1 # Divergence in age-patterns of mortality change drives

2 # international divergence in lifespan inequality

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21

1   In the past six decades, lifespan inequality has varied greatly within and among

2   countries even while life expectancy has continued to increase. How and why does

3   mortality change generate this diversity? We derive a precise link between changes

4   in age-specific mortality and lifespan inequality, measured as the variance of age at

5   death. Key to this relationship is a young–old threshold age, below and above which

6   mortality decline respectively decreases and increases lifespan inequality. First, we

7   show that shifts in the threshold's location modified the correlation between changes

8   in life expectancy and lifespan inequality over the last two centuries. Second, we

9   analyze the post Second World War trajectories of lifespan inequality in a set of

10 developed countries, Japan, Canada and the United States (US), where thresholds

11 centered on retirement age. Our method reveals how divergence in the age-pattern

12 of mortality change drives international divergence in lifespan inequality. Most

13 strikingly, early in the 1980s, mortality increases in young US males led lifespan

14 inequality to remain high in the US, while in Canada the decline of inequality

15 continued. In general, our wider international comparisons show that mortality

16 change varied most at young working ages after the Second World War,

17 particularly for males. We conclude that if mortality continues to stagnate at young

18 ages, yet declines steadily at old ages, increases in lifespan inequality will become a

19 common feature of future demographic change.

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1 Introduction

2 Lifespan inequality is the defining measure of social and health disparity and, alongside

3 life expectancy (the mean age at death), is a key indicator of population health

4 (Tuljapurkar et al. 2000; Edwards and Tuljapurkar 2005). Changes in life expectancy are

5 well understood in terms of the underlying changes in mortality: mortality reduction at

6 any age increases life expectancy (Keyfitz 1977; Goldman and Lord 1986; Vaupel 1986;

7 Vaupel and Canudas-Romo 2003). However, the precise link between lifespan inequality

8 and age-specific mortality is less clear. First, only mortality decline at ages below a

9 young–old threshold can decrease lifespan inequality (Zhang and Vaupel 2009; Vaupel et

10 al. 2011; van Raalte and Caswell 2013). Second, there are several ways to quantify

11 lifespan inequality and understand its change through time (Wilmoth and Horiuchi 1999;

12 Cheung et al. 2005; Edwards and Tuljapurkar 2005; Horiuchi et al. 2008; Vaupel et al.

13 2011). Although highly correlated, these measures behave differently in response to

14 change in the age structure of mortality (van Raalte and Caswell 2013). Here, we measure

15 lifespan inequality by the variance of age at death, which measures the dispersion in age

16 at death relative to life expectancy (Edwards and Tuljapurkar 2005). The variance of age

17 at death is a central parameter in population and economic modeling (Tuljapurkar 2008;

18 Caswell 2009; Tuljapurkar and Edwards 2011; Edwards 2012; Schindler et al. 2012) and

19 it is therefore important to understand how it responds to mortality change. We present an

20 exact relationship between age-specific mortality and the variance of age at death (our

21 Eq. 2 below), which is a more transparent and demographically interpretable relationship

22 than that derived by Caswell (Eq. 42 in Caswell (2009)). Our framework provides a

1 powerful tool for quantifying how trajectories of age-specific mortality affect the

2 variance, both within countries and in an international sample of countries.

3

4 Given period age-specific mortality, $\mu(x)$, and the corresponding probability of survival to

5 each age $l(x)$, the age-distribution of death is $\varphi(x) = \mu(x)l(x)$. Figure 1 contrasts the age-

6 distribution of death in Sweden in 1800 and 2000, illustrating the standard outcomes of

7 development: (i) reduction of child death; (ii) increase of life expectancy; (iii) emergence

8 and advance of a modal age at adult death; (iv) decrease of lifespan inequality (Lee and

9 Carter 1992; Bongaarts 2005; Canudas-Romo 2008; Vaupel et al. 2011). These arise from

10 an initial focus of mortality decline on children and young adults followed by a shift of

11 mortality decline to older ages (Cutler et al. 2006).

12

13 Since about 1950 in the developed countries, life expectancy has increased consistently

14 but change in lifespan inequality among countries has varied greatly (Edwards and

15 Tuljapurkar 2005; Peltzman 2009; Smits and Monden 2009; Engelman et al. 2010). This

16 is in striking contrast to the strong negative correlation between changes in life

17 expectancy and lifespan inequality present during the first century of mortality decline

18 (Vaupel et al. 2011). The recent variability of this relationship, we show, results from the

19 very different responses of life expectancy and lifespan inequality to age-specific

20 mortality change. First, we show that in Sweden, the threshold for the variance of age at

21 death increased from childhood in the late 18th century to around 65 years (y) in 1950.

22 This movement of the threshold altered the relationship between changes in life

23 expectancy and lifespan inequality. Second, we examine the pattern of post Second

1   World War lifespan inequality across many countries, and then focus on Japan, Canada

2   and the United States (US). The application of our decomposition to these post war

3   trajectories of lifespan inequality showed that fluctuations in lifespan inequality resulted

4   primarily from mortality change at young working ages.

5

6   Results

7   **The analysis of change**

8   The variance of age at death after a specified index age A is

9    $$V(A) = \frac{1}{l(A)} \int_A^\infty \varphi(x)[x - M(A)]^2 dx, \qquad (1)$$

10   where $M(A)$ is the mean age at death after age A and is equal to the life expectancy after

11   age A plus A, i.e. $M(A) = e(A) + A$. If we set $A=0$, then $M(A) = e(0)$, the life expectancy at

12   birth and the variance, $V(0)$, quantifies the dispersion among deaths at all ages. However,

13   for developed countries it can be more informative to focus on adult ages, e.g. using

14    $V(15)$[1].

15

16   What is the change in $V(A)$ due to a proportional mortality reduction at an age x greater

17   than A? Starting from Eq. 1, we find

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[1] $V(0)$ is necessarily dominated by the (now usually small) fraction of infant deaths. If we set $A=15$, the mean $M(15)$ and the variance $V(15)$ describe the dispersion of adult deaths. The advantage of focusing on adult ages is that the effects of infant mortality change are removed. Infant mortality has fallen steadily, driving steady declines in $V(0)$ (Edwards and Tuljapurkar 2005; Tuljapurkar and Edwards 2011). Considering only mortality after particular index ages A can often reveal quite different trajectories of $V(A)$ (Engelman et al. 2010). Even with low infant mortality, the inclusion of the few youngest ages can obscure the lifespan inequality effects of adult mortality change. This makes $V(15)$ an ideal measure for investigating how the variability in age-specific mortality trajectories contributes to lifespan inequality change.

1    $$\frac{dV(A)}{d\ln\mu(x)} = \frac{-2\mu(x)}{l(A)}\int_x^\infty l(z)[z - M(A)]dz,$$ (2)

2   (for details, see Supplementary Information). The integral in Eq. 2 has a negative term:

3   the contribution from ages between x and $M(A)$, and a positive term: the contribution

4   from ages above $M(A)$. If mortality decreases at an age above $M(A)$, the variance $V(A)$

5   will increase. Now suppose that we reduce mortality at an age below $M(A)$. It is clear

6   from Eq. 2 that reducing mortality at younger ages will gradually cause the negative

7   contribution to dominate, thus decreasing $V(A)$. We therefore define a young–old

8   threshold age, which we call $T(A)$, before which mortality decline decreases $V(A)$, and

9   after which mortality decline increases $V(A)$. The threshold age $T(A)$ is always less than

10    $M(A)$ because the accumulated increases in $V(A)$ incurred above $M(A)$ must be fully offset

11   by decreases below $M(A)$ before reduction in $V(A)$ can occur.

