

1 Endocrinology of thermoregulation in birds in a changing climate

2

3 Suvi Ruuskanen*¹, Bin-Yan Hsu¹, Andreas Nord²

4 ¹Department of Biology, University of Turku, Finland

5 ²Lund University, Department of Biology, Section for Evolutionary Ecology, Ecology
6 Building, Sölvegatan 37, SE-22362 Lund, Sweden

7 *Corresponding author: Suvi Ruuskanen, Present address: Department of Biology, University
8 of Turku, Vesilinnantie 5, Turku, FINLAND; email: skruus@utu.fi

9

10 Abstract

11 The ability to maintain a (relatively) stable body temperature in a wide range of thermal
12 environments by use of endogenous heat production is a unique feature of endotherms such as
13 birds. Endothermy is acquired and regulated via various endocrine and molecular pathways,
14 and ultimately allows wide aerial, aquatic, and terrestrial distribution in variable environments.
15 However, due to our changing climate, birds are faced with potential new challenges for
16 thermoregulation, such as more frequent extreme weather events, lower predictability of
17 climate, and increasing mean temperature. We provide **an overview** on thermoregulation in
18 birds and its endocrine and molecular mechanisms, pinpointing gaps in current knowledge and
19 recent developments, focusing especially on non-model species to understand the generality
20 of, and variation in, mechanisms. We highlight plasticity of thermoregulation and underlying
21 endocrine regulation, because thorough understanding of plasticity is key to predicting
22 responses to changing environmental conditions. To this end, we discuss how changing climate
23 is likely to affect avian thermoregulation and associated endocrine traits, and how the interplay
24 between these physiological processes may play a role in facilitating or constraining adaptation
25 to a changing climate. We conclude that while the general patterns of endocrine regulation of
26 thermogenesis are quite well understood, at least in poultry, the molecular and endocrine
27 mechanisms that regulate, e.g. mitochondrial function and plasticity of thermoregulation over
28 different time scales (from transgenerational to daily variation), need to be unveiled. Plasticity
29 may ameliorate climate change effects on thermoregulation to some extent, but the increased
30 frequency of extreme weather events, and associated **changes** in resource availability, may be
31 beyond the scope and/or speed for plastic responses. This could lead to selection for more
32 tolerant phenotypes, if the underlying physiological traits harbour genetic and individual
33 variation for selection to act on – a key question for future research.

34

35 Keywords: avian, thermoregulation, thyroid hormone, corticosterone, NST, avUCP, BMR,
36 plasticity, climate change, temperature, weather, metabolic rate, heterothermy

37 1. Aims and motivation

38 Birds maintain a high and (relatively) stable body temperature (T_b), on average $41.02 \pm 1.29^\circ\text{C}$
39 (s.d.) at rest during the active phase (Prinzinger et al., 1991), across a wide range of thermal
40 environments via physiological, morphological and behavioural modifications, including
41 endocrine regulation. This endothermic lifestyle enables the wide aerial, aquatic, and terrestrial
42 distribution of birds in variable habitats across the globe (Yahav, 2015). For example, desert
43 birds are able to live and reproduce in arid conditions where the environment can be hotter than
44 their own bodies, while resident species in temperate regions have to deal with winter
45 temperatures that may be 80°C below T_b . Due to our changing climate, all organisms, including
46 birds, are faced with potential new challenges for thermoregulation, such as more frequent
47 extreme weather events, lower predictability of climate, and increasing mean temperature
48 (IPCC 2014). The key question is how they will respond and potentially adapt.

49 This review is aimed for both endocrinologists interested to embrace the links of their
50 own field with thermoregulation and climate change, and for (thermal) ecologists interested to
51 embrace the underlying endocrine regulation of thermoregulation. Thus, the first aim of this
52 review is to provide an overview on thermoregulation in birds and its endocrine and molecular
53 mechanisms, pinpointing gaps in current knowledge and recent developments. We focus on
54 birds, because they are researched widely across the globe, and because recent work has
55 identified their substantial vulnerability to climate change (Conradie et al., 2019; Riddell et al.,
56 2019). However, many of the future challenges in light of climate change are not taxon-
57 specific. We especially focus on various aspects of (across and within-generation) plasticity in
58 thermoregulation and its underlying endocrine mechanisms, because proper understanding of
59 plasticity is a key to predicting responses to changing environmental conditions. Because
60 current literature on endocrinology and thermoregulation is biased towards work on poultry,
61 we have put special emphasis on studies in non-model species and wild populations to

62 understand the generality of, and variation in, mechanisms. To our knowledge, there are no
63 previous reviews that tie together the complexity of the endocrine basis of T_b regulation in birds
64 with plasticity of thermoregulation under climate change and also discuss the recent advances
65 in molecular mechanisms of thermoregulation. This summary will set the stage for the second
66 set of goals: discussing challenges for avian thermoregulation in the face of climate change,
67 how this may affect endocrine traits, and how these processes combine to facilitate or constrain
68 adaptation to the changing world. **Understanding the scope of physiological plasticity and**
69 **potential physiological constraints may help to understand the responses at individual and even**
70 **population level.** We purposely use the wording ‘climate change’ over ‘global warming’
71 throughout, to account for the multitude of direct and indirect changes in the environment that
72 challenge avian thermoregulation.

73

74 **Box 1. Glossary of key terminology concerning thermoregulation (following IUPS Thermal commission 2003)**

75 **Acclimatization** physiological or behavioural changes that occur within the lifetime of an organism to reduce
76 the strain of variation in the natural climate in the wild, such as geographic or seasonal responses to variation in
77 ambient temperatures

78 **Basal Metabolic rate (BMR)** Metabolic energy transformation calculated from measurements of heat
79 production or oxygen consumption in a rested and awake organism that is within its thermoneutral zone and has
80 fasted sufficiently long to be in a postabsorptive state

81 **Endothermy** The pattern of thermoregulation of animals in which the body temperature depends on a high and
82 controlled rate of endogenous heat production

83 **Epigenetic temperature adaptation** Lifelong(?) thermal adaptation that is triggered during prenatal
84 (embryogenesis) or early posthatching ontogeny, influencing the individuals’ capacity to produce or dissipate
85 heat

86 **Hyperthermia** The condition of an animal where body core temperature is above its range specified for the
87 normal active state of the species

88 **Hypothermia** The condition of an animal where body core temperature is below its range specified for the
89 normal active state of the species

90 **Non-shivering thermogenesis (NST)** Heat production due to metabolic energy transformation by processes that
91 do not involve contraction of skeletal muscles

92 **Resting Metabolic Rate (RMR)** The metabolic rate of an animal at rest in a specified environmental context,
93 and not necessarily in a postabsorptive state.

94 **Shivering thermogenesis (ST)** Heat production due to increased contractile activity of skeletal muscles (not
95 involving voluntary movements)

96 **Thermoneutral zone (TNZ)** the range of ambient temperatures at which normothermic body temperature is
97 maintained without regulatory changes in metabolic heat production or heat dissipation

98

99 **2. A brief overview of thermoregulation in birds**

100 The thermoregulatory system that enables maintenance of a relatively constant T_b over a wide
101 range of environmental temperatures in birds consists of (Fig 1, modified from Yahav, 2015):

102 (1) a *sensory part*, which detects changes in the environment (thermo-, osmo-, and baro-
103 receptors), (2) *an integrating part*, the thermoregulatory center at preoptic anterior
104 hypothalamus (PO/AH), in which temperature-sensitive neurons monitor local temperature
105 changes and temperature information received from peripheral thermoreceptors. The T_b set
106 point is then defended by mechanisms for heat production or heat loss depending on the thermal
107 status of the bird; and (3) *the command part*, involving neurological and endocrine signals that
108 lead to downstream mechanisms for T_b control, viz. shivering thermogenesis (ST), non-
109 shivering thermogenesis (NST), evaporative heat loss (including respiratory- and cutaneous
110 heat loss), peripheral vasoconstriction or vasodilation, and behavioural changes (e.g. basking,
111 huddling, shade/cover seeking).

112 Potential mechanisms for elevating the capacity for thermogenesis in birds include (i)
113 increasing muscle mass devoted to ST and possibly NST (but see Milbergue et al., 2018 for
114 recent contrasting results) (ii) increasing mass-specific aerobic enzyme capacity of muscle
115 tissue (Bicudo et al., 2002; Liknes and Swanson, 1996; potentially also liver, see Liu et al.,
116 2006), and (iii) increasing mitochondrial density and/or respiration rate to fuel aerobic
117 metabolism, and (iv) possibly increasing NST (Collin et al., 2003b; Dridi et al., 2004). In ST,
118 the birds increase the rate of heat production by increased contractile activity in the skeletal
119 muscles, whereas, in NST, heat production is increased via metabolic energy transformations
120 which do not include contraction of muscles. ST contributes most to thermogenesis in birds
121 (e.g. Hohtola, 2002). NST (in muscle and liver tissue, in contrast to mammalian brown adipose
122 tissue NST) is probably widespread in birds (e.g. Dridi et al., 2008; Mozo et al., 2005;
123 Raimbault et al., 2001; Talbot et al., 2004; Vianna et al., 2001a; Vianna et al., 2001b), but
124 direct evidence for a significant contribution of NST to heat production is still scarce (Teulier
125 et al., 2010; Teulier et al., 2014). The molecular mediators of NST in mitochondria have been
126 heavily discussed, and may include (i) the avian homolog of mammalian uncoupling protein

127 (avUCP) - an anion-carrier protein that, by dissipating the proton gradient across the inner
128 mitochondrial membrane, potentially uncouples respiration from ATP synthesis (Dridi et al.,
129 2008; Mozo et al., 2005; Raimbault et al., 2001; Talbot et al., 2004; Vianna et al., 2001a;
130 Vianna et al., 2001b); (ii) adenine nucleotide translocase (ANT) as the uncoupling protein
131 (Walter and Seebacher (2009) or (iii) Ca²⁺ slippage to produce heat via binding of the peptide
132 sarcolipin (SLN), to Ca²⁺ATPase in muscle tissue (SERCA) (reviewed in Nowack et al.,
133 2017). In this review we focus on endocrine and molecular mechanisms underlying
134 thermoregulation, while neuronal mechanisms in vertebrates have been reviewed elsewhere
135 (e.g. Morrison et al., 2008).

136

137

138 **3. Endocrine and molecular mechanisms of thermoregulation in birds**

139 3.1. The role of the hypothalamus-pituitary-thyroid (HPT) axis in avian thermoregulation

140 Thyroid hormones (THs, triiodothyronine, T3 and thyroxine, T4) are the most important
141 hormones controlling thermogenesis; a link that was established already in the late 1950's (e.g.
142 Decuyper et al., 2005; Klandorf et al., 1981; Mellen and Wentworth, 1958; Mellen and
143 Wentworth, 1962). The proposed hormonal and molecular pathways with HPT-axis
144 involvement on thermogenesis are outlined in Fig 2.

145 PO/AH is activated by input from **thermoreceptors**. **PO/AH then** stimulate the
146 hypothalamic paraventricular nucleus (PVN) and leads to an increase in thyrotropin releasing
147 hormone (TRH) synthesis and secretion (Arancibia et al., 1996). TRH stimulates the
148 thyrotrophs in the anterior pituitary to secrete thyroid stimulating hormone (TSH), which
149 interacts with the follicular cell membrane receptors in the thyroid gland. This results increased
150 thyroid hormone (mainly T4) synthesis and release. **T4 is the precursor form of T3, the**

151 biologically active form. T4 is converted to T3 in tissues by deiodinase enzymes (DIO1-3).

152 The secretion of TSH by the pituitary is (besides hypothalamic TRH) modulated by a negative
153 feedback mechanism of T3. Alternatively, cold exposure can lead to increased conversion of
154 T4 to T3 (and less to inactive rT3) by deiodinase enzymes (DIO1-3) in tissues, mostly in the
155 liver (Collin et al., 2003a; Van der Geyten et al., 1999), thus leading to higher circulating T3
156 levels. In tissues, T3 binds to both nuclear and mitochondrial receptors and influences gene
157 expression to modulate metabolic rates and respiration (see below).

158 There is experimental evidence supporting the modulatory role of THs on
159 thermoregulation within the thermoneutral zone (TNZ), also coined ‘obligatory
160 thermogenesis’: For example, experiments where birds were made **hypothyroid (i.e., lacking**
161 **THs) using drugs blocking TH release**, or when thyroid glands were removed (thyroidectomy),
162 reported reduced heat production in poultry (e.g. Mellen and Wentworth, 1962), whereas
163 experimental administration of THs stimulated thermogenesis (Arieli and Berman, 1979).
164 Experimental elevation of THs in blood increased thermogenesis also in non-model species,
165 little buntings (*Emperiza pusilla*) (Liu et al., 2006), and **positive** correlations between TH
166 **concentration** and thermogenesis were observed in goldfinches (*Carduelis tristis*)(Dawson et
167 al., 1992), great tits (*Parus major*) and willow tits (*Poecile montanus*) (Silverin et al., 1989).
168 In addition, a growing body of (mostly correlational) evidence suggests a positive association
169 between TH **concentration (T3)** and basal metabolic rate (BMR) in several non-model bird
170 species measured in free-ranging populations (Bobek et al., 1977; Chastel et al., 2003; Kim,
171 2008; Liu et al., 2006; Vezina et al., 2009; Zheng et al., 2014a).

