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Comparing Cohort Survival in Good Health: A Research Note on Decomposing Sex Differentials in the United States

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ABSTRACT We introduce a method for decomposing differences in healthy cross-sectional average length of life (HCAL). HCAL provides an alternative to the health expectancy (HE) indicator by including the health and mortality history of all cohorts present at a given time. While decompositions of HE differences account for contributions made by health and mortality, differences in HCAL are further disentangled into cohort-specific contributions. In this research note we illustrate the technique by analyzing the sex gap in health and mortality for the United States. We use the harmonized version of the Health and Retirement Survey data and define the health status in terms of activities of daily living. Our results suggest that the female advantage in cohort survival is partly compensated by women's lower cohort-specific health levels. At older ages, however, the sex differences in health are not large enough to compensate men's disadvantage in cohort survival.

KEYWORDS Disability-free life expectancy • HCAL • Cohort analysis • Formal demography • Decomposition

Introduction

Researchers and public health officials usually measure and compare population health on the basis of the health expectancy measure (HE) (Wang et al. 2020). HE can be calculated as a period indicator or refer to birth cohorts. While period indicators are essential for examining period effects (e.g., a sudden health crisis in a calendar year, such as COVID-19), they are limited in providing information on the health and mortality experience for any actual group of individuals (Goldstein and Wachter 2006; Guillot 2003; Schoen and Canudas-Romo 2005). This is because the period concept relies on simulating a synthetic cohort, which is usually subjected to a very different health and mortality experience than actual cohorts (Caselli and Vallin 2006).

As an example, differences in health and mortality between American women and men have been ascribed to different health behaviors, such as diet, smoking, physical activity, and alcohol consumption (Levine and Crimmins 2018; Li et al. 2018; Montez et al. 2016). These are usually life course events rather than period shocks,

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and so might be best understood by looking at cohort-specific data (Beltrán-Sánchez et al. 2015; Guillot and Payne 2019; Preston and Wang 2006). Yet, previous studies on sex differences in health and mortality have mostly focused on comparing period HE (Crimmins et al. 2008; Cui et al. 2019; Solé-Auró et al. 2015).

The healthy cross-sectional average length of life (HCAL) was first introduced by Sauerberg et al. (2020). It extends the cross-sectional average length of life (CAL) (Brouard 1986; Guillot 2003) to the health dimension. In contrast to the conventional HE indicator, HCAL takes into account the past health and mortality history of cohorts. Similar measures have been recently introduced to study life span inequality (Nepomuceno et al. 2022) and childlessness (Mogi et al. 2022). HCAL can be interpreted as the sum, over all cohorts present in the observation period, of the proportions being alive and in good health.

This research note aims at further developing HCAL by proposing a decomposition method, which allows one to disentangle the age- and cohort-specific contribution between two HCALs. The decomposition distinguishes between a mortality effect (reflecting the age- and cohort-specific differences in mortality) and a disability effect (reflecting the corresponding differences in disability). Thus, it extends the method for decomposing differences in conventional HE introduced by Nusselder and Looman (2004). Their approach has been frequently used to decompose sex differentials in HE into health and mortality components (Mairey et al. 2014; Nusselder et al. 2010; Van Oyen et al. 2013). The new method makes it possible to identify age- and cohort-specific contributions as well. This enables researchers to take into account cohort effects and examine differences in health and mortality from a life course perspective.

Data and Methods

We obtained age-specific death rates by sex for the United States from the Human Mortality Database (2022). This database uses vital statistics to provide high-quality mortality data for industrialized countries, processing the data in a harmonized procedure that ensures comparability across countries and over time (Wilmoth et al. 2017). We used period age-specific death rates to reconstruct cohort survivorship by age and sex in accordance with conventional life table techniques (Preston et al. 2001). More detailed information on the performed calculations appears in the online supplementary material.

The health data come from the Gateway to Global Aging Data (2022). The Gateway provides survey-specific harmonized data sets containing a subset of the survey data with variables defined to be as comparable as possible between surveys and over time (Lee et al. 2021). We selected the harmonized data set with the longest time series, that is, the Health and Retirement Survey (HRS). HRS is a nationally representative longitudinal survey of more than 37,000 individuals over age 50 from the United States (Beaumaster et al. 2018).