12

13   Hereafter, we refer to the rate of change in Eq. 2 as the sensitivity of $V(A)$. Figure 2a

14   shows the sensitivity of the variance for $A=15$, for Sweden in 1950 and 2011. Three

15   features of the plot are typical of mortality in developed countries: (i) mortality decline at

16   ages from 15 to about 65 y decreases V; (ii) mortality decline after about 65 y increases

17   V; (iii) there is a threshold age, $T(15)$, at approximately 65 y, which separates 'young'

18   ages, where mortality decline decreases V, from 'old' ages, where mortality decline

19   increases V. The sensitivity of life expectancy $e(15)$ to a proportional mortality decline at

20   age x (Goldman and Lord 1986; Vaupel 1986; Vaupel and Canudas-Romo 2003) is

21   shown for comparison in Figure 2b. The obvious distinctions are that mortality decline at

22   any age increases life expectancy; and that mortality decline close to the threshold has

23   least effect on V. The great difference in the shape of these sensitivities of life expectancy

6

1   and lifespan inequality, especially below the threshold age, is the critical factor driving

2   their divergent responses to the same age structure of mortality change.

3

4   **Long-term mortality change**

5   Sweden was the first country to record ages at death systematically, with records from

6   1751 to the present (Human Mortality Database 2012). These data provide the best

7   opportunity to understand the long-term association of the young–old threshold with

8   changes in lifespan inequality. Figure 3 displays the annual change in the thresholds $T(A)$,

9   for index ages A=0, 15, and 65 y. Figure 4 shows the concurrent changes in $e(A)$ and

10 $V(A)$.

11

12 To provide some basic intuition on how the threshold depends on the age structure of

13 mortality, we note that a lower bound on the threshold for A=0 (derived from Eq. 2 in the

14 Supplementary Information) is

15 $T(0) \geq 2e(0) - \omega$, (3)

16 where ω is the longest lifespan. In the early years of transition to low mortality, before

17 the late 19th century, the lower bound defined by Eq. 3 was below or close to zero. In the

18 first half of the 20th century, life expectancy increased rapidly, which substantially

19 increased the threshold age—e.g. with $e(0)$=65 and ω=100 we have a lower bound at 30

20 y. More recently, life expectancy has begun to converge on ω. This convergence is

21 commonly known as 'rectangularization' of the age structure (Wilmoth and Horiuchi

22 1999), and it causes the lower bound on the threshold to advance. We now turn to exact

23 values of the young–old threshold.

1

Before about 1875, the threshold $T(0)$ followed a fluctuating increase to about 20 y (Fig. 3), so only mortality decline in children and very young adults could decrease V. However, $V(0)$ changed little (Fig. 4a), indicating an even distribution of mortality decline below and above the threshold age. From 1875 to about 1950, the threshold advanced to near 60 y, so mortality decline at a greater range of young ages could now decrease V. This reinforced the strong negative correlation between changes to life expectancy and lifespan inequality. In this period, V decreased rapidly and life expectancy increase accelerated, indicating much faster mortality declines below the threshold age. After 1950, the threshold continued advancing to 70–75 y. In this recent period, decreases in V slowed, despite continued increases in life expectancy, indicating the switch to more even mortality decline below and above the threshold age.

Increasing the index age after which we measure lifespan inequality advances the young-old threshold. To investigate changes in lifespan inequality among adults, we use an index of 15 y. $V(15)$ did not begin to decrease rapidly until ca. 1925 (Fig. 4b), when the threshold $T(15)$ was 57 y (Fig. 3). That this decrease began around 50 y later than the decrease in $V(0)$ indicates the much later spread of rapid mortality decline from below 15 y to 15–57 y. By 1950, mortality reduction below 15 y had converged the thresholds $T(0)$ and $T(15)$ to 60–65 y. This initiated a period when the distribution of mortality change between working and retired ages was critical in shaping the trajectory of lifespan inequality.

1   Consider now an index age of 65 y: the obvious feature of mortality change is the

2   consistent positive relationship of changes in life expectancy and lifespan inequality (Fig.

3   4c). The threshold $T(65)$ was always near 70 y, so only mortality decline at a few young

4   ages could decrease $V(65)$. Therefore, even with mortality reduction by an equal

5   proportion at each age, there was a strong bias for variance increase. The only deviation

6   occurred after 1980, when the trajectory of $V(65)$ flattened while $e(65)$ increased; the

7   threshold was 75 y in 1980. Comparison of mortality change at ages 65–75 y, and >75 y

8   showed an abrupt increase in mortality decline among males, which was greatest at 65–

9   75 y (Fig. S1). This was large enough to overwhelm the bias for variance increase and,

10 for the first time since 1751, disrupted the positive correlation between increases in life

11 expectancy and lifespan inequality.

12

13 **The young–old threshold for mortality in developed countries**

14 Now we focus on mortality in developed countries after the Second World War, when

15 deaths became concentrated at older adult ages. This gave the age-distribution of death its

16 characteristic 'modern' pattern, with a well-defined modal age in adulthood (Fig. 1).

17 Before investigating the age-specific drivers of lifespan inequality, we present an

18 approximation to the threshold age that is specific to modern mortality. The modern

19 mortality age-pattern is a reasonable fit to the Gompertz model in which mortality

20 increases with age as

21 $\mu(x) = Be^{kx}$,   (4)

1 where B is the initial level of mortality and k is the exponential rate of mortality increase.

2 From Eq. 4 (see Supplementary Information and Tuljapurkar and Edwards (2011)) the

3 mode (m) and standard deviation (σ) of age at death are

$$4 \quad m \approx \frac{1}{k}\ln\frac{k}{B}, \tag{5}$$

5 and

$$6 \quad \sigma \approx \frac{1}{k}. \tag{6}$$

7 Life expectancy is given to a good approximation by

$$8 \quad e(0) \approx m - \frac{\sigma}{2}, \tag{7}$$

9 and our threshold is approximated by

$$10 \quad T(0) \approx m - \frac{3\sigma}{2}. \tag{8}$$

11 This places the threshold at 1.5 standard deviations of the age at death below the modal

12 age, and (using Eq. 7) 1 standard deviation below life expectancy. The threshold's

13 advance is therefore driven by increases in both adult life expectancy and modal age at

14 death.

15

16 **Age-specific drivers of lifespan inequality change in developed countries**

17 We now focus on the post Second World War changes to $V(15)$ in developed countries,

18 for which the young–old threshold was near ages 60–70 y. Our analysis shows that

19 changes in lifespan inequality were shaped by striking differences in mortality change for

20 young versus old adults. We begin with a brief international overview: Figure 5 (solid

21 lines) shows the average trajectories of $V(15)$ for each sex across 40 regional data series

1   from the Human Mortality Database (Vaupel et al. 2011). $V(15)$ fluctuated more for

2   males, and the annual directions of $V(15)$ change were also less regionally consistent in

3   males (Fig. S2). Our decomposition (dashed lines) showed that the variance effects of

4   mortality change at young ages (below the threshold) fluctuated more than at old ages

5   (above the threshold), particularly in males. So, fluctuations in $V(15)$ clearly come from

6   mortality change at young ages.

7

8   We now examine in more detail Japan, Canada and the United States (US), which

9   illustrate the main features of post-1947 mortality change in developed countries:

10   relatively steady increase in life expectancy (Fig. S3), but large fluctuation in V (Fig. S4).

