REDUCED TELOMERE LENGTH IN EMBRYOS EXPOSED TO PREDATOR CUES

Jose C. Noguera [1*], Alberto Velando [1]

[1] Grupo de Ecología Animal (GEA), Dpto. de Ecología y Biología Animal, Universidad de Vigo, Vigo 36310, Spain

[*]Author for correspondence; e-mail: josec.noguera.amoros@gmail.com; Phone number: +34 660335815

Summary statement

Bird embryos detect the presence of predator while still in the egg. This environmental stressor affected early postnatal telomere length, an effect that may link prenatal conditions to future fitness.

ABSTRACT

It is often assumed that embryos are isolated from external influences, but recent studies indicate that environmental stressors during prenatal stages can exert long-term negative effects on fitness. A potential mechanism by which predation risk may lastingly shape life-history traits and phenotypes is via effects on telomeres. However, whether prenatal exposition to environmental stressors, such as cues of predator presence, affects postnatal telomere length has not hitherto been investigated. Using an experimental design in which we modified the exposure of yellow-legged gull (*Larus michahellis*) embryos to social cues of predator presence (i.e. alarm calls), we show that prenatally exposed chicks had shorter telomeres after hatching. Since young birds with shorter telomere length have reduced fledging success, reproductive success and lifespan, the reduced telomere length in the exposed chicks is likely to have long-term fitness consequences. Moreover, our results provide a mechanistic link through which predators may negatively affect population dynamics.

Keywords: ageing, predation risk, stressors, yellow-legged gull

INTRODUCTION

Across taxa, evidence indicates that conditions during embryo development can exert long-term effects on important life-history traits such as growth and lifespan (DuRant et al., 2013; Entringer et al., 2012; Thiéry et al., 2014; Vaiserman, 2014). An important mechanism through which early life development may lastingly shape life-history traits and phenotypes is via effects on telomeres (reviewed in Price et al., 2013). Telomeres are protective non-coding nucleoprotein structures located at the end of eukaryotic chromosomes that play a key role in preventing genome degradation (O'Sullivan and Karlseder, 2010). In the absence of restoration (e.g. via telomerase activity), average cellular telomere length decreases with age in many taxa, particularly during the growth period (Frenck et al., 1998; Noguera et al., 2015), and young individuals with shorter telomeres have increased risk of diseases and reduced longevity and reproductive success (Blackburn et al., 2015; Eastwood et al., 2019; Heidinger et al., 2012; van Lieshout et al., 2019). Thus, telomere shortening during prenatal stages may potentially have long-lasting consequences through life (Entringer et al., 2018; Noguera et al., 2016).

One important route through which telomere shortening may arise during embryo development is by the exposition to environmental stressors. In humans and lab rodents, for instance, environmental and social stressors acting on mothers during gestation have been related to reduced postnatal telomere length in the offspring (see e.g. Entringer et al., 2011; Tarry-Adkins et al., 2009). However, unlike most mammals, embryos of oviparous species develop outside the maternal influence and therefore, it is often assumed that the embryos are relatively more isolated from external stimuli during their development. However, recent empirical evidence indicates that embryos of different oviparous species can also be affected by a variety of environmental stressors (DuRant et al., 2013; Henriksen et al., 2011), including the presence of predators (see e.g. Mathis et al., 2008; Noguera and Velando, 2019). Indeed, predator presence is one of the most important environmental stressors in animal populations (Clinchy et al., 2013). During the postnatal life, the simple presence of predators (and their cues) induce stress responses in the prey, presumably leading to telomere shortening (Burraco et al., 2017; Olsson et al., 2010).

Although commonly overlooked, the exposure to predation risk is not limited to postnatal life since embryos are able to perceive chemical, tactile or acoustic cues of predator presence (Gilbert and Epel, 2009). For instance, it has recently been shown that bird embryos exposed to adult alarm calls show increased glucocorticoids levels (i.e. corticosterone; Noguera and Velando, 2019). While an increased secretion of glucocorticoids during embryo

development may directly or indirectly lead to telomeres to shorten due to the negative effects that glucocorticoids exert on oxidative status (Haussmann et al., 2011; Reichert and Stier, 2017) and/or telomerase activity (Choi et al., 2008), whether the presence of predators during embryonic life affects telomere dynamics has not hitherto been investigated.

Here, we study whether prenatal exposition to social cues of predator presence affects early postnatal telomere length and corticosterone levels. To answer this question, we carried out a field experiment where we experimentally modified the exposition of yellow-legged gull (*Larus michahellis*) embryos to cues of predator presence (i.e. adult alarm calls) and then we assessed its effects on telomere length at hatching and after 5 days of postnatal life. We predict that gull chicks hatched from eggs exposed to predator cues will show reduced telomere length. Additionally, we also measured hatchlings' basal corticosterone levels. Corticosterone is the main stress hormone in birds, and we have recently shown that prenatal exposition to adult alarm calls promotes important physiological and molecular changes in the hatchlings, including a higher secretion of corticosterone (Noguera and Velando, 2019). Hence, we expected increased basal corticosterone levels in hatchlings from eggs exposed to predator presence.

