CONTRIBUTIONS OF AGE GROUPS AND CAUSES OF DEATH TO THE SEX GAP IN LIFESPAN VARIATON IN EUROPE

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Data sharing statement:

The data on which this study is based are available from the web pages of the Human Mortality Database (www.mortality.org), the Human Causes-of-Death Database (www.causesofdeath.org) and the World Health Organization Mortality Database (https://www.who.int/data/data-collection-tools/who-mortality-database). The R code and the data selections that were used as input for the figures and tables will be made available in the Github repository of the first author.

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Abstract

Much less is known about the sex gap in lifespan variation, reflecting inequalities in the length of life, than about the sex gap in life expectancy, reflecting the average length of life. We examined the contributions of age groups and causes of death to the sex gap in lifespan variation for 28 European countries, grouped into five European regions, mainly for 2010-2015. In Europe in 2010-2015, males had a 2.3-year higher standard deviation and a 6.8-year lower life expectancy than females, with clear regional differences. The sex differences in lifespan variation are largely attributable to higher external mortality among males aged 30-39, whereas the sex differences in life expectancy are predominantly due to higher smoking-related and cardiovascular disease mortality among males aged 60-69. The distinct findings for the sex gap in lifespan variation and the sex gap in life expectancy provide additional insights into the survival differences between the sexes.

Key words: Sex gap, lifespan variation, life expectancy, Europe, cause-specific mortality

1. Introduction

It is well known that worldwide, males live, on average, shorter lives than females (WHO 2018a; Thornton 2019). In Europe, a male disadvantage in life expectancy has been recorded for more than 200 years (Glei and Horiuchi 2007). Currently in Europe, the sex gap in life expectancy amounts to almost seven years, albeit with substantial regional differences (Janssen 2020a). The many previous studies on the sex differences in life expectancy generally show that both biological factors and sex differences in risky health behaviors contribute to the lower life expectancy among males than among females (see, for example, Rogers et al., 2010; McCartney et al., 2011; Austad et al., 2016; Luy and Wegner-Siegmundt 2015). There is also evidence that mortality related to cardiovascular disease, smoking, alcohol consumption, and external causes, mainly at adult ages, contributes substantially to the sex gap in life expectancy (Beltrán-Sánchez et al., 2015; Janssen 2020a; Trias-Llimós and Janssen 2018; Spijker and Blanes-Llorens 2009; Zarulli et al., 2021). However, much less is known about the sex gap in the inequality in the length of life or the age at death, also known as lifespan variation. This is the case even though in demography, the added academic and societal value of studying lifespan variation as well as life expectancy has been clearly demonstrated in recent years (e.g., van Raalte et al., 2018; Tuljapurkar 2010).

The extensive body of literature on the sex gap in life expectancy has shown that the female advantage in life expectancy can be explained by both biological and social factors, with differences in health-related behaviors being a clear manifestation of the latter (Rogers et al., 2010; McCartney et al., 2011; Austad et al., 2016; Luy and Wegner-Siegmundt 2015).

Among the biological factors that have been documented are that females have two X chromosomes, whereas males have only one, which increases men's susceptibility to disease (Marais et al., 2018; Viña et al., 2005, Migeon 2006). It should, however, be noted that the most recent literature paints a more complex picture involving several additional mechanisms, such as cellular senescence, protein synthesis, and epigenetic alterations (Hägg & Jylhävä 2021). The role

of biological differences in the sex gap in life expectancy has been empirically demonstrated by studies showing that even in conditions in which males and females have similar lifestyles – such as in convents of nuns and cloistered monks (Luy 2004); and in adverse situations, such as famines and epidemics (Zarulli et al., 2018) – females have, on average, higher survival rates than males.

However, in addition to biological factors, sex differences in health behavior also play an important role in the sex gap in life expectancy. In particular, young males' higher propensity to engage in risky and violent behaviors appear to explain part of the male disadvantage in life expectancy (Gjonça et al., 2005; Rogers et al., 2010). For example, compared to females, males have historically consumed more tobacco, alcohol, and psychoactive substances; have been more likely to engage in dangerous driving; and have exhibited less knowledge and awareness about the dangers of risky behavior (Waldron 1985; Courtenay 2000; Wardle et al., 2004, Natterson-Horowitz and Bowers 2019). Moreover, unhealthy dietary habits and low levels of engagement with preventive health behaviors among males may contribute to their observed disadvantage (Vaidya et al., 2012). Of the different lifestyle factors, cigarette smoking has been identified as a particularly important factor in determining the sex differences in life expectancy in high-income countries (Beltrán-Sánchez et al., 2015; Janssen 2020a; Janssen et al., 2021). Janssen (2020a) estimated that smoking-attributable mortality contributed, on average, three out of seven years to the sex differences in life expectancy in 30 European countries in 2014. Trias-Llimós and Janssen (2018b) found that in eight Central and Eastern European countries, alcohol-attributable mortality accounted for at least 15% of the sex gap in life expectancy in 2012 (which was, on average, 10 years). These contributions are substantially larger than that of the biological component of the sex gap in life expectancy, which is estimated to range from 0.5 to 2.0 years (Luy and Wegner-Siegmundt 2015).

