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Female but not male zebra finches adjust heat output in response to increased incubation demand

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SUMMARY

1
2 In many incubating birds heat transfer from parent to egg is facilitated by the brood
3 patch, an area of ventral abdominal skin that becomes highly vascularised, swells and
4 loses its down feathers around the time of laying. Only the female develops a brood patch
5 in most passerine species, but males of some species can incubate and maintain the eggs
6 at similar temperatures to females even without a brood patch. Here we used a novel
7 application of infra-red thermography (IRT) to examine sex differences in parental care
8 from a physiological perspective. Using incubating male and female zebra finches
9 (*Taeniopygia guttata*), a species in which the male lacks a brood patch, we measured the
10 surface temperature of the ventral plumage overlying the abdomen and a reference area
11 that does not contact the eggs (thorax) twice per pair. In half of the pairs clutch size was
12 experimentally enlarged between the two sets of measurements to increase incubation
13 demand. We found that the temperature differential between abdomen and thorax
14 plumage was greater in females than in males, and that abdomen plumage was warmer
15 after clutch enlargement than before it in females but not in males. These findings are
16 consistent with morphological sex differences in brood patch development and suggest
17 that male and female zebra finches differ in the way they regulate abdomen versus
18 general body surface temperature in response to variation in incubation demand.

19
20 **KEYWORDS:** brood patch, clutch size manipulation, infra-red thermography, IRT,
21 parental care, *Taeniopygia guttata*

22

23

Introduction

24 Incubating birds must keep their eggs within the narrow range of temperature and
25 humidity that favours optimal embryonic development by transferring heat from their
26 body to the eggs (DuRant et al., 2013; Rahn and Ar, 1974; Webb, 1987). They can
27 regulate heat transfer behaviourally by adjusting their body position and the duration and
28 tightness of contact with the eggs (e.g. Drent et al., 1970; Gorman et al., 2005; White and
29 Kinney, 1974) and physiologically by increasing their metabolic rate (de Heij et al., 2007;
30 Nord et al., 2010; Vleck, 1981) or output of blood flow to the brood patch (Midtgard et
31 al., 1985). The brood patch is typically a defeathered, swollen and highly vascularised
32 area of ventral abdominal skin that develops under hormonal control around the time of
33 egg-laying and incubation in many bird species (Bailey, 1952; Jones, 1971; Lea and
34 Klandorf, 2002). As well as facilitating heat transfer during contact incubation, the brood
35 patch contains sensory receptors that enable incubating birds to detect suboptimal egg
36 temperatures (Drent et al., 1970; Lea and Klandorf, 2002; White and Kinney, 1974).

37 Even in biparental incubators, where both males and females contribute to
38 warming the eggs, brood patch development can differ between the sexes. In most
39 passerines only the female develops a brood patch (Lea and Klandorf, 2002). Although
40 we might expect the sex with the more developed brood patch to maintain higher steady-
41 state incubation temperatures or re-warm cold eggs more rapidly, empirical evidence of
42 this is mixed. Females warm eggs more rapidly (Kleindorfer et al., 1995) or to a higher
43 temperature (Voss et al., 2008) than males in many passerine species, but in others the
44 males warm eggs to a similar or even higher temperature than the females, even in
45 species in which males lack a brood patch (Auer et al., 2007; Zann and Rossetto, 1991).
46 While these studies focussed on the temperature of the egg, few have compared sex
47 differences in heat output at the parental body surface itself (for exceptions see Bartlett et
48 al. (2005) and Deeming and Du Feu (2008) in passerines, and Massaro et al. (2006) in
49 yellow-eyed penguins, *Megadyptes antipodes*). Such measurements are useful because
50 they enable heat output from the parents to be studied independently of potentially
51 confounding behavioural effects on egg temperature, which might also differ between the
52 sexes.

53 Here we examined sex differences in heat output from incubating zebra finches,
54 *Taeniopygia guttata* (Vieillot, 1817). During the day, free-living males and females
55 invest an equal share of time in incubation (Zann and Rossetto, 1991), whereas females in
56 captive domesticated populations spend more time incubating than males (Burley, 1988;
57 Gorman and Nager, 2003; Hill et al., 2011), and females incubate alone at night in the
58 wild and in captivity (Zann and Rossetto, 1991). Females develop the morphological
59 characteristics of a brood patch (e.g. skin colour change and oedema formation) before
60 the clutch is complete, although without the degree of vascularisation seen in most other
61 passerine species (Zann and Rossetto, 1991; Zann, 1996). These characteristics do not
62 develop in male zebra finches. The apterium is relatively bare throughout the year in both
63 sexes, and the female loses the few down feathers she has during laying.

64 Based upon these morphological observations we hypothesised that incubating
65 females will emit more heat from the ventral abdomen than males, and we measured the
66 temperature of the ventral plumage using infra-red thermography (IRT). IRT uses known
67 properties of an object's surface and simple physical laws to determine the object's
68 surface temperature from the infra-red radiation it emits (Speakman and Ward, 1998). We
69 compared plumage temperature in males and females at two ventral sites: one over the
70 area where the brood patch occurs in females (abdomen) and another away from the
71 brood patch (thorax) to give an approximation of general body surface temperature.