11   We focus on the slowing of variance decrease and, in some regions, onset of variance

12   increase in the 1980s. The US in particular showed a striking variance increase in the

13   early 1980s. The threshold ages were close to the conventional age of retirement,

14   although there was a steady increase in thresholds over time—by a maximum of 28 y in

15   Japanese females (Fig. S5).

16

17   Figure 6 shows how mortality change at young ages (below the threshold) and at old ages

18   (above the threshold) generated the contrasting variance trajectories of each country[2]. In

19   Japan, each sex followed the same basic trajectory of variance change: a rapid decrease

20   from 1947 to about 1975, and increase after about 1990 (Fig. 6a & b). The sexes differed

21   in that V initially decreased faster for females, and the reversal from variance decrease to

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[2] We also computed the components of variance change from below and above the fixed age of 65 y (Fig. S6). These components were near identical to those either side of the shifting threshold, indicating that mortality change at ages near the threshold had minimal influence.

11

1   increase was earlier for females. Our decomposition showed that the initial variance

2   decrease before 1977 was driven by the variance contracting effects of mortality decline

3   at young ages, which dominated the effects of mortality decline at old ages (Fig. 6a & b).

4   Around the 1980s, these opposing effects reached a rough equilibrium and so V changed

5   little. However, after about 1990, the negative effects of mortality decline at young ages

6   weakened further, leading the positive effects of mortality decline at old ages to

7   dominate. This shift in the focus of mortality decline to old ages consequently led V to

8   increase (Fig. S7).

9

10   *Canada and the US*

11   In Canada and the US, the variance changes after 1947 were much smaller than in Japan

12   (note the difference in *y*-axis scales in Fig. 6). Prior to 1983, Canada and the US followed

13   similar trajectories, each with little net variance change. However, after 1983, V increased

14   and continued to fluctuate in the US, but began a rapid and consistent decrease in Canada.

15   The result was that, from 1983 to 2007, the Canadian variance (for females and males

16   respectively) change from 8% and 9% lower than the US, to 20% and 15% lower.

17

18   We now focus on the period 1983–1994, which captures the major variance divergence

19   between Canada and the US (Fig. 6 c–f). In Canada, mortality decline at young ages

20   produced percentage variance changes of −10.8% for females and −10.1% for males (Fig.

21   6c & d). From old ages the changes were 1.0% in females and 2.9% in males. In the US,

22   mortality change at young ages produced variance changes of −3.3% in females and 3.6%

23   in males, and from old ages 1.5% and 4.8% respectively (Fig. 6e & f). Thus, due mainly

1   to differences in male mortality change, the US produced a larger component of variance

2   increase from old ages, and a much smaller component of variance decrease (and for

3   males, variance increase) from young ages.

4

5   How did mortality change differ at young ages between Canada and the US? In the US,

6   male mortality increased at ages 15–22 and 27–45 y, with increases greater than 30% at

7   34–37 y (Fig. 7). US females showed a similar pattern, but of smaller magnitude (a

8   maximum increase of 20% at 35 y). By contrast, mortality increase for Canadian males

9   was limited to ages 32–40 y, with a maximum increase of 17%; mortality generally

10 declined for Canadian females. The age-specific changes in mortality therefore differed

11 most between Canada and the US at young working ages, particularly in males. As a

12 result, variance diverged sharply between Canada and the US. When looked at in terms of

13 life expectancy this divergence is almost completely missed (Fig. S3). Thus, diagnosing

14 mortality trends based on life expectancy alone is inadequate and lifespan inequality

15 should feature routinely in demographic monitoring.

16

17 **Discussion**

18 We have shown how change in lifespan inequality, as measured by V, depends strongly

19 on the balance of mortality change around a young–old threshold. The threshold advances

20 with increases in life expectancy, the modal age at death, and with the compression of

21 mortality into a narrower range of ages. Before about 1950, changes to life expectancy

22 and lifespan inequality had a strong negative correlation (Smits and Monden 2009;

23 Vaupel et al. 2011). This arose because the emphasis of mortality decline was on ages

1 below the threshold (Vaupel et al. 2011). Since 1950, lifespan inequality decrease has

2 slowed, and occasionally even reversed. We show that the post Second World War

3 fluctuations lifespan inequality were driven by fluctuations in mortality at young working

4 ages, below the threshold age, while at old ages mortality decline was relatively

5 consistent. The implication of these trends is clear: if mortality at young ages continues to

6 fluctuate, and mortality at old ages continues its steady decline, lifespan inequality

7 increases will become more common.

8

9 But what drives these trajectories of age-specific mortality, causing them to vary both

10 within and among countries? This question brings the focus of our attention to the social

11 determinants of mortality (Graham 2009), and so to the realization that international

12 divergence in lifespan inequality must largely be due to divergence in age-patterns of the

13 social determinants. Mortality is ultimately associated with education, income, social

14 support (from family or public institutions, including the provision of healthcare),

15 lifestyle, disease and living conditions. These interact with the proximate, health related,

16 causes of death at each age to generate lifespan inequality (Edwards and Tuljapurkar

17 2005; Shkolnikov et al. 2011; Nau and Firebaugh 2012). For example, Japanese

18 development after 1947, including the start of universal healthcare in 1961, generated

19 rapid mortality decline at mainly working ages. It is possible that this rapid progress

20 against mortality gradually left the remaining causes of death in young adults in the

21 category 'hard to prevent'. However, society—and hence the array of social

22 determinants—was also changing, characterized by widening differences in mortality by

23 education and income, particularly in working aged males (Fukuda et al. 2004;

1   Kagamimori et al. 2009). This could also have slowed mortality declines in young adults,

2   e.g. if progress against the social determinants became limited to the most educated or

3   affluent.

4

5   A great deal of research is aimed at understanding why young adult mortality remains

6   high in the US compared to other high-income countries (Crimmins et al. 2011; IOM

7   2012). One source may be high geographic disparity in young adult mortality within the

8   US. For example, Cullen et al. (2012) showed that mortality differences below age 70

9   among US counties and racial groups resulted largely from differences in education and

10   income, particularly for males (see also Backlund et al. 2007; Crimmins et al. 2009).

11   Current evidence also suggests that life expectancy differences between educational

12   groups in the US have widened in recent decades (Olshansky et al. 2012). A part of this

13   variation is likely due to differences in healthcare access among young adults (Crimmins

14   et al. 2011). Indeed, any explanation of trends in US mortality must address the

15   hypothesis that the correlation of social deprivation with low healthcare access raises the

16   sensitivity of working-age mortality to macro-economic change. In the US, healthcare

17   access at working ages depends largely on employer-provided health insurance; in 1994,

18   18.6% of non-elderly adults in the US had no insurance (Holahan and Kim 2000). Being

19   without insurance limits care, particularly preventive care at young ages (Lasser et al.

20   2006), with evidence for consequently higher mortality (Wilper et al. 2009). The 1980s

21   lifespan inequality divergence between Canada and the US could be explained by such

22   social factors: It is not possible to exclude the explanation that macro-economic change

23   resulted in more people in the US in poor health and with no social safety net to ensure

15

1 appropriate healthcare (Brenner and Mooney 1983; Siddiqi and Hertzman 2007). A

2 slightly different understanding is gained by looking at the common causes of death at

3 young, working, ages (Harper et al. 2007; Nau and Firebaugh 2012). Harper et al. (2007)

4 show that in the 1980s US, mortality in young adults rose and the black-white gap in life

5 expectancy increased. This was due to differential rises in mortality from human

6 immunodeficiency virus (HIV), heart disease, and homicide. HIV became prevalent in

7 the 1980s and early 1990s, particularly among males aged 25–64 y, more so in the US

8 than Canada (Armstrong et al. 1999; UNAIDS 2013). Nau and Firebaugh (2012) also

9 highlight heart disease and homicides as key contributers to the high US variance of age

10 at death. Heart disease is a leading cause of premature death and accidents and

11 homicides, although being a less common cause, account for a high proportion of deaths

12 at the youngest adult ages where, as we show, the variance is highly sensitive to mortality

13 change.

