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Coupling lifespan and aging? The age at onset of body mass decline associates positively with sex-specific lifespan but negatively with environment-specific lifespan

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ABSTRACT

Whether lifespan scales to age-associated changes in health and disease is an urgent question in societies with increasing lifespan. Body mass is associated with organismal functioning in many species, and often changes with age. We here tested in zebra finches whether two factors that decreased lifespan, sex and poor environmental quality, accelerated the onset of body mass declines. We subjected 597 birds for nine years to experimentally manipulated foraging costs (harsh = H, benign = B) during development (small vs large brood size) and in adulthood (easy vs hard foraging conditions) in a 2×2 design. This yielded four treatment combinations (HH, HB, BH, BB) for each sex. Harsh environments during development and in adulthood decreased average body mass additively. The body mass aging trajectory showed a short steep increase in early adulthood, followed by a plateau and then a decline after 5 years. This decline occurred in all groups except for HB females, which gained mass until death. Surprisingly, the onset of body mass decline was earlier in experimental groups with a longer lifespan. In contrast, the onset of body mass decline was one year earlier in females, which lived two months (4%) shorter than males. Thus, the onset of body mass aging associated positively with the sex-specific differences in lifespan, but negatively with the environmental modulation of lifespan. Thus, body mass aging trajectories did not generally scale to lifespan, and we discuss the possible causes and implications of this finding.

1. Introduction

Healthspan is the maintenance of full organismal functioning as nearly as possible to the end of life (Rowe and Kahn, 1987). Senescence is the decline in organismal functioning resulting in decreasing reproduction and survival probability with age (Williams, 1957; Hamilton, 1966). The (implicit) assumption is often made that factors changing lifespan will consistently alter healthspan and senescence. However, whether this is the case remains to be identified (Bansal et al., 2015; Christensen et al., 2009; Williams, 1999). The association between lifespan and healthspan is at the heart of contemporary society: human life expectancy has increased continuously since the 19th century, but to what extent this increase is accompanied by a prolonged healthspan and delayed senescence remains unclear (Christensen et al., 2009). Thus, to what extent lifespan and healthspan are scaled and affected by the same factors remains an open question in our ever longer-living society.

Aging trajectories describe how traits change with age, irrespective of their association with residual reproduction and/or survival (reproductive value or fitness). Here, we investigate the aging trajectory of body mass in zebra finches, and test whether factors that shorten lifespan concomitantly accelerate the onset of body mass aging. Body mass is highly repeatable over the lifetime (e.g. Briga and Verhulst, 2017). Adult body mass predicts survival or lifespan in a variety of species, including zebra finches, rodents and humans (Briga, 2016; Miller et al., 2002; Whitlock et al., 2009). Declines in mass with age are observed in many species and are associated with behavioral and physical deterioration including foraging efficiency (Catry et al., 2006), loss of muscle mass and strength (Colman et al., 2008; Sayer et al., 2008) and of body fat (Kuk et al., 2009). Hence body mass is a key trait associated with organismal functioning and survival in several species.

We monitored from birth till natural death a captive population of zebra finches living in outdoor aviaries and hence exposed to natural weather fluctuations (Briga et al., 2017; Briga and Verhulst, 2015a). We

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here investigated whether body mass aging trajectories were modulated by two factors we previously showed to affect lifespan in this population (Briga et al., 2017). The first factor is sex: females on average lived two months (4%) shorter than males. The second factor is experimental variation in environmental quality. The environment can affect lifespan at all ages, but the development phase is thought of as a particularly important for adult lifespan and health (Lindström, 1999; Lummaa and Clutton-Brock, 2002; Metcalfe and Monaghan, 2001). In our study, we altered developmental conditions by cross fostering chicks to either small or large broods. Growing up in large broods impairs growth and hence, large broods represent a harsh environment (Briga et al., 2017; Griffith and Buchanan, 2010). However, the long-term effects of developmental conditions on lifespan can depend on the environmental conditions in adulthood (Bateson et al., 2004; Hanson and Gluckman, 2014). We thus experimentally manipulated foraging costs during adulthood and exposed birds from both developmental conditions to either low or high foraging costs in a 2×2 design. In the remaining text we abbreviate the high foraging cost group as harsh (H) and the low foraging cost group as benign (B). Hence, we have four treatment combinations (BB, HB, BH, HH). The group that experienced a harsh environment during development and in adulthood (HH group) lived 6 months (12%) shorter compared to all other treatment combinations. Thus, if lifespan and aging trajectories are scaled, we expect an earlier onset of body mass decline in females relative to males, and in the HH group relative to all other treatment combinations.

