The Implications of Increased Survivorship for Mortality Variation in Aging Populations

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Most nations pursue longer life spans for their citizens and celebrate the achievement of higher life expectancy. Trajectories of improved survival have been documented around the globe (Riley 2001, 2005), with life expectancy trends routinely used to summarize progress in population health (Robine 2006). Increased longevity has sparked predictions of compression in mortality and morbidity, a scenario under which nearly all people—rather than a fortunate few—will live long and healthy lives, ending at or very close to the maximum human life span (Fries 1980, 2003). Balanced against this expectation, however, is concern that the gap between those who achieve high longevity and those who fall short of the mark may be widening (Myers and Manton 1984a; Rothenberg et al. 1991; Murray et al. 2006).

Classic health transition theories attribute rising life expectancy to initial declines in childhood and reproductive-age mortality, followed by reductions in causes of death that operate in mid and later life (Horiuchi 1999; Riley 2001). This age-specific pattern of change is reflected in the transformation of the overall mortality distribution, with deaths increasingly concentrated around the most frequent age of death in adulthood, and with both the mean and modal age at death rising (Kannisto 2001; Canudas-Romo 2008). Most accounts of mortality change have focused on life expectancy at birth (e_0), a common measure of reference in studies of survival improvements (e.g., Oeppen and Vaupel 2002; White 2002) and health disparities (e.g., Wilkinson and Pickett 2006; Harper et al. 2007). While life expectancy at birth is a useful summary of mortality across all age groups, e_0 provides little insight into differences or variation in the ages

at death within populations. Mortality is arguably the ultimate measure of health, and thus inequalities in the length of life are the most fundamental manifestations of health disparities. As the 2005 *Human Development Report* (UNDP) asserted, addressing inequalities and uncertainties in mortality requires a fuller understanding of the changing age distribution of deaths—a task that, in turn, necessitates a more complete account of the distribution's variance.

In this article, we briefly chart the evolution of ideas about variation in ages at death, linking concepts from the literature on demographic transitions with the debates surrounding mortality compression. We then present analyses showing that although overall mortality variation decreased as life expectancy rose, survivors to older ages have become increasingly heterogeneous in their mortality risks. We argue that mortality disparities are shifting to older ages as survival in early life improves, and that growing inequalities in later life may be a byproduct of successfully delaying death.

From error to variation

Investigations of human mortality have taken place in the context of improved survival, with theories and methods evolving in conjunction with a growing stock of data. Early in the nineteenth century, the Belgian astronomer and social scientist Adolphe Quetelet demonstrated that, like celestial observations, human traits and certain social acts are subject to systematic variation. Quetelet concluded that variability among humans could be measured relative to an idealized *homme moyen* (average man) and that it was simply an error destined to be minimized. In 1835, he wrote:

> One of the principal acts of civilization is to compress more and more the limits within which the different elements relative to man oscillate. The more that enlightenment is propagated, the more will deviations from the mean diminish; moreover, as a consequence we tend to unite ourselves with what is beautiful and with what is good (Quetelet 1835, Vol. 2, p. 326. trans. Porter 1986, p. 104).[1]

In many ways this prognosis has influenced both theoretical and analytic approaches to human behavior, and Quetelet's configuration of the error law (or normal distribution) as a tool ultimately moved social scientists to pay more attention to variation about the mean and to investigate its underlying causes (Porter 1986).

These ideas influenced the nascent discipline of demography through the work of Wilhelm Lexis, a German statistician who studied mortality through the lens of distributional regularities (Véron and Rohrbasser 2003). Lexis's *theory of normal life* emphasized a "normal age"—corresponding to the

mode of old-age mortality—which represented the length of life that each individual could expect in the absence of premature mortality (Lexis 1877, 1878). Like Quetelet, Lexis attached a normative as well as descriptive value to the center of the mortality distribution (Véron and Rohrbasser 2003). He calculated the probability of deviation from the normal age for various European populations (1878) and interpreted the consistency of this variability measure across populations as a mathematical regularity representing the randomness inherent in natural phenomena. Changes over time in the observed patterns of mortality variation, however, indicated to subsequent researchers that more than statistical randomness was at work.

Declining deaths and visible variation

During the twentieth century, awareness of substantial survival improvements prompted the formulation of demographic and epidemiologic transition theories (Thompson 1929; Notestein 1945; Omran 1971, 1983), while the accumulation of data and expansion of statistical techniques permitted increasingly rigorous analyses of mortality distributions and their dynamics.

The notion of rectangularization of the survival curve was introduced by Comfort (1956) and later propagated by Fries (1980), who argued that the population survival trajectory (the complement of the mortality curve) becomes rectangular as life expectancy at birth approaches a fixed upper limit of the human life span. Full rectangularization in survival would require a true maximum human life span, or a complete lack of variability in ages at death (Manton and Singer 1994). Empirical trends of survival rectangularization are clear in many countries (see, for example, Wilmoth and Horiuchi 1999; Shkolnikov, Andreev, and Begun 2003; Cheung et al. 2005), and some demographers project that increases in life expectancy will eventually slow or cease (Carnes and Olshansky 2007). Ongoing research has shown no evidence for an approaching upper limit to human life expectancy (Caselli and Vallin 2001; Oeppen and Vaupel 2002), however, and has thus forced upward revision of both life expectancy and the postulated life span limit of the compression hypothesis (Fries 2003; Carnes and Olshansky 2007).

Fries (1980) maintained that rectangularization reflects a compression of both mortality and morbidity toward the very end of life, defining the ideal survival curve as having a standard deviation of four years around a maximum life expectancy of 85, with the upper limit life span of 100 years approximately four standard deviations away. Fries's notion of compression, with its normative emphasis on the average life span and its anticipation of diminished variation resulting from the elimination of premature mortality, is thus closely related both to Lexis's characterization of an ideal normal age and Quetelet's conception of declining variation as a social good.

Subsequent studies attempted to challenge or buttress the notion of mortality compression by exploring trends in the standard deviation of the mortality distribution. Myers and Manton (1984a) showed that when all deaths were considered, the standard deviation had a negative correlation with the level of life expectancy, but when the analysis was focused on deaths above age 60 the correlation was positive—with the standard deviation around mean adult mortality rising over time, in contrast to the compression hypothesis. Fries (1984) criticized the arbitrary choice of 60 years as the cutoff age and called for a focus on the main theme of survival improvement, rather than the variation around it. In response, Myers and Manton (1984b) showed that calculations of standard deviations based on a range of survival percentiles were approximately constant in the US population between 1962 and 1979. In a later study, Rothenberg et al. (1991) reported that rising life expectancy in the United States was accompanied by an increase in the standard deviation, and he projected an "expansion of mortality."

Nusselder and Mackenbach (1996) and Robine (2001) also examined trends in the standard deviation for the Netherlands and France, respectively. They showed that results depended markedly on whether the distribution of ages at death was complete or truncated (i.e., conditional on survival to a particular age), and on the starting age used in the truncated calculations. Because survival has improved dramatically over the course of the twentieth century, conclusions regarding the compression of mortality and morbidity are not only dependent on the age range selected for analysis, but also potentially contingent on the time frame of the analysis and the demographic trajectory of a given population.

In reviewing empirical findings about the dispersion in life spans and the polemics inspired by the use of numerous variability indicators, Robine (2001: 187) noted that measures conditional on survival past childhood exclude information on deaths at younger ages and concluded that "only a calculation which includes all life spans or deaths is beyond criticism." Subsequent studies, however, have presented strong arguments for using variability measures conditional on survival to age 10 (Edwards and Tuljapurkar 2005) or age 15 (Smits and Monden 2009) in order to focus on adult mortality in aging populations. These studies have highlighted the advantages of conditional measures in revealing both unexpected patterns in adult mortality variability and cross-country differences otherwise obscured by unconditional measures that are, necessarily, weighted toward mortality in early life. Kannisto (2001: 170) likewise argued that dispersion *above* the modal age of death "may give clues as to any limits to human life and to the length-of-life distribution that may be expected." This is consistent with recent improvements in old-age survival that extend the upper tail of the survival curve further out to the right, thereby countering the

rectangularization trend (Yashin et al. 2001). Thus, in recent decades, studies of mortality have moved from the assumption of variation as random error to examination of shifting variation in years of life as an indicator of changes in underlying population health. In biology, too, advances in theory and technology have led to more thorough investigations of the nature of variation in phenotypic traits both within and across populations (Lewontin 1982).

We now explore the linkage between the dynamics of mortality selection and the persistence and increase of mortality variation in later life. Rather than stake a claim about which indicator is preferable, we juxtapose trends in unconditional as well as successive conditional measures and seek an explanation accounting for the systematic differences these trends reveal. The mortality compression hypothesis posits that as an upper limit to the human life span is approached, variation in mortality will almost completely disappear (Fries 1980, as anticipated by Quetelet 1835). Our analysis challenges this assertion and provides further evidence that mortality variability does not fully conform to the mortality compression hypothesis.

Data and methods

The Human Mortality Database (HMD 2009) contains detailed time series of mortality data and life tables for populations with virtually complete[2] registration and census data. To examine the changing distribution of ages at death during periods of notable mortality transitions, we analyzed life tables for males and females from 23 national populations with at least five decades of data.[3] Table 1a and Table 1b list these populations and life expectancy for females and males at four selected ages. The upper panels in each table include 12 national populations with data stretching back to 1900; the lower panels list 11 additional countries with reliable data from 1950 onward. The tables present a percent-change summary along with the absolute values of each measure at the beginning and end of the time series. It is clear that life expectancy at all ages increased during the twentieth century, with the relative increase at the oldest ages exceeding that of life expectancy at birth in numerous cases. For each population, we investigated variability patterns in the complete distribution of ages at death as well as in distributions conditional on survival to successively older ages. While most analyses described below are based on period life tables, we also made use of the available cohort life tables and compared the observed trends.

