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House sparrows mitigate growth effects of post-natal glucocorticoid exposure at the expense of longevity

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ABSTRACT

Acute, short-term effects of early-life stress and associated glucocorticoid upregulation on physiology and survival are widely documented across vertebrates. However, the persistence and severity of these effects are largely unknown, especially through the adult stage and for natural systems. Here, we investigate physiological, morphological, and survival effects of post-natal glucocorticoid upregulation across the nestling, juvenile, and adult life stages in house sparrows (*Passer domesticus*). We manipulate circulating corticosterone concentration in wild, free-living house sparrow nestlings and monitor body size, size-corrected mass, two measures of health (hematocrit and phytohemagglutinin-induced skin swelling), and survival in a captive environment until adulthood. We find that early-life corticosterone exposure depresses nestling size-corrected mass in both sexes, with no strong effect of the treatment on body size or our two measures of health. Birds are able to compensate for negative effects of high early-life corticosterone exposure in the long-term and this effect largely disappears by the juvenile and adult stages. However, treatment has a negative effect on survival through one year of age, suggesting that long-term compensation comes at a price.

1. Introduction

Exposure to early-life stress and associated glucocorticoid upregulation can have long-term effects on physiology and fitness (Cottrell and Seckl, 2009; Drummond and Ancona, 2015; Schoech et al., 2011; Seckl, 2004; Welberg and Seckl, 2001). However, the persistence and severity of such "programming" or "organizational" effects (Seckl, 2004; Welberg and Seckl, 2001) over the lifespan of an animal (Schoech et al., 2011) and their relevance for wild species are not well established (Drummond and Ancona, 2015; Schoech et al., 2011). Altricial birds are useful models to study the effects of post-natal glucocorticoid exposure because they lack a physiological link between mothers and offspring (i.e., maternal lactation) making it easier to disentangle postnatal maternal effects and endogenous effects in offspring, compared with mammalian studies (Spencer et al., 2009). An increasing body of avian research manipulating or observing early-life stressors (i.e., brood enlargement, parasitic infection, food stress, natal habitat quality), or manipulating early glucocorticoid exposure directly, generally supports mammalian findings of some negative effects of high early-life stress on behavior (e.g., poor anti-predator behavior; Grace et al., 2017), physiology (e.g. telomere attrition; Angelier et al., 2017), and/or fitness later in life (although some of these "negative effects" may be adaptive, and positive effects also exist; Crino and Breuner, 2015; Monaghan, 2008; Sih, 2011) (see Drummond and Ancona, 2015; Schoech et al., 2011 for review). In contrast and consistent with expectations, positive early-life conditions (i.e., being raised with a "silver spoon") are often beneficial throughout life (Van De Pol et al., 2006). However, results can be sex-specific (Arnold et al., 2007; Schmidt et al., 2012; Spencer et al., 2010), and species-specific (Schoech et al., 2011), and are highly dependent on the timing (Marasco et al., 2012), quality (Crino and Breuner, 2015), severity (Hull et al., 2007), and duration of the stressor. Further research is required to better understand the prolonged physiological effects of post-natal short-term stressors in wild vertebrates.

Field and laboratory studies both suggest that early-life glucocorticoid exposure generally (but not always; Schmidt et al., 2012) acutely depresses avian structural size and mass gain when the exposure is repeated, or chronic (Schoech et al., 2011), in some cases by increasing standard metabolic rate (Schmidt et al., 2012; although this was a sex-specific effect), or by increasing variability in overnight standard metabolic rate (Spencer and Verhulst, 2008). Smaller nestling body size before fledging can have adverse fitness

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consequences by impairing post-fledging resilience to nutritional stress, dominance rank, territory acquisition, and mating success (Hegyi and Török, 2007; Metcalfe and Monaghan, 2001), and is associated with impaired immunocompetence (Lochmiller et al., 1993). Poor size-corrected mass at fledging can negatively influence post-fledging survival (Both et al., 1999; Magrath, 1991; Tinbergen and Boerlijst, 1990), reproductive potential (Haywood and Perrins, 1992), and sexual attractiveness (Gustafsson et al., 1995). However, acute growth depression is not always observed in association with early-life stress (Kitaysky et al., 2003), and results can be sex-specific (Schmidt et al., 2012), or contradictory within a species (Hull et al., 2007; Loiseau et al., 2008a,b; Marasco et al., 2012). When effects of early-life stress on growth are observed they are usually short-term (Schoech et al., 2011) because of compensatory growth following cessation of stress (Spencer et al., 2009). Compensatory growth, however, can come at a cost to other physiological, behavioral, and life history parameters (Metcalfe and Monaghan, 2001; Monaghan, 2008).

Previous research in wild house sparrows (*Passer domesticus*) has revealed long-term effects of early-life corticosterone (CORT) treatment on adult anti-predator behavior (Grace et al., 2017), and acute effects of circulating CORT concentration ([CORT], the primary avian glucocorticoid) on nestling T-cell mediated immune response, and both an acute negative effect of on mass gain of nestlings (Loiseau et al., 2008b), and no effect on nestling mass gain (Loiseau et al., 2008a). Here, we clarify these previous early-life results, and extended the investigation time span of physiological and fitness effects through the juvenile and adult stages. We manipulated circulating CORT concentration in wild, free-living house sparrow nestlings to simulate a strong, but short-term stressor and monitored body size, size-corrected mass, two measures of health (phytohemagglutinin-induced skin swelling and hematocrit), and survival in a captive environment until adulthood. If birds were able to compensate for high early-life CORT exposure, we expected that negative effects of CORT treatment on body size, size-corrected mass, and survival will weaken across life stages (i.e., nestling, juvenile, adult). Alternatively, if early-life CORT exposure imposes a lifetime handicap (i.e., being raised without a "silver spoon"), we expected that negative effects of CORT treatment will persist throughout life. As a third alternative, if compensation for early-life CORT exposure imposes trade-offs between growth and survival, we expected to see no effect of CORT treatment on growth, but a negative effect on survival and health, or vice versa (Criscuolo et al., 2011; Hales and Ozanne, 2003; Metcalfe and Monaghan, 2001).

2. Methods

Permission to capture, sample, and hold house sparrows in captivity was issued by the French government (DREAL Poitou-Charentes, permit delivered to FA) and by the Muséum National d'Histoires Naturelles. All experimental procedures were approved by the French Government (R45GRETAF1-10) and Centre National de la Recherche Scientifique, and conform to guidelines set forth by the French Ministry of Higher Education and Research and Ministry of Agriculture and Fisheries.

2.1. Study population and reproductive monitoring

House sparrows were part of free-living populations breeding in nest boxes in the vicinity of Prissé la Charrière (46 °09′12″N 0 °28′59″W), a small rural and agricultural town located in Deux-Sèvres, France. Nest boxes were monitored for clutch initiation (first laid egg) and hatching dates, clutch size, hatching success, and chick mortality until eight days post-hatching. House sparrow eggs hatch synchronously within a clutch, thus, hatching date was the date that the first egg hatched within a clutch. Brood size was the number of nestlings in the nest at hatching (max = 6, min = 2, mean = 4.4). Nestling age was calculated with hatch date being day zero, one day post-hatching being day one, and so on. All nests with more than one chick in the study areas were used in the study, and all nestlings were used in each nest (n = 131 nestlings).

