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Veröffentlichungsversion / Published Version
Zeitschriftenartikel / journal article

Empfohlene Zitierung / Suggested Citation:
Di Lego, V., & Sauerberg, M. (2023). The Sensitivity of the Healthy Life Years Indicator: Approaches for Dealing with Age-Specific Prevalence Data. *Comparative Population Studies - Zeitschrift für Bevölkerungswissenschaft*, *48*, 117-150. https://doi.org/10.12765/CPoS-2023-06

Comparative Population Studies
Vol. 48 (2023): 117-150 (Date of release: 06.04.2023)

The Sensitivity of the Healthy Life Years Indicator: Approaches for Dealing with Age-Specific Prevalence Data*

Vanessa di Lego, Markus Sauerberg

Abstract: The Healthy Life Years (HLY) indicator is the official European Union indicator and a cornerstone of many health policies used in over 15 countries in the EU region to set national health plans and monitor targets. It is also used to investigate trends over time in the proportion of total life years spent in good or poor health, socioeconomic inequalities in health and mortality and the male-female health survival paradox. Based on the Global Activity Limitation Indicator (GALI) included in the European Union Statistics on Income and Living Conditions (EU-SILC), a great amount of effort has been directed at harmonising and making HLY comparable across countries. Nonetheless, the characteristics of the age-specific prevalence distribution are still rarely accounted for, regardless of the fact that patterns of prevalence often fluctuate considerably by age. In addition, the impact of assumptions used at very young ages on HLY estimates are seldom discussed, despite the fact that the majority of policies and initiatives at the EU level use HLY at birth, while data on health is only available after age 16. In this paper, we assess whether smoothing the age-specific prevalence distributions by different methods, extrapolating to older ages and changing assumptions at younger ages affect HLY estimates. Overall, assumptions made before age 15 are the most important and affect women and men differently, thus affecting HLY at birth for some countries. Estimates at age 65 are very slightly impacted. Generalised linear models (GAMs) seem promising for harmonising and extrapolating to older ages, while using polynomials or aggregating into 5-year age groups seem best for younger ages. As most EU policies use HLY at birth and by sex for developing and monitoring health policies, caution is needed when estimating HLY at birth.

Keywords: Healthy Life Years · Sensitivity · Age-Specific Prevalence · Life Table · Sullivan Method · GALI · Smoothing · Gender differences

* This article belongs to a special issue on "Levels and Trends of Health Expectancy: Understanding its Measurement and Estimation Sensitivity".

** This article has an Online Appendix with supplementary material URL: http://www.comparativepopulationstudies.de/index.php/CPoS/article/view/476/374.

URL: www.comparativepopulationstudies.de
DOI: https://doi.org/10.12765/CPoS-2023-06
URN: urn:nbn:de:bib-cpos-2023-06en7

1 Introduction

The Healthy Life Years (HLY) indicator is one of the most important indicators for monitoring population health, developing policies and addressing different research questions. It is the official European Union indicator for developing strategies for national health plans and monitoring health policy targets such as the 2000 Lisbon Strategy and the European Innovation Partnership on Active and Healthy Ageing to increase the average HLY of Europeans by two years by 2020 (*Robine et al.* 2013; *Bogaert et al.* 2018; *Eurostat* 2020). It has also been used to investigate important research questions, such as trends over time in the proportion of total life years spent in good or poor health (the "compression-expansion debate"), socioeconomic inequalities in health and mortality, compositional effects of education on health indicators across regions and the male-female health survival paradox (*Murray et al*. 2002; *Bocquet-Appel* 2008; *Ekholm/Brønnum-Hansen* 2009; *Nusselder et al.* 2010, 2019; *Van Oyen et al*. 2013; *Jagger et al.* 2013; *Füssenich et al.* 2019; *di Lego et al.* 2020; *Welsh et al.* 2021; *Sauerberg* 2021).

The HLY is a disability-free life expectancy (DFLE) indicator based on the Global Activity Limitation Indicator (GALI) included in the European Union Statistics on Income and Living Conditions (EU-SILC) (*Robine et al.* 2003). It combines mortality information from period Eurostat life tables with the disability prevalence data obtained from EU-SILC (*Saito et al.* 2014). Even though several other methods are available for estimating health expectancy indicators for different contexts and health data (*Robine/Mathers* 1993; *Lynch/Brown* 2005, 2010; *McCallum/Mathers* 2008; *Crimmins et al.* 2009; *Nepomuceno/Turra* 2015), the approach developed by Sullivan is the most employed up until now (*Sullivan* 1971; *Mathers et al*. 2001; *Saito et al.* 2014). This is mainly due to its parsimonious approach and requirement for age-specific prevalence data that are readily available from cross-sectional surveys (*Robine/Jagger* 2003; *Yokota et al.* 2019). In addition, the Sullivan method and the GALI instrument have been extensively tested for consistency and comparability across European countries (*Robine/Jagger* 2003; *Van Oyen et al.* 2006; *Berger et al.* 2015), with a wide range of sensitivity analyses performed to attest its harmonised features (*Cox et al.* 2009; *Jagger et al*. 2010; *Rubio-Valverde et al.* 2019).

However, the sensitivity of the age pattern of disability in the context of the HLY has been less explored. The distribution of age-specific prevalence is very uneven, with a profile that often fluctuates across ages and with alternating last-age intervals. Since information on disability is usually derived from population surveys, health information is limited to specific ages and subject to specific survey characteristics, such as individual responsiveness, sample design and reporting behaviour (*Jürges* 2007; *Peracchi/Rossetti* 2012; *Hardy et al.* 2014; *Cigolle et al.* 2018; *Spitzer/Weber* 2019). Hence, the age pattern may also be sensitive to particular technical features that directly affect age-specific prevalence estimates, which in turn can impact the HLY indicator. For instance, despite many health policies in the EU region using HLY at birth as the main indicator, the EU-SILC survey includes only people above age 16. In addition, the last open age interval available for most countries is 80+, with some countries not only having different last age intervals available, but also experiencing changes over time, like Germany, which starting from 2015 only has data available for ages 74+ (*GESIS* 2022). Therefore, assumptions for very young and old persons are required. The conventional approach used by Eurostat for the official estimates assumes that the prevalence of being unhealthy for individuals younger than age 15 is half of the prevalence of the 16-19 age group (*Eurostat* 2020; *Welsh et al*. 2021). Further, a common strategy to deal with the erratic behaviour of age-specific prevalence is to aggregate data into 5-year age groups prior to combining it with abridged life tables, which is the current procedure adopted by Eurostat. In this case, it assumes a constant proportion of unhealthy individuals in each age group as a means to deal with single-age inconsistencies. Although a number of issues related to the sensitivity of health expectancy indicators have been addressed and discussed (*Crimmins et al.* 1994; *Robine et al.* 2001; *Mathers* 2002), the majority of the effort has been directed at evaluating the role of the GALI instrument, harmonisation issues and comparability across countries (*Van Oyen et al.* 2006; *Berger et al.* 2015). Nonetheless, the characteristics of the age-specific prevalence distribution is not as often considered when empirically analysing levels and trends of health expectancy and their role when interpreting the results. In part, this is due to the fact that age-specific prevalence is usually combined with mortality data in order to derive health expectancy indicators, so little attention is given to the age pattern of prevalence prior to combining it with mortality.

In this paper, we assess whether adopting different age-specific prevalence distributions and changing the most commonly used assumptions prior to combining the health information with the mortality data may affect HLY estimates. First, instead of simply aggregating age-specific prevalence into 5-year age groups, we evaluate whether smoothing the age prevalence distribution of disability by different methods as measured by the GALI instrument has any implication on the posterior HLY estimates. Second, as HLY is estimated using survey data that only has health information available after the age of 16, we test whether changing assumptions of the prevalence proportions before that age affects the distributions, as well as computing prevalence by single age intervals. Third, as the last age interval available from health surveys varies and is limited to either age 80+ or 74+, we extrapolate the maximum observed age to 100+ using a generalised additive model (GAM), in order to test whether extrapolating the age profile has any impact on the HLY estimates and whether this is a viable strategy for computing HLY at older ages. We then compute HLY at birth and at age 65 for all smoothing and extrapolation methods using period life tables from Eurostat. Estimates are for the year 2017 and for all the EU-28 countries (in this year it includes United Kingdom as part of the EU member states), as well as Switzerland, Norway and Iceland as non-members. We finally estimate the proportion of total life expectancy spent in healthy life years for each method and discuss implications of these results when estimating HLY. By further exploring the sensitivity of the HLY indicator with regard to the characteristics of age-specific prevalence, we seek to address the extent to which differences in health status across European countries are vulnerable to these technical features. The standard practice of combining age-specific prevalence proportions with person-years lived without proper attention to the distribution profile of the former may affect the estimation of healthy life years. Overall, differences are small, but oftentimes they are not trivial and vary by smoothing method, country, sex and age. This suggests that it is important to be more cautious with the age distribution of health prevalence prior to combining it with mortality data, especially when the indicator of interest is estimated at birth. Further research is needed to understand what the optimal strategy would be to deal with the age-specific prevalence and this will more likely depend on the data available and the purpose in using the indicator. However, according to the results of the sensitivity analyses presented in this paper, we suggest a routine practice as regards estimating the HLY, as summarised in the flowchart in Figure 9, which includes first and foremost considering whether HLY is to be estimated at birth or age 65. Second, plot the age-specific disability prevalence and evaluate its pattern, as well as whether aggregating into 5-year age groups already smooths the pattern. GAMs adjust well at ages 65 and older and their impact on HLY is very small, but they can impact HLY at birth. In this case, either just estimating HLY based on the usual aggregation by 5-year age groups or smoothing by a polynomial fit can be best. Most importantly, always test age profiles for women and men separately, as well as country-specific patterns. The most important recommendation is to consider the purpose of the indicator carefully beforehand and to assess its pattern by age before combining it with the person-years lived by age.

