Limits to fitness benefits of prolonged post-reproductive lifespan in women

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Summary

Recent advances in medicine and life expectancy gains have fuelled multidisciplinary research into the limits of human lifespan [1–3]. Ultimately, how long humans can live for may depend on selection favouring extended longevity in our evolutionary past [4]. Human females have an unusually extended post-reproductive lifespan, which has been explained by the fitness benefits provided from helping to raise grandchildren following menopause [5,6]. However, formal tests of whether such grandmothering benefits wane with grandmother age and explain the observed length of post-reproductive lifespan are missing. This is critical for understanding prevailing selection pressures on longevity, but to date has been overlooked as a possible mechanism driving the evolution of lifespan. Here, we use extensive data from pre-industrial humans to show that fitness gains from grandmothering are dependent on grandmother age, affecting selection on the length of post-reproductive lifespan. We find both opportunities and ability to help grandchildren declined with age, whilst the hazard of death of women increased greatly in their late 60s and 70s compared to menopausal ages, together implying waning selection on subsequent longevity. The presence of maternal grandmothers aged 50-75 increased grandchild survival after weaning, confirming the fitness advantage of post-reproductive lifespan. However, co-residence with paternal grandmothers aged 75+ was detrimental to grandchild survival, with those grandmothers close to death and presumably in poorer health particularly associated with lower grandchild survival. The age limitations of gaining inclusive fitness from grandmothering suggests that grandmothering can select for post-reproductive longevity only up to a certain point.

Keywords: altruism, competition, conflict, cooperation, grandmother hypothesis, inclusive fitness, intergenerational effects, kin selection, mortality

Results and Discussion

Extended post-reproductive lifespan is a rare trait, known to occur in only a limited number of wild mammals [7], and its evolution is still a major puzzle [8]. Post-reproductive individuals can no longer increase their direct fitness, but helping kin raise offspring offers another route to higher lifetime fitness, and is well-documented in humans [9]. The 'Grandmother Hypothesis' relies on such indirect fitness explanations, and predicts that post-reproductive life is the outcome of the adaptive benefits gained by investing in the reproductive efforts of offspring (i.e. caring for grandoffspring) [6]. Though such helping benefits are likely insufficient alone to explain the evolution of reproductive cessation in the first place [10,11], they may still have selected for the length of post-reproductive life [5,6]. Theory predicts that the opportunities to provision grandchildren should decline after certain age, when fewer close relatives continue to be born, thus leading to reduced selection for continued survival. Previous studies have found grandmother effects on grandchild survival to differ between maternal and paternal grandmothers [9,12] and by grandchild age [12,13], thus showing that help can vary contextually. However, grandmother age has not yet been explicitly investigated as a potential mediator of helping effects on grandchild survival, despite the importance of age-specific grandmother help to the evolution of longevity. Here, we use long-term life-history data from pre-industrial Finnish church registers to first quantify at which age the availability of grandchildren in need of grandmother care declines, and how this compares against acceleration in the mortality rate of grandmothers. We then explore whether grandchild survival is associated with a) the presence of grandmothers of different ages, and b) with differing remaining lifespan (proxy of health, implemented as time until grandmother death), and the possible consequences for selection on longevity and extended post-reproductive lifespan.

The pre-industrial Finnish population was subject to large fluctuations in rates of mortality and fertility, and sensitive to harsh climatic conditions [14], famines caused by poor crop yields [15] and basic farming techniques [16], and outbreaks of disease [17]. Child mortality was high [5,18], with nearly a third of the population dying before age of 5 and almost half by age 15, often from infectious diseases. During our study period (1731-1895), grandchildren mostly died from respiratory diseases (particularly tuberculosis), smallpox, measles, severe diarrhoea, accidents, or 'other diseases', a broad category of mostly unidentified infectious diseases. Life expectancy in adulthood was over 60 years [14], and for the women that did survive to adulthood and managed to reproduce at least once, more than half survived until the age of 50 to become 'post-reproductive', producing an average of 5.5 ± 3.1 children. Church records provide detail not only on survival and reproduction, but also socio-economic status, sex, and dispersal, allowing us to control for such factors in analyses, and to score the presence of grandmothers, making this population ideal for studying the age-specific effects of grandmothering. Throughout the study period, a grandmother and grandchild would live at the same time for an average of between 5-10 years [19]. The population was

predominantly patrilocal [20,21], with the eldest son typically inheriting the farm, and dispersal rates were generally low, such that most adult siblings lived nearby [22], and therefore both maternal and paternal grandmothers would often be close to their grandchildren but typically only paternal grandmothers were co-resident [23].

