

# Unravelling the contribution of financial and longevity risks to changes over time in life annuities

Jesús-Adrián Álvarez\*<sup>1</sup> and Andrés M. Villegas<sup>2</sup>

<sup>1</sup>Interdisciplinary Centre on Population Dynamics, University of Southern Denmark

<sup>2</sup>School of Risk and Actuarial Studies and ARC Centre of Excellence in Population Ageing Research (CEPAR),  
UNSW Business School, Sydney, Australia

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## Abstract

Actuaries and risk managers are interested in developing strategies to ensure that changes in interest rates do not affect the value of a portfolio (commonly known as immunization). Similarly, there is a long-standing tradition among demographers to measure how changes over time in mortality affect summary measures such as life expectancy. In this paper, we bring these two perspectives together. We develop a new decomposition method to quantify the contribution of changes in mortality and interest rates to the change in life annuity prices. We introduce neat and intuitive formulations that allow actuaries and risk managers to easily assess stochastic changes in financial and longevity risks embedded in their life annuities' portfolios.

To illustrate our method, we look at the long-term development of life annuity prices using financial and mortality data from the United Kingdom since 1841. We found that there is clear interplay between longevity and financial risk, where the former one is at times masked by high financial risk.

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\*alvarez@sdu.dk

# 1 Introduction

Mortality and interest rates are the driving forces behind fluctuations over time in life annuity factors. Who contributes the most to such changes? mortality or interest rates? This question depends on many factors such as the onset age of calculation of life annuities, time frame of analysis and, of course, the population to be analysed. However, even by considering all those factors, there is not such a tool to disentangle the sources of stochastic change in life annuity factors. The main reason for this is that fluctuations in mortality and interest rates and their impact in life annuities have been widely studied separately but rarely together.[HERE WE SHOULD EMPHASISE WHY IS IT IMPORTANT TO HAVE A METHOD TO ASSESS TOGETHER THESE TWO ISSUES? BESIDES KNOWING WHAT CONTRIBUTES THE MOST, WHAT ELSE CAN WE GAIN BY USING THIS METHOD AND NOT USING OTHER MORE SOPHISTICATED ONES ADDRESSING ONLY LONGEVITY (E.G. LONGEVITY GREEKS)]

## 1.1 Interest rate immunization

Interest-rate immunization (Courtois et al., 2007; Fisher and Weil, 1971; Redington and Clarke, 1951; Santomero and Babbel, 1997; Shiu, 1990) is the starting point for any study dealing with unexpected changes in interest rates (commonly known as financial risk). Duration (denoted by  $D$ ), is the central quantity used in interest-rate immunization and it is defined as the sensitivity of a life annuity (or any other financial product) to changes in the force of interest,  $\delta$  (Charupat et al., 2016; Milevsky, 2013). Modified and dollar durations are the most used types of durations in finance. Both assume parallel shifts in the force of interest (WE SHOULD ELABORATE MORE ON THIS TOPIC).

## Demographic perspective on changes in mortality

Does it exist a similar measure to duration that captures the sensitivity to changes in mortality rates? Mathematical demographers and populations biologists (Demetrius, 1974; Fernandez and Beltrán-Sánchez, 2015; Goldman and Lord, 1986; Hakkert, 1987; Keyfitz, 1968, 1977; Leser, 1955; Mitra, 1978; Vaupel, 1986) have analysed this issue for many decades. In particular, Demetrius (1974); Keyfitz (1977); Leser (1955) introduced an indicator known as the *life table entropy* (denoted by  $H$ ), that measures changes in life expectancy consequent on a proportional change in the force of mortality,  $\mu$ . The higher the life table entropy; the higher the sensitivity of life expectancy to mortality rates (Aburto et al., 2019, 2020; Vaupel et al., 2011).

Several demographers have also been interested in understanding the sources of fluctuations over time in life expectancy (Arriaga, 1984; Beltrán-Sánchez et al., 2008; Beltrán-Sánchez and Soneji, 2011; Pollard, 1988). Key among these contributions is the work done by Vaupel and Canudas-Romo (2003) who develop a neat method in continuous time to separate changes in life expectancy over time in terms of the general pace of mortality improvement,  $\bar{\rho}$ , and the entropy,  $H$ . The advantage of Vaupel and Canudas-Romo (2003) decomposition method relies on the fact that it allows further decomposition of age-specific and cause-specific contributions into the average pace of mortality improvement and entropy.

## Longevity risk immunization

The concept of entropy (Demetrius, 1974; Keyfitz, 1977; Leser, 1955) was first extended to the case of life annuity factors by Haberman et al. (2011). They define the entropy as the sensitivity of a life annuity

to proportional changes in the force of mortality. The entropy is particularly useful in the measurement of longevity risk (unexpected changes of mortality).

Indeed, there is an growing line of research dealing with longevity risk that have used the entropy<sup>1</sup> in the context of mortality rate immunization<sup>2</sup>. In particular, Li and Hardy (2011); Tsai and Chung (2013); Tsai and Jiang (2011); Wang et al. (2010) derive discrete formulas for life annuity entropy and convexities assuming constant and proportional changes in the force of mortality,  $\mu$ . Mortality-rate immunization has been recently extended to different types of life insurance and annuity products (Levantesi and Menzietti, 2018; Li and Luo, 2012a,b; Luciano et al., 2015; Wong et al., 2015). The growing interest on mortality-rate immunization is due to the current scenario that developed countries are facing: low interest rates and continuous mortality improvements. These two factors expose life annuities (and other life contingent products) to higher longevity risk, allowing the capital market of mortality-link securities to grow (Blake et al., 2019).

## Bringing both perspectives together

Literature on analysis of sensitivity in mortality (mostly developed by mathematical demographers) and literature on sensitivity to interest rates (mostly developed by actuaries and financial managers) have remained largely disconnected<sup>3</sup>. Paradoxically, both strands of literature direct efforts at the same objective: gain a better understanding of the inherent sources of risks in life contingent instruments. Recently, Lin and Tsai (2020a) made strides on this regard by deriving discrete formulas to calculate sensitivity of life annuities (and whole life insurances) to simultaneous changes mortality and interest rates. They introduced a synthetic variable called ‘the force of mortality-interest’, which results from the addition of the force of mortality and interest ( $\mu^* = \mu + \delta$ ). While the application of Lin and Tsai (2020a) is interesting since it combines sensitivity in mortality and interest rates, it is unlikely that  $\mu$  and  $\delta$  change at the same pace over time.

In this study, we bring together the demographic and actuarial perspectives to the analysis of changes in life annuities. We develop a new decomposition method to quantify the contribution of stochastic changes in mortality and interest rates to stochastic changes in life annuity prices. We introduce neat and intuitive formulations that allow actuaries and risk managers to easily asses stochastic changes in financial and longevity risks embedded in their life annuities’ portfolios. To illustrate our method, we first look at the long-term development of life annuity prices using financial and mortality data from the United Kingdom since 1841. Next, we forecast trends in mortality and interest rates under various scenarios to gain insights about how both components interplay in future life annuity prices. From the actuarial perspective, our formulations are useful in devising strategies for better risk management (longevity and financial) by leveraging on well-known results from mathematical demography and immunization.

## 2 Preliminaries

All of the quantities expressed here vary over time  $t$ . According to standard actuarial notation, we define the following quantities:

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<sup>1</sup>with the name of mortality durations but it is essentially the same formulation

<sup>2</sup>similar to interest-rate immunization, mortality-rate immunization is defined as a set of strategies to ensure that the value of a portfolio will be little affected in response to changes in mortality rates

<sup>3</sup>with exception of Haberman et al. (2011) that made clear the links between both literatures

- $\mu(x, t)$  is the force of mortality at age  $x$ .
- ${}_s p_x(t) = e^{-\int_0^s \mu(x+y, t) dy}$  is the probability of surviving from age  $x$  to age  $x + s$ .
- $\delta(s, t)$  is the force of interest at time  $s$ . This measure is a general form to express the term-structure of interest rates.
- $v(s, t) = e^{-\int_0^s \delta(y, t) dy}$  is the discount factor, where  $s$  is the length of the interval from issue of the life annuity to death.