2.2. Nestling manipulation

Corticosterone (CORT) was delivered to CORT-fed nestlings non-invasively following the method of Breuner et al. (1998) and used successfully in subsequent studies (Breuner and Wingfield, 2000; Lohmus et al., 2006; Saldanha et al., 2000). Meal worms were injected with 20 μl of 0.6 mg mL^{-1} CORT or 0.9 mg mL^{-1} CORT in dimethyl sulfoxide (DMSO). Control nestlings were fed worms injected with 20 μl of DMSO. CORT concentrations were determined based on previous work with house sparrow nestlings (Loiseau et al., 2008 b) and Gambel's white-crowned sparrows (*Zonotrichia leucophrys*, Breuner and Wingfield, 2000; Breuner et al., 1998), scaled to the average mass of house sparrow nestlings at days of treatment. Worms were chilled at -20 °C prior to injection to limit movement, and were injected ventrally, into the central abdomen, between exoskeletal segments. If any fluid leaked from the mealworm it was discarded.

All nestlings were given a plastic color band to facilitate individual identification and at eight days post-hatching hormonal manipulation began. The hypothalamic-pituitaryadrenal (HPA) axis may develop slowly in altricial species such as the house sparrow (Wada, 2008), hence we began treatment in the mid-late nestling period (8 d post-hatching), when eyes are open and white-crowned sparrow nestlings are able to mount a strong HPA axis stress response (Wada et al., 2007). Half the nestlings in each nest were assigned to CORT-fed and control groups. Assignment was alternated between nestlings (CORT-fed first, control second, etc...) as they were removed from the nest and assignment order was alternated between nests (CORT-fed first, control second; control first, CORT-fed second). CORT- and vehicle-injected worms were fed to nestlings with blunt-end forceps, at their nest box. The schedule of feedings was designed to be unpredictable, to discourage habituation by nestlings. To this end, CORT-fed nestlings received a CORT-injected worm on day 8 (0.6 mg mL^{-1}), day 9 (twice – morning and evening; 0.6 mg mL^{-1}), and day 11 post-hatching (0.9 mg mL^{-1}), while control nestlings received a vehicle injected worm on the same schedule (see Fig. 1 for timeline of experiment). Treatment lasted only three days to simulate a shorter-term nestling (as opposed to juvenile) stressor, and was stopped after day 11 post-hatching to prevent premature fledging from nest disturbance. Worms were delivered in the mornings (8:00–12:00), except for on day 9 when a worm was delivered in the morning and evening (18:00–20:30). On day 9 post-hatching, all nestlings were banded with a uniquely numbered permanent aluminum ring.

2.3. Immediate changes in [CORT] in response to treatment

To evaluate immediate changes in circulating [CORT] after treatment we collected a small blood sample (~75 μL) from all nestlings on day 8 post-hatching, following ingestion of a CORT- or vehicle-injected worm. We collected blood samples at 10, 20, 30 or 40 min following worm ingestion because we were interested in the timescale of response. Blood samples were obtained via brachial venipuncture with 27-gauge needles and heparinized microcapillary tubes. Plasma was separated from the cellular fraction by centrifugation at 2000g for 7 min and then preserved by freezing at −20 °C until analysis. All laboratory analyses were

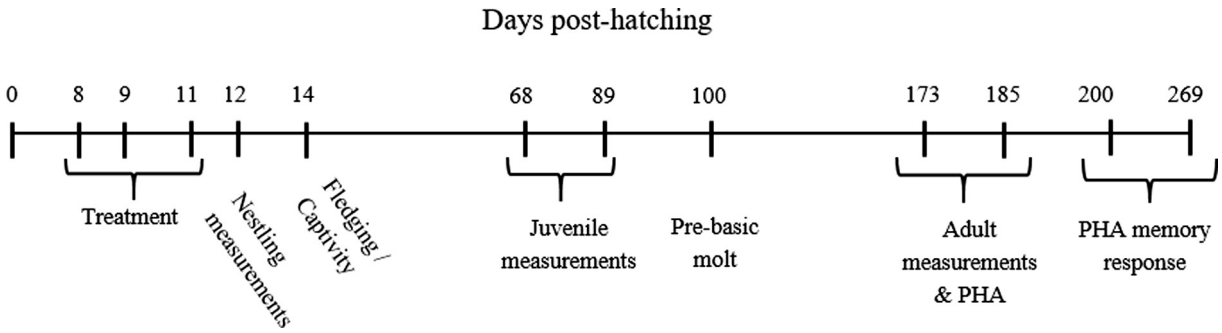

Fig. 1. Timeline of experimental procedures from day zero post-hatching (not to scale). Days post-hatching are above the line, procedures below.

performed at the Centre d'Etudes Biologiques de Chizé (CEBC). Plasma [CORT] was determined by radioimmunoassay, as described in Lormée et al. (2003). The minimum detectable [CORT] was 0.83 ng/ml, and the intra- and inter-assay coefficients of variation were 7.07% and 9.99% respectively.

2.4. Molecular sexing

At 12 days post-hatching, a small blood sample (75 μl) was obtained by brachial venipuncture with a 27-gauge needle and heparinized microcapillary tubes for genetic sexing. Plasma was separated from the cellular fraction and frozen as described, above. Genomic DNA was extracted from frozen red blood cells using DNeasy Blood and Tissue Kits (Qiagen, Cat. No. 69504), a silica-based extraction method, according to the manufacturers protocol. Sex was assigned following the PCR protocol of Fridolfsson and Ellegren (1999) using two highly conserved genes (CHD) on the avian sex chromosomes.

2.5. Captive housing

At and after twelve days post-hatching, nests were checked daily and nestlings that appeared ready to fledge (alert, active, and showing signs of flight) were taken into captivity to avoid high juvenile dispersal and enable us to observe mortality events. Two to four nestlings were removed from each nest, resulting in a sample size of 97 birds from 23 nests in captivity. Equal numbers of control and CORT-fed fledglings from each nest were brought into captivity, except in three instances where only three fledglings were in the nest, all were small, and we were concerned for survival. In these cases we brought all fledglings into captivity. Fledglings were hand-fed until they were capable of feeding on their own by caretakers who were blind to treatment group. Age of independence was determined by the date at which a fledgling was either observed eating or exhibited a full crop, and was able to maintain its weight without hand-feeding (mean ± s.e. m = 26.8 ± 4.8 d, max = 41 d, min = 18 d). Fledglings were housed in wire bird cages (Vision S01, 45.5 × 35.5 × 51 cm) with all siblings (2–4 birds per cage) until birds reached basic plumage, after which (and for the rest of the experiment) pairs consisting of one CORT-fed and one control bird were housed together. When possible these pairs were siblings, otherwise pairs were age- and sex-matched. Birds were supplied with mixed seeds *ad libitum*, vitamin and mineral soaked cat food, salt/mineral blocks, water (changed daily), and millet on the stalk. Grit was supplied three times per week and cages were equipped with perches of varying heights. Birds were kept on natural daylight schedules.

2.6. Size and weight measurements

All birds were weighed on days 8, 9, 11 and 12 post-hatching, to evaluate the short-term effect of treatment on nestling mass (n = 131). After transfer to captivity, we weighed birds daily from 12 to 22 days post-hatching, then every two days until day 48 post-hatching. Afterward, birds were weighed regularly until 192 days post-hatching. To evaluate long-term effects of treatment on body size and mass, all birds were weighed, and tarsus (caliper: ±0.1 mm) was measured at the nestling (12 d post-hatching), juvenile (68–89 d post-hatching, juvenile plumage), and adult (173–185 d post-hatching, definitive basic plumage) stages. Tarsus length was chosen to represent body size because it is least prone to temporary damage that could alter measurements.

2.7. Hematocrit measurements

Hematocrit is the fraction of whole blood comprised of erythrocytes, the blood component that carries oxygen to tissues (Bowers et al., 2014). We obtained a small blood sample (5 μl) by brachial venipuncture with a 27-gauge needle and a 10 μl microcapillary tube for hematocrit measurement at the nestling (12 d post-hatching), juvenile (68–89 d post-hatching), and adult (173–185 d post-hatching) stages. Blood samples were immediately centrifuged at 10100*g* for 3 min. Plasma and globules were measured (caliper: ±0.1 mm). Hematocrit percentage was calculated by dividing the length of the globule portion by the total length of the blood sample.

