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Review article

Applications of thermal imaging in avian science

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Thermal imaging, or infrared thermography, has been used in avian science since the 1960s. More than 30 species of birds, ranging in size from passerines to ratites, have been studied using this technology. The main strength of this technique is that it is a non-invasive and non-contact method of measuring surface temperature. Its limitations and measurement errors are well understood and suitable protocols have been developed for a variety of experimental settings. Thermal imaging has been used most successfully for research on the thermal physiology of captive species, including poultry. In comparison with work on mammals, thermal imaging has been less used for population counts, other than for some large bird species. However, more recently it has shown greater success for detection of flight paths and migration. The increasing availability and reduced cost of thermal imaging systems is likely to lead to further application of this technology in studies of avian welfare, disease monitoring, energetics, behaviour and population monitoring.

Keywords: bird surveys, infrared thermography, thermal physiology, welfare.

Technology has an important role in answering ecological and behavioural questions in avian science. For example, our understanding of bird migration has been transformed by the use of satellite tracking devices, seabird diving behaviour by the deployment of time depth recorders, and energy expenditure by the use of heart rate loggers (Takahashi & Yoda 2010, Green 2011). These new technologies are highly valued because they allow measurement of the behaviour of free-ranging animals. One technology that is increasingly used in avian research is thermal imaging, otherwise known as infrared thermography. Although this technique was first used on birds as far back as the 1960s to identify sites of heat loss in Arctic species (Veghte & Herreid 1965), it is now widely used to study thermoregulation, energy expenditure welfare for monitoring animal populations (Kastberger & Stachl 2003, Stewart *et al.* 2005, McCafferty 2007, Tattersall & Cadena 2010), and also on a small scale in ecological and behavioural studies. Thermal imaging is one of a number of technologies applicable to nocturnal studies of birds, including spotlighting, radar and image enhancement, all of which have strengths and weaknesses (Allison & Destefano 2006). Cost is likely to have been one of the most important reasons why this technology has not been widely used in field research. However, thermal imaging cameras are becoming more affordable, ranging in price from hand-held detection cameras (< £1000) to high level research and development systems (>£30 000).

This review is aimed at researchers who may be interested in using thermal imaging in laboratory or field studies of birds, and builds on earlier work which focused on mammals and the use of thermal imaging in biophysical modelling (McCafferty 2007, McCafferty *et al.* 2011). A literature search was undertaken using knowledge of existing literature, together with a recent reference search using Web of Knowledge™. This was not intended to produce an exhaustive review of the literature but to examine critically the use of thermal imaging for avian research, provide guidelines for its appropriate use, and identify research questions that can be tackled using this technology.

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THERMAL IMAGING: THEORY AND MEASUREMENT

Thermal imaging involves the detection of infrared radiation (heat) emitted from an object (Speakman & Ward 1998). Any object that has a temperature above absolute zero (−273.15 °C, or 0 °K) emits infrared radiation and the temperature of the object will determine the wavelength of the radiation emitted. At biologically relevant temperatures (−40 to 100 °C) radiation peaks in the infrared wavelength (longwave) range of approximately 8–12 μm. Infrared radiation is readily absorbed by water and therefore thermography can only be used in air and not for objects underwater. Thermal cameras work by measuring infrared radiation R (W/m^2) and computing temperature T (°K), from the Stefan Boltzmann Law: $R = \varepsilon\sigma T^4$, where ε is the emissivity of the surface and σ is the Stefan Boltzmann constant (5.67×10^{-8} W/m^2/K^4). Emissivity is defined as the ability of a surface to emit and absorb radiation (Monteith & Unsworth 1990). The emissivity of biological tissues is close to a blackbody (perfect emitter) and for plumage has been recorded in the range 0.96–0.98 (Hammel 1956, Best & Fowler 1981). Plumage colour does not influence emissivity but may influence solar absorbance and hence dark plumages may have higher surface temperature than pale-coloured plumages in strong sunshine (McCafferty 2007).

A thermal imaging camera produces a grey or colour-scaled image made up of pixels that represent individual temperatures (Fig. 1). With most systems there is a choice of colour palette available. Some palettes are only suitable for colour display/printing, whereas proportional intensity palettes can be used for both colour and greyscale printing. Thermal imaging records only surface temperature and for un-feathered areas this is the temperature of the skin surface or tissue. However, plumage is not a smooth solid surface and radiation will be emitted from different layers from within the feather matrix. Depending on spacing between outer feathers, the temperature recorded is effectively the temperature of the plumage a few millimetres below the physical surface of the plumage (McCafferty *et al.* 2011).

