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► **To cite this version:**

Pauline Vuarin, Loïc Lesobre, Gwènaëlle Levêque, Michel Saint Jalme, Frédéric Lacroix, et al.. Paternal age negatively affects sperm production of the progeny. *Ecology Letters*, 2021, 24 (4), pp.719-727. 10.1111/ELE.13696 . hal-03257302

**HAL Id: hal-03257302**

**<https://hal.science/hal-03257302>**

Submitted on 10 Jun 2021

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1 **Paternal age negatively affects sperm production of the progeny**

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14 *Running title* : Paternal age and offspring sperm production

15 *Article type* : Letters

16 *Key words*: Aging, ejaculate quality, male gametes, offspring phenotype, paternal age, post-  
17 copulatory sexual selection, reproductive senescence

18 *Word count*: abstract (125), main text (4209).

19 *References*: 60

20 *Tables*: 2

21 *Figures*: 2

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25 *Author contribution* : PV, MSJ, LL, YH and GS conceived the study; LL, GL, FL, and YH supervised the  
26 long-term data collection; PV and GS analysed the data and wrote the first draft of the manuscript;  
27 PV, LL, GL, MSJ, FL, YH and GS revised the manuscript and approved its final version.

28 *Data availability statement*: Data will be deposited in DRYAD upon acceptance of the manuscript.

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30

31 **Abstract**

32 Parental age has profound consequences for offspring's phenotype. However, whether patrilineal  
33 age affects offspring sperm production is unknown, despite the importance of sperm production for  
34 male reproductive success in species facing post-copulatory sexual selection. Using a longitudinal  
35 dataset on ejaculate attributes of the houbara bustard, we showed that offspring sired by old fathers  
36 had different age-dependent trajectories of sperm production compared to offspring sired by young  
37 fathers. Specifically, they produced less sperm (-48%) in their first year of life, and 14% less during  
38 their lifetime. Paternal age had the strongest effect, with weak evidence for grandpaternal or great  
39 grandpaternal age effects. These results show that paternal age can affect offspring reproductive  
40 success by reducing sperm production, establishing an intergenerational link between aging and  
41 sexual selection.

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53 **Introduction**

54 The idea that the parental phenotype can affect offspring's phenotype has been investigated in many  
55 species, and there is ample evidence showing that these "parental effects" have important  
56 consequences for offspring fitness and for the evolutionary dynamics of phenotypic traits (Mousseau  
57 and Fox 1998; Badyaev and Uller 2009; Crean and Bonduriansky 2014).

58 Age is among the parental traits that can affect offspring phenotype (Hercus and Hoffmann  
59 2000; Kern et al. 2001; Priest et al. 2002; Carnes et al. 2012; Qazi et al. 2017; Gillespie et al. 2013;  
60 Lippens et al. 2017; Arslan et al. 2017). Reproductive senescence is a widespread phenomenon in  
61 nature (Nussey et al. 2013; Jones et al. 2014), and involves the sequential alteration of several  
62 functions from gamete production to parental care, ultimately resulting in an age-associated  
63 reduction in the number of offspring produced (Lemaître and Gaillard 2017). Furthermore, negative  
64 effects of aging can extend well beyond the number of offspring produced, since parental age can  
65 also impinge on the performance of the progeny, including traits that are expressed at early (e.g.,  
66 embryo or juvenile survival, offspring development) and late life (e.g., lifetime reproductive success  
67 or longevity, the so-called Lansing effect) (Tarin et al. 2005; Garcia-Palomares et al. 2009; Lind et al.  
68 2015; Bouwhuis et al. 2015; Schroeder et al. 2015; Fay et al. 2016).

69 Deleterious effects of parental age on offspring traits can be mediated by different  
70 mechanisms, involving environmental, epigenetic and genetic effects (Beamonte et al. 2010; Kong et  
71 al. 2012; Jenkins et al. 2014; Chen et al. 2016; Herati et al. 2017; Jónsson et al. 2017; Noguera et al.  
72 2018; Bauch et al. 2019).

73 While few studies have investigated the effect of parental age on offspring lifespan and  
74 lifetime reproductive success (e.g., Bouwhuis et al. 2015; Schroeder et al. 2015), even less have  
75 focused on how parental age shapes the production of male gametes. In species where females mate  
76 with several males during the same reproductive bout, investment into sperm production is a key  
77 trait affecting male fitness (Parker and Pizzari 2010). Sperm competition and female cryptic choice  
78 have been shown to be strong selective forces shaping investment into ejaculate traits and sperm