MATERIAL AND METHODS

Study area and general procedures

We performed the field experiment from April to June 2018 and 2019 at a colony of yellow-legged gulls (*Larus michahellis*) in Salvora Island, Spain. We used in total 87 nests (N=54 in 2018 and N=33 in 2019) containing a clutch of three eggs with known laying date and egg order. We visited each study nest beginning when the second-laid egg in each clutch had 20 days of incubation. Every morning we monitored the nests, collected the second eggs and immediately transported them in a thermal container to our field station. We selected second-laid eggs because previous data suggest that they may be more susceptible to external stimuli due to their more advanced sensory systems (Noguera and Velando, 2019). Once in the field station, we measure the eggs (±0.001mm) to calculate their volume and randomly assigned them to two experimental groups: 'exposed' or 'unexposed' to social cues of predator presence (thereafter, 'exposed' and 'unexposed' groups, respectively). We placed the eggs into artificial incubators where they were kept at 38ºC and 55% relative humidity and turned once per hour (Noguera and Velando, 2019). Eggs collected on the same day (range: 10-20) and assigned to the same experimental treatment were placed together in the same incubator so that each experimental

treatment was replicated in 5 different incubators (3 in 2018 and 2 in 2019) to avoid possible incubator effects.

To experimentally modify the exposition of gull embryos to social cues of predator presence we followed the methodology previously described for yellow-legged gulls (Noguera and Velando, 2019). Briefly, every day between day 21 and 27 of incubation, we removed the eggs assigned to the 'exposed' group from their incubators and placed them inside of a sound-proof box for three minutes (see Noguera and Velando, 2019 for further details on box dimension). During that time, we exposed the eggs to continuous playback stimuli of adult alarm calls that had been previously recorded in the same colony. Adult alarm calls audio files were broadcasted with a speaker (BSP60, Les Ulis, China) placed in the lid of the box, at 30 cm from the eggs and a standard sound intensity of ca. 80 dB. After the payback stimuli, the eggs were immediately returned to the incubator. We exposed the eggs to the playback stimuli 4 times a day from 9:00 am to 8:00 pm on a random time schedule to avoid habituation but using each time a different audio file from a subset of 4 files. In the 'unexposed' group, the eggs were subjected to the same experimental procedure during the 3-min playback trials but audio files only contained a control acoustic stimuli i.e. stonechat (*Saxicola torquata*) breeding calls previously recorded in the same breeding colony. On day 27 of incubation (i.e. 24 h before the expected time of hatching), once the experimental eggs (exposed and unexposed) received their last playback stimuli, we returned the eggs to the colony. To disrupt any potential antipredator covariation between parental and offspring phenotype, we cross-fostered the eggs between pairs of nests that had the same laying date (± 1 day). The duration of the playback stimuli, sound intensity and the daily frequency of exposition to the playback were within the natural range of variation in the study colony (see Noguera and Velando, 2019 for further details).

At hatching, we marked all experimental chicks (exposed and unexposed) with numbered leg flags for their identification. Nine eggs failed to hatch but hatching success did not differ among experimental groups (see SM, Table S1). We blood-sampled and measured all experimental chicks at two-time points, day 1 and 5 of age. Although near in time, these two samples allowed us to assess whether or not any effect of our experimental treatment on early postnatal telomere length and body size remained after hatching. We collected blood samples (approx. 90 µl) from the brachial vein with heparinized capillary tubes and weighed them in a Pesola spring balance (±1g). We always collected blood samples within 3 min of capture to avoid any increase of baseline corticosterone levels as a consequence of handling (Romero and Reed, 2005).

Laboratory analyses

Quantification of plasma corticosterone

We measured corticosterone concentration in plasma sampled at day 1 of age using a commercially available enzyme-linked immunosorbent assay (ELISA Kit EIA-4164 from DRG Diagnostics, Marburg, Germany), and following the manufacturer's instructions. Briefly, plasma samples (20µl) were incubated with a corticosterone-horseradish peroxidase conjugate for 60 min in a microtiter plate. Afterwards, microtiter plate was washed three times and allowed to react with a substrate solution leading to a blue–green complex. The change in absorbance at 450 nm (Synergy™ 2 Multi-Mode Microplate Reader, Bio-Tek Instruments, Inc.) of the blue–green complex was reverse proportional to the concentration of corticosterone. Plasma samples were analysed in duplicated and the assay showed high repeatability (Intra-class Correlation Coefficient [ICC]=0.86, $P<0.001$, N=71). The cross-reactivity of the polyclonal corticosterone-antisera with respectively related substances was negligible in this species (see Noguera et al., 2017 for further details).

