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Patterns in age and cause of death contribution to the sex gap in life expectancy: a comparison among ten countries

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Abstract

Women live longer than men and the absolute difference between male and female mortality risk reaches its maximum at old ages. We decomposed the sex gap in life expectancy and investigated the changes over time of the profile of the age–cause specific contributions with indicators of location, magnitude and dispersion in ten countries. Data were retrieved from the Human Cause-of-Death Database. The decomposition analyses revealed that neoplasm, heart diseases and external causes were the main drivers of the gender gap. We also find two main patterns in the development of age-specific contributions. With mortality delay, regarding neoplasm-related mortality and heart disease-related mortality, the shift (i.e., movement of the modal age at contribution towards older ages) and compression (i.e., dispersion concentrated on a shorter age interval) of the survival advantage of women over a narrower age range reveal that men are gradually improving their survival. This might be linked to improvements in survival, diagnosis and access to treatment, at least to those ages no longer affected by the most significant differences.

Keywords: Sex gap, Life expectancy, Causes of death, Age- and cause-specific decomposition

Introduction

On average and worldwide, women live longer than men (Austad, 2006; Barford et al., 2006). From the beginning of the 1920s, in most industrialized countries the gap in life expectancy between the two sexes widened until the 1970s, when the difference started to narrow (Glei & Horiuchi, 2007; Oksuzyan et al., 2008, 2010). The literature shows that where some convergence has taken place, men have experienced more rapid gains in survival than women (Meslé & Vallin, 2011; Oksuzyan et al., 2008; Thorslund et al., 2013). Throughout the twentieth century, mortality became concentrated at older ages, non-communicable diseases became the prevailing causes of death and a female survival advantage emerged (Goldin & Lleras-Muney, 2019; Hollingshaus et al., 2019). Moreover, especially in the Eastern European countries, excess male mortality rested on factors related to individual behaviours and lifestyle, such as alcohol consumption and cigarette smoking (Baykalova, 2016; Trias-Llimós & Janssen, 2018). Until today, some researchers

focussed their investigations on the high survival of women, while others concentrated their explanations on the mortality experiences of men (Luy & Wegner-Siegmundt, 2015; Trovato & Heyen, 2006). The debate is still open on whether the changes in sex differences in life expectancy are mainly due to changes in female mortality or changes in male mortality.

Several studies, particularly in low mortality countries, revealed that the absolute difference between male and female mortality risk reaches its maximum at old ages (King et al., 2012). On the one hand, some studies argued that old-age deaths should become compressed at advanced ages; on the other hand, others argued that old-age deaths should become more dispersed with age (Bongaarts, 2005; Canudas-Romo, 2008; Cheung & Robine, 2007; Edwards, 2008; Janssen & de Beer, 2019; Kannisto et al., 1994; Robine, 2008; Robine et al., 2007; Zuo et al., 2018). As survival patterns at old ages become more important in driving the overall mortality decline in low mortality countries, old ages are also becoming more crucial in determining the sex difference in life expectancy. Even though decreasing differences persist over time, from the middle of the twentieth century the increase in the contribution of ages 80 + to the sex difference in life expectancy accelerated (Beltrán-Sánchez et al., 2015; Zarulli et al., 2020). The current study aims at understanding which age groups and cause of deaths have mostly contributed to the changes in the sex gap in life expectancy over time in several countries. Particularly, we study the evolution and the patterns of the distributions of the age–cause-specific contributions by analysing variations in shift and shape.

Literature review

To explain the recent narrowing in the sex gap in LE, several studies have focused on the causes of death that contributed to the sex gap in mortality rates and, thereby, either narrowed or widened this gap (Chisumpa & Odimegwu, 2018; Désesquelles et al., 2012; Glei et al., 2010; Klenk et al., 2016; Nusselder et al., 2010; Rasul, 2013; Yang et al., 2010; Zatonski & Bhala, 2012).

Glei and Horiuchi (2007) demonstrated that the gap in life expectancy between women and men is explained only in part by declining sex ratios in mortality. Indeed, the reduction in the sex gap in 29 high-income countries (1751–2004) resulted in large part from sex differences in the age pattern of mortality. Recently, Trias-Llimós and Janssen (2018) showed that, between 1990 and 2012, relative contribution of alcohol-attributable mortality increased in most of Central and Eastern European countries, until 2005 and declined afterward. In 44 European countries, Luy and Wegner-Siegmundt (2015) found that between 1950 and 2009 the trend of the sex gap in life expectancy can be attributed to smoking habits in most populations of Western Europe, whereas in many Eastern European populations other factors such as alcohol consumption, nutritional habits and external mortality (accidents, poisoning, homicides) have a stronger impact than smoking. In addition, the impact of smoking-related causes, which increase the risk of death from lung cancer, heart disease, chronic obstructive pulmonary disease and stroke, played an important role in the reduction of the gap in life expectancy. In Europe, especially among men, the contribution of smoking was the highest around 1990 and declined afterwards (Janssen, 2020; Janssen & van Poppel, 2015; Luy & Wegner-Siegmundt, 2015; Martikainen & Östergren, 2017; Meslé, 2004; Sundberg et al., 2018).

Among American men, smoking prevalence rates were the highest in individuals born in the 1910s, whereas prevalence among women was the highest among those born in the early 1940s, thus contributing to narrowing the sex gap decades later (Preston & Wang, 2006). Meslé (2004) showed that, in the most recent years, in some European countries the reduction of the sex gap in mortality was due to cardiovascular mortality and the reversal of the trend of male cancer mortality, which is now decreasing, especially from lung cancer (Meslé, 2004). Conversely, in Japan, the gap was still increasing, especially due to mortality from cancer and respiratory diseases (Meslé, 2004).

Among other studies, Le et al. (2015) showed that in China between 2005 and 2010, cancers, circulatory diseases and respiratory diseases made the largest contributions to the sex gap. In addition, the age group 60–79 reported the largest mortality difference between men and women in all 6 years (Le et al., 2015). Between 1983 and 2005 the reductions in cardiovascular diseases contributed most to longer life expectancy in South Korea (Yang et al. 2012). Similarly, the reduced sex differences in life expectancy was obtained mainly from the effects of reduced sex differences in heart diseases-related mortality in Canada between the 1980s and the 1990s (Trovato, 2005) and in Brazil 1996–2015 (Baptista et al. 2018). Finally, Arriaga's age- and cause-specific decomposition of the sex gap in life expectancy in Zambia 2010–2012 revealed that major contributors of the sex gap were infectious and parasitic diseases, accidents and injuries, suicide and violence. Furthrmore, neoplasms deaths among females contributed negatively to the sex gap in life expectancy (Chisumpa & Odimegwu, 2018).

