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Smart nest box: a tool and methodology for monitoring of cavity-dwelling animals

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Summary

1. Camera recording and video analysis have emerged as a successful non-invasive method for collecting a wide range of biological data on many different taxa of animals. However, camera monitoring has rarely been applied to long-term surveillance of cavity or box-nesting species and ordinary off-the-shelf cameras are employed.

2. We present methodology and data on the effectiveness of nest box monitoring using a camera system embedded in four ‘smart nest boxes’ (SNBoxes). We applied the SNBoxes to eight Tengmalm’s owl (*Aegolius funereus*) nests in the Czech Republic during a 5-month period in 2014. Each SNBox consisted of a pair of cameras with infrared lighting, an event detector, a radiofrequency identification reader, auxiliary sensors and a 60 Ah 12 V battery to power the whole system. All devices used were centrally managed by an embedded computer with specifically developed software.

3. Using four SNBoxes, we observed owl nesting continually during the incubation, nestling and fledgling phases, in total 309 days, resulting in 3382 owl video events. Batteries were changed every 6·5 days. A memory of 4 GB was found sufficient to store monthly data. We identified 12 types of male and female parental activities and their timing, the diet composition and frequency of prey delivery, the manner of prey storage, the light intensity at the time of each parental activity, the temperature inside the clutch and outside the box and the duration of nestling period of each young. We also produced a video on owl nesting for the general public.

4. The SNBox and related methodology show enormous potential as a non-invasive tool for monitoring animals using boxes or natural cavities. The main advantage of the SNBox is the possibility to study both nocturnal and diurnal animal species and great flexibility in use of the software and hardware for different tasks. As a result, the SNBox provides an opportunity for novel insights into the breeding, roosting, hibernating, and food storage activities of a wide range of cavity-living birds, mammals and reptiles.

Key-words: animal activity, camera monitoring, cavity, event detector, hole, infrared light, nest box, non-invasive method, parental care, RFID reader

Introduction

Camera-based surveillance is a non-invasive method for collecting data on many taxa of animals (reviewed by Reif & Tornberg 2006; Trolliet *et al.* 2014). Camera technologies are most often used for monitoring the trends over time and space in vertebrate populations (e.g. Gregory *et al.* 2014), their activity patterns (e.g. Gray & Phan 2011), behaviour and feeding ecology (e.g. Miller, Carlisle & Bechard 2014), or for the identification of nest predators (e.g. DeGregorio, Weatherhead & Sperry 2014). This approach is an effective substitute for standard observational methods, and it especially reduces disturbance of the animals or monitored nests. It also allows to gather information during inclement weather or time, and saves on human resources and financial costs (Cutler & Swann 1999). However, despite technological advancements, application of camera systems for animal monitoring continues to have its limitations and difficulties. Especially, data storage and power source limit the duration of recording; weather conditions, humidity, rain and dust limit the functionality of the technical devices; and insufficient light limits the quality of video recordings of nocturnal animals (Delaney, Grubb & Garcelon 1998; Reif & Tornberg 2006). Moreover, the camera systems used usually work without time synchronization with other devices (e.g. data loggers) and without power saving when the animals are inactive.

The camera system design usually depends on logistical and practical constraints, in particular on the remoteness and accessibility of nests (Reif & Tornberg 2006). Cavity or hole-using animals are especially difficult to monitor due to accessibility difficulties of natural cavities, which are usually located high up off the ground (Franzreb & Hanula 1995) or underground (Bloomquist & Nielsen 2009). Moreover, the space constraints in cavity interiors hamper the installation of monitoring apparatus. Fortunately, many birds, mammals, as well as reptiles, and insects are willing to use artificial boxes, making

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them easier to monitor (see Appendix S1 for detailed information, Supporting Information).

Artificial boxes provide a wide range of opportunities for animal use, including breeding (Kölliker *et al.* 1998), roosting (Tyller, Paclík & Remeš 2012), hibernating (Madikiza *et al.* 2010) or food storing (Halonen *et al.* 2007). In particular, bird species using the boxes to breed allow us to study some of the key topics of evolutionary biology, especially questions about parental care (i.e. parental investment in offspring, which involves egg laying, incubation and provisioning of young; Clutton-Brock 1991). Parental care intensity may vary during the breeding season (Podlaszczuk *et al.* 2015), with increasing nestling age (Liu *et al.* 2014), changing food supply (Zárybnická, Sedláček & Korpimäki 2009), ambient temperature (Conway & Martin 2000) or day length variation (Shaw & Cresswell 2014). However, few studies have applied camera systems for monitoring and data collection to parental care and nestling development of birds breeding in artificial boxes.

In this study, we report on the suitability of an electronic hardware and software design for collecting data on parental care and feeding ecology in cavity-nesting bird species. Specifically, we applied the technology to Tengmalm's owl (*Aegolius funereus*) – the strictly nocturnal species with divided parental duties during nesting (e.g. Zárybnická, Korpimäki & Griesser 2012). We monitored eight owl nests using four 'smart nest boxes' (SNBoxes) in the wild. We aimed at these specific objectives: (i) to create a camera system that would work for 6–8 days without replacement of the battery, with sufficient data memory capacity, and with the possibility to set the awake time of the system according to actual sunset/sunrise timing, including assessment of the battery longevity in such arrangement, (ii) to document entire nesting process, including specific parental care and develop a short promotional video on owl nesting, (iii) to identify the diet composition of prey delivered by individual parents to the nest, (iv) to evaluate the frequency and timing of parental activities in relation to the nestling age and the interseasonal variability in sunset and sunrise timing, including changes in outdoor light intensity at time of parental activities during the breeding season (i.e. from April to August) and (v) to evaluate the effect of outdoor temperature on time spent by the female outside the clutch and the consequent decrease in temperature inside the clutch.

