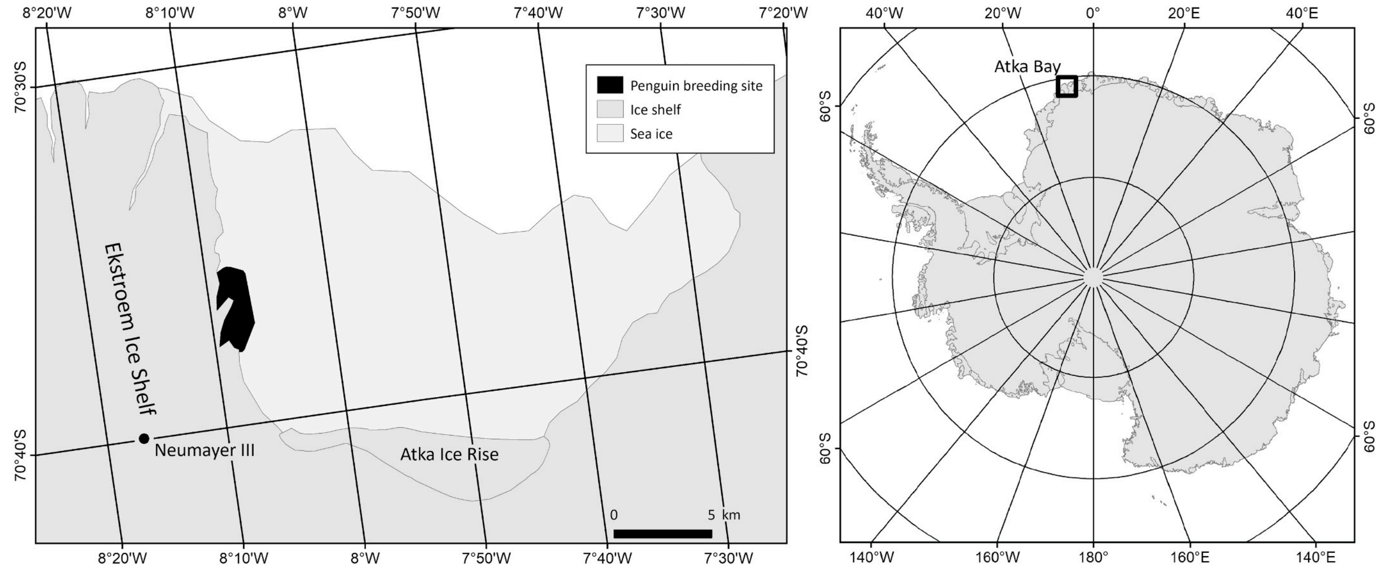

Fig. 1. Map of the study site (left) and its location on the Antarctic continent (right).

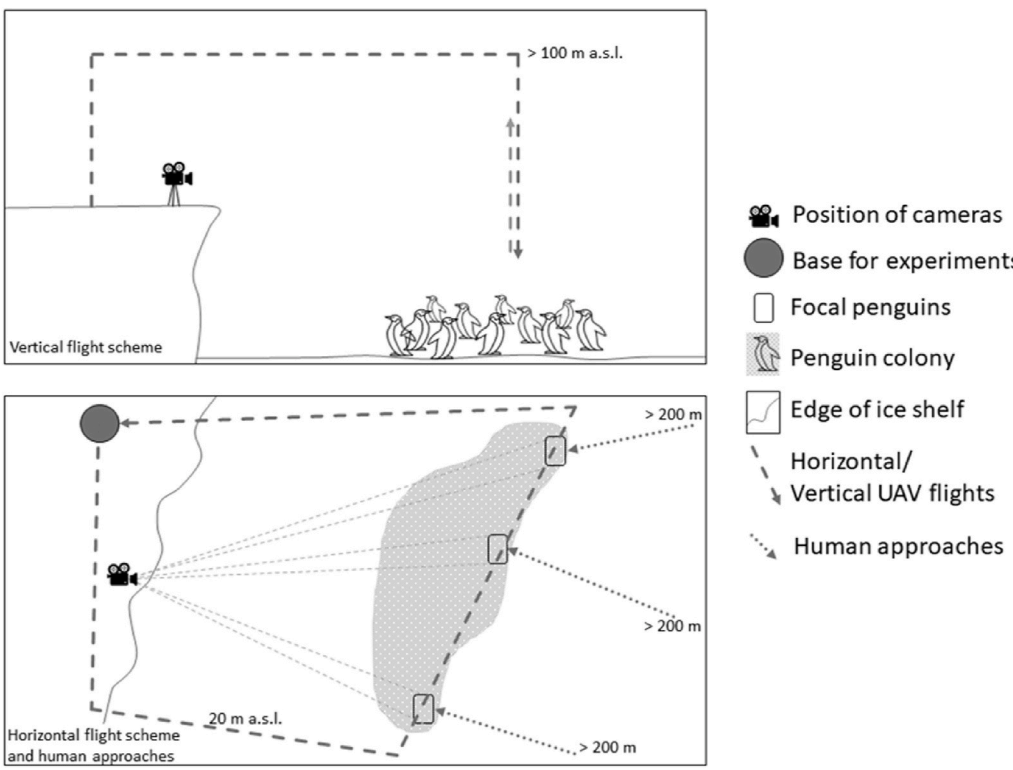

Fig. 2. Schematic representation of experimental setup. Above: Side-view of the experimental setup; with the position of the cameras on the ice shelf, the penguin colony and the flight path of vertical flights. Below: Top-view of the experimental setup, with the position of the cameras and their focal image frames, the base for experiments (starting and landing of UAVs, researchers), the penguin colony and the flight path of horizontal flights as well as the paths of human approaches.

reduced effects in later breeding states. They reported frequent neck movements and wing flapping during overflights of an aircraft (LC 130) at 1500 m altitude in November. Single passes of the same aircraft at 500 m altitude are safe when chicks reach the crèche stage. Budd (1962) reported that an aircraft at 150 m altitude induced movement in incubating birds and thereby caused substantial reductions in breeding success. Giese and Riddle (1999) observed emperor penguin chicks during and after overflights by a helicopter at 1000 m altitude and noted strong reactions that lasted for at least 5 min after the flights. One study (Regel and Pütz, 1997) examined the physiological consequences of human appearance in the colony as well as helicopter overflights by measuring stomach temperature. They found changes in body temperature and thereby energy expenditure even without visible behavioural changes.

Studies on the sensitivity of other penguin species like Adélie penguins (*Pygoscelis adeliae*) or gentoo penguins (*P. papua*) to UAV disturbance (Gardner et al., 2010; Korczak-Abshire et al., 2016; Rümmler et al., 2016, 2018) show signs of disturbance being caused by flight at altitudes of 50 m a.g.l. (above ground level) and below. To what extent these results are transferable to emperor penguins remains at least questionable. Emperor penguins are much larger, have a different breeding and population structure (no nests, strong colony dynamics) and are under less pressure from predatory birds, namely skuas and giant petrels (Shirihai and Kirwan, 2007). Weimerskirch et al. (2018) conducted experiments on numerous Antarctic and Sub-Antarctic species including the sister species of the emperor penguin, the king penguin (*Aptenodytes patagonicus*). They observed strong differences between adults of different breeding states. Non-breeders reacted strongly to the UAV but breeding adults hardly reacted at all even at very low flight altitudes (2 m). Reactions of chicks (fast wing flapping) occurred at 50 m flight altitude and below. At 10 m, escape behaviours were observed.

Our study provides a first insight into the reactions of emperor penguins to UAV activities. We compared the behaviour of adult animals and chicks during horizontal and vertical flights of a multirotor UAV as well as during human approaches on foot.

2. Methods

2.1. Study site and experimental setup

We did all tests in the Atka Bay Penguin Colony (70.6125° S, 8.1236° W, Fig. 1) in November 2019. The colony is located at Atka Bay and consists of about 8000–11000 emperor penguins breeding on the sea ice (Harris et al., 2015). It is a designated important bird area (IBA ANT109).

We avoided disturbing the colony on the sea ice by ensuring that our ground activity (setting up cameras and UAV take-offs/landings, camera corrections during the experiment) was conducted on the ice shelf. This location is at least 100 m horizontally distant from the colony and 15 m above it (Fig. 2). UAV take-off and landing took place here out of sight of the penguins. The researchers, likewise, remained out of sight here during the experiments. We set up three video cameras to record penguin behavioural responses. These cameras stood at the edge of the ice shelf and each camera focused on a different part of the colony. The parts we filmed lay in a straight line roughly parallel to the edge of the ice shelf so as to closely match the optimum flight path.

For the flights we used a quadcopter UAV (1388 g, 38 × 22 × 32.51 cm, white, Phantom 4 Pro, DJI, Shenzen, PR China). We determined the sound pressure level of the UAV with a digital sound level meter (30 dBA - 130 dBA, accuracy: ± 1.5 dB, resolution: 0.1 dB, GM1356, Beaspire, PR China). Flights were either conducted in manual flight mode (vertical approaches) or by creating a flight plan beforehand using Map Pilot for DJI software (dronesmadeeasy.com). During all flights, the UAV recorded position, altitude, flight speed and time in a log file for later analysis. Altitude was measured internally by the UAV using a combination of GNSS (global navigation satellite system) and barometric measurement. To ensure safety, during the flights, one of us continually monitored the UAV using binoculars.