2. Material & methods

2.1. Experimental setup

The birds were reared in either experimentally small broods (with 2 or 3 chicks, modal = 2) and large broods (between 5 and 8 chicks, modal = 6). These brood sizes are within the range observed in the wild and in captivity (Zann, 1996; Griffith et al., 2017). Chicks that grow up in large broods beg more per food reward and experience impaired growth (Briga, 2016; Briga et al., 2017). After nutritional independence and before the start of the foraging cost manipulation, i.e. between 35 days and approximately 120 days, young were housed in larger indoor cages with up to 40 other young of the same sex and two male and two female adults. Once adult, birds were subject to a long-term foraging experiment, (Koetsier and Verhulst, 2011). Briefly, birds were housed in eight single sex outdoor aviaries (LxHxW 310x210x150 cm) located in Groningen, the Netherlands (53° 13' 0" N/6° 33' 0" E). Food (tropical seed mixture) water, grit and cuttlebone were provided ad libitum and fortified canary food in weighed portions. In the low foraging cost group, food containers were provided with a perch and hence birds could perch while eating. In the high foraging cost group, perches were removed from the food containers and birds had to hover to get the seeds. Birds were kept in this foraging cost treatment throughout adulthood until natural death. Each aviary contained an approximately equal number of birds. To keep densities within aviaries within a limited range, we added new birds in 12 batches to replace the birds that died. The first batch was 3–24 months old when the experiment started and birds added in the later batches were 3 to 4 months old when starting the long-term foraging experiment. By December 2015, the endpoint of the data for this manuscript, all birds from the first batches had died. The surviving birds were birds of the later batches and hence were not long-lived: their median lifespan at the end of the experiment was 2.6 years (95 CI: 2.2–2.6 years), which is below the median lifespan of the population at 4.0 years (95 CI: 3.8–4.2 years; see below).

2.2. Lifespan estimates

Survival data were previously analyzed in Briga et al. (2017). To confirm previous results, we here repeated the analyses with one

Table 1

Median lifespan and description of the changes with age and onset of the body mass decline (second threshold) per experimental group and per sex. *Increase. Total sample size is 15,433 measurements on 597 individuals.

Developmental environment	Benign		Harsh	
Adult environment	Benign	Harsh	Benign	Harsh
Males				
N individuals	75	75	73	81
N measurements	2073	2007	2055	1965
median lifespan (years)	4.2	4.6	3.8	4.0
95% CI	3.8–5.4	3.8–5.7	3.2–5.9	2.9–4.7
onset of decline (years)	5.9	5.4	6.4	6.5
CI onset (4 AICc range)	5.4–7.0	4.9–6.0	5.5–7.3	5.6–7.2
Females				
N individuals	68	75	73	77
N measurements	1900	2066	1782	1595
median lifespan (years)	3.9	4.2	3.8	3.3
95% CI	3.3–5.0	3.9–5.1	3.6–4.9	2.5–3.9
onset of decline (years)	5.4	5.4	4.0*	6.4
CI onset (4 AICc range)	4.6–6.6	5.3–5.5	3.8–4.3*	5.6–6.8

additional year of survival data (8 years instead of 7) and 67 more birds ($N = 617$ instead of 550). We used, as before, Kaplan-Meier analyses and Cox proportional hazards (Cox, 1972) with the function 'coxph' of the package 'survival', which gives median lifespans, coefficients and for both their confidence intervals estimated using Wald approximations (Therneau, 2018; Therneau and Grambsch, 2000 p. 57). The median lifespan of females was two months (4%) shorter than that of males ($\Delta\text{AICc} = -5.3$). Birds from harsh developmental conditions lived shorter than birds from benign developmental conditions but only in the harsh adult environment (Table 1; benign: $\Delta\text{AICc} = +2.0$; harsh: $\Delta\text{AICc} = -6.1$), where the difference in median lifespan was 6 months (12%). The environmental effect on lifespan was more pronounced in females than males, but this difference was not statistically significant (Table 1; $\Delta\text{AICc} = +5.6$). These results are consistent with what we reported previously (Briga et al., 2017). In the best fitting Cox proportional hazards model, model assumptions of proportionality, linearity and no influential data points were fulfilled, checked with respectively the function 'cox.zph', the scaled deviance residuals and the martingale residuals (Therneau and Grambsch, 2000).