14

15 *Alternate inequality metrics*

16 There are several established metrics of lifespan inequality (van Raalte and Caswell

17 2013). For the same mortality data, the young–old threshold can differ widely among

18 these metrics, e.g. by around 20 y between V and the metric known as lifespan disparity

19 or $e^{\dagger}$ (Zhang and Vaupel 2009). Our results indicate that the major post Second World

20 War mortality changes occurred outside the zone of threshold disagreement among

21 metrics, indicating that our qualitative conclusions are robust to the choice of metric. We

22 use V for several reasons: it is easily understood and interpreted as a measure of relative

23 dispersion, easily decomposed (Edwards and Tuljapurkar 2005; Edwards 2011; Nau and

1 Firebaugh 2012), and finds direct use in analyzing the demographic and economic

2 consequences of mortality change (Tuljapurkar 2008; Edwards 2012; Schindler et al.

3 2012).

4

5 *The future*

6 The young–old threshold in developed countries is now approaching 75–80 y (Figure 2a),

7 so only mortality decline at the oldest retired ages can increase lifespan inequality. Given

8 the ongoing fluctuation of social gradients in age-specific health and mortality, and the

9 importance of social gradients for generating lifespan inequality (Cullen et al. 2012;

10 Olshansky et al. 2012), we suggest that future work focus on the population-level effects

11 of mortality change within specific social groups (Edwards 2011; Shkolnikov et al. 2011;

12 van Raalte et al. 2011; Nau and Firebaugh 2012; van Raalte et al. 2012). The great good

13 of development has been the consistent improvement of medical technology and care for

14 the elderly, reflected in steadily declining old-age mortality (Vaupel 2010). However, our

15 results suggest that without comparable progress against young adult mortality, through

16 action on the social determinants, mortality change is unlikely to follow the historical

17 pattern of rising life expectancy and falling lifespan inequality. Hence, we should be

18 prepared for increases in lifespan inequality to become a more common feature of

19 demographic change.

20

21 **Materials and Methods**

22 We downloaded our data from the Human Mortality Database in January 2013 (Human

23 Mortality Database 2012), see the Background Information for each country,

17

1 www.mortality.org. For international comparisons, we used the same data series as

2 Vaupel et al. (2011). Table S1 shows the range of years between 1947 and 2011 covered

3 by these data. We conducted all calculations in the R environment (R Development Core

4 Team 2012). The Supplementary Information gives the derivation of each formula

5 presented. For our age-decomposition of change in $V(15)$, we adapted Eq. 2 to

6 $$\frac{dV(15)}{dt} = -2\int_{15}^{\infty}\frac{a(x)\mu(x)}{l(15)}\int_{x}^{\infty}l(z)[z - M(15)]dzdx\,,\qquad(9)$$

7 which gives the change in $V(15)$ over time interval dt. The observed proportional changes

8 in age-specific mortality, $a(x)$, between years t and $t+1$ were computed as

9 $$a(x) = \frac{\mu(x,t+1) - \mu(x,t)}{\mu(x,t)}\,.\qquad(10)$$

10 To convert time in these formulae to discrete 1 y intervals, we discretized the probability

11 density function of age at death, considered survivorship to the mid-point of each age-

12 interval, and substituted instantaneous mortality for central death rates. We counted age

13 in 1 y intervals starting from 0.5 y. Where we present mortality change over wider age

14 intervals, we compute a weighted average of the 1 y central death rates in each interval,

15 using the probability of survival to each age as weights (Ahmad et al. 2001).

16

17 **Acknowledgements**

20

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1 **Figures**

2 **Fig. 1** The period age-distributions of death for years 1800 and 2000 in Sweden. The

3 vertical lines show life expectancy at birth, $e(0)$. The modal age at death in adulthood

4 became prominent only after the major process of mortality decline
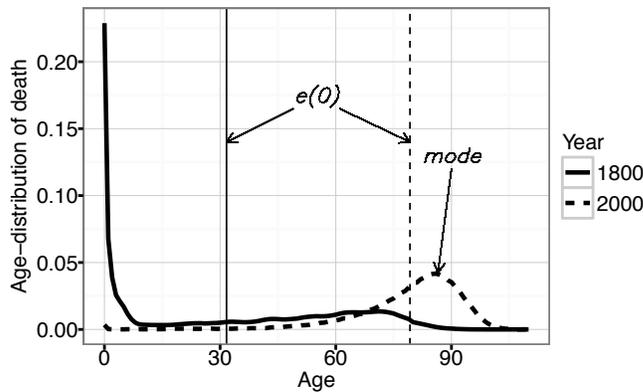
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7 **Fig. 2** The age-specific sensitivities to proportional mortality reduction in Sweden for

8 1950 (solid lines) and 2011 (dashed lines) of: (a) the variance of age at death after 15 y;

9 and (b) the mean age at death, i.e. life expectancy, after this age. The vertical lines show

10 the mean age at death after 15 y, $M(15)$, which equals the life expectancy at age 15 y plus

11 15 y, $e(15)+15$
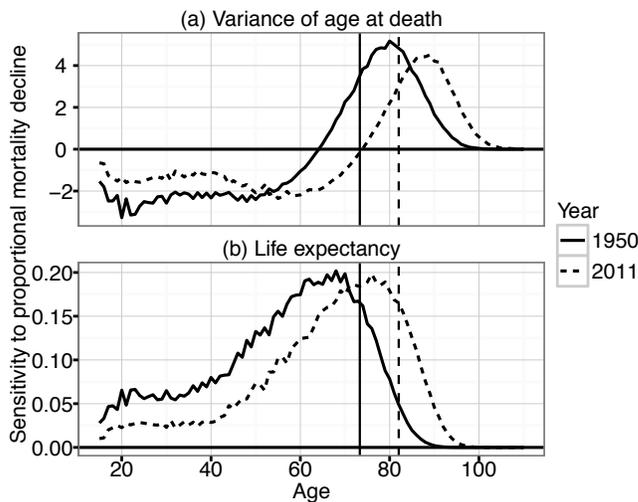
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2   **Fig. 3** The young–old thresholds, $T(A)$ for A=0, 15 and 65 y from 1751 to 2011 in