79 phenotype (Firman and Simmons 2009; Fitzpatrick and Lüpold 2014; Vuarin et al. 2019b). Therefore,  
80 if parental age impinges on traits involved in post-copulatory sexual selection, this is likely to have  
81 consequences for offspring reproductive success, establishing a link between aging and sexual  
82 selection (Bonduriansky et al. 2008). Despite its potential ecological and evolutionary relevance, to  
83 the best of our knowledge, the effect of parental age on male offspring reproductive function has  
84 only been investigated in humans (Sharma et al. 2015) and inbred strains of mice (Caballero-Campo  
85 et al. 2018; Xie et al. 2018). While findings generally point towards a negative effect of advanced  
86 parental age on male reproductive function, no study has investigated the persistence of these  
87 effects over more than two generations. However, such data might prove very valuable to indirectly  
88 infer the underlying mechanisms and the possible ecological and evolutionary consequences of such  
89 intergenerational effects. For instance, if parents reproducing at old age are more likely to transmit  
90 *de novo* mutations to their offspring, we might expect that deleterious effects of parental age persist  
91 across generations. Conversely, if parental effects arise because old parents provide different  
92 environmental conditions to their offspring, or due to epigenetic changes transmitted with gametes,  
93 we might expect strongest effects between parents and offspring (compared to  
94 grandparents/grandoffspring or great grandparents/great grandoffspring). However, exceptions to  
95 this expected pattern do exist, since epigenetic effects have been shown to persist across two  
96 generations (see for instance, Eisenberg et al. 2012), and deleterious age-associated mutations of the  
97 germline can be purged by negative selection.

98         Here, we took advantage of a longitudinal dataset that has been collected in a long-lived bird  
99 species, the North African houbara bustard (*Chlamydotis undulata undulata*), maintained in a  
100 conservation breeding program, to explore the effect of parental age on age-specific ejaculate traits  
101 of the progeny. Previous work conducted on this species has shown that number of sperm and an  
102 index of sperm motility improve with age and then decline as birds become older (Preston et al.  
103 2011). Reproductive success of old males is also impaired, since eggs fertilized by senescing males  
104 have lower hatching success, hatchlings have reduced growth, and suffer higher post-release

105 mortality (for female offspring) (Preston et al. 2015; Vuarin et al. 2019a). Moreover, post-copulatory  
106 sexual selection has been shown to operate on ejaculate traits in this species (Vuarin et al. 2019a,b).

107 We first explored the effect of maternal and paternal age on offspring ejaculate traits. Since  
108 we found evidence for paternal age effects on sperm production, we subsequently extended the  
109 analysis including grandpaternal and great grandpaternal age, to investigate whether the effects  
110 persisted through patriline.

111

## 112 **Materials and methods**

113 All birds used in this study are part of the Emirates Center for Wildlife Propagation (ECWP), a  
114 conservation breeding program located in eastern Morocco, aiming at reinforcing natural  
115 populations of the North African houbara bustard. This program relies entirely on artificial  
116 inseminations (Lesobre et al. 2010).

117 Ejaculates are routinely collected using a dummy female and immediately brought into an  
118 adjacent laboratory where the proportion of motile sperm, the number of sperm, the volume and  
119 the proportion of morphologically normal sperm in the ejaculate are assessed (see online material  
120 for details). Females are regularly checked for reproductive status and inseminated with freshly  
121 collected semen when ready to lay. Laid eggs are collected every morning and incubated following a  
122 standard protocol.

123 We investigated the potential effect of parental age on the following ejaculate traits: i) the  
124 mean number of sperm in the ejaculate per breeding season, ii) the mean mass motility index per  
125 breeding season, iii) the mean proportion of sperm with normal morphology in the ejaculate per  
126 breeding season. Data on age-specific sperm quantity and mass motility index were available for  
127 1,708 individuals, from 1 to 17 years old, born from 2002 to 2018 and collected between 2003 and  
128 2019. These 1,708 individuals were produced by 989 dams and 682 sires. The overall data set  
129 included 11,107 observations. Dam age ranged from 1 to 13 years (mean  $\pm$  sd = 3.78  $\pm$  1.85), and sire  
130 age from 1 to 14 years (mean  $\pm$  sd = 3.88  $\pm$  1.90). Owing to small sample size, individuals older than

131 15 years were grouped in the same age class; similarly, dams and sires aged from 10 to 14 years were  
132 grouped in the same age class. The correlation coefficient between maternal and paternal age was  
133 low ( $r = 0.095$ ,  $n = 1,708$ ), showing that the two variables convey independent information on  
134 parental age. Data on the proportion of normal sperm were available for a smaller number of  
135 individuals (1,270 individuals produced by 758 dams and 543 sires, for a total of 2,273 observations).

136 The overall data set only included birds for which paternal identity (and therefore paternal  
137 age at fertilization) was certain. This was ensured because females were either inseminated with the  
138 semen of a single male, or in case of multiple inseminations with different males, microsatellite  
139 markers were used to perform parentage analyses and identify the sire (Lesobre et al. 2010).

140

#### 141 *Statistical analyses*

142 We used general additive models (GAM) to infer the shape of age-dependent variation of  
143 each of the three ejaculate attributes considered here. GAM is a nonparametric regression that  
144 relaxes the assumption of linearity and allows to explore traits that vary non-linearly without the  
145 constraints that are usually associated with polynomial models.

