Polar Biol
DOI 10.1007/s00300-017-2187-z

ORIGINAL PAPER

Flights of drones over sub-Antarctic seabirds show species- and status-specific behavioural and physiological responses

Henri Weimerskirch[1] · Aurélien Prudor[1] · Quentin Schull[2]

Received: 28 April 2017 / Revised: 24 July 2017 / Accepted: 24 July 2017

Abstract Drones and unmanned aerial vehicles are increasingly used in research on wildlife. Their wide applications can also give interesting insights into habitat use and population distribution. However, the disturbance they might be responsible for, on species and especially in protected areas has yet to be investigated. We assessed and compared the behavioural response of 11 southern seabird species at the Crozet Islands, Southern Indian Ocean, to drone approaches at specific altitudes. We first show that the behavioural response differed between species depending on the altitude of the drone approach. At 50 m of altitude, only one of the studied species showed a detectable reaction, whereas at 10 m, most species showed strong behavioural postures of stress. Adult penguins breeding in large colonies, and some albatross species showed little behavioural response even when the drone was as close as 3 m, whereas other species such as giant petrels or cormorants appeared highly sensitive to drone approaches. Among King Penguins, although incubating adults showed little signs of behavioural stress, non-breeding adults and fledglings in crèches exhibited strong behavioural responses to the drone approach. Monitoring heart rate allowed us to investigate the link between behavioural and physiological response to that specific potential stressor in king penguins. Whereas we confirmed the expected link between physiological and behavioural response in chicks, breeding adults showed no behavioural sign of stress but had a significant increase in heart rate, the relative increase being higher than in chicks. All together these results have important implications for the conservation of species and should be helpful for future legislations on the use of drones.

Keywords Albatrosses · Petrels · Penguins · Disturbance · Altitude · UAV

Electronic supplementary material The online version of this article (doi:10.1007/s00300-017-2187-z) contains supplementary material, which is available to authorized users.

✉ Henri Weimerskirch
henri.weimerskirch@cebc.cnrs.fr

[1] CEBC, CNRS - Université de La Rochelle, UMR 7273, 79360 Villiers en Bois, France

[2] DEPE- IPHC, CNRS-Université de Strasbourg, 67000 Strasbourg, France

Introduction

The last decade has shown that there is an increased interest in the use of drones or unmanned aerial vehicles (UAVs) for filming and taking aerial pictures for military, private and also scientific purposes. As indicated by the growing literature on the use of drone for ecological studies, research can benefit from their use in many ways (Jones et al. 2006; Sardà-Palomera et al. 2012; Anderson and Gaston 2013). However, using drones may also lead to negative consequences on wildlife. For instance, human disturbance, especially during breeding period, is well known to reduce breeding success and it has especially been shown for colonial species that can be very responsive to disturbance (Carney and Sydeman 1999). Therefore, the sensitivity of wildlife to drone approaches has to be studied, and guidelines should be developed for the use of this relatively new technology (Vas et al. 2015). This is especially important in areas where threatened species are present, such as reserves and national parks where drones have a great potential for monitoring and surveying the population (Anderson and Gaston 2013).

Previous studies that focused on animal behaviour in response to drone flights showed that they may disturb various species, and that the altitude at which they overfly individually plays an important role (Vas et al. 2015; Rümmler et al. 2016). Studies also suggested that the sensitivity to drones in animals at different breeding status within a species should be compared, and reaction thresholds have to be thoroughly investigated (Vas et al. 2015). Whereas, most studies focused on behavioural observations only, it has been shown that animals can experience stress before changes in behaviour occurs (Wilson et al. 1991). Indeed stress may lead to an increase in heart rate in birds without being associated to any behavioural modifications (Wilson et al. 1991). Therefore it is suggested that future studies on drone impacts should record physiological parameters along with behavioural observations when possible (Vas et al. 2015).

The aim of this study was therefore twofold. First, we examined the sensitivity to drone disturbance of 11 different seabird species breeding on a sub-Antarctic island. We hypothesized that the disturbance sensitivity varies between species and we examined whether the individuals of different status (breeding or non-breeding adults and fledglings) react differently to drones approaching at various altitudes. Secondly, in one specific species, the king penguin, we assessed simultaneously the behaviour, the heart rate and activity patterns in response to drone approaches to investigate whether one physiological stress response (heart rate) was related to behavioural observations.

Methods

The study was carried out on Possession Island, Crozet Islands (51.5°E–46.4°S) between 12 November and 7 December 2016. We used a white quadricopter drone (Phantom 3, SZ DJI Technology Co.) with a diagonal length of 350 mm, a mass of 1030 g, equipped with a GoPro 4 camera. The maximum speed is 15 m s^{-1} and noise level measured with a decibel meter at 2 m was 60 dB (Vas et al. 2015).

