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Human Longevity: Trends and Determinants

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The duration of life has captured the attention of people for thousands of years. Deaths at younger ages are now unusual in developed countries. Most deaths occur there at older ages, and survival at older ages is now a hot topic. If death at older ages can be further postponed, then the rate of growth of the population of the oldest old will quicken, which will have major economic and social consequences. These may include escalation in the costs of health care and retirement programs. In this paper we review selected recent findings on survival at older ages. We first examine mortality in relation to age, and here we emphasize the intriguing result that mortality deceleration occurs in human and non-human populations. In a next step we investigate trends in late life mortality in recent decades. There were marked improvements in survival at older ages, which is in contrast to the belief that there are fixed limits to length of life and life expectancy. In a concluding section we focus on behavioral and psychological factors that may be relevant for determining mortality outcomes.

Mortality Deceleration

Demographers have long been interested in the shape of the age-trajectory of human mortality. The general nature of this trajectory from birth to age 80 or so is well known. Mortality is high immediately after birth. It falls to a very low level around the age of 10 or 12 and then rises more or less exponentially, apart from some excess mortality among teenagers and young adults. A key hypothesis is that mortality continues to accelerate with age as reproduction declines. Gompertz (1825) proposed that the force of mortality increases exponentially with age for humans, at least for the range of adult ages for which he had reliable data. As a rough approximation at younger adult ages, Gompertz' exponential formula also captures the rise in mortality in a great variety of species. Until recently it was very difficult to examine data on survival at advanced ages because very few published life tables provide age-specific data after age 85. Thanks to substantial efforts by Kannisto (1994), Thatcher (Thatcher, Kannisto, & Vaupel, 1998), and others, reliable data on mortality after age 80 are now available for Japan and 13 Western European countries. When these data are pooled, it is possible to estimate the age trajectory for human female mortality up to about the age of 110. Death rates for an aggregation of the 14 countries are shown in Figure 1, as well as three curves fitted to death rates (Vaupel et al., 1998). Most older people are women, so for the sake of simplicity only female data are presented in most of the figures and tables in this paper.

--- insert Figure 1

It can clearly be seen that human mortality does not follow Gompertz' exponential formula after age 80. Rather, it appears that at age 85 or so mortality deceleration sets in. That is, the rate of increase in mortality slows down. A logistic curve that best fits the entire data set indicates that death rates may reach a plateau (Thatcher et al., 1998). A quadratic curve fit to the data at ages 105 and above suggests a decline in mortality after age 110. However, reliable data were available on only 82 persons who survived past age 110. Due to the sparse data at the highest ages it is unknown whether mortality increases slowly, remains level, decreases slowly, or decreases rapidly after age 110.

Mortality deceleration has been observed not only in humans but also in some other species for which large populations have been followed to death, including nematode worms and yeast as well as various insects (Vaupel et al., 1998). Why does mortality decelerate in human and other populations? One reason is that all populations are heterogeneous. Some individuals are frailer than others, and the frail die first. As time goes by, the residual population is increasingly made up of those individuals that were always the most resilient. Consequently, the individuals alive at older ages may be fundamentally different from the individuals alive at younger ages. On the one hand, the age-trajectory of mortality reflects the underlying age-trajectories of mortality for individuals in the population. On the other hand, it also reflects the effects of compositional changes as the frailer individuals drop out of the population. Some of the deceleration of mortality at advanced ages may be due to deceleration at the individual level resulting from behavioral and physiological changes that occur with age. Caution is required here, however, since mortality for individuals might actually increase more quickly than a Gompertz curve, which would imply that heterogeneity is even more important in explaining the deceleration of mortality. More research is required on the extent to which the deceleration of mortality at older ages is attributable to changes at the individual level on the one hand and to changes in the composition of the surviving cohort on the other. A better understanding of this question may lead to new insights into aging and survival.

Remarkable Improvements in Survival at Older Ages

How plastic is mortality at older ages? Gerontological research has often been guided by the notion that there is a fixed maximum life span, that life expectancy in Germany and similar countries is close to the limit imposed by biology, and that little can be done to increase survival among the oldest old (Fries, 1980; Hayflick, 2000). Several types of evidence challenge the notion of fixed limits. Far from being fixed, mortality at older ages has fallen dramatically since 1950, and especially since 1970, in developed countries (Kannisto, Lauritsen, Thatcher, & Vaupel, 1994; Vaupel, 1997a). One can determine whether the level of mortality has declined at a given age by considering average annual rates of mortality improvement, that is, percentage reductions in death rates (Kannisto et al., 1994). Table 1 documents the acceleration of mortality improvements for women in the Nordic countries of Denmark, Finland, Norway, and Sweden; countries for which reliable mortality data for older ages are available well back into the 19th century. For people in their eighties and nineties, there was little or no improvement early in the 20th century. Mortality improvements became evident in the 1940s to 1960s, and they accelerated in the 1960s to 1980s. Mortality reductions among octogenarians and nonagenarians are a remarkable achievement, and they are in stark contrast with the view that little can be done to increase survival among the oldest old.

