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Disability and morbidity among US birth cohorts, 1998-2018: a multidimensional test of dynamic equilibrium theory

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Abstract

A substantial body of prior research has explored patterns of disability-free and morbidity-free life expectancy (LE) among older populations. However, these distinct facets of later-life health are almost always studied in isolation, even though they are very likely to interact with each other. Using data from the US Health and Retirement Study (HRS) and a multistate life table approach, this paper explores the interactions between disability, morbidity, and mortality among four successive US birth cohorts, born from 1914-1923 to 1944-1953. These 10-year cohorts are compared in the periods 1998-2008 and 2008-2018. The LE and health expectancies (HEs) are calculated via demographic microsimulation, and are modelled separately by sex, educational attainment and race/ethnicity. We find little compression of disability but a substantial expansion of morbidity across cohorts in each of the three age ranges. Investigating interactions between morbidity and disability, we find that disability-free life expectancy (DFLE) among those living with chronic morbidities has increased, but that at the population level DFLE is largely unchanged across successive cohorts. Investigating patterns in population sub-groups, we find that less advantaged populations (low educated and non-white groups) live substantially fewer years free of disabilities or chronic morbidities. Broadly, these patterns suggest that the link between chronic morbidities and disability has weakened over time in the US population. However, at the population level, successive cohorts are spending fewer years of life free of both chronic morbidities and disability.

Keywords: *Morbidity, Disability, Aging, Dynamic equilibrium, Health expectancy*

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Introduction

Notwithstanding a recent period of stagnation and decline prior to and during the COVID-19 pandemic, life expectancy in the United States both at birth and age 65 has also experienced nearly linear growth over the past decades (National Center for Health Statistics 2021). Americans alive today can expect to live nearly a decade longer than the average person in their parents' generation, and two decades longer than the average person in their grandparents' generation. Although these increases in longevity are undoubtedly a substantial achievement, there is considerable concern about the economic consequences of rising longevity, particularly in the expected growth of pension and healthcare expenditure (e.g., Louria 2005; Rice and Fineman 2004). In response to these changes in population composition, many countries, including the USA, UK, and Australia, have either raised or plan to raise their legal retirement/pension age to bolster the welfare system. If longer-living populations are able live their later years in good health and remain economically active, the fiscal impacts of population ageing may not be as severe as predicted (e.g., Ferreira and Pessôa 2007; Vogel et al. 2017). However, the evidence-base is mixed as to whether these additional years of longevity are being matched by increases in healthy life.

Two conceptual frameworks have predominated discussions of trends in health in later life: the expansion of morbidity framework of Gruenberg (1977) and the compression of morbidity theory, promoted by Fries (1980, 2005). Considerable debate still exists as to whether recent expansions in lifespan are being met, or exceeded, by an expansion of time spent healthy. Fries' conceptual framework positing a compression of morbidity relied heavily on an assumed strong linkage between chronic morbidities, disability, and mortality: "Disability and lowered quality of life due to the most prevalent chronic diseases are thus unescapably linked with eventual mortality" (Fries 1980:132). As pointed out by Beltrán-Sánchez et al. (2014), most work investigating the compression of morbidity has followed Fries assumed strong connection between morbidity and disability and focused on disability as the primary outcome of interest. The dynamic equilibrium model developed by Manton (1982) takes a different approach to understanding population health change over time and across generations. A key tenant of this model is that over time, advances in medical technology, treatments, and early diagnoses may weaken the linkage between chronic morbidities and disability. In essence, the dynamic equilibrium model suggests that different facets of population health may move in different directions over time: as life expectancy increases, the fraction of remaining life spent with chronic morbidities may increase (due to improved diagnoses of diseases at early stages and improved treatment effectiveness prolonging lifespan), while simultaneously the fraction of remaining life spent with functional disability may stay constant or decline (due to better management of these chronic morbidities). However, little research has explicitly tested whether the patterns predicted by dynamic equilibrium theory are occurring in the US population.

Background

Previous studies present a contrasting picture of the change in different facets of health in the US population. Analyses looking at morbidity, as defined by the presence of a set of chronic health conditions, generally find that an expansion of morbidity is happening in the US population over time (e.g., Beltrán-Sánchez et al. 2015; Crimmins and Beltrán-Sánchez 2011; Payne 2022). Crimmins et al. (2019) suggest that the prevalence of cancer, stroke and diabetes has increased over successive 10-year cohorts, but that mortality associated with these diseases has declined significantly. However, the evidence is more mixed on trends in disability. Research investigating changes in disability through the 1980s, 1990s, and early 2000's primarily found improvements in disability-free LE, both in period and cohort perspective (e.g., Cai and Lubitz 2007; Freedman et al. 2002; Manton et al. 2008; Manton and Land 2000). However, more recent studies have suggested that trends in disability-free life may have stagnated since the start of the new millennium. Crimmins and Beltrán-Sánchez (2011) found an expansion in functional loss and major chronic diseases in the US from 1998 to 2008. Recent evidence on changes in LE and DFLE from 1998 to 2016 found that disability-free LE remained largely unchanged across cohorts during this period (Payne 2022).

A limitation of the existing evidence base on patterns of healthy longevity is that most existing studies explore variation in later-life well-being on only a single axis—that is, most studies look at functional ability/disability, chronic morbidities, self-rated health, or other domains of health in isolation. Of the few studies investigating multiple dimensions of health simultaneously, none of them can be truly called multidimensional. A recent paper by Huang et al. (2021) combined physical and cognitive impairment into one state and computed the life expectancy for each combination. However, their state-space was not complete, including only "Active and cognitive-impairment-free", "Not active and cognitive-impairment-free" and "Death". Rahman et al. (2022) on the other hand, combined morbidity and disability into one state. Yet, in their state space, they did not separate disability with and without diseases since their data contained few individuals with disability but without diseases. Conceptually, a

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disabled person without chronic diseases is likely to differ quite substantially from a disabled person with chronic disease (as their disability is clearly not linked to chronic illness). Therefore, they are unlikely to experience the same transition probabilities as a disabled individual with chronic disease. Other papers have focused on differences in disability-free LE between populations with and without individual chronic conditions such as cancer (Payne and Kobayashi 2022) or diabetes (Bardenheier et al. 2016). Although useful for understanding disparities in healthy longevity by disease status, the focus on a single health condition means that these papers cannot speak more broadly to trends and interactions between morbidity and disability.

In this paper, we propose a multidimensional extension to prior work on health expectancy by simultaneously modelling changes in morbidity and disability across a set of cohorts in the US population. Our focus on exploring the interplay between these two facets of health draws on both the disablement process model of Verbrugge and Jette (1994) and the dynamic equilibrium theory of Manton (1982). In the disablement process, the main path of disability onset connects physiological dysregulation to functional impairments/limitations. However, unlike the more deterministic morbidity-disability linkage posited by Fries, the disablement process explicitly allows for these connections to be moderated by personal, environmental, and contextual factors that speed or slow disablement. They divided these factors into three groups: extra-individual factors, such as medical access and physical environment; intra-individual factors, such as psychosocial attributes and behavioral changes; and risk factors such as demographics and lifestyle. The flexibility of the disablement process also conceptually aligns with the dynamic equilibrium model—both recognize that linkages between health conditions and functional deficits are malleable. Guided by these frameworks, this research aims to jointly analyze connections between morbidity, disability, and mortality to better understand the relationship and transitions between these dimensions of health.

Our approach to exploring the population health consequences of interactions between morbidity and mortality centers on measuring changes in healthy longevity from a cohort perspective. This approach builds on both foundational work on connections between period and cohort measures of disability-free life expectancy (DFLE) (e.g., Manton et al. 2008; Manton and Land 2000; Manton et al. 1997; Soneji 2006) and recent work exploring cohort changes in disability, chronic diseases, and health in the United States (e.g., Beltrán-Sánchez et al. 2016; Crimmins et al. 2019; Payne 2022). A cohort perspective on healthy longevity more closely represents the lived experience of individuals within the population, allowing us to measure whether a change in healthy longevity (i.e., a compression of morbidity) is being experienced by an actual group of individuals in the population. This approach contrasts with the usual approach of measuring period estimates of healthy longevity as generated through synthetic cohorts, which is more applicable to monitoring and comparing aggregate-level changes in health conditions over time (Manton et al. 2008). Cohort measures of LE and HEs also have the advantage of limiting the amount of potential bias that could be introduced by secular changes occurring to the population over time (Payne 2022). The downside to focusing on cohort measures of later life health is that we cannot measure full-cohort life and health expectancies—that is, total remaining life expectancy, and expectancies of life lived with/without disability or morbidity. Instead, our analyses focus on comparing partial LE and HEs within bounded age-ranges.