146 We used linear mixed models (LMM) to explore the effect of maternal and paternal age on  
147 age-dependent variation of ejaculate traits of the offspring. We fitted separate models for each  
148 response variable [i.e., number of sperm in the ejaculate (log-transformed), mass motility index, and  
149 the proportion of sperm with normal morphology]. All models had the same structure (normal  
150 distribution of errors), with the following terms fitted as fixed effects: offspring age (log-  
151 transformed), squared offspring age, maternal age, and paternal age. We also fitted the two-way  
152 interactions of parental age with offspring age and squared offspring age to test whether age-  
153 dependent trajectories were affected by parental age. The random effects included offspring,  
154 maternal and paternal identities, year of birth and year of data collection. If individuals with  
155 particular phenotypic traits enter or exit from the sampled population at different ages (selective  
156 appearance and disappearance), this might generate a pattern of age-dependent variation at the



157 population level, potentially leading to erroneous conclusions about the age-dependent trajectories  
158 at the individual level. To infer the within-individual variation with age, independently from the  
159 population-level (between-individual) variation caused by selective appearance and/or  
160 disappearance, we followed the methods advocated by van de Pol and Verhulst (2006), and included  
161 age at first insemination (that determines at which age a given individual enters the breeding  
162 population), and age at last insemination (that determines at which age a given individual exits the  
163 breeding population) as fixed effects. We started with the model that included all single effects and  
164 interactions and we sequentially dropped those that were not statistically significant, starting first  
165 with interactions and then with single effects, until obtaining a minimal adequate model. Note that  
166 age at first and last insemination were always kept in the models.

167         To investigate the effect of patrilineal age (over three generations) on sperm production, we  
168 used two approaches. First, we grouped birds according to the age of their fathers, grandfathers and  
169 great grandfathers. Ascendants that bred between 1 and 5 years were considered young, ascendants  
170 that bred when older than 5 years were considered old. Therefore, birds that consistently had young  
171 (y) ascendants were considered to have a “yyy” patrilineal age (the first letter referring to paternal  
172 age, the last letter to great grandpaternal age); birds that consistently had old (o) ascendants were  
173 considered to have a “ooo” patrilineal age. Two age classes and three generations give 8 possible  
174 patrilineal age groups (yyy, yyo, yoo, ooo, oyy, ooy, yoy, oyo). The effect of patrilineal age on sperm  
175 production was assessed running 6 LMMs where different patrilineal age groups were contrasted.  
176 Due to small sample size, we could not include ooy, oyo, ooy, ooo groups in the models. Each model  
177 had the same structure, with offspring age and squared age, patrilineal age (plus interactions), age at  
178 first and age at last insemination included as fixed effects. The random effects included offspring  
179 identity, maternal and paternal identity, year of birth and year of data collection. Restricting the  
180 sample size to individuals with known father, grandfather and great grandfather reduced the number  
181 of individuals included in the model to 888, for a total of 5,504 observations. Second, we ran a LMM  
182 where the three ascendant ages were included in the same model, as continuous variables. This

183 model therefore relaxed the constraint associated with the cutoff used to categorize birds as young  
184 or old. The model included offspring identity, maternal and paternal identity, year of birth and year  
185 of data collection as random effects.

186 GAMs and LMMs were performed using PROC GAM and PROC MIXED (SAS, 14.3),  
187 respectively.

188

## 189 **Results**

190 The GAMs showed that both the number of sperm in the ejaculate (i.e., sperm production),  
191 and the mass motility index increased up to the age of 5 years and then gradually declined as  
192 individuals became older, with a strong quadratic pattern (number of sperm in the ejaculate:  $\chi^2 =$   
193 582.04, df = 3, n = 11,107; p < 0.0001; mass motility index:  $\chi^2 = 413.47$ , df = 3, n = 11,107, p < 0.0001;  
194 fig. S1A,B). The proportion of morphologically normal sperm showed a more complex pattern of  
195 variation with age, suggesting a higher-order behavior and a later peak value (7 years,  $\chi^2 = 22.87$ , df =  
196 3, n = 2,273, p < 0.0001; fig. S1C).

197 The LMM performed on the number of sperm in the ejaculate showed that offspring age-  
198 dependent trajectory was modulated by paternal age, as indicated by the highly significant  
199 interactions between paternal and offspring age (both linear and quadratic components, table 1).  
200 Maternal age was not a significant predictor of sperm production, nor of its age-dependent variation  
201 (table 1).

202 Grouping paternal age into two age classes [up to the peak age (i.e., from 1 to 5 years) and  
203 post-peak age (i.e., older than 5 years)], allowed to visualize the effect of sire age on the trajectories  
204 of age-dependent offspring sperm production (fig. 1; table S1). Offspring sired by old fathers had a  
205 lower sperm production (-16.9% difference in LS-MEANS on back-transformed values) during their  
206 early life (1-5 years) compared to offspring sired by young fathers (LMM, paternal age: t = -2.78, p =  
207 0.0055, age at first insemination: t = 0.97, p = 0.3299; age at last insemination: t = 19.44, p < 0.0001;  
208 number of observations = 5,640). The difference was very strong at the age of 1, with offspring sired

209 by old fathers showing a 47.9% reduction in their sperm production (LMM, paternal age:  $t = -2.52$ ,  $p = 0.0122$ , age at last insemination:  $t = 1.48$ ,  $p = 0.1388$ ; number of observations = 401; fig. 2A). During  
210 = 0.0122, age at last insemination:  $t = 1.48$ ,  $p = 0.1388$ ; number of observations = 401; fig. 2A). During  
211 the post-peak age (over 5 years), offspring sired by old fathers still had a lower sperm production (-  
212 7.6%) compared to offspring sired by young fathers, but this difference was not statistically  
213 significant (LMM, paternal age:  $t = -1.11$ ,  $p = 0.2651$ , age at first insemination:  $t = 0.54$ ,  $p = 0.5907$ ;  
214 age at last insemination:  $t = 8.41$ ,  $p < 0.0001$ ; number of observations = 5,467). Nevertheless, over  
215 the entire lifespan, offspring sired by old fathers produced 14% less sperm per ejaculate than  
216 offspring sired by young fathers (LMM, paternal age:  $t = -2.19$ ,  $p = 0.0283$ , age at first insemination:  $t$   
217 = 2.64,  $p = 0.0083$ ; age at last insemination:  $t = 16.55$ ,  $p < 0.0001$ ; number of observations = 11,107;  
218 fig. 2B).