It should be acknowledged, however, that some of the sex differences in behaviors may be explained by the higher concentration of certain sex hormones in males, like testosterone, which

has been linked to an increased tendency to engage in high-risk behaviors (Archer 2006). It is also important to acknowledge the influence of social factors (Rogers et al. 2010), such as culturally defined gender roles, responsibilities, and experiences. Indeed, many male- or female-typical behaviors might be dictated by social roles and social norms (for example, women are encouraged to engage in healthy behaviors and caregiving roles, while men are encouraged to engage in hazardous behaviors). Moreover, while there has been a tendency to consider environmental and social factors as non-biological and genetic factors as biological, recent discoveries have led to a blurring of this classic dichotomy. It thus appears that the magnitude of the sex gap in aging and survival is variable, and depends on complex interactions between genetic and environmental factors, which, in humans, also include sociocultural factors (Lemaître et al., 2020).

In particular, the biological factors and the health behavior-related factors that contribute to the male life expectancy disadvantage can be translated into specific sex differences in causes of death. For example, the higher levels of estrogen in females provide protection from certain cardiovascular diseases, such as ischemia/reperfusion, hypertensive heart diseases, and heart failure (Xiang et al., 2021). Sex differences in cigarette smoking can be linked to sex differences in mortality from lung cancer, other smoking-related cancers, and chronic obstructive pulmonary diseases (COPD) (Freedman et al., 2008). Similarly, sex differences in heavy drinking can be tied to sex differences in mortality from liver cirrhosis or alcohol poisoning (Room et al., 2005); and sex differences in dangerous driving and intentional injuries can be linked to sex differences in external causes of death, such as accidents (Room et al., 2005). Indeed, previous research has documented the large contributions of cardiovascular diseases (Beltrán-Sánchez et al., 2015), smoking-related mortality (Janssen, 2020a), alcohol-related mortality (Trias-Llimós and Janssen 2018), and external causes of death (Spijker and Blanes-Llorens 2009) to the male life expectancy disadvantage. Importantly, however, the causes of death that contribute the most to the sex differences in life expectancy are not the same in different countries or regions (Trias-Llimós and Janssen 2018; Janssen 2020a; Beltrán-Sánchez et al., 2015; Feraldi and Zarulli 2022).

Next to the causes of death that contribute the most to the sex gap in life expectancy, the age groups that contribute the most to the sex gap in life expectancy are well known. For example, higher premature mortality among males than among females contributed substantially to the sex gap in life expectancy in Europe in the 1950-1970 period (Glei and Horiuchi 2007). Moreover, since 1950, the contribution of mortality at older ages has been increasing because levels of old-age mortality have been declining more rapidly among females than among males (Zarulli et al., 2020; Zarulli et al., 2021). Nonetheless, the contributions of the different age groups to the sex gap in life expectancy vary across European regions (Glei and Horiuchi 2007; Zarulli et al., 2020; Feraldi and Zarulli 2022).

However, much less is known about the sex gap in the inequality in length of life, or in the age at death, which is also known as lifespan variation. Although interest in researching lifespan variation alongside life expectancy has increased over the last decade (Aburto et al., 2020), studies that focus on the sex differences in lifespan variation are still lacking. This is an important omission, because as an indicator of the average length of life, life expectancy conceals the variation in length of life, which is substantial, and which may differ considerably between males and females (Vaupel et al., 2021; Bergeron-Boucher et al., 2022). Lifespan variation, which can be captured by indicators of dispersion in age at death, such as the standard deviation, provides additional information about longevity that is not conveyed by life expectancy alone (Edwards and Tuljapurkar 2005; Aburto and van Raalte 2018). Lifespan variation is an important concept in the study of longevity, as it reflects inequality in the length of life at the population level (Smits and Monden 2009), and can be interpreted as an indicator of the uncertainty in the age at death at the individual level (Gillespie et al., 2014). High levels of lifespan variation, which indicate high levels of uncertainty about the remaining length of life for individuals and patients, could negatively affect both personal and medical spending or investments because of their lower – or at least less certain – expected utility (Edwards 2013; Nepomuceno et al., 2022). Moreover, when monitoring

the health conditions across nations, lifespan variation is a powerful measure for assessing the degree of heterogeneity in population health (van Raalte et al., 2018).

From previous studies that reported the levels of lifespan variation among both males and females, we know that males have higher levels of lifespan variation than females (Edwards and Tuljapurkar 2005; Colchero et al., 2016). However, we know far less about the causes of death or the age groups that contribute the most to either increasing or decreasing the sex gap in lifespan variation, which could shed light on the factors underlying the sex differences in lifespan variation. We cannot assume that the factors that contribute to the sex gap in lifespan variation are similar to those that contribute to the sex gap in life expectancy, given that lifespan variation and life expectancy are generally negatively correlated, with higher life expectancy usually being accompanied by lower levels of lifespan variation (van Raalte et al., 2014; Permanyer et al., 2018). Moreover, a negative correlation between their trends over time has been observed: i.e., throughout the 20th century, life expectancy at birth increased while lifespan variation declined, (Vaupel et al., 2011; Engelman et al., 2010; Permanyer and Scholl 2019; Aburto et al., 2020).

Therefore, our objective is to analyze the contribution of different causes of death and age groups to the sex gap in lifespan variation, and to assess how these contributions differ from those to the sex gap in life expectancy. Our analysis covers 28 European countries, both individually and combined, and grouped into five European regions, using data from 2000 to 2015. We focus on the results for Europe as a whole, and for five European regions, for the 2010-2015 period.

In addition to providing a recent picture of the sex gap in lifespan variation in Europe, our paper is, to our knowledge, the first to assess the contributions of age groups and causes of death to the sex gap in lifespan variation. Our findings are expected to add to the literature on lifespan variation, and, in particular, to our understanding of (regional differences in) the sex gap in lifespan variation.