3   Sweden. Note that even in 2011, $T(65)$ was only 14 years above age 65 y, a considerably

4   smaller gap than for $T(0)$ and $T(15)$
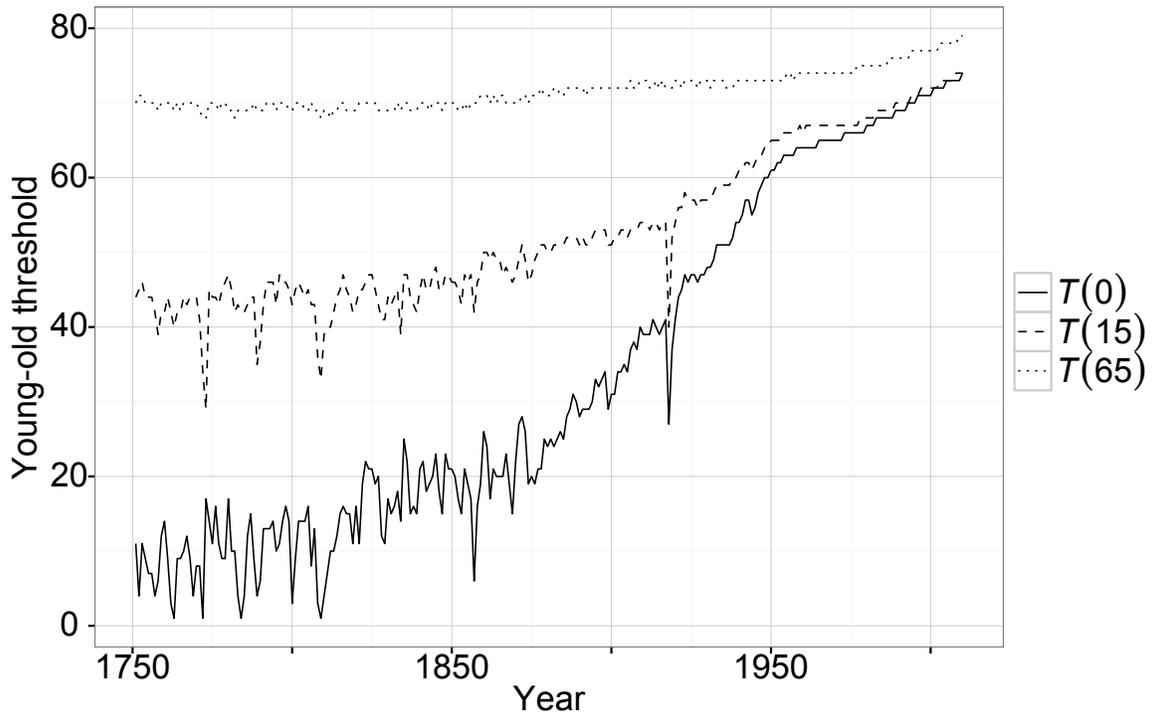
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1   **Fig. 4** The trajectories of the variance $V(A)$ for A=0, 15 and 65 y, in panels (a), (b) and (c)

2   respectively, alongside the corresponding trajectories of life expectancy, $e(A)$. Each

3   trajectory has been scaled so that it ranges between zero and one during the study period
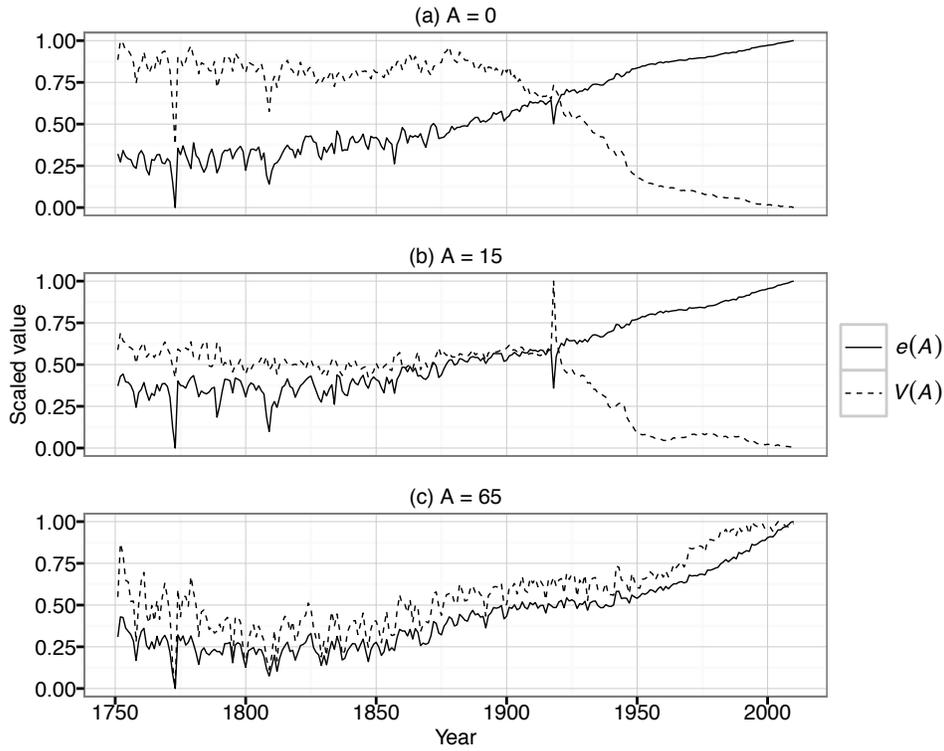
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1   **Fig. 5** For females (a) and males (b), solid lines show the average trajectory of the

2   variance of age at death after 15 y, $V(15)$, across 40 regions in the Human Mortality

3   Database (see Table S1 for details). The upper dotted lines show this average trajectory as

4   it would have been only with mortality change above the threshold age, $T(15)$. The lower

5   dashed lines show this for mortality change below the threshold. Note that the lines do

6   not show the variance change at each time t ($1947 \leq t \leq 2011$), but show the cumulative

7   effects of mortality change from 1947 to time t. Thus, if W is the annual change in V due

8   to mortality change below or above the threshold in each year, the dotted and dashed

9   lines are given by $V(15, 1947) + \int_{1947}^{t} W(15,u)du$. The grey shading around the dotted and

10 dashed lines shows the annual 95% range of variability among regions in each component

11 of change
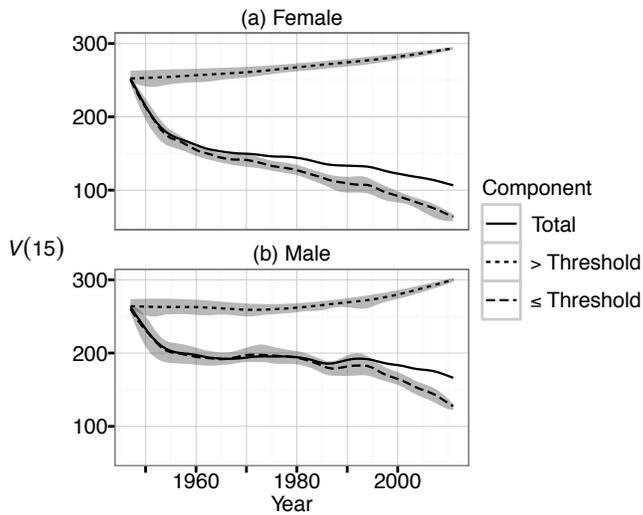
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1   **Fig. 6** Decomposition of the variance of age at death after 15 y, $V(15)$ into the effects of

2   mortality change below and above the young–old threshold age, $T(15)$. Solid lines show

3   the overall variance change, dashed lines the change produced from ages below the

4   threshold, and dotted lines the change produced from ages above the threshold. We show

5   separate decompositions for females and males in Japan (a & b), Canada (c & d) and the