219         Given that sperm number and mass motility index positively covaried ( $r = 0.736$ ,  $n = 11,107$ ),  
220 we ran an additional LMM where the latter variable was included as a covariate. This model  
221 therefore aimed to investigate whether the effect of paternal age on sperm number still holds when  
222 keeping mass motility index constant. The model provided similar results than the previous one  
223 (table S2), suggesting that the effect of parental age on sperm number did not arise because of the  
224 covariation between sperm number and motility.

225         We also found that paternal age affected the age-dependent variation in offspring mass  
226 motility index [significant paternal age x offspring age (and squared age); table S3]. However, this  
227 pattern was entirely driven by the covariation with the number of sperm in the ejaculate (table S4).  
228 As for number of sperm in the ejaculate, maternal age had no effect on mass motility index, nor on  
229 its age-dependent variation (table S3).

230         Neither paternal nor maternal age modulated the proportion of morphologically normal  
231 sperm in the ejaculate or its age-dependent trajectory (table S5).

232         To go further, we investigated if the paternal age effect on sperm production persisted over  
233 generations. We grouped birds according to the age of their father, grandfather and great  
234 grandfather and ran separate models contrasting different patrilineal ages (table 2). Overall, we

235 found that paternal age had the strongest effect on sperm production. For instance, comparing  
236 sperm production of birds with young or old fathers, but young grandfathers and great grandfathers,  
237 showed a marked reduction in early production of sperm in birds sired by old fathers (table 2, fig. S2).  
238 Unfortunately, some of the patrilineal age groups had very few birds making impossible to run all  
239 possible comparisons. Nevertheless, comparing birds that only differed in the great grandpaternal  
240 age class (yyy vs. yyo), also showed a negative effect of great grandpaternal age on sperm production  
241 (table 2, fig. S3), suggesting a persisting effect of paternal age over generations. A seemingly  
242 contradictory result came from the comparison between birds with young ascendants over the three  
243 generations (yyy) and birds with old grandfathers and great grandfathers (yoo). Indeed, in this  
244 comparison, yoo birds had the highest sperm production (table 2). It should be noted however, that  
245 the number of birds in this patrilineal age group was particularly small, compared to the yyy group  
246 (34 vs. 519), and as such the result of this model should be taken with caution.

247         Running a LMM where paternal, grandpaternal and great grandpaternal age were included in  
248 the same model as continuous variables provided similar results to those reported above, with  
249 paternal age having the strongest effect on offspring sperm production (table S6).

250

## 251 **Discussion**

252         We found that paternal but not maternal age affected sperm production of the progeny, and  
253 that this effect was the strongest over the one-generation transmission. Other ejaculate traits (mass  
254 motility index and the proportion of sperm with a normal morphology) were not affected by parental  
255 age.

256         Although the effect of parental age on offspring phenotype has been studied in several  
257 systems, most of this previous work has focused on maternal age, because it was believed that  
258 mothers had higher control over offspring phenotype. This view is, however, rapidly changing, and  
259 evidence is accumulating i) showing that paternal age is associated with several offspring phenotypic  
260 traits (Garcia-Palomares et al. 2009; Fay et al. 2016; Arslan et al. 2017; Caballero-Campo et al. 2018;

261 Wylde et al. 2019); ii) identifying the possible underlying mechanisms (Curley et al. 2011; Kong et al.  
262 2012; Soubry et al. 2014; Xie et al. 2018).

263         Assessing male reproductive function is a hard task in free-ranging animals because this  
264 requires repeated samples of ejaculates. Recent work has shown that paternal age negatively  
265 impinges on lifetime reproductive success of male house sparrows (*Passer domesticus*) (Schroeder et  
266 al. 2015), suggesting that one or several components of the male reproductive function are impaired  
267 when individuals are sired by an old father. Our results suggest that reduced gamete production  
268 might be one of the physiological mechanisms underlying the negative effect of paternal age on male  
269 offspring lifetime reproductive success, and especially so in species where males face post-  
270 copulatory sexual selection through sperm competition. This might be particularly relevant when  
271 paternal age affects the production of gametes during the early life of the descendants, when the  
272 force of selection is at its highest value. Number of gametes transferred during the mating is an  
273 important driver of siring success and especially so in species where females mate with several males  
274 and ejaculates compete for egg fertilization (Parker and Pizzari 2010). In the houbara bustard, we  
275 have previously shown that ejaculate attributes, such as motility, improve male siring success during  
276 competitive fertilizations (when sperm from different males compete within the female reproductive  
277 tract) (Vuarin et al. 2019b). Similarly, when females are inseminated with ejaculates of two males,  
278 the probability of siring success of the last male (last male precedence) decreases as the number of  
279 sperm of the first male used to inseminate the female increases (L. Lesobre, unpublished results).  
280 Therefore, the finding that paternal age impinges on sperm production has potentially far reaching  
281 ecological and evolutionary consequences. At the ecological level, parental age effects can be a  
282 phenotypic source of variation contributing to shape offspring quality and life history traits, with  
283 possible consequences in terms of population dynamics. In agreement with this hypothesis,  
284 experimental work conducted on soil mites (*Sancassania berlesei*) has shown that changes in life  
285 history traits (longer developmental time and larger size at maturity) due to maternal age lead to  
286 different population dynamics that persist over generations (Benton et al. 2008). At the evolutionary

