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2
3

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4

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6

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(Unstructured) Abstract (up to 350 words)

The present study aimed to determine, for the first time in turkeys, the most important body regions and environmental factors that could be used to monitor heat stress through infrared thermography imaging. To this goal, 11,093 thermal images were collected from 50 commercial toms, 23 Andalusian toms, and 27 Andalusian hens raised outdoors throughout the summer of 2022. The body areas studied included the overall head, snood, beak, dorsal body (open and closed), ventral body (open and closed), breast, underwing, and shank. Moreover, temperature, humidity, and wind variables were measured using an environmental meter device, and live weight and average daily gain were also recorded for each bird and measurement. After some variables reported non-normal distribution, a non-parametric Spearman correlation analysis was conducted to study the association between body surface and environmental variables. On the other hand, a type III ANOVA and Bonferroni-adjusted post hoc tests were performed to determine differences across the birds' sex and genotype groups. The environmental variables most strongly correlated with body temperature were the temperature-humidity and thermal stress indices, as well as wind chill and dry bulb temperatures ($p < 0.001$). On the other hand, the most variable surface body temperatures were those of the shank, head, and open-dorsal areas, but varied according to the breed and sex groups. The week of measurement and the interaction between week and bird group significantly ($p < 0.05$) influenced all body surface variables, while bird group itself showed significant influence on specific regions. Pairwise post hoc contrasts reported significant ($p < 0.05$) differences between bird groups in all body surface variables, but differences were highly dependent on the week of measurement. Commercial toms had generally higher body surface temperature than Andalusian toms, while the differences in temperature with the Andalusian hens varied with the body region. Contrarily, the Andalusian toms had lower body surface temperature than females for all the variables under study. Therefore, the higher body surface temperature of the commercial toms, together with their greater influence of environmental events, highlights the greater adaptability of the Andalusian turkeys to free-range, uncontrolled weather conditions compared to specialized strains.

Keywords (3 to 6):

Free-range farming; heat stress; infrared thermography; poultry; thermal window; thermoregulation.

Introduction

Free-range farming is making a comeback in emerging markets, despite having been outdated and abandoned in the 1950s [1]. The growing demand for naturally produced turkey meat, with low environmental impact and high regard for animal welfare, is the basis for the organic and related production systems [2]. However, the worldwide turkey industry and research have focused on highly productive strains confined in environmentally controlled pens [1]. For this reason, the research into turkey performance in uncontrolled and suboptimal rearing conditions has become increasingly popular during the last few years [1-5].

Heat stress is one of the key environmental factors influencing poultry welfare and performance [6-9]. Thermal stress activates the hypothalamic-pituitary-adrenal axis, with catabolic effects mediated by

corticosteroids, causing muscle wasting and reduced growth [10]. Birds also reduce their feed intake to decrease the thermogenesis generated during digestion, which affects growth and lay [8], and nutrient absorption is also hindered [10]. Moreover, heat stress can lead to diseases such as pendulous crops and air sacculitis [8]. It also causes undesirable behaviors such as preening, pecking, and feather ruffling [10]. Lastly, the quality of the meat from heat-stressed birds also worsens, resulting in pale, soft, exudative carcasses [8].

Heat dissipation is particularly challenging in poultry species [9, 11]. Birds have a higher body temperature than mammals (41°C) and lack sweat glands [10]. This is exacerbated by the role of plumage in temperature insulation. Feathers prevent heat loss during cold conditions but hinder heat dissipation when birds are exposed to heat [12]. However, birds have special physiological mechanisms for heat dissipation. These include heat-avoiding conduct such as lying down, digging into cooler soil layers, panting, and spreading the wings to enhance air circulation [10, 13]. Moreover, peripheral vasodilatation increases blood flow to body surface areas, allowing heat to be radiated from featherless regions such as the head, shanks, and the featherless underwing areas [10, 14]. Nevertheless, the most significant heat dissipation mechanism in birds involves the evaporative losses in the respiratory tract [9, 14]. This is due to the increased surface area of the complex air sac system compared to that of mammals [10].

In this regard, several techniques have been proposed to study the thermal stress in poultry. Among them, the cloacal temperature is considered a biomarker for heat stress in poultry because it reflects their core body temperature [10]. However, less invasive measurements, such as pulse and respiratory rates [7, 15, 16], or the use of conventional and infrared thermometers have also been proposed [6]. However, infrared thermography (IRT) is the most popular of the emerging techniques used in the study of animals' thermal status [12, 16]. This rapid, non-invasive, non-contact technique reflects changes in skin surface temperature, which are an indirect measure of local blood flow and metabolic rate [16, 17]. Therefore, animals experiencing heat stress have an increased peripheral blood flow, which can be measured by surface temperature [8]. Furthermore, the literature has shown that skin temperature determined through thermographic imaging is a more reliable indicator of environmental temperature than rectal temperature [16].

Most IRT studies have focused on heat stress rather than cold stress, and have concentrated on commercial layers rather than other genotypes and species [12]. However, there is little literature on heat status in turkeys using IRT [14]. The only five studies available are focused on the feed efficiency monitoring [13], the prediction of footpad dermatitis [18, 19], and the effect of ventilation [20] and cold stress [8] on body temperature. However, no research has yet been conducted on the use of IRT in relation to heat stress in the turkey species.

The objective of this study is therefore to use IRT technology to investigate the body regions that could be monitored in the study of heat stress in growing turkeys of both commercial and locally adapted

genotypes that are reared outdoors during the summer. Studying the relationship between thermographic imaging of different body areas and the most significant environmental and growth factors related to heat stress would allow an effective measurement protocol to be defined. Therefore, identifying the variables that most influence body temperature and determining the most informative body regions would contribute to the design of future studies addressing IRT in turkeys. Additionally, the differences in the thermoregulatory ability between the genotypes involved would be highlighted.

Materials and Methods

Experimental design

Bird management and housing

The study was conducted in the facilities of the Agropecuario Provincial Centre of Diputación de Córdoba (Spain, 3754050.900N–442040.400W). The experiment involved two turkey genotypes: the indigenous, locally adapted “Andalusian” breed and a fast-growing strain. The experimental unit of this study comprised a flock of 50 Andalusian turkeys (23 toms and 27 hens) and a single flock of 50 commercial toms from the ‘British United Turkey Premium’ strain. On the other hand, hens from the commercial strains were not included in this study due to not having a realistic role in meat production, even in alternative production systems [21-24].

Birds from the commercial flock were purchased from a local hatchery and arrived at the facilities when they were six weeks old. On the other hand, the indigenous flock hatched from fertile eggs obtained from the conservation flock of the breed in the same facilities where the study was carried out. The eggs were collected daily during the breeding season (from February and March 2022) and stored at 17°C and 80% of relative humidity until their incubation. To minimize the age difference between the two flocks of genotypes used in the study, incubation began on 21st March 2022. The eggs were incubated in an automatic-turning incubator (Masalles, M240-I, Barcelona, Spain) at 37.2°C and 55% relative humidity for 26 days. On day 26, eggs were placed in a hatchery cabinet (Masalles, 25-N HLC, Barcelona, Spain) at 36.7°C and 60% humidity until hatching (after 2 days), on 18th April 2022. Animals were then placed in closed pens (with a stocking density of 5 birds/m²) with electric heaters (Copele LGA; Copele, Murcia, Spain). Birds had free access to ad libitum feed and water. Animals remained in these facilities until 24th May 2022, when the commercial poults arrived.

In this moment on, animals were individually identified using leg bands and were vaccinated following the same hatchery prophylaxis procedure (Newcastle, fowl pox, chronic respiratory disease, and fowl cholera). Birds were then placed in outdoor, dirt pens, simulating the organic-like conditions. The Andalusian and commercial flocks were separately kept in identical, side-by-side pens of 56 m² (8 m² of roofed area and 48 m² courtyard). The pens were enclosed by a metal fence on the north, east, and south sides, while a brick wall enclosed the west side (Figure 1). In addition, the pens were enclosed at the top

with a metal mesh to prevent access by predators or other birds. Both pens were covered by trees, which protected the birds from the sun's rays at their strongest during the day. The turkeys remained in these enclosures from 24th April to 6th September, when the study ended.