Quantification of RBCs telomere length

Telomere length was measured in RBCs DNA samples using real-time PCR (qPCR) on a StepOnePlus (Applied Biosystems) and following a previously established protocol for bird samples (Criscuolo et al., 2009) but with some minor modifications described for yellow-legged gull samples (Kim and Velando, 2015). Prior to the analyses, DNA was extracted from RBCs samples taken on day 1 and 5 of age with DNeasy Blood and Tissue kit (Qiagen, Crawley, UK), following the manufacturer's protocol. The qPCR method 'normalises' the quantity of telomere product (T) to a single-copy gene (S) to provide a mean TL for the cell population (T/S ratio). Briefly, the DNA samples were assayed using the Absolute blue qPCR SYBR green Low Rox master mix (Thermo scientific; UK) with telomere (Tel1b and Tel2b) and GADPH primers (GapF and GapR) and following the assay condition described in Kim and Velando (2015). Each plate also included a reference (gold) sample and a negative control sample. The efficiency of each amplicon was estimated from the slopes of the amplification curves for each qPCR reaction using LinRegPCR software (Ruijter et al., 2009) (TEL: range 1.83–1.84; GAPDH: range 1.89–1.91). All DNA samples were run in triplicate, and average values were used to calculate the relative T/S ratios, controlling for plate efficiency as described in Pfaffl (2001). T/S values were repeatable (ICC=0.87, $P<0.001$, N=137).

Molecular sexing

Gull chicks were sexed following the methodology and primer sequences described by (Fridolfsson and Ellegren, 1999). The method is based on polymerase chain reaction (PCR) to amplify part of the W-linked avian CHD gene (CHD-W) in females, and its non-W-linked homologue (CHD-Z) in both sexes. The DNA products were run on a 2% agarose gel and stained with Greensafe Premium (NZYtech, Portugal).

Statistical analyses

We used linear mixed-effects models (LMMs) to test the effect of prenatal exposition to predator cues on incubation time and basal corticosterone levels at day 1 of age. The model included the experimental treatment (exposed and unexposed), year and their two-way interaction as fixed terms, and the incubator identity (ID) as a random term. We assessed the effect of the experimental treatment on postnatal telomere length and growth rate during the first 5 days of age using LMMs. These models included the experimental treatment, chick age (day 1 and 5 of age), year and their three-and two-way interactions as fixed factors, and incubator ID and chick ID as random terms. Sex and egg volume were also included in all the above models. Since any effect of experimental treatment on telomere length may be related to an effect on experimental treatment on basal corticosterone levels (see e.g. Herborn et al., 2014), we reran the model on telomere length but including basal corticosterone levels and its interaction with age as covariates.

Before running the analyses, corticosterone levels were log-transformed to improve data distribution. We confirmed there was no initial bias in laying date, egg volume, sex-ratio or hatching success between experimental groups (see SM, Table S1). Note that differences in sample sizes in some analyses reflect missing values owing to the death or loss of chicks and/or insufficient volume sample (see SM, Table S2 for further details). We report results for full models after removing nonsignificant interactions (Engqvist, 2005). All analyses were conducted in IBM SPSS statistics v.24 using Satterthwaite's degrees of freedom, the significance level was set at $\alpha=0.05$ and all statistical test were two-tailed.

Ethics

The study complied with the standards of animal experimentation and animal welfare established under current Spanish law (RD53/2013), and permissions were granted by the authorities of Parque Nacional de las Islas Atlánticas and approved by the Xunta de Galicia review board (45/RX97704 and 263/RX583146).

RESULTS AND DISCUSSION

Our experimental treatment did not affect incubation time (treatment: $F_{1,72}$=2.517, P=0.117; treatment x year: $F_{1,71}$=3.091, P=0.083) but on average, the exposure to alarm calls during embryo development increased basal corticosterone levels in gull hatchlings although differences were marginally significant (treatment: $F_{1,66}$=3.542, P=0.064; year: $F_{1,66}$=0.921, P=0.341; treatment x year: $F_{1,65}$=0.210, P=0.648; Fig. 1A). On average, the incubation time was longer in 2018 than in 2019 ($F_{1,72}$= 23.866, P=<0.001) but neither egg volume nor the sex were significant in the models (P>0.190 in both cases). From a mechanistic point of view, the repeated exposure to alarm calls probably exposed the embryos to increased corticosterone levels during their last week of development (see e.g. Noguera and Velando, 2019), although in our study the difference at hatching was marginally significant. Alternatively, it might be also possible that prenatal stress exposure had a remodelling effect on the hypothalamic-pituitary-adrenal (HPA) axis in the gull embryos that resulted in a higher HPA axis activity after hatching (e.g. increased basal or stress-induced levels of glucocorticoids; see Haussmann et al. 2011; Vallée et al. 1999). To elucidate the precise mechanism through which prenatal stressors affect basal glucocorticoids levels early after hatching, future studies in which glucocorticoids levels are measured at the time of stress exposure (i.e. embryonic development) would be particularly helpful.