As a result of the HMD's requirements for complete and comprehensive population data, the countries and areas included in the database are for the most part highly industrialized. While not representative of all of the world's countries, they nonetheless allow a systematic analysis of the relationship between rising longevity and inequality in the ages of death.

TABLE 1a Female life expectancy at birth (e_0) and for survivors at ages 10 (e_{10}), 50 (e_{50}), and 75 (e_{75}): Two period measures and a summary of relative change

	(e_0) (years)			(e_{10}) (years)			(e_{50}) (years)			(e_{75}) (years)		
Country	**1900**	**2006**	Δe_0 (%)	**1900**	**2006**	Δe_{10} (%)	**1900**	**2006**	Δe_{50} (%)	**1900**	**2006**	Δe_{75} (%)
Belgium	48.4	82.2	69.9	52.8	72.6	37.5	21.5	33.7	56.7	6.4	12.5	95.8
Denmark	53.5	80.5	50.4	54.0	70.9	31.3	22.7	31.9	40.5	6.8	11.8	73.7
England and Wales	48.2	81.7	69.5	52.0	72.2	38.8	20.3	33.3	64.2	6.6	12.4	89.3
Finland	43.2	82.8	91.8	50.8	73.1	43.9	21.9	34.2	56.2	6.4	12.8	99.8
France	46.9	84.2	79.5	50.4	74.5	47.9	20.9	35.7	71.1	6.1	14.1	131.1
Iceland	49.6	82.8	66.9	49.8	73.0	46.5	20.4	33.9	66.0	6.9	12.8	86.1
Italy*	41.8	83.7	100.2	50.3	74.1	47.3	20.5	34.9	69.9	5.6	13.1	135.2
Netherlands	49.8	81.9	64.4	53.5	72.3	35.0	21.9	33.3	52.1	6.6	12.3	86.6
New Zealand (non-Maori)***	60.8	82.1	35.1	57.2	72.6	26.8	24.2	33.7	39.4	8.5	12.6	48.4
Norway	55.2	82.7	49.9	53.9	73.0	35.4	24.6	34.0	38.4	8.0	12.6	58.6
Sweden	53.6	82.9	54.6	54.0	73.2	35.7	23.9	34.1	42.9	7.3	12.8	74.7
Switzerland	48.8	84.0	71.9	50.5	74.4	47.2	19.5	35.3	80.9	5.5	13.5	144.8
	1950	**2006**	Δe_0 (%)	**1950**	**2006**	Δe_{10} (%)	**1950**	**2006**	Δe_{50} (%)	**1950**	**2006**	Δe_{75} (%)
Australia**	71.8	83.4	16.2	63.9	73.9	15.5	26.6	34.9	31.1	8.7	13.4	54.3
Austria*	67.3	82.2	22.1	62.3	72.7	16.6	25.6	33.7	31.8	7.9	12.3	56.3
Canada*	70.6	82.5	16.9	64.0	73.0	14.2	26.8	34.2	27.5	8.9	13.2	48.2
Czech Republic	66.9	79.9	19.5	61.8	70.2	13.6	25.0	31.2	24.7	7.4	10.7	44.6
Hungary*	64.3	77.2	20.1	60.9	67.7	11.2	25.0	29.4	17.5	7.8	10.2	31.2
Ireland	66.7	81.9	22.7	60.3	72.2	19.8	24.9	33.3	33.6	7.9	12.1	53.9
Japan	60.9	85.8	40.9	57.1	76.1	33.3	23.9	37.1	55.2	7.5	15.0	99.5
Portugal	61.0	82.2	34.7	61.1	72.5	18.6	26.2	33.7	28.4	8.5	12.0	42.2
Slovakia	62.6	78.4	25.3	61.0	69.0	13.1	25.3	30.1	19.2	8.2	10.1	23.9
Spain	64.2	84.1	30.9	61.4	74.4	21.2	26.2	35.4	35.2	8.5	13.3	56.0
United States*	71.0	80.4	13.2	63.6	71.0	11.7	26.6	32.7	23.0	9.1	12.7	39.9

NOTE: Last year of data: *2005; **2004; ***2003. Country calculations for all years relate to populations in the same geographic territory, even in cases where borders have changed. For any given population with data ranging from year $t–n$ to year t, the percent change in life expectancy at age a (Δe_a) was calculated relative to the starting year with the formula: $\Delta e_a = 100*(e_{a,t} - e_{a,t-n})/e_{a,t-n}$.
SOURCE: Period life tables from the Human Mortality Database 2009.

TABLE 1b Male life expectancy at birth (e_0) and for survivors at ages 10 (e_{10}), 50 (e_{50}), and 75 (e_{75}): Two period measures and a summary of relative change

	(e_0) (years)			(e_{10}) (years)			(e_{50}) (years)			(e_{75}) (years)		
Country	**1900**	**2006**	Δe_0 (%)	**1900**	**2006**	Δe_{10} (%)	**1900**	**2006**	Δe_{50} (%)	**1900**	**2006**	Δe_{75} (%)
Belgium	44.8	76.5	70.8	50.7	67.0	32.2	19.5	29.0	49.2	5.9	10.0	69.3
Denmark	50.2	75.9	51.2	52.0	66.3	27.4	20.8	28.2	36.0	6.2	9.7	57.7
England and Wales	44.4	77.5	74.7	49.2	68.0	38.2	18.4	29.9	62.1	6.0	10.5	74.8
Finland	40.3	75.8	88.0	48.9	66.1	35.3	20.1	28.6	42.3	5.8	10.1	74.4
France	43.2	77.2	78.6	47.9	67.7	41.2	19.0	29.9	57.4	5.5	11.1	101.4
Iceland	43.7	79.4	81.5	43.7	69.5	59.2	17.4	31.3	79.8	6.5	11.2	71.7
Italy*	41.6	78.2	88.2	50.6	68.6	35.5	20.1	30.2	50.3	5.7	10.5	84.5
Netherlands	47.0	77.6	65.1	52.3	68.1	30.2	20.9	29.5	41.0	6.4	9.8	54.6
New Zealand (non-Maori)***	58.6	77.9	32.8	56.0	68.4	22.1	22.9	30.3	32.4	7.5	10.4	38.9
Norway	51.8	78.1	50.9	51.3	68.5	33.7	23.2	30.3	30.6	7.4	10.4	41.3
Sweden	50.8	78.7	54.9	52.2	69.0	32.2	22.3	30.5	36.5	6.7	10.5	56.2
Switzerland	46.1	79.1	71.4	49.3	69.6	41.2	18.4	31.1	68.9	5.7	11.0	94.9
	1950	**2006**	Δe_0 (%)	**1950**	**2006**	Δe_{10} (%)	**1950**	**2006**	Δe_{50} (%)	**1950**	**2006**	Δe_{75} (%)
Australia**	66.5	78.6	18.1	59.2	69.1	16.8	22.8	31.0	36.4	7.4	11.1	50.3
Austria*	62.2	76.7	23.2	58.1	67.1	15.4	22.4	29.1	29.7	7.1	10.2	44.4
Canada*	66.2	77.9	17.7	60.3	68.4	13.6	23.9	30.4	26.8	8.0	10.9	37.3
Czech Republic	62.0	73.5	18.5	57.7	63.9	10.7	22.0	26.0	18.4	6.8	8.8	29.3
Hungary*	59.9	68.7	14.8	57.5	59.3	3.2	22.8	22.7	–0.5	7.2	8.3	14.8
Ireland	64.5	77.3	19.8	58.8	67.7	15.2	23.1	29.4	27.5	7.1	9.8	37.7
Japan	57.6	79.0	37.2	54.0	69.4	28.5	21.0	31.0	47.7	6.4	11.3	76.8
Portugal	55.8	75.5	35.3	56.1	65.9	17.4	22.7	28.6	26.1	7.1	9.8	37.7
Slovakia	59.1	70.4	19.0	58.5	61.1	4.5	23.5	23.9	1.6	7.3	8.1	10.2
Spain	59.4	77.6	30.7	56.7	68.0	19.9	22.7	29.9	32.0	7.2	10.8	50.9
United States*	65.4	75.2	15.0	58.4	65.9	12.9	22.6	28.9	27.7	7.8	10.8	38.2

NOTES: Last year of data: *2005; **2004; ***2003. Country calculations for all years relate to populations in the same geographic territory, even in cases where borders have changed. For any given population with data ranging from year $t–n$ to year t, the percent change in life expectancy at age a (Δe_a) was calculated relative to the starting year with the formula: $\Delta e_a = 100*(e_{a,t} - e_{a,t-n})/e_{a,t-n}$.
SOURCE: Period life tables from the Human Mortality Database 2009.

Measures of variability

The life table function describing the distribution of deaths by age is denoted by *d(x)*. Using data for males and females, we examined both the complete distribution of ages at death and left-truncated or conditional distributions comprising only individuals who survived up to a specified age *a*. For the complete distribution, the mean age of death is equal to life expectancy at birth, or e_0. For the distributions conditional on survival to age *a*, the mean age at death is equal to the sum of *a* and the remaining life expectancy at that age, e_a.