The derivative with respect to time  $t$  is denoted by adding a point on top of the function of interest. For example, time derivatives for the forces of mortality and interest are expressed as:

$$\dot{\mu}(x, t) \equiv \frac{\partial \mu(x, t)}{\partial t}, \quad (1)$$

and

$$\dot{\delta}(s, t) \equiv \frac{\partial \delta(s, t)}{\partial t}. \quad (2)$$

The rate of mortality improvement (or progress in reducing mortality) is defined as

$$\rho(x, t) = -\frac{\frac{\mu(x, t)}{\partial t}}{\mu(x, t)} = -\frac{\dot{\mu}(x, t)}{\mu(x, t)}. \quad (3)$$

Similarly, the relative change in interest rates over time is captured by

$$\varphi(s, t) = -\frac{\frac{\delta(s, t)}{\partial t}}{\delta(s, t)} = -\frac{\dot{\delta}(s, t)}{\delta(s, t)}. \quad (4)$$

The actuarial present value of a life annuity at age  $x$  evaluated at time  $t$  is given by

$$\bar{a}_x(t) = \int_0^\infty {}_s p_x(t) v(s, t) ds = \int_0^\infty {}_s E_x(t) ds, \quad (5)$$

where  ${}_s E_x(t) = {}_s p_x(t) v(s, t)$ .

A life annuity deferred  $s$  years starting to be paid at age  $x + s$  is expressed as

$${}_s |\bar{a}_x(t) = {}_s E_x(t) \bar{a}_{x+s}(t) \quad (6)$$

### 3 Dynamics of a life annuity

We are interested on measuring changes in  $\bar{a}_x(t)$  with respect to the time variable  $t$ . To achieve this aim, we first need to describe how  $\bar{a}_x(t)$  reacts to changes in the forces of mortality and interest. We denote the *entropy of a life annuity*<sup>4</sup> as the measure that captures changes in  $\bar{a}_x(t)$  with respect to  $\mu(x, t)$ . Formally,

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<sup>4</sup>Lin and Tsai (2020b); Tsai and Chung (2013); Tsai et al. (2011) denoted this measure as *mortality duration*. We reserve the term duration to denote changes in  $\bar{a}_x(t)$  with respect to interest rates.

it is defined as

$$H_x(t) = \frac{\frac{\partial \bar{a}_x(t)}{\partial \mu(x,t)}}{\bar{a}_x(t)}. \quad (7)$$

The measure that captures the sensitivity of  $\bar{a}_x(t)$  to changes in interest rates is commonly known as *duration* and it is the foundation of interest rates' immunization. For a life annuity, it is defined as the relative derivative of the annuity factor with respect to changes in the force of interest (Milevsky, 2012):

$$D_x(t) = \frac{\frac{\partial \bar{a}_x(t)}{\partial \delta(s,t)}}{\bar{a}_x(t)}. \quad (8)$$

Greater values for  $H_x(t)$  and  $D_x(t)$  indicate that  $\bar{a}_x(t)$  is highly sensitive to changes in  $\mu(x,t)$  and  $\delta(s,t)$  respectively. The entropy and the duration of a life annuity can be measured either by assuming constant or proportional changes in  $\mu(x,t)$  and  $\delta(s,t)$ . In the following section we develop formulations for both cases.

### 3.1 Changes in $\bar{a}_x(t)$ with respect to $\mu(x,t)$

The entropy of a life annuity is denoted by  $H_x^c(t)$  when changes in  $\mu(x,t)$  are held constant at all ages and by  $H_x^p(t)$  when changes are performed proportional. Based on the results developed by Tsai and Chung (2013) and Lin and Tsai (2020b), when  $\mu(x,t)$  is changed constantly to  $\mu(x,t) + \gamma$  such that  $\gamma$  is a small number (see proof in the Appendix), the entropy of  $\bar{a}_x(t)$  becomes

$$H_x^c(t) = -\frac{\int_0^\infty s_s p_x(t) v(s,t) ds}{\bar{a}_x(t)} = \frac{h_x^c(t)}{\bar{a}_x(t)}, \quad (9)$$

where  $h_x^c(t) = -\int_0^\infty s_s p_x(t) v(s,t) ds$ . The term  $h_x^c(t)$  is expressed in absolute (monetary) terms, whereas the entropy  $H_x^c(t)$  is dimensionless because it does not depend on the absolute value of  $\bar{a}_x(t)$ .

In two separate articles, Haberman et al. (2011) and Tsai and Chung (2013) show that when changes in  $\mu(x,t)$  are assumed to be proportional to a small number  $\gamma$  such that  $\mu(x,t)(1 + \gamma)$ , the entropy of  $\bar{a}_x(t)$  becomes

$$H_x^p(t) = -\frac{\int_0^\infty s p_x(t) \ln[s p_x(t)] v(s,t) ds}{\int_0^\infty s p_x(t) v(s,t) ds}. \quad (10)$$

Alternatively, we show (see proof in Section A.2 of the Appendix) that Equation 10 can be expressed as

$$H_x^p(t) = \frac{\int_0^\infty \mu(x+s,t) \bar{a}_x(t) ds}{\bar{a}_x(t)} = \frac{h_x^p(t)}{\bar{a}_x(t)}, \quad (11)$$

where  $h_x^p(t) = \int_0^\infty \mu(x+s,t) \bar{a}_x(t) ds$ . Analogous to the case where changes are assumed to be constant, quantities  $h_x^p(t)$  and  $H_x^p(t)$  are expressed in absolute and relative terms respectively. The formulations shown in this section are closely related to the ones developed in the mortality immunization literature (Lin and Tsai, 2020b; Tsai and Chung, 2013). We extended them to the continuous case.

### 3.2 Changes in $\bar{a}_x(t)$ with respect to $\delta(s, t)$

Similar to the entropy, changes in  $\bar{a}_x(t)$  with respect to  $\delta(s, t)$  can be assumed to be either constant or proportional. Duration assuming constant changes in  $\delta(s, t)$  is denoted by  $D_x^c(t)$ , whereas  $D_x^p(t)$  refers to the duration assuming proportional changes. For the former case we have that:

$$\begin{aligned} D_x^c(t) &= -\frac{\int_0^\infty s_s p_x(t) v(s, t) ds}{\bar{a}_x(t)} \\ &= \frac{d_x^c(t)}{\bar{a}_x(t)}, \end{aligned} \quad (12)$$

where  $d_x^c(t) = -\int_0^\infty s_s p_x(t) v(s, t) ds$ . Thus, assuming constant changes in  $\delta(s, t)$  results into common types of duration known in finance as *dollar duration*,  $d_x^c(t)$ , and *modified duration*,  $D_x^c(t)$  (see Milevsky (2012) and Tsai and Chung (2013) for further details). It is worth noting that Equations 9 and 12 are identical such that  $d_x^c(t) = h_x^c(t)$ . This means that constant (parallel) changes in the force of mortality have essentially the same effect as parallel changes in the force of interest.

Assuming proportional changes in  $\delta(s, t)$  (see proof in Section A.4 of the Appendix) results in:

$$D_x^p(t) = -\frac{\int_0^\infty s_s p_x(t) v(s, t) \ln(v(s, t)) ds}{\bar{a}_x(t)}. \quad (13)$$

Note that when assuming constant force of mortality such that  $v(s, t) = e^{-\delta(t)s}$ , we have that  $D_x^p(t) = \delta(t)D_x^c(t)$ ,

$$\begin{aligned} D_x^p(t) &= -\frac{\int_0^\infty s_s p_x(t) v(s, t) \ln(v(s, t)) ds}{\bar{a}_x(t)} \\ &= -\delta(t) \frac{\int_0^\infty s_s p_x(t) e^{-\delta(t)s} ds}{\bar{a}_x(t)} \\ &= \delta(t) D_x^c(t). \end{aligned} \quad (14)$$

Equation 13 can also be re-expressed as:

$$\begin{aligned} D_x^p(t) &= \frac{\int_0^\infty \delta(s, t)_s \bar{a}_x(t) ds}{\bar{a}_x(t)} \\ &= \frac{d_x^p(t)}{\bar{a}_x(t)}. \end{aligned} \quad (15)$$

where  $d_x^p(t) = \int_0^\infty \delta(s, t)_s \bar{a}_x(t) ds$ .