2.8. Phytohemagglutinin-induced skin swelling

At the adult stage (173–185 d post-hatching) we conducted a phytohemagglutinin (PHA) response test (Martin et al., 2006; Smits et al., 1999) on all birds. The PHA response is a reliable indicator of acquired T-cell immunocompetence in birds (Tella et al., 2008). The left wing patagium was cleaned of down and dampened to separate feathers. Thickness of the centre of the patagium was measured with a specimeter (Mitutoyo Absolute Digimatic Thickness Gauge, model 547–301: ±20 μm) 3–5 times, until the same measurement was obtained at least twice. 100 μl of 1 mg/mL PHA dissolved in cell culture-grade phosphate-buffered saline (PBS) was then injected subcutaneously into the centre of the left wing patagium using a 0.5 mL syringe. The injection site was measured again, 24 h later. PHA response was calculated as the second patagium thickness reading minus the first reading (Smits et al., 1999). To determine PHA memory response, identical PHA testing was conducted again, 27–84 days later. Number of days between the two PHA challenges was not significantly correlated with PHA memory response ($r = -0.12$, $p = 0.43$, $n = 49$),

2.9. Statistical analyses

All statistical analyses were conducted in R (version 3.0.3) and were evaluated within a multimodel inference framework using the R packages 'lme4' (Bates and Mæchler, 2013) and MuMIn (Barton, 2015). Multimodel inference has the benefit of evaluating

the relative strength of evidence for multiple alternative hypotheses (Anderson, 2008). Models were derived from subsets of a global model and ranked using Akaike's Information Criterion corrected for small sample size (AICc), where AICc = N*log(RSS/N) + (2 K(K + 1))/(N − K − 1) + 2 K; N is the sample size, RSS is the residual sums of squares for the model, and K is the number of parameters, including error (Burnham et al. 2011). Thus, AICc balances information explained and complexity of a model (Burnham et al. 2011). For General Linear Mixed Models (GLMMs), estimates were first chosen to optimize the log likelihood for AICc model comparison, then to optimize the restricted maximum likelihood for final beta coefficients of top models. We evaluated models first by ΔAICc (the difference in AICc between the candidate model and the model with the lowest AICc), followed by examination of the beta coefficient and associated 95% confidence interval (95% CI) (Anderson, 2008; Arnold, 2007). We only report results for models whose AICc value was less than that of the null. For GLMMs, we report both marginal r-squared values (i.e., proportion of variance explained by fixed factors alone) and conditional r-squared values (i.e., the proportion of variance explained by both random and fixed factors) obtained using the r.squarredGLMM function in R (Johnson, 2014; Nakagawa and Schielzeth, 2013).

2.9.1. Calculation of size-corrected mass

Prior to twelve days post-hatching we did not take morphometric measurements, thus we analyzed mass and not size-corrected mass for this period. Later, we had the benefit of morphometric measurements in addition to bird mass and calculated size-corrected mass as the residuals of a regression of mass on tarsus. Size-corrected mass is a widely used proxy for "body condition", but does not distinguish between fat, water, protein, and skeletal tissue, and is thus different from body composition (Clancey and Byers, 2014). Size-corrected mass was calculated for each life stage separately, because the relationship between mass and tarsus length changes throughout development. Thus, the effect of treatment on size-corrected mass could not be analyzed in a repeated measure framework. All other long-term data were likewise analyzed by life stage for parallelism in analyses.

2.9.2. Immediate changes in [CORT] in response to treatment

We evaluated the immediate effect of treatment on nestling circulating [CORT] on the first day of treatment (8 d post-hatching) via General Linear Mixed Models (GLMM) (Gaussian family, identity link) predicting [CORT] obtained 8–40 min following worm ingestion (log-transformed). The global model consisted of the random effect of nest of origin, and the fixed effects of treatment (1 = control, 2 = CORT-fed), mass at 8 days post-hatching ("Mass D8", centered by z-scoring), time elapsed since worm ingestion (approximately 10, 20, 30, or 40 min following worm ingestion), and hour of blood sampling. The first two fixed effects were allowed to interact, while the last two were only additive effects due to sample size limitations and after consideration of logical interactions. Sex was not known for all birds at day 8 post-hatching, but a reanalysis of the data using the subset of birds for which sex was known (n = 96) reveals no effect of sex or interaction between sex and treatment (see Supplementary Information).

2.9.3. Effect of CORT treatment on age of independence

Age of independence (i.e., self-feeding) was analyzed by GLMM (Gaussian family, identity link), with the global model consisting of the fixed effects of treatment, Mass D8 (z-scored), sex (1 = male, 2 = female), and brood size (z-scored), and the random effect of nest of origin. Due to sample size limitation, brood size was not allowed to interact with any other predictors, but all other interactions were allowed. Mass D8 was included as a fixed factor because effective dosage of CORT could have varied by individual body mass.

2.9.4. Effect of CORT treatment on mass

Nestling mass on the first day of treatment was analyzed by GLMM (Gaussian family, identity link) to ensure that our initial assignment of nestlings to treatment and control groups was not biased by bird mass. The global model consisted of the random effect of nest of origin, and the fixed effects of brood size (centered by z-scoring), treatment, and their interaction.

We examined the effect of CORT treatment on mass throughout life using linear mixed modeling with a continuous autoregressive covariance structure. We conducted three separate analyses to reflect the three different periods when we expected the effect of treatment to differ. The first analysis examined the mass of nestlings from days 8–12, during treatment and while nestlings were in the wild being fed by their parents. We expected treatment to have the strongest effect during this period. The second analysis examined mass of fledglings during the hand-feeding period, from the first day in captivity through day 27 post-hatching. The last analysis examined mass of self-feeding birds, from day 28 post-hatching until the end of the experiment. For each analysis, the global model consisted of the fixed effects of age, treatment, nestling age (z-scored), their interactions, and brood size (z-scored). Sex was not known for 31 nestlings that were not taken into captivity, and thus was not included as a fixed effect. A reanalysis of the data using the subset of birds for which sex was known (n = 100) reveals no effect of sex or interaction between sex and other fixed effects (see Supplementary Information). For the second and third analysis, sex was included as a fixed effect and allowed to interact with all other fixed effects except brood size (genetic material from six birds failed to amplify, so these were excluded from analyses). Random effect structure of bird ID (random slope, intercept, and correlation between intercept and slope) was determined by AIC model comparison, where we used the model with the lowest AIC. For the first and third analyses, we included a random intercept for each bird ID. For the second period, we included a random slope in age for each bird ID, but no random intercept.

2.9.5. Effect of CORT treatment on nestling, juvenile, and adult body size, size-corrected mass, and hematocrit

Differences in tarsus length, size-corrected mass and hematocrit between CORT-fed and control birds were examined at the nestling, juvenile, and adult stages. Hematocrit was not obtained for ten of the 115 nestlings due to centrifuge malfunction, thus our nestling sample size for hematocrit is 105 individuals. Visual inspection of tarsus length and size-corrected mass indicated they were normally distributed. Effects of treatment on tarsus, size-corrected mass, and hematocrit were evaluated for each life stage by GLMM (Gaussian family, identity link) with the global model consisting of treatment, sex, brood size (z-scored), and Mass D8 (z-scored) as fixed effects, and nest of origin as a random factor. Due to sample size limitation, brood size was not allowed to interact with any other predictors. All other interactions were allowed.