Selection of thermal camera will depend on measurement requirements of your study. The main choices relate to whether the researcher wishes to make temperature measurements or simply detect the difference between warm and cold surfaces, what temperature and spatial resolution is required, what the measurement distance is, and whether the researcher wishes to record still or

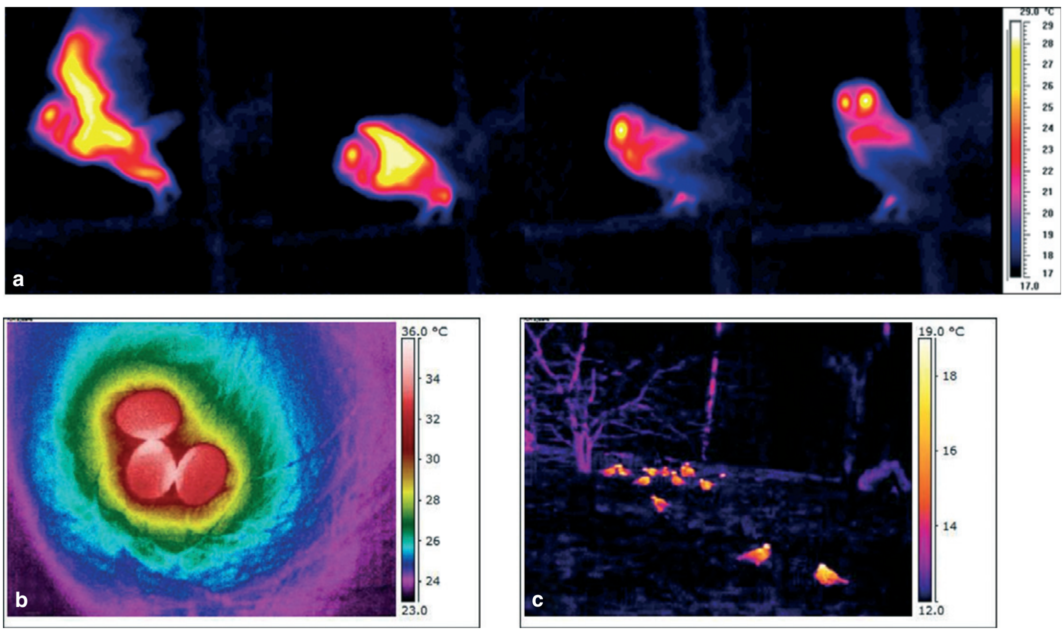

Figure 1. Thermal images showing (a) sequence of female Barn Owl *Tyto alba* in flight (AGA 782), (b) Zebra Finch *Taeniopygia guttata* clutch in nestbox (FLIR E300), and (c) thermal survey of Feral Pigeons *Columba livia* (FLIR E300).

moving images. An un-cooled camera capable of resolving 0.1 °K and with image resolution of 320 × 240 pixels or greater is appropriate for most applications in avian science where temperature measurement is required. Where greater temperature resolution, < 0.05 °K, and higher image capture frequency is needed, a cooled camera should be used. Many high level infrared cameras can use a variety of lenses including wide-angle, telephoto and macro. This will influence the spatial resolution; for example, each pixel with a wide-angle lens at a given distance will represent a larger spatial area compared with a lens with smaller angle of view. Most cameras will record still images in jpeg or similar format. These are radiometric files that contain thermal information for each pixel that is translated into colour/greyscale. This means that radiometric images can be rescaled *post hoc* without losing any measurement precision or content. Higher level cameras will allow thermal images to be recorded to memory or streamed to a computer as a radiometric video file. Again, this file format contains temperature data for each pixel rather than a standard video file. For detecting or counting birds, temperature data are not necessarily required and a surveillance system that simply identifies a 'hot body' against a cool background may be the most appropriate.