## 4 Time derivative of $\bar{a}_x(t)$

We compute the derivative of  $\bar{a}_x(t)$  with respect to the time variable  $t$ ,  $\dot{\bar{a}}_x(t) = \frac{\partial \bar{a}_x(t)}{\partial t}$ , such that

$$\dot{\bar{a}}_x(t) = \int_0^\infty {}_s\dot{p}_x(t)v(s,t)ds + \int_0^\infty {}_sp_x(t)\dot{v}(s,t)ds. \quad (16)$$

To develop a closed-form solution for Equation 16 we consider the general case where  ${}_sp_x(t) = e^{-\int_0^s \mu(x+y,t)dy}$  and  $v(s,t) = e^{-\int_0^s \delta(s,t)dy}$ . We analyse separately each of the two terms in the right side of Equation 16. Let us first focus on the first term:

$$\begin{aligned} \int_0^\infty {}_s\dot{p}_x(t)v(s,t)ds &= \int_0^\infty v(s,t)e^{-\int_0^s \dot{\mu}(x+y,t)dy}ds \\ &= -\int_0^\infty v(s,t){}_sp_x(t) \int_0^s \dot{\mu}(x+y,t)dyds \\ &= -\int_0^\infty \dot{\mu}(x+s,t) \int_s^\infty v(y,t){}_yp_x(t)dyds \\ &= -\int_0^\infty \dot{\mu}(x+s,t){}_sE_x(t)\bar{a}_{x+s}(t)ds \\ &= \int_0^\infty \rho(x+s,t)\mu(x+s,t)|\bar{a}_x(t)ds \end{aligned} \quad (17)$$

The second part equals:

$$\begin{aligned} \int_0^\infty {}_sp_x(t)\dot{v}(s,t)ds &= \int_0^\infty {}_sp_x(t)e^{-\int_0^s \dot{\delta}(y,t)dy}ds \\ &= -\int_0^\infty {}_sp_x(t)v(s,t) \int_0^s \dot{\delta}(y,t)dyds \\ &= -\int_0^\infty \dot{\delta}(s,t) \int_s^\infty {}_yp_x(t)v(y,t)dyds \\ &= \int_0^\infty \varphi(s,t)\delta(s,t)|\bar{a}_x(t)ds \end{aligned} \quad (18)$$

Thus,  $\dot{\bar{a}}_x(t)$  can be expressed as

$$\begin{aligned} \dot{\bar{a}}_x(t) &= \int_0^\infty \rho(s,t)\mu(s,t)|\bar{a}_x(t)ds + \int_0^\infty \varphi(s,t)\delta(s,t)|\bar{a}_x(t)ds \\ &= \int_0^\infty \rho(s,t){}_sM_x(t)ds + \int_0^\infty \varphi(s,t){}_sW_x(t)ds, \end{aligned} \quad (19)$$

where  ${}_sM_x(t) = \mu(s,t)|\bar{a}_x(t)$  and  ${}_sW_x(t) = \delta(s,t)|\bar{a}_x(t)$ . We can express Equation 19 in terms of the duration and entropy

$$\dot{\bar{a}}_x(t) = \frac{\dot{\bar{a}}_x(t)}{\bar{a}_x(t)} = \underbrace{\bar{\rho}(t)H_x^p(t)}_{\text{longevity component}} + \underbrace{\bar{\varphi}(t)D_x^p(t)}_{\text{financial component}}, \quad (20)$$

where  $\bar{\rho}(t) = \frac{\int_0^\infty \rho(s,t) {}_sM_x(t) ds}{\int_0^\infty {}_sM_x(t) ds}$  and  $\bar{\varphi}(t) = \frac{\int_0^\infty \varphi(s,t) {}_sW_x(t) ds}{\int_0^\infty {}_sW_x(t) ds}$  are the average paces of change in mortality and interest rates respectively. Functions  $\bar{\rho}(t)$  and  $\bar{\varphi}(t)$  capture the stochastic change in the forces of mortality and interest whereas  $H_x^p(t)$  and  $D_x^p(t)$  capture the sensitivity due to changes in  $\mu$  and  $\delta$ . In other words, Equation 20 entails that changes over time in  $\bar{a}_x(t)$  are driven by  $\bar{\rho}(t)$  and  $\bar{\varphi}(t)$ , which are modulated by  $H_x^p(t)$  and  $D_x^p(t)$  respectively. Equation 20 is an extension of the decomposition formula to changes over time in life expectancy developed by Vaupel and Canudas-Romo (2003). Here we extended it to life annuities.

## 4.1 Assuming constant force of interest

It is common to use a single interest rate (without using the term-structure of interest rates,  $\delta(s,t)$ ) for the calculation of life annuity factors. Thus, we re-express the decomposition formula for  $\bar{a}_x(t)$  by assuming  $v(s,t) = e^{-\delta(t)s}$ . This assumption affects only the second part of Equation 16:

$$\begin{aligned} \int_0^\infty {}_s p_x(t) \dot{v}(s,t) ds &= \int_0^\infty {}_s p_x(t) \frac{\partial [e^{-\delta(t)s}]}{\partial t} ds \\ &= -\dot{\delta}(t) \int_0^\infty {}_s p_x(t) e^{-\delta(t)s} ds \\ &= \dot{\delta}(t) d_x^c(t). \end{aligned} \tag{21}$$

Substituting Equations 17 and 21 in Equation 16 results into:

$$\dot{\bar{a}}_x(t) = \bar{\rho}(t) H_x^p(t) + \dot{\delta}(t) D_x^c(t). \tag{22}$$

Given that  $D_x^p(t) = \delta(t) D_x^c(t)$  (see Equation 14), it is straight-forward to show that in the case of a single interest rate, Equations 20 and 22 are equivalent. Thus, it suffices to use the entropy ( $H_x^p(t)$ ) and the modified duration ( $D_x^c(t)$ ) together with  $\bar{\rho}(t)$  and  $\dot{\delta}(t)$  to determine the contribution of financial and longevity risks to changes over time in life annuities.

## 4.2 Recap of formulations

[Here I am planning to add a table with all the formulas, I will do it at the end]

# 5 Historical contribution of mortality and interest to changes in life annuities

In this section we illustrate the decomposition method developed in Section 4 by examining the long-term development of life annuities in the UK. We use two centuries of data from 1841 to 2018. Age-specific mortality rates come from the (Human Mortality Database, 2020). Long-term interest rates are represented by the yield on 2.5% consols up to 2015, then by the yield of 20 year maturity bills (Bank



of England, 2020). We smoothed mortality and interest rates using splines (Camarda et al., 2012; Green and Silverman, 1993) to obtain continuous estimates of the forces of mortality and interest respectively (Figure 1). Using our estimates of  $\mu$  and  $\delta$ , we construct time series for life annuities at different ages and for both sexes. In this section we first focus on life annuity factors calculated for males at age 65. Then, we extend the analysis to both sexes and older ages (i.e. 70 and 75) to understand how the longevity and financial components react to different onset ages.