2.3. Data collection

Between December 2007 and December 2015, 597 birds were weighed between 1 and 95 times during adulthood with a total of 15,443 measurements (Fig. S1A). Data were collected from individuals covering an age range from 4 months till 9.4 years (Fig. S1B). Measurements were randomized across experimental groups. We have shown previously that the repeatability of adult body mass is high at 0.72 and hence individuals can be characterized by their body mass (Briga and Verhulst, 2017). At the average age of 120 days (SD: 29 days), we measured body size, using the average of the tarsus and the head + bill after transforming both to a standard normal distribution.

2.4. Statistical analyses

We here performed four analyses. In the first three, we analyzed variation in body mass due to (i) seasonal variation, (ii) sex & experimental manipulations and (iii) age. These analyses were performed with one statistical model, with body mass as dependent variable and in which for each analysis we added a group of terms capturing the variables of interest. This model has the form: *Body mass ~ seasonal variation + sex & experimental manipulations terms + age terms + random terms*. In the fourth analyses, we investigated the association between

Fig. 1. Schematic representation of four aging shapes tested in this manuscript. Aging may be determined by chronological age, following a shape that is linear (A), quadratic (B) or with one (C) or two (D) thresholds. Alternatively, aging may be better described by years before death resulting in a terminal decline (E). Note that slopes shown here are for illustrative purposes only and that shapes can take any slopes possible.

the median lifespan and the age at onset of body mass declines per sex-experimental group combination. Below we first explain the statistical approach used and then one by one the terms and analyses.

2.4.1. Approach

All analyses of body mass were done using a general linear mixed modeling approach with the function ‘lmer’ of the package ‘lme4’ version 1.1–17 (Bates et al., 2015) in R version 3.5 (R Core Team, 2018). We describe the statistical model step-by-step in the sections below. To find the model best supported by the data we used the model selection approach proposed by Burnham and Anderson (Burnham and Anderson, 2002; Burnham et al., 2011) based on second order Akaike Information Criterion (AICc) with the function ‘dredge’ of the package ‘MuMIn’ version 1.40.4 (Barton, 2018). In brief, this is a hypothesis-based approach that generates, given a global model, subset models that best fit the data. Better fitting models are indicated by their lower AICc. Model fitting should be considered as a continuum for which alternative models within 4 Δ AICc are plausible and become increasingly equivocal up to 14 Δ AICc, after which they become implausible (Burnham and Anderson, 2002; Burnham et al., 2011). For models within 4 Δ AICc, we report coefficients which are the result of model averaging from the function ‘model.avg’ of the package ‘MuMIn’. Confidence intervals of model parameters were estimated with the Wald approximation in the function ‘confint’. Correlations were estimated with the function ‘cor’. Residuals of all final models were normally distributed and without outliers. In selected cases we report effect sizes, estimated as Cohen’s d, i.e. the ratio of the coefficient to the variable’s standard deviation (Cohen, 1988; Nakagawa and Cuthill, 2007).

2.4.2. Seasonal variation

Body mass data were collected at any hour of the day and throughout the year at almost monthly intervals (Fig. S2A & B). To avoid confounding age patterns with daily or seasonal effects, we

corrected for daily and seasonal variation in body mass in all analyses. To this end, we first investigated how best to correct for daily and seasonal variation (Table S1). Model selection indicated that daily and seasonal variations in body mass were best captured using three variables: (i) day length, (ii) photoperiod dynamics (increase vs. decrease), (iii) time of day and their interactions (Table S1; Δ AICc = -23). Hence to obtain unbiased age estimates we ran all the models below including these three variables and their interactions as covariates.

2.4.3. Effects of sex and environmental manipulations

To test for the effects of sex and experimental treatments during development (small vs. large broods) and in adulthood (low vs. high foraging costs) these variables and their interaction were included as categorical variables (Table S2).

2.4.4. Age associated changes

2.4.4.1. Decomposing within individual change and selective disappearance. Population level associations between trait values and age can be composed of two processes: (i) a within individual change in trait value with age and (ii) a between individual difference due to selective disappearance of individuals with certain trait values. We distinguished the contributions of these two processes using a within subjects centering approach (van de Pol and Verhulst, 2006; van de Pol and Wright, 2009). In this approach selective disappearance is captured in the term lifespan. For censored birds, i.e. those still alive on 09-12-2015 ($N = 179$) or that died from an accidental death ($N = 16$), lifespan is unknown and thus received a lifespan of zero. In this way, these birds have no effect on the estimates of between-individual differences and contribute only to the estimate of within individual trait change (see below). Hence, to correct for selective disappearance, all models included the term lifespan.