Age-specific availability of grandchildren in need of help, and acceleration in mortality

First, we show that the availability of grandchildren towards whom ageing women can direct their care starts to rise from a woman's 40s onwards, reaches its peak whilst they are in their early 60s, and then rapidly declines so that by age 75, the majority of grandchildren are already born (Figure 1). The contribution of each grandchild to fitness is half that of the birth of a child, and great-grandchildren contribute still half of that, indicating that the opportunities to improve fitness by extending longevity to help kin wane off from 70s onwards in this population, simply due to declines in the availability of grandchildren in need of help.

We therefore next investigated age-specific changes in the hazard of death of women, where an acceleration in mortality indicates when senescence rates are increasing across the population and the force of selection on lifespan declines [24]. For grandmothers, the most common causes of death listed in the parish registers were old age, weakness, stroke, and tuberculosis. We find an acceleration in mortality in our population starting when women were in their 60s (Figure 1), before the mean age at last grandchild birth (maternal: 66.2 ± 9.8; paternal: 69.1 ± 10.7). By 70, hazard of death was over 3 times greater than at 50, and by 80 it was over 6 times larger. This adult mortality pattern in pre-industrial Finland is similar across non-industrial societies [4], indicating a relatively low influence of environmental conditions on age-specific mortality, in turn suggesting that it is chiefly the influence of modern medicine that has allowed post-reproductive lifespan to increase beyond past limitations.

Age-specific grandmother effects

Given the apparent reduction in the opportunity to provide care to grandchildren with age, we determined whether grandmother presence at different grandmother and grandchild ages has a different impact on grandchild survival, and whether women gain fitness benefits from improving their grandchildren's survival throughout their lifespan or not. Though grandmother effects can also manifest through improved fertility [5,6], their quantification according to (grand)mother age is difficult, because (grand)mother age and the daughter's own reproductive senescence are highly correlated. We therefore limited our approach to measuring grandmother age effects on grandchild survival only. We quantified whether grandmother presence increased grandchild survival as predicted by the Grandmother Hypothesis. Grandfathers were not investigated here, as their presence or absence did not affect offspring lifetime reproductive success in Finland [25]. Whilst men have nearly similarly long lifespans, this is not considered to be due to

'grandfather effects' [25]; male longevity is either under different selective pressures than female longevity, or, because human lifespans are sex-biased towards women [14], it may be an unselected consequence of the evolution of female longevity [25].

To assess the impact of grandmother presence across their post-reproductive lifespan on grandchild survival, we implemented time-event binomial generalised linear mixed-effects models (GLMMs) on a pre-industrial population of Finns (*n* = 5815 grandchildren), which allowed us to include variables that can change through time, such as which grandmothers were alive and present in a given year of the child's life and what age that grandmother was. One limitation of this approach is that it supposes benefits occur for each child, whereas a grandmother has an increasing cumulative number of grandchildren with age, and may strategically invest depending on where she is most required. To account for this, we control for the number of living cousins and siblings that a grandmother could invest in each year.

As grandmothers aged, their presence had decreasing importance for grandchild survival, with the presence of an older grandmother not as beneficial as that of younger grandmothers. The diminishing effect on grandchild survival started after 70 years (Figure 2A, Data S1). This analysis assesses how grandmothers of a particular age differ from those of other ages, but, critically, lacks a baseline point of comparison (i.e. no grandmother; see STAR Methods). Therefore, we divided grandmothers into three age categories to investigate in more detail how they might differ by their age, and to compare the effects of their presence to a situation without grandmothers (already deceased): under 50 years of age, as grandmothers under this age can still be physiologically capable of reproduction by themselves, 50-75, and 75 plus. The age limit of 75 years for 'older' grandmothers was chosen because previous evidence shows that in other non-industrial populations, women become net consumers between 70 and 80 [26,27], and may no longer provide calories for grandchildren during their 70s [28]. All models controlled for important confounders (see STAR Methods).