Social inequalities in the US population are also likely to lead to heterogeneity in the dynamic pathways connecting chronic morbidities, disability, and mortality. Prior research on healthy longevity has also highlighted the considerable social inequalities existing in the US population by race, level of education, and occupational status (Chiu et al. 2016; Solé-Auró et al. 2015; Zaninotto et al. 2020). Again, however, these prior research efforts have generally focused on morbidity or disability in isolation. The role of social inequalities in shaping healthy longevity is likely multifaceted—that is, the combination of stress processes, material deprivation, and unequal access to and treatment by the healthcare system experienced by disadvantaged subgroups is likely to impact on different pathways of the disablement process (Boen and Hummer 2019; Di Cesare et al. 2013; Williams et al. 2019). However, prior research has not explicitly sought to understand how connections between chronic morbidities, disability onset, and mortality stratify by social groupings, nor has it explored how these connections may change over time. Taking a cohort perspective on social inequalities in healthy longevity may also produce different results as compared to a period perspective. Beltrán-Sánchez et al. (2015) found that the period-based studies produce more consistent results in terms of the disparities by sex, race and education, while cohort studies usually give mixed results on the inequality across groups. They attribute these contradictory findings to the methodological differences between period and cohort measures--period measures rely on synthetic cohort approaches that combines data across numerous cohorts, aggregating age-specific death rates and age-specific morbidity/disability conditions for that period. As such, a period-based analyses do not represent the real-life experience of any individual or social group within the population.

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Our analyses center on two primary objectives. Firstly, we explore how patterns of life expectancy with chronic morbidities and functional disability have changed over successive cohorts in the US population. By taking a multidimensional perspective, we seek to illuminate whether connections between chronic morbidities and disability have changed over cohorts, and how these changing links are impacting healthy longevity. Secondly, we investigate whether there is heterogeneity in these connections by sex, race/ethnicity, and educational attainment. These sociodemographic characteristics could theoretically moderate the pathway between chronic diseases and disability through their interaction with risk factors and social environment. The results offer an in-depth understanding of disparities between subpopulations in the pathways connecting these different facets of health, and how they have changed across successive cohorts.

Data & Methods

Data

Data are from the US Health and Retirement Survey (HRS), a bi-annual national longitudinal survey (Sonnega et al. 2014). Our analyses use the RAND HRS Longitudinal File 2018 (V1) developed at RAND with funding from the National Institute on Aging and the Social Security Administration (Health and Retirement Study 2021). We use data from the 1998 to 2018 waves of data collection, focusing on individuals aged 60 and above to compare the change in time spent with disability and/or morbidity between consecutive cohorts. Table 1 presents the four birth cohorts used in the analysis highlighted in different colors (also see Supplemental Figure S1 for a Lexis diagram presenting the cohort comparison for the youngest age group). Depending on the period and age that the cohort is observed, the four birth cohorts are labelled as early or later cohorts.

Measures

Two dimensions of health are measured: morbidity and disability. Morbidity is measured by five variables in the survey inquiring "whether the respondent has ever been diagnosed by the physician with ___ (a chronic disease)". These five chronic diseases include cancer, diabetes, heart disease, lung disease and stroke, which are selected because they are identified as the top causes of death from chronic non-communicable disease in the US and may directly lead to functional loss or premature death (Kochanek et al. 2020). Individuals without any of the five chronic diseases are classified as "morbidity-free (MF)" and "morbid (M)" otherwise.

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Disability is conceptualized as difficulty in doing basic daily living that could result from physical, mental or cognitive impairment or the individual's living environment. Five Activities of Daily Living (ADL) are used to define whether the individual is classified as "disabled (DF)" or "disability-free (D)": bathing, dressing, eating, transferring in/out of bed, and walking across a room. Where necessary, ADL data from a proxy respondent are used. Individuals are classified as disabled if they report difficulty on any of the five ADLs.

Morbidity and disability are combined into one measure with 4 combinations of health status: morbidity-free & disability-free (MF-DF), morbidity-free & ADL disabled (MF-D), morbid & disability-free (M-DF) and morbid & ADL disabled (M-D). Death is shared by these two dimensions of health. The Incidence of death is captured through linkages to the National Death Index (NDI) as well as 'exit' interviews with the respondent's family members (Sonnega et al. 2014). The age of death is calculated from the date of death variable in the interview.

Covariates include age as a continuous variable, sex as a dichotomous variable (female and male) and a 10-year birth cohort as a categorical variable with 4 consecutive cohorts 1914-1923, 1924-1933, 1934-1943 and 1944-1953 for all models. Our analyses exploring educational and racial inequality include additional covariates for self-reported race and ethnicity with three categories (non-Hispanic White, non-Hispanic Black and Hispanic), and level of attained education with three categories: 1) less than high school diploma, 2) high school graduate (including GED), and 3) above high school diploma (including some college and bachelor's degree or higher). Individuals that are not in these three categories of race/ethnicity are excluded from the analysis due to small sample sizes. Table 2 summarizes the baseline characteristics in the sample by age group and birth cohort. The baseline of birth cohort 1934-1943 in 1998 includes respondents from 55 to 64 years old for example, this comparison as demonstrated in a Lexis diagram as Supplemental Figure S1. The proportion of MF-DF and MF-D at the start of each age group decreased over birth cohorts, while M-DF, in particular, and M-D increased.

Methods

We apply a five-state multistate life table model to estimate the population-based partial cohort life expectancy (PC-LE) and partial cohort health expectancy (PC-HE). The transitions among these five states are depicted in Figure 1. Transitions from Morbid (M) to Morbidity-free (MF) are not allowed since the definition of morbidity in our analysis is "ever diagnosed". To estimate transition probabilities, we convert the survey data with two-year intervals to single-year intervals, randomly assigning the missing state in to either the last observed state or the next observed state. We obtain the exact age of death from the HRS data, and individuals who die between survey waves are assumed to stay in their last observed state until death. Three multinomial regression models are built to model the annual transition probabilities with different covariates (Cai et al. 2010). Different cohorts are pooled together to estimates the transition probability of each age group. For example, transition probabilities in ages 60-69 are estimated from ages 55-74 for cohort 1934-1943 during the 1998-2008 time period and cohort 1944-1953 during the 2008-2018 time period. The first model is the population-level analysis with age, age-squared, sex, birth cohorts and interactions between age, sex and birth cohorts. The second and third models explore racial and educational disparity by including all covariates in the population-level model and their respective covariates: race and ethnicity/level of attained education, and two interaction terms between race and ethnicity/level of attained education and sex, and race and ethnicity/level of attained education and birth cohorts.

Two types of weights are used in the analysis, sample weight and attrition weight. The sample weight is available in the HRS dataset (combined respondent weight and nursing home resident weight). The attrition weight is used to account for potential bias resulting from differential loss to follow-up. We generate and use an inverse probability weight to rescale individuals who do not attrit according to their age, sociodemographic and health status shown in Table 2 (Dugoff et al. 2014; Payne 2022). The final weights are the product of sample weights and attrition weights.

These transition probabilities are then used as inputs for a microsimulation-based multistate life table model (Cai et al. 2010; Liu et al. 2019). To estimate population-based LE, we generate a synthetic cohort of 100,000 individuals for each age and cohort group in Table 1 with sociodemographic and initial health distribution as in the observed data (sample characteristics in Table 2 with sample weights). These individuals are aged year by year using age- and sex-specific estimated transition probabilities between different states. The process is repeated from the starting age to the ending age for each model, age group, and birth cohort. For example, we generate the synthetic cohort of 100,000 individuals with the same baseline characteristics of the 1934-1943 birth cohort and simulate life-courses of these individuals from age 60 to 69 based on the transition probabilities described above. The average time spent in different states over these ten years is our estimate of PC-HE. Only the point estimates from the multinomial regression models are used; confidence intervals (CIs) are estimated by bootstrap resampling from the original dataset. We re-estimate and simulate based on these 500

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bootstrap samples. The final point estimates presented in the results are from the full dataset, and the central 95% of the 500 bootstrap resamples times is taken as the 95% CI. All analyses are conducted in R software (R Core Team 2022).

Results

The baseline sample characteristics of each cohort and age-group in the analyses are presented in in Table 2. Educational attainment is slightly higher in the later cohorts as compared to the early ones, and within each age group, successive cohorts are more diverse in terms of race/ethnicity. The proportions of people with one or more chronic diseases (M-DF + M-D) increases markedly over successive cohorts. There is no substantial change to the proportion of each cohort reporting limitations on ADL activities, but there is a small, consistent drop in the proportion of ADL disabled individuals without chronic diseases and a rise in ADL disabled individuals with chronic diseases.