In most of the studies, the topic of the variability in the sex gap in mortality has usually been tackled comparing age trajectories of cause-specific death rates between men and women by fitting specific parametric models on cause-specific life table death rate for women and men separately (Horiuchi & Wilmoth, 1997; Horiuchi et al., 2013; Li et al., 2013; Missov et al., 2015; Wrigley-Field, 2014). Other studies used life table or aggregated mortality indicators to provide summary measures of mortality levels (e.g., life expectancy) and dispersion (e.g., lifespan variation) both separately for men and women and with the decomposition of the difference between sexes according to age and causes of death (Aburto et al., 2020; Baykalova, 2016; Canudas-Romo, 2008; Diaconu et al., 2016; Gamboni, 2018; Hollingshaus et al., 2019; Le et al., 2015; Luy & Gast, 2014; Orru & Aström, 2017; van Raalte et al., 2011).

Aims and contributions

Although numerous studies have decomposed the sex gap in life expectancy according to age and causes of death, they did not focus on the evolution of the distributions of the age-specific contributions and on how these would determine the overall sex gap in life expectancy over time. To fill this gap, we study the evolution and the patterns of the distributions of the age–cause-specific contributions by analysing variations in shift and shape. In particular, the study addresses the following research questions: Which causes of death are the main drivers for the sex gap in life expectancy and how do their relative contributions develop over time? How do the relative age-specific contributions and their distributions develop over time, especially at older ages and combined with different causes of death? Are there similar patterns among the countries? To do so, we construct summary measures of trend and dispersion of the absolute as well as of the

relative contributions to the overall sex gap, for each cause of death, between and within age groups, to evaluate how each distribution of age-specific contributions behaved over time. This approach gives a new and non-conventional insight into the trends of the sex gap in life expectancy. In particular, calculating the changes over time of the modal age at contribution, of the magnitude of contribution, and of the dispersion of the distribution of age-specific contributions, we provide information on shift, increasing or decreasing contributions, and compression or expansion of their distribution for each cause of death. With magnitude of contribution we refer to the relative cause-specific contribution to the sex gap in life expectancy. Thus, an increase (decrease) of the magnitude indicates an intensification (reduction) of the relative contribution of a specific cause to the overall sex gap in life expectancy over time. Considering differences in mode and shape of the distribution of the age-specific contributions sheds more light on the impact of the specific causes of death on the mortality differentials and health issues between men and women over time.

We analyse the evolution of the age-specific contributions to the sex gap for different causes of death in ten European (four Eastern and four Western European) and non-European countries (United States and Japan). We show that different patterns in terms of age groups and causes of death have contributed to the declining sex gap in life expectancy in the recent years. In addition, we uncover different patterns that specific causes have on the male–female mortality differences at various ages.

With the delay of mortality to later ages, most populations have experienced mortality compression and a shift to older ages of the most relevant age-contributors to the sex gap in mortality. However, these changes are not necessarily mirrored by the age–cause-specific contributions to the overall sex gap in LE. These, in fact, may either compress or expand, independently of the level of male–female difference in survival, which may decrease or increase. Compression implies that the mortality inequality between men and women happens on a shorter age interval, thus indicating that, at least at some ages, the inequality has been reduced. Expansion, on the contrary, implies that the male–female mortality inequality spread over a wider age interval and new ages become theatre of some male–female inequality in survival, independently of the overall difference. This could indicate the presence of age-specific criticalities. Therefore, understanding the composition, the compression or dispersion of the distribution of the age–cause-specific contributions to the sex gap in mortality has also relevant public policy implications, allowing to develop policies able to better target the cause specific age ranges involved in the changes of the gap. Finally, investigating the role played by different causes of death provides a new understanding of how the trends developed and offers an epidemiological explanation about the recent evolution of the sex gap. In this paper we are mainly interested in the relative contributions/differences. Using the relative rather than absolute age-distribution of contributions allows to appreciate the changes (increase/decrease) in the cause-specific contributions. Considering that the overall gender gap in life expectancy decreased over time, the absolute cause-specific contributions (i.e., years) most of the time decrease as well, although the contribution of some causes may be increased in relative terms. It allows to appreciate differences between countries and over time in a standardized way, thus abstracting from the potential differences in magnitude related to absolute measurements.

Variations in the cause-specific magnitude implies changes in the shape of the distribution of the age-specific contributions, especially at older ages, those more affected by these two groups of causes. Figure 1 provides a visual (stylized) representation of the two kinds of patterns which can be identified from the analysis. Black lines display the relative age-specific contributions to the sex gap at the beginning (solid) and at the end of the observation period (dashed) for a specific country and a specific cause of death. Changes over time in the modal age at contribution (shift) are shown by green lines. Compression or expansion of the distribution is displayed by red lines. Both patterns are characterized by a shift to the right of the modal age at contribution. The shift describes decreasing differences in mortality between women and men at younger ages and increasing differences at older ages. In addition, (panel a) when the cause-specific magnitude increases (i.e., intensification of the relative cause-specific contribution), the distribution of the age-specific contributions compresses at older ages (i.e., reduction in the C indicator). Oppositely, (panel b) when the cause-specific magnitude decreases (i.e., reduction of the relative cause-specific contribution), the distribution of the age-specific contributions lower and widen (i.e., increase in the C indicator), with the largest reduction occurring at old ages.

Data and methods

Data

Cause-specific and all-cause mortality data were retrieved by sex, age (0 1–4, 5–9, …, 85 +) and year from the Human Cause of Death Database (HCD 2019). The HCD is an open-source project that offers harmonized data on reconstructed long-term trends in cause-specific mortality for sixteen countries over time. For Eastern Europe (EE), we selected Russia, Ukraine, Poland and the Czech Republic; for Western Europe (WE), we chose France, Spain, Germany and the United Kingdom (UK); to have a broader view outside of Europe, we included in the analysis also Japan and the United States (US).

In the HCD, the reconstructed time series cover longer periods for the Eastern European countries (starting around 1960) than for the Western European countries (starting around 1990). Since this study aims at comparing patterns among several countries, we focussed on the last 15 years available in each country, within the period 1998–2016. Within this time frame, not only data for more countries is available, but all the causes

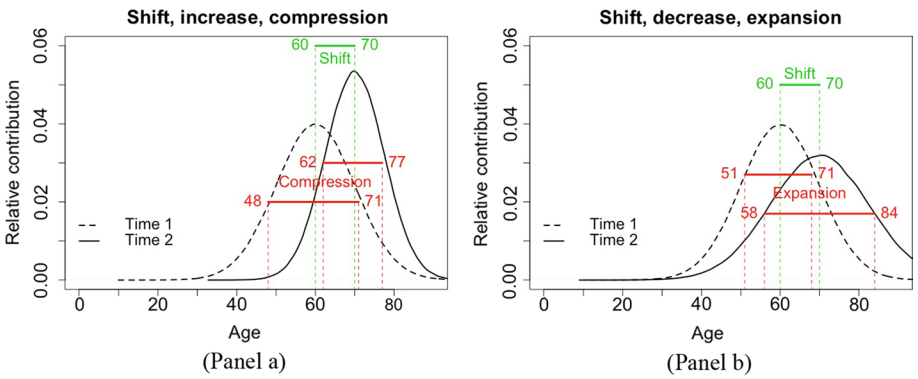

Fig. 1 Patterns of distribution of relative age-specific contributions to the sex gap in life expectancy over time. **Panel a**: shift, increase, compression; **Panel b**: shift, decrease, expansion