Materials and methods

STUDY SITE

We conducted the study in the Ore Mountains, in the northern part of the Czech Republic (50°N, 13°E), in habitat composed of Norway spruce (*Picea abies*) forests, secondary growth of young trees (mainly non-native prickly spruce, *Picea pungens*), open areas, and solitary trees (mostly European beech, *Fagus sylvatica*). In this habitat, Tengmalm's owl breeds primarily in artificial nest boxes (>90% nests), as natural cavities can only be found rarely in solitary beech trees (Zárybnická *et al.* 2015a). We installed nest boxes to provide nest-sites for Tengmalm's owl in this area since 1999 under the project of the Czech University of Life Sciences Prague. The number of installed boxes varied from 100 to 212 in different years during 1999–2014 (133·9 ± 8·4 boxes per year, an area of 100 km^2). Tengmalm's owl used to breed from 10 to 26 boxes every year (12·6 ± 1·5% of installed boxes per year). We made all boxes manually of raw wooden boards (20 mm thick) with dimensions of 250 × 250 × 400 mm, and filled up with wood chips. The distance from the top of the layer of wood chips to the box entrance was 220–240 mm, and the diameter of the opening was 80 mm. We typically installed the boxes at a height of 3–5 m above the ground, and we regularly repaired, cleaned and relocated them.

FIELD PROCEDURES

We conducted the present study between April and August 2014. In this year, 212 nest boxes were available for Tengmalm's owl. We inspected all nest boxes at intervals of 1–3 weeks, to detect new breeders. We replaced ongoing nesting in the regular nest boxes with SNBoxes (the design described below). Throughout the study period, we found a total of ten nests; eight of which we monitored by four SNBoxes (two sequential nests per SNBox). We monitored five nests from the incubation to fledgling phase, and other three nests from the hatchling to fledgling phase. We checked the nests weekly to measure, weigh and ring the nestlings, and we also chip-ringed the adult females.

DESIGN OF THE SMART NEST BOX

We mention here only main characteristics of the SNBox, detailed hardware and software information is available in Appendix S2. We designed the SNBox as a regular nest box augmented with additional space for embedding all the required components (Fig. 1a). The overall dimensions of the SNBox were 320 × 250 × 820 mm, and the weight was 15 kg (without the battery). Most of the outer box surface was covered with an aluminium plate to protect against nest predation by pine marten (*Martes martes*) (Fig. 1b). The SNBox electronics consisted of a control board (computer, Fig. 2a), a pair of cameras with infrared lighting (with a peak wave length of 830 nm, Fig. 2b), an event detector (Fig. 2c), a radiofrequency identification reader, auxiliary sensors and a 60 Ah 12 V battery to power the whole system.

We designed the control board with a dual-core processor to run two operating systems in parallel, a 256 MB operating memory, and both Ethernet and Wi-Fi integrated circuits (the latter was not available during the study). We used a 4 GB micro SD memory card to store the output video records and metadata, and a Linux FTP server to fetch the data over the Ethernet cable.

We used two USB monochromatic industrial cameras, without an IR-cut filter, that provided the video in resolution of 1280 × 1024 pixels, with up to 10 frames per second (fps). We placed the 'door camera' on the back side of the box (opposite the SNBox opening), and the 'floor camera' on the ceiling of the box, allowing a view of the nest box floor (Fig. 1a).

We designed an event detector in the form of an IR light barrier consisting of an IR light beam transmitter and a receiver set opposite the transmitter. We assembled the device on a U-shaped board and placed it in the SNBox opening (Fig. 2c).

In Tengmalm's owl, it is difficult to distinguish between males and females. For easier recognition of individuals, we equipped female parents with RFID tags fixed to their legs (chip ring). We used a 125 kHz RFID reader module, and a custom circular antenna embedded in a groove around the SNBox opening to scan the tags. At the moment when a female passed through the opening, the tag was scanned and its unique numerical ID was stored as part of the simultaneously triggered video event.

