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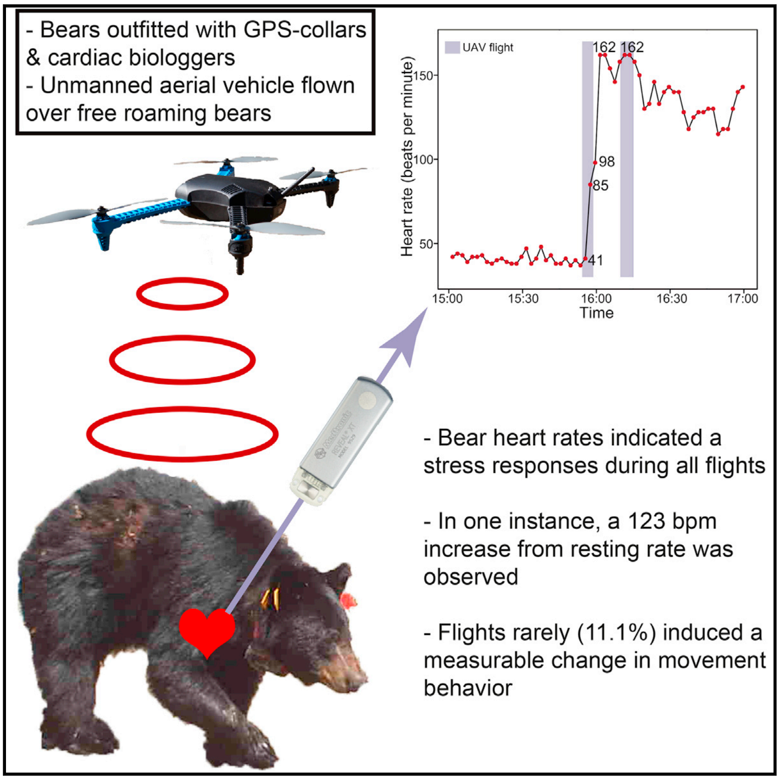
Report

Bears Show a Physiological but Limited Behavioral Response to Unmanned Aerial Vehicles

Graphical Abstract



Highlights

- Cardiac biologgers reveal that bears exhibit a stress response to UAV flights
- Bears rarely display a behavioral response, measured by GPS collars, to UAV flights
- Magnitudes of heart rate spikes were correlated with wind speed and proximity of UAV

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In Brief

Unmanned aerial vehicles (UAVs; i.e., “drones”) are increasingly popular tools for ecological research. Ditmer et al. used GPS collars and cardiac biologgers to assess effects of UAV flights on free-roaming bears. All bears exhibited a stress response to UAV flights as evidenced by elevated heart rates while rarely exhibiting a behavioral response.

Ditmer et al., 2015, Current Biology *25*, 2278–2283
August 31, 2015
http://dx.doi.org/10.1016/j.cub.2015.07.024

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Current Biology
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Bears Show a Physiological but Limited Behavioral Response to Unmanned Aerial Vehicles

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http://dx.doi.org/10.1016/j.cub.2015.07.024

SUMMARY

Unmanned aerial vehicles (UAVs) have the potential to revolutionize the way research is conducted in many scientific fields [1, 2]. UAVs can access remote or difficult terrain [3], collect large amounts of data for lower cost than traditional aerial methods, and facilitate observations of species that are wary of human presence [4]. Currently, despite large regulatory hurdles [5], UAVs are being deployed by researchers and conservationists to monitor threats to biodiversity [6], collect frequent aerial imagery [7–9], estimate population abundance [4, 10], and deter poaching [11]. Studies have examined the behavioral responses of wildlife to aircraft [12–20] (including UAVs [21]), but with the widespread increase in UAV flights, it is critical to understand whether UAVs act as stressors to wildlife and to quantify that impact. Biologger technology allows for the remote monitoring of stress responses in free-roaming individuals [22], and when linked to locational information, it can be used to determine events [19, 23, 24] or components of an animal's environment [25] that elicit a physiological response not apparent based on behavior alone. We assessed effects of UAV flights on movements and heart rate responses of free-roaming American black bears. We observed consistently strong physiological responses but infrequent behavioral changes. All bears, including an individual denned for hibernation, responded to UAV flights with elevated heart rates, rising as much as 123 beats per minute above the pre-flight baseline. It is important to consider the additional stress on wildlife from UAV flights when developing regulations and best scientific practices.