of death are coded in each country according to the 10th version of International Classification of Diseases (ICD-10). This allows us to avoid problems related to differences in the classification and to obtain comparable information for all the countries under study. We further restricted our focus on the short list of the ICD-10, in which all the causes are grouped into sixteen major categories, each including a set of similar diseases: (1) certain infectious diseases, (2) neoplasms, (3) diseases of the blood and blood-forming organs, (4) endocrine, nutritional and metabolic diseases, (5) mental and behavioral disorders, (6) diseases of the nervous system and the sense organs, (7) heart diseases, (8) cerebrovascular diseases (9) other and unspecified disorders of the circulatory system (10) Acute respiratory diseases, (11) other respiratory diseases, (12) Diseases of the digestive system, (13) Diseases of the skin and subcutaneous tissue, musculoskeletal system and connective tissue, (14) Diseases of the genitourinary system and complications of pregnancy, childbirth and puerperium, (15) Certain conditions originating in the perinatal period and congenital malformations/anomalies, (16) External causes. Table 2 in "Appendix" shows the group of causes of death with related International Classification of Diseases codes according to the 10th revision (ICD-10) (HCD, 2019). Finally, we grouped all the ages above 85 in the open-end age interval 85+, to avoid problems related to the data quality, which are particularly common at very old ages.

Analysis

The sex gap in life expectancy (LE) was calculated for each country and over time using life tables from the Human Mortality Database (HMD, 2019). Arriaga age- and cause-specific decomposition technique was used to decompose the sex gap in life expectancy, in each country (Andreev et al., 2002; Arriaga, 1984). This decomposition method allows to decompose the difference in life expectancy into contributions of ages and causes of death. Higher mortality rates for males than females (in a particular age and for a defined cause) correspond to a positive contribution to the sex gap in LE, thus contributing to widen the gap. On the contrary, higher mortality rates for females than males (in a defined age and for a defined cause) correspond to a negative contribution to the sex gap in LE, thus contributing to narrow the gap. The total sex gap in life expectancy is obtained by summing up the number of years attributed negatively or positively to each age group across all causes of death; similarly, the total contributions from any given cause are obtained through the sum of the contributions from each cause of death across all age groups. Relative contributions are computed with respect to the overall gender gap in life expectancy (all causes and all ages), so that dividing all the absolute age- and cause-specific differences to the overall gender gap in life expectancy (in years). Accordingly, the sum of the relative contributions for each and each cause is equal to 1, the sum of the relative contributions for each and each cause is equal to the overall gender gap in life expectancy (in years).

In addition, we used the Pearson's correlation coefficient (r) to assess the association between the changes in the relative cause-specific contributions and the overall changes in the sex gap in LE over time; we based all estimates on life expectancy at birth. Afterwards, to assess the evolution of the distribution of the age- and cause-specific contributions, we compared their variations in shift and shape between the first and the last time point within the 15-year interval under consideration in this study.

Recently, several studies have shown the advantage of using the modal age at death, which is determined by adult mortality only, as a proper indicator to evaluate the longevity extension (shift in mortality) (Canudas-Romo, 2008; Cheung & Robine, 2007; Clay, 2014; Horiuchi et al., 2013; Kannisto, 2001; Zuo et al., 2018). Similarly, due to the fact that the most recent extension of human life is primarily due to the reduction of old-age mortality (Bengtsson & Keilman, 2019), we used the modal age at contribution M and its change over time to summarize the shift of the distribution of the age-specific contributions, for each cause of death. Changes in M over time describe the shift of the distribution towards older ages. It denotes decreasing differences in mortality between women and men at younger ages and increasing differences at older ages. For each cause of death, the magnitude is defined as the relative cause-specific contribution to the sex gap in life expectancy. An increase of magnitude occurs when the relative contribution of a specific cause to the overall sex gap in life expectancy increases over time. Oppositely, a decrease occurs when the relative contribution of a specific cause to the overall sex gap in life expectancy reduced over time. We also measured the dispersion of the distribution of the age-specific contributions through several compression indicators belonging to the C-Family developed by Kannisto (2001), who defined mortality compression as occurring when a given proportion of deaths take place in a shorter age interval than before (Kannisto, 2001). Specifically, we defined the compression indicators C40 and C50 as the shortest age interval in which, respectively, 40% and 50% of each cause-specific contribution occurred in 1 year. Free from both the age and the percentile scale, they indicate the ages where male–female differences in mortality are highly concentrated. Thus, a reduction in the C indicators denoted compression, whereas an increase denoted a dispersion of the most relevant age-specific contributions over time (see Fig. 1).

Finally, as Kannisto (2000) suggested to calculate the modal age at death and C indicators using smoothed life table deaths, the original 5-year age-specific contributions (between 0 and 85, with 85 + being the last, open end interval) were smoothed into 0.1-year age groups to obtain mode and C40 in more accurate forms (i.e., with decimals, e.g., modal age at contribution equals to 65.3 denotes a mode within the range 65.3–65.4). For this purpose, we applied the standard function *spline* implemented in the program R (R Development Core Team, 2010), which performs cubic spline interpolations of given data points, to each distribution of age-specific contributions to the sex gap in LE (for each period, country and cause of death). All analyses are performed in R 3.6.1 (http://www.r-project.org/).

Results

Sex gap in life expectancy across time and countries

The sex gap in life expectancy between females and males decreased over the last 15-year period in all the countries. Only Russia and Ukraine showed a slight increase of the gap in the first half of the observation period (Fig. 2). At both the first and the last time points, the sex gap in LE in the Eastern European (EE) countries was the highest (on average from 9.8 years to 8.7 years over time). Among EE countries, the lowest difference was found in Czech Republic in 2002 (6.6 years), and the largest in Russia in 2014 (11.2 years). In the Western European (WE) countries and in the US, the sex gap

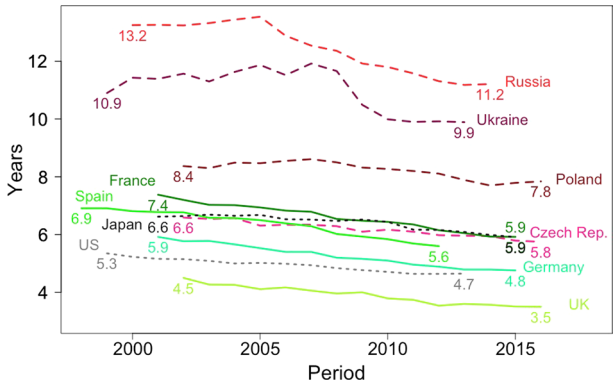

Fig. 2 Sex gap in life expectancy between females and males decreased over the last 15-year period in all the countries