2.1.1. Horizontal overflights

For these flights we launched the UAV from the base and then flew it to 20 m above sea level (a.s.l.). This height was chosen to have enough vertical distance to the ice shelf (about 5–8 m) to avoid crashes, but still be mostly hidden by the edge of the ice shelf so as to be undetectable from the colony. Then we flew it horizontally for about 400 m southward (see Fig. 2). At the southernmost position it turned and flew approximately northwards over the colony at a speed of 5 m/s. The flight height of 20 m a.s.l. (and thereby likewise above penguins) was maintained. We chose this flight height to ensure an observable reaction. The flight speed was chosen for two reasons: first, it is an often-used speed for acquiring video footage. Secondly, if monitoring must be conducted at such altitudes, this is the maximum flight speed to take images with sufficient overlap for mosaicking. After the overflight, the UAV returned to base where it landed. We then prepared it for the next overflight, changing the battery when necessary. We applied three repetitions, each passing over all three locations in the colony. An example of a horizontal flight path and the setup is shown in Supplementary Fig. 1.

To analyse the impact of the absolute distance from an overflying UAV we measured the distances between the triangulated position of the focal penguins (see 2.2.) and the GNSS position of the UAV from the log file. No distinction was made between approaching and receding UAV. In order to analyse the temporal patterns of the reaction, we determined the time of direct overflight (TDO). This is the time when the UAV was closest to the focal penguins. The time before TDO describes the approaching UAV, and the time after TDO describes it moving away again.

2.1.2. Vertical approaches

The UAV again started from the base and ascended to about 100 m. At this height, there is minimal risk of the penguins detecting the UAV. The UAV was then flown manually to the position of the focal penguins (defined in “Video recording and behavioural analysis”). From 100 m above the penguins, the UAV descended at a constant speed of 1 m/s until it reached the planned minimum altitude. It then ascended and hovered at about 100 m for about 3 min or until obvious behavioural reaction ended. Only then did we repeat a flight. We did not repeat the experiment if a large number of the focal penguins reacted or if the intensity of reaction was high. Such reactions occurred particularly when the UAV changed flight direction before ascending again.

2.1.3. Human approaches

To determine the impact of human approaches, a researcher went onto the sea ice by skidoo. They parked about 400 m from the edge of the colony and from the first focal group. From this position, the researcher approached the group on foot, walking as steadily as possible. Their trajectory was saved on a GNSS device (eTrex 20x, Garmin, Schaffhausen, Switzerland) so as to be able to measure exact distances. When the focal penguins started moving away from the person approaching, the researcher retreated along approximately the same track until about 200 m away. They then moved around the colony at this distance and then approached the next group. Another researcher stayed on the ice shelf base coordinating direct approaches to the focal penguins and operating the cameras. For human approach experiments, general disturbance of the colony was avoided by selecting only focal penguins at the edge of the colony.

2.2. Video recording and behavioural analysis

On arriving at the base, we installed three video cameras (1/5.8 type BSI MOS sensor, 2.51 MP, F1.8-F4.2, focal length 2.06–103 mm (28–1740 mm 35 mm equivalent), HC-V380, Panasonic, Kadoma, Japan). The cameras were focused on three parts of the colony so that they included a large number of individuals (chicks and adults) that we were able to see clearly. Those parts consisted of 94–288 focal penguins (mean = 174.4; adults: 31–96 (mean = 54.8); chicks: 60–206 (mean = 119.6)).

We determined the distance to the focal penguins using a handheld laser rangefinder (measuring range: 5–600 m, precision: average ± 1 m, LR 600P, SUAOKI, Shenzhen, PR China) and their direction using a magnetic compass (magnetic declination $\delta = -14°$). Distance and direction allowed us to calculate the cartesian coordinates of the penguins by triangulation. The camera locations were as close as was safe to the edge of the ice shelf. Each camera stood on a tripod anchored to the ice with an ice screw. To protect them against wind and cold, we enclosed each camera in a modified neoprene bottle insulator. A power bank (20100 mAh, 74.37 Wh, PowerCore 20100, Anker, Shenzhen, PR China) supplied electricity. In order to maintain battery life, the power bank was kept warm by a heat pack. We enclosed each power bank and heat pack in a box insulated with expanded polystyrene foam. And we fixed each box, inside a bag, to the camera tripod to prevent the box being blown away by the wind. The camera setup can be seen in Supplementary Fig. 2. Video recording continued all day. One of us also carried an audio recording device (zoom H6 handy recorder) for recording notable occurrences and any experimental activity. We synchronised time (UTC-0, measured with a GNSS receiver) across devices several times a day. Over the whole season we recorded 120 h and 1.4 TB of video (1920 × 1080 interlaced, 25/50 fps). We subsequently extracted the phases of experimental activity using a custom Python script (Python 3.8.0, MoviePy 1.01, Openpyxl 3.03). We used Openpyxl to retrieve the UTC times of activity, as recorded in the audio files, from an MS-Excel sheet (Microsoft Corporation, 2007). Since the cameras automatically produced multiple files per day, we first concatenated the files and then cut them into videoclips containing relevant activity using MoviePy. The clips were exported in mp4-format with 25 fps in H264 Codec. The behavioural state of the focal penguins was analysed using ClickPoints software (Gerum et al., 2017) for one frame every 3 s in the videoclips. All individuals (adults and chicks) in the frame that were clearly visible and not covered by other penguins were counted and allocated to the following behavioural categories (Kooyman and Mullins 1990):

- flipper-flapping (wing-flapping)
  rapid movement of flippers, mostly accompanied by vigilant head movements; sometimes accompanied by nervous running in small circles but staying on location; flipper-flapping is assumed to be an alarm signal (Giese and Riddle, 1999).
- vigilance
  looking around/scanning the vicinity; defined by head movements extending the neck or vertical positioning of the bill.
- sleeping
  head turned backward and beak tucked behind flipper
  note: sleeping also occurs lying or just standing without head turning, however, such sleeping cannot be clearly distinguished from standing and lying when awake, in consequence only the behaviour described above was included in this category.
- undefined
  all individuals not clearly in one of the categories described above.

Inter-specific aggressive behaviour or threatening gestures are not known in emperor penguins and we did not observe any during our field work either. Because emperor penguins are not threatened by any predators on land and do also not compete against each other for territories, evolutionary development of energy-consuming threatening behaviours would be of no use for the species.

We also obtained measurements of undisturbed behaviour from the videos to act as controls. We analysed behaviour in 30 random frames per camera within a video recording phase before any experimental activity and without any other human disturbance (e.g. airplane activity) on that investigation day.

2.3. Statistics

All statistical analyses were carried out using R in RStudio (R Core Team, 2018; RStudio Team, 2016). Models were tested using the lme4-package (Bates et al., 2015).

For analyses of the impact of the different disturbance sources, binomial generalized linear mixed effect models (GLME) were compiled separately for disturbance source (human approach, vertical UAV approach, horizontal UAV overflights), age of individuals (chicks, adults) and behaviours observed (sleeping, vigilance, flipper-flapping). The proportions of individuals displaying each behaviour were used as response variable. The fixed factors were distance of disturbance source from focal group (for horizontal flights additionally time before and after closest distance from focal penguins). The random factor, to account for repeated measures, was the videoframe within the appropriate video clip. To define the direction of associations and to check against undisturbed controls, we categorized distances and times (including controls). We then made pairwise comparisons between categories (Games-Howell-test).

3. Results and discussion

For details and model outputs of all results see Appendices A-C.

The noise level on the ground directly below the UAV was 74 dB(A) when the drone was flying 5 m above the ground at 15 m/s.

3.1. Control phases

The controls revealed relatively constant proportions of individuals showing different behaviours (Fig. 3). Sleeping had the largest range with about 0–50% of adults and 10–45% of chicks observed. Vigilance was observed in fewer than 10% of individuals during most of the controls and flipper-flapping in even fewer, <3% of individuals in most of the frames. Vigilance and flipper-flapping are thus likely to be good indicators for disturbance since they only rarely occur in undisturbed situations.

3.2. Horizontal overflights

The models revealed a significant association in chicks between the absolute distance of the UAV and the proportion of individuals showing different behaviours. There were, however, no significant relationships for adults (Appendix A, Fig. 4).

Even though we detected no significant association between UAV distance and behaviour in adults, there were differences between control levels and nearly all distance classes in the pairwise comparisons for sleeping and vigilant adults (Appendix A.1-A.3; Fig. 5 left). Flipper-flapping does not seem to significantly exceed control level at any UAV distance.

