Assessing educational differentials in Healthy Life Years among women and men in 16 European populations

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Abstract

In the light of ageing populations, researchers and policy makers are concerned, whether gained life years are spent primarily in good or poor health. For this reason, monitoring trends in healthy life years (HLY) as an addition to the classic life expectancy measure has become of great importance. However, populations do not experience trends in HLY uniformly and especially socioeconomic differences are closely related to disparities. Due to data restrictions and comparability issues, the assessment of socioeconomic differences in HLY across Europe remains largely unexplored. With this paper, we want to close this research gap by estimating HLY for educational subpopulations in 16 European countries. We constructed life tables by educational attainment from life expectancy at age x estimates provided by EUROSTAT. Individuals are defined as healthy based on the Global Activity Limitation Indicator (GALI) obtained from EU-SILC. We calculated HLY using a Markov chain with "rewards" model and the Sullivan method in order to take into account both, uncertainty and variability in the estimates. Our preliminary results suggest that higher educated individuals can expect to live more healthy life years in all 16 countries. The stochasticity in healthy life is greater than the uncertainity in the estimates. Further, gender differences in HLY are strongly affected by the level of educational attainment. The female advantage in HLY is particularly pronounced in the low-educated group and loses importance among higher-educated population share.

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1 Introduction

Declining fertility along with increasing life expectancy will lead to a decisive shift to an older age structure in Europe, challenging the sustainability of the traditional social welfare state (Lutz, O'Neill, and Scherbov 2003; Christensen et al. 2009). In this light, policy makers have recognized the importance of promoting not only longer lives but also healthy lives and therefore, the European Commission set the target to increase the average healthy lifespan in the EU by two years by 2020 (Eurostat 2019). However, populations do not uniformly experience improvements in health and mortality. Especially, socioeconomic factors lead to substantial variation in healthy ageing across Europe (Jagger et al. 2008; Fouweather et al. 2015). Knowledge on these inequalities are key for implementing targeted public health policies, but several methodological issues hamper the assessment of differentials in healthy ageing between social groups (Crimmins and Cambois 2003). For example, results are extremely sensitive with respect to the underlying method, data, as well as the choice of health- and socioeconomic indicators. This is why previous research findings (e.g., Majer et al. 2010; Mäki et al. 2013) are only to an limited extent applicable for assessing socioeconomic inequalities in the healthy life years indicator (HLY) used by the EU[1]. In order to obtain more reliable information about the magnitude of inequalities in HYL across Europe, one should rather use the offical HLY indicator and calculate it seperated for different socioeconomic groups. To our knowledge, this has not been done yet, and accordingly, the aim of this paper is to close this research gap. Furthermore, not only information regarding the expected length of total, healthy, and unhealthy life is vital for policy makers. Also knowledge about the uncertainty and the degree of variability associated with the estimates is highly relevant, because this allows an appropriate evaluation of the future disease burden (Wolf and Laditka 1997; Laditka and Hayward 2003). Yet, most research studies have ignored the variability in life courses taken by individuals (Caswell and Zarulli 2018) and potential disparties have remained largely unexplored. For this reason, the analysis in this paper includes statistics on variances in order to shed more light on the variability in the life course of healthy longevity.

The central research idea of this paper is to assess the impact of educational attainment on HLY, i.e., to which extent the levels, trends, and variances differ among educational groups across Europe. For this purpose, we calculate HLY separated for educational subpopulations based on the same health and mortality data as used for the official HLY statistic. Thus, our estimates will subdivide the official HLY estimates into estimates for three different educational groups, i.e., the high-educated, middle-educated, and low-educated subpopulation. Further, we will report the corresponding statistics of variability (e.g., standard deviation) in order to investigate whether educational groups differ in their life course variability. Thus, the research has the potential to give new insights into health inequalities among educational subpopulations in different European regions.

[1] https://ec.europa.eu/eurostat/cache/metadata/en/hlth_hlye_esms.htm (last access 28.09.2019).

2 Data and method

2.1 Data

The calculation of HLY requires health and mortality data for European populations by age, gender, and educational attainment. In accordance with the HLY indicator used by the EU, we obtained the prevalence of being in the healthy state based on the Global Activity Limitation Indicator (GALI[2]) from the European Union Statistics on Income and Living Conditions (EU-SILC).
The mortality data is accessible in the Eurostat database[3]. Unfortunately, the database provides single age-specific life tables only separated by gender, but not by educational attainment. Nevertheless, single age-specific estimates of remaining life expectancy at age x are available in the required format for several European countries. We used the estimates of remaining life expectancy at age x to reconstruct life tables by educational attainment (see next section). This was possible for 16 European countries (Bulgaria, Croatia, Czechia, Denmark, Estonia, Finland, Greece, Hungary, Italy, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, and Sweden).

2.1.1 Deriving life tables by educational attainment based on life expectancy at age x estimates

Usually, the remaining life expectancy at a specific age x (e_x) is the outcome of a computed life table. In this case, we use e_x to reconstruct the complete life table, i.e., we calculated the life table backwards. After assuming that deaths are distributed evenly in every age interval (a_x equals 0.5 at every age) and using the life table function relationships (see e.g., Preston, Heuveline, and Guillot 2001), we are able to express the life table survivors l_x as:

$$l_{x+1} = \frac{l_x^2 - 2l_xT_x}{(e_x - e_{x+1}) \cdot 2l_x - 2T_x - l_x} \tag{1}$$

where l_x refers to the life table survivors at age x and T_x gives the number of person-years lived above age x. The remaining life expectancy at age x is presented as e_x. Please note that l_0 defines the life table radix (e.g., 100 000) and will not be estimated. Once l_x is estimated, all the remaining life tables functions, such as the probability of surviving (p_x), can be easily derived:

$$p_x = \frac{l_{x+1}}{l_x} \tag{2}$$

where p_x is the survival probability of the age class x.