After applying cross-sectional survey weights, we calculated the age- and sex-specific prevalence of being unhealthy in terms of activities of daily living (ADLs). ADLs refer to self-reported difficulties in bathing, dressing, eating, getting in and

out of bed, and using the toilet. Accordingly, we examine women and men regarding differences in disability and problems with physical functioning. Several other health indicators, such as cognitive functioning, global self-rated health, or grip strength, exist, reflecting different health domains; the extent of sex differentials depends on the choice of the health indicator (Crimmins et al. 2011; Di Lego et al. 2020; Oksuzyan et al. 2010). There are two practical reasons why we decided to use ADLs. First, the ADL question was consistently asked in the HRS survey, enabling us to analyze a long time series without any breaks. Second, ADL prevalence is usually comparatively low before age 50, while other indicators may already show large sex differentials at younger ages (Case and Paxson 2005; Centers for Disease Control and Prevention 2015).

Individuals are defined as being healthy if they do not report any ADLs. Consequently, the age- and sex-specific prevalence of being unhealthy is given by the ratio of individuals with no self-reported ADLs and the total number of individuals in the corresponding age group. We used the generalized additive model (GAM) with binomial distribution to model the age- and sex-specific prevalence proportions in order to obtain prevalence data for single years, which is required for our analysis (see, e.g., Wood (2017) for information on GAM). The analysis is performed by using the "mgcv" package in R (R Core Team 2021) and refers to cohorts above age 50, living between 1980 and 2019 (see the online supplementary material for details).

The Healthy Cross-Sectional Average Length of Life

Let the HCAL at time t be computed as

$$HCAL(t) = \int_0^{\omega} l_c^*(x, t-x)\, dx, \tag{1}$$

where $l_c^*(x, t-x)$ denotes the age- and cohort-specific health survivorship function, for the cohort born in year $t-x$. The health-adjusted survival is defined in accordance with Sullivan (1971) as

$$l_c^*(x, t-x) = l_c(x, t-x)\pi_c(x, t-x), \tag{2}$$

where $l_c(x, t-x)$ is the age- and cohort-specific survivorship function for the cohort born in time $t-x$ (proportion of being alive) and $\pi_c(x, t-x)$ denotes the corresponding proportions of those who are healthy. Thus, HCAL combines two comparable and theoretically consistent cohort-specific proportions, namely, the mortality and health components (Sauerberg et al. 2020).

The Truncated Healthy Cross-Sectional Average Length of Life

Health data are usually not available for long consecutive time series. Thus, we introduce a truncated version of HCAL—which we refer to as THCAL. Defining

THCAL enables researchers to calculate the measure for populations with partially available information. $THCAL(t, Y_1)$ covers the time span between the earliest year with available health and mortality data Y_1 and time t, which is the observation period. Thus, $THCAL(t, Y_1)$ is computed as

$$THCAL(t, Y_1) = \int_{50}^{\omega} l_c^*(x,\ t-x,\ Y_1)\, dx, \tag{3}$$

where $l_c^*(x, t-x, Y_1)$ denotes the age- and cohort-specific health survivorship function with incomplete data, that is, data are available from Y_1 to time t, for the cohort born in year $t-x$. The upper age limit, ω, is the age 100 years. Canudas-Romo and Guillot (2015) introduced the truncated cross-sectional average length of life $TCAL(t, Y_1)$ calculated in a similar fashion as in Eq. (3), but using the overall survivorship function, $l_c(x, t-x, Y_1)$, without adjusting for health. Hence, $TCAL(t, Y_1)$ represents the average number of years lived by all the population present at a given time t, accounting for all the cohort survival information between the two years Y_1 and t. Its complement $THCAL(t, Y_1)$ corresponds to the average number of years lived in good health between years Y_1 and t.

Decomposing the Difference of Two THCALs

Using the notation of a dot on top of the variable to denote derivatives, then the change in $THCAL(t, Y_1)$, or comparison of the measure between two populations, can be calculated as

$$\dot{THCAL}(t, Y_1) = \int_{50}^{\omega} \dot{l}_c^*(x, t-x, Y_1)\, dx, \tag{4a}$$

or including the definition of the health-adjusted survival function presented in Eq. (2) as

$$\begin{aligned} \dot{THCAL}\ (t, Y_1) = &\int_{50}^{\omega} \dot{l}_c(x, t-x, Y_1)\pi_c(x, t-x, Y_1)\, dx \\ &+ \int_{50}^{\omega} l_c(x, t-x, Y_1)\dot{\pi}_c(x, t-x, Y_1)\, dx. \end{aligned} \tag{4b}$$

The two terms on the right of Eq. (4b) correspond to the changes in THCAL owing to mortality and the health prevalence, respectively.