Health expectancies

The estimated PC-HEs in each state in our analysis are presented by sex (Figures 2, 3 & Supplemental Figure S2), race/ethnicity (Figures 4, 5 & Supplemental Figure S3) and the highest level of education attained (Figures 6, 7 & Supplemental Figure S4). The bars are the aggregated average time spent in each health status for an individual with those characteristics or initial health state. In Figures 2, 4 & 6, there are two panels: A) by morbidity and B) by disability. Panel A of Figure 2 shows the time without (MF) and with chronic diseases (M) combined across disability status, while panel B illustrates the time without (DF) and with disability (D) combined across morbidity status. Note that the PC-HE estimates in these two panels are identical—the only difference is how they are grouped. Figures 3, 5 & 7 additionally disaggregate by initial morbidity state to more clearly identify into how disability-free and disabled life have changed across cohorts. Supplemental Figure S2, S3 & S4 further disaggregate by all initial states. The sum of MF & M or DF & D in each age range and cohort for all the figures is the total PC-LE of that group of individuals. For example, the partial cohort morbidity-free LE (PC-MFLE) of both sexes in panel A of Figure 2 at age 60-69 (the top left section) is 5.42 years for the early cohort and partial morbid life expectancy is 3.89 years, and hence the total PC-LE is 9.31 years. The corresponding section in panel B shows partial disability-free life expectancy at 8.19 years and partial disabled life expectancy at 1.12 years, which also sums to total PC-LE of 9.31 years.

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Morbidity-free life expectancy (PC-MFLE)

Across all age ranges in our study, life expectancy spent free of chronic morbidities has declined across successive cohorts, and life expectancy with one or more chronic diseases has climbed significantly (Figure 2 panel A). The total PC-LE has increased for all age ranges, but PC-MFLE has decreased significantly. In general, females spent more years of life morbidity-free than their male counterparts. This gender gap in PC-MFLE widens as people grew older—by ages 80-89, a woman in the earlier cohort could expect to spend 3.07 (95% CI: 2.90, 3.25) years free of chronic morbidities, compared with only 1.80 years (95% CI: 1.63, 1.97) for a man. However, the gap appears to be smaller in the later cohorts for all ages. Focusing on the morbidity-free column, the red color represents LE spent morbidity-free and disability-free (MF-DF) while the blue color represents LE spent morbidity-free and disabled (MF-D). For both males and females, time spent free of disability and morbidity decreased substantially over successive cohorts in all age groups. Small declines in the proportion of life spent morbidity-free but disabled were also seen across cohorts, although these differences are not universally significant. Turning to LE with chronic morbidities (the "Morbid" column of Panel A), we find that partial cohort morbid LE (PC-MLE) rises substantially across cohorts for both men and women. Comparing the green bar across the earlier and later cohorts demonstrates that partial life expectancy spent with chronic morbidities but without disability (M-DF) has risen substantially across cohorts—in ages 60-69, women in the more recently-born cohort can expect to spend an additional 0.79 years with chronic morbidities, but without disability, as compared to those in the earlier cohort (this figure is 0.52 for men). We also find gender differences in these cohort patterns. Men spend fewer years morbid and disabled (M-D), suggesting that men are more likely to stay disability-free while having chronic diseases than women. Interestingly, this rise in MLE is not driven by individuals starting out in a specific health state—rather, we observe a steady increase in MLE in almost all age ranges and initial states for both men and women (presented in panel A of Supplemental Figure S2).

Disability-free life expectancy (PC-DFLE)

Panel B of Figure 2 provides partial cohort DFLE ("Disability-free" column) and DLE ("Disabled" column) by sex. Overall, males spend roughly the same time disability-free as females, but spend fewer years disabled, leading to the gap in total PC-LE between males and females. The PC-DFLE and disabled LE remained largely unchanged across cohorts, though we do see consistent, although mostly not significant, rises in PC-DFLE across cohorts. In

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successive cohorts, the portion of life expectancy spent disability-free is increasingly made up of years with chronic diseases—for both men and women, the proportion of disability-free life spent with chronic diseases increased substantially. Similarly, the proportion of PC-DLE spent with chronic morbidities also increased across cohorts, though to a lesser extent.

In Figure 3, the PC-HEs are further disaggregated by the initial morbidity state to account for the changes in baseline composition across cohorts (as shown in Table 2). There is again a consistent rise across cohorts in PC-DFLE for individuals free of chronic diseases at the state of each age range (Initial State: Morbidity-free), although these differences rarely reach statistical significance. The increase in PC-DFLE is much more substantial for individuals starting morbid (Initial State: Morbid), particularly in ages 60-69 and 70-79. PC-DFLE is higher for males who initially had chronic morbidities than for their female counterparts after the disaggregation by initial state. This improvement in disability-free life among those with chronic morbidities is more evident in panel B of Supplemental Figure S2 where all initial states are distinguished. The results in Supplemental Figure S2 suggest that cohort improvements in DFLE may have been stopped by the growing proportion of individuals who were both disabled and had chronic morbidities at baseline (as shown in Table 2). Additionally, we broadly observe a small increase in PC-DFLE for people without chronic diseases at the initial age, although this difference is not universally significant.

Morbidity- & Disability-free life expectancy (PC-MDFLE)

As discussed above, time spent free of both disability and chronic morbidities (i.e., PC-MDFLE) declined significantly across cohorts for both sexes (Figure 2). Females' PC-MDFLE is consistently higher than males' for all age ranges. However, controlling for the initial morbidity state (Figure 3), the time spent morbidity- and disability-free is almost unchanged across cohorts, and discrepancies between males and females seem to be closing.

Racial/ethnic differences in health expectancies

Figures 4 and 5, and Supplemental Figure S3, present our results separately by racial and ethnic groups. The overall pattern described above—increasing time spent with chronic morbidities and relatively stable time spent disability-free—is found across all racial/ethnic groups, and partial life expectancies have also increased among all groups (Figure 4). Overall patterns of PC-MFLE and PC-MLE (Panel A of Figure 4) are similar across racial and ethnic groups. However, turning to partial LE by disability (Panel B of Figure 4), non-Hispanic Whites appear to be living significantly more years free of ADL disability than the other two groups. PC-

MDFLE decreases substantially across cohorts for all racial/ethnic groups. Non-Hispanic Whites also have the higher PC-MDFLE, especially compared to non-Hispanic Blacks, although this gap shrinks somewhat at ages 80-89.

These racial/ethnic differences become more apparent when disaggregating by initial morbidity state (Figure 5) and by initial disability and morbidity state (Supplemental Figure S3). For individuals without chronic morbidities at the initial age, only non-Hispanic Whites seem to have a consistent increase in PC-DFLE and PC-MDFLE in all age ranges. Their PC-DFLE is also significantly higher than their non-Hispanic Black or Hispanic counterparts for all age ranges. Regarding people with chronic diseases at the start, all racial/ethnic groups experienced some degree of compression of disability below age 80, although these differences were not universally significant.

Educational differences in health expectancies

Figures 6 and 7, and Supplemental Figure S4, present our results separately by schooling attainment. PC-MFLE, PC-DFLE and PC-MDFLE of the most educated individuals (beyond high school diploma) is significantly greater than that of the least educated ones (those without a high school diploma) for almost all age ranges and cohorts (Figure 6). In all educational groups, both PC-MFLE and PC-MDFLE decreased across cohorts for all age ranges (Panel A of Figure 6). However, the magnitude of these declines varied substantially—increases in LE with chronic morbidities were smallest for the highest educated group and largest among those with less than a high school diploma. Among time spent with chronic morbidities, those in the lowest schooling group could expect to spend four to five times (depending on cohort) more years with ADL disability as compared to those with beyond a high school diploma in ages 60-69, although this gap shrinks with increasing age. Trends in PC-DFLE by level of schooling (Panel B of Figure 6) show that contrasting trends are occurring among the lowest- and highest-educated groups. Successive cohorts of individuals without a high school diploma appear to be experiencing an expansion of time spent with disability, although these differences are not universally significant. In contrast, those with more than a high school diploma are living more time disability-free across successive cohorts. For all groups, the portion of disability-free life spent without chronic morbidities has declined across cohorts.

More detail on disparities between levels of education can be found in Figures 7 and Supplemental Figure S4, where individuals are separated by their initial state. Figure 7 indicates that only for ages 70-79 do individuals with a high school diploma or above have

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significant improvement in PC-DFLE across cohorts, conditional on having chronic morbidities at age 70. Yet, with further disaggregation in Supplemental Figure S4 (Panel B), the expansion in PC-DFLE can be seen in all age-ranges for the more educated group when starting from the M-DF or M-D groups. Comparing PC-MDFLE, the lowest educated group shows slight declines for all age ranges among those without initial morbidities.