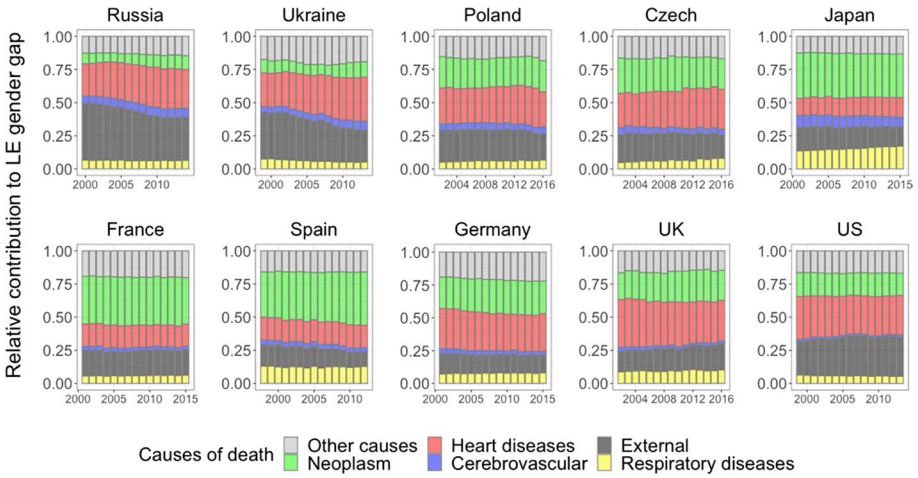

Fig. 3 Relative contribution of causes of death to sex gap in life expectancy in each country

decreased from 6.1 years to 5.1 years on average over time, with the lowest gap reported in UK (4.5 years in 2002 and 3.5 years in 2016). In Japan, the sex gap decreased from 6.6 years in 2001 years to 5.9 years in 2015. Compared to the other countries, the largest relative reductions of the sex gap in LE over time were reported in the WE countries, with an average reduction of 18.0% (1.2 years). EE countries, US and Japan showed similar relative reductions, with an average reduction of 11.0%, from 0.6 years in US and Poland to 2.0 years in Russia (Fig. 2).

Contribution of causes of death to LE sex gaps

As shown in Fig. 3, neoplasms, heart diseases and external causes of death made the largest contributions to the sex gap in LE in all the countries, explaining together more than two third of the overall gap. Over the 15-year periods, in WE countries and in Japan, the gap was mainly due to differences in neoplasms, explaining 30.4% (1.8 years) on average, whereas this category contributed for not more than 18.0% on average in all the other countries. Heart diseases and external causes made the largest contributions in EE countries and in the US, the former explaining on average 2.3 years (30.0%) of the gap, and the latter explaining 2.4 years on average (26.9%). In WE countries and in Japan,

heart diseases and external causes gave lower contributions 1.2 years on average (22.2%) and 0.9 years (15.9%), respectively. Absolute cause-specific contributions to the sex gap in life expectancy are reported in Fig. 5 in the "Appendix".

Cerebrovascular and respiratory diseases were identified as secondary contributors in most of the countries, with relative contributions lower than 9.3% (4.4% on average) in most of the countries. Relative contributions of secondary causes of death stayed constant over time. Only in Japan and in Spain the relative contribution of respiratory diseases ranged between 13.6% in 2001 and 17.1% in 2015 (15.3% on average) and between 11.6% in 1998 and 13.2% in 2012 (15.3% on average). Finally, relative contributions of each of the remaining causes of death were lower than 8.3% (1.7% on average) and, therefore, grouped into a unique category called "other causes".

The analysis of the trends of the relative contributions of the various causes of death to the sex gap in LE revealed that the differences due to external causes decreased in EE countries, while the differences due to heart diseases and neoplasms increased over time. In EE countries, the reduction of the sex gap in LE was significantly associated with an increase of the contribution of heart diseases as well as of neoplasms (correlation coefficient $r < -0.7$, $p < 0.01$ for both). Conversely, the reduction of the gap in WE countries was significantly associated with decreasing contributions of heart diseases ($r > 0.8$, $p < 0.01$) and increasing contributions of neoplasms ($r < -0.7$, $p < 0.01$). In Japan, the decreasing sex gap in LE was significantly associated with reductions of the differences in mortality from neoplasms ($r = 0.6$, $p < 0.01$) and, especially, from external causes ($r = 0.9$, $p < 0.01$), even though increasing differences in heart diseases ($r < -0.7$, $p < 0.01$) and respiratory diseases were reported ($r < -0.9$, $p < 0.01$). Finally, in the US the reduction of the sex gap in LE was significantly associated with a reduction of the contribution of heart diseases ($r = 0.8$, $p < 0.01$) as well as with an increase of the contribution of external causes of death ($r = -0.8$, $p < 0.01$).

Contribution of age groups to LE sex gap, according to causes of death

Our results show that the largest contributions to the sex gap in LE were given by old ages and that over time these differences shifted to even older ages. Regarding neoplasms and heart diseases, the age group 70–75 years made the largest relative contributions in WE countries, in US and in Japan. Neoplasms contributed on average 5.4% (0.3 years), ranging from 3.1% in US in 2013 (0.1 years) to 7.3% in Spain in 2012 (0.4 years); heart diseases accounted on average for 3.4% (0.2 years), ranging from 2.0% in France in 2011 (0.1 years) to 5.5% in UK in 2003 (0.2 years). In EE countries, the largest contributions were reported at younger age groups. For neoplasms, the largest contribution came from the age group 65–70 years, which contributed on average 3.2% (0.3 years), ranging from 0.8% in Russia in 2003 (0.1 years) to 5.2% in Czech Republic in 2016 (0.3 years). For heart diseases, the largest contribution was made by even younger ages, the group 60–65, which contributed on average 4.3% (0.4 years), ranging from 3.2% in Russia in 2000 (0.4 years) to 5.7% years in Ukraine in 2013 (0.6 years). Finally, external causes of death gave the largest relative contributions at the age group 25–30 (2.6%, 0.2 years on average) in all the countries, ranging from 0.9% (0.1 years) in Spain in 2012 to 6.1% (0.8 years) in Russia in 2000. However, for external causes, the second largest relative contributions were found at age 40–45 (2.2%, 0.2 years on average) in all the countries, especially in

Russia in 2002 (5.1%, 0.7 years). Figure 6 in "Appendix" reports for each main cause of death the country-specific relative age-specific contributions to the sex gap at the beginning and at the end of the observation period.

Patterns of age-specific contribution to LE sex gap, according to causes of death

The analysis of the trends of the relative age–cause specific contributions to the sex gap in LE for the two major groups of causes of death, which are neoplasms and heart diseases, revealed two main patterns. In the first pattern, when the overall differences increased (or remained constant) over time, the distributions of the age-contributions compressed; vice versa, in the second pattern, when the differences decreased, the distributions of the age-contributions widened. Relative age- and cause-specific contributions to the sex gap in life expectancy are intended also as relative age- and cause-specific differences. Accordingly, the age (or the cause of death) with the largest contribution is the age (or the cause) which shows the largest relative difference in life expectancy between women and men. We identified a general shifting pattern to the right of the modal age at contribution (M was rising the majority of the countries). For certain causes of death, shifts to older ages were accompanied by decreasing differences in mortality between women and men at younger ages and increasing differences at older ages. When the cause-specific magnitude increased (i.e., intensification in the contribution of M), the distribution of the age-specific contributions tended to be compressed towards older ages (i.e., reduction in the C indicator), while when the cause-specific magnitude decreased (i.e., reduction in the contribution of M), the distribution of the age-specific contributions lowered and widened (i.e., increase in the C indicator), with the largest reduction occurring at old ages. Therefore, variations in the magnitude of neoplasms and cardiovascular diseases implied changes in the shape of the distribution of the age-specific contributions, especially at older ages, those more affected by these two groups of causes.