Grandmother help may be most critical during high-risk periods such as weaning age [5]. In line with this, we found that, although the presence of paternal grandmothers of any age was not significantly associated with grandchild survival for grandchildren aged 2-5 ($\beta = 0.028 \pm 0.099$, $p = 0.780$; Figure 2B; Data S1), the presence of maternal grandmothers aged 50-75 was associated with increased grandchild survival at ages 2-5 (binomial GLMM estimate for maternal grandmother only compared to no living grandmother: $\beta = 0.258 \pm 0.098$, p=0.009; odds-ratios [OR] = 1.295 [1.068, 1.569]; Figure 2C). Thus, a grandchild with a living maternal grandmother aged 50-75 had a 29.5% higher chance of surviving from 2 to 5 than a grandchild whose grandmother was deceased. This result confirms that prolonged longevity of women, even beyond menopause, can be favoured by natural selection through post-reproductive indirect fitness gains, at least until age 75.

Strikingly, we find that once women reached their mid-70s, their presence was correlated with reduced grandchild survival in their families. Our results show that the presence of paternal, but not maternal, grandmothers over 75 years of age was significantly detrimental to infant grandchild survival from their birth to age 2 (time-event binomial GLMMs for survival of grandchildren): old paternal grandmothers were significantly worse than dead grandmothers ($\beta = -0.463 \pm 0.209$, $p = 0.027$, OR = 0.629 [0.418, 0.948]), whilst old maternal grandmothers did not have a significant effect in either direction ($\beta = -0.377 \pm 0.250$, $p = 0.131$, OR = 0.686 [0.420, 1.119]) (Figure 2D and E; Data S1). In other words, a grandchild with a living paternal grandmother aged 75+ had a 37.1% lower probability of surviving from birth to age 2 than a grandchild with a deceased paternal grandmother.

Our finding indicates that, at the population level, the negative effect of old grandmother presence on infant survival would result in balancing selection on the length of post-reproductive lifespan; grandmother effects could select for some increase in post-reproductive lifespan, but against unlimited rises. The negative effects of old paternal grandmothers may be a consequence of a number of factors working in concert. For example, the negative effect of elderly grandmothers on early-childhood survival could result from stresses the co-resident grandmother imposes on mother during pregnancy [12]. Another possibility is that age-related health declines of the grandmother may lead to a reduced ability to care and an increased need of assistance from their families, intensifying resource competition [29] that was common in the population [15,30], particularly with the co-resident paternal grandmother [11]. It is noteworthy that the effect is only significant with older paternal grandmothers, and is confined to infant grandchildren, not all ages of (possibly) co-resident grandchildren.

Beneficial effects absent close to grandmother death

Human lifespan is known to have increased, and continues to increase, with social and medical advances [2]. As grandmother health affects the direction of intergenerational transfers in contemporary society [31], it is highly likely that upwards transfers of resources (e.g. time, energy) would also have been required in the past for the deteriorating elderly. We therefore also investigated directly how the number of years until grandmother death affected the survival of grandchildren using time-event GLMMs, again with time-varying covariates to allow grandmother status to change. In the absence of health records, this can act as a proxy for the general health of grandmothers: healthy women are unlikely to die in the following year. We set time to death as 1, 2, or 3+ years, as women more than a couple of years from death in a pre-healthcare era would likely have been most able to invest in taking care of their grandchildren (see also STAR Methods). To test whether the period of potential ill-health prior to death increases as grandmothers age, we also ran an additional interaction between continuous time to death and grandmother age on grandchild survival (see STAR Methods for details and caveats). The interactions were not significant

(maternal grandmothers β = -0.003 ± 0.003, p = 0.256; paternal grandmothers β = 0.002 ± 0.003, p = 0.510), indicating that the effect of time to death on grandchild survival does not differ by age.