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If death rates at older ages were approaching a biological limit, then countries with the lowest death rates would be closer to such limits than other countries. Consequently, we might expect that improvements in countries with the lowest death rates would tend to be slower than in countries with death rates further away from the irreducible minimum. However, there is no correlation, neither for males nor females, between the levels of mortality and the rates of mortality improvement (Kannisto et al., 1994; Vaupel, 1997a). Furthermore, males suffer higher mortality than females, while rates of improvement are higher for females than for males (Kannisto, 1994; Kannisto et al., 1994). There is also evidence that the maximum age at death is not immutable. Swedish national demographic data provide the longest available series of reliable data on achieved human life spans. Swedish data suggest that the maximum age at death has been increasing steadily for more than 100 years, and most of this increase came as a result of reductions in death rates at older ages (Wilmoth, Degan, Lundström, & Horiuchi, 2000).

Life expectancy is a synthetic measure of current mortality conditions in a particular year, and it is widely used as a general indicator of health and mortality. It is calculated as the average number of years newborns will live assuming death rates remain constant at current levels. Life expectancy rose dramatically during the 20th century. In industrialized countries female life expectancy increased by 30 to 35 years, and males gained about 25 to 30 years. Life expectancy is clearly influenced by environmental and public health factors. Up to 1950 or so, most of the gain in life expectancy was because of reductions in infant, childhood, and early adult mortality. These improvements in life expectancy came as the result of rising standards of living, public health interventions, and medical developments that reduced deaths from infectious diseases. Since 1950, and particularly since 1970, however, the increase in life expectancy in developed countries is largely attributable to reductions in mortality at older ages.

This can be illustrated using mortality information from Germany. Figure 2 shows gains in life expectancy for East and West German women from 1980 to 1996. During this period life expectancy for East German women increased by 5.3 years. Decreases in infant and child mortality contributed relatively little to this increase. The early and middle adulthood ages contributed virtually nothing. The increase in life expectancy was largely determined by improvements in survival at older ages. More than 71 percent of the total increase came from ages over 60, and a remarkable 31 percent came from ages above 80. A similar pattern is evident for West German women and for men, although it is somewhat less pronounced (Gjonça, Brockmann, & Maier, 2000).

--- insert Figure 2

The different segments of the bars in Figure 2 represent shorter historical time periods. If we examine the bars designating the ages above 60 in East Germany, then it appears that some, but relatively little improvement occurred in the period prior to German unification in 1990. In contrast, the periods around (1987-1992) and after (1992-1996) unification were characterized by a pronounced mortality reduction for the ages above 60, which is reflected in substantial contributions to gains in life expectancy. A different pattern is observed in West Germany, where the period prior to unification contributed most to the gain in life expectancy when compared to the two other periods.

Gjonça et al. (2000) examined trends in death rates among Germans aged 80 to 99. East and West Germany had similar levels of oldest-old mortality until about 1975. After 1975 the mortality trends diverged. Death rates at older ages in West Germany decreased with a low gradient for both sexes, while East German old-age mortality improved only little until the late 1980s. In the late 1980s oldest-old mortality was 20 to 50 percent higher in East Germany than in West. With the collapse of the socialist government in 1989 and German unification a year later, old age mortality in East Germany began to decrease at an accelerated pace. Consequently, the diverging trends in oldest-old mortality came to a halt, and old age death rates in East and West Germany have now started to converge. Oldest-old death rates were remarkably sensitive to the cultural, political, and economic changes associated with German unification, attesting to the plasticity of late life survival. Speculation about the specific factors responsible focuses on the health care system and individuals' economic resources (Gjonça et al., 2000).

The mortality reductions have an impact on the growth of the elderly population. Table 2 provides information about the size of the older population of various countries, from age 60 and up, for both sexes combined. Estimates are also given for the size of these populations in 2025. The projections assume slow improvements in mortality, and it is likely that the estimates for 2025 will prove to be too low (Tuljapurkar, Li, & Boe, 2000; Vaupel 1997a). Nonetheless, the size of the older population shows substantial increases, not only in Germany but also in Japan, the United States, China, and India as well.