2.9.6. Effect of CORT treatment on adult PHA-induced skin swelling

Birds for which any leaking of the PHA solution occurred were eliminated from the data set prior to analysis. Preliminary analysis indicated that hour of sampling was not significantly correlated with PHA response (Pearson's product-moment r = 0.14, p = 0.16, n = 105, 56 individuals), and number of days between the two PHA challenges was not significantly correlated with PHA memory response (r = −0.12, p = 0.43, n = 49), hence we did not include these variables in the model set. Effects of treatment on PHA response were evaluated via GLMM (Gaussian family, identity link)

for which the global model consisted of the fixed effects of treatment, sex, sample number (1 for first PHA challenge, 2 for the second), Mass D8 (z-scored), and brood size (z-scored), and the random effects of bird ID and nest of origin. Due to sample size limitation, brood size and Mass D8 were not allowed to interact with any other predictors. All other interactions were allowed.

2.9.7. Effect of CORT treatment on survival

Nestling mortality was defined as occurring between the onset of treatment and fledging, when fledglings were brought into captivity; juvenile mortality was between this point and 68–89 days post-hatching, while in juvenile plumage; and adult mortality from this point until the end of the experiment (274–342 days post-hatching). House sparrows in this wild population do not have the opportunity to reproduce until one year post-hatching, thus this was just before the first reproductive attempts. Mortality was coded as "0" for "survived" and "1" for "died" at each life stage.

The effect of treatment on survival from the start of treatment until the end of the experiment was analyzed via Accelerated Failure Time (AFT) modeling (interval censoring, Weibull distribution) using the package 'survival' in R (Therneau, 2017). When exact age of death was unknown, the age interval within which death occurred was used in the analysis. Because mass was collected more frequently than tarsus and some nestlings died before their first measurements (but not their first weighing), we used mass alone (at most recent weighing before death), and not size-corrected mass for this analysis. The global model included the effects of treatment, z-scored mass, stage (i.e., nestling, juvenile, adult), their interactions, and z-scored nestling brood size. Sex was not known for nestlings that died before 12 days post-hatching, thus sex could not be included in this analysis. However, analyses using the subset of birds for which sex was known revealed no important effect of sex (the next best model had a ΔAICc of only 0.3) or interaction between sex and other explanatory variables (see Supplementary Information).

To explicitly test whether growth compensation was related to survival probability, we conducted a separate AFT modeling exercise (interval censoring, Weibull distribution) using the difference between mass at age of death/censoring and that at the end of treatment (12 d post-hatching), z-scored within life stage, as an explanatory variable instead of current mass. The global model included the effects of treatment, z-scored mass, stage (i.e., nestling, juvenile, adult), their interactions, and z-scored nestling brood size. Because birds that did not survive until the end of treatment did not have an initial mass for this analysis, we used only birds that survived through the treatment and continued in the experiment ($n = 97$ individuals). The global model included the effects of treatment, z-scored difference in mass, stage (i.e., juvenile, adult), their interactions, and z-scored nestling brood size.

3. Results

See Supplementary Information for full model sets and AIC comparison parameters.

3.1. Immediate changes in [CORT] in response to treatment

Nestling [CORT] on the first day of treatment (8 d post-hatching) increased within 10 min in response to worm ingestion (Fig. 2), and remained elevated for at least 40 min. The top model predicting nestling [CORT] was the regression including only the fixed effect of treatment (beta coefficient ± 95% CI = 2.16 ± 0.38), and random effect of nest of origin (top model: [CORT] ~ Treatment + (1|Nest); marginal $r^2 = 0.50$, conditional $r^2 = 0.53$, ΔAICc of the null model = 85.81, $n = 127$). Time elapsed since worm ingestion, hour of blood sampling, nestling mass, and method of worm ingestion were not important predictors of nestling [CORT].

3.2. Effects of CORT treatment on age of independence

There was no effect of treatment on age of independence (the null was the top model, ΔAICc of the first model including treatment = 1.61, $n = 73$).

3.3. Effect of CORT treatment on bird mass

There was no effect of treatment group on mass for the first day of treatment, validating our random assignment of nestlings to treatment and control groups (top model: Mass ~ (1|Nest); ΔAICc of the model including treatment = 0.77, $n = 131$). We did detect an effect of treatment on nestling mass during treatment while in the wild, during the hand-feeding stage in captivity, and once birds were self-feeding until the end of the experiment. The top model predicting nestling mass during treatment, from days 8 to 12 post-hatching, was the model that included treatment, nestling age, brood size, and the interactions between nestling age and treatment (top model: Mass ~ Age * Treatment + Brood Size + (0 + Age | ID); marginal $r^2 = 0.05$, conditional $r^2 = 0.28$, ΔAICc of first model not including treatment = 23.81, $n = 505$, individuals = 131). Nestling mass increased with brood size and age, although the mass gain for CORT-fed birds was smaller as age increased than for control birds (Table 1). Mass was depressed for CORT-fed nestlings by the 4th day of treatment (11 d post-hatching) and mass remained depressed at 12 days post-hatching (birds were not treated on this day) (Fig. 3).

The top model predicting bird mass during the hand-feeding phase (days 13–27 post-hatch), in captivity was the model that included treatment, nestling age, brood size, and the interactions between nestling age and treatment (top model: Mass ~ Age + Treatment + Mass D8 + (0 + Age | ID); marginal $r^2 = 0.38$, conditional $r^2 = 0.71$, ΔAICc of first model not including treatment = 5.36, $n = 1116$, individuals = 91). Mass increased with age, was lower in CORT-fed birds, and was positively related to mass at 8 days post-hatching (Table 1; Fig. 4).

The top model predicting bird mass following the hand-feeding phase (day 28 + post-hatch), while self-feeding in captivity was the model that included treatment, nestling age, brood size, and the interactions between nestling age and treatment (top model: Mass ~ Age + Treatment * Mass D8 + Sex + (1 | ID); marginal $r^2 = 0.22$, conditional $r^2 = 0.39$, ΔAICc of first model not including treatment = 4.68, $n = 1568$, individuals = 87). Mass increased with age, although much less than during the hand-feeding period (Table 1; Fig. 4). Mass was lower in CORT-fed birds however this effect was conditional on mass at 8 days post-hatching, such that the negative effect of treatment was reduced by higher day 8 masses (Table 1).

3.4. Effect of CORT treatment on nestling, juvenile, and adult body size

For both nestlings and juveniles, the top model predicting tarsus length was the model including the fixed effects of treatment and mass at the beginning of the experiment (top model: Tarsus ~ Treatment + Mass D8 + (1|Nest); nestlings: marginal $r^2 = 0.62$, conditional $r^2 = 0.68$, ΔAICc of the null model = 90.85, $n = 115$; juveniles: marginal $r^2 = 0.47$, conditional $r^2 = 0.54$, ΔAICc of the null model = 36.90, $n = 71$; Table 2). However, the next model not including treatment had a ΔAICc of only 0.25 for nestlings and of only 0.66 for juveniles indicating that the effect of treatment was quite weak and that most variance was explained by Mass D8 (marginal $r^2 = 0.61$ for nestlings and 0.45 for juveniles, when treatment was excluded). Thus, we interpret this as a trend

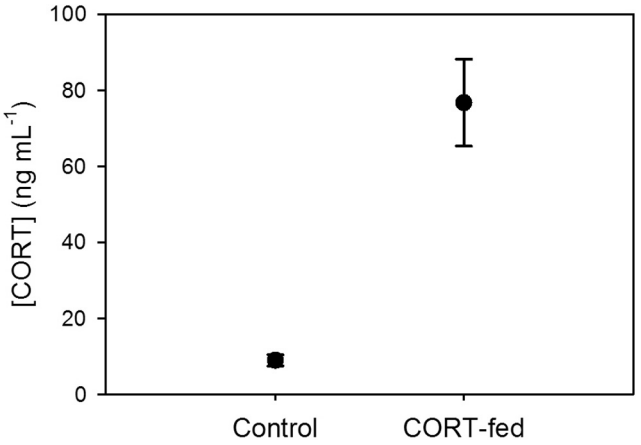

Fig. 2. Circulating [CORT] in nestlings 10–40 min. following ingestion of a control worm or CORT-fed worm (n = 127 individuals). There was no difference in [CORT] between time points (10, 20, 30, 40 min.) for control or CORT-fed nestlings, thus they are combined, here. Treatment increased circulating [CORT] (top model by AICc selection). Nestlings were all at 8 days post-hatching, the first day of treatment. Points and bars are mean ± s.e.m. Control standard errors are too small to be visible. Previous work in house sparrows has shown that 9-day old nestlings can reach between 65 and 70 ng/ml and in some cases over 100 ng/ml during a standardized capture-restraint test (Angelier et al., 2016). Thus, the CORT concentrations we obtained were within physiological range for a strong, acute stressor.