The mortality component in Eq. (4b) can be further age- and cohort-decomposed by adapting the same procedure as in Canudas-Romo and Guillot (2015):

$$\begin{aligned} &\int_{50}^{\omega} \dot{l}_c(x, t-x, Y_1)\pi_c(x, t-x, Y_1)\ dx \\ &= \int_{50}^{\omega} l_c(x, t-x, Y_1)\pi_c(x, t-x, Y_1) \left[\sum_{i=1}^{x-1} \frac{{}_1\dot{p}_i(t)}{{}_1p_i(t)} \right] dx, \end{aligned} \tag{5}$$

where ${}_1p_i(t)$ is the cohort probability of surviving from age i to age $i+1$, and related to the overall survival to age x by the equation $l_c(x, t-x, Y_1) = {}_1p_0(t)\ {}_1p_1(t)\ {}_1p_2(t) \cdots {}_1p_{x-1}(t)$. Unlike a pure mortality age and cohort decomposition of TCAL, Eq. (5) also includes the proportion of those who are healthy.

An analogous expression can be found for the healthy proportion element of Eq. (4b) as

$$\begin{aligned}&\int_{50}^{\omega} l_c(x, t-x, Y_1)\dot{\pi}_c(x, t-x, Y_1)\,dx \\ &= \int_{50}^{\omega} l_c(x, t-x, Y_1)\pi_c(x, t-x, Y_1)\left[\sum_{i=1}^{x-1} \frac{{}_1\dot{\mathbb{P}}_i(t)}{{}_1\mathbb{P}_i(t)}\right]dx, \end{aligned} \tag{6}$$

where ${}_1\mathbb{P}_i(t)$ is the cohort change in the proportion of healthy individuals from age i to age $i+1$, or ${}_1\mathbb{P}_i(t) = \dfrac{\pi_c(i+1, t-x)}{\pi_c(i, t-x)}$, and related to the overall prevalence of health to age x by the equation $\pi_c(x,t-x,Y_1) = {}_1\mathbb{P}_0(t)\,{}_1\mathbb{P}_1(t)\,{}_1\mathbb{P}_2(t)\cdots{}_1\mathbb{P}_{x-1}(t)$. It is useful to assume that the prevalence of health is equal to 1, or 100% for the first age $\pi_c(0, t-x) = 1$, similar to having the radix of the population equal to 1, $l_c(0, t-x) = 1$. As for Eq. (5), the age and cohort decomposition in Eq. (6) includes a term for the survival function in its estimation, making it a component of the change in the overall THCAL.

Similar to life tables, which can start at any age, our calculations of TCAL and THCAL are restricted to the age interval 50 or more, where data were available for health prevalence.

Our proposed decomposition method could also be adapted to a purely incidence-based model such as the multistate life table, which has been used in the field of HE research as well (e.g., Rogers et al. 1990; Schoen 2013). It is well documented that the multistate life table is usually the preferred method for calculating HE, but the lack of data hampers its empirical applications (Laditka and Hayward 2003; Saito et al. 2014). This is also the reason why we rely on prevalence data, which provide a shortcut as they can be seen as representing the net effect of past transitions between health states. More details are provided in the online supplementary material. In addition, our R code can be found in the GitHub repository at https://github.com/THCAL/THCAL.

Results

Figure 1 shows the comparison of overall cohort survival and cohort survival in good health. As described earlier, THCAL is truncated at age 50, that is, we begin our analysis at this age with 100% of our cohort healthy. Starting from age 50 to 51, the THCAL cohorts are subjected to the corresponding health and mortality data. For instance, the proportion of being alive for the birth cohort of 1939 is 99.6%, and 91.7% of them are also healthy, resulting in a proportion of healthy cohort survivors at age 51 of 88.6% (.886 = .966 × .917). The cohort comparison reveals that mortality improvements have led to an increasing relative number of individuals surviving up to age 80. This is more pronounced among men than among women. Health-adjusted survival declines faster with age. For instance, about 20% of women born in 1931 remain healthy and alive at age 88, while overall survival is about 35%. Further, the difference between overall survival and health-adjusted survival is larger among women than among men, which is due to higher morbidity rates for women (Crimmins et al. 2011; Di Lego et al. 2020; Oksuzyan et al. 2018).