The strengths and limitations of thermal imaging for measuring surface temperature or locating animals are well understood (Table 1). Thermal imaging is highly suited for work on captive birds that can be approached to within a few metres. It is possible to take images through metal aviary cages where the distance between bird and cage is relatively small relative to the distance between cage and camera. The cage wire will block some of the infrared radiation emitted from the bird and the temperature of the wire cage will introduce inaccuracies in measurement if the camera is held close to the cage. Calibration can be made using an object of known temperature in these circumstances. Glass is transparent to visible wavelengths but opaque to infrared. Specialised transparent infrared windows composed of a number of metal-based compounds allow transmission of infrared radiation of different wavelengths (see: http://iriss.com/) A thin polyethylene film (e.g. a Ziploc© freezer bag) allows the partial transmission of infrared radiation, for example for studies in metabolic chambers. These materials selectively absorb certain wavelengths, giving inaccurate tempera-

Table 1. Summary of advantages, limitations and constraints in study design for thermal imaging. Further details in McCafferty (2007) and McCafferty *et al.* (2011).

Advantages
Non-invasive, remote measurement of surface temperature
Long-distance detection in open habitats at night, avoiding disturbance from spotlights
High spatial (e.g. 320 × 240 pixels) and temperature (< 0.1 °C, accuracy ± 2% of full temperature range) resolution
Portable devices, still or moving thermal images recorded
Analytical software for image analysis and summary statistics
Limitations
Surface temperature dependent on environmental variables (solar and reflected radiation), precipitation and evaporation. IR radiation absorbed by water and cloud cover
Limited detection probability with high environmental temperatures and daytime detection poor due to thermal heterogeneity of environment
Temperature of bird influenced by time of day, age, stress and range of physiological factors
Low temperatures recorded at edge of curved surface (Watmough *et al.* 1970)
Expensive (although prices have fallen)
Low spatial resolution of temperature at distance
Thermal signals blocked by vegetation or terrain
Constraints in study design
Take measurements in controlled conditions and allow animal to equilibrate with surroundings
Measure temperature of reference blackbody
Record air temperature and relative humidity
Minimized environmental variation by recording in dark/low light. Control for physiological variables
For detection work, thermal contrast greatest at night against cold substrate or clear sky
For diagnosis of disease or injury look for asymmetry in thermal patterns (e.g. adjacent limbs)
Use area analysis tools to avoid curvature effects or take readings from centre of distant objects

tures, but it is possible to calibrate for this using objects of known surface temperatures. The environmental temperature on the camera side of the plastic film should remain constant because some infrared radiation is reflected from the room onto the plastic film (Tattersall & Milsom 2003, Scott *et al.* 2008). Most cameras are designed for working in industrial environments which also makes them suitable for fieldwork with high humidity and extremes of temperature. Thermal cameras can be used for bird detection at considerable distances. Desholm (2003) was able to detect a duck at distances of up to 3000 m and migrants have been recorded from the ground at 3000 m altitude (Zehnder *et al.* 2001).

Depending on the choice of system, images can be recorded manually, programmed to record at set time intervals or recorded as moving images onto computer/storage device. It is recommended that visual images are recorded along with thermal images for subsequent analysis. Image analysis can be undertaken with proprietary software available to derive summary statistics from different regions of the image (McCafferty *et al.* 2011). This allows *post hoc* adjustment of environmental parameters such as temperature and humidity that influence radiative properties. Statistical data (e.g. mean, minimum, maximum) can be obtained quickly by fitting polygons from regions of interest in the image. Analytical software is becoming increasingly complex, with functionality for time sampling and target tracking for automated analytical procedures.

OTHER INFRARED TECHNOLOGIES

Other technologies that may be confused with thermal imaging are (1) infrared photography, which uses photographic film/digital sensor sensitive to near-infrared light (0.7–0.9 μm), (2) night-infrared cameras that are sensitive to visible light and near-infrared where the visual field is illuminated by an infrared beam or (3) night vision devices that rely on the collection and amplification of small amounts of light in the visible and near-infrared spectrum (Kastberger & Stachl 2003). Night cameras are effective where filming or detection of nocturnal animals from a fixed point is required (e.g. camera traps or CCTV). Night vision devices (e.g. night vision goggles) are useful for navigation or searching for birds. These three systems do not measure temperature but are cost-effective for behavioural observations. Finally, recent mobile phone and computer cameras produce pseudo-thermal images that simply substitute colours to give the appearance of a thermal image.