72 Incubating a large clutch requires greater energy expenditure than a small clutch
73 (Biebach, 1984; de Heij et al., 2007; Nord et al., 2010) and so we experimentally
74 enlarged clutch size between measurement days to test whether birds would respond to
75 the increased demands of keeping eggs warm by increasing heat output. We expected to
76 see a greater increase in abdominal heat output in response to clutch enlargement in
77 females than in males due to the presence of the brood patch in females, which enhances
78 blood flow and sensory perception in the region in contact with the eggs. The results of
79 this experiment will provide a better understanding of how parent birds physiologically
80 adjust expenditure to variation in incubation demand.

81
82
83

Results

84 Male and female zebra finches incubating natural clutch sizes did not differ in the
 85 thickness of plumage on the ventral surface ($\beta = 0.31$, Credible Interval (CI) = -0.57 to
 86 1.20, $P = 0.488$, $N = 66$ measurements from 33 individuals and 17 pairs on incubation
 87 day 6; Table 1). Thorax plumage was thicker than abdomen plumage ($\beta = 1.22$, CI = 0.32
 88 to 2.08, $P < 0.007$; Table 1) and the effects of body part (thorax or abdomen) on plumage
 89 thickness did not depend on the bird's sex ($\beta = -0.72$, CI = -2.38 to 1.03, $P = 0.407$).
 90 Abdomen plumage thickness measurements were repeatable between incubation days 6
 91 and 8 in females ($F_{15,16} = 7.31$, $r = 0.75 \pm 0.11$, $P < 0.001$) and males ($F_{15,16} = 7.43$, $r =$
 92 0.75 ± 0.11 , $P < 0.001$); thorax plumage thickness was repeatable in males ($F_{15,16} = 5.34$, $r =$
 93 0.67 ± 0.14 , $P < 0.001$) but not in females ($F_{15,16} = 0.97$, $r = -0.05 \pm 0.25$, $P = 0.523$).

94 Thorax plumage temperature did not differ between the sexes and was not
 95 associated with thorax plumage thickness or clutch size in birds incubating natural clutch
 96 sizes (incubation day 6; Table 1, Table 2A). Abdomen plumage temperature, by contrast,
 97 decreased with abdomen plumage thickness and the relationship between thorax plumage
 98 temperature and abdomen plumage temperature differed between the sexes (Table 2B): in
 99 females, the abdomen plumage was warmer than the thorax plumage ($\beta = -1.42$, CI = -
 100 2.43 to -0.48, $P = 0.007$; Table 1), but there was no difference between thorax and
 101 abdomen plumage temperature in males ($\beta = -0.42$, CI = -1.62 to 0.74, $P = 0.473$).

102 Abdomen and thorax plumage temperatures did not differ between incubation
 103 days 6 and 8 in control birds. There was a non-significant trend towards warmer
 104 abdomens in control females ($32.5 \pm 0.53^\circ\text{C}$; Table 3) than in control males ($31.7 \pm 0.61^\circ\text{C}$),
 105 but the sexes did not differ in thorax plumage temperature (females: $30.5 \pm 0.35^\circ\text{C}$, males:
 106 $30.9 \pm 0.47^\circ\text{C}$; $\beta = 0.01$, CI = -0.02 to 0.05, $P = 0.510$). Abdomen plumage temperature was
 107 repeatable between incubation days 6 and 8 in control females ($F_{7,8} = 9.98$, $r =$
 108 0.82 ± 0.12 , $P = 0.002$) but not significantly so in control males ($F_{7,8} = 3.46$, $r =$
 109 0.55 ± 0.25 , $P = 0.052$). Thorax plumage temperature was not repeatable in control males
 110 ($F_{7,8} = 2.32$, $r = 0.34 \pm 0.32$, $P = 0.131$) or females ($F_{7,8} = 1.30$, $r = 0.07 \pm 0.36$, $P = 0.361$).

111 Thorax plumage temperature was warmer in treatment group females than in
 112 treatment males on incubation days 6 and 8, but was not influenced by the clutch size
 113 enlargement or an interaction between sex and clutch enlargement (Table 4A; Fig. 1).
 114 However, the effects of incubating an enlarged compared with a control clutch on

115 abdomen plumage temperature differed between the sexes (Table 4B): female abdomens
116 were warmer after the clutch size enlargement than before it, but male abdomen plumage
117 temperature did not change (Fig. 1). This result was qualitatively similar when the ventral
118 temperature differential (abdomen plumage temperature minus thorax plumage
119 temperature) was used as a response variable (Linear Mixed effects Model controlling for
120 plumage thickness, individual identity and pair identity: sex \times clutch enlargement $\beta = -$
121 1.13, CI = -2.14 to -0.15, $P = 0.026$).