172 Thyroid hormones are important for thermogenesis below thermoneutrality (also
173 coined ‘facultative thermogenesis’ see Fig 2). **They are likely involved in regulating non-**
174 **shivering thermogenesis (NST), while shivering thermogenesis (ST) may be predominantly**
175 **controlled directly via neuronal mechanisms (Morrison et al., 2008). Mitochondria in avian**

176 skeletal muscle have recently been found to express thyroid hormone receptors (see e.g. Cioffi
177 et al., 2013 for reviews on mammals; Lanni et al., 2016; Lassiter et al., 2018). For example, an
178 increase in potential uncoupling protein, avUCP, expression was associated with increased
179 plasma T3 levels and heat production in chicken (Collin et al., 2003a). Furthermore,
180 experimental elevation of T3 caused an overexpression of avUCP mRNA, while a thyroid
181 blocker (methimazole) treatment significantly downregulated its expression (Collin et al.,
182 2003b; Walter and Seebacher, 2009), supporting the involvement of THs in avUCP regulation.
183 The other potential uncoupling protein, adenine nucleotide translocase (ANT) may also be
184 controlled by THs, because its expression was decreased by TH blockers (Walter and
185 Seebacher, 2009). Finally, THs also influenced expression of, a known metabolic mediator
186 (PGG-1) in mammals (Walter and Seebacher, 2007; 2009), providing another potential
187 molecular mediator for NST in birds. However, the exact molecular mechanisms how THs may
188 be controlling the uncoupling proteins and, thus, NST in birds are not understood, while in
189 mammals, UCP and PGC1 sequences show response elements for thyroid hormone receptor
190 (e.g. Rabelo et al., 1996; Wulf et al., 2008). Also non-genetic pathways of TH action have been
191 characterized, mostly in rodents (reviewed in Cheng et al., 2010; Davis et al., 2016; Davis et
192 al., 2018; Singh et al., 2018), yet some indication of non-genomic influence of THs on
193 mitochondria e.g. glucose uptake was observed in chicken embryos (Segal and Gordon, 1977).

194 In most studies, associations between THs and thermogenesis are based on circulating
195 hormone measurements. However, the final availability of THs is influenced by plasma binding
196 proteins, conversion of THs by deiodinase enzymes (DIO1-3) in the target tissues, and the
197 responsiveness to THs depends on receptor densities (Darras et al., 2006). As expected,
198 ambient temperature has also been found to influence deiodination: Increased hepatic T4 to T3
199 conversion via increased DIO2 expression was detected in cold-exposed chickens (Ikegami et
200 al., 2015; Rudas and Pethes, 1984; Rudas and Pethes, 1986), while heat stress decreased DIO2

201 expression (Jastrebski et al., 2017). Cold exposure also decreased hepatic DIO3 activity in
202 **domestic** chicks (Collin et al., 2003a), leading to less T3 **degradation. To our knowledge,**
203 variation in TH receptor expression (either nuclear or mitochondrial) has not been studied in
204 response to temperature variation in birds. In mice and rats, mitochondrial receptor (p43)
205 overexpression was recently found to be associated with higher T_b (Bertrand-Gaday et al.,
206 2016). In vivo (knockout) and in vitro studies in mice revealed that p43 is associated with
207 mitochondrial biogenesis, activity, mito-nuclear crosstalk and even muscle metabolic and
208 contractive phenotype (reviewed in Wrutniak-Cabello et al., 2017; Wrutniak-Cabello et al.,
209 2018), but similar data is lacking from birds.

210

211 3.2. The role of the hypothalamus-pituitary-adrenal (HPA) axis in avian thermoregulation

212 **Glucocorticoids are crucial for maintaining physiological and energetic homeostasis.**
213 **Following a stressor, corticosterone (CORT) - the avian glucocorticoid -** is released from the
214 adrenals (stress-induced CORT) in response to adrenocorticotrophic hormone (ACTH) from the
215 hypothalamus. Fast temperature changes, induced by both cooling and heating, have been
216 shown to increase circulating CORT across captive and wild species in both correlative and
217 experimental studies (Bize et al., 2010; de Bruijn and Romero, 2011; Frigerio et al., 2004;
218 Jessop et al., 2016; Jimeno et al., 2018; Krause et al., 2016; Wingfield, 2015; Wingfield et al.,
219 2017; Xie et al., 2017); Shipley et al. 2019). **Both baseline and stress-induced CORT may be**
220 **affected by temperature (reviewed e.g. in Jessop et al. 2016).** Thus, it has been suggested that
221 CORT may play a role in how the individual responds and adapts to rapid temperature changes.
222 Despite repeated observations of such patterns, the exact mechanism for how CORT may be
223 linked to thermoregulation, either physiologically or behaviourally, is not well understood.
224 Because CORT is needed for the synthesis of glucose from liver glycogen or fat reserves, the
225 most likely explanation is that this hormone mobilises internal energy reserves, and/or activates

226 food searching behaviour to fuel the higher metabolic rate in cold conditions (de Bruijn and
227 Romero, 2011; Jimeno et al., 2018). Finally, recent correlative studies also suggest an
228 association between baseline CORT, peripheral body temperature, and slow changes in
229 environmental temperature over winter and summer (blue tits, Jerem et al., 2018), which may
230 indicate that CORT is not only involved in short-term heat/cold stress.

231 In addition to its potential role in responses to thermal stress, the HPA-axis probably
232 also plays a role in the ontogeny of avian thermoregulation, interacting with the HPT-axis
233 (reviewed in Debonne et al., 2008). In neonatal chicks, injection of corticotropin releasing
234 hormone (CRH) induced thermogenesis and increased T_b (Tachibana et al., 2004; Takahashi et
235 al., 2005). CRH injection in chicken embryos also increased TSH and circulating T4 and T3
236 concentrations (Meeuwis et al., 1989), **potentially via CRH-receptors, expressed in the**
237 **thyrotrophs** (De Groef et al., 2005), suggesting interactions between CRH and THs on
238 thermoregulation. Interestingly, the HPT-axis became less responsive to CRH in adult chickens
239 (Geris et al., 2003), likely due to altered interaction with the peripheral TH deiodinase enzymes
240 (Darras et al., 2006), thus showing that such interactions between hormones on
241 thermoregulation may vary across stages in ontogeny.

242

243 3.3. The role of potential other endocrine mechanisms in thermoregulation

244 There is a plethora of other neuropeptides and hormones that may be linked to
245 thermoregulation, but the role of these is largely unexplored, especially beyond chicken
246 models. It is also well understood that many hormonal axes are likely to interact (see also
247 above). (i) **Nguyen et al. (2015)** discovered that hypothalamic orexigenic neuropeptide Y
248 (NPY) responds to cold exposure in poultry. (ii) **Melatonin**, an indoleamine produced in the
249 pineal gland, has been implicated to play a role in avian thermal homeostasis (John and George,

250 1991). Experimental melatonin administration increased T_b in chickens (e.g. Sinkalu et al.,
251 2015), and induced improved cold resistance, thermal insulation and maximal heat production
252 (similar to cold acclimatization) in quails (Saarela and Heldmaier, 1987; Saarela and Reiter,
253 1994). This is in line with melatonin showing seasonal and circadian patterns, and thus
254 conveying information on seasonal progression in birds and mammals (Nelson and Demas,
255 1997; Reierth et al., 1999).

256 Balancing energetic needs is essential for thermoregulation: both ST and NST, and
257 (some routes of) evaporative heat loss require energy, the availability of which often fluctuates
258 with high/low environmental temperatures. A few key hormones are likely to be involved with
259 energy balance during thermal stress: (iii) **Leptin** was found to be elevated following acute heat
260 and cold stress in liver and plasma in chicken (Dridi et al., 2008). It has been suggested to be
261 involved in regulating feed intake and lipid metabolism (reviewed in Zhang 2018), which are
262 tightly linked with thermoregulation. (iv) **Ghrelin**, a peptide hormone produced mainly in the
263 gastrointestinal tract, may also be indirectly linked to thermoregulation: peripheral
264 administration of ghrelin in turkeys increased levels of plasma CORT, glucose and T4
265 (Shahryar and Lotfi, 2017), suggesting indirect effects via e.g. thyroid hormones. Moreover,
266 experimentally increased leptin and ghrelin was associated with mass gain in the coal tit
267 (*Parus ater*, Henderson et al., 2018), which is likely to also (indirectly) influence
268 thermoregulation during winter.

269 In hot and dry environments, thermoregulation is often directed towards heat
270 dissipation which is mostly achieved by evaporative cooling. Because this is costly in terms of
271 water (Nord and Williams, 2015; Tieleman and Williams, 1999), it is important to understand
272 endocrine regulation of water balance. One of the key regulators is (v) **arginine vasotocin**
273 (AVT), produced in the posterior pituitary gland (neurohypophysis) of the brain. In a series of
274 experiments on starlings (*Sturnus vulgaris*), Nephew et al. (2005) showed that peripheral AVT

275 can decrease heart rate, feeding, drinking, preening, and overall activity. AVT also reduced
276 shivering and T_b but had no effects on blood pressure, heart rate or respiratory rate in pigeons
277 (*Columba livia*) (Hassinen et al., 1994; Hassinen et al., 1999). Finally, AVT was further found
278 to increase plasma levels of T4, and a decrease in that of T3 (John and George, 1992), which
279 may be one of the mechanisms linking AVT to thermoregulation.

280

281 3.4. Conclusions and notes

282 The majority of the known endocrine mechanisms in thermoregulation concern thermogenesis,
283 i.e. the production of heat below the TNZ. However, it is equally important to understand the
284 endocrine and neurological mechanisms of thermoregulation above the TNZ where heat needs
285 to be dissipated to keep T_b at set point and prevent overheating. These include evaporative heat
286 loss, facultative hyperthermia, vasodilation and multiple behavioural responses, such as
287 seeking cooler microclimates. Heat loss, vasomotor action, as well as many of the behavioural
288 effects are likely under neuronal control, including dopamine, as suggested in mammals
289 (Madden and Morrison, 2019; Terrien et al., 2011). However, there are few corresponding data
290 for birds. Filling these knowledge gaps can be important to understand responses to climate-
291 change driven extreme weather, such as heat waves and droughts, which is expected to become
292 more frequent in the coming years (see section §5).

293 Furthermore, as thermoregulation requires excess energy (in cold environments) and water
294 (in hot environments), the associated endocrine pathways of water and energy intake should
295 also be considered for a more complete understanding of the physiological state. Thus, the
296 relative contributions of other hormonal controllers of organismal thermal biology beyond HPT
297 and HPA axis on thermoregulation need to be further clarified.

298

299

300 4. Plasticity in thermoregulation and its endocrine control – five time-scales

301 Many bird species have a large capacity to plastically respond to varying environmental
302 temperature on different time scales via: (i) rapid stress-induced hyperthermia (ii) short-term
303 facultative hypo- or hyperthermia (iii) acclimatization, (iv) epigenetic temperature adaptation
304 or (v) transgenerational plasticity, as summarised in Fig 3.

305

306 4.1. Rapid stress-induced hyperthermia

307 Birds, like other endotherms, respond to acute ecological and psychological stressors (e.g.
308 predation) via immediate, stress-induced hyperthermia (Cannon, 1915). The response reflects
309 increased T_b set point regulated by the sympathetic-adrenal-medullary pathway, while CORT
310 could also play some role (Briese and Cabanac, 1991; Yahav, 2015). For certain stimuli, the
311 thermoregulatory changes during stress are sensitive to variation in environmental temperature
312 (Nord and Folkow, 2018). However, it is unlikely such immediate response will be
313 significantly altered in a climate change context. Thus, stress-induced T_b responses are not
314 discussed further.

315

316 4.2. Facultative hypo- and hyperthermia

317 T_b of birds fluctuates substantially around the normothermic mean ($41.02 \pm 1.29^\circ\text{C}$ (s.d.))
318 during the circadian cycle (Prinzinger et al., 1991). Many bird species deviate even further
319 from normothermia over time periods ranging from a few hours to several days, referred to as
320 facultative hypothermia (T_b below the normothermic range) and hyperthermia (T_b above the
321 normothermic range) (reviewed in Gerson et al., 2019) (McKechnie and Lovegrove, 2002; Ruf
322 and Geiser, 2015).