6   United States (e & f) from 1947 to 2007. Lines show the cumulative variance effects of

7   mortality change plus $V(15, 1947)$, see details in the legend of Fig. 5

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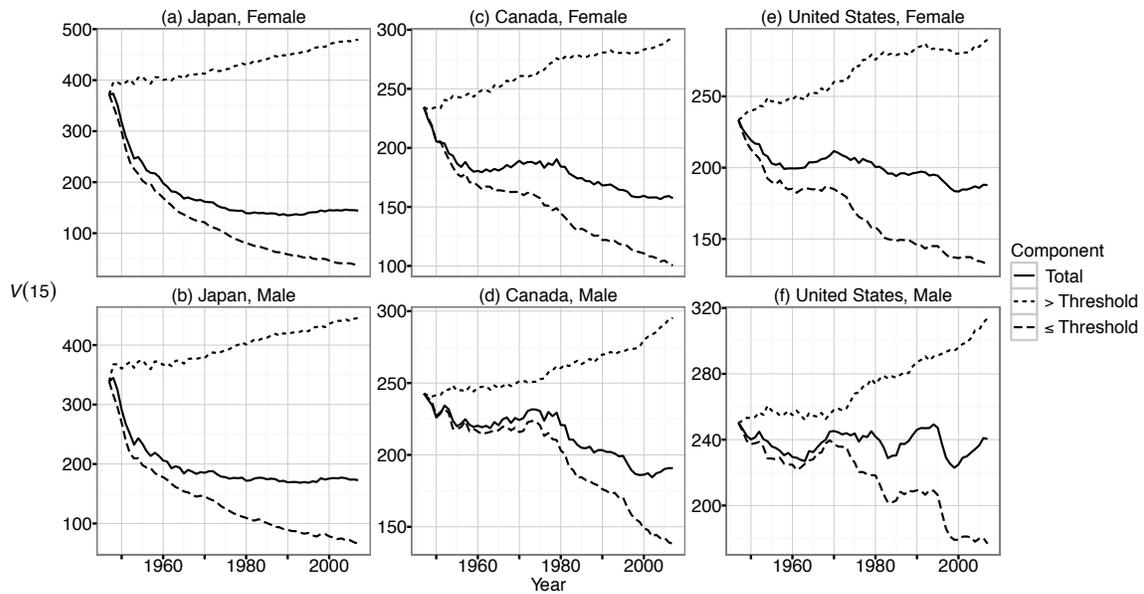
Fig. 7 The percentage changes to the central one-year death rates at ages from 15 years to

2   the average young–old threshold for females (71 years) and males (64 years) between

3   1983 and 1994 in (a) Canada and (b) the United States. Separate lines show the 5-year

4   moving averages of the percentage change in females and males

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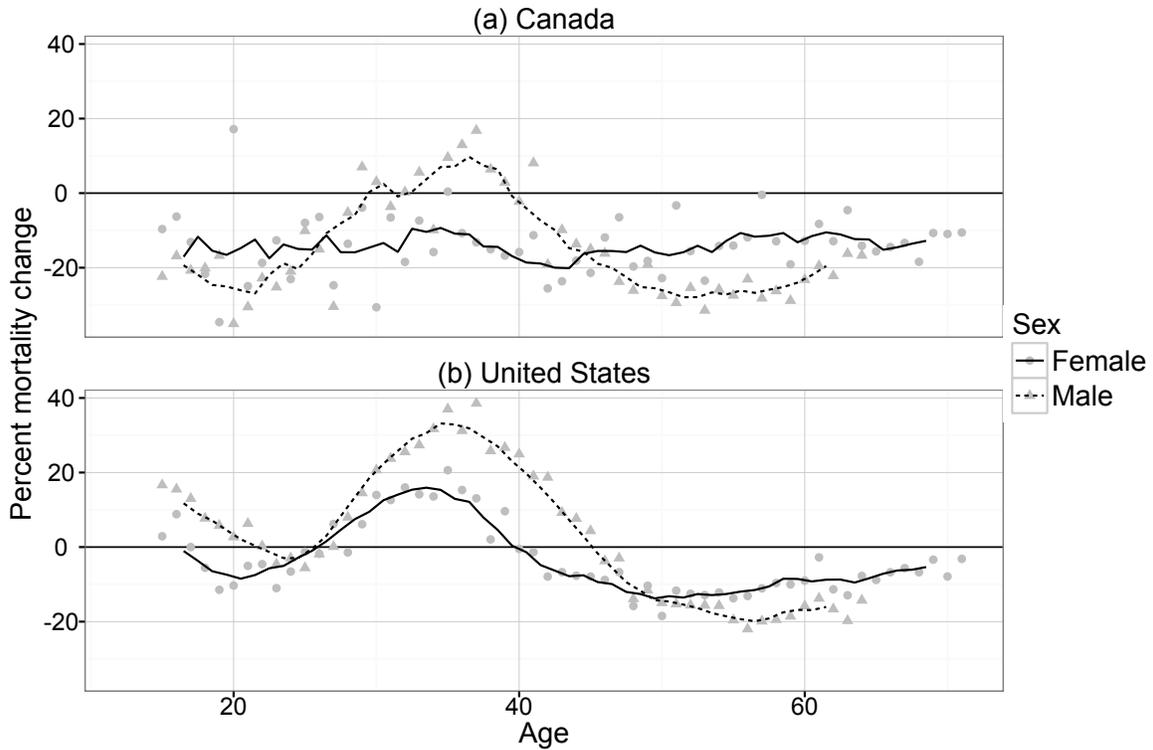
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1 **Fig. S1** Weighted average one-year central death rates between 65–75 years and above 75

2 years for each sex in Sweden from 1950 to 2010. The weights used in the calculation

3 were proportional to the probability of survival to each age. The trajectories have been

4 standardized so that each ranges between zero and one


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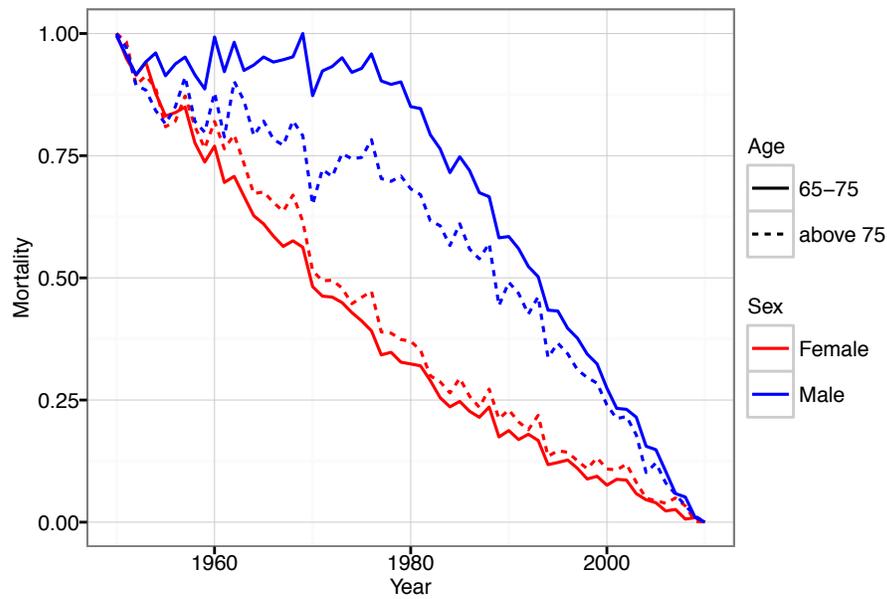
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1   **Fig. S2** The average trajectories of the variance of age at death after 15 years, $V(15)$, in

2   40 regions from the Human Mortality Database for females (solid lines) and males

3   (dashed lines). The grey shading shows the 95% range among regions of the direction of

4   variance change in each year. The maximum extent of years is 1947–2011, but not all

5   regions have data for each year; see details in Table S1

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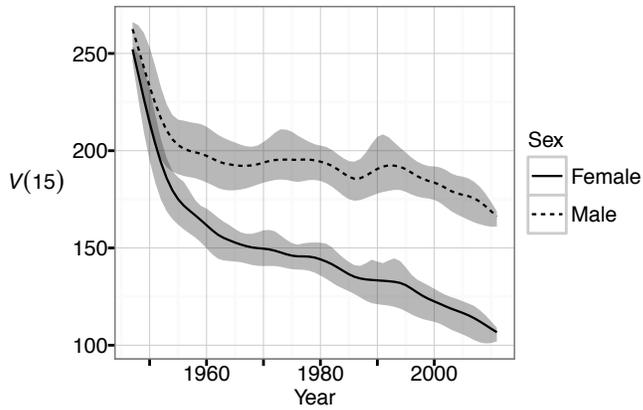
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1 **Fig. S3** Life expectancy after zero years i.e. at birth, *e*(0) and 15 years, *e*(15) respectively

2 in (a) & (b) Japan, (c) & (d) Canada and (e) & (f) the United States from 1947 to 2007.