In addition, ; our findings can help policy-makers seeking to reduce health inequalities by identifying which age groups and which causes of death should be the focus of efforts to reduce the sex gap in both life expectancy and lifespan inequality in Europe.

We expect to find that the causes of death and the age groups that contributed the most to the sex gap in lifespan variation differ from those that contributed the most to the sex gap in life expectancy. This hypothesis is driven in part by the observation by Seligman et al. (2016) that the causes of death that contribute to increases in life expectancy over time are not necessarily the same as those that contribute to decreases in lifespan variation over time. Moreover, while saving lives at younger ages is known to reduce lifespan variation because it compresses the age-at-death distribution, saving lives at older ages is known to increase lifespan variation because it expands the age-at-death distribution (e.g., van Raalte et al., 2014). Today, life expectancy levels are mainly driven by developments in mortality at older ages (Aburto et al., 2020).

2. Data & Methods

2. 1. Data

Using data for 28 European countries, we analyze Europe as a whole, five European regions (Nordic countries, Western Europe, Southern Europe, Central Eastern Europe, and former Soviet republics), and 28 individual countries for the 2000-04, 2005-2009, and 2010-15 time periods. We selected all European countries for which data were available from our two main data sources (see below), unless they had a population of less than one million (Luxembourg, Iceland). We combined the data for several years to obtain more robust results.

The allocation of countries to the regions follows the broader geographical concept of the "Iron Curtain" in Europe, which historically reflected different economic, political, and demographic dynamics (Emanuele et al., 2018). The non-Eastern European regions are the Nordic countries (Finland, Denmark, Norway, and Sweden), the Western European countries (Austria,

Belgium, Germany, France, Ireland, the Netherlands, Switzerland, and the United Kingdom), and the Southern European countries (Greece, Spain, Italy, and Portugal). The Eastern European regions are the Central Eastern European countries (Bulgaria, the Czech Republic, Hungary, Poland, Slovakia, and Slovenia) and the former Soviet republics (Belarus, Estonia, Latvia, Lithuania, Ukraine, and Russia).

We retrieved exposure, death count, and life table data by sex, single age (0-110+), and year from the Human Mortality Database (HMD) (HMD 2019). The HMD is well known for its high data quality due to its strict protocols (Barbieri et al., 2015).

For information on causes of death by age, sex, country, and year, we used two data sources. For the non-Eastern European countries and the Central Eastern European countries, we used death counts from the World Health Organization (WHO) Mortality Database (WHO 2019); while for the former Soviet republics, we used cause-specific death counts from the Human Cause-of-Death Database (HCD) (2021). We relied on two different data sources because in the WHO database, a condensed list of causes of death is available for Belarus, Russia, and Ukraine, while a more detailed list of causes of death is available for the rest of the countries. Drawing on the HCD information for Belarus, Russia, and Ukraine enabled us to use the same causes of death for these countries as we did for the rest of the countries. See Appendix Table 1 for the availability of data by country in the three data sources.

Cause-specific death counts from both the WHO and the HCD are categorized into five-year age groups, and the last open-ended age group is either 85+ or 90+, depending on the country. To end up with data by single year of age – in line with the HMD data, and in line with the aim of our analysis – we smoothed the age-specific deaths from the WHO and the HCD, and created a last open-ended age group of 110+. For this purpose, we used – in line with Aburto et al. (2018) and

Wensink et al. (2020) – the efficient estimation of smooth distributions by Rizzi et al. (2015), which was implemented in the R package "ungroup" (Pascariu et al., 2018). This smoothing technique maintains the total deaths across ages for the different causes of death. Supplementary Material 1 illustrates, for those regions for which we had data up to high ages, that the smoothing technique captured the original age-at-death distribution very well.

2.2 Cause-of-death classification

We selected 11 cause-of-death groups: 1) cancers attributable to smoking, 2) sex-specific cancers, 3) rest of cancers, 4) ischemic heart diseases and stroke, 5) rest of circulatory diseases, 6) mental disorders and nervous system diseases, 7) alcohol-attributable causes of death, 8) external causes of death, 9) infectious (respiratory) diseases, 10) non-infectious respiratory diseases, and 11) rest of causes of death. The detailed causes of death covered within each cause-of-death group, and the associated ICD-9 and ICD-10 codes, can be found in Appendix Table 2.

The cause-of-death groups were selected based on two main criteria. The first was related to their known contributions to the sex gap in life expectancy. The second was related to their expected effects on either premature or old-age mortality because of the differential effects of premature and old-age mortality on lifespan variation (see introduction). See Appendix Table 3.

The contributions to the sex gap in life expectancy of smoking-related mortality (e.g., Janssen 2020a; Wensink et al., 2020), alcohol-related mortality (e.g., Trias-Llimós et al., 2018a; Trias-Llimós, et al., 2018a), external causes of death (e.g., Spijker and Blanes-Llorens 2009), and circulatory diseases (e.g., Beltrán-Sánchez et al., 2015) are well documented. In addition, alcohol-related mortality has contributed substantially to recent trends in lifespan variation in Eastern European countries (Aburto and van Raalte 2018). Furthermore, we selected the cause-of-death group "mental disorders and nervous system diseases" because these causes substantially affect

old-age mortality (Bergeron-Boucher et al., 2020), and we selected the cause-of-death group "infectious (respiratory) diseases" because mortality at very young ages is mostly due to infectious diseases (Ferkol and Schraufnagel 2014).