Since a previous study indicated that the take-off of a drone at 50 m distance may still cause a reaction from penguins (Rümmler et al. 2016), in our study the drone was launched at a minimum distance of 100 m from the birds. While one operator was flying the drone, a hidden observer monitored the birds with 10 × 40 binoculars at a distance of 20–50 m. From the take-off point, the drone ascended vertically to 50 m. This altitude was chosen based on previous studies showing that at such altitude drones did not cause any reaction in penguins (Goebel et al. 2015) or limited reactions (Rümmler et al. 2016). Horizontal flights above the target birds were then carried out at a speed of 2 m s^{-1}. After passing from a vertical perspective above the birds, the drone continued its flight horizontally away from the birds to 100 m away, then descended to a lower altitude (25 m), and passed again over the targeted birds (Fig. 1). A last passage was carried out at 10 m. Finally, by starting 100 m away from the target birds, the drone returned at 10 m above the target, and was flown down for a final vertical approach flight to an altitude of 10–3 m (Fig. 1). The same procedure was used for all species and at different breeding stages. All tests were conducted under similar conditions, i.e. during periods of low wind (<5 m s^{-1}), and during midday hours (9:00–16:00), i.e. under good light conditions and visibility.

A total of 1406 observations were obtained and 389 individuals of 11 different species were tested for reaction to the passage and approach of the drone (Table 1). The size of nesting groups differed between species, from solitarily nesters (Skuas) to large monospecific colonies including thousands of individuals. Observations were assessed at the individual level, from single individuals to a recognizable group of a maximum of 10 individuals among a large colony for penguins, such as for penguins (excluding Gentoo Penguins) (Table 1).

Behavioural response

Following (Rümmler et al. 2016), but using a different number of levels, behavioural response of birds to the passage or approach of the drone was classified as one value per drone over-flight per individual into five levels, instead: resting (0), vigilance (1), take a look at the drone (2), agonistic (3) and escape (4). Resting included sleeping (beak under wing or flipper, or eyes closed), and all sorts of comfort movements such as cleaning and preening movements and breeding behaviour (e.g. mutual displays, nest,

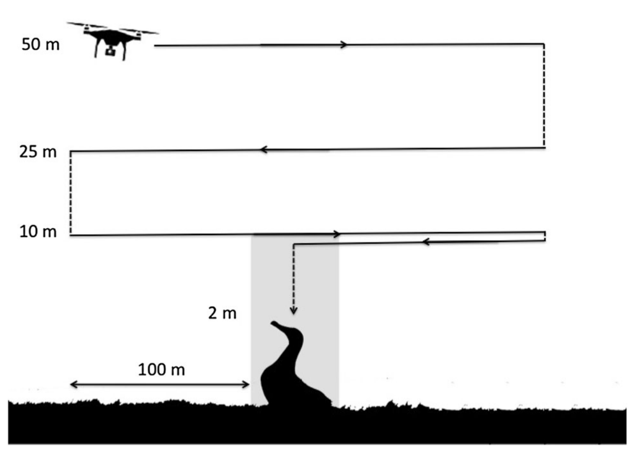

Fig. 1 Flight plan and altitudes of the birds approach by the Phantom drone

Table 1 Species considered in the study, number of individuals observed, size of groups and breeding stages

Species	Code	Number individual tested	Status	Average size of groups observed
King Penguin (*Aptenodytes patagonicus*)	KIP	140	Adults Incubating, Adults Moulting, Chicks	10
Macaroni Penguin (*Eudyptes chrysolophus*)	MAP	46	Adults Incubating	8 (5–10)
Southern Rock-hopper Penguin (*Eudyptes chrysochome*)	RHP	26	Adults incubating	6 (5–8)
Gentoo Penguin (*Pygoscelis papua*)	GEP	19	Adults guarding chicks, chicks	2 (1–3)
Wandering Albatross (*Diomedea exulans*)	WAL	42	Adults non breeding, fledglings	5 (3–8)
Sooty Albatross (*Phoebetria fusca*)	SOA	53	Adults incubating	5 (3–8)
Light-mantled Sooty Albatross (*Phoebetria palpebrata*)	LMA	6	Adults incubating	4 (2–5)
Southern Giant Petrel (*Macronectes giganteus*)	SGP	22	Adults brooding	4 (3–7)
Northern Giant Petrel (*Macronectes halli*)	NGP	23	Adults non breeding	4 (3–6)
Imperial Cormorant (*Phalacrocorax atriceps*)	ICO	8	Adults incubating	8
Sub-Antarctic Skua (*Stercorarious antarcticus*)	SKU	4	Adults incubating	1