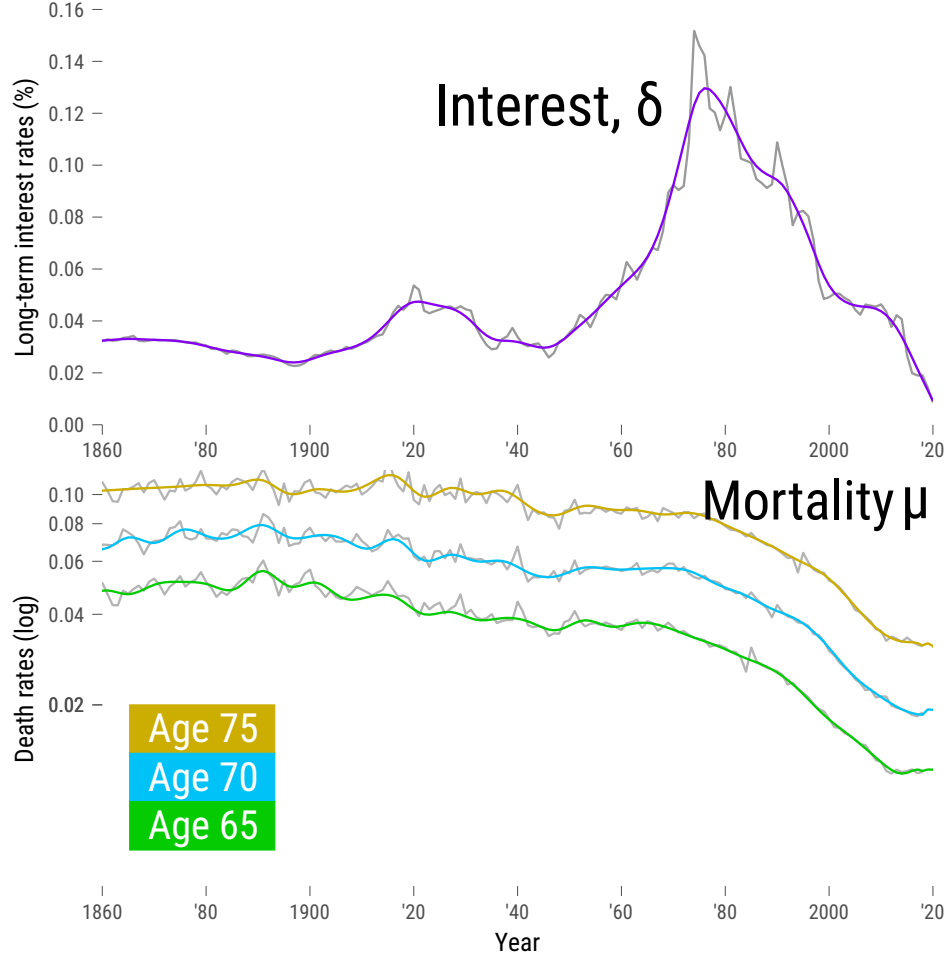


Figure 1: Trends over time in interest and mortality rates calculated at ages 65, 70 and 75. Males, 1841-2018.

How has the value of life annuities changed over time? Figure 2 (upper panel) depict values for  $\bar{a}_x(t)$  from 1841 to 2018 for males at age 65. We observe that during the second half of the 19th century and up to the decade of 1940s,  $\bar{a}_{65}(t)$  remained at similar levels with small fluctuations. Thereafter,  $\bar{a}_{65}(t)$  exhibited a sharp decline up to the decade of 1980s followed by an increasing pattern that has remained until recent years. The lower panel of Figure ?? show the relative derivative of  $\bar{a}_{65}(t)$  with respect to time ( $\dot{\bar{a}}_{65}(t)$ ). It is clear that  $\dot{\bar{a}}_{65}(t)$  captures well the changes over time in life annuity; positive values indicate that  $\bar{a}_{65}(t)$  goes up and negative values indicate a decrease in  $\bar{a}_{65}(t)$ . In the following sections we analyse the sources of change in the time trend of  $\dot{\bar{a}}_{65}(t)$  by making use of the decomposition method developed in Section 4.

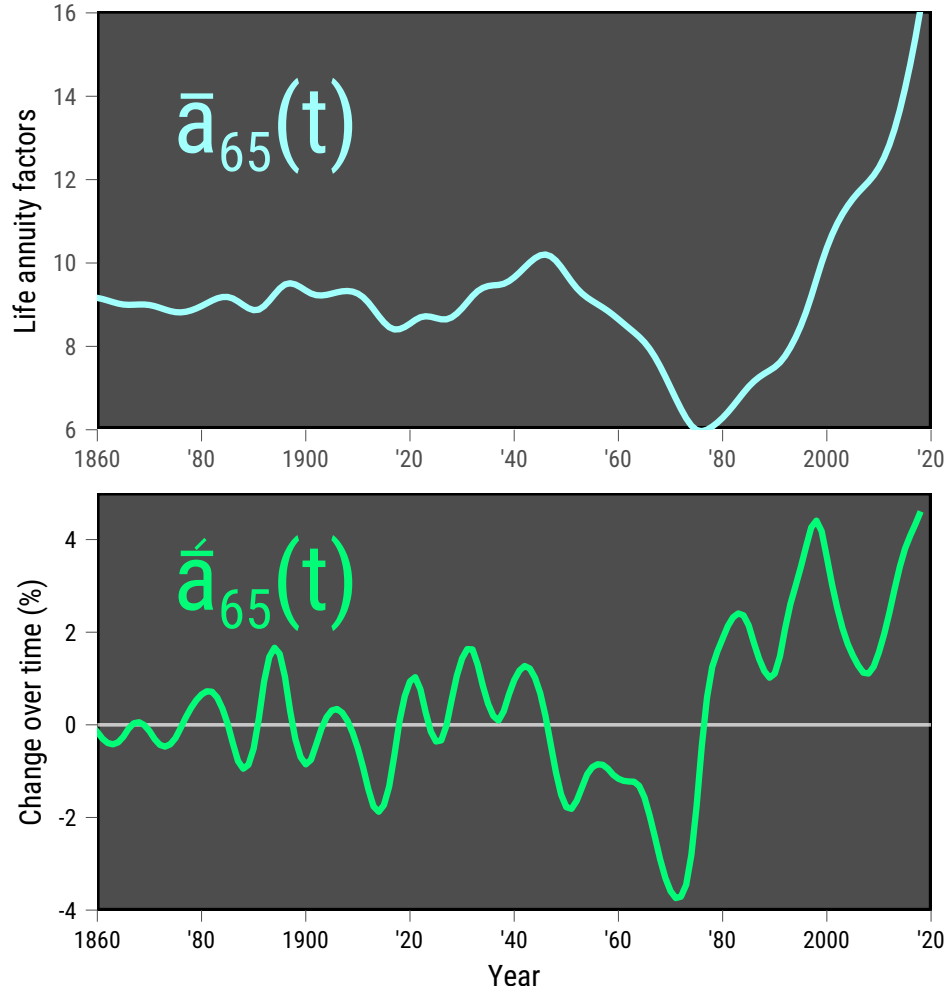


Figure 2: Trends over time in life annuity factors and relative change in  $\bar{a}_x(t)$  calculated at age 65. Males, 1841-2018.

### 5.1 Contribution of financial and longevity risks to changes in $\bar{a}_x(t)$

According to the decomposition formula developed (Equation 22), changes over time in  $\bar{a}_x(t)$  can be explained in terms of longevity and financial components. Each component depends on the stochastic fluctuations of  $\mu(x, t)$  and  $\delta(s, t)$  (captured by  $\bar{\rho}(t)$  and  $\hat{\delta}(t)$  respectively) which are modulated by the sensitivity of  $\bar{a}_x(t)$  to changes in the forces of mortality and interest (entropy,  $H_x^p(t)$  and modified duration,  $D_x^c(t)$ ). Figure 3 depicts all the components responsible of fluctuations over time in  $\bar{a}_x(t)$ .