Figure 4 shows the two main trends for neoplasms in Spain between 1998 and 2012 and for heart diseases in France between 2001 and 2015, respectively. Trends related to all the other countries are shown in Fig. 6 in the "Appendix". The first pattern, a shift of the largest age-specific contributions to older ages and, at the same time, an increase

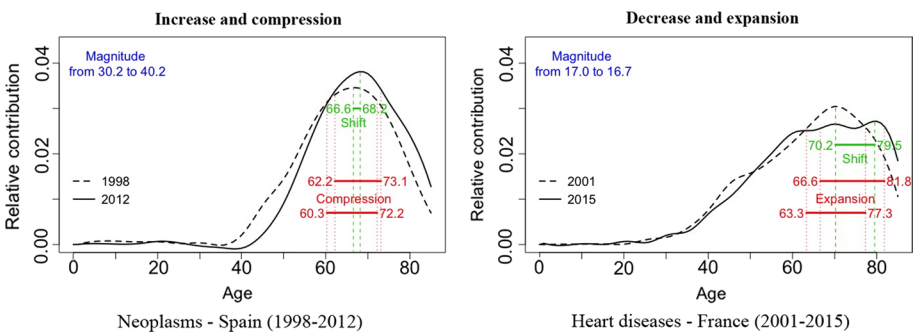

Fig. 4 Trends in the mode, measure of variation and magnitude of distributions of relative age-specific contributions to the sex gap in life expectancy at the beginning (dashed line) and at the end of the observation period (solid line), for neoplasms in Spain 1998–2012 and for heart diseases in France 2001–2015. Increase/decrease denotes increasing/decreasing relative cause-specific contributions (i.e., magnitude) to the overall sex gap

and a compression of the contributions, took place for heart diseases in Russia, Ukraine, Japan and Poland. This pattern was also shown by neoplasms in all the countries, except for US, Japan, Poland and Germany, where, instead, the second pattern occurred. The second pattern, which depicts shifts to older ages of the main contributors together with lowering and widening of the distribution of age-specific contributions, was shown also by heart diseases in the four WE countries, in US and in Poland. The only exception is for heart diseases in Russia where, although the magnitude increases, the distribution of age-specific contributions widened rather than compressing, as it would be according to the first major identified pattern. For external causes of death, which affect mostly younger ages, the second pattern occurs in most of the countries: over time the differences decreased but more ages got to be involved, as the distributions of the age-specific contributions widened. Two relevant exceptions are the UK and the US, where the distribution of the age-specific contributions due to external causes indeed shifted forward and widened, but the overall difference increased. In Russia and Ukraine, although the intensities decreased, the distributions compressed and shifted to older ages. Finally, respiratory diseases, which had the most relevant contribution only in Japan and in Spain, showed increasing differences over all the ages, together with a compression and a shift of the most relevant contributions towards older ages (first pattern).

All the absolute and relative contributions of the three main causes of death to the sex gap in LE across the countries are presented in Table 1, as well as the compression indicators of the distribution of the age-specific contributions. The trend columns in Table 1 indicate the developing pattern of relative age-specific contribution for each cause of death over time (A for first pattern, B for second pattern, E for exceptions to general pattern).

Discussion

This study showed the patterns of age-specific contributions to the sex gap in LE according to causes of death overtime and across countries. It further focused on the role played by these distributions in determining the overall sex gap in life expectancy rather than focusing on mortality evolution and trends with analyses done separately by sex and highlighted the presence of dynamics of compression or dispersion of the age-contributions that are independent on the overall level of sex differences in mortality.

In accordance with previous studies, our findings showed that the sex gap in LE was increasingly driven by differences in mortality at older ages for all the countries within the period 1998–2016 and that, overall, the gain in LE was larger for males than for females (Meslé & Vallin, 2011; Oksuzyan et al., 2009; Thorslund et al., 2013). The sex gap in life expectancy was mainly due to neoplasms, heart diseases, and external causes of death (injury/accidents/self-harm/violence) in all the countries examined, with minor differences. Neoplasms were more predominant in the Western European countries and in Japan than in the Eastern European countries and the US. This may be partly due to the greater male–female differential in the prevalence of some risk factors, in the former countries and partly to a possible reduced availability or use of screening programmes for cancers affecting men, leading to lower survival rates after diagnosis (Nusselder et al., 2019; OECD, 2015; Ostan et al., 2016). Unfortunately, the data available in this study do not allow to control for these factors. Finally, external causes of death were more

Table 1 Absolute (years) and relative (%) contributions of the main cause-specific mortality to the sex gap in life expectancy at birth at first and at last time within 15-year periods, compression indicator (C40), standard deviation (SD) and trends of age-specific relative contributions within the 15-year period, across countries

	Period	Neoplasm												
		First year				Last year				Trend	First year			
		Years (%)	C40	Age interval	SD	Years (%)	C40	Age interval	SD		Years (%)	C40	Age interval	SD
Russia	(2000–2014)	1.1 (8.2)	9.3	53.6–62.9	101.6	1.2 (10.6)	9.0	57.0–66.0	92.8	A	3.2 (24.3)	13.8	45.9–59.7	131.1
Ukraine	(1999–2013)	1.1 (10.1)	9.6	53.2–62.8	103.6	1.2 (11.6)	9.0	56.1–65.1	83.9	A	2.8 (25.4)	14.1	49.2–63.3	140.7
Poland	(2002–2016)	2.0 (23.1)	9.9	58.6–68.5	105.3	1.8 (22.6)	10.6	61.7–72.3	108.4	B	2.3 (27.3)	13.2	52.4–65.6	120.8
Czech Republic	(2002–2016)	1.8 (25.1)	10.1	58.5–68.6	100.8	1.3 (25.1)	8.9	63.6–72.5	52.1	A	1.7 (26.0)	12.1	54.8–66.9	117.2
France	(2001–2015)	2.7 (36.0)	12.6	60.0–72.6	120.6	2.1 (36.0)	11.7	60.2–71.9	106.1	A	1.3 (17.0)	14.0	63.3–77.3	150.2
Spain	(1998–2012)	2.4 (34.2)	11.9	60.3–72.2	123.3	2.2 (40.2)	10.9	62.2–73.1	99.1	A	1.2 (17.3)	13.5	57.8–71.3	137.8
Germany	(2001–2015)	1.4 (23.9)	10.0	63.1–73.1	92.0	1.2 (22.7)	10.3	63.8–74.1	99.3	B	1.8 (30.6)	12.7	60.5–73.2	128.6
UK	(2002–2016)	0.9 (20.2)	8.3	67.8–76.1	41.5	0.8 (22.6)	7.3	71.2–78.5	40.1	A	1.6 (36.2)	13.6	60.5–74.1	137.3
US	(1999–2013)	1.0 (18.0)	9.8	64.8–74.6	89.9	0.8 (16.7)	10.5	66.8–77.3	90.9	B	1.7 (32.4)	14.4	58–72.4	139.8
Japan	(2001–2015)	2.3 (34.1)	9.4	64.8–74.2	91.6	1.9 (32.9)	9.4	66.4–75.8	98.6	B *	0.9 (12.9)	15.3	58.2–73.5	176.0

