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Descriptive Finding

Taylor's power law in human mortality

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Demographic Research: Volume 33, Article 21
Descriptive Finding

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Abstract

BACKGROUND AND OBJECTIVE
Taylor's law (TL) typically describes a linear relationship between the logarithm of the variance and the logarithm of the mean of population densities. It has been verified for many non-human species in ecology, and recently, for Norway's human population. In this article, we test TL for human mortality.

METHOD
We use death counts and exposures by single age (0 to 100) and calendar year (1960 to 2009) for countries of the Human Mortality Database to compute death rates as well as their rates of change in time. For both mortality measures, we test temporal forms of TL: In *cross-age-scenarios*, we analyze temporal variance to mean relationships at different ages in a certain country, and in *cross-country-scenarios*, we analyze temporal variance to mean relationships in different countries at a certain age.

RESULTS
The results reveal almost log-linear variance to mean relationships in both scenarios; exceptions are the cross-country-scenarios for the death rates, which appear to be clustered together, due to similar mortality levels among the countries.

CONCLUSIONS
TL appears to describe a regular pattern in human mortality. We suggest that it might be used (1) in mortality forecasting (to evaluate the quality of forecasts and to justify linear mortality assumptions) and (2) to reveal minimum mortality at some ages.

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1. Introduction

Taylor (1961) established a power law that describes a pattern in ecology regarding the (spatial or temporal) variability of populations. For many species, it describes a linear relationship between the logarithms of the variance (Var) of population size or density (P) and its mean (E):

$$Var(P) = aE(P)^b \quad (1)$$

Although the interpretation of the two parameters *a* and *b* is controversial, Taylor (1961: 735) calls the constant *a* a (less relevant) *computing factor* and suggests that the slope *b* is a species-specific *index of aggregation*. Kilpatrick and Ives (2003) report that many empirical analyses identify values between 1 and 2 for the slope *b,* due to environmental and demographic stochasticity as well as competitive interactions between species. Kendal (2004b) gives a detailed overview of the history of TL. He shows that TL has mostly been found for population densities in ecology, but that power laws have also been identified in other contexts, such as outbreaks of infectious diseases (Anderson and May 1988; Rhodes and Anderson 1996) and for physical distributions of gene structures within chromosomes (Kendal 2004a). In these non-ecological realizations of TL, Taylor's interpretation of the exponent is obviously not viable.

In human demography, TL has been applied by Cohen, Xu, and Brunborg (2013), who verify a log-linear variance to mean relationship for Norway's population (disaggregated in 19 counties) from 1978 to 2010; they suggest using TL as an evaluation criterion for population forecasts, i.e., to determine if such a linear relationship can be found in both observed population data and in forecasts.

Vaupel, Zhang, and van Raalte (2011) analyzed variation in the age at death by e†, which is the average number of life-years lost in a population (Vaupel and Canudas Romo 2003). They showed that populations with very low variation typically also had the lowest mean, as measured by life expectancy at birth. In this article, we quantify further the relationship between the variation and the mean of human mortality by testing the application of TL to human death rates and to rates of improvement in mortality: We compute variances and means of human mortality (change) for single ages over time for different countries to analyze their temporal variability across ages and across countries.

1.1 Hypothesis 1

In our so-called *cross-age-scenarios*, we analyze temporal variance to temporal mean relationships of mortality in multiple countries on the logarithmic scale *across ages*. We hypothesize that these relationships are almost log-linear for all ages in each country. Such a finding might indicate that TL could be used to evaluate mortality forecasts and to justify linear assumptions in mortality forecasts on a logarithmic scale.

If TL were confirmed in observed mortality data, then TL could be tested in mortality forecasts, and the results of this consistency test would be available immediately after generating a forecast. In contrast, forecast errors can typically only be computed after the mortality of forecast years occurs. Of course, in the long run, the empirical usefulness of using TL as a consistency test would have to be evaluated post hoc.

Justifying linear assumptions in mortality forecasting with TL would be beneficial, since many models (Lee and Carter 1992; Renshaw and Haberman 2003, 2006) rely on linear predictors for death rates on a logarithmic scale. Tuljapurkar, Li, and Boe (2000) use the observed long-term linear mortality decline in the G7 countries on the logarithmic scale to justify the modeling of log-linear mortality forecasts. If we found support for our hypothesis of (almost) linear variance to mean relationships for death rates and their rates of change, TL might also justify linear assumptions for forecasting models relying on the change of mortality (Mitchell et al. 2013; Haberman and Renshaw 2012; Bohk and Rau 2014).

1.2 Hypothesis 2

In our so-called *cross-country-scenarios*, we compare temporal variance to temporal mean relationships of mortality at a given age on the logarithmic scale *across countries*. We hypothesize that these relationships are almost linear as long as mortality differs sufficiently among countries. If mortality is similar among the countries, we expect no clear variance to mean relationships.

While there is some debate about the linearity (Vallin and Meslé 2010), it has been shown by Oeppen and Vaupel (2002) that record life expectancy at birth for women increased almost linearly by 2.5 years per decade for more than 150 years. TL might offer a way to determine if mortality reaches a minimum at selected ages; if some ages approached a hypothetical minimum mortality, we would expect that the variation of their variance to mean relationships on the logarithmic scale would be small among demographically advanced countries. However, unanticipated medical breakthroughs or similar events could further reduce even temporarily minimum mortality at certain ages.