RESULTS

We investigated the influence of unmanned aerial vehicle (UAV) flights on the behavior and physiology of free-roaming American black bears (*Ursus americanus*) in northwestern Minnesota by capturing their location and movement with Iridium satellite GPS collars and heart rate (HR) in beats per minute (bpm) using cardiac biologgers developed for human use (Medtronic, Reveal XT Model 9529). Both GPS collars and biologgers recorded values at 2-min intervals, so it was possible to discern how individual bears responded, at fine temporal and spatial scales, to short-duration UAV flights. We flew a small quadcopter UAV (3D Robotics) using a fully autonomous mission plan that loitered and circled approximately 20 m over the location of the bear (pre-programmed just before takeoff) during the course of a 5-min flight. We hypothesized that bears would respond to the UAV in one of four ways: (1) no discernable behavioral or physiological response, (2) behavioral response only (i.e., increased movement rates and/or moving away from the area of the UAV), (3) no behavioral response, but a physiological response (measurable increase in HR), and (4) both a behavioral response and physiological response.

We conducted 18 UAV flights above or near four bears from September 21, 2014 to October 12, 2014. For 17 of these flights, we were able to collect associated HR and location data (Figure 1; Movie S1). Nine flights were conducted over two adult female bears with cubs (eight over one and one over the other), three flights were conducted over a 1-year-old male bear, and six flights were conducted over an adult female bear that entered a den for winter hibernation 2 days prior to the first UAV flight. Flight times averaged 5 min 3 s (SE = 16.7 s). Absolute altitude (height above ground) was influenced by vegetation and averaged 21.0 m per flight (SE = 1.45) including takeoff and landing. The minimum distance between the UAV and the target bear averaged 43 m (SE = 5.67). On average, the UAV was launched 215 m (range: 184–245) from the targeted location of the bear.

Bears responded to UAV flights with elevated HRs in all 17 flights with corresponding HR data (Figure S1). We calculated the "maximum HR anomaly" for bears by comparing the observed differences between maximum bear HRs and predicted values during UAV flights (see Figure 2A for brief description or Experimental Procedures for full description). The maximum HR anomalies associated with UAV flight times were significantly higher than the maximum HR anomalies during days without flights (Figure 2B). Maximum HR anomalies were the largest for the female with cubs, followed by the hibernating adult female, and finally the young male (Figure 2C). The

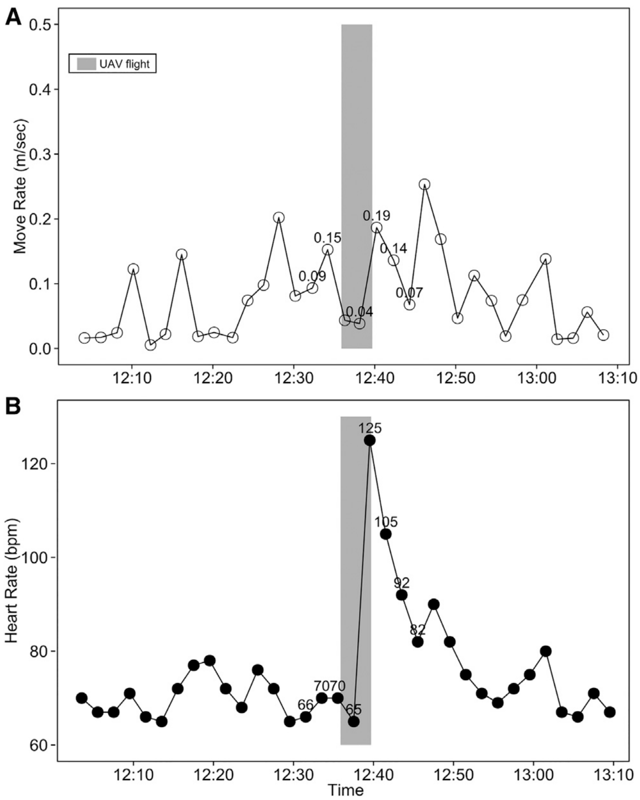

Figure 1. Illustration of Bear Movement and HR during a UAV Flight

(A) Movement rates (meters per hour) of an adult female black bear with cubs of the year as estimated using 2 min GPS locations prior to, during, and after a UAV flight (gray bar).