In our analysis, we separated IHD & stroke from the rest of circulatory diseases because IHD & stroke affect females more than males, especially at older ages (Gao et al., 2019), and may therefore affect the sex gap in lifespan variation differently than other circulatory diseases. We studied the effects of smoking-related mortality by examining cancers sensitive to smoking, in line with Aburto et al. (2018); and by examining non-infectious respiratory diseases, which includes COPD, again following Aburto et al. (2018). We studied alcohol-related mortality by focusing on the causes of death wholly related to alcohol (e.g., poisoning due to alcohol), in line with Trias-Llimós et al. (2018a). In addition, we studied sex-specific cancers (breast and prostate cancer) as a separate cause of death group because breast cancer is much more prevalent among females, while prostate cancer is much more prevalent among males (López-Abente et al., 2014).

To minimize the potential effects of differences between countries in classifying causes of death (Alter & Carmichael 1996), we used – in line with common practice – rather broad cause-of-death groups, as well as more selected causes of death, particularly for cancer mortality, for which national differences in coding are less important. However, national differences in the contributions of IHD & stroke in particular to the sex differences in lifespan variation and life expectancy should be interpreted with caution, given that the tendency to attribute deaths to "symptoms and ill-defined conditions" instead of to cardiovascular disease varies across countries (e.g., Lozano et al. 2001). External causes of death and smoking-related cancers are less likely to be affected.

2.3 Methods

We focus in our main analysis on the results for Europe as a whole, and for five European regions, over the 2010-2015 period. We report the results for 2000-04 and 2005-2009 for the European regions in Supplementary Material 2, and we report the results for the individual countries for the 2010-2015 period in Supplementary Material 3. In applying our methodology, we first aggregated the death numbers and the population numbers over the different countries comprising the different regions, and we then aggregated the yearly data over the different years.

To estimate the sex gap in both lifespan variation and life expectancy, we aggregated by sex the yearly all-cause death numbers and exposure numbers from the HMD, and obtained the relevant age-specific all-cause mortality rates. To the age-, sex-, and year-specific all-cause mortality rates, we applied standard period life table calculations (Preston et al., 2000) to obtain life expectancy at birth by sex. To measure lifespan variation, we computed the standard deviation (σ) of the age-at-death distribution – the d_x column in the life table – from age zero up to age 110+. While there are several absolute and relative measures of lifespan variation, all of them are highly correlated (van Raalte and Caswell 2013). We used the standard deviation because, being an absolute measure of variation, it is expressed in years, which makes it easy to interpret when combined with life expectancy (Edwards and Tuljapurkar 2005; García and Aburto 2019).

To quantify the contributions of different ages and cause-of-death groups to the sex gap in life expectancy and lifespan variation, we applied the stepwise replacement decomposition method by Andreev et al., (2002) (see as well van Raalte and Nepomuceno 2020). This demographic decomposition method allows for the accurate estimation of the contributions of the ages and the causes of death to the differences in aggregate measures, such as the sex differences in life expectancy and lifespan variation. In both instances, we decomposed the female advantage; thus, we decomposed the larger e_0 and the smaller lifespan variation for females than for males. To

obtain robust outcomes, we applied the decomposition method to data from age zero up to age 100 (instead of up to age 110+).

As the input for the decomposition method we used the smoothed cause-specific mortality rates by age (0-100), sex, and period, which we aligned with the all-cause mortality rates by age, sex, and period based on the HMD. That is, we first calculated by period and by sex the share of the smoothed age-specific cause-of-death numbers as part of age-specific all-cause mortality (obtained by taking the sum of the smoothed age-specific, cause-specific deaths over the different causes of death). Second, we multiplied these shares by the respective HMD all-cause mortality rates to obtain the cause-specific mortality rates by age, sex, and period that were used – in matrix format – as the input to the decomposition. We used the R package Demodecomp to perform the decomposition analysis (Riffe, 2018).

3. Results

Over the 2010-2015 period, European males had a 6.8-year lower life expectancy at birth and a 2.3-year higher standard deviation in lifespan than European females (Table 1). However, there were clear regional differences in the sex gap in both life expectancy and lifespan variation. The sex gap in both life expectancy (9.2 versus 4.8 years) and lifespan variation (2.0 versus 1.3 years) was considerably larger in Eastern Europe compared to in Western Europe. The sex differences in both life expectancy and lifespan variation were largest in the former Soviet republics (FSR), and were smallest in the Nordic countries.

TABLE 1: ABOUT HERE

Figure 1 shows the contributions of the different age groups to the sex gap in both life expectancy and lifespan variation. We expressed the contributions in terms of their contributions to the female advantage, or, conversely, to the male disadvantage. For example, for Europe, we decomposed the 6.8-year higher life expectancy among females than among males, and the 2.3-year lower lifespan variation among females than among males. Thus, for both life expectancy and lifespan variation, a positive contribution means that it contributed to the female advantage (= the male disadvantage). It is clear that all age groups contributed positively to the higher life expectancy among females than among males, which indicates that females had lower mortality than males across all age groups. However, when we look at lifespan variation, we see that the 70+ age groups were – unlike the other age groups – negatively contributing to the sex gap in lifespan variation. The 60-69 age group contributed the most to the male disadvantage in life expectancy, predominantly in the FSR. However, the 30-39 age group contributed the most to the male disadvantage in lifespan variation, again mainly in the FSR. More generally, it can be observed that infant mortality was still playing an important role in sex differences in longevity. The contribution of mortality at young adult ages to these differences was particularly large in Eastern Europe, and especially in the FSR.