122

123

124

Discussion

125 We examined sex differences during incubation by comparing the ventral heat output of
126 male and female zebra finches using infra-red thermography. The plumage of females
127 incubating natural clutch sizes was warmer at the abdomen than the thorax, which we
128 used as a proxy for general body surface temperature, but the two areas did not
129 significantly differ in temperature in males. Similarly, in incubating female house
130 sparrows, *Passer domesticus*, the abdomen was warmer than a control area (the back) in
131 females but not in males (Bartlett et al., 2005). Moreover, female zebra finches appeared
132 to respond to the challenge of incubating experimentally enlarged clutch sizes by
133 increasing heat output from the abdomen (adjusted for general body temperature) relative
134 to their own output before the clutch size manipulation. By contrast, we observed no
135 change in heat output in males.

136 A sex difference in plumage temperature could be due to males and females
137 generating different amounts of heat, differing in insulation in layers above the heat-
138 generating tissue (plumage, skin and subcutaneous tissue) or both. Plumage thickness is
139 the main contributor to insulation in several bird species (McCafferty et al., 1997), but we
140 found no sex difference in plumage thickness in our population, suggesting that the
141 differences measured here are due to differences in the output of generated heat. These
142 results are consistent with differences between male and female zebra finches in brood
143 patch morphology (Zann and Rossetto, 1991; Zann, 1996) and suggest that the sexes
144 differ in their ability or willingness to increase abdomen temperature above general body

145 temperature in response to variation in incubation demand. To our knowledge this has not
146 been demonstrated previously.

147 It is worth emphasising that we did not measure brood patch skin temperature but
148 the temperature of the contour feathers overlying the egg-contact region. The aim of this
149 was to minimise variability between measurements and disturbance to the birds
150 associated with instrument attachment and handling. The difference between the
151 abdomen temperatures presented here ($32.5 \pm 0.33^\circ\text{C}$ for females on incubation day 6) and
152 the higher temperatures reported elsewhere for brood patch skin ($41.2 \pm 0.11^\circ\text{C}$, mean \pm
153 SE for 24 passerine species, mainly measured in females (Deeming, 2008)) highlights the
154 excellent insulating capacity of the plumage, even during incubation when the down
155 feathers have been lost. In addition, we found that abdomen plumage temperatures
156 decreased as plumage thickness increased, in agreement with studies of mounted
157 specimens of passerines, quails and owls (McCafferty et al. 1997; Walsberg, 1988). The
158 exact gradient of heat loss from the skin to the surface of the plumage is likely to be more
159 complex than is currently understood, and may depend on the type, quality, number and
160 placement of feathers overlying the skin (Wolf & Walsberg, 2000). Although plumage
161 temperature measurements are not a substitute for direct measurements of brood patch
162 temperature, they are valuable in studies such as this where the aim is to detect relative
163 changes in heat output. In particular they are likely to improve the precision of within-
164 individual studies where the greatest source of variability is due to measurement error.

165 While females incubating enlarged clutches on incubation day 8 had warmer
166 abdomen plumage than on day 6, there was no change in abdomen heat output in control
167 birds incubating unmanipulated clutch sizes. The response in the former group of females
168 is therefore most likely due to clutch size enlargement rather than changes over the
169 incubation period. Females may respond to increased incubation demand by directing
170 warm blood to arterioles that lie close to the brood patch surface and that typically
171 increase in musculature as part of brood patch development (Midtgard et al., 1985;
172 Peterson, 1955). This might occur to even a greater extent in females of other passerine
173 species whose brood patches exhibit more pronounced vascularisation than in zebra
174 finches.

175 Treatment male zebra finches, unlike females, did not respond to the clutch size
176 enlargement by increasing their abdomen temperature. While this could imply a reduced
177 ability or willingness to transfer heat in incubating males compared with females, Zann
178 and Rossetto (1991) did not observe a sex difference in steady-state incubation
179 temperature or the rate of re-warming cool eggs in this species and speculated that male
180 zebra finches increase heat transfer to the eggs by increasing metabolic rate. Our findings
181 do not support this idea because male thorax temperature was not higher than female
182 thorax temperature and did not increase in response to clutch enlargement. Indeed,
183 females allocated to the treatment group had warmer thoraxes than males and there was
184 no sex difference in thorax temperature in control birds. Nevertheless, metabolic rate has
185 rarely been measured in incubating males and it would be valuable to compare the
186 metabolic rates of incubating males and females directly.

187 A new question raised by this study is whether the difference in temperature
188 between the abdomen and thorax in females exists only in incubating birds. As the
189 temperature of the abdomen plumage relative to the thorax changed with incubation
190 demand we believe that it is reasonable to suggest that at least some of these differences
191 are related to incubation. A better understanding of this issue would provide information
192 on brood patch function and could be tested by comparing abdomen and thorax
193 measurements taken during incubation with those from the same females before the
194 brood patch develops or after it regresses. If the female has a true brood patch, we would
195 predict that the abdomen would be warmer in incubating than in non-incubating females
196 and that there would be no difference between incubating and non-incubating females in
197 thorax temperature nor between abdomen and thorax temperature in non-incubating
198 females.

