



**HAL**  
open science

## Do trace metals select for darker birds in urban areas?.An experimental exposure to lead and zinc

Marion Chatelain, Julien Gasparini, A Frantz

### ► To cite this version:

Marion Chatelain, Julien Gasparini, A Frantz. Do trace metals select for darker birds in urban areas?.An experimental exposure to lead and zinc. *Global Change Biology*, 2015, 22 (7), pp.2380-2391. 10.1111/gcb.13170 . hal-01311602

**HAL Id: hal-01311602**

**<https://hal.sorbonne-universite.fr/hal-01311602>**

Submitted on 4 May 2016

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# **Do trace metals select for darker birds in urban areas?**

## **An experimental exposure to lead and zinc**

Running title: trace metals and plumage melanin selection

Chatelain M<sup>1\*</sup>, Gasparini J<sup>1</sup> and Frantz A<sup>1</sup>

<sup>1</sup> Sorbonne Universités, UPMC Univ Paris 06, UPEC, Paris 7, CNRS, INRA, IRD, Institut d'Ecologie et des Sciences de l'Environnement de Paris, F-75005, Paris, France

\*Corresponding author: marion.chatelain@upmc.fr ; +0033 1 44 27 52 04

**Key words:** ecotoxicology, urban pollution, plumage colouration, eumelanin, pheomelanin, feral pigeon, reproduction

**Type of paper:** Primary Research Article

Words: 8703

Table: 2

Figures: 5

1 **ABSTRACT**

2

3 Trace metals from anthropogenic activities are involved in numerous health impairments and  
4 may therefore select for detoxification mechanisms or a higher tolerance. Melanin,  
5 responsible for the black and red colourations of teguments, plays a role in metal ions  
6 chelation and its synthesis is positively linked to immunity, to antioxidant capacity and to  
7 stress resistance due to pleiotropic effects. Therefore, we expected darker birds to 1) store  
8 higher amounts of metals into their feathers, 2) maintain lower metal concentrations in blood  
9 and 3) suffer less from metal exposure. We exposed feral pigeons (*Columba livia*) exhibiting  
10 various plumage darkness levels to low but chronic concentrations of zinc and/or lead, two of  
11 the most abundant metals in urban areas. First, we found negative and positive effects of lead  
12 and zinc respectively on birds' condition and reproductive parameters. Then, we observed  
13 positive relationships between plumage darkness and both zinc and lead concentrations in  
14 feathers. Interestingly, though darker adults did not maintain lower metal concentrations in  
15 blood and did not have higher fitness parameters, darker juveniles exhibited a higher survival  
16 rate than paler ones when exposed to lead. Our results show that melanin-based plumage  
17 colouration does modulate lead effects on birds' fitness parameters but that the relationship  
18 between metals, melanin, and fitness is more complex than expected and thus stress the need  
19 for more studies.

20

21

## 22 INTRODUCTION

23

24 Current human activities generate considerable environmental disturbances, such as light,  
25 noise and chemical pollutions. Like other chemical pollutions, trace metals emissions are of  
26 particularly timely concern, given their implication in several human diseases (reviewed in  
27 Jarup, 2003) and their noxious effects on wildlife (Hsu *et al.*, 2006). In birds, trace metals  
28 negatively affect immunity in great tits and zebra finches (Snoeijs *et al.*, 2004, 2005) and  
29 learning abilities in young herring gulls (Burger & Gochfeld, 2004). In addition, high levels  
30 of trace metals in the environment correlate with reproduction impairments (e.g. higher nest  
31 desertion, hatching failure and mortality; Eeva & Lehikoinen, 1996; Janssens *et al.*, 2003;  
32 Eeva *et al.*, 2009), and oxidative damages (Berglund *et al.*, 2007) in passerine birds.

33 Because concentrations of trace metals are higher in the cities than in rural areas (Azimi *et al.*,  
34 2003; Roux & Marra, 2007), trace metals likely have ecological and evolutionary  
35 consequences on urban wildlife, though the exact levels organisms experience remain  
36 unknown and most probably depend on the taxonomic group considered. Because of their  
37 toxicity, trace metals may select for detoxification mechanisms (such as higher elimination  
38 rate of ingested metals) or for higher resistance to their toxic effects (such as higher oxidative  
39 stress resistance). Environments polluted with trace metals thus represent exciting  
40 opportunities to study ongoing evolutionary mechanisms in the wild.

41 Interestingly, highly melanic plumage may be advantageous in environments polluted with  
42 trace metals (i.e. darker individuals may suffer less in these habitats), both through direct and  
43 indirect effects of melanogenesis. First, melanin is composed of negatively-charged free  
44 carboxyl, hydroxyl and amine functions known to bind metal ions in vitro (Larsson & Tjälve,  
45 1978; Liu *et al.*, 2004; Bridelli & Crippa, 2007). For this reason, metal chelation is suggested  
46 as one of the main biological functions of melanin (McGraw, 2003; Hong & Simon, 2007;

47 Chatelain *et al.*, 2014). In birds, metal transfer from the bloodstream into melanic feathers  
48 during their growth could represent an efficient detoxification mechanism through metal  
49 sequestration and elimination during moulting, a hypothesis already proposed for keratin in  
50 feathers (Burger, 1993). Consequently, more melanic feathers would be able to store higher  
51 amounts of metals, a hypothesis supported by a positive correlation between concentrations of  
52 some metals in feathers and melanin-based plumage colouration in feral pigeons, white-tailed  
53 eagles and barn owls (Niecke *et al.*, 1999, 2003; Chatelain *et al.*, 2014). In habitats where  
54 metals indeed have noxious effects, highly melanic birds would thus have a better  
55 detoxification ability than paler birds by lowering their circulating metal burden. Although  
56 this detoxification mechanism could represent a significant driver of melanin-based plumage  
57 colouration polymorphism maintenance, it has been poorly investigated. Positive correlations  
58 have been shown between melanin-based plumage colouration and concentrations of some  
59 metals (zinc, calcium and manganese; Niecke *et al.*, 1999, 2003; Zduniak *et al.*, 2014), while  
60 no such link has been demonstrated for highly toxic metals such as lead and cadmium, maybe  
61 because of the correlative nature of the studies (Gochfeld *et al.*, 1991; Chatelain *et al.*, 2014).  
62 Then, to the best of our knowledge, no study compared metal concentrations in feathers  
63 between differently melanin-coloured birds in controlled environmental conditions (ie. under  
64 the same metal exposure).

65 Second, both the pleiotropic effect of the gene coding for melanin synthesis (POMC) and its  
66 linkage disequilibrium with various loci result in correlations between variation in melanin-  
67 based plumage colouration and several biological traits, including immunity, antioxidant  
68 capacity and stress resistance (Ducrest *et al.*, 2008; Mckinnon & Pierotti, 2010). Indeed,  
69 darker pigeons exhibit both a lower endoparasite intensity and a greater cellular immune  
70 response than paler pigeons (Jacquin *et al.*, 2011). Moreover, eumelanin level in the barn owl  
71 positively correlates with resistance to oxidative stress (Ducrest *et al.*, 2008; Roulin *et al.*,