From 1841 to 1940, there were no mortality improvements after age 65 since  $\bar{\rho}(t)$  fluctuated around 0% (upper panel of Figure 3). However, as of 1980s,  $\bar{\rho}(t)$  increased steadily indicating an average mortality improvement above age 65 of 2% and 3% for the decade of 2000s. In recent years,  $\bar{\rho}(t)$  trended downwards, which coincides with the mortality deterioration currently prevailing in the United Kingdom (REF). Regarding changes over time in the force of interest, we observe that  $\hat{\delta}(t)$  has also remained at similar levels for most of the observation period with some fluctuations between 1930 and 1950. Since the 1960s,  $\hat{\delta}(t)$  went up rapidly reaching the highest increase (of around 8% in the decade of 1970s). Thereafter,  $\hat{\delta}(t)$  declined faster and moved towards negative values entailing a decline in interest rates, which is still ongoing until recent time. Trends in  $\bar{\rho}(t)$  and  $\hat{\delta}(t)$  are responsible for the time trend we observe in  $\bar{a}_x(t)$ , which is modulated by the entropy,  $H_x^p(t)$ , and modified duration,  $D_x^c(t)$ .

The lower panel of Figure 3 shows that during most of the observation period,  $H_x^p(t)$  was higher than

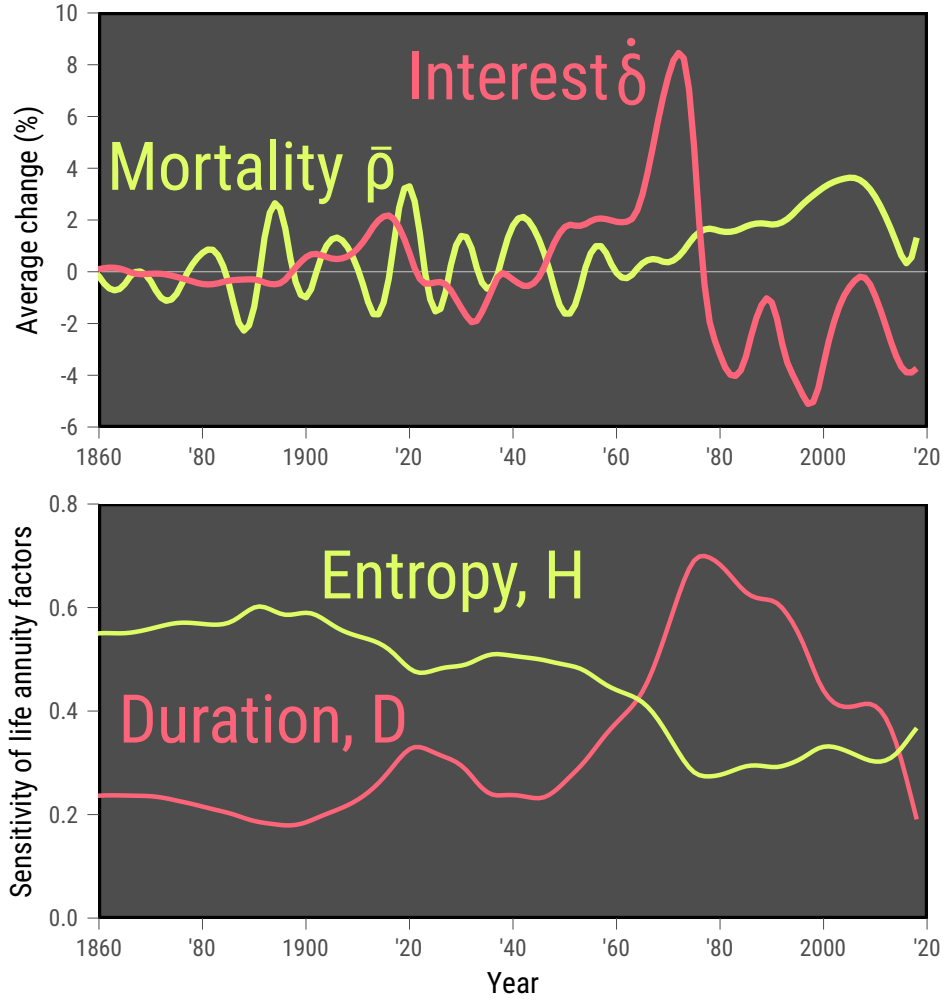


Figure 3: Upper panel shows the average change in mortality ( $\bar{\rho}(t)$ ) and interest rates ( $\dot{\delta}(t)$ ). Lower panel shows Entropy ( $H$ ) and modified duration ( $D$ ). Males at age 65, 1841-2018.

$D_x^c(t)$ . This indicates that  $\bar{a}_x(t)$  has been more sensitive to changes in mortality than to changes in interest rates. However, this has changed over time. The entropy shows a decreasing trend up to the 1980s where it started to rise. Modified duration, on the other hand, remained somewhat constant over time but as of the 1950s, it trended upwards reaching its maximum in the 1980s (of about 0.8). Thereafter, it declines again. It is worth noting that there are some specific years where  $H_x^p(t)$  and  $D_x^c(t)$  depict the same values. This means that during these years,  $\bar{a}_x(t)$  was equally sensitive to changes in mortality and interest rates.

Using all the measures shown in Figure 3, we next calculate the contributions of financial ( $\dot{\delta}(t)D_x^c(t)$ ) and longevity risks ( $\bar{\rho}(t)H_x^p(t)$ ) to changes over time in  $\bar{a}_{65}(t)$  using the decomposition method developed in Equation 19. The upper panel of Figure 4 shows  $\dot{\bar{a}}_{65}^5$  and the lower panel shows the outcome of the decomposition method. Positive/negative values contribute to increase/decrease in  $\bar{a}_x(t)$ . From Figure 4 it is clear that both, longevity and financial risks have played an important role in the long-term development of  $\bar{a}_x(t)$ .

We can distinguish among 4 periods where life annuity factors fluctuated in response to specific changes in financial and longevity risks. From 1841 to 1945, we observe stable annuity factors with contributions of longevity and financial risks to the time trend. In a second period, from 1945 to 1970, we observe decreasing annuity factors mainly driven by the financial component. Around 1970, interest rates reached

<sup>5</sup>This is the same as Figure 2. We show it here so the reader can make sense of the decomposition method

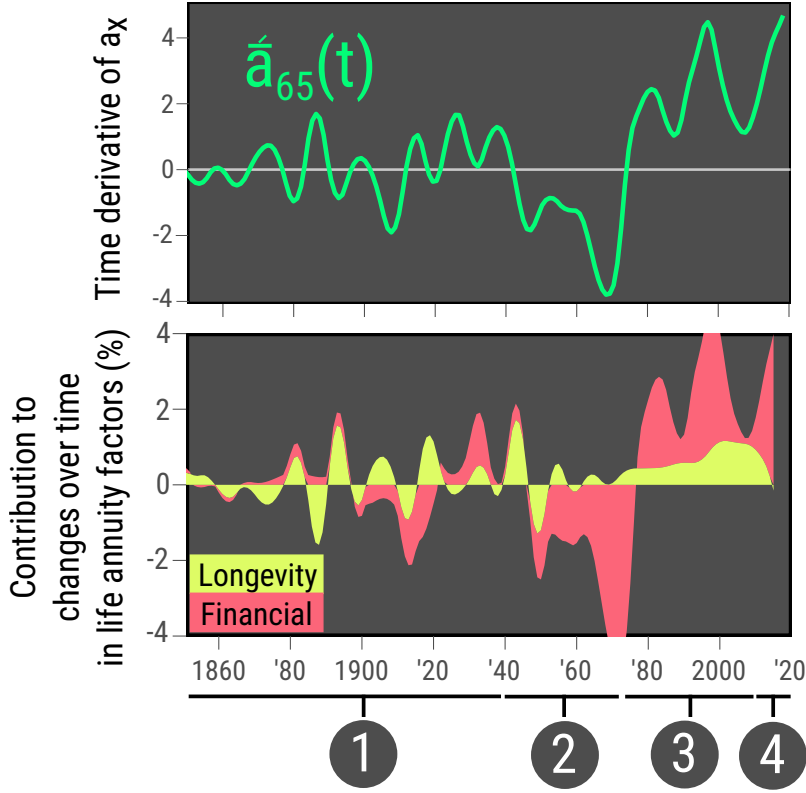


Figure 4: *Decomposition of changes over time in life annuity factors calculated at ages 65. Males, 1841-2018.*

the highest point, which translates into a negative contribution of the financial component. In the next period, from 1970 to 2015, the time trend changed. Annuity prices went up due to positive contributions of the financial and longevity components. Both, interest and mortality rates went down. In the last period, from 2015 onwards,  $\bar{a}_x(t)$  continue to increase with the longevity component contributing less to the trend. This reflects the deceleration of mortality improvements occurring in the UK (REFERENCE).