egg or chick manipulation). A bird was recorded as vigilant if its eyes were open and movements of the head indicated attention to the surrounding environment, with regular horizontal movements of the head. “Looking at the drone” was noted when the bird turned its head upwards and looked at/followed the drone in the sky. Agonistic behaviour included aggressive behaviour directed against the drone (and not toward congeners), such as threatening with their beak, calls (for skuas) or flipper flapping as in king penguin chicks. “Escape” corresponded to the strongest reaction to disturbance, for which the individual leaves its nest, its egg or unprotected chick, or in the case of chicks in crèches or non-breeding birds when they leave their resting site. During all flights, videos were recorded from the drone using the GoPro 4 camera, and in the case of King Penguins colonies a second camera located at 50 m from the observed birds recorded from a lateral point of view.

Physiological response

Heart rate (HR) was monitored in five adult and five chick King Penguins using external cardio-frequency meters (Polar model RS800; Polar Electro Oy, Kempele, Finland) as previously described in (Groscolas et al. 2010), including details on logger attachment, technology and accuracy of HR measurement (Groscolas et al. 2010). We flew the drone over a sector of a large ~20,000 breeding pair colony (Baie du Marin) where a physiological study was carried out. Loggers were attached to penguins the day preceding the drone tests, and recovered several hours to several days after the drone tests. The logger transmitter was attached to the dorsal feathers of the adults and chicks using adhesive tape (Tesa, Tesa SE, Hamburg, Germany) and the receptor was secured to a temporary flipper band following (Groscolas et al. 2010). Loggers did not appear to interfere with the usual routine of the birds, as individuals soon resumed normal activity (courting, preening, stretching, sleeping and fighting) after handling (Groscolas et al. 2010). The monitored birds could not be distinguished in term of behaviour the following days and successfully bred. HR was sampled continuously at 5 s intervals.

A measure of physical activity was recorded for each individual equipped with HR monitors, using externally attached physical activity monitoring systems (Actical; Respironics, Bend, OR, USA). The omni-directional accelerometer sensors monitored the occurrence and intensity of motion. Actical devices stored the sampled information in the form of activity counts. Acceleration was sampled at 32 Hz. The highest of the 32 values recorded each second were summed over 30 s and archived on the data logger. All datasets (drone camera, HR monitors and accelerometers) were synchronised from the clock of a single computer.

Statistical analysis

The analysis is presented under several approaches. Because of a lack of heteroscedasticity, the Generalized mixed model follows a poisson distribution, where the ID of the birds was specified as a random factor. This aimed to explain the reaction of the birds by the interaction between species and altitude which failed to converge when taking into account the five bird reaction levels (levels 0–4). Therefore, first, we gave a description of the changes in behaviours (ranging between levels 0–4) in relation to the altitude of the drone. We thus averaged the observed reactions from all individuals within a species for each altitude class and present them in the Fig. 2. Secondly, to assess statistical changes in response to disturbance, individual reactions were grouped into undisturbed and disturbed groups. The undisturbed group includes the individuals presenting behavioural response levels of 0 or 1. The disturbed group contains the individuals presenting behavioural response levels of 2–4 (Rümmler et al. 2016). We ran a binomial generalized linear mixed model (GLMM), with a logit function, where species and flight altitude were considered as fixed factors in interaction, and the ID of the birds as random factor. Skuas, Cormorants and Light-mantled Sooty Albatross all having small sample size (<10), and therefore the statistical model could not converge.

We then focused on a specific species, the King Penguin to investigate whether disturbance (0/1) reaction may differ depending on the status of the bird (resting chick, resting/molting adult or breeding bird). We ran a binomial GLMM by specifying the ID of the bird as a random factor, and both altitude and status as fixed factors in interaction. Finally, on a subset of five chicks and five breeding adults we discussed the pattern of association between behavioural and physiological responses of the birds in reaction to the drone approach. The Statistical parts of the analysis were conducted in Statistica 12. Average values of heart rates were calculated for each individual and each altitude over 20 s periods centred on the time when the drone was at the vertical of the birds equipped with recorders.