2. Data and methods

We measure human mortality by death rates $m_{x,t}$ at age x in year t, where

$$m_{x,t} = \frac{d_{x,t}}{L_{x,t}} \tag{2}$$

The numerator $d_{x,t}$ is the density of deaths at age x in year t. The denominator $L_{x,t}$ is the number of person-years-lived. We also investigate the annual rate of change of mortality, defined as in Kannisto et al. (1994)

$$\rho_{x,t} = -\left[\frac{m_{x,t+1}}{m_{x,t}} - 1\right] \tag{3}$$

Equation (3) gives positive or negative values if mortality declines or increases, respectively. The basic calculations of means (*E*) and variances (*Var*) for single ages x in a given country c in time period t = 1, …, *N* differ only marginally for both mortality measures. We have *N* observations for the death rates:

$$E\left(m_{x,c}\right) = \frac{1}{N}\sum_{t=1}^{N} m_{x,t,c} \tag{4}$$

$$Var\left(m_{x,c}\right) = \frac{1}{N}\sum_{t=1}^{N}\left(m_{x,t,c} - E\left(m_{x,c}\right)\right)^2 \tag{5}$$

We have *N*−1 observations for the rates of mortality improvement:

$$E\left(\rho_{x,c}\right) = \frac{1}{N-1}\sum_{t=1}^{N-1} \rho_{x,t,c} \tag{6}$$

$$Var\left(\rho_{x,c}\right) = \frac{1}{N-1}\sum_{t=1}^{N-1}\left(\rho_{x,t,c} - E\left(\rho_{x,c}\right)\right)^2 \tag{7}$$

If mortality is improving, the temporal mean (6) will be positive and its logarithm will be defined.

To test for linearity, we fit the data on log mean and log variance with linear and quadratic regression models; if the coefficient of the quadratic term is not statistically significant, or if the linear model has a smaller Akaike information criterion (AIC) than the quadratic model, we conclude that a linear model is sufficient and that the variance to mean relationship is (approximately) linear.

To ascertain if the slopes differ among countries (in cross-age-scenarios) or among ages (in cross-country-scenarios), we perform covariance analyses (ANCOVA),

including country or age as an additional categorical variable; if the interaction terms between mean mortality (change) and country or age are statistically significant, we conclude that the slopes are different and, therefore, country- or age-specific.

To conduct these analyses, we use the lm() function of the statistical software *R* (2014). Death counts and corresponding exposures by single age (from 0 to 100) and calendar year (from 1960 to 2009) were downloaded from the Human Mortality Database (2014). Parallel analyses for men gave results very similar to those for women. In some cases, however, the slopes b differed between men and women. These analyses have been deposited in the supplementary material.

3. Results

Figure 1 depicts how strongly female life expectancy at birth differs among countries (gray) of the Human Mortality Database (2014) between 1960 and 2009. Japan (black) is the current record life expectancy holder with 86.4 years for women in 2009, closely followed by France (blue), Spain (yellow), Italy (red) and Australia (green). In contrast, Russian life expectancy (magenta) lags far behind these values with 74.7 years for women in 2009. Other Eastern European countries like Hungary (orange) or Poland (turquoise) also experienced an irregular mortality development between 1960 and 2009, including periods of stagnating and increasing mortality, but their current life expectancy at birth is substantially higher than Russia's.

3.1 Temporal cross-age-scenarios

Despite these diverse mortality developments, Figure 2 depicts, for twelve selected countries, a relatively strong linear $\log_{10}$ variance to $\log_{10}$ mean relationship for the temporal variation of female death rates at ages 0 to 100. Each circle represents the log mean and log variance (over time) at a certain age in a given country; younger ages are depicted in yellow and red, older ages are depicted in blue and green. All ages are on (almost) straight lines with slopes ranging between 1.7 and 1.86 and squared correlation coefficient r^2 values ranging from 0.96 to 0.99. Adjacent ages are shown together on these lines with younger ages (orange to red) exhibiting smaller means and variances than higher ages (blue to green). Exceptions are the youngest ages zero to five (yellow) with higher means and variances than later childhood ages. The preservation of the (natural or ascending) order of adult ages might be due to the smooth mortality function of chronological age. The log-linear pattern could particularly result from the exponential mortality increase at adult ages, and from the positive association (and even

monotonic and proportional relationship) between mean (mortality) and its variance on an absolute scale. Since older ages demonstrated higher death rates than younger ages, their variance also (often) happened to be larger.

Figure 3 depicts the $\log_{10}$ variance to $\log_{10}$ mean relationship for temporal variation in the female rates of mortality improvement at ages 0 to 100. While the log variance to log mean relationship is almost linear in the twelve selected countries in both cases, Russia and Japan hold special positions: Russia has a smaller slope (1.44) and r^2 value (0.67) than Japan with 2.62 (slope) and 0.9 (r^2 value). Except for the youngest (yellow) and oldest (green) ages, adjacent ages are also placed side by side for survival improvements, but higher ages (blue) usually have had smaller means and variances than younger ages (orange and red). In the future, this descending order of ages could change or reverse, if relatively large survival improvements advanced to higher ages.