2.2 Estimating statistics of healthy life years

The most popular approach to derive HLY expectancies from prevalence data and life tables is the Sullivan method (Sullivan 1971). More recently, Caswell and Zarulli (2018) introduced an alternative method for estimating statistics of healthy life based on a matrix population model. Their model

[2]Please see for example Berger et al. (2015) for a description and evaluation of GALI.
[3]https://ec.europa.eu/eurostat/data/database (last access 28.09.2019).

provides estimates of HLY expectancies as well, but has the additional feature of giving also statistics of variances (i.e., standard deviation) associated with these expectancies (Caswell and Zarulli 2018). This variance refers to inter-individual variability, i.e., the stochasticity in the life course of individuals (see Caswell 2009, for more details). It is important to note, the stochasticity in a process (e.g., health and survival) should not be confused with uncertainty due to parameter estimation errors. Since subdividing the survey data in three educational groups (separated for men and women) will reduce the sample size substantially, the uncertainty in the HLY estimates is likely to increase. Therefore, not only the variance in HLY, but also the standard errors associated with the estimates are relevant for the analysis in this paper. We used both methods, the Sullivan method and the Caswell & Zarulli method, in order to assess variability and uncertainty in HLY. More specifically, we used the Sullivan method to estimate standard errors of HLY and the Caswell & Zarulli method for deriving the variance arising from differences in the trajectory of healthy life. Both methods are described further in the appendix and more details can be found in Caswell and Zarulli (2018) and Jagger, E., and Brouard (2001). For the estimation procedure of healthy life for European populations, we followed the official HYL protocol provided by the EU[4]. The model (no matter whether it refers to the Sullivan method or the Caswell & Zarulli method) is based on single age-specific survival probabilities and prevalence data corresponding to 5-year age groups. Individuals are defined as being in the healthy state if they did not report any limitations because of a health problem in activities people usually do. In contrast to the EU protocol, we do not define a open-age interval for people at age 85 or older. Instead, the age 85 defines the absorbing state, i.e., everyone dies at this age. This is an inevitable assumption because health and mortality data for individuals above age 85 is not available.

3 Preliminary results

Figure 1 presents HLY at age 50 with 95% confidence intervals (upper panel) and the lower panel shows the standard deviation (SD) in healthy life for women in 16 European countries. While the blue squares correspond to Europeans with a lower level of education, the yellow triangles reflect estimates for the middle group. HLY values for high-educated women are shown as red circles. The ranking of the countries (top to bottom) is based on the total HLY value (not shown in the figure). Thus, Swedish females show the highest number of total HLY and Slovak women the lowest. All countries vary greatly by the level of education and the high-educated group shows the highest number of HLY50 (in most countries significant higher). For example, the number of HLY at age 50 (HLY50) for middle-educated Czech women is about 18 years. However, high-educated women in the Czech Republic can expect to live about three healthy life years more and low-educated women about 4 years. The lower panel presents the SD statistic and follows the same legend. Sweden shows the highest SD in HLY50 and is therefore on the top of the figure. The relationship between SD and the level of education is not as clear as the relationship between HLY50 and educational attainment. The high-educated sub-population might show higher or lower SD compared to the low-educated group. For example, the inter-individual variability in the life course of low-educated Croatian women is lower compared to the high-educated

[4] https://ec.europa.eu/eurostat/cache/metadata/Annexes/hlth_hlye_esms_an1.pdf (last access 10.09.2019).

group. In contrast, the variability pattern in Sweden indicates that especially Swedish women with low education vary greatly in their life course trajectory. Further, the figure depicts that the stochasticity in health life is greater than the uncertainty in HLY, i.e., SD in HLY50 has its minimum at about three years (Slovakia, low-educated) and its maximum at about 6.5 years (Sweden, low-educated), while the confidence intervals never exceed three years of healthy life. The results for males are presented in figure 2. The educational inequalities are most pronounced in Hungary and in the Czech Republic. The variability among individuals as measured by SD is generally higher in the male populations. The gender differences in HLY50 are illustrated in figure 3. The symbols on the left side of the dashed line at zero indicate that HLY50 for males is higher compared to women. The gender gap varies strongly by the level of education. For example, the gap for high-educated Danes is relatively small, while low-educated Danes show a clear male advantage in HLY50 and the middle-educated a female advantage. Especially, the low-educated sub-populations are associated with a female-advantage in HLY50. Only in Portugal, Finland, and Denmark, low-educated men are expected to live more healthy life years than low-educated women. The exact values of HLY50 can be found in table 1 and 2. The HLY50 estimates based on the Sullivan method are almost equal to the ones based on the Caswell & Zarulli method. This is not surprising since both are calculated exactly from the same health and mortality data. However, the former allows estimating standard errors and confidence intervals, i.e., uncertainty in the estimates and the latter provides information about the variability associated with the estimates.