Animal feeding

The Andalusian flock was fed with a commercial starter (NANTA© 'Aves Starter') until the 6 weeks of life. Then the commercial poults arrived and both flocks were fed with the same commercial grower feed (NANTA© 'Broiler') from this moment on. The grower diet provided in both flocks had 24.0% of crude protein, 3.10% of lipids, 3.40 of fiber, and 9.40% of ashes. Animals always had free access to ad libitum feed and water. Fresh and clean water was provided in automatic metallic drinkers, and feed was provided in plastic poultry hoppers in the roofed area.

Data collection

Animals were weighed weekly and photographed with the IRT camera from 14th June to 6th September 2022, between 07:34 and 13:02. To avoid bias based on different measurement times, the birds were measured in an alternating order schedule. Therefore, each animal has been measured 13 times during the whole summer. Birds were first weighed using a suspended electronic balance (Kern CH50K100, Kern & Sohn, Balingen, Germany, precision = 5.0 g). Then, the body surface temperature was recorded using an Hti-Xintai HT-18 thermal imaging camera (220 × 160 IR resolution, 35,200 pixels, -20°C/+120°C detection range, and a sensitivity of <0.05°C). Thermal emissivity was set at 0.95, as stated by Cangar et al. [25]. A sum of 9 pictures was taken in each animal during the measurement, including the following perspectives:

- Head: this picture was taken from the left side of the bird's head at approximately 30 cm.
- Eye: this picture was a detailed picture of the left eye, taken from a distance to fill the entire camera screen.
- Dorsal with closed wings: this photo was taken from above the bird, at a distance of ± 50 cm. The birds stood with their wings gently folded for the photograph.
- Dorsal with open wings: this picture was taken from above the bird, at a distance of ± 50 cm. Birds were standing and their wings were fully extended for the photography.
- Ventral with closed wings: this picture was taken from above the bird, at a distance of ± 50 cm. Birds were lying on their back with their wings folded for the photography.
- Ventral with open wings: this photo was taken facing the animal at the front, at a distance of ± 50 cm. Birds were standing and their wings were fully extended for the photography.
- Breast: This was a detailed picture of the bird's breast, taken from a distance to fill the entire camera screen.
- Underwing: this was a detailed picture of the featherless skin surface of the bird's armpit, taken from enough distance to fill the entire camera screen.

• Shank: this was a detailed picture of the left shank at a distance of ± 30 cm.

All these static thermal images were taken at a 90° angle, following the recommendations of Iglesias Pastrana et al. [17]. Animals were individually measured, and measurements were carried out in the same location of the pens during the whole experiment, with enough shade coverage impeding direct solar radiation. Birds were handled kindly and maintained floor contact throughout the entire handling procedure, being placed in the various positions described on a padded mat. To minimize errors derived from different handling practices, all measurements were developed by the same trained technicians.

Moreover, the environmental conditions at the moment of measurement were recorded using an environmental meter device (PCE-EM 890, PCE Instruments SE, Messtechnik, Germany). This gadget enabled the dry bulb temperature (0.1°C of resolution and $\pm 1.2^\circ\text{C}$ of precision), relative humidity (0.1% of resolution, $\pm 4\%$ of precision), dew point (0.1°C of resolution), wet bulb temperature (0.1°C of resolution), thermal stress (0.1°C of resolution, $\pm 2^\circ\text{C}$ of precision), UV radiation (0.1 $\mu\text{W}/\text{m}^2$ of resolution, $\pm 4\%$ of precision), barometric pressure (0.1 hPa of resolution, ± 1.5 hPa of precision), air speed (0.1 m/s of resolution, $\pm 3\%$ of precision), and wind chill (0.1°C of resolution, $\pm 2^\circ\text{C}$ of precision). The environmental conditions were recorded at the beginning of the experiment and were subsequently recorded every 30 minutes.

Data curation and preparation

The experiment began with 100 animals. After data cleansing, a total of 1,221 weights (584 from commercial toms, 287 from Andalusian toms, and 350 from Andalusian hens) formed the database used in this study. Using these measurements, the average daily weight gain (ADG) of each individual was computed, yielding up to 859 records, considering week 2 until week 13.

A total of 11,093 thermal images were recorded during the whole experiment. Thermal information was extracted from the images using the Batch Flir Image Converter software [17]. This program enables the maximum, minimum, and mean temperatures of a defined area within the image, all of which were measured in degrees Celsius. One body area per image was defined in the software in each body region picture, except for the head, which was split into ‘overall head’, ‘beak’, and ‘snood’. Therefore, the maximum, minimum, and mean temperatures of 13,577 body areas have been recorded. Examples of the different body regions’ pictures and the defined areas in the software are shown in Figure 2.

Lastly, a total of 134 records of each environmental parameter were obtained. The weekly evolution of the main environmental factors during the measurements and the live weights of each bird group is graphically depicted in Figure 3. The variable ‘air speed’ was removed because no wind speeds over 0 m/s were obtained. However, the specific environmental parameters at the moment of each one of the 1,221 bird measurements were estimated. To this aim, the precise hour at which each bird was measured was recorded, and the precise environmental parameters at the time of measurement were estimated using the prior and subsequent environmental records. Additionally, the present study also aimed to analyze the

effect of varying thermal-humidity indices (THI) on the surface temperature of the birds. Due to the lack of description of specific combined indices in domestic turkeys, the following 5 THIs developed in other species were computed through the following formulae described in the literature:

- THI 1 (generic) = $0.8 \text{ DBT} + \text{RH} * (\text{DBT} - 14.4) + 46.4$ [26]
- THI 2 (generic) = $0.72 * (\text{WBT} + \text{DBT}) + 40.6$ [27]
- THI 3 (generic) = $\text{DBT} - [(0.31 - 0.31 \text{ RH}) * (\text{DBT} - 14.4)]$, [28]
- THI 4 (broilers) = $0.85 \text{ DBT} + 0.15 \text{ WBT}$, [29]
- THI 5 (layers) = $0.6 \text{ DBT} + 0.4 \text{ WBT}$, [30]

where ‘DBT’ is dry bulb temperature, ‘WBT’ is wet bulb temperature and ‘RH’ is relative humidity.

The thermal stress index estimated by the environmental meter device used the following formula, according to the manufacturer:

$$\text{Thermal Stress} = c_1 + c_2 \text{ AT} + c_3 \text{ RH} + c_4 \text{ RH AT} + c_5 \text{ AT}^2 + c_6 \text{ RH}^2 + c_7 \text{ AT}^2 \text{ RH} + c_8 \text{ AT RH}^2 + c_9 \text{ AT}^2 \text{ RH}^2$$

where ‘AT’ is air temperature, ‘RH’ is relative humidity and ‘c’ are constants whose values are the following ones: $c_1 = -42.38$, $c_2 = -2.05$, $c_3 = -10.14$, $c_4 = -0.22$, $c_5 = -6.84 \times 10^{-3}$, $c_6 = -5.48 \times 10^{-2}$, $c_7 = -1.23 \times 10^{-3}$, $c_8 = 8.53 \times 10^{-4}$ and $c_9 = -1.99 \times 10^{-6}$.

Data analysis

Once all the data were collected and curated, each observation in the dataset included the following variables: bird’s attributes (individual identification, breed, sex, week, weight, and ADG), the surface temperature (maximum, minimum, and mean) of the body regions, and the specific environmental parameters at the moment of measurement. The observations were then classified according to the genotype and sex of the birds into three groups: commercial males, Andalusian males, and Andalusian females. Except for the normality test, all the analyses conducted in this work were performed considering these three groups separately.

Normality test

The first statistical procedure was aimed at testing the distribution of the included variables, in order to determine whether a parametric or non-parametric approach was needed. Considering the non-independent nature of observations, as animals were repeatedly measured over 13 weeks, the normality test was carried out based on the residuals obtained through a linear mixed model, conducted with the following formula:

$$y_{ijk} = \mu + \text{WK}_i \beta_1 + \text{GR}_j \beta_2 + (\text{WK} \times \text{GR})_{ij} \beta_3 + \text{ID}_k u + \varepsilon_{ijk} ,$$

where ‘ y_{ij} ’ is the body surface temperature record for the k^{th} animal from the j^{th} group during the i^{th} week of measurement; ‘ μ ’ is the overall mean; ‘ β_1 ’, ‘ β_2 ’ and ‘ β_3 ’ are respectively the vectors of fixed effect coefficients for week (WK; $i = 13$ weeks), bird group (GR; $j = 3$ groups) and their interaction (WK x GR) $_{ij}$; ‘ u ’ is the vector of random effects for each bird identification (ID $_k$; $k = 100$ turkeys) incidence matrices that link the registers to their fixed effects; and ‘ ϵ_{ijk} ’ is the vector of the random residual error.