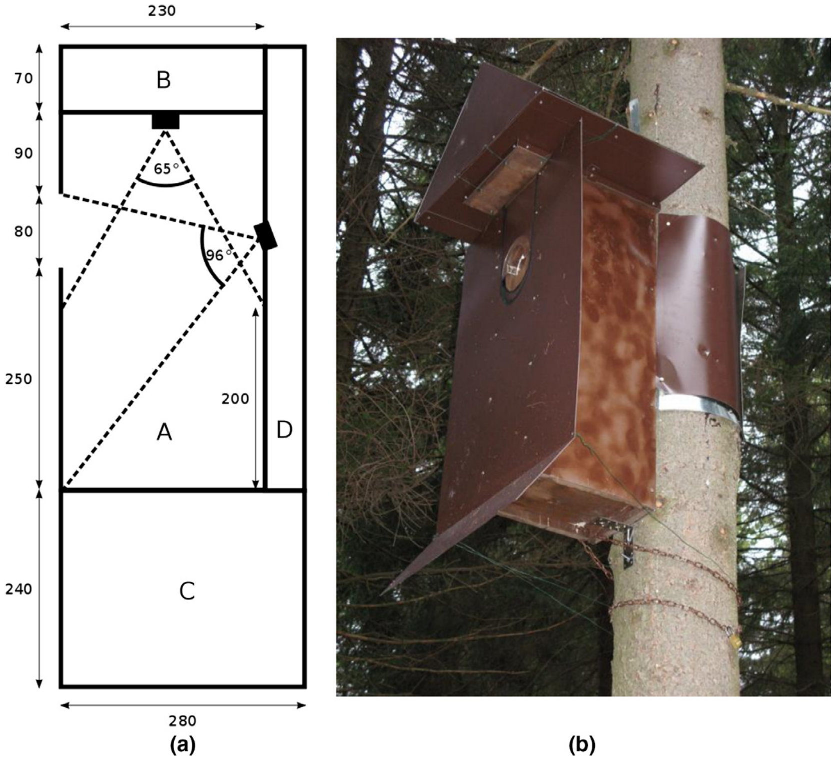

Fig. 1. (a) Design of the smart nest box (SNBox) and its individual parts: (A) nesting area; (B) electronic area – located in the top part of the box, used for storing the control board; (C) battery area – located on the bottom of the box; and (D) the wiring area – located on the back side of the box. Dimensions are shown in millimetres. (b) Application of the SNBox in the field. Note that most of the outer box surface was covered with aluminium plates and equipped with an extended front plate and a gabled roof to protect against pine marten predation.

We used interior and exterior temperature sensors, with ±0·25°C accuracy, and an exterior light sensor that yielded dimensionless numbers from 0 to 4095 (i.e. light intensity index). We attached the exterior device to the casing of the SNBox and embedded the interior device in a groove on the bottom of the SNBox. The values were measured both every 30 seconds and at the moment of every owl activity event.

We developed a special software for central management of all devices used (Fig. S1). We designed the software such that the door camera was activated by the interruption of the IR light barrier and worked for 5 s, while the floor camera was activated at the moment when the door camera stopped recording and worked for 30–120 s (depending on the user settings). The frames from each camera were stored in a fast volatile memory (110 MB) in the raw image format (pgm, Portable Graymap) and later compressed into two avi video files, one for each camera. We reduced the trigger speed, that is the time delay between disruption of the light barrier by the owl entering the SNBox opening and triggering the first camera frame, to 16 ms.

We designed the system to switch between a sleep and awake mode. During the sleep mode, the cameras, light barrier and RFID reader were powered off, while during the awake mode all peripherals were powered on. Because Tengmalm's owl is active only during night-time and the night length varies up to four hours from April to August in the Central Europe, we set an awake time of the system after each 6–8 days (when the battery was changed) according to actual sunset and sunrise.

We developed a user interface for the system, that is a set of equipment that allowed the user to interact with the system, download recorded data and adjust the settings. We strictly defined the structure of the accessible file system consisting of 4 top-level directories. The 'config' directory contained two configuration files, allowing us to customize the camera properties (exposure, signal gain), video properties (duration, frame rate) and power-saving settings (start and end of the awake time). The 'data' directory stored the video records, each event in an individual subdirectory named by respective timestamp (with an accuracy of one-second). Each such subdirectory contained the video files and a text file with metadata (temperature and light conditions, scanned RFID code, exact date and time). The 'sensors' directory contained text files and stored the climate conditions (temperature, light). The 'log' directory contained numerous files with the system debug logs, for development purposes.

VIDEO ANALYSIS PROCESS

After collecting all data in the field, we extracted biological information available in the 'data' directory into Microsoft Office Excel spreadsheet. First of all, we recorded the date and time of each owl activity, sex of the owl parent, temperature inside the clutch and outside the SNBox, and light intensity outside the SNBox. Afterwards we analysed each 'video event' which included two video records made by two cameras. From the door camera, we checked visually whether the owl parent arrived or departed the SNBox, if the parent brings the prey or not, the type of prey, and if the prey was decapitated or not. Video recording captured by floor camera provided us additional information on the number of eggs and nestlings, and the location of the stored prey inside the box.

STATISTICAL ANALYSES

We performed all statistical tests with generalized linear mixed models (GLMM) using *lmer* function in R statistical software, version 3.02 (R Development Core Team 2011). Statistical significance was obtained by comparing each model with a relevant previous model using the ANOVA command. Factors were added to the model based on the Akaike's information criterion. The values of chi-squared statistics were shown. First, we tested the effect of the night length on the voltage decrease of battery. We used Gaussian distribution of a dependent variable, and individual battery as a random factor. We further tested the effect of the nestling age (expressed as the number of days since egg laying) on the time spent by females outside the nest and the number of prey items delivered by males. We used quasi-distributions of dependent variables, the day in the season (i.e. the number of days since January 1) as a covariate, and nest as a random factor. We also tested the effect of intraseasonal variability in sunset and sunrise timing on timing of prey delivery by males and females leaving the nest. We used quasi-distributions of dependent variables, and nest as a random factor. Further, we tested the effect of a month (April–July) on the outdoor light intensity (measured as light intensity index) at time of prey delivery by males and females leaving the nest. We used quasi-distribution of dependent variable, and nest as a random factor. We performed *post hoc* comparisons using *glht* function. Finally, we tested the effect of outdoor temperature on time spent by female outside the nest, as well as the effect of both temperature outside the SNBox and time spent by female outside the nest on the decrease of temperature in the clutch during female absence (i.e. difference in temperature of the clutch between female departure from the nest and female entering the nest). We used Gaussian distributions of dependent variables, and nest as a random factor. All values are reported as means ± SE.