4 Conclusion

With this paper, we want to investigate the impact of educational attainment on healthy longevity in Europe. The effect of educational attainment on LE is well documented but the relation to HLY has been studied only to some extent. On the one hand, data limitations have hampered the calculation of HLY by educational attainment, and on the other hand, the limited comparability of research findings based on different health and mortality data challenges the assessment of health inequalities in Europe further. We estimated HLY for 16 European countries, which are comparable to official HLY indicator used by the EU, but separated for three different educational sub-populations. Moreover, we estimated SD associated with these values in order to take also the variability in these estimates into account. Our results suggest, that the level of education has a large impact on HLY50 in Europe. First, high-educated Europeans can expect to live more healthy life years. Second, the stochasticity in healthy life is larger compared to the uncertainty in the estimates. Third, the gender gap is strongly affected by educational attainment. In the lower-educated sub-population women outlive men in healthy life years in almost all analyzed countries. This advantage reduces in the high-educated group and might even reverse in more healthy life years for men compared to women.

5 References

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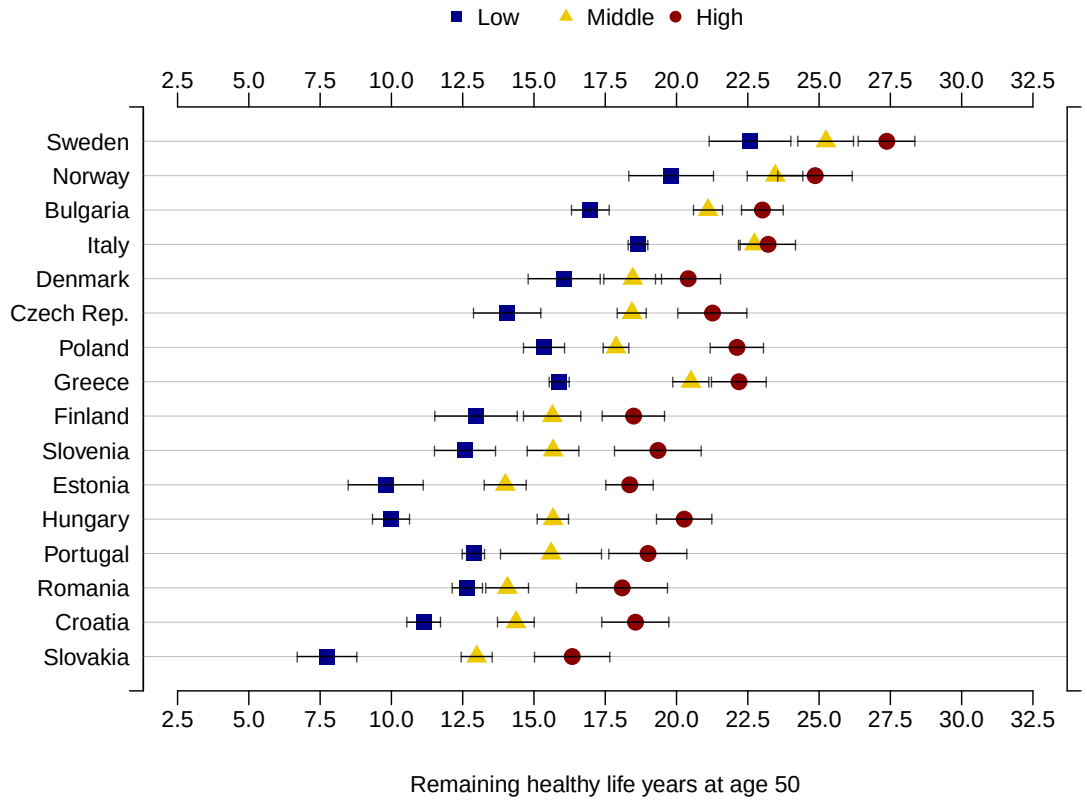
6 Appendix

Figure 1: HLY50 for 16 European countries in 2016 separated by educational attainment, females