287 level, negative parental age effects on the progeny contribute to the age-associated decline of fitness  
288 and increase the strength of selection for earlier reproduction (Priest et al. 2002). Paternal age  
289 effects on the progeny might also alter the shape of the trade-off between early and late trait  
290 expression. One of the best supported predictions of the theory on the evolution of senescence is  
291 that high investment into early expressed traits comes at the price of reduced investment in late life,  
292 resulting in a negative correlation between early and late traits (Lemaître et al. 2015). However,  
293 offspring produced by old parents might have compromised quality and have impaired expression of  
294 fitness related traits over their entire reproductive life, flattening the relationship between early and  
295 late life traits. Finally, the extent of the costs associated with mating with an old partner also  
296 suggests that selection might have promoted mechanisms of avoidance of senescing males. In  
297 agreement with this hypothesis, we recently showed that female houbara bustards concomitantly  
298 inseminated with sperm from males at prime and post-prime age had a higher proportion of their  
299 eggs fertilized by prime age males (Vuarin et al., 2019a). This finding, therefore, suggests that post-  
300 copulatory selection might allow them to avoid the cost of being fertilized by senescing males.

301           Whether such paternal age effects persist over generations remains an open question. We  
302 only found a moderate evidence for a negative effect of great grandparental age on sperm  
303 production, and the comparison between birds produced by consistently young ascendants and birds  
304 produced by young fathers and old grandfathers and great grandfathers, showed the opposite  
305 pattern (higher sperm production for the latter group). These results should be interpreted with  
306 caution, due to the heterogeneity in sample size (number of birds) in each patrilineal age group.

307           In species where males only contribute to the reproduction through their ejaculate, paternal  
308 age effects might arise because of age-associated changes in ejaculate attributes (Sharma et al.  
309 2015). These effects have been named ejaculate-mediated paternal effects and can involve purely  
310 environmental, epigenetic or genetic mechanisms (see Immler 2018 and Evans et al. 2019 for recent  
311 reviews). During aging, both the cellular and non-cellular fraction of the ejaculate undergo profound  
312 changes that have the potential to further affect offspring phenotype. Sperm are particularly

313 sensitive to oxidant attack which might compromise DNA integrity (Aitken 2020). Antioxidants  
314 contained in seminal plasma play a crucial role for the preservation of sperm DNA integrity (Wai-sum  
315 et al. 2006) and during aging some of this protective function might be lost. Epigenetic changes can  
316 also occur in male germline cells (Xavier et al. 2019). DNA methylation in sperm is associated with  
317 advanced male age (Jenkins et al. 2014), can be transmitted to the progeny and affect offspring  
318 phenotype (Xie et al. 2018). However, epigenetic reprogramming can reverse methylation patterns  
319 (Law and Jacobsen 2010; Rando and Chang 2012; Zhang et al. 2020), resetting the system and  
320 explaining why epigenetic effects can be lost across generations. Other epigenetic factors such as  
321 histone modification, noncoding RNAs contained in the seminal plasma, or inheritance of shortened  
322 telomeres can also be at play (Chen et al. 2016; Immler 2018; Bauch et al. 2019). Finally, male  
323 germline is particularly prone to accumulate *de novo* mutations due to the process of cell division  
324 that occurs throughout the entire reproductive life of males. In agreement with this hypothesis,  
325 paternal age and the length of male reproductive life are good predictors of the number of *de novo*  
326 mutations passed on to the progeny in primates (Thomas et al. 2018); and inheritance of age-  
327 associated *de novo* mutations has been identified as a possible risk factor for several offspring  
328 pathologies (e.g., Kong et al. 2012). In addition to the sperm nuclear contribution to the offspring,  
329 abnormalities in sperm centrioles can also affect offspring phenotype, although evidence has mostly  
330 been reported in humans (Avidor-Reiss et al. 2019).

331 Our experimental design allows us to discard several other possible causes of the negative  
332 parental age effects on sperm production. A common confounding factor in studies of parental age  
333 effects derives from the possible differential investment of females according to the perceived  
334 phenotypic quality of mates (Sheldon 2000). If old partners are perceived as poor mates, females  
335 might adaptively adjust their investment into eggs or offspring care, producing an apparent  
336 association between father age and offspring phenotype. However, reproduction of houbara  
337 bustards kept in the captive breeding program is entirely based on artificial inseminations which  
338 implies that i) the paternal contribution is restricted to the ejaculate; ii) females are never in contact

339 with males and therefore cannot adjust their investment into eggs according to male phenotype; iii)  
340 eggs are collected as soon as they are laid and thus there is no maternal care that might  
341 subsequently affect offspring quality. This last point might explain why we did not find any evidence  
342 for maternal age effects, if such effects occur through differential environmental conditions  
343 experienced by offspring of old vs. young mothers (Beamonte-Barrientos et al. 2010; Plaistow et al.  
344 2015).