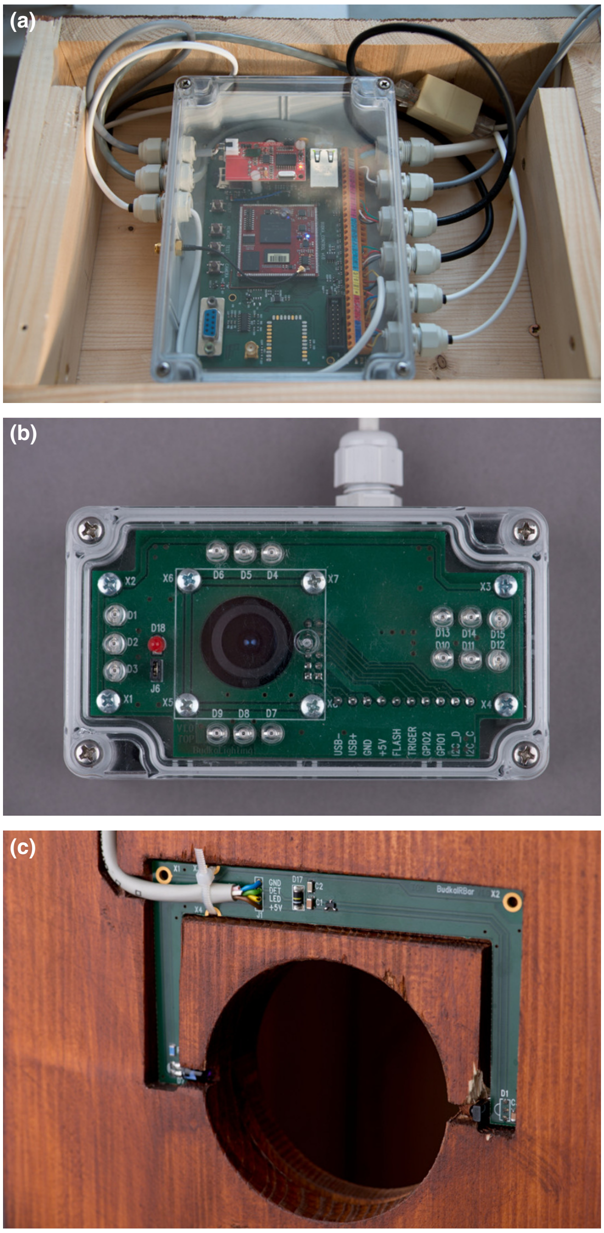

Fig. 2. Components of the smart nest box (SNBox): (a) the connected and housed control board, placed in the top area of the SNBox; (b) the camera with a lighting board, housed in a box with a transparent cover; (c) infrared light barrier, laid in a shallow groove in the front of the SNBox. During the SNBox application, it was hidden by a thin wooden cover.

Results

TECHNOLOGICAL INFORMATION

We changed the batteries on average every 6·5 days (SE = 0·15, $N = 56$). We measured 13·0 ± 0·02 V ($N = 56$) at the time of connecting the battery to the camera system and 12·1 ± 0·02 V ($N = 56$) at the time of disconnecting the battery. The battery was never fully discharged at the time of disconnection. The voltage decrease of the battery varied during the breeding season depending on the night length ($\chi^2 = 10{\cdot}9$, d.f. = 48, $P < 0{\cdot}001$, Fig. 3).

Depending on the total number of recorded events and the configuration of video parameters, the recordings required different amounts of memory space. The highest registered amount of space used for data collected in a 1-week period was 890 MB. The typical configuration, 5 s of 10 fps video recorded by the door camera and 60 seconds of 4 fps video recorded by the floor camera, led to use of about 101 MB of the 110 MB fast temporary memory.

Downloading the data recorded during each period took us about 5 min. Maintenance of one SNBox, including all related operations (battery replacement, nestling measurements, bird ringing, checking of stored prey, etc.), took about one hour

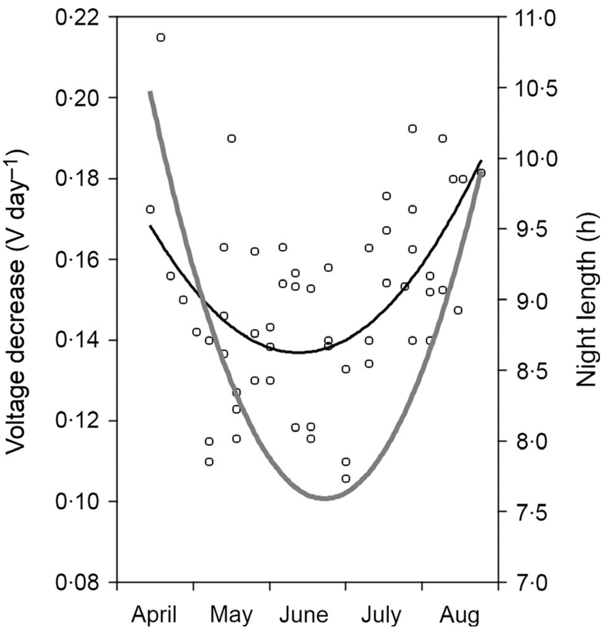

Fig. 3. Changes in power consumption of the smart nest box, expressed by the voltage decrease of a 60 Ah 12 V traction battery per a day, during the breeding season (i.e. from April to August). Row data are presented. Night length is fitted by grey line, battery consumption by black line.

every 6–8 days. At the end of the season, after collecting data from eight nests, we analysed the video data by one person in 60 h total.

The sensors did not work on 38 out of a total 309 days when the SNBoxes were applied (this problem involved three SNBoxes applied to five nests), and the RFID codes were not successfully scanned in 26·4% of all bird passes (four SNBoxes applied to eight nests).

The cost of one SNBox, including the wooden box and all electronics reached €1,000, without taking the development costs into account.

BIOLOGICAL INFORMATION

During 309 days of the data collection (38·6 ± 4·2 days per nest), we recorded a total of 3382 owl video events (422·8 ± 47·2 events per nest, and 10·9 ± 0·3 events per day, respectively), and only one video event without any owl activity. We identified a total of 2761 owl parental activities (345·1 ± 54·6 activities per nest), which we categorized into 12 types (Table 1). We made an original video containing unique information on owl nesting (Video S1).