Discussion

This study evaluates cohort patterns in time spent in disability and/or morbidity in the US by sex, race/ethnicity and level of education. We identified a number of key findings on cohort trends in health from our results. Firstly, consistent with other studies on life expectancy, PC-LE increases across successive cohorts, with females living longer than males at all age ranges. Secondly, life expectancy spent with chronic morbidities has expanded over cohorts, especially among younger age ranges. PC-MFLE of females is much higher compared to their male counterparts. Thirdly, PC-DFLE remains at the same level or grows marginally, but within life expectancy without ADL disability, the proportions of time without chronic diseases decrease significantly. However, PC-DFLE has increased significantly among individuals with one or more morbidities, even though the overall PC-DFLE stays largely unchanged. Lastly, time spent free of both chronic morbidities and disability declined significantly across cohorts for both sexes. Again, females' PC-MDFLE is consistently higher than males' for all age ranges. Nevertheless, PC-MDFLE remains largely unchanged across cohorts when controlling for initial state.

Beyond the population level, we find substantial heterogeneity in PC-LE and PC-HEs by race/ethnicity and level of education. More advantaged subpopulations generally spend more years without disabilities and/or morbidities and longer total life expectancy. Apart from these advantages at the overall level, these subpopulations are also likely to experience improvements in PC-DFLE if they start morbid. These disparities can be most easily spotted between non-Hispanic whites and non-Hispanic blacks, as well as between the lowest education group and the highest education groups. Successive cohorts of lower-schooled individuals with chronic morbidities and non-Hispanic Black individuals with chronic morbidities hardly experience any compression in disability. It is worth noting that, at ages 80-89, there is little expansion or compression of morbidity and disability across cohorts for most subpopulations after controlling for the initial state. This finding likely stems from the

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relatively low life expectancies of these two very selective groups of older individuals, which leaves less time for differences between subpopulations to arise.

We find that increases in both the prevalence of chronic diseases and life expectancy with morbidity are ubiquitous across the birth cohorts and groups in this paper. At the same time, the prevalence of disability and life expectancy with disability are not increasing in tandem with this expansion of time spent with morbidity. These trends appear to contradict either the compression of morbidity speculated by (Fries 1980) or the expansion of morbidity and disability predicted by (Gruenberg 1977). Our results demonstrate that the overarching trend in population health among older Americans is towards an increase in disability-free life years lived with chronic diseases. From a public health perspective, advancements in treatment to control the symptoms and progression of diseases may have played a major role in producing these findings (Crimmins 2015). Broadly constructed, we provide strong evidence that successive cohorts of the US population are experiencing patterns that most closely align with Manton's Dynamic Equilibrium framework (Manton 1982), where life expectancy improvements have resulted from reductions in the severity and rate of progression of chronic diseases.

However, although delays in the onset of disability are observed across successive cohorts for individuals with chronic morbidities, the overall life expectancy free from disabilities has not improved. Even though DFLE for people with chronic morbidities has expanded significantly, DFLE is still much higher for individuals without chronic morbidities. Said another way, the expanding prevalence of chronic morbidities at the population level appears to be an important factor impeding the compression of disability.

Our findings also demonstrate the value of looking beyond a purely disability-based framework for understanding healthy longevity, as suggested by Beltrán-Sánchez et al. (2014). Across cohorts, we find declines in lifetime free of both chronic morbidities and disability, which may translate to rising costs of healthcare, medications, and disability services. These patterns are particularly salient given the age compositional changes occurring in the US population as the baby boom generation enters later life. Current projections estimate that the costs of Medicare-funded health services rise to nearly 6% of US gross domestic product by 2040, up from just under 4% in 2020—a difference largely driven by overall population aging (House of Representatives 2020). However, these projections do not account for changing cohort patterns of morbidity, which could further inflate these costs. Thus, the focus of public health, and public policy, should not be only on reducing the consequences of diseases but also on delaying the onset of chronic diseases (Beltrán-Sánchez et al. 2015). At the individual level, the financial and social costs resulting from a longer time spent with chronic diseases may also explain some of the disparities by race/ethnicity and level of education, as inequality in access to medicines and services could restrict individuals' ability to control the progression, and limit the disabling impacts, of chronic diseases.

There are a few limitations that should be borne in mind when interpreting the results of our estimation. The MSLT model is a Markov model (Schoen 1988), where the immediate future state only depends on the current state and is not impacted by the past trajectory of health states. Although this assumption is common across MSLT estimation methods, there is the potential that it may overlook some unobserved effects from earlier states. Another limitation results from the biannual nature of the Health and Retirement Survey. Our modeling assumes that only one transition occurs between waves. However, in real life, there could be short-term transitions back and forth, and potentially a deterioration in health before death. Morbidity in this paper is defined by a somewhat blunt measure of ever diagnosed with a chronic disease. In addition, our analysis uses a partial cohort measure of healthy longevity. This approach is useful for direct applications of the results because it examines the actual lived experience of a group of individuals in a population, in contrast to aggregated period measures of DFLE and MFLE which instead rely on a synthetic cohort approach. The benefits of this measure have been emphasized in multiple studies (e.g., Beltrán-Sánchez et al. 2016; Manton et al. 2008; Payne 2022). However, results from these partial cohort methods may not always align with patterns of the completed cohort measures, especially in the case of rapid advancements in disease treatment (Payne & Kobayashi 2022). Therefore, these partial cohort estimates should not be understood as a substitute for the estimates of full cohort LE, DFLE, and MFLE.

Future research could potentially extend this paper in several ways. First, the microsimulation approach used in this article provides rich information on the synthetic cohort beyond what is available from a classic MSLT; such detailed information could be used to investigate quantities other than life and health expectancies such as average ages of transition between states. Second, this paper only explores inequality by basic sociodemographic factors, but there are more personal and environmental factors in the model by Verbrugge and Jette (1994) that may be worth consideration and incorporation into the estimation. Third, this paper only includes two dimensions of health, each of which is measured by a binary variable. Prior research has pointed out that different combinations of comorbidity might have different risks

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of disabling older people (Quiñones et al. 2016). However, such nuances are difficult to incorporate in existing multistate life table models, as increasing the number of health dimensions or categories of measurement greatly increases the number of state spaces in the model. As the state-space increases, “the number of transition schedules to be estimated increases multiplicatively” (Saito et al. 2014:216), which makes some observed transitions very rare and thus difficult to estimate. Last, health expectancies are determined by both the initial population structure and the observed schedule of transition probabilities. As mentioned above, the potential compression in disability may be counteracted by expansion in the prevalence of morbidity at the initial age. Therefore, it could be interesting and informative to use a decomposition approach to determine the source of change across cohorts.

Conclusion

In conclusion, this study provides an empirical test of dynamic equilibrium theory, filling in a knowledge gap on how chronic morbidities and disability are interacting across successive cohorts in the US population. We find that partial cohort morbidity-free life expectancy and partial cohort morbidity- & disability-free life expectancy have declined for all age groups, but the partial cohort disability-free life expectancy remains remarkably stable across cohorts. However, this relative stability in disability-free life is underpinned by substantial changes in the population prevalence of chronic morbidities: disability-free life expectancy has increased significantly for most subpopulations (in particular the younger ages) for individuals who start with chronic morbidities. These trends align with dynamic equilibrium theory, and are likely the result of i) improvements in healthcare, which can control the progression of chronic disease, and ii) earlier diagnoses of chronic conditions at less severe stages. Given continued increases in the prevalence of chronic morbidities, our findings suggest that the future trajectory of disability-free life expectancy in the US is increasingly contingent on efforts to improve disease management and avoid the severe consequences of chronic morbidities.

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Table 1. Age, period, and birth cohort comparisons

Period Observed	**1998-2008**	**2008-2018**
Age Group	Early Cohort	Later Cohort
60-69	1934-1943	1944-1953
70-79	1924-1933	1934-1943
80-89	1914-1923	1924-1933

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Table 2. Baseline sample characteristics of the birth cohorts

Age	60		70		80	
Birth Cohort	1934-43	1944-53	1924-33	1934-43	1914-23	1924-33
	Early	Later	Early	Later	Early	Later
N	6,976	4,315	5,278	5,670	3,358	3,525
Sex	(%)	(%)	(%)	(%)	(%)	(%)
Men	45.3	41.9	46.4	43.7	40.5	43.4
Women	54.7	58.1	53.6	56.3	59.5	56.6
Race/ethnicity						
White	74.6	72.1	80.8	74.9	81.0	81.2
Black	16.2	15.9	11.9	15.6	13.0	11.3
Hispanic	9.1	12.0	7.3	9.5	6.0	7.5
Educational attainment						
<HS	24.1	13.5	29.4	22.9	35.9	26.2
HS grad	37.6	32.5	35.8	37.5	35.1	37.2
>HS	38.3	54.0	34.7	39.5	29.1	36.7
1+ ADL-disabled	11.8	11.7	13.8	14.3	22.7	23.1
1+ Morbidity	32.3	38.1	46.7	55.5	56.8	65.8
State						
MF-DF	62.5	57.7	49.1	41.6	36.3	29.4
MF-D	5.2	4.2	4.2	3.4	6.9	4.8
M-DF	25.7	30.6	37.1	44.1	41.0	47.5
M-D	6.6	7.5	9.6	10.9	15.8	18.3

