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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 progress has stalled in the UK and declined in the USA. Lifespan variation is a complementary measure of mortality, which increased 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, the UK and Canada 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 an 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 substantially 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, but recent analysis for the UK shows a fall in e0 of 0.9 and 1.2 years for females and males, respectively.3

Increases in e0 over time have been consistent enough in most high-income nations that any stalling of life expectancy trends—i.e. prolonged 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 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 (LV) is a term for a class of complementary measures to e0, which measure the variability of age at death among individuals within a defined population.5 Typically, as e0 increases, LV decreases; those countries with the highest e0 also have the lowest LV:6 a phenomenon also observed in other primate species.7 The measure of LV we use is life disparity (LD), which measures the average gap between an individual’s age at death and their remaining life expectancy at that age.6 Some have argued that LD has a ‘crucial’ public health interpretation, not least because LD can differ between societies with similar life expectancies.8 9

One example of the public health interpretation comes from research by van Raalte et al which showed that in the USA, where e0 increased by approximately 10% for men and 5% for women over 1980-2014, LV (measured as standard deviation) fluctuated then increased.10 e0 in the USA then declined every year since 2015,11 driven by what have been termed “deaths of despair”,12 13 from alcohol, other drugs, and suicide.13 Researchers concluded that had LV been monitored more closely, the mid-life mortality crisis in the USA could perhaps have been identified earlier.10

To explore the added value of LV in population health statistics and the recent divergence of e0 trends in the UK as well as the USA, we extend the analysis of LV to four other high-income countries: the UK, where like the USA, gains in e0 have trailed behind those in other industrialised countries,14 Japan, which has seen sustained progress, and France and Canada, neighbours of the UK and USA respectively, which lie in the middle. We explore if e0 and LV in combination can be used to a) identify changes that could otherwise be missed and b) detect changes in trends earlier.

# Terminology

To ensure consistency and understanding of the terms used throughout this paper, Box 1 provides definitions from leading experts in the fields of demography and population health, with references for further reading.

|  |  |  |
| --- | --- | --- |
| Term | Definition | Source |
| Age-standardised mortality rate (ASMR) | A mortality rate that can be calculated based on age-specific mortality rates for two or more populations, based on applying these populations’ separate age-specific mortality rates to a common (‘reference’ or ‘standard’) population age-structure. A number of different standard age structures exist; the [European Standard Population](https://ec.europa.eu/eurostat/documents/3859598/5926869/KS-RA-13-028-EN.PDF/e713fa79-1add-44e8-b23d-5e8fa09b3f8f) is one of the most commonly used. Without using a standard population structure, differences in average mortality rates in a population may be due to differences in population structure rather than age-specific mortality risks, as with comparisons between (typically older) Northern European populations and (typically younger) Sub-Saharan African populations. |  |
| Life expectancy | A population-based statistical measure of the average number of years a person has before death. Life expectancies can be calculated for any age and give the further number of years a person can, on average, expect to live given the age they have attained.  Life expectancy of a population at a certain point in time reflects the average number of years and individual would live if they faced during their entire life the current ASMRs thus it gives the expected average length of life based on the current mortality pattern. Because age-specific mortality rates change over time, life expectancy does not accurately predict the actual number of years an individual will live. | Office for National Statistics (ONS), 202015  Smits and Monden, 200916 |
| Life expectancy at birth, (e0) | Life expectancy at birth can be denoted as e0, life expectancy at 5 years old as e5, and so on.  e0 is often simply referred to as life expectancy and is the most common metric of survival. It is the hypothetical average age at deaths given age-specific death rates in a given year. | Van Raalte AA et al, 201810 |
| Lifespan variation (LV) | Lifespan variation is a class of measures which calculate the amount of heterogeneity in age at death across all individuals in a population.  LV can be measured by using an index of variation or inequality. | Seamen et al, 20195  Van Raalte AA et al, 201810 |
| Life disparity (LD) | Life disparity is one measure of lifespan variation, representing the average remaining life expectancy at the age when death occurs.  It is a measure of life years lost due to death. | Vaupel JW et al, 20116 |
| Threshold age | Calculated from life tables, the ‘cut-off’ age where averting deaths before that age reduces LD, and averting deaths after it increases LD. | Zhang and Vaupel, 200917 |

# Methods

## Data source

We extracted sex- and age-specific mortality rates from the Human Mortality Database (HMD) from 1947 until the latest available year (2017 or later) for the USA, Japan, UK, France, and Canada. We present data from 1975 to the latest available year, unless otherwise stated. Ethical approval was not required.

