PROCEEDINGS THE ROYAL
— OF — SOCIETY

B | **BIOLOGICAL**
SCIENCES

Grandma plays favourites: X-chromosome relatedness and sex-specific childhood mortality

Molly Fox, Rebecca Sear, Jan Beise, Gillian Ragsdale, Eckart Voland and Leslie A. Knapp

Proc. R. Soc. B published online 28 October 2009

Supplementary data	"Data Supplement" http://rspb.royalsocietypublishing.org/content/suppl/2009/10/27/rspb.2009.1660.DC1.html
References	**This article cites 41 articles, 7 of which can be accessed free** http://rspb.royalsocietypublishing.org/content/early/2009/10/27/rspb.2009.1660.full.html#ref-list-1 **Article cited in:** http://rspb.royalsocietypublishing.org/content/early/2009/10/27/rspb.2009.1660.full.html#related-urls
P<P	Published online 28 October 2009 in advance of the print journal.
Subject collections	Articles on similar topics can be found in the following collections developmental biology (100 articles) evolution (1425 articles)
Email alerting service	Receive free email alerts when new articles cite this article - sign up in the box at the top right-hand corner of the article or click **here**

Advance online articles have been peer reviewed and accepted for publication but have not yet appeared in the paper journal (edited, typeset versions may be posted when available prior to final publication). Advance online articles are citable and establish publication priority; they are indexed by PubMed from initial publication. Citations to Advance online articles must include the digital object identifier (DOIs) and date of initial publication.

To subscribe to *Proc. R. Soc. B* go to: **http://rspb.royalsocietypublishing.org/subscriptions**

Grandma plays favourites: X-chromosome relatedness and sex-specific childhood mortality[†]

Molly Fox[1], **Rebecca Sear**[2,‡], **Jan Beise**[3,†,‡], **Gillian Ragsdale**[1], **Eckart Voland**[4] and **Leslie A. Knapp**[1,*]

[1]*Department of Biological Anthropology, University of Cambridge, Pembroke Street, Cambridge CB2 3QY, UK*
[2]*Department of Social Policy, London School of Economics, Houghton Street, London WC2A 2AE, UK*
[3]*Statistics Division, Department of Economic and Social Affairs, United Nations, New York, USA*
[4]*Zentrum für Philosophie und Grundlagen der Wissenschaft, Universität Giessen, Otto-Behaghel-Strasse 10C, 35394 Giessen, Germany*

Biologists use genetic relatedness between family members to explain the evolution of many behavioural and developmental traits in humans, including altruism, kin investment and longevity. Women's post-menopausal longevity in particular is linked to genetic relatedness between family members. According to the 'grandmother hypothesis', post-menopausal women can increase their genetic contribution to future generations by increasing the survivorship of their grandchildren. While some demographic studies have found evidence for this, others have found little support for it. Here, we re-model the predictions of the grandmother hypothesis by examining the genetic relatedness between grandmothers and grandchildren. We use this new model to re-evaluate the grandmother effect in seven previously studied human populations. Boys and girls differ in the per cent of genes they share with maternal versus paternal grandmothers because of differences in X-chromosome inheritance. Here, we demonstrate a relationship between X-chromosome inheritance and grandchild mortality in the presence of a grandmother. With this sex-specific and X-chromosome approach to interpreting mortality rates, we provide a new perspective on the prevailing theory for the evolution of human female longevity. This approach yields more consistent support for the grandmother hypothesis, and has implications for the study of human evolution.

Keywords: longevity; grandmother; altruism; human evolution; X-chromosome; kin investment

1. THE GRANDMOTHER HYPOTHESIS

With menopause occurring around age 50, women survive several decades longer than their gametes (Dorland *et al.* 1998; Hawkes 2003). Why should women have such conservative life histories that they save up enough energy for 25 years of reproductive retirement? Human females represent a particular conundrum in evolutionary studies: after menopause they are unable to reproduce and have no obvious way to increase their genetic contribution to future generations. As this is the basis for natural selection, many researchers have sought to explain how post-menopausal longevity is adaptive in women.

Among evolutionary biologists, the 'grandmother hypothesis' is the most widely recognized explanation for human female post-reproductive longevity. It suggests that vigorous, skilled, elderly women are able to contribute to their grandchildren's survivorship through nutritional provisioning (Hawkes *et al.* 1998; Hawkes 2003). According to Hamilton's relatedness coefficients (Hamilton 1966), grandmothers share a quarter of their DNA with grandchildren, and so a woman can increase her genetic contribution to subsequent generations by keeping her grandchildren alive and healthy. Supporters of this model often refer to the Hadza, a modern foraging society in Tanzania, where grandmothers are more effective than children at extracting tubers from the dry ground. While a mother is breastfeeding an infant, and thus unable to forage enough to provide for weaned children, the grandmother provides food for the older siblings (Hawkes 2003; Hawkes & Jones 2005). The grandmother hypothesis posits that during the Plio–Pleistocene (1.7–1.9 Myr), the African savannah climate became more arid, and tubers became a more important component of the hominid diet (Vrba 1985; Foley & Lee 1991). Extracting tubers from the ground takes strength and skill, so recently weaned children required an adult provider. The mother usually filled this role, but when the mother was occupied with a newborn, the grandmother would step in. The grandmother's invaluable role in care-taking led to higher fertility in her daughter, and thus provided a strong inclusive fitness advantage to those grandmothers who survived longer. In recent years, the grandmother hypothesis has also been interpreted to include all tactics a grandmother could use to increase the fitness of her grandchildren, as opposed to Hawkes' original hypothesis that focused on dietary provisioning (Cant & Johnstone 2008). Among our species, alloparents play an important role in assisting mothers with childcare,