The variance of each distribution was calculated by averaging the squared distance of all ages at death from their mean value.[4] The standard deviation of the mortality distribution for survivors to age *a* in any year *t* is the square root of the variance and is given by:

$$s_{a,t} = \sqrt{\frac{\int_a^{\omega} (x-a)^2 d(x)dx}{l_a} - (e_a)^2} \qquad (1)$$

where *x* represents age at death, l_a represents the population of survivors to age *a*, and ω is the last age attained by a person in the life table. Note that this general formula applies to the complete (unconditional) mortality distribution when *a*=0. The three life table functions in equation (1)— l_a, *d(x)*, and e_a—are taken from a period life table at time *t*. For the HMD data used in this analysis, $\omega = 110$, and all deaths at or above age 110 are included in this final category. This right-truncation in the terminal age category means that our calculations may slightly underestimate the true variation if the mortality distribution is becoming more skewed toward the upper ages.

Tracking relative change

Both the standard deviation and the magnitude of its change over time vary by the age cutoff. Distributions that cover younger ages have a wider range and thus a larger potential variance. In order to compare trends in each age-specific measure on a single scale, we also constructed a standardized measure of deviation that allows simultaneous comparisons across all ages and historical periods with available data. In particular, we standardized each age-specific standard deviation ($s_{a,t}$) in year *t* to its value in 1900 (or 1950, in the case of populations with later data only) and tracked the trend in this relative ratio, $r_{a,t}$, given by:

$$r_{a,t} = s_{a,t} / s_{a,1900} \qquad (2)$$

The resulting ratios are equal to 1 if there was no change in the standard deviation for survivors to any given age *a* since 1900, and the comparison of

trends in the age-specific relative deviation measures allows us to distinguish rising and falling patterns on the same scale.

These relative deviation ratios are displayed using contour plots for males and females. The plots allow a representation of each ratio's three dimensions. Each square on the plot was defined by year on the horizontal *(x)* axis and age on the vertical *(y)* axis. Color was assigned according to the value of the ratio calculated by dividing the standard deviation in year *x* and conditional on survival to age *y* by the age-specific value in the reference year, 1900. (For the 11 populations with a time series of data starting after 1900, we standardized each value relative to its 1950 level.) White represents the reference value (a ratio equal to one); successively darker shades of blue represent declining values below the reference; and successively darker shades of red represent increasing values above the reference.

Historical populations contained very few centenarians, making longitudinal comparisons impractical for the oldest segment of the population. While data on mortality at all ages (0–110 years) were used to calculate standard deviations, the highest conditional measure displayed in the contour plots is the relative standard deviation for survivors to age 100.

In addition to country-specific measures, we also followed trends in two measures meant to capture respectively the average and record-low mortality variation across all populations included in this analysis. The first of these measures was the mean relative ratio, which averages the age-specific standardized ratios across national populations. The mean relative ratio was calculated as

$$\bar{r}_{a,t} = \frac{\bar{s}_{a,t}}{\bar{s}_{a,1900}} \tag{3}$$

where $\bar{s}_{a,t}$ is the mean standard deviation in the distribution of mortality for survivors to age *a* (on the *y*-axis) in year *t* (*x*-axis) across the national populations with data for year *t*. By dividing the age-specific mean at year *t* by the age-specific mean in 1900, we obtained a relative ratio. The trend over time in this ratio describes the change in average age-specific variability across the populations we examined. For the years 1900–50, our sample thus included 12 countries, while the calculations from 1950 onward incorporated data on up to 23 countries with data available for analysis, depending on the exact length of each country's time series.

The record-low mortality variation measure denotes the minimum value of a given age- and time-specific measure across all countries. Lower variation indicates less uncertainty and inequality in the morality distribution, and the minimum measure suggests that the country holding the record has a more equal distribution of deaths relative to other countries. To identify the record-low variability for every age, we calculated the minimum measure across all countries with available data in a given year ($\underline{s}_{a,t} = \min(s^i_{a,t})$, with the index

i for country). As described above, we tracked the trend in this measure via a relative ratio calculated as

$$\underline{r}_{a,t} = \frac{\underline{s}_{a,t}}{\underline{s}_{a,1900}} \quad (4)$$

where the minimum value for each age- and year-specific value of $s_{a,t}$ was divided by the age-specific minimum value in 1900 to obtain the relative ratio $\underline{r}_{a,t}$. Again, the minimum calculation for the years 1900–50 incorporated data for the 12 national populations with available data, while the calculations for 1950 onward incorporated data from up to 23 populations.

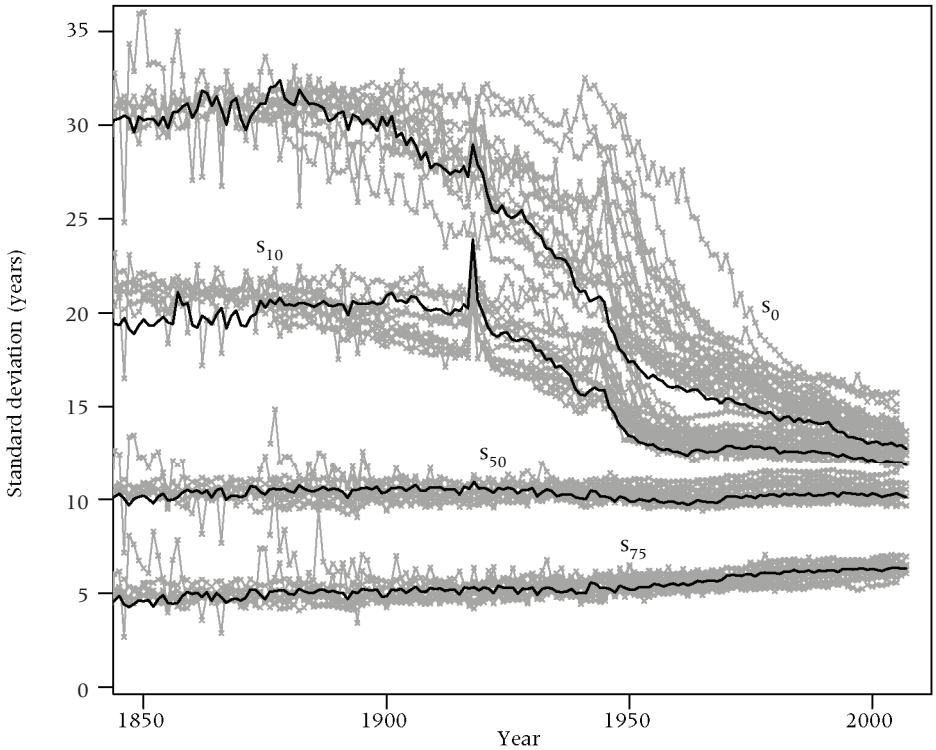
Results

Figures 1a and 1b present trends in four standard deviation measures in 23 populations for females and males, respectively. The figures highlight Sweden, which has the longest available record. The upper curve depicts the declining value of the standard deviation of the complete mortality distribution (s_0) over time. The curve immediately below shows the trajectory for survivors to age 10 (s_{10}), indicating the trend in mortality variability beyond childhood. The third line from the top represents the standard deviation of mortality for survivors to age 50 (s_{50}), an approximate threshold between younger and older ages coinciding with the end of the main reproductive years, particularly for women. Finally, the lower line tracks the standard deviation of mortality for those aged 75 and above (s_{75}), marking the survivors into old age.

Trends in these measures reflect the profound demographic changes of the past century for males and females alike. Variability in the complete mortality distribution (s_0) fluctuated at high levels during the nineteenth century, declined markedly during the first half of the twentieth century, and continued declining at a slower pace in recent decades. The age of death rose on average, and it also became more certain as the mortality distribution grew less dispersed. Upward spikes in the curve reflect the high mortality associated with the 1918 influenza epidemic and World War II, both of which disturbed the otherwise downward trend. Swedish females and males have experienced lower mortality variability than most of their international counterparts, but the pattern of decline applies across national populations. Variability in the mortality distribution for survivors to age 10 (s_{10}) followed a similar trajectory to s_0, albeit at lower levels. Notably, the gap between the two measures of variability narrowed considerably over time.

The same decline is not evident in the other two conditional measures. For survivors to age 50, the variability trend (s_{50}) is nearly flat. For survivors to age 75, mortality variability (s_{75}) appears to have increased, most noticeably in the past half century. The convergence of the three trend lines is thus due

FIGURE 1a Trends in standard deviations of mortality distributions for females: full population (s_0) and survivors at ages 10 (s_{10}), 50 (s_{50}), and 75 (s_{75})



NOTE: Calculated using life tables from 23 national populations, 1850–2006. Trends for Sweden are shown by the black lines.
SOURCE: HMD 2009.

not only to the decline in s_0 and s_{10} but to some extent also to a countervailing increase in the variability of mortality among survivors to older ages.