Interestingly, adult alarm calls during embryo stage affected early postnatal telomere length ($F_{1,11.77}$=5.534, P=0.037; see SM, Table S3); one-day-old chicks in the prenatally exposed group had shorter telomeres than chicks in the unexposed group, and such difference was still evident at 5 days of age (Fig. 1B). Chick body mass increased with age and was positively related to egg volume (P<0.001 in both cases; see Table S3), but did not differ between experimental groups or sexes (P>0.103 in all cases; see Table S3). An early (prenatal) exposition to increased corticosterone levels may have contributed to increased oxidative damage in the embryos (Costantini et al., 2011) which in turn, may be responsible for telomere shortening observed in the gull chicks (Reichert and Stier, 2017). Similarly, predator-induced stress may have also

contributed to reducing telomerase activity (Choi et al., 2008) and therefore the capacity of the embryos to restore their telomeres before hatching (Schaetzlein et al., 2004). However, differences in telomere length seemed to be not directly related to the observed variation in basal corticosterone level as neither basal corticosterone level nor its interaction with age were significant when added into the model (basal corticosterone: $F_{1,60.64}$=0.108, P=0.744; basal corticosterone x age: $F_{1,63.55}$=2.284, P=0.136) This interesting result suggest that the observed reduction of telomeres may not be directly mediated by an increase in corticosterone secretion. It might be plausible that predator risk induced oxidative damage in the embryos as a result of corticosterone-independent mechanisms. For instance, embryos exposed to predator cues may have increased their motor activity and therefore skeletal muscle contraction (Noguera and Velando, 2019), resulting in an overproduction of oxidizing free radical species (McArdle et al., 2001). Additionally, adult alarm calls may have induced epigenetic alterations during embryo development (see Noguera and Velando, 2019) with negative consequences on other important telomere regulatory pathways rather than telomerase activity (reviewed in Blasco, 2007). Regardless of the mechanism, our results indicate that exposition to predator cues, even during embryo development, may shape early postnatal telomere length.

In conclusion, our findings indicate that bird embryos are not passive agents but rather they are sensitive to environmental stressors. We have provided clear evidence that prenatal exposition to predator cues can negatively affect early postnatal telomere length in gull chicks. Moreover, the reduced telomere length in gull hatchling prenatally exposed to adult alarm calls lasts for several days after hatching (day 5 of age), suggesting that predator-induced effects were not transient and may be potentially dragged through the postnatal growth period (see e.g. Entringer et al., 2018; Noguera et al., 2016). As young birds with shorter telomere length have reduced fledging success and lifespan (Heidinger et al., 2012; Watson et al., 2015), the reduction of telomere length in the exposed chicks is likely to have long-term fitness consequences. Our results further provide a link explaining, for instance, why predation risk may itself reduce future survival in wild populations (MacLeod et al., 2018; Zanette et al., 2011) and influence life-history decisions (Taborsky, 2017 and references therein). Future studies should investigate the mechanisms underlying the predator-induced telomere shorting in embryos and whether these prenatal effects affect life-history trajectories and modulate population trends and dynamics.

ACKNOWLEDGEMENTS

We thank M. Haussmann and an anonymous referee for their constructive and helpful comments. We are grateful to the staff at the Atlantic Islands of Galicia National Park, especially to Pablo Mallo, Roberto Castiñeira and José Arca. We also thank Alberto da Silva for helping with the telomere analyses, Naya Alvarez-Quintero for her assistance during the fieldwork and Laura Sáez for the language corrections.

COMPETING INTERESTS

The authors declare no competing or financial interests.

AUTHOR CONTRIBUTIONS

J.C.N designed the study, conducted the experimental work and analyzed the data. A.V. had input on study design and data analysis and both J.C.N and A.V wrote the manuscript.

FUNDING

J.C.N. was supported by Programa de Retención de Talento (Universidad de Vigo) and the project was funded by MICINN (PGC2018-095412-B-I00) and Xunta de Galicia (ED431F 2017/07).

DATA AVAILABILITY

All data needed to evaluate the conclusions of the study are presented in the paper and/or the Supplementary Materials. Raw data can also be found in the Figshare digital repository: 10.6084/m9.figshare.10560218.

REFERENCES

Blackburn, E. H., Epel, E. S. and Lin, J. (2015). Human telomere biology: a contributory and interactive factor in aging, disease risks, and protection. *Science* **350**, 1193-1198.

Blasco, M. A. (2007). The epigenetic regulation of mammalian telomeres. *Nature Rev. Gen.* **8**, 299-309.

Burraco, P., Díaz-Paniagua, C. and Gomez-Mestre, I. (2017). Different effects of accelerated development and enhanced growth on oxidative stress and telomere shortening in amphibian larvae. *Scientific Rep.* **7**, 7494.

Choi, J., Fauce, S. R. and Effros, R. B. (2008). Reduced telomerase activity in human T lymphocytes exposed to cortisol. *Brain Behav. Imm.* **22**, 600-605.