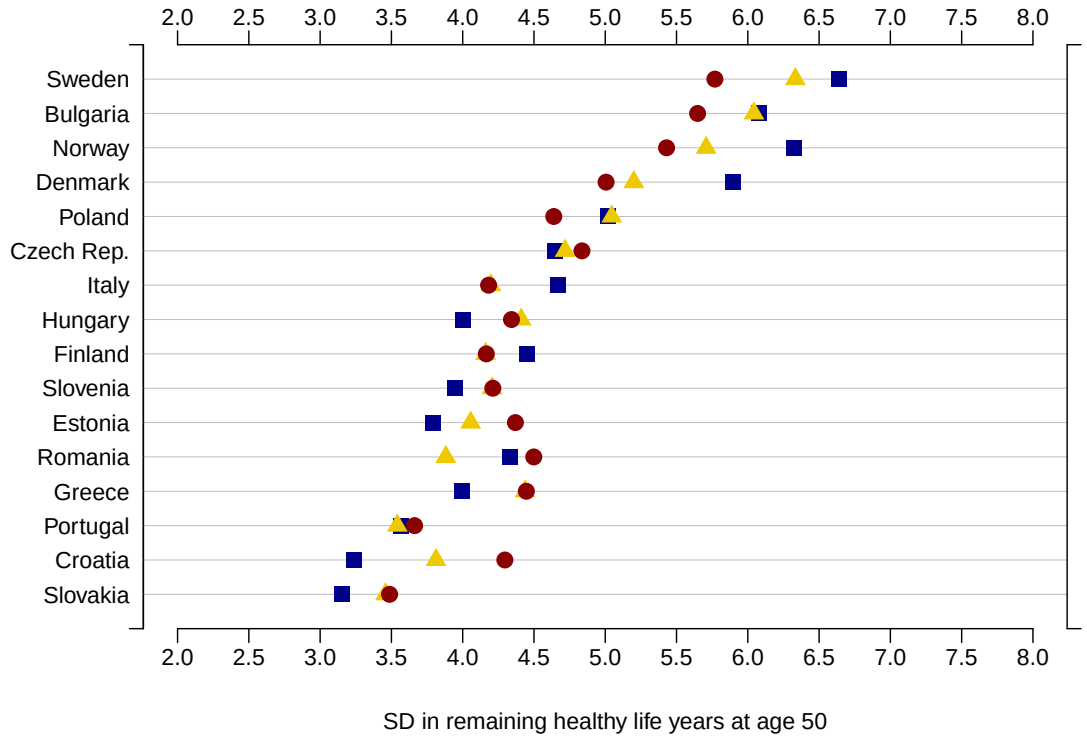
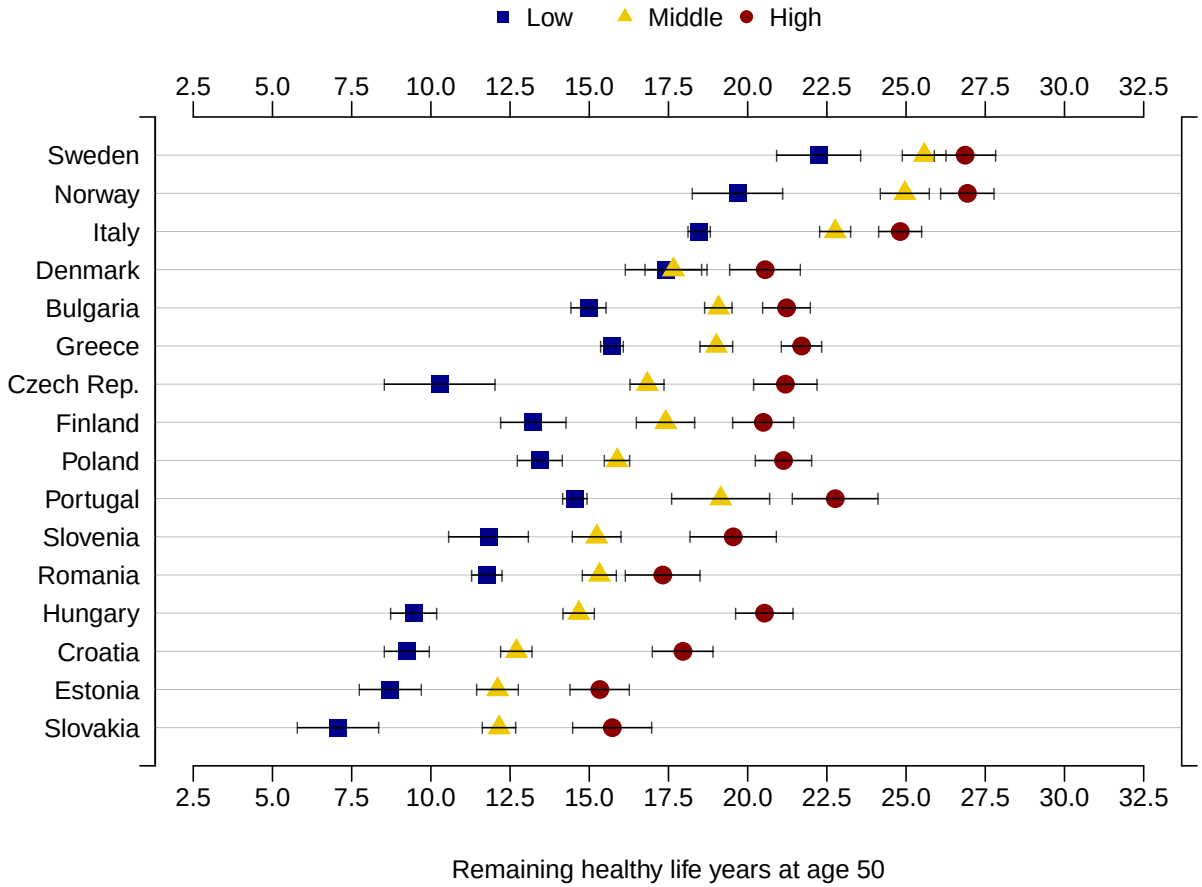


Figure 2: HLY50 for 16 European countries in 2016 separated by educational attainment, males