The pattern identified above is common to industrialized countries with sufficiently long time series of data.[5] Table 2a and Table 2b summarize the changing magnitude of the four deviation measures for females and males in these 23 populations over time. They also provide the percent change in each measure relative to its starting point. Despite differing demographic trajectories, the similarities across populations are clear. In all cases, variation in the complete mortality distribution decreased dramatically. A similarly large decline is apparent in the distribution of mortality among survivors to age 10 (except in the case of the United States, which is discussed below). The opposite phenomenon—increased mortality variation—is observed for the older population in all settings. Variation in mortality for survivors to age 50 does not show a distinctive pattern, and changes are relatively small, particularly for females. Across countries, the trajectories for men and women are very

TABLE 2a Two period measures and a summary of relative change in standard deviations of mortality distributions for females: Full populations (s_0) and survivors at ages 10 (s_{10}), 50 (s_{50}), and 75 (s_{75})

	(s_0) (years)			(s_{10}) (years)			(s_{50}) (years)			(s_{75}) (years)		
Country	**1900**	**2006**	Δs_0 (%)	**1900**	**2006**	Δs_{10} (%)	**1900**	**2006**	Δs_{50} (%)	**1900**	**2006**	Δs_{75} (%)
Belgium	30.9	13.7	–55.6	19.0	12.5	–34.4	10.0	10.4	3.7	4.6	6.3	37.4
Denmark	29.4	13.6	–53.5	19.6	12.7	–35.4	10.1	10.9	7.1	4.8	6.5	37.3
England and Wales	30.0	14.0	–53.2	18.2	12.6	–30.8	10.4	10.6	1.9	4.8	6.6	37.2
Finland	32.1	13.2	–58.8	21.0	12.4	–40.9	9.9	10.2	3.0	4.6	6.3	36.6
France	30.3	13.9	–54.1	19.9	12.8	–35.7	9.9	10.6	6.5	4.5	6.7	49.5
Iceland	28.9	13.0	–55.0	20.4	11.9	–41.4	10.4	10.5	0.5	4.5	6.5	44.8
Italy*	31.7	12.9	–59.4	19.7	11.7	–40.6	9.4	10.0	6.3	4.4	6.5	47.6
Netherlands	30.7	13.5	–56.1	18.9	12.2	–35.2	10.1	10.4	2.9	4.7	6.3	33.2
New Zealand (non-Maori)***	26.5	14.0	–47.0	18.8	12.7	–32.5	11.1	10.4	–6.4	5.6	6.5	15.1
Norway	29.4	13.1	–55.5	21.5	12.1	–43.7	10.8	10.2	–5.9	5.3	6.3	19.1
Sweden	30.0	13.0	–56.8	20.9	11.8	–43.5	10.4	10.2	–1.8	4.8	6.3	30.9
Switzerland	28.8	13.4	–53.4	18.5	11.9	–35.3	9.5	10.1	7.1	4.2	6.5	52.7
	1950	**2006**	Δs_0 (%)	**1950**	**2006**	Δs_{10} (%)	**1950**	**2006**	Δs_{50} (%)	**1950**	**2006**	Δs_{75} (%)
Australia**	18.9	13.9	–26.5	14.5	12.5	–13.6	10.5	10.3	–1.8	5.7	6.7	18.0
Austria*	23.1	13.4	–42.0	14.8	12.1	–18.6	10.1	10.1	–0.5	5.3	6.2	18.3
Canada*	21.0	14.4	–31.5	14.7	12.9	–12.1	10.6	10.8	1.5	5.8	6.8	18.1
Czech Republic	22.9	13.0	–43.4	14.7	12.0	–18.2	9.9	10.1	2.7	5.1	6.0	17.4
Hungary*	25.5	14.8	–42.1	16.0	12.3	–16.6	10.3	10.9	5.9	5.2	6.1	16.0
Ireland	22.1	13.3	–40.0	16.5	12.3	–25.6	10.5	10.3	–2.0	5.5	6.5	18.5
Japan	25.9	13.5	–47.8	18.3	12.5	–31.6	10.4	10.4	0.1	5.1	7.0	37.6
Portugal	29.3	13.1	–55.3	17.4	12.0	–31.0	10.5	9.8	–6.8	5.7	6.2	7.7
Slovakia	27.4	13.8	–49.6	16.3	12.1	–25.5	10.4	10.2	–1.7	5.4	5.9	10.8
Spain	26.7	12.9	–51.5	17.0	11.8	–30.9	10.5	9.8	–7.3	5.8	6.4	10.2
United States*	19.9	15.7	–20.8	15.0	14.2	–6.0	11.0	11.4	3.8	6.0	7.0	16.9

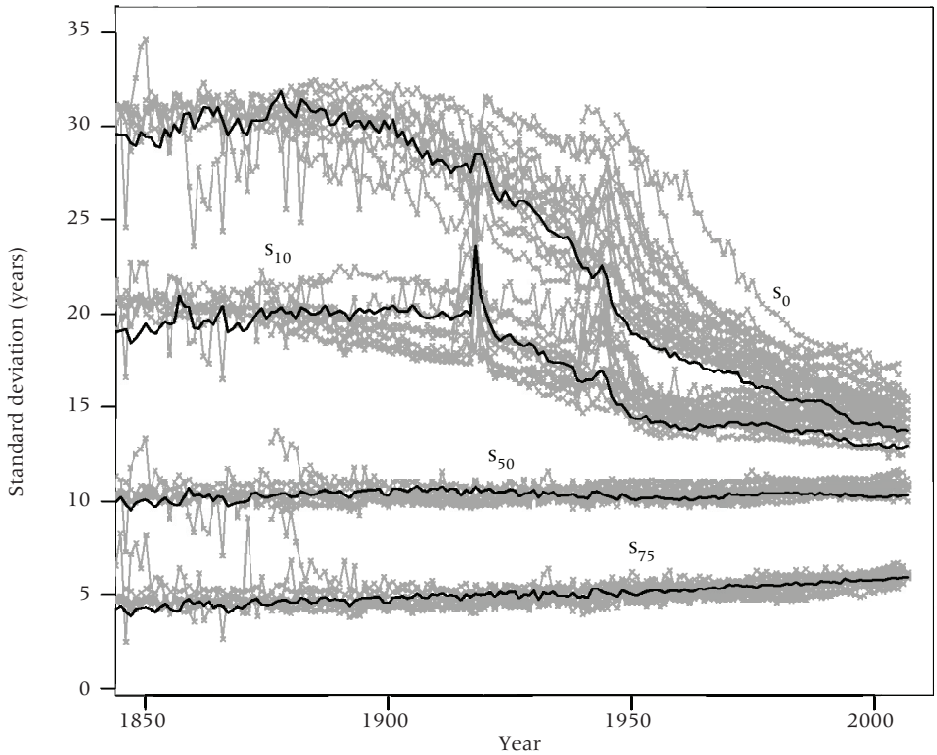
NOTES: Last year of data: *2005; **2004; ***2003. For any given population with data ranging from year $t–n$ to year t, the percent change in s_a (Δs_a) was calculated relative to the starting year with the formula: $\Delta s_a = 100*(s_{a,t} - s_{a,t-n})/(s_{a,t-n})$.
SOURCE: Period life tables from the Human Mortality Database 2009.

TABLE 2b Two period measures and a summary of relative change in standard deviations of mortality distributions for males: Full populations (s_0) and survivors at ages 10 (s_{10}), 50 (s_{50}), and 75 (s_{75})

	(s_0) (years)			(s_{10}) (years)			(s_{50}) (years)			(s_{75}) (years)		
Country	**1900**	**2006**	Δs_0 (%)	**1900**	**2006**	Δs_{10} (%)	**1900**	**2006**	Δs_{50} (%)	**1900**	**2006**	Δs_{75} (%)
Belgium	30.5	15.1	–50.6	18.2	14.0	–23.3	10.0	10.8	7.6	4.3	5.9	36.5
Denmark	29.3	14.8	–49.3	18.7	13.7	–26.6	10.0	10.9	8.5	4.3	6.0	69.2
England and Wales	29.6	15.1	–48.9	17.9	13.8	–23.2	10.1	10.8	6.2	4.5	6.3	40.6
Finland	31.4	15.6	–50.4	20.4	14.8	–27.2	9.9	11.2	13.2	4.1	6.0	46.9
France	29.8	15.8	–47.1	19.3	17.8	–23.4	9.8	11.5	17.4	4.1	6.4	55.4
Iceland	27.3	14.0	–48.8	20.0	13.0	–35.1	10.2	10.0	–1.7	5.6	5.9	5.8
Italy*	31.8	14.4	–54.8	19.1	13.3	–30.5	9.7	10.5	8.4	4.4	6.1	39.8
Netherlands	31.0	13.9	–55.2	18.7	12.5	–33.0	10.0	10.2	1.7	4.5	5.8	29.0
New Zealand (non-Maori)***	26.7	15.0	–43.8	18.1	13.7	–24.2	10.6	10.3	–3.0	5.4	6.1	12.8
Norway	29.6	14.5	–50.9	21.8	13.5	–38.2	10.7	10.4	–3.2	4.9	5.9	21.3
Sweden	29.9	13.8	–53.9	20.2	13.0	–35.9	10.3	10.3	–0.2	4.6	5.9	30.4
Switzerland	29.0	14.4	–50.4	18.1	13.3	–26.5	9.9	10.6	6.9	4.2	6.2	47.2
	1950	**2006**	Δs_0 (%)	**1950**	**2006**	Δs_{10} (%)	**1950**	**2006**	Δs_{50} (%)	**1950**	**2006**	Δs_{75} (%)
Australia**	19.7	15.3	–22.5	15.1	13.9	–7.7	10.4	10.6	1.6	5.4	6.4	19.4
Austria*	24.2	15.2	–37.3	15.6	14.0	–10.2	10.4	10.9	5.6	4.9	6.0	24.0
Canada*	22.1	15.5	–30.0	15.5	14.1	–9.0	10.7	10.9	1.5	5.4	6.4	18.3
Czech Republic	23.9	14.9	–37.6	15.6	13.9	–10.8	10.2	10.9	6.9	4.7	5.6	17.4
Hungary*	26.4	16.2	–38.9	16.8	14.8	–12.1	10.5	11.5	9.7	5.0	5.8	15.4
Ireland	22.4	14.4	–35.8	15.7	13.3	–15.7	10.4	10.2	–1.4	5.1	5.9	17.2
Japan	25.2	14.7	–41.7	17.5	13.7	–21.7	10.0	11.0	10.5	4.6	6.5	41.7
Portugal	28.7	15.3	–46.6	17.7	14.4	–18.2	10.3	10.8	4.7	5.0	5.9	16.9
Slovakia	28.0	15.8	–43.6	16.8	14.2	–15.2	10.4	10.9	4.3	5.0	5.6	12.1
Spain	26.4	15.2	–42.4	17.4	14.1	–18.9	10.5	11.1	6.3	5.2	6.3	22.1
United States*	20.8	17.4	–16.5	15.8	15.8	0.0	11.0	11.7	6.4	5.5	6.7	22.4