APPLICATIONS

Thermal physiology

The main emphasis of early thermography studies of birds was to identify variation in heat loss and insulative capacity of different areas of plumage (Table 2). Traditionally, solid sensors such as thermocouples and thermistors have been used to measure plumage or skin temperature (Goldsmith & Sladen 1961). These are inexpensive but a large number of sensors would be required to give good spatial coverage and solid sensors may disrupt and influence the insulation properties of the plumage (Cena 1974) as well as interfering with movement of the bird. Infrared thermometers that measure infrared radiation emitted from an object can also be used to obtain single spot/area temperature measurements (Wilson *et al.* 1998). It is also possible to measure body conductance from cooling curves of dead birds (Herreid & Kessel 1967) and the thermal conductivity of plumage samples on a heated flat plate or cylinder (Scholander *et al.* 1950, Ward *et al.* 2007). More realistic measures of metabolic heat loss and operative temperature of birds can be made using heated taxidermic mounts (Bakken *et al.* 1999). The obvious advantage of thermal imaging is that it provides measurement of the temperature across the entire body of a live bird without the need for restraint or capture.

Thermal imaging has shown that areas around the head and in particular the eye-auricular region have the highest temperature, while well–feathered regions are closer to ambient temperature. Relationships between surface temperature and air temperature for different parts of the body have been used to estimate coat conductance and metabolic heat loss (Veghte & Herreid 1965, Hill *et al.* 1980). For species with large feather-free areas, such as the ratites, regions of the bill, leg and neck were estimated to dissipate 40% of metabolic heat, even though these structures represent < 20% of surface area (Phillips & Sanborn 1994). Similarly in the Humboldt Penguin *Spheniscus humboldti*, flippers and feet are important thermal windows for heat dissipation in warm conditions (Despin

Table 2. Applications of thermal imaging for research on the thermal physiology and welfare of birds.

Species	Research topic	Thermal imaging system	Reference
Anna's Hummingbird *Calypte anna*	Modelling metabolic rate	Fluke, Everett, WA	Evangelista *et al.* (2010)
Arctic birds (four species)	Heat loss and air temperature	Barnes Model I-8A IR radiometer	Veghte and Herreid (1965)
Barn Owl *Tyto alba*	Temperature variation and heat loss	AGA 782 Thermovision	McCafferty *et al.* (1998)
Black-capped Chickadee *Parus atricapillus*	Heat loss and air temperature	AGA 680/102B Thermovision	Hill (2009), Hill *et al.* (1980)
Domestic Fowl *Gallus domesticus*	Heat and water stress	–	Yahav *et al.* (2005)
Domestic Fowl *Gallus domesticus*	Naked neck and feathered birds	IRTIR, Inframetrics 760	Yahav *et al.* (1998)
Domestic Fowl *Gallus domesticus*	Bumblefoot screening	ThermaCAM PM695, FLIR Systems	Wilcox *et al.* (2009)
Domestic Fowl *Gallus domesticus*	Feather cover score	ThermaCAM S60, FLIR Systems	Cook *et al.* (2006)
Domestic Fowl *Gallus domesticus*	Spatial patterns and age	AGEMA Thermovision 570	Cangar *et al.* (2008)
Domestic Fowl *Gallus domesticus*	Metabolic heat production and diet	Testo® 880	Ferreira *et al.* (2011)
Domestic Fowl *Gallus domesticus*	Skin temperature variation	Inframetrics, model 760, FLIR Systems	Tessier *et al.* (2003)
Domestic Fowl *Gallus domesticus*	Egg temperature and cold exposure	Model PM545, FLIR Systems	Shinder *et al.* (2009)
Domestic Fowl *Gallus domesticus*	Facial and cloacal temperature	PM545; FLIR Systems	Giloh *et al.* (2012)
Domestic Fowl *Gallus domesticus*	Temperature response to distress	E4 ThermaCAM, FLIR Systems	Edgar *et al.* (2011)
Domestic Fowl *Gallus domesticus*	Temperature response to palatable reward	Thermovision A40, FLIR Systems	Moe *et al.* (2012)
House Finch *Carpodacus mexicanus*	Effect of wind	AGEMA, 782 Thermovision	Zerba *et al.* (1999)
Humboldt Penguin *Spheniscus humboldti*	Temperature responses to cold	AGA 680 Thermovision	Despin *et al.* (1978)
Mallard ducklings *Anas platyrhynchos*	Prediction of body temperature	ThermaCAM PM 575, FLIR Systems	Bakken *et al.* (2005)
Mallard ducklings *Anas platyrhynchos*	Heat loss during swimming	ThermaCAM PM 575, FLIR Systems	Banta *et al.* (2004)
Mallard ducklings *Anas platyrhynchos*	Effect of radio-transmitters	Model 525, Inframetrics	Bakken *et al.* (1996)
Nests (12 species)	Cooling rate of eggs	THI-300, Tasco, Japan	Lamprecht and Schmolz (2004)
Ratites (three species)	Heat loss and thermoregulation	Inframetrics 525	Phillips and Sanborn (1994)
Common Starling *Sturnus vulgaris*	Metabolism and heat loss in flight	AGEMA, Thermovision 880	Ward *et al.* (1999, 2004)
Toco Toucan *Ramphastos toco*	Heat loss from bill	Mikron Instruments Model 7515	Tattersall *et al.* (2009)
Waterfowl (three species)	Responses to hypoxia	Mikron Instruments Model 7515	Scott *et al.* (2008)
White Peking Duck *Anas platyrhynchos*	Bill thermoregulation	AGA Thermovision 680	Hagan and Heath (1980)
Zebra Finch *Taeniopygia guttata*	Egg and brood patch temperature	E300, FLIR Systems	Hill (2009)