Our analyses reveal that infant grandchild survival was significantly compromised by the presence of a paternal grandmother within a year of grandmother death (β = -0.463 ± 0.210, *p* = 0.028; OR 0.628 [0.416, 0.949]; Figure 3A), but not by a maternal grandmother within a year of her death (Figure 3B). Survival of toddlers (ages 2-5) was not compromised by whether the maternal or paternal grandmother was soon to die (Figure 3C and D; Data S2). However, if the maternal, but not the paternal, grandmother was three or more years away from death, her presence was significantly beneficial (β = 0.220 ± 0.098, *p* = 0.024; OR 1.246 [1.029, 1.508]; Figure 3D). Taken together, these results show that grandmother health is of great importance for grandchild outcomes: the presence of those closest to death had either a detrimental effect (when co-resident) or no benefit for grandchild survival, whilst only maternal grandmothers a number of years from death (and therefore likely to be healthier) had a positive influence. As only paternal grandmothers were detrimental when of ill health, there may be some competition between grandchildren and co-resident grandmothers for parental resources. Child mortality when the grandmother was nearing death was rarely due to contracting an infectious disease from the grandmother: in this sample, only seven grandchildren dying either in the years preceding or the year of a grandmother's death died of the same cause as their grandmother.

Conclusions

We find support that post-reproductive longevity of women is under positive selection through the fitness benefits that grandmothers accrue by helping to improve grandchild survival. Importantly, we also find that these beneficial effects of grandmothers on their grandchildren wane off with increasing age and/or declining health of the grandmother. We must note, however, that we cannot disentangle whether age *per se* or time to death is more important, and it is highly likely that the results we see for each are influenced by the other. Grandmother mortality is drastically increased once opportunities to help grandchildren and ability to do so decline. These finding are intriguing, given that to date very few genes with highly specific-age effects beyond development are known, and the evolution of ageing trajectories are therefore commonly thought to be determined by lifelong processes [32]. Our results call for further research by showing that positive effects from the presence of grandmothers favours the evolution of post-reproductive lifespan, but the detrimental effect of older and/or weaker paternal grandmothers suggests that selection may also limit the evolution of further increases in lifespan. As this limit to lifespan is consistent across many environmentally distinct pre-industrialised human populations, it may be that the advent of modern medicine to combat age-related health declines has overcome the natural limit to post-reproductive lifespans.

Our work also adds further support to the idea that, besides helping effects, kin can also act as major competitors. However, much of this work has focused on competition between pre-reproductive siblings [29,33], or on reproductive conflict within [30,34] or between generations [10,11]. Instead, here we find possible indications of indirect intergenerational resource competition between non-reproductive individuals, opening avenues for further research into types of conflict that have received little consideration in an evolutionary biological context.

Author Contributions

SNC, JEP, ML, and VL conceptualised the paper. SNC analysed the data and drafted the manuscript. All authors were involved in interpretation of results and significantly revised the manuscript.

Acknowledgements

We thank the genealogists involved in collecting the data used in this study (especially Kimmo Pokkinen), which was funded by the Academy of Finland (grant 292368; VL, JEP, and SNC) and the Kone Foundation (ML). We are particularly grateful to Adam Hayward, Robin Cristofari, Rob Griffin, and two anonymous reviewers for constructive feedback, and also to Vérane Berger, Emily Lynch, and Robert Lynch for their helpful comments.

Declaration of Interests

The authors declare no competing interests.

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Figure Legends

Figure 1. Acceleration in mortality in later life and age-specific birth rates. The black line represents hazard of death for women, whilst the blue regions indicate the age-specific birth rates of mothers (lighter blue) and grandmothers (via their grandchildren; darker blue). Symbols denote key milestones in grandmotherhood for maternal (black symbols) and paternal (open symbols) grandmothers: circles show the mean age at becoming a grandmother, and diamonds indicate mean age at the birth of the last grandchild. The grey square denotes the oldest grandmother alive at the birth of a grandchild. Vertical dashed lines leading from the key milestones show when they occur in regards to fitness gains and hazard of death. The vertical line at age 75 shows the age at which grandmothers are considered 'old' in this study and no longer benefit survival of grandchildren.