Table 1 (continued)

Heart diseases					External causes								
Last year				Trend	First year				Last year				Trend
Years (%)	C40	Age interval	SD		Years (%)	Age interval	C40	SD	Years (%)	C40	Age interval	SD	
3.3 (29.1)	12.1	52.0–64.1	130.2	A	5.6 (42.5)	14.5	18.3–32.8	180.9	3.6 (32.3)	14.4	23.5–37.9	148.7	E^1
3.3 (33.4)	13.0	53.7–66.7	134.1	A	3.9 (35.1)	16.3	26.9–43.2	146.0	2.3 (23.9)	16.2	24.1–40.3	141.4	E^1
2.1 (26.7)	13.2	53.9–67.1	123.3	B *	2.0 (23.6)	18.0	27.6–45.6	155.4	1.5 (19.8)	20.0	18.0–38.0	248.4	B
1.7 (30.3)	12.0	59.6–71.6	113.0	A	1.4 (20.6)	18.8	17.3–36.1	235.4	1.0 (17.2)	21.2	18.0–39.2	275.7	B
1.0 (16.7)	15.2	66.6–81.8	203.9	B	1.4 (18.8)	16.4	16.0–32.4	230.9	1.1 (18.0)	20.3	23.9–44.2	243.3	B
1.0 (17.0)	13.9	58.5–72.4	145.5	B	1.1 (15.7)	14.6	17.7–32.3	220.1	0.6 (10.6)	20.3	26.7–47.0	224.2	B
1.4 (28.8)	13.5	60.2–73.7	130.5	B	0.9 (15.2)	16.1	14.7–30.8	238.7	0.6 (13.2)	20.3	17.8–38.1	279.3	B
1.1 (30.7)	14.2	61.1–75.3	137.5	B	0.7 (14.9)	13.3	17.1–30.4	191.6	0.7 (19.6)	16.0	25.3–41.3	198.9	E^2
1.4 (29.9)	15.1	54.8–69.9	135.8	B	1.3 (24.8)	13.6	14.8–28.4	216.2	1.4 (29.3)	14.3	17.0–31.3	225.0	E^2
0.9 (14.7)	15.1	59.1–74.2	142.9	A	1.1 (17.3)	22.0	36.1–58.1	201.8	0.8 (14.4)	24.0	17.0–41.0	306.3	B

A: first pattern: Increasing (constant) magnitude (i.e., relative cause-specific contribution to the overall sex gap) and Compression in C40

B: second pattern: decreasing magnitude and Expansion in C40

E^1: (Exception) decreasing magnitude and Compression in C40

E^2: (Exception) increasing magnitude and Expansion in C40

C40: shortest age interval in which the 40% of the difference occurred

C35: shortest age interval in which the 35% of the difference occurred

SD: standard deviation from the modal age at difference

*Constant C40 but increasing SD (from 91.6 to 98.6 for neoplasm in Japan; from 120.8 to 123.3 for heart diseases in Poland)

predominant in the Eastern European countries and in the US (Goldin & Lleras-Muney, 2019; Luy & Wegner-Siegmundt, 2015; Meslé, 2004).

Trends in age- and cause-specific contributions

By analysing the trends of the age- and cause-specific contributions according to the main causes of death, we identified two main distinct patterns, each of which can be related to different stages of the health transition in each country. In the Western European countries and in the US, the narrowing sex gap in LE was mainly driven by decreasing differences in heart diseases. In these countries, the largest age-specific contributions to the gap in heart diseases-related mortality shifted to older ages, even though the relative contributions decreased, especially at older ages (expansion of the distribution). This trend suggests that progress in reducing mortality due to heart diseases was faster for men than for women, although slower at older ages than at younger ages (Gjonça et al., 2005; Pinkhasov et al., 2010). Reductions in cardiovascular mortality may be attributed to medical advances and improved lifestyle habits. Medical and technical advances related to cardiovascular health and mortality may have favoured survival among men to a greater extent than women, but less at the oldest ages (Thorslund et al., 2013). Conversely, in the Eastern European countries (except Poland) and in Japan, we found increasing relative differences in heart diseases-related mortality, with the largest differences being compressed to a shorter and older age interval, confirming the findings of previous studies (Di Girolamo et al., 2020; Klenk et al., 2016).

In almost all the countries, the relative contributions of neoplasm-related mortality increased over the 15-year periods, with a shift of the distribution and a compression of the differences to older ages. Therefore, progress in reducing mortality due to neoplasms was slower for men than for women both in Western (except in Germany) and Eastern European countries (except in Poland). On the other hand, the compression of the distribution of suggests some improvements in male survival for those ages that, given the compression process, are not anymore representing a significant contributor to the sex difference survival. This could derive from both improvements in survival and in the level of access to treatment for men (Ferlay et al., 2013, 2018; Gjonça et al., 2005). In Germany and Poland, instead, the sex gap in neoplasm-related mortality shifted to older ages, while the relative age-specific contribution decreased and dispersed over a larger age interval, meaning that, while the overall sex difference become smaller, progress in neoplasm-related mortality was faster for women than for men at older ages (Beltrán-Sánchez et al., 2015; Klenk et al., 2016; Luy & Wegner-Siegmundt, 2015; Ostan et al., 2016) and that more ages now see a male penalty in survival from neoplasms. In the US between 1999 and 2013, and in Japan between 2001 and 2015, larger reductions in neoplasm-related mortality as well as higher improvements for men than for women occurred, with the greatest differences spreading over a large age range over time. In the US, women at every age had lower mortality rates due to external causes. Progress against those causes of death has been slower for men than for women, but larger at older ages. This implies an expansion of the distribution of the age-specific contributions within the period 1999–2013 (Pinkhasov et al., 2010; Rogers et al., 2010) that, in turn, seems to suggest an expansion of the potential risk factors responsible for external mortality. Only in Japan, decreasing differences in both neoplasms and in external causes of

death drove the decreasing sex gap in LE. This suggests higher level of access to treatment and/or survival for men compared to women over time, as well as larger improvements in external causes of death for men than for women. In addition, for both causes the distributions of the age-specific contributions widened over time, which indicated a lower reduction at older ages (Katanoda et al., 2015; Oksuzyan et al., 2008).