and so the participation of a grandmother in child-rearing could make a serious impact on a child's likelihood of survivorship (Hrdy 2009). For criticism of the grandmother hypothesis, see Peccei (2001) and Zeller (2004).

Tests of the grandmother hypothesis have been carried out on modern and historical populations. Most of the data correlate grandchild survivorship with grandmother survival and/or proximity, and it is often reported that only maternal grandmothers (MGMs) are found to have a positive effect on grandchild survivorship (Sear *et al.* 2002; Voland & Beise 2002). Studies that have not distinguished between MGMs and paternal grandmothers (PGMs) have found no correlation between grandmother's presence and grandchild survivorship (Hill & Hurtado 1991; Lahdenperä *et al.* 2004). To date, only two previous studies known to the authors have distinguished between boys and girls when investigating the effect of both grandmothers. A study of a Japanese population found that the presence of a PGM had a negative effect on boys and a positive effect on girls, while the presence of an MGM had a positive effect on children of both sexes, especially on boys (Jamison *et al.* 2002). They point to cultural features of the society as a possible mechanism for these findings. A study of an Ethiopian population reported the sex-specific information, but it was not analysed in the paper (Gibson & Mace 2005). More tests of the grandmother hypothesis are summarized in Sear & Mace (2007).

2. A NEW PERSPECTIVE ON THE GRANDMOTHER HYPOTHESIS

The grandmother hypothesis is based on the fact that women are genetically related to their grandchildren, and we should not overlook the nature of that genetic relatedness. Grandsons and granddaughters differ in the proportion of their X-chromosomes shared with MGMs and PGMs (figure 1). According to our proposed X-linked grandmother hypothesis, if grandmothers invest in grandchildren because of their genetic relatedness with them, then their adaptive incentive to invest may vary in a way that mirrors this variation in genetic relatedness. As a consequence, grandmothers' differential investment in grandchildren could cause differential survivorship of those grandchildren.

(a) *Differential X-relatedness between grandmothers and grandchildren*

(i) *Paternal grandmother–girl: 50 per cent*

The PGM has two X-chromosomes, and passes one of them to her son. Therefore, any individual gene on her X-chromosome has a 50 per cent likelihood of being inherited by her son. This is the one and only X-chromosome a man has. He passes this chromosome on to his daughter, and so the X-relatedness between a PGM and granddaughter is, just as between a woman and her son, 50 per cent (figure 1).

(ii) *Patneral grandmother–boy: 0 per cent*

Because the only heterosomal relatedness boys have with their fathers is the Y-chromosome, they have no X-relatedness with the PGM.

(iii) *Maternal grandmother–boy and maternal grandmother–girl: 25 per cent*

The MGM has two X-chromosomes, and so any given X-linked gene of hers has a 50 per cent chance of being transmitted to her daughter. Her daughter has one X from the MGM and one X from the maternal grandfather ('MGF'). She will pass down one of those two X chromosomes to each child, regardless of whether the child is a male or a female. Thus, the transmission likelihood for any particular X-linked gene is 0.5 inheritance from MGM to mother, and 0.5 from mother to child. Therefore, the likelihood of a grandchild inheriting any particular gene from the MGM is 25 per cent ($0.5 \times 0.5 = 0.25$). It is worth noting that females exhibit X-inactivation, so the likelihood that any particular X-linked gene in granddaughters will be expressed is only 50 per cent compared with 100 per cent in grandsons, but for the purpose of this analysis, we have focused on probability of genetic transmission, and not the probability of gene expression.

Although the X-chromosome contains only about 4.4 per cent of our DNA, with its estimated 1529 genes, it contains perhaps approximately 8 per cent of all human genes (Pennisi 2003; NIH 2007; Parang *et al.* 2008; NCBI 2009*a*). The dramatic differences in X-relatedness between grandmothers and grandchildren confound the Hamiltonian concept that grandchildren are 25 per cent genetically related to each grandparent. If approximately 92 per cent of our genes are autosomes, then a grandmother shares one-quarter of that, or approximately 23 per cent of her total genes with a grandchild, plus X-relatedness.[1] If a grandmother shares no X-chromosome with a grandchild, then their overall genetic relatedness is approximately 23 per cent, and if they share an entire X-chromosome, then it would be approximately 31 per cent. Therefore, MGMs and grandchildren are likely to share 25 per cent of their genomes, while PGM and granddaughter may share a total of approximately 31 per cent of their genes, with a likelihood of 27 per cent inheritance, while a PGM and grandson may share only approximately 23 per cent.