Results

Before the launch of the drone at the beginning of the experiment, all individuals were undisturbed. Whereas individuals of most species showed either postures of comfort or rest (level 0), all skuas (SKU), most giant petrels (NGP and SGP), Light-mantled Sooty Albatrosses

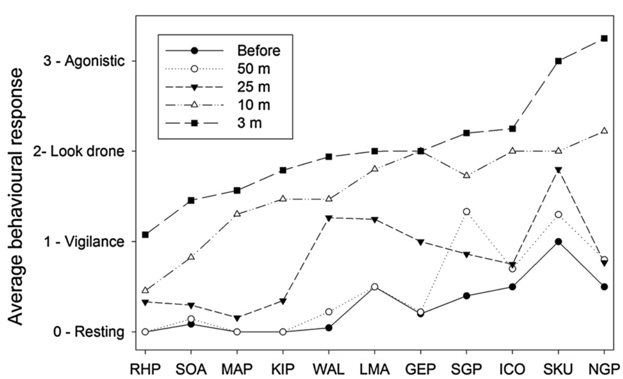

Fig. 2 Average of the behavioural postures of 11 adult seabird species to the horizontal flight of a drone passing above the individuals at different altitudes. The 3 m height corresponds to a vertical approach from 10 to ca. Three meters from the tested individuals. The species are ranked in relation to the average posture recorded during vertical approaches, postures ranging from 0 to 4

(LMA) and cormorants (ICO) were already vigilant (level 1) before the drone took-off (Fig. 2). The overall observed reaction of birds to the flight of the drone was an increase in the behavioural response when the altitude of the drone decreased (Fig. 2).

At 50 m, SGP that were not already vigilant reacted to the presence of the drone changing from a resting (level 0) to a vigilant status (level 1). All other species did not present an important modification in their behaviour (Fig. 2). At 25 m, LMA and SKU appeared relatively sensitive to the approach of the drone expressed by an increase in individuals showing agonistic behaviour toward the drone. At 10 m, MAP, LMA and GEP showed an important increase in the number of individuals expressing agonistic behaviour toward the drone. Southern Rockhopper Penguins (RHP) and Sooty Albatrosses (SOA) only remained relatively calm (mean close to level 0), whereas, all other species showed a high proportion of individuals at least at a vigilant status (level 1). Finally at 3 m, all species showed a higher proportion of individuals in more stressed status with a relative important increase between 10 and 5 m only for RHP, SOA, WAL, SKU and NGP. The other species expressed their maximum behaviour in response to the drone (Fig. 2). At 10 m, interestingly, species showing signs of vigilance before the experiment (Skuas and Giant Petrels) were also those showing the strongest reaction to the drone approach (Fig. 2).

We observed a significant effect of the factor of species and the altitude of the flight on the response of individuals to the drone approach (Binomial GLMM: species, $P < 0.0001$, Wald statistics $W = 129.4$; altitude, $P < 0.0001$, $W = 194.2$). Altitude had a significant effect on all species except two that showed no significant changes in their behaviour (LMA and WAL) and for three others for which the model did not converged for the individual analysis because of the small sample size (GEP, ICO and SKU) (Table 2).

A similar procedure (horizontal flights followed by a vertical approach up to 3 m) was carried out over king penguins of different breeding/age status: breeding adults (incubating eggs), non-breeding moulting adults and large chicks in crèches, the latter being aged 10–11 months, but prior to the loss of down. Our binomial (disturbed/undisturbed) GLMM revealed that the status of birds had a strong significant effect on the reaction to flight disturbance ($W = 115.2$, $P < 0.0001$) as well as the altitude ($W = 109.1$, $P < 0.0001$), with significant interactions. Whereas breeding adults showed little to no reaction to the presence of the drone at any altitude, even when approaching as close as 3 m, chicks and moulting adults showed extreme behaviour modifications. They expressed signs of panic (chicks in particular very rapidly flapped their flippers) when the drone was at 25 m and moved

Table 2 Results of Binomial GLMMs testing the effect of the altitude on whether individuals among each species show behavioural changes to the flight and approach of the drone

Species code	Wald statistic	
KIP	29.1	$P < 0.0001$
MAP	39.2	$P < 0.0001$
RHP	7.9	$P = 0.049$
GEP	Too small sample size	
SOA	28.1	$P < 0.0001$
LMA	1.8	$P = 0.61$
WAL	4.1	$P = 0.276$
NGP	8.0	$P = 0.045$
SGP	16	$P = 0.0011$
ICO	Too small sample size	–
SKU	Too small sample size	–

away from the approached area in mass movement. Neighbouring breeding adults showed no visible signs of stress, with few birds staring at the drone when it was very close (Fig. 3). Non-breeding adults presented responses similar to chicks, although they did not execute the flapping behaviour observed in chicks.