3.2 Temporal cross-country-scenarios

Figures 4 and 5 depict the temporal cross-country-scenarios with log variance to log mean relationships of female death rates and rates of mortality improvement, respectively, for all countries of the Human Mortality Database (2014) (gray circles) at certain ages (0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100); Australia (green), France (blue), Italy (red), Spain (yellow) and Japan (black) are highlighted because they had the highest life expectancies in 2009. While the rates of mortality improvement show relatively strong linear variance to mean relationships on a logarithmic scale for all ages, the death rates do not: Their variance to mean relationships are clustered together, and the position of the highlighted countries is rather in the center (than at the borders) of these clouds. The differences in the means and the variances appear to increase between countries from age 10 onwards as the level of mortality increases. While people at age 10 experience a mortality that is so low that it cannot be reduced much further in any country, older ages show a mortality rate that is high, variable across countries, and allowing for further reductions. This may explain why variance to mean relationships are more clearly linear, the higher mortality is at a given age and the more it varies among multiple countries.

Figure 1: Period life expectancy at birth for women of countries in the Human Mortality Database (2014) between 1960 and 2010

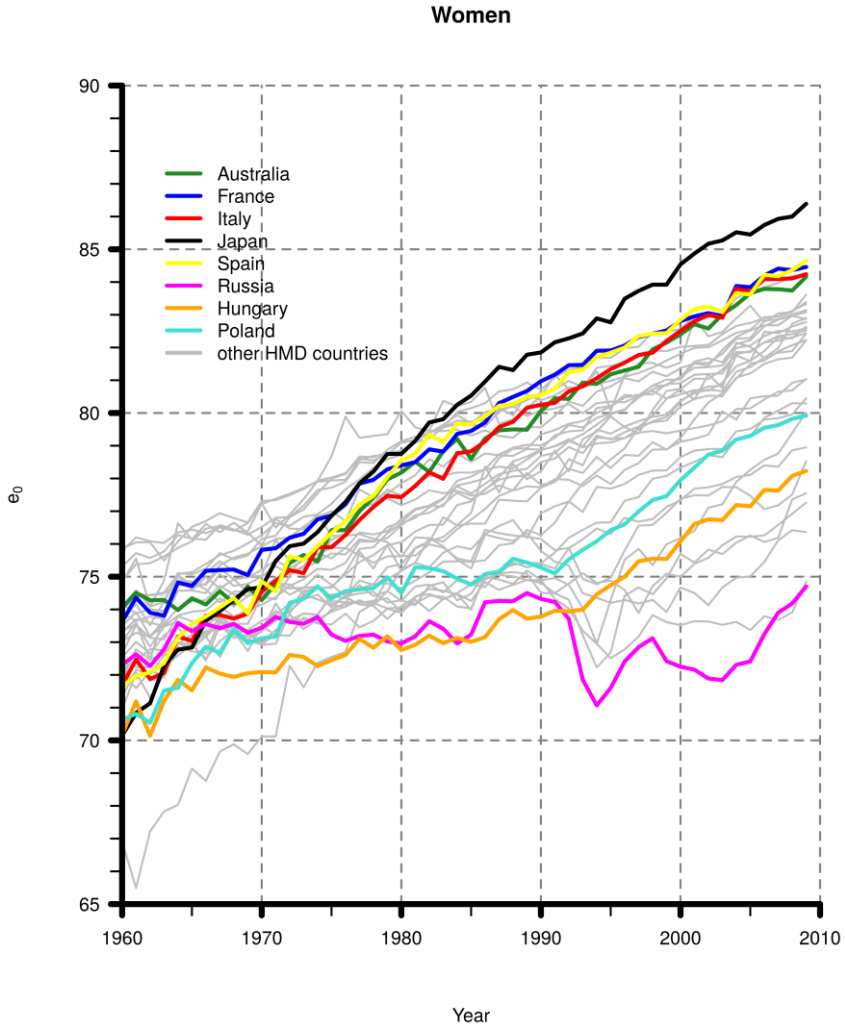


Figure 2: Temporal cross-age variances (Var) and means (E) over 1960−2009 for female death rates (m) show a linear relationship for ages 0 (yellow) to 100 (green) on a logarithmic scale (base 10) in multiple countries