Studies on the grandmother hypothesis often suggest that grandmother provisioning is only adaptive along the maternal line owing to paternity uncertainty (Hawkes *et al.* 1998; Ragsdale 2004). Uncertainty, which ranges from 0.4 to 10 per cent in extant societies (Simmons *et al.* 2004; Bellis *et al.* 2005) would diminish the genetic relatedness factor between PGMs and their grandchildren. Therefore, it is generally believed that grandmother provisioning is more adaptive along the maternal line. We suggest here that boys are even further removed in their genetic relatedness with PGMs, but girls are so closely genetically related to their PGMs that it may counteract, or even overshadow, the adaptive influence of paternal discrepancy.

(b) *Predicted trends for grandmother investment in grandchildren*

We predict that this variation in genetic relatedness should cause the following pattern in the amount of investment grandmothers provide grandchildren (table 1): PGM–girl should be the combination exhibiting the highest amount of grandmaternal investment, as they share 50 per cent X-relatedness. The least grandmaternal investment should be with PGM–boy, as they share no X-relatedness. Between those two groups should rank

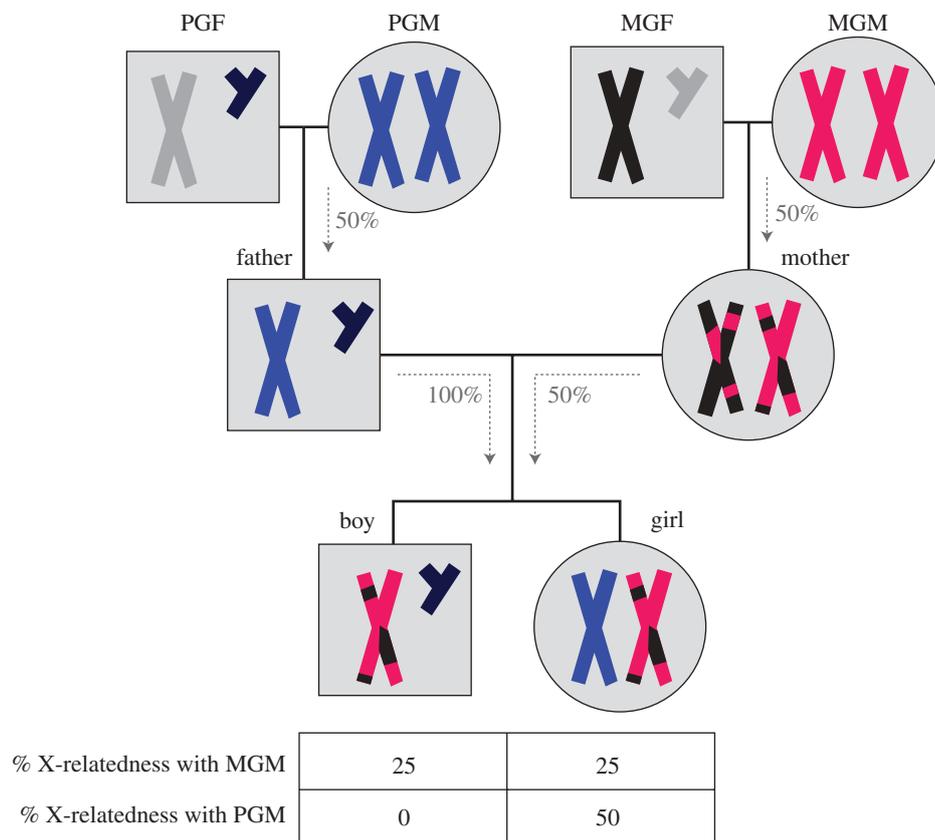|	boy	girl
% X-relatedness with MGM	25	25
% X-relatedness with PGM	0	50

Figure 1. X-Chromosome relatedness between grandmothers and grandchildren. For any given gene expressed on a child's X-chromosome, what is the likelihood that it was inherited from the MGM versus the PGM? Boys have only a maternal X-chromosome, which may contain genes from both the MGM and MGF owing to crossing-over in the mother. Girls also inherit the maternal chromosome with MGM and MGF genes, in addition to a paternal X, which the father inherited from the PGM.

Table 1. Predicted effect grandmothers should have on grandchildren based on X-relatedness. If grandmothers invest in grandchildren because of their genetic relatedness, then that investment should vary according to the variation in genetic relatedness. Because genetic relatedness between grandmothers and grandchildren varies by the inheritance of X-chromosomes, this model predicts that grandmothers will invest more in grandchildren with whom they have higher X-relatedness, and vice versa.

most beneficial ◄——————————— least beneficial

PGM–girl　　MGM–girl and MGM–boy　　PGM–boy

MGM–girl and MGM–boy, who share 25 per cent X-relatedness. This genetic model predicts that boys should receive greater investment from MGMs than from PGMs, and girls should receive greater investment from PGMs than from MGMs. Also, PGMs should invest more in girls than in boys.