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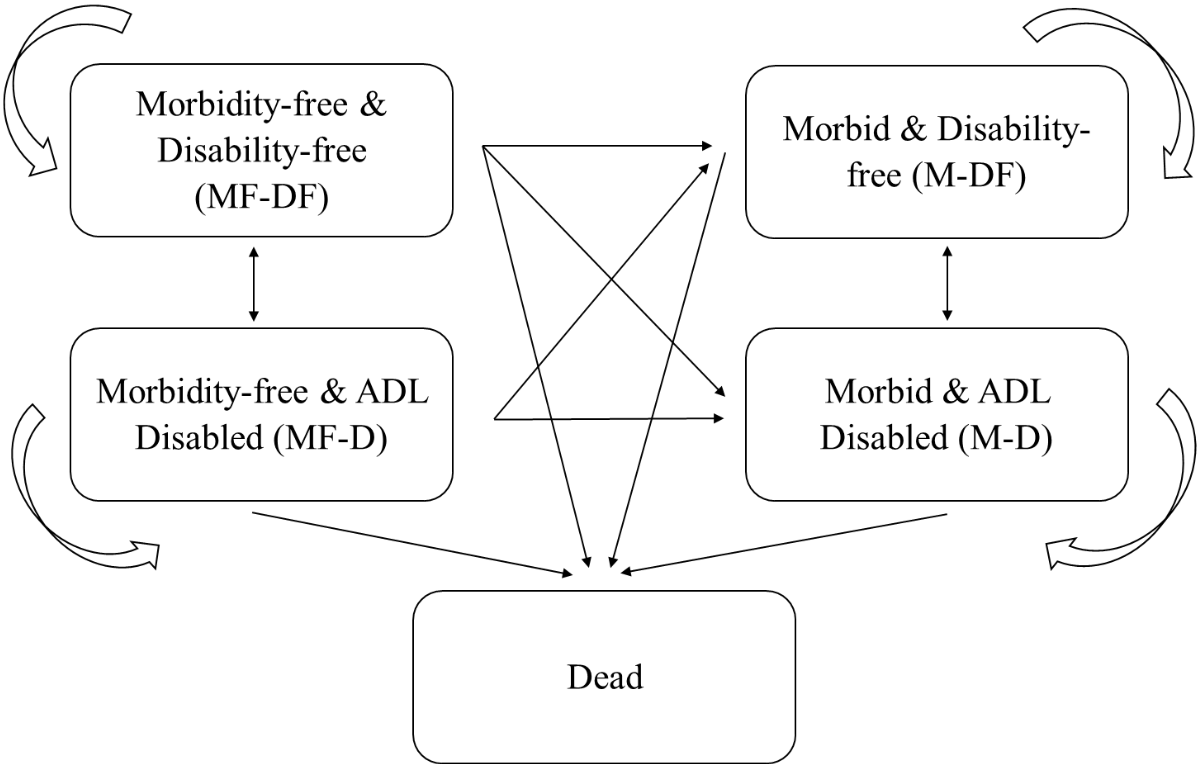

Figure 1. State-space and transition relationships between health states

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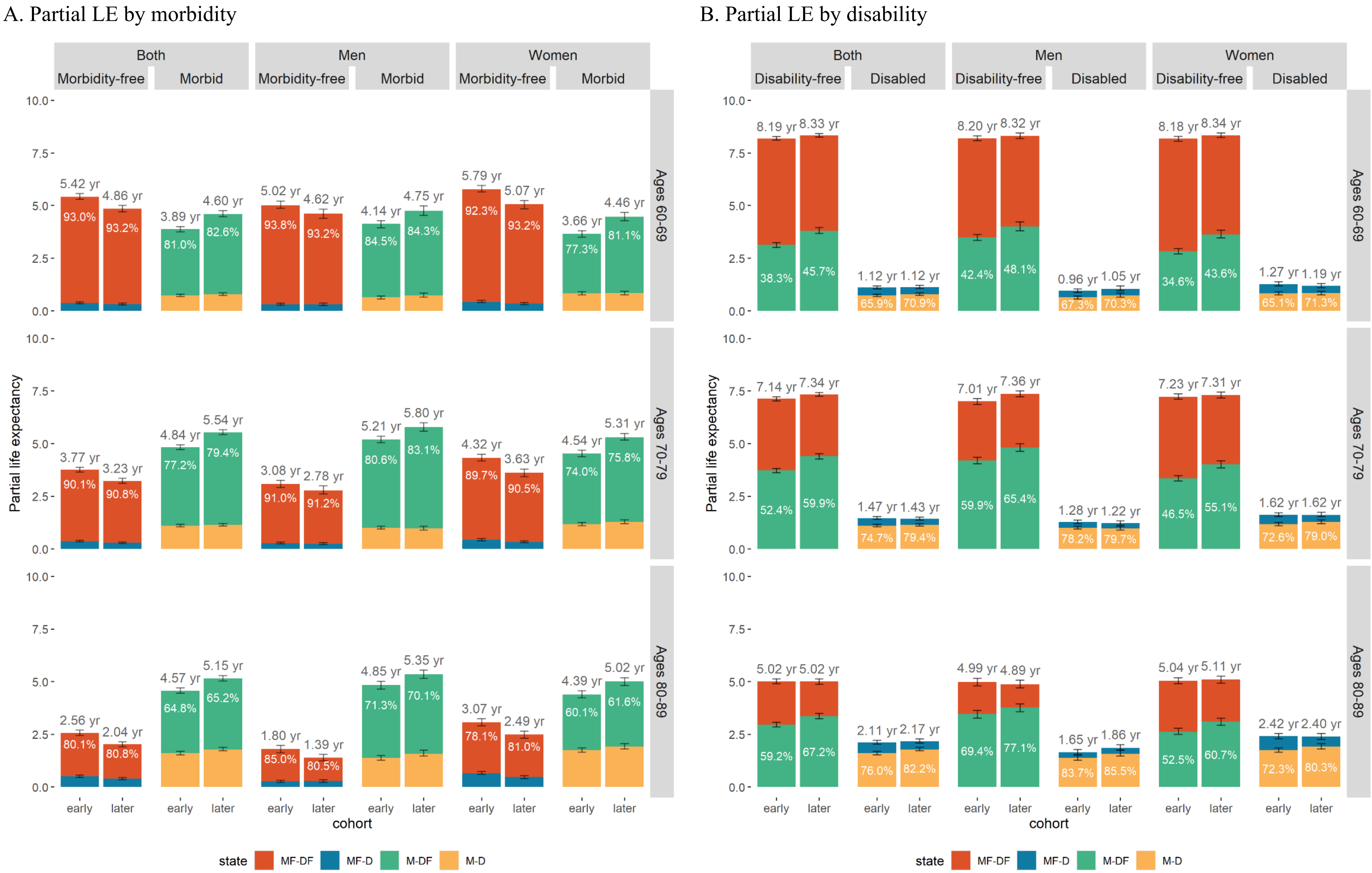

Figure 2. Estimated PC-HE across birth cohorts with 95% CI. *Notes*: The figure above each bar shows the total partial LE of that bar and the percentage figure in each bar shows the precent of partial LE spent in that state (the state beneath the percentage) over the total partial LE of that bar.