72 2011) and to physiological stress (corticosterone synthesis; Almasi *et al.*, 2010, 2012).  
73 Therefore, melanin-based plumage colouration may shape birds' tolerance to trace metals.  
74 Both direct (metal binding) and indirect (resistance to parasites, oxidative stress and  
75 physiological stress) associations between biological traits and plumage melanism may favour  
76 darker birds in environments polluted with trace metals. Accordingly, previous studies  
77 observed a higher frequency of darker feral pigeons in European cities (Obukhova, 2007;  
78 Jacquin *et al.*, 2013a), where environmental concentrations of metals are the highest (Azimi *et al.*  
79 *et al.*, 2005; Scheifler *et al.*, 2006; Roux & Marra, 2007; Kekkonen *et al.*, 2012). However, there  
80 is no experimental evidence for fitness advantages of being more melanistic in habitats  
81 polluted with trace metals. Still, the existence of such melanin-based plumage polymorphism  
82 in cities raises questions about its evolutionary maintenance, which could result from either a  
83 transitory polymorphism (i.e. the hypothesized selective pressure induced by trace metals is  
84 ongoing), some imperfect linkage disequilibrium between loci involved in melanogenesis and  
85 other biological traits under selection or the co-occurrence of antagonistic selective pressures.  
86  
87 Partly due to large emissions by anthropogenic activities (beginning during the Roman  
88 Empire and increasing with the Industrial Revolution of the 19<sup>th</sup> century Nriagu, 1996), lead is  
89 the most abundant toxic metal in the environment (Azimi *et al.*, 2005; Roux & Marra, 2007).  
90 Although lead used in gasoline drastically diminished since the 70s (Jarup, 2003), it remains  
91 of high ecological importance due to its accumulation into the soil (Roux & Marra, 2007) and  
92 to the negative biological effects of a chronic exposure, even at low levels (Patrick, 2006). In  
93 addition, zinc is the most abundant metal in the environment (Azimi *et al.*, 2005). While it  
94 may induce harmful effects at high concentrations (Greenberg & Briemberg, 2004; Bozym *et al.*  
95 *et al.*, 2010), it is overall an essential nutrient (Mertz, 1981; Prasad, 1998, 2009), also able to  
96 compensate the negative effects induced by other traces metals (Chichovska & Anguelov,

97 2006; Prasanthi *et al.*, 2006, 2010). Therefore, lead and zinc likely induce the strongest  
98 (negative or positive) effects on urban wildlife. While lead and zinc effects on condition and  
99 reproductive success may greatly modulate birds' fitness and population dynamics, to the best  
100 of our knowledge, no experimental study demonstrated such effects and the previous  
101 correlative studies cannot exclude confounding urban factors also known to impair birds'  
102 reproduction (Halfwerk *et al.*, 2011; Dominoni *et al.*, 2013).

103 In this work, we chronically exposed feral pigeons (*Columba livia*) to lead and/or zinc in  
104 experimentally controlled concentrations inferred from previous measures in urban areas. The  
105 feral pigeon is a highly polymorphic bird species with respect to its melanin-based plumage  
106 colouration and experiences an extended moulting period (Johnston & Janiga, 1995). First, we  
107 evaluated the effects of such exposures on lead and zinc concentrations in feathers and in  
108 blood, and on bird condition and reproductive parameters. Then, we investigated whether the  
109 ability of feathers to store zinc and lead depends on their melanin-based colouration and, as a  
110 consequence, whether melanistic birds maintain lower lead concentrations in blood; because  
111 zinc concentration in blood is under strict homeostatic regulation in eukaryotes (Gaither &  
112 Eide, 2001), no relationship was expected between plumage colouration and blood levels of  
113 zinc. Finally, we tested whether melanin-based plumage colouration could be advantageous in  
114 environments polluted with metals by investigating the interaction between plumage  
115 colouration and metal exposure on birds' condition and reproductive parameters.

116

## 117 **MATERIALS AND METHODS**

118

### 119 *Biological model*

120 Free-living feral pigeons are considered to originate from the continuous reproduction  
121 between wild, synanthropic and domesticated pigeons (Johnston & Janiga, 1995). Contrasting

122 artificial selective pressures on various phenotypic traits linked to past domestication has  
123 generated polymorphism in the degree of melanin-based plumage colouration. Free-living  
124 feral pigeons have then evolved in natural environments in close proximity with human  
125 populations for centuries and maintained one of the highest melanin-based plumage  
126 colouration polymorphism amongst birds. This polymorphism involves melanin type  
127 (eumelanin and pheomelanin, respectively responsible for the black and reddish colour of  
128 teguments) and melanin degree (i.e. the area of pigmentation; see below). Both parameters of  
129 melanin-based plumage colouration in feral pigeons are highly heritable (heritability of  
130 melanin degree:  $0.82 \pm 0.12$ ; Jacquin *et al.*, 2013b).

131

### 132 *Subjects and Housing*

133 Ninety six (48 males and 48 females genetically sexed) free-living adult feral pigeons  
134 (*Columba livia*) exhibiting various melanin-based plumage colourations were caught during  
135 winter 2013 (February/March) in several pigeon flocks within Paris (Supplementary  
136 material). Birds were all adults as indicated by reliable morphological criteria such as well-  
137 formed caruncle, absence of juvenile plumage and presence of iridescent neck feathers  
138 (Johnston & Janiga, 1995). The birds were immediately transferred in 8 outdoor aviaries (3.10  
139 m x 2.00 m x 2.40 m) at the CEREEP field station (Centre d'Ecologie Expérimentale et  
140 Prédictive-Ecotron Ile-de-France, UMS 3194, Ecole Normale Supérieure, Saint-Pierre-lès-  
141 Nemours, France). Birds were fed *ad libitum* with a mix of maize, wheat and peas. The  
142 aviaries were enriched with a bowl of water used for bathing and with branches as perches.  
143 Birds were individually identified with a numbered plastic ring. At the end of the experiment,  
144 all birds were released back to the wild at their site of capture. All experiments were carried  
145 out in strict accordance with the recommendations of the “European Convention for the  
146 Protection of vertebrate Animals used for Experimental and Other Scientific Purposes” and

147 were conducted under the authorizations of the “Ministère de l’éducation nationale, de  
148 l’enseignement supérieur et de la recherche” (authorization N\_00093.02) and the “Direction  
149 Départementale des Services Vétérinaires de Seine et-Marne” (authorization N\_77-05).

150

#### 151 *Plumage colouration measurement*

152 At their capture, birds were first categorised as eumelanic (grey to black pigmented; 37 males  
153 and 45 females) or pheomelanic (red pigmented; 11 males and 3 females), which defines what  
154 we called their melanin type. Pheomelanic birds are usually in low frequencies in cities  
155 worldwide (Obukhova, 2007), and are particularly scarce in Paris (about 3%; based on  
156 personal data on 2074 pigeons captured over 5 years); despite the particularly strong capture  
157 effort provided to capture pheomelanic pigeons, their amount remained small (14 out of 96).  
158 Then, birds were individually photographed to precisely quantify their eumelanin or  
159 pheomelanin level. Eumelanin or pheomelanin level was calculated as the percentage of black  
160 or red on the wing surface of birds respectively (number of black pixels/number of white  
161 pixels x 100) using the Gimp image retouching and editing software, which is a reliable and  
162 repeatable estimation of melanin concentration (Jacquin *et al.*, 2011). At the end of the  
163 experiment, fledglings born during the experiment were also photographed to assess their  
164 eumelanin or pheomelanin level. The percentage of pigmented surface did not significantly  
165 differ between eumelanic and pheomelanic birds ( $F_{1,94}=0.27$ ,  $P=0.606$ ).

166

#### 167 *Treatments*

168 Two weeks before the start of the experiment, the birds were distributed in the aviaries in  
169 order to equilibrate both sex (6 females and 6 males per aviaries) and plumage colouration  
170 ( $F_{1,94}<0.01$ ,  $P=0.974$ ). However, because of their lower number (n=14), pheomelanic  
171 individuals were split in 6 aviaries only. Importantly, because birds’ precise location origin in

172 Paris is likely to affect their previous exposure to trace metals and consequently their initial  
173 (prior to the experiment) trace metal body concentrations (Frantz *et al.*, 2012), birds were  
174 randomly distributed in the aviaries according to their flock ( $\text{Chi}^2=71.09$ ,  $\text{df}=70$ ,  $P=0.441$ ).  
175 This randomization should also avoid any other correlation between birds' history (e.g. age)  
176 and aviary. The aviaries were then randomly assigned to one of the 4 following metal  
177 exposure treatments: exposed to lead only (*lead* group; 1ppm lead acetate in tap water,  
178 Sigma-Aldrich), exposed to zinc only (*zinc* group; 10ppm zinc sulphate in tap water, Prolabo),  
179 exposed to both lead and zinc (*lead+zinc* group; 1ppm lead acetate and 10ppm zinc sulphate  
180 in tap water) or control (*control* group; tap water without any metal addition). This resulted in  
181 2 aviaries with 12 pigeons each (24 pigeons in total) per treatment. We chose these  
182 concentrations based on both lead concentrations in blood measured in feral pigeons (ranging  
183 from 110 to 154ppb; personal data on feral pigeons captured in 2009 in Paris) and the  
184 gastrointestinal absorption rate of lead in zebra finches (<10%) calculated from Dauwe *et al.*  
185 (2002). Zinc concentrations were approximated using zinc/lead concentrations ratio in the  
186 environment and bird feathers in Paris (Azimi *et al.*, 2005; Frantz *et al.*, 2012). Drinking  
187 troughs and baths were filled with the corresponding treated water every other day, miming  
188 part of birds' exposure to trace metals in the wild (i.e. through ingestion and deposition onto  
189 the plumage).