323 Facultative hypothermia is typically employed when birds are energy limited, either
324 because they feed on ephemeral resources, have high energy turnover rates, or reside in
325 challenging (e.g. resource-poor, cold) environments (McKechnie and Lovegrove, 2002;
326 Nilsson and Nord, 2017; Ruf and Geiser, 2015). It leads to energetic savings and significant
327 fitness benefits (Brodin et al., 2017). Facultative hyperthermia is frequent in in hot and dry
328 climate, reducing the need for evaporative cooling, and hence demand for water (reviewed by
329 Gerson et al., 2019).

330 The molecular and endocrine mechanisms underlying facultative hypo- and
331 hyperthermia are not well understood. CORT or testosterone could play a role in regulating
332 facultative hypothermia. In hummingbirds external CORT increased the use of torpor (Hiebert
333 et al., 2000). In mammals, experimental administration of testosterone has been shown to
334 inhibit torpor (Mzilikazi and Lovegrove, 2002). A potential testosterone-dependence could also
335 explain why, in birds, torpor was restricted to females in the Puerto Rican tody (*Todus*
336 *mexicanus*) (Merola-Zwartjes and Ligon, 2000), and hypothermia was deeper in females
337 compared to males in Eurasian skylarks (*Alauda arvensis*) and blue tits (*Cyanistes caeruleus*)
338 (Nord et al., 2009; Powolny et al., 2016). Finally, in chicken models, low temperature
339 combined with fasting, suppressed hepatic thyroid hormone deiodinase enzyme (DIO2) and
340 serum T3 level (Ikegami et al., 2015), which suggest that THs may also function as a regulatory
341 mechanism for facultative hypothermia in cold and food-restricted conditions.

342

343 4.3. Acclimatization

344 Acclimatization of thermoregulation refers to reversible physiological or behavioural changes
345 that occur within the lifetime of an organism to allow the individual to cope with longer-term
346 temperature variation over days or weeks. This allows maintained performance over a range of
347 environmental conditions, such as between seasons and across the species' distribution range

348 among populations (Fig 3). There is evidence that THs play a role in seasonal acclimatization:
349 For example, in wild migratory birds such as white-crowned sparrows (*Zonotrichia*
350 *leucophrys*) and red knots (*Calidris canutus canutus*), annual cycles of THs are correlated with
351 seasonal changes in BMR, suggesting that seasonal changes in TH could be involved in
352 adjusting energy expenditure to environmental conditions (Jenni-Eiermann et al., 2002). In
353 resident birds, passerines showed enhanced thermogenic capacity via seasonal increases of
354 muscle tissue used for thermogenesis (several muscle types, Hohtola, 2002; Milbergue et al.,
355 2018) and growth of metabolically active organs such as the liver and heart (reviewed by
356 Swanson and Vezina, 2015). These changes were coupled to increased activity of respiratory
357 enzymes and higher levels of T3 (Burger and Denver, 2002; Liknes and Swanson, 2011a;
358 Liknes and Swanson, 2011b; Silverin et al., 1989; Smit and McKechnie, 2010; Zheng et al.,
359 2014a; Zheng et al., 2014b), supporting the role of THs in seasonal acclimatization.

360

361 4.4. Epigenetic adaptation

362 Epigenetic temperature adaptation (e.g. Yahav, 2015) means that exposure to temperature
363 variation during the ontogeny of the thermoregulatory system (and HPT- and HPA-axes) alters
364 thermal physiology, presumably via changes to DNA methylation, which influences the
365 capacity of the individual to respond to variation in thermal environment in early and later life.
366 For example, chickens that are exposed to a short cold challenge exactly during the HPT and
367 HPA axis development in the egg are better heat-producers after hatching and later in life while
368 in contrast, chickens exposed to similar short-duration d heat challenges prenatally cope better
369 in higher ambient temperatures later in life (Kamanli et al., 2015; Loyau et al., 2015; Morita et
370 al., 2016; Piestun et al., 2009; Piestun et al., 2008a; Piestun et al., 2008b; Piestun et al., 2015;
371 Shinder et al., 2009; Yahav et al., 2004). For non-domesticated species, Nord & Nilsson (2011)

372 and DuRant et al. (2011), found that blue tits and wood ducks (*Aix sponsa*) that were incubated
373 in cold temperature throughout the incubation period had higher metabolic rate close to
374 independence, which was interpreted in the same way – i.e. a response that might improve
375 thermogenic capacity. However, wood ducks incubated in this manner were worse, not better,
376 at dealing with a cold challenge shortly after hatching (DuRant et al., 2013; DuRant et al.,
377 2012). Similar results have been obtained for chickens when incubated in chronically
378 hypothermic conditions (Black and Burggren, 2004), which suggests that there are switch
379 points were a thermal dose during embryogenesis transitions from being ameliorating to being
380 constraining.

381 Altered temperature tolerance is assumed to be associated with altered HPT-axis
382 function across species: chickens exposed to pre-natal heat showed reduced TH levels and
383 altered deiodinase enzyme expression in response to a thermal challenge later in life (Loyau et
384 al., 2014; Nassar et al., 2015; Piestun et al., 2009; Piestun et al., 2008a; Piestun et al., 2008b)
385 and thermal manipulation also influenced TH levels in hatching wood ducks (although later life
386 THs nor responses to thermal stress were not studied, DuRant et al., 2014). Unfortunately, no
387 data on the effects of prenatal temperatures on endocrine or other physiological mechanisms is
388 available from wild birds. Interestingly, heat exposure also altered stress-induced CORT later
389 in life in domestic chicken (e.g. Wilsterman et al., 2015). Thermal manipulation affected the
390 proportion of thermosensitive neurons, which can then influence the downstream neuronal and
391 hormonal responses involved in thermoregulation (Loh et al., 2004; Tzschentke and Basta,
392 2002). At the cellular level, expression of heat shock proteins (HSPs, i.e. protective protein
393 chaperones) was lower in birds that were heat-challenged in the egg compared to controls when
394 chicks were exposed to a thermal challenge after hatching. Interestingly, this was accompanied
395 with altered DNA methylation of the HSP promotor regions (Vinoth et al., 2018). Recent
396 transcriptomic studies suggest that pre-natal heat exposure may further affect vascularization

397 and angiogenesis in the chicken, likely influencing their ability to thermoregulate (Loyau et al.,
398 2013; Loyau et al., 2016). The neuronal/endocrinological pathways involved in these responses
399 have, however, not been studied.

400 In addition to prenatal temperatures, we believe that an important avenue for further
401 research will be to also address if post-hatching temperature could also have similar
402 developmental programming functions, because chicks are arguably poorly buffered against
403 temperature variation before their thermoregulatory system fully develops. For example,
404 pigeons and chicken raised in very hot ambient temperatures in early life were found to have
405 improved capacity for evaporative cooling as adults (Loyau et al., 2015; Marder and Arieli,
406 1988). Birds differ in the timing of development of thermoregulation and maturation of the
407 HPT-axis: in altricial species development occurs post-hatch, while in precocial species it
408 occurs largely during the embryonic period (reviewed by Debonne et al., 2008; McNabb, 2007;
409 Price and Dzialowski, 2018). This suggests that altricial species might be particularly
410 susceptible to epigenetic thermal adaptation post-hatching. Here again, studies extending
411 beyond captive models, such as the precocial chicken, has high potential to reveal important
412 pathways present in other bird taxa. Importantly, it is currently also not understood how
413 permanent such adaptations are, as studies in chicken hardly extend beyond 30 days.

414

415 4.5. Transgenerational plasticity

416 Ambient temperature variation in the parental environment may also influence offspring
417 thermoregulation and temperature tolerance, so called transgenerational plasticity, as shown
418 recently in multiple taxa (*Drosophila*: Cavieres et al., 2019; fish: Donelson et al., 2012;
419 reviewed in Donelson et al., 2018; marine invertebrates: Morley et al., 2017; terrestrial
420 invertebrates: Zizzari and Ellers, 2014). Similar data from birds are lacking. However, in birds,

421 low ambient temperature increased the transfer of THs to eggs in great tits (Ruuskanen et al.,
422 2016c), which may have consequences for development (Hsu et al., 2017; Ruuskanen et al.,
423 2016a; Ruuskanen and Hsu, 2018), later HPT-axis function (Hsu et al., 2017), and thus
424 potentially also thermoregulation. Furthermore, in chicken, maternal heat stress influenced
425 embryonic heat shock protein expression and caused global DNA hypomethylation, but also
426 increased oxidative damage (Zhu et al., 2017), while any corresponding influence on
427 thermoregulation and adaptive plasticity has not been studied. Transgenerational plasticity
428 could include a multitude of mediators of parental temperature effects, such as DNA
429 methylation/histone modification, transfer of (small)mRNAs, hormones and other components
430 in the eggs and sperm, with possible links to (the development of) thermoregulation, as shown
431 in other taxa (Adrian-Kalchhauser et al., 2018; Kekalainen et al., 2018; Salinas and Munch,
432 2012; Weyrich et al., 2016a; Weyrich et al., 2016b).

433

434 4.6. Conclusions and notes

435 What becomes clear in this section is that there are correlative links showing that expression
436 of thermoregulatory traits (and related energy and water balance) have an endocrine basis (on
437 five time-scales), but that the responses may be either adaptive or mal-adaptive.

438

439

440 5. **Thermoregulation in a changing climate:** What is changing, and what are the challenges
441 for thermoregulation?

442 Climate change brings about various types of challenges for thermoregulation, the most
443 important of which are summarized in Fig 4. It is likely that the predicted average increase of
444 some 1.5°C compared to pre-industrial times by the end of the 21st century will pose, at most,

445 a minor **direct threat per se**, as both the absolute increase and the slow rate of temperature
446 change is arguably well within scope of short- and long-term adaptations (see plasticity, section
447 §4). **Yet, indirect effects are likely. However**, we caution on concluding on general trends,
448 because (i) the changes in temperature are not likely to be uniform across the globe (e.g.
449 warming is faster in the arctic region), and (ii) the scope for further adaptation may be limited
450 in some species, e.g. in tropics and subtropics already enduring considerable heat load (cf.
451 DuRant et al. 2019).

452 What is likely to be a more relevant challenge for thermoregulation is the predicted
453 increases in the frequency of weather irregularities, such as heat waves (IPCC, 2014; Rahmstorf
454 and Coumou, 2011; Stillman, 2019; Wingfield et al., 2017), which can bring negative and even
455 lethal consequences in wild bird populations (desert populations of birds Gardner et al., 2017;
456 McKechnie and Wolf, 2010) and for the poultry industry (Kumari and Nath, 2018). The
457 challenge may be especially severe for species adapted to relatively narrow temperature ranges
458 (Boyles et al., 2011a; Boyles et al., 2011b), such as birds in the tropic (Huey et al., 2012; Khaliq
459 et al., 2014), and those already operating close to their upper thermal limit such as desert birds
460 **(Gerson et al., 2019). However, even birds inhabiting far less extreme, thermally variable, and**
461 **generally colder habitats, may suffer the negative consequences of acute heat stress (blue tits**
462 **and great tits (Andreasson et al., 2018; Nord and Nilsson, 2019; Rodriguez et al., 2016).**

463 In addition to heat waves, climate change is likely to lead to milder and more unstable
464 winter weather (IPCC, 2014). This aspect has received much less attention than summer heat
465 waves in both physiological and ecological research. Even moderate warming events in winter
466 may cause problems in cold-acclimatized birds: for example Adelie penguins (*Pygoscelis*
467 *adeliae*) suffered very low reproduction already at temperatures just above 0°C and rainy
468 conditions (Ropert-Coudert, 2014), though it is unclear if this was directly or indirectly linked

469 to thermoregulation. Thus, relative, not only absolute, temperature changes, and the effects of
470 changing temperature on the ecosystem, should always be considered.

471 Importantly, the most severe challenges may not be posed by temperature per se, but
472 indirectly because mean temperature changes, extremes and changes in humidity are likely to
473 influence food and water availability for birds at all trophic levels (Boyles et al., 2011a;
474 Tieleman and Williams, 1999). We suggest that these indirect changes due to climate change
475 can lead to challenges not only for energy acquisition, but also directly for thermoregulation
476 for birds in hot and dry climates. Specifically, heat loss in birds is only by evaporation **when**
477 **ambient temperature exceeds T_b** , and dry heat loss is increasingly less effective as the latter
478 approaches the **former**. **A modelling** approach of avian evaporative water requirements and
479 survival times revealed that the IPCC-predicted increases in maximum air temperatures will
480 result in large 150-200% increases in water requirements relative to current values in small
481 birds, which might severely reduce survival during extremely hot weather if water is not
482 available (McKechnie and Wolf, 2010).