The heart rate (HR) and activity patterns of King Penguins, five chicks and five incubating adults, under drone approach were recorded as well as their behavioural response (Figs. 4, 5; Table 3). The strong behavioural response of chicks to horizontal flights at low altitude and to vertical approach up to 3 m height was associated with an increase in HR of 30–40% from levels prior to the approach. Increase in HR was generally, but not always, associated with increased activity, corresponding to the rapid flapping of the flippers (Fig. 4; Table 3). Surprisingly in adult King Penguins, the heart rate increase in response to the flight of the drone was not followed by a behavioural

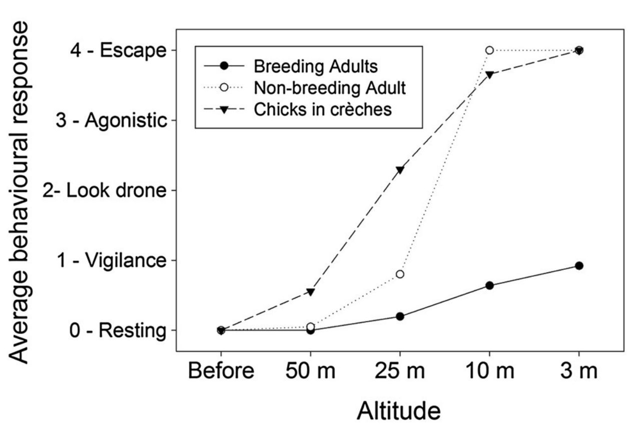

Fig. 3 Average of the behavioural posture of breeding and non-breeding king penguins adult and of king penguin chicks

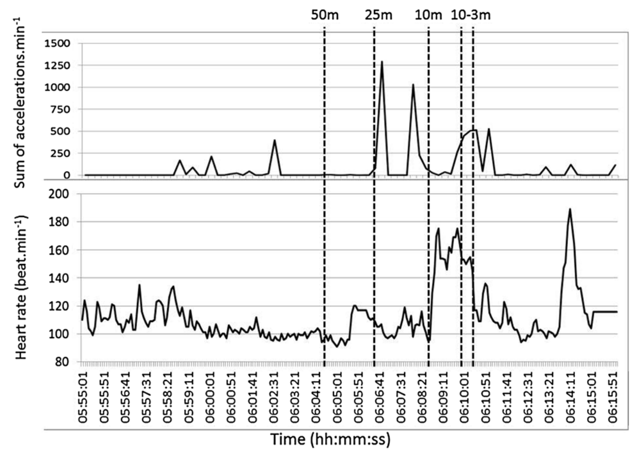

Fig. 4 Heart rate and activity pattern of a king penguin chick in relation to horizontal flights at 50, 25 and 10 m height followed by a vertical approach from 10 to 2 m height

change or activity increase as indicated by accelerometers data (Table 3). The adult heart rate increase was similar to that observed in chicks, although up to lower values (Table 3). It remained a strong variability in the increase in heart rates between individuals (Fig. 5).

Discussion

The reaction of birds to the horizontal flights and vertical approaches of the drone varied extensively depending on the species, the status of birds and the altitude. For the groups of ten birds standing nearby watching simultaneously, the behaviour of individuals is sometimes challenging because of the risk of overlooking brief behavioural changes of a single individual, with the risk of slight underestimation of behavioural changes. In our study camera recordings were not systematic, and just used to verify that observations of groups allow a good estimation of behavioural changes at the individual level. We recommend that future studies should use camera recordings in all flights to avoid potential bias.

Flights at 50 m induced behavioural changes in SGP only, and no visible behavioural modification where observed in other species. At lower altitudes (25–10 m), drone flights led to few reactions by some species Southern Rock-hopper Penguin (RHP), Sooty Albatross (SOA) and Wandering Albatross (WAL), whereas Macaroni Penguin (MAP), Light-mantled Sooty Albatross (LMA), Giant petrels (NGP, SGP) and Sub-Antarctic Skua (SKU) expressed strong stress response. Adult penguins (KIP, RHP), breeding in large colonies showed little to no visible behavioural reaction at all, even when the drone approached at 3 m (Online Resource). It is known that UAVs can approach closer to birds than mammals before being