Clinchy, M., Sheriff, M. J. and Zanette, L. Y. (2013). Predator-induced stress and the ecology of fear. *Funct. Ecol.* **27**, 56-65.

Costantini, D., Marasco, V. and Møller, A. P. (2011). A meta-analysis of glucocorticoids as modulators of oxidative stress in vertebrates. *J. Comp. Phys. B* **181**, 447-456.

Criscuolo, F., Bize, P., Nasir, L., Metcalfe, N. B., Foote, C. G., Griffiths, K., Gault, E. A. and Monaghan, P. (2009). Real-time quantitative PCR assay for measurement of avian telomeres. *J. Avian Biol.* **40**, 342-347.

DuRant, S. E., Hopkins, W. A., Hepp, G. R. and Walters, J. (2013). Ecological, evolutionary, and conservation implications of incubation temperature-dependent phenotypes in birds. *Biol. Rev.* **88**, 499-509.

Eastwood, J. R., Hall, M. L., Teunissen, N., Kingma, S. A., Hidalgo Aranzamendi, N., Fan, M., Roast, M., Verhulst, S. and Peters, A. (2019). Early-life telomere length predicts lifespan and lifetime reproductive success in a wild bird. *Mol. Ecol.* **28**, 1127-1137.

Engqvist, L. (2005). The mistreatment of covariate interaction terms in linear model analyses of behavioural and evolutionary ecology studies. *Anim. Behav.* **70**, 967-971.

Entringer, S., Buss, C. and Wadhwa, P. D. (2012). Prenatal stress, telomere biology, and fetal programming of health and disease risk. *Sci. Signal*. **5**, pt12.

Entringer, S., de Punder, K., Buss, C. and Wadhwa, P. D. (2018). The fetal programming of telomere biology hypothesis: an update. *Phil. Trans. R. Soc. B* **373**, 20170151.

Entringer, S., Epel, E. S., Kumsta, R., Lin, J., Hellhammer, D. H., Blackburn, E. H., Wüst, S. and Wadhwa, P. D. (2011). Stress exposure in intrauterine life is associated with shorter telomere length in young adulthood. *Proc. Natl. Acad. Sci. USA* **108**, E513-E518.

Frenck, R. W., Blackburn, E. H. and Shannon, K. M. (1998). The rate of telomere sequence loss in human leukocytes varies with age. *Proc. Natl. Acad. Sci. USA* **95**, 5607-5610.

Fridolfsson, A.-K. and Ellegren, H. (1999). A simple and universal method for molecular sexing of non-ratite birds. *J. Avian Biol.* **1**, 116-121.

Gilbert, S. F. and Epel, D. (2009). *Ecological developmental biology: integrating epigenetics, medicine, and evolution*. Sunderland, MA: Sinauer Associates.

Haussmann, M. F., Longenecker, A. S., Marchetto, N. M., Juliano, S. A. and Bowden, R. M. (2011). Embryonic exposure to corticosterone modifies the juvenile stress response, oxidative stress and telomere length. *Proc. R. Soc. B* **279**, 1447-1456.

Heidinger, B. J., Blount, J. D., Boner, W., Griffiths, K., Metcalfe, N. B. and Monaghan, P. (2012). Telomere length in early life predicts lifespan. *Proc. Natl. Acad. Sci. USA* **109**, 1743-8.

Henriksen, R., Rettenbacher, S. and Groothuis, T. G. (2011). Prenatal stress in birds: pathways, effects, function and perspectives. *Neurosci. Biobehav. Rev.* **35**, 1484-1501.

Herborn, K. A., Heidinger, B. J., Boner, W., Noguera, J. C., Adam, A., Daunt, F. and Monaghan, P. (2014). Stress exposure in early post-natal life reduces telomere length: an experimental demonstration in a long-lived seabird. *Proc. Biol. Sci.* **281**, 20133151.

Kim, S.-Y. and Velando, A. (2015). Antioxidants safeguard telomeres in bold chicks. *Biology Letters* **11**, 20150211

MacLeod, K. J., Krebs, C. J., Boonstra, R. and Sheriff, M. J. (2018). Fear and lethality in snowshoe hares: the deadly effects of non-consumptive predation risk. *Oikos* **127**, 375-380.

Mathis, A., Ferrari, M. C., Windel, N., Messier, F. and Chivers, D. P. (2008). Learning by embryos and the ghost of predation future. *Proc. R. Soc. B* **275**, 2603-2607.

McArdle, A., Pattwell, D., Vasilaki, A., Griffiths, R. and Jackson, M. (2001). Contractile activity-induced oxidative stress: cellular origin and adaptive responses. *Am. J. Physiol. -Cell Physiol.* **280**, C621-C627.

Noguera, Metcalfe, N. B., Boner, W. and Monaghan, P. (2015). Sex-dependent effects of nutrition on telomere dynamics in zebra finches (*Taeniopygia guttata*). *Biol. Lett.* **11**, 20140938.