483 **Finally, climate change also concerns production animals, as temperatures in rearing**
484 **facilities cannot always be controlled. Poultry are genetically selected for a fast growth rate in**
485 **a stable temperature, and express high metabolic rate which has impacted their temperature**
486 **tolerance (Tickle et al., 2018), making them susceptible to both high and low environmental**
487 **temperatures (Tickle and Codd, 2019). To this end, a vast amount of work has been performed**
488 **to identify the physiological and behavioural responses to heat (and cold) stress to improve**
489 **production strategies (reviewed in Kumari and Nath, 2018)**

490

491 **6. How to respond to climate change, and the role of endocrine control**

492 Bird species may respond to new thermoregulatory challenges that follow climate change by
493 three mechanisms: 1) populations may shift distributions to track their original environment

494 (range shifts, reviewed e.g in Devictor et al., 2008; La Sorte and Jetz, 2012); 2) individuals
495 within a population may show phenotypic plasticity of thermal and metabolic responses to
496 temperature, either within or across generations; 3) selection may lead to microevolutionary
497 changes (i.e., adaptation) in temperature tolerance or plasticity and its underlying
498 endocrinological and molecular mechanisms. Endocrine mechanisms could play a role in 2 and
499 3, and are thus discussed here.

500

501 6.1. Climate change and plasticity in thermoregulation: scope and speed, costs and constraints

502 Within-species plasticity of thermoregulation and associated endocrine traits were reviewed in
503 section §4. The potential role of transgenerational plasticity in adapting to climate change has
504 been recently addressed across taxa (Bonduriansky et al., 2012; Cavieres et al., 2019; Donelson
505 et al., 2018; Meylan et al., 2012; Ruuskanen et al., 2016c; Shama et al., 2014; Stillman, 2019).

506 We argue that plasticity via transgenerational/epigenetic adaptation may allow birds to cope
507 better with climate-change related higher/lower mean temperature. However, we also speculate
508 that transgenerational effects may cause maladaptation. For example, if developmental
509 temperature is predisposing for the thermoregulatory phenotype, this could occur if
510 temperatures during parental/pre-natal/early postnatal stages differ from those that the
511 individual will **experience in its future environment, e.g. for birds that develop under the**
512 **influence of a heat wave (cf. Burness et al., 2013). Alternatively, birds that develop during**
513 **spells of extreme weather may suffer costs to normal growth and maturation, with potentially**
514 **lasting negative effects on their metabolic phenotype. However,** it has been recently suggested
515 that embryos may also express considerable physiological and even behavioural plasticity in
516 reptiles and birds (reviewed in Du and Shine, 2015). The capacity for early-life plasticity can
517 be crucial for survival: if extreme events would kill off young before they reach maturity,
518 plasticity in adult individuals will be irrelevant (cf. Burggren, 2018).

519 Many bird species have excellent capacities to plastically acclimatize to different
520 ambient temperatures during their lifetime (see sections 4.2, 4.3). Yet, there is also some
521 evidence (from invertebrates) that higher basal temperature tolerance may constrain further
522 thermal acclimatization (Gerken et al., 2015), which should be addressed in future studies.
523 Furthermore, the speed of acclimation may be crucial in responding to unpredictable weather
524 (see also Dubois et al., 2016; Swanson and Olmstead, 1999). There are indications that the
525 acclimatization to increasing and decreasing temperature is not uniform: Dubois et al. (2016)
526 found in experimental conditions that thermogenic capacity was lost at a faster rate when
527 temperature increased, than it was gained when temperature decreased. When considering that
528 thermogenic performance may be linked to overwinter survival (Petit et al., 2017), we propose
529 that a reduction of thermogenic capacity during increasingly frequent spells of mild winter
530 weather in the temperate region (IPCC 2014) could prove challenging for resident bird species.

531 A potential endocrine constraint for plasticity may lie in the fact that hormones have
532 highly pleiotropic functions on physiology apart from their functions on thermoregulation and
533 metabolism. For example, THs are critical in developmental programming, and CORT
534 influences behavior and even memory. It is currently not understood if such pleiotropy may
535 constrain optimal hormonal responses in temperature regulation. On the other hand, we may
536 speculate that hormonal and associated transcriptomic changes in the above-mentioned plastic
537 responses are likely to be relatively fast, and will not constrain the speed of acclimation. For
538 example, there is evidence for very rapid cellular responses, such as $\text{Na}^+\text{K}^+\text{ATPase}$ and oxygen
539 consumption to heat treatment in non-model species (house sparrow, *Passer domesticus*
540 Jimenez and Williams, 2014). Behavioral changes are likely to be immediate and may, at least
541 partly, mitigate effects of acute thermal stress. For example, several studies show that the
542 amount of physical work in birds is reduced at high ambient temperature (du Plessis et al.,
543 2012; Powers et al., 2017), presumably to avoid somatic costs of overheating (Nilsson and

544 Nord, 2018), though at the potential cost of reduced reproductive success (Nord and Nilsson,
545 2019). Beyond endocrine regulation, a major constraint on plasticity is likely to be the energetic
546 (heat production) or water constraint (of by evaporative cooling), see §3.

547 All in all, while physiological and behavioural plasticity may be sufficient to respond
548 to thermoregulatory needs to average temperature increases, inherent constraints and costs of
549 acclimatization means that responses to weather extremes and an unpredictable climate in the
550 future may not be sufficient in the long-term, and microevolution of thermal physiology may
551 be needed.

552

553 6.2. Climate change, microevolution in thermoregulation and its underlying physiological 554 mechanisms

555 A requirement for microevolutionary change in temperature tolerance is that the underlying
556 physiological, endocrine and molecular mechanisms show genetic variation on which selection
557 can act. Several key aspects in thermoregulation show individual and potentially genetic
558 variation across taxa: Multiple studies in wild and captive birds report individual variation in
559 BMR, reflected in moderate heritability and repeatability of these traits (Nilsson et al., 2009;
560 Ronning et al., 2007; Tieleman et al., 2009). In one of the rare studies on potential heritability
561 of heat loss mechanisms, Versteeg et al. (2008) reported that evaporative water loss also shows
562 individual variation (repeatability). Moreover, several studies indicated that there is individual
563 consistency in thermoregulatory reaction norms over a temperature gradient. This has been
564 reported in ectotherms such as common lizards (*Zootoca vivipara*, (Artacho et al., 2013) and
565 Western slimy salamanders (*Plethodon albagula* (Careau et al., 2014), and in endotherms such
566 as mouse lemurs (*Microcebus murinus*, (Vuarin et al., 2013) and zebra finches (*Taeniopygia*

567 *guttata*, Briga and Verhulst (2017). The potential genetic background of such individual
568 plasticity in thermoregulatory reaction norms, has, however, not yet been studied.

569 Along with variation in metabolic rate, individual differences in hormonal and
570 molecular responses to temperature variation is predicted, and will be a key in adapting to
571 changing climate. To our knowledge, individual variation in responses to temperature
572 challenges in circulating THs, the key hormones underlying thermoregulation, or associated
573 molecular pathways (DIOs, receptors) has not been tested. However, there is some evidence
574 on heritability of the mean levels of T3 in eggs (Ruuskanen et al., 2016b), suggesting scope for
575 microevolutionary responses of THs to climate change. Interestingly, endocrine responses to
576 thermal stress have been shown to vary among poultry breeds, potentially suggestive of genetic
577 variation in temperature tolerance (Xie et al., 2018). Moreover, there is rather good evidence
578 that individuals consistently differ in their CORT responses to standard stressor (Cockrem,
579 2013) as well as food stress (Lendvai et al., 2014), while CORT shows also moderate
580 heritability (Stedman et al., 2017; Taff et al., 2018). To our knowledge, there is no data on
581 individual plasticity in thermogenic mechanisms (ST, NST), mitochondrial function or its
582 molecular basis (such as ANT, avUCP or SERCA expression, see §3) in birds.

583 Taken together, we still have very limited knowledge on the capacity for
584 microevolution of thermoregulation and its associated endocrine and molecular mechanisms,
585 and we currently lack direct studies on microevolution of thermal physiology in birds.
586 However, some key thermoregulatory and endocrine traits seem to show individual variation
587 with a genetic basis. In mammals, artificial selection for BMR led to changes in 10 generations
588 (Sadowska et al., 2015), which suggests that a response to temperature changes could
589 potentially be rather fast. However, even if there would be variation for selection to act on, the
590 most important open question is which traits and mechanisms will/may be under selection in a
591 changing climate. Is there selection on the mean values, or on scope and speed of plasticity

592 when weather changes abruptly? What is the main selective agent? If selective agents like heat
593 waves are rare, selective pressure is low, and microevolution likely plays a little role (Boyles
594 et al., 2011b). However, increasing frequency of extreme events may increase the selective
595 pressure on speed or scope of plasticity, at least if they occur frequently enough to be
596 experienced more than once over the lifetime of an individual.

597

598 **7. Conclusions and future directions**

599 We conclude that while the general patterns in the endocrine regulation of thermogenesis are
600 quite well understood, at least in poultry, the molecular and endocrine mechanisms controlling
601 e.g. mitochondrial function need to be unveiled. In contrast, we have rather poor knowledge on
602 the molecular mechanisms controlling heat loss. Birds express plasticity on a wide range of
603 time scales, from transgenerational and developmental to day-to-day changes in response to
604 environmental temperature variation, but the molecular mechanisms are also poorly described.
605 Importantly, many of those can only be studied in non-model species that live under fluctuating
606 temperature and experience climate change as it is, emphasizing the need for a wide range of
607 study species to understand the scope of plasticity. Plasticity can ameliorate climate change
608 effects on thermoregulation to some extent. However, the increased frequency of extreme
609 weather events may be beyond the scope or speed for plastic responses, and so may potentially
610 result in mass mortality (Gardner et al., 2017; McKechnie and Wolf, 2010) and selection for
611 more tolerant phenotypes. To understand which traits can respond to selection, more studies
612 on genetic variation in thermoregulation, its plasticity, and underlying endocrine and molecular
613 mechanisms are needed. The combination of climate change related effects, that include
614 alterations in humidity, precipitation patterns and primary production, are likely to pose even
615 greater challenges for plastic thermoregulatory phenotypes. The underlying endocrine and
616 molecular mechanisms involved in such responses to the changing world, and their costs and

617 constraints, should be studied more closely. We must also remember that even minor changes
618 in absolute temperature can bring cascading effects to the ecosystems in which birds live, with
619 potential negative feedback on several aspects of thermoregulation. Below, we outline some
620 future directions:

621 (i) *Individual and population-level variation in endocrine responses to temperature*

622 To understand if and how endocrine mechanism may adapt or constrain how populations and
623 species may respond to changing temperatures, we need more experimental studies on the
624 individual reaction norms on endocrine and metabolic traits, and underlying molecular
625 mechanisms, as well as on the correlation between baseline and speed and slope of change.
626 Data on heritability and plasticity could be acquired by measuring hormones in pedigreed
627 populations, combined with within-subject experimental thermal exposures (relevant to climate
628 change scenarios), measuring relevant hormones. It is especially important to not only consider
629 the well-known endocrine pathways including THs, but extend to include other associated
630 endocrine pathways such as CORT, melatonin and leptin.

631 (ii) *Transgenerational/epigenetic adaptation and endocrine mechanisms*

632 To understand transgenerational effects and developmental programming of thermoregulation,
633 the molecular and endocrine mechanisms of transgenerational and epigenetic adaptation should
634 be further addressed. This could be achieved via e.g. parental and prenatal manipulations (such
635 as hormones) combined with post-natal/adult thermal challenges, and tracking the underlying
636 molecular (e.g. DNA methylation) signatures.

637 (iii) *More realistic experimental designs*

638 Results of laboratory studies on acclimation are difficult to use in predicting how thermal
639 physiology will be affected in wild populations where climate-change effects on temperature,
640 humidity, and food availability can act synergistically on selection for thermal phenotypes.
641 Similarly, behavioural strategies and movement that influence temperature tolerance in the

642 field populations can only be simulated in the lab with difficulty. Following from the previous
643 points, experimental designs testing thermal physiology should include multiple interacting
644 factors as well as temporal stochasticity to yield more realistic estimates of how
645 thermoregulatory and endocrine traits may be affected by climate change.