3. RESULTS: GRANDMOTHERS' EFFECTS ON GRANDCHILD SURVIVORSHIP

We analysed sex-specific grandchild survival in the presence of grandmothers in seven populations in Japan, Germany, England, Ethiopia, The Gambia, Malawi and Canada (electronic supplementary material, table S1). These are all traditional populations in which grandparents are an integral part of the family unit, and we

defined a grandmother as 'present' if she resided in the home with a child, or in the same village as the child, depending on the residential customs of each population, and 'absent' if she lived in a different village or died (electronic supplementary material). The results demonstrate that the effect of a grandmother's presence on grandchild mortality corresponds to the degree of X-relatedness to the grandchild (figure 2; electronic supplementary material, tables S2–S15). The higher the X-relatedness between a grandmother and grandchild, the more beneficial effect the grandmother has on that child's survivorship. As far as we are aware, this is the first analysis to describe the relationship between X-relatedness and grandchild mortality rates.

These data follow the predicted trends based on X-relatedness (table 2). In all seven populations, boys survive better in the presence of MGMs than PGMs. In all but one population, PGMs have a more beneficial effect on girls than they do on boys. It is evident that PGM–boy is the least beneficial combination, ranking last in five of the seven populations. All of the populations exhibit a detrimental effect of PGMs on boys (figure 2; electronic supplementary material, tables S2–S15). They share no heterosomal relatedness at all, making their overall relatedness approximately 23 per cent. Less consistently upheld was our hypothesis that girls would survive better in the presence of their PGM than their MGM, yet this was still true in the majority of cases.

We performed a statistical meta-analysis to evaluate the dataset as a whole (electronic supplementary material).
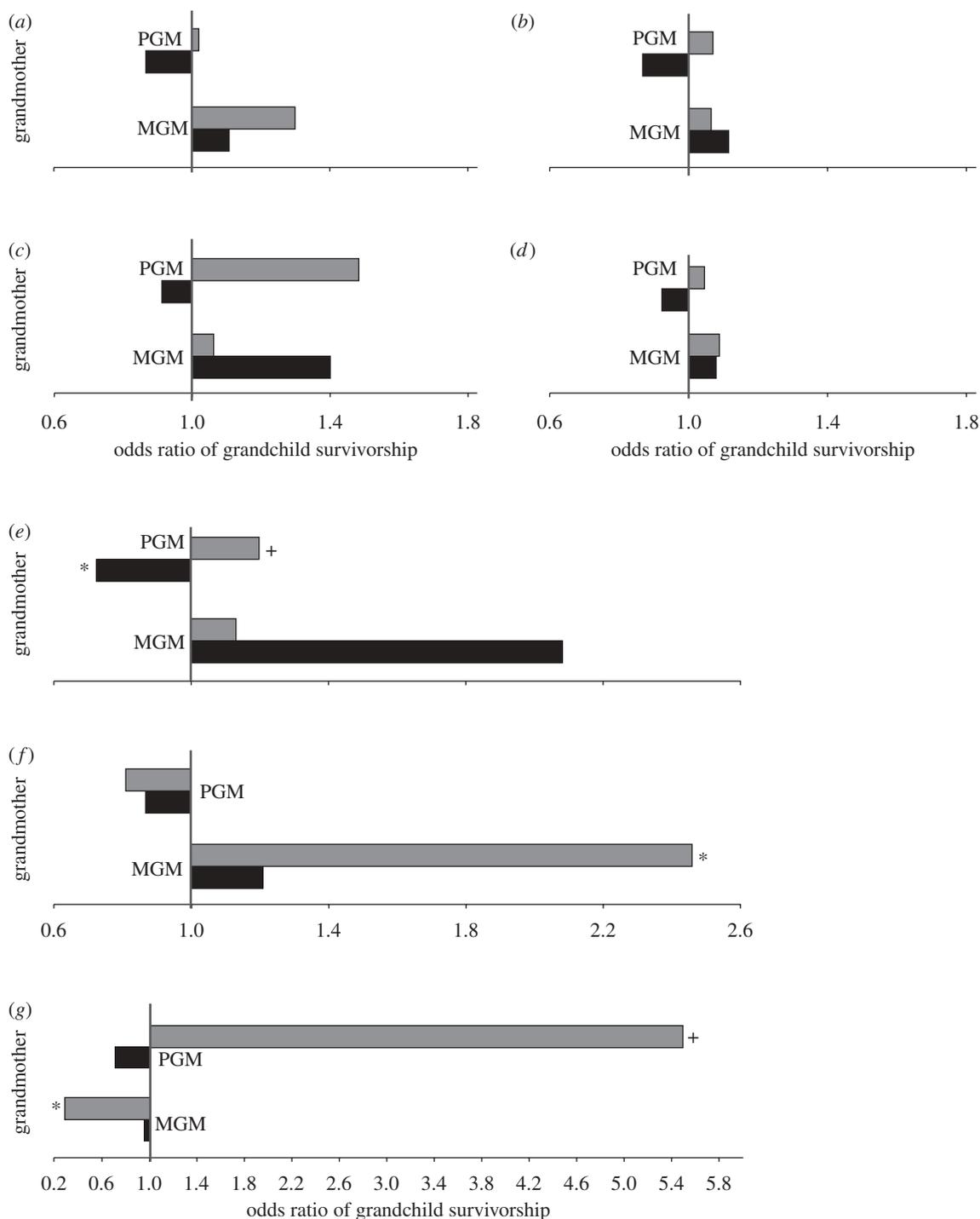
Figure 2. Grandmother's effect on grandchild survivorship. Grey bars, girls; black bars, boys. These graphs represent a grandchild's odds ratio of survivorship based on the presence of a grandmother. Values above 1.0 indicate that the presence of the grandmother has a positive effect on the grandchild's survivorship, and therefore a beneficial effect. Values of 1.0 indicate no effect. Values below 1.0 indicate that the grandmother has a negative impact on the grandchild's survivorship, and therefore a detrimental effect. There were not many instances of statistical significance, but the consistent patterns between the different populations are noteworthy. The overall opposite effect of the PGM on boys versus girls was significant ($p = 0.0046$). *$p < 0.05$, +$p < 0.10$. (a) Germany (Krummhörn) 1720–1874, (b) England (Cambridgeshire) 1770–1790, (c) Ethiopia (Arsi) 1998–2003, (d) Canada (Quebec) 1680–1750, (e) Japan (Nagano) 1671–1871, (f) Gambia (West Kiang) 1950–1975, and (g) Malawi (southern region) 1994–1997.