To this goal, the linear mixed model routine of the “lme4” package of RStudio [31] was followed, running one analysis per body surface temperature variable. Once the model’s residuals were obtained, the Lilliefors test of the Kolmogorov-Smirnov was carried out due to sample size ($n > 50$). This routine was executed through the “nortest” package of RStudio [32], specifically developed for normality testing.

Correlation analyses

A correlation analysis between the body temperatures and the environmental and growth variables was carried out for each bird group. This was conceived to determine the interactions between the different body regions’ temperatures and the weather and growth variables. Due to the non-parametric nature of the dataset, a Spearman correlation analysis was conducted using the pairwise correlation routine of the software SPSS Statistics v29.0.2 (IBM Corp., Armonk, NY).

Non-parametric comparison of surface temperature across groups

Lastly, the present work aimed to understand the differences in body surface temperatures between the three bird groups (commercial toms, Andalusian toms and Andalusian hens). Nevertheless, the non-independent nature of the observations, together with the non-parametric distribution of the variables, impeded the use of conventional approaches such as ANOVA or Kruskal-Wallis analyses. Therefore, the selected statistical approach was to conduct a generalized linear mixed model, to then run a type III ANOVA, which would determine if the bird group has a significant implication in body temperature considering the effect of the week of measurement and their combined interaction. Additionally, a post hoc analysis was conducted to determine precise differences by pairs of groups considering the week of measurement.

The generalized linear mixed models followed the same structure of fixed and random effects of the model employed to study normality, but included the Gamma distribution to better adjust the non-parametric data distribution of the dataset:

$$\log(\mu) = \beta_0 + \text{WK}_i \beta_1 + \text{GR}_j \beta_2 + (\text{WK} \times \text{GR})_{ij} \beta_3 + \text{ID}_k u, \\ y \sim \text{Gamma}(\mu, v)$$

To this aim, the generalized linear mixed model routine of the “lme4” package of RStudio [31] was followed. Then, a type III ANOVA was carried out to test the influence of the fixed effects on the body for every surface temperature variable, using the ‘car’ package of RStudio [33]. Lastly, the post hoc analysis based on the Bonferroni adjustment was carried out using the ‘emmeans’ package of RStudio [34].

Results

Normality test

The Kolmogorov-Smirnov test exhibited significance ($p < 0.05$) in almost all the variables except from relative humidity, average snood temperature, average and maximum closed-ventral temperature, and maximum underwing temperature. Therefore, as the majority of the variables violated the parametric assumption of normal distributions, a non-parametric approach was subsequently conducted.

Correlation analysis

The correlation analysis found significant correlations in almost all the body surface temperature and environmental and weight variables in the three sexes. Correlation values varied between +0.916 to – 0.700, and highly statistical significance (< 0.001) was reported in almost all the environmental variables across bird groups. The whole correlation matrices are available in the Supplementary Table 1 for the commercial toms, Supplementary Table 2 for the Andalusian toms, and Supplementary Table 3 for the Andalusian hens. Figure 4 depicts a summary of the whole Spearman's correlation matrix. Color intensity increases with positive (red) and negative (blue) correlation between the variables.

Table 1 summarizes the effect of the environmental and growth variables on the body surface temperature of birds. This table was created by computing the average correlation values of all body regions for each bird group, IRT temperature (maximum, mean, and minimum), and environmental and growth variables. Therefore, with independence of the body region studied, the most influential factors on body surface temperature were the temperature-humidity thermal indices (THI), thermal stress, wind chill, and dry bulb temperature. Moderate average correlations were also found in environmental humidity and wet bulb temperature. Commercial toms exhibited the highest correlation values, especially for dew point and wet bulb temperature. Moreover, they were the only group with a positive association between body temperature and average daily gain.

Table 2 summarizes the variation in temperature of each body area with respect to environmental and growth variables. This table was created by computing the average correlation value of each environmental and growth factor for each bird group, IRT temperature (maximum, mean, and minimum), and the body area studied. Moreover, to avoid the conflicting effects of including both positive and negative values, the absolute correlation values were estimated in order to compute the average. Therefore, color intensity increases with rising absolute average correlations between the specific body area and environmental variables. In this regard, open and closed dorsal, shank, and head exhibited the greatest average correlation values, with independence of the environmental and growth factors considered. The commercial toms exhibited generally higher correlation values across the body regions, particularly appealing in the case of eye, open, and closed ventral and underwing temperatures.

In Table 3, the Spearman correlation matrix between the weather variables and the mean area temperature of the different body regions studied is represented. The dry bulb temperature and wind chill

were found to be strongly positively associated with the body surfaces. Relative humidity generally showed strong, negative correlations with body temperature, particularly for Andalusian females. Moreover, dew point and wet bulb temperature variables were the most correlated with the eye area in commercial toms, exhibiting considerable differences with the Andalusian birds. In Table 4, the same procedure was followed for thermal stress and temperature-humidity indices, which achieved the strongest correlation values of the whole analysis. A clear trend of open dorsal for commercial toms, head for Andalusian toms, and shank for Andalusian hens is observed in the maximum correlation variables across indices. Lastly, Table 5 was created for the growth variables. In general, weight showed weak, negative correlations with body temperature, while average daily gain was weakly positively associated with body temperature, but only in commercial toms.

Genotype and sex groups' differences

The results of the type III ANOVA are exhibited in the Supplementary Table S4. The analysis reported a significant influence ($p < 0.05$) of the week of measurement and the interaction between the week and the bird group for all the surface body temperature variables of the study. On the other hand, bird group alone reported influence on head (maximum temperature), beak (mean, maximum and minimum temperature), snood (maximum and minimum temperature), eye (maximum temperature), open dorsal (minimum temperature), underwing (maximum temperature) and shank (minimum temperature).

Lastly, the complete results from the Bonferroni-adjusted post hoc analysis correction for each group pairwise contrast variable are represented in Supplementary Table S5. On the other hand, Table 6 represents the average corrected ('real') estimates of the model for each bird group contrast and for these body surface temperature variables that have reported significance ($p < 0.05$) at least once in the post hoc analysis. The commercial toms generally exhibited significantly higher body surface temperatures than Andalusian toms, while, when compared to the Andalusian hens, the group reporting the highest temperature varied with the body region. The commercial toms exhibited by far the highest temperatures in ventral (open and closed) and underwing temperatures in the comparative. On the other hand, comparing Andalusian males and females, higher temperatures were reported for the hens.

Discussion

The temperature-humidity and thermal stress indices, alongside wind chill and dry bulb temperatures, were the most influential parameters on body temperature. In this regard, a significant influence of dry bulb temperature was expected, as widely described in the literature [7, 10]. Turkeys' thermoneutral zone ranges from 16 to 28°C, a temperature that was exceeded in most parts of the measurement [8]. However, the dry bulb temperature did not show the strongest correlation in the analysis. This is because perceived heat is not only a consequence of the environmental temperature, but also of the combined effects of humidity, solar radiation, and the temperature and speed of the wind [9, 16]. Therefore, higher correlations were observed in the indices combining some of these variables, primarily temperature and

humidity (THIs, heat stress, and wind chill). These indices were developed to provide a more accurate assessment of the effect of determined environmental conditions on animals' heat stress [7]. Furthermore, almost every temperature-humidity index (THI) or the heat stress index could be successfully implemented to study heat stress in every bird group. However, the most strongly correlated index for the commercial birds was THI 5, which was developed for measuring heat stress in commercial chicken layers [30]. Nevertheless, there is still the need to develop specific combined indices to study heat stress in the species, and more specifically, in growing turkeys.

Conversely, wind chill outperformed in the correlation matrix, particularly for the Andalusian birds. This index reflects the perceived temperature by the combined effect of wind temperature and speed [20]. However, wind speed was discarded as an influencing variable in the present study due to the absence of wind effect during the measurement period. Therefore, if there is no air speed, the results of wind chill in the present analysis represent the isolated effect of air temperature [35], rather than actual wind chill. In this regard, wind acts as an alleviating factor in heat-stressed animals by enhancing evaporative cooling [20]. However, as air temperature rises, this alleviation effect is reduced, and airspeed alone is not enough to help mitigate heat stress [20].