2.4.4.2. Identifying the within individual aging trajectory. Within individual changes were captured in the age term(s). To identify the

Fig. 2. Harsh environments decreased mass. Shown are boxplots with median, quartiles and 95% CI. Statistical analysis showed the effects of sex and developmental and adult environments to be additive for mass. Horizontal lines connect groups from different brood sizes in the same foraging treatment. Sample sizes as in Table 1.

best age trajectory (Fig. 1), we fitted models with different within individual age terms (Table S3). A model without aging excludes any age term. A linear change (Fig. 1A) is captured in the term 'age'. A quadratic change (Fig. 1B) includes the terms $\text{age} + \text{age}^2$. A terminal change (Fig. 1E) includes the term terminal year, coded as a binomial factor for whether or not an individual died within the year following the measurement. We further tested the combination of a linear and terminal change (Fig. 1A & E) with the terms $\text{age} + \text{terminal year}$.

Changes in body mass with age can occur abruptly at threshold ages (Fig. 1C & D). To estimate these threshold ages we used the above statistical model in combination with the approach developed by Douhard et al. (2017). In brief, this approach estimates for a group or a population a threshold age by testing, using the AICc, the fit on the data of statistical models, each with one threshold age. Hence, we fitted on the data a large number of models which differed only in threshold age. This threshold age was assessed with a monthly accuracy, which was the interval with which birds were weighed (Fig. S2). This accuracy permitted to clearly identify a best fitting threshold: in all cases AICc profile plots revealed a convex shape with the minimum being the best fitting threshold (Fig. S4). We computed the 'confidence' around the threshold age by inverting the 4 ΔAICc acceptance region of the model fit in these convex shapes.

2.4.5. Random terms

To capture the between individual variance in mean mass, all analyses included individual identity as a random intercept. To capture the between individual variance in aging trajectories, we included age as 'random slopes' in the model (Schielzeth and Forstmeier, 2009). Random slope models however require large sample sizes to accurately estimate coefficients (van de Pol, 2012). This power issue is particularly true for more complex statistical models such as threshold models, which require several random slopes per individual. Hence, here we

included random slopes only for analyses that used all data, while for the analyses per group we included a random intercept only. Random slopes were included as smoothing splines with one degree of freedom for models with a linear age term (Fig. 1A & E), two degrees of freedom for models with two age terms (quadratic age and 1-threshold models, Fig. 1B & C) and three degrees of freedom for models with three age terms (2-threshold model, Fig. 1D). This was done with the function 'bs' from the packages 'splines'.

2.4.6. Statistical model: summary

Given the above explanations, we tested the following predictors in the aforementioned statistical model:

seasonal variation (Table S1): $\text{time} + \text{night time} + \text{time} * \text{night time} + \text{photoperiod} + \text{time} * \text{photoperiod}$

experimental manipulations (Table S2A): $\text{brood size} + \text{foraging costs} + \text{brood size} * \text{foraging costs}$.

sex-specific experimental manipulation effects (Table S2A): $\text{sex} + \text{brood size} * \text{sex} + \text{foraging costs} * \text{sex} + \text{brood size} * \text{foraging costs} * \text{sex}$.

age terms (Table S3): all models included lifespan to account for selective disappearance. Aging trajectories are tested for by including different age terms.

random terms: all models included bird identity as a random intercept. For models that use the whole dataset we included their respective age terms as random slopes.

2.4.7. Scaling lifespan and the onset of aging

To investigate the association between median lifespan and the threshold age at onset of the body mass decline for the different sex-experimental treatments combinations, we used a linear model with the function 'lm'. To account for the error around the threshold age estimate, we used the inverse confidence around the threshold age as weight in the model.

3. Results

3.1. Average mass, the effects of environmental manipulation and sex

We first investigated the effect of the environmental manipulations on mass in adulthood. Birds in our population weighed on average 15.6 g (sd: 1.57 g; range: 10.2 g–24.4 g). Birds reared in large broods weighed 0.60 g (95% CI: $-0.39, -0.80$) less than birds reared in small broods ($\Delta\text{AICc} = -27$; Table S2A), and birds in the harsh adult environment weighed 0.65 g (95% CI: $-0.45, -0.86$) less than birds in the benign adult environment ($\Delta\text{AICc} = -32$; Table S2A). The effects of both manipulations on mass were additive (Fig. 2; Table S2A; developmental * adult environment $\Delta\text{AICc} = +3.1$). The effects of the environmental manipulations might be mediated via size. Indeed, growing up in large broods resulted in a smaller adult body size (Cohen's $d = 0.09$; $N = 594$ individuals; $\Delta\text{AICc} = -17$), but all the aforementioned conclusions remained when correcting for size ($-8.1 < \Delta\text{AICc} < -26$; Supplementary Data 2; Table S2B). Thus, harsh developmental and adult environments had additive negative effects on adult body mass which were minimally mediated by size.