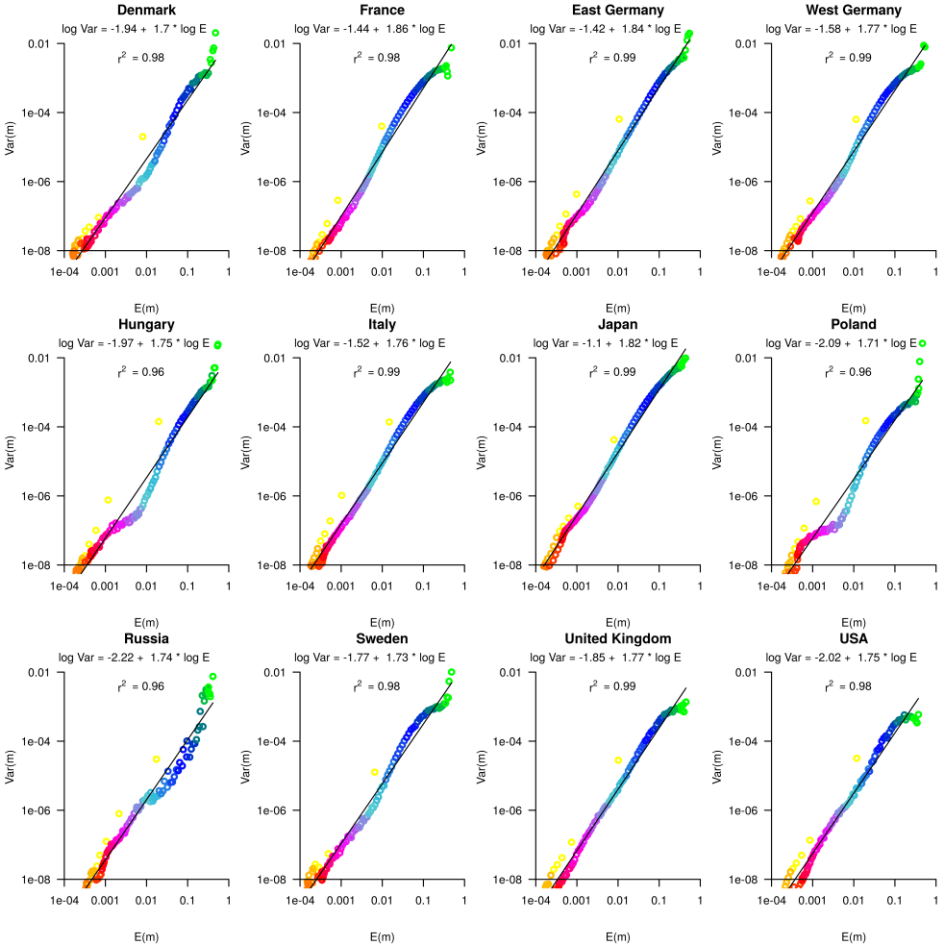
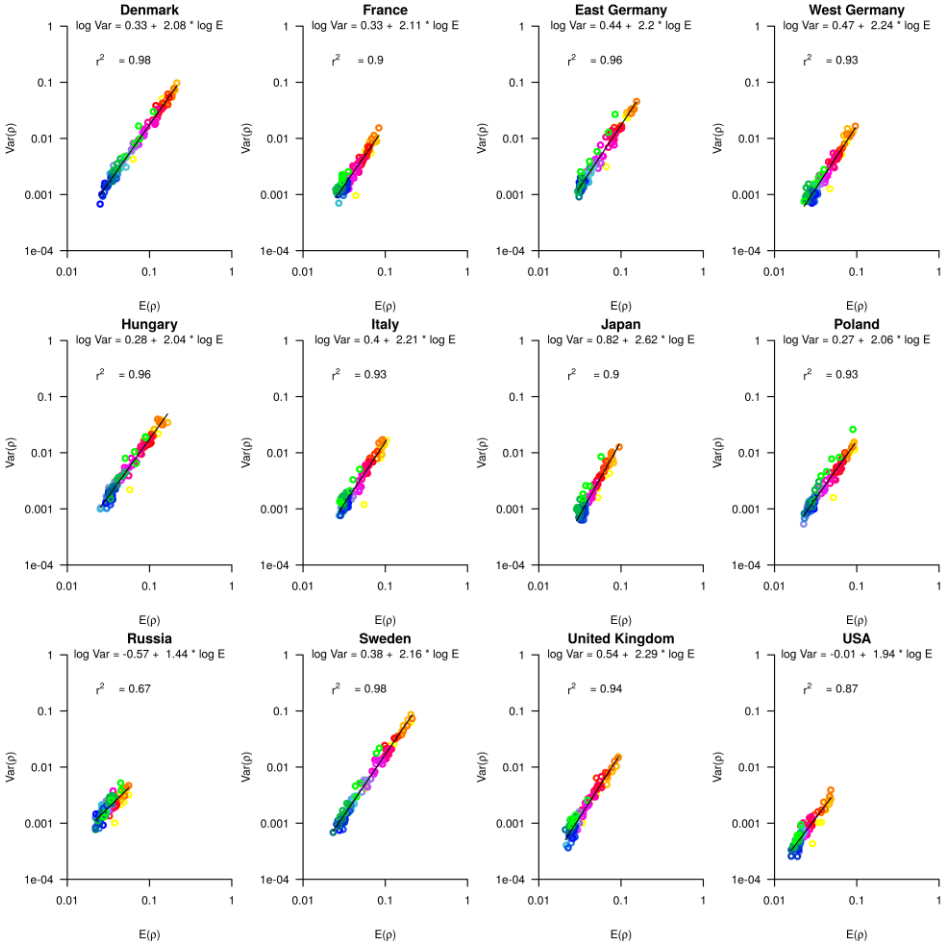


Figure 3: Temporal cross-age variances (Var) and means (E) for female rates of mortality improvement (ϱ) over 1960−2009 show a linear relationship for ages 0 (yellow) to 100 (green) on a logarithmic scale (base 10) in multiple countries



For every country in the cross-age-scenarios, the slope for death rates (Figure 2) is notably less than 2. The country with the highest slope, 1.86, is France. By contrast, in the cross-age-scenarios, the slope for rates of mortality improvement (Figure 3) is notably greater than 2 except for Russia with slope 1.44 and USA with slope 1.94. In the cross-country-scenarios, the slope for rates of mortality improvement (Figure 5) is likewise notably greater than 2 except for age 100. These differences in slopes indicate that a given proportional increase in the temporal mean rate of mortality improvement is generally associated with a greater proportional increase in the temporal variance of the rate of mortality improvement than the parallel in the case of death rates.

3.3 Statistical tests

Tests for linearity

Based on the statistical significance of linear and quadratic regression terms as well as on values for the Akaike information criterion and for r^2, our tests reveal for rates of mortality improvement that the linear regression models are more appropriate than the quadratic regression models. For death rates, the quadratic regression model performs marginally better than the linear model in the cross-age-scenario (Figure 2). However, both linear and quadratic models appear to be appropriate since, for instance, r^2 values are very similar. In the cross-country-scenario, by contrast, neither the linear nor the quadratic regression models fit the clumped variance to mean relationships of the death rates (Figure 4).