For chicks, there were significant differences between controls and several distance groups as well as between distances (Appendix A.4-A.6; Fig. 5 right). In general, proportions of disturbance-indicating behaviours (vigilance, flipper-flapping) increased with closer UAV distances except for the closest distance group and were larger or similar to the control measurements. It seems that the response to a close UAV is higher than when the UAV is directly overhead. Interestingly,

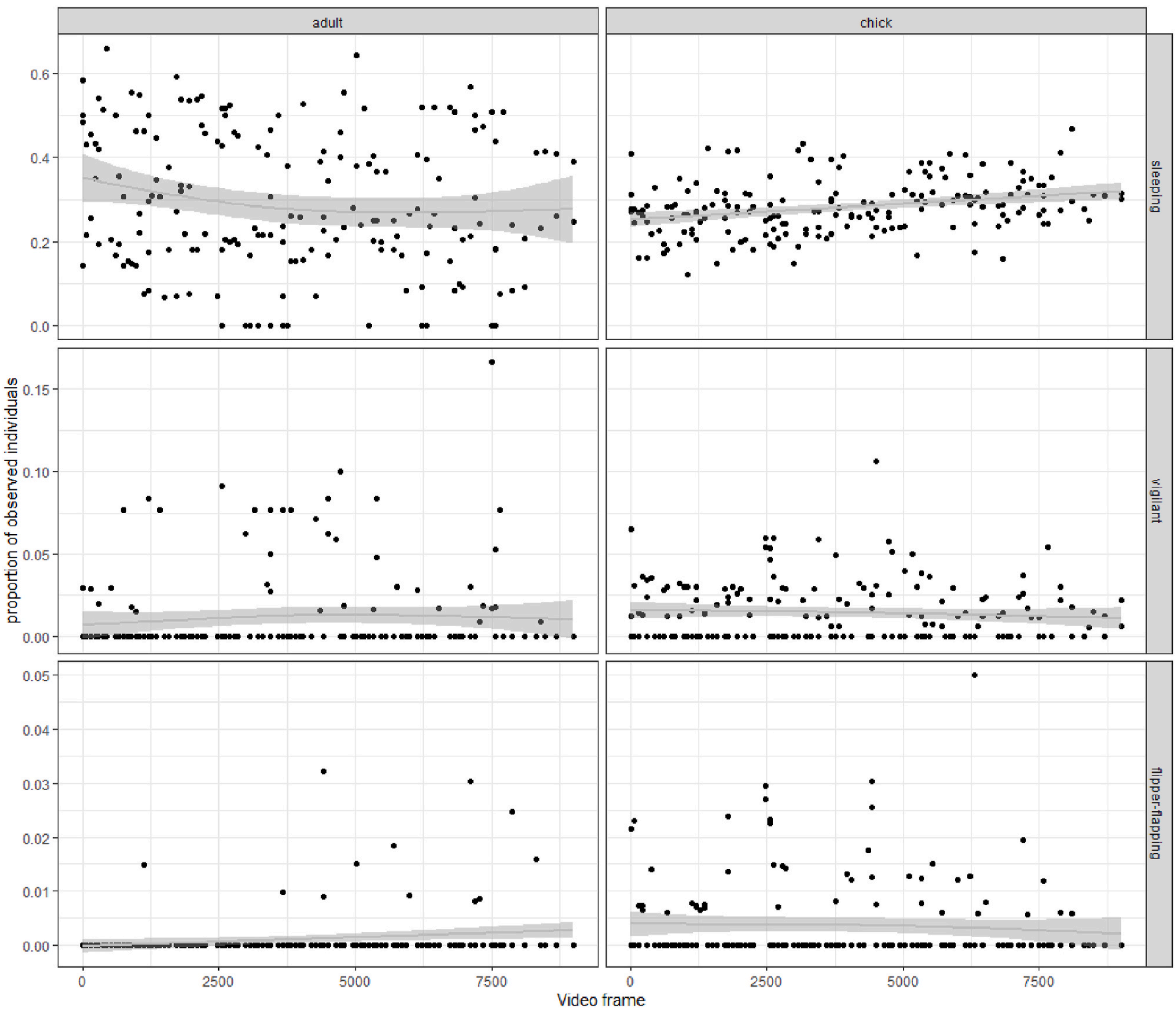

Fig. 3. Observed proportions of individuals showing behavioural reactions during control videos. Grey curves: gam-fit with 0.95 confidence interval.

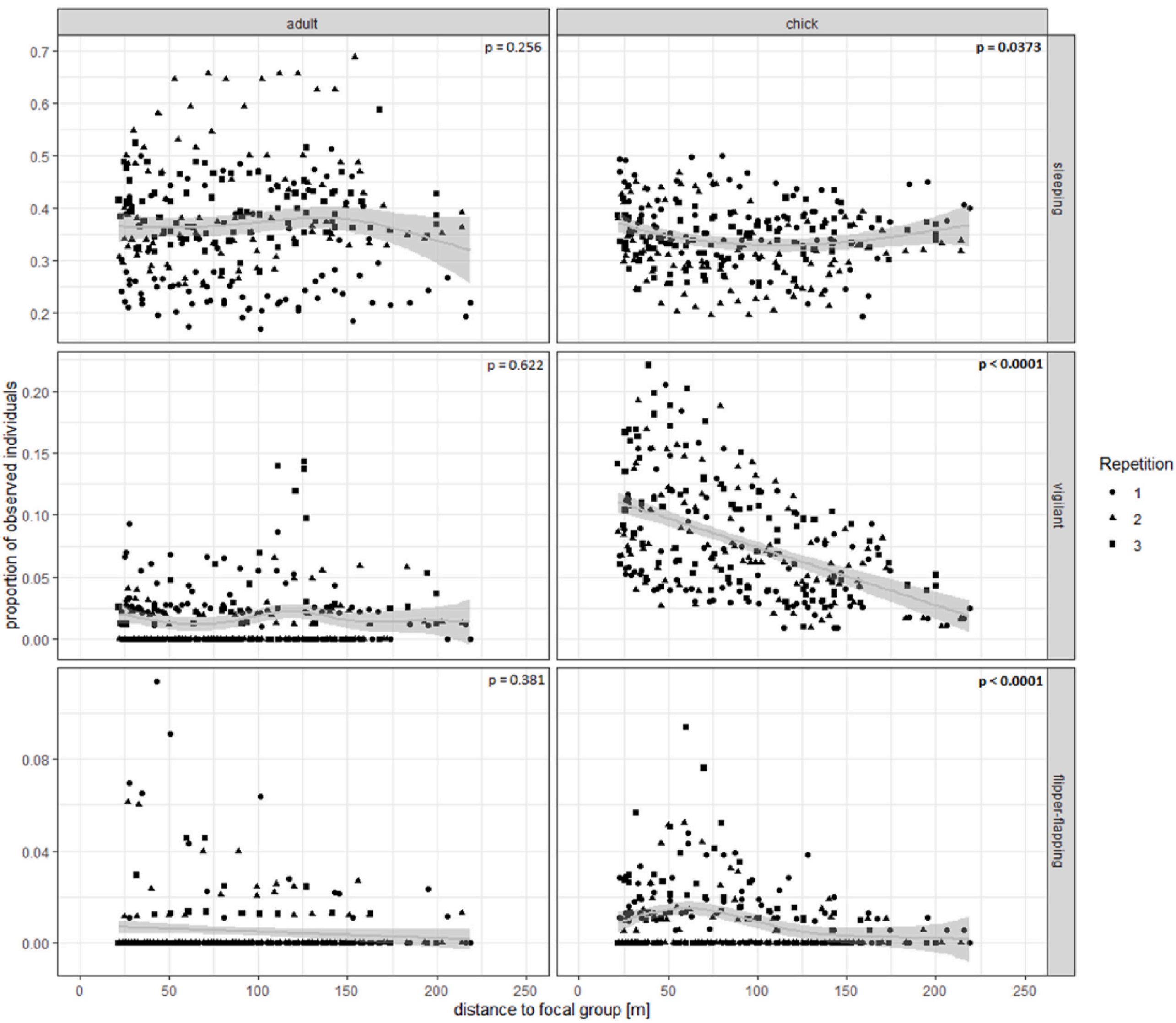

Fig. 4. Observed proportions of individuals showing behavioural reactions during horizontal overflights (for three repetitions) at 20 m above focal penguins. P-values (significant relationships are given in bold) refer to the results of GLMEs, grey curves: gam-fit with 0.95 confidence interval.