Table 1
Beta coefficients and 95% confidence intervals (CIs) for parameters in the top model bird mass during treatment (while being fed by free-living parents in wild nests), during hand-feeding in captivity post-treatment, and while self-feeding for the rest of the experiment.

Predictor	Beta	±95% CI
During treatment		
Treatment (CORT-fed)	4.27	2.73
Age[a]	0.64	0.18
Brood size	0.32	0.54
Age * Treatment	−0.44	0.25
Hand-feeding (post-treatment)		
Treatment (CORT-fed)	−0.77	0.56
Age	0.18	0.03
Mass D8[b]	1.21	0.28
Self-feeding		
Treatment (CORT-fed)	−0.74	0.61
Age	0.02	0.004
Mass D8	0.64	0.41
Sex (Female)	0.43	0.54
Treatment * Mass D8	0.56	0.61

[a] Age and brood size are z-scored.
[b] Mass D8 is z-scored.

and not an important difference in tarsus length at the nestling or juvenile stages. By the adult stage the effect of treatment was not in the top model (top model: Tarsus ~ Mass D8 + (1 | Nest); marginal r^2 = 0.48, conditional r^2 = 0.63, ΔAICc of the null model = 30.68, n = 59; Table 2). To evaluate whether results were influenced by differential mortality between life stages, we re-analyzed nestling and juvenile data using only birds that survived to adulthood, and found no difference in top models (see Supplementary Information).

3.5. Effect of CORT treatment on nestling, juvenile, and adult size-corrected mass

Treatment was an important predictor of nestling size-corrected mass; the top model included the additive effects of treatment, brood size, and Mass D8 (top model: Size-corrected mass ~ Treatment + Brood Size + Mass D8 + (1 | Nest); marginal r^2 = 0.19, conditional r^2 = 0.19, ΔAICc of the null model = 18.03, n = 115). Size-corrected mass was lower in CORT-fed nestlings compared to control nestlings (Table 3, Fig. 5A). At the juvenile stage, treatment was not an important predictor of size-corrected mass; the top model was the null model (ΔAICc of the first model including treatment = 2.10, n = 71, Fig. 5B). At the adult stage, the effect of treatment was in the top model (top model: Size-corrected mass ~ Treatment + (1 | Nest); marginal r^2 = 0.05, conditional r^2 = 0.09, ΔAICc of the null model = 0.55, n = 59). However, that effect was quite weak (Table 3, Fig. 5C): the null model had a ΔAICc of only 0.55, and r^2 values were small. Thus, we interpret this as only a trend toward lower size-corrected mass in treated adults. To evaluate whether results were influenced by differential mortality between life stages, we re-analyzed data using only birds that survived to adulthood, and found no difference in top models (see Supplementary Information).

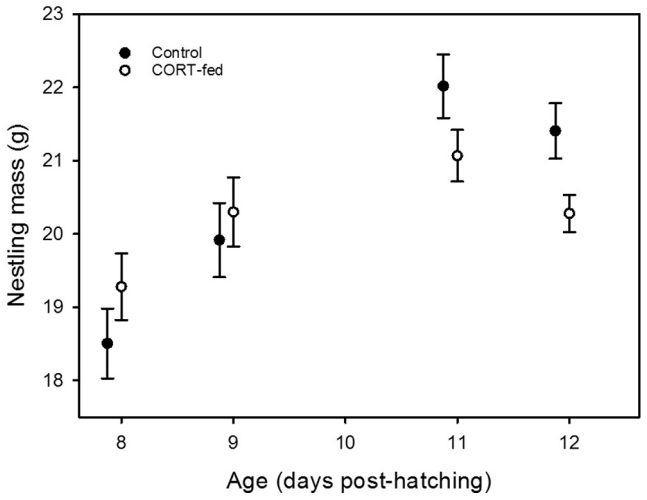

Fig. 3. Nestling mass by age and treatment (n = 131 individuals). Points and bars are mean ± s.e.m. Treatment decreased mass over time (top model by AICc selection). Although there appears to be a slight bias for CORT-fed nestlings to be larger at day 8 post-hatching, this was not an important effect (the null was the top model in predicting mass at day 8). Treatment did not affect nestling mass until 11 days post-hatching (the 4th day of treatment). We did not weigh nestlings on day 10 post-hatching. All nestling were weighed immediately after worm ingestion.

3.6. Effect of CORT treatment on nestling, juvenile, and adult hematocrit

Treatment had no effect on nestling hematocrit; the top model included the fixed effects of sex, mass at 8 days post-hatching, and their interaction (top model: Hematocrit ~ Sex * Mass D8 + (1| Nest), marginal r^2 = 0.18, conditional r^2 = 0.41, ΔAICc of the first model that included treatment = 1.71, n = 105). At the juvenile stage, there was still no effect of treatment on hematocrit: the null was the top model (top model: Hematocrit ~ (1 | Nest), ΔAICc of the closest model including treatment = 1.94, n = 71). And at the adult stage, there was similarly no effect of treatment, the top model predicting adult hematocrit included only the effects of sex (females had lower hematocrit, Table 4), and brood size (birds from larger broods had lower hematocrit) (top model: Hematocrit ~ Sex + Brood Size + (1|Nest), marginal r^2 = 0.13, conditional r^2 = 0.29, ΔAICc of the null model = 3.78, n = 59).

3.7. Effect of CORT treatment on adult PHA-induced skin swelling

Initial PHA response and PHA memory response were unaffected by treatment; the top model predicting PHA response was the null model (top model: PHA ~ Sample Number + (1 | Nest)