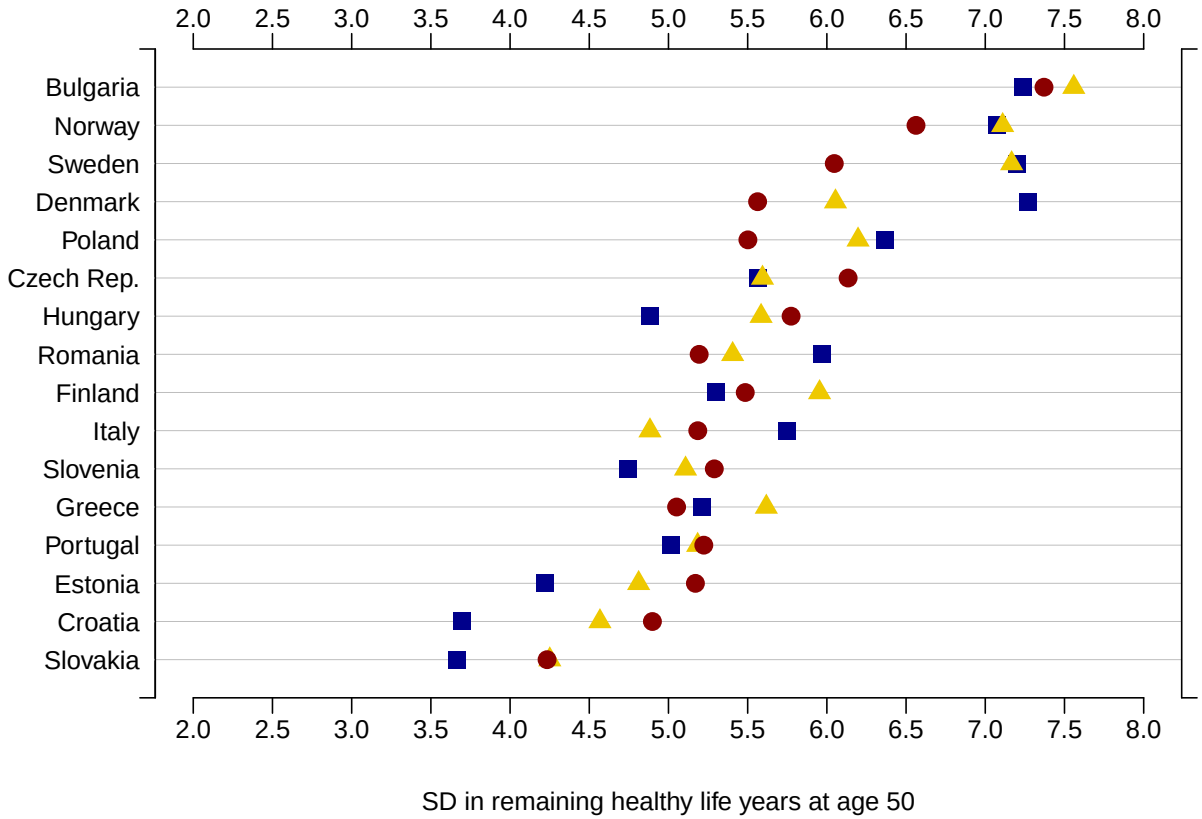


Figure 3: Gender gap in HLY50 for 16 European countries in 2016 separated by educational attainment

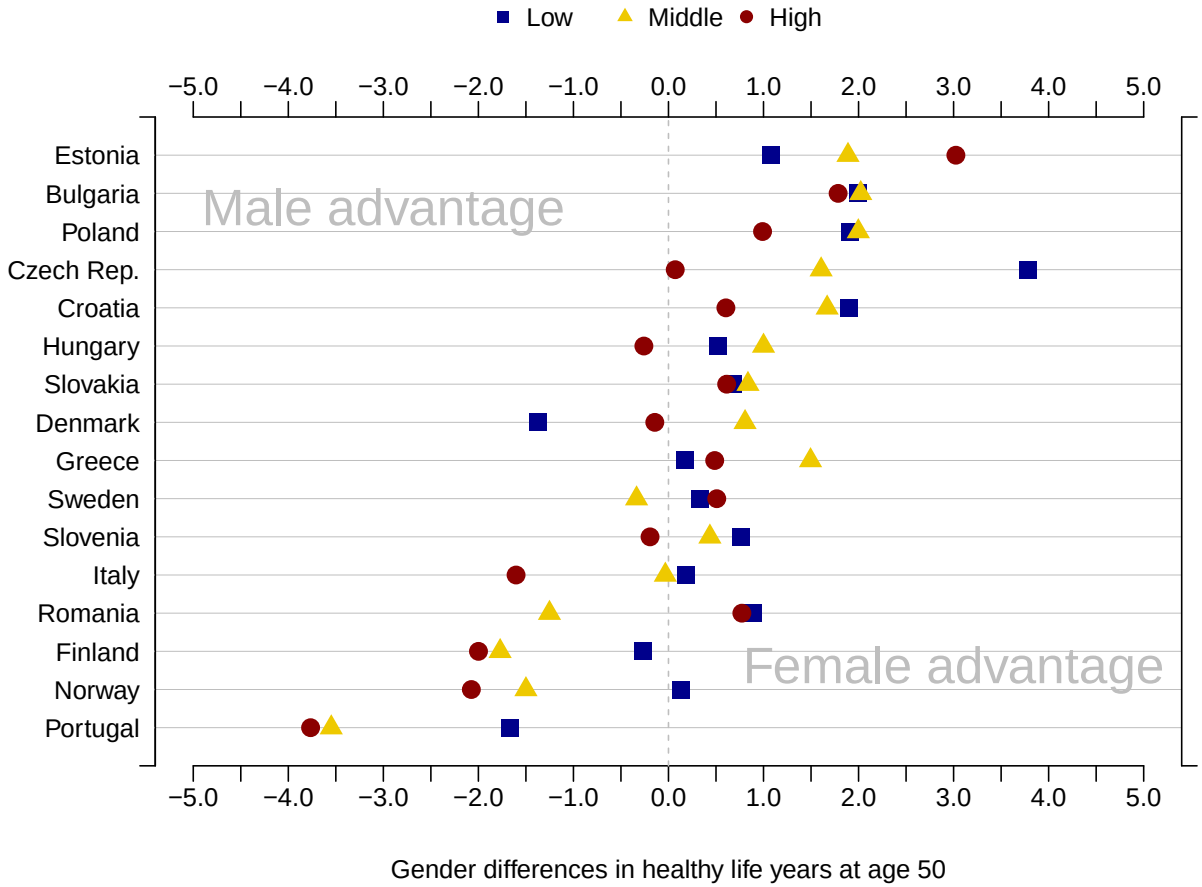


Table 1: Healthy Life Years at age 50 by educational attainment based on the Sullivan method