et al. 1978). Domestic Fowl *Gallus domesticus* showed warmest areas on bare skin (bill, face, wattles and feet) and cooler regions on well-insulated feathered areas. Average surface temperature was shown to decrease with chick age (due to increased insulation from feather development), but there was greatest variability in temperature across the body at late stages of development (Cangar *et al.* 2008). Posture (bill, leg and feet covering) and piloerection (raising of plumage) influenced exposure of regions of high heat loss and increased thickness of the insulative layer (Veghte & Herreid 1965, Hill *et al.* 1980).

Thermal imaging can provide new insights into the functions of different parts of the body. Hagan and Heath (1980) showed that the temperature of the bill decreased with air temperature and variation across the bill was associated with arterial vasculature. More recently, Symonds and Tattersall (2010) revealed that the bill of the tropical Toco Toucan *Ramphastos toco* also acts as a thermal radiator. On average, 30–60% of body heat is dissipated by blood flow to this region. Adults have the ability to control heat loss from the bill from 5% in the cold to up to 100% of total heat loss in warm conditions (Tattersall *et al.* 2009). In hypoxic (low oxygen) conditions, birds control peripheral heat loss by warming the bill to bring about a reduction in body temperature. Bar-headed Geese *Anser indicus*, a high-altitude species, tolerated greater hypoxia before body temperature was reduced compared with lower altitude species (Scott *et al.* 2008). Thermal imaging can be a valuable tool to examine energy expenditure, and energy costs of different behaviours that cannot be measured on restrained birds. For example, the relationship between activity and metabolic heat production has been investigated in a number of thermal imaging studies. Wind tunnel experiments with House Finches *Carpodacus mexicanus* indicated that there was no difference between the surface temperature of resting and active birds exposed to the same convective conditions, indicating that exercise-generated heat is likely to be a common mechanism of thermoregulation in natural conditions (Zerba *et al.* 1999). McCafferty *et al.* (1998) showed that considerable amounts of heat are released from flight muscles. For a Barn Owl *Tyto alba* the temperature was greatest overlying the main flight muscles, from both the pectoralis and the ventral wing region. Heat generated from the leg muscles was also obvious during take-off (Fig. 1a). Ward *et al.* (1999) took thermal images of Common Starlings *Sturnus vulgaris* in a wind tunnel and using a heat transfer model demonstrated that during flight, heat loss from radiation accounted for only 8% of total heat loss, whereas convection accounted for 81%. Most heat loss occurred from the wings and the trailing feet could increase heat loss by up to 12%. These estimates of total heat loss agreed well with metabolic rates measured by doubly labelled water and oxygen consumption (Ward *et al.* 2004), giving confidence in the use of heat transfer modelling for studying avian energetics. In Anna's Hummingbirds *Calypte anna*, Evangelista *et al.* (2010) compared heat loss by convection and radiation derived from thermal images, metabolic rate using flow-through respirometry and aerodynamic power calculated from wing beat kinematic data and found they gave similar estimates of power output. However, at higher temperatures heat transfer models underestimated metabolic heat output and indicated that evaporative and heat storage changes as well as enhanced convective heat loss from the wings may have accounted for this difference.