In terms of environmental humidity, strong to moderate negative correlations with body temperature were reported, particularly for Andalusian hens. In this regard, it is known that environmental humidity affects both heat and cold stress [10]. However, in this case, it was expected that higher humidity levels during summer days would increase body temperature. This lies in the fact that a high environmental humidity hinders the evaporative losses and therefore reduces the heat dissipation potential [20]. Therefore, the effect of humidity is most likely a consequence of its correlation with reduced temperature events, rather than an actual cooling effect. On the other hand, dew point, wet bulb temperature, UV irradiation, and atmospheric pressure showed weaker correlations. This is reinforced in the lack of inclusion of these isolated variables in IRT studies [12, 16].

Growth variables generally exhibited weak correlations with body temperature, which is supported by the literature [13, 20]. The negative association between body weight and surface temperature could be a consequence of the lower functional maturity of the thermoregulatory system in the early stages of development [8, 17]. It could also be due to the down feathers' lack of insulating properties during the poultry's early life, which could result in reduced heat retention and increased heat radiation [25]. Lastly, this negative correlation could also be derived from the heat gradient from the core of the body to its surface, which increases with rising body mass [6, 20].

The most environmentally-dependent regions in the analysis were the open and closed dorsal, shank, and head (>0.579). However, breast, closed, and open ventral, and snood were also important areas (>0.500). In this regard, IRT studies the main body regions involved in thermoregulation, commonly known as "thermal windows" [36]. Among them, those providing highly informative thermal images are

known as “regions of interest” (ROI) [16]. The main ROIs in poultry are the featherless or lightly feathered areas, such as the head and shanks, where heat dissipation can be measured [11, 13, 36]. In turkeys, the head, neck, wing, the whole body, and shanks have been included in IRT studies for different purposes [8, 13, 20]. Thus, a standard image recording protocol is needed to measure different body regions and perspectives homogeneously in heat stress studies [12].

Since most ROIs involve featherless areas [16], the obtention of strong correlation in feathered regions (such as the dorsal and ventral perspectives) could be surprising. However, previous studies have proved the ability of feathered regions such as the torso [20] or the whole body [14] to vary in temperature with the environment. Moreover, breast and wings are also included in IRT studies and are considered thermal windows [8]. However, despite their high correlations, the feathered areas might not represent the most accurate ROIs for measuring heat stress. It is firstly due to the lack of contact with the body [20] and their thermal insulating properties [16]. For this reason, feathered areas exhibit lower temperatures than the direct skin [25], and could therefore be more susceptible to environmental changes than featherless, warmer regions. Uemura [14] made this same suggestion, even though they found greater variability in feathered perspectives (torso) than in the head.

The head is an area containing highly vascularized organs and with a particularly shallow depth [11]. Moreover, it receives blood directly from the heart, which is considered to be at core temperature [14]. Snood was also an interesting region, which is in consonance with the description of face structures highly performing in IRT studies in fowl [12]. By contrast, the eye exhibited more moderate associations with environmental changes. This could be a consequence of its highly effective thermoregulation, given that changes in temperature in the eye pose a significant risk to its tissues and those of adjacent brain structures [17]. Lastly, the high correlations obtained between shank temperature and the environmental conditions are consistent with the general assumption that this organ is one of the most significant ROI in papers [12].

Of all the temperature parameters, the mean area temperature showed the greatest correlation in the analysis, followed closely by the minimum and then the maximum temperatures. This was particularly remarkable when considering the average correlations of each environmental and growth variables (Table 1), especially for the most-correlated thermal indices. A similar conclusion was reached in a study analyzing the effect of exercise on the body temperature of dromedaries [17]. On the other hand, the post hoc pairwise test suggests that minimum surface temperature could be more variable across the sex and genotype groups, since it shows the most increased ‘estimates’. Therefore, if variable reduction is needed in future studies, the use of the mean area temperature or minimum temperature could be suggested depending of the aim of the study.

In terms of breed and sex differences, the Andalusian toms had the lowest surface temperatures in the analysis. This could be due to their greater ability to thermoregulate and reduced body heat production,

possibly resulting from lower metabolic stress derived from their slower growth rate [9]. Within the Andalusian birds, sex differences could mainly be attributed to the hormonal balance (e.g., androgen-mediated effects) and the different body mass in each sex [17, 20]. Therefore, hens could have a hormonally mediated higher metabolic heat production due to their precocious sexual maturation compared to males. Similarly, as evidenced in the negative correlation of weight and body temperature, a reduced body mass in females could expose their core temperatures more easily. However, these differences might not reflect actual heat tolerance differences between sexes, as previously evidenced by Yakubu et al. [15].

On the other hand, the commercial birds showed the strongest correlations for almost all of the parameters analyzed. Furthermore, these birds had some of the largest body surface areas of all the birds in comparison. Therefore, a higher susceptibility to environmental changes and a higher predisposition to heat stress could be suggested. Similar results have been reported by Yakubu et al. [15], who evidenced the increased heat tolerance of indigenous Nigerian turkeys compared to commercial birds and their crosses. Additionally, commercial birds were the only group to exhibit a positive correlation between body temperature and ADG, which has been described in other fast-growing strains [13]. Therefore, this higher body temperature and difficulty in thermoregulation could primarily be attributed to their increased metabolic stress. Metabolic heat production generally increases with genotype production rate, and highly selected strains typically exhibit reduced thermoneutral zones and heat tolerance compared to unselected breeds [7, 9]. This is evident from the increased heat production of modern commercial turkey strains, which is up to 70% higher than that of commercial lines developed 20 years ago [8, 20]. This is supported in the huge growth exhibited by commercial birds compared to the Andalusian flock (Figure 3).

Additionally, the greater susceptibility of commercial males could be a consequence of differences in the proportional surface area in relation to body weight [7, 14]. Commercial hybrids generally exhibit a proportionally lower surface area per unit mass and deeper cores that reduce their heat loss potential [20].

It is therefore surprising that commercial toms exhibited lower temperatures than Andalusian hens for some variables. This suggests that not all measured variables are useful for identifying breed and sex differences, or that they do not all accurately reflect heat stress conditions. For example, obtaining higher eye temperatures in commercial birds might suggest that the eyes better reflect the bird's metabolic status, as is commonly assumed in the literature [13, 16]. Similarly, the higher temperature of the ventral and underwing approaches of commercial birds, and its particularly strong association with average daily gain (Table 5), could suggest this body area as an ROI for breed comparison analysis.

Finally, the correlation between shank temperatures and environmental variables was stronger in females. Additionally, Andalusian hens exhibited higher shank temperatures than both toms' groups. This could be because the lower heat dissipation potential of other regions compared to males. For example, sexual dimorphism in turkeys influences plumage surface, with females having more feathers on their

heads and necks. These regions were critical for heat dissipation in the present work, as well as in other studies [11]. Therefore, the higher performance of the shank in females could be a consequence of their reduced featherless areas compared to the males. This same conclusion was reached in a study of naked-neck hens, in which the shank temperature was unexpectedly low [11].

The present work is the first study to use infrared thermography imaging to investigate heat stress in the turkey species. It also contributes to the limited research on outdoor, organic-like poultry farming, in which the animals are particularly exposed to heat stress due to uncontrolled temperature and humidity levels. Furthermore, comparing the fast-growing commercial birds with the locally adapted Andalusian turkeys ensures that results are representative. Nevertheless, future studies including females from the commercial, fast-growing strain should be conducted in order to address the physiological sex-related mechanisms underlying the differences observed. Another potential limitation of this work is the risk of an inflated overall Type I error rate due to the multiple correlations performed, suggesting these results should be interpreted with caution until validated by future, deeper studies. The present results highlight the significant impact of the thermal indices, especially those developed for broilers and layers, on birds' body temperature. Additionally, the surface temperatures of the head, shank, and open dorsal perspectives are the most influenced by environmental stress conditions. Therefore, these areas are recommended for the study of heat stress in turkeys. Moreover, commercial birds exhibited a lower thermoregulation ability and greater body heat production than the locally adapted genotype. Therefore, the use of fast-growing strains in organic production warrants a careful evaluation on the effects of heat stress, and therefore, their implications on animal welfare. Further studies are needed to improve our understanding of the underlying physiological mechanisms of heat stress in the species and to determine the best strategy for breed characterization and comparison studies. Additionally, future works should address a determined combined thermal-humidity index specific for turkeys, and may explore the environmental threshold that causes actual heat stress in the animals.