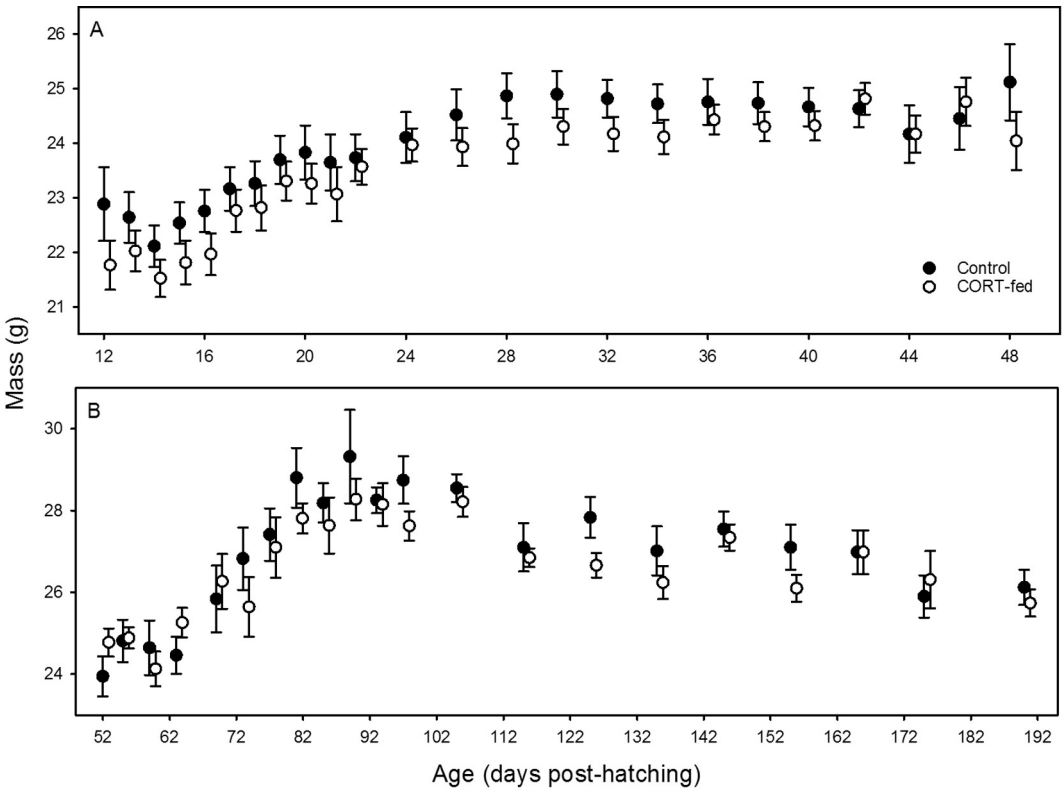

Fig. 4. Bird mass by treatment between (A) 12–50 and (B) 52–192 days of age (post-hatching) (n = 73 individuals). Points and bars are mean ± s.e.m. CORT-treatment ended at 12 days post-hatching, birds were transferred to captivity between days 13 and 15. Hand-feeding occurred until 27 days post-hatching after entering captivity. Mass was taken every day until 22 days post-hatching, every two days until 48 days post-hatching, and then regularly (approximately every 10 days) until 192 days post-hatching.

Table 2
Beta coefficients and 95% confidence intervals (CIs) for parameters in the top models predicting nestling and juvenile tarsus length.

Predictor	Beta	±95% CI
Nestlings		
Treatment (CORT-fed)[a]	−0.13	0.17
Mass D8	0.63	0.10
Juveniles		
Treatment (CORT-fed)	−0.18	0.21
Mass D8	0.45	0.12
Adults		
Mass D8	0.46	0.13

[a] For fixed factors, the non-reference factor is indicated in parenthesis.

Table 3
Beta coefficients and 95% confidence intervals (CIs) for parameters in the top models predicting nestling and adult size-corrected mass (juvenile size-corrected mass was best predicted by the null model). For juveniles, the top model was the null model and there was therefore no predictor of size-corrected mass.

Predictor	Beta	±95% CI
Nestlings		
Treatment (CORT-fed)	−1.03	0.46
Mass D8[a]	0.31	0.24
Brood Size[a]	−0.25	0.24
Adults		
Treatment (CORT-fed)	−0.49	0.55

[a] Mass D8 and Brood Size are z-scored.

+ (1 | ID), marginal r^2 = 0.06, conditional r^2 = 0.26; n = 105, 56 individuals). PHA memory response was higher than initial PHA response (beta coefficient ± 95% CI = 0.11 ± 0.08).

3.8. Effect of CORT treatment on survival

Between the beginning of treatment (8 d post-hatching) and when we began to take fledglings into captivity (12 d post-hatching), four nestlings (3.5% of all birds) died from causes other than total nest failure (two nests, likely due to predation events): two CORT-fed (1.7% of CORT-fed birds), and two control (1.7% of control birds). Eighteen birds died between the fledgling and juvenile stages (20.5% of all birds alive at the juvenile stage): ten CORT-fed (22% of CORT-fed birds) and eight control (19% of control birds). Twenty birds died between reaching adult plumage and the first year of life (27.8% of total birds alive at the adult stage): 14 CORT-fed (37.8% of CORT-fed birds), six control (17.1% of living control birds).

Treatment did have an effect on survival (Fig. 6). The AFT top model included the interaction between treatment and mass, and life stage and mass (top model: ~Treatment * Mass + Life Stage * Mass, ΔAICc of the closest model including treatment = 11.42, n = 114 individuals; Table 5). AFT models model time to failure (i.e., death), thus, positive coefficients can be interpreted as extending survival (i.e., longer time to death), and negative coefficients as shortening survival. In contrast, proportional hazard models model the death rate (i.e., "hazard"), thus positive coefficients increase the death rate, while negative coefficients decrease the death rate. Treatment and mass had conditional effects on survival (Table 5). CORT-fed birds had lower survival than control birds (Fig. 6), but that effect was reduced when bird mass was very low (Fig. 7). Heavier birds had higher survival, but the positive effect of mass was reduced for CORT-fed birds (Fig. 7) and reduced as birds aged (Table 5).

To explicitly test whether growth compensation could account for differences in survival, we re-ran the AFT models with the dif-

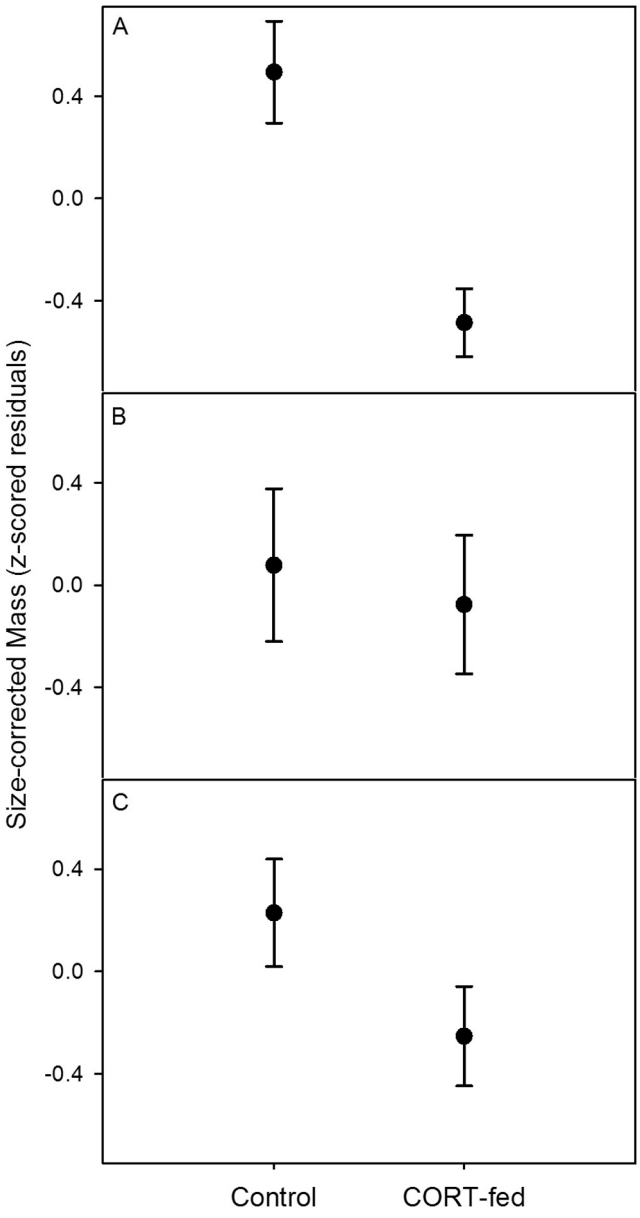

Fig. 5. Size-corrected mass by treatment group at the (A) nestling (n = 115), (B) juvenile (n = 71), and (C) adult life stages (n = 59 individuals). Points and bars are mean ± s.e.m. Size-corrected mass values were calculated separately for each life stage and are the residuals of a regression of mass on tarsus, the structural size parameter that was most consistently correlated with mass at each life stage and which was least prone to temporary damage. The top model in predicting size-corrected mass in nestlings included the fixed effects of treatment, brood size, and mass at 8 days post-hatching, and the random effects of nest of origin. For juveniles, the top model was the null model. Adult size-corrected mass was best predicted by the model that included treatment (and the random effect of nest of origin), but the effect of treatment was very weak and we consider this effect to be a trend.