Tests for different slopes

Based on covariance analyses (ANCOVA), our tests reveal that slopes differ more or less depending on the selected reference country or age in the respective regression model. For the rates of mortality improvement, the slopes differ much more among countries than among age groups. In the cross-age-scenarios (Figure 3), the slopes range between 1.44 and 2.62, whereas they range only between 1.97 and 2.54 in the cross-country-scenarios (Figure 5). The slopes of the death rates differ less among countries than those of the rates of mortality improvement.

Figure 4: Temporal cross-country variances (Var) and means (E) for female death rates are clustered for the countries of the Human Mortality Database (2014) in certain ages between 1960 and 2009. The legend in the right of the bottom line represents the colors for the countries

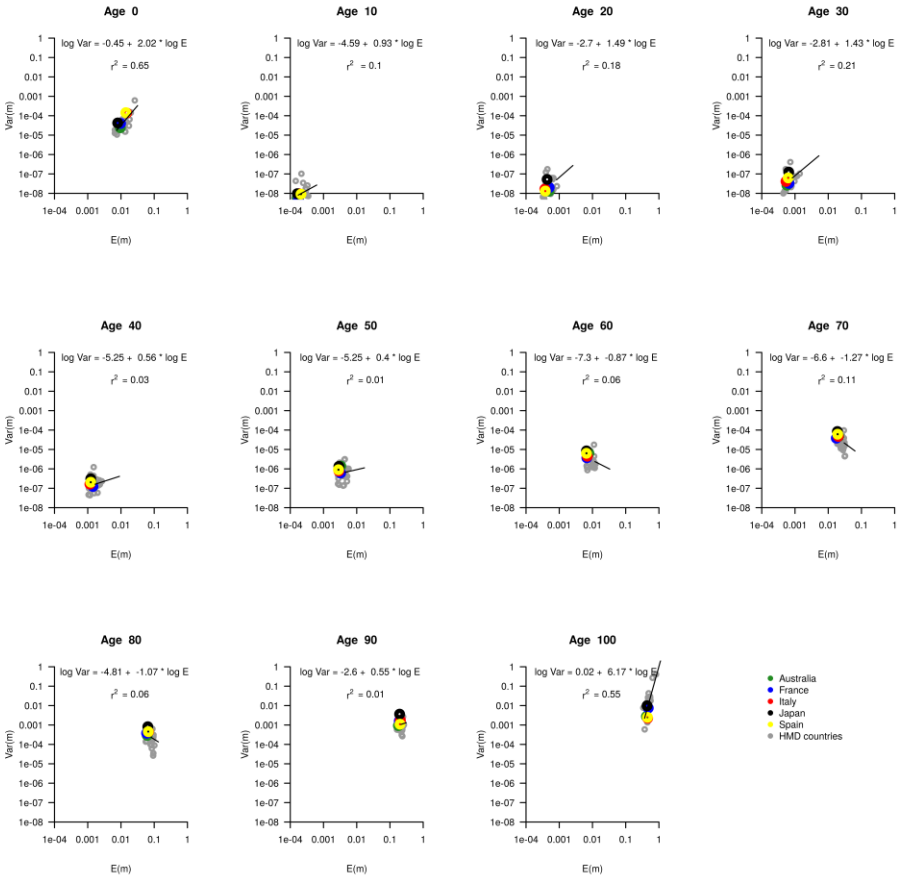
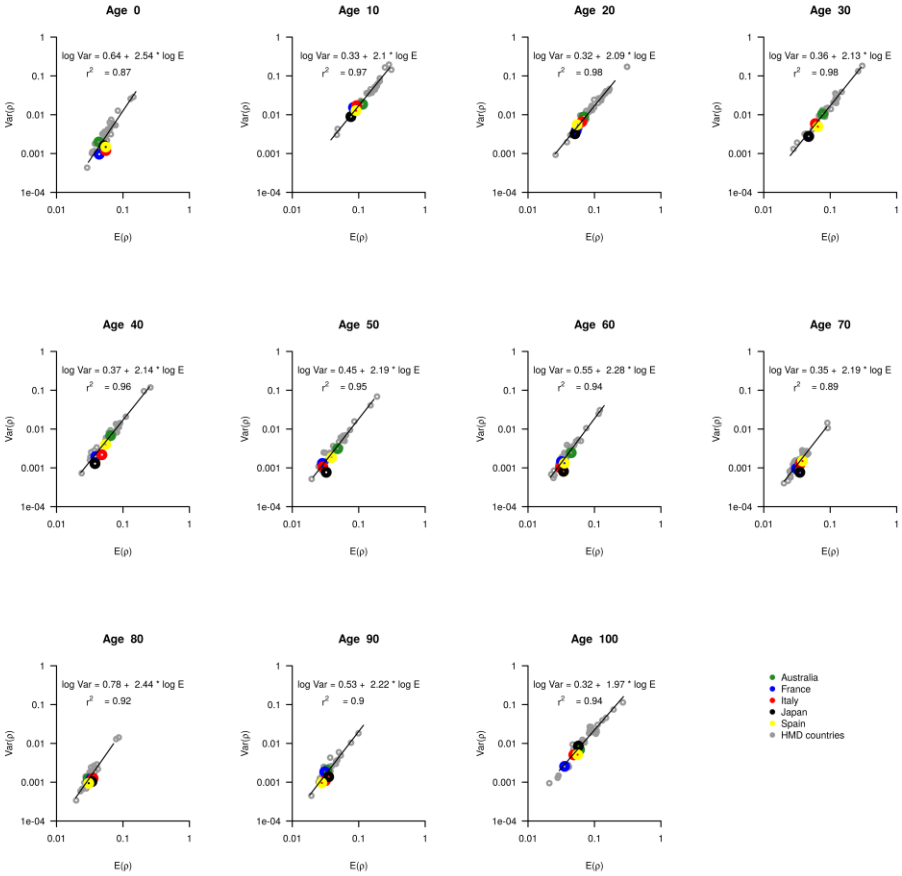