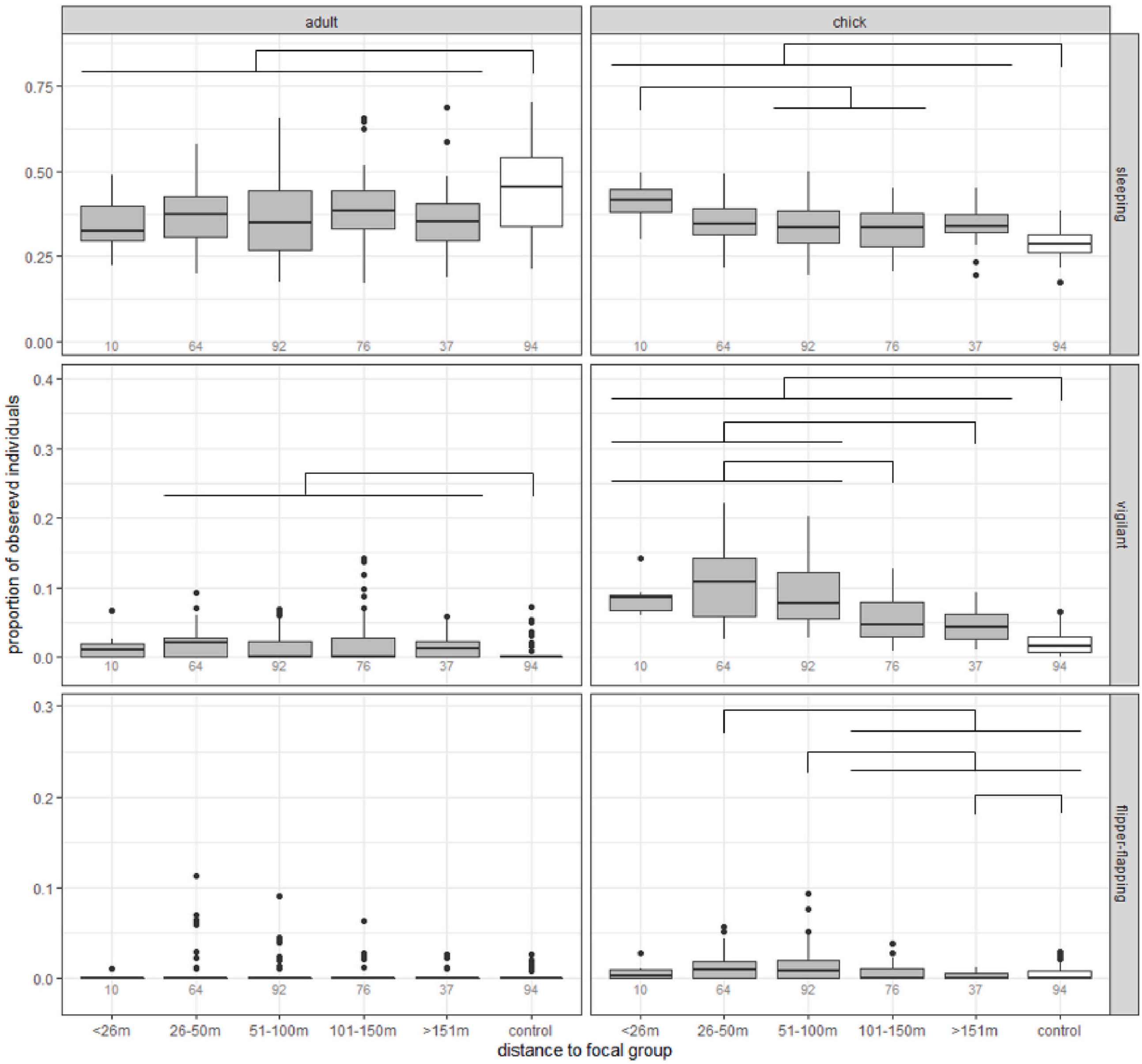

Fig. 5. Boxplot of grouped distances of UAV to focal penguins during horizontal overflights at 20 m altitude above penguins. Grey numbers = n (number of frames analysed for the respective class), horizontal lines represent significant differences between groups.

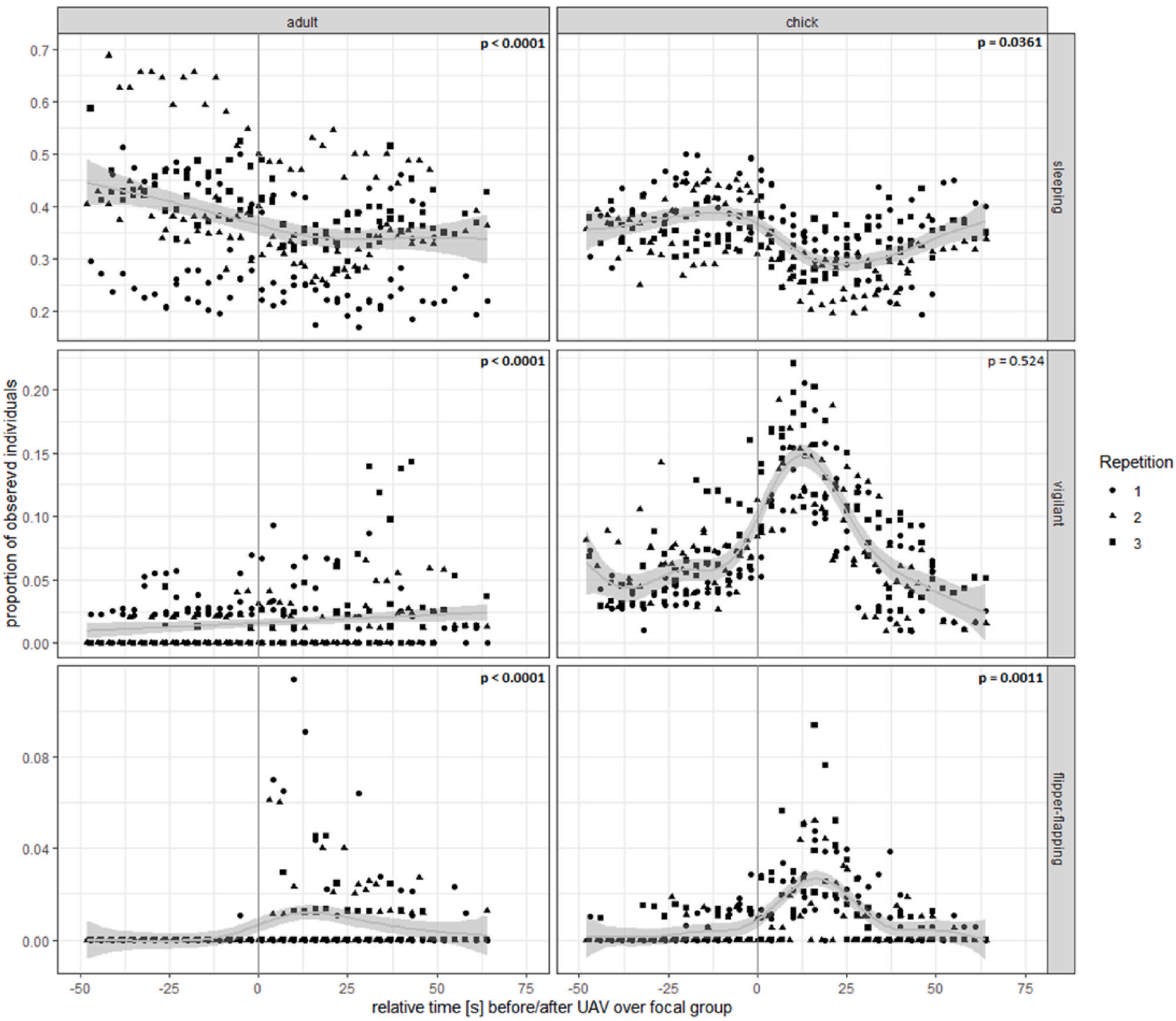

Fig. 6. Observed proportions of individuals showing behavioural reactions during horizontal overflights at 20 m above focal penguins. P-values (significant relations are given in bold) refer to the results of GLMEs, grey curves: gam-fit with 0.95 confidence interval.

proportions of individuals sleeping were significantly higher during overflights than in the control phase, the same occurred for the closest distance group, where significantly more chicks were sleeping than 50–150 m away.

Models for the temporal reaction to UAV overflights revealed a significant association between relative time and proportion of individuals showing any behaviour in adults and chicks, except for vigilant chicks (Appendix A, Fig. 6). For disturbance-indicating behaviours, an increase in proportion of observed individuals can be seen in all plots (Fig. 6) directly after the UAV passes the focal group (TDO/time of direct overflight), even though it is not as distinct in adults as in chicks. After about 50 s the proportions decrease to precedent levels again.

In adult penguins, the pairwise comparisons revealed a lower proportion of sleeping individuals any time after TDO than in the controls or more than 30 s before TDO (see Appendix A.1-A.3, Fig. 7). The only significant difference in vigilance represented an increased level directly after TDO compared to the control. Flipper-flapping was found to occur significantly more often 31–40 s after TDO than until 9 s before TDO.

For chicks, the pairwise comparisons revealed a complex pattern (Appendix A.4-A.6, Fig. 7). In sleeping chicks, the control had a lower proportion of sleeping individuals than all time periods except 11–40 s after TDO. Correspondingly, the time from 11 to 40 s after TDO showed a lower rate of sleeping chicks than most of the remaining in-flight time.

Chick vigilance was lower in the control than during any time when being tested by UAV flight. Furthermore, there was a clear reaction to TDO as the time classes from TDO until 30 s after TDO showed higher levels of vigilance than before TDO and higher than levels recorded during UAV flights later than 30 s after TDO.

The TDO was also clearly recognizable in the chick flipper-flapping data. The time classes from TDO until 30 s after TDO showed higher rates of flipper-flapping than most of the time classes before TDO and later than 30 s after TDO. The control levels were lower than from TDO to 30 s after TDO but not different from most of the other flight classes.

The maximum proportion of reaction during those overflights was reached about 14 s after TDO in chicks (13.7778 s, SD = 4.4096, 6–22 s for vigilance; 14.4444 s, SD = 5.1747, 7–25 s for flipper-flapping). In adults, the reaction was less distinct and more variable (25.7778 s, SD = 23.8106, -5–55 s for vigilance; 24.7778 s, SD = 17.817, 3–55 s for flipper-flapping).