ference between current mass and that at the end of the treatment, z-scored within life stage. The top model included the effects of treatment, life stage, difference in mass, and the interaction between treatment and difference in mass (top model: ~Treatment * Difference in Mass + Life Stage * Difference in Mass, ΔAICc of the closest model including treatment = 4.72, n = 97 individuals; Table 6). Again, treatment had a conditional effect on survival; CORT-fed birds had shorter survival times, and this effect was enhanced when the difference in current mass and mass at the end of treatment was large. In other words, when birds exhibited

Table 4
Beta coefficients and 95% confidence intervals (CIs) for parameters in the top models predicting nestling and adult hematocrit (the top model predicting juvenile hematocrit was the null model). For juveniles, the top model was the null model and there was therefore no predictor of juvenile hematocrit.

Predictor	Beta	±95% CI
Nestlings		
Sex (Female)	0.072	0.076
Mass D8[a]	0.124	0.062
Sex * Mass D8	−0.058	0.076
Adults		
Sex (Females)	−0.079	0.057
Brood Size[a]	−0.028	0.033

[a] Mass D8 and Brood Size are z-scored.

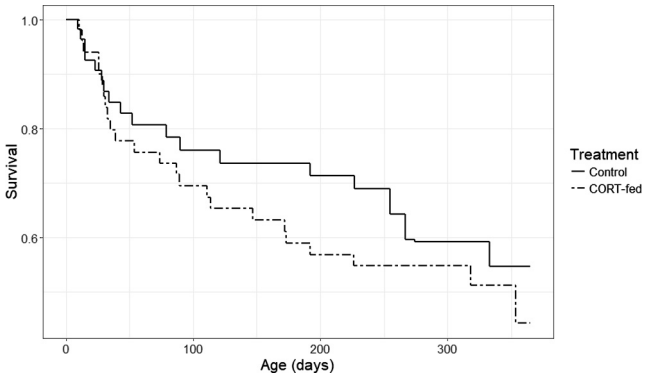

Fig. 6. Kaplan-Meier survival curves for CORT-fed and control birds across ages (n = 114).

Table 5
AFT beta coefficients (Weibull distribution) and 95% confidence intervals (CIs) for parameters in the top model predicting survival. We also present transformed proportional hazards (PH) coefficients for those more familiar with that output (PHβ = −AFTβ/scale).

Predictor	AFT Beta	±95% CI	PH Beta
Treatment (CORT-fed)	−0.31	0.27	0.78
Mass[a]	1.23	0.82	−3.05
Life Stage (Juvenile)	−0.14	1.12	0.35
Life Stage (Adult)	2.45	1.09	−6.06
Treatment * Mass	−0.61	0.29	1.51
Mass * Life Stage (Juvenile)	−0.75	0.82	1.85
Mass * Life Stage (Adult)	−0.88	0.81	2.18

[a] Mass was z-scored within life stage.

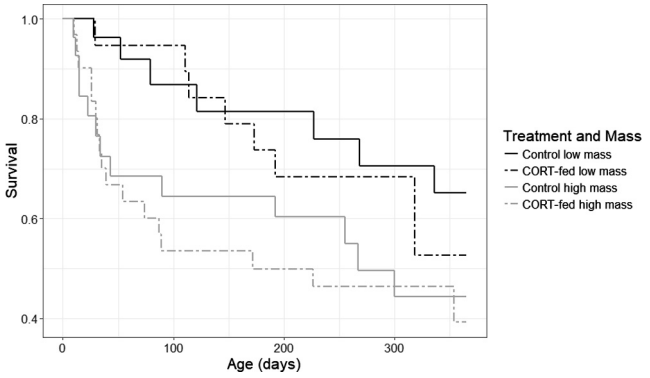

Fig. 7. Kaplan-Meier survival curves illustrating the interaction between CORT treatment and mass (n = 114). For illustration purposes, CORT-fed and control birds are binned by mass into "large mass" and "small mass" groups based on z-scored mass being above or below zero (mass was z-scored within life stage).

Table 6
AFT beta coefficients (Weibull distribution) and 95% confidence intervals (CIs) for parameters in the top model predicting survival. We also present transformed proportional hazards (PH) coefficients for those more familiar with that output (PHβ = −AFTβ/scale).

Predictor	AFT Beta	±95% CI	PH Beta
Treatment (CORT-fed)	−0.30	0.30	0.64
Difference in Mass[a]	0.62	0.19	−1.30
Life Stage (Adult)	2.54	0.36	−5.34
Treatment * Difference in Mass	−0.47	0.35	0.99
Life Stage * Difference in Mass	−0.75	0.26	1.58

[a] Difference in Mass was z-scored within life stage.

a large increase in mass and were CORT-fed, they had a greater chance of dying than when mass gain was small and birds were CORT-fed. Survival was higher in adults than juveniles, but that effect was reduced when birds had large gains in mass.

4. Discussion

Our long-term study of a semi-wild bird supports the prediction of later life compensation for early-life CORT exposure: treated nestlings exhibited an acute decrease in size-corrected mass, but that effect weakened or disappeared by the juvenile and adult stages. However, we observed an effect of treatment on survival. CORT-fed birds had decreased survival until one year of age compared to control birds, and this was especially true of heavier birds and those that exhibited evidence of growth compensation. These results support the hypothesis that early-life CORT exposure imposes long-term trade-offs between mass and longevity, and are consistent with the concept of being raised without a "silver spoon". Our results suggest that sparrows are able to compensate for early-life glucocorticoid upregulation (i.e., not being raised with a "silver spoon") if conditions improve, however that compensation may come at a cost, even when food is abundant and predators are absent.

4.1. Short-term effects of CORT treatment on nestling body size and size-corrected mass

We observed an acute depression in size-corrected mass and a trend toward smaller structural size in CORT-fed nestlings, results which are consistent with other avian studies (Schoech et al., 2011; Spencer et al., 2009) and correspond with previous findings for nestling house sparrows subjected to a more invasive delivery of corticosterone by injection (Loiseau et al., 2008a,b). Negative effects on size-corrected mass may have resulted from increased standard metabolic rate or variability in metabolic rate (Schmidt et al., 2012; Spencer and Verhulst, 2008; Verhulst et al., 2006), and/or changes in parental food delivery in response to CORT treatment (Wada, 2008). Circulating glucocorticoids typically increase in vertebrates in response to non-voluntary fasting (Landys et al., 2006) and appear to play an activational role in increasing nestling begging behavior (Kitaysky et al., 2001; Loiseau et al., 2008b; Wada, 2008). Parents can respond to increased begging by increasing food delivery (e.g., black-legged kittiwakes, *Rissa tridactyla*, Kitaysky et al., 2001), but do not always do so (e.g., house sparrows, Loiseau et al., 2008b). Previous work in house sparrows identified brightness of flange color as a trait negatively affected by corticosterone (interacting with body mass) that parents may use to preferentially deliver food to nestlings with lower circulating corticosterone (Loiseau et al., 2008a). We did not monitor parental behavior or nestling metabolic rates in this study, and so cannot discriminate between these two hypotheses linking nestling corticosterone concentration and depressed size-corrected mass.