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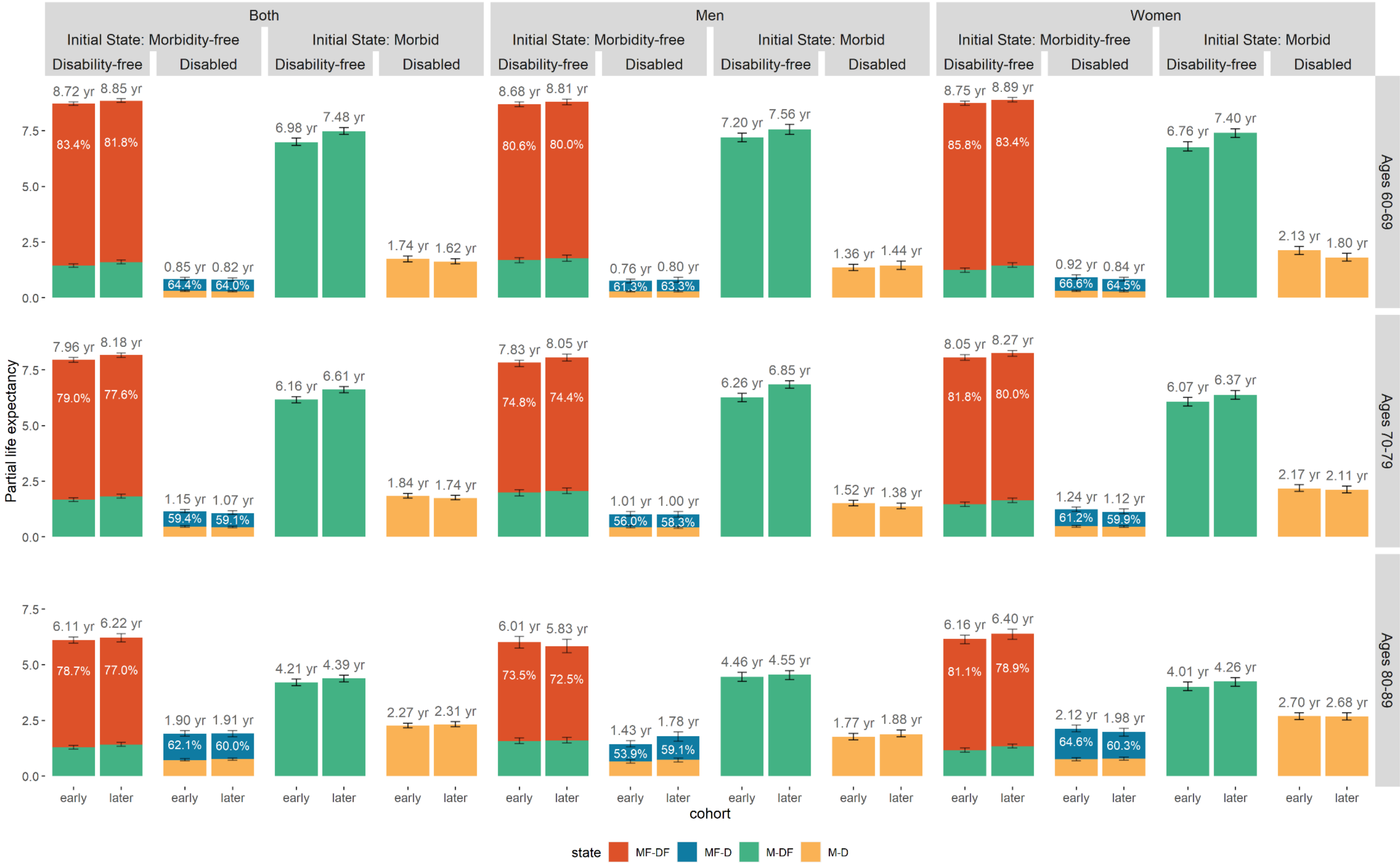

Figure 3. Estimated PC-HE across birth cohorts by initial state of morbidity with 95% CI. *Notes*: The figure above each bar shows the total partial LE of that bar and the percentage figure in each bar shows the precent of partial LE spent in that state (the state beneath the percentage) over the total partial LE of that bar.

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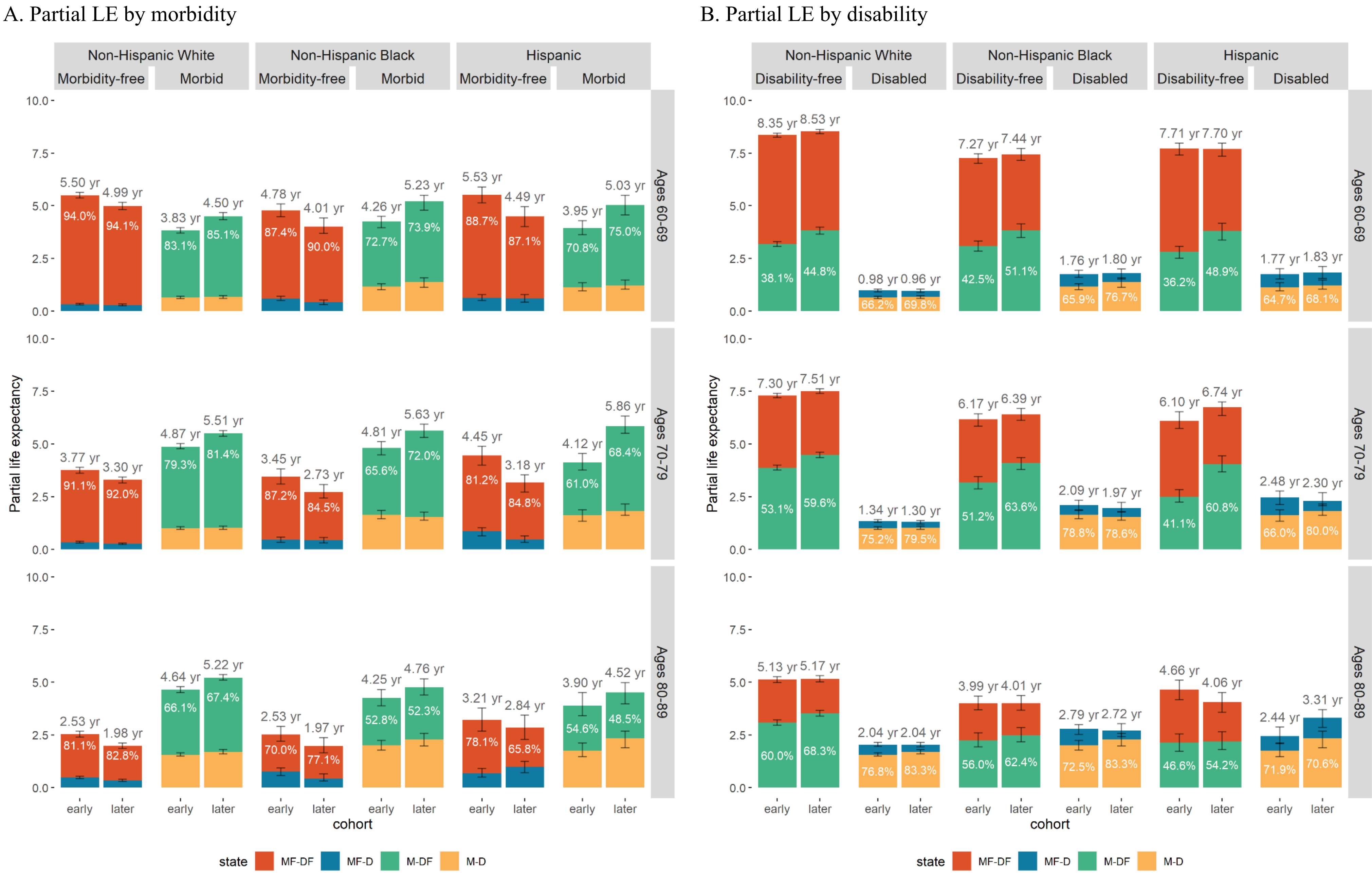

Figure 4. Estimated PC-HE across birth cohorts by race/ethnicity with 95% CI. *Notes*: The figure on top of each bar shows the total partial LE of that bar and the percentage figure in each bar shows the precent of partial LE spent in that state (the state beneath the percentage) over the total partial LE of that bar.