Figure 5: Temporal cross-country variances (Var) and means (E) for female rates of mortality improvement show a linear relationship for the countries of the Human Mortality Database (2014) in certain ages between 1960 and 2009. The legend in the right of the bottom line represents the colors for the countries



4. Concluding remarks

Studies of fundamental patterns of mortality often focus either on the mean or on the variation of mortality. Our analysis of the mean and the variance of mortality in combination detected a regular pattern, TL, not only for the level, but also for the change of mortality over time.

Mean of mortality
Average age profiles of human mortality are typically described by laws of mortality, but they also gained attention from a biodemographic perspective regarding theories of aging in recent years. Gompertz's (1825) law describes the profile of adult mortality with an exponential increase, whereas, e.g., Thiele (1871) and Siler (1983) added terms to model mortality for the young and the old. Burger, Baudisch, and Vaupel (2012) look at the evolution of the fundamental age schedule of human mortality, describing its progress from hunter-gatherers to present highly developed populations; although they state that human mortality levels dropped extraordinarily compared to other species, particularly since 1900, they also show that the shape of human mortality remains fairly stable. Bronikowski et al. (2011) show that this age profile of mortality is not only stable for humans over time, but also for primates, whereas Jones et al. (2014) emphasize the diversity in these age profiles across various species.

Variance of mortality
Fundamental patterns and trends in the variation of age at death are typically detected with indices of lifespan variability, which have been reviewed by, for example, van Raalte and Caswell (2013) and Wilmoth and Horiuchi (1999). Among these indices are, for instance, simple measures such as the variance, the standard deviation or the interquartile range, but also more complex measures such as $e^{\dagger}$ (Vaupel and Canudas Romo 2003). Engelman, Caswell, and Agree (2014) point out that the variation of longevity declined in highly developed countries, but they also show that the variability regarding the progress of relatively high survival improvements in older ages persists in those countries.

Mean and variance of mortality
Our analyses show that TL describes a regular pattern in human mortality: the log temporal mean and the log temporal variance of death rates and of rates of mortality improvement have a strong linear relationship. The approximately linear log variance to log mean relationships of mortality appear to be robust in the temporal cross-age-scenarios for death rates and their rates of improvement (Figures 2, 3) as well as in the temporal cross-country-scenarios for the rates of mortality improvement (Figure 5). The

slopes are comparable to those of ecological studies (Kilpatrick and Ives 2003) of population density. Cross-country-scenarios for death rates (Figure 4) show clustered variance to mean relationships on the logarithmic scale due to similar mortality levels among the countries at single ages. Our results support the two hypotheses in section 1 and suggest that TL could be used (1) to evaluate the quality of mortality forecasts immediately after their generation and to justify linear mortality assumptions on the logarithmic scale, as well as (2) to reveal minimum mortality at certain ages for countries with very low mortality − although our analyses do not bring such limits to light.

5. Acknowledgements

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Appendix: Supplementary material

Figure A1: Temporal cross-age variances (Var) and means (E) over 1960−2009 for male death rates (m) show a linear relationship for ages 0 (yellow) to 100 (green) on a logarithmic scale (base 10) in multiple countries