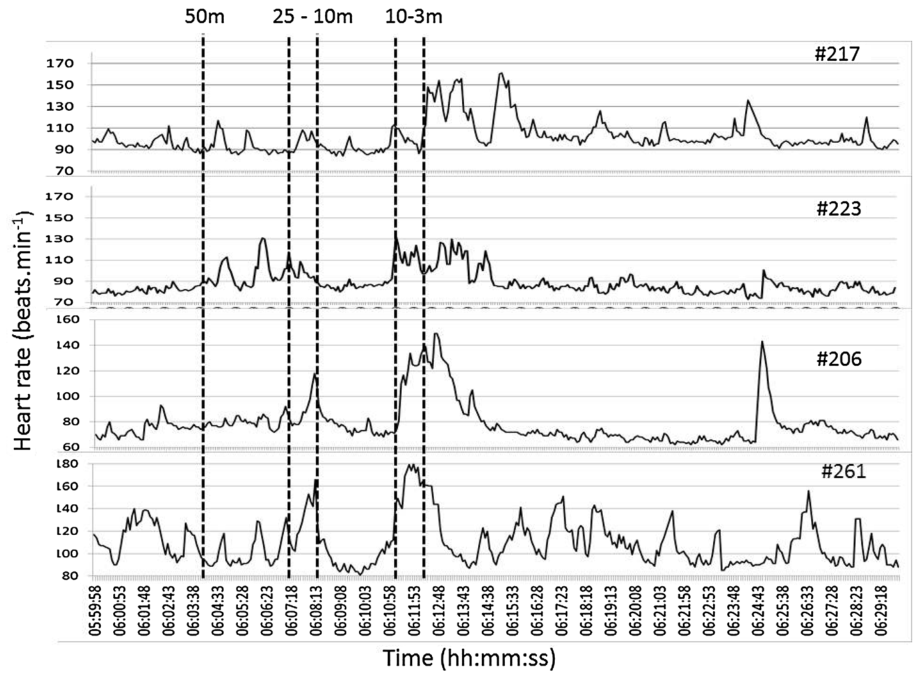

Fig. 5 Heart rate of the five egg incubating adult king penguins in relation to horizontal flights at 50, 25 and 10 m height followed by a vertical approach from 10 to 3 m height. The incubating adults were a few meters away from each other

Table 3 Behavioural response and heart rate of five incubating adults and five large king penguin chicks in crèche before, during and after a drone approach at different altitudes

	Adults			Chicks		
	Average behavioural response	Average HR (beats min^{-1})	% Basal HR	Average behavioural response	Average HR (beats min^{-1})	% Basal HR
Before drone take-off	0	90.5 ± 21.6	–	0	143 ± 38	–
Horizontal flight at 50 m	0	87.5 ± 6.4	−3%	0	140 ± 36	−2%
Horizontal flight at 25 m	0	100.0 ± 18.2	+11%	0.9	151.7 ± 36	+6%
Horizontal flight at 10 m	0.6	112 ± 20.6	+24%	1.6	173 ± 23	+21%
Vertical Approach from 10- > 2 m	0.6	120 ± 14.1	+33%	2.8	186.7 ± 21	+30%
End of the approach at 2 m	0.6	127 ± 25.7	+41%	4	183 ± 25	+28%
10 min after the end of the experiment	0	85.2 ± 13.2	−5%	0	136.6 ± 35	−5%

detected (Scobie and Hugenholtz 2016). In colonial seabirds, birds are mostly territorial and constantly fighting for their breeding spot (Côté 2000; Viera et al. 2011; Viblanc et al. 2012b) and therefore individuals are constantly disturbed by a congener's intrusion. The noisy environment of such breeding colonies may help to understand why penguins show weaker reactions to the intrusion of a novel object.

On the contrary, species breeding in small opened colonies such as giant petrels (NGP, SGP) and cormorants (ICO) or lonely breeder such as Sub-Antarctic Skua (SKU) or Light-mantled Sooty Albatrosses (LMA) appeared to be highly sensitive to drone disturbance. Interestingly species that expressed the strongest stress response (Giant petrels, skuas and cormorants) are also those, in which several individuals were already vigilant (level 1) before the drone took-off. Giant petrels (NGP, SGP), Light-mantled Sooty Albatrosses (LMA) or cormorants (ICO) are species known to leave their active nests when humans are too close (Carey 2009)(pers observ). The Sub-Antarctic Skua (SKU) is the only non-colonial and highly territorial species of this study. Incubating individuals are highly vigilant, and known to actively react to intruders, congeners or other species (Viblanc et al. 2012b). This suggests that the sensitivity to disturbance by drones, unknown object or by human approach may be predicted by the level of vigilance observed in undisturbed population. Finally, Sooty Albatrosses (SOA), breeding in small groups, showed little reaction to the flights and approaches of drones, whereas, the closely related Light-mantled Sooty Albatross (LMA), a more solitarily nester, show significant behavioural changes. This highlights that within the same genus, species may differ substantially in their sensitivity and that phylogeny relatedness between species should not prevail over new experimental expertise in predicting species sensitivity.