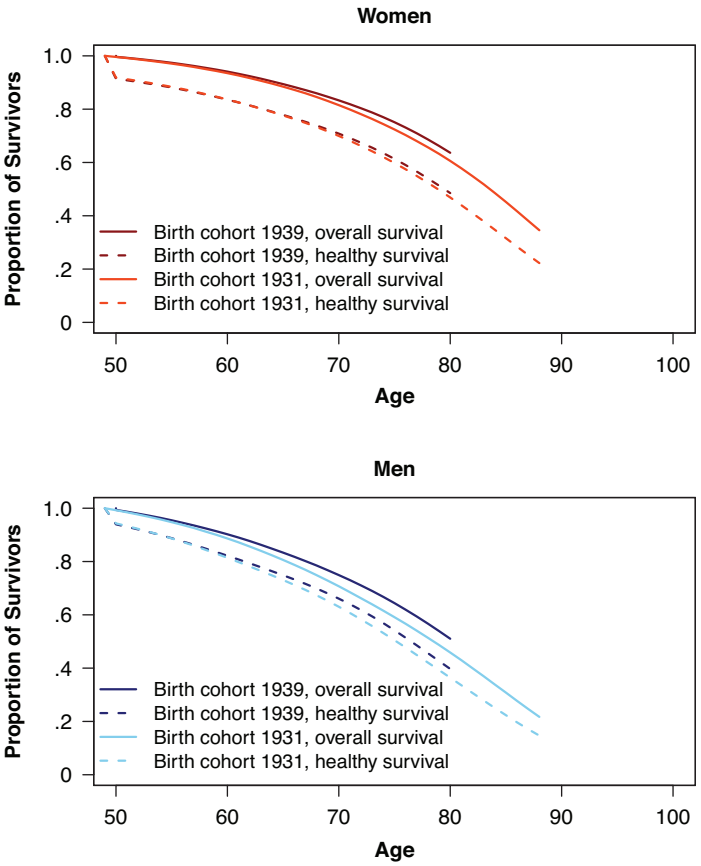

Fig. 1 Overall cohort survival and health-adjusted cohort survival for two selected birth cohorts in the United States, cohorts 1931 and 1939 observed until 2019. *Source:* Authors' calculations based on data from the Gateway to Global Aging Data (2022) and Human Mortality Database (2022).

We would like to point out that uncertainty should be considered when interpreting these results. For instance, the differences in healthy cohort survival between the two birth cohorts (Figure 1) are relatively small and might stem from randomness. We address this by providing 95% confidence intervals for TCAL and THCAL estimates as shown in Table 1.

Figure 2 presents sex differentials in health and mortality in terms of log ratios of age-specific proportions of survivors and age-specific prevalence proportions. The log ratios are presented in a Lexis surface, depicting differences between women and men across age and over time. While proportions alive are consistently larger for women (blue colors), the proportions that are healthy are always higher among men (red colors). Sex differentials in both proportions show increasing trends over time. However, the sex gap in surviving is considerably larger than the health gap measured through ADLs (log ratios of prevalence data are plotted on a smaller color scale). As mentioned in the Introduction, the extent of health differences between women and men depends on the underlying health indicator and may be larger based on other measures. The figure

Table 1 TCAL and THCAL in 2019 at age 50 for U.S. women and men, and THCAL decomposition into mortality and disability contributions

	TCAL	THCAL
Women	33.3 (33.2, 33.3)	27.1 (27.1, 27.1)
Men	29.7 (29.6, 29.7)	25.2 (25.2, 25.2)
Difference	3.6	1.9
	Simple Method	By Age and Cohort
Decomposition of THCAL Difference		
Mortality effect	2.7	2.7
Disability effect	−0.8	−0.8
Total effect	1.9	1.9

Notes: Simple Method refers to the calculations in Eq. (4b), and By Age and Cohort refers to the calculations in Eqs. (5) and (6). 95% confidence intervals are shown in parentheses.

Source: Authors' calculations based on data from the Gateway to Global Aging Data (2022) and Human Mortality Database (2022).