3 Separate lines show the total population, females only and males only
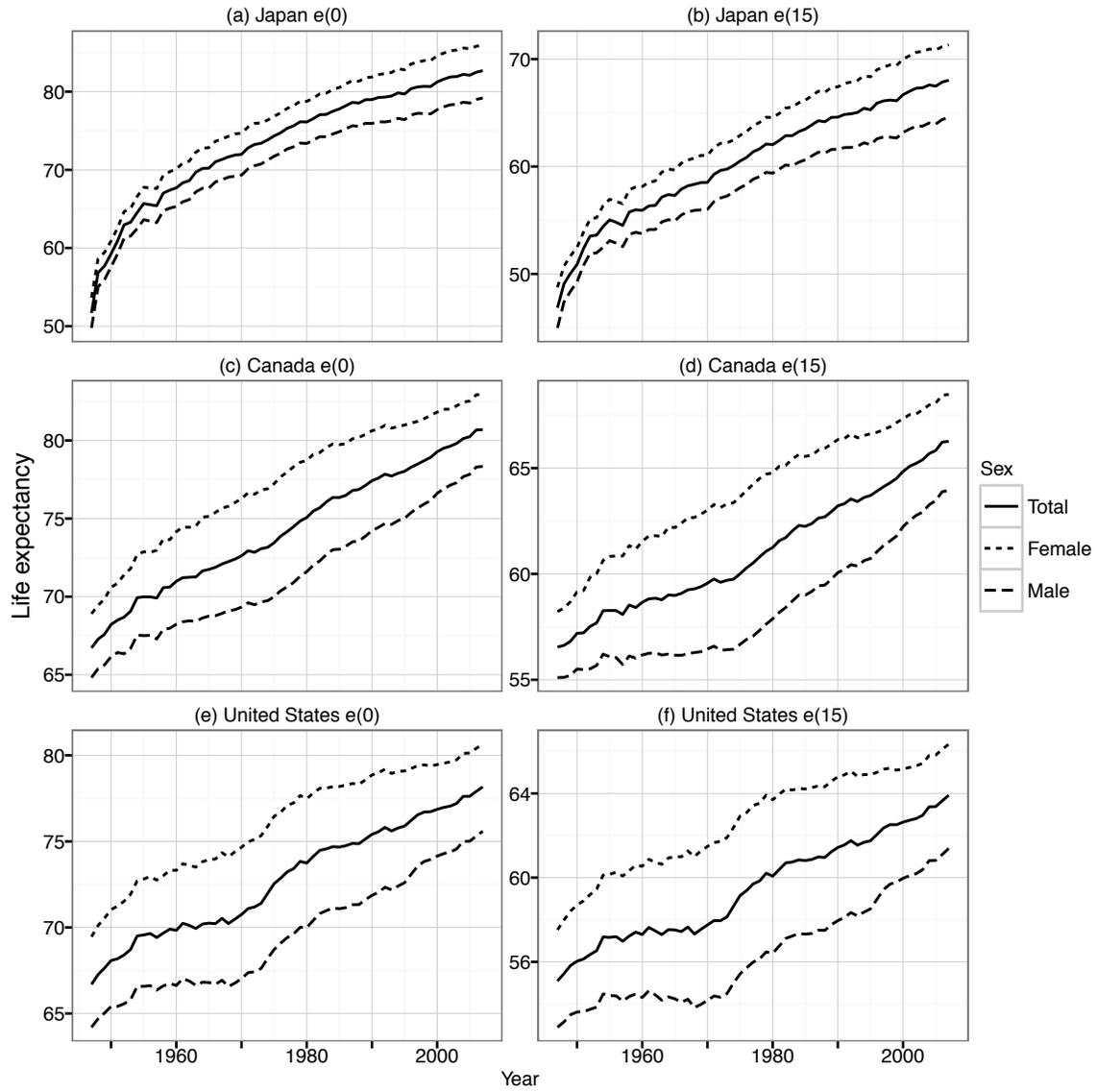
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1   **Fig. S4** The variance of age at death after 15 years, $V(15)$ in (a) Japan, (b) Canada and (c)

2   the United States from 1947 to 2007. Separate lines show the total population, females

3   only and males only
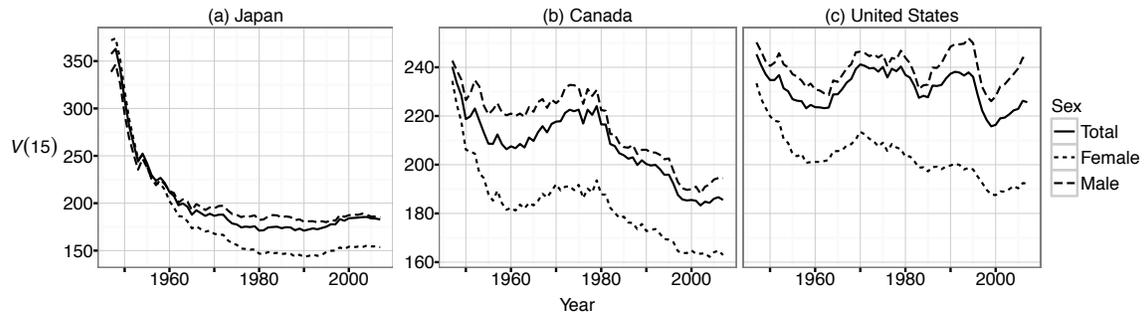
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1 **Fig. S5** The young–old threshold for individuals alive at 15 years, $T(15)$, for (a) Japan,

2 (b) Canada and (c) the United States from 1947 to 2007. Separate lines show the total

3 population, females only and males only. The blue lines show the fit of a loess smooth to

4 the integer values that arise from our use of mortality data in discrete one-year age and