2 Data and methods

The observed prevalence of limitations in activities of daily living (ADLs) is obtained from the GALI. The exact wording of the GALI is: "For at least the past 6 months, to what extent have you been limited because of a health problem in activities people usually do? Would you say you have been (1) severely limited, (2) limited but not severely, or (3) not limited at all?". This is the official Eurostat indicator used to monitor health status, where individuals are defined as healthy if they report no limitations at all (*Jagger et al.* 2013; *Eurostat* 2020). The advantage of using the GALI instrument in order to estimate health expectancy is that it has been systematically assessed in order to ensure the highest level possible of harmonisation and comparability of health dimensions, age and time across European countries (*Van Oyen et al.* 2006; *Jagger et al.* 2010; *Berger et al.* 2016). We employ the most commonly used approach for estimating the HLY and also the one officially adopted by the European Union, which is the Sullivan method (*Imai/Soneji* 2007; *Saito et al.* 2014; *Sullivan* 1971). Sullivan applies the age-specific prevalence (proportions) of a population in an unhealthy state to the age-specific person-years lived from the life table. In this way, the total life years in each age interval can be partitioned into years spent in good and poor health. Before we combine the age-specific prevalence with the person-years lived using Eurostat life tables, we employ a series of smoothing techniques and extrapolations methods as shown in Table 1. We choose this set of smoothing techniques because they are flexible, demand few or no assumptions

Tab. 1: Smoothing techniques used on the age-specific prevalence of ADLs

Smoothing and Extrapolation methods	Specification	Optimal Value Criteria	Smoothing parameter
Smoothing spline	$RSS(f,\lambda) = \sum_{i=1}^{N}(y_i - f(x_i))^2 + \lambda\int[f''(t)]^2\,dt$	Generalised cross-validation (GCV)	No extra smoothing parameter, df used for the degree of smoothing
Spline with penalty	*penalised log likelihood is* $L = (y - f)'W(y - f) + \lambda c'\sum c$	Generalised cross-validation (GCV)	Spar added so the coefficient λ from the penalised log likelihood criterion is a monotone function of spar = 0.7
Polynomial	$y = \beta_0 + \beta_{1x} + \beta_{2x}^2 + \beta_{3x}^3 + \ldots + \beta_{nx}^n + \varepsilon.$	Fix the degree or usecross-validation to choose	Selected degree 4
GAM	$y \sim ExpoFam(\mu, \text{etc.})$ $E(y) = \mu$ $g(\mu) = b_0 + f(x_1) + f(x_2) + \ldots + f(x_p)$	Mixed model approach via restricted maximum likelihood (REML)	Binomial link to constrain the interval to [0,1] and k = -5

Note: For the Polynomial, see also the implementation and discussion at https://patrickaubert.github.io/healthexpectancies/index.html. The variables for all models are age, country and sex.

Source: *Gareth James, Daniela Witten, Trevor Hastie, Robert Tibshirani* 2021: An Introduction to Statistical Learning: with Applications in R. New York: Springer (*James et al.* 2021).

about the age distribution but at the same time have slightly different approaches and smoothing parameters allowing for different test setups.

The polynomial smoothing provides us with a single model for the data, while the splines approach gives us a piecewise continuous function composed of many polynomials to model age-specific prevalence (*Eilers/Marx* 1996; *Gu* 2014; *James et al.* 2021). The smoothing splines are set both with and without penalty and the polynomial fit is of fourth degree, as suggested by previous applications of this approach to age-specific health prevalence (*Aubert* 2021). Lastly, Generalised Linear Models (GAMs) were computed for each country and by sex in order to smooth and extrapolate the last age interval until 100+.[1] GAMs have the advantage that the shape of the predictor functions are fully determined by the data, allowing for a more flexible estimation while still capturing underlying patterns (*Rigby/Stasinopoulos* 2005; *Wood* 2006). We used the population size at each age as weights in the model to account for age structure and the binomial link to constrain the prevalence into the interval [0,1]. The estimates were performed using the *mgcv* package in R. In addition, three different assumptions regarding the age-specific prevalence below age 15 were tested: 1. The official EU assumption that the prevalence between ages 0-15 is half of the observed in the age group 16-19 (*Eurostat* 2020); 2. The prevalence between ages 0-15 is zero and so there is no observed disability below age 15; and 3. Smooth increase since birth for the cases where age-specific prevalence was extrapolated and smoothed using GAMs. These three alternative scenarios of disability at younger ages allow for evaluating the sensitivity of the HLY indicator when estimated at birth.

In order to choose the smoothing parameter that best fits the data, we used restricted maximum likelihood (REML) for the GAMs and generalised cross-validation (GCV) for the splines. Likewise, in order to compare the estimated outputs across all smoothing methods, we used the root mean square error (RMSE). The RMSE is defined as the square root of the mean of the square of all of the errors and it measures how far predicted values are from observed values or how concentrated the data is around the best fit (*Christie/Neill* 2022). Smaller RMSE score values indicate that the estimated curve is closer to the true curve and used as an indicator of best fit. We use this approach since we compare different methods and the RMSE is advised as a general purpose approach to assess error metrics when performing comparisons, including across different smoothing methods (*Malloy et al.* 2009; *Ben Ghoul et al.* 2019). For a more detailed explanation of the REML used for GAMs and the RMSE for comparing all approaches, refer to the Technical Note in the Appendix (scores for each method and all countries by sex, considering the official EU assumption that the prevalence between ages 0-15 is half of the observed in the age group 16-19 are presented in Table A7 in the Appendix).

1 We tested whether the same methods usually employed to extrapolate mortality would also work with health, in addition to using more flexible approaches. Several attempts to extrapolate the age pattern of disability using Kannisto-Makeham, Gamma-Gompertz and Gompertz mortality models were employed, but yielded unsound results as shown in Figures A6 and A7 in the Appendix.

Because the age-specific prevalence in disability in the EU-SILC survey is only available until 80+, we recalculated Eurostat life tables adopting a new open-ended age interval of 80+ for most countries – as the official life tables close at age 85+ – using the standard approach by *Preston et al.* (2001). One exception was Germany, where we close the life table at age 74+ (because for Germany the last age observed in the EU-SILC starting from 2015 is 74+). For the case of age-specific prevalence that we smoothed and extrapolated until age 100+ using GAMs, we also extrapolated the life tables until 100+ using the Makeham mortality law. After smoothing the estimated age-specific prevalence $\hat{\pi}_{i+ni}$ from the surveys and adjusting the open-end age interval from life tables accordingly, we combined the many different distributions with the person-years lived by age L_{i+ni} adjusted from the Eurostat life tables to estimate the disability-free life expectancy $\hat{e}_x^{DF}$, or in this case, the HLY, following the formulation by *Imai* and *Soneji* (2007):

$$\hat{e}_x^{DF} = \frac{1}{l_x} \sum_{\{i \in x\}} (1 - \hat{\pi}_{i+ni}) L_{i+ni} \tag{1}$$

Differences in our estimates and the official HLY may occur not only because we are computing the estimates for single ages, while Eurostat computes for 5-year age group intervals, but also because we are using life tables with different open-age limits. The health data Eurostat has available to estimate HLY may also be slightly different from the EU-SILC microdata we have access to. Nonetheless, the calculations are internally consistent with the method for each variant of smoothing and extrapolation we use, which allows for performing the comparisons across the scenarios we have built between smoothed/unsmoothed and extrapolated/non-extrapolated. As our goal in this paper is not to provide a direct comparison between our estimates and the official ones across countries, but to showcase the sensitivity of the indicator for different smoothing methods, we present the results for single ages, the case of highest fluctuation and sensitivity possible. Nonetheless, in the Appendix we have added the analysis with the 5-year age group intervals so that the reader can evaluate the consistency in our estimates, which are in this case very close or the same as the official estimates.

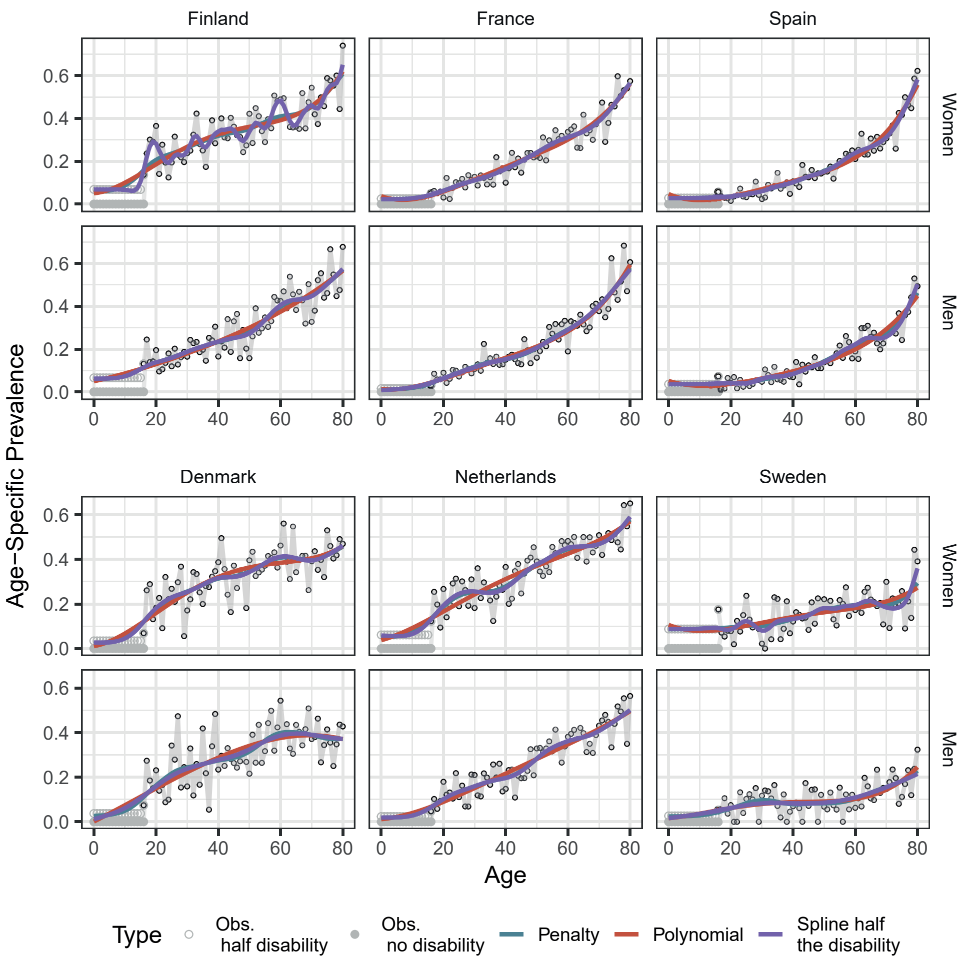
All results were computed for the year 2017 since that is the latest year for which we can compute the estimates including the most comprehensive set of the EU-28 Member States that included UK as well as Switzerland, Norway and Iceland as non-members, but before the COVID-19 pandemic, which can cause an additional layer of sensitivity that would be difficult to isolate. As our particular aim in this paper is to test the sensitivity of age-specific prevalence to various smoothing techniques, we believe that the specific choice of year is not of particular importance to test the sensitivity of the indicator itself.