In seven out of seven populations, grandsons survived significantly better in the presence of their MGM than their PGM (Wilcoxon signed ranks test $p = 0.0081$). In six of the seven populations, the presence of a PGM improved the likelihood of the granddaughters' survival more than the grandsons' (Wilcoxon signed ranks test

$p = 0.0587$). Additionally, in seven out of seven populations, PGMs had a negative effect on grandsons, and in six of the seven populations, PGMs had a positive effect on granddaughters. Using a Fisher's exact test to measure the strength of the PGM's sex-specific effect, the result was highly significant ($p = 0.0046$).

Table 2. Child mortality in presence of grandmothers corresponds to X-relatedness. Because genetic relatedness between grandmothers and grandchildren varies by the inheritance of X-chromosomes, this model predicts that grandmothers will invest more in grandchildren with whom they have higher X-relatedness. We tabulate here how often our hypotheses were consistent with the data. A check mark indicates that in that population, the predicted trend was consistent with the survivorship data. Boys survived significantly better in the presence of their MGM than their PGM ($p = 0.0081$), and the presence of a PGM increased girls' survivorship more than boys' ($p = 0.0587$).

population	boys survive better with MGM than PGM	girls survive better with PGM than MGM	PGM better for girls than boys
Japan 1671–1871	✓	✓	✓
Germany 1720–1874	✓	✗	✓
England 1770–1790	✓	✓	✓
Ethiopia 1998–2003	✓	✓	✓
The Gambia 1950–1975	✓	✗	✗
Malawi 1994–1997	✓	✓	✓
Canada 1680–1750	✓	✗	✓

4. DISCUSSION

The data used here range across time and geographical space: from the seventeenth to the twenty-first centuries, spanning four continents. The consistency of our results suggests that this sex-specific pattern may be the result of a mechanism common to many populations, rather than the consequence of life in any one particular culture.

The effect that grandmothers have on grandchildren parallels the X-relatedness between the two individuals. Whether the grandmother effect is dependent on proportion of shared genes or only X-relatedness is difficult to discern at this point, as the two would seem to be so closely correlated.

In previous tests of the grandmother hypothesis, the effect of the PGM is inconsistent, ranging from harmful (Voland & Beise 2002; Ragsdale 2004) to neutral (Griffiths *et al.* 2001; Sear *et al.* 2002; Ladusingh & Singh 2006) to beneficial (Kemkes-Grottenthaler 2005; Sear 2008). Our sex-specific analysis shows that PGMs have a consistent opposite effect on boys and girls: the presence of a PGM increases a girl's likelihood of survivorship, and decreases a boy's (figure 2). Earlier studies pool mortality rates for boys and girls. As a consequence, the effect of the PGM may have appeared neutral only because the opposing sex-specific effects cancel each other out. Also, if the effect of PGMs on one sex is stronger, then the PGM's effect on all grandchildren may appear beneficial or harmful. By re-evaluating the data from these seemingly incompatible studies (Sear *et al.* 2000; Beise 2005; Sear 2008), we found that the sex-specific effect of a PGM is consistent across six of the seven populations.