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Tables and Figures

Table 1. Average correlation values between the bird's thermographic temperatures and the environmental and growth thermoregulation factors.

Variable	Bird group	Maximum	Mean	Minimum	Average within groups	Overall average
Dry bulb temp.	COMM	0.785	0.828	0.817	0.810	0.768
	AND.M.	0.725	0.744	0.730	0.733	
	AND.F.	0.762	0.773	0.747	0.761	
Humidity	COMM	-0.482	-0.460	-0.402	-0.448	-0.494
	AND.M.	-0.522	-0.483	-0.439	-0.481	
	AND.F.	-0.597	-0.561	-0.499	-0.552	
Dew point	COMM	0.224	0.291	0.339	0.285	0.177
	AND.M.	0.064	0.141	0.182	0.129	
	AND.F.	0.041	0.125	0.188	0.118	
Wet bulb temp.	COMM	0.550	0.624	0.651	0.609	0.546
	AND.M.	0.469	0.555	0.586	0.536	
	AND.F.	0.416	0.507	0.553	0.492	
UV radiation	COMM	0.241	0.242	0.223	0.235	0.271
	AND.M.	0.389	0.316	0.256	0.321	
	AND.F.	0.341	0.250	0.185	0.259	
Atmospheric pressure	COMM	-0.067	-0.078	-0.088	-0.078	-0.102
	AND.M.	-0.071	-0.091	-0.090	-0.084	
	AND.F.	-0.140	-0.158	-0.138	-0.145	
Wind chill	COMM	0.787	0.829	0.816	0.811	0.772
	AND.M.	0.724	0.757	0.749	0.743	
	AND.F.	0.757	0.774	0.759	0.763	
Thermal stress	COMM	0.793	0.836	0.823	0.817	0.771
	AND.M.	0.721	0.750	0.741	0.738	
	AND.F.	0.747	0.771	0.753	0.757	
THI 1	COMM	0.768	0.818	0.818	0.801	0.758
	AND.M.	0.707	0.745	0.741	0.731	
	AND.F.	0.720	0.756	0.753	0.743	
THI 2	COMM	0.779	0.838	0.840	0.819	0.759
	AND.M.	0.696	0.741	0.742	0.726	
	AND.F.	0.697	0.746	0.750	0.731	
THI 3	COMM	0.785	0.831	0.824	0.813	0.770
	AND.M.	0.721	0.751	0.742	0.738	
	AND.F.	0.747	0.772	0.758	0.759	
THI 4	COMM	0.792	0.838	0.829	0.820	0.772
	AND.M.	0.722	0.750	0.740	0.738	
	AND.F.	0.748	0.772	0.755	0.758	
THI 5	COMM	0.793	0.846	0.843	0.827	0.767
	AND.M.	0.706	0.746	0.744	0.732	
	AND.F.	0.715	0.757	0.756	0.743	
Weight	COMM	-0.115	-0.113	-0.082	-0.103	-0.125
	AND.M.	-0.228	-0.144	-0.078	-0.150	
	AND.F.	-0.191	-0.119	-0.055	-0.122	
ADG	COMM	0.164	0.174	0.154	0.164	-0.002
	AND.M.	-0.056	-0.075	-0.067	-0.066	
	AND.F.	-0.042	-0.118	-0.157	-0.105	

The strongest correlation value for each bird group and environmental or growth variable is marked in bold. Increasing cell color intensity indicates positive (red) and negative (blue) correlations.

Table 2. Average correlation values between the thermoregulation factors and bird's thermographic temperatures by body region.

Variable	Bird group	Maximum	Mean	Minimum	Average within groups	Overall average
Head	COMM	0.567	0.597	0.575	0.580	0.579
	AND.M.	0.534	0.588	0.597	0.573	
	AND.F.	0.552	0.601	0.597	0.583	
Beak	COMM	0.543	0.508	0.500	0.517	0.498
	AND.M.	0.491	0.496	0.513	0.500	
	AND.F.	0.483	0.455	0.491	0.476	
Snood	COMM	0.559	0.533	0.535	0.542	0.531
	AND.M.	0.517	0.531	0.539	0.529	
	AND.F.	0.517	0.513	0.535	0.522	
Eye	COMM	0.419	0.478	0.463	0.454	0.411
	AND.M.	0.334	0.411	0.400	0.382	
	AND.F.	0.269	0.469	0.458	0.399	
Closed Dorsal	COMM	0.582	0.621	0.631	0.611	0.584
	AND.M.	0.515	0.569	0.600	0.561	
	AND.F.	0.542	0.581	0.613	0.579	
Open Dorsal	COMM	0.567	0.634	0.618	0.606	0.596
	AND.M.	0.533	0.595	0.612	0.580	
	AND.F.	0.565	0.612	0.627	0.601	
Closed Ventral	COMM	0.550	0.611	0.585	0.582	0.542
	AND.M.	0.516	0.513	0.502	0.510	
	AND.F.	0.548	0.535	0.520	0.534	
Open Ventral	COMM	0.528	0.604	0.608	0.580	0.509
	AND.M.	0.502	0.457	0.408	0.455	
	AND.F.	0.545	0.487	0.443	0.491	
Breast	COMM	0.554	0.589	0.586	0.576	0.555
	AND.M.	0.520	0.564	0.521	0.535	
	AND.F.	0.558	0.577	0.524	0.553	
Underwing	COMM	0.515	0.588	0.597	0.566	0.463
	AND.M.	0.494	0.405	0.338	0.412	
	AND.F.	0.492	0.404	0.333	0.410	
Shank	COMM	0.589	0.599	0.598	0.595	0.595
	AND.M.	0.575	0.585	0.598	0.586	
	AND.F.	0.595	0.603	0.611	0.603	

The strongest absolute correlation value for each bird group and body region is marked in bold.

Increasing cell color intensity indicates a higher absolute correlation value.

Table 3. Correlations between the mean area surfaces under study and the weather and climate thermoregulation influencing factors.