		Healthy Life Years at age 50 (Sullivan Method)			
Country		Low (CI)	Middle (CI)	High (CI)	Total (CI)
Bulgaria	Females	16.98 (16.32 - 17.64)	21.11 (20.60 - 21.61)	23.01 (22.28 - 23.74)	20.33 (19.99 - 20.66)
	Males	14.98 (14.43 - 15.54)	19.08 (18.65 - 19.51)	21.23 (20.47 - 21.98)	18.22 (17.92 - 18.52)
Czech Rep.	Females	14.07 (12.89 - 15.25)	18.44 (17.93 - 18.95)	21.26 (20.05 - 22.47)	18.06 (17.63 - 18.49)
	Males	10.28 (8.54 - 12.03)	16.83 (16.30 - 17.37)	21.19 (20.19 - 22.19)	17.06 (16.60 - 17.53)
Denmark	Females	16.06 (14.80 - 17.33)	18.46 (17.45 - 19.48)	20.41 (19.27 - 21.55)	18.47 (17.85 - 19.09)
	Males	17.43 (16.14 - 18.72)	17.66 (16.76 - 18.55)	20.55 (19.44 - 21.67)	18.34 (17.74 - 18.94)
Estonia	Females	9.80 (8.49 - 11.12)	14.00 (13.26 - 14.73)	18.36 (17.53 - 19.19)	15.18 (14.70 - 15.66)
	Males	8.72 (7.75 - 9.70)	12.11 (11.45 - 12.76)	15.33 (14.40 - 16.27)	12.48 (12.03 - 12.93)
Finland	Females	12.97 (11.53 - 14.42)	15.64 (14.64 - 16.65)	18.49 (17.40 - 19.59)	16.13 (15.57 - 16.70)
	Males	13.24 (12.21 - 14.27)	17.42 (16.50 - 18.34)	20.49 (19.53 - 21.45)	16.94 (16.43 - 17.46)
Greece	Females	15.89 (15.54 - 16.24)	20.51 (19.87 - 21.14)	22.19 (21.23 - 23.15)	17.69 (17.43 - 17.96)
	Males	15.72 (15.37 - 16.08)	19.01 (18.50 - 19.53)	21.70 (21.07 - 22.34)	17.62 (17.37 - 17.87)
Croatia	Females	11.14 (10.55 - 11.72)	14.37 (13.73 - 15.01)	18.56 (17.39 - 19.73)	13.35 (12.98 - 13.73)
	Males	9.24 (8.53 - 9.95)	12.70 (12.21 - 13.19)	17.96 (17.00 - 18.91)	12.55 (12.17 - 12.92)
Italy	Females	18.66 (18.31 - 19.00)	22.73 (22.18 - 23.28)	23.21 (22.24 - 24.18)	20.04 (19.78 - 20.30)
	Males	18.48 (18.13 - 18.82)	22.76 (22.28 - 23.25)	24.82 (24.14 - 25.50)	20.37 (20.12 - 20.63)
Hungary	Females	9.99 (9.34 - 10.64)	15.67 (15.12 - 16.22)	20.27 (19.30 - 21.24)	14.72 (14.35 - 15.09)
	Males	9.46 (8.74 - 10.19)	14.67 (14.18 - 15.16)	20.53 (19.62 - 21.44)	14.42 (14.06 - 14.79)
Norway	Females	19.82 (18.33 - 21.30)	23.46 (22.49 - 24.44)	24.86 (23.56 - 26.17)	22.81 (22.15 - 23.47)
	Males	19.68 (18.25 - 21.11)	24.96 (24.19 - 25.74)	26.94 (26.09 - 27.78)	24.10 (23.54 - 24.65)
Poland	Females	15.36 (14.64 - 16.08)	17.88 (17.43 - 18.33)	22.12 (21.19 - 23.05)	17.83 (17.51 - 18.15)
	Males	13.45 (12.74 - 14.15)	15.88 (15.48 - 16.28)	21.13 (20.24 - 22.02)	16.00 (15.68 - 16.31)
Portugal	Females	12.88 (12.49 - 13.27)	15.60 (13.83 - 17.37)	19.00 (17.64 - 20.37)	13.80 (13.44 - 14.15)
	Males	14.55 (14.16 - 14.93)	19.15 (17.60 - 20.70)	22.77 (21.41 - 24.12)	15.69 (15.34 - 16.05)
Romania	Females	12.67 (12.14 - 13.20)	14.07 (13.32 - 14.82)	18.09 (16.50 - 19.69)	13.73 (13.34 - 14.12)
	Males	11.77 (11.29 - 12.25)	15.32 (14.79 - 15.86)	17.32 (16.14 - 18.50)	14.45 (14.10 - 14.79)
Slovenia	Females	12.58 (11.51 - 13.66)	15.67 (14.76 - 16.58)	19.35 (17.83 - 20.87)	15.31 (14.70 - 15.91)
	Males	11.82 (10.56 - 13.08)	15.24 (14.47 - 16.01)	19.54 (18.19 - 20.90)	15.44 (14.85 - 16.03)
Slovakia	Females	7.75 (6.70 - 8.80)	12.99 (12.45 - 13.53)	16.34 (15.02 - 17.66)	12.44 (12.02 - 12.87)
	Males	7.07 (5.79 - 8.36)	12.16 (11.63 - 12.68)	15.73 (14.48 - 16.98)	12.18 (11.74 - 12.62)
Sweden	Females	22.58 (21.15 - 24.02)	25.24 (24.27 - 26.22)	27.37 (26.38 - 28.37)	24.86 (24.26 - 25.46)
	Males	22.25 (20.92 - 23.57)	25.58 (24.88 - 26.27)	26.87 (25.90 - 27.83)	24.84 (24.32 - 25.36)