In summary, an increase of reactions, particularly for vigilant and flipper-flapping chicks, was observed after the UAV passed the focal group that lasted about 40 s. Chicks seemed to react faster than adults, and the time of adult maximum reaction had a larger range. As the reaction was not as clearly associated with distance as it was with time

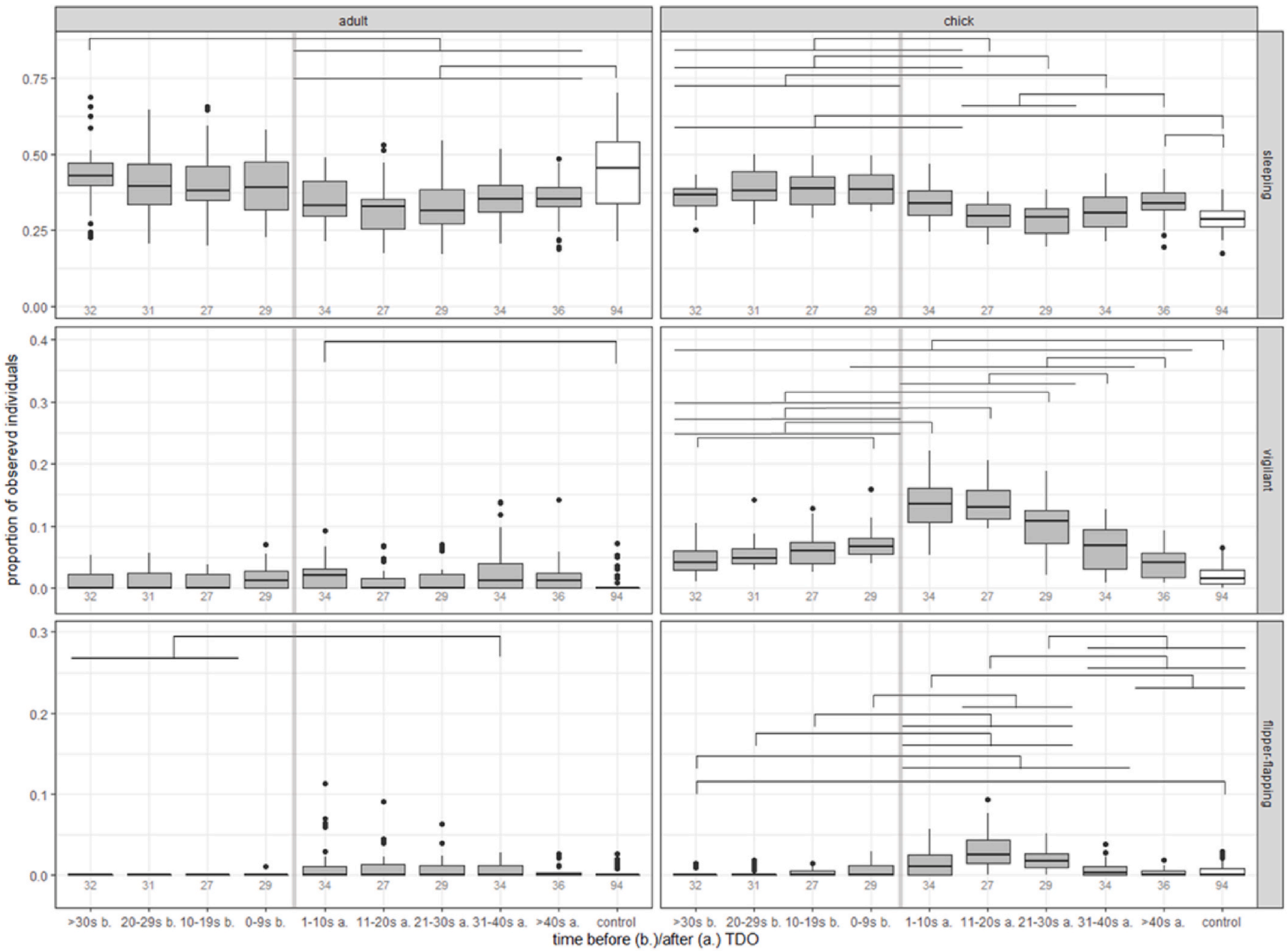

Fig. 7. Boxplot of grouped relative times before and after TDO (grey vertical bar) during horizontal overflights at 20 m altitude above penguins. Grey numbers = n (number of frames analysed for each class), horizontal lines represent significant differences between groups.

during horizontal overflights, we assume that emperor penguins seemingly react immediately to the appearance of a trespassing UAV but do not regard them as a threat and therefore calm down quickly again.

Of interest is that proportions of sleeping chicks were lower in controls than during horizontal flights. We assume that this is caused by daily rhythms of activity since controls had to be recorded before any potential disturbances occurred on this day.

3.3. Vertical UAV approaches

Modelling revealed significant correlations between the UAV altitude during vertical approaches and proportions of all observed behaviours (Appendix B, Fig. 8).

The pairwise comparisons revealed few significant interactions for adults (Appendix B.1-B.3; Fig. 9). Sleeping individuals were observed significantly less often when the UAV was lower than 75 m than in controls. Vigilance was observed in more individuals when the UAV was flying below 20 m than when it was above 76 m. Flipper-flapping was more frequent at UAV heights below 20 m than during those above 30 m. It is intriguing why the higher altitudes induced less flipper-flapping than was observed during the controls.

A significantly higher proportion of chicks was observed sleeping during the control than during the entire UAV activity (Appendix B.4-B.6; Fig. 9). The same was observed for vigilant behaviour, but additionally, individuals were significantly more vigilant when the UAV was flying low (below 30 m) than when it was at higher altitudes. Flipper-flapping was observed significantly more often with UAV altitudes below 20 m than for all altitudes above 30 m. There was also more flipper-flapping with low altitudes than with control levels.

In general, during vertical approaches, there was a gradual increase in the proportion of individuals showing vigilant or flipper-flapping behaviours, increasingly so as the UAV descended below 30 m. There were strong reactions particularly in emperor penguin chicks when the UAV turned to ascend again. The reactions included running and group movements on some occasions. These strong reactions probably occur because the UAV is louder on ascent because of greater rotor speed. However, this situation is not controllable and so comparison is not possible. We were therefore unable to analyse in detail these strong reactions at the point when the UAV ascends.

3.4. Human approaches

There were significant relationships between human approach and all stress-indicating behaviours in adults and chicks except for flipper-flapping in chicks. However, sleeping was not significantly connected to human approach distance (Appendix C; Fig. 10).

The pairwise comparisons revealed differences in the proportion of sleeping adults between control and almost all human approach distances. Control levels, however, had greater proportions of sleeping adults (Appendix C.1-C.3, Fig. 11). Vigilant adults were more frequent in the closest human distance class than in all distances of 21 m and greater. Control levels were significantly lower than this closest class

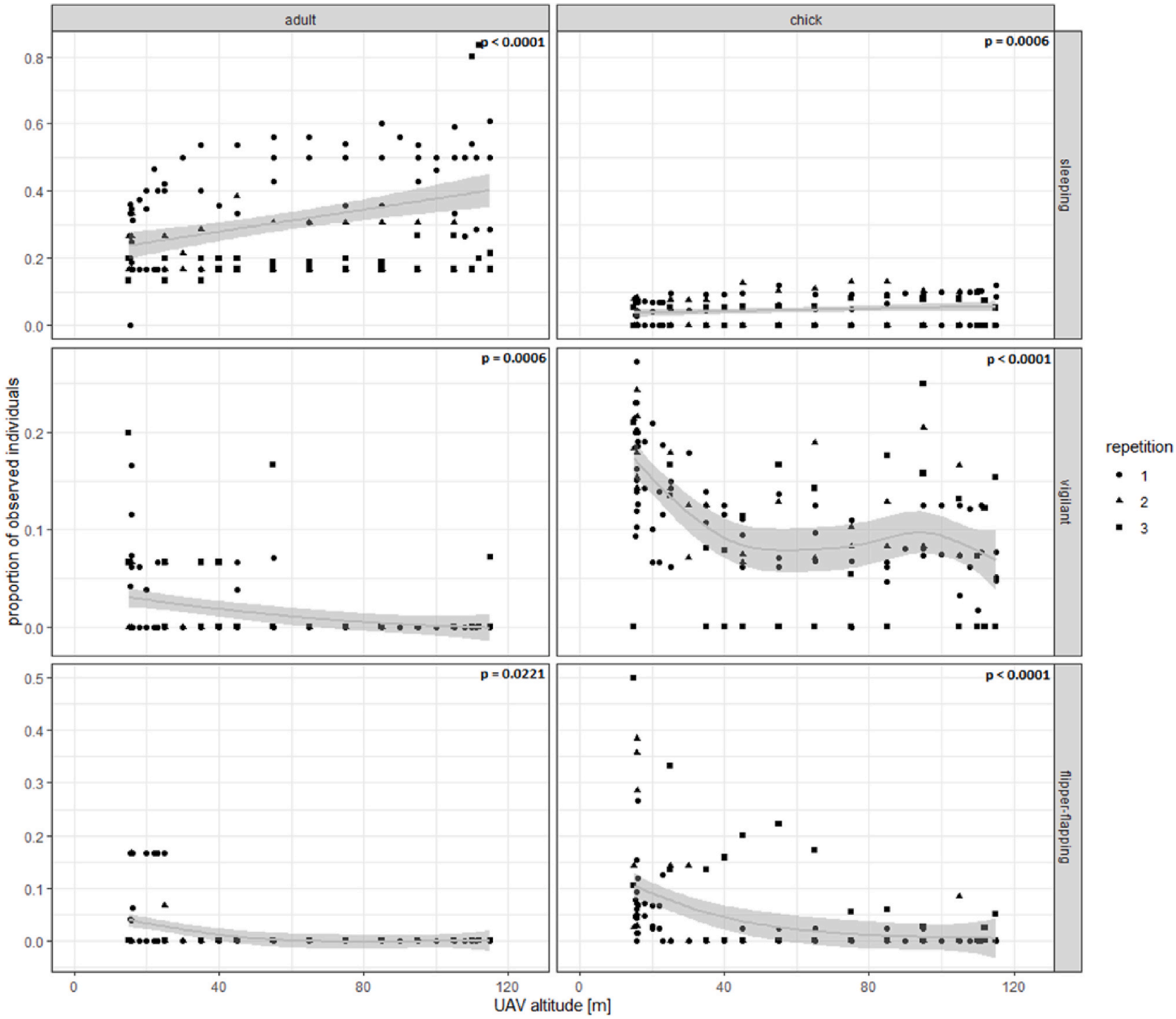

Fig. 8. Observed proportions of individuals showing behavioural reactions during vertical UAV approaches towards focal penguins. P-values refer to the results of GLMEs, significant relationships are given in bold, grey curves: gam-fit with 0.95 confidence interval.

and than 51–100 m. Flipper-flapping was not found to show strong differences between classes, only one significant relationship was found between control and 21–30 m.