		Head	Beak	Snood	Eye	Closed dorsal	Open dorsal	Closed ventral	Open ventral	Breast	Underwing	Shank
Dry bulb	Comm	0.869 <0.001	0.725 <0.001	0.759 <0.001	0.638 <0.001	0.897 <0.001	0.908 <0.001	0.884 <0.001	0.873 <0.001	0.853 <0.001	0.845 <0.001	0.861 <0.001
	And	0.845	0.722	0.770	0.604	0.802	0.838	0.735	0.642	0.806	0.589	0.835
	Tom	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	Fem	0.871 <0.001	0.680 <0.001	0.762 <0.001	0.684 <0.001	0.847 <0.001	0.889 <0.001	0.760 <0.001	0.684 <0.001	0.843 <0.001	0.595 <0.001	0.884 <0.001
Humidity	Comm	-0.482 <0.001	-0.378 <0.001	-0.376 <0.001	-0.203 <0.001	-0.558 <0.001	-0.526 <0.001	-0.506 <0.001	-0.491 <0.001	-0.504 <0.001	-0.567 <0.001	-0.468 <0.001
	And	-0.508	-0.473	-0.472	-0.356	-0.587	-0.578	-0.442	-0.408	-0.544	-0.405	-0.535
	Tom	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	Fem	-0.617 <0.001	-0.470 <0.001	-0.528 <0.001	-0.480 <0.001	-0.682 <0.001	-0.700 <0.001	-0.490 <0.001	-0.453 <0.001	-0.635 <0.001	-0.468 <0.001	-0.644 <0.001
Dew point	Comm	0.280 <0.001	0.296 <0.001	0.355 <0.001	0.433 <0.001	0.221 <0.001	0.281 <0.001	0.284 <0.001	0.289 <0.001	0.256 <0.001	0.195 <0.001	0.311 <0.001
	And	0.215	0.070	0.147	0.110	0.110	0.129	0.229	0.154	0.143	0.060	0.189
	Tom	<0.001	0.188	0.013	0.058	0.052	0.029	<0.001	0.009	0.016	0.246	0.001
	Fem	0.185 0.001	0.074 0.166	0.110 0.041	0.095 0.073	0.077 0.146	0.090 0.091	0.249 <0.001	0.198 0.000	0.129 0.017	0.017 0.749	0.156 0.003
Wet bulb	Comm	0.624 <0.001	0.580 <0.001	0.642 <0.001	0.676 <0.001	0.598 <0.001	0.654 <0.001	0.644 <0.001	0.644 <0.001	0.593 <0.001	0.546 <0.001	0.664 <0.001
	And	0.648	0.510	0.583	0.475	0.546	0.556	0.634	0.535	0.570	0.420	0.624
	Tom	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	Fem	0.596 <0.001	0.442 <0.001	0.501 <0.001	0.441 <0.001	0.488 <0.001	0.506 <0.001	0.607 <0.001	0.538 <0.001	0.530 <0.001	0.352 <0.001	0.574 <0.001
UV radiation	Comm	0.242 <0.001	0.175 <0.001	0.185 <0.001	0.137 <0.001	0.325 <0.001	0.304 <0.001	0.276 <0.001	0.258 <0.001	0.231 <0.001	0.270 <0.001	0.256 <0.001
	And	0.358	0.336	0.341	0.247	0.444	0.496	0.181	0.201	0.381	0.100	0.396
	Tom	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.002	0.001	<0.001	0.084	<0.001
	Fem	0.302 <0.001	0.269 <0.001	0.281 <0.001	0.233 <0.001	0.363 <0.001	0.405 <0.001	0.112 0.036	0.112 0.037	0.310 <0.001	0.052 0.328	0.309 <0.001
Atmospheric pressure	Comm	-0.087 0.036	-0.140 0.001	-0.052 0.210	-0.001 0.969	-0.085 0.041	-0.102 0.014	-0.065 0.118	-0.043 0.294	-0.147 <0.001	-0.082 0.048	-0.057 0.167
	And	-0.063	-0.081	-0.039	-0.064	-0.120	-0.135	-0.011	-0.131	-0.100	-0.199	-0.061
	Tom	0.282	0.170	0.500	0.278	0.044	0.022	0.847	0.027	0.090	0.001	0.298
	Fem	-0.181 0.001	-0.142 0.008	-0.120 0.026	-0.175 0.001	-0.192 <0.001	-0.182 0.001	-0.031 0.559	-0.134 0.012	-0.179 0.001	-0.265 <0.001	-0.141 0.008
Wind chill	Comm	0.872 <0.001	0.721 <0.001	0.764 <0.001	0.634 <0.001	0.901 <0.001	0.906 <0.001	0.890 <0.001	0.876 <0.001	0.845 <0.001	0.848 <0.001	0.865 <0.001
	And	0.848	0.722	0.772	0.606	0.805	0.850	0.781	0.657	0.810	0.633	0.845
	Tom	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	Fem	0.867 <0.001	0.671 <0.001	0.747 <0.001	0.675 <0.001	0.836 <0.001	0.885 <0.001	0.831 <0.001	0.699 <0.001	0.834 <0.001	0.584 <0.001	0.885 <0.001

The strongest correlation values in each bird group and body region are marked in bold.

Table 4. Correlations between the mean area surfaces under study and the thermal indices estimated and the thermal stress variables recorded by the hygrometer.

		Head	Beak	Snood	Eye	Closed dorsal	Open dorsal	Closed ventral	Open ventral	Breast	Underwing	Shank
Thermal stress	Comm	0.871 <0.001	0.729 <0.001	0.768 <0.001	0.661 <0.001	0.901 <0.001	0.914 <0.001	0.895 <0.001	0.882 <0.001	0.854 <0.001	0.852 <0.001	0.868 <0.001
	And	0.848 <0.001	0.721 <0.001	0.771 <0.001	0.613 <0.001	0.799 <0.001	0.837 <0.001	0.753 <0.001	0.658 <0.001	0.808 <0.001	0.607 <0.001	0.839 <0.001
	Tom	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	And	0.866 <0.001	0.686 <0.001	0.759 <0.001	0.693 <0.001	0.829 <0.001	0.873 <0.001	0.781 <0.001	0.689 <0.001	0.831 <0.001	0.593 <0.001	0.876 <0.001
	Fem	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
THI 1	Comm	0.855 <0.001	0.723 <0.001	0.756 <0.001	0.678 <0.001	0.864 <0.001	0.889 <0.001	0.869 <0.001	0.857 <0.001	0.842 <0.001	0.814 <0.001	0.852 <0.001
	And	0.852 <0.001	0.706 <0.001	0.766 <0.001	0.605 <0.001	0.788 <0.001	0.831 <0.001	0.759 <0.001	0.658 <0.001	0.801 <0.001	0.592 <0.001	0.835 <0.001
	Tom	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	And	0.855 <0.001	0.654 <0.001	0.744 <0.001	0.666 <0.001	0.810 <0.001	0.854 <0.001	0.789 <0.001	0.703 <0.001	0.819 <0.001	0.567 <0.001	0.860 <0.001
	Fem	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
THI 2	Comm	0.869 <0.001	0.753 <0.001	0.798 <0.001	0.722 <0.001	0.871 <0.001	0.904 <0.001	0.886 <0.001	0.875 <0.001	0.844 <0.001	0.819 <0.001	0.878 <0.001
	And	0.845 <0.001	0.703 <0.001	0.763 <0.001	0.615 <0.001	0.781 <0.001	0.808 <0.001	0.765 <0.001	0.669 <0.001	0.789 <0.001	0.580 <0.001	0.829 <0.001
	Tom	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	And	0.849 <0.001	0.650 <0.001	0.734 <0.001	0.655 <0.001	0.792 <0.001	0.826 <0.001	0.788 <0.001	0.709 <0.001	0.802 <0.001	0.555 <0.001	0.849 <0.001
	Fem	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
THI 3	Comm	0.871 <0.001	0.729 <0.001	0.764 <0.001	0.659 <0.001	0.891 <0.001	0.907 <0.001	0.885 <0.001	0.873 <0.001	0.855 <0.001	0.839 <0.001	0.864 <0.001
	And	0.854 <0.001	0.722 <0.001	0.774 <0.001	0.609 <0.001	0.801 <0.001	0.840 <0.001	0.757 <0.001	0.658 <0.001	0.809 <0.001	0.598 <0.001	0.841 <0.001
	Tom	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	And	0.870 <0.001	0.675 <0.001	0.760 <0.001	0.680 <0.001	0.834 <0.001	0.878 <0.001	0.788 <0.001	0.707 <0.001	0.839 <0.001	0.585 <0.001	0.881 <0.001
	Fem	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
THI 4	Comm	0.877 <0.001	0.737 <0.001	0.773 <0.001	0.662 <0.001	0.901 <0.001	0.915 <0.001	0.892 <0.001	0.882 <0.001	0.859 <0.001	0.847 <0.001	0.873 <0.001
	And	0.852 <0.001	0.726 <0.001	0.776 <0.001	0.613 <0.001	0.802 <0.001	0.836 <0.001	0.753 <0.001	0.657 <0.001	0.808 <0.001	0.592 <0.001	0.840 <0.001
	Tom	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	And	0.870 <0.001	0.679 <0.001	0.763 <0.001	0.680 <0.001	0.836 <0.001	0.876 <0.001	0.779 <0.001	0.700 <0.001	0.838 <0.001	0.584 <0.001	0.883 <0.001
	Fem	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
THI 5	Comm	0.881 <0.001	0.754 <0.001	0.795 <0.001	0.706 <0.001	0.891 <0.001	0.916 <0.001	0.897 <0.001	0.887 <0.001	0.857 <0.001	0.838 <0.001	0.883 <0.001
	And	0.851 <0.001	0.709 <0.001	0.767 <0.001	0.617 <0.001	0.790 <0.001	0.820 <0.001	0.766 <0.001	0.667 <0.001	0.798 <0.001	0.584 <0.001	0.836 <0.001
	Tom	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	And	0.857 <0.001	0.662 <0.001	0.746 <0.001	0.665 <0.001	0.810 <0.001	0.846 <0.001	0.792 <0.001	0.710 <0.001	0.816 <0.001	0.564 <0.001	0.863 <0.001
	Fem	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

The strongest correlation values in each bird group and body region are marked in bold.

579 Table 5. Correlations between the mean area surfaces under study and the weekly live weight and
580 estimated average daily gain.