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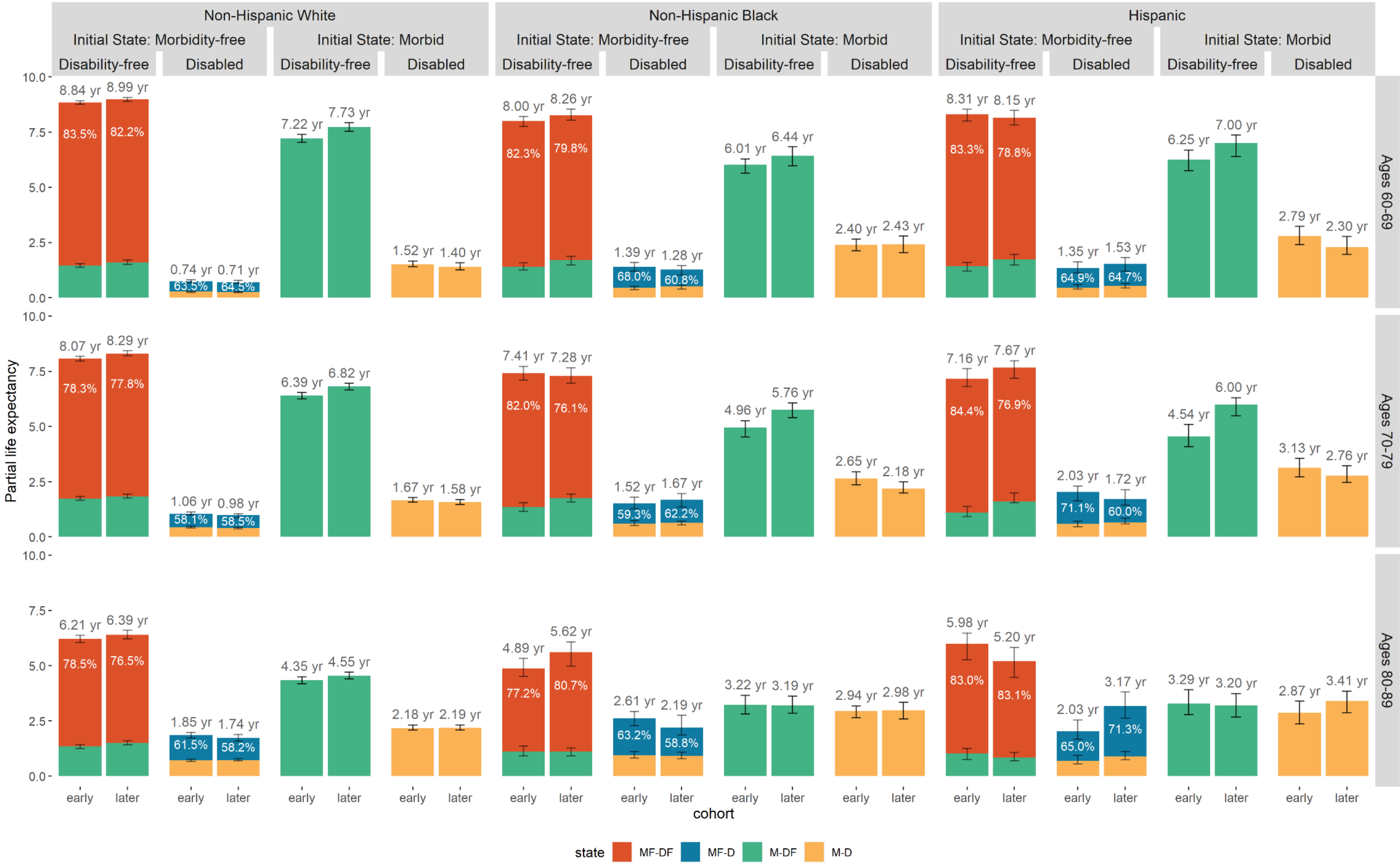

Figure 5. Estimated PC-HE across birth cohorts by race/ethnicity and initial state of morbidity with 95% CI. *Notes*: The figure above each bar shows the total partial LE of that bar and the percentage figure in each bar shows the precent of partial LE spent in that state (the state beneath the percentage) over the total partial LE of that bar.

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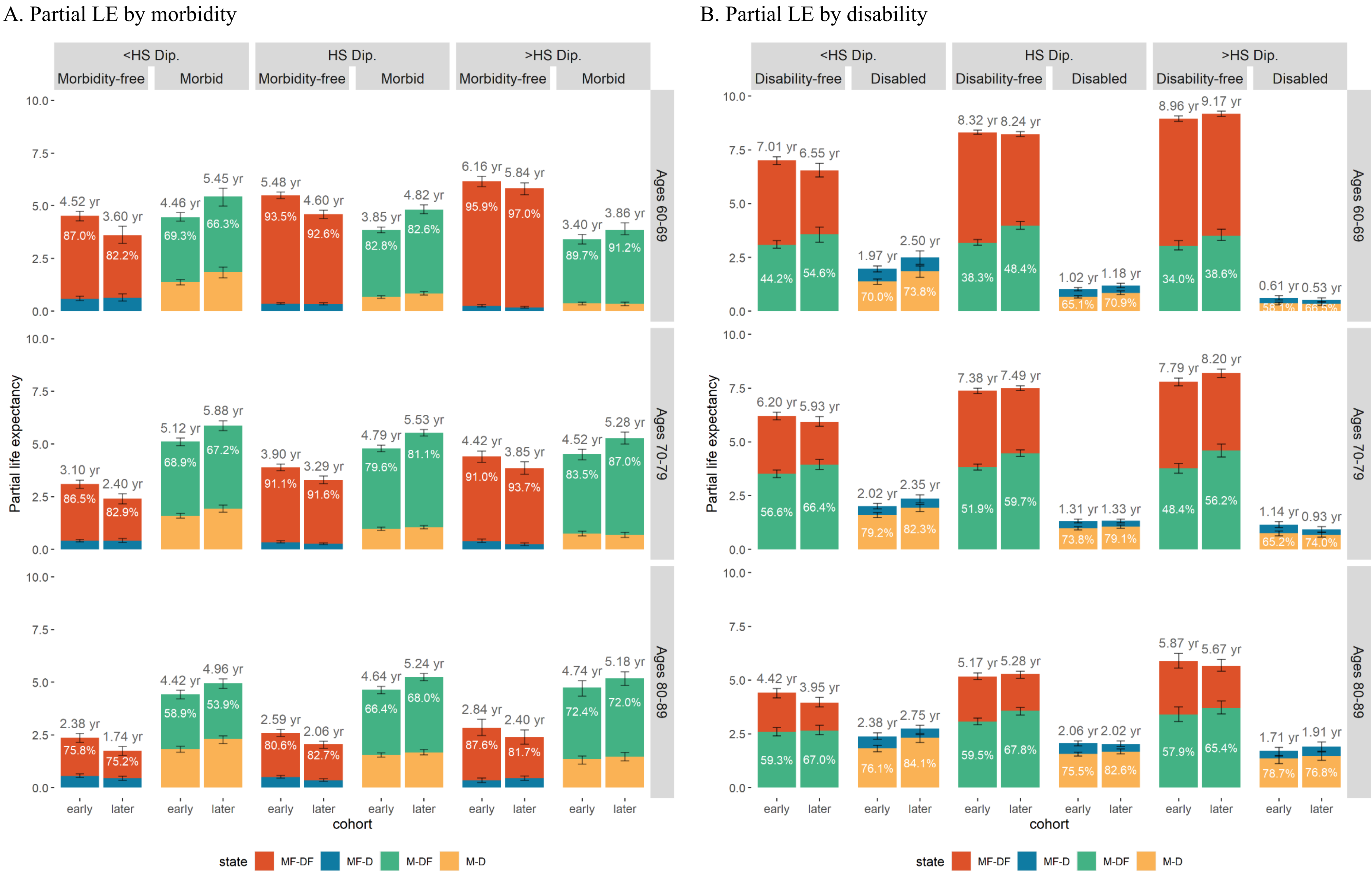

Figure 6. Estimated PC-HE across birth cohorts by educational attainment with 95% CI. *Notes*: The figure above each bar shows the total partial LE of that bar and the percentage figure in each bar shows the precent of partial LE spent in that state (the state beneath the percentage) over the total partial LE of that bar.

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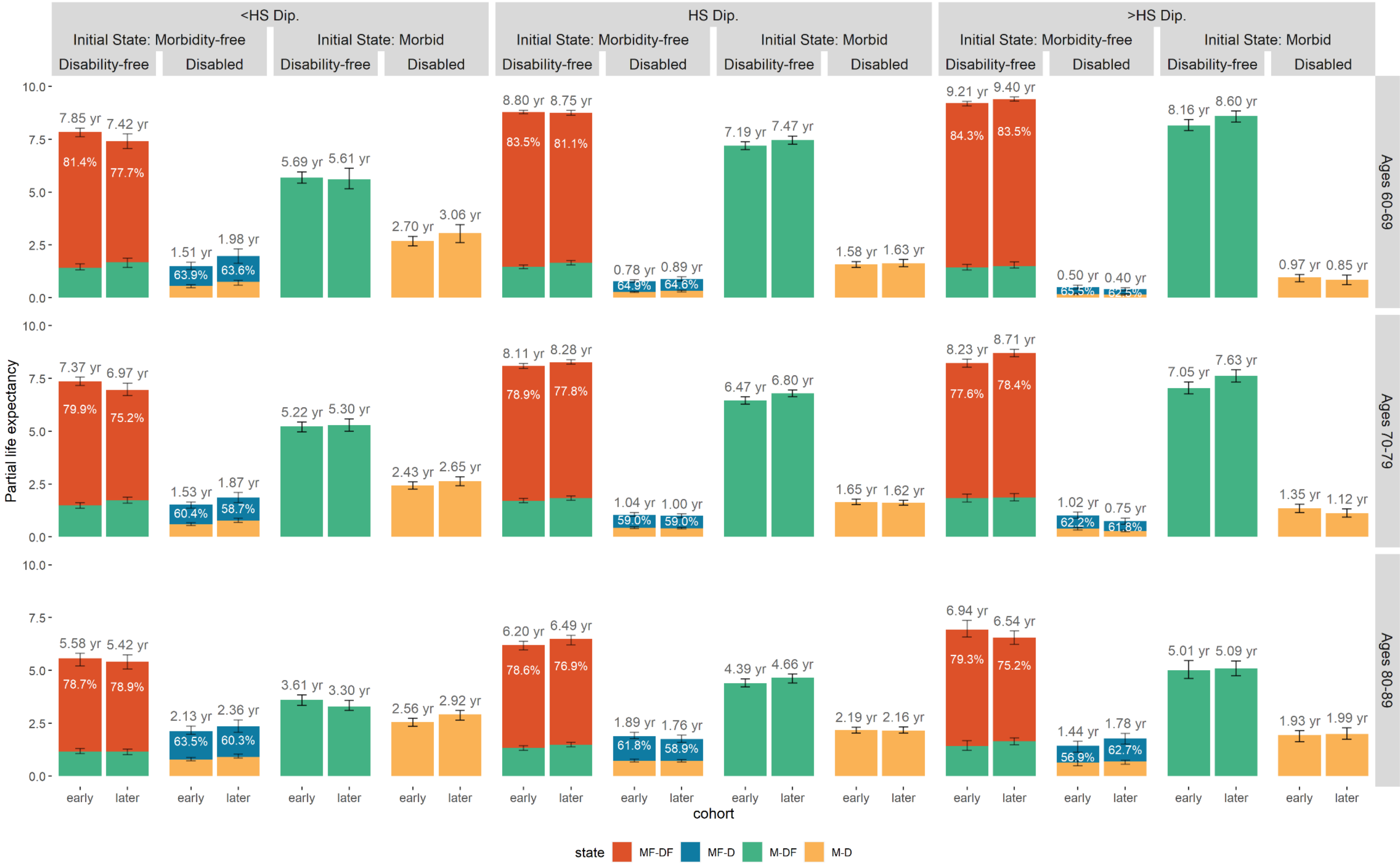