4.2. Effect of CORT treatment on juvenile and adult body size and mass

Mass of CORT-fed birds in our study remained slightly reduced throughout the experiment, however this effect was small in adults and offset by early-life mass. This interaction between early-life mass and treatment suggests that positive early conditions (pre-stressor) can make birds more resilient to long-term effects of corticosterone. Generally, CORT-fed birds were able to compensate over the long-term for poor nestling size-corrected mass and more weakly, structural size. The negative effect of CORT elevation on size-corrected mass was almost entirely an acute effect and persisted very weakly throughout the lifetime, indicating compensation for early-life effects once [CORT] manipulation ceased and under conditions of abundant food (i.e., captive conditions with food *ad libitum*). Compensatory growth can occur as a result of two non-exclusive processes: parallel growth (i.e., an extended period of growth, extending time to independence; Emlen et al., 1991) and catch-up growth (i.e., accelerated growth relative to age; Bohman, 1955) (Hegyi and Török, 2007). We found no difference in age of independence between CORT-fed and control fledglings, providing no support for an extended period of "parental" care corresponding to parallel growth. Visual inspection of mass measurements throughout the fledgling period also suggests a steeper slope of mass gain over time for CORT-fed birds, consistent with catch-up growth, and in agreement with findings for zebra finches given a similar early-life CORT treatment (Spencer et al., 2009). However, birds in this study were in captivity and fed by caretakers who did not employ tactics to accelerate independence that can be used by parents (e.g., food restriction; Corbel and Groscolas, 2008). Thus, we cannot totally eliminate parallel growth as a compensatory mechanism in free-living house sparrows.

We have thus far discussed the weakening effect of CORT treatment on size-corrected mass over time as "compensation" by individual birds, to make up for early-life deficits. However, effects may also appear to weaken if birds that displayed poor size-corrected mass disappeared from the population by dying. To address this possibility, we re-analyzed our data using only survivors until adulthood for each life stage, and there was no change in results (see Supplementary Information), indicating that individual compensation was at least partly responsible for the weakening of effects of early-life CORT exposure across time.

4.3. Effects of CORT treatment on hematocrit and PHA-induced skin swelling

We found no effect of CORT treatment on our measures of health: hematocrit at the nestling, juvenile, and adult stages; or PHA response at the adult stage. Hematocrit is a measure of oxygen delivery capacity, and can have long-term fitness consequences (Bowers et al., 2014), however increased adult mortality among CORT-fed birds cannot be attributed to changes in hematocrit in our study. Previous research in house sparrows identified an acute negative effect of CORT treatment on nestling PHA response (Loiseau et al., 2008a). Together with our results, this suggests that effects of early-life CORT exposure on acquired T-cell mediated immunity are short-term and do not persist into adulthood (when food is not limiting, at least), and CORT has no immediate or long-term effect on hematocrit.

4.4. Effects of CORT treatment on survival

Despite an acute depression in size-corrected mass in CORT-fed nestlings, we detected no effect of CORT treatment on survival during treatment. Only four nestling died during treatment, two control and two CORT-fed birds. This finding is supported by Loiseau et al. (2008a,b) who also reported no effect of exogenous CORT

treatment on survival in wild house sparrow nestlings or fledglings. In contrast, prenatal CORT exposure is related to increased embryonic mortality in gallinaceous species (*Gallus gallus*, *Coturnix japonica*) and barn swallows (*Hirundo rustica*) (see Schoech et al., 2011 for review). Together, these results suggest that the prenatal period may be a more sensitive period to immediate lethal effects of CORT exposure than mid-nestling development.

Over one year of life, however, we did detect a decrease in survival for CORT-fed birds. These results are a clear exception to our general findings of little long-term effects of CORT treatment. These results appear to contrast with those of other studies of wild altricial birds raised in captivity that have not noted a decrease in survival associated with postnatal CORT exposure, although this was not explicitly tested (Farrell et al., 2015; Schmidt et al., 2012). Methodological differences may explain this variation. Experimental birds in both other studies were brought into captivity earlier than birds in our study, and were only treated in captivity during the hand-feeding phase. In contrast, nestlings in our experiment were raised by their natural parents in the wild during treatment. It is possible that negative effects on survival were mitigated in these other experiments by aspects of the captive environment during treatment, such as low exposure to parasites/pathogens, consistent food delivery, or altered sibling competition dynamics. Species differences may also account for lower later-life lethality of CORT-treatment in starlings and song sparrows, although species-specific lifespan is unlikely to do so because house sparrows are intermediate in maximal lifespan between starlings and song sparrows (Cabe, 1993; Lowther and Cink, 2006; Arcese et al., 2002).

CORT-fed birds in our study displayed catch-up growth in a strikingly similar pattern to that due to poor neonatal nutrition (Metcalfe and Monaghan, 2001) and CORT treatment may have affected mortality indirectly through poor early-life growth. CORT-fed birds in our study that exhibited evidence of catch-up growth (i.e., a large mass gain) were more likely to die than those who did not, suggesting that compensatory growth may come at a cost. Laboratory rodents, humans, and some other taxa including a few wild birds exhibit long-term costs associated with catch-up growth and low neonatal mass (Ali et al., 2003; Bowers et al., 2014; Criscuolo et al., 2011; Hales and Ozanne, 2003; Metcalfe and Monaghan, 2001). It is widely hypothesized that growth rate may impose an evolutionary trade-off with longevity at the within- and between- species scales (Metcalfe, 2003), and is perhaps the best example of long-term trade-offs associated with early-life stressors. Our research highlights the probable importance of glucocorticoids in initiating this trade-off.

The exact proximate mechanism for mortality in our study, however, is unclear and probably varied between cases. Higher mortality in CORT-fed adults was not due to differences in adult acquired T-cell mediated immunocompetence or health parameters reflected by hematocrit, because we saw no effect of treatment on phytohemagglutinin-induced skin swelling in adults, or effect on hematocrit at any life stage. Similarly, zebra finches (*Taeniopygia guttata*) raised on poor quality diets, also exhibit increased mortality up to 500 days of age, despite no long-term differences in mass or hematocrit (Birkhead et al., 1999). No obvious disease was present at any part of the study, and poor health and mortality did not follow a pattern consistent with contagion. Mortality was especially high during periods of growth and molt, thus changes in energetic requirements may be related to mortality. Our finding of an interaction between treatment and size-corrected mass, such that CORT treatment reduced the protective effect of high size-corrected mass, supports the hypothesis that treatment may have affected energy efficiency mechanisms. Repeated and chronic early-life stressors can also accelerate the rate of telomere shortening and increase oxidative stress over the long-term in birds (Angelier et al., 2017; Hau et al., 2015; Haussmann et al., 2012) including house sparrows (Meillère et al., 2015). These factors are associated with biological aging and longevity and may play a role in the decreased longevity we observed in this study.

Early-life CORT exposure can have positive fitness effects on reproduction that may balance negative fitness effects on longevity (Crino and Breuner, 2015). For another altricial avian species, the zebra finch (*Taeniopygia guttata*), elevated CORT exposure as a nestling is positively related to paternal investment and reproductive success (Crino et al., 2014). Mortality in our study, however, occurred before the first reproductive attempt (typically at approximately one year of age in this population), allowing for no reproductive compensation for a shortened lifespan. Instead, early-life CORT exposure was linked to an increased probability of complete loss of direct fitness. It is notable that the increased mortality that we observed occurred in a captive environment where food and water was almost never restricted, and predators did not exist. Previous work in this species found that early-life CORT treatment was linked to later-life impaired anti-predator behavior (Grace et al., 2017). Thus, we expect that the negative effect of CORT exposure on survival would be more pronounced under the stronger selection pressures of the wild.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ygcen.2017.08.011.

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