(B) The corresponding HR in bpm during the same day and time measured using a remote cardiac biologger developed by Medtronic. We flew unmanned aerial vehicles over American black bears living in northwestern Minnesota during September and October 2014.

See also Figure S1 and Movie S1.

maximum difference between observed and predicted HR values during UAV flights was 123 bpm for a female with cubs (Figure S2), 56 bpm for the hibernating adult female, and 47 bpm for the 1-year-old male. Bear HRs recovered after the completion of every UAV flight to within the 99% confidence interval associated with HRs 30 min prior to a given flight, with median recovery times of 10 min (range: 2–204 min), 16 min (range: 4–20 min), and 5 min (range: 4–6 min) for the female with cubs of the year, hibernating adult female, and young male, respectively. These durations in HR elevations were likely associated with sympathetic activations of catecholamine releases from the adrenal glands (e.g., [26]).

During controlled test flights in different habitats (forest, shrub, open) and different wind speed conditions (methods found in Supplemental Information), variation in ambient noise (dB(A)) was largely explained by distance to the UAV (negative association), absolute altitude of the UAV (negative association), and an interaction of the two (positive association, average multiple r^2: $\overline{X} = 0.84$, SE = 0.05). HR anomalies were positively associated with wind speed (Figure 3A) and negatively associated with the distance between the UAV and the bear (Figure 3B). These relationships suggest that stress responses were stronger when UAV flights involved an element of surprise: bears likely could not hear the approach of the UAV in windier conditions, so they were more startled.

Despite significant physiological reactions to UAV flights, movement rates (meters per hour) increased during or immediately following only one UAV flight (12.5% of flights with available data, Figure S1). On this occasion, the bear increased its rate of movement beyond all previous recorded movement rates for that individual (Figure 4). The same flight resulted in a maximum displacement distance (maximum straight line distance [m] from location 10 min prior to UAV to each location 40 min post-flight) of 576 m, which far exceeds maximum displacement distances observed on days without a UAV flight (flight #8 in Figure S3). No other flight or set of flights resulted in a displacement distance that differed from distances observed on days without UAV flights. However, the bear that exhibited the greatest increase in HR (Figure S2) also responded behaviorally from the same set of back-to-back flights (two total instances of a behavioral response; 11.1%). This bear moved at least 6.8 km within 28 hr of the flight, into a neighboring collared female's home range where the individual had never previously been observed.

DISCUSSION

Our results support hypothesis #3: UAV flights induced a physiological response, but most bears did not respond behaviorally by increasing movement rates or moving to a different location. Prior to this study, little was known about the potential impacts of UAV flights on wildlife. Vas et al. [21] tested whether UAV flights triggered a behavioral response in three bird species. Birds exhibited a response to 20% of UAV flights, and the authors remarked about the ability to fly their UAV as close as 4 m from the birds typically without any detectable behavioral response. Importantly, without the use of cardiac biologger technology, we would also have concluded that bears rarely responded to UAV flights.

HRs returned to pre-flight values relatively quickly after most flights. Bears in this population live in a highly human-altered landscape (~50% agriculture) and frequently encounter potential stressors (e.g., roads and agricultural fields, with associated noises from traffic and farm equipment) and therefore may exhibit lower stress responses and quicker recovery times than animals in populations that encounter human-related stressors less frequently [25]. Stress responses to UAVs are also likely to be species specific, and the strength of the response may vary among sex and age classes as our results suggest. Numerous web-based videos demonstrate that some species react aggressively toward UAV flights. When stress responses are accompanied by an extreme behavioral response, as we recorded twice with our bears, individuals may become more vulnerable to sources of mortality (e.g., traffic collisions when fleeing, interactions with bears in home ranges that they have encroached).

