Title: New trend in the Old-age Mortality: Mortality Deceleration Fading Away

Authors: Leonid A. Gavrilov, Ph.D. and Natalia S. Gavrilova, Ph.D.

Affiliation: Academic Research Centers, NORC at the University of Chicago, Chicago, IL, USA

Corresponding author:
Natalia S. Gavrilova, Ph.D.
NORC at the University of Chicago
1155 E 60th Street
Chicago, IL 60637, USA
Email: gavrilova@longevity-science.org

Abstract

What is happening with the old age mortality trajectories over time and how do the trends vary by region? This study attempts to answer these questions by analyzing historical evolution of the old-age mortality in three countries: United States, Canada and the United Kingdom. Earlier studies demonstrated that exponential growth of mortality with age (the Gompertz law) slows down after age 80 years resulting in mortality deceleration. However more recent studies of the U.S. birth cohorts failed to observe mortality deceleration up to very old ages of 105 years. We compared performance (goodness-of-fit) of two competing mortality models - the Gompertz model and the "mortality deceleration" Kannisto model at ages 80-105 years using data for 1880-1899 single-year birth cohorts of men and women in the U.S., Canada and the United Kingdom. The mortality modeling approach suggests a transition from mortality deceleration in earlier birth cohorts to the Gompertzian mortality pattern in later birth cohorts for both men and women. Transition from mortality deceleration to the Gompertz law occurs later in Canada and the United Kingdom compared to the United States. These results are consistent with the hypothesis about mortality deceleration fading away over time due to improvement in the accuracy of age reporting. This leads to more conservative estimates for future human longevity records and the proportion of older people (population aging).

It was long believed that the exponential growth of the force of mortality with age (the Gompertz law) is followed by the period of deceleration when mortality growths slower than predicted by the Gompertz law (Greenwood and Irwin 1939; Horiuchi and Wilmoth 1998; Thatcher, Kannisto et al. 1998; Thatcher 1999). However, later studies challenged these conclusions and reported no mortality deceleration up to very old ages of 105 years (Gavrilov and Gavrilova 2011; Gavrilova and Gavrilov 2015). In another study, the Gompertz-like mortality was found for Australia, Canada and the United States (Bebbington, Green et al. 2014).

The estimation of the force of mortality at very old ages faces difficulties because of very small number of survivors to these ages and because of age misreporting by older persons. The age misreporting may be a problem affecting estimates of mortality at older ages (Coale and Li 1991; Hill, Preston et al. 2000; Black, Hsu et al. 2017; Gavrilova and Gavrilov 2018). In most cases, age misreporting at older ages leads to mortality underestimation (Preston, Elo et al. 1999; Gavrilov and Gavrilova 2019) and even rare errors in age reporting can accumulate at extreme old ages leading to spurious mortality deceleration (Newman 2018). Taking into account historical improvement in age registration, we can hypothesize that better accuracy in age reporting should lead to less prevalent mortality deceleration. Preliminary data suggest that mortality at advanced ages in earlier U.S. birth cohorts shows stronger deceleration compared to mortality in later birth cohorts (Gavrilov and Gavrilova 2011).

Here we analyze historical evolution of mortality trajectories at advanced ages using age-specific death rates for 20 birth cohorts in the United States, Canada and the United Kingdom. We study two competing models describing mortality trajectories (the Gompertz model and the "mortality deceleration" Kannisto model) with Akaike goodness-of-fit criterion. We hypothesize that mortality deceleration should fade away in more recent birth cohorts due to improvement in age reporting over time.

Data and Methods. The Human Mortality Database (HMD) provides mortality and population data (Human Mortality Database). Age-specific death rates are used as empirical estimates for the force of mortality. Datasets of age-specific cohort death rates (central mortality rates) of men and women are available in HMD for ages up to 110 years or older. For all three studied countries we analyze mortality of 1880–1899 single-year birth cohorts for men and women separately.

Age-specific women to men ratios confirm that the U.S. data are of sufficiently good quality up to ages 106-107 years (Gavrilov and Gavrilova 2011). However, age misreporting rapidly increases after age 105 years (Young, Desjardins et al. 2010; Gavrilova and Gavrilov 2018). So the mortality was fitted with competing models in the age interval 80-105 years for all countries.