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Inter-individual Differences and Survival

This world-wide growth in the population of older people heightens the interest in a fundamental question: why do some people die at 60, others at 80, and a few at 100? Why is the chance of dying at 80 rather than 60 increasing? Why are the chances of surviving from age 80 to 100 rapidly increasing, albeit from a very low level? How important are genetic, environmental, behavioral, and psychological factors in determining how long an individual will live? Research on twins and other populations of related individuals suggests that the length of one's life is moderately heritable. It seems that about 25 percent of the total variation in adult life spans can be attributed to genetic variation among individuals (McGue, Vaupel, Holm, & Harvald, 1993). Another 20 to 30 percent can be perhaps explained by non-genetic survival attributes that are fixed for individuals by the time they are 30 years old (Vaupel et al., 1998). Among these non-genetic fixed factors are health conditions early in life, socioeconomic conditions in childhood, and the socio-economic position a person has attained at about age 30.

It is probably the case that a large number of environmental and genetic factors interact to determine life span. There is some evidence that variation in the genetic factor apolipoprotein E, the most potent “longevity gene” yet discovered in humans, explains only 1% of the variation in life span (Christensen & Vaupel, 1996). It should also be noted that the one-quarter or so of the variation in life span that is due to genetic factors is not necessarily beyond intervention. Insights into the function of genes can immediately open up possibilities for modifying adverse genetic effects, especially if gene-environment interaction plays a part in the etiology (Christensen & Vaupel, 1996).

Many studies have addressed the effects of behavioral and life-style factors on morbidity and mortality. In today’s western world, cigarette smoking is the most prominently known environmental risk factor influencing life span. The association between alcohol consumption and mortality appears to be U-shaped, with an elevated risk of death for both abstainers and heavy drinkers. There are also reports that the risk of death increases throughout the range of moderate to severe overweight. Declining cigarette smoking as well as changes in diet and physical activity may be important factors in raising life expectancy, at least in some countries.

A long-standing debate concerns the extent to which intra-uterine and perinatal exposures influence late life morbidity and mortality. Barker’s (1992) “fetal-origins hypothesis” suggests that nourishment and infections in utero and during infancy program the development of risk factors for several important diseases of middle and old age. To the extent this is true, longevity may in part be determined by conditions in early childhood and perhaps before birth. There is, however, conflicting evidence suggesting that conditions at older ages are much more important than conditions early in life. For example, twins tend to be born prematurely and at low birth weights, but they suffer the same age-specific death rates as singletons from age 6 up to the oldest ages (Christensen, Vaupel, Holm, & Yashin, 1995). Furthermore, Kannisto, Christensen, and Vaupel (1997) found no increased mortality in later life for Finnish cohorts that were born during or just before the famine of 1866-1869. Understanding the nature and magnitude of possible lingering effects of early life conditions on survival at advanced ages remains an important research priority.

Psychological traits and dispositions may also have some influence on longevity. Most psychological research on mortality has focused on the relation between psychological factors measured late in life and survival within a few subsequent years. Lower cognitive functioning was consistently associated with an increased mortality risk across a number of studies (Small & Bäckman, 1999). There is also some evidence that aspects of subjective well-being and happiness are related to a longer life (Idler & Benyamini, 1997), while psychological distress and depression may increase the risk of death (Huppert & Whittington, 1995). It is not known whether lower cognitive functioning and a lower level of well-being are merely concomitant to bodily changes that occur with nearness to death, or whether they have a causal effect on mortality.

Only very few studies have examined the effects of psychological factors early in life on late-life survival. In a study of gifted children, Friedman et al. (1995) related childhood personality to vital status 70 years later. The trait of conscientiousness (that is, being responsible, dependable, well organized) was associated with a longer life. Danner, Snowdon, and Friesen (in press) studied Catholic sisters and examined the relationship between the emotional content of texts written early in life and survival late in life. Positive emotional content in autobiographies written when sisters were a mean age of 22 was strongly related to survival at the ages 75 to 95. Both Friedman et al. (1995) and Danner et al. (in press) speculate that the way individuals deal with stress may be an important explanatory factor in their findings. It could be that more conscientious persons are better able to cope with life's stress and are thus less likely to become ill. Positive emotional content in writings is possibly indicative of a general readiness to express emotion, and these writings may reflect a beneficial response pattern that avoids the adverse effects of suppressing the expression of emotion.

Conclusion

In recent decades we have witnessed remarkable improvements in survival at older ages. The improvements are in stark contrast with the view that old age mortality is immutable. Extrapolating the rates of improvement into the future leads to an astonishing result: half of the girls born today in Germany and other developed countries may live to the age of 100 (Vaupel, 1997b, 1998, 2000). Boys are disadvantaged, but half of the males born today in the post-industrialized world may survive to age 95.