Figure 2. Age-mediation of grandmother effects. (A) Survival for grandchildren aged 0-2 is lower with older grandmothers. Survival probabilities come from the continuous GLMM models, where black = maternal grandmother, and red = paternal grandmother. Dashed lines show non-parametric 95% confidence intervals. Note that the maternal and paternal lines cannot be compared, as there is no baseline point of comparison for these lines (see STAR Methods). Lines for 2-5 not shown (see Data S1). B-E show boxplots of model-predicted values for grandchild survival probability, obtained from binomial time-event GLMMs for different grandmother age classes at different grandchild ages. *p*-values are shown where there were significant differences between grandmother ages, and numbers below each box indicate the number of observation years. (B) There were no paternal grandmother effects on survival of grandchildren age 2-5. (C) Maternal grandmothers aged 50-75 were associated with a significant increase in the survival of grandchildren aged 2-5. (D) The presence of old (75+ years old) paternal grandmothers were detrimental to the survival of grandchildren aged 0-2. (E) For grandchildren aged 0-2, old maternal grandmothers were not significantly worse than no grandmother. See also Data S1.

Figure 3. Beneficial effects absent close to grandmother death. Boxplots of binomial time-event GLMM-predicted values for grandchild survival probability at different grandchild ages by number of years until focal grandmother death. *p*-values are shown where there were significant differences between grandmother times until death, and numbers below each box indicate the number of observation years. (A) Paternal grandmothers within a year of death were significantly detrimental to infant grandchildren. (B) Time until maternal grandmother death did not affect survival probability of grandchildren age 0-2. (C) Time to death of paternal grandmothers had no effect on survival probability of children aged 2-5. (D) Only maternal grandmothers three or more years from death were beneficial to grandchildren aged 2-5. See also Data S2.

STAR Methods

Contact for Reagent and Resource Sharing

Further information and requests for resources should be directed to and will be fulfilled by the Lead Contact, Virpi Lummaa (virpi.lummaa@utu.fi). This information is also available in the Key Resources table.

Experimental Model and Subject Details

Study population

We investigated grandmother effects on grandchild survival using an extensive pre-industrial demographic dataset collected from parish population registers (see e.g. [5]) for lineages originating in eight parishes in four regions of Finland (Hiittinen, Kustavi and Rymättylä in Southwest Finland, Ikaalinen and Tyrvää in Pirkanmaa, Pulkkila in Northern Ostrobothnia, and Rautu and Jaakkima in Karelia) from 1731-1895. These registers were kept by the Lutheran Church, and detailed births, deaths, marriages, children, and occupations, allowing the acquisition of full life-histories of individuals and their descendants. From 1749, these records covered nearly the entire population of Finland.

Data selection

For this study, we included individuals born between 1731 and 1890 with the status of both grandmothers known (*n* = 5815 children; 1034 maternal grandmothers and 1003 paternal grandmothers). Our study period largely pre-dates the industrialisation of Finland and the accompanying medical advances, higher standards of living, and birth control, which increased survival and reduced birth rate [35]. Despite some children in our sample being born after the onset of industrialisation, the biggest changes in childhood mortality rates occurred in the 20th century [36]. As precise housing information is unavailable, grandmother distance to a grandchild was done at the parish level by comparing the last known parish of a grandmother to the birth parish of a grandchild. All grandmothers that were coded as “alive” (i.e. present) lived in the same parish at the same time as the grandchild; individuals with one or both grandmothers alive but in a different parish were not included in the sample, as they cannot be treated as either present or dead.

Quantification and Statistical Analysis

All analyses were conducted with R 3.5.1 [37], and statistical significance was defined at the level of $\alpha = 0.05$. Boxplots were created from model-predicted values using the *predict()* function.