3 Results

3.1 The Sensitivity of Age-specific Health Prevalence

The first set of results refers to the prevalence data by different smoothing and extrapolation methods. Across countries two overall major clusters of age-specific patterns of disability were identified: an exponential-like and a linear-like. We separated the results into selected countries to emphasise the two clusters of age patterns that were observed. One interesting exception is Germany, which falls in the middle of these two clusters. We will present its results separately. As presented in Figure 1, Spain, France and Finland have a more exponential-like pattern –

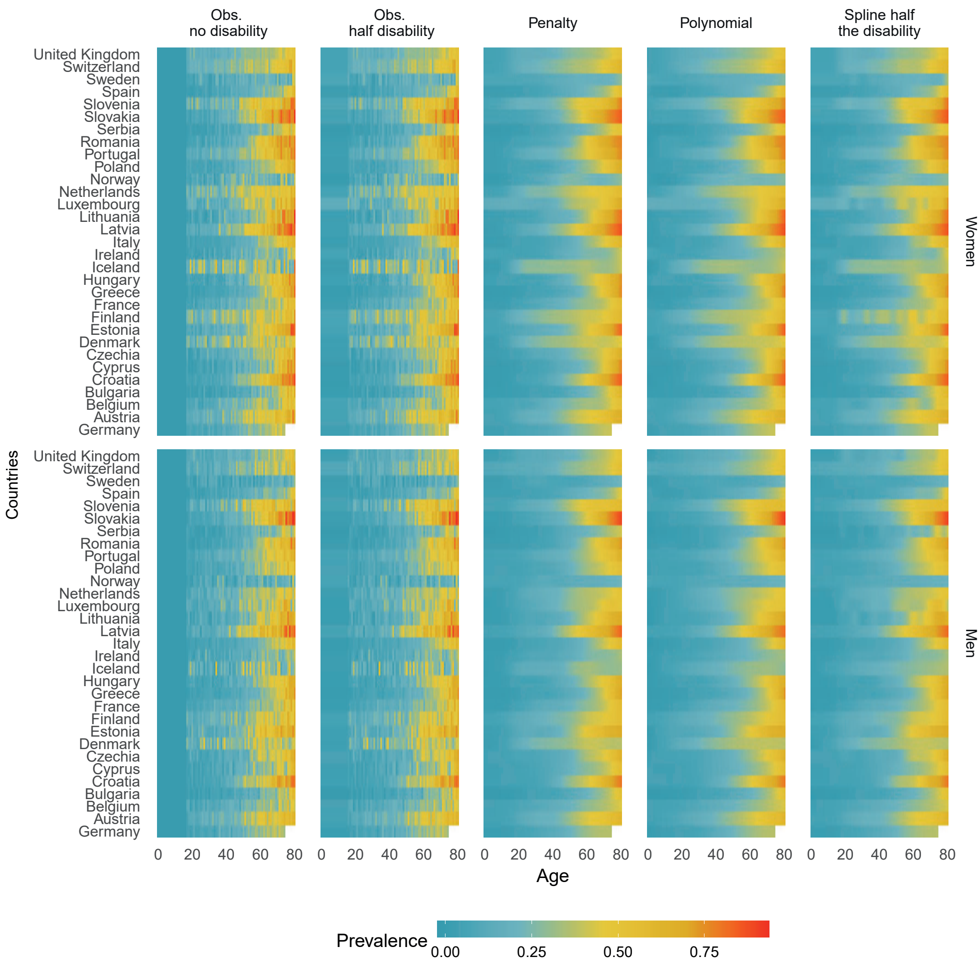
Fig. 1: Prevalence for women and men aged 0-80+, by different smoothing methods, year 2017, selected EU countries



Source: Own calculations using EU-SILC prevalence data based on the GALI instrument

especially Spain and France –, while Denmark, the Netherlands and Sweden have a linear pattern with remarkable stability over most ages for Sweden (overall, most countries fall within these two patterns by age. Refer to country-specific age patterns for all countries in Fig. A1 in the Appendix). For all countries and for both sexes, the polynomial fit is the smoothing that most evens out the distribution. In addition, for some countries, like Spain and France, the visual difference between the assumption of no disability below age 15 and half the disability is smaller for both sexes than in other countries, particularly women in Finland and the Netherlands. For Danish men, the age-specific pattern of prevalence shows signs of decline from

Fig. 2: Heatmap of age-specific prevalence for women and men, by different smoothing methods, year 2017, EU-28* countries and Switzerland, Norway and Iceland



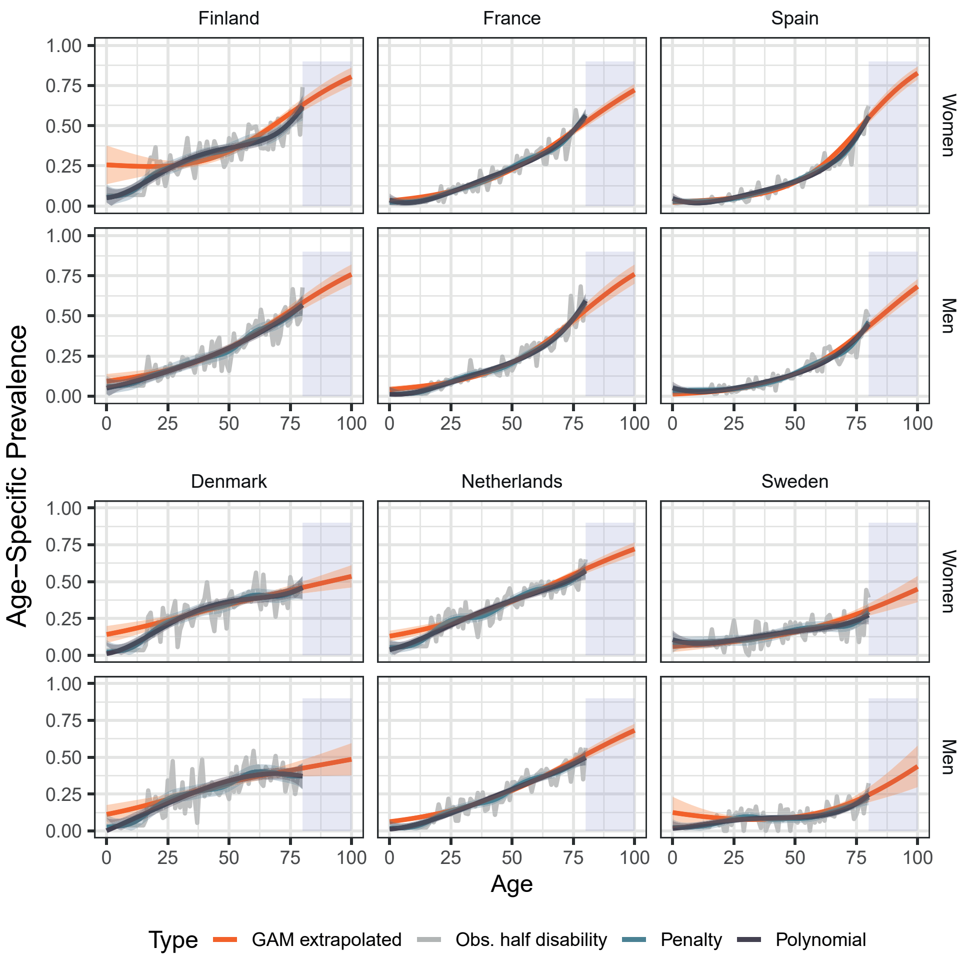
* Germany until 74+, EU-28 in 2017 still includes United Kingdom.

Source: Own calculations using EU-SILC prevalence data based on the GALI instrument

around age 65 on. It is difficult to infer from these patterns alone whether this shape is due to data or period artifacts, sample size, selectivity or a real effect (*Engberg et al*. 2008; *Lin et al.* 2012).

Figure 2 presents an overview for all EU-28 countries in 2017, together with Switzerland, Norway and Iceland. The heatmap shows the observed and smoothed age-specific prevalence, placing countries in perspective. It shows how the proportion of disability is higher among women for most countries and in some contexts at relatively younger ages (see Iceland, Netherlands, Finland and Denmark). In general, the smoothing methods perform well in retaining the original structure of observed data, with the exception of smoothing splines, which appear to be extremely flexible for some countries and most likely overfitting the data (see

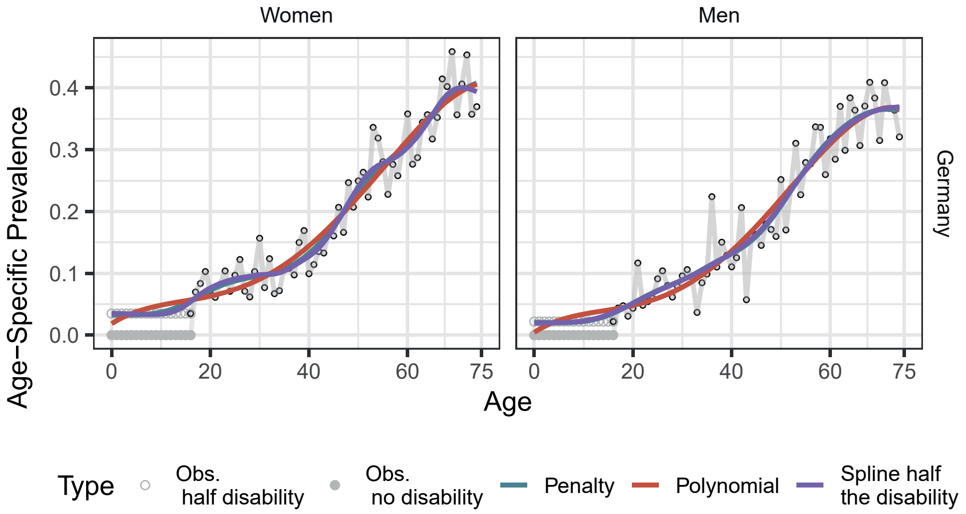
Fig. 3: Age-specific prevalence by sex smoothed by different methods and extrapolated to age 100+ by GAM, year 2017, selected EU countries



Source: Own calculations using EU-SILC prevalence data based on the GALI instrument

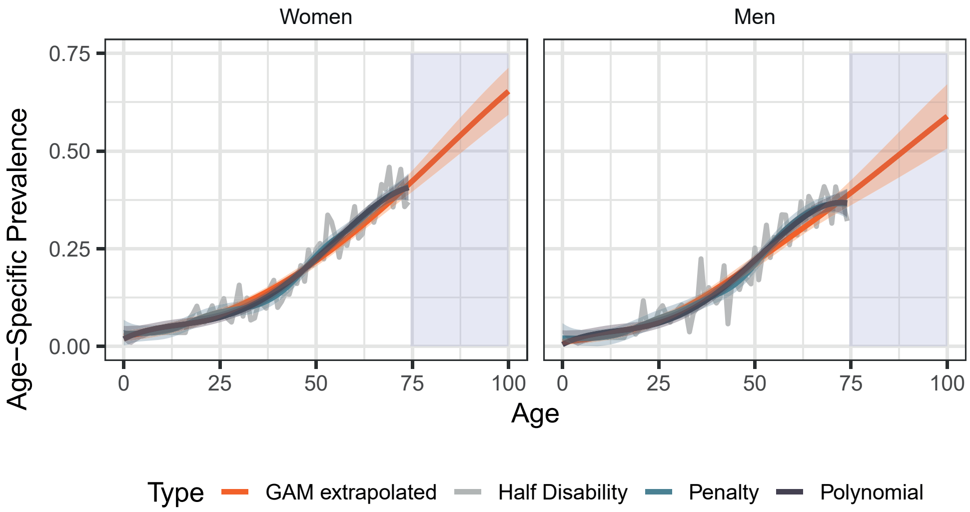
Luxembourg, women in Finland and men in Serbia). In Figure 3, we present the same set of countries but now extrapolating by fitting a GAM model and predicting until age 100 with the respective confidence intervals, as shown in the shaded area. We use the fit from the penalty spline and polynomial smoothing to predict age-specific values until age 80+.