It has long been established that low-altitude flights by helicopters and fixed-wing aircraft can produce stress responses in wildlife [19], yet we believe UAV flights introduce a new and unique stressor that has the potential to be more frequent and induce higher levels of stress. UAVs can fly extremely low (some with maneuverability to fly under a forest canopy) and

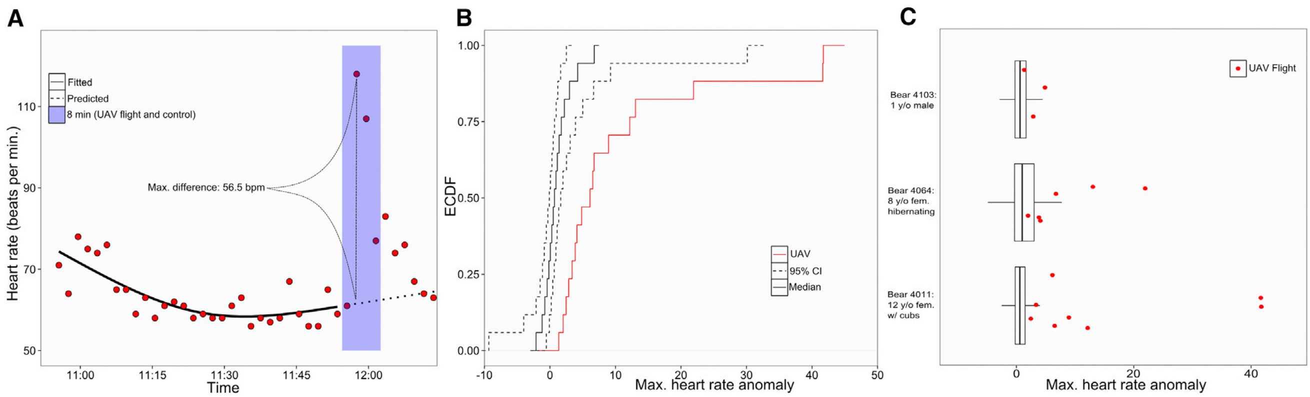

Figure 2. Method and Results of Bear Maximum HR Anomalies during UAV Flights

(A) Method for calculating HR anomalies during an 8-min period starting at the takeoff of UAV flights and on days without UAV flights during the same time period. We fit a linear regression model to HR data collected 1 hr prior to the flight (or control observation window), using natural cubic regression splines with 2 degrees of freedom to account for temporal trends in the HR values. We used the fitted model to predict HR values during the subsequent 8-min period. We measured the physiological response to the UAV flight (and also control measurements) as the maximum difference between observed and predicted values, divided by the SD of the observed values (from the hour prior to the flight or control observation window).

(B) The empirical cumulative distribution function (ECDF) for the HR anomalies associated with UAV flights and the median and 95% simulation envelope calculated using controls taken from days without UAV flights.

(C) Maximum HR anomaly data for non-UAV flight times are shown as boxplots along with the values associated with UAV flight times (red dots) for the three individual bears with HR data.

See also Figure S2.

are rapidly gaining popularity with industry, hobbyists, and researchers due to the widespread availability of off-the-shelf units, decreasing costs, and ease of use. Additionally, rules and regulations on their use are nascent or nonexistent in many countries. Oversight of UAV use for research, conservation, and commercial purposes needs to be more carefully considered in light of our findings. Examples of UAVs making frequent flights near endangered species or highly sensitive regions are increasingly common: endangered rhinoceros (*Diceros bicornis* and *Ceratotherium simum*) are monitored regularly to deter poaching in South Africa [11]; oil and gas companies regularly operate UAVs in the arctic near species already affected by climate change [27]; and ecotourism experts anticipate increasing wildlife-watching opportunities via UAV tracking [28]. Further research must be conducted to determine the relative distances at which species respond both physiologically and behaviorally to UAV flights, whether a species can habituate to the presence of UAVs and the types of UAVs that may minimize stress and whether responses of animals differ by habitat type, time of year, or life cycle (e.g., rearing young).

Our results support the 2014 decision by the U.S. National Park Service to ban all public use of UAVs within park boundaries after a low-flying UAV caused a herd of big horn sheep (*Ovis canadensis*) in Zion National Park to scatter, separating lambs from their mothers. Until important questions are answered about the impacts of UAV use, we echo the recommendations of Vas et al. [21] for the use of the precautionary principle when formulating regulations and scientific best practices regarding the use of UAVs, especially with regard to endangered species or areas of refuge.