FIGURE 1: ABOUT HERE

Figure 2 shows the contributions of the different causes of death to the sex gap in life expectancy and to the sex gap in lifespan variation. In the 28 European countries combined, smoking-related cancers, IHD & stroke, and external causes contributed the most to the male disadvantage in life expectancy, at 4.2 years out of 6.8 years. Thus, these causes accounted for 65.6% of the male disadvantage. In the former Soviet republics, the contribution of external causes of death was particularly large (3.5 out of 11 years). In the Nordic countries, the contribution of IHD & stroke

was especially large (1.2 out of 4.4 years). In the remaining European regions, the contribution of smoking-related cancers was the largest.

Turning to the sex differences in lifespan variation, external causes of death contributed the most to the male disadvantage in lifespan variation across all European regions (1.4 out of 2.3 years). Interestingly, however, smoking-related cancers and IHD & stroke only contributed very marginally to the sex gap in lifespan variation. In the non-Eastern European countries, with the exception of the Nordic countries, smoking-related cancers contributed positively to the higher lifespan variation among males than among females. However, in the Eastern European region, smoking-related cancers contributed negatively to the sex gap in lifespan variation.

The sex-specific cancers made a negative contribution to the male disadvantage in both life expectancy and lifespan variation. This result is likely driven by breast cancer mortality among females occurring at younger ages than prostate cancer mortality among males.

FIGURE 2. ABOUT HERE

By simultaneously examining the contributions of the age groups and the causes of death to the sex gap in life expectancy (Figure 3), we found that the sex gap in life expectancy in Europe was mainly attributable to higher mortality among males aged 60-64 from smoking-related cancers and circulatory diseases. While IHD & stroke and smoking-related cancers at ages 75-79 contributed the most to the male disadvantage in life expectancy in non-Eastern Europe, external mortality at ages 30-34 contributed the most to this gap in Eastern Europe. The sex-specific cancers had a slightly counterbalancing impact at ages 30-79.

FIGURE 3: ABOUT HERE

When simultaneously examining the contributions of the age groups and the causes of death to the sex gap in lifespan variation (Figure 4), it is relevant to consider what is happening below and above what we refer to as the threshold age. We have defined the threshold age as the age below which sex differences in mortality contribute positively to the higher lifespan variation among males than among females, and above which sex differences in mortality contribute negatively to the higher lifespan variation among males than among females. In the 28 European countries combined, the threshold age was between ages 70 and 75; but in the former Soviet republics, the threshold age was much lower, between ages 60 and 65; and in the Nordic and Southern regions, the threshold age was highest, between ages 75 and 80. External causes mainly operated below the threshold age, and thus contributed substantially to the higher lifespan variation among males. Smoking-related cancers and IHD & stroke operated at ages both below the threshold age (negative contribution) and above the threshold age (positive contribution); hence, when added up, they contributed only marginally to the sex gap in lifespan variation. Sex-specific cancer was the only cause of death that contributed negatively to the sex gap in lifespan variation below the threshold age.

FIGURE 4: ABOUT HERE

Figure 5 categorizes the different age groups according to their contributions to the sex gap in both life expectancy and lifespan variation. It is clear that mortality below age 60 contributed to the higher life expectancy among females, and therefore contributed to an increase in the sex gap in life expectancy. Similarly, mortality below age 60 contributed to the lower lifespan variation among females, and therefore also contributed to an increase in the sex gap in lifespan variation. However, mortality at ages 60+ contributed to an increase in the sex gap in life expectancy, but to

a decrease in the sex gap in lifespan variation. Figure 5 also indicates that mortality at younger ages, particularly at ages 10-29, contributed to an increase in the sex gap in lifespan variation more than to an increase in the sex gap in life expectancy. However, mortality at older ages, particularly at ages 70-89, contributed to an increase in the sex gap in life expectancy more than to a decrease in the sex gap in lifespan variation.

FIGURE 5 ABOUT HERE

Similarly, we classified the causes of death according to their contributions to the sex gap in both life expectancy and lifespan variation (Figure 6). While external causes of death contributed to an increase in the female advantage in both lifespan variation and life expectancy, sex-specific cancers contributed to a decrease in the sex differences in both lifespan variation and life expectancy. The relative contributions of external causes of death were larger for the sex differences in lifespan variation than in life expectancy. In the majority of regions, smoking-related cancers and IHD & stroke, contributed substantially to an increase in the sex differences in life expectancy, but not as much as to the sex differences in lifespan variation. Moreover, we see that in the former Soviet republics, these two groups of causes contributed to a decrease in the sex gap in lifespan variation.

FIGURE 6: ABOUT HERE

The results of additional analyses are shown in the Supplementary Material. Our analysis that covered the 2000-2004 and 2005-2009 periods as well (Supplementary Material 2) showed a modest decline in the sex gap in lifespan variation in Europe, but a modest increase in Eastern Europe, from 2000-2004 to 2010-2015 (Supplementary Material 2: Figure 1). The threshold age

we defined increased slightly over time (Supplementary Material 2: Table 2). However, the contributions of the age groups and the causes of death remained largely similar over time (Supplementary Material 2: Figures 2-7).

Supplementary Material 3 reports the results for the individual European countries over the 2010-2015 period, indicating important differences between countries within the different European regions.