## 5.2 Analysis for both sexes and at older ages

Hitherto, we focused our analysis in trends over time in  $\bar{a}_x(t)$  for males calculated at age 65. In Section A.5 in the Appendix, we extend the analysis to females and to ages 70 and 75 (see Figures 5, 6, 7 and 8). [SHOULD WE INCLUDE THIS SECTION IN THE APPENDIX INSTEAD]

In Figure 5 Sex-specific trends appear to be very similar between sexes with the absolute level of  $\bar{a}_x(t)$  for females being slightly higher than the one depicted for males. Similar trends over time also replicate at any onset age of calculation analysed here (e.g. age 65, 70 and 75). However, a closer look reveal that  $\bar{a}_x(t)$  changes more abruptly at younger ages (age 65) than at older ages (age 75). This pattern is clear when analysing the time derivative of  $\bar{a}_x(t)$  portrayed by  $\dot{\bar{a}}_x(t)$  (see Panels C and D of Figure 5).

We observe two regularities from Figure 7. First,  $H_x^p(t)$  is lower for females than for males whereas  $D_x^c(t)$  is higher for females than for males. This means that, in general,  $\bar{a}_x(t)$  for females is less sensitive to  $\mu$  and more sensitive to  $\delta$  than for males. Second,  $\bar{a}_x(t)$  becomes more sensitive to  $\mu$  (higher  $H_x^p(t)$ ) and less sensitive to  $\delta$  (lower  $D_x^c(t)$ ) when calculating  $\bar{a}_x(t)$  at older ages. This finding is key to understand how the contributions of longevity and financial risks are moderated differently across ages.

We observe that longevity contributions to changes in  $\bar{a}_x(t)$  are more pronounced in males than in females

throughout the whole period of observation. From Figure 8 we observe that the longevity component takes more relevance at older ages. For example, in recent years the longevity component is responsible for a greater contribution of changes in  $\bar{a}_{75}(t)$  than for changes in  $\bar{a}_{65}(t)$ . This pattern is magnified for males. All in all, the analysis performed here provides evidence of the contribution of financial and longevity components to changes in the long-term development of life annuity factors.

## **6 Projection of the decomposition of changes in annuities**

## References

- Aburto, J. M., Alvarez, J.-A., Villavicencio, F., and Vaupel, J. W. (2019). The threshold age of the lifetable entropy. *Demographic Research*, 41:83–102.
- Aburto, J. M., Villavicencio, F., Basellini, U., Kjærgaard, S., and Vaupel, J. W. (2020). Dynamics of life expectancy and life span equality. *Proceedings of the National Academy of Sciences*, 117(10):5250–5259.
- Arriaga, E. E. (1984). Measuring and explaining the change in life expectancies. *Demography*, 21(1):83–96.
- Beltrán-Sánchez, H., Preston, S. H., and Canudas-Romo, V. (2008). An integrated approach to cause-of-death analysis: cause-deleted life tables and decompositions of life expectancy. *Demographic research*, 19:1323.
- Beltrán-Sánchez, H. and Soneji, S. (2011). A unifying framework for assessing changes in life expectancy associated with changes in mortality: The case of violent deaths. *Theoretical Population Biology*, 80(1):38–48.
- Blake, D., Cairns, A. J., Dowd, K., and Kessler, A. R. (2019). Still living with mortality: The longevity risk transfer market after one decade. *British Actuarial Journal*, 24.
- Camarda, C. G. et al. (2012). Mortalitysmooth: An R package for smoothing poisson counts with p-splines. *Journal of Statistical Software*, 50(1):1–24.
- Charupat, N., Kamstra, M. J., and Milevsky, M. A. (2016). The sluggish and asymmetric reaction of life annuity prices to changes in interest rates. *Journal of Risk and Insurance*, 83(3):519–555.
- Courtois, C., Denuit, M., et al. (2007). On immunization and s-convex extremal distributions. *Annals of Actuarial Science*, 2(1):67–90.
- Demetrius, L. (1974). Demographic parameters and natural selection. *Proceedings of the National Academy of Sciences*, 71(12):4645–4647.
- Fernandez, O. E. and Beltrán-Sánchez, H. (2015). The entropy of the life table: A reappraisal. *Theoretical population biology*, 104:26–45.
- Fisher, L. and Weil, R. L. (1971). Coping with the risk of interest-rate fluctuations: returns to bondholders from naive and optimal strategies. *Journal of business*, pages 408–431.
- Goldman, N. and Lord, G. (1986). A new look at entropy and the life table. *Demography*, 23(2):275–282.
- Green, P. J. and Silverman, B. W. (1993). *Nonparametric regression and generalized linear models: a roughness penalty approach*. Crc Press.
- Haberman, S., Khalaf-Allah, M., and Verrall, R. (2011). Entropy, longevity and the cost of annuities. *Insurance: Mathematics and Economics*, 48(2):197–204.
- Hakkert, R. (1987). Life table transformations and inequality measures: Some noteworthy formal relationships. *Demography*, pages 615–622.
- Human Mortality Database (2020). University of California, Berkeley (USA), and Max Planck Institute for Demographic Research (Germany). [www.mortality.org](http://www.mortality.org).

- Keyfitz, N. (1968). Introduction to the mathematics of population. Technical report.
- Keyfitz, N. (1977). What difference would it make if cancer were eradicated? an examination of the taeuber paradox. *Demography*, 14(4):411–418.
- Keyfitz, N. (1985). *Applied Mathematical Demography*. Springer Texts in Statistics. Springer New York.
- Leser, C. (1955). Variations in mortality and life expectation. *Population Studies*, 9(1):67–71.
- Levantesi, S. and Menzietti, M. (2018). Natural hedging in long-term care insurance. *ASTIN Bulletin: The Journal of the IAA*, 48(1):233–274.
- Li, J. S.-H. and Hardy, M. R. (2011). Measuring basis risk in longevity hedges. *North American Actuarial Journal*, 15(2):177–200.
- Li, J. S.-H. and Luo, A. (2012a). Key q-duration: A framework for hedging longevity risk. *ASTIN Bulletin: The Journal of the IAA*, 42(2):413–452.
- Li, J. S.-H. and Luo, A. (2012b). Key q-duration: A framework for hedging longevity risk. *Astin Bulletin*, (July).
- Lin, T. and Tsai, C. C.-I. (2020a). Natural hedges with immunization strategies of mortality and interest rates. *ASTIN Bulletin: The Journal of the IAA*, 50(1):155–185.
- Lin, T. and Tsai, C. C. L. (2020b). Natural Hedges with Immunization Strategies of Mortality and Interest Rates. *ASTIN Bulletin*, 50(1):155–185.
- Luciano, E., Regis, L., and Vigna, E. (2015). Single- and Cross-Generation Natural Hedging of Longevity and Financial Risk. *Journal of Risk and Insurance*, pages n/a–n/a.
- Milevsky, M. A. (2012). *Life Annuities: An Optimal Product for Retirement Income*. Research Foundation of the CFA Institute.
- Milevsky, M. A. (2013). Life annuities: An optimal product for retirement income. *CFA Institute Research Foundation Monograph*.
- Mitra, S. (1978). A short note on the taeuber paradox. *Demography*, 15(4):621–623.
- Pollard, J. H. (1988). On the decomposition of changes in expectation of life and differentials in life expectancy. *Demography*, 25(2):265–276.
- Redington, F. M. and Clarke, R. (1951). The papers of the royal commission on population. *Journal of the Institute of Actuaries (1886-1994)*, 77(1):81–97.
- Santomero, A. M. and Babbel, D. F. (1997). Financial risk management by insurers: An analysis of the process. *Journal of risk and insurance*, pages 231–270.
- Shiu, E. S. (1990). On redington’s theory of immunization. *Insurance: Mathematics and Economics*, 9(2-3):171–175.
- Tsai, C. C. L. and Chung, S. L. (2013). Actuarial applications of the linear hazard transform in mortality immunization. *Insurance: Mathematics and Economics*, 53(1):48–63.
- Tsai, C. C.-L. and Jiang, L. (2011). Actuarial applications of the linear hazard transform in life contingencies. *Insurance: Mathematics and Economics*, 49(1):70–80.