Table 2: Healthy Life Years at age 50 by educational attainment based on the Caswell & Zarulli Method

		Healthy Life Years at age 50 (Caswell & Zarulli Method)			
Country		Low (SD)	Middle (SD)	High (SD)	Total (SD)
Bulgaria	Females	16.92 (6.08)	21.10 (6.04)	23.04 (5.65)	20.30 (5.87)
	Males	14.76 (7.24)	18.92 (7.56)	21.10 (7.37)	18.05 (7.35)
Czech Rep.	Females	14.06 (4.65)	18.45 (4.72)	21.30 (4.84)	18.07 (4.66)
	Males	10.11 (5.56)	16.76 (5.59)	21.11 (6.13)	16.98 (5.72)
Denmark	Females	16.22 (5.89)	18.58 (5.20)	20.55 (5.01)	18.62 (5.38)
	Males	17.43 (7.27)	17.73 (6.05)	20.65 (5.56)	18.39 (6.28)
Estonia	Females	9.81 (3.79)	14.02 (4.06)	18.44 (4.37)	15.21 (4.09)
	Males	8.61 (4.22)	12.01 (4.81)	15.23 (5.17)	12.38 (4.75)
Finland	Females	13.02 (4.45)	15.71 (4.16)	18.62 (4.17)	16.20 (4.17)
	Males	13.19 (5.30)	17.44 (5.95)	20.57 (5.48)	16.93 (5.55)
Greece	Females	15.92 (4.00)	20.63 (4.44)	22.30 (4.45)	17.73 (4.02)
	Males	15.65 (5.21)	19.03 (5.62)	21.78 (5.05)	17.58 (5.19)
Croatia	Females	11.13 (3.24)	14.39 (3.81)	18.59 (4.30)	13.34 (3.49)
	Males	9.18 (3.70)	12.63 (4.57)	17.92 (4.90)	12.48 (4.41)
Italy	Females	18.72 (4.67)	22.91 (4.20)	23.39 (4.18)	20.12 (4.38)
	Males	18.47 (5.75)	22.84 (4.88)	24.90 (5.18)	20.39 (5.43)
Hungary	Females	9.95 (4.00)	15.65 (4.41)	20.26 (4.34)	14.69 (4.36)
	Males	9.28 (4.88)	14.57 (5.58)	20.43 (5.77)	14.29 (5.69)
Norway	Females	19.96 (6.32)	23.67 (5.71)	25.20 (5.43)	23.01 (5.82)
	Males	19.73 (7.07)	25.11 (7.11)	27.10 (6.56)	24.21 (6.99)
Poland	Females	15.37 (5.02)	17.93 (5.05)	22.25 (4.64)	17.87 (4.84)
	Males	13.30 (6.37)	15.78 (6.20)	21.08 (5.50)	15.89 (6.11)
Portugal	Females	12.92 (3.56)	15.56 (3.54)	19.09 (3.66)	13.85 (3.57)
	Males	14.50 (5.02)	19.19 (5.18)	22.96 (5.22)	15.66 (5.05)
Romania	Females	12.63 (4.33)	14.05 (3.88)	18.06 (4.50)	13.70 (4.06)
	Males	11.59 (5.97)	15.20 (5.41)	17.21 (5.19)	14.31 (5.55)
Slovenia	Females	12.63 (3.95)	15.75 (4.21)	19.53 (4.21)	15.38 (4.13)
	Males	11.79 (4.74)	15.23 (5.11)	19.63 (5.29)	15.43 (5.28)
Slovakia	Females	7.72 (3.16)	12.96 (3.46)	16.34 (3.49)	12.42 (3.39)
	Males	6.95 (3.66)	12.08 (4.25)	15.70 (4.23)	12.10 (4.31)
Sweden	Females	22.79 (6.64)	25.52 (6.33)	27.71 (5.77)	25.10 (6.13)
	Males	22.28 (7.20)	25.69 (7.17)	26.97 (6.05)	24.93 (6.92)

The Caswell and Zarulli Method

In the Caswell and Zarulli (2018) model, the life course of individuals is defined as an absorbing Markov chain process (death is irreversible and therefore, an absorbing state). The following will describe this approach based on previous work by Caswell (e.g., Caswell 2018). The absorbing Markov chain process is deterimined by the transition matrix $\mathbf{P}$, which is constructed as:

$$\mathbf{P} = \left(\begin{array}{c|c} \mathbf{U} & \mathbf{0} \\ \hline \mathbf{m} & \mathbf{1} \end{array}\right) \text{of dimension} \left(\begin{array}{c|c} s \times s & s \times 1 \\ \hline 1 \times s & 1 \times 1 \end{array}\right) \tag{3}$$

where the matrix $\mathbf{U}$ refers to the transitions probabilities between the states. In this model, states are defined as age classes and transitions are reflected by the probability of surviving from one age class to the next. Thus, $\mathbf{U}$ contains p_x on the sub-diagonal and zeros elsewhere. The row vector $\mathbf{m}$ consist of the age-specific probability of death (q_x), i.e., the complement of the probability of surviving which is given by $q_x = 1 - p_x$. The right-hand side of $\mathbf{P}$ refers to the absorbing state "death". This state will eventually reached by all individuals (with the probability of 1) and transitioning back from it is impossible. As a result, $\mathbf{P}$ will be a $s + 1$ dimensional transition matrix if there are s stages (or age classes). The goal is to calculate the fundamental matrix $\mathbf{N}$. This matrix indicates how much time (e.g., years) individuals are expected to stay in each state and allows calculating the statistics of overall longevity.