199 Maintaining a brood patch is likely to be costly in terms of increased heat loss
200 (Haftorn and Reinertsen, 1985), and we would expect such costs to be offset by an
201 associated fitness benefit, such as an increased ability to keep the eggs at favourable
202 conditions for optimal embryo development and survival. Lower egg temperatures in
203 males than females during steady-state incubation have indeed been reported in some
204 species of biparentally incubating passerine (Reid et al., 2002; Voss et al., 2008).
205 However, no sex differences in steady state incubation were found in other species,

206 including zebra finches, as noted above, in spite of the absence of a brood patch in males
207 (Kleindorfer et al., 1995; Zann and Rossetto, 1991), and in chestnut-vented tit-babblers,
208 *Parisoma subcaeruleum*, eggs were warmer when incubated by males than by females
209 (Auer et al., 2007). Males have been observed to re-warm clutches after an incubation
210 break more slowly than females in some species (Kleindorfer et al., 1995; Voss et al.,
211 2008), while in others males re-warmed clutches more quickly than females (Reid et al.,
212 2002), and no clear difference between the sexes was seen in others, including zebra
213 finches (Auer et al., 2007; Hill, 2009). These conflicting results may seem to suggest that
214 the brood patch is not associated with improved performance during incubation.
215 However, we need to know more about sex differences in the costs of incubation and how
216 the brood patch might moderate these costs before we can draw a conclusion. The
217 presence of a brood patch might reduce the risk of tissue damage due to the protective
218 thickening of the epidermal skin (Jones, 1971), allow individuals to sustain longer or
219 more frequent incubation bouts or expend less effort to achieve the same thermal output
220 (Auer et al., 2007) or enable them to detect non-optimal egg temperatures through the
221 sensory receptors it contains (Drent et al., 1970; White and Kinney, 1974).

222 In our study, up-regulation of heat transfer to the brood patch in females after the
223 clutch size manipulation could be a tactile response to the increased number of eggs or a
224 thermal response to a decrease in mean egg temperature. Mean egg surface temperature
225 (both sexes pooled) was inversely related to natural variation in clutch size in our
226 population (Hill, 2009), and so we would expect the clutch enlargement in the present
227 study to produce a similar decrease in egg temperature. However, males might fail to
228 perceive such changes in temperature or clutch size without a brood patch. They do,
229 however, seem able to respond to variation in clutch size by adjusting the amount of time
230 spent incubating. Male European starlings, *Sturnus vulgaris*, increased incubation
231 attentiveness following clutch size enlargement and decreased it when clutch size was
232 reduced (Komdeur et al., 2002) and incubation attentiveness was positively related to
233 natural clutch size in male zebra finches (Hill et al., 2011). These results suggest that the
234 absence of a brood patch does not impair a male's ability to detect changes in clutch size,
235 although what cues they use is unknown.

236 Sex differences in the regulation of heat transfer to offspring have also been
237 recorded in humans. Studies of ‘kangaroo care’, where a newborn human infant is placed
238 in skin-to-skin contact upon the parental breast, show that mothers adjust their breast
239 temperature in response to their infants’ immediate thermal needs whereas fathers
240 maintain a high heat output that can cause infants to become overheated and even
241 hyperthermic (Chiu et al., 2005; Ludington-Hoe et al., 1992; Ludington-Hoe et al., 2006).
242 These findings, in combination with our own, point to interesting differences between
243 male and female parents in the modulation of offspring temperature, and suggest that
244 such differences may be more widespread in endotherms than is currently recognized.

245 Our results suggest that males and females respond differently to the demands of
246 incubation. Understanding sex differences in the effectiveness of parental care has
247 implications for our understanding of sex role divergence and for interpreting empirical
248 studies of sexual conflict over parental effort. It might be maladaptive for males to
249 increase their incubation effort to levels shown by females because they are less certain
250 of their relatedness to the offspring (Queller, 1997; Trivers, 1972) and can potentially
251 obtain greater fitness benefits from seeking extra-pair copulations (EPCs) than attending
252 to the eggs or offspring, depending on the availability of receptive females (Bateman,
253 1948; Kokko and Jennions, 2008; Magrath and Komdeur, 2003). Perhaps for this reason
254 the complex morphological adaptations associated with the brood patch have not evolved
255 to the same extent or have not been conserved in male passerines. The sex difference we
256 observed in the birds’ response to the clutch size enlargement could reflect the outcome
257 of a conflict that has been resolved over evolutionary time or differences in willingness to
258 respond (even if individuals are capable of doing so) measured over ecological time. In
259 practice it may not be possible to determine whether males are unable or unwilling to
260 adjust abdominal temperature, and in any case sex differences in ability and willingness
261 are likely to have arisen as a consequence of the same evolutionary pressures.
262 Nevertheless, by contributing to incubation, males play an important role in relieving the
263 female in times of energetic stress (Kleindorfer et al., 1995; Smith and Montgomerie,
264 1992) and in reducing the substantial energetic demands of re-warming cold eggs after
265 the female returns from a foraging bout (Vleck, 1981; Voss et al., 2008).