5 period form
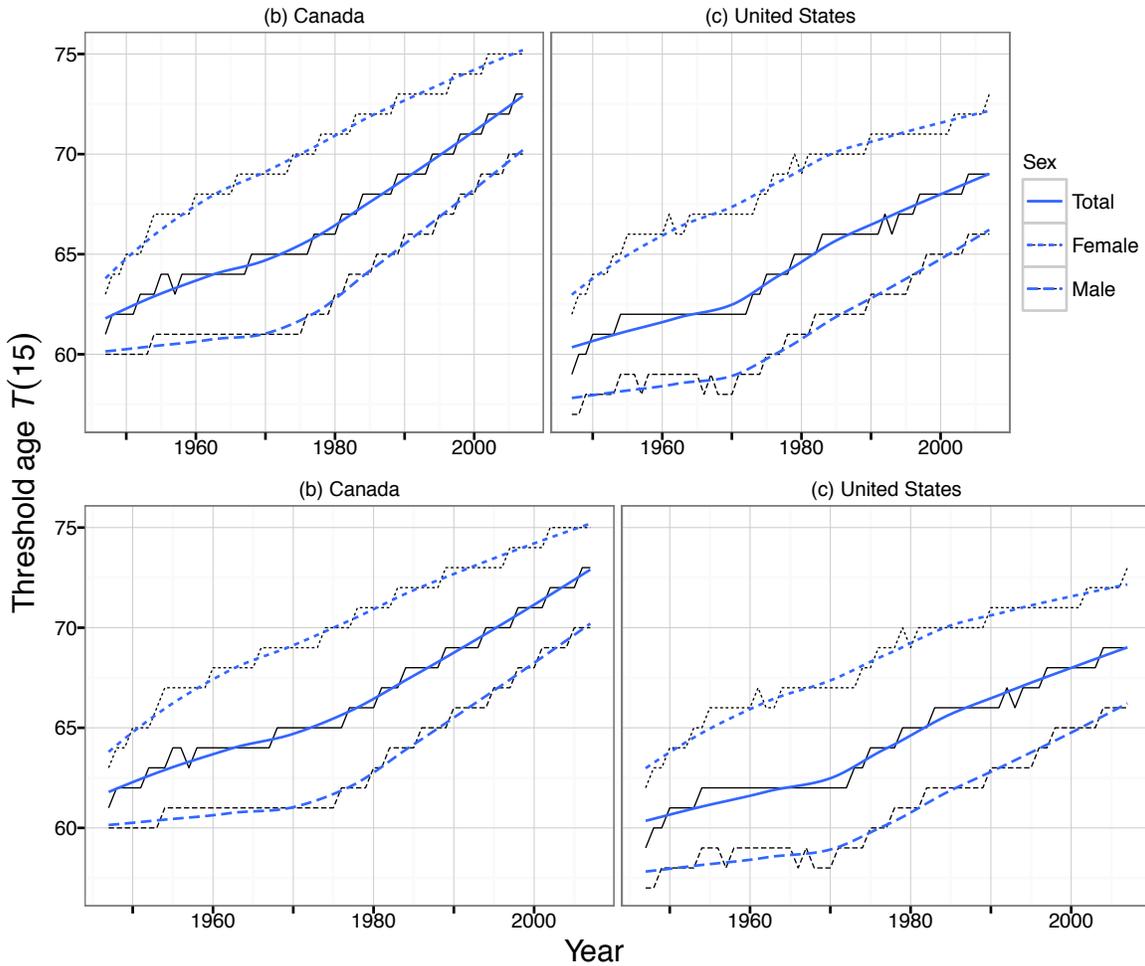
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1 **Fig. S6** Decomposition of the variance of age at death after 15 years, $V(15)$ into the

2 effects of mortality change at working ages (15–65 years) and retired ages (>65 years).

3 Solid lines show the total cumulative change, dashed lines the cumulative change

4 produced by working ages only, and dotted lines the cumulative change produced by

5 retired ages only. We computed separate decompositions for females and males in Japan

6 (a & b), Canada (c & d) and the United States (e & f) from 1947 to 2007

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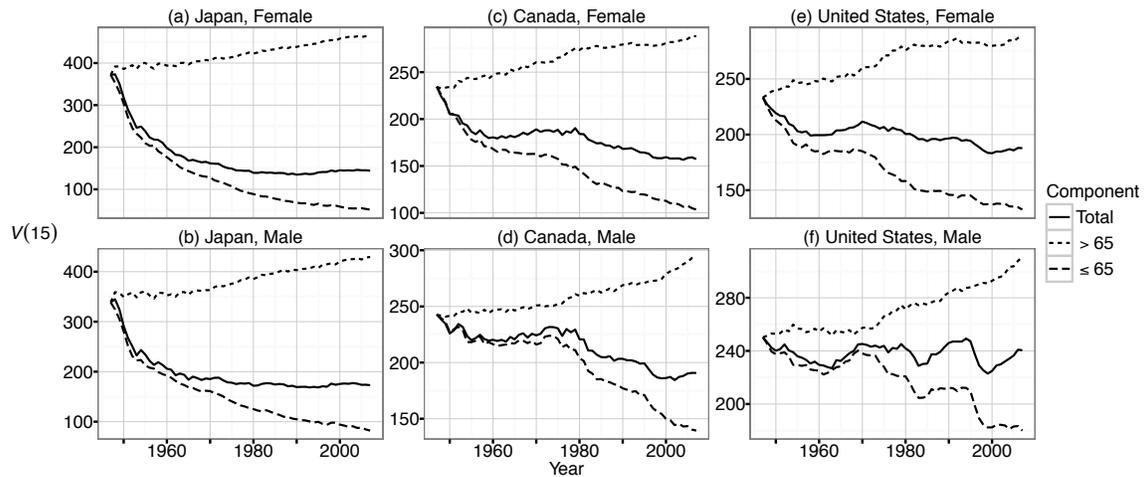
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1   **Fig. S7** Weighted average one-year central death rates between 15–65 years and above 65

2   years for each sex in Japan from 1947 to 2007. The weights used in the calculation were

3   proportional to the probability of survival to each age. The trajectories have been

4   standardized so that each ranges between zero and one

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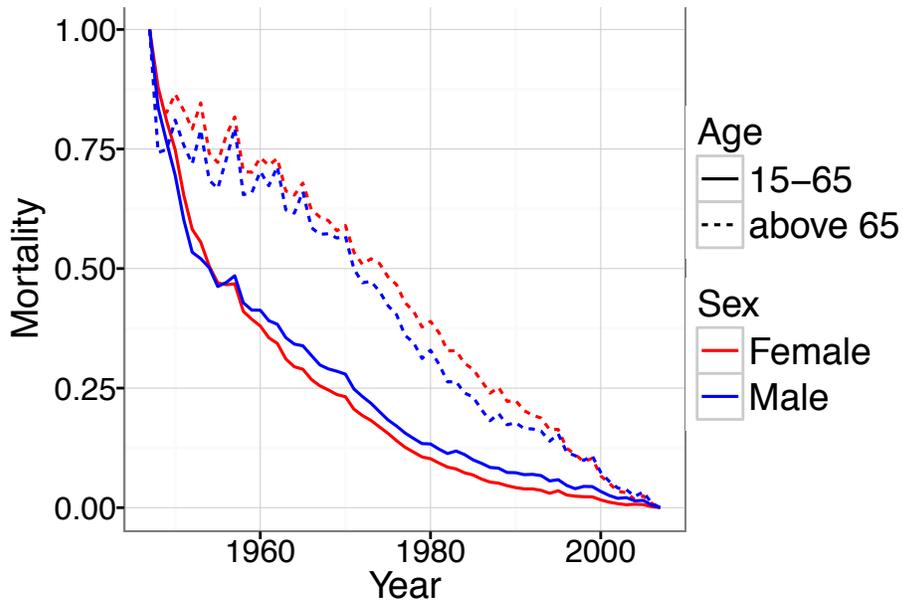
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1 **Table S1** Regional data series in the Human Mortality Database used in our international

2 comparisons. The earliest and latest years show the data availability for each series in the

3 period 1947–2011

4

Country or region	Earliest year	Latest year
Australia	1947	2009
Austria	1947	2010
Belgium	1947	2009
Bulgaria	1970	2010
Belarus	1970	2010
Canada	1947	2007
Switzerland	1947	2011
Chile	1992	2005
Czech Republic	1950	2011
West Germany	1956	2010
East Germany	1956	2010
Denmark	1947	2011
Spain	1947	2009
Estonia	1959	2010
Finland	1947	2009
France	1947	2010
England & Wales	1947	2009
Northern Ireland	1947	2009
Scotland	1947	2009
Hungary	1950	2009
Ireland	1950	2009
Iceland	1947	2010

Israel	1983	2009
Italy	1947	2009
Japan	1947	2009
Latvia	1970	2010
Luxembourg	1960	2009
Lithuania	1959	2010
Netherlands	1947	2009
Norway	1947	2009
New Zealand non-Maori	1947	2008
Poland	1958	2009
Portugal	1947	2009
Russia	1959	2010
Slovakia	1950	2009
Slovenia	1983	2009
Sweden	1947	2011
Taiwan	1970	2010
Ukraine	1970	2009
USA	1947	2010

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