As expected, in the Eastern European countries, the sex gap in LE from external causes of death was still persistent. Notably, however, in these countries decreasing differences in external causes of death were significantly associated with an overall decreasing sex gap in LE, suggesting that an important reduction in risky behaviours and lifestyles among men occurred over time. In most of the countries, progress in reducing mortality due to external causes was faster for men than for women and the difference spread to a larger age interval over time. However, in Russia and Ukraine, although the reduction occurred, the largest differences compressed around age 40 (Baykalova, 2016; Trias-Llimós & Janssen, 2018).

Among the Western European countries, only in the UK was the sex difference in external deaths considerably higher than in the past. However, the absolute number of deaths from these causes was relatively small and even if changes occurred, the impact on the overall longevity was small as well (Leon et al., 2019; Sanders, 2018). Finally, the sex gap in survival due to respiratory disease-related mortality was more pronounced among the elderly only in Japan, within the period 2001–2015, and in Spain, within the period 1998–2012, presumably reflecting a divergence of long-term smoking habits with time and with largest differences that compressed towards older ages (Beltrán-Sánchez et al., 2015; Janssen, 2020; Oksuzyan et al., 2008).

Strength and limitations

Our study provided a detailed examination of the impact of causes of death on sex differences in LE, with a special focus on the trends of relative age-specific contributions over the last 15-year periods available for ten countries. Focusing on the changes of the distributions of age-specific contributions for different causes of death gave a new and non-conventional insight into the decreasing sex gap in life expectancy.

Such an international comparison deepens our knowledge about past social and sanitary developments, highlighting ways in which causes of death and patterns of age contributions were related to the sex gap in LE, as well as patterns of increasing/decreasing and compression/expansion of age contributions over time. For some groups of causes of death and in some countries, even though the sex difference in survival might still be widening, it is getting concentrated on a narrower age range, indicating that some progress in reducing sex survival differences is gradually taking place, at least at some ages. For other causes of death and other countries, instead, independently of the overall sex differences in survival, and even in the presence of a reduction of the gap, there is evidence for a widening of the age range interested. This could indicate emerging criticalities at new ages that were previously not affected by the mortality sex inequality (for example related to both survival and/or access to treatment), which would not be readily apparent without an analysis of the changes in the shape of the age-distributions of the sex gap in survival.

Our analysis presents a number of limitations. Any comparison of cause-specific mortality between countries and over time may be affected by differences in coding practices. We tried to overcome this by choosing the period 1998–2016, for which all the causes of death were classified according to the ICD-10 in all the countries included in this study. Furthermore, observations at ages 85 or older were collapsed in a single age group due to the available information in the official data set used. Thus, the description of the mortality pattern among the oldest old was less detailed. Disaggregated mortality data at ages older than 85 would help to better focus on the relevant contributions to the sex gap of these very old ages that are becoming more and more important in determining the sex gap in LE (Zarulli et al., 2020). It is important to highlight that this study analyses only the differences in life expectancy by the decomposition of the age-specific and cause-specific contributions. This decomposition analysis cannot directly reflect for example, the development status of each country or the availability of the health care systems and sex differences in health behaviours long before deaths occur. For external causes, it is less relevant, whereas for example, sex differences in cardiovascular diseases at ages above 80 could stem from sex differences in health behaviours in early and mid-life.

Nevertheless, this work gives a deeper insight of the evolution of the main contributing factors to the sex differences in life expectancy, highlighting different trends in the evolution of the age contributions. For most of the causes of death, both absolute and relative cause-specific contributions to the sex gap in life expectancy decreased over time. The decreasing trend was most of the time accompanied by a spreading of the contributions over a wider age-range; however, inequalities between women and men for these causes of death reduced over time. Even though for some causes of death in some specific counties (e.g., neoplasms in France and UK, and cardiovascular diseases in Russia and Ukraine) the cause-specific relative contributions increased over time, the absolute differences still decreased for these causes. In addition, differences compressed over a shorter and older age interval. These patterns show the overall reduction of the inequalities in life expectancy between women and men over time. Investigating this reduction trend, the study highlights for which causes of death and age groups the female–male differences in life expectancy became more important over time.

Conclusions

Our findings introduced an additional aspect of an earlier proposal that mortality hazards have, over the years, shifted rigidly to older ages. Our findings showed that with mortality delay (Bongaarts, 2005; Canudas-Romo, 2008; Edwards, 2008; Janssen & de Beer, 2019; Kannisto et al., 1994; Robine, 2008; Zuo et al., 2018), the most relevant age contributors to the sex gap in mortality, with regards to both premature mortality and old-age mortality (e.g., due to cancer, cardiovascular diseases and external causes), indeed shifted towards older ages, but the shift was not rigid. On the contrary, it could involve, depending on the cause of death and the country, either a compression of the most relevant age-contributors or a dispersion. Regarding neoplasm-related mortality,

for example, in most of the countries shifts to older ages were often accompanied by an increase and a compression of the distribution of the age-specific differences, as well as regarding heart disease-related mortality in the Eastern European countries and in Japan. The shift and compression of the survival advantage of women over a shorter age range may reveal that men are gradually improving in terms of survival, diagnosis and access to treatment, at least to those age no longer affected by the most significant differences, even though the data at our disposal do not allow to investigate this aspect. It is possible to speculate that in the future, for those causes of death for which relative differences increase, the most sizeable differences will also compress towards older ages.

The findings from our analysis could be extended by studying similar patterns (i.e., shift, compression and dispersion) of the distribution of the age and cause-specific contributions to other indicators of sex difference in longevity, for example lifespan variation. These further analyzes could provide a more accurate understanding of the epidemiological changes that are leading to variations in lifespan, considering a large and comprehensive set of causes of death. Finally, previous studies of the sex gap in life expectancy have emphasized the importance of social conditions and social change (Fedotenkov & Derkachev, 2019; Luy & Gast, 2014; Mondal & Shitan, 2014; Rogers et al., 2010; Tarkiainen et al., 2012; Thorslund et al., 2013; Trias-Llimós & Janssen, 2018). Hence, future studies should put emphasis on the impact of a broad range of modifiable life style factors and avoidable mortality to understand the ongoing shifts in cause-specific sex gaps in life expectancy, their compression or dispersion, as well as the scope for future improvements.

Appendix

See Figs. 5, 6 and Table 2.