Noguera, J. C., Kim, S.-Y. and Velando, A. (2017). Family-transmitted stress in a wild bird. *Proc. Natl. Acad. Sci. USA* **114**, 6794-6799.

Noguera, J. C., Metcalfe, N. B., Reichert, S. and Monaghan, P. (2016). Embryonic and postnatal telomere length decrease with ovulation order within clutches. *Scientific Rep.* **6**, 25915.

Noguera, J. C. and Velando, A. (2019). Bird embryos perceive vibratory cues of predation risk from clutch mates. *Nature Ecol. Evol.* ***3***, 1225-1232.

O'Sullivan, R. J. and Karlseder, J. (2010). Telomeres: protecting chromosomes against genome instability. *Nature Rev. Mol. Cell Biol.* **11**, 171-181.

Olsson, M., Pauliny, A., Wapstra, E. and Blomqvist, D. (2010). Proximate determinants of telomere length in sand lizards (*Lacerta agilis*). *Biol. Lett.* **6**, 651-653.

Pfaffl, M. W. (2001). A new mathematical model for relative quantification in real-time RT–PCR. *Nucleic Acids Research* **29**, e45-e45.

Price, L. H., Kao, H.-T., Burgers, D. E., Carpenter, L. L. and Tyrka, A. R. (2013). Telomeres and early-life stress: an overview. *Biol. Psychiatry* **73**, 15-23.

Reichert, S. and Stier, A. (2017). Does oxidative stress shorten telomeres *in vivo*? A review. *Biol. Lett.* **13**, 20170463.

Romero, L. M. and Reed, J. M. (2005). Collecting baseline corticosterone samples in the field: is under 3 min good enough? *Comp. Biochem. Physiol. A* **140**, 73-79.

Ruijter, J. M., Ramakers, C., Hoogaars, W. M. H., Karlen, Y., Bakker, O., van den Hoff, M. J. B. and Moorman, A. F. M. (2009). Amplification efficiency: linking baseline and bias in the analysis of quantitative PCR data. *Nucleic Acids Res.* **37**, e45-e45.

Schaetzlein, S., Lucas-Hahn, A., Lemme, E., Kues, W. A., Dorsch, M., Manns, M. P., Niemann, H. and Rudolph, K. L. (2004). Telomere length is reset during early mammalian embryogenesis. *Proc. Natl. Acad. Sci. USA* **101**, 8034-8038.

Taborsky, B. (2017). Developmental plasticity: preparing for life in a complex world. *Adv. Study Behav.* **49**, 49-99.

Tarry-Adkins, J., Chen, J., Smith, N., Jones, R., Cherif, H. and Ozanne, S. (2009). Poor maternal nutrition followed by accelerated postnatal growth leads to telomere shortening and increased markers of cell senescence in rat islets. *FASEB J.* **23**, 1521-1528.

Thiéry, D., Monceau, K. and Moreau, J. (2014). Different emergence phenology of European grapevine moth (*Lobesia botrana*, Lepidoptera: Tortricidae) on six varieties of grapes. *Bull. Entomol. Res.* **104**, 277-287.

Vaiserman, A. (2014). Early-life nutritional programming of longevity. *J. Dev. Origins Health Dis.* **5**, 325-338.

van Lieshout, S., Bretman, A., Newman, C., Buesching, C., Macdonald, D. and Dugdale, H. (2019). Individual variation in early-life telomere length and survival in a wild mammal. *Mol. Ecol.* **28**, 4152-4165.

Watson, H., Bolton, M. and Monaghan, P. (2015). Variation in early-life telomere dynamics in a long-lived bird: links to environmental conditions and survival. *J. Exp. Biol.* **218**, 668-674.

Zanette, L. Y., White, A. F., Allen, M. C. and Clinchy, M. (2011). Perceived predation risk reduces the number of offspring songbirds produce per year. *Science* **334**, 1398-1401.