Fig. 4: Prevalence for women and men aged 0-74+, by different smoothing methods, year 2017, Germany



Source: Own calculations using EU-SILC prevalence data based on the GALI instrument

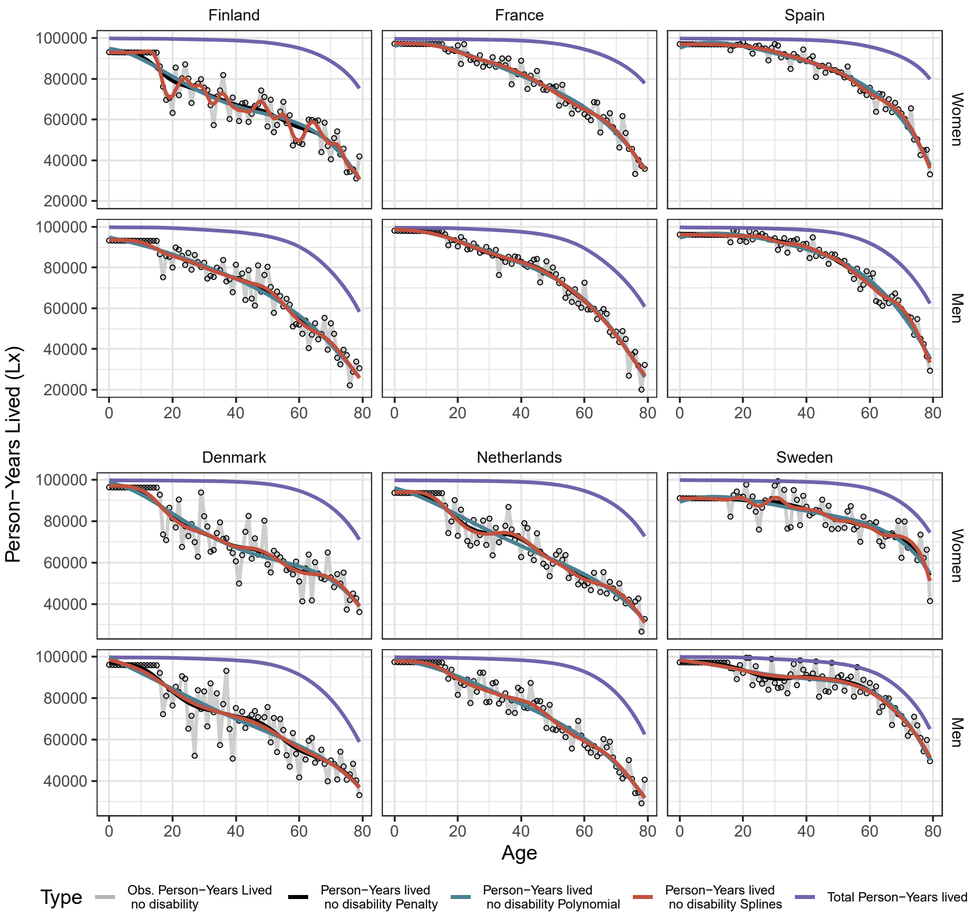
Fig. 5: Age-specific prevalence by sex smoothed by different methods and extrapolated to age 100+ by GAM, year 2017, Germany



Source: Own calculations using EU-SILC prevalence data based on the GALI instrument

Figure 3 presents these estimates in comparison with the official assumption used by the EU to estimate HLY, which considers that below age 15 the prevalence of disability is half of the observed in the age group 16-19. The model extrapolates reasonably well until age 100 and retains most of the pattern observed until age 80+. Denmark and Sweden have the most uncertainty with regard to the extrapolation after age 80 and before age 15 for men, as shown by the wider confidence intervals. The same is observed for Finnish women before age 15. Overall, similar to what was observed in Figure 1, countries for which smoothing the age pattern seem to show the largest differences are Finland (especially at younger ages for women), Denmark and Sweden.

Fig. 6: Total person-years lived and person-years lived without disability, by smoothing method and sex, selected EU countries age 80+, 2017



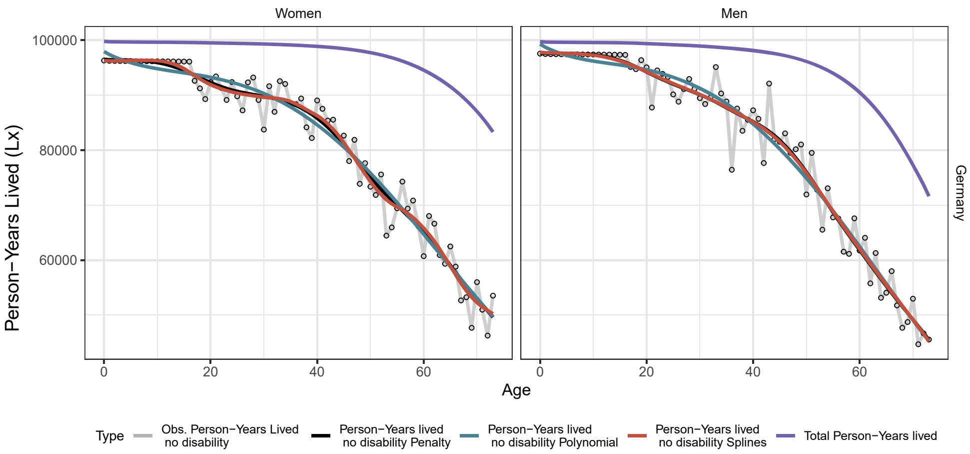
Source: Own calculations using EU-SILC prevalence data based on the GALI instrument; Eurostat

We present the case of Germany separately due to the particularity of its age pattern and the last observed age available in the EU-SILC change from year 2015. Before 2015, Germany had the last age available at 80+. However, from year 2015 on, the age changed to 74+ affecting not only the comparability with other countries where the available ages remain 80+, but also the comparability of Germany across the years. Interestingly, as Figure 4 shows, the age pattern for Germany is neither as linear-like as in Denmark, the Netherlands and Sweden nor as exponential-like as Spain, Finland and France, but follows an almost linear pattern until around age 40, when the prevalence of disability increases. Similar to the shape for Danish men, the prevalence starts to decline from around ages 70 on. As shown in Figure 5, a GAM fits well to German data. The extrapolation has higher uncertainty starting from age 80 on but it is still a good fit considering that no information is available and thus may be a good model to harmonise data at older ages.

After smoothing and extrapolating the age-specific prevalence, we compute the person-years lived without disability for the observed and smoothed age-specific prevalence, by multiplying the estimated age-specific prevalence subtracted from one (1-$\hat{\pi}_{i+ni}$) from the surveys with the total person-years lived by age L_{i+ni} retrieved from the Eurostat life tables for each country, following Equation 1. In Figure 6, we present the total person-years lived and person-years lived without disability, considering each smoothing method, until age 80+.

In terms of person-years lived without disability, the different smoothing methods yield almost the same profiles by age when compared to the observed values, represented by the grey line with dots. The exception is for Finnish women, where, as already previously noted in Figures 1-2, the smoothing splines are very flexible, overfitting the data, instead of providing a smoothed curve. Irrespective of smoothing methods, Figure 6 shows how the age pattern of person-years lived

Fig. 7: Total person-years lived and person-years lived without disability, by smoothing method and sex, Germany, age 74+, 2017



Source: Own calculations using EU-SILC prevalence data based on the GALI instrument; Eurostat

without disability is more compressed for Sweden and Spain for both sexes in 2017, as evidenced by the shorter distance between the curve of total person-years lived and person-years lived without disability. In addition, men present a more compressed profile than women across the majority of countries. For Denmark and the Netherlands, we observe an almost linear pattern in the decline of person-years lived without disability across age, with a steeper decline in the proportion of person-years lived without disability as age increases, when compared to other countries. For Germany, as shown in Figure 7, the age pattern of person-years lived without disability is also more compressed for men than women and the pattern of decline is less steep until age 40, when the decline is steeper and linear until age 74+.

3.2 The Sensitivity of Healthy Life Years (HLY)

We combine the estimated and smoothed age-specific prevalence as presented in section 3.1 with the person-years lived in order to compute the HLY indicator and evaluate whether there are any differences by smoothing technique. Total HLY and the proportion of total life expectancy (LE) spent in healthy life years (%HLY = HLY/LE) for selected countries by different smoothing technique and extrapolation by sex are presented in Tables 2-3, for age 0 (Table 2) and age 65 (Table 3), respectively. Overall, differences across smoothing methods are greater for HLY estimates at birth (Table 2) than at age 65 (Table 3). Furthermore, if one considers HLY estimated using half the disability as the benchmark for comparison, differences are greater for women than for men across methods for the majority of countries.

The proportion of total life expectancy in healthy state (%HLY) is barely affected for most smoothing approaches used, with the exception of GAMs, with varying magnitudes across countries. Again, using half the disability as the benchmark for comparison, GAMs underestimate both HLY at birth and at age 65 for all countries presented here. This most likely reflects the fact that we are extrapolating age-specific prevalence to ages above 100, so estimating a higher burden of prevalence in the population. For the splines penalty and polynomial fits the results are virtually the same, varying only in the second or third decimal.