- Tsai, J. T., Tzeng, L. Y., and Wang, J. L. (2011). Hedging Longevity Risk When Interest Rates are Uncertain. *North American Actuarial Journal*, 15(February 2015):201–211.
- Vaupel, J. W. (1986). How change in age-specific mortality affects life expectancy. *Population Studies*, 40:147–157.
- Vaupel, J. W. and Canudas-Romo, V. (2003). Decomposing change in life expectancy: a bouquet of formulas in honor of Nathan Keyfitz’s 90th birthday. *Demography*, 40(2):201–16.
- Vaupel, J. W., Zhang, Z., and van Raalte, A. A. (2011). Life expectancy and disparity: an international comparison of life table data. *BMJ open*, 1(1).
- Wang, J. L., Huang, H., Yang, S. S., and Tsai, J. T. (2010). An optimal product mix for hedging longevity risk in life insurance companies: The immunization theory approach. *Journal of Risk and Insurance*, 77(2):473–497.
- Wong, A., Sherris, M., and Stevens, R. (2015). Natural Hedging Strategies for Life Insurers: Impact of Product Design and Risk Measure. *Journal of Risk and Insurance*, pages n/a–n/a.



# A Appendix

## A.1 Entropy with constant changes in $\mu(x + s, t)$

To measure constant changes we make  $\mu(s, t) + \gamma$ , then

$$\begin{aligned}\bar{a}_x(t) &= \int_0^\infty v(s, t) e^{-\int_0^s [\mu(x+y, t) + \gamma] dy} ds \\ &= \int_0^\infty v(s, t) e^{-\int_0^s \mu(x+y, t) dy} e^{-\gamma s} ds \\ &= \int_0^\infty v(s, t) {}_s p_x(t) e^{-\gamma s} ds\end{aligned}\tag{23}$$

We expand  $e^{-\gamma s}$  to  $1 - \gamma s + \frac{\gamma^2}{2} s^2 + \dots$ , so that

$$\bar{a}_x(t) = \int_0^\infty {}_s p_x(t) v(s, t) [1 - \gamma s + \frac{\gamma^2}{2} s^2 + \dots] ds\tag{24}$$

We take the derivative  $\bar{a}_x(t)$  with respect to  $\gamma$  and evaluate  $\gamma = 0$

$$\begin{aligned}H_x^c(t) &= \frac{1}{\bar{a}_x(t)} \left. \frac{\partial \bar{a}_x(t)}{\partial \gamma} \right|_{\gamma=0} \\ &= - \frac{\int_0^\infty {}_s p_x(t) v(s, t) ds}{\bar{a}_x(t)} \\ &= \frac{h_x^c(t)}{\bar{a}_x(t)},\end{aligned}\tag{25}$$

where  $h_x^c(t) = - \int_0^\infty {}_s p_x(t) v(s, t) ds$

## A.2 Alternative expression for $H_x^p(t)$

$$\begin{aligned}
H_x^p(t) &= -\frac{\int_0^\infty {}_s p_x(t) \ln[{}_s p_x(t)] e^{-\int_0^s \delta(y,t) dy} ds}{\int_0^\infty {}_s p_x(t) e^{-\int_0^s \delta(y,t) dy} ds} \\
&= \frac{\int_0^\infty {}_s p_x(t) v(s,t) \int_0^s \mu(x+y,t) dy ds}{\bar{a}_x(t)} \\
&= \frac{\int_0^\infty \mu(x+s,t) \int_s^\infty {}_y p_x(t) v(y,t) dy ds}{\bar{a}_x(t)} \\
&= \frac{\int_0^\infty \mu(x+s,t) {}_s p_x(t) v(s,t) \int_s^\infty \frac{{}_y p_x(t) v(y,t)}{{}_s p_x(t) v(s,t)} dy ds}{\bar{a}_x(t)} \\
&= \frac{\int_0^\infty \mu(x+s,t) {}_s p_x(t) v(s,t) \bar{a}_{x+s}(t) ds}{\bar{a}_x(t)} \\
&= \frac{\int_0^\infty \mu(x+s,t) {}_s \bar{a}_x(t) ds}{\bar{a}_x(t)} \\
&= \frac{h_x^p(t)}{\bar{a}_x(t)},
\end{aligned} \tag{26}$$

where  $h_x^p(t) = \int_0^\infty \mu(x+s,t) {}_s \bar{a}_x(t) ds$ .

## A.3 Duration with constant changes in $\delta(s,t)$

To measure constant changes we make  $\delta(s,t) + \gamma$ , then

$$\begin{aligned}
\bar{a}_x(t) &= \int_0^\infty {}_s p_x(t) e^{-\int_0^s [\delta(y,t) + \gamma] dy} ds \\
&= \int_0^\infty {}_s p_x(t) e^{-\int_0^s \delta(y,t) dy} e^{-\gamma s} ds \\
&= \int_0^\infty {}_s p_x(t) v(s,t) e^{-\gamma s} ds
\end{aligned} \tag{27}$$

We expand  $e^{-\gamma s}$  to  $1 - \gamma s + \frac{\gamma^2}{2} s^2 + \dots$ , so that

$$\bar{a}_x(t) = \int_0^\infty {}_s p_x(t) v(s,t) [1 - \gamma s + \frac{\gamma^2}{2} s^2 + \dots] ds \tag{28}$$

We take the derivative  $\bar{a}_x(t)$  with respect to  $\gamma$  and evaluate  $\gamma = 0$

$$\begin{aligned}
D_x^c(t) &= -\frac{1}{\bar{a}_x(t)} \left. \frac{\partial \bar{a}_x(t)}{\partial \gamma} \right|_{\gamma=0} \\
&= \frac{\int_0^\infty {}_s p_x(t) v(s,t) ds}{\bar{a}_x(t)} \\
&= \frac{d_x^c(t)}{\bar{a}_x(t)},
\end{aligned} \tag{29}$$

where  $d_x^c(t) = \int_0^\infty s p_x(t) v(s, t) ds$

#### A.4 Duration with proportional changes in $\delta(s, t)$

To calculate duration with proportional changes in  $\delta(s, t)$ , we assume that  $\gamma$  is a small number such that  $\delta(s, t)(1 + \gamma)$  and  $v(s, t) = e^{-\int_0^s \delta(y, t)(1 + \gamma) dy}$ .

$$\begin{aligned}\bar{a}_x(t) &= \int_0^\infty s p_x(t) e^{-\int_0^s \delta(y, t)(1 + \gamma) dy} ds \\ &= \int_0^\infty s p_x(t) e^{-\int_0^s \delta(y, t) dy} e^{-\int_0^s \delta(y, t) \gamma dy} ds \\ &= \int_0^\infty s p_x(t) v(s, t) v(s, t)^\gamma ds\end{aligned}\tag{30}$$