266

267

268

Materials and methods

269

Subjects and maintenance

270 This study was carried out on domesticated zebra finches bred at the University of
271 Glasgow and conforms to the ‘Guidelines for the treatment of animals in behavioural
272 research and teaching’ (Buchanan et al., 2012). Prior to pairing, the sexes were kept
273 separately at a density of six individuals per cage (122 × 41 × 45 cm length × width ×
274 height) under a ‘short day’ light regime (10 ½ h L: 13 ½ h D) using daylight-spectrum
275 fluorescent tubes (Arcadia Bird Lamp FB36) with a gradual change in light at dawn and
276 dusk. Birds received *ad libitum* mixed seed consisting of canary millets (Foreign Finch
277 Mixture: Galloway MacLeod, UK), oyster grit, cuttlefish bone and water. Egg biscuit
278 protein with vitamin (Daily Essentials 2: The Birdcare company, Nailsworth, UK) and
279 calcium (Calcivet: The Birdcare company) supplements were provided three times a
280 week and fresh spinach leaves twice a week.

281 Males and females without previous breeding experience were size matched
282 according to tarsus length. To stimulate breeding, we increased daylight hours to 12 h L:
283 12 h D one week before birds were paired and maintained this ‘long day’ regime until the
284 end of the experiment. Each pair was kept in a breeding cage (60 × 40 × 50 cm length ×
285 width × height) with access to a nestbox and coconut fibre nesting material. Nestboxes
286 were checked daily from pairing, and lay date (the date that the first egg of a clutch was
287 laid) and clutch size were recorded. All pairs that laid in the nestbox were included in the
288 study.

289

290

Experimental design

291 We compared ventral plumage temperature in male and female zebra finches incubating
292 unmanipulated (‘control’, $N = 9$ pairs) and experimentally enlarged clutch sizes where we
293 increased incubation effort by adding two dummy eggs (see below) to a pair’s natural
294 clutch size (‘treatment’, $N = 10$). Each pair was alternately allocated to control or
295 treatment group according to lay date. Control and treatment birds did not differ in the
296 number of eggs they laid (control: 4.8 ± 0.52 eggs (mean \pm SE); treatment: 5.4 ± 0.54
297 eggs; $F_{1,17} = 0.68$, $P = 0.422$) or tarsus length (control males: 13.9 ± 0.16 mm; treatment

298 males: 14.2 ± 0.15 mm; $F_{1,17} = 1.84$, $P = 0.193$; control females: 14.3 ± 0.21 mm;
299 treatment females: 14.5 ± 0.17 mm (one measurement missing); $F_{1,16} = 0.69$, $P = 0.780$).

300 We assumed that zebra finches begin incubating ('day 0') on the fourth day of
301 laying in clutches of five eggs or more, and on the final day of laying in smaller clutches;
302 the incubation period spans 11-15 (median 14) days using these criteria (Zann and
303 Rossetto, 1991). On day 2 of incubation, we replaced all eggs with an equivalent number
304 of dummy eggs made of Fimo modelling clay (Eberhard Faber, Neumarkt, Germany).
305 Fimo eggs have similar thermal properties to fresh zebra finch eggs (Gorman, 2005) and
306 do not bring about changes in incubation behaviour compared to natural eggs (Gorman et
307 al., 2005). At dusk on incubation day 7, we added two additional Fimo eggs to the
308 clutches of the 10 treatment pairs; the 9 control pairs incubated unmanipulated clutch
309 sizes throughout. This design enabled us to test for sex differences in the ventral heat
310 output of incubating birds both within and between experimental groups.

311

312

Temperature measurements

313 We used infra-red thermography (IRT) to measure temperature at the surface of the
314 ventral plumage. IRT is a non-invasive, non-contact technique that can provide quick and
315 accurate measurements of avian skin and plumage temperatures (McCafferty, 2013). We
316 simultaneously measured the surface temperature of the undisturbed contour feathers
317 overlying two regions on the ventral side of the birds: the area that comes into contact
318 with the eggs, corresponding to the brood patch in females (hereafter abdomen
319 temperature) and a control area anterior to the brood patch that does not contact the eggs
320 (hereafter thorax temperature). This allowed us to test whether the output of heat from the
321 abdomen is regulated independently of the rest of the body. We measured plumage rather
322 than skin temperature to remove potential biases and variability associated with parting
323 the contour feathers by hand to expose the brood patch and thorax skin, which could
324 influence temperature and handling time. The insulating properties of plumage increase
325 with plumage thickness in several species of terrestrial birds (McCafferty et al., 1997;
326 Walsberg, 1988) and so we measured plumage thickness at the abdomen and thorax (see
327 below) to account for this variation.