We fit mortality with two competing models used earlier in the study by Thatcher and coauthors (1998): the Gompertz model and the "mortality deceleration" logistic model (a simplified two-parameter logistic model, also called the Kannisto model):

Gompertz: $$\mu(x) = a e^{bx} \quad (1)$$

Kannisto: $$\mu(x) = \frac{a e^{bx}}{1 + a e^{bx}} \quad (2)$$

where μ(x) is the force of mortality, x is age, a and b are parameters.

We test these two models for their performance of fitting the empirical data. We run a weighted nonlinear regression model in the age interval 80-105 years (using program *nlin* in Stata). Age-specific exposure values are used as weights in nonlinear regression analyses.

Akaike Information Criterion (AIC) is used to evaluate goodness of fit for the Gompertz and the Kannisto models:

$$AIC = 2k - 2\ln(L) \qquad (3)$$

where *lnL* is the maximized log-likelihood of the model and *k* is the number of parameters estimated.

Analyses were conducted using Stata statistical software, release 14.

Data analyses produced the following results described below.

United States

Figure 1 presents the results of model fitting (AIC values) for the U.S. 1880-1899 birth cohorts. It demonstrates clear transition from lower values for AIC (better fit) for the Kannisto model in the case of earlier birth cohorts to lower values (better fit) of AIC for the Gompertz model in the case of later birth cohorts. This phenomenon means that mortality deceleration, which is observed for both men and women in earlier birth cohorts, disappears in more recent birth cohorts. This historical change in the pattern of mortality trajectories from mortality deceleration to the Gompertz law occurs for persons born around 1886-1887 (Figure 1).

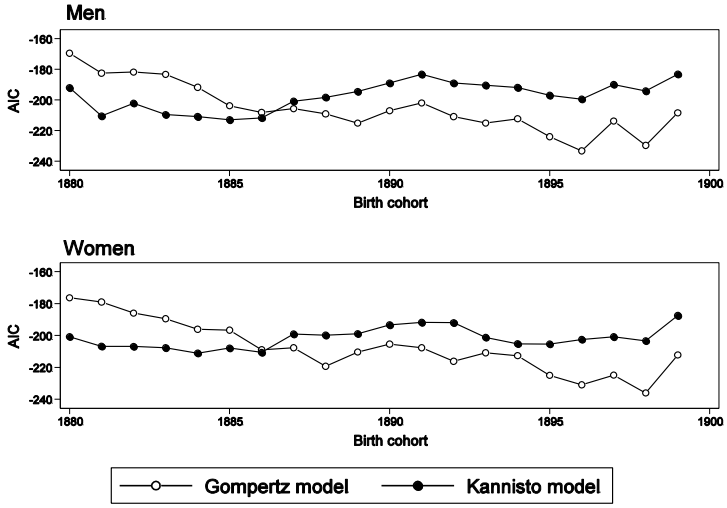

Figure 1. Changes of Akaike Information Criterion (AIC) across birth cohorts for the Gompertz and the Kannisto models fitting the U.S. mortality. Lower AIC values correspond to better model fit.

Thus, we may conclude that mortality in the past indeed demonstrated deceleration while later it changed to the Gompertz pattern.

Canada

Figure 2 presents AIC for Kannisto and Gompertz models across birth cohorts in Canada. As in the case of U.S. birth cohorts, for earlier birth cohorts we observe better fit by the "mortality deceleration" Kannisto model. However, for male cohorts born after 1890 and female cohorts born after 1887 mortality shows better fit by the Gompertz model.