NOTES: Last year of data: *2005; **2004; ***2003. For any given population with data ranging from year $t–n$ to year t, the percent change in s_a (Δs_a) was calculated relative to the starting year with the formula: $\Delta s_a = 100*(s_{a,t} - s_{a,t-n})/(s_{a,t-n})$.
SOURCE: Period life tables from the Human Mortality Database 2009.

FIGURE 1b Trends in standard deviations of mortality distributions for males: full population (s_0) and survivors at ages 10 (s_{10}), 50 (s_{50}), and 75 (s_{75})



NOTE: Calculated using life tables from 23 national populations, 1850–2006. Trends for Sweden are shown by the black lines.
SOURCE: HMD 2009.

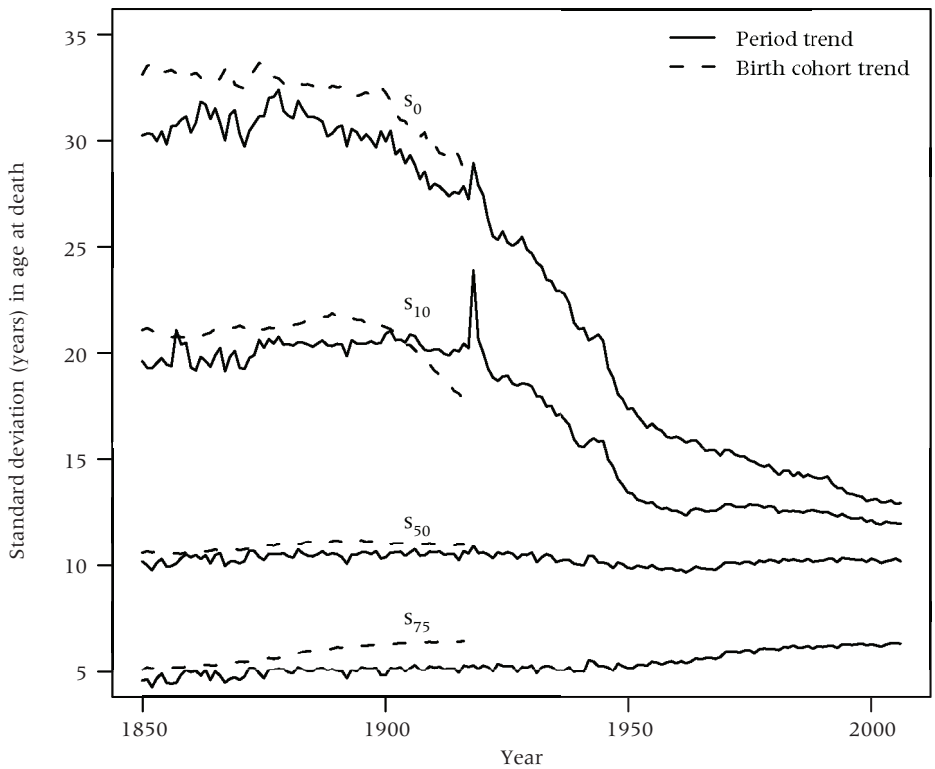
similar, although the current s_0 levels are somewhat higher for men than for women, while s_{75} levels tend to be higher for women.

A few countries with unique population histories diverge from the above paradigm. Although both males and females in the United States had one of the lowest levels of s_0 and s_{10} in 1950, American females saw the smallest decline in variability relative to other countries included in the lower panel of Table 2a, while American males registered a relatively small change in s_0 and practically no change in s_{10} over time. The high levels of variability in 2006 reflect greater and more persistent internal mortality differences in the United States than in other countries in recent years (Edwards and Tuljapurkar 2005; Murray et al. 2006). A historical composition of highly selected migrants sets the trajectories of New Zealand's non-Maori population and Australia's population apart from those of other countries (Vallin and Meslé 2009). Finally, women in Spain and Portugal show the smallest relative increase in old-age

mortality variability, possibly due to past political circumstances (specifically, dictatorial regimes) that may have delayed improvements in the Iberian populations' health and mortality profiles (Navarro et al. 2003).

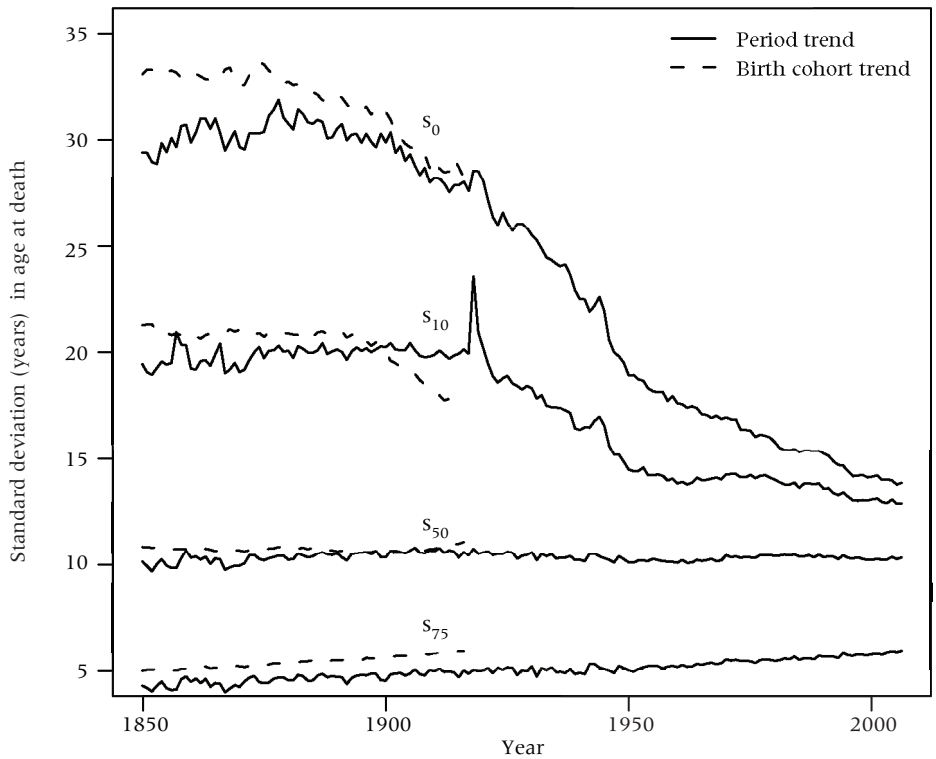
While there has been much research emphasizing the importance of period changes in social, medical, and public health factors underlying improved survival, mechanisms that operate throughout the life span and thus within cohorts have also been shown to be influential for morbidity and mortality patterns in older ages (Finch and Crimmins 2004). Figures 2a and 2b demonstrate that the patterns in unconditional and truncated variation measures observed using period life tables are likewise present in the cohort data for females and males. Because the HMD provides life tables only for extinct cohorts (or those aged 90 and above), the most recent cohort life tables available are for cohorts born in 1916. While the cohort trend consequently offers only a partial picture of the mortality transition, it is nonetheless clear that

FIGURE 2a Period (1850–2006) and birth cohort (1850–1916) trends in standard deviations of mortality distributions for Swedish females: full population (s_0) and survivors at ages 10 (s_{10}), 50 (s_{50}), and 75 (s_{75})



SOURCE: HMD 2009.

FIGURE 2b Period (1850–2006) and birth cohort (1850–1916) trends in standard deviations of mortality distributions for Swedish males: full population (s_0) and survivors at ages 10 (s_{10}), 50 (s_{50}), and 75 (s_{75})



SOURCE: HMD 2009.