None of the Tengmalm's owl parents deserted the nest after initiating use of the SNBox. However, male parents showed partial perception of the glow from the IR light source during the first days after camera installation. In particular, they usually escaped of the glow from the IR light at the moment when they entered the SNBox opening and the camera system was triggered. It resulted in their immediate escape from the nest opening without delivering the prey to the female (Video S2). The proportion of realized prey deliveries, that is the male handed over the prey to the female, increased with the number of monitored days (1st day: 27·5 ± 6·4%, 2nd day: 43·4 ± 5·4%, 3rd day: 66·7 ± 12·8%, 4th day: 100%). All males adapted to the glow of IR light, that is they realized all prey deliveries, on average 1·9 ± 0·7 days after SNBox application.

We found that females incubated eggs and brood nestlings continually, leaving the nests only for a few minutes per night, while males provided most of the food (more than 94%) during the incubation and nestling phases (Table 1). We recorded three types of parental behaviour of Tengmalm's owl that were not previously documented. First, males never threw a prey inside the SNbox. Instead, they handed over each prey directly to the female or the young, typically from bill to bill (Figs. 4d–f, Video S1). Secondly, when the young reached the fledgling phase and the female was absent from the nest, males sometimes visited the SNBox with a prey item, but they did not give the prey directly to the fledglings. Instead, they stayed usually 1–3 s holding the prey in the bill displaying it to their fledglings, and then flew away, still holding the prey. This activity was rarely recorded in females (Table 1). Thirdly, in five cases (four shrews and one bird), the female staying inside the SNBox took the prey from the male and then she left the nest with this prey (Fig. 4b). At this time, other prey items (3·8 ± 1·0 prey items), eggs (1·8 ± 0·9 eggs) and nestlings (1·6 ± 0·7 nestlings at age of 4·7 ± 1·2 days) were present at the nest. A few minutes later, the female came back to the nest without the prey.

Every time when the female left the SNBox, we were able to check the content of the nest using the camera images (Fig. 4a, c). We found eight females laid in total 29 eggs (3·6 ± 0·2 eggs per nest), 22 of which hatched (2·8 ± 0·5 eggs per nest), and 17 fledglings left the SNBoxes (2·1 ± 0·4 fledglings per nest). Young stayed in the nests for a period of 29–36 days (32·2 ± 0·8 days), and they left the SNBoxes during different

Table 1. Types and numbers of Tengmalm's owl parental activities recorded using smart nest boxes (SNBoxes). Eight sequential nests were monitored by four SNBoxes

	Male		Female	
Type of parental activity	Number of activities	% of total activities	Number of activities	% of total activities
Entering the SNBox opening with prey, giving the prey to nestlings or the female (from bill to bill)*, and leaving	1062	72·4	56	4·4
Entering the SNBox opening without prey, and leaving	19	1·3	21	1·6
Entering the SNBox with prey, giving the prey to nestlings, and leaving	253	17·2	12	0·9
Entering the SNBox with prey, and leaving with the same prey*	133	9·1	3	0·2
Entering the SNBox without prey, and incubation or brooding			471	36·4
Interruption of incubation or brooding, and leaving the SNBox without prey			466	36·0
Interruption of incubation or brooding, and leaving the SNBox with prey*			5	0·4
Peeping out of the SNBox during incubation or brooding			260	20·1
Total	1467	100	1294	100

*Previously undocumented parental activities.

