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**Title:** What can lifespan variation reveal that life expectancy hides? Comparison of five high-income countries.

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**Data availability:**

* Data are available in a public, open access repository
* Data are available from the Human Mortality Database: <https://www.mortality.org/>
* Code and analyses used are available from GitHub: <https://github.com/JonMinton/rising_tide> (accessed 22nd September 2020)

# Abstract

## Objectives

Life expectancy at birth (e0) has tended to improve over time in most countries for many decades. However, in recent years the USA and UK have seen progress stall and, in the USA, decline. Lifespan variation is a complementary measure of mortality, which worsened in the USA a few years before the fall in life expectancy at birth. We sought to explore these measures in four other high-income countries—the UK, France, Japan and Canada.

## Design, setting, participants

We calculated life expectancy and life disparity (a specific measure of lifespan variation) in five countries—USA, UK, France, Japan and Canada—using sex-and age-specific mortality rates from the Human Mortality Database for 1975 to 2017. We then examined trends in age-specific mortality to identify the age groups contributing to these changes.

## Main outcome measures

Life expectancy at birth, life disparity and age-specific mortality.

## Results

The UK, USA, and Canada show stalls and falls in life expectancy for both males and females, each preceded by rising life disparity. These changes are driven by worsening mortality in middle-age for males and females in the USA, and males in the UK. Japan, by contrast, continues on previous trajectories.

## Conclusions

This study demonstrates that life disparity is a useful complementary measure alongside life expectancy at birth. Something unusual is happening in mid-age in the USA and the UK when compared to other high-income countries, and policy responses must prioritise interventions that reduce premature mortality and narrow inequalities. Japan’s experience demonstrates that sustained economic growth is not always necessary for continued population health improvements.

# Introduction

Life expectancy at birth (denoted e0) is a highly efficient summary of population health and how it changes over time. In the absence of extraordinary events—such as wars, environmental disasters and pandemics—in recent decades e0 has tended to trend steadily upwards in most populations. Where e0 has fallen, it has usually been associated with major crises, such as the AIDS pandemic, wars, famines, or state collapse (as for populations formerly part of the USSR);1, 2 the final impact of the COVID-19 pandemic cannot yet be ascertained.3

Improvements in e0 over time have been consistent enough in most high-income nations that any stalling of life expectancy trends—i.e., increases slower than the long-term average—demand explanation. Identifying the cause of a falling e0 requires careful examination of mortality data by sex, age group, and cause of death. This is especially important as improvements in some subgroups may, to some extent, compensate for declines or stalls in other subgroups. For example, in the 1980s, concern about the slowdown in what had, until then, been increasing life expectancy in countries of Central and Eastern Europe might have been greater if it had been widely recognised that continued mortality gains in infancy and childhood were obscuring worsening in adult mortality.4 Similarly, a transient slowing in the rate of improvement in life expectancy in Spain in the 1980s concealed an approximate doubling of mortality in young adult men, largely due to HIV/AIDS and road traffic accident deaths.5 Thus, like any summary measure, e0 can conceal details with practical or policy importance, and so should be complemented by other population health measures which may reveal what e0 alone conceals.

Lifespan variation is one such complementary measure. It measures the average gap between an individual’s age at death and their remaining life expectancy at that age.6 Typically, as life expectancy increases, lifespan variation decreases; those countries with the highest life expectancy also have the lowest lifespan variation.6 This phenomenon has also been observed in other primate species.7

This association suggests a demographic analogue of the political slogan, “a rising tide raises all boats”: as the tide (life expectancy) increases, so the individual mortality risks at different ages (the ‘boats’) will each fall, often in lockstep. If they do not, then lifespan variation will increase rather than decrease. In the USA, for example, life expectancy increased by approximately 10% for men and 5% for women over 1980-2014, but lifespan variation fluctuated then increased.8 Life expectancy in the USA then declined every year since 2015,9 driven by what have been termed “deaths of despair”,10, 11 from alcohol, other drugs, and suicide.11 Authors of one study argued that had lifespan variation been monitored more closely, the mid-life mortality crisis in the USA could perhaps have been identified earlier.8

Here we extend the analysis of lifespan variation to four other high-income countries: the UK, where like the USA, gains in life expectancy have trailed behind those in other industrialised countries,12 Japan, which has seen sustained progress, and France and Canada, neighbours of the UK and USA respectively, which lie in the middle. We show how life expectancy and lifespan variation in combination can be used to a) identify changes that could otherwise be missed and b) detect changes in trends earlier.