For now, we can only hypothesize a mechanism to explain the sex-specific grandmother effects. Perhaps there is a behavioural adaptation in women that they should favour certain grandchildren based on sex. Or, perhaps there is some signal the grandchild sends or presents to the grandmother to indicate genetic relatedness, such as physical resemblance, a certain smell or a pheromone. Smells and pheromones have been shown to influence physiological processes and behaviour in humans, such as mate choice and maternal/neo-natal recognition (Bergquist *et al.* 1979; Porter *et al.* 1986; Horth 2007; Thom *et al.* 2007), and physical resemblance has been shown to affect investment patterns among kin (Platek *et al.* 2002). This could result in differential investment from the grandmother that could cause the differential survivorship (e.g. provisioning, protecting, teaching). Haig (2000) pointed to X-relatedness to explain favouritism within kin. He theorized that X-relatedness could be a factor encouraging female philopatry in mammals, as the genetic relatedness between mothers and daughters is greater than the genetic relatedness between fathers and sons, owing to X-inheritance as well as paternity uncertainty.

However, there is evidence against a behavioural mechanism. Two studies (Chrastil *et al.* 2006; Pollet *et al.* 2009) that used questionnaires to measure the relationship between preferential care and heterosomal relatedness among grandparents found no support for a correlation. The preferences cited by grandchildren and grandparents did not consistently correspond to genetic relatedness (Chrastil *et al.* 2006; Pollet *et al.* 2009), which could be evidence for the possibility that the correlation in survivorship demonstrated here is due to a mechanism other than conscious behaviour.

The X-chromosome contains a high percentage of genes affecting reproductive success. Many genes associated with fertility and intelligence are X-linked (Vines 1997; Zechner *et al.* 2001; Ananthaswamy 2002). A study by Zechner *et al.* (2001) illuminated the X-chromosome's importance in other realms. By looking at a random assortment of heritable defect phenotypes, Zechner *et al.* (2001) found that these phenotypes were an average of 2.35 times more likely to be X-linked than to derive from any single autosome (range: 2.14–2.76). This finding implies that the X-chromosome could account for a high proportion of our general phenotypic variation, or at least that it accounts for a high proportion of abnormal conditions. As a result, variation in X-chromosome relatedness could cause wide variation in fitness.

We are not the first to suggest that there is distinct intergenerational genomic inheritance in humans. The genetic connection between grandparents and grandchildren is complex, and previous students have shown that grandparental behaviour, physiology, life experience and genetics have an influence on trends in grandchild mortality rates and other aspects of grandchild growth and development. For example, Susser & Stein (1994) and Lumey & Stein (1997) report that women who had restricted nutrition during pregnancy not only gave birth to underweight children, but also the grandchildren were underweight at birth. Harper (Harper 2005) argues that imprinting in the germ line responsible for X-chromosome inactivation exemplifies epigenetic

intergenerational transfer, as it involves pathways carrying patterns of gene expression from one generation to the next.

Cropley *et al.* (2006) showed that environmentally induced epigenetic modifications in mice (i.e. a diet rich with methyl donor foods, which alters the methylation of the agouti-controlling gene) can persist through the epigenetic reprogramming of the germ line. In this case, two mothers with identical genotypes and phenotypes could produce phenotypically dissimilar offspring and grandoffspring as a consequence of environmental changes during pregnancy.

The genetic relationship between girls and PGMs is particularly unique, as the X-chromosome they share is not subject to extensive crossing-over (figure 1). At fertilization, much of the maternal and paternal imprinting from the gamete genome is erased, but there are some parts of the embryonic genome that escape erasure and thus maintain maternal or paternal imprinting. Among these are the paternally methylated imprinted genes (Morgan *et al.* 2005). Therefore, epigenetic markers on the X-chromosome may be conservative along the paternal line, as the X-chromosome itself is uniquely unaltered in its inheritance from a PGM to a granddaughter. It is possible, therefore, that there is some imprinting passed down the paternal line to a girl, potentially contributing to PGMs' beneficial effect on granddaughters.

5. CONCLUSION

Genetic relatedness between kin is often used to explain behavioural phenomena associated with altruism and caretaking, as well as biological traits and developmental trends. The grandmother hypothesis is the prevailing theory to explain why human female longevity extends beyond menopause. It suggests that elderly women are able to contribute to their grandchildren's survivorship through nutritional provisioning, which would increase a woman's inclusive fitness because she shares one-quarter of her genes with a grandchild. In seven previously studied populations, separating grandchild survivorship rates by sex reveals that X-chromosome relatedness correlates with grandchild survival in the presences of MGMs and PGMs. In all seven populations, boys survive better in the presence of their MGM than PGM. In all bar one population, the PGM has a more beneficial effect on girls than on boys. Our X-linked grandmother hypothesis demonstrates how the effects of grandmothers could be sex-specific because of the unusual inheritance pattern of the X-chromosome. This provides a more universally applicable model to explain differential survival of grandchildren in the presence of their grandmothers.

ENDNOTES

[1]The Y-chromosome contains only 89 genes, accounting for only approximately 0.4 per cent of all human genes (NCBI 2009*b*), and so it has been left out of this analysis.

REFERENCES

Ananthaswamy, A. 2002 X-rated brains. *New Sci.* **174**, 26–30.