Hazard of death and age-specific birth rates

First, to determine the age-specific hazard of death for all women who died or were last recorded in the registers before 1895 (n = 16583), we obtained Kaplan-Meier hazard estimates using the *kphaz.fit* function from the package *muhaz* 1.2.6 [38], which accounts for censoring (*n* = 3433 individuals). To assess whether hazard of death differed between women who had reproduced at least once (*n* = 5425) and those who never reproduced (n = 11158), we repeated this procedure. Following this, we then calculated the mean age at first and last birth of maternal and paternal grandchildren for grandmothers included in this study. This was calculated for all grandmothers, regardless of whether they were alive or dead at the birth of their first or last grandchild, and also for those grandchildren born during the lifetime of their grandmothers.

We quantified age-specific birth rates for women for the births of their own offspring, and for births of their grandchildren (including posthumous births), to see where selection on longevity from grandmothering may begin to wane. Only women aged 15 or older (the youngest age at birth) with a known date of death and who died before 1895 were included for this analysis (*n* = 5541). We calculated the birth rates for each age by adding all the births for mothers age_x, then dividing this by the number of women of age_x (including those with 0 children in that year), and then repeating this process for grandmothers and their grandchildren. As this approach incorporated posthumous births, we calculated births of children/grandchildren for every year of life from 0 to over 100, and therefore the number of women of age_x always equalled the sample size.

Grandmother age

We then analysed the annual survival of grandchildren by the presence of grandmothers of different ages. This was done for two age categories of child: 0-2 (early infancy when the child is breast-fed; maternal *n* = 5815, 11073 observation years [where each row in the data is one observation year]; paternal *n* = 5811, 11066 observation years), 2-5 (as a toddler; maternal *n* = 4823, 13811 observation years; paternal *n* = 4821, 13804 observation years). We selected grandchildren up to the age of 5, as this is when grandmother effects have previously been observed in this population [5,18], and as the majority of childhood mortality occurred before 5. There were separate models for maternal and paternal grandmothers in the grandchild age categories investigated (8 models: 4 continuous and 4 categorical), as it would not be possible to investigate age effects of both grandmothers at the same time whilst also accounting for their living status (i.e. issues with complete separation). However, the presence of the other grandmother was controlled for in all analyses (as dead vs. alive).

We implemented time-event analyses with generalised linear mixed models (GLMMs) and the logit link function using *glmer* from the R package *lme4* 1.1-12 [39], with grandchild survival status each year set as the response variable (binomial: 1, alive; 0, dead). Individuals lacking a recorded date of death were censored at their last date known to be alive, as were those with either grandmother disappearing from the

401 records before they themselves died or reached age 2/5 (depending on the model). We removed
402 observation years (but not individuals) in which the mother and child were both censored (indicative of a
403 family level event), or if an individual died within a week of their mother's death (indicative of disease or
404 high dependency, and therefore not preventable by grandmother intervention). As the number of removals
405 due to the latter were very low in this population (n = 4; all mothers had died during childbirth), this will not
406 have affected the results.

407 We constructed initial models with grandchild age (linear; time-varying continuous), maternal survival
408 status (time-varying 3-level factor: alive, dead, censored), maternal age (continuous; linear and quadratic),
409 childhood social class (2-level factor: landed, landless), whether the child was a twin, sex of the child, birth
410 order (continuous), region of Finland (4-level factor: Southwest Finland, Pirkanmaa, Northern Ostrobothnia,
411 Karelia), number of living siblings and cousins under the age of 5 (time-varying continuous; to control for
412 within-family competition [33]), other lineage grandmother presence (time-varying 2-level factor: alive,
413 dead), and grandmother age as fixed effects. Father survival status was not included, as father death has
414 been found not to affect offspring risk of death [40]. Grandmother age, our main explanatory variable, was
415 a continuous (linear and quadratic) variable. We centred continuous grandmother age on 50 by subtracting
416 50 from each value, to make coefficients more interpretable in these models. However, for all maternal (n_{0-2} = 3502, n_{2-5} = 2725) and paternal grandmother models (n_{0-2} = 3166, n_{2-5} = 2394), we excluded all
418 observations that were 'focal grandmother was dead', as we could not include age as continuous whilst
419 also keeping this baseline point of comparison: to be able to conclude that grandmother effects are
420 present, it is vital that a situation with no grandmothers present is in the same model. Therefore, the
421 outputs of these continuous models (Data S1) should be viewed with caution, and the lines showing
422 survival probabilities with maternal and paternal grandmothers (given in Figure 2A) cannot, and should not,
423 be compared. Individuals with mother survival status as censored were excluded to improve model fit, due
424 to exceptionally low sample sizes at this level of the factor (between 3 and 10 individuals in each subset).