Proportions of sleeping chicks were found to differ between controls and almost all distances of human approaches, with more individuals sleeping during controls (Appendix C.4-C.6, Fig. 11). The proportion of vigilant chicks was significantly higher at the closest human approach distance than all distances of 31 m and greater, including controls. There were, in addition, significant differences between the more distance approach distances. These differences describe a stepwise increase of vigilance with distance. Proportions of flipper-flapping in chicks were significantly lower at distances of 31–50 m than at distances of more than 100 m. However, the highest proportions were at the closest human approach distance.

To summarize, the proportion of vigilant individuals was highest at a distance of about 30 m, and flipper-flapping increased starting at about 20 m. At closer distances, penguins moved away from the approaching human. These movements stopped for most individuals as soon as the human stopped approaching. The birds then, after a few minutes, returned to their previous behaviours.

3.5. Comparison of disturbance sources

Reactions to horizontal overflights were in general less severe than to human and vertical UAV approaches (see Fig. 12). In adults, the mean percentage of individuals reacting 11–20 s after the UAV was directly overhead during horizontal overflights did not distinctly exceed that in controls. In chicks, however, flipper-flapping occurred more frequently and vigilance distinctly more often. Chicks reacted strongly to a vertically approaching UAV at altitudes below 20 m, both by being strongly vigilant and also by more than 10% of individuals flipper-flapping. Adults remained relatively calm under the same circumstances with fewer than 5% showing vigilance and flipper-flapping.

Vigilance in reaction to human approaches of less than 5 m was high in adults and in chicks. Flipper-flapping, in contrast, was low (less than 5% of individuals on average) in chicks but high in adults.

The white and relatively small UAV is not very clearly distinguishable against the sky. It is particularly difficult to see against clouds.

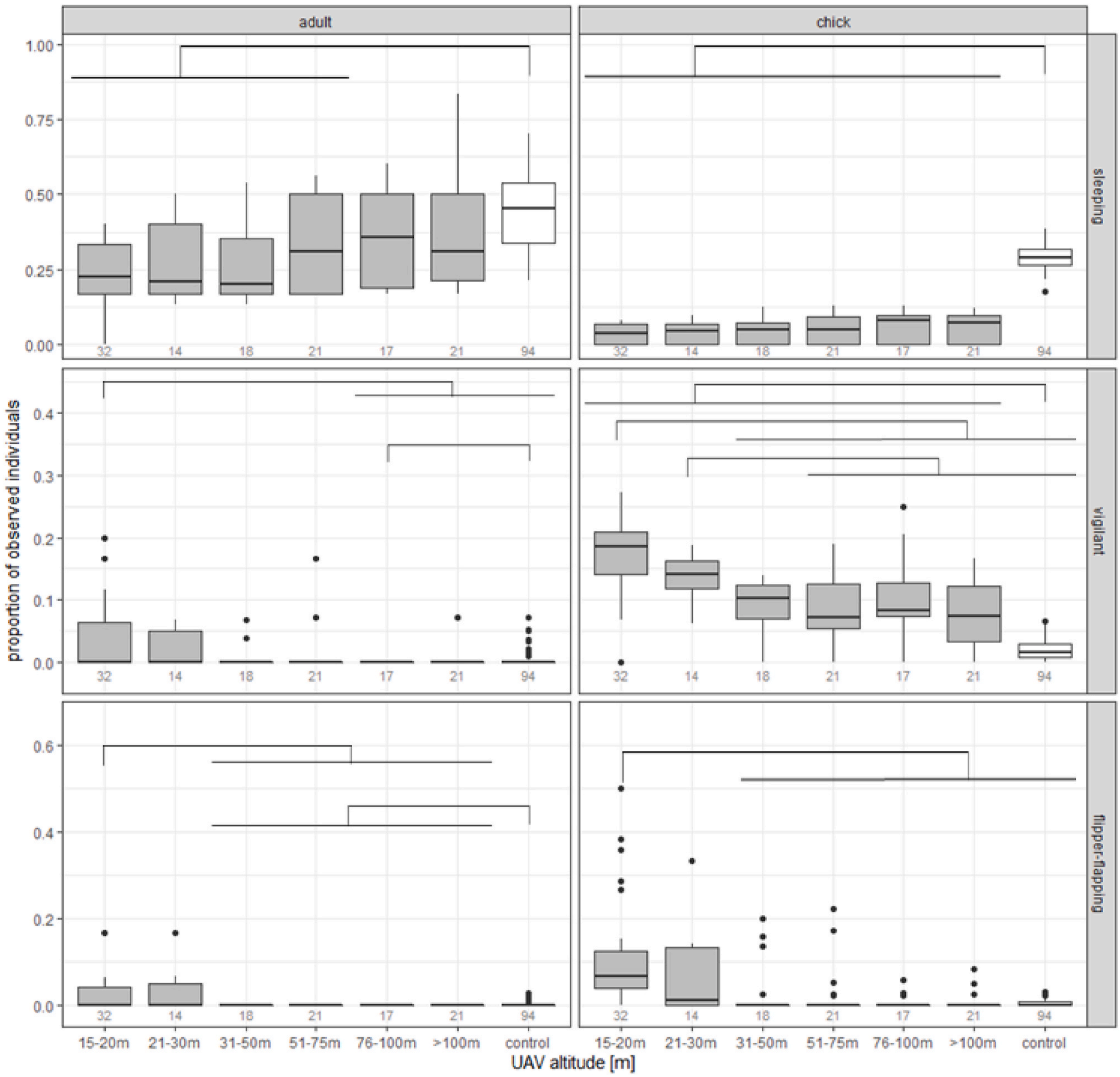

Fig. 9. Boxplot of grouped UAV altitude during vertical UAV approaches. Grey numbers = n (number of frames analysed for the respective class), horizontal lines represent significant differences between groups.

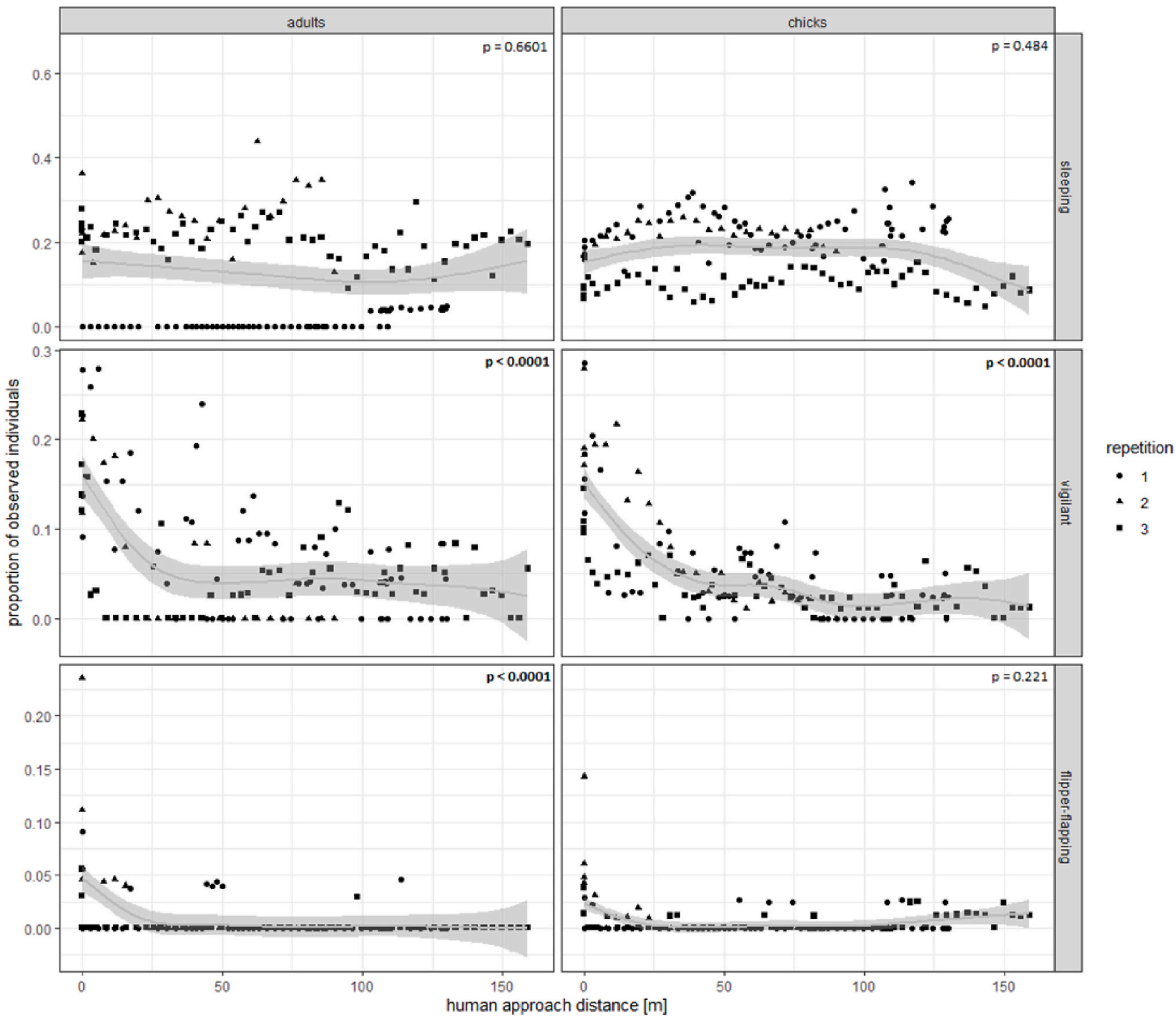

Fig. 10. Observed proportions of individuals showing behavioural reactions during human UAV approaches on foot towards focal penguins. P-values refer to the results of GLMEs, significant relationships are given in bold, grey curves: gam-fit with 0.95 confidence interval.