As expected, for the HLY estimates at age 65 there are no differences between the no disability and half the disability assumption, as these assumptions do not affect estimates for HLY beyond age 0. In order to provide a clearer picture of the variation across methods, Table 4 summarises the absolute differences in values at age 0, where differences between no disability and half the disability (columns (1)-(2)) range from 1.2 years at birth for women in Finland to 0.5 in Spain and 1.2 years at birth for men in Finland to 0.6 for men in Spain (See Tables A1-A2 in the Appendix for the values for all countries available in EU-SILC for each smoothing technique and Tables A3 and A4 with the values with 95% confidence intervals). Not surprisingly, for the assumption of no disability below age 15 in the population, the HLY is larger when compared to the assumption that the population below age 15 experiences half of the observed disability of the age group 16-19 (columns (1)-(2)).

Tab. 2: Healthy Life Years (HLY) and %HLY of total life expectancy at birth, by different smoothing methods, extrapolation and sex, selected EU countries, 2017

Country	Assumptions and smoothing methods, HLY at age 0									
	No disability		Half the disability†		Splines penalty		Polynomial		GAM*	
	HLY	%HLY	HLY	%HLY	HLY	%HLY	HLY	%HLY	HLY	%HLY
	Women									
Denmark	60.4	72.7	59.8	72.0	59.9	72.0	59.9	72.0	57.4	69.1
Spain	70.3	81.6	69.8	81.0	70.3	81.6	70.3	81.6	68.8	79.9
Finland	57.8	68.4	56.6	67.0	57.5	68.0	57.4	68.0	53.4	63.2
France	66.7	77.8	66.2	77.3	66.3	77.4	66.3	77.4	65.6	76.5
Netherlands	58.0	69.6	56.9	68.3	57.4	68.8	57.4	68.9	55.2	66.2
Sweden	72.1	85.7	70.5	83.9	71.2	84.6	71.3	84.8	70.8	84.2
Germany**	68.1	81.6	67.5	80.9	67.1	80.4	67.1	80.4	66.2	79.4
	Men									
Denmark	59.7	75.4	59.1	74.6	59.3	74.8	59.3	74.9	57.1	72.1
Spain	69.3	86.0	68.6	85.2	68.8	85.3	68.9	85.4	68.5	85.0
Finland	59.0	74.8	57.8	73.3	58.3	73.9	58.3	73.9	57.0	72.2
France	63.8	80.1	63.5	79.8	63.6	79.9	63.6	79.9	62.8	78.9
Netherlands	62.1	77.4	61.6	76.9	61.9	77.2	61.9	77.2	60.4	75.3
Sweden	73.1	90.5	72.7	89.9	73.1	90.5	73.0	90.4	70.9	87.7
Germany**	66.1	83.9	65.7	83.5	65.3	83.0	65.3	83.0	64.8	82.4

Note: Small differences between the official EU HLY indicator may occur since Eurostat uses life tables that close at age 85+, while we recalculate the Eurostat life tables to close at either 80+ or 74+ by summing the person-years lived at each age and then computing the life table following the conventional procedure of *Preston et al.* (2001).

† Half the disability is the official EU assumption for ages below 16 and more closely reflects the official EU statistics. However, we are using age-specific prevalence and Eurostat life tables by single years of age, while the official estimates are from 5-year age groups, so differences may occur for some countries. Refer to the Appendix for calculations using 5-year age groups and that match or have very little difference from the official estimates. %HLY=HLY/LE represents the proportion of life expectancy spent in a healthy state.

* For the HLY estimates performed by smoothing and extrapolating the age-specific prevalence using GAM, we extrapolated the Eurostat life tables to age 100+ using the Makeham Law of Mortality.

** For Germany, exceptionally, the closeout age was 74+ in all variants except GAM, when both the age-specific prevalence and the life tables are extrapolated to age 100+.

Source: Own calculations using EU-SILC prevalence data based on the GALI instrument; Eurostat

When comparing the no disability below age 15 scenario versus any of the smoothing methods (see differences computed for columns (1)-(2), (1)-(3), (1)-(4) and (1)-(5)), which were applied on half the disability curve, GAMs present the

Tab. 3: Healthy Life Years (HLY) and %HLY of total life expectancy at age 65, by different smoothing methods, extrapolation and sex, selected EU countries, 2017

Country	Assumptions and smoothing methods, HLY at age 65									
	No disability		Half the disability†		Splines penalty		Polynomial		GAM*	
	HLY	%HLY	HLY	%HLY	HLY	%HLY	HLY	%HLY	HLY	%HLY
	Women									
Denmark	12.0	57.7	12.0	57.7	11.9	57.3	11.9	57.1	11.4	55.0
Spain	12.5	53.3	12.5	53.3	12.9	55.3	12.9	55.1	11.3	48.5
Finland	9.5	42.8	9.5	42.8	10.3	46.8	10.2	46.3	8.8	39.8
France	12.2	51.5	12.2	51.5	12.3	51.8	12.2	51.6	11.8	49.6
Netherlands	9.6	45.5	9.6	45.5	10.1	47.5	10.0	47.4	9.3	43.9
Sweden	15.7	72.8	15.7	72.8	16.3	75.6	16.3	75.8	15.2	70.7
Germany**	13.2	62.1	13.2	62.1	12.8	60.2	12.8	60.3	11.8	55.8
	Men									
Denmark	11.0	60.4	11.0	60.4	11.3	62.0	11.3	62.0	10.7	58.6
Spain	12.3	63.9	12.3	63.9	12.4	64.1	12.4	64.0	11.7	60.5
Finland	8.8	47.8	8.8	47.8	9.2	49.7	9.1	49.6	8.5	46.0
France	10.1	51.7	10.1	51.7	10.2	52.0	10.1	51.6	9.9	50.7
Netherlands	10.1	54.2	10.1	54.2	10.3	55.3	10.3	55.1	9.7	51.7
Sweden	15.1	78.9	15.1	78.9	15.6	81.4	15.6	81.2	14.9	77.8
Germany**	11.9	65.7	11.9	65.7	11.5	63.6	11.5	63.5	10.8	59.6

Note: Small differences between the official EU HLY indicator may occur since Eurostat uses life tables that close at age 85+, while we recalculate the Eurostat life tables to close at either 80+ or 74+ by summing the person-years lived at each age and then computing the life table following the conventional procedure of *Preston et al.* (2001).

† Half the disability is the official EU assumption for ages below 16 and more closely reflects the official EU statistics. However, we are using age-specific prevalence and Eurostat life tables by single years of age, while the official estimates are from 5-year age groups, so differences may occur for some countries. Refer to the Appendix for calculations using 5-year age groups and that match or have very little difference from the official estimates. %HLY=HLY/LE represents the proportion of life expectancy spent in a healthy state

* For the HLY estimates performed by smoothing and extrapolating the age-specific prevalence using GAM, we extrapolated the Eurostat life tables to age 100+ using the Makeham Law of Mortality.

** For Germany, exceptionally, the closeout age was 74+ in all variants except GAM, when both the age-specific prevalence and the life tables are extrapolated to age 100+.

Source: Own calculations using EU-SILC prevalence data based on the GALI instrument; Eurostat

largest differences, with Finnish women experiencing a difference of 4.4 years. Noteworthily, the GAM scenario is with both the prevalence extrapolated to age 100 and with a life table closed at age 100+, which can also reflect on the absolute values.

Tab. 4: Healthy Life Years (HLY) at age 0 and absolute differences across different assumptions, extrapolation and smoothing methods, by sex, selected EU countries, 2017

Country	Assumptions, smoothing and extrapolation methods, HLY at age 0					Abs. Diff HLY							
	No disability	Half the disability†	Splines penalty	Polynomial	GAM*								
	(1)	(2)	(3)	(4)	(5)	(1)-(2)	(1)-(3)	(1)-(4)	(1)-(5)	(2)-(3)	(2)-(4)	(2)-(5)
Women													
Denmark	60.4	59.8	59.9	59.9	57.4	0.6	0.5	0.6	3.0	-0.1	-0.1	2.4
Spain	70.3	69.8	70.3	70.3	68.8	0.5	0.0	0.0	1.5	-0.5	-0.5	1.0
Finland	57.8	56.6	57.5	57.4	53.4	1.2	0.3	0.4	4.4	-0.9	-0.8	3.2
France	66.7	66.2	66.3	66.3	65.6	0.4	0.4	0.3	1.1	-0.1	-0.1	0.6
Netherlands	58.0	56.9	57.4	57.4	55.2	1.1	0.7	0.6	2.8	-0.4	-0.5	1.7
Sweden	72.1	70.5	71.2	71.3	70.8	1.6	1.0	0.8	1.3	-0.6	-0.8	-0.2
Germany**	68.1	67.5	67.1	67.1	66.2	0.6	1.0	1.0	1.8	0.4	0.4	1.2
Men													
Denmark	59.7	59.1	59.3	59.3	57.2	0.7	0.4	0.4	2.5	-0.2	-0.2	1.9
Spain	69.3	68.6	68.8	68.9	68.6	0.6	0.5	0.4	0.7	-0.1	-0.2	0.0
Finland	59.0	57.8	58.3	58.3	57.4	1.2	0.7	0.7	1.6	-0.5	-0.5	0.4
France	63.8	63.5	63.6	63.6	62.1	0.3	0.2	0.2	1.7	-0.1	-0.1	1.4
Netherlands	62.1	61.6	61.9	61.9	60.6	0.4	0.1	0.1	1.5	-0.3	-0.3	1.0
Sweden	73.1	72.7	73.1	73.0	71.0	0.5	0.0	0.1	2.1	-0.4	-0.4	1.7
Germany**	66.1	65.7	65.3	65.3	64.9	0.4	0.7	0.7	1.1	0.3	0.4	0.7

Note: Small differences between the official EU HLY indicator may occur since Eurostat uses life tables that close at age 85+, while we recalculate the Eurostat life tables to close at either 80+ or 74+ by summing the person-years lived at each age and then computing the life table following the conventional procedure of *Preston et al.* (2001).

† Half the disability is the official EU assumption for ages below 15 and more closely reflects the official EU statistics. However, we are using age-specific prevalence and Eurostat life tables by single years of age, while the official estimates are from 5-year age groups, so differences may occur for some countries. Refer to the Appendix for calculations using 5-year age groups and that match or have very little difference from the official estimates.

* For the HLY estimates performed by smoothing and extrapolating the age-specific prevalence using GAM, we extrapolated the Eurostat life tables to age 100+ using the Makeham Law of Mortality.

** For Germany, exceptionally, the closeout age was 74+ in all variants except GAM, when both the age-specific prevalence and the life tables are extrapolated to age 100+.