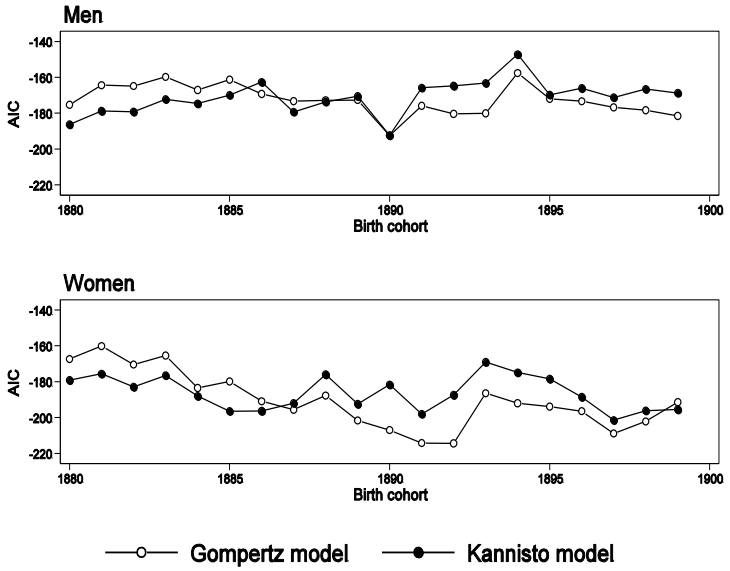

Figure 2. Changes of Akaike Information Criterion (AIC) across birth cohorts for the Gompertz and the Kannisto models fitting the Canadian mortality. Lower AIC values correspond to better model fit.

In the case of Canada the transition to the Gompertz-like mortality at older ages is less clear-cut compared to the U.S. mortality, so that for the most recent birth cohort both models have similar level of accuracy for women. For men the Gompetz model provides a better fit for recent birth cohorts

United Kingdom

Figure 3 demonstrates AIC changes for Kannisto and Gompertz models across birth cohorts in the case of the United Kingdom. In this country we also observe a transition from mortality deceleration pattern to the Gompertz-like mortality. This transition occurred for cohorts born after 1893 in both men and women.

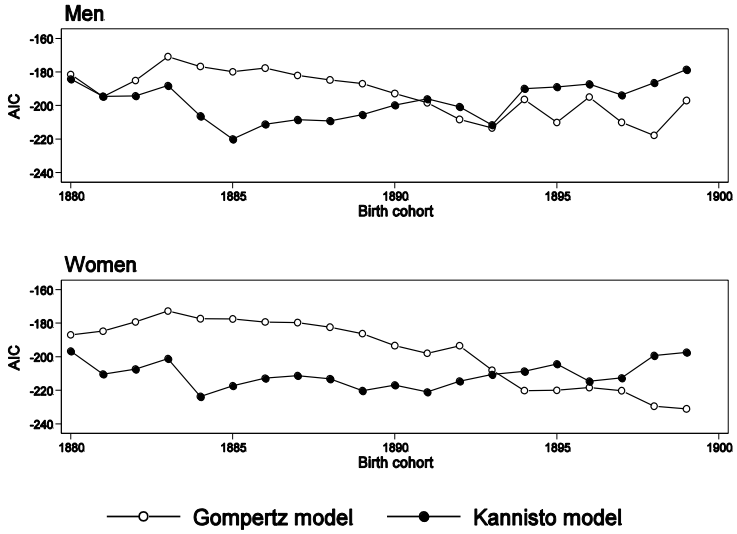

Figure 3. Changes of Akaike Information Criterion (AIC) across birth cohorts for the Gompertz and the Kannisto models fitting the UK mortality. Lower AIC values correspond to better model fit.

Thus, we may conclude that the transition to the Gompertzian mortality occurred in the United Kingdom much later compared to the United States.

Illustration of these changes in old-age mortality trajectories can be seen at Figure 4.