EXPERIMENTAL PROCEDURES

Bear Capture, Collaring, and Biologger Implantation

During the summer of 2007–2011, we captured bears in baited barrel traps and fit them with either store-on-board GPS devices (Telemetry Solutions) or GPS

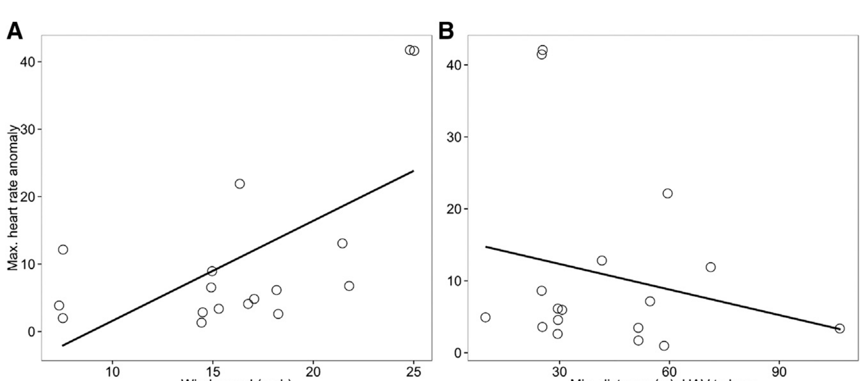

Figure 3. Factors Influencing Bear HRs during UAV Flights

(A and B) Relationships, including an ordinary-least-squares regression line, between the maximum HR anomaly values (see Figure 2A) and ambient wind speed (mph) (A), and minimum distance (m) (B) between the UAV and the bear during each flight. UAV flights occurred above or near American black bears located in northwestern Minnesota during September and October 2014.