Females weighed on average 0.30 g more than males (95% CI: 0.09, 0.51; $\Delta\text{AICc} = -4.6$; Table S2A). Females were also a little larger than males (Cohen's $d = 0.03$; $N = 594$ individuals; $\Delta\text{AICc} = +1.9$) and hence the difference in weight was partially due to size ($\Delta\text{AICc} = -0.7$; Table S2B). The effect of the developmental manipulation on body mass tended to be more pronounced in males than in females, but this effect had little statistical support ($\Delta\text{AICc} = +0.4$; Table S2A). In contrast, the effect of the adult manipulation on body mass tended to be more pronounced in females than in males, but also this effect had little statistical support ($\Delta\text{AICc} = +1.1$; Table S2A). The effects of the manipulations were additive in both sexes (Fig. 2; Table S2A;

developmental * adult environment * sex $\Delta AICc = +5.8$). Adding size as a covariate in the model confirmed that there were no sex-specific effects of the environmental manipulations on body mass ($+6.4 < \Delta AICc < +8.5$; Supplementary Data 2; Table S2B). Hence, females were heavier than males, but we found little evidence for sex-specific effects of the environmental manipulations.

3.2. Aging trajectories for the population

We first investigated which model best described the body mass aging trajectories, comparing the scenarios in Fig. 1. In the pooled dataset, i.e. pooling sexes and experimental treatments, there was strong support for an aging trajectory with two thresholds relative to all other trajectories ($-1250 < \Delta AICc < -133$; Table S3), including relative to the 1-threshold trajectory ($\Delta AICc < -155$; Table S3). There was also strong support for an aging trajectory with two thresholds when fitting models with only bird identity as random intercept, excluding any random slopes ($-240 < \Delta AICc < -70$; Table S3). Thus, the body mass aging trajectory of our population was best described by a two-threshold model.

We then investigated the directions of age-associated changes in body mass. In the pooled dataset, zebra finches gained in the first three months of adulthood, i.e. till the first threshold at 0.7 years, on average 0.70 g (Fig. 3A; 95%CI = 0.56–0.85). This increase was statistically significant ($\Delta AICc = -143$ relative to a model without ‘age 1’ term in Table S4A). This steep increase was followed by a shallow increase of 0.05 g/year till the age of 5.4 years (Fig. 3A; 95%CI = 0.03–0.08). Although shallow, this increase was also statistically significant ($\Delta AICc = -32$ relative to a model without ‘age 2’ term in Table S4A). Then body mass dropped 0.30 g/year (Fig. 3A; 95%CI = 0.19–0.36). This decline was statistically significant ($\Delta AICc = -46$ relative to a model without ‘age 3’ term in Table S4A). The latter effect may be considered the senescence part of the aging trajectory. Its effect size relative to the within-individual variation in body mass was $d = 0.37$. We found no evidence that the slope of this decline was different in the terminal year of individuals ($\Delta AICc = +32$) or between individuals of different lifespans ($\Delta AICc = +30$). There was selective disappearance of individuals with low body mass, with a one year shorter lifespan for 0.08 g lower mass (95%CI = 0.03–0.14; $\Delta AICc = -6.1$; Table S4A). Thus, the overall shape of the body mass aging trajectory was a short steep increase in early adulthood, followed by a long shallow increase and a moderate decline after 5 years.

3.3. Aging trajectories per sex-experimental group combination

Aging trajectories might differ between sexes or between environmental manipulations. We thus fitted the trajectories in Fig. 1 for each sex-experimental group combination. Consistent with the results for the population as a whole, the two-threshold model was the best fitting aging trajectory in all groups ($-91 < \Delta AICc < -3$; Table S3). Thus, the body mass aging trajectory was best described by a two-threshold model in all environments and for both sexes.

We then tested whether the direction of age-associated changes in body mass differed between the sex-experimental group combinations. We thus tested the interactions between the age terms and all sex-experimental group combinations. The best fitting model contained three age terms that differed between all sex-experimental group combinations ($\Delta AICc < -54$, Table S4A).