# Methods

## Data source

We extracted sex- and age-specific mortality rates from the Human Mortality Database (HMD) from 1975 until the latest available year (2017 or later) for the USA, Japan, UK, France, and Canada. Ethical approval was not required.

## Analytical approach

First, we report e0. Second, we measure life disparity using the method developed by Vaupel et al.6 The code and analyses undertaken can be found on Github[[1]](#footnote-1). Finally, we present trends in age-specific mortality to identify which age groups contributed to these changes.

# Results

Figure 1 shows the contribution of deaths at different ages to overall life disparity using the example of Japan for 1947, 1975 and 2017. The top panel shows improvements in period survival by age over time, with age on the x axis and the proportion of people surviving to a given age on the y axis. Over time, as people live longer, the curve shifts to the right. The lower panel shows the contributions to life disparity of different ages: infancy on the left, early childhood and adulthood on the right. In 1947 life disparity was driven both by infant mortality and deaths throughout working and retirement ages, but the dramatic fall in deaths in younger people means that, by 2017, lifespan disparity is largely due to variations in age of deaths at older ages.

Chart, histogram

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Figure 1: Changing mortality hazard and lifespan disparity contributions in Japan, 1947, 1975 and 2017

Figures 1a and 1b in the web appendix repeat Figure 1 for the USA, to allow a USA-Japan comparison. This shows that lifespan disparity was higher in Japan than the USA in 1947, but by 2017 was higher in the USA, with both infant mortality and older working and retirement age mortality risks higher, and ‘spread across’ older adult ages.

## Life expectancy at birth and life disparity

Next, we present trends in life expectancy at birth and life disparity for each country from 1975 to at least 2017. Japan has had the highest e0 for females since approximately 1980 and for males from 1975, and it improved annually, except for a brief fall after 2011, coinciding with the Tōhoku earthquake and tsunami, when almost 16,000 people were killed on one day.13 For females, the USA and UK consistently perform worst, with stalling from 2010 onwards. A similar pattern is seen for males, although France also appears to perform poorly. Canada shows steady progress for both males and females, with a slight stalling seen for males in most recent years.

For life disparity, all countries demonstrate a downward trend between 1975 and 2000, albeit with a transient interruption among males in France and the USA in the 1980s and among females in Japan in the 1990s. Since 2010, life disparity has increased markedly in Canada and the USA, and slightly in the UK, also. In Japan, life disparity increased in 2011 for males especially, which may reflect the impact of the earthquake, before falling again.

Chart

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Figure 2: Life expectancy at birth (top) and life disparity over time (bottom) 1975 to 2017

Figure 3 zooms in on life disparity since 2000, since the majority of changes occur after 2010. Increases in life disparity in USA, Canada, and the UK are even clearer.

A close up of a map

Description automatically generated

Figure 3: Life disparity for females and males 2010 to 2017

## Probability of dying in the next 12 months

Which age groups are driving changes in life disparity? To answer this, we next examine 12-month death risks at birth, 40, 80 and 90 years of age (see White13 and Christensen14). In Figure 4, the y axis is log scale; a straight line means constant percentage rate reduction per year over time. For some countries/ages, such as older Japanese females, the series looks like a straight line, but for others it does not. At aged 40 years, Figure 4 shows a reversal of improving trends in mortality for all countries since 2010, more marked in some populations.

A close up of a map

Description automatically generated

Figure 4: Probability of dying in the next 12 months by age in years, 1975-2017

At under 1 year (age 0), previously declining trends reversed in the UK, France and Canada, in females, and in males for the UK and France. Although the USA has the highest risk, trends have not reversed. Conversely, at aged 40, the USA has markedly higher risk for both males and females, clearly increasing since 2010, more markedly in males. In Canada, and the UK, risk at age 40 increased more recently. In France, trends continued to improve. At ages 80 and 90 years, the USA no longer has the highest risk; the UK does.

## To what extent are mortality trends at different ages log-linear in the five countries?

As it would require 111 graphs to show the series in Figure 4 for all ages, we instead summarise the consistency in improvement by calculating the correlation in logged age-specific mortality rates at different ages over a fixed period of time, as R-squared for each individual age. If traditional demographic forecasting assumptions are correct,15 (see Box 1) the correlation in logged mortality rates over time, within a population, should be close to 1; a high R-squared indicates straighter, more consistent and continual improvement over time.