190

### 191 *Scaled mass index*

192 From the start to the 20<sup>th</sup> week of the experiment, all adults were captured once a week to be  
193 weighed to the nearest gram with a Pesola Newton scale. Scaled mass index was calculated  
194 according to the method described by Peig & Green (2009, 2010). Briefly, scaled mass index  
195 was calculated using  $\widehat{M}_i = M_i \left[ \frac{L_0}{L_i} \right]^{b_{SMA}}$  where  $M_i$  and  $L_i$  are the body mass and tarsus length  
196 of individual  $i$  respectively;  $b_{SMA}$  is the scaling exponent estimated by the Standardized Major

197 Axis regression of  $M$  on  $L$ ;  $L_0$  is the arithmetic mean of tarsus length in the study population;  
198 and  $\widehat{M}_i$  is the predicted body mass for individual  $i$  when tarsus length is standardized to  $L_0$ .  
199 Scaled mass index is a better indicator of the relative size of energy reserves and of other  
200 body components than the ordinary least squares (OLS) regression of body mass against size  
201 (Peig & Green, 2009), broadly used amongst ecologists.

202

### 203 *Reproductive success measurements*

204 *Breeding success.* A week after the start of the treatments six nest boxes per aviary were  
205 opened to allow birds to mate and breed (a box per couple). A bird was considered as  
206 reproducing when it had laid (female) or incubated (female and male) at least one egg during  
207 the breeding season. Overall, 52 pigeons (25 eumelanic and 3 pheomelanic females and 17  
208 eumelanic and 7 pheomelanic males) successfully reproduced.

209 *Eggs' quality measurement.* Feral pigeons commonly produce two-egg clutches, one to 6  
210 times a year. The day it had been laid, the egg was removed from the nest, weighed and  
211 measured (3 measures of eggs' maximum length and maximum width were taken, and then  
212 averaged). Egg volume was calculated as  $V = 0.4866 \times Length \times (Width^2)$  (Paillisson *et*  
213 *al.*, 2007). Eggs of the first, third and fifth clutches were put back in the nest to allow  
214 incubation (n=83) whereas the others were frozen (n=65). Shell, albumen and yolk of frozen  
215 eggs were separated, then weighed to the nearest  $\mu\text{g}$  (eggshells were previously oven-dried).  
216 Dried shell thickness was measured to the nearest  $\mu\text{m}$  with a specimeter (Mitutoya 0-1mm).

217 *Hatching success.* The hatch was considered as successful when the chick was completely  
218 cleared from its shell and alive. 52 eggs successfully hatched out of 83.

219 *Nestlings' growth measurement.* Each one-day-old hatchling was weighed and measured (3  
220 measures of tarsus and wing length were taken, and then averaged; n=52). Weight, tarsus and  
221 wing measures were reiterated every day until 25 days old (note that nestlings' body mass

222 slow down at 16 days old on average; Johnston & Janiga 1995). Growth (for body mass,  
223 tarsus and wing length) was calculated as  $W = \frac{A}{1 + \exp(-k(t - t_i))}$ , where  $W$ =morphological  
224 measure (body mass, tarsus length or wing length),  $A$ =asymptote (final body mass, tarsus  
225 length or wing length at the end of growth),  $k$ =growth rate constant  $t$ =age and  $t_i$ =the  
226 inflexion point of the curve (Newbrey & Reed, 2009; Jacquin *et al.*, 2012). Therefore we  
227 characterized nestlings' growth by its growth rate ( $k$ ) and its age of slowing growth ( $t_i$ ). Only  
228 the growth of nestlings which successfully fledged was calculated (n=41). Three months after  
229 the birds stopped growing, their weight, tarsus length and wing length were measured to  
230 assess their scaled mass index (n=40).

231 *Fledging success.* Chick was considered as successfully fledged when it was found outside  
232 the parental nest and was able to fly and to feed by itself.

233 *Juveniles' condition.* At the end of the experiment, while the younger bird was 3 months old  
234 and the older was 6 months old, we measured juvenile haematocrit, corresponding to the  
235 erythrocyte volume fraction of a blood sample (n=40). It is expected to be an indicator of  
236 general health state (Cooper, 1975; Averbek, 1992). In addition, the number of leukocytes  
237 per 10000 erythrocytes was counted from blood smear. Slides were fixed with methanol  
238 during 5 minutes and coloured with GIEMSA (diluted 1:20) during 45 minutes. We identified  
239 heterophils, eosinophils, lymphocytes and monocytes. Because glucocorticoid decreases the  
240 number of circulating lymphocytes while it stimulates the influx of heterophils from the bone  
241 marrow, leukocyte profiles are suitable for identifying some physiological stress (Davis *et al.*,  
242 2008). Therefore, we calculated the heterophils/lymphocytes ratio. We also considered the  
243 total number of white blood cells (total number of leukocytes per 10000 erythrocytes) that is  
244 suggested to be an indication of birds' immunity (Davis *et al.*, 2008).

245 Laying date was measured to ensure that trace metals effects on reproductive parameters  
246 would not be due to cumulative effects but was not considered as a reproductive success  
247 measurement.

248

#### 249 *Metal quantitative analyses*

250 *In blood.* 10 weeks after the start of the experiment, 50µl of blood were collected from the  
251 brachial vein of each 96 adult pigeons and were immediately frozen until analyzed. Prior to  
252 metal measurement, blood was defrosted and vortexed. Then, 200mg ( $\pm 0.1$  mg) were digested  
253 with 1ml HNO<sub>3</sub> solution (68%) during 24h at 80°C.

254 *In feathers.* 13 weeks after the start of the experiment, a secondary remige (the 5<sup>th</sup>) was  
255 removed a first time. Once the regrown feather finished its development and was  
256 devascularized, it was plucked off and conserved in an individual plastic bag. Feathers were  
257 washed vigorously with 0.25M NaOH solution, rinsed energetically 3 times in ultrapure water  
258 (Milli-Q purified) to remove external contamination (Scheifler *et al.*, 2006; Frantz *et al.*,  
259 2012), left 1h in ultrapure water and dried 12h at 80°C to dry mass. Barbs were removed from  
260 the rachis, weighed to the nearest 0.1 mg and digested following the method described above.  
261 The product of digestion was transferred into plastic tubes and water was added to reach a  
262 final volume of 8ml; then, each sample was diluted by 2.5. Total lead and zinc concentrations  
263 were determined in all of the 96 feather samples and 48 blood samples (6 females and 6 males  
264 amongst each of the four treatments) by mass spectrometry (quadrupole ICP-MS, XSeries II)  
265 and optical emission spectrometry (ICP-OES, JY 2000) respectively.

266

#### 267 *Statistical analyses*

268 To distinguish the respective effects of lead and/or zinc exposure treatments on the variables  
269 measured, we binary coded (absence/presence) the exposure to lead on one hand and the

270 exposure to zinc on the other (table 1). First, we tested for the existence of correlations  
271 between the explanatory variables considered (lead exposure, zinc exposure, plumage melanin  
272 type and plumage eumelanin level among adults and among juveniles separately). Colinearity  
273 between eumelanin level and metal exposure among juveniles did not allow to include metal  
274 exposure and juvenile eumelanin level in the same model (see results). There was no  
275 significant relation between adult eumelanin level and metal exposure whatever the adult  
276 group (all adults or adults that bred, produced hatchlings or fledglings successfully).