To better understand the aging trajectories, we fitted the two-threshold model separately for each sex-experimental group combination. For all groups, there was a steep increase in body mass up to the first threshold (Fig. 3, ‘age 1’ slope Table S4B–I). This increase differed between all sex-experimental group combinations (‘group * age 1’ interaction in Table S4A). Post-hoc analyses showed that mass increased more in the more benign groups (BB > BH > HB > HH) and in females more than in males, both consistent with the results in Section

3.1 (Fig. 2). Between the first and second threshold, all groups showed a shallow change, either increasing or decreasing, which in many instances did not differ from 0 (Fig. 3, ‘age 2’ slope in Table S4B–I). After the second threshold, all groups showed a decline, except for females in the HB group for which body mass increased (Fig. 3, ‘age 3’ slope in Table S4B–I). Tukey post-hoc analysis revealed that this was the only group that differed from all others ($F = 4.8$, $p = 0.03$). Hence all groups showed a decline in body mass after the second threshold except for females in the HB group.

3.4. Scaling lifespan and the onset of aging

We investigated whether sex-group combinations with longer lifespans also had a later onset of the body mass decline (i.e. the second threshold), excluding the female HB group which increased in mass till death. Males had a median lifespan of 4.2, 4.6, 3.8 and 4.0 years in the BB, BH, HB and HH respectively. Their body mass started declining at 5.9, 5.4, 6.4 and 6.5 years respectively and the difference in threshold ages between groups were statistically indistinguishable (within 4 $\Delta AICc$, Table 1, Fig. 4). The association between median lifespan and onset of body mass decline was negative, opposite to our expectation (Fig. 4, $r = -0.92$, $F_{1,4} = 30$, $p = 0.031$). Females had a median lifespan of 3.9, 4.2 and 3.3 in the BB, BH and HH respectively. Their body mass started declining at 5.4, 5.4 and 6.4 years respectively and the differences between these groups were also statistically indistinguishable (within 4 $\Delta AICc$ Table 1, Fig. S4). As in males, threshold ages associated negatively with median lifespan in females, but for females this association was not significant (Fig. 4, $r = -0.92$, $F_{1,3} = 9.6$, $p = 0.20$). Combining data on both sexes yielded a statistically marginally significant negative association between median lifespan and threshold ages ($r = -0.62$, $F_{1,7} = 5.4$, $p = 0.067$). Females lived on average two months shorter than males and their decline in body mass started almost one year earlier ($F_{1,7} = 18$, $p = 0.013$). Thus, the effects of the environmental manipulations on the onset of the body mass decline were opposite to what we expected: the decline started *later* in the short-lived groups. In contrast, the effect of sex on the onset of the body mass decline was consistent with our expectation: females lived on average two months shorter than males and had a one year *earlier* onset of the body mass decline.

4. Discussion

Identifying how phenotypes change with age (Fig. 1), what affects these changes and how they scale to lifespan are key questions in an ever longer living society and for understanding the mechanisms of senescence. We here investigated whether environmental manipulations that shortened lifespan accelerated body mass declines in zebra finches. Harsh environments during development and in adulthood decreased average body mass additively. The body mass aging trajectory showed a short steep increase in early adulthood, then plateaued which was followed by a decline after 5 years. This decline occurred in all groups except for females in the HB group. We found a negative association between the effect of the environmental manipulation on lifespan and on their age at onset of body mass decline. However, females lived on average two months shorter than males and their body mass decline started one year earlier. Hence, environment-specific and sex-specific differences in lifespan were differentially associated with the age at onset of the body mass decline.

4.1. Scaling lifespan and the onset of aging

To what extent lifespan and aging are scaled remains poorly understood. A previous study using long-lived *C. elegans* mutants found that for several traits, declines in functioning started at the same age for long-lived mutants as for wild types (Bansal et al., 2015). Hence these long-lived mutants spent a larger proportion of their lives in a senescent

Fig. 3. Within individual mass aging trajectories. Boxplots show median, quartiles and 95% CI per year. Mass is adjusted for seasonal variation and selective disappearance. All = all data; other abbreviations indicate sex-experimental group combinations, e.g. MBH: males from benign development and in harsh adult environment. Fitted lines are the model predictions from the models in Table S4. Sample sizes as in Table 1.

state. Our study shows that the longest-living groups spent proportionally more time with a decreasing body mass (Fig. 4). Hence our results are consistent with the study of Bansal et al., 2015. It is unclear however whether these results also apply to other traits. Within individuals, aging trajectories can differ in rate and shape between traits (Gaillard and Lemaitre, 2017; Hayward et al., 2015; Herndon et al., 2002), as we also observed in zebra finches (Briga, 2016; Simons et al., 2016). This complexity is illustrated by rapamycin experiments which extends rodent lifespan and postpones aging of some traits, including body mass, but not of others (Fischer et al., 2015; Neff et al., 2013). Hence in our study, the longest-living groups spent a larger fraction of their lives with decreasing body mass, but to what extent this can be extrapolated to other traits and manipulations of lifespan requires further study.