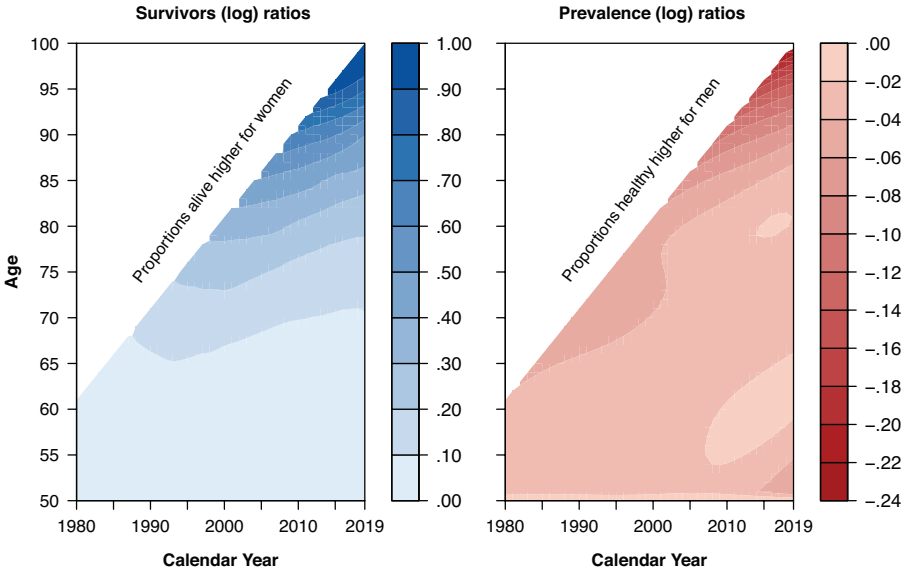

Fig. 2 Lexis surface of survivor ratios and prevalence ratios between women and men (both log-transformed) in the United States from 1980 to 2019. Positive values correspond to higher values for women (blue colors), while negative values correspond to higher values for men (red colors). *Source:* Authors' calculations based on data from the Gateway to Global Aging Data (2022) and Human Mortality Database (2022).

suggests narrowing sex differentials over time for both health and mortality. Especially in recent years, ADL prevalence is very similar for women and men between the ages 55 and 65, as well as at age 80 (indicated by areas shaded in light red).

Table 1 presents the values for U.S. TCAL and THCAL at age 50 by sex. TCAL for women exceeds TCAL for men (33.3 years vs. 29.7 years), reflecting the female

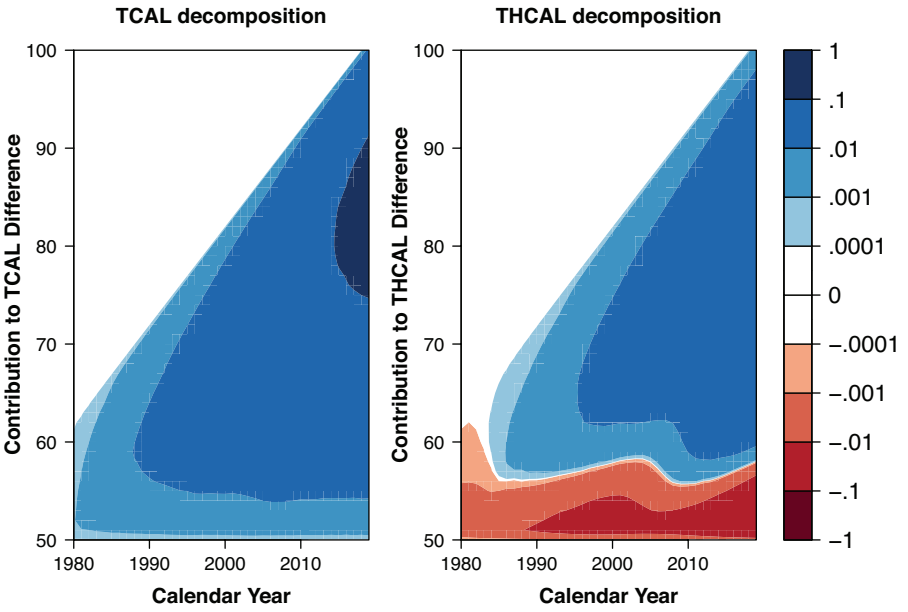

Fig. 3 Age- and cohort-specific contributions to the difference in TCAL and THCAL between women and men at age 50 or more in the United States, from 1980 to 2019. Positive values correspond to higher values for women (blue colors), while negative values correspond to higher values for men (red colors). *Source:* Authors' calculations based on data from the Gateway to Global Aging Data (2022) and Human Mortality Database (2022).

advantage in cohort survival. After taking into account the health dimension in survivorship, the sex gap shrinks considerably (from 3.6 years for TCAL to 1.9 years for THCAL). This is because the female advantage in survival is partly compensated for by lower health levels among women. Sex differences in mortality contribute to the lower TCAL value for men (the mortality effect is +2.7 years), but the impact of health contributes negatively to the overall THCAL difference between women and men (the health effect is −0.8 years). Both the mortality and health effects sum to the total THCAL difference between women and men in the United States (1.9 years = −0.8+2.7).