Penguins are assumed to be emmetropic on land with a slight tendency to myopia (about 2 dioptres, or for king penguins even 10 dioptres, Howland and Sivak (1984); Martin (1999); Sivak and Millodot (1977)). They have a small binocular field, so three-dimensional vision is limited. Thus, they will not be able to see the UAV any better than human observers. Indeed, their ability is probably even worse. Therefore, we assume that penguins perceive UAVs by sound, at least in part. However, it is not known how well emperor penguins are able to hear on land.

The parts of the colony observed during the experiments varied in the total numbers of clearly-visible individuals. This variation was due to the conditions current on the day of the experiments (distance of colony to ice shelf edge, density of individuals within colony). Since nothing is known on the area of effect of the disturbance sources we tested, we cannot ensure that all the individuals within the focal group were subject to the potential disturbance (schematic in Fig. 13B). If the area affected by the disturbance is larger than the focal group, some individuals that are disturbed are not observed. However, all individuals within the observation borders are likely to be affected (Fig. 13A).

To estimate the area of potential effect in relation to the number of focal penguins in the focal group, we compared the number of focal individuals to the proportion of individuals showing behavioural reactions to both human and UAV disturbance. The proportions tend to be higher in focal parts of the colony with fewer individuals for human approaches and vertical UAV flights (Fig. 14). We therefore presume that the area of effect of vertical approaches and human disturbances is limited. This implies that, in focal parts of the colony with higher individual numbers, we also analysed several inherently unaffected individuals. Thus, the mean proportions of disturbed individuals that we reported possibly underestimate the real proportions within the area of effect. There was no such tendency for horizontal UAV overflights. This is probably because the disturbance in this case is moving. In contrast to vertical approaches, where the disturbance source is one invariant point (regarding x-y-position, not altitude), the disturbance source in horizontal flights moves through the colony and thereby effects a larger number of individuals. The probability is thus higher that all individuals of the focal group are within the area of effect, even for large groups. For the assessment of the impact of UAVs on emperor penguins it is possible to conclude that vertical flights induce greater disturbance in a smaller

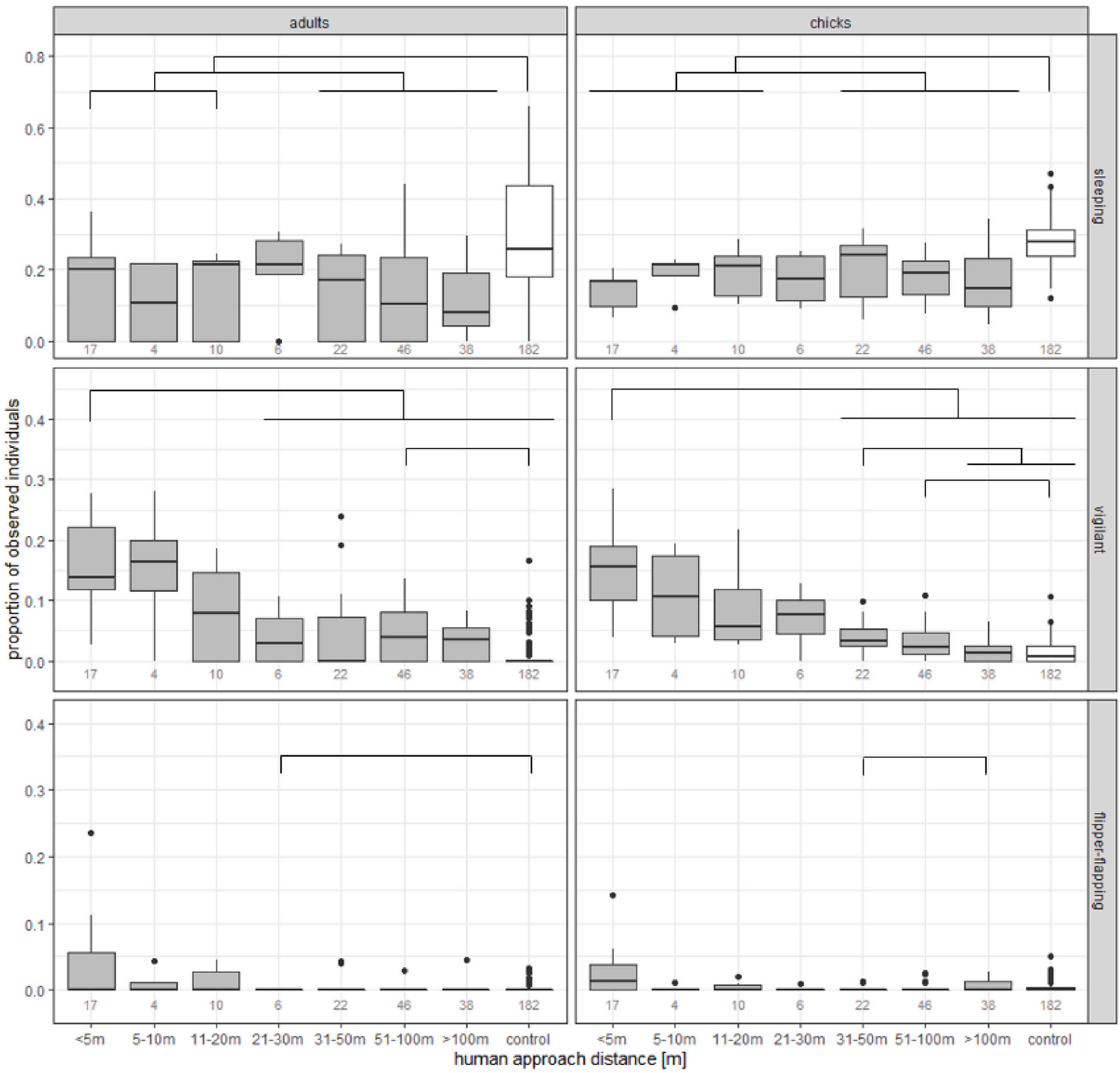

Fig. 11. Boxplot of grouped distances during human approaches. Grey numbers = n (number of frames analysed for the respective class), horizontal lines represent significant differences between groups.

group (more individuals of this group reacting), while horizontal overflights cause weaker reactions but over a larger area. Further studies should investigate the extent of the area affected by UAVs on a sounder level to verify these conclusions.

Giese and Riddle (1999) observed 20 to 25% of emperor penguin chicks flipper-flapping during overflights of a helicopter at 1000 m altitude. This is a much greater proportion than we observed during comparable UAV flights (horizontal overflights). The maximum proportion of penguins flipper-flapping was below 10% and most of the time below even 5%. Thus, UAVs, even at very low altitudes, clearly cause less disturbance than helicopters.

We only examined behavioural changes. We therefore are unable to estimate whether and, if so, how strongly behavioural changes have physiological consequences and thereby cause higher energy expenditure. However, Regel and Pütz (1997) measured emperor penguin body temperatures to calculate energy expenditure during stress. They found an increase of 1.5 K as a reaction to contact with humans. During helicopter overflights, they calculated the “additional energy requirements due to excitement as a percentage of total daily energy expenditure during moult” (Regel and Pütz, 1997, Table 4). These were 9.9% for chicks and 1.7% for adults. For chicks, this was the highest observed energy loss although other disturbances caused higher temperature rises in adults. This matches our results of chicks being more sensitive to aerial disturbances than adults and shows how disturbances can affect a