277 For each dependent variable listed in table 1, we performed three successive models:

278 - in models 1, we tested ecotoxicological effects of lead exposure, zinc exposure and their  
279 interaction in all birds whatever their plumage melanin type (pheomelanic and eumelanic,  
280 thus not included in the model);

281 - in models 2, we tested the effects of melanin type (pheomelanic vs. eumelanic), lead and  
282 zinc exposures and their interactions in all birds; note that the interaction between zinc  
283 exposure and lead exposure was not tested because no pheomelanic birds have been exposed  
284 to both zinc and lead;

285 - in models 3, we tested the effects of plumage eumelanin level in interaction with lead and  
286 zinc exposure in eumelanic birds only (note that the number of pheomelanic pigeons was too  
287 low to test the effect of pheomelanin level).

288 First, we investigated metal concentrations in feathers using linear mixed models. Age (adult  
289 vs. juvenile) was added into the models when testing the effects of metals alone (model 1) and  
290 of melanin type (model 2). However, there were too few pheomelanic juveniles (N=4) to test  
291 the interaction between melanin type and age. When testing the effects of eumelanin level  
292 (model 3), colinearity issues (see above) did not allow us to test the effects of metal exposure  
293 and eumelanin level in the same model, so that we performed separate models for adults and  
294 juveniles. In juveniles, we first tested the effect of eumelanin level alone; when significant,

295 we then tested the effect of lead exposure, zinc exposure and their interaction, and compared  
296 the two models using their AIC. Lead is undetectable in the feathers after one year of  
297 captivity in our study site (Chatelain *et al.*, 2014). Therefore, lead detected in the feathers of  
298 adult not experimentally exposed to this metal arose mostly from birds' original environment  
299 prior to our experiment, which could conceal the potential link between plumage colouration  
300 and lead concentrations in feathers. Thus, we performed additional models investigating lead  
301 concentrations in feathers according to plumage colouration in birds exposed to lead (*lead* and  
302 *lead+zinc* groups), both in adults and juveniles, which exhibited significantly higher lead  
303 feather concentrations (see results).

304 Second, we investigated metal concentrations in blood using linear mixed models.

305 Third, we performed linear mixed models with time (expressed as the number of weeks after  
306 the beginning of the experiment) and its interactions with the other variables listed above as  
307 fixed effects to explain adult scaled mass index variation along time; individual was added as  
308 a random effect.

309 Finally, we investigated the effects of metal exposure on reproductive parameters using linear  
310 mixed models (egg quality, nestling growth and scaled mass index at 3 days of age) or general  
311 linear mixed models for binomial distribution (breeding success, hatchling success, fledging  
312 success, juvenile total white blood cell and heterophils/lymphocytes ratio); mother identity  
313 was added as random effect. When testing the effect of plumage colouration (parental or  
314 juveniles), plumage colouration was included as melanin type (model 2) or eumelanin level  
315 (model 3) of both parents for egg quality and reproductive success (breeding, hatchling,  
316 fledging), or eumelanin level of juvenile (model 3) for juvenile growth, scaled mass index and  
317 physiological state (the effect of melanin type was not tested for these variables because  
318 pheomelanic juveniles were rare (4 birds out of 40)). When testing the effects of juvenile  
319 eumelanin level (model 3) and to take colinearity issues into account (see above), we first

320 tested the effect of eumelanin level alone; if significant, we then tested the effect of lead  
321 exposure, zinc exposure and their interaction, and compared the two models using the AIC  
322 (i.e. when performing linear mixed models). In all performed models, the aviary was added as  
323 random effect. There was no significant relationship between laying date and trace metal  
324 exposure, suggesting that even though cumulative effect might exist, it would not be  
325 significantly different between the treatments. Therefore, laying date was not added as  
326 random effect in the models.

327

328 Statistical analyses were performed using R software (version 3.0.2) and a type 3 approach  
329 was used to take the unbalance of the design into account. We did not correct p-values for  
330 multiple testing as suggested by Moran (2003), García (2004) and Nakagawa (2004).

331

## 332 **RESULTS**

333

### 334 **Trace metal concentrations in feathers**

335 Among all pigeons (pheomelanic and eumelanic), zinc concentrations in feathers were higher  
336 in birds exposed to zinc (*zinc* and *lead+zinc* groups;  $F_{1,104}=4.25$ ,  $P=0.042$ ; table 1) and in  
337 juveniles ( $F_{1,104}=6.64$ ,  $P=0.011$ ;  $91.36\text{ppm}\pm 1.68$  and  $99.27\text{ppm}\pm 2.28$  in adults and in  
338 juveniles respectively). Moreover, lead concentrations in feathers were higher in birds  
339 exposed to lead (*lead* and *lead+zinc* groups) than in the others (*zinc* and *control* groups;  
340  $F_{1,105}=15.09$ ,  $P<0.001$ ; table 1).

341 Among all pigeons (pheomelanic or eumelanic), zinc concentrations in feathers were higher in  
342 eumelanic birds than in pheomelanic ones ( $F_{1,104}=25.64$ ,  $P<0.001$ ;  $96.26\text{ ppm}\pm 1.15$  in  
343 eumelanic birds and  $72.54\text{ ppm}\pm 5.13$  in pheomelanic birds). Melanin type was not retained in

344 the final model fitted for lead concentrations in feathers (among all birds and among birds  
345 exposed to lead).

346 Among eumelanic adults, zinc concentrations in feathers increased with eumelanin level  
347 ( $F_{1,63}=11.21$ ,  $P<0.001$ ; Fig. 1). Among eumelanic adults exposed to lead (*lead* and *lead+zinc*  
348 groups), lead concentrations in feathers increased with plumage eumelanin level ( $F_{1,33}=5.12$ ,  
349  $P=0.030$ ; Fig. 2). Among eumelanic juveniles, eumelanin level was not retained for the  
350 models fitted for zinc and for lead concentrations in feathers among all juveniles and juveniles  
351 exposed to lead.

352

### 353 **Trace metal concentrations in blood**

354 Among all adults (pheomelanic and eumelanic), lead concentrations in blood tended to  
355 depend on the interaction between zinc exposure and lead exposure ( $F_{3,43}=3.64$ ,  $P=0.063$ ;  
356 table 1): birds exposed to zinc only (*zinc* group) exhibited lower lead concentrations in blood  
357 than birds exposed to both lead and zinc (*lead+zinc* group;  $F_{1,21}=10.79$ ,  $P=0.004$ ), birds  
358 exposed to lead only (*lead* group;  $F_{1,21}=6.04$ ,  $P=0.023$ ) and controls (*control* group;  
359  $F_{1,21}=4.18$ ,  $P=0.054$ ). None of the considered variables were retained in the models fitted for  
360 zinc concentrations in blood.

361

### 362 **Scaled mass index variation**

363 Among all adults (pheomelanic and eumelanic), scaled mass index depended on the  
364 interaction between time, zinc exposure and lead exposure ( $F_{1,96}=8.93$ ,  $P=0.003$ ): scaled mass  
365 index decreased along time in *lead* ( $F_{1,24}=52.39$ ,  $P<0.001$ ), *control* ( $F_{1,24}=28.11$ ,  $P<0.001$ ) and  
366 *lead+zinc* groups ( $F_{1,24}=57.92$ ,  $P<0.001$ ) while time was not retained in the final model fitted  
367 for scaled mass index in *zinc* group.

368 Among eumelanic adults, scaled mass index depended on the interaction between time, zinc  
369 exposure, lead exposure and eumelanin level ( $F_{1,82}=19.29$ ,  $P<0.001$ ; Fig. 3): scaled mass  
370 index decreased along time in *control* ( $F_{1,20}=35.64$ ,  $P<0.001$ ) and *lead+zinc* group  
371 ( $F_{1,24}=57.92$ ,  $P<0.001$ ). In *lead* group, scaled mass index depended on the interaction between  
372 time and eumelanin level ( $F_{1,19}=40.02$ ,  $P<0.001$ ), with scaled mass index decreasing along  
373 time among the darkest birds only ( $F_{1,9}=87.10$ ,  $P<0.001$ ). Neither time nor eumelanic level  
374 was retained in the final model fitted for scaled mass index among *zinc* group.