The proposed decomposition method allows one to quantify the age- and cohort-specific contributions to the difference in THCAL. The left panel of Figure 3 shows the decomposition of TCAL. Cohort survival is consistently higher for women than for men at every single age and for all cohorts. Further, the figure depicts the corresponding THCAL decomposition (right panel). Between age 50 and about 55, cohort survival in good health is higher for men. At older ages, however, the sex gap reverses with women showing an advantage in survival in good health. In other words, the female advantage in survival is offset by their lower health levels at younger ages, but not at older ages when the sex differences in health cannot compensate for the disadvantage in cohort survival for U.S. men.

Finally, the 1.9 years of THCAL difference (see Table 1) is decomposed in terms of two components, the health and mortality effects (Figure 4). Naturally, the mortality

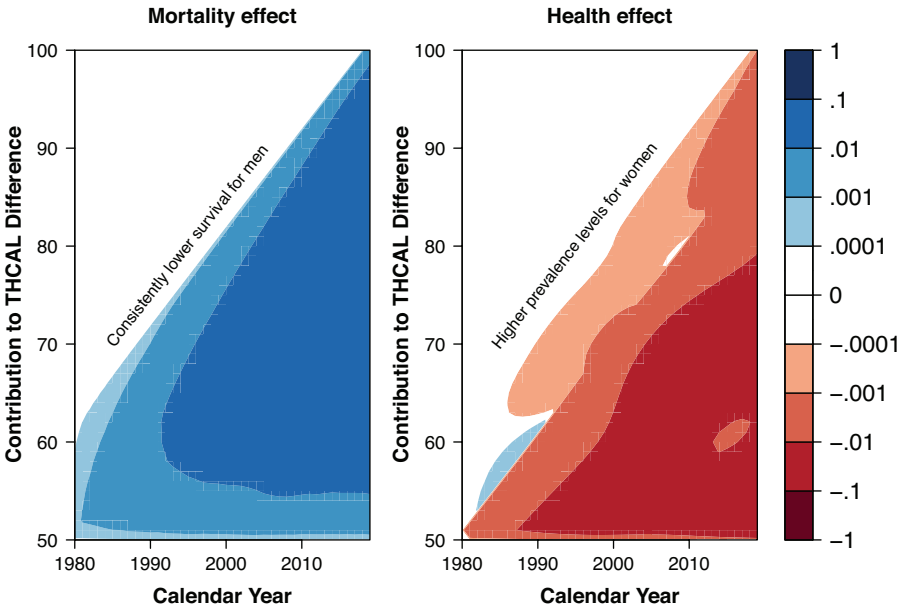

Fig. 4 Age- and cohort-specific contributions, by mortality and disability effects, to the difference in THCAL between women and men at age 50 or more in the United States, from 1980 to 2019. Positive values correspond to higher values for women (blue colors), while negative values correspond to higher values for men (red colors). *Source:* Authors' calculations based on data from the Gateway to Global Aging Data (2022) and Human Mortality Database (2022).

effect is similar to the TCAL decomposition shown in Figure 3, corresponding to a THCAL difference if the health component were the same between females and males (2.7 years in Table 1). The health effect, however, highlights the importance of examining health and mortality from a cohort perspective. Even though sex differences in cross-sectional prevalence proportions have been narrowing over time (see Figure 2), the accumulation process still puts U.S. women at a large disadvantage in terms of their health trajectory (−0.8 years in Table 1).

Conclusion

We have introduced a new decomposition method for the alternative health and mortality summary THCAL. The tool builds upon the previously introduced decomposition method by Nusselder and Looman (2004) but makes it possible to identify age- and cohort-specific contributions. The advantage of the THCAL approach lies in examining health and mortality from a cohort perspective, and for all cohorts above age 50 present at a given time. This enables researchers to take into account cohort effects, that is, backtracking to identify where today's health differences are stemming from. Additionally, the truncated version of HCAL is less demanding in terms of data availability, which provides the possibility to apply our HCAL decomposition to populations with only partially available health and mortality data. ■

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