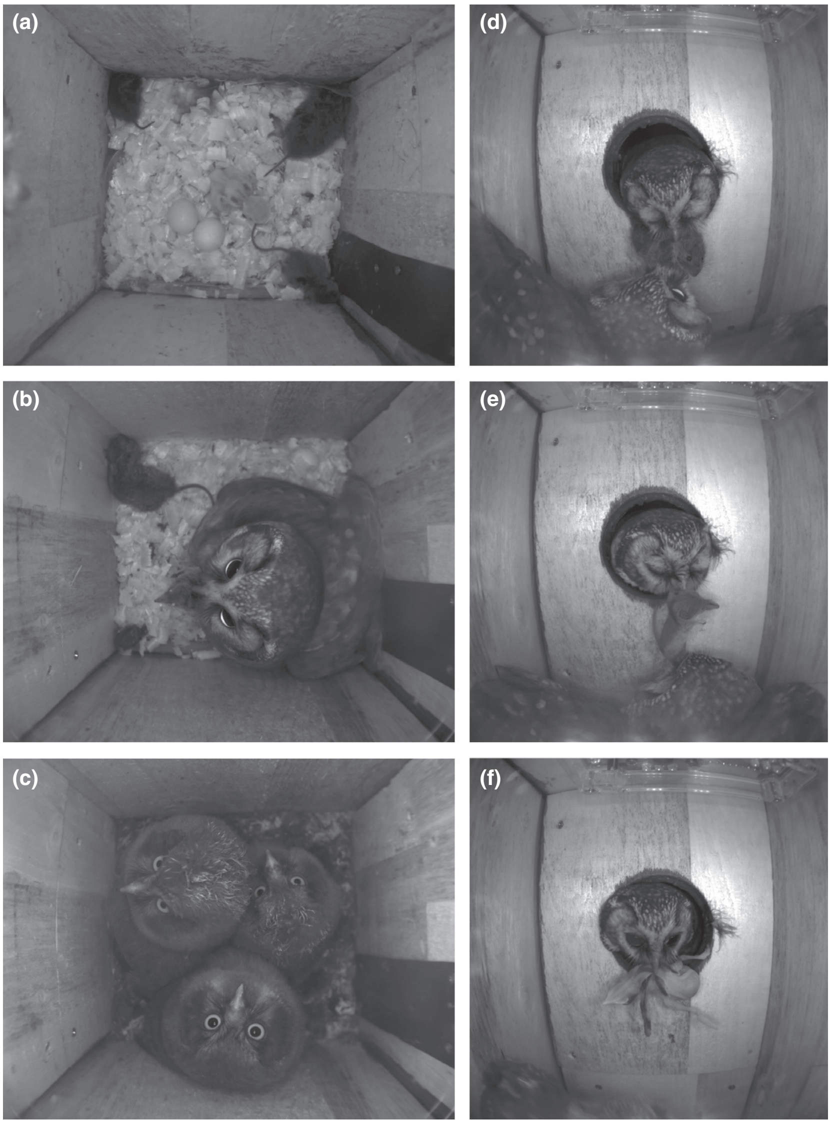

Fig. 4. Nesting of Tengmalm's owl photographed by the camera system of the smart nest box (SNBox): (a) stored prey, eggs and hatchlings in the nest; (b) the female with a shrew (Soricinae) preparing to leave the nest; (c) fledglings at the nest; (d) the male in the SNBox opening giving a prey item (Arvicolinae) to the female; (e) the male in the SNBox opening giving a prey item (Soricinae) to the female; (f) the male in the SNBox opening giving a prey item (bird nestling) to the female.

times (4 fledglings between 8 and 9 PM, 6 between 9 and 10 PM, 5 between 4 and 5 AM and 2 between 7 AM and 8 PM).

We recorded 1448 prey deliveries by males and 76 deliveries by females in eight nests (Table 2). Of all prey items delivered, we identified 71·2% as mammals and 26·8% as birds. We did not identify 2·0% prey items. We further identified 98·1% of all mammals as Arvicolinae (Fig. 4d), Murinae, Soricinae (Fig. 4e) and Gliridae (Table 2). Among birds, we were able to distinguish 25·2% to genus or species level, and 84·8% to age (adult or juvenile, Fig. 3f). We further recorded that 14·7% of all prey items delivered to owl nests were decapitated. Moreover, females nearly always (>95% of cases) stored the prey side-by-side, with their heads in the corner (Fig. 4a).

Time spent by females with nestlings decreased ($\chi^2 = 260948$, d.f. = 460, $P < 0{\cdot}0001$, Fig. 5a), while the number of prey delivered by males increased ($\chi^2 = 10{\cdot}51$, d.f. = 282, $P = 0{\cdot}001$, Fig. 5b), with increasing age of the nestlings. Simultaneously, both male and female owls adjusted their activity according to sunset and sunrise timing (females: $\chi^2 = 2548{\cdot}3$, d.f. = 469, $P < 0{\cdot}001$, males: $\chi^2 = 32011$, d.f. = 1441, $P < 0{\cdot}001$, Figs. 5c,d), and outdoor light intensity index at time of parental activity did not differ significantly among months (females: P at least 0·288, males: P at least 0·052).

The temperature inside the clutches ($N = 5$) dropped by 0·25–9·00°C (3·22 ± 0·17°C per female leaving, $N = 147$) during female absence, and this temperature drop increased with both increasing time spent by female outside the nest and decreasing outdoor temperature ($\chi^2 = 19{\cdot}90$, d.f. = 141, $P < 0{\cdot}0001$, Fig. 6). Finally, females reduced the time spent outside the clutch with decreasing outdoor temperature ($\chi^2 = 78{\cdot}82$, d.f. = 141, $P = 0{\cdot}02$, Fig. 6).

Discussion

TECHNOLOGICAL INFORMATION

We created a system that worked for a week without replacement of the 60 Ah 12 V battery and with sufficient data

Table 2. Diet composition of prey items delivered to the nests ($N = 8$) by male and female Tengmalm's owls identified using the camera system of the smart nest box

	Male		Female	
Prey species/group	Number of prey items delivered	% of total prey items delivered	Number of prey items delivered	% of total prey items delivered
Mammals				
Murinae	101	7·0	10	13·2
Arvicolinae	420	29·0	26	34·2
Soricinae	463	32·0	30	39·5
Gliridae	14	1·0		
Unidentified mammals	20	1·4	1	1·3
Birds				
Erithacus rubecula	11	0·7		
Turdus sp.	18	1·2		
Sylvia atricapilla	13	0·9		
Phylloscopus sp.	37	2·5	2	2·6
Ficedula sp.	1	0·1		
Parus sp.	13	0·9	2	2·6
Fringilla sp.	5	0·3		
Carduelis chloris	1	0·1		
Unidentified birds	301	20·8	5	6·6
Unidentified prey	30	2·1		
Total	1448	100	76	100