$$\mathbf{N} = (\mathbf{I} - \mathbf{U})^{-1} \tag{4}$$

with $\mathbf{I}$ being the identity matrix. In the next step, the age-specific health information will be included in order to distinguish between overall longevity and healthy longevity. This is done by extending the Markov chain model to a Markov chain model with "rewards" (Caswell and Zarulli 2018). As an individual moves through its life course, it collects a "reward" at each transition as long as it lives. In this paper, a "reward" is defined as the age-specific prevalence of being in the healthy state. The reward matrix $\mathbf{R}$ has the same dimensions as the transition matrix $\mathbf{P}$, but refers to the "reward" associated with each transition:

$$\mathbf{R} = \left(\begin{array}{c|c} \mathbf{H} & \mathbf{0} \\ \hline \mathbf{v} & \mathbf{0} \end{array}\right) \text{of dimension} \left(\begin{array}{c|c} s \times s & s \times 1 \\ \hline 1 \times s & 1 \times 1 \end{array}\right) \tag{5}$$

where the matrix $\mathbf{H}$ contains the age-specific prevalence of being healthy (π_x) on the sub-diagonal. The row vector $\mathbf{v}$ quantifies the "reward" for individuals who transition from a given state (or age class) into the absorbing state. Caswell and Zarulli (2018) suggest assuming that these individuals experience half a year of the "reward", i.e., one-half of the age-specific prevalence of being healthy ($\mathbf{v}_j = \pi_x/2$). Further, they assume that no "rewards" are collected in the absorbing state, which turns the final column of $\mathbf{R}$ into zeros. Accordingly, healthy life can only be accumulated in the living states (i.e., transient states) $1, \ldots, s$. The truncation matrix $\mathbf{Z}$ takes this into account by restricting the

accumulation of healthy life exclusively to the transient states.

$$\mathbf{Z} = (\mathbf{I}_{s\times s}|\mathbf{0}_{s\times 1}) \tag{6}$$

with $\mathbf{I}$ being the identity matrix and $\mathbf{0}$ a column vector of zeros. As shown by Caswell and Zarulli (2018) the moments of remaining lifetime rewards, for individuals starting in any of the transient states, are then given by the entries of the moment vectors $\tilde{\rho}_i$:

$$\tilde{\rho_1} = \mathbf{N}^{\mathrm{T}}\mathbf{Z}(\mathbf{P}\circ\mathbf{R})^{\mathrm{T}}\mathbf{1}_s \tag{7}$$

$$\tilde{\rho_2} = \mathbf{N}^{\mathrm{T}}[\mathbf{Z}(\mathbf{P}\circ\mathbf{R})^{\mathrm{T}}\mathbf{1}_s + 2(\mathbf{U}\circ\mathbf{H})^{\mathrm{T}}\tilde{\rho_1}] \tag{8}$$

with 1_s being a vector of ones with length s. The first moment vector $\tilde{\rho_1}$ contains the age-specific means of remaining life years in good health, i.e., the expectancies of healthy life years at age x. Thus, $\mathrm{HLY}(x) \coloneqq \tilde{\rho_1}$. The variance (V) and standard deviation (SD) of remaining life years in good health are derived from the moment vectors as:

$$V(\tilde{\rho}) = \tilde{\rho_2} - \tilde{\rho_1}\circ\tilde{\rho_1} \tag{9}$$

$$SD(\tilde{\rho}) = \sqrt{V(\tilde{\rho})} \tag{10}$$

The Sullivan method

The Sullivan method (Sullivan 1971) is based on the classic period life table ßmodel. The age-specific person-years lived (L_x) are derived from applying age-specific survival probabilities to an hypothetical life table population (see Preston, Heuveline, and Guillot 2001, for more details). Then, the estimates of L_x are divided into healthy person-years lived and unhealthy person-years lived by using the age-specific prevalence of being in the unhealthy state (π_x). Summing only the healthy L_x and dividing them by the life table survivors in the same age interval (l_x) yields HLY at age x.

$$HLY_x = \frac{1}{l_x}\sum_{i=x}^{\omega}(1 -_n \pi_x)_n L_x \tag{11}$$

According to Jagger, E., and Brouard (2001), the standard error of the age-specific prevalence ($SE(\pi_x)$) can approximated by:

$$SE({}_n\pi_x) = \sqrt{\frac{\pi_x(1 -{}_n\pi_x)}{{}_nN_x}} \tag{12}$$

with ${}_nN_x$ being the number of persons in the age interval x to $x+n$. Since the uncertainty in the HLY estimates will come from the prevalence data (uncertainty from the mortality data is negligible), the standed error of HLY can be estimated as:

$$SE(HLY_x) = \sqrt{\frac{1}{l_x^2}\sum_{x=0}^{\omega}{}_nL_x^2 SE({}_n\pi_x)^2} \tag{13}$$

Thus, 95% confidence intervals for HLY based on the Sullivan method are approximated from:

$$CI(HLY_x) = HLY_x \pm 1.96 \cdot SE(HLY_x) \tag{14}$$