King Penguins expressed high differences in term of behaviour depending on their breeding status. Incubating adults showed almost no behavioural reaction to the presence of the drone, even at 2 m height. Only few birds stared at the novel object (Online Resource). Conversely, non-breeding adults (moulting at the edge of the colony) massively moved away from their moulting area leading to large group movement. Large chicks, still down, are fully mobile and grouped in crèches waiting for their parents' return to be fed. At 25 m, (already at 50 m during some experiments), chicks in crèches actively reacted by flapping their flippers when the drone passed over the crèche. This movement appeared contagious, and spread through the whole colony. When the drone was at 10 m, or approached vertically, in addition to the flipper movements, crèches spread in small groups of individuals leaving their resting place to escape the approach of the drone. This result highlighted the need to investigate species at different stages of the life, stages at which disturbance might be more or less harmful.

Several studies have pointed out that observed behavioural response may not fully reflect the stress felt under disturbance by a drone or an approaching human (Wilson et al. 1991; Vas et al. 2015; Rümmler et al. 2016). Indeed birds may be stressed while not showing any detectable behavioural response. Physiological response to approaches or handling may be measured as corticosterone level (Angelier and Chastel 2009; Bokony et al. 2009; Viblanc et al. 2014) or heart rate (Weimerskirch et al. 2002; Viera et al. 2011; Viblanc et al. 2012b). Our results showed that the extensive behavioural response of chicks was associated with an increase in heart rate of 30% higher than basal levels (Table 3). This result is in line with the prediction that behavioural response is correlated to physiological changes. On the other hand, the monitoring of incubating adults revealed unexpected results. Indeed, they showed no or little behavioural responses to the approach of the drone whereas heart rate increased extensively. Although the mean heart rate level of resting adults was lower than those of resting chicks, adults showed a proportionally higher heart rate (30%) increase compared to chicks (Table 3). A few minutes after the end of the experiment, all birds returned to resting behaviour followed by basal heart rate and low activity levels (see Figs. 4, 5). The peaks of stress recorded as maximum heart rates during the experiment were similar to the regular peak values observed in individuals not disturbed by the drone or humans (during the days preceding the experiments), where stress could be explain by agonistic interactions with congeners or the presence of a predator. The increase in heart rate by King Penguin adults was similar to that observed after approached by humans (Viblanc et al. 2012a) as well as for Wandering Albatrosses (Weimerskirch et al. 2002); however it was much lower than that observed for giant petrels whose increase reached 200% from basal level when approached by human (de Villiers et al. 2006). We do not know how giant petrel or wandering albatross heart rates would change in response to the drone, but all these results together suggest that further studies are required to examine more precisely the link between behavioural response and physiological response.

Heart rate has been used as a proxy of metabolic expenditure (Green 2011), especially in King Penguins by previous studies (Groscolas et al. 2010). The rapid return to normal heart rate after the end of the experiment suggests that the stress induced by the drone approach on incubating adults was acute and transitory (on the short-term scale). Since this increase in heart rate was not associated with an increase in movement (as recorded by accelerometry) the increase in metabolic rate due to the drone was probably limited (Willener et al. 2015). Conversely, the handling of birds induces a much longer time of recovery that can last more than one hour in albatrosses (Weimerskirch et al. 2002), but only 10 min in King Penguins (Viblanc 2011; Viblanc et al. 2012a).

Conclusion

This study has important implications for species conservation when considering the use of drones in protected areas such as national parks and natural reserves, or concerning protected wildlife. It shows that sensitivity to drone disturbance differs between species, and even within species depending on the stage of the birds within its life cycle. This suggests that sensitivity to drone flight disturbance may be predicted from their behaviour when undisturbed. Overall, the measurements of heart rates highlighted that individuals may show no sign of stress through behavioural postures, but experience increased physiological stress. Yet, when used at an altitude of 50 m, the drone impact is likely to be negligible for all species, and constitute a very practical and low cost tool for essential ecological studies such as monitoring of populations (numbers, breeding success), mapping or behavioural studies (Online Resource). The results of this study may be used to develop future regulations on the use of drones in protected areas.

Acknowledgements The study is part of program 109 financed by the Institut Polaire Français Paul Emile Victor (IPEV), and was commissioned by the Reserve National des TAAF. The recorded heart rates and activity patterns of king penguins were part of the IPEV program 119 (PIs J.P. Robin-V. Viblanc). We thank C.A. Bost for helpful comments on an earlier version of the manuscript, and three referees for helpful comments on the ms.