Christensen and Vaupel (1996) reviewed the determinants of longevity and concluded that surprisingly little is known. The chance of reaching age 80 (or 90 or 100) is better for women than men, for people born in the 20th century rather than earlier, for people born in developed countries, and for people who have some favorable genes. Smoking is certainly a health hazard for young and old, and other life-style factors are probably also important. Little is yet know about why mortality among the oldest old has been so plastic since 1950 or about the long-term effects of early-life psychological factors on late-life health and mortality.

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Table 1

Average Annual Rates of Improvement in Female Mortality (in Percent) for an Aggregation of Denmark, Finland, Norway and Sweden, for Sexagenarians, Septuagenarians, Octogenarians, and Nonagenarians, Over Successive Periods 20 Years Apart

	Age Category			
Time Period	60s	70s	80s	90s
1900s – 1920s	0.3	0.2	0.1	0.0
1920s – 1940s	0.7	0.4	0.2	0.0
1940s – 1960s	1.7	1.0	0.6	0.5
1960s – 1980s	1.5	2.1	1.7	1.2

Note. See Kannisto et al. (1994) for a description how average annual rates of improvement are calculated. Source: Vaupel (1997a).

Table 2

Estimated Population Above Age 60 (in Millions) and Proportion of Population (in Percent) for Selected Countries in 2000 and Projected for 2025

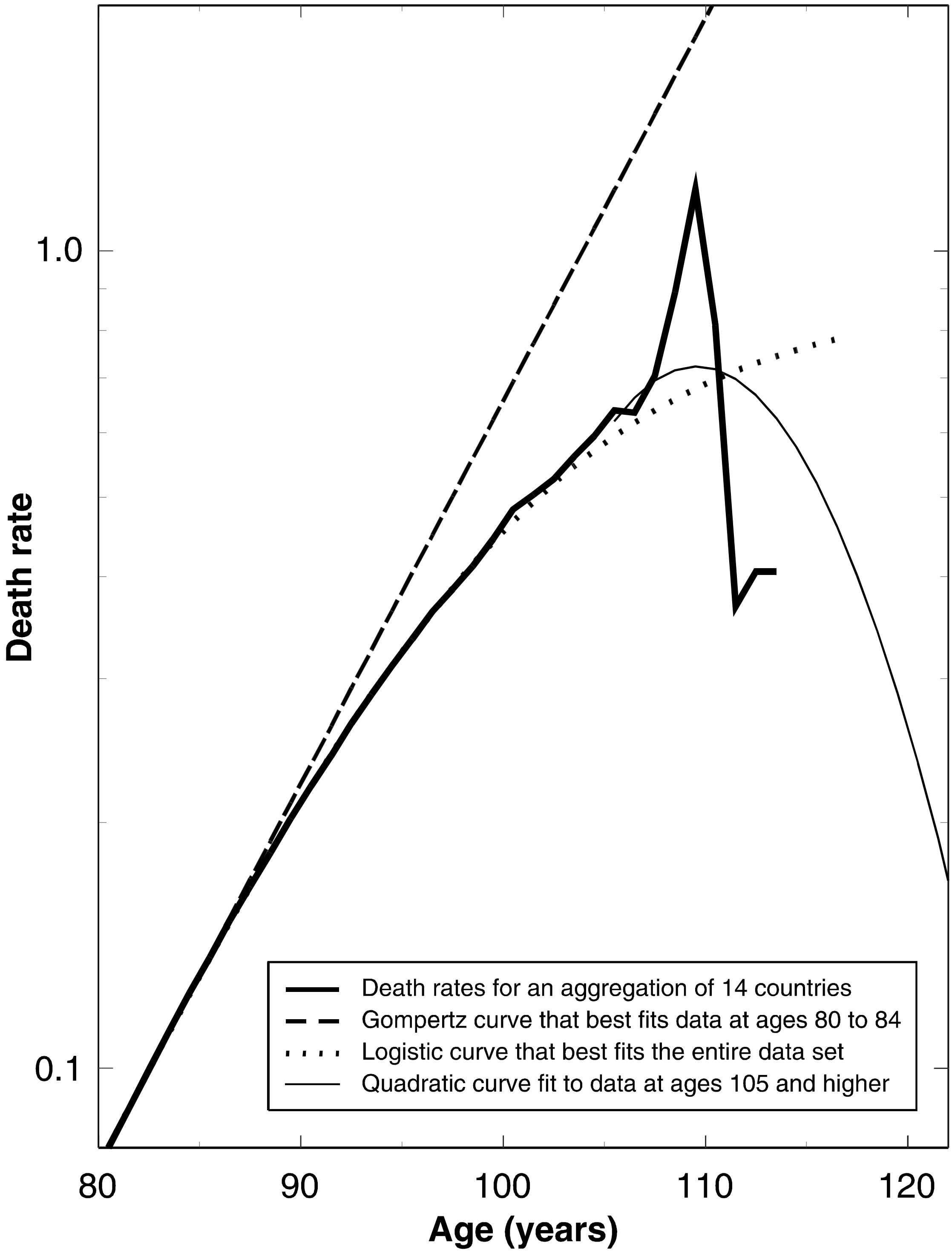
	Millions 60+		Percent 60+	
Country	2000	2025	2000	2025
Germany	19	27	23	31
Japan	29	41	23	34
United States	46	83	17	25
China	129	288	10	20
India	71	162	7	12