Beise, J. 2005 The helping and the helpful grandmother: the role of maternal and paternal grandmothers in child mortality in the seventeenth- and eighteenth-century population of French settlers in Québec, Canada. In *Grandmotherhood: the evolutionary significance of the second half of female life* (eds E. Voland, A. Chasiotis & W. Schiefenhovel), pp. 215–238. Piscataway, NJ: Rutgers University Press.

Bellis, M. A., Hughes, K., Hughes, S. & Ashton, J. R. 2005 Measuring paternal discrepancy and its public health consequences. *Br. Med. J.* **59**, 749–754.

Bergquist, C., Nillius, S. J. & Wide, L. 1979 Intranasal gonadotropin-releasing hormone agonist as a contraceptive agent. *Lancet* **2**, 215–217.

Cant, M. A. & Johnstone, R. A. 2008 Reproductive conflict and the separation of reproductive generations in humans. *Proc. Natl Acad. Sci. USA* **105**, 5332–5336. (doi:10.1073/pnas.0711911105)

Chrastil, E., Getz, W., Euler, H. & Starks, P. 2006 Paternity uncertainty overrides sex chromosome selection for preferential grandparenting. *Evol. Hum. Behav.* **27**, 206–223. (doi:10.1016/j.evolhumbehav.2005.09.002)

Cropley, J. E., Suter, C. M., Beckman, K. B. & Martin, D. I. K. 2006 Germ-line epigenetic modification of the murine Avy allele by nutritional supplementation. *Proc. Natl Acad. Sci. USA* **103**, 17 308–17 312. (doi:10.1073/pnas.0607090103)

Dorland, M., Van Kooij, R. J. & Velde, E. R. T. 1998 General ageing and ovarian ageing. *Maturitas (Amsterdam)* **30**, 113–118. (doi:10.1016/S0378-5122(98)00066-8)

Foley, R. A. & Lee, P. C. 1991 Ecology and energetics of encephalization in hominid evolution. *Phil. Trans. R. Soc. Lond. B* **334**, 223–232. (doi:10.1098/rstb.1991.0111)

Gibson, M. A. & Mace, R. 2005 Helpful grandmothers in rural Ethiopia: a study of the effect of kin on child survival and growth. *Evol. Hum. Behav.* **26**, 469–482. (doi:10.1016/j.evolhumbehav.2005.03.004)

Griffiths, P., Hinde, A. & Matthews, Z. 2001 Infant and child mortality in three culturally contrasting states of India. *J. Biosoc. Sci.* **33**, 603–622. (doi:10.1017/S0021932001006034)

Haig, D. 2000 Genomic imprinting, sex-biased dispersal, and social behavior. *Ann. NY Acad. Sci.* **907**, 149–163.

Hamilton, W. D. 1966 The moulding of senescence by natural selection. *J. Theor. Biol.* **12**, 12–45. (doi:10.1016/0022-5193(66)90184-6)

Harper, L. V. 2005 Epigenetic inheritance and the intergenerational transfer of experience. *Psychol. Bull.* **131**, 340–360. (doi:10.1037/0033-2909.131.3.340)

Hawkes, K. 2003 Grandmothers and the evolution of human longevity. *Am. J. Hum. Biol.* **15**, 380–400. (doi:10.1002/ajhb.10156)

Hawkes, K. & Jones, N. B. 2005 Human age structures, paleodemography, and the grandmother hypothesis. *Grandmotherhood: the evolutionary significance of the second half of female life* (eds E. Voland, A. Chasiotis & W. Schiefenhovel), pp. 118–140. Piscataway, NJ: Rutgers University Press.

Hawkes, K., O'Connell, J. F., Jones, N. G. B., Alvarez, H. & Charnov, E. L. 1998 Grandmothering, menopause, and the evolution of human life histories. *Proc. Natl Acad. Sci. USA.* **95**, 1336–1339.

Hill, K. & Hurtado, A. M. 1991 The evolution of premature reproductive senescence and menopause in human females. *Hum. Nat.* **2**, 313–350. (doi:10.1007/BF0269 2196)

Horth, L. 2007 Sensory genes and mate choice: evidence that duplications, mutations, and adaptive evolution alter variation in mating cue genes and their receptors. *Genomics* **90**, 159–175. (doi:10.1016/j.ygeno.2007.03.021)

Hrdy, S. B. 2009 *Mothers and others: the evolutionary origins of mutual understanding*. Cambridge, MA: Harvard University Press.

Jamison, C. S., Cornell, L. L., Jamison, P. L. & Nakazato, H. 2002 Are all grandmothers equal? A review and a preliminary test of the 'grandmother hypothesis' in Tokugawa, Japan. *Am. J. Phys. Anthropol.* **119**, 67–76. (doi:10.1002/ajpa.10070)

Kemkes-Grottenthaler, A. 2005 Of grandmothers, grandfathers and wicked step-grandparents. Differential impact of paternal grandparents on grandoffspring survival. *Hist. Soc. Res.* **30**, 219.