345 To conclude, we showed that paternal but not maternal age reduced sperm production in  
346 offspring. These delayed paternal effects have the potential to affect the strength of selection  
347 operating on post-copulatory traits and male reproductive fitness in the wild, establishing a link  
348 between ageing and sexual selection.

349

### 350 **Acknowledgments**

351 This study was funded by the Emirates Center for Wildlife Propagation (ECWP), a project of the  
352 International Fund for Houbara Conservation (IFHC). We are grateful to H.H. Sheikh Mohammed bin  
353 Zayed Al Nahyan, Crown Prince of Abu Dhabi and Chairman of the International Fund for Houbara  
354 Conservation (IFHC) and H.E. Mohammed Al Bowardi, Deputy Chairman of IFHC, for their support.

355 This study was conducted under the guidance of Reneco International Wildlife Consultants LLC., a  
356 consulting company managing ECWP. We are thankful to all Reneco staff who helped collecting the  
357 data.

358

### 359 **Competing interest statement**

360 The authors declare no competing interest.

361

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495 Zhang, W., Qu, J., Liu, G.-H. & Belmonte, J.C.I. (2020). The ageing epigenome and its rejuvenation.  
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497 Table 1. Linear mixed effects model exploring the effect of parental age on the number of sperm in  
 498 the ejaculate (log-transformed). The model included offspring age (log-transformed), squared  
 499 offspring age, maternal age, paternal age, the interactions between offspring age and parental age,  
 500 and age at first and last insemination as fixed effects. Offspring, maternal and paternal identities,  
 501 year of birth and year of data collection were included as random effects. The analysis was based on  
 502 11,107 observations collected over 17 years on 1,708 individuals (produced by 989 dams and 682  
 503 sires over 17 cohorts). We report parameter estimates (with SE and 95% CI), t and p values for the  
 504 initial model and the minimal adequate model.  
 505

<b>Initial model</b>					
<i>Fixed effects</i>	<i>Parameter estimate</i>	<i>SE</i>	<i>t</i>	<i>p</i>	<i>95% CI</i>
Intercept	0.491	0.306			
Age at first insemination	-0.009	0.025	-0.37	0.7109	-0.057/0.039
Age at last insemination	0.180	0.010	17.95	<0.0001	0.161/0.200
Offspring age	1.538	0.146	10.52	<0.0001	1.251/1.824
Offspring age <sup>2</sup>	-0.774	0.056	-13.85	<0.0001	-0.883/-0.664
Dam age	-0.001	0.022	-0.03	0.9739	-0.044/0.043
Sire age	-0.107	0.022	-4.84	<0.0001	-0.150/-0.064
Offspring age x Dam age	-0.010	0.027	-0.36	0.7209	-0.063/0.043
Offspring age x Sire age	0.130	0.028	4.73	<0.0001	0.076/0.184
Offspring age <sup>2</sup> x Dam age	0.005	0.009	0.48	0.6306	-0.014/0.023
Offspring age <sup>2</sup> x Sire age	-0.038	0.010	-3.97	<0.0001	-0.057/-0.019
<i>Random effects</i>	<i>Variance</i>	<i>SE</i>	<i>z</i>	<i>p</i>	
Individual ID	0.574	0.038	14.91	<0.0001	
Dam ID	0.107	0.031	3.41	0.0003	
Sire ID	0.030	0.020	1.47	0.0713	
Year of birth	0.014	0.010	1.42	0.0778	
Year of data collection	1.177	0.444	2.65	0.0040	
Residual	0.521	0.008	67.76	<0.0001	

506

<b>Minimal adequate model</b>					
<i>Fixed effects</i>	<i>Parameter estimate</i>	<i>SE</i>	<i>t</i>	<i>p</i>	<i>95% CI</i>

Intercept	0.489	0.295			
Age at first insemination	-0.009	0.025	-0.38	0.7006	-0.058/0.039
Age at last insemination	0.180	0.010	17.95	<0.0001	0.160/0.200
Offspring age	1.509	0.113	13.36	<0.0001	1.287/1.730
Offspring age <sup>2</sup>	-0.758	0.046	-16.54	<0.0001	-0.848/-0.669
Sire age	-0.106	0.022	-4.83	<0.0001	-0.150/-0.063
Offspring age x Sire age	0.129	0.027	4.70	<0.0001	0.075/0.183
Offspring age <sup>2</sup> x Sire age	-0.038	0.010	-3.93	<0.0001	-0.057/-0.019
<i>Random effects</i>	<i>Variance</i>	<i>SE</i>	<i>z</i>	<i>p</i>	
Individual ID	0.573	0.038	14.93	<0.0001	
Dam ID	0.107	0.031	3.42	0.0003	
Sire ID	0.030	0.020	1.46	0.0721	
Year of birth	0.014	0.010	1.42	0.0775	
Year of data collection	1.165	0.439	2.66	0.0039	
Residual	0.521	0.008	67.77	<0.0001	