4.2. Sex-specific onset of aging

The onset of the body mass decline was earlier in the shortest living sex, i.e. females, consistent with theory on sex-specific aging which predicts that the shortest living sex also ages fastest (Bonduriansky et al., 2008; Maklakov and Lummaa, 2013). Sex-specific body mass aging trajectories were observed in two species of wild mammals and the shorter living sex also showed earlier body mass aging (Alpine marmot *Marmota marmota*, Tafani et al., 2013; European badger *Meles meles*, Beirne et al., 2015). There are however exceptions. Most notably, women typically outlive men but their body mass decline starts a decade earlier (reviewed in Kuk et al., 2009).

In zebra finches, some studies found that females were more sensitive to developmental conditions than males (e.g. de Kogel, 1997; Martins, 2004), although this may not be a general finding (Griffith and Buchanan, 2010). Sex biased environmental sensitivity was described in

Fig. 4. Association between the age at onset of body mass decline and the median lifespan per sex-experimental group combination. The onset of body mass aging (second threshold age) was earlier in females than in males, but did not differ significantly between environmental manipulations. Consistent with the expectation, females have a lower median lifespan than males and their body mass decline starts earlier. In contrast, experimental groups with longer lifespans have an earlier onset of body mass aging, creating a negative association between the lifespan and the onset of body mass aging. Groups are from left to right HH, BB, and BH in females, and HB, HH, BB and BH in males. There are only three groups for females as the HB group showed an increase in body mass till death and hence no decline. Error bars for median lifespan show 95% CI and, for age at onset model fits within 4 Δ AICc of the best fitting model (Fig. S4).

many species, but the direction and strength of the effect varies across taxa (Jones et al., 2009). In our study, females lived shorter than males, but we found no evidence for body mass or body mass aging to be more sensitive to environmental conditions in females than in males. Thus, we found no evidence for female biased environmental sensitivity.

4.3. Aging trajectories and environment-specific aging

We found that two-threshold models best fitted the body mass aging trajectory. Threshold shapes of body mass aging trajectories are not always tested. A quadratic shape, which is the most similar to the threshold shape observed here, is commonly observed in humans (reviewed in Kuk et al., 2009) and in laboratory rodents (Miller et al., 2002; Murtagh-Mark et al., 1995; Turturro et al., 1999; Yu et al., 1985). It was also observed in wild yellow-bellied marmots *Marmota flaviventris* (Kroeger et al., 2018). However, other aging shapes have also been reported: accelerating declines in Roe deer *Capreolus capreolus* (Nussey et al., 2011), terminal declines in Soay sheep *Ovis aries* (Hayward et al., 2015), accelerating and terminal declines in European badgers *Meles meles* (Beirne et al., 2015) and in male Alpine marmots *Marmota marmota* (Tafari et al., 2013). Note that most of these studies are in mammals. Previous data in captive zebra finches found that males gained weight with age, while females did not, but this was based on a small sample with an age range that did not include the age from which we observed body mass declines here (Moe et al., 2009). Hence body mass shows a variety of aging trajectories, and this variation is not yet understood.

Environmental quality can affect the onset and rate of aging of some

traits, most notably, reproduction (Bouwhuis et al., 2010; Lemaitre and Gaillard, 2017; Nussey et al., 2013, 2007), as suggested by population differences in the onset or rate of body mass aging (Douhard et al., 2017; Hämäläinen et al., 2014). While there were differences in the onset of body mass aging between groups, these were not statistically significant (Table 1), except that for females from the HB group which did not show body mass declines. This result expands our view on the flexibility of body mass aging by showing experimentally that the presence of aging can be environment-specific.

4.4. Body mass aging and its impact on health and fitness

A major theme is to what extent the observed aging is relevant in other environments and, more generally, for the evolutionary process (Briga and Verhulst, 2015b; Speakman et al., 2015). To this end, we first assess the impact of the observed body mass aging on health and survival in the study environment. In the declining phase, birds lose on average 0.30 g/year. Relative to the within-individual variation in body mass, this is an effect size of 0.37, which is at least average in evolutionary biology (Cohen, 1988; Møller and Jennions, 2002). The biological significance of this effect size can be inferred from the selective disappearance coefficient. This coefficient is 0.08 g/year (Tables S2 and S4A) and means that, on average, a mass loss of 0.08 g translates into one year shorter life. Furthermore, in our population body mass decline starts, on average, at the threshold age of 5 years. While this is after the median lifespan of 4 years, survival curves indicate that approximately 40% of the birds in our study system will experience body mass aging (Briga et al., 2017). However, this estimate ignores individual variation in threshold ages. Our results indicate that threshold ages can occur earlier in shorter-living birds (increasing the fraction of aged individuals in the population), although this should be investigated quantitatively. Taken together, these results indicate that the observed aging patterns are biologically meaningful in our study system.