375 Melanin type was not retained in the model fitted for scaled mass index.

376

### 377 **Reproductive success**

378 None of the variables considered was retained in the final model fitted for birds' breeding  
379 success.

380 Among all parents (pheomelanic and eumelanic), metal exposure was not retained in the  
381 models fitted for egg weight and volume, albumen or eggshell weight. However, yolk was  
382 heavier in eggs from parents exposed to zinc (*zinc* and *lead+zinc* groups) than from the others  
383 (*control* and *lead* groups;  $F_{1,53}=7.36$ ,  $P=0.007$ ; mean $\pm$ se 4.22g $\pm$ 0.08 and 3.89g $\pm$ 0.09  
384 respectively; table 1). Moreover, eggshell was thicker in eggs from parents exposed to zinc  
385 (*zinc* and *lead+zinc* groups;  $F_{1,62}=5.18$ ,  $P=0.023$ ; mean $\pm$ se 0.49mm $\pm$ 0.01 and 0.47mm $\pm$ 0.00  
386 respectively; table 1) while it was thinner in eggs from parents exposed to lead (*lead* and  
387 *lead+zinc* groups;  $F_{1,62}=8.24$ ,  $P=0.004$ ; mean $\pm$ se 0.47mm $\pm$ 0.00 and 0.49mm $\pm$ 0.01  
388 respectively; table 1).

389 None of the variables considered was retained in the model fitted for hatching success.

390 Among all parents, nestlings of parents exposed to lead (*lead* and *lead+zinc* groups) were  
391 significantly lighter than the other ones (*control* and *zinc* groups;  $F_{1,52}=4.17$ ,  $P=0.041$ ;  
392 mean $\pm$ se 14.94g $\pm$ 0.72 and 17.20g $\pm$ 0.67 respectively; table 1). None of the variables

393 considered was retained in the models fitted for tarsus and wing length of one-day-old chick.  
394 With regard to nestling growth, none of the variables considered was retained in the models  
395 fitted for weight, tarsus and wing growth rate. However, the age at which weight and tarsus  
396 growth slowed down depended on the interaction between lead and zinc exposure ( $F_{1,24}=5.53$ ,  
397  $P=0.019$ ; and  $F_{1,41}=9.66$ ,  $P=0.002$ ; Fig. 4). Indeed, growth slowed down earlier in juveniles of  
398 parents exposed to lead only (*lead* group) than in juveniles of parents exposed to both lead  
399 and zinc (*lead+zinc* group;  $F_{1,24}=5.53$ ,  $P=0.019$  and  $F_{1,24}=6.01$ ,  $P=0.014$  respectively) and of  
400 controls parents (*control* group;  $F_{1,25}=11.46$ ,  $P=0.002$  and  $F_{1,25}=19.52$ ,  $P<0.001$  respectively).  
401 Zinc and lead exposure was not retained in the models fitted for the age at which wing growth  
402 slowed down, and melanin type and eumelanin level were not retained in any of the models  
403 fitted for nestlings' growth.

404 In all parents, fledging success was lower in juveniles from pheomelanic fathers ( $F_{1,59}=8.13$ ,  
405  $P=0.004$ ) and tended to be also lower among birds exposed to lead (*lead* and *lead+zinc*  
406 groups;  $F_{1,59}=3.62$ ,  $P=0.057$ ). Eumelanin level was not retained in the model fitted for  
407 fledging success.

408 In all juveniles, scaled mass index was smaller in lead groups (*lead* and *lead+zinc* groups)  
409 than in the other groups (*control* and *zinc* groups;  $F_{1,40}=6.43$ ,  $P=0.011$ ;  $\text{mean}\pm\text{se}$   
410  $293.91\pm 19.11$  and  $349.73\pm 20.02$  respectively; table 1). Moreover, the number of white blood  
411 cells was higher in zinc groups (*zinc* and *lead+zinc* groups) than in the other groups  
412 ( $F_{1,40}=5.14$ ,  $P=0.023$ ;  $6.0\%\pm 0.5$  and  $4.8\%\pm 0.3$  respectively; table 1). The number of  
413 heterophils among the number of lymphocytes depended on the interaction between lead and  
414 zinc exposure ( $F_{1,37}=5.79$ ,  $P=0.016$ ,  $P=0.016$ ; table 1): it was higher in *lead* group than in  
415 *control* group ( $F_{1,20}=4.65$ ,  $P=0.031$ ) and *lead+zinc* group ( $F_{1,19}=4.01$ ,  $P=0.046$ ). Among  
416 eumelanic juveniles, eumelanin level was not retained in the model fitted for scaled mass  
417 index, the number of white blood cells and for the heterophils/lymphocytes ratio.

418 Finally, the plumage eumelanin level of surviving juveniles significantly depended on lead-  
419 exposure ( $F_{3,30}=6.69$ ,  $P=0.015$ ; Fig. 5), with eumelanin level being higher among juveniles  
420 exposed to lead only (*lead* group) than among juveniles from other groups (*zinc*, *control*, and  
421 *lead+zinc* groups).

422

## 423 **DISCUSSION**

424

425 To investigate whether and how trace metals may affect pigeons and may select for darker  
426 pigeons in urban areas, we tested whether 1) trace metals have ecotoxicological effects, 2)  
427 darker individuals store higher amounts of metals into their feathers, 3) darker individuals  
428 maintain lower metal levels in their blood and 4) darker individuals are more tolerant to the  
429 exposure to toxic metals. To this aim, we used an experimental approach; zinc and lead  
430 supplementations successfully increased zinc and lead concentrations in feathers respectively,  
431 while exposure to a given metal did not raise its concentration in the blood (table 1). Overall,  
432 metal concentrations in blood may not always reliably estimate recent exposure as they can  
433 result from numerous mechanisms (lead clearance from bones, lead and zinc transfer into  
434 organs, bones and feathers (Cosson, 1989; Gulson *et al.*, 1996; Kim *et al.*, 1998; Agusa *et al.*,  
435 2005)).

436

437 First, our study consistently demonstrated detrimental effects of lead and beneficial effects of  
438 zinc on some of bird condition and reproductive success parameters (table 2). The scaled  
439 mass index decreased over the 20-week-long experiment in birds exposed to lead (*lead* and  
440 *lead+zinc* groups) and in *control* group, while remaining constant in *zinc* group. Eggshell was  
441 thinner in eggs from lead-exposed parents. This negative effect, previously observed in pied  
442 flycatchers (Eeva & Lehikoinen, 1995) and likely due to limitation of calcium deposition

443 (Clunies *et al.*, 1992; Simons, 1993), may impair eggshell permeability and resistance to  
444 impacts (King & Robinson, 1972). On the contrary, zinc increased eggshell thickness. Zinc  
445 also increased yolk mass, potentially elevating egg nutritive content (Noy & Sklan, 1998).  
446 Accordingly, previous work reported a positive link between plasma zinc and vitellogenin  
447 production (Mitchell & Carlisle, 1991). Since zinc exposure did not influence egg size nor  
448 one-day-old chick size, this extra yolk mass may have been allocated to other physiological  
449 traits, such as immunity (see Li *et al.*, 1998). Accordingly, juveniles exposed to zinc (*zinc* and  
450 *lead+zinc* groups) had a higher amount of white blood cells, an index of the immune system  
451 (Davis *et al.*, 2008), than the other groups (*lead* and *control* groups). In addition, lead-  
452 exposure induced lighter one-day-old chicks. Because lead did not affect egg total, yolk nor  
453 albumen mass, it may not alter maternal investment in eggs but may be maternally transferred  
454 into the eggs and affect embryonic development (Burger, 2002). Juveniles exposed to lead  
455 only (*lead* group) tended to have a lower fledging success, possibly a consequence of a poorer  
456 condition at hatching (Grant, 2008). Among fledglings, lead exposure also induced a shorter  
457 growth period of body mass and tarsus and a smaller scaled mass index at three months of  
458 age, which could impair their future survival or reproduction (“catch-up” hypothesis, see  
459 Criscuolo *et al.*, 2008). Consistently, juveniles exposed to lead only (*lead* group) had a higher  
460 number of heterophils/lymphocytes ratio, suggesting a higher stress hormone level (Davis *et*  
461 *al.*, 2008). Finally, zinc-exposure had protective effects against lead: when provided along  
462 with zinc, lead did not induce negative effects on several of the measured traits (table 1, Fig.  
463 4). This protective effect may result from zinc ability to reduce the absorption and retention of  
464 ingested lead (Cerklewski & Forbes, 1976; El-Gazzar *et al.*, 1978), as suggested by lower lead  
465 concentrations in blood in birds exposed to zinc only (*zinc* group) than in the other birds  
466 (*control*, *lead zinc+lead* groups). The effects of trace metals observed on juveniles may be

467 due to either direct effects on juveniles or to indirect effects through parental investment that  
468 further experimental studies should disentangle.