Our additional analysis in which we used the lifespan disparity measure e-dagger (Vaupel et al., 2011; Vaupel, and Canudas-Romo, 2003) instead of the standard deviation (SD) (see Supplementary Material 4) revealed small differences in the sex gap in lifespan variation, except in the FSR, where the sex difference when using e-dagger was 36% larger than when using SD. This is because lifespan disparity measures like e-dagger are generally more sensitive than SD to the variation at early ages (Vaupel et al., 2011). We observed no large differences in the contributions of the ages and the causes of death (Supplementary Material 4: Figure 1).

Our additional analysis in which we analyzed the sex gap in lifespan variation after age 15 instead of from birth (see Supplementary Material 4: Table 1) resulted in a 20-30% smaller sex gap in lifespan variation for the different regions, with the largest declines being found in Central and Eastern Europe (CEE). This illustrates that the sex gap in lifespan variation is sensitive to the first years of life (Edwards and Tuljapurkar, 2005), particularly in CEE. The contributions of age groups and causes of death to the sex gap in lifespan variation were largely similar.

4. Discussion and concluding remarks

4.1 The sex gap in lifespan variation in Europe explained

We showed that in the 28 European countries studied ("Europe") in 2010-2015, males had, on average, a 2.3-year higher standard deviation in lifespan than females. This was in addition to the,

on average, 6.8-year lower life expectancy for males than for females in Europe. Our findings contribute to the health inequalities literature by closely examining for the first time the sex differentials in survival through the lens of lifespan variation. Our findings indicate that in Europe, males can not only expect to live fewer years than females, but also there is greater uncertainty about their age at death, and, consequently, about their remaining length of life. Uncertainty about the length of life can have important implications at both the individual level, such as when planning for one's further life course (e.g., additional schooling); and at the population level, such as in the areas of public health policy, medical spending, and/or investments by public health professionals (Nepomuceno et al., 2022). Moreover, our results provide a more complete picture of the heterogeneity in survival patterns in Europe.

The observed sex gap in SD of 2.3 years in the 28 European countries combined ("Europe") was larger than in any of the separate European regions (see Table 1). This is because of large cross-country differences in mortality profiles, particularly for males. In Eastern Europe, the age pattern of mortality was relatively young for males; whereas in non-Eastern Europe, the age pattern of mortality was more concentrated at older ages, and was more alike for males and females (see Supplementary Material 5 – Figure 1). As a consequence, the lifespan variation for European males was rather large, and was close to that for non-Eastern European males, because it resulted from the combination of the two age patterns mentioned above. However, for European females, the age pattern of mortality was more similar across countries, and the lifespan variation better represented a weighted average of the lifespan variation for females in the different regions. Consequently, the sex differences in lifespan variation were larger in Europe as a whole than in any of the separate European regions, including in Eastern Europe.

We observed that sex differences in mortality at ages 30-39 contributed the most to the sex differences in lifespan variation. This can be partly explained by the large role of (sex differences in) mortality in this age group in determining (sex differences in) lifespan variation. While this age group is well below the central age of death, mortality levels were higher at ages 30-39 than at younger ages because mortality increases exponentially starting at age 30 (Gompertz 1825). More importantly, sex differences in mortality were larger in this age group than in younger age groups, as the first plot of Figure 1 in Supplementary Material 5 indicates. Specifically, it shows that from approximately ages 18-20 onward, sex differences in mortality slowly increased, and had grown rather large in the 30-39 age group.

It appears that the tendency of males to engage in more unhealthy and risky health behaviors (e.g., dangerous driving resulting in accidents, violence, extreme sports) (see introduction) started at young ages, and eventually led to large sex differences in mortality in the 30-39 age group. Indeed, previous research has highlighted that mortality differences at young adult ages contribute substantially to sex differentials in mortality (e.g., Remund et al., 2018), and has demonstrated that sex differences in the likelihood of engaging in unhealthy and risky health behaviors start at young ages (e.g., Bina et al. 2006). Our observation that external mortality was the cause of death that contributed the most to the sex gap in lifespan variation, both in general, and specifically at these young ages, further supports these findings. Indeed, there is ample evidence that violence, (transport) accidents, and (accidental) poisoning, which account for a large share of external mortality, are much more common among European males than among European females (WHO 2020), especially at young ages (Aburto and van Raalte 2018).

The reasons why young adult men are more likely than (young adult) women to engage in risky behaviors have been previously discussed (e.g., Byrnes et al. 1999, Archer 2006; Rogers et al. 2010). Biological factors are among these reasons. For example, the higher concentration of testosterone in males might lead men to take more risks than women (Archer 2006; Batrinos,

2012). However, most previous studies focused on the role of psychological and social factors. Thus, they linked the finding that men are more likely than women to engage in risky health behaviors to men having a sensation-seeking personality in response to their lower levels of arousal; to men regarding risk as a positive value (in line with the "risk as value" hypothesis); and, more generally, to (perceived) gender roles and social norms (e.g., restrictions placed on risk-taking by society) (Byrnes et al. 1999; Waldron et al. 2005; Roger et al. 2010; Hawkes and Buse 2020, Courtenay 2000). Gender roles and stereotypes are important in determining how we interact with society, how we are perceived, how we perceive others, and what type of risks we are or choose to be exposed to (Hawkes and Buse 2020, Courtenay 2000). Indeed, the construction of masculinity in modern societies in which men are expected to be strong, independent, and resilient has likely spurred their greater propensity to take risks. Moreover, in line with the "risk as value" hypothesis, risk-taking is regarded as a highly valued masculine tendency.