Source: Own calculations using EU-SILC prevalence data based on the GALI instrument; Eurostat

Again, the overall differences between half the disability and GAMs are larger for women than for men, with the exception of France and Sweden. When considering the official assumption of half the disability (presented in columns (2)-(3), (2)-(4), (2)-(5)), the differences invert signs for splines with penalty and polynomial fit for some countries, meaning that the smoothed HLY values are slightly higher than without smoothing, but the differences are very small. Between the splines with penalty and polynomial fit there is virtually no difference in the smoothed HLY, so that the difference between these two smoothing methods and the official assumption is very similar, with differences in the second or third decimal order (not shown as the values are all rounded to one decimal only). The difference for splines with penalty (columns (2)-(3)) is -0.9 and -0.6 years for Finnish and Swedish women respectively, while it is -0.8 for both Swedish and Finnish women for the polynomial (columns (2)-(4)). For all other countries, the differences between splines with penalty and polynomial are the same. Comparing the official assumption of half disability with GAMs (columns (2)-(5)), the signs are positive again with Finnish women leading the greatest difference of 3.2 years, followed by German women with 2.4 years. For men, the magnitude of these differences is smaller than for women, but is also the highest across all approaches, with Danish men experiencing a difference of 1.9 in HLY at birth when comparing half the disability with GAM (columns (2)-(5)), followed by Swedish men (1.7 years).

Unsurprisingly, when considering HLY at age 65, there are no differences between estimating HLY with no disability and half the disability for any country and for any of the smoothing and extrapolation approaches, as shown in columns (1) and (2) of Table 5. The assumptions of no disability and half the disability for ages below 16 do not affect HLY estimates at age 65, so there is no difference between these two scenarios. As with the HLY estimates at birth, there is almost no difference between splines with penalty and polynomial fit across countries for both sexes, with differences appearing only in the second decimal. In addition, the differences between HLY estimates at age 65 and at birth are smaller across all smoothing methods. The largest differences observed are between either no disability at birth and half the disability and GAMs extrapolated to age 100+ for both sexes in Germany, with differences of 1.3 years for women and 1.1 for men (columns (1)-(5) and (2)-(5)). However, unlike for HLY estimates at birth, the difference between the assumption half the disability and GAMs is not higher than for other smoothing methods. While for women in Germany, Denmark, Spain and France this is true, for women in Finland, Netherlands and Sweden the differences are actually higher between the assumption half the disability and polynomial or penalty fits (columns (2)-(3) and (2)-(4)), albeit in the negative direction (i.e., considering half the disability as the benchmark, HLY estimated with the smoothing methods is higher than the assumption of half the disability). For men in Denmark and Finland, the magnitude of the difference between half the disability and GAMs and half the disability and penalty or polynomial at age 65 is the same, but in opposite directions (i.e., HLY estimated by GAM is higher, by the other methods it is lower than the assumption half the disability).

Tab. 5: Healthy Life Years (HLY) at age 65 and absolute differences across different assumptions, extrapolation and smoothing methods, by sex, selected EU countries, 2017

Country	Assumptions, smoothing and extrapolation methods, HLY at age 65					Abs. Diff HLY							
	No disability	Half the disability†	Splines penalty	Polynomial	GAM*								
	(1)	(2)	(3)	(4)	(5)	(1)-(2)	(1)-(3)	(1)-(4)	(1)-(5)	(2)-(3)	(2)-(4)	(2)-(5)
Women												
Denmark	12.0	12.0	11.9	11.9	11.4	0.0	0.1	0.1	0.6	0.1	0.1	0.6
Spain	12.5	12.5	12.9	12.9	11.3	0.0	-0.5	-0.4	1.1	-0.5	-0.4	1.1
Finland	9.5	9.5	10.3	10.2	8.8	0.0	-0.9	-0.8	0.7	-0.9	-0.8	0.7
France	12.2	12.2	12.3	12.2	11.8	0.0	-0.1	0.0	0.4	-0.1	0.0	0.4
Netherlands	9.6	9.6	10.1	10.0	9.3	0.0	-0.4	-0.4	0.3	-0.4	-0.4	0.3
Sweden	15.7	15.7	16.3	16.3	15.2	0.0	-0.6	-0.7	0.4	-0.6	-0.7	0.4
Germany**	13.2	13.2	12.8	12.8	11.8	0.0	0.4	0.4	1.3	0.4	0.4	1.3
Men												
Denmark	11.0	11.0	11.3	11.3	10.7	0.0	-0.3	-0.3	0.3	-0.3	-0.3	0.3
Spain	12.3	12.3	12.4	12.4	11.7	0.0	0.0	0.0	0.7	0.0	0.0	0.7
Finland	8.8	8.8	9.2	9.1	8.5	0.0	-0.4	-0.3	0.3	-0.4	-0.3	0.3
France	10.1	10.1	10.2	10.1	9.9	0.0	-0.1	0.0	0.2	-0.1	0.0	0.2
Netherlands	10.1	10.1	10.3	10.3	9.7	0.0	-0.2	-0.2	0.5	-0.2	-0.2	0.5
Sweden	15.1	15.1	15.6	15.6	14.9	0.0	-0.5	-0.4	0.2	-0.5	-0.4	0.2
Germany**	11.9	11.9	11.5	11.5	10.8	0.0	0.4	0.4	1.1	0.4	0.4	1.1

Note: Small differences between the official EU HLY indicator may occur since Eurostat uses life tables that close at age 85+, while we recalculate the Eurostat life tables to close at either 80+ or 74+ by summing the person-years lived at each age and then computing the life table following the conventional procedure of *Preston et al.* (2001).

† Half the disability is the official EU assumption for ages below 15 and more closely reflects the official EU statistics. However, we are using age-specific prevalence and Eurostat life tables by single years of age, while the official estimates are from 5-year age groups, so differences may occur for some countries. Refer to the Appendix for calculations using 5-year age groups and that match or have very little difference from the official estimates.

* For the HLY estimates performed by smoothing and extrapolating the age-specific prevalence using GAM, we extrapolated the Eurostat life tables to age 100+ using the Makeham Law of Mortality.

** For Germany, exceptionally, the closeout age was 74+ in all variants except GAM, when both the age-specific prevalence and the life tables are extrapolated to age 100+.

Source: Own calculations using EU-SILC prevalence data based on the GALI instrument; Eurostat

In other words, if we consider the assumption of half the disability the benchmark for comparison, GAMs tend to underestimate HLY at birth and at age 65 while penalty and polynomial tend to slightly overestimate HLY for all countries. However, at age 65, the magnitude of these differences is smaller.

The magnitude of these differences across HLY estimates are in line with what was observed by visual inspection in Figures 1-3, where, for example, the distribution of the observed prevalence by age for countries like Spain is already relatively smoother than the profiles of Denmark, Finland and the Netherlands, with seemingly shorter distances between the observed values and the smoothed curves. In any case, the differences are larger for HLY at birth. Indeed, the confidence intervals for those estimates are also wider so they have more uncertainty than the estimates for HLY at age 65, as shown in Tables 6 and 7 (See Tables A3 and A4 for all countries).

Tables 6 and 7 show how while the confidence intervals for HLY estimates at birth can be as high as 8 years within the selected countries (women in Finland, 57.5 (95% CI 53.5-61.4) and men in Denmark, 59.3 (95% CI 55.0-63.0, both splines penalty), the interval for HLY estimates at age 65 does not exceed 2.6 years (women in Finland, 10.3 (95% CI 9.1-11.6) splines penalty). The estimates with the wider confidence intervals are splines with penalty while GAMs present lower uncertainty in the measures. Irrespective of method and whether the prevalence was extrapolated or not, the estimates for HLY at age 65 have lower uncertainty.

As a means of comparatively assessing the performance across the methods, we estimated the root mean square error (RMSE) as presented in Table 8 (see Table A7 for all countries). Indeed, with the exception of Denmark for both sexes and for Finnish women where GAMs deviate more strongly from the other models, for most countries the performance of the models are similar, with GAM presenting slightly higher scores. The higher the score, the poorer the performance of the method, relatively. Nonetheless, other factors are important to account for in order to evaluate performance and which method is more appropriate. Even though the smoothing splines present the lowest scores in most cases, this may in part be due to the extreme flexibility, which can lead to overfitting the data (as Fig. 1 and 2 show for the case of Finland). As shown in Tables 6 and 7 they also yield the widest confidence intervals and the most uncertainty when estimating HLY at birth, suggesting that at least for some countries smoothing age specific prevalence with a very flexible model yields overfitted results. Alternatively, splines with penalty and polynomial provide a similar result with an adjustment that is not as flexible as smoothing splines, also shown in Figures 1 and 3, and with lower uncertainty in the estimates. However, these methods are still sensitive to variations throughout the age structure, for example capturing the decreasing prevalence after age 75 in Denmark, which is not guaranteed to be a real effect or simply a data artifact and upticks in older ages for France. In this case, polynomials may be best when there is not so much variance in the data, as their estimated HLY values have lower uncertainty than the penalty. GAMs present the highest RMSE scores and thus have the highest distance from the observed data, despite the differences being small for the majority of countries (with the exception of Denmark and Finnish women). It is unclear whether this is due to the fact that GAMs seem to be particularly affected

Tab. 6: Healthy Life Years (HLY) at birth with 95% confidence intervals, by different smoothing methods, extrapolation and sex, selected EU countries, 2017, half-disability assumption

Country	Smoothing and extrapolating methods, HLY at Age 0								
	Splines penalty			Polynomial			GAM*		
	HLY	95%CI		HLY	95%CI		HLY	95%CI	
				Women					
Denmark	59.9	55.8	63.5	59.9	56.7	62.6	57.4	54.7	60.2
Spain	70.3	68.4	72.1	70.3	68.8	71.8	68.8	67.3	70.3
Finland	57.5	53.5	61.4	57.4	54.4	60.4	53.4	49.7	57.1
France	66.3	64.1	68.4	66.3	64.6	68.1	65.6	64.3	66.9
Netherlands	57.4	54.3	60.4	57.4	54.9	59.9	55.2	53.1	57.3
Sweden	71.2	67.6	74.7	71.3	68.6	73.9	70.8	68.5	73.1
Germany**	67.1	65.2	68.9	67.1	65.6	68.5	66.2	64.8	67.7
				Men					
Denmark	59.3	55.0	63.0	59.3	56.0	62.1	57.1	53.9	60.3
Spain	68.8	66.9	70.7	68.9	67.4	70.4	68.5	67.6	69.5
Finland	58.3	55.1	61.5	58.3	55.9	60.7	57.0	54.7	59.2
France	63.6	61.3	65.6	63.6	61.8	65.0	62.8	61.3	64.3
Netherlands	61.9	59.2	64.3	61.9	59.9	63.7	60.4	58.9	61.9
Sweden	73.1	70.5	75.5	73.0	71.0	74.8	70.9	68.0	73.7
Germany**	65.3	63.5	67.1	65.3	63.8	66.7	64.8	63.5	66.2

Note: Small differences between the official EU HLY indicator may occur since Eurostat uses life tables that close at age 85+, while we recalculate the Eurostat life tables to close at either 80+ or 74+ by summing the person-years lived at each age and then computing the life table following the conventional procedure of *Preston et al.* (2001). However, we are using age-specific prevalence and Eurostat life tables by single years of age, while the official estimates are from 5-year age groups, so differences may occur for some countries. Refer to the Appendix for calculations using 5-year age groups and that match or have very little difference from the official estimates.