469

470 Second, we predicted a positive relationship between plumage darkness and metal  
471 concentrations in feathers. Our prediction was validated for both zinc, confirming previous  
472 work (Chatelain *et al.*, 2014) and lead (table 2). Our results suggest that more melanic  
473 feathers would be able to store higher amounts of both zinc and lead. Although washed  
474 feathers may still have some amounts of trace metals on their surface, such residual  
475 concentrations likely do not correlate with plumage eumelanin level. Therefore, melanin  
476 contained in the plumage could play a significant role in metal detoxification. Interestingly,  
477 zinc concentrations in feathers were higher in eumelanic pigeons than in pheomelanic ones;  
478 such differences could be due to differences in chemical composition between melanin types  
479 (e.g. more carboxylic acid groups in eumelanin; Hong & Simon, 2007), to different  
480 physiological requirements of zinc (e.g. oxidative stress; Prasad, 2009) or to differences in  
481 immune responses (Chatelain *et al.* unpublished data).

482

483 Third, we did not find the negative correlation between plumage eumelanin level and metal  
484 concentrations in blood expected from our detoxification hypothesis (table 2). Metal  
485 concentration in blood does not reliably reflect recent exposure as it results from numerous  
486 mechanisms (Cosson, 1989; Gulson *et al.*, 1996; Kim *et al.*, 1998; Agusa *et al.*, 2005) that  
487 may hide detoxification process. Future work should investigate whether such potential  
488 detoxification through melanin lowers metal burden in organs. Although feral pigeons moult  
489 all over the year (Johnston & Janiga, 1995), metal detoxification may be more efficient when  
490 moulting is most intense (i.e. fall) and during juvenile growth (i.e. synchronized growth of all  
491 feathers).

492

493 Fourth, we did find a statistical interaction between plumage eumelanin level and metal  
494 exposure on scaled mass index (table 2). In birds exposed to lead only (*lead* group), paler  
495 birds maintained their initial condition over the course of the experiment, while darker birds  
496 lost weight. Note however that darker birds had an initial lower scaled mass index than the  
497 paler ones, so that we cannot distinguish whether this result was due to the effect of initial  
498 scaled mass index or to eumelanin level. In the latter case, this result may suggest a  
499 disadvantage of a more melanic plumage in environments polluted with lead; alternatively, it  
500 may also be the result of a trade-off between condition maintenance and other biological  
501 traits, such as parental investment, which would be in line with the higher survival rate of  
502 darker juveniles among birds exposed to lead only (*lead* group). Indeed, plumage eumelanin  
503 level of three-month-old juveniles was higher in *lead* group than in the other groups (table 2).  
504 This result was not due to different reproductive success (breeding, hatching and fledging  
505 success) between differently coloured adults. In addition, because melanin-based plumage  
506 colouration is highly heritable in feral pigeons ( $0.82 \pm 0.12$ ; Jacquin *et al.*, 2013b), it is  
507 unlikely that a direct effect of lead on melanogenesis explains the higher plumage darkness of  
508 juveniles under lead-exposure. More likely, this result may reflect higher survival rate of  
509 darker juveniles when exposed to lead only as compared to paler ones. Indeed, fledging  
510 success tended to be lower under lead-exposure, which could be due to higher mortality in  
511 paler offspring. This hypothesis is in accordance with the higher survival rate of darker  
512 pigeon juveniles in a Parisian suburban environment (Récapet *et al.*, 2013) and with the  
513 higher frequency of darker pigeons observed in European cities (Obukhova, 2007).

514

515 In conclusion, we found several lines of evidence supporting the possibility that trace metals  
516 exert selective pressures on melanin-based plumage colouration (table 2). Indeed, darker birds

517 stored higher amounts of zinc and lead in their feathers and likely had a higher juvenile  
518 survival under lead-exposure. However, scaled mass index of darker birds decreased over  
519 time when exposed to lead only. Moreover, bird sensitivity to trace metals did not depend on  
520 their plumage colouration for several traits. The lack of results may originate from the low  
521 beneficial effect of plumage melanin under metal exposure, from the experimental exposure  
522 to metal concentrations underestimating the natural range (zinc and lead in the feathers were  
523 respectively 80 and 1.5 times less concentrated than measured in wild feral pigeons (Nam *et*  
524 *al.*, 2004; Adout *et al.*, 2007; Brait & Filho, 2011; Frantz *et al.*, 2012; Chatelain *et al.*, 2014)),  
525 from high inter-individual variation (i.e. in trace metal exposure prior to the experiment)  
526 reducing the probability to detect some effects, or from ongoing selection ultimately  
527 favouring dark plumage along with a series of other traits. More experimental studies  
528 involving exposure to a cocktail of metals in their urban range of concentrations are needed to  
529 better understand how this new selective pressure may favour particular phenotypes,  
530 especially melanin-based colouration.

531

#### 532 **ACKNOWLEDGMENTS**

533

534 We thank the “Mairie de Paris” (Thomas Charachon) for allowing the capture of birds and the  
535 Centre de Recherche en Ecologie Expérimentale et Prédictive (CEREEP) which provided  
536 logistic support for the field work of this study. We are very thankful to S. Leclaire, T. Gayet,  
537 S. Pollet, S. Hasnaoui, F. Lorente, S. Perret and B. Decencière for their help all along the field  
538 work. We have no conflict of interest.

539

#### 540 **REFERENCES**

541

542 Adout A, Hawlena D, Maman R, Paz-Tal O, Karpas Z (2007) Determination of trace elements  
543 in pigeon and raven feathers by ICPMS. *International Journal of Mass Spectrometry*,  
544 **267**, 109–116.

545 Agusa T, Matsumoto T, Ikemoto T et al. (2005) Body distribution of trace elements in black-  
546 tailed gulls from Rishiri Island, Japan: Age-dependent accumulation and transfer to  
547 feathers and eggs. *Environmental Toxicology and Chemistry*, **24**, 2107–2120.

548 Almasi B, Jenni L, Jenni-Eiermann S, Roulin A (2010) Regulation of stress response is  
549 heritable and functionally linked to melanin-based coloration. *Journal of Evolutionary*  
550 *Biology*, **23**, 987–996.

551 Almasi B, Roulin A, Korner-Nievergelt F, Jenni-Eiermann S, Jenni L (2012) Coloration  
552 signals the ability to cope with elevated stress hormones: effects of corticosterone on  
553 growth of barn owls are associated with melanism: Plumage coloration and stress  
554 sensitivity. *Journal of Evolutionary Biology*, **25**, 1189–1199.

555 Averbeck C (1992) Haematology and blood chemistry of healthy and clinically abnormal  
556 great black-backed gulls (*Larus Marinus*) and herring gulls (*Larus Argentatus*). *Avian*  
557 *Pathology*, **21**, 215–223.

558 Azimi S, Rocher V, Muller M, Moilleron R, Thevenot DR (2005) Sources, distribution and  
559 variability of hydrocarbons and metals in atmospheric deposition in an urban area  
560 (Paris, France). *Science of The Total Environment*, **337**, 223–239.

561 Berglund A, Sturve J, Forlin L, Nyholm N (2007) Oxidative stress in pied flycatcher  
562 (*Ficedula hypoleuca*) nestlings from metal contaminated environments in northern  
563 Sweden. *Environmental Research*, **105**, 330–339.