Box 1: Demographic assumptions underlying analysis for Figure 5

This analysis draws on two key assumptions made in some of the most well-used families of demographic forecasting models, starting with Lee-Carter’s paper:15

1, Mortality trends at all ages within a high-income population (USA in the original example) change at similar percentage rates over time, improving in ‘lock step’ with each other, and

2. This percentage rate of change over time remains constant over long periods, referred to as the population’s ‘drift’ parameter in the modelling approach.

Both of these assumptions, that there remains a fixed ‘drift’ in improvement, and that this ‘drift’ affects all ages’ percentage mortality change over time equally, can be investigated empirically. If the assumption of a fixed ‘drift’ in improvement were appropriate, then the model fit (R-squared) of log mortality at each age over time would be close to 1; and if the assumption that this ‘drift’ applies to all ages equally were appropriate, then the correlation (r) in log-mortality rate trends at all ages would be close to 1. This modelling assumption can be explored empirically by calculating the correlation in logged age-specific mortality rates at different ages over a fixed period of time. If the assumption were appropriate, then the correlation in logged mortality rates over time, within a population, will be close to 1.

Figure 5 shows the extent to which mortality trends at different ages are log-linear in the five countries.

A close up of a map

Description automatically generated

Figure 6: Linearity in log mortality improvement rates, males and females, 1975 to 2017

If mortality trends at all individual ages are log-linear, a horizontal line at ‘1’ will be seen for all populations. Dips below 1 indicate that for some ages, trends are less consistent and continuous. In general, trends are largely log-linear between age 0 and around 55-80 years for all populations. Deviations from log-linearity are more pronounced above age 80-90, and in younger working ages; differences between countries are also greatest at these ages, which also differ by sex. The greatest departure from log-linearity is in the USA, most pronounced near age 30, and in the USA (and the UK for males) departure from log-linearity begins at younger elderly ages than in other populations.

The key finding is how different the trajectories for the UK and USA are to those of France, Canada and Japan. There has not been consistent improvement in young adulthood in males in the UK, and both sexes in the USA, suggesting something unusual is occurring in these cohorts. It could be that the deviation from linearity is due to faster improvements in these than other groups, but as Figure 4 shows, this is not the case.

This approach represents a novel contribution, as the deviation from log-linear improvements points to factors that impact adversely on those of working age that, in the first instance, affect lifespan disparity, and eventually male life expectancy trends.

# Discussion

We tested two demographic assumptions. First, that lifespan variation decreases as life expectancy increases.6 Second, that mortality improvements at different ages should occur in ‘lockstep’ with each other, demonstrating linearity.15, 16 Of the 5 countries examined, the USA, UK and Canada have deviated from improving trends in both life expectancy and lifespan variation. In addition, even though the assumptions of log linearity and correlation in trends at different ages were built into a model designed to forecast mortality trends in the USA, we can see that it is within the USA that the greatest violations in these assumptions are observed, followed by the UK. By contrast, both types of assumption largely hold for Japan, and, to a lesser extent, France.

In the USA, UK and Canada, the departure from previously improving trends in life expectancy was preceded by increases in life disparity, driven by an increase in working-age mortality. These findings reiterate the importance of looking beyond life expectancy.17

## What is happening in mid-age in the UK and the USA?

The USA has seen an unprecedented reversal in life expectancy, with decreases seen every year since 2015.18 Immediate causes include mid-age ‘deaths of despair’ (deaths from suicide, drug and alcohol overdoses, and alcoholic liver disease),10, 11 and more recently stagnation in rates of cardiovascular diseases (CVD) mortality improvement, which improved markedly from 1970 to 2010.19 Other research finds that these largely reflect ‘worsening health among working-age individuals of lower socioeconomic status’. This is consistent with evidence that increasing numbers of people are experiencing ever more precarious lives. 17

Similarly, the UK has had a decade of worsening health outcomes: stalling life expectancy, rising infant mortality rates, widening inequalities and failure to maintain growth in health and social care spending in line with demand, with many attributing these adverse trends to austerity policies.20, 21 Looking within Europe, although both the UK and France saw slowing of improvements in CVD mortality prior to 2010, only the UK saw absolute worsening in non-CVD mortality thereafter.22 Furthermore, consistent with the findings of this study, there is now evidence of rising mid-age mortality due to ‘deaths of despair’ in England.23 While the debate continues on whether to prioritise protecting health or the economy during COVID-19, even though this is a false dichotomy,24 it is clear the UK has managed to do neither, with the highest excess mortality in Europe from January to June 2020,25 and the UK one of the worst economic declines when compared with 38 countries where GDP data are available.26

In both the UK and USA, we show that stalling and falling life expectancy was preceded by worsening life disparity, driven by increasing mid-age mortality. This is consistent with evidence that countries that have been successful in increasing life expectancy have done so by reducing premature mortality.6, 27 The more lives saved at younger ages, the stronger the relationship between life expectancy and life disparity.27

## What can be learned from Japan?

Japan is a longevity success story.28 Except when the earthquake hit in 2011, Japan continued to make good progress in the 2010s, while the USA and UK did not.