## Analytical approach

First, we report e0. Second, we measure LV using LD, replicating the method developed by Vaupel et al.6 Box 2 provides an overview of this methodology, for which the full 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.

|  |
| --- |
| Life disparity calculations Life disparity (denoted e†) is defined as ‘the average remaining life expectancy at the ages when death occurs’. It is calculated by summing up age-specific contributions for all ages up to a maximum lifespan age (ω) which in our calculations is set to 100 years of age. These age-specific contributions are defined as the product of ex and fx, where ex is defined as the remaining life expectancy at age x and fx the lifetable distribution of deaths up to age x. See the supplementary appendix to Vaupel, Zhang and van Raalte (2011) for a more complete definition.  The values shown in the bottom row of figure 1 are these age-specific contributions, exfx, with select values of age, x, on the horizontal axis. The values shown in the bottom row of figure 2 are life disparity (e†), which is the sum of these age-specific contributions up to age ω. All calculations are based on period lifetables. |

# Results

Figure 1 shows the contribution of deaths at different ages to overall LD 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 due to ‘compression of mortality’ or the ‘rectangularisation’ of the survival curve: mortality decreases are steeper at younger than older ages.18 19

The lower panel shows the age-specific components of LD of different ages: infancy on the left, early childhood and adulthood on the right. In 1947, LD 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, LD is largely due to variations in age of deaths at older ages.

Chart, histogram

Description automatically generated

Figure 1: Changing mortality survivorship curve and life 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 LD 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 LD 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 rank lower than the other countries, with stalling e0 from 2010 onwards. A similar pattern is seen for males, but with France following a similar trajectory to the UK. Canada shows steady improvements for both males and females, with a slight stalling seen for males in most recent years.

For LD, 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, LD has increased markedly in Canada and the USA, and slightly in the UK, also. In Japan, LD increased in 2011 for males especially, which may reflect the impact of the earthquake, before falling again.

Chart

Description automatically generated

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

Figure 3 zooms in on LD since 2000, since the majority of changes occur after 2010. Increases in LD in USA, Canada, and the UK are even clearer. It is important to note fluctuations do occur over time, and in particular for most recent changes such as the UK after 2015, it may be that these are within limits of year-on-year variability rather than predicting future trends. However, whether these fluctuations were significant or not before 2020, a decrease in life expectancy in the UK has already been seen due to the COVID-19 pandemic.20

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 LD? To answer this, we next examine 12-month death risks at birth, 40, 80 and 90 years of age (see White21 and Christensen22). 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 stalled 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.

# Discussion

We aimed to explore whether LV, measured as LD, could a) identify changes that otherwise would be missed and b) detect changes in trends earlier, in the context of the recent divergence from predicted trajectories for e0 in five high-income countries, and thus whether LD could serve as a complementary measure to e0 when examining population health. We found that the USA, UK and Canada deviated from trends in e0 and LD. The departure from predicted trajectories in e0 was preceded by increases in LD, suggesting close monitoring of this measure may have detected these changes earlier. By contrast, existing trends largely held for Japan, and, to a lesser extent, France.

When mortality by age was examined, it seems the increase in LD in the UK, USA and Canada may be being driven by an increase in young- and mid-age mortality. This is consistent with existing research demonstrating the role of reducing premature mortality on decreasing LD.6 17

## Can life disparity be used to detect changes in trends earlier?

An increase in LD in isolation may, however, cause a public health ‘false alarm’. Research exploring two populations with increasing longevity, Japan and Hong Kong, showed that LD can increase where no adverse trends in mortality are occurring at any age, and while e0 continues to increase.8 Conversely, analysis of the burden of COVID-19 on mortality in the UK found lifespan inequality decreased during the first year of the pandemic, while e0 decreased.3 In both examples, the utility of LD is as complementary to e0—a rising LD in the context of stagnating or falling e0 may indicate emerging public health challenges in a given population, and a decreasing LD in isolation does not indicate a healthy population.

The concept of the ‘threshold age’ is another measure which may complement the utility of LD in monitoring population health. The negative correlation between increasing e0 and reducing LD is often due to progress in reducing premature mortality—reducing deaths at older ages can increase LD,6 as demonstrated in the Hong Kong example.8 Zhang and Vaupel classified the different effects of “early” deaths from “late” deaths on LD, separated by the calculation of a ‘threshold age’—averting deaths before that age reduces LD, while averting deaths after increases LD.17 Vaupel et al show the ‘threshold age’ classifies deaths at late ages as premature or early: for example, in Japanese females, deaths up to the age of 85 years were considered premature.6 While considering a death aged 85 years as premature may be counterintuitive for public health and policy makers, monitoring of the ‘threshold age’ through life tables may provide additional insights. In Hong Kong, LD increased alongside increased threshold age with no apparent slowdown in e0 gains.8 By contrast, we show that in the USA LD increased alongside slowdown and decreases in e0. Thus, it may be that the threshold age in the USA also fell, in contrast to the increase in Hong Kong, and a rising LD in the context of stalling or falling threshold age may also indicate population health challenges.