564 Bozym RA, Chimienti F, Giblin LJ et al. (2010) Free zinc ions outside a narrow concentration  
565 range are toxic to a variety of cells in vitro. *Experimental Biology and Medicine*, **235**,  
566 741–750.

567 Brait HCH, Filho ANR (2011) Use of feathers of feral pigeons (*Columba livia*) as a technique  
568 for metal quantification and environmental monitoring. *Environmental Monitoring*  
569 *and Assessment*, **179**, 457–467.

570 Bridelli MG, Crippa PR (2007) Theoretical analysis of the adsorption of metal ions to the  
571 surface of melanin particles. *Adsorption*, **14**, 101–109.

572 Burger J (1993) Metals in avian feathers: bioindicators of environmental pollution. *Reviews of*  
573 *Environmental Contamination and Toxicology*, **5**, 203–311.

574 Burger J (2002) Food chain differences affect heavy metals in bird eggs in Barnegat Bay,  
575 New Jersey. *Environmental Research*, **90**, 33–39.

576 Burger J, Gochfeld M (2004) Effects of lead and exercise on endurance and learning in young  
577 herring gulls. *Ecotoxicology and Environmental Safety*, **57**, 136–144.

578 Cerklewski FL, Forbes RM (1976) Influence of dietary zinc on lead toxicity in the rat. *The*  
579 *Journal of Nutrition*, **106**, 689–696.

580 Chatelain M, Gasparini J, Jacquin L, Frantz A (2014) The adaptive function of melanin-based  
581 plumage coloration to trace metals. *Biology Letters*, **10**, 20140164–20140164.

582 Chichovska M, Anguelov A (2006) Study on the influence of L-lysine and zinc administration  
583 during exposure to lead and ethanol in rats. *Veterinarski arhiv*, **76**, 65–73.

584 Clunies M, Parks D, Leeson S (1992) Calcium and phosphorus metabolism and eggshell  
585 thickness in laying hens producing thick or thin shells. *Poultry Science*, **71**, 490–498.

586 Cooper J. (1975) Haematological investigations in east american birds of prey. **11**, 389–394.

587 Cosson RP (1989) Relationships between heavy metal and metallothionein-like protein levels  
588 in the liver and kidney of two birds: The greater flamingo and the little egret.  
589 *Comparative Biochemistry and Physiology Part C: Comparative Pharmacology*, **94**,  
590 243–248.

- 591 Criscuolo F, Monaghan P, Nasir L, Metcalfe NB (2008) Early nutrition and phenotypic  
592 development: “catch-up” growth leads to elevated metabolic rate in adulthood.  
593 *Proceedings of the Royal Society B: Biological Sciences*, **275**, 1565–1570.
- 594 Dauwe, L. Bervoets, R. Blust, M. Eens T (2002) Tissue levels of lead in experimentally  
595 exposed zebra finches (*Taeniopygia guttata*) with particular attention on the use of  
596 feathers as biomonitors. *Archives of Environmental Contamination and Toxicology*,  
597 **42**, 88–92.
- 598 Davis AK, Maney DL, Maerz JC (2008) The use of leukocyte profiles to measure stress in  
599 vertebrates: a review for ecologists. *Functional Ecology*, **22**, 760–772.
- 600 Dominoni D, Quetting M, Partecke J (2013) Artificial light at night advances avian  
601 reproductive physiology. *Proceedings of the Royal Society B: Biological Sciences*,  
602 **280**, 20123017–20123017.
- 603 Ducrest A, Keller L, Roulin A (2008) Pleiotropy in the melanocortin system, coloration and  
604 behavioural syndromes. *Trends in Ecology & Evolution*, **23**, 502–510.
- 605 Eeva T, Lehikoinen E (1995) Egg shell quality, clutch size and hatching success of the great  
606 tit (*Parus major*) and the pied flycatcher (*Ficedula hypoleuca*) in an air pollution  
607 gradient. *Oecologia*, **102**, 312–323.
- 608 Eeva T, Lehikoinen E (1996) Growth and mortality of nestling great tits (*Parus major*) and  
609 pied flycatchers (*Ficedula hypoleuca*) in a heavy metal pollution gradient. *Oecologia*,  
610 **108**, 631–639.
- 611 Eeva T, Ahola M, Lehikoinen E (2009) Breeding performance of blue tits (*Cyanistes*  
612 *caeruleus*) and great tits (*Parus major*) in a heavy metal polluted area. *Environmental*  
613 *Pollution*, **157**, 3126–3131.
- 614 El-Gazzar RM, Finelli VN, Boiano J, Petering HG (1978) Influence of dietary zinc on lead  
615 toxicity in rats. *Toxicology Letters*, **1**, 227–234.

616 Frantz A, Pottier M-A, Karimi B et al. (2012) Contrasting levels of heavy metals in the  
617 feathers of urban pigeons from close habitats suggest limited movements at a  
618 restricted scale. *Environmental Pollution*, **168**, 23–28.

619 García LV (2004) Escaping the Bonferroni iron claw in ecological studies. *Oikos*, **105**, 657–  
620 663.

621 Gaither LA, Eide DJ (2001) Eukaryotic zinc transporters and their regulation. In: *Zinc*  
622 *Biochemistry, Physiology, and Homeostasis* (ed Maret W), pp. 65–84. Springer  
623 Netherlands, Dordrecht.

624 Gochfeld M, Saliva J, Lesser F, Shukla T, Bertrand D, Burger J (1991) Effects of color on  
625 cadmium and lead levels in avian contour feathers. *Archives of environmental*  
626 *contamination and toxicology*, **20**, 523–526.

627 Grant MC (2008) Relationships between egg size, chick size at hatching, and chick survival in  
628 the whimbrel *Numenius phaeopus*. *Ibis*, **133**, 127–133.

629 Greenberg SA, Briemberg HR (2004) A neurological and hematological syndrome associated  
630 with zinc excess and copper deficiency. *Journal of Neurology*, **251**, 111–114.

631 Gulson B, Mizon KJ, Korsch MJ, Howarth D, Phillips A, Hall J (1996) Impact on blood lead  
632 in children and adults following relocation from their source of exposure and  
633 contribution of skeletal tissue to blood lead. *Bulletin of Environmental Contamination*  
634 *and Toxicology*, **56**, 543–550.

635 Halfwerk W, Holleman LJM, Lessells CkM, Slabbekoorn H (2011) Negative impact of traffic  
636 noise on avian reproductive success: Traffic noise and avian reproductive success.  
637 *Journal of Applied Ecology*, **48**, 210–219.

638 Hong L, Simon JD (2007) Current understanding of the binding sites, capacity, affinity, and  
639 biological significance of metals in melanin. *The Journal of Physical Chemistry B*,  
640 **111**, 7938–7947.

641 Hsu MJ, Selvaraj K, Agoramoorthy G (2006) Taiwan's industrial heavy metal pollution  
642 threatens terrestrial biota. *Environmental Pollution*, **143**, 327–334.

643 Jacquin L, Lenouvel P, Haussy C, Ducatez S, Gasparini J (2011) Melanin-based coloration is  
644 related to parasite intensity and cellular immune response in an urban free living bird:  
645 the feral pigeon *Columba livia*. *Journal of Avian Biology*, **42**, 11–15.

646 Jacquin L, Recapet C, Bouche P, Leboucher G, Gasparini J (2012) Melanin-based coloration  
647 reflects alternative strategies to cope with food limitation in pigeons. *Behavioral*  
648 *Ecology*, **23**, 907–915.

649 Jacquin L, Récapet C, Prévot-Julliard A-C et al. (2013a) A potential role for parasites in the  
650 maintenance of color polymorphism in urban birds. *Oecologia*, **173**, 1089–1099.

651 Jacquin L, Haussy C, Bertin C, Laroucau K, Gasparini J (2013b) Darker female pigeons  
652 transmit more specific antibodies to their eggs than do paler ones. *Biological Journal*  
653 *of the Linnean Society*, **108**, 647–657.