Figures

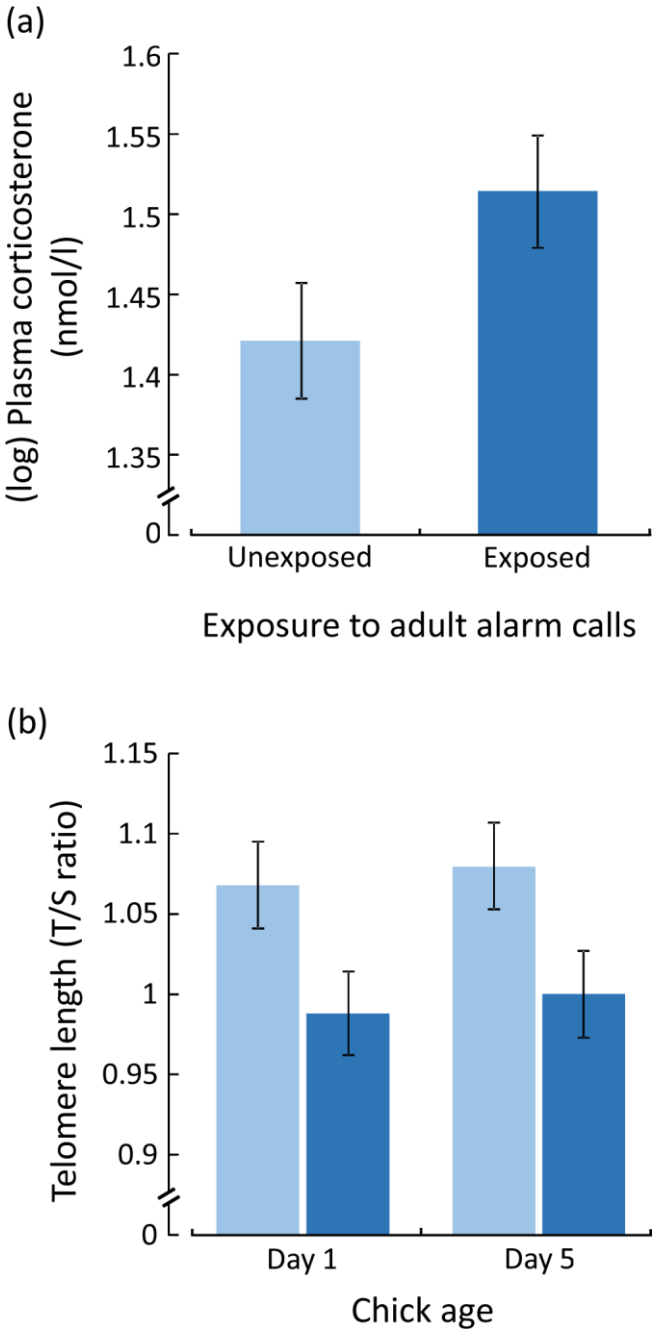

Figure 1. Basal corticosterone level and telomere length in yellow-legged gull chicks. (a) Plasma corticosterone level at day 1 of age (N=71) and (b) telomere length at day 1 (N=73) and 5 (N=64) of age in gull chicks prenatally unexposed (light blue bars) or exposed (dark blue bars) to adult alarm calls. Data are estimated marginal means ± s.e.m.

Table S1. Summary of linear models (LMs) and generalised linear models (GLMs) for initial differences in laying date, egg volume, sex-ratio and hatching success. All models include the experimental treatment, year and their two-way interaction as fixed factor. The two-way interaction between the experimental treatment and year was never significant and therefore, removed from full models (Laying date: $F_{1,83}$=0.010, P=0.922; Egg volume: $F_{1,83}$=0.098, P=0.754; sex-ratio: Wald χ^2=0.512, DF=1, P=0.474; hatching success: Wald χ^2=1.042, DF=1, P=0.307). Significant terms are highlighted in bold.

	Source of variation	Estimate	DF	F or Wald χ^2	P
Laying date	Intercept	4359.221			
	Treatment (unexposed)	-0.018	1,84	0.006	0.932
	Year (2018)	-732.804	1,84	$97.83e^3$	**P<0.001**
Egg volume	Intercept	84.123			
	Treatment (unexposed)	0.272	1,84	0.026	0.872
	Year (2018)	0.257	1,84	0.022	0.882
Sex-ratio	Intercept	0.058			
	Treatment (unexposed)	0.163	1	0.130	0.719
	Year (2018)	-0.264	1	0.321	0.571
Hatching success	Intercept	-2.198			
	Treatment (unexposed)	-0.227	1	0.102	0.749
	Year (2018)	0.227	1	0.093	0.761

Table S2. Summary of final sample sizes used in the statistical analyses. Differences in sample sizes reflect missing values owing to the death or loss of chicks and/or insufficient volume sample.

	2018		2019		
	unexposed	exposed	unexposed	exposed	Total
Egg volume	27	27	16	17	87
Plasma corticosterone	23	22	12	14	71
Telomere length (day 1)	22	23	13	15	73
Telomere length (day 5)	20	20	12	12	64
Body mass (day 1)	24	23	13	16	76
Body mass (day 5)	20	20	14	14	68

Table S3. Summary of linear models for the effect of embryo treatment [unexposed vs exposed] and covariates on telomere length and body mass in gull chicks at day 1 and 5 of age. The two- and three-way interactions between the experimental treatment, age and year were never significant and therefore, removed from full models [Telomere length model: treatment x age; $F_{1.66.32}$=1.270, P=0.264; treatment x year: $F_{1,13.29}$=0.293, P=0.597; age x year: $F_{1,65.56}$=0.008, P=0.930; treatment x age x year: $F_{1,64.46}$=0.154, P=0.696; Body mass model: treatment x age: $F_{1,73.82}$=1.177, P=0.281; treatment x year: $F_{1,71.59}$=0.399, P=0.529; age x year; $F1_{,72.78}$=0.747, P=0.390; treatment x age x year: $F_{1,71.63}$=1.993, P=0.162). Significant terms are highlighted in bold.