646

647 **Acknowledgements**

648 We thank Laurence Besseau and Laura Nisembaum for invitation to the special issue, and
649 two anonymous reviewers for comments that improved a previous version of the manuscript.
650 SR was financially supported by the Academy of Finland. BYH was financially supported by
651 the Academy of Finland and Ella and Georg Ehrnrooth Foundation. AN was supported by the
652 Birgit and Hellmuth Hertz Foundation / The Royal Physiographic Society of Lund (grant no.
653 2017-39034)

654

655

656 **References**

657

- 658 Adrian-Kalchauer, I., et al., 2018. RNA sequencing of early round goby embryos reveals that
659 maternal experiences can shape the maternal RNA contribution in a wild vertebrate. *Bmc*
660 *Evolutionary Biology*. 18, 14.
- 661 Andreasson, F., et al., 2018. Experimentally increased nest temperature affects body temperature,
662 growth and apparent survival in blue tit nestlings. *Journal of Avian Biology*. 49, 14.
- 663 Arancibia, S., et al., 1996. Neuroendocrine and autonomous mechanisms underlying
664 thermoregulation in cold environment. *Neuroendocrinology*. 64, 257-267.
- 665 Arieli, A., Berman, A., 1979. EFFECT OF THYROXINE ON THERMOREGULATION IN THE MATURE
666 DOMESTIC-FOWL (*GALLUS-DOMESTICUS*). *Journal of Thermal Biology*. 4, 247-249.
- 667 Artacho, P., et al., 2013. Interindividual Variation in Thermal Sensitivity of Maximal Sprint Speed,
668 Thermal Behavior, and Resting Metabolic Rate in a Lizard. *Physiological and Biochemical*
669 *Zoology*. 86, 458-469.
- 670 Bertrand-Gaday, C., et al., 2016. Temperature homeostasis in mice lacking the p43 mitochondrial T3
671 receptor. *Febs Letters*. 590, 982-991.
- 672 Bicudo, J., et al., 2002. Adaptive thermogenesis in hummingbirds. *Journal of Experimental Biology*.
673 205, 2267-2273.
- 674 Bize, P., et al., 2010. Sudden weather deterioration but not brood size affects baseline
675 corticosterone levels in nestling Alpine swifts. *Hormones and Behavior*. 58, 591-598.
- 676 Black, J. L., Burggren, W. W., 2004. Acclimation to hypothermic incubation in developing chicken
677 embryos (*Gallus domesticus*) - I. Developmental effects and chronic and acute metabolic
678 adjustments. *Journal of Experimental Biology*. 207, 1543-1552.
- 679 Bobek, S., et al., 1977. AGE-RELATED-CHANGES IN OXYGEN-CONSUMPTION AND PLASMA THYROID-
680 HORMONE CONCENTRATION IN YOUNG CHICKEN. *General and Comparative Endocrinology*.
681 31, 169-174.
- 682 Bonduriansky, R., et al., 2012. The implications of nongenetic inheritance for evolution in changing
683 environments. *Evolutionary Applications*. 5, 192-201.

684 Boyles, J. G., et al., 2011a. Adaptive Thermoregulation in Endotherms May Alter Responses to
685 Climate Change. *Integrative and Comparative Biology*. 51, 676-690.

686 Boyles, J. G., et al., 2011b. Can generalized models of thermoregulation predict responses of
687 endotherms to climate change? *Integrative and Comparative Biology*. 51, E15-E15.

688 Briese, E., Cabanac, M., 1991. STRESS HYPERTHERMIA - PHYSIOLOGICAL ARGUMENTS THAT IT IS A
689 FEVER. *Physiology & Behavior*. 49, 1153-1157.

690 Briga, M., Verhulst, S., 2017. Individual variation in metabolic reaction norms over ambient
691 temperature causes low correlation between basal and standard metabolic rate. *Journal of*
692 *Experimental Biology*. 220, 3280-3289.

693 Brodin, A., et al., 2017. Adaptive temperature regulation in the little bird in winter: predictions from
694 a stochastic dynamic programming model. *Oecologia*. 185, 43-54.

695 Burger, M. F., Denver, R. J., 2002. Plasma thyroid hormone concentrations in a wintering passerine
696 bird: Their relationship to geographic variation, environmental factors, metabolic rate, and
697 body fat. *Physiological and Biochemical Zoology*. 75, 187-199.

698 Burggren, W., 2018. Developmental phenotypic plasticity helps bridge stochastic weather events
699 associated with climate change. *Journal of Experimental Biology*. 221, 9.

700 Burness, G., et al., 2013. Post-hatch heat warms adult beaks: irreversible physiological plasticity in
701 Japanese quail. *Proceedings of the Royal Society B-Biological Sciences*. 280, 6.

702 Cannon, W., 1915. *Bodily*
703 *Changes in Pain, Hunger, Fear and Rage*. D. Appleton and Company, New York.

704 Careau, V., et al., 2014. Individual (co)variation in thermal reaction norms of standard and maximal
705 metabolic rates in wild-caught slimy salamanders. *Functional Ecology*. 28, 1175-1186.

706 Cavieres, G., et al., 2019. Transgenerational and within-generation plasticity shape thermal
707 performance curves. *Ecology and Evolution*. 9, 2072-2082.

708 Chastel, O., et al., 2003. Pre-breeding energy requirements: thyroid hormone, metabolism and the
709 timing of reproduction in house sparrows *Passer domesticus*. *Journal of Avian Biology*. 34,
710 298-306.

711 Cheng, S. Y., et al., 2010. Molecular Aspects of Thyroid Hormone Actions. *Endocrine Reviews*. 31,
712 139-170.

713 Cioffi, F., et al., 2013. Thyroid hormones and mitochondria: With a brief look at derivatives and
714 analogues. *Molecular and Cellular Endocrinology*. 379, 51-61.

715 Cockrem, J. F., 2013. Corticosterone responses and personality in birds: Individual variation and the
716 ability to cope with environmental changes due to climate change. *General and Comparative*
717 *Endocrinology*. 190, 156-163.

718 Collin, A., et al., 2003a. Cold-induced enhancement of avian uncoupling protein expression, heat
719 production, and triiodothyronine concentrations in broiler chicks. *General and Comparative*
720 *Endocrinology*. 130, 70-77.

721 Collin, A., et al., 2003b. Thyroid status, but not insulin status, affects expression of avian uncoupling
722 protein mRNA in chicken. *American Journal of Physiology-Endocrinology and Metabolism*.
723 284, E771-E777.

724 Conradie, S. R., et al., 2019. Chronic, sublethal effects of high temperatures will cause severe
725 declines in southern African arid-zone birds during the 21st century. *Proceedings of the*
726 *National Academy of Sciences of the United States of America*. 116, 14065-14070.

727 Darras, V. M., et al., 2006. Thyroid hormone deiodination in birds. *Thyroid*. 16, 25-35.

728 Davis, P. J., et al., 2016. Nongenomic actions of thyroid hormone. *Nature Reviews Endocrinology*. 12,
729 111-121.

730 Davis, P. J., et al., *Molecular Basis of Nongenomic Actions of Thyroid Hormone*. In: G. Litwack, (Ed.),
731 *Thyroid Hormone*. Elsevier Academic Press Inc, San Diego, 2018, pp. 67-96.

732 Dawson, W. R., et al., 1992. METABOLIC ASPECTS OF SHIVERING THERMOGENESIS IN PASSERINES
733 DURING WINTER. *Ornis Scandinavica*. 23, 381-387.

734 de Bruijn, R., Romero, L. M., 2011. Behavioral and physiological responses of wild-caught European
735 starlings (*Sturnus vulgaris*) to a minor, rapid change in ambient temperature. *Comparative*
736 *Biochemistry and Physiology a-Molecular & Integrative Physiology*. 160, 260-266.

737 De Groef, B., et al., 2005. Hypothalamic control of the thyroïdal axis in the chicken: Over the
738 boundaries of the classical hormonal axes. *Domestic Animal Endocrinology*. 29, 104-110.

739 Debonne, M., et al., 2008. Involvement of the hypothalamic-pituitary-thyroid axis and its interaction
740 with the hypothalamic-pituitary-adrenal axis in the ontogeny of avian thermoregulation: a
741 review. *Worlds Poultry Science Journal*. 64, 309-321.

742 Decuyper, E., et al., 2005. Thyroid hormone availability and activity in avian species: A review.
743 *Domestic Animal Endocrinology*. 29, 63-77.

744 Devictor, V., et al., 2008. Birds are tracking climate warming, but not fast enough. *Proceedings of the*
745 *Royal Society B-Biological Sciences*. 275, 2743-2748.

746 Donelson, J. M., et al., 2012. Rapid transgenerational acclimation of a tropical reef fish to climate
747 change. *Nature Climate Change*. 2, 30-32.

748 Donelson, J. M., et al., 2018. Transgenerational plasticity and climate change experiments: Where do
749 we go from here? *Global Change Biology*. 24, 13-34.

750 Dridi, S., et al., 2004. Gene expression, tissue distribution and potential physiological role of
751 uncoupling protein in avian species. *Comparative Biochemistry and Physiology a-Molecular*
752 *& Integrative Physiology*. 139, 273-283.

753 Dridi, S., et al., 2008. Acute cold- and chronic heat-exposure upregulate hepatic leptin and muscle
754 uncoupling protein (UCP) gene expression in broiler chickens. *Journal of Experimental*
755 *Zoology Part a-Ecological and Integrative Physiology*. 309A, 381-388.

756 du Plessis, K. L., et al., 2012. The costs of keeping cool in a warming world: implications of high
757 temperatures for foraging, thermoregulation and body condition of an arid-zone bird. *Global*
758 *Change Biology*. 18, 3063-3070.

759 Du, W. G., Shine, R., 2015. The behavioural and physiological strategies of bird and reptile embryos
760 in response to unpredictable variation in nest temperature. *Biological Reviews*. 90, 19-30.

761 Dubois, K., et al., 2016. Basal and maximal metabolic rates differ in their response to rapid
762 temperature change among avian species. *Journal of Comparative Physiology B-Biochemical*
763 *Systemic and Environmental Physiology*. 186, 919-935.

764 DuRant, S. E., et al., 2014. Are thyroid hormones mediators of incubation temperature-induced
765 phenotypes in birds? *Biology Letters*. 10.

766 DuRant, S. E., et al., 2013. Incubation Conditions Are More Important in Determining Early
767 Thermoregulatory Ability than Posthatch Resource Conditions in a Precocial Bird.
768 *Physiological and Biochemical Zoology*. 86, 410-420.

769 DuRant, S. E., et al., 2011. Embryonic Developmental Patterns and Energy Expenditure Are Affected
770 by Incubation Temperature in Wood Ducks (*Aix sponsa*). *Physiological and Biochemical*
771 *Zoology*. 84, 451-457.

772 DuRant, S. E., et al., 2012. Incubation temperature affects the metabolic cost of thermoregulation in
773 a young precocial bird. *Functional Ecology*. 26, 416-422.

774 Frigerio, D., et al., 2004. Excreted corticosterone metabolites co-vary with ambient temperature and
775 air pressure in male Greylag geese (*Anser anser*). *General and Comparative Endocrinology*.
776 137, 29-36.

777 Gardner, J. L., et al., 2017. Effects of extreme weather on two sympatric Australian passerine bird
778 species. *Philosophical Transactions of the Royal Society B-Biological Sciences*. 372, 11.

779 Geris, K. L., et al., 2003. In vitro study of corticotropin-releasing hormone-induced thyrotropin
780 release: ontogeny and inhibition by somatostatin. *General and Comparative Endocrinology*.
781 132, 272-277.

782 Gerken, A. R., et al., 2015. Constraints, independence, and evolution of thermal plasticity: Probing
783 genetic architecture of long- and short-term thermal acclimation. *Proceedings of the*
784 *National Academy of Sciences of the United States of America*. 112, 4399-4404.

785 Gerson, A. R., et al., 2019. The functional significance of facultative hyperthermia varies with body
786 size and phylogeny in birds. *Functional Ecology*. 33, 597-607.

787 Hassinen, E., et al., 1994. VASOTOCIN AND ANGIOTENSIN-II AFFECT THERMOREGULATION IN THE
788 PIGEON, COLUMBA-LIVIA. *Comparative Biochemistry and Physiology a-Physiology*. 107, 545-
789 551.

790 Hassinen, E., et al., 1999. Cardiovascular and thermoregulatory responses to vasotocin and
791 angiotensin II in the pigeon. *Comparative Biochemistry and Physiology a-Molecular and
792 Integrative Physiology*. 123, 279-285.

793 Henderson, L. J., et al., 2018. Peripherally injected gherlin and leptin reduce food hoarding and mass
794 gain in the coal tit (*Periparus ater*). *Proceedings of the Royal Society B-Biological Sciences*.
795 285, 8.

796 Hiebert, S. M., et al., 2000. Corticosterone and nocturnal torpor in the rufous hummingbird
797 (*Selasphorus rufus*). *General and Comparative Endocrinology*. 120, 220-234.

798 Hohtola, E., 2002. Facultative and obligatory thermogenesis in young birds: a cautionary note.
799 *Comparative Biochemistry and Physiology a-Molecular & Integrative Physiology*. 131, 733-
800 739.

801 Hsu, B. Y., et al., 2017. Maternal thyroid hormones enhance hatching success but decrease nestling
802 body mass in the rock pigeon (*Columba livia*). *General and Comparative Endocrinology*. 240,
803 174-181.

804 Huey, R. B., et al., 2012. Predicting organismal vulnerability to climate warming: roles of behaviour,
805 physiology and adaptation. *Philosophical Transactions of the Royal Society B-Biological
806 Sciences*. 367, 1665-1679.

807 Ikegami, K., et al., 2015. Low Temperature-Induced Circulating Triiodothyronine Accelerates
808 Seasonal Testicular Regression. *Endocrinology*. 156, 647-659.

809 IPCC, Climate change 2014 synthesis report. 2014.

810 Jastrebski, S. F., et al., 2017. Chicken hepatic response to chronic heat stress using integrated
811 transcriptome and metabolome analysis. *Plos One*. 12.