425 Random terms included mother identity (ID) nested in maternal grandmother ID, to account for variation
426 between groups of siblings (from mother ID) and cousins (from grandmother ID), and birth cohort (16-level
427 factor, with ten year bins e.g. 1731-1740 etc.), to account for uneven spread of data and differential social
428 and environmental conditions across the study period. For the paternal grandmother models, mother ID
429 nested in maternal grandmother ID was replaced as a random effect by father ID nested in paternal
430 grandmother ID.

431 Each fixed term (with the exceptions of grandmother age, grandchild age, and other lineage grandmother
432 presence) was removed with the function *drop1*, with their values for the Akaike information criterion (AIC)
433 then compared to the AIC of the full model. Terms were only retained if AIC increased by >2 upon removal.

Following this procedure, the following terms were omitted from models: for both age 0-2 models, maternal age (linear and quadratic), childhood social class, number of living siblings and cousins under age 5, and birth order, and region of Finland; for both age 2-5 models, maternal age (linear and quadratic), childhood social class, number of living siblings and cousins under age 5, sex, birth order, region of Finland, and twin status. Reference levels in all models were as follows: region (Southwest Finland), other grandmother status (dead), mother status (alive). In Figure 2A, non-parametric 95% confidence intervals were calculated by bootstrapping model-predicted values of the full sample 100,000 times.

We additionally ran these models with grandmother age as a time-varying 4-level factor, as this allows assessment of grandmother effects via comparison to the situation if the grandmother is dead (i.e. a control category). The categories were 'dead', '<50', '50-75', and '75+', with intervals inclusive of the left border and exclusive of the right border. Sample sizes were as follows, with number of observation years in brackets: 0-2 paternal grandmothers n_{dead} = 2755 (5152), $n_{<50}$ = 292 (492), $n_{50\text{-}75}$ = 2789 (5115), n_{75+} = 187 (307); 2-5 paternal grandmothers n_{dead} = 2585 (7168), $n_{<50}$ = 131 (284), $n_{50\text{-}75}$ = 2177 (5830), n_{75+} = 229 (522); 0-2 maternal grandmothers n_{dead} = 2418 (4480), $n_{<50}$ = 505 (874), $n_{50\text{-}75}$ = 2993 (5527), n_{75+} = 121 (192); 2-5 maternal grandmothers n_{dead} = 2308 (6282), $n_{<50}$ = 266 (603), $n_{50\text{-}75}$ = 2458 (6576), n_{75+} = 173 (350). The reference level for grandmother age was 'dead'.

The same terms as in the above models were initially included. Following the AIC procedure, the terms omitted in the categorical models were also omitted in these continuous models, with the exception of region of Finland, which was retained in both 0-2 models. Additionally, we conducted a sensitivity analysis by running the models again, but with all terms included. These models did not differ in their conclusions, demonstrating the result was not affected by our model selection procedure.

Grandmother time to death

Finally, we investigated whether the health of a grandmother, measured as number of years until the grandmother's death, affected survival of grandchildren, using binomial time-event GLMMs with survival as the response variable. These models were run on the same age categories of grandchild as before (0-2 and 2-5), again for paternal and maternal grandmothers separately (maternal 0-2 n = 5694, 10844 observation years; paternal 0-2 n = 5693, 10846 observation years; maternal 2-5 n = 4786, 13702 observation years; paternal 2-5 n = 4789, 13711 observation years). The subsets used in the previous analyses were used again, but with observation years removed if the grandmother was censored within two years of the current year. In this way, we knew that grandmothers were definitely one or two years from death in a given year.