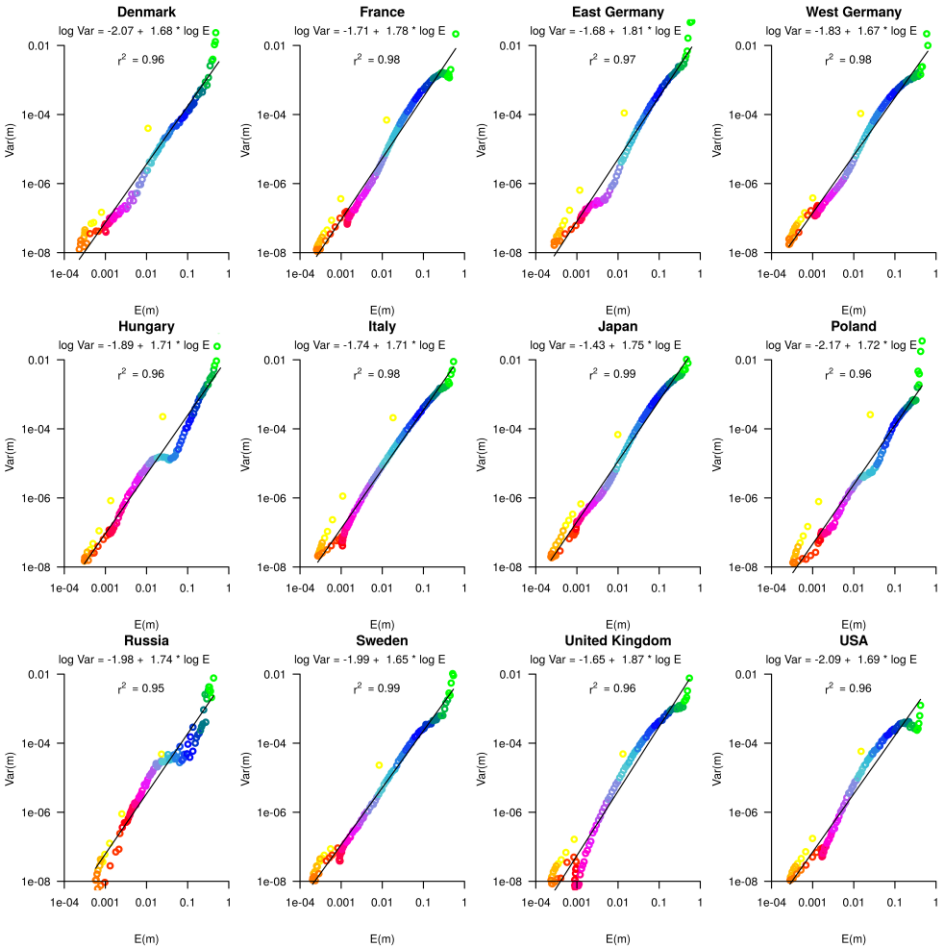

Figure A2: Temporal cross-age variances (Var) and means (E) for male rates of mortality improvement (ϱ) over 1960-2009 show a linear relationship for ages 0 (yellow) to 100 (green) on a logarithmic scale (base 10) in multiple countries

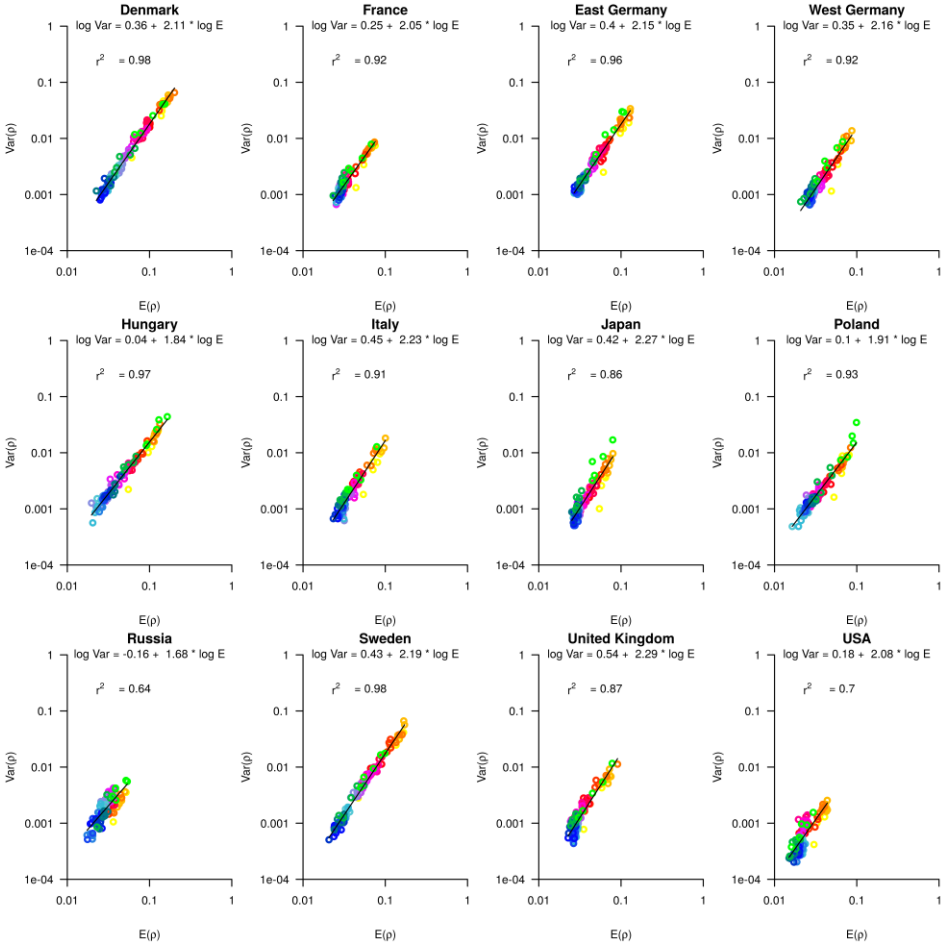

Figure A3: Temporal cross-country variances (Var) and means (E) for male death rates are clustered for the countries of the Human Mortality Database (2014) in certain ages between 1960 and 2009. The legend in the right of the bottom line represents the colors for the countries