328 IRT images were taken using the ThermaCamTM E300 (FLIR Systems,
329 Burlington, Canada) on incubation days 6 and 8, that is, just before and after treatment
330 pairs experienced the clutch size manipulation (incubation day 7) and when nest
331 attentiveness reaches its maximum (Gorman and Nager, 2003). We gently displaced each
332 incubating bird with a tap to the nestbox and caught the bird without touching its
333 underside. The bird was then held with its ventral surface at a distance of 0.20 m from the
334 camera, which was supported on a fixed tripod. We took three replicate images of the
335 bird's ventral surface and recorded the time elapsed between the displacement of the bird
336 from the nest and the image being taken ('image latency', mean 65.8 ± 3.97 s, $N = 70$
337 images from 38 birds and 19 pairs; all reported values are based on the single best-
338 resolved of the three replicate images). Some individuals were not observed incubating
339 on the designated days, and so thermal images are missing for day 6 for two treatment
340 pairs and one control female and on day 8 for the partner of the latter female. Neither
341 abdomen plumage temperature ($\beta = -0.96$, Credible Interval (CI) = -2.53 to 0.65, $P =$
342 0.227 controlling for pair identity and plumage thickness) nor thorax plumage
343 temperature ($\beta = -0.001$, CI = -0.004 to 0.001, $P = 0.211$ controlling for pair identity;
344 plumage thickness was not significant) was associated with image latency ($N = 33$
345 individuals from 17 pairs on day 6 of incubation). Immediately after taking thermal
346 images on incubation days 6 and 8, we measured plumage thickness at the thorax and
347 abdomen to the nearest 0.5 mm by pushing a discarded primary feather, marked along the
348 shaft at 1 mm intervals, through the plumage down to the skin.

349 We used the software ThermaCAMTM QuickReport 1.1 (FLIR Systems, 2007a) to
350 visualise the digital images and ThermaCAMTM Reporter 8.3 (FLIR Systems, 2007b) to
351 analyse the best resolved of the three replicates taken for each individual and incubation
352 day. The radiation measured by the camera is a function of the object's surface
353 temperature and emissivity, ambient temperature and absorption and scattering by
354 atmospheric humidity. We set the surface emissivity value to 0.98 for the bird's plumage
355 (Hammel, 1956) and temperature and relative humidity to the mean values recorded in
356 the room during the measurement period ($22.2 \pm <0.01$ °C and 13.6 ± 0.04 %,
357 respectively). To standardise the size and positioning of measurement areas between
358 images we placed a sagittal line along the image of the bird's ventral surface (Fig. 2)

359 consisting of three transects that were scaled to the length of the bird's leg ring, which
360 was visible on all images. This was done by tracing a straight digital line along the length
361 of the ring (Fig. 2, Li1) with the polygon tool in ThermaCAMTM Reporter 8.3, noting the
362 ring's length in pixels, and then producing three transects of the same pixel length (Fig. 2,
363 Li2, Li3, Li4). The first transect (Li2 = abdomen) was extended by a factor of three, since
364 the brood patch was at least three times the length of the ring, and placed along the
365 sagittal plane on the region of the thermal image corresponding to the plumage over the
366 brood patch in females. Li3 and Li4 were placed at the apex of Li2 and Li3, respectively
367 to standardise the distance between the two measurement areas (Li2 = abdomen and Li4
368 = thorax). We then calculated the mean pixel temperature along Li2 (abdomen plumage
369 temperature) and Li4 (thorax plumage temperature).

370

371

Statistical analysis

372 All data were analysed in R version 3.0.1 (R Development Core Team, 2013). Thorax
373 plumage temperature measurements were normalised by log transformation when used as
374 a response variable and abdomen plumage temperature measurements were squared to
375 allow parametric tests to be carried out.

376 We tested whether the thickness of plumage overlying the abdomen and the
377 thorax differs between the sexes and the body part in birds incubating unmanipulated
378 clutch sizes (incubation day 6). We fitted a general Linear Mixed effects Model (LMM)
379 with plumage thickness as the response variable, sex and body part (abdomen or thorax)
380 as fixed factors and individual and pair identity as random factors. We included the
381 interaction between sex and body part to test whether a difference in plumage thickness
382 between the two parts of the body depends on the bird's sex. We calculated the within-
383 individual repeatability (r) of plumage thickness between incubation days 6 and 8
384 (following Lessells and Boag, 1987) and its standard error (Becker, 1984) to allow us to
385 assess measurement precision.

386 To see whether males and females incubating unmanipulated clutch sizes differed
387 in heat output, we fitted LMMs to data from incubation day 6. This first involved testing
388 whether the sexes differed in general body temperature using thorax plumage temperature
389 as the response variable, and then whether males and females differentially regulate

390 abdomen temperature relative to general body temperature by fitting thorax plumage
391 temperature and the interaction between sex and thorax plumage temperature as fixed
392 effects. We included pair identity as a random factor, sex as a fixed factor and clutch size
393 and plumage thickness measured on incubation day 6 as covariates in both models.
394 Variance inflation factors calculated by the car package (Fox and Weisberg, 2012) were
395 <1.23 in both models.

396 If females have a true brood patch but males do not, we should expect only
397 females to maintain brood patch temperature above the temperature of the rest of the
398 trunk. To test whether this is likely to be the case, we ran two separate LMMs, one for
399 each sex, with thorax and abdomen plumage temperature (which were normally
400 distributed when pooled) on incubation day 6 as a single response variable, pair identity
401 as a random factor, body part as a fixed factor and plumage thickness on day 6 as a
402 covariate.

403 To see whether ventral heat output changed between incubation days 6 and 8 in
404 unmanipulated birds, we compared temperature measurements between the two days in
405 control birds using separate LMMs for thorax and abdomen plumage temperature. In both
406 models we fitted plumage thickness, sex, day of incubation and the interaction between
407 sex and day of incubation as fixed effects and individual and pair identity as random
408 effects. Where abdomen plumage temperature was the response variable, we also
409 controlled for thorax plumage temperature.