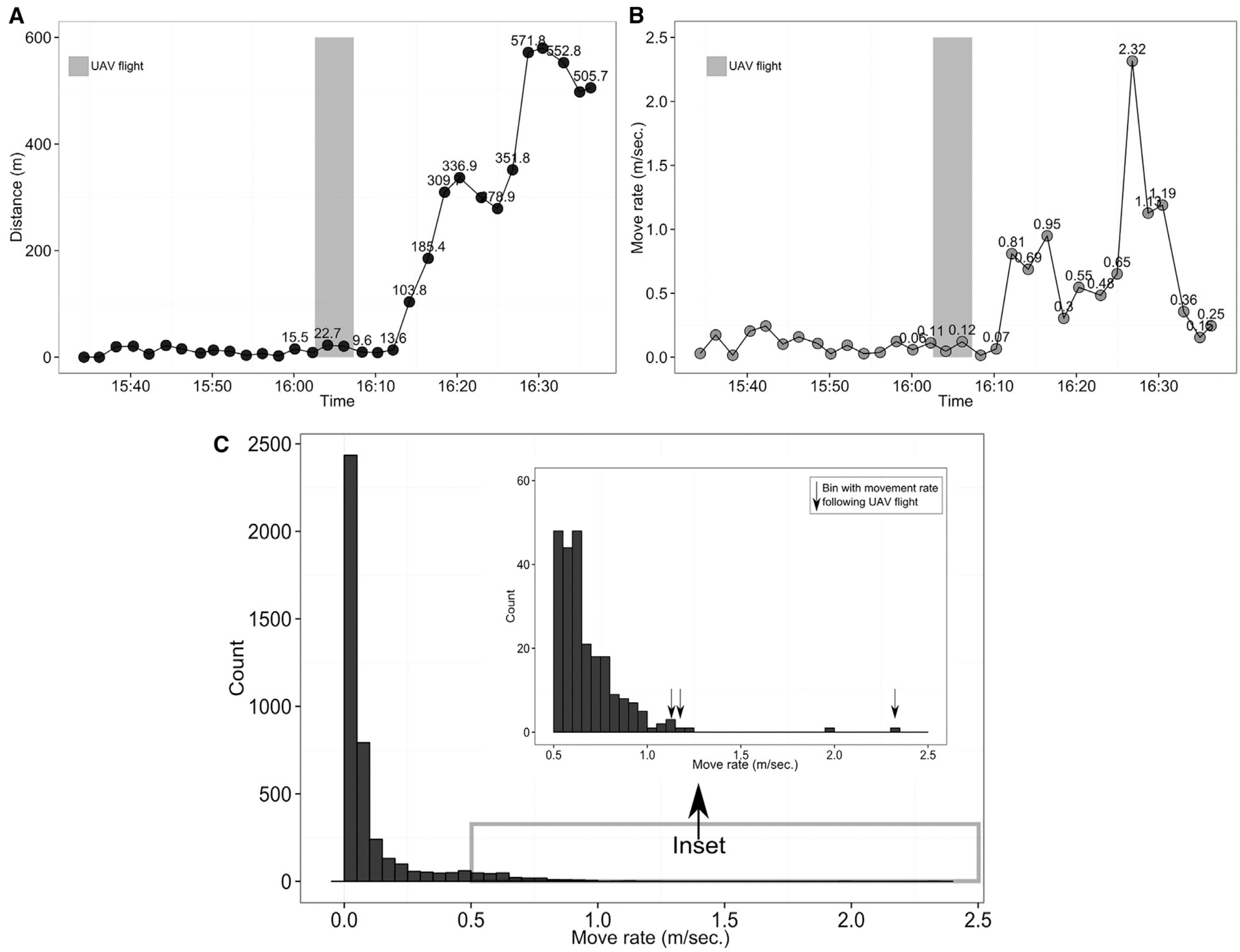

Figure 4. Most Extreme Bear Behavioral Response to UAV Flights

Behavioral response, as measured by changes in location recorded by a GPS collar, of an adult American black bear and her cubs after a UAV flight. Video footage of the flight can be found in Movie S1.

(A) The relocation distance (m) from the location of the bear 30 min prior to the flight continuing until 30 min after the flight.

(B) The movement rate (meters per hour) of the same individual during that time period.

(C) A histogram of all the movement rates from the same individual during all days with 2-min relocation intervals. The inset depicts the three largest value bins of movement rate data.

See also Figure S3.

collars capable of relaying fixes remotely via the Iridium satellite system (Vectronic Aerospace). We visited all collared bears in winter dens to change or refit collars, download stored GPS data, obtain morphometric and physiological measurements, and check on their general health status. During the winter of 2013–2014, we outfit three bears living within the U.S. Federal Aviation Administration (FAA) defined study area (see Supplemental Experimental Procedures) with Vectronic collars and one bear with a store-on-board GPS device. We programmed GPS collars to collect fixes at 1–3 hr intervals when we were not flying UAV missions. We increased the fix rate of Vectronic collars to every 2 min for a minimum of 9 hr prior to each UAV flight and programmed the Iridium data uplink system to email every location. Locations were accurate to within 5 m.

During den visits in 2009–2013, we surgically implanted cardiac monitors developed for humans by Medtronic in all bears (specifications: 9 cc; 8 mm × 19 mm × 62 mm; 15 g). Monitors were sterilized in ethylene oxide and inserted subcutaneously in a peristernal location using aseptic techniques. Monitors recorded each heart beat and reported average bpm for each 2-min HR interval using software (BearWare) developed by Medtronic to collect data more frequently than in normal human use. All HR data related to UAV flights were downloaded noninvasively during December 2014 using transcutaneous telemetry (CareLink Model 2090 Programmer with software Model SW007, Medtronic). All methods and animal handling were approved by the University of Minnesota's Institutional Animal Care and Use Committees (1002A77516).

Four collared bears containing cardiac biologgers were located within the study area. Two adult female bears (ages 10 and 11) had cubs of the year throughout 2014 and were active during the dates of the UAV flights. A third adult female bear (age 8) was with yearling bears earlier in the year but was unaccompanied during the fall when we conducted the flights. This bear only received a GPS store-on-board collar with VHF and had already entered her winter den prior to the UAV flights (Figure S3). The last individual was a yearling male bear wearing a Vectronic collar.

UAV Description, Mission Planning, and Data Collected by UAV

We conducted UAV flights over bears from September 21, 2014 to October 12, 2014 using an unmodified 3DR IRIS quadcopter UAV (http://3drobotics.com/) mounted with a GoPro HERO3+. The 3DR IRIS is equipped with a Pixhawk open source auto pilot system, which makes it capable of programmable fully autonomous flight. We used the APM Planner 2.0 software (http://planner.ardupilot.com/) to program and fly each flight. In brief, each mission was flown according to the protocol below, but there was some variation among flight plans due to weather conditions, distance to the animal, and the ability to pinpoint the bear's location (the only means to track the denning bear was with VHF telemetry).