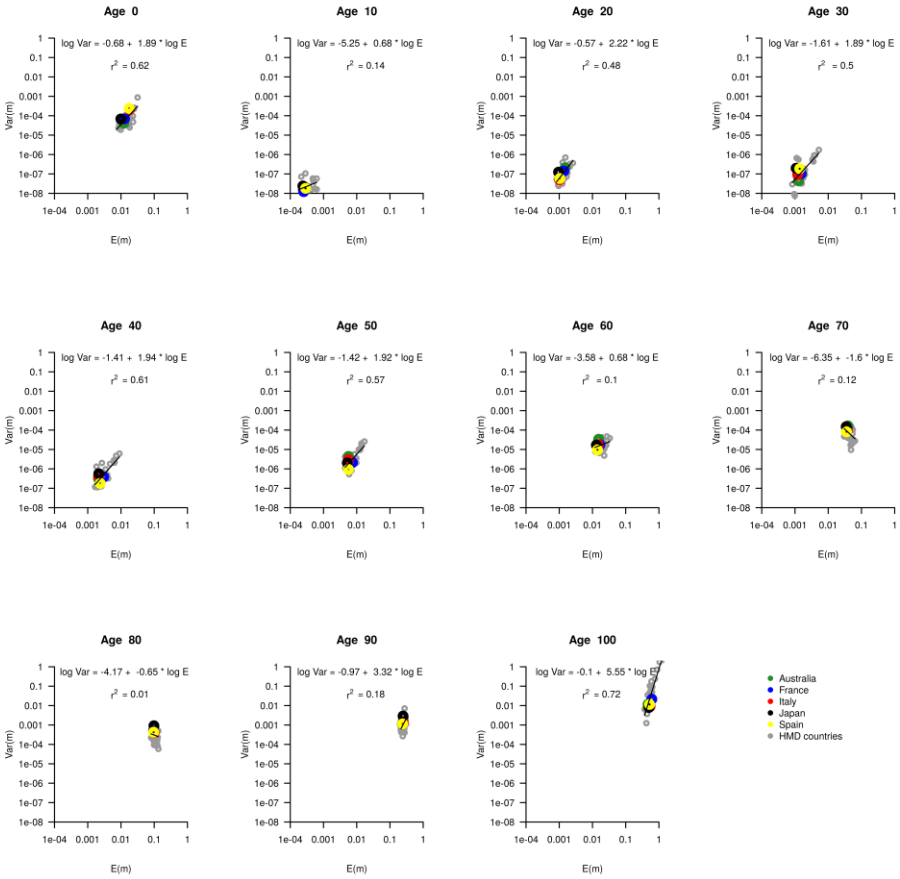

Figure A4: Temporal cross-country variances (Var) and means (E) for male rates of mortality improvement show a linear relationship for the countries of the Human Mortality Database (2014) in certain ages between 1960 and 2009. The legend in the right of the bottom line represents the colors for the countries

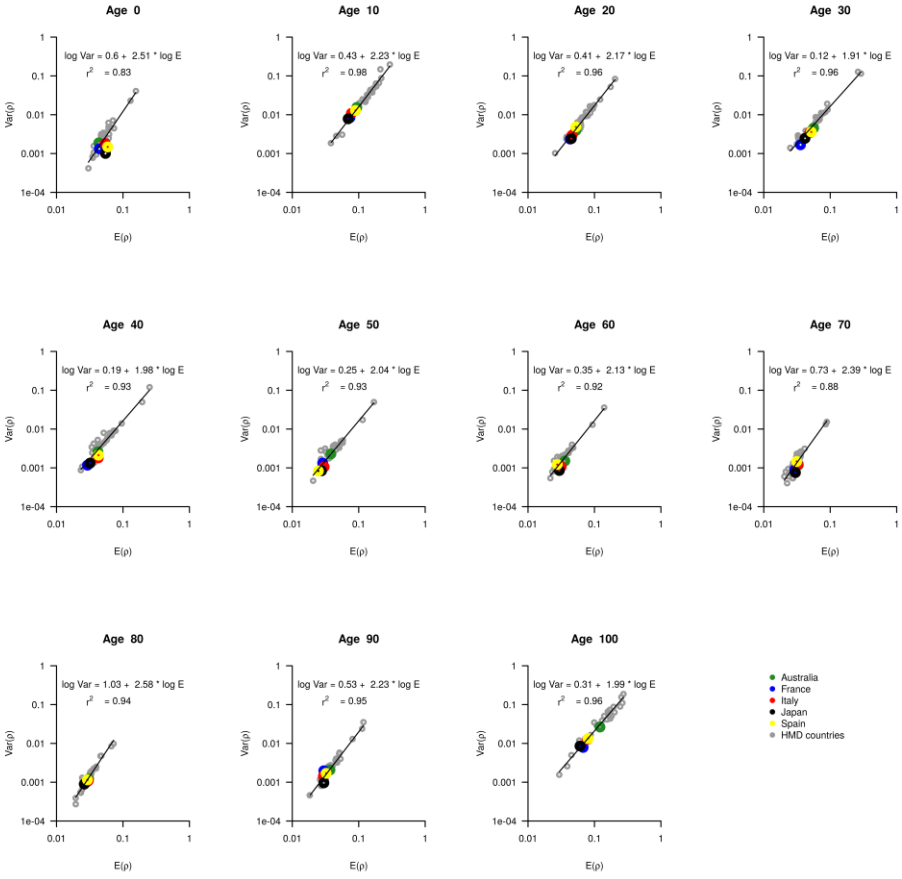

Table A1: Cross-Age-Scenarios: Do the slopes of TL differ between women and men?

	Death rates	Rates of mortality improvement
Denmark	0.644	0.525
France	0.031*	0.533
East Germany	0.306	0.379
West Germany	0.0009***	0.347
Hungary	0.426	0.0002***
Italy	0.126	0.789
Japan	0.003**	0.007**
Poland	0.827	0.048
Russia	0.936	0.134
Sweden	0.005**	0.511
United Kingdom	0.042*	0.969
USA	0.171	0.348

To answer this question, we estimated TL with a linear model that uses the logarithm of mean mortality (change), sex, and an interaction term between these two variables to predict the logarithm of the variance of mortality (change). The p-values for the interaction terms are given for death rates and rates of mortality improvement for each country. A very low p-value indicates that there is strong evidence that the coefficient for the interaction term is non-zero, and that the slopes in TL differ between women and men. This is the case in only a few countries, i.e., in most of the countries, the slopes in TL do not differ between women and men.