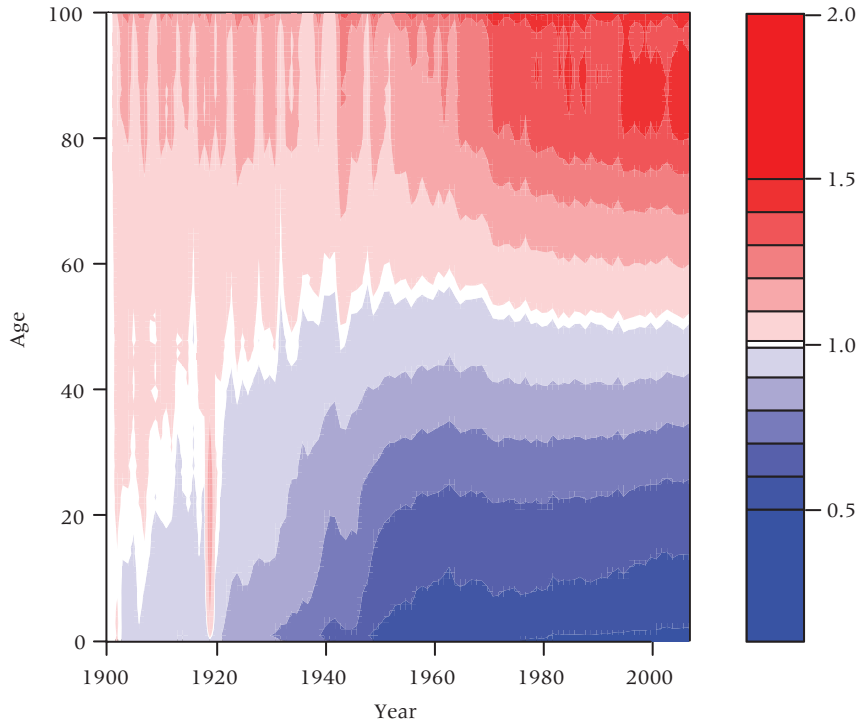
the magnitude of the displayed age-specific mortality variation measures is initially higher for cohorts than for corresponding periods. The cohort decline in s_0 proceeds in parallel with the period change, while the cohort trajectory of decline in s_{10} is steeper relative to the period measure. While the period and cohort s_{50} measures show little difference, the increase in s_{75} begins earlier and is more pronounced for successive cohorts than across successive periods.

Although the four cutoff ages selected for the above analysis represent conceptually meaningful thresholds, the exact boundaries defining the post-reproductive and older age groups may vary across time and region. We thus conducted a more extensive analysis, tracing trends in the ratio of each age-specific standard deviation to its value in 1900, when variation in the full mortality distribution began its most visible decline in the populations we studied. Standardizing each measure relative to both period and

age also allowed multiple comparisons to be made simultaneously on a uniform scale.

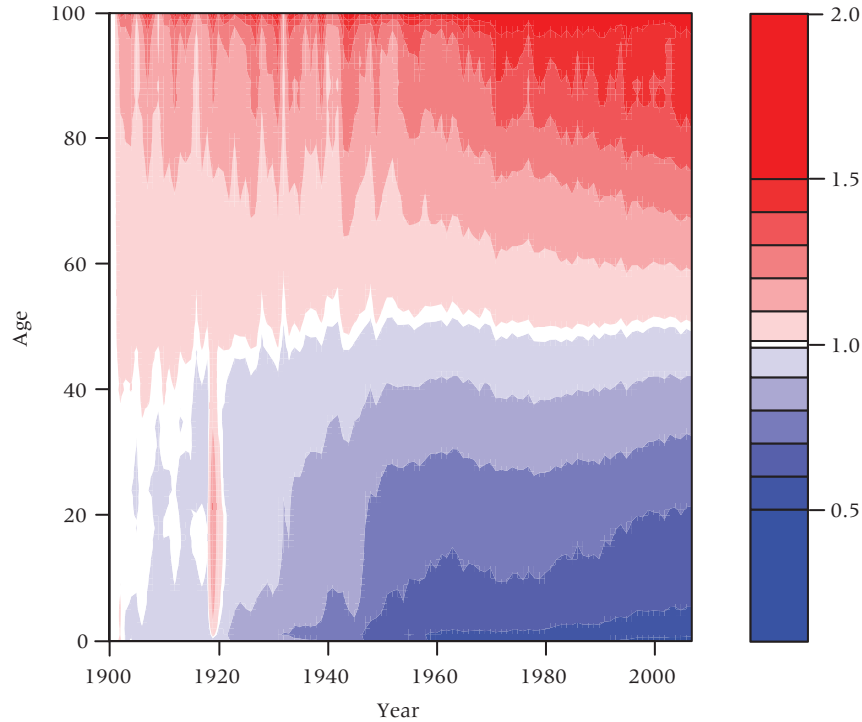
Figures 3a and 3b illustrate the full range of age-specific trends for Swedish females and males using a contour plot. Each contour plot visually demonstrates the robustness of the variability pattern across the full age and period ranges. The division of the surface into distinct upper red and lower blue segments confirms that variability trends proceed in opposite directions for the young and old. The darkening of the contour plot toward the horizontal boundaries indicates that the contrasting age trends become more pronounced as the distribution is allowed to include deaths at very young ages or, conversely, is limited to deaths in later life. While the distributions including younger people are becoming increasingly homogeneous, distributions encompassing only the growing older population show rising heterogeneity, especially among the oldest old. Variation in mortality for the current older

FIGURE 3a Trends in age-specific standard deviations of the mortality distribution for Swedish females, 1900–2006



NOTE: Color is assigned according to the ratio of the standard deviation in the distribution of mortality for survivors to a given age (*y*-axis) in a given year (*x*-axis), relative to the age-specific value in 1900. White represents a ratio of 1 (no change); successively darker blue represents declining values <1; successively darker red represents increasing values >1.
SOURCE: HMD 2009.

FIGURE 3b Trends in age-specific standard deviations of the mortality distribution for Swedish males, 1900–2006

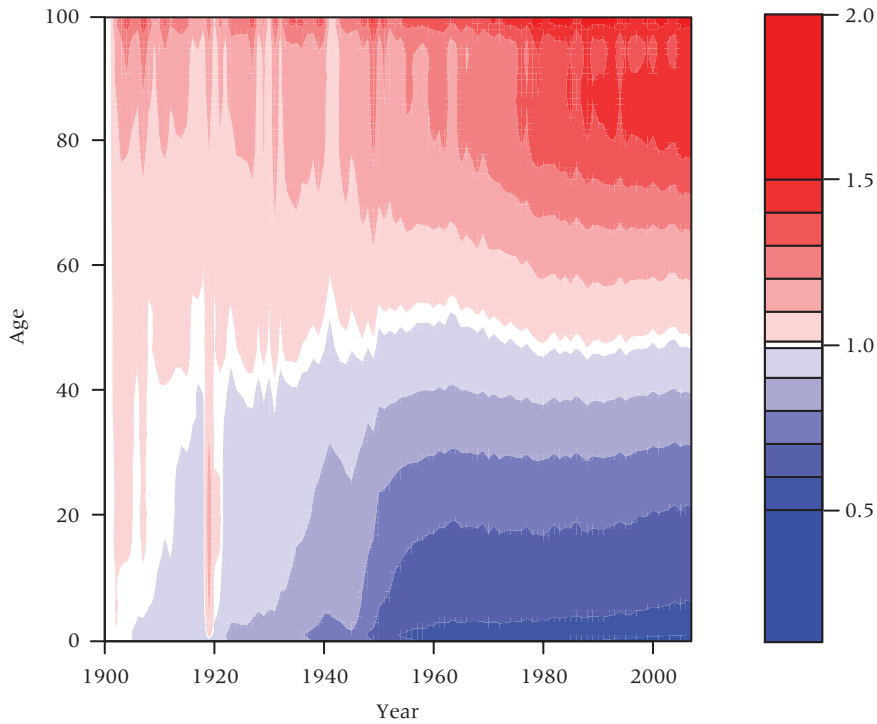


NOTE: Color is assigned according to the ratio of the standard deviation in the distribution of mortality for survivors to a given age (*y*-axis) in a given year (*x*-axis), relative to the age-specific value in 1900. White represents a ratio of 1 (no change); successively darker blue represents declining values <1; successively darker red represents increasing values >1.
SOURCE: HMD 2009.

population is higher than it was for the older population a century ago, when the challenges of reaching older ages may have fashioned a more highly selected group of survivors.

Notably, for survivors to middle age, variance in the mortality distribution remains fairly constant over the course of the historical transition. The white strip forming the border between the ages of increasing and decreasing variance fluctuates by year, but for most of the century it remains between ages 40 and 50, with light bands of red and blue indicating the direction of change for survivors to younger and older ages. With only slight variation, this pattern holds among the other national populations examined. Given historical life expectancies and biological schedules, the post-reproductive years may represent a threshold between young and aged mortality, differentiating mortality associated with earlier stages of the demographic transition (when acute diseases were leading causes of death) from the chronic disease mortality that gained prominence in later stages.