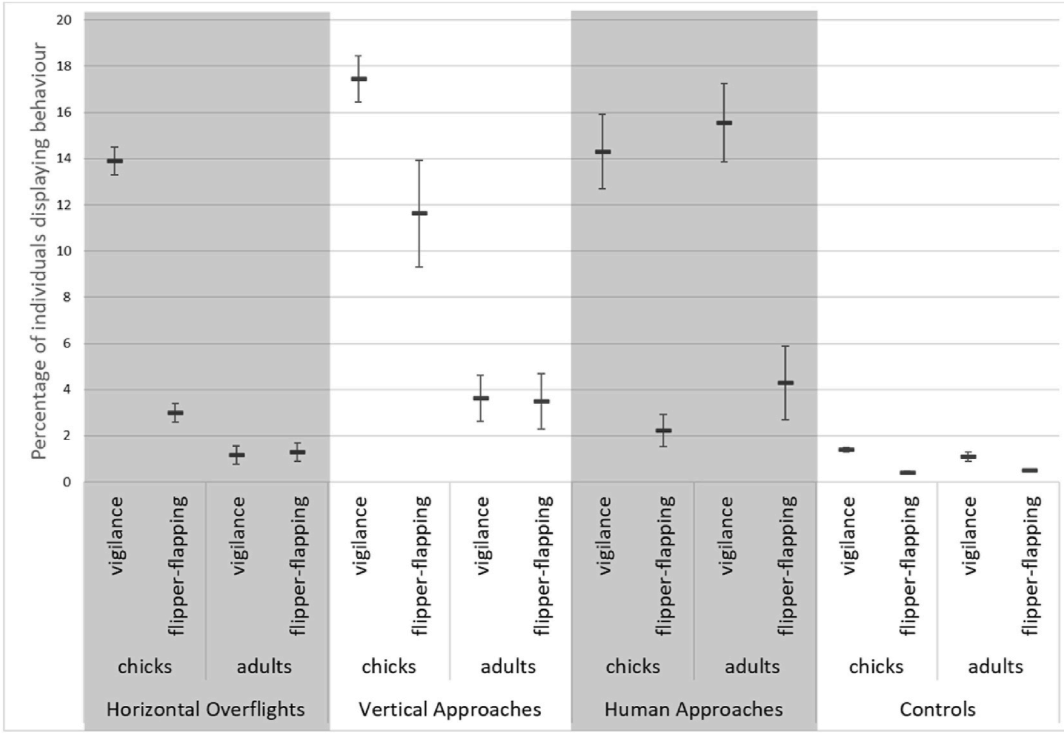

Fig. 12. Comparison of observed behavioural reactions (percentage of individuals showing vigilance & flipper-flapping) to different disturbance sources. Displayed is the mean ± standard error during the class of the highest observed disturbance (i.e. 11-20 s after TDO in horizontal flights, <5 m in human approaches, 15–20 m for vertical approach).

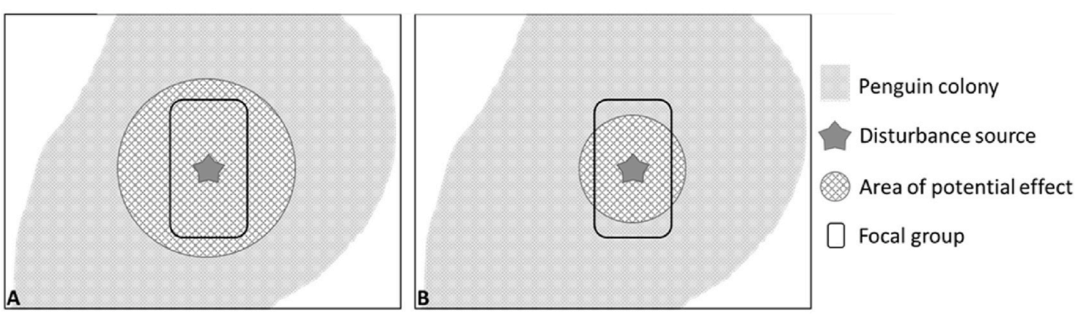

Fig. 13. Schematic representation of the consequences of different assumed areas of effect and the range or size of the focal group on individuals within observation range being subject to the disturbance. A: Focal group within effect range; all individuals observed are potentially disturbed. B: Effect range smaller than focal group or not 100% overlapping (disturbance has a small effect size or parts of the colony chosen were too large); some of the observed individuals are not within effect range and are therefore taken into account even though not potentially disturbed.

species in an environment where energy loss can have severe consequences.

4. Conclusions

Our observations show that emperor penguins, particularly chicks, do perceive overflying UAVs and react to them. Vertical approaches directly towards the individuals cause a stronger reaction than horizontal passes, but horizontal flights probably influence a larger group of individuals. In general, the observed reactions are not very intense even at the low altitudes we tested. Less than 20% of observed individuals showed distinct reactions. For scientific population survey purposes, flight altitudes of at least 50 m are more reasonable where individuals can still be distinguished while a large area can be covered in one flight.

The comparison with human approaches on ground showed that the proportion of reacting adults was much higher during human approaches than in any UAV activity. In contrast, chicks reacted more strongly to vertical UAV approaches than to humans on the ground. We conclude that for both chicks and adults, population surveys by UAV (where flight paths are normally exclusively horizontal) induce less disturbance than manual surveys on the ground. For other UAV uses, recreational use, tourism and journalism, where flight patterns are less structured and contain more changes of direction and altitude and UAVs are manoeuvred towards individuals more frequently, the disturbance can be higher than direct human contact, particularly in chicks. Such activities should be limited to greater distances from colonies. In this study, we analysed the reaction of the individuals to one UAV model flying in two distinct flight modes. Other UAV models, particularly fixed-wing UAVs, probably cause different reactions because these models are usually flying more silently and faster. In addition, they also resemble a flying bird and so can be perceived as an aerial predator by some species. For the development of environmental guidelines and application in environmental impact assessments, information on higher flight altitudes is essential so as to find conditions under which it is

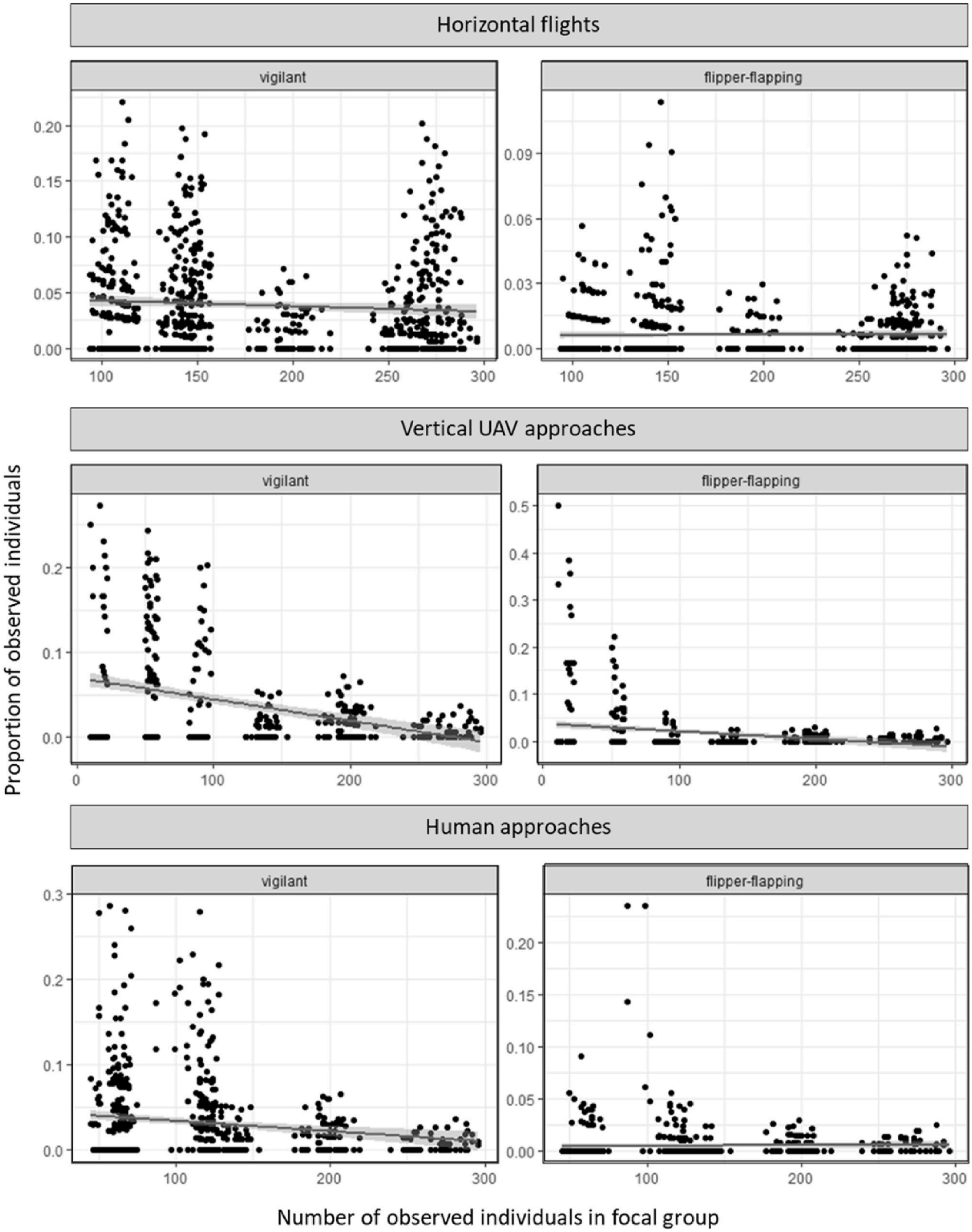

Fig. 14. Correlations of number of individuals in the focal part of the colony (individual numbers) and proportion of individuals observed showing behavioural reactions with a linear fit (0.95 confidence interval).

possible to conduct UAV surveys without causing disturbance. Thus, further studies should elaborate on the impact induced by different overflight altitudes, on the influence of other UAV models which differ in shape, colour, noise level and/or size, and on differences between breeding stages/age of the chicks.

Author declaration

Marie-Charlott Rümmler: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Funding acquisition. Osama Mustafa: Conceptualization, Methodology, Validation, Investigation, Resources, Writing - Review & Editing, Supervision, Project administration, Funding acquisition. Jan Esefeld: Methodology, Validation, Formal analysis, Writing - Review & Editing. Manuel Tim Hallabrin: Data Curation. Christian Pfeifer: Conceptualization, Software, Resources, Writing - Review & Editing.

Ethical statement

The study was commissioned by the German Environment Agency, Dessau-Rosslau. All applicable international, national and/or institutional guidelines for the care and use of animals were followed.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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