* For the HLY estimates performed by smoothing and extrapolating the age-specific prevalence using GAM, we extrapolated the Eurostat life tables to age 100+ using the Makeham Law of Mortality.

** For Germany, exceptionally, the closeout age was 74+ in all variants except GAM, when both the age-specific prevalence and the life tables are extrapolated to age 100+.

Source: Own calculations using EU-SILC prevalence data based on the GALI instrument; Eurostat

by the pattern below age 15. This effect is relatively smaller when the modelling is done by 5-year age groups, but not enough to eliminate this effect (see Appendix, Fig. A3-5 and Tables A5-6).

As previously shown, differences across methods varied for women and men depending on the smoothing method and country. For example, we showed that for some countries the difference between half the disability and GAMs is larger for

Tab. 7: Healthy Life Years (HLY) at age 65 with 95% confidence intervals, by different smoothing methods, extrapolation and sex, selected EU countries, 2017, half-disability assumption

Country	Smoothing and extrapolating methods, HLY at age 65								
	Splines penalty			Polynomial			GAM*		
	HLY	95%CI		HLY	95%CI		HLY	95%CI	
					Women				
Denmark	11.9	10.7	13.2	11.9	10.8	13.0	11.4	10.7	12.2
Spain	12.9	12.3	13.6	12.9	12.3	13.4	11.3	10.7	12.0
Finland	10.3	9.1	11.6	10.2	9.1	11.3	8.8	8.0	9.6
France	12.3	11.5	13.0	12.2	11.5	12.9	11.8	11.1	12.4
Netherlands	10.1	9.1	11.0	10.0	9.2	10.9	9.3	8.7	9.9
Sweden	16.3	15.2	17.3	16.3	15.4	17.2	15.2	14.4	16.0
Germany**	12.8	12.1	13.4	12.8	12.2	13.4	11.8	11.2	12.5
					Men				
Denmark	11.3	10.1	12.5	11.3	10.2	12.3	10.7	9.8	11.5
Spain	12.4	11.8	12.9	12.4	11.9	12.9	11.7	11.2	12.2
Finland	9.2	8.2	10.1	9.1	8.3	9.9	8.5	7.8	9.1
France	10.2	9.5	10.9	10.1	9.5	10.7	9.9	9.3	10.6
Netherlands	10.3	9.6	11.1	10.3	9.7	11.0	9.7	9.1	10.2
Sweden	15.6	14.9	16.4	15.6	14.9	16.2	14.9	14.1	15.8
Germany**	11.5	10.9	12.1	11.5	11.0	12.0	10.8	10.2	11.4

Note: Small differences between the official EU HLY indicator may occur since Eurostat uses life tables that close at age 85+, while we recalculate the Eurostat life tables to close at either 80+ or 74+ by summing the person-years lived at each age and then computing the life table following the conventional procedure of *Preston et al.* (2001). However, we are using age-specific prevalence and Eurostat life tables by single years of age, while the official estimates are from 5-year age groups, so differences may occur for some countries. Refer to the Appendix for calculations using 5-year age groups and that match or have very little difference from the official estimates.

* For the HLY estimates performed by smoothing and extrapolating the age-specific prevalence using GAM, we extrapolated the Eurostat life tables to age 100+ using the Makeham Law of Mortality.

** For Germany, exceptionally, the closeout age was 74+ in all variants except GAM, when both the age-specific prevalence and the life tables are extrapolated to age 100+.

Source: Own calculations using EU-SILC prevalence data based on the GALI instrument; Eurostat

women than men. Hence, in order to provide a clearer picture of these differences and whether existing sex gaps in HLY estimates are affected by the smoothing methods, we used the estimates to calculate gender differences in HLY across countries for all the methods used, as presented in Figure 8. The absolute gender differences in HLY estimates are higher at birth than at age 65 and more markedly so for some countries, like the Netherlands and Finland. As already shown in Tables 4

Tab. 8: Root Mean Square Error (RMSE) by different smoothing methods, extrapolation and sex, selected EU countries, 2017, half-disability assumption

Country	Root Mean Square Error (RMSE)							
	Women				Men			
	Splines	Penalty	Polynomial	GAM*	Splines	Penalty	Polynomial	GAM*
Denmark	0.068	0.069	0.073	0.092	0.079	0.077	0.081	0.092
Spain	0.028	0.029	0.031	0.038	0.029	0.032	0.036	0.039
Finland	0.048	0.064	0.067	0.107	0.056	0.057	0.060	0.063
France	0.036	0.036	0.038	0.041	0.042	0.041	0.042	0.047
Netherlands	0.049	0.051	0.057	0.069	0.046	0.046	0.050	0.055
Sweden	0.051	0.057	0.059	0.063	0.047	0.045	0.047	0.061
Germany**	0.026	0.028	0.030	0.032	0.031	0.031	0.033	0.036

Note: Smoothing methods evaluated with the exception of GAM are until age 80+.

* For the HLY estimates performed by smoothing and extrapolating the age-specific prevalence using GAM, we extrapolated the Eurostat life tables to age 100+ using the Makeham Law of Mortality.

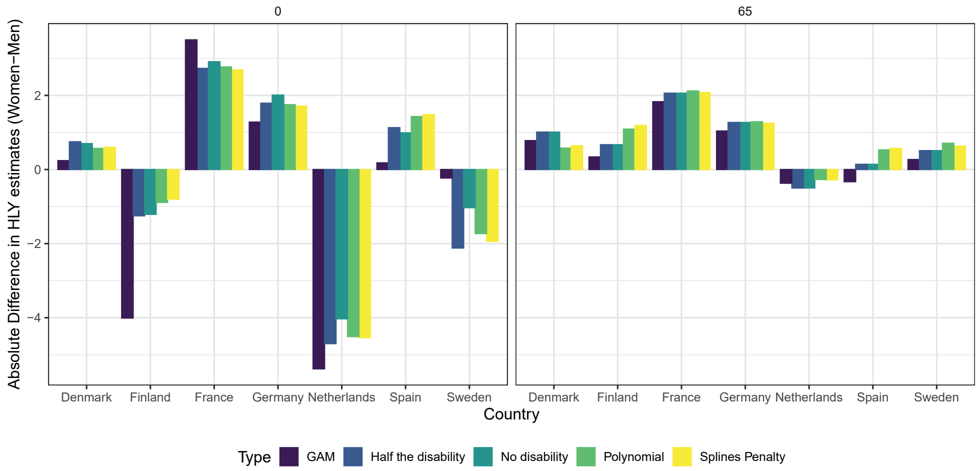
** For Germany, exceptionally, the closeout age was 74+ in all variants except GAM, when both the age-specific prevalence and the life tables are extrapolated to age 100+.

Source: Own calculations using EU-SILC prevalence data based on the GALI instrument and smoothing methods; Eurostat

and 5, the HLY at birth for women estimated using GAM in Finland is 3.2 years lower than the estimated value using the official EU assumption of half the disability below age 15. For men, the difference is only of 0.4 years. Thus, the higher gender gap of -4.01 shown in Figure 8 for the GAM is driven by the HLY estimate for women (i.e., a higher gender gap driven by a larger underestimation of the GAM compared to the benchmark of half the disability), while the HLY estimates using the other methods are similar, varying from -1.25 (half disability) and -0.80 (penalty). In addition, the overall positive gender gap in Spain has its sign reversed at age 65 when comparing the gender gap using GAM versus the other methods for HLY estimates.

Finally, we performed some additional exercises that are presented in the Appendix (see section *The Role of Mortality)*, as we found it intriguing that the differences between smoothed versus unsmoothed HLY estimates seemed far smaller than what we expected when comparing the curves of observed versus smoothed persons-years lived without disability in Figures 6 and 7. It appears that it does not matter very much whether the person-years lived, the L_{i+ni} function, when weighted by the age-specific prevalence, has a fluctuating pattern or not, as the Sullivan approach sums the persons-years lived across all ages and evens out the fluctuating pattern of disability. In order to test to what extent the summing procedure from the Sullivan method ends up capturing the mortality pattern of the L_{i+ni} function more than the health prevalence itself, we calculate HLY with standardised mortality information, with country-specific prevalence data and the EU-28 average mortality

Fig. 8: Absolute differences in HLY at birth and at age 65 between women and men, by different smoothing methods, selected EU countries, 2017



Note: Smoothing methods evaluated with the exception of GAM are until age 80+.

* For the HLY estimates performed by smoothing and extrapolating the age-specific prevalence using GAM, we extrapolated the Eurostat life tables to age 100+ using the Makeham Law of Mortality.

** For Germany, exceptionally, the closeout age was 74+ in all variants except GAM, when both the age-specific prevalence and the life tables are extrapolated to age 100+.

Source: Own calculations using EU-SILC prevalence data based on the GALI instrument and smoothing methods; Eurostat

information. Consequently, differences in these standardised HLY estimates stem solely from differences in country-specific prevalence data. In Figure A8 we show how EU countries would rank from best to worst after controlling for differences in the country's mortality level. Among men, the country ranking is more affected by the mortality information, with changes of up to 8 ranks. This effect is less prominent for women in all countries. Changing mortality never affects rankings for women more than 3 points. In part, this is due to the fact that there is a larger variation in mortality among men across EU countries than among women. However, that is not the full story. Even if we replace the EU-28 standard with that of Bulgaria for Swedish women who rank high in terms of HLY, their change in ranking would only be of 3 points below. This suggests that the HLY indicator appears to reflect mostly differences in GALI prevalence among women, with mortality levels playing a less important role, while the opposite is true for men.