		Head	Beak	Snood	Eye	Closed dorsal	Open dorsal	Closed ventral	Open ventral	Breast	Underwing	Shank
Weight	Comm	-0.128	-0.040	0.000	0.161	-0.247	-0.189	-0.143	-0.161	-0.162	-0.238	-0.091
		<i>0.002</i>	<i>0.258</i>	<i>0.945</i>	<i><0.001</i>	<i><0.001</i>	<i><0.001</i>	<i>0.001</i>	<i><0.001</i>	<i><0.001</i>	<i><0.001</i>	<i>0.029</i>
	And	-0.166	-0.132	-0.122	0.010	-0.272	-0.357	-0.054	-0.045	-0.211	-0.039	-0.192
	Tom	<i>0.005</i>	<i>0.026</i>	<i>0.039</i>	<i>0.871</i>	<i><0.001</i>	<i><0.001</i>	<i>0.362</i>	<i>0.441</i>	<i><0.001</i>	<i>0.511</i>	<i>0.001</i>
	Fem	-0.140	-0.001	-0.039	-0.089	-0.231	-0.310	-0.057	-0.032	-0.180	-0.069	-0.156
ADG	Comm	<i>0.009</i>	<i>0.972</i>	<i>0.465</i>	<i>0.096</i>	<i><0.001</i>	<i><0.001</i>	<i>0.282</i>	<i>0.550</i>	<i>0.001</i>	<i>0.193</i>	<i>0.003</i>
	Comm	0.149	0.145	0.202	0.203	0.165	0.190	0.147	0.167	0.129	0.213	0.200
		<i>0.001</i>	<i>0.001</i>	<i><0.001</i>	<i><0.001</i>	<i><0.001</i>	<i><0.001</i>	<i>0.001</i>	<i><0.001</i>	<i>0.003</i>	<i><0.001</i>	<i><0.001</i>
	And	-0.070	-0.114	-0.098	-0.024	-0.084	-0.017	-0.068	-0.115	-0.086	-0.076	-0.072
	Tom	<i>0.254</i>	<i>0.063</i>	<i>0.109</i>	<i>0.691</i>	<i>0.173</i>	<i>0.777</i>	<i>0.267</i>	<i>0.061</i>	<i>0.162</i>	<i>0.217</i>	<i>0.241</i>
	And	-0.086	-0.069	-0.094	-0.117	-0.093	-0.061	-0.177	-0.230	-0.072	-0.214	-0.080
	Fem	<i>0.124</i>	<i>0.212</i>	<i>0.091</i>	<i>0.036</i>	<i>0.094</i>	<i>0.269</i>	<i>0.001</i>	<i><0.001</i>	<i>0.197</i>	<i><0.001</i>	<i>0.152</i>

581 The strongest correlation values in each bird group and body region are marked in bold.

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Table 6. Week $\times$ group ANOVA p -values, mean re-scaled contrasts (% estimates) for statistically significant weeks in the post hoc analysis and overall average body area surface temperature by bird group.

Variable		ANOVA III p -value (week*group)	% estimates			Average temperature		
			Commercial toms vs Andalusian toms	Commercial toms vs Andalusian hens	Andalusian toms vs Andalusian hens	Commercial toms	Andalusian toms	Andalusian hens
Head	Max.	<0.001	-	0.945	1.000	38.87	38.66	38.95
	Mean	0.006	-	-	0.939	32.63	32.24	32.62
	Min.	<0.001	1.107	-	0.867	25.30	24.86	25.55
Beak	Max.	<0.001	1.078	1.009	0.978	36.25	35.48	36.25
	Mean	<0.001	1.079	0.961	0.973	32.89	32.75	33.63
	Min.	<0.001	-	0.884	1.002	27.39	27.68	28.62
Snood	Max.	<0.001	0.953	0.967	0.997	35.70	35.94	36.49
	Mean	<0.001	-	0.966	0.999	32.05	32.08	32.42
	Min.	0.013	1.098	0.881	0.887	26.57	26.57	27.41
Eye	Max.	0.010	-	0.999	-	36.90	37.12	37.30
	Mean	<0.001	1.079	1.063	-	33.25	32.26	32.06
	Min.	<0.001	1.060	1.072	0.936	32.78	31.67	31.50
Closed Dorsal	Max.	<0.001	1.044	0.989	0.937	35.85	35.62	35.99
	Mean	0.001	-	0.941	0.930	29.67	29.58	30.54
	Min.	<0.001	1.006	0.932	0.912	24.30	24.40	25.56
Open Dorsal	Max.	<0.001	1.042	1.000	0.953	35.85	35.14	35.51
	Mean	<0.001	1.063	1.012	0.942	30.04	29.39	30.16
	Min.	<0.001	1.003	0.928	0.926	24.37	24.52	25.36
Closed Ventral	Max.	<0.001	1.056	1.046	0.952	36.78	35.06	35.84
	Mean	<0.001	1.137	1.150	0.929	30.82	29.41	30.46
	Min.	<0.001	1.594	1.205	0.819	24.42	23.39	24.43
Open Ventral	Max.	<0.001	1.048	1.020	0.950	36.47	35.39	35.96
	Mean	<0.001	1.150	1.184	0.912	29.75	27.12	28.18
	Min.	<0.001	1.407	1.472	0.871	23.77	20.77	21.96
Breast	Max.	<0.001	1.070	1.066	-	35.82	34.76	35.24
	Mean	<0.001	1.057	0.981	0.947	31.29	30.68	31.34
	Min.	<0.001	0.901	0.921	0.909	25.38	26.15	27.06
Underwing	Max.	<0.001	0.967	0.943	0.995	37.13	37.25	37.62
	Mean	<0.001	1.132	1.170	0.885	32.40	31.07	31.58
	Min.	<0.001	1.695	1.571	0.781	26.36	22.90	24.00
Shank	Max.	<0.001	1.071	1.036	0.935	34.07	33.02	33.79
	Mean	<0.001	1.074	1.025	0.936	29.91	29.04	29.89
	Min.	<0.001	0.971	0.890	0.921	25.72	26.04	26.87

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Fig. 1. Images from the pens where birds were kept during the experiment. Images taken facing west (a) and south-east (b) sides.