Thermal imaging can also be used to estimate indirectly the internal body temperature of birds. Bakken *et al.* (2005) showed that by removing a small area of plumage ($\leq$ 1 cm^2) from the scalp of 2–3-day-old Mallard *Anas platyrhynchos* ducklings, cloacal temperature could be estimated to within 1 °C using only scalp temperature and ambient temperature at wind speeds up to 2.5 m/s. In this study there was concern that convective cooling from the shaved area would occur. However, model tests using a polyethylene convective shield (0.025 mm) over the measurement site increased measurement error. The investigators suggested that the relationship between scalp temperature and internal temperature may decline with body size as tissue thickness increases. It is unlikely to be a substitute for direct measurements of core temperature in birds but where appropriate may minimise effects on behaviour and physiology associated with instrument attachment, surgery or handling. As yet, this technique has not been widely used but it has provided a non-invasive method of measuring the internal temperature of ducklings, estimating that a minimum of 70% of metabolic heat production is lost to water (Banta *et al.* 2004).

Thermography and heat transfer modelling has been extended to examine the energy cost of different behaviours. Ward and Slater (2005) used this approach to estimate that male Canaries *Serinus canaria* increased their metabolic rate by 14% when singing. Previously the energy cost of different behaviours had been confined to studies in captivity; however, this approach could also be applied to estimate the energy cost of different behaviours in free-ranging birds (e.g. courtship displays, fighting) or different stages of the lifecycle such as moult. There is therefore considerable scope for estimating the relative energy cost of different behaviours or environmental conditions (e.g. precipitation, wind) that are either difficult or impossible to measure with respirometry or doubly labelled water methods. Further details on approaches to heat transfer modelling are given in McCafferty *et al.* (2011).

There has been relatively little use of thermal imaging for examination of egg temperature. Lamprecht and Schmolz (2004) evaluated the insulating effect of different types of nests by determining the cooling rate of eggs. Thermal imaging revealed strong thermal gradients within the clutch between relatively warm inner contact regions and cooler outer regions (Fig. 1b). Clearly, thermal imaging cannot measure the temperature of the clutch while a bird is incubating and therefore solid sensors attached to eggs or model eggs must be used. However, thermal imaging can provide further information on temperature variation within a clutch. Hill (2009) successfully used thermography in the laboratory to monitor egg incubation temperature of the Zebra Finch *Taeniopygia guttata* by taking into account the time incubating birds were off the nest. This approach could be applied in field studies by using an automated thermal imaging system to record egg temperature when birds left the nest. Moreover, thermal imaging may be able to answer questions related to the energetic cost of incubation. Hill (2009) showed that female but not male Zebra Finches had higher abdominal temperatures when incubating enlarged clutches, suggesting that females showed a greater physiological response to the demands of incubation. Surprisingly, thermal imaging has rarely been used to study the temperature of nestlings: Ovadia *et al.* (2002) found that the energy cost of begging inferred from surface temperature was not affected by nestling rank in House Sparrows *Passer domesticus*. There appears to be considerable scope for studies on the development of thermogenic capacity, social thermoregulation and energetic consequences of nest position (see comparative studies on Rabbit *Oryctolagus cuniculus* pups: Gilbert *et al.* 2012).

Welfare

In contrast to the extensive use of thermography for detection of disease and injury in farm, zoo and domestic mammals (Eddy *et al.* 2001, Stewart *et al.* 2005, Hilsberg-Merz 2007), there have been few studies on birds. Wilcox *et al.* (2009) found that thermal imaging was successful in detecting cases of bumblefoot (chronic inflammation: podermatitis), and better at detecting cases at the subclinical infection stage than by eye. Thermal imaging was also an effective method of assessing feather cover of laying hens (Cook *et al.* 2006). Thermography has the potential to examine the health and welfare of wild birds, especially to assess research impacts. Bakken *et al.* (1996) used thermography to reveal disruption of feathers by radio-transmitters mounted by harnesses on Mallard ducklings (although this did not increase metabolic rate). Thermal imaging would be suited to further studies examining the possible impacts of other externally mounted sensors or assessing recovery from surgery. Validation of using eye and facial temperature to study stress-induced hyperthermia may also allow the development of a useful tool of monitoring avian welfare (Fig. 2). For example, when hens were exposed to a minor stressor, eye and comb temperature decreased and when their chicks were exposed to the same stressor, hens showed an empathetic decrease in eye temperature associated with an increase in heart rate and time spent standing alert (Edgar *et al.* 2011). Animals respond to stress or pain by rapid changes in their pattern of blood flow, from the periphery to the core via sympathetically mediated vasoconstriction, which reduces skin temperature (Stewart *et al.* 2008). The skin is the first body