To what extent the results in our system will occur in more natural environments is difficult to assess. The lifespan of wild zebra finches is poorly known, but will be shorter than in our population, e. g. due to predation. Whether aging occurs in wild zebra finches remains unknown. However, several studies have shown aging in wild small short-lived songbirds like zebra finches (reviewed in Nussey et al., 2013). For example, physiological traits such as metabolic rate, the immune system and resistance to oxidative stress decline with age within individuals in free-living great tits *Parus major* (e.g. Bouwhuis et al., 2011; Bize et al., 2014; Vermeulen et al., 2017). Great tits also show declines in residual reproductive value and hence body mass declines may have evolutionary potential (Bouwhuis et al., 2012). Thus we believe that body mass aging in wild small songbirds is likely, but its evolutionary potential needs to be quantified.

4.5. Manipulation effects on mass

Birds reared in large broods had lower mass in adulthood, in agreement with earlier studies (reviewed in Griffith and Buchanan, 2010), and 30% of this effect was due to their smaller structural size. Increased foraging costs during adulthood also resulted in lower mass, additively to the effect of rearing brood size. The effect of both manipulations was 0.60 and 0.65 g respectively. Relative to the mean mass of 15.6 g (sd: 1.57 g), these manipulations had an effect size of 0.40 (Cohen's d). The average body mass of (human) adults in the US and Europe is 78 kg ($N = 114,751$ individuals; sd: 15 kg; Locke et al., 2015). An effect size of 0.40 translates to 6.6 kg in human adults. Hence, the effect sizes of the manipulations on mass are considerable.

Size independent mass variation typically reflects variation in energy reserves, and theory predicts that energy reserves increase with increasing starvation risk (reviewed in Brodin, 2007). Starvation risk is higher in the high foraging cost treatment because it increases vulnerability to factors that increase energy needs (e.g. temperature) or

impair foraging (e.g. illness). However, increased energy reserves also incur energetic costs (Hambly et al., 2004; Kvist et al., 2001; Schmidt-Wellenburg et al., 2008). This reduces optimal energy reserves, an effect which will also be stronger in the high foraging costs treatment because birds spend more time flying (Koetsier and Verhulst, 2011). The lower mass of birds experiencing higher foraging costs suggests that the birds weighed the energetic costs of carrying extra mass more than the decrease in starvation risk (i.e. starvation being the result of effort per food reward; e.g. Brodin, 2007). This result is consistent with the findings in experiments with captive birds and mammals in which foraging costs were increased which consistently resulted in lower mass (reviewed in Wiersma and Verhulst, 2005).

The functional significance of body mass aging trajectories remains poorly understood, i.e. we know little of how costs and benefits of carrying extra mass change with age and explain the observed aging trajectory. Related to this is the question whether body mass changes are due to changes in the mass of fat, skeletal muscle or other body components such as the mass of organs (Ballak et al., 2014; Kuk et al., 2009). While age related changes in body composition in birds are poorly known, body mass changes within individuals are likely to largely reflect changes in energy reserves. We previously showed that mass-adjusted standard metabolic rate, i.e. the minimum energy expenditure of a post-absorptive adult animal measured during the rest phase at temperatures below thermoneutrality, increased with age (Briga, 2016). Because optimal energy reserves will be larger with increasing energy turnover (Gosler, 1996), this may explain why mass increased with age over the largest part of the age range.

With respect to the decline in mass in old finches we can only speculate as to the functional explanation. We are aware of one cross-sectional study indicating sarcopenia in Japanese quails *Coturnix japonica* (Siu et al., 2005), but, to best of our knowledge, whether sarcopenia occurs in birds that fly more abundantly remains unknown. Given the importance of flight muscles when hovering for food, we speculate that the observed body mass aging is more driven by age-associated changes in energy reserves. Hence the declining mass in older birds indicates that these birds gave the costs of carrying extra mass more weight at the cost of increased starvation risk. This may be due to the cost of carrying of extra mass increasing with age, but this remains to be investigated. Lastly, it is worth noting that the mass aging-trajectory is the net outcome of all these processes, and both the effects of increasing energy needs and increasing costs of carrying mass play a role throughout life. It is only the changing relative importance that causes the complex aging trajectory.

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Declarations of interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.exger.2019.01.030>.

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