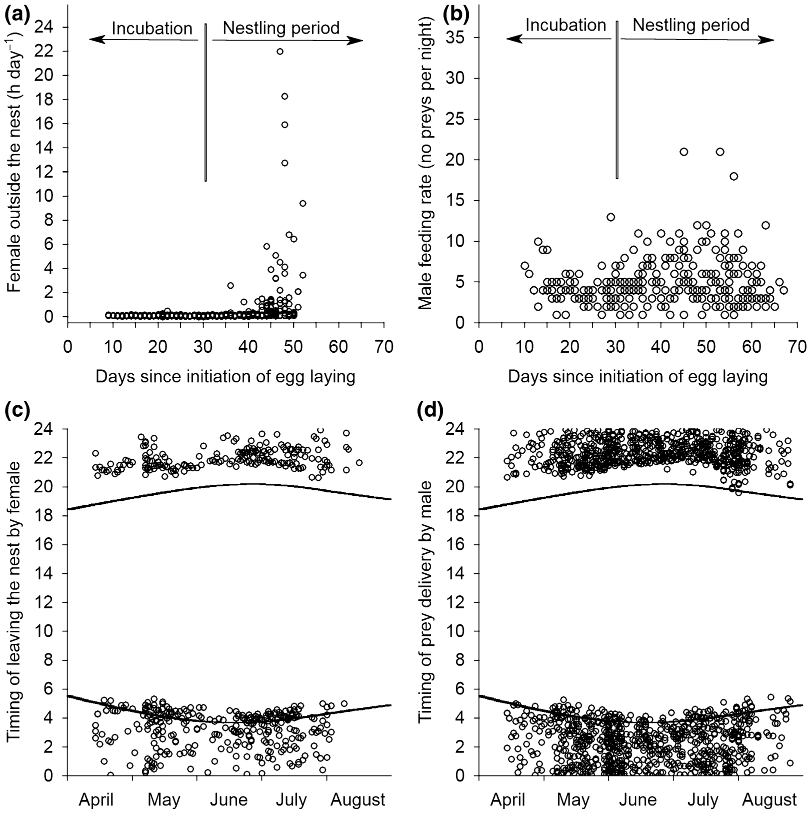

Fig. 5. Female and male Tengmalm's owl activities found using the smart nest boxes: (a) time (in hours per a day) spent by owl females outside the nests ($N = 8$) during the nesting period; (b) male feeding rate, that is the number of prey items delivered by male owls to the nests ($N = 8$) during the nesting period (note that the period 0–30 days indicates the incubation phase and the period 31–70 days indicates the nestling and fledgling phase); (c) timing of leaving the nest by females during the breeding season (i.e. from April to August); and (d) timing of prey delivery by males during the breeding season. Row data are presented. Timing of sunset and sunrise is fitted by black lines.

memory capacity. We suggest that the sufficient reserves of battery capacity were achieved through the periodic switching of the system between the awake and sleep mode according to sunset and sunrise which varied greatly throughout the breeding season and which determined activity of owls. The lowest power consumption was found during the mid-summer, that is around June 21, when the night length was about 7·5 h, and the highest power consumption was in April and August, when the night length was more than 10 h.

We used a customized event detector characterized by the unique short trigger speed (16 ms) which was fast enough to snap fast moving owls and simultaneously it ignored the

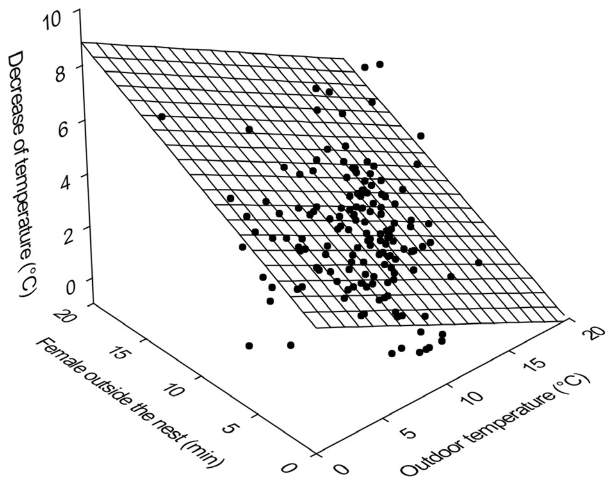

Fig. 6. The temperature decrease in Tengmalm's owl clutches (i.e. difference in temperature of the clutch between female departure from the nest and female entering to the nest, row data are presented) in relation to both outdoor temperature (°C) and time (in min) spent by owl females outside the nests ($N = 5$ clutches).

sunlight and insects (we recorded only one video event without any owl activity). The event detector helped to record only actions of interest, which resulted in 1 GB card capacity used in 1 week. Sufficient reserves of memory card capacity were achieved despite the system using two consecutive cameras – the door camera which recorded the male provisioning in detail, followed by the overview of the activities of the female and the nestlings recorded by the floor camera. A more serious limitation was posed by the size of the temporary storage for individual video frames, which was 110 MB. About 101 MB of this temporary memory was typically used, and thus, it was important to bear this limitation in mind during system configuration. However, all acquired video recordings were of sufficiently high quality, both for the research objectives and for the promotional video. Finally, we appreciate that the time needed for the data download and the battery replacement, including the handling of nestlings, ringing, and identification of stored prey, took only one hour per SNBox, which allowed us to service all four SNBoxes in 1 day.

While RFID technology is commonly used and well accepted in veterinary medicine, animal-farming and animal-tracking (e.g. Voulodimos *et al.* 2010; Catarinucci *et al.* 2014), we applied this technology for recognition of sex of bird parents during nesting in the wild. However, the chip reader device, which was embedded inside the SNBox, worked unreliably. Post-season laboratory experiments showed that the metal cover, the antenna shape, and the movement speed of individual could have significant impact on the RFID reader performance (see Appendix S3 for detailed information). Despite these limitations, we obtained a good overview of the individuals using this method (the RFID code was successfully scanned in 74% of all owl passes). Moreover, the pair of cameras helped us to identify the sex of the owl parents when RFID reader failed. We suggest the chip reader shows a high potential as a simply applicable and cheap tool with low power consumption for identification of individuals living under natural conditions which regularly visit the same place, and its use in other camera systems will depend on the subject being monitored and the research questions in particular.

The temperature and light sensors were the least reliable parts of the system. Post-season analyses showed that the I2C bus connected with the sensors was not resistant to interference. The problem was fixed by detecting bus failures and recovering from the state by bus or system reset.