4.2 Outcomes for the sex gap in lifespan compared to outcomes for the sex gap in life expectancy

Our finding that external mortality, predominantly at young adult ages, was the main cause of death driving the sex differences in *lifespan variation* might seem to contradict our (and previous) findings that in recent decades, the sex gap in *life expectancy* in high-income countries has been largely attributable to higher mortality among males from smoking-related cancers and IHD & stroke at older ages, and particularly at ages 60-69 (Janssen 2020a; Beltrán-Sánchez et al., 2015). However, these differences (and other observed differences) in the contributions of causes of death to either the sex gap in lifespan variation or the sex gap in life expectancy can be linked to the observation by Seligman (2016) that the causes of death that contributed to increases in life expectancy over time are not necessarily the same as those that contributed to decreases in lifespan variation. This observation appears to be relevant not only when studying trends over time, but also when studying sex differences.

The differences in the contributions of causes of death to the sex gap in either lifespan variation or life expectancy can be largely explained by the different contributions of different age groups to the sex gap in either lifespan variation or life expectancy. That is, while sex differences in (cause-specific) mortality in all age groups were contributing to increases in the sex gap in life expectancy, this was not the case for the sex gap in life span variation. Instead, sex differences in (cause-specific) mortality below age 70 were contributing to increases in the sex gap in lifespan variation, while (cause-specific) mortality differences above age 70 were contributing to decreases in the sex gap in lifespan variation. Because females have longer lifespans than males (Zarulli et al., 2021), higher mortality at higher ages compressed the age-at-death distribution more among males than among females, and thus contributed to a decrease in the sex gap in lifespan variation.

Smoking-related cancers and IHD & stroke, which are known to contribute substantially to the sex gap in life expectancy (Beltrán-Sánchez et al., 2015), were found to have only a very small effect on the sex differences in lifespan variation in Europe as a whole, because these causes of death were reported both above and below the threshold age (i.e., the age below which sex differences in mortality contributed positively to the higher lifespan variation among males than among females, and above which sex differences in mortality contributed negatively to the higher lifespan variation among males than among females). Thus, their effects were offset.

On the other hand, external mortality at young adult ages contributed much less to the sex gap in life expectancy than to the sex gap in lifespan variation, because the sex gap in life expectancy is determined less by the distance of that particular age (and cause of death) group to the central age of death, and more by the size of the mortality gap between males and females. The first plot of Figure 1 of Supplementary Material 5 clearly shows that at ages 60-69, males had a much higher mortality than females. Consequently, that age group contributed the most to the sex differences in life expectancy.

However, our findings regarding the sex differences in both lifespan variation and life expectancy indicate that the sex gap in longevity is mainly attributable to sex differences in mortality from causes of death that are (partly) linked to health behaviors (smoking, alcohol abuse, risky behavior resulting in accidents, violence).

The link between the importance of external mortality (particularly at ages 30-39) for the sex differences in lifespan variation and the sex differences in risky health behaviors were already discussed in section 4.1. However, the causes of death that contributed the most to the sex differences in life expectancy can also be linked to health behaviors. That is, although not all deaths from IHD & stroke can be attributed to health behaviors, sex differences in mortality from IHD & stroke can be largely explained by sex differences in health behaviors (Beltran et al., 2015). Moreover, there is evidence of large sex differences in health behaviors in Europe. For instance, in Europe in 1980, the smoking prevalence was 39% among males and 18% among females (IHME 2017), which has led to much higher smoking-attributable mortality among European males than among European females today (25% versus 8%) (Janssen 2020b). Alcohol-attributable mortality in Europe is also higher among males than among females (Janssen et al., 2020), which is in line with reports of higher levels of alcohol abuse among males than among females (Gjonca et al., 2005; Allamani et al., 2000). In 2016 in Europe, the percentage of current drinkers among people aged 15 and older differed by sex, at 69.9% for males and 51.7% for females (WHO 2018b). Moreover, among these current drinkers, the prevalence of heavy episodic drinking was 56.5% for males and 24.5% for females (WHO 2018b).

While the sex differences in lifespan variation were particularly driven by health behaviors related to age – for example, by men engaging in more risky behaviors at young adult ages than women (see previous section) – the sex differences in life expectancy were particularly driven by the longer-term effects of men engaging in more unhealthy behaviors, such as smoking and drinking, than women (Rogers et al., 2010). However, the short-term effects of men engaging in

more limited healthcare-seeking behaviors than women may have also played a role (Courtney W. 2002).

4.3 Regional differences in the sex gap in lifespan variation

The clear regional differences we observed in the sex gap in lifespan variation are consistent with the regional differences in the sex gap in life expectancy (e.g., Janssen 2020a). That is, in Eastern Europe, males have a greater overall longevity disadvantage compared to females; whereas in the Nordic countries, males have the smallest overall longevity disadvantage compared to females in Europe. These findings highlight the heterogeneity in survival patterns in Europe.