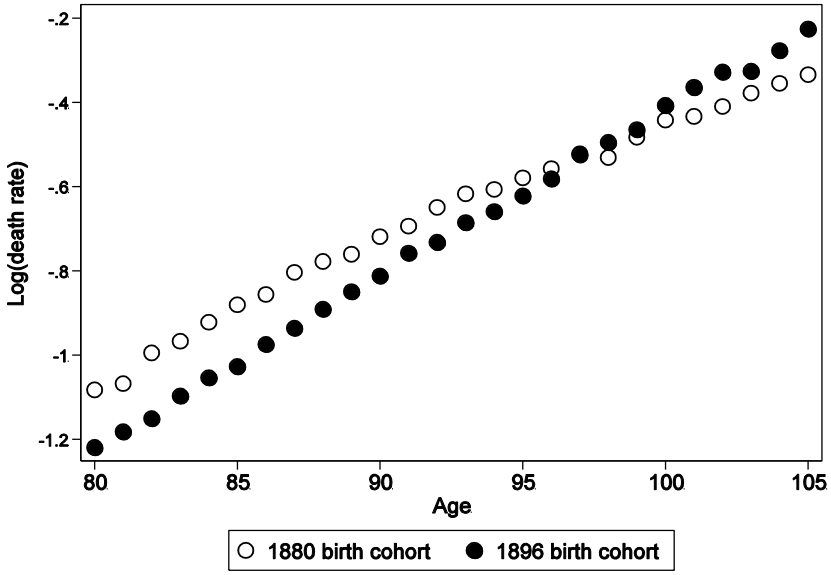

Figure 4. Late-life mortality of U.S. women. Differences in mortality pattern for earlier (1880) and later (1896) birth cohorts.

Note that U.S. mortality of earlier 1883 birth cohort demonstrates an obvious deceleration of mortality growth with age, while mortality of later 1896 birth cohort demonstrates Gompertz-like mortality pattern. It is interesting that mortality of earlier birth cohort is even lower than mortality of later birth cohort after age 100 years. This paradoxical observation is most likely related to better quality of age reporting in more recent birth cohort.

This study of 1880-1899 single-year birth cohorts in three English-speaking countries found that mortality deceleration is more prevalent in historically earlier birth cohorts while more recent birth cohorts tend to demonstrate the Gompertzian pattern of mortality. These results support the hypothesis that mortality deceleration fades away over time perhaps due to improvement in age reporting.

These results may help to understand why earlier studies of old-age mortality found mortality deceleration and mortality leveling-off (Kannisto 1994; Horiuchi and Wilmoth 1998; Thatcher, Kannisto et al. 1998; Thatcher 1999), while more recent studies did not confirm these initial findings (Gavrilov and Gavrilova 2011; Gavrilova and Gavrilov 2015). More frequent age misreporting in the past by older individuals is one of the most likely reasons for this phenomenon (Coale and Kisker 1986; Gavrilov and Gavrilova 2011; Newman 2018). Studies conducted more than 15 years ago used data for older birth cohorts when age reporting was not particularly accurate (Jdanov, Jasilionis et al. 2008). Later study found that old-age mortality in Australia, Canada and the United States is compatible with the Gompertzian model confirming our findings (Bebbington, Green et al. 2014). These authors also found that mortality in European countries does show deceleration, but the age at onset of mortality deceleration is shifting over time to older ages (Bebbington, Green et al. 2014).

In addition to age misreporting, some other causes of transition from late-life mortality deceleration to Gompertzian mortality may be involved. Recent observation is that mortality of centenarians in the United States did not decrease noticeably in the past decades, despite a significant decline in mortality of younger age groups (Gavrilov, Gavrilova et al. 2017). In some countries (Japan, France, Switzerland and Sweden) historical decline of mortality among

centenarians has stopped about 10-20 years ago (Robine and Cubaynes 2017). Historical stagnation of mortality at ages 100 years and older may lead to steeper mortality curves for cohorts at extreme old ages, while historical mortality decline after age 100 may produce apparent decelerating pattern of mortality with age. Our results do not completely exclude possibility that the age at onset of mortality deceleration in the United States has moved beyond 105 years of age. It is possible that both the improvement of age reporting and stagnation of mortality among centenarians contribute to the observed historical transition from mortality deceleration to the Gompertz law. Overall, it appears that the onset of mortality deceleration occurs now at much older ages than was reported earlier (Wilmoth 1995; Horiuchi and Wilmoth 1998; Thatcher, Kannisto et al. 1998; Thatcher 1999).

Our results demonstrate that there is no single universal answer to the question about mortality pattern at extreme old ages, because this answer depends on the historical period of mortality analysis. In old historical data the late-life mortality deceleration is observed. In more recent data mortality continues to grow exponentially with age even at very old ages. This leads to more conservative estimates for future human longevity records and proportion of older people (population aging).

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