FIGURE 4a Trends in average age-specific standard deviations of the mortality distribution for females across countries, 1900–2006



NOTE: Calculated from life tables for females in 12 countries for the period 1900–1949 and life tables for females in up to 23 countries for 1950–2006. Color is assigned according to the ratio of average standard deviations:

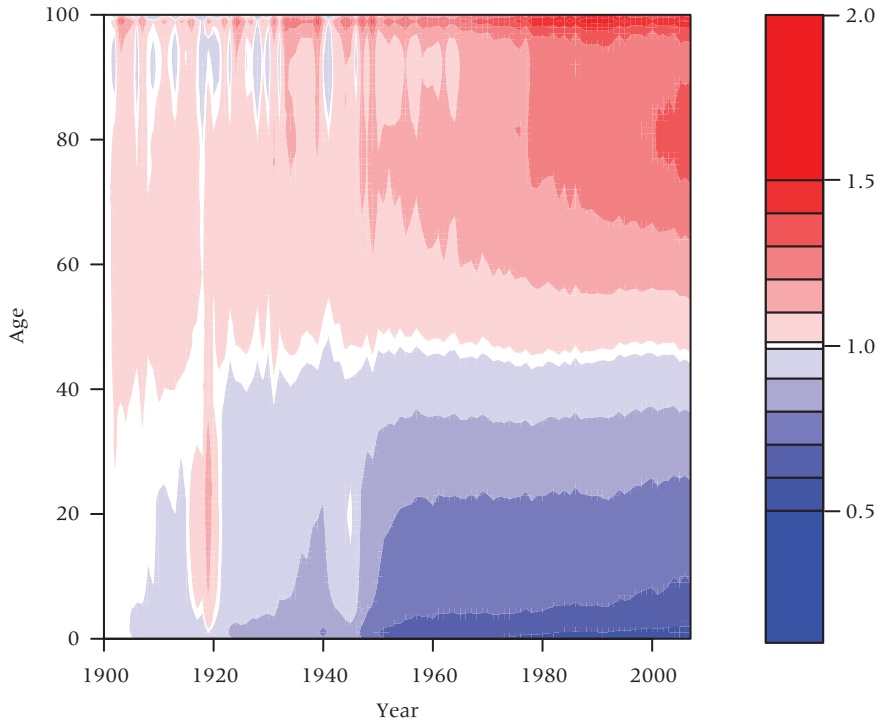
$$\bar{r}_{a,t} = \frac{\bar{s}_{a,t}}{\bar{s}_{a,1900}} .$$

White represents a ratio of 1 (no change); successively darker blue represents declining values <1; successively darker red represents increasing values >1.
SOURCE: HMD 2009.

The overall pattern for males again closely resembles the results for females. Plots for males and females in the other 22 populations included in this analysis are consistent in distinguishing a declining (blue) pattern in the variability of distributions including deaths at young ages and an increasing (red) pattern in the variability of distributions conditional on survival to older ages.

As can be seen in Figures 4a and 4b, the systematic difference in variability trends among the old and the young is maintained for both women and men when we consider the mean variability across all countries with data available in a given year. Furthermore, Figures 5a and 5b show that the same results hold when we examine the minimum variability across countries—despite the fact that using a minimum measure renders the estimated trend in older ages more conservative (i.e., closer to one). Thus, whether we examine

FIGURE 4b Trends in average age-specific standard deviations of the mortality distribution for males across countries, 1900–2006



NOTE: Calculated from life tables for males in 12 countries for the period 1900–1949 and life tables for males in up to 23 countries for 1950–2006. Color is assigned according to the ratio of average standard deviations:

$$\bar{r}_{a,t} = \frac{\bar{s}_{a,t}}{\bar{s}_{a,1900}} .$$

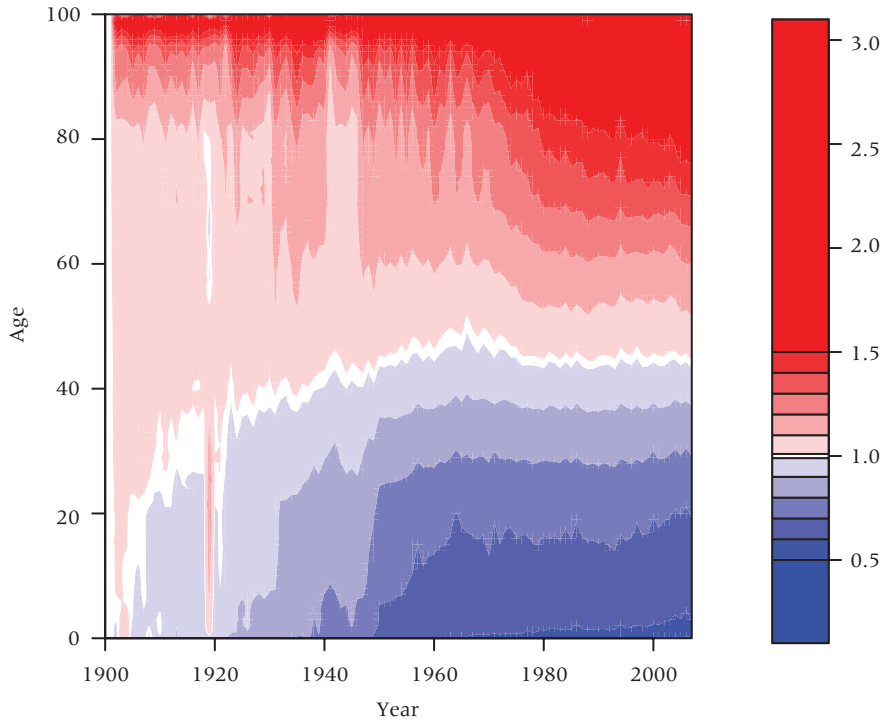
White represents a ratio of 1 (no change); successively darker blue represents declining values <1; successively darker red represents increasing values >1.
SOURCE: HMD 2009.

trends within individual countries, compare the cross-country average, or look at the best-performing countries with record-low levels of age-specific variability, the pattern remains consistent: while the distribution of deaths by age in the population as a whole is becoming more homogeneous, the older population is growing increasingly heterogeneous in its mortality risks.

Discussion

While the data indicate a compression of mortality across the full distribution of ages of death, they also reveal an expansion of life span inequalities among survivors to older ages. Our results raise key questions about the plausibility of the variability levels predicted under the compression hypothesis and about the mechanisms that underlie the observed trends.

FIGURE 5a Trends in minimum age-specific standard deviations of the mortality distribution for females across countries, 1900–2006



NOTE: Calculated from life tables for females in 12 countries for the period 1900–1949 and life tables for females in up to 23 countries for 1950–2006. Color is assigned according to the ratio of average standard deviations:

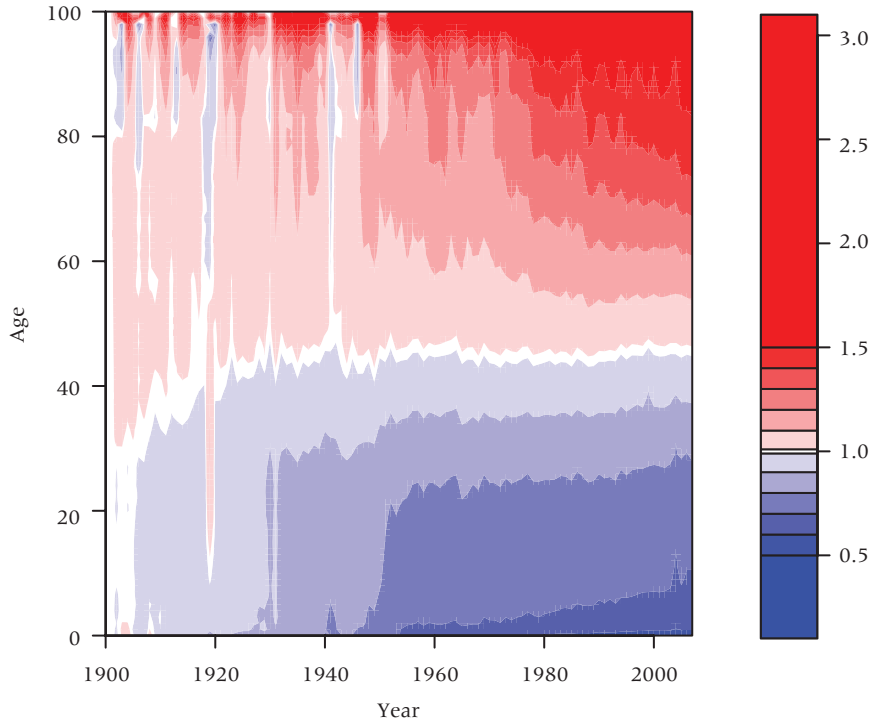
$$\underline{r}_{a,t} = \frac{\underline{s}_{a,t}}{\underline{s}_{a,1900}} .$$

White represents a ratio of 1 (no change); successively darker blue represents declining values <1; successively darker red represents increasing values >1.
SOURCE: HMD 2009.

The increasing proximity of the complete (s_0) and conditional (s_{10}, s_{50}, and s_{75}) variation measures (see Figures 1a and 1b) suggests that they may eventually merge. But at what level? Because total variation has been consistently higher in magnitude than the conditional measures, reaching an s_0 level as low as that forecasted by the compression hypothesis would require a dramatic departure from historical trends in the variability conditional on survival to older ages. Thus, while life expectancy does not seem to be approaching a ceiling (Caselli and Vallin 2001; Oeppen and Vaupel 2002), variability in the full mortality distribution does appear to have a floor defined by the growing heterogeneity in old-age mortality.