For each ~5-min flight, the UAV was programmed with a GPS fix based on the last known location of the focal bear obtained from the GPS collars or, in the case of the VHF-collared bear, the triangulation of the bear's location. The UAV was launched and climbed to an altitude of ~20 m, and then flew straight to the programmed GPS fix. Upon reaching this point, the UAV loitered in place for ~1 min before initiating two consecutive large turns, each with a radius of ~20 m (~1 min for each turn) around the GPS point. After completing the turns, the UAV returned to the programmed fix to loiter in place for ~1 min. After completing its mission over the bear, the UAV flew back to the launch point and automatically landed. Each mission was initiated by an FAA-certified pilot who armed the quadcopter and increased the throttle to 50%. The programed mission commenced automatically at this point, and each flight was flown and landed fully autonomously with no further user input.

Following each flight we downloaded the data logged by the UAV flight computer (Pixhawk) using APM Planner 2.0. We used PyMAVLink Tools (https://pixhawk.org/dev/pymavlink) to extract the time stamps, GPS locations, speed, and absolute altitude of the UAV (height of UAV above the ground) throughout each flight. These data are logged at 3–5 times per second by the Pixhawk flight computer. Following their extraction, these data were processed so they could be linked with the HR and movement data from each bear (see Statistical Methods).

Statistical Methods

All statistical analyses were carried out in R [29], an open source statistical programming language. We fit linear regression models to the HR data collected 1 hr prior to each UAV flight, using natural cubic regression splines (ns function in package: splines [29]) with 2 degrees of freedom to account for temporal trends in the HR values. We used this model to predict the HR values occurring during an 8-min window covering the time period of the UAV flight and a few minutes post-flight (see Figure 2A). If two UAV flights occurred over the same individual, with less than 20 min between each flight, we used the HR values for the hour prior to the first flight to estimate the predicted values for the second flight. We formed HR anomalies, representing the increase in HR beyond what might be expected given the trend in HR for the hour prior to the flight, as the difference between the observed and predicted HR values during the 8-min window, divided by the SD of HR values from the hour prior to the UAV flight.

We generated control observations by repeating this process using HR data from all dates without a UAV flight (female with cubs of the year: 175 days; young male: 181 days; hibernating adult female: 79 [winter hibernation days only]) but collected during the same time of day as the UAV flights. We formed a null distribution for the empirical distribution function (ECDF), assuming no effect of the UAV, by repeatedly subsampling these "control" data, keeping the same number of observations per bear as in the original UAV-flight dataset. We calculated the ECDF for each of 10,000 subsampled control datasets and created a 95% simulation envelope to compare to the ECDF of the HR anomalies associated with the UAV flights (Figure 2B). An ECDF of the UAV HR flight data that did not fall within the 95% simulation envelope suggested that the maximum HR anomaly values from control and experimental conditions were drawn from two different distributions.

We calculated the recovery time of bear HRs post-flight for each flight and reported the median and range for each individual. We defined recovery time as the number of minutes until HR returned to values below the upper 99% confidence interval based on values from 30 min prior to each flight. If a set of flights occurred such that the second flight began prior to recovery after the first flight, we considered only recovery after the second flight.

SUPPLEMENTAL INFORMATION

Supplemental Information includes Supplemental Experimental Procedures, three figures, and one movie and can be found with this article online at http://dx.doi.org/10.1016/j.cub.2015.07.024.

AUTHOR CONTRIBUTIONS

M.A.D. analyzed the data and wrote the paper. M.A.D., J.B.V., L.K.W., and J.C.T. designed the study and performed the UAV fieldwork. J.R.F. suggested and helped develop the statistical approach. P.A.I. and T.G.L. performed the biologger surgery and consulted on the physiological aspects of the study. D.L.G. was the lead researcher for winter fieldwork and consulted on interpretation of bear behavior. All authors reviewed the final version of the manuscript.

ACKNOWLEDGMENTS

The Institute on the Environment (University of Minnesota) and the International Association for Bear Research and Management provided financial support. We thank T. Baker, L. Dillard, and B. Taylor of the University of Minnesota for advice and technical help. T. Iles, H. Martin, H. Severs-Wilkerson, and M. McMahon assisted with fieldwork. J. Huener and K. Arola of the Minnesota Department of Natural Resources and G. Knutsen of the USFWS allowed us to use their facilities for fieldwork.

Received: June 1, 2015
Revised: July 7, 2015
Accepted: July 9, 2015
Published: August 13, 2015

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