Compliance with ethical standards

Ethical approval The study took place in the National Reserve of 'Terres Australes Françaises' and was approved by the Préfet des TAAF (Arrêté n° 2016-155 du 6 décembre 2016 autorisant l'usage d'un drone à Crozet dans le cadre de la gestion de la réserve naturelle).

References

Anderson K, Gaston KJ (2013) Lightweight unmanned aerial vehicles will revolutionize spatial ecology. Front Ecol Environ 11:138–146

Angelier Fdr, Chastel O (2009) Stress, prolactin and parental investment in birds: a review Gen Comp. Endocr 163:142–148

Bokony V, AmZ Lendvai, As Liker, Fdr Angelier, Wingfield JC, Chastel O (2009) Stress response and the value of reproduction: are birds prudent parents? Am Nat 173:589–598

Carey MJ (2009) The effects of investigator disturbance on procellariiform seabirds: a review New Zeal. J Zool 36:367–377

Carney KM, Sydeman WJ (1999) A review of human disturbance effects on nesting colonial waterbirds. Waterbirds 22:68–79

Côté SD (2000) Aggressiveness in king penguins in relation to reproductive status and territory location. Anim Behav 59:813–821

de Villiers M, Mt Bause, Giese M, Fourie A (2006) Hardly hard-hearted: heart rate responses of incubating Northern Giant Petrels (Macronectes halli) to human disturbance on sub-Antarctic Marion Island. Polar Biol 29:717

Goebel ME, Perryman WL, Hinke JT, Krause DJ, Hann NA, Gardner S, LeRoi DJ (2015) A small unmanned aerial system for estimating abundance and size of Antarctic predators. Polar Biol 38:619–630

Green JA (2011) The heart rate method for estimating metabolic rate: review and recommendations. Comp Biochem Phys A 158:287–304

Groscolas R, Viera V, Guerin N, Handrich Y, Côté SD (2010) Heart rate as a predictor of energy expenditure in undisturbed fasting and incubating penguins. J Exp Biol 213:153–160

Jones GP, Pearlstine LG, Percival HF (2006) An assessment of small unmanned aerial vehicles for wildlife research. Wildlife Soc B 34:750–758

Rümmler M-C, Mustafa O, Maercker J, Peter H-U, Esefeld J (2016) Measuring the influence of unmanned aerial vehicles on Adélie penguins. Polar Biol 39:1329–1334

Sardà-Palomera F et al (2012) Fine-scale bird monitoring from light unmanned aircraft systems. Ibis 154:177–183

Scobie CA, Hugenholtz CH (2016) Wildlife monitoring with unmanned aerial vehicles: quantifying distance to auditory detection. Wildlife Soc B 40:781–785

Vas E, Lescroël A, Duriez O, Boguszewski G, Grémillet D (2015) Approaching birds with drones: first experiments and ethical guidelines. Biol Lett 11:20140754

Viblanc VAV (2011) Coping with energy limitation, social constraints and stress in a colonial breeder, the king penguin (*Aptenodytes patagonicus*). University of Strasbourg, Strasbourg

Viblanc VA, Smith AD, Gineste B, Groscolas R (2012a) Coping with continuous human disturbance in the wild: insights from penguin heart rate response to various stressors. BMC Ecol 12:10. doi:10.1186/1472-6785-12-10

Viblanc VA, Valette V, Kauffmann M, Malosse N, Groscolas R (2012b) Coping with social stress: heart rate responses to agonistic interactions in king penguins. Behav Ecol 23:1178–1185

Viblanc VA, Gineste B, Stier A, Robin J-P, Groscolas R (2014) Stress hormones in relation to breeding status and territory location in colonial king penguin: a role for social density? Oecologia 175:763–772

Viera VM, Viblanc VA, Filippi-Codaccioni O, Côté SD, Groscolas R (2011) Active territory defence at a low energy cost in a colonial seabird. Anim Behav 82:69–76

Weimerskirch H, Shaffer SA, Mabille G, Martin J, Boutard O, Rouanet JL (2002) Heart rate and energy expenditure of incubating wandering albatrosses: basal levels, natural variation, and the effects of human disturbance. J Exp Biol 205:475–483

Willener AS, Halsey LG, Strike S, Enstipp MR, Georges J-Y, Handrich Y (2015) Reassessment of the cardio-respiratory stress response, using the king penguin as a model. Stress 18:115–120

Wilson RP, Culik B, Danfeld R, Adelung D (1991) People in Antarctica -how much do Adélie Penguins *Pygoscelis adeliae* care? Polar Biol 11:363–370