These regional differences in the sex gap in longevity are mainly driven by regional variation in the sex differences in premature mortality. That is, the sex differences in premature mortality were larger in FSR and CEE than in the non-Eastern European countries, and were smallest in the Nordic countries (See Supplementary Material 5, Figure 1). The higher premature mortality among males in Eastern European countries is largely attributable to males having higher mortality from external causes of death than females (see Supplementary Material 2 Figure 3b & Figure 4b). In non-Eastern Europe, and particularly in the former Soviet republics, mortality from external causes of death was much higher among males than among females (Aburto and van Raalte 2018). Indeed, in the former Soviet republics, mortality from external causes of death among males was the highest in Europe (Grigoriev et al., 2014). However, the sex differences in mortality from smoking-related cancers around ages 60-69, circulatory disease mortality around ages 50-79, and alcohol-related mortality around ages 50-59 were larger in Eastern Europe than in non-Eastern Europe (See Figure 4).

Although most of the sex difference in external mortality, CVD mortality, alcohol-related mortality, and smoking-related mortality in Eastern Europe can be attributed to sex differences in risky and unhealthy behaviors – which can, in turn, be attributed to gender roles and social norms – these findings do not reflect the full story, as regional differences in health policies and medical

progress might also play an important role in the regional variation in the sex differences in mortality. For example, compared to Western Europe, CEE and FSR have benefited much more recently from the so-called cardiovascular revolution, which was brought about through the adoption of health policies aimed at reducing cardiovascular mortality by changing health behaviors, and through advances in medical interventions such as cardiovascular surgery, and advances in pharmacology and technology (Grigoriev et al. 2014, Hrzic et al. 2021; Vallin and Meslé, 2004; Meslé and Vallin, 2017). For example, Grigoriev and Andreev (2015) reported that alcohol-attributable mortality declined in Belarus and Russia in 2005-2006 and 2012 (Belarus) as a result of the anti-alcohol measures introduced in these two countries in the 2000s. This late start of the cardiovascular revolution in Eastern Europe was also due to the severe economic crisis that Eastern Europe experienced in the early 1990s (Aburto and van Raalte, 2018). Moreover, this crisis aggravated the tendency to engage in risky behaviors (including drinking patterns) among adult Eastern European men (Shkolnikov et al., 1998). Although premature mortality among Eastern European men has been converging with premature mortality among Eastern European women and non-Eastern European men (Aburto and van Raalte, 2018), some differences between these groups remain today, partly due to the large initial differences between them.

4.4 Overall conclusion

Our results shed light on sex differences in longevity through the lens of lifespan variation, and contribute to a broader understanding of the survival gap between men and women, and the regional differences in this gap. Adding to previous studies that examined sex differences in life expectancy, and that showed that the current lower life expectancy among males than among females was mainly driven by higher smoking-related mortality and cardiovascular disease mortality at older ages, we demonstrated that the higher lifespan variation among males was primarily driven by higher external mortality at younger ages.

Our observation that age groups and causes of death contributed very differently to the sex gap in lifespan variation than to the sex gap in life expectancy not only provides important insights into the survival differences between the sexes and their effects; it also indicates that life expectancy at birth and lifespan variation should be studied simultaneously.

Both increasing the average level of health and reducing health inequality are prominent goals of most countries around the world. Our findings suggest that further actions aimed at improving health behaviors, particularly among males, are needed to achieve health equity, and that these actions should be focused on relatively young age groups in order to simultaneously reduce the sex differences in life expectancy and in lifespan variation.

List of tables and figures:

Figure 4 - The absolute contributions of different age groups and cause-of-death groups to the sex gap in lifespan variation (males minus females) for the 28 European countries combined, and by European region, in 2010-2015. Nordic = Nordic countries; Western = Western Europe; Southern = Southern Europe; CEE = Central Eastern Europe; FSR = former Soviet republics. The dashed line indicates what we define as the threshold age: i.e., the age below which mortality contributes positively to the higher lifespan variation among men than among women, and above which mortality contributes negatively to the higher lifespan variation among men than among women. The threshold age falls somewhere in the first five-year age group above the dashed line

Figure 5 – Comparison of the relative contributions (%) of the different age groups to the sex gap in life expectancy (females minus males) versus to the sex gap in lifespan variation (males minus females) for the 28 European countries combined, and by European region, in 2010-2015. Nordic = Nordic countries; Western = Western Europe; Southern = Southern Europe; CEE = Central Eastern Europe; FSR = former Soviet republics.

Figure 6 - Comparison of the relative contributions (%) of the different cause-of-death groups to the sex gap in life expectancy (females minus males) versus to the sex gap in lifespan variation (males minus females) for the 28 European countries combined, and by European region, in 2010-2015. Nordic = Nordic countries; Western = Western Europe; Southern = Southern Europe; CEE = Central Eastern Europe; FSR = former Soviet republics.

Appendix:

Table A1. List of the selected countries by European region and their data availability for the two main data sources we used: the Human Mortality Database (HMD) and the WHO Mortality Database.

Table A2. List of the selected cause-of-death groups, the specific causes of death assigned to each group, and the associated ICD-9* and ICD-10 codes.

Table A3. The different cause-of-death groups according to the two criteria we used to select them: whether they are known to contribute to the sex gap in life expectancy, and their expected effects on either premature or old-age mortality.

List of supplementary material:

- Supplementary Material 1. Original versus smoothed age-specific death numbers for different causes of death, and selected regions.
- Supplementary Material 2. Results for the European regions over the different periods (2000-2004, 2005-2009, 2010-2015).
- Supplementary Material 3. Results for the individual European countries for the 2010-2015 period.
- Supplementary Material 4. Results of sensitivity analyses using different outcome measures for lifespan variation.
- Supplementary Material 5. Age-at-death distributions and share-of-death distributions for European regions for the 2010-2015 period by sex.

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