654 Janssens EJ, Dauwe T, Pinxten R, Eens M (2003) Breeding performance of great tits (*Parus*  
655 *major*) along a gradient of heavy metal pollution. *Environmental Toxicology and*  
656 *Chemistry*, **22**, 1140–1145.

657 Jarup L (2003) Hazards of heavy metal contamination. *British Medical Bulletin*, **68**, 167–182.

658 Johnston R, Janiga M (1995) *Feral pigeons*. Oxford University Press.

659 Kekkonen J, Hanski IK, Väisänen RA, Brommer JE (2012) Levels of heavy metals in house  
660 sparrows (*Passer domesticus*) from urban and rural habitats of southern Finland. *Ornis*  
661 *Fennica*, **89**; 91–98.

662 Kim EY, Goto R, Tanabe S, Tanaka H, Tatsukawa R (1998) Distribution of 14 elements in  
663 tissues and organs of oceanic seabirds. *Archives of Environmental Contamination and*  
664 *Toxicology*, **35**, 638–645.

665 King NR, Robinson DS (1972) The use of the scanning electron microscope for comparing  
666 the structure of weak and strong egg shells. *Journal of Microscopy*, **95**, 437–443.

667 Larsson B, Tjälve H (1978) Studies on the melanin-affinity of metal ions. *Acta Physiologica*  
668 *Scandinavica*, **104**, 479–484.

669 Li X, Nakano T, Sunwoo HH, Paek BH, Chae HS, Sim JS (1998) Effects of egg and yolk  
670 weights on yolk antibody (IgY) production in laying chickens. *Poultry Science*, **77**,  
671 266–270.

672 Liu Y, Hong L, Kempf VR, Wakamatsu K, Ito S, Simon JD (2004) Ion-exchange and  
673 adsorption of Fe (III) by sepia melanin. *Pigment Cell Research*, **17**, 262–269.

674 McGraw KJ (2003) Melanins, metals, and mate quality. *Oikos*, 402–406.

675 Mckinnon JS, Pierotti MER (2010) Colour polymorphism and correlated characters: genetic  
676 mechanisms and evolution. *Molecular Ecology*, **19**, 5101–5125.

677 Mertz W (1981) The essential trace elements. *Science*, **213**, 1332–1338.

678 Mitchell M., Carlisle A. (1991) Plasma zinc as an index of vitellogenin production and  
679 reproductive status in the domestic fowl. *Comparative Biochemistry and Physiology*  
680 *Part A: Physiology*, **100**, 719–724.

681 Moran MD (2003) Arguments for rejecting the sequential Bonferroni in ecological studies.  
682 *Oikos*, 403–405.

683 Nakagawa S (2004) A farewell to Bonferroni: the problems of low statistical power and  
684 publication bias. *Behavioral Ecology*, **15**, 1044–1045.

685 Nam D-H, Lee D-P, Koo T-H (2004) Monitoring for lead pollution using feathers of feral  
686 pigeons (*Columba livia*) from Korea. *Environmental Monitoring and Assessment*, **95**,  
687 13–22.

- 688 Newbrey JL, Reed WL (2009) Growth of yellow-headed blackbird *Xanthocephalus*  
689 *xanthocephalus* nestlings in relation to maternal body condition, egg mass, and yolk  
690 carotenoids concentrations. *Journal of Avian Biology*, **40**, 419–429.
- 691 Niecke M, Heid M, Krüger A (1999) Correlations between melanin pigmentation and element  
692 concentration in feathers of white-tailed eagles (*Haliaeetus albicilla*). *Journal für*  
693 *Ornithologie*, **140**, 355–362.
- 694 Niecke M, Rothlaender S, Roulin A (2003) Why do melanin ornaments signal individual  
695 quality? Insights from metal element analysis of barn owl feathers. *Oecologia*, **137**,  
696 153–158.
- 697 Noy Y, Sklan D (1998) Yolk utilisation in the newly hatched poult. *British Poultry Science*,  
698 **39**, 446–451.
- 699 Nriagu JO (1996) A history of global metal pollution. *Science*, **272**, 223–224.
- 700 Obukhova N (2007) Polymorphism and phene geography of the blue rock pigeon in Europe.  
701 *Russ. J. Genet*, **43**, 492–501.
- 702 Paillisson J-M, Reeber S, Carpentier A, Marion L (2007) Reproductive parameters in relation  
703 to food supply in the whiskered tern (*Chlidonias hybrida*). *Journal of Ornithology*,  
704 **148**, 69–77.
- 705 Patrick L (2006) Lead toxicity, a review of the literature. Part 1: Exposure, evaluation, and  
706 treatment. *Alternative Medicine Review: A Journal of Clinical Therapeutic*, **11**, 2–22.
- 707 Peig J, Green AJ (2009) New perspectives for estimating body condition from mass/length  
708 data: the scaled mass index as an alternative method. *Oikos*, **118**, 1883–1891.
- 709 Peig J, Green AJ (2010) The paradigm of body condition: a critical reappraisal of current  
710 methods based on mass and length: The paradigm of body condition. *Functional*  
711 *Ecology*, **24**, 1323–1332.
- 712 Prasad AS (1998) Zinc and immunity. *Molecular and cellular biochemistry*, **188**, 63–69.

713 Prasad AS (2009) Zinc: role in immunity, oxidative stress and chronic inflammation: *Current*  
714 *Opinion in Clinical Nutrition and Metabolic Care*, **12**, 646–652.

715 Prasanthi RPJ, Reddy GH, Reddy GR (2006) Calcium or zinc supplementation reduces lead  
716 toxicity: assessment of behavioral dysfunction in young and adult mice. *Nutrition*  
717 *Research*, **26**, 537–545.

718 Prasanthi RPJ, Devi CB, Basha DC, Reddy NS, Reddy GR (2010) Calcium and zinc  
719 supplementation protects lead (Pb)-induced perturbations in antioxidant enzymes and  
720 lipid peroxidation in developing mouse brain. *International Journal of Developmental*  
721 *Neuroscience*, **28**, 161–167.

722 Récapet C, Dauphin L, Jacquin L, Gasparini J, Prévot-Julliard A-C (2013) Eumelanin-based  
723 colouration reflects local survival of juvenile feral pigeons in an urban pigeon house.  
724 *Journal of Avian Biology*, **44**, 583–590.

725 Roulin A, Almasi B, Meichtry-Stier KS, Jenni L (2011) Eumelanin- and pheomelanin-based  
726 colour advertise resistance to oxidative stress in opposite ways: Melanin colour and  
727 resistance to oxidative stress. *Journal of Evolutionary Biology*, **24**, 2241–2247.

728 Roux KE, Marra PP (2007) The presence and impact of environmental lead in passerine birds  
729 along an urban to rural land use gradient. *Archives of Environmental Contamination*  
730 *and Toxicology*, **53**, 261–268.

731 Scheifler R, Cœurduassier M, Morilhat C et al. (2006) Lead concentrations in feathers and  
732 blood of common blackbirds (*Turdus merula*) and in earthworms inhabiting  
733 unpolluted and moderately polluted urban areas. *Science of The Total Environment*,  
734 **371**, 197–205.

735 Simons TJ (1993) Lead-calcium interactions in cellular lead toxicity. *Neurotoxicology*, **14**,  
736 77–85.

- 737 Snoeijs T, Dauwe T, Pinxten R, Vandesande F, Eens M (2004) Heavy metal exposure affects  
738 the humoral immune response in a free-living small songbird, the great tit (*Parus*  
739 *major*). *Archives of Environmental Contamination and Toxicology*, **46**, 399–404.
- 740 Snoeijs T, Dauwe T, Pinxten R, Darras V, Arckens L, Eens M (2005) The combined effect of  
741 lead exposure and high or low dietary calcium on health and immunocompetence in  
742 the zebra finch. *Environmental Pollution*, **134**, 123–132.
- 743 Zduniak P, Surmacki A, Erciyas-Yavuz K, Chudzińska M, Barałkiewicz D (2014) Are there  
744 different requirements for trace elements in eumelanin- and pheomelanin-based color  
745 production? A case study of two passerine species. *Comparative Biochemistry and*  
746 *Physiology Part A: Molecular & Integrative Physiology*, **175**, 96–101.