Source of variation	Telomere length				Body mass			
	Estimate	$DF_{n,d}$	F or Z	P	Estimate	$DF_{n,d}$	F or Z	P
Intercept	0.782				37.239			
Treatment (unexposed)	0.080	1,11.77	5.534	**0.037**	3.640	1,72.50	2.713	0.104
Sex (female)	-0.044	1,66.52	2.629	0.110	-3.476	1,72.98	2.327	0.131
Year (2018)	0.060	1,66.47	2.567	0.157	4.125	1,72.17	3.286	0.074
Age (day 1)	-0.012	1,67.41	0.455	0.502	41.984	1,74.79	435.953	**<0.001**
Egg volume	0.002	1,68.80	1.501	0.225	0.766	1,78.97	23.794	**<0.001**
Random effects								
Incubator ID	0.001		0.800	0.423	0*		-	1
Chick ID	0.006		2.656	0.008	16.200		0.856	0.392

*Parameter estimate bound at zero; hence, no Z was estimated.

Table S1. Summary of linear models (LMs) and generalised linear models (GLMs) for initial differences in laying date, egg volume, sex-ratio and hatching success. All models include the experimental treatment, year and their two-way interaction as fixed factor. The two-way interaction between the experimental treatment and year was never significant and therefore, removed from full models (Laying date: $F_{1,83}$=0.010, P=0.922; Egg volume: $F_{1,83}$=0.098, P=0.754; sex-ratio: Wald χ^2=0.512, DF=1, P=0.474; hatching success: Wald χ^2=1.042, DF=1, P=0.307). Significant terms are highlighted in bold.

	Source of variation	Estimate	DF	F or Wald χ^2	P
Laying date	Intercept	4359.221			
	Treatment (unexposed)	-0.018	1,84	0.006	0.932
	Year (2018)	-732.804	1,84	$97.83e^3$	**P<0.001**
Egg volume	Intercept	84.123			
	Treatment (unexposed)	0.272	1,84	0.026	0.872
	Year (2018)	0.257	1,84	0.022	0.882
Sex-ratio	Intercept	0.058			
	Treatment (unexposed)	0.163	1	0.130	0.719
	Year (2018)	-0.264	1	0.321	0.571
Hatching success	Intercept	-2.198			
	Treatment (unexposed)	-0.227	1	0.102	0.749
	Year (2018)	0.227	1	0.093	0.761

Table S2. Summary of final sample sizes used in the statistical analyses. Differences in sample sizes reflect missing values owing to the death or loss of chicks and/or insufficient volume sample.

	2018		2019		
	unexposed	exposed	unexposed	exposed	Total
Egg volume	27	27	16	17	87
Plasma corticosterone	23	22	12	14	71
Telomere length (day 1)	22	23	13	15	73
Telomere length (day 5)	20	20	12	12	64
Body mass (day 1)	24	23	13	16	76
Body mass (day 5)	20	20	14	14	68

Table S3. Summary of linear models for the effect of embryo treatment [unexposed vs exposed] and covariates on telomere length and body mass in gull chicks at day 1 and 5 of age. The two- and three-way interactions between the experimental treatment, age and year were never significant and therefore, removed from full models [Telomere length model: treatment x age; $F_{1.66.32}$=1.270, P=0.264; treatment x year: $F_{1,13.29}$=0.293, P=0.597; age x year: $F_{1,65.56}$=0.008, P=0.930; treatment x age x year: $F_{1,64.46}$=0.154, P=0.696; Body mass model: treatment x age: $F_{1,73.82}$=1.177, P=0.281; treatment x year: $F_{1,71.59}$=0.399, P=0.529; age x year; $F1_{,72.78}$=0.747, P=0.390; treatment x age x year: $F_{1,71.63}$=1.993, P=0.162). Significant terms are highlighted in bold.

Source of variation	Telomere length				Body mass			
	Estimate	$DF_{n,d}$	F or Z	P	Estimate	$DF_{n,d}$	F or Z	P
Intercept	0.782				37.239			
Treatment (unexposed)	0.080	1,11.77	5.534	**0.037**	3.640	1,72.50	2.713	0.104
Sex (female)	-0.044	1,66.52	2.629	0.110	-3.476	1,72.98	2.327	0.131
Year (2018)	0.060	1,66.47	2.567	0.157	4.125	1,72.17	3.286	0.074
Age (day 1)	-0.012	1,67.41	0.455	0.502	41.984	1,74.79	435.953	**<0.001**
Egg volume	0.002	1,68.80	1.501	0.225	0.766	1,78.97	23.794	**<0.001**
Random effects								
Incubator ID	0.001		0.800	0.423	0*		-	1
Chick ID	0.006		2.656	0.008	16.200		0.856	0.392

*Parameter estimate bound at zero; hence, no Z was estimated.