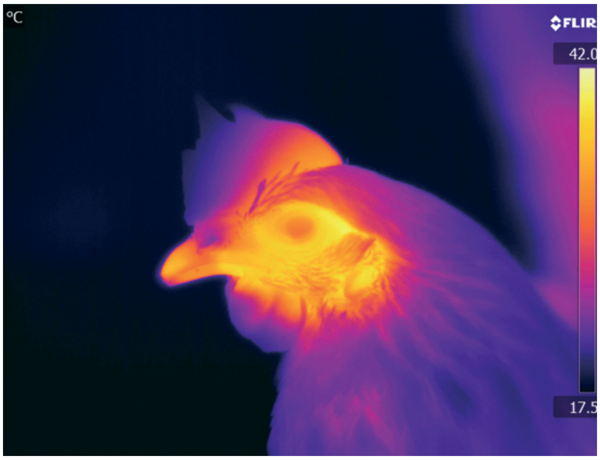

Figure 2. Head of Domestic Fowl *Gallus domesticus* showing spatial variation of head, comb and wattles (FLIR SC640, high resolution 640 × 480 pixels).

region to be affected by any injury and the short-term metabolic requirements of the skin are not essential, so that blood flow can be used for other metabolic requirements. In some species, perception of psychosocial threats may also illicit cutaneous vasoconstriction (Blessing 2003). Recently, thermal imaging showed that comb temperature may also change in response to positive anticipation and consumption of palatable rewards (Moe *et al.* 2012). These recent findings indicate the potential for applying methods developed on poultry to monitor physiological stress in laboratory or wild bird populations, for example to detect the impact of disturbance or handling on wild birds as a comparative approach to heart rate monitoring (Nimon *et al.* 1996).

Behaviour

Thermal imaging is advantageous for studying the behaviour of birds at night (Table 3). Kuwae (2007) monitored the nocturnal feeding behaviour of Kentish Plovers *Charadrius alexandrines*, as the thermal camera was able to pick up warm excreta when deposited on the ground. Defecation rate was therefore used as an index of feeding rate. Similarly, Tillmann (2009a) used thermal imaging to study the relationship between defecation and escape behaviour in roosting coveys of Grey Partridges *Perdix perdix*, and also found that anti-predator behaviour was different at night compared with day in terms of roost location, circadian shifts in behaviour, tightness of groups and flight distances to avoid predation (Tillmann 2009b). Further insights into the behaviour of both nocturnal species and the nocturnal roosting behaviour of diurnal species may be possible with thermal cameras. Although the cost of thermal cameras is high compared with conventional infrared CCTV, no infrared source is required for illumination and therefore greater viewing distance is possible (Kuwae 2007).

Field surveys

Relatively few studies have used thermal imaging for field surveys. This may be because more cost-effective alternatives are available for counting and locating birds. Thermal surveys can be used to locate nests, individuals and flocks of birds in a variety of open habitats (Fig. 1c, Table 3). These can be conducted on foot, from a boat or, where greater spatial coverage is required, even from aircraft. Early studies were not encouraging for this technique because of vegetation blocking the thermal signal, especially for cavity nesters, and practical considerations such as the large size and cost of cameras (Boonstra *et al.* 1995). Since then, there have been a number of successful thermal aerial surveys of some large species (turkeys and cranes). More recently, portable hand-held cameras have been used to locate nests and nestlings (Galligan *et al.* 2003, Mattsson & Niemi 2006). Most suitable thermal surveys are for ground-nesting species where incubating birds can be located in relatively open habitats. A study of Malleefowl *Leipoa ocellata* used an airborne thermal scanner to count incubator nest mounds in *Eucalyptus* scrub (Benshemesh & Emison 1996). Malleefowl open their incubation mound on most mornings to adjust the incubation temperature and aerate the mound, and the surveys were able to locate up to 36% of active mounds.