410 There was no effect among control birds of incubation day on either abdomen or
411 thorax plumage temperature (see Results). Consequently, differences in temperature
412 between incubation days in the treatment group are likely to be related to the clutch size
413 manipulation. We therefore compared treatment group individuals before (day 6) and
414 after (day 8) the clutch size enlargement. We tested for an effect of sex and clutch
415 enlargement as well as the interaction between the two on abdomen and thorax plumage
416 temperature in LMMs to determine whether the sexes respond differently to the challenge
417 of incubating an enlarged clutch.

418 We fitted LMMs by Restricted Maximum Likelihood using the lme4 package
419 (Bates et al., 2013). We removed interaction terms $P \geq 0.05$ in order of least significance
420 and then non-significant main effects to reach the final model. Significance is denoted by

421 a two-tailed P -value < 0.05 or a Credible Interval (CI) that does not include zero. We
422 present the intercept (constant) for all models containing significant fixed effects.
423 Random effects were fitted with random intercepts only, and were controlled for even
424 when not statistically significant. For all fixed effects tested we present the model
425 coefficient β with CIs calculated at the 95 % confidence level using Markov chain Monte
426 Carlo (MCMC) sampling with the chain length fixed at 10,000 and P -values based upon
427 the posterior probability distribution. These estimates were calculated using the `pvals`
428 function from the `languageR` library (Baayen, 2013). Means are presented \pm SE.

429

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Competing interests statement

437 The authors have no conflict of interest.

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Author contributions

440 All authors conceived and designed the experiment. DLH carried out the experiment,
441 thermal and statistical analyses and wrote the manuscript. RGN, JL and DJM commented
442 on the manuscript.

443

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Fig 1. Abdomen and thorax plumage temperature (means + 1 SE) in incubating male and female zebra finches before (incubation day 6, $N = 8$ pairs) and after (incubation day 8, $N = 10$ pairs) a clutch enlargement manipulation. There was a clutch enlargement \times sex interaction on abdomen plumage temperature (see Table 4) whereby females but not males increased abdomen plumage temperature following clutch enlargement. Thorax plumage temperature was warmer in females than in males, but was not influenced by the clutch size enlargement nor an interaction between sex and clutch enlargement.

Fig 2. Sample thermal image of the ventral surface of a male on day 6 of incubation illustrating the procedure used for measuring plumage temperature along a transect following the sagittal plane of the ventral surface, and (inset) a digital reference image of the same bird. We standardised the relative size and positioning of transects across all thermal images using the length of the bird's leg ring (Li1) as a scale measured in pixels. Three lines were generated from Li1: Li2 was placed on the abdomen, Li3 was placed at the apex of Li2, and Li4 was placed on the thorax at the apex of Li3; all were arranged along the same ventral transect. We then calculated the mean pixel temperature along Li2 (abdomen plumage temperature) and Li4 (thorax plumage temperature). The values accompanying Li2 and Li4 in the figure are mean temperatures along the two lines.

Table 1 Mean \pm SE plumage thickness and plumage temperature in 17 male and 16 female zebra finches incubating natural clutch sizes on day 6 of incubation.

	Plumage thickness (mm)		Plumage temperature ($^{\circ}$ C)	
	Thorax	Abdomen	Thorax	Abdomen
Male	5.3 \pm 0.48	4.4 \pm 0.52	30.9 \pm 0.43	31.7 \pm 0.59
Female	5.3 \pm 0.42	3.7 \pm 0.31	31.1 \pm 0.39	32.5 \pm 0.33

Table 2. The effects of a bird's sex and other variables on (A) thorax and (B) abdomen plumage temperature on day 6 of incubation (33 measurements from 17 pairs of zebra finches; see Table 1). Coefficients (β and Credible Interval) are estimated using General Linear Mixed effects Models controlling for pair identity (random intercepts). P -values are based on the posterior probability distribution (see Methods). Significant fixed effects are shown in bold, non-significant fixed effects were removed from the models.

2A) thorax plumage temperature			
	β	Credible Interval	P
Plumage thickness	-0.01	-0.020 to 0.002	0.104
Natural clutch size	0.004	-0.01 to 0.02	0.572
Sex ^a	-0.01	-0.04 to 0.03	0.718
2B) abdomen plumage temperature			
	β	Credible Interval	P
Constant	344.46	-412.46 to 1133.34	0.371
Plumage thickness	-20.90	-37.04 to -4.25	0.016
Thorax plumage temperature	25.46	1.50 to 50.02	0.039
Sex ^a	-1242.54	-2269.04 to -280.42	0.015
Sex \times thorax plumage temperature	39.37	7.53 to 71.43	0.016
Natural clutch size	-0.88	-18.73 to 16.44	0.922

^a 'female' is the reference sex

Table 3. The effects of incubation day (6 vs 8) and other variables on (A) thorax and (B) abdomen plumage temperature in control pairs (34 measurements from 18 individuals from 9 pairs) of zebra finches. Coefficients (β and Credible Interval) were estimated using General Linear Mixed effects Models controlling for pair and individual identities (random intercepts). Significant fixed effects are shown in bold, non-significant fixed effects were removed from the models.