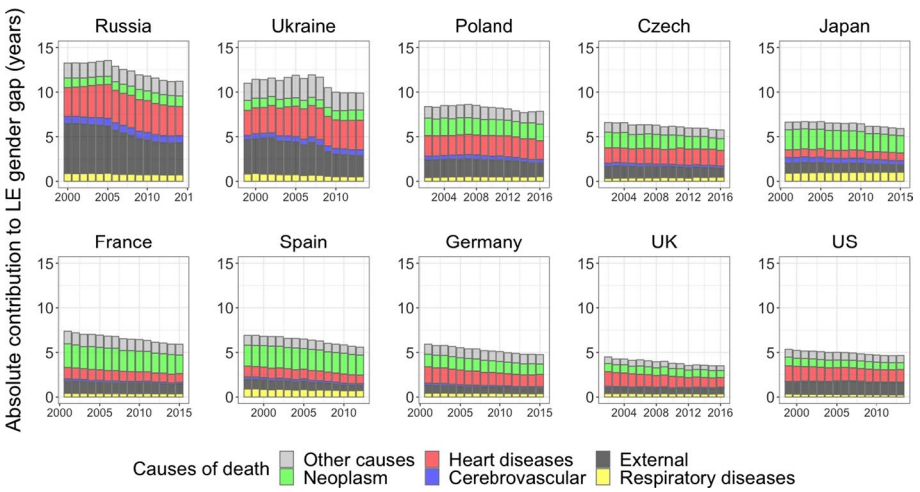

Fig. 5 Absolute cause-specific contributions to the sex gap in life expectancy over time

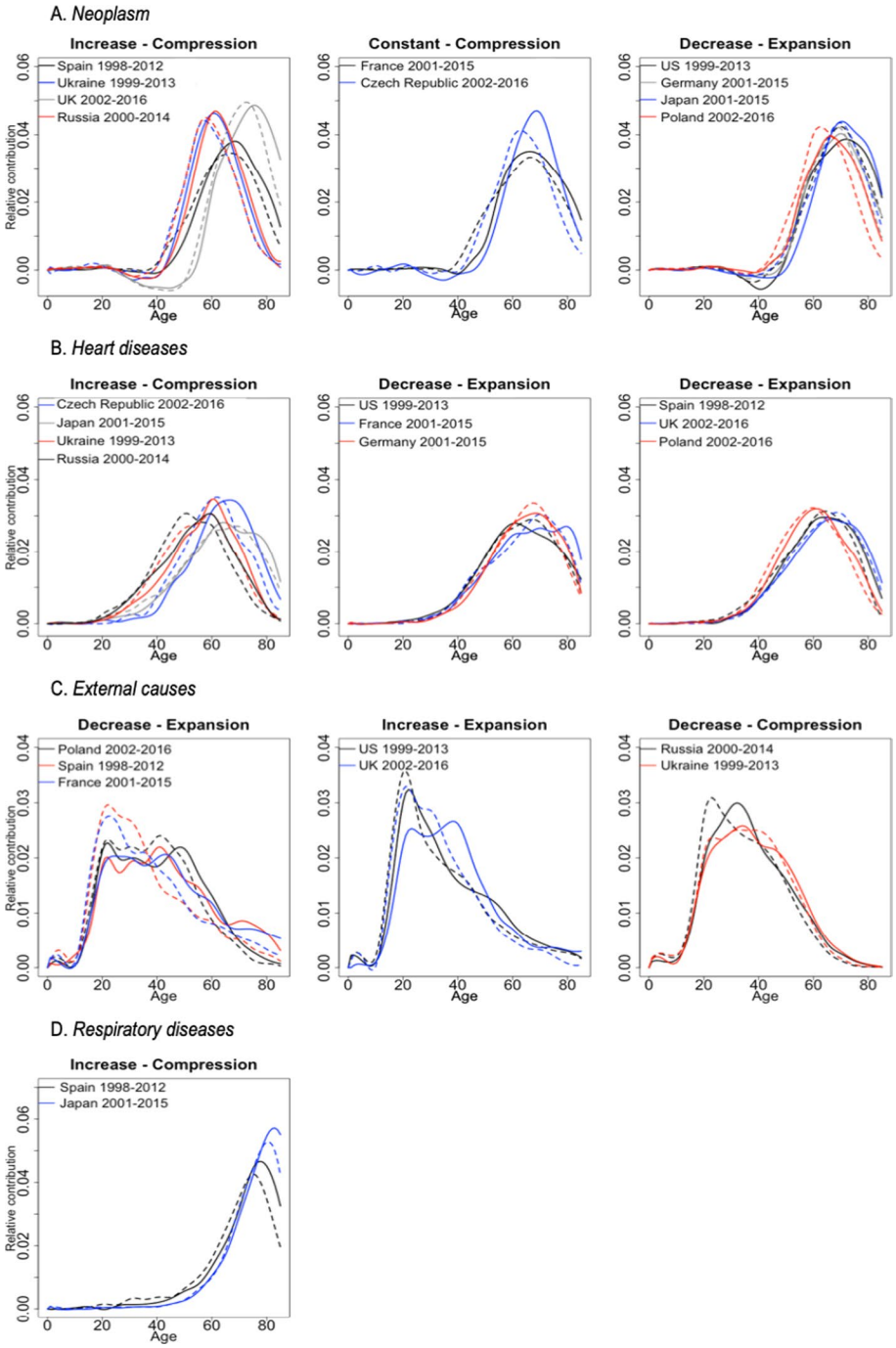

Fig. 6 Country-specific relative age-specific contributions to the sex gap in life expectancy at the beginning (dashed line) and at the end of the observation period (solid line), for each main cause of death. Increase (decrease) denotes increasing (decreasing) relative cause-specific contributions to the overall sex gap (i.e., magnitude)

Table 2 Classes of causes of death with related International Classification of Diseases codes according to the 10th revision (ICD-10)

Group of causes od death	Category codes (ICD-10)
Certain infectious diseases	A00–B99
Neoplasms	C00–D48
Diseases of the blood and blood-forming organs	D50–D89
Endocrine, nutritional and metabolic diseases	E00–E90
Mental and behavioral disorders	F00–F99
Diseases of the nervous system and the sense organs	G00–G44, G47–H95
Heart diseases	100–152
Cerebrovascular diseases	G45, 160–169
Other and unspecified disorders of the circulative system	I70–199
Acute respiratory diseases	J00–J22, L'04
Other respiratory diseases	J30–J98
Diseases of the digestive system	K00–K93
Diseases of the skin and subcutaneous tissue, musculoskeletal system and connective tissue	L00–M99
Diseases of the genitourinary system and complications of pregnancy, childbirth and puerperium	N00–O99
Certain conditions originating in the perinatal period and congenital malformations/anomalies	P00–Q99, R95
External causes	V01–Y98

Abbreviations

EE	Eastern Europe
HCD	Human Causes-of-death Database
HMD	Human Mortality Database
ICD	International Classification of Diseases
LE	Life expectancy
UK	United Kingdom
US	United States of America
WE	Western Europe

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Author contributions
Both authors contributed to the study concept and design. AF conducted the analyses and wrote the first draft of the manuscript, with input from VZ. VZ provided edits and feedback on subsequent versions of the manuscript. Both authors read and approved the final manuscript.

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Availability of data and materials
The data analysed during the current study is freely available from the Human Mortality Database (https://www.mortality.org/) and from the Human Cause-of-Death Database (https://www.causesofdeath.org).

Declarations

Ethics approval and consent to participate
The authors confirm that the ethical policies of the journal, as noted on the journal's author guidelines page, have been adhered to.

Competing interests
The authors declare no conflicts of interest.

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