4 Discussion

The HLY indicator is not only used by researchers to address topics related to health and mortality, but is also the cornerstone of many health goals and policies developed by the EU. HLY has been used by different Directorate Generals (DG) for a variety of initiatives and policies such as Social Protection & Social Inclusion (HLY at birth and age 65, by sex), European Pillar of Social Rights on Social Scoreboard (HLY at the age of 65, by sex), European Innovation Partnership on Active and Healthy Ageing: target 2020 (HLY at birth by sex) and the European Sustainable Development Indicator (HLY and life expectancy at birth, by sex), just to mention a few (*Leonardi* 2010; *Lagiewka* 2012; *Bogaert et al.* 2018). It is also used in the United Nations Active Ageing Index (HLY at the age of 65, by sex) and in over 15 countries in the EU region to set health targets and national plans as well as evaluate budget and pension policy issues (*Oortwijn et al.* 2007; *Economic and Financial Affairs* 2017). Hence, it is an important indicator and thus a deep understanding of its potential, limitations and sensitivity is key. Indeed, the HLY indicator has been recognised as the most suitable indicator for cross-national comparisons, with the GALI instrument being harmonised and developed to increase comparability across countries (*Van Oyen et al.* 2006, 2018; *Jagger et al.* 2010; *Berger et al.* 2015). Nonetheless, the characteristics of the age-specific prevalence distribution are still rarely considered when employing the indicator and interpreting results, regardless of the fact that patterns of prevalence often fluctuate considerably by age, especially when using single ages. In addition, the impact of assumptions used at very young ages on HLY estimates are seldom discussed, despite the fact that data on health is only collected after age 15 and the majority of policies and initiatives at the EU level use HLY at birth.

A common strategy to deal with the erratic behaviour of age-specific prevalence has often been to aggregate data into 5-year age groups and combine it with abridged life tables in order to estimate HLY (*Eurostat* 2020). Research has also been directed to account for uncertainty in HLY measures caused by survey characteristics (*Murray et al.* 1993; *Jagger et al.* 2014) and developing confidence limits for HLY estimates that do not require the assumption of a constant proportion of unhealthy individuals in an age interval (*Andreev/Shkolnikov* 2010). In our exploratory analysis, we focus on the age-specific prevalence behaviour and instead of grouping data into 5-year age groups we test whether there is any effect on HLY estimates of smoothing and extrapolating the prevalence of disability by age by different methods, country, sex and assumptions below age 15.

Overall, absolute differences across methods are not very substantial and smoothing performance is also similar, as supported by the RMSE scores. However, the analyses indicate caution when handling age-specific prevalence, particularly when considering the assumptions below age 15, with differences across methods being in general larger for estimates of HLY at birth and larger for women than men in the majority of countries. When using the official EU assumption of half the disability as a benchmark for comparison across the three main smoothing and extrapolation variants tested (penalty, polynomial and GAMs), the difference between methods compared to the benchmark was larger for HLY at birth than at age 65 and usually higher for women than for men, with penalty and polynomial smoothing yielding similar results. The GAMs extrapolated to ages 100+ provided slightly lower values of HLY at age 65 when compared to half the disability benchmark, but differences between GAMs and half the disability for age 65 were small. However, differences between GAMs and half the disability for HLY estimates at birth were sometimes as high as 3 years (see women in Finland).

In addition, the assumption of no disability before age 15 had the highest impact on HLY at birth, mainly because it directly impacts the younger ages with higher values of person-years lived. Even though the official EU indicator does not assume no disability before age 15, comparing estimates with this scenario helps to demonstrate the magnitude of the impact of assumptions at younger ages. As expected, these assumptions have no impact on the HLY estimates at age 65.

This indicates that assumptions made at young ages are important and that the strategies used to deal with this age group merits attention. Likewise, the fact that assumptions affect women and men differently may suggest that different parameters by gender are important when the aim is to design gender-specific policies. This is relevant as most EU policies use HLY at birth and by sex for developing and monitoring health policies, like the target by the European Innovation Partnership on Active and Healthy Ageing (EIP-AHA), which was set in 2011 with the aim of increasing healthy life years at birth by 2 years by 2020 (*Jagger et al.* 2008; *Nusselder et al.* 2010; *Lagiewka* 2012; *Van Oyen et al.* 2013; *Luy/Minagawa* 2014; *UNECE/European Commission* 2015).

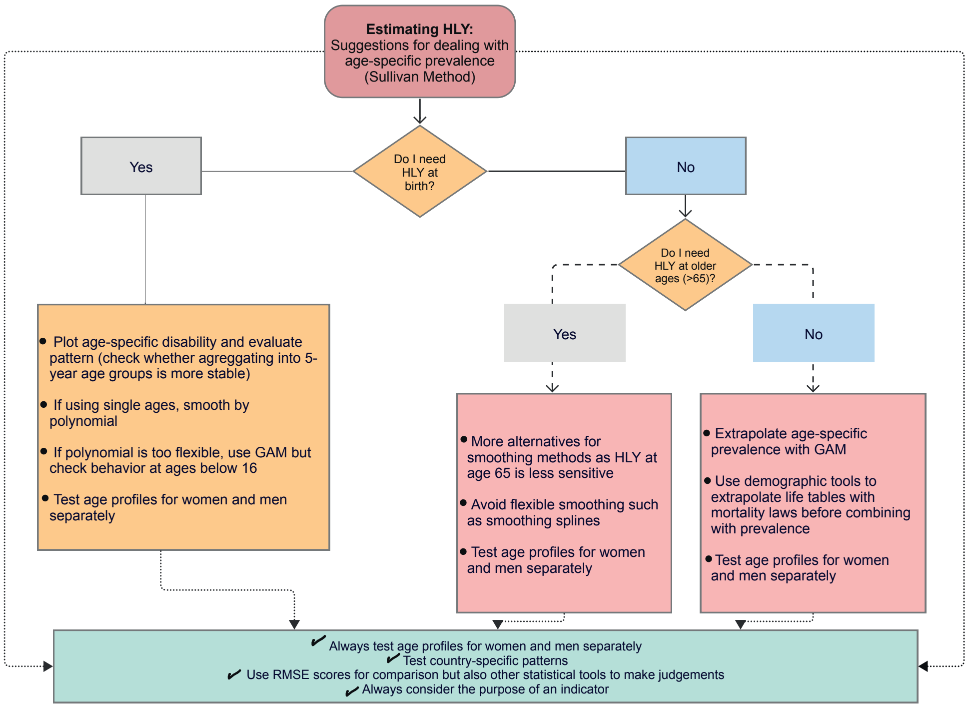
Furthermore, the fact that even after extrapolating to ages 100+ and applying different smoothing methods did not impact HLY estimates at age 65 indicates that at this age the indicator is less sensitive to age patterns of prevalence than at birth. Hence, the Generalised Additive Model (GAM) approach may be a promising tool to model and harmonise age-specific profiles of disability for cases where there is limited or erratic information for older ages or where there is a break in the time series with changes in the coverage across ages like the case of Germany. However, it is important to note that the level of uncertainty with the extrapolation can be higher with GAMs depending from which age the extrapolation occurs. One alternative could be to extrapolate only 5 or 10 years in order to harmonise the data and have a more robust comparison across countries. This would be an interesting avenue for further investigation, as while there is a wide array of demographic and statistics methods available to interpolate, graduate and smooth mortality data both at young and older ages, strategies for dealing with age-specific prevalence are still limited in health research, often relying on multistate methods (*van der Gaag et al.* 2015). In part, this is due to the fact that contrary to mortality, health prevalence by age may not increase monotonically, as recovery from certain conditions is possible. In addition, health is a stock variable sensitive to past experience (*Barendregt et al.* 1997; *Brouard/Robine* 1992; *Murray et al*. 2002) and with a complex interaction between health and mortality, making it difficult to accurately model age-specific health prevalence (*Riffe et al*. 2016, 2017). In this regard, it has been shown that some relational models provide a good fit for modelling some types of disabilities by age (*Marshall et al.* 2013), while alternative summary measures that incorporate the mortality history of cohorts and therefore combine health and mortality information have also been proposed (*Sauerberg et al.* 2020). However, these methods are more important to capture the relationship between age-specific prevalence of disability and various disability types rather than to harmonise and extrapolate prevalence at older ages. In addition, since the EU-SILC does not include individuals living in institutions, the prevalence of being unhealthy at older ages is likely to be systematically biased downwards. Since health data for the institutionalised population at a European level is not easy to obtain, extrapolating prevalence data to higher ages might be one alternative to account for this issue in the lack of more reliable information.

5 Conclusions and recommendations

The standard practice of combining age-specific prevalence proportions with person-years lived without proper attention to the distribution profile of the former may affect the estimation of HLY. Although the overall differences seem to be small, oftentimes they are not trivial and vary by smoothing method, country, sex and age. This suggests that it is important to be more cautious with the age distribution of health prevalence prior to combining it with mortality data, especially when the indicator of interest is estimated at birth. We have shown in what ways and in which direction HLY is sensitive to some assumptions at younger ages and the age-specific prevalence. However, further research is needed to understand what the optimal strategy would be to deal with the age-specific prevalence and this will more likely depend on the data available and the purpose in using the indicator. According to the results of the sensitivity analyses presented in this paper, we suggest a routine practice as regards estimating the HLY, as summarised in the flowchart in Figure 9 below. First, as the main sensitivity in the results refers to HLY at birth, it is important to consider whether HLY is to be estimated at birth or age 65. Second, plot the age-specific disability prevalence and evaluate its pattern, as well as whether aggregating into 5-year age groups already smooths the pattern. GAMs adjust well at ages 65 and older and their impact on HLY is very small, but they can impact HLY at birth. In this case, either just estimating HLY based on the usual aggregation by 5-year age groups or smoothing by a polynomial fit can be best. Most importantly, always test age profiles for women and men separately, as well as country-specific patterns. The most important recommendation is to consider the purpose of the indicator carefully beforehand and to assess its pattern by age before combining it with the person-years lived by age.

It is noteworthy to mention that this recommendation is based on very flexible smoothing methods that we chose since they do not require any assumptions about the pattern of prevalence by age. However, future research is needed to develop techniques that employ a more robust treatment of those profiles and test whether standard demographic procedures used for adjusting age-specific distributions are equally suitable for health.

Fig. 9: Flowchart recommendation for dealing with age-specific prevalence before estimating HLY with Sullivan



Source: Own elaboration

Acknowledgements

We would like to thank two anonymous reviewers who contributed to improving the first version of this paper. This project received funding from the European Research Council under the EU's Horizon 2020 Research and Innovation Programme, Grant Agreement No. 725187 (LETHE). This paper is based on data from Eurostat, European Union Statistics on Income and Living Conditions European Health Interview Survey (EU-SILC), cross-sectional 2017, version release 2 in 2020.

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Date of submission: 23.01.2022 *Date of acceptance: 05.01.2023*

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www.comparativepopulationstudies.de

ISSN: 1869-8980 (Print) – 1869-8999 (Internet)

Published by
Federal Institute for Population Research (BiB)
65180 Wiesbaden / Germany

Managing Publisher
Dr. Nikola Sander