3A) thorax plumage temperature			
	β	Credible Interval	<i>P</i>
Plumage thickness	-0.01	-0.015 to 0.003	0.177
Sex ^a	0.01	-0.02 to 0.05	0.510
Day of incubation ^b	-0.01	-0.05 to 0.02	0.493
Sex \times day of incubation	0.02	-0.05 to 0.09	0.576
3B) abdomen plumage temperature			
	β	Credible Interval	<i>P</i>
Constant	-41.43	-722.14 to 612.66	0.896
Plumage thickness	-21.67	-41.45 to -0.20	0.039
Thorax plumage temperature	38.10	16.96 to 58.59	<0.001
Sex ^a	-54.17	-115.62 to 3.45	0.075
Day of incubation ^b	7.12	-51.13 to 64.25	0.808
Sex \times day of incubation	-33.94	-152.09 to 78.23	0.536

^a 'female' is the reference sex

^b 'day 6' is the reference day of incubation

Table 4. The effects of sex and clutch size enlargement on (A) thorax and (B) abdomen plumage temperature on days 6 and 8 of incubation (repeated measures) in 10 treatment pairs (36 measurements; see Fig. 1). Coefficients (β and Credible Interval) were estimated using General Linear Mixed effects Models controlling for pair and individual identities (random intercepts). Significant fixed effects are shown in bold, non-significant effects that were not components of a significant interaction were removed from the models.

4A) thorax plumage temperature			
	β	Credible Interval	<i>P</i>
Constant	3.46	3.44 to 3.49	< 0.001
Sex ^a	-0.04	-0.08 to -0.001	0.047
Clutch enlargement ^b	0.01	-0.03 to 0.04	0.719
Plumage thickness	0.0002	-0.01 to 0.01	0.962
Sex \times clutch enlargement	0.01	-0.07 to 0.08	0.762
4B) abdomen plumage temperature			
	β	Credible Interval	<i>P</i>
Constant	-769.75	-1115.08 to -411.72	< 0.001
Plumage thickness	-24.04	-39.17 to -9.23	0.003
Thorax plumage temperature	60.66	50.39 to 71.62	< 0.001
Sex ^a	11.54	-39.01 to 64.53	0.657
Clutch enlargement ^b	46.51	-1.28 to 93.25	0.056
Sex \times clutch enlargement	-74.92	-139.36 to -3.71	0.031

^a 'female' is the reference sex

^b 'pre-treatment' is the reference stage of the experiment

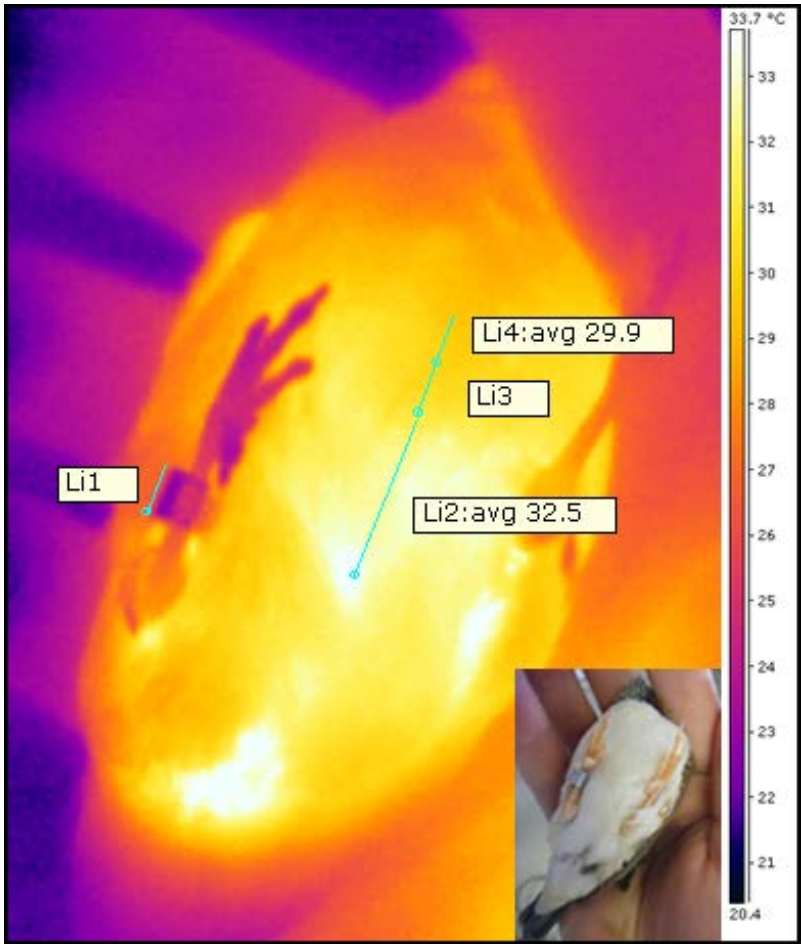


Fig. 2