Figure 7. Estimated PC-HE across birth cohorts by educational attainment and initial state of morbidity with 95% CI. *Notes*: The figure above each bar shows the total partial LE of that bar and the percentage figure in each bar shows the precent of partial LE spent in that state (the state beneath the percentage) over the total partial LE of that bar.

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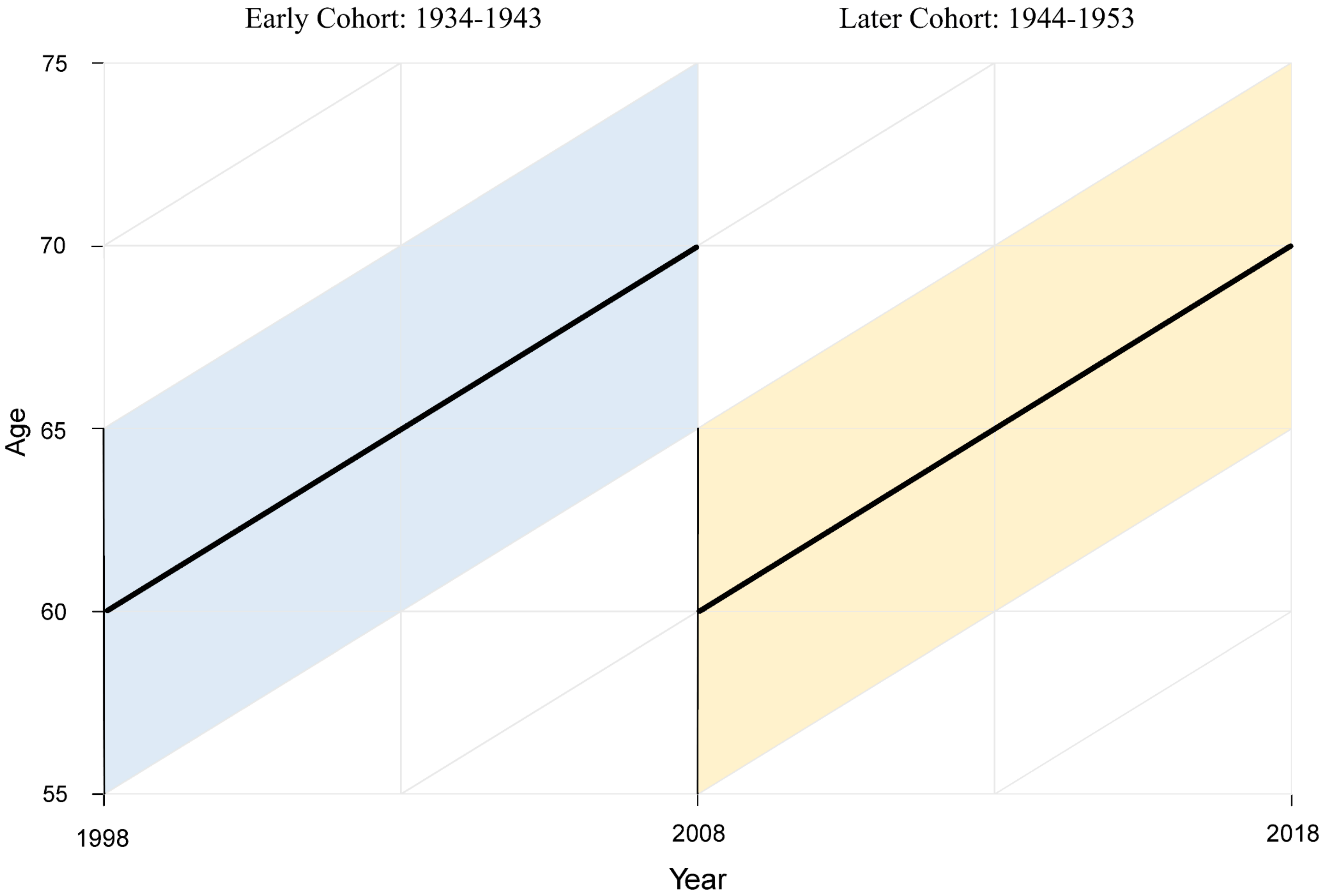

Figure S1. Lexis diagram of birth cohorts 1934-1943 and 1944-1953

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a

b

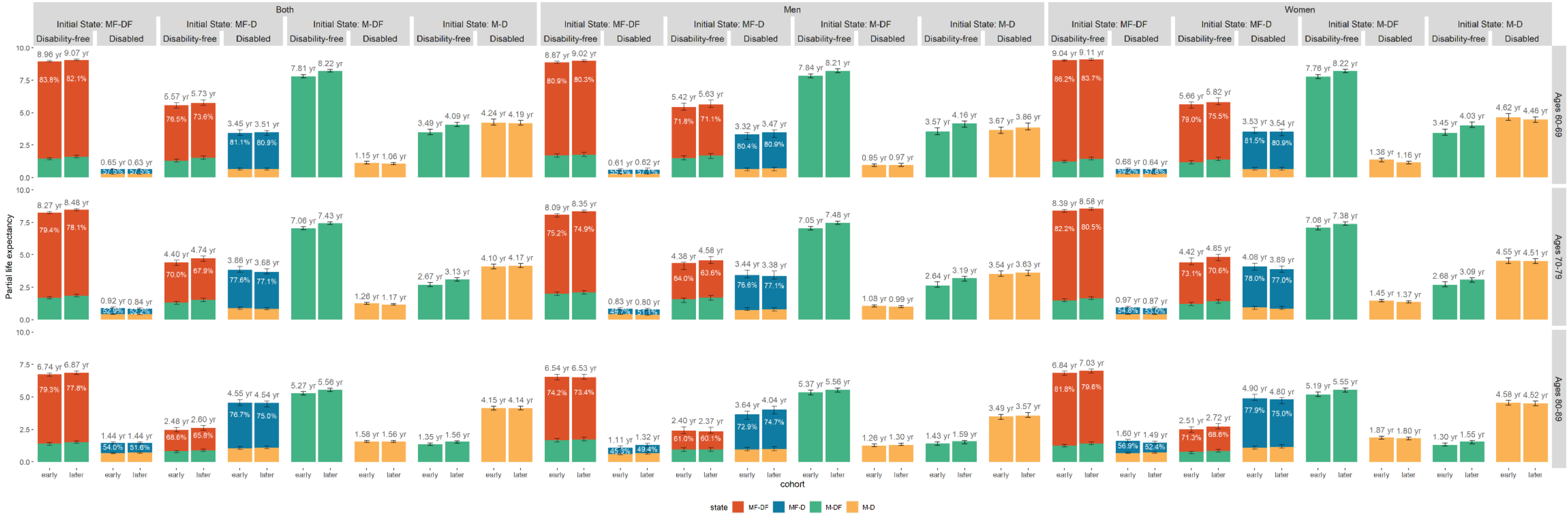

Figure S2. Population

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Figure S3. Racial inequality

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Figure S4. Educational inequality

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