The contour plots illustrate that, in stark contrast to variation in the full distribution of mortality and variation in distributions truncated in childhood, young adulthood, or midlife, variation in mortality at older ages has

FIGURE 5b Trends in minimum age-specific standard deviations of the mortality distribution for males across countries, 1900–2006



NOTE: Calculated from life tables for males in 12 countries for the period 1900–1949 and life tables for males in up to 23 countries for 1950–2006. Color is assigned according to the ratio of average standard deviations:

$$\underline{r}_{a,t} = \frac{\underline{s}_{a,t}}{\underline{s}_{a,1900}} .$$

White represents a ratio of 1 (no change); successively darker blue represents declining values <1; successively darker red represents increasing values >1.
SOURCE: HMD 2009.

increased as life expectancy has risen. This pattern is consistent within national populations (Figures 3a and 3b), as well as for average (Figures 4a and 4b) and record-low (Figures 5a and 5b) measures calculated across countries. The incorporation of all deaths at ages 110 and above into the open-ended terminal category of each life table suggests that if the mortality distribution is becoming increasingly skewed toward the upper ages as maximum life spans increase, our calculations of variability at older ages may even be relatively conservative. The differences in mortality variation among the young and old may seem puzzling given that at all ages, including the oldest, life expectancies have increased (see Tables 1a and 1b) and mortality rates have declined (Vaupel et al. 1998; Wilmoth et al. 2000; Rau et al. 2008). Furthermore, both recent (Kannisto et al. 1994) and projected (Vaupel 1986; Vaupel and Yashin

1986; Lee and Carter 1992; Tuljapurkar, Li, and Boe 2000) increases in life expectancy at birth for women and men in low-mortality countries are a function of ongoing survival improvements among older people rather than among the young. Likewise, the increase in the number of the oldest-old people—and particularly centenarians—is not simply a function of larger birth cohorts (Vaupel and Jeune 1995). Rather, it is due to survival improvements at increasingly older ages (Wilmoth et al. 2000, Rau et al. 2008). Why, then, are the age-specific trends in variability so systematically different?

Part of the answer may rest in the fact that the trends we see unfolding across successive *periods* reflect changes within successive *cohorts*. Goldstein and Wachter (2006) demonstrated that period life expectancy is a lagged indicator of cohort experiences in populations with improving survival. More specifically, they showed that under conditions of declining mortality, cohort life expectancy at birth is consistently higher than the corresponding period measure, although it can only be fully calculated once the entire cohort is extinct. Their results concur with findings by Finch and Crimmins (2004) suggesting that progressive reductions in mortality are more pronounced for cohorts than for periods, particularly at older ages. As seen in Figures 2a and 2b, the age pattern of variability we observe in the period life tables is likewise apparent earlier and with more pronounced magnitude in analyses of cohort data. Contour plots constructed using the cohort data also indicate earlier declines in total variability concomitant with increases in variability conditional on survival to older ages.[6]

The consistency of the variability pattern within periods and cohorts is notable because mortality selection is a mechanism that operates within cohorts. According to the theory of heterogeneity (Vaupel, Manton, and Stallard 1979), frail members of a cohort—those who are more vulnerable to the risks of mortality—tend to die earlier. As a result, surviving members of the cohort tend to be a selected subgroup of individuals who are more similar to each other in terms of increased robustness or reduced susceptibility to mortality relative to their frailer peers. While this compositional change may operate slowly, over a sufficiently long time it can manifest itself in observed population measures (Vaupel and Yashin 1985). When mortality is declining, however, period trends may reflect the improved survival (and thus growing proportion) of frail members in successive cohorts.

The conditional variation measures we examined are influenced by the growing proportion of people surviving past the modal age of death (Fuchs and Ersner-Hershfield 2008). Still, the variability pattern revealed by the contour plots suggests that the demographic and epidemiologic changes that have led to population aging have potentially done more than raise the number and relative proportion of survivors to older ages; they also appear to have altered the older population's composition, at least with respect to mortality risks. Delayed selection may be tempering the ongoing improvements in

mortality rates and contributing to the growing variation observed in older populations. Our results thus suggest that declining mortality in early life may be contributing to the increased conditional variability of mortality in later life. This idea is further supported by results from Smits and Monden (2009) showing that countries reaching a high level of life expectancy earlier and countries that improved their life expectancy more quickly than others experience higher levels of inequality in adult mortality. These findings, like the ones we report above, suggest that the pattern of mortality change influences the force of selective mortality and subsequent levels of life span inequality.

Lewontin (1982) showed that within-group variation in genes and phenotypes often exceeds variation between groups, and this is a key consideration when comparing populations with respect to inequality in age at death. Across countries, both differing levels of internal heterogeneity and different historical trajectories of demographic change may contribute to the diversity of variability trends observed by Edwards and Tuljapurkar (2005) in populations with similar levels of life expectancy at birth.

Delayed mortality potentially means that a more heterogeneous population is reaching every age, and that health disparities in early life are delayed and manifest themselves instead in mortality variation at increasingly older ages. Mortality and morbidity do not necessarily change along parallel or proportional courses (Riley 1990, 1999), and improved survival has led to pessimistic predictions of expanding chronic morbidity (Gruenberg 1977) as well as the optimistic expectation of compressed morbidity (Fries 1980, 2003). The complex interplay between morbidity and mortality has been the subject of ongoing investigation by networks of scholars (e.g., REVES 2009; TRENDS 2009). Reviewing evidence across international health-trend surveys, Parker and Thorslund (2007) concluded that while measures of disability tend to improve over time, chronic disease and functional impairment indicators have shown an increase in recent periods. Compression or reduction in disability may be taking place even as the prevalence and range of health problems expand, complicating the evaluation of trends in overall morbidity.

While morbidity's role as a precursor to mortality is well recognized, not all illnesses lead to death and not all deaths are the result of illness. Alter and Riley (1989) used frailty models, computer simulations, and historical records in an attempt to explain an observed inverse association between mortality and morbidity over a 30-year period in the latter part of the nineteenth century. Their results support an explanation that combines both reduced demographic selection and increased susceptibility to morbidity in adulthood over time. As longevity increases, the health profile of survivors—both on average and in its variability—may thus be systematically different from the health of those who survived to older ages in the past. The growing population of survivors to older ages may increasingly encompass both robust individuals and those at various degrees of frailty.

Progress in medicine, public health, and standards of living may have benefited frailer members of the population by increasing their life spans—although perhaps not as much as the life spans of their more advantaged peers. Thus, although frailer people have "caught up" to their counterparts in reaching older ages, there is still a great deal of uncertainty about their subsequent survival and health in later life. Without devaluing the achievement of higher life expectancies, one must also recognize the exacerbation of health inequalities in later life that may accompany this success.

By analyzing the variance of distributions across age and time, we have shown that heterogeneity in mortality among the old has increased concomitantly with survival improvements throughout the life span. Our findings suggest that as a result of continuing improvements in survival, delayed mortality selection has shifted health disparities from early to later life, where they manifest themselves in the growing variation in longevity. While Quetelet's projection of compressed variability applies for the younger people whose mortality experiences influence the full distribution of deaths, demographic change has brought about increased, rather than decreased, heterogeneity for the growing aging population in low-mortality countries.

In the future, the industrialized countries examined in this study will likely have a growing and increasingly diverse population of older people, comprising robust and frail individuals of varying capacities and needs. Although HIV/AIDS and re-emerging infectious diseases are slowing the pace of population aging in low-income countries, understanding the dynamics of mortality variability in those challenging circumstances will be no less important. Policies and programs that aim to address the needs of aging populations and to mitigate inequalities throughout the life span must recognize that heterogeneity is an increasingly salient feature of older populations.

Notes

Figures 3–5 in this article are available in color in the electronic edition of the journal.

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1 Un des principaux faits de la civilisation est de resserrer, de plus en plus, les limites dans lesquelles oscillent les différents élémens relatifs à l'homme. Plus les lumières se répandent, plus les écarts de la moyenne vont en diminuant; plus, par conséquent, nous tendons à nous rapprocher de ce qui est beau et de ce qui est bien.

2 Fifteen of the 23 countries included in our analysis have complete age-specific mortality rates for ages up to 110 years or higher for the majority of years being examined. In the remaining eight countries, the final, open-ended interval begins at ages 95 or 100 for some years. According to the HMD Methods Protocol (Appendix C), in these cases the aggregated deaths are apportioned into

specific ages using the extinct cohort method and smoothed using a Kannisto-logistic function. While the smoothing may contribute to the similarity between these eight countries and the countries with more complete data, the overall pattern of increasing variability at all older ages leads us to believe that these procedures are not likely to have a significant impact on our computations.

3 Data for Bulgaria are available in the Human Mortality Database starting in 1947. However, because the quality of Bulgarian data up to 1969 is known to be poor (HMD 2009), that country was not included as one of the populations in this analysis.

4 Note that the average age at death may be described by the expected value equation

$$E_0[X] = \frac{\int_0^\omega x d(x) dx}{l_0} = e_0,$$

where X is a random variable representing age at death, $d(x)$ represents the number of deaths at exact age x, and e_0 denotes life expectancy at birth. Correspondingly, the expected number of remaining years conditional on survival to age a is given by:

$$E_a[X] = \frac{\int_a^\omega (x-a) d(x) dx}{l_a} = e_a,$$

where e_a represents remaining life expectancy at age a. Thus, using the standard formula

$$Var_a[X] = E_a[X^2] - (E_a[X])^2,$$

the variance of age at death conditional on survival to age a may be written as

$$Var_a[X] = \frac{\int_a^\omega (x-a)^2 d(x) dx}{l_a} - e_a^2,$$

as in equation (1) in the text.

5 Rising mortality following the dissolution of the Soviet Union placed the nations it comprised (including Russia, Ukraine, Belarus, Estonia, Latvia, and Lithuania, whose data are included in the HMD) on a different demographic trajectory. Since the mid-1960s, s_0 declined only slightly, while s_{50} and s_{75} decreased somewhat rather than increasing as in other populations. These results may reflect problems with data quality as well as real trends.

6 Results are available upon request from mengelma@jhsph.edu.

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