Finally, we found that male parents showed partial perception of the glow from the IR light source during the first days after camera installation. However, all males adapted to the glow of IR light suggesting the glow did not affect data collection.

BIOLOGICAL INFORMATION

The SNBox allowed us to monitor owl nesting continually during the incubation, nestling and fledgling phases. We identified 12 types of Tengmalm's owl activities in total, three of which were not previously documented. We also produce a video containing unique information on owl nesting. In the light of previous studies (Zárybnická 2009; Zárybnická & Vojar 2013), we confirmed that male Tengmalm's owls deliver most of the prey to the nest, while females incubate the eggs and brood nestlings. Simultaneously, male owls increased their feeding frequency with the nestling age, while the females decreased their time spent in the nest. Both male and female parents shifted timing of their activities according to sunset and sunrise. The period of their activity gradually got narrower from April to late June with shortening the night length, and it again spread after mid-summer with prolonging the night length (see also Zárybnická, Korpimäki & Griesser 2012). As a result, outdoor light intensity at time of owl activities did not differ significantly among months.

For the first time, we observed that males hand over each prey directly to the female or their fledgling, typically from bill to bill. It has previously been documented in other owl species that males hand over the prey to the female's bill during copulation (König & Weick 2008); however, our findings extend this behaviour to the entire nesting period. Another specific activity of parents was observed during fledgling phase, when young were preparing to leave the nest. At this time, both males and females (independent of each other) were seen to deliver prey to the nest, showing it to the fledglings, and then leaving the nest with the prey. Studies of black kites (*Milvus migrans*) and loggerhead shrikes (*Lanius ludovicianus*) demonstrated that parents decreased their feeding rate during the time of fledgling or called to fledglings from afar to entice them out of the nest (Bustamante & Hiraldo 1990; Woods 1993). We speculate that the behaviour observed in Tengmalm's owl parents can be a strategy to lure the young to fledge. Finally, we observed several cases when the female left the nest box with a prey item (four times with shrews and once with a bird), which the male had delivered a few seconds before, and she returned to the nest with no prey a few minutes later. Newton (1979) mentioned that the prey that is unfinished at one meal may be stored by the parent away from the nest and brought back to the nest on another occasion. Because both shrews and birds represent an alternative prey of Tengmalm's owls (Zárybnická, Riegert & Šťastný 2013), one explanation for this behaviour could be to take a non-preferred prey away from the nest. However, we cannot exclude the possibility that female owls fly out from the nest in this manner to consume the prey themselves, away from their young.

Since the amount and structure of diet in birds of prey may be underestimated using prey-remain collections and pellet analyses, prey identification with camera monitoring may be a more suitable method (Zárybnická, Riegert & Šťastný 2011). Using the SNBoxes, we were able to recognize 98% of all prey items delivered to owl nests as mammals or birds, and to identify 77% of all prey items to family, subfamily, genus or species level. Moreover, this method allowed us to evaluate the number of prey delivered by male and female separately, the frequency of prey decapitation, the proportion of bird adults and nestlings in the diet, as well as the location of the stored prey inside the nest box. In more detailed study, we could also evaluate changes in the structure of the owl diet during the breeding season, time of the night, or the nesting phase.

It was shown that heat losses from the egg to the environment represent an important limitation during the incubation process (Deeming 2002). We found that the temperature decrease inside owl clutches during female absence was on average 3·2°C and increased with both increasing time spent by the female outside the nest and decreasing outdoor temperature. As a result, female parents reduced the time spent away from the nest with decreasing outdoor temperature, suggesting that the heat losses from the clutch are a limiting factor for Tengmalm's owl.

USING SMART NEST BOXES FOR OTHER ANIMAL SPECIES

The SNBox can be easily adjusted for research on other animal species. Specifically, one could simply change the user system configuration by adjusting the awake/sleep time, depending on activity pattern of monitored species. Moreover, modifications to the software would allow a deep system adjustment and replacing the individual hardware components would enable the system to monitor many different tasks. As a result, the system could be used for both diurnal and nocturnal animals breeding in nest boxes or bigger cavities, as well as for research on other animals in which the action of interest is triggered by actively crossing a specific spot. We believe the system can be applied to birds, mammals or reptiles using nest boxes to breed, roost, hibernate, or store food so as to monitor their activities and circadian rhythms, feeding ecology, parental care or sibling competition. Additionally, the modification of sensitivity of the event detector would allow monitoring of insects using cavities and nest boxes. The most expensive part of the system for monitoring the Tengmalm's owl nests was the pair of industrial cameras, which were necessary to collect the required data and which allowed high-quality video recordings. We suggest the use of cheaper cameras could reduce the system cost to two-thirds of the actual price (€1000). Moreover, further development of the system could allow significant improvements, including audio recording, Wi-Fi connectivity, online video transmission and self-acting setting of the awake/sleep time of the system depending on the outdoor light intensity. We believe this monitoring system will provide unique insights into the lives of cavity-dwelling animals, as we show by results of the present study on Tengmalm's owl.

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Data accessibility

Data for the statistical analyses can be found at Dryad entry doi:10.5061/dryad.c89g9 (Zárybnická *et al.* 2015b).

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

Figure S1. Architecture of the embedded system in the smart nest box (SNBox).

Appendix S1. Examples of animals using artificial boxes.

Appendix S2. Hardware and software design of the SNBox.

Appendix S3. Post seasonal laboratory experiment on reasons for the failure of the chip reader.

Video S1. An original video containing unique biological information on Tengmalm's owl nesting.

Video S2. An original video records showing partial perception of male Tengmalm's owl to the glow from the IR light during the first days after camera installation (notice that the male leaves the nest opening without delivering the prey to the females, perhaps out of fear).