Ladusingh, L. & Singh, C. 2006 Place, community education, gender and child mortality in north-east India. *Popul. Space Place* **12**, 65–76.(doi:10.1002/psp.393)

Lahdenperä, M., Lummaa, V., Helle, S., Tremblay, M. & Russell, A. F. 2004 Fitness benefits of prolonged post-reproductive lifespan in women. *Nature* **428**, 178–181. (doi:10.1038/nature02367)

Lumey, L. H. & Stein, A. D. 1997 Offspring birth weights after maternal intrauterine undernutrition: a comparison within sibships. *Am. J. Epidemiol.* **146**, 810–819.

Morgan, H. D., Santos, F., Green, K., Dean, W. & Reik, W. 2005 Epigenetic reprogramming in mammals. *Hum. Mol. Genet.* **14**, 47–58.

NCBI. 2009a *Homo sapiens* Chromosome: X. *Map Viewer.* Bethesda, MD: US National Library of Medicine.

NCBI. 2009b *Homo sapiens* Chromosome: Y. *Map Viewer.*

NIH. 2007 *A guide to your genome*. Bethesda, MD: National Human Genome Research Institute.

Parang, M., Mural, R. & Adams, M. 2008 *Human genome project frequently asked questions*. Washington, DC: US Department of Energy Office of Science. http://www.genome.gov/11006943.

Peccei, J. S. 2001 A critique of the grandmother hypotheses: old and new. *Am. J. Hum. Biol.* **13**, 434–452. (doi:10.1002/ajhb.1076)

Pennisi, E. 2003 Human genome: a low number wins the GeneSweep pool. *Science* **300**, 1484. (doi:10.1126/science.300.5625.1484b)

Platek, S. M., Burch, R. L., Panyavin, I. S., Wasserman, B. H. & Gallup, G. G. 2002 Reactions to children's faces: resemblance affects males more than females. *Evol. Hum. Behav.* **23**, 159–166. (doi:10.1016/S1090-5138(01)00094-0)

Pollet, T., Nelisson, M. & Nettle, D. 2009 Lineage based differences in grandparental investment: evidence from a large British cohort study. *J. Biosoc. Sci.* **41**, 355–379. (doi:10.1017/S0021932009003307)

Porter, R. H., Balogh, R. D., Cernoch, J. M. & Franchi, C. 1986 Recognition of kin through characteristic body odors. *Chem. Senses* **11**, 389–395. (doi:10.1093/chemse/11.3.389)

Ragsdale, G. 2004 Grandmothering in Cambridgeshire, 1770–1861. *Hum. Nat.* **15**, 301–317. (doi:10.1007/s12110-004-1011-y)

Sear, R. 2008 Kin and child survival in rural Malawi. *Hum. Nat.* **19**, 277–293. (doi:10.1007/s12110-008-9042-4)

Sear, R. & Mace, R. 2007 Who keeps children alive? A review of the effects of kin on child survival. *Evol. Hum. Behav.* **29**, 1–18.

Sear, R., Mace, R. & McGregor, I. A. 2000 Maternal grandmothers improve nutritional status and survival of children in rural Gambia. *Proc. R. Soc. B* **267**, 1641–1647. (doi:10.1098/rspb.2000.1190)

Sear, R., Steele, F., McGregor, I. A. & Mace, R. 2002 The effects of kin on child mortality in rural Gambia. *Demography* **39**, 43–63. (doi:10.1353/dem.2002.0010)

Simmons, L. W., Firman, R. C., Rhodes, G. & Peters, M. 2004 Human sperm competition: testis size, sperm production and rates of extra-pair copulations. *Anim. Behav.* **68**, 297–302. (doi:10.1016/j.anbehav.2003.11.013)

Susser, M. & Stein, Z. 1994 Timing in prenatal nutrition—a reprise of the Dutch famine study. *Nutr. Rev.* **52**, 84–94.

Thom, M. D., Stockley, P., Beynon, R. J. & Hurst, J. L. 2007 Scent, mate choice and genetic heterozygosity. *Chem. Signals Vertebr.* **11**, 269–279.

Vines, G. 1997 Where did you get your brains? *New Sci.* **154**, 34.

Voland, E. & Beise, J. 2002 Opposite effects of maternal and paternal grandmothers on infant survival in historical Krummhörn. *Behav. Ecol. Sociobiol.* **52**, 435–443. (doi:10.1007/s00265-002-0539-2)

Vrba, E. S. 1985 Environment and evolution: alternative causes of the temporal distribution of evolutionary events. *S. Afr. J. Sci.* **81**, 229–236.

Zechner, U., Wilda, M., Kehrer-Sawatzki, H., Vogel, W., Fundele, R. & Hameister, H. 2001 A high density of X-linked genes for general cognitive ability: a run-away process shaping human evolution? *Trends Genet.* **17**, 697–701. (doi:10.1016/S0168-9525(01)02446-5)

Zeller, A. 2004 Socioecology or tradition. *Rev. Anthropol.* **33**, 19–41. (doi:10.1080/713649338)