507

508 Table 2. Linear mixed effects models exploring the effect of patrilineal age (paternal, grandpaternal  
509 and great grandpaternal ages) on the number of sperm in the ejaculate (log-transformed). We ran 6  
510 models contrasting patrilineal ages (yyy vs. oyy; yyy vs. yyo; yyy vs. yoo; yoo vs. oyy; yyo vs. yoo; yoo;  
511 oyy; the first letter referring to the paternal age, the second letter to the grandpaternal age, the third  
512 letter to great grandpaternal age). Offspring age (log-transformed), squared offspring age, patrilineal  
513 age, the interactions between offspring age and patrilineal age, age at first and last insemination  
514 were included as fixed effects. Offspring, maternal and paternal identities, year of birth and year of  
515 data collection were included as random effects. The analysis was based on 5,504 observations  
516 collected over 15 years on 888 males (produced by 624 dams and 394 sires over 16 cohorts). We  
517 report parameter estimates (with SE and 95% CI), t and p values. Only the results of the fixed effects  
518 are reported.

<i>Fixed effects</i>	<i>Parameter estimate</i>	<i>SE</i>	<i>t</i>	<i>p</i>	<i>95% CI</i>
<i>yyy vs. oyy</i>					
Intercept	0.161	0.328			
Age at first insemination	-0.010	0.046	-0.21	0.8324	-0.100/0.081
Age at last insemination	0.244	0.021	11.68	<0.0001	0.203/0.285
Offspring age	1.729	0.099	17.42	<0.0001	1.534/1.923
Offspring age <sup>2</sup>	-0.881	0.057	-15.36	<0.0001	-0.993/-0.768
Patrilineal age (oyy)	-0.949	0.210	-4.52	<0.0001	-1.360/-0.538
Offspring age x patrilineal age (oyy)	1.127	0.276	4.08	<0.0001	0.586/1.669
Offspring age <sup>2</sup> x patrilineal age (oyy)	-0.287	0.103	-2.79	0.0053	-0.489/-0.085
<i>yyy vs. yyo</i>					
Intercept	0.442	0.288			
Age at first insemination	-0.019	0.040	-0.48	0.6288	-0.097/0.058
Age at last insemination	0.205	0.018	11.28	<0.0001	0.169/0.241
Offspring age	1.679	0.095	17.75	<0.0001	1.494/1.865
Offspring age <sup>2</sup>	-0.817	0.050	-16.38	<0.0001	-0.915/-0.719
Patrilineal age (yyo)	-0.434	0.140	-3.11	0.0019	-0.708/-0.161
Offspring age x patrilineal age (yyo)	0.484	0.160	3.02	0.0025	0.170/0.798
Offspring age <sup>2</sup> x patrilineal age (yyo)	-0.120	0.055	-2.18	0.0292	-0.228/-0.012
<i>yyy vs. yoo</i>					
Intercept	0.305	0.311			
Age at first insemination	-0.01	0.047	-0.20	0.8390	-0.102/0.083
Age at last insemination	0.224	0.021	10.84	<0.0001	0.184/0.265
Offspring age	1.671	0.096	17.39	<0.0001	1.483/1.859
Offspring age <sup>2</sup>	-0.827	0.055	-15.00	<0.0001	-0.935/-0.719
Patrilineal age (yoo)	0.890	0.293	3.04	0.0024	0.315/1.465
Offspring age x patrilineal age (yoo)	-0.901	0.356	-2.53	0.0113	-1.599/-0.204
Offspring age <sup>2</sup> x patrilineal age (yoo)	0.278	0.132	2.10	0.0356	0.019/0.538



<i>yyo vs. oyy</i>					
Intercept	0.719	0.331			
Age at first insemination	-0.049	0.060	-0.82	0.4135	-0.166/0.068
Age at last insemination	0.119	0.030	3.93	<0.0001	0.059/0.178
Offspring age	2.214	0.158	14.03	<0.0001	1.904/2.523
Offspring age <sup>2</sup>	-0.667	0.063	-10.57	<0.0001	-0.791/-0.544
Patrilineal age (oyy)	-0.679	0.240	-2.83	0.0047	-1.150/-0.209
Offspring age x patrilineal age (oyy)	0.736	0.302	2.44	0.0147	0.145/1.328
Offspring age <sup>2</sup> x patrilineal age (oyy)	-0.211	0.110	-1.91	0.0566	-0.427/0.006
<i>yyo vs. yoo</i>					
Intercept	1.329	0.241			
Age at first insemination	-0.090	0.057	-1.59	0.1130	-0.201/0.021
Age at last insemination	0.028	0.022	1.29	0.1967	-0.015/0.071
Offspring age	2.139	0.148	14.43	<0.0001	1.848/2.430
Offspring age <sup>2</sup>	-0.640	0.059	-10.94	<0.0001	-0.755/-0.526
Patrilineal age (yoo)	1.317	0.298	4.42	<0.0001	0.732/1.902
Offspring age x patrilineal age (yoo)	-1.286	0.367	-3.51	0.0005	-2.006/-0.567
Offspring age <sup>2</sup> x patrilineal age (yoo)	0.337	0.135	2.49	0.0129	0.071/0.602
<i>yoo vs. oyy</i>					
Intercept	1.667	0.514			
Age at first insemination	0.005	0.104	0.05	0.9596	-0.200/0.210
Age at last insemination	0.134	0.051	2.63	0.0087	0.034/0.235
Offspring age	1.473	0.405	3.64	0.0003	0.678/2.269
Offspring age <sup>2</sup>	-0.581	0.165	-3.52	0.0005	-0.905/-0.257
Patrilineal age (oyy)	-1.859	0.361	-5.16	<0.0001	-2.567/-1.151
Offspring age x patrilineal age (oyy)	1.760	0.454	3.88	0.0001	0.868/2.652
Offspring age <sup>2</sup> x Patrilineal age (oyy)	-0.443	0.170	-2.61	0.0093	-0.776/-0.110