Note. Countries are ranked by percent 60+ in 2000. Source: United States Census Bureau International Data Base (updated 10 March 2000, available at http://www.census.gov/ipc/www/idbnew.html).

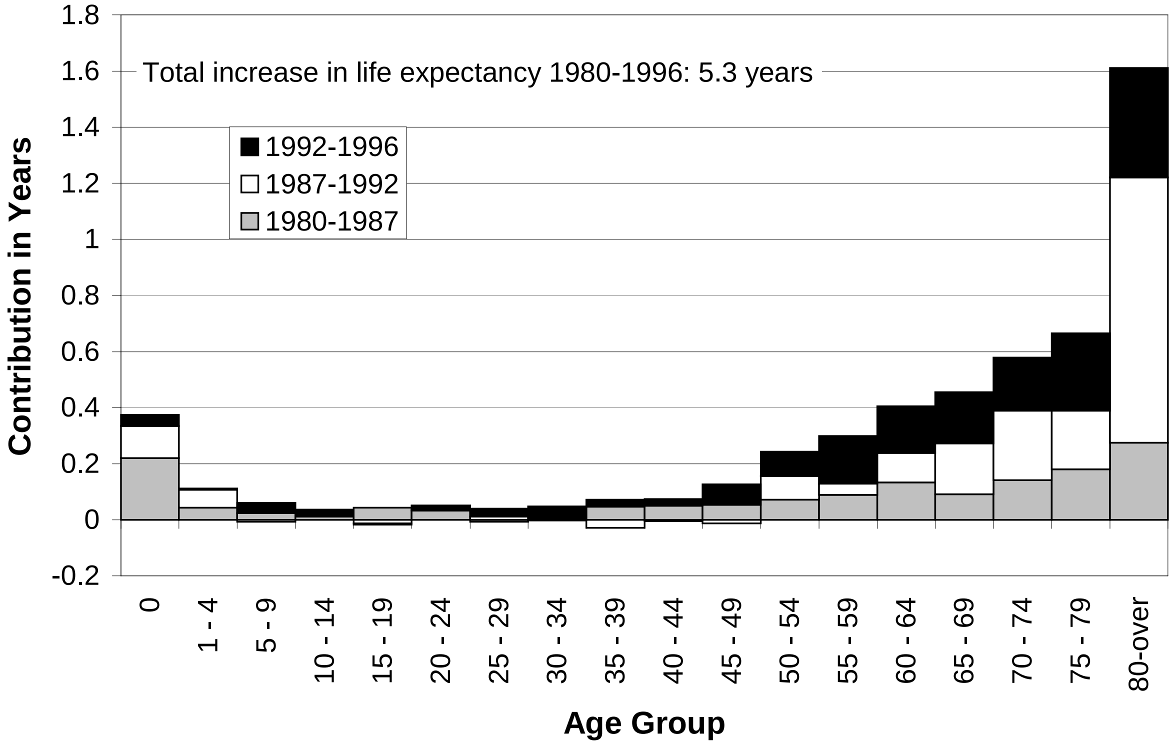
Figure Captions

Figure 1. Age trajectories of death rates from age 80 to 122 for females. Pooled data are from 14 countries (Japan and 13 Western European countries) with the most reliable information, over the period from 1950 to 1990 for ages 80 to 109 and to 1997 for ages 110 and above. Source: Vaupel et al. (1998).

Figure 2. Contribution of age group and historical period to the overall changes in female life expectancy between 1980 and 1996 in East and West Germany. Source: Gjonça et al. (2000).


1.0
0.1
Death rate
80
90
100
110
120
Age (years)
Death rates for an aggregation of 14 countries
Gompertz curve that best fits data at ages 80 to 84
Logistic curve that best fits the entire data set
Quadratic curve fit to data at ages 105 and higher

A – East Germany



B – West Germany