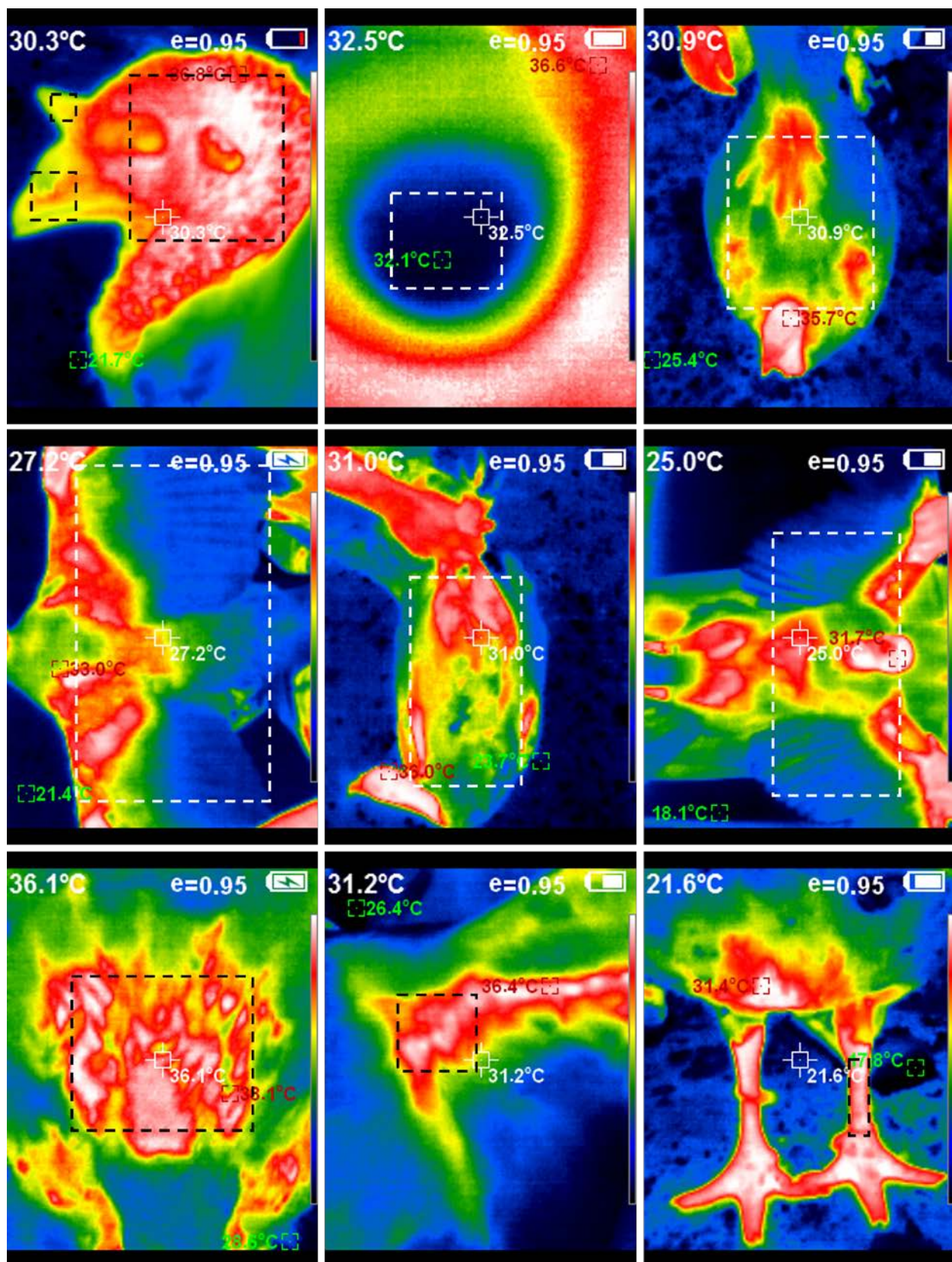


Fig. 2. Perspectives photographed with the thermal camera and delimited body areas for the thermal scale software.

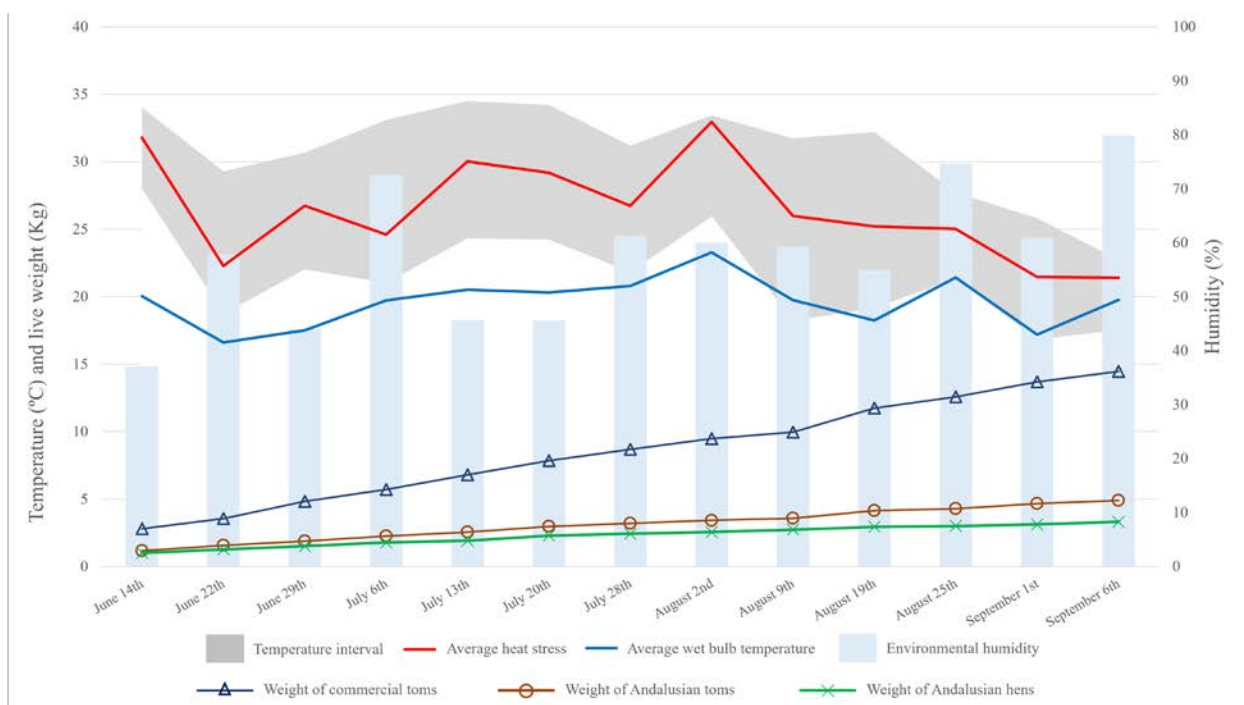


Fig. 3. Evolution of the main environmental conditions (temperature and humidity) and live weights of the animals in every recording session.

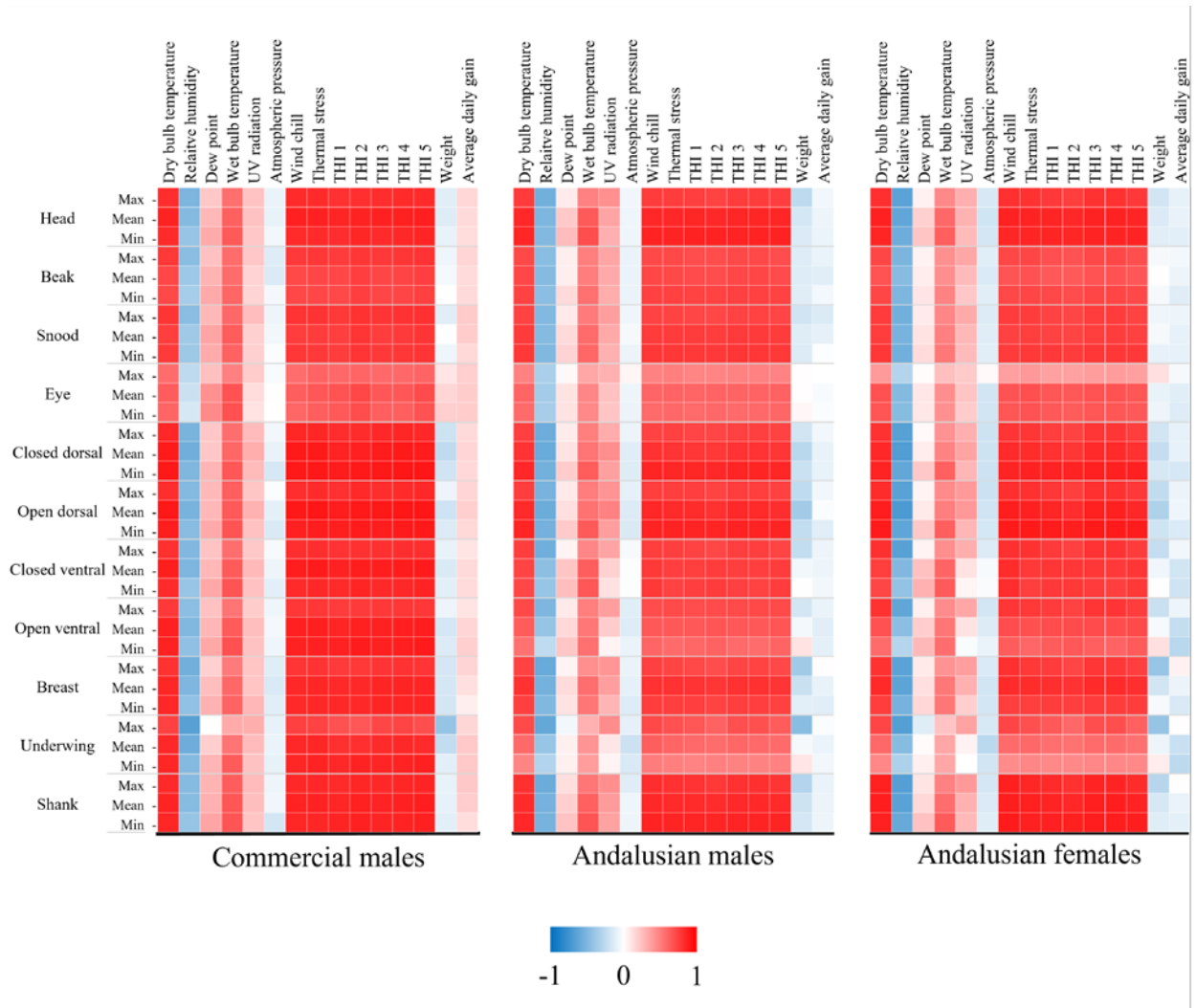


Fig. 4. Heat map of the correlation values between the different environmental factors and the thermographic values in each bird group.