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527 **Figure legends**

528

529 Figure 1. Age-dependent trajectories of offspring sperm number in the ejaculate (log-transformed  
530  $\times 10^6$ ) as a function of paternal age. A) We report the raw data (blue boxes = 1-5 years old; red boxes  
531 = over 5 years old) and B) the LMM predictions. Data on the x-axis were slightly jittered to improve  
532 readability.

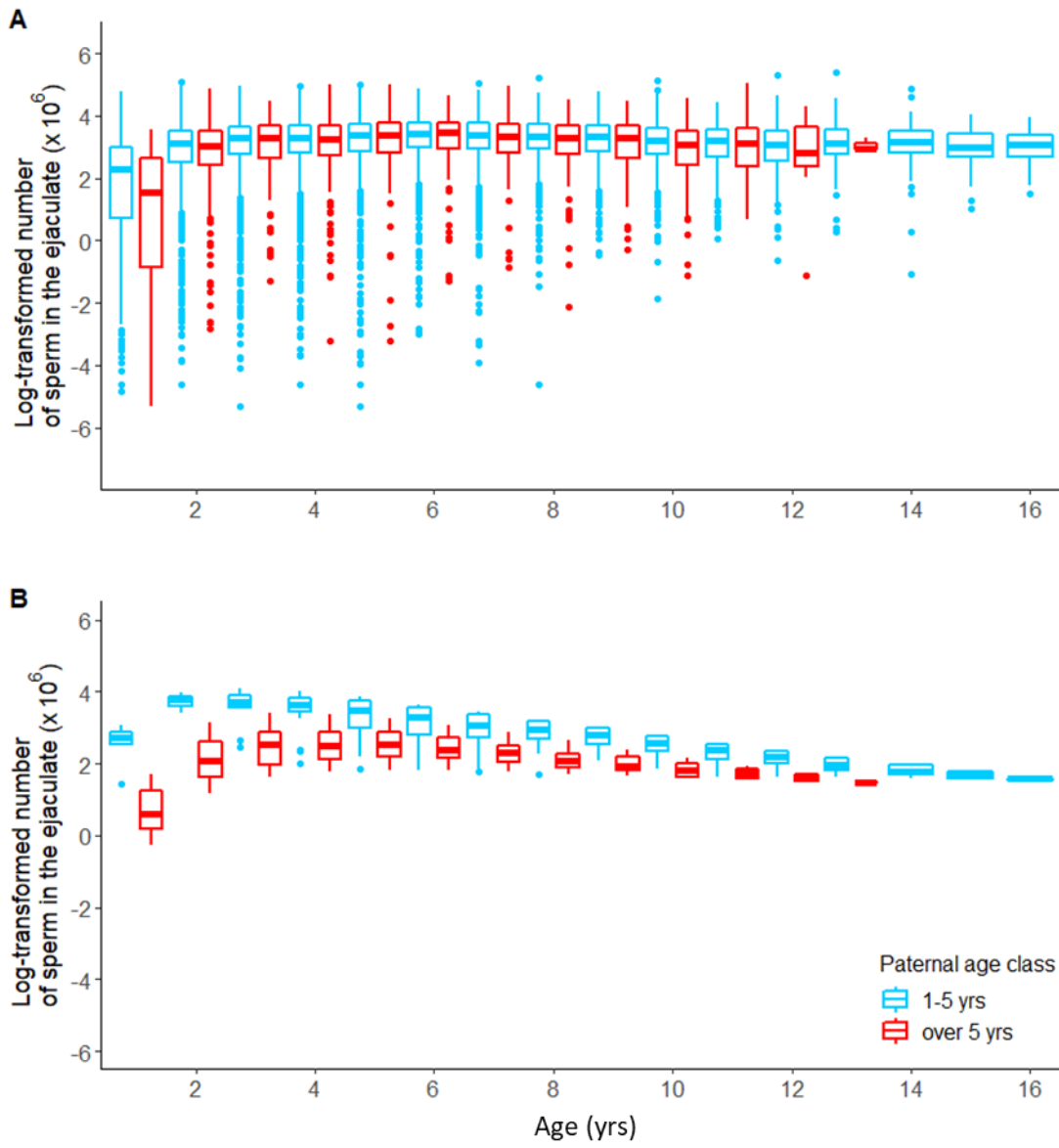
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534 Figure 2. A) Least-square means ( $\pm$  SE) of number of sperm in the ejaculate (log-transformed  $\times 10^6$ ) at  
535 the age of 1 year, for the two paternal age classes. B) Least-square means ( $\pm$  SE) of number of sperm  
536 in the ejaculate (log-transformed  $\times 10^6$ ) over the whole life, for the two paternal age classes.

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539 Figure 1.



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547 Figure 2.

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