We therefore propose LD can be an early warning of deteriorating population health with the following considerations: where LD has increased, has this coincided with 1) stalling or falling e0, 2) stalling or falling threshold age, and/or 3) been caused by adverse trends in infancy and young/middle-age mortality? If increasing LD is not accompanied by these conditions, it may be a ‘false alarm’ and in isolation is unlikely to be a useful measure.

To explore this possibility, future research could focus on populations where LD increases while threshold age falls, followed by stalling or declining e0. Assuming there is a lag in the impact on e0, this would provide extremely useful early warning of declining population health and potential societal problems. This also gives caution to viewing e0 as a measure of population health in isolation—we suggest it should be considered alongside the measures outlined.

## What are the practical implications of our findings?

Japan has shown that increasing LD and stalling e0 trends in the UK and USA are not inevitable. Except when the earthquake hit in 2011, Japan continued to make good progress in the 2010s and this is not simply due to steady economic growth—both e0 and LD trends continued during periods of long-term low economic growth and health inequalities did not worsen,23 although occupational differences in mortality in men aged 30-59 years did change significantly.24

In the UK and USA, we show that stalling and falling e0 was preceded by worsening LD, with increases seen in young- and mid-age mortality. These findings occur in the context of the unprecedented reversal in e0 in the USA since 2015,25 and a decade of worsening health outcomes in the UK, with stalling e0 since 2014.26 First identified in the USA, in both countries rise in mid-age mortality from ‘deaths of despair’12 13 27 and stagnating rates in improvements from cardiovascular disease moratlity28 29 appear to be important contributors to stagnating and declining e0. In the USA, research suggest that these largely reflect ‘worsening health among working-age individuals of lower socioeconomic status’ consistent with evidence that increasing numbers of people are experiencing ever more precarious lives.30

An historical example of ‘mortality crises’ comes from the breakdown of the USSR in the 1990s in central and Eastern Europe. Aburto et al found the impact of these crises was more pronounced in the fluctuation of LV than e0, and that the changes in LD were due to changes in midlife mortality.31 Furthermore, they found e0 and LD varied independently of each other, in contrast to existing literature. It may be that something similar is occurring in mid-life in the USA and the UK to the former Soviet Union.

Canada?

## 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. While the debate continues on whether to prioritise protecting health or the economy during COVID-19, it is clear the UK has managed to do neither, with the highest excess mortality in Europe from January to June 2020,32 and one of the worst economic declines.33 The USA has one of the highest death rates internationally, and Japan remains an outlier with substantially lower changes in both measures.33 We show that e0, LD, and midlife mortality trends were less favourable in the USA and UK than comparator nations before the pandemic; evidence of higher excess and COVID-related deaths in the USA and UK may therefore be no coincidence.

## Strengths and limitations of the study

The Human Mortality Database has rigorous data quality requirements and standardisation procedures and is widely accepted as reliable for international comparison.34 The methods used to calculate LD 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 21 22 We examine trends rather than year-on-year changes, avoiding problems of annual fluctuations.35 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,14 thus removing bias from country selection; comparison with geographically and politically similar nations demonstrated reversal of trends is not inevitable.

There are some limitations. For example, the UK is treated as a single entity, concealing differences between the devolved nations. Research comparing inequality in age of death in Scotland to England and Wales found Scotland had higher LV due to lower old age mortality and higher premature mortality.36

Furthermore, the data are aggregated, so it is not possible to examine differences by factors such as race, gender, or the social determinants of health such as employment status. This is undoubtedly relevant: evidence from Denmark and Finland showed inequalities in improvements in LV, with stagnation in lower income quartiles and manual occupational classes compared to mortality compression i.e. LV decreases among those in ‘more favourable social positions’.19 37 In addition, evidence from Europe shows those with lower educational attainment not only experience shorter life expectancies, but also greater uncertainty about the age they will die due to higher LV.38

Finally, examining five countries precluded considering each individual trajectory in depth, or exploring all fluctuations.

As such, future research might consider two broad areas. First, the development and testing of complementary measures to e0 for monitoring population health, as outlined above. Second, the public health and policy implications of the findings presented here at both international and national level in order to inform appropriate public health interventions and health policy.

# Conclusion

Life disparity can be a useful complementary measure to life expectancy for use in public health, but not in isolation.

1. Complementary measure / development
2. Results and meaning

The data presented here show that the worsening of life expectancy and LD 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 LD. Governments must focus on reducing inequalities, and in particular premature mortality, in order to improve life expectancy and to decrease LD.

Include summary in conclusion:

To explore this possibility, future research could focus on populations where LD increases while threshold age falls, followed by stalling or declining e0. Assuming there is a lag in the impact on e0, this would provide extremely useful early warning of declining population health and potential societal problems.

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