812 Jenni-Eiermann, S., et al., 2002. Temporal uncoupling of thyroid hormones in Red Knots: T3 peaks in
813 cold weather, T4 during moult. *Journal of Ornithology*. 143, 331-340.

814 Jerem, P., et al., 2018. Eye region surface temperature reflects both energy reserves and circulating
815 glucocorticoids in a wild bird. *Scientific Reports*. 8, 10.

816 Jessop, T. S., et al., 2016. Multiscale Evaluation of Thermal Dependence in the Glucocorticoid
817 Response of Vertebrates. *American Naturalist*. 188, 342-356.

818 Jimenez, A. G., Williams, J. B., 2014. Rapid changes in cell physiology as a result of acute thermal
819 stress House sparrows, *Passer domesticus*. *Journal of Thermal Biology*. 46, 31-39.

820 Jimeno, B., et al., 2018. Glucocorticoid-temperature association is shaped by foraging costs in
821 individual zebra finches. *Journal of Experimental Biology*. 221, 4.

822 John, T. M., George, J. C., 1991. PHYSIOLOGICAL-RESPONSES OF MELATONIN-IMPLANTED PIGEONS
823 TO CHANGES IN AMBIENT-TEMPERATURE. *Photobiology: the Science and Its Applications*.
824 597-605.

825 John, T. M., George, J. C., 1992. EFFECTS OF ARGININE VASOTOCIN ON CARDIORESPIRATORY AND
826 THERMOREGULATORY RESPONSES IN THE PIGEON. *Comparative Biochemistry and
827 Physiology C-Pharmacology Toxicology & Endocrinology*. 102, 353-359.

828 Kamanli, S., et al., 2015. Effect of prenatal temperature conditioning of laying hen embryos:
829 Hatching, live performance and response to heat and cold stress during laying period.
830 *Journal of Thermal Biology*. 51, 96-104.

831 Kekalainen, J., et al., 2018. Sperm pre-fertilization thermal environment shapes offspring phenotype
832 and performance. *Journal of Experimental Biology*. 221.

833 Khaliq, I., et al., 2014. Global variation in thermal tolerances and vulnerability of endotherms to
834 climate change. *Proceedings of the Royal Society B-Biological Sciences*. 281, 8.

835 Kim, B., 2008. Thyroid hormone as a determinant of energy expenditure and the basal metabolic
836 rate. *Thyroid*. 18, 141-144.

837 Klandorf, H., et al., 1981. THE RELATIONSHIP BETWEEN HEAT-PRODUCTION AND CONCENTRATIONS
838 OF PLASMA THYROID-HORMONES IN THE DOMESTIC HEN. *General and Comparative*
839 *Endocrinology*. 45, 513-520.

840 Krause, J. S., et al., 2016. The effect of extreme spring weather on body condition and stress
841 physiology in Lapland longspurs and white-crowned sparrows breeding in the Arctic. *General*
842 *and Comparative Endocrinology*. 237, 10-18.

843 Kumari, K. N. R., Nath, D. N., 2018. Ameliorative measures to counter heat stress in poultry. *Worlds*
844 *Poultry Science Journal*. 74, 117-129.

845 La Sorte, F. A., Jetz, W., 2012. Tracking of climatic niche boundaries under recent climate change.
846 *Journal of Animal Ecology*. 81, 914-925.

847 Lanni, A., et al., 2016. Mitochondrial Actions of Thyroid Hormone. *Comprehensive Physiology*. 6,
848 1591-1607.

849 Lassiter, K., et al., 2018. Identification of mitochondrial hormone receptors in avian muscle cells.
850 *Poultry Science*. 97, 2926-2933.

851 Lendvai, A. Z., et al., 2014. Experimental Food Restriction Reveals Individual Differences in
852 Corticosterone Reaction Norms with No Oxidative Costs. *Plos One*. 9.

853 Liknes, E. T., Swanson, D. L., 1996. Seasonal variation in cold tolerance, basal metabolic rate, and
854 maximal capacity for thermogenesis in White-breasted Nuthatches *Sitta carolinensis* and
855 Downy Woodpeckers *Picoides pubescens*, two unrelated arboreal temperate residents.
856 *Journal of Avian Biology*. 27, 279-288.

857 Liknes, E. T., Swanson, D. L., 2011a. Phenotypic flexibility in passerine birds: Seasonal variation of
858 aerobic enzyme activities in skeletal muscle. *Journal of Thermal Biology*. 36, 430-436.

859 Liknes, E. T., Swanson, D. L., 2011b. Phenotypic flexibility of body composition associated with
860 seasonal acclimatization in passerine birds. *Journal of Thermal Biology*. 36, 363-370.

861 Liu, J. S., et al., 2006. Thyroid hormones increase liver and muscle thermogenic capacity in the little
862 buntings (*Emberiza pusilla*). *Journal of Thermal Biology*. 31, 386-393.

863 Loh, B., et al., 2004. Prenatal development of epigenetic adaptation processes in poultry: Changes in
864 metabolic and neuronal thermoregulatory mechanisms. *Avian and Poultry Biology Reviews*.
865 15, 119-128.

866 Loyau, T., et al., 2015. Cyclic variations in incubation conditions induce adaptive responses to later
867 heat exposure in chickens: a review. *Animal*. 9, 76-85.

868 Loyau, T., et al., 2013. Thermal manipulation of the embryo modifies the physiology and body
869 composition of broiler chickens reared in floor pens without affecting breast meat
870 processing quality. *Journal of Animal Science*. 91, 3674-3685.

871 Loyau, T., et al., 2016. Thermal manipulation of the chicken embryo triggers differential gene
872 expression in response to a later heat challenge. *Bmc Genomics*. 17, 15.

873 Loyau, T., et al., 2014. Thermal Manipulation during Embryogenesis Has Long-Term Effects on
874 Muscle and Liver Metabolism in Fast-Growing Chickens. *Plos One*. 9, 13.

875 Madden, C. J., Morrison, S. F., 2019. Central nervous system circuits that control body temperature.
876 *Neuroscience Letters*. 696, 225-232.

877 Marder, J., Arieli, Y., 1988. HEAT-BALANCE OF ACCLIMATED PIGEONS (*COLUMBA-LIVIA*) EXPOSED TO
878 TEMPERATURES UP TO 60-DEGREES-C TA. *Comparative Biochemistry and Physiology a-*
879 *Physiology*. 91, 165-170.

880 McKechnie, A. E., Lovegrove, B. G., 2002. Avian facultative hypothermic responses: A review.
881 *Condor*. 104, 705-724.

882 McKechnie, A. E., Wolf, B. O., 2010. Climate change increases the likelihood of catastrophic avian
883 mortality events during extreme heat waves. *Biology Letters*. 6, 253-256.

884 McNabb, F. M. A., 2007. The hypothalamic-pituitary-thyroid (HPT) axis in birds and its role in bird
885 development and reproduction. *Critical Reviews in Toxicology*. 37, 163-193.

886 Meeuwis, R., et al., 1989. THYROTROPIC ACTIVITY OF THE OVINE CORTICOTROPIN-RELEASING
887 FACTOR IN THE CHICK-EMBRYO. *General and Comparative Endocrinology*. 76, 357-363.

888 Mellen, W. J., Wentworth, B. C., 1958. STUDIES WITH THYROXINE AND TRIIODOTHYRONINE IN
889 CHICKENS. *Poultry Science*. 37, 1226-1226.

890 Mellen, W. J., Wentworth, B. C., 1962. OBSERVATIONS ON RADIOTHYROIDECTOMIZED CHICKENS.
891 *Poultry Science*. 41, 134-&.

892 Merola-Zwartjes, M., Ligon, J. D., 2000. Ecological energetics of the Puerto Rican Tody:
893 Heterothermy, torpor, and intra-island variation. *Ecology*. 81, 990-1003.

894 Meylan, S., et al., 2012. Hormonally mediated maternal effects, individual strategy and global
895 change. *Royal Society Philosophical Transactions Biological Sciences*. 367, 1647-1664.

896 Milbergue, M. S., et al., 2018. Large muscles are beneficial but not required for improving
897 thermogenic capacity in small birds. *Scientific Reports*. 8.

898 Morita, V. S., et al., 2016. Incubation temperature alters thermal preference and response to heat
899 stress of broiler chickens along the rearing phase. *Poultry Science*. 95, 1795-1804.

900 Morley, S. A., et al., 2017. Can acclimation of thermal tolerance, in adults and across generations, act
901 as a buffer against climate change in tropical marine ectotherms? *Journal of Thermal*
902 *Biology*. 68, 195-199.

903 Morrison, S. F., et al., 2008. Central control of thermogenesis in mammals. *Experimental Physiology*.
904 93, 773-797.

905 Mozo, J., et al., 2005. Thermoregulation: What role for UCPs in mammals and birds? *Bioscience*
906 *Reports*. 25, 227-249.

907 Mzilikazi, N., Lovegrove, B. G., 2002. Reproductive activity influences thermoregulation and torpor in
908 pouched mice, *Saccostomus campestris*. *Journal of Comparative Physiology B-Biochemical*
909 *Systemic and Environmental Physiology*. 172, 7-16.

910 Nassar, M., et al., 2015. Detection of long-term influence of prenatal temperature stimulation on
911 hypothalamic type-II iodothyronine deiodinase in juvenile female broiler chickens using a
912 novel immunohistochemical amplification protocol. *Comparative Biochemistry and*
913 *Physiology a-Molecular & Integrative Physiology*. 179, 120-124.

914 Nelson, R. J., Demas, G. E., 1997. Role of melatonin in mediating seasonal energetic and
915 immunologic adaptations. *Brain Research Bulletin*. 44, 423-430.

916 Nephew, B. C., et al., 2005. Effects of arginine vasotocin (AVT) on the behavioral, cardiovascular, and
917 corticosterone responses of starlings (*Sturnus vulgaris*) to crowding. *Hormones and*
918 *Behavior*. 47, 280-289.

919 Nguyen, P., et al., 2015. Chronic Mild Cold Conditioning Modulates the Expression of Hypothalamic
920 Neuropeptide and Intermediary Metabolic-Related Genes and Improves Growth
921 Performances in Young Chicks. *Plos One*. 10, 22.

922 Nilsson, J. A., et al., 2009. Heritability of resting metabolic rate in a wild population of blue tits.
923 *Journal of Evolutionary Biology*. 22, 1867-1874.

924 Nilsson, J. A., Nord, A., 2017. The use of the nest for parental roosting and thermal consequences of
925 the nest for nestlings and parents. *Behavioral Ecology and Sociobiology*. 71.

926 Nilsson, J. A., Nord, A., 2018. Testing the heat dissipation limit theory in a breeding passerine.
927 *Proceedings of the Royal Society B-Biological Sciences*. 285.

928 Nord, A., Folkow, L. P., 2018. Seasonal variation in the thermal responses to changing environmental
929 temperature in the world's northernmost land bird. *Journal of Experimental Biology*. 221, 10.

930 Nord, A., Nilsson, J. A., 2011. Incubation Temperature Affects Growth and Energy Metabolism in Blue
931 Tit Nestlings. *American Naturalist*. 178, 639-651.

932 Nord, A., Nilsson, J. A., 2019. Heat dissipation rate constrains reproductive investment in a wild bird.
933 *Functional Ecology*. 33, 250-259.

934 Nord, A., et al., 2009. Patterns and dynamics of rest-phase hypothermia in wild and captive blue tits
935 during winter. *Journal of Comparative Physiology B-Biochemical Systemic and Environmental*
936 *Physiology*. 179, 737-745.

937 Nord, A., Williams, J. B., The energetic costs of incubation. In: D. C. Deeming, S. J. Reynolds, Eds.),
938 Nests, Eggs, and Incubation: New Ideas About Avian Reproduction. Oxford Univ Press, New
939 York, 2015, pp. 152-170.

940 Petit, M., et al., 2017. Increasing Winter Maximal Metabolic Rate Improves Intrawinter Survival in
941 Small Birds. *Physiological and Biochemical Zoology*. 90, 166-177.

942 Piestun, Y., et al., 2009. Thermal manipulations of broiler embryos-The effect on thermoregulation
943 and development during embryogenesis. *Poultry Science*. 88, 2677-2688.

944 Piestun, Y., et al., 2008a. Thermal manipulations during broiler embryogenesis: Effect on the
945 acquisition of thermotolerance. *Poultry Science*. 87, 1516-1525.

946 Piestun, Y., et al., 2008b. The effect of thermal manipulations during the development of the thyroid
947 and adrenal axes on in-hatch and post-hatch thermoregulation. *Journal of Thermal Biology*.
948 33, 413-418.

949 Piestun, Y., et al., 2015. Thermal manipulations of turkey embryos: The effect on thermoregulation
950 and development during embryogenesis. *Poultry Science*. 94, 273-280.