Thermal imaging from a boat has increased the catch rates of some species at night (Mills *et al.* 2011). Small hand-held devices produced for hunting show considerable scope for studies in which birds must be caught at night and may avoid some of the disturbance effects of spot-lighting. There is interest in the use of thermal surveys for the purposes of environmental impact assessments. Desholm (2003) used an automated system mounted on a wind turbine for monitoring collision rates of birds at an offshore wind farm and from thermal signatures was able to differentiate between species ranging in size from passerines to ducks. However, due to the considerable research and development costs of this system, there has been limited application. Nevertheless, European Nightjar *Caprimulgus europaeus* flight altitude and directions have been tracked readily with a thermal camera on a tripod to assess possible collisions from wind turbines (Calbrade & Henderson 2009). Combined thermal imaging and radar systems have also been deployed to count large numbers of birds on nocturnal migration (Zehnder *et al.* 2001, Gauthreaux & Livingston 2006). Advanced image detection systems have been successfully used to count large bat roosts (Hristov *et al.* 2005, Betke *et al.* 2008) and similar approaches could be taken for population counts of birds at night in open habitats. Some analytical methods of image detection based on wing beat frequency have been explored (Lazarevic 2009) but there is a need for

Table 3. Field surveys and behavioural studies of wild birds using thermal imaging.

Species	Research Topic	Habitat	Maximum distance/altitude (m)	Thermal imaging system	Author(s)
Ten species (range of body sizes)	Bird detection system	Offshore wind farm	3000	Thermovision IRMV 320V	Desholm (2003)
Nine species (range of body sizes)	Counts and nests	Trees, open habitat and Arctic tundra	–	Thermovision 210	Boonstra *et al.* (1995)
Ammodramus sparrows (two species)	Nests	Grassland	3–5	ThermaCAM PM575, FLIR Systems	Galligan *et al.* (2003)
Clapper Rail *Rallus longirostris*	Capture success	Tidal marshes	–	Thermal-Eye 250D and X200xp, L-3 Communications Infrared Products	Mills *et al.* (2011)
Grey Partridge *Perdix perdix*	Night-time roosting and anti-predation behaviour	Arable land	250	Palm IR-250 D, Raytheon	Tillmann (2009a,b)
Kentish Plover *Charadrius alexandrinus*	Nocturnal behaviour: defecation rate	Intertidal flat	–	ThermaCAM SC-3000 with telescopic lens, FLIR Systems	Kuwae (2007)
Malleefowl *Leipoa ocellata*	Aerial survey of nests	Forest and shrubs	305	Daedalus 1240/60 Scanner	Benshemesh and Emison (1996)
Europoean Nightjar *Caprimulgus europaeus*	Bird flight heights for windfarm survey	Forest	100–200	P640, FLIR Systems	Calbrade and Henderson (2009)
Not given	Migration counts	Open sky	2800	Radiance 1, Amber, Raytheon	Gauthreaux and Livingston (2006)
Not identified	Nocturnal migration counts	Coastal	3000	LORIS, IRTV-445, Inframetrics	Zehnder *et al.* (2001)
Ovenbird *Seiurus aurocapillus* Hermit Thrush *Catharus guttatus*	Nests and fledglings	Forest	30	NIGHTSIGHT^{TM} PalmIR 250, Raytheon Systems	Mattsson and Niemi (2006)
Sandhill Crane *Grus canadensis*	Aerial survey: flock distribution and density	River	300–1200	Mitsubishi IR-M600	Kinzel *et al.* (2006)
Wild Turkey *Meleagris gallopavo*	Aerial survey	Uplands	398	2000 A/B FLIR Systems	Garner *et al.* 1995

further development of automated avian surveillance systems. Development of appropriate systems for bird monitoring may benefit from commercial testing of thermal surveillance systems. For example, applications to automatically detect animals during harvesting (Steen *et al.* 2012) and as early warning systems for bird strike prevention (Müenzberg *et al.* 2011) show promise in this field.

CONCLUSIONS

The development and reduced cost of thermal imaging has led to greater exploitation of this technology in pure and applied research. The strengths and limitations for research on birds and other animals are well understood. Thermography is most frequently used on captive species in studies of thermal physiology. However, the ability to measure temperature non-invasively and remotely has considerable advantages for further behavioural and ecological studies on free-ranging birds, especially studies of avian welfare, disease, energetics, behaviour and population monitoring.

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