Japan’s continually improving life expectancy is not simply due to steady economic growth;28 both life expectancy and life disparity trends appear unperturbed by periods of long-term low economic growth; and health inequalities did not worsen,29 although occupational differences in mortality in men aged 30-59 years did change significantly.30 Japan has shown that increasing disparity and stalling life expectancy trends in the UK and USA, during their periods of slower economic growth, are not inevitable, and may be in part due to political choices, including austerity in the UK, and economic and drug policies in the USA.

## What implications does this have for understanding the COVID-19 response?

At the time of writing, COVID-19 dominates both the health and political discourse. We show that life expectancies, life disparities, and midlife mortality trends were less favourable in the USA and UK than comparator nations, even before the pandemic; evidence of higher excess and COVID-related deaths in the USA and UK may therefore be no coincidence. Those countries that entered the pandemic with better and more consistent health trends seem to have avoided the worst effects of the economic shock and been less likely to see excess mortality from non-COVID deaths. These areas of course require further investigation, but it is noteworthy that when both changes to the economy (measured as change in GDP) and confirmed deaths due to COVID-19 are compared, the UK performs worst in both, the USA in number of deaths, and Japan is once again an outlier with substantially lower changes in both measures.26

## Strengths and weaknesses of the study

The Human Mortality Database has rigorous data quality requirements and standardisation procedures, and are widely accepted as reliable for international comparison.31 The methods used to calculate life disparity and probability of dying at 12 months replicate those of experts in the field, and were checked against code supplied by one of the pioneers in using these methods.6, 13, 14 We also examine trends rather than year-on-year changes, as this avoids problems of annual fluctuations.32 We compared the countries with the best and worst rates of average annual increase in period life expectancy at birth, as identified by the ONS,12 thus removing bias from country selection; comparison with geographically and politically similar nations demonstrated reversal of trends is not inevitable, as well as the unexpected finding of Canada’s deteriorating life disparity.

There are some limitations. For example, the UK is treated as a single entity, concealing differences between the devolved nations. This has been shown to be important, for example in Scotland where intentional investment was made to reduce IMR, with good effect, and more recently, the devolved nations varying responses and policy decisions during COVID-19.

Furthermore, the data are aggregated, so it is not possible to examine differences by factors such as race, employment status, and others outlined below. In addition, although political and economic decisions by states are of huge importance in population health, and ‘natural experiments’ are a key way to investigate these,17, 33 unavoidably, it is difficult to assert causality without additional research.34

Finally, examining five countries precluded considering each individual trajectory in depth, or exploring all fluctuations, leaving many unanswered questions. This is considered further under ‘future research’.

## Future research and unanswered questions

These observations should encourage more detailed analyses of each country. Firstly, the ‘social gradient’ in health outcomes is well-documented in both the UK and the USA.35, 36 Examining life disparity through the lens of the social determinants of health—to include analysis of factors such as education, housing, income and employment—would likely reveal deeper inequalities, but may also provide information vital for targeted public health interventions and health policy.

Secondly, these aggregate data do not allow for exploration of the impact of race and ethnicity. As with many health outcomes, in the UK the impact of COVID-19 on people from Black Asian Minority Ethnic backgrounds has been disproportionately high,37 and while official analyses noticeably ignored the role of structural, systemic racism, others called for urgent investigation.38

Thirdly, although the data are presented by gender, further analysis of the differences have not been carried out and are essential to fully understand the implications of what is seen. For example, in England, women in the most deprived areas saw a fall in life expectancy between 2010-2012 and 2016-2018.36 Fourthly, Canada was selected as a geographical neighbour to the USA, but revealed an unexpected finding. This requires further investigation of its own into health inequalities in Canada.

# Conclusion

The data presented here show that the worsening of life expectancy and life disparity in the USA and the UK were not inevitable, and neither are continuing adverse trends. France and Japan both experienced periods of downturn but recovered and have been able to continue with improving trajectories in both life expectancy and life disparity. Governments must focus on reducing inequalities, and in particular premature mortality, in order to improve life expectancy and to decrease life disparity.

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