951 Powers, D. R., et al., 2017. Hovering in the heat: effects of environmental temperature on heat
952 regulation in foraging hummingbirds. *Royal Society Open Science*. 4, 14.

953 Powolny, T., et al., 2016. Cold Tolerance and Sex-Dependent Hypothermia May Explain Winter
954 Sexual Segregation in a Farmland Bird. *Physiological and Biochemical Zoology*. 89, 151-160.

955 Price, E. R., Dzialowski, E. M., 2018. Development of endothermy in birds: patterns and mechanisms.
956 *Journal of Comparative Physiology B-Biochemical Systemic and Environmental Physiology*.
957 188, 373-391.

958 Prinzinger, R., et al., 1991. BODY-TEMPERATURE IN BIRDS. *Comparative Biochemistry and Physiology*
959 *a-Molecular & Integrative Physiology*. 99, 499-506.

960 Rabelo, R., et al., 1996. Interactions among receptors, thyroid hormone response elements, and
961 ligands in the regulation of the rat uncoupling protein gene expression by thyroid hormone.
962 *Endocrinology*. 137, 3478-3487.

963 Rahmstorf, S., Coumou, D., 2011. Increase of extreme events in a warming world. *Proceedings of the*
964 *National Academy of Sciences of the United States of America*. 108, 17905-17909.

965 Raimbault, S., et al., 2001. An uncoupling protein homologue putatively involved in facultative
966 muscle thermogenesis in birds. *Biochemical Journal*. 353, 441-444.

967 Reierth, E., et al., 1999. Seasonal and daily variations in plasma melatonin in the high-arctic Svalbard
968 ptarmigan (*Lagopus mutus hyperboreus*). *Journal of Biological Rhythms*. 14, 314-319.

969 Riddell, E. A., et al., 2019. Cooling requirements fueled the collapse of a desert bird community from
970 climate change. *Proceedings of the National Academy of Sciences of the United States of*
971 *America*. 116, 21609-21615.

972 Rodriguez, S., et al., 2016. Negative effects of high temperatures during development on immediate
973 post-fledging survival in Great Tits *Parus major*. *Acta Ornithologica*. 51, 235-244.

974 Ronning, B., et al., 2007. Basal metabolic rate: heritability and genetic correlations with
975 morphological traits in the zebra finch. *Journal of Evolutionary Biology*. 20, 1815-1822.

976 Ropert-Coudert, 2014. A complete breeding failure in an Adélie penguin colony correlates with
977 unusual and extreme environmental events. *Ecography*. 37, 1-3.

978 Rudas, P., Pethes, G., 1984. THE IMPORTANCE OF THE PERIPHERAL THYROID-HORMONE
979 DEIODINATION IN ADAPTATION TO AMBIENT-TEMPERATURE IN THE CHICKEN (*GALLUS-*
980 *DOMESTICUS*). *Comparative Biochemistry and Physiology a-Physiology*. 77, 567-571.

981 Rudas, P., Pethes, G., 1986. ACUTE CHANGES OF THE CONVERSION OF THYROXINE TO
982 TRIIODOTHYRONINE IN HYPOPHYSECTOMIZED AND THYROIDECTOMIZED CHICKENS
983 EXPOSED TO MILD COLD (10-DEGREES). *General and Comparative Endocrinology*. 63, 408-
984 413.

985 Ruf, T., Geiser, F., 2015. Daily torpor and hibernation in birds and mammals. *Biological Reviews*. 90,
986 891-926.

987 Ruuskanen, S., et al., 2016a. Effects of experimentally manipulated yolk thyroid hormone levels on
988 offspring development in a wild bird species. *Hormones and Behavior*. 81, 38-44.

989 Ruuskanen, S., et al., 2016b. Heritable variation in maternally derived yolk androgens, thyroid
990 hormones and immune factors. *Heredity*. 117, 184-190.

991 Ruuskanen, S., et al., 2016c. Temperature-induced variation in yolk androgen and thyroid hormone
992 levels in avian eggs. *General and Comparative Endocrinology*. 235, 29-37.

993 Ruuskanen, S., Hsu, B. Y., 2018. Maternal Thyroid Hormones: An Unexplored Mechanism Underlying
994 Maternal Effects in an Ecological Framework. *Physiological and Biochemical Zoology*. 91,
995 904-916.

996 Saarela, S., Heldmaier, G., 1987. EFFECT OF PHOTOPERIOD AND MELATONIN ON COLD RESISTANCE,
997 THERMOREGULATION AND SHIVERING NONSHIVERING THERMOGENESIS IN JAPANESE-
998 QUAIL. *Journal of Comparative Physiology B-Biochemical Systemic and Environmental*
999 *Physiology*. 157, 625-633.

1000 Saarela, S., Reiter, R. J., 1994. FUNCTION OF MELATONIN IN THERMOREGULATORY PROCESSES. *Life*
1001 *Sciences*. 54, 295-311.

1002 Sadowska, E. T., et al., 2015. Evolution of basal metabolic rate in bank voles from a multidirectional
1003 selection experiment. *Proceedings of the Royal Society B-Biological Sciences*. 282.

1004 Salinas, S., Munch, S. B., 2012. Thermal legacies: transgenerational effects of temperature on growth
1005 in a vertebrate. *Ecology Letters*. 15, 159-163.

1006 Segal, J., Gordon, A., 1977. EFFECT OF 3,5,3'-TRIODO-L-THYRONINE ON KINETIC-PARAMETERS OF
1007 SUGAR-TRANSPORT IN CULTURED CHICK-EMBRYO HEART-CELLS. *Endocrinology*. 101, 1468-
1008 1474.

1009 Shahryar, H. A., Lotfi, A., 2017. Effect of Ghrelin Administration on Serum Corticosterone, T-3, T-4 and
1010 Some Biochemical Indices in the Turkey (*Meleagris gallopova*). *International Journal of*
1011 *Peptide Research and Therapeutics*. 23, 541-547.

1012 Shama, L. N. S., et al., 2014. Transgenerational plasticity in marine sticklebacks: maternal effects
1013 mediate impacts of a warming ocean. *Functional Ecology*. 28, 1482-1493.

1014 Shinder, D., et al., 2009. Effect of repetitive acute cold exposures during the last phase of broiler
1015 embryogenesis on cold resistance through the life span. *Poultry Science*. 88, 636-646.

1016 Silverin, B., et al., 1989. SEASONAL-CHANGES IN BODY-WEIGHT, FAT DEPOTS, AND PLASMA-LEVELS
1017 OF THYROXINE AND GROWTH-HORMONE IN FREE-LIVING GREAT TITS (*PARUS-MAJOR*) AND
1018 WILLOW TITS (*PARUS-MONTANUS*). *General and Comparative Endocrinology*. 73, 404-416.

1019 Singh, B. K., et al., 2018. Novel Transcriptional Mechanisms for Regulating Metabolism by Thyroid
1020 Hormone. *International Journal of Molecular Sciences*. 19, 14.

1021 Sinkalu, V. O., et al., 2015. Effects of melatonin on cloacal temperature and erythrocyte osmotic
1022 fragility in layer hens during the hot-dry season. *Journal of Applied Animal Research*. 43, 52-
1023 60.

1024 Smit, B., McKechnie, A. E., 2010. Avian seasonal metabolic variation in a subtropical desert: basal
1025 metabolic rates are lower in winter than in summer. *Functional Ecology*. 24, 330-339.

1026 Stedman, J. M., et al., 2017. Heritable variation in circulating glucocorticoids and endocrine flexibility
1027 in a free-living songbird. *Journal of Evolutionary Biology*. 30, 1724-1735.

1028 Stillman, J. H., 2019. Heat Waves, the New Normal: Summertime Temperature Extremes Will Impact
1029 Animals, Ecosystems, and Human Communities. *Physiology*. 34, 86-100.

1030 Swanson, D. L., Olmstead, K. L., 1999. Evidence for a proximate influence of winter temperature on
1031 metabolism in passerine birds. *Physiological and Biochemical Zoology*. 72, 566-575.

1032 Swanson, D. L., Vezina, F., 2015. Environmental, ecological and mechanistic drivers of avian seasonal
1033 metabolic flexibility in response to cold winters. *Journal of Ornithology*. 156, S377-S388.

1034 Tachibana, T., et al., 2004. Comparison of brain arginine-vasotocin and corticotrophin-releasing
1035 factor for physiological responses in chicks. *Neuroscience Letters*. 360, 165-169.

1036 Taff, C. C., et al., 2018. The repeatability of glucocorticoids: A review and meta-analysis. *General and*
1037 *Comparative Endocrinology*. 260, 136-145.

1038 Takahashi, H., et al., 2005. Regulation of body temperature. by thyrotropin-releasing hormone in
1039 neonatal chicks. *Developmental Brain Research*. 157, 58-64.

1040 Talbot, D. A., et al., 2004. Uncoupling protein and ATP/ADP carrier increase mitochondrial proton
1041 conductance after cold adaptation of king penguins. *Journal of Physiology-London*. 558, 123-
1042 135.

1043 Terrien, J., et al., 2011. Behavioral thermoregulation in mammals: a review. *Frontiers in Bioscience-
1044 Landmark*. 16, 1428-1444.

1045 Teulier, L., et al., 2010. Cold-acclimation-induced non-shivering thermogenesis in birds is associated
1046 with upregulation of avian UCP but not with innate uncoupling or altered ATP efficiency.
1047 *Journal of Experimental Biology*. 213, 2476-2482.

1048 Teulier, L., et al., 2014. Ontogeny of non-shivering thermogenesis in Muscovy ducklings (*Cairina
1049 moschata*). *Comparative Biochemistry and Physiology a-Molecular & Integrative Physiology*.
1050 175, 82-89.

1051 Tickle, P. G., Codd, J. R., 2019. Thermoregulation in rapid growing broiler chickens is compromised by
1052 constraints on radiative and convective cooling performance. *Journal of Thermal Biology*. 79,
1053 8-14.

1054 Tickle, P. G., et al., 2018. Energy allocation and behaviour in the growing broiler chicken. *Scientific
1055 Reports*. 8.

1056 Tieleman, B. I., et al., 2009. Quantitative genetics parameters show partial independent evolutionary
1057 potential for body mass and metabolism in stonechats from different populations. *Journal of
1058 Zoology*. 279, 129-136.

1059 Tieleman, B. I., Williams, J. B., 1999. The role of hyperthermia in the water economy of desert birds.
1060 *Physiological and Biochemical Zoology*. 72, 87-100.

1061 Tzschentke, B., Basta, D., 2002. Early development of neuronal hypothalamic thermosensitivity in
1062 birds: influence of epigenetic temperature adaptation. *Comparative Biochemistry and
1063 Physiology a-Molecular and Integrative Physiology*. 131, 825-832.

1064 Van der Geyten, S., et al., 1999. Regulation of thyroid hormone metabolism during fasting and
1065 refeeding in chicken. *General and Comparative Endocrinology*. 116, 272-280.

1066 Versteegh, M. A., et al., 2008. Repeatability and individual correlates of basal metabolic rate and
1067 total evaporative water loss in birds: A case study in European stonechats. *Comparative
1068 Biochemistry and Physiology a-Molecular & Integrative Physiology*. 150, 452-457.

1069 Vezina, F., et al., 2009. Hormonal Correlates and Thermoregulatory Consequences of Molting on
1070 Metabolic Rate in a Northerly Wintering Shorebird. *Physiological and Biochemical Zoology*.
1071 82, 129-142.

1072 Vianna, C. R., et al., 2001a. Cloning and characterization of a novel uncoupling protein homologue in
1073 hummingbirds. *Faseb Journal*. 15, A412-A412.

1074 Vianna, C. R., et al., 2001b. Cloning and functional characterization of an uncoupling protein
1075 homolog in hummingbirds. *Physiological Genomics*. 5, 137-145.

1076 Vinoth, A., et al., 2018. Evaluation of DNA methylation and mRNA expression of heat shock proteins
1077 in thermal manipulated chicken. *Cell Stress & Chaperones*. 23, 235-252.

1078 Vuarin, P., et al., 2013. Individual flexibility in energy saving: body size and condition constrain torpor
1079 use. *Functional Ecology*. 27, 793-799.

1080 Walter, I., Seebacher, F., 2007. Molecular mechanisms underlying the development of endothermy
1081 in birds (*Gallus gallus*): a new role of PGC-1 alpha? *American Journal of Physiology-
1082 Regulatory Integrative and Comparative Physiology*. 293, R2315-R2322.

1083 Walter, I., Seebacher, F., 2009. Endothermy in birds: underlying molecular mechanisms. *Journal of
1084 Experimental Biology*. 212, 2328-2336.

1085 Weyrich, A., et al., 2016a. Paternal heat exposure causes DNA methylation and gene expression
1086 changes of Stat3 in Wild guinea pig sons. *Ecology and Evolution*. 6, 2657-2666.