Grandmother age was replaced as the main explanatory variable by number of years until grandmother death. This was a time-varying 4-level factor, with the categories 'dead', '1 year', '2 years', '3 years and

above', as grandmothers within a couple of years of death may be of deteriorating health and could compete with grandchildren for parental care. There is, however, the potential for periods of ill health to last longer with age and to lead to differences in child survival, so we also ran an interaction between continuous grandmother age and continuous time to death across the 0-5 age range, with grandchild survival as the response variable. These interactions were non-significant, so we did not modify the 4-level time to death factor on the basis of grandmother age. No dead grandmothers were included in this interaction, however, as neither interacting variable should have a value for a deceased grandmother. Furthermore, the observations used in the analysis were only those who had 10 or fewer years until grandmother death, as there is unlikely to be a linear effect across the entirety of a grandmother's age range. Running these interactions with the cut off at 5 years also returns non-significant interactions.

The numbers of grandchildren for each level of the years to grandmother death factor were as follows, with number of observation years in brackets: 0-2 paternal grandmothers n_{dead} = 2818 (5285), n_1 = 235 (235), n_2 = 210 (210), n_{3+} = 2740 (5116); 2-5 paternal grandmothers n_{dead} = 2687 (7404), n_1 = 288 (288), n_2 = 307 (307), n_{3+} = 2083 (5712); 0-2 maternal grandmothers n_{dead} = 2487 (4618), n_1 = 242 (242), n_2 = 257 (257), n_{3+} = 3057 (5727); 2-5 maternal grandmothers n_{dead} = 2417 (6579), n_1 = 314 (314), n_2 = 298 (298), n_{3+} = 2359 (6511). Other fixed effects were the same as above: grandchild age, maternal age at birth and survival status, twin status, region of Finland, grandchild sex, number of living siblings and cousins under age 5, birth order, other grandmother lineage, and childhood social class. Random effects were also as outlined above. Though grandmother age could also theoretically be of some importance regarding time to death, we did not include this term: grandmother age in these models would be uninterpretable due to our study design including dead grandmothers to act as a reference point, and their age is not time-varying.

We followed the same model reduction procedure as before (AIC approach). The following terms were omitted: for both age 0-2 models, number of living siblings and cousins under age 5, birth order, childhood social class, and maternal age (linear and quadratic); for both age 2-5 models, twin, number of living siblings and cousins under age 5, birth order, childhood social class, sex, maternal age (linear and quadratic), and region of Finland. Reference levels were grandmother time to death (dead), region (Southwest Finland), other grandmother status (dead), mother status (alive), sex (male). We again checked the sensitivity of our results to the AIC procedure by running the models again with all terms included, but this did not alter our conclusions.

We also initially categorised those grandmothers who were in the '2 years' category together with those in the '1 year' category if they were known to have died from slow/debilitating afflictions (listed as 'cancer', 'tuberculosis', 'weakness', or variations thereof in the death registers), as these individuals may have

required more care. However, this was only in a couple of hundred cases in total, and did not affect the results. The results presented in this paper are from models which did not take cause of death into account.

Data and Software Availability

Data and R code can be found as supplementary files. See Key Resources table for details.

Data S1. Generalised linear mixed-effects models of grandchild survival between ages 0-2 and 2-5 years for grandmother ages and lineages. GM = grandmother, MGM=maternal grandmother, PGM=paternal grandmother. Reference levels: GM age (dead); Region (Archipelago); PGM/MGM status (dead); Mother status (alive). Related to Figure 2.

Data S2. Generalised linear mixed-effects models of grandchild survival between ages 0-2 and 2-5 years for grandmother lineages by number of years to grandmother death. GMD = grandmother time to death, MGM=maternal grandmother, PGM=paternal grandmother. Reference levels: GMD (dead); Region (Archipelago); PGM/MGM status (dead); Mother status (alive); Sex (male). Related to Figure 3.

Data S3. Hazard of death and birth data. Related to STAR Methods.

Data S4. Time-event data for grandmother age models. Related to STAR Methods.

Data S5. Time-event data for time-to-death models. Related to STAR Methods.

Data S6. Annotated R code used for all analyses. Related to STAR Methods.