1087 Weyrich, A., et al., 2016b. Paternal intergenerational epigenetic response to heat exposure in male
1088 Wild guinea pigs. *Molecular Ecology*. 25, 1729-1740.

- 1089 Wilsterman, K., et al., 2015. The timing of embryonic exposure to elevated temperature alters stress
1090 endocrinology in domestic chickens (*Gallus domesticus*). *General and Comparative*
1091 *Endocrinology*. 212, 10-16.
- 1092 Wingfield, J. C., 2015. Coping with change: A framework for environmental signals and how
1093 neuroendocrine pathways might respond. *Frontiers in Neuroendocrinology*. 37, 89-96.
- 1094 Wingfield, J. C., et al., 2017. How birds cope physiologically and behaviourally with extreme climatic
1095 events. *Philosophical Transactions of the Royal Society B-Biological Sciences*. 372, 10.
- 1096 Wrutniak-Cabello, C., et al., 2017. Mitochondrial T3 receptor and targets. *Molecular and Cellular*
1097 *Endocrinology*. 458, 112-120.
- 1098 Wrutniak-Cabello, C., et al., Thyroid Hormone Action: The p43 Mitochondrial Pathway. In: M.
1099 Plateroti, J. Samarut, (Eds.), *Thyroid Hormone Nuclear Receptor: Methods and Protocols*.
1100 Humana Press Inc, Totowa, 2018, pp. 163-181.
- 1101 Wulf, A., et al., 2008. T3-mediated expression of PGC-1 alpha via a far upstream located thyroid
1102 hormone response element. *Molecular and Cellular Endocrinology*. 287, 90-95.
- 1103 Xie, S. S., et al., 2018. Thyroid transcriptome analysis reveals different adaptive responses to cold
1104 environmental conditions between two chicken breeds. *Plos One*. 13, 28.
- 1105 Xie, S. Z., et al., 2017. Stress Responses to Heat Exposure in Three Species of Australian Desert Birds.
1106 *Physiological and Biochemical Zoology*. 90, 348-358.
- 1107 Yahav, S., Regulation of Body Temperature: Strategies and Mechanisms. In: C. G. Scanes, (Ed.),
1108 *Sturkie's Avian Physiology*, 6th Edition. Academic Press Ltd-Elsevier Science Ltd, London,
1109 2015, pp. 869-905.
- 1110 Yahav, S., et al., 2004. Thermal manipulations during broiler chick embryogenesis: Effects of timing
1111 and temperature. *Poultry Science*. 83, 1959-1963.
- 1112 Zheng, W. H., et al., 2014a. Seasonal Variation of Metabolic Thermogenesis in Eurasian Tree
1113 Sparrows (*Passer montanus*) over a Latitudinal Gradient. *Physiological and Biochemical*
1114 *Zoology*. 87, 704-718.
- 1115 Zheng, W. H., et al., 2014b. Seasonal Phenotypic Flexibility of Body Mass, Organ Masses, and Tissue
1116 Oxidative Capacity and Their Relationship to Resting Metabolic Rate in Chinese Bulbuls.
1117 *Physiological and Biochemical Zoology*. 87, 432-444.
- 1118 Zhu, Y. W., et al., 2017. Maternal dietary manganese protects chick embryos against maternal heat
1119 stress via epigenetic-activated antioxidant and anti-apoptotic abilities. *Oncotarget*. 8, 89665-
1120 89680.
- 1121 Zizzari, Z. V., Ellers, J., 2014. Rapid shift in thermal resistance between generations through maternal
1122 heat exposure. *Oikos*. 123, 1365-1370.

1123

1124

1125

1126 **Figure legends**

1127

1128 Fig 1. A simplified schematic figure of the mechanisms of thermoregulation in birds and
1129 putative key endocrine and neuronal mechanisms underlying each response (modified from
1130 Yahav, 2015). PO/AH = preoptic anterior hypothalamus, THs = thyroid hormones, CORT=
1131 corticosterone, AVT= arginine vasotocin, CNS = central nervous system, SNS= sympathetic
1132 nervous system, TNZ = thermoneutral zone. See text for references.

1133

1134 Fig 2. A schematic diagram of the potential pathways of THs on thermogenesis below
1135 thermoneutral zone. UCP = uncoupling protein, ANT = adenine nucleotide translocase,
1136 SERCA = Ca²⁺ ATPase. See text for references.

1137

1138 Fig 3. Schematic diagram of plasticity in thermoregulation at different time-scales, and
1139 associated putative molecular and endocrine mechanisms. See text for references.

1140

1141 Fig. 4. Key thermoregulatory challenges in birds in changing climate. See text for references.

1142

1143

1144

1145

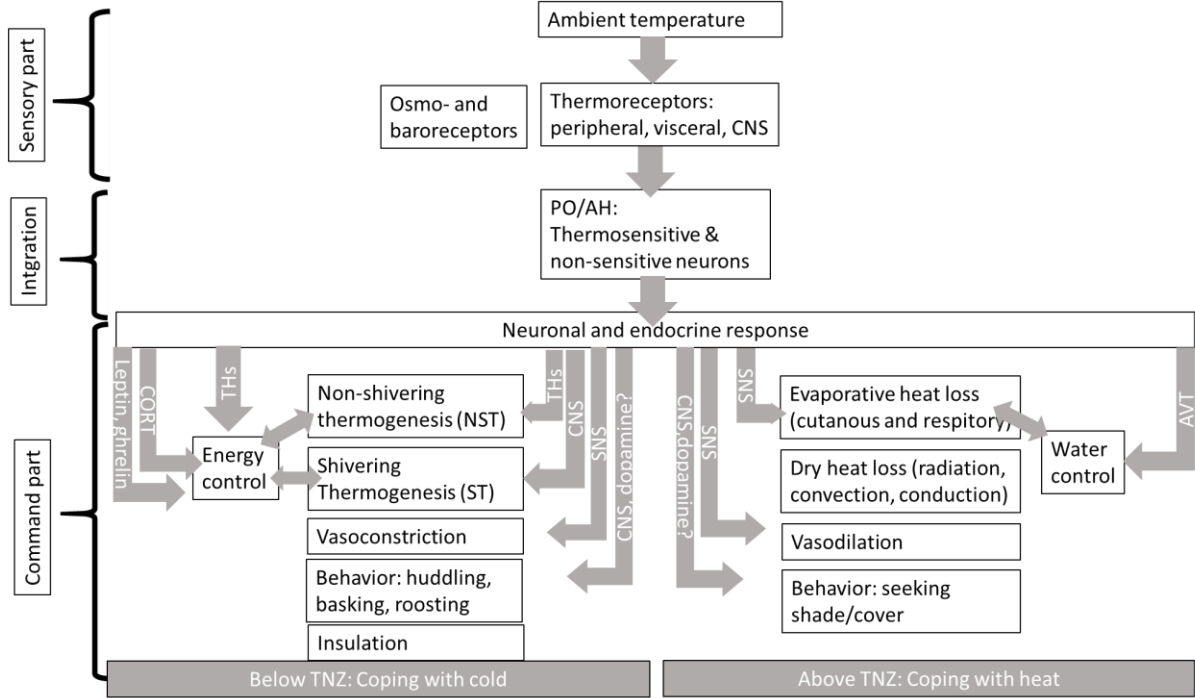
1146

1147

1148

Fig

1.



1149

1150

1151

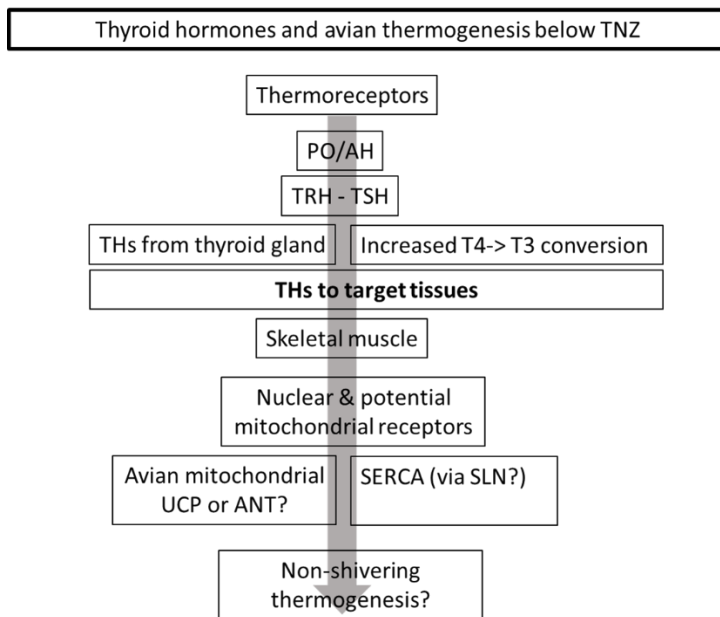
1152

1153

1154 Fig 2.

1155

1156



1157

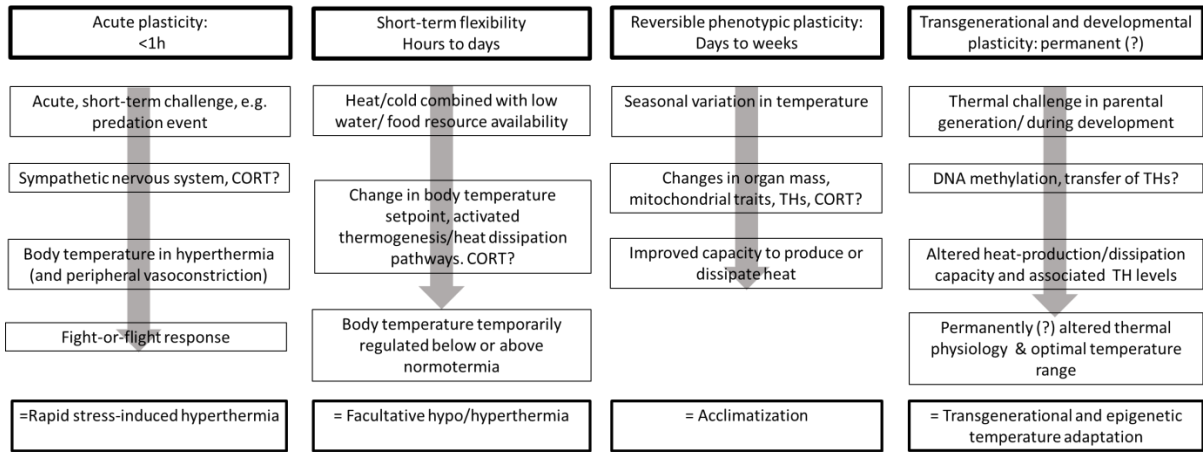
1158

1159

1160 Fig 3.

1161

1162

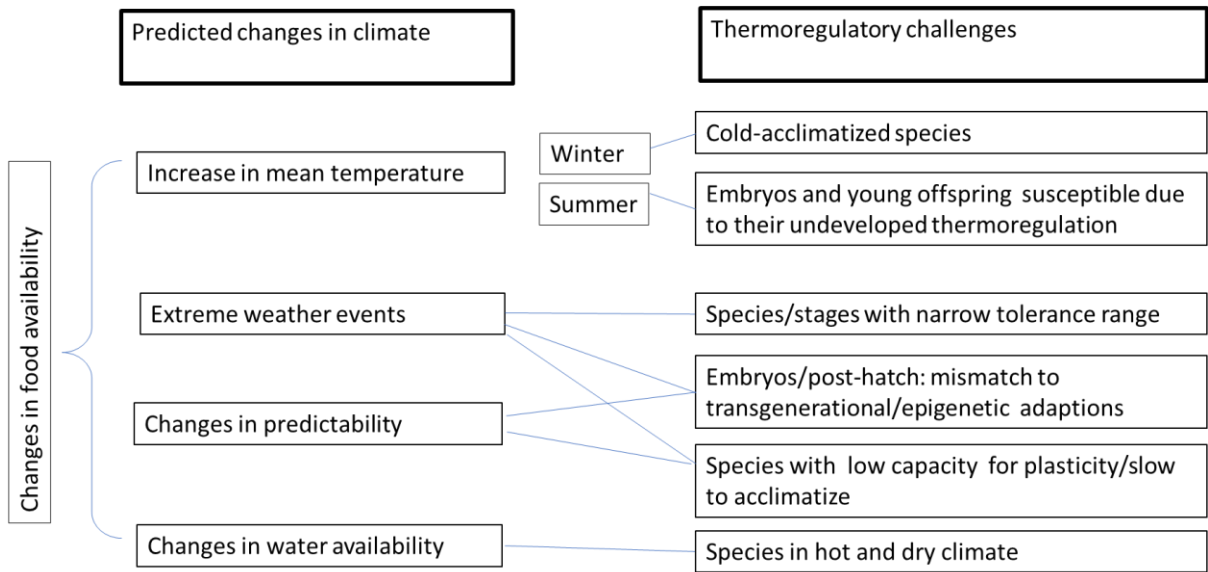


1163

1164

1165 Fig. 4.

1166



1167

1168