We expand  $v(s, t)^\gamma$  to  $1 + \ln(v(s, t))\gamma + \ln(v(s, t))^2 \frac{\gamma^2}{2} + \dots$ , so that

$$\bar{a}_x(t) = \int_0^\infty s p_x(t) v(s, t) [1 + \ln(v(s, t))\gamma + \ln(v(s, t))^2 \frac{\gamma^2}{2} + \dots] ds\tag{31}$$

To calculate the duration  $D_x^p(t)$  we take the derivate of the expression above with respect to  $\gamma$  and make  $\gamma = 0$

$$\begin{aligned}D_x^p(t) &= -\frac{1}{\bar{a}_x(t)} \left. \frac{\partial \bar{a}_x(t)}{\partial \gamma} \right|_{\gamma=0} \\ &= -\frac{\int_0^\infty s p_x(t) v(s, t) \ln(v(s, t)) ds}{\bar{a}_x(t)}\end{aligned}\tag{32}$$

Equation 32 can be re-expressed as

$$\begin{aligned}D_x^p(t) &= -\frac{\int_0^\infty s p_x(t) v(s, t) \ln(v(s, t)) ds}{\bar{a}_x(t)} \\ &= \frac{\int_0^\infty s p_x(t) v(s, t) \int_0^s \delta(y, t) dy ds}{\bar{a}_x(t)} \\ &= \frac{\int_0^\infty \delta(s, t) \int_s^\infty y p_x(t) v(y, t) dy ds}{\bar{a}_x(t)} \\ &= \frac{\int_0^\infty \delta(s, t) s p_x(t) v(s, t) \bar{a}_{x+s}(t) ds}{\bar{a}_x(t)} \\ &= \frac{\int_0^\infty \delta(s, t) s \bar{a}_x(t) ds}{\bar{a}_x(t)} \\ &= \frac{d_x^p(t)}{\bar{a}_x(t)}.\end{aligned}\tag{33}$$

where  $d_x^p(t) = \int_0^\infty \delta(s, t) s \bar{a}_x(t) ds$ .

## A.5 Historical decomposition of life annuities: both sexes at ages 65, 70 and 75

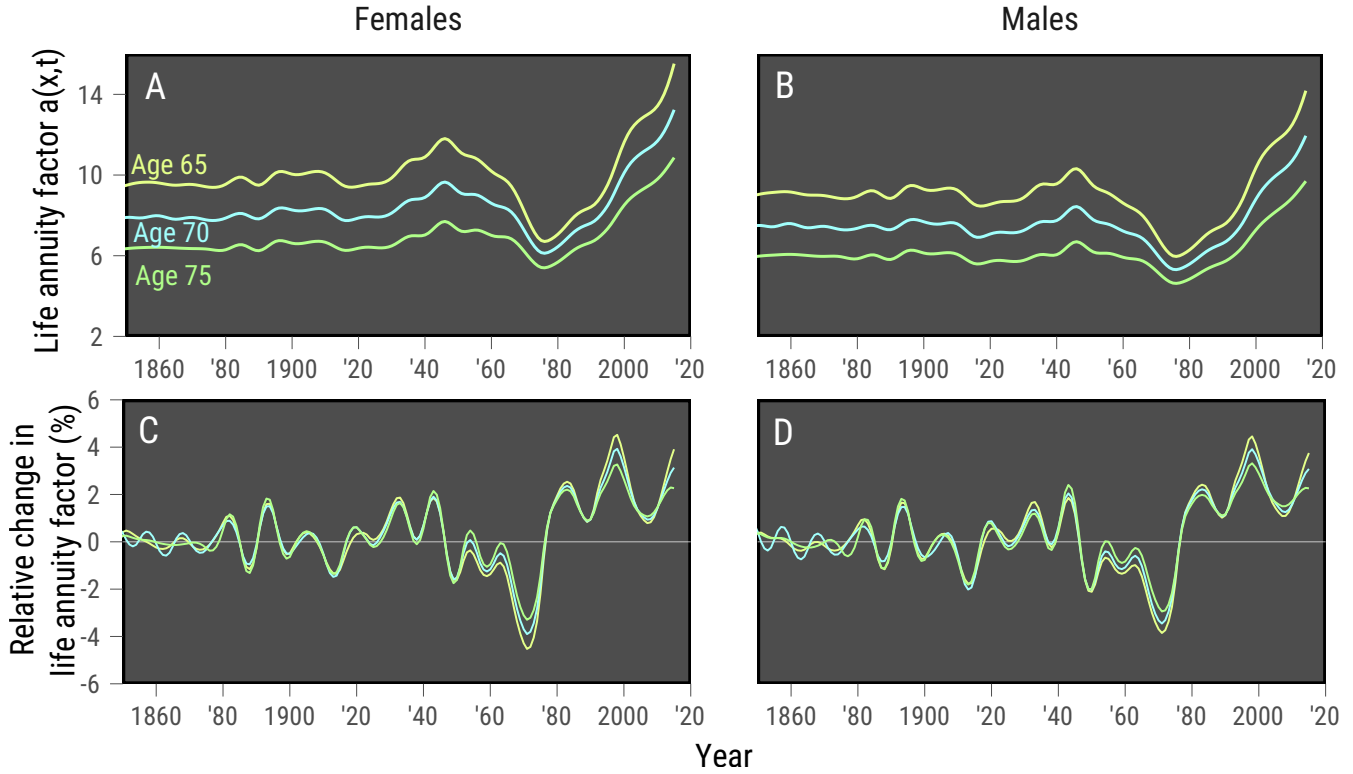


Figure 5: Trends over time in life annuity factors and relative change in  $\bar{a}_x(t)$  calculated at ages 65, 70 and 75. Both sexes, 1841-2018.

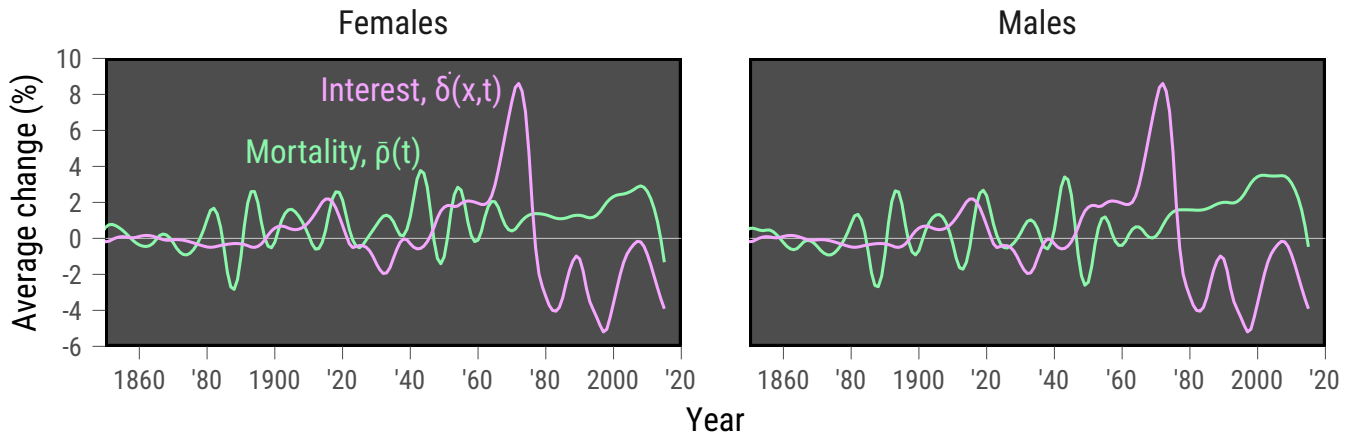


Figure 6: Average change in mortality ( $\bar{\rho}(t)$ ) calculated for all ages above age 65 and rate of change in interest rates ( $\delta(t)$ ). Note that  $\delta(t)$  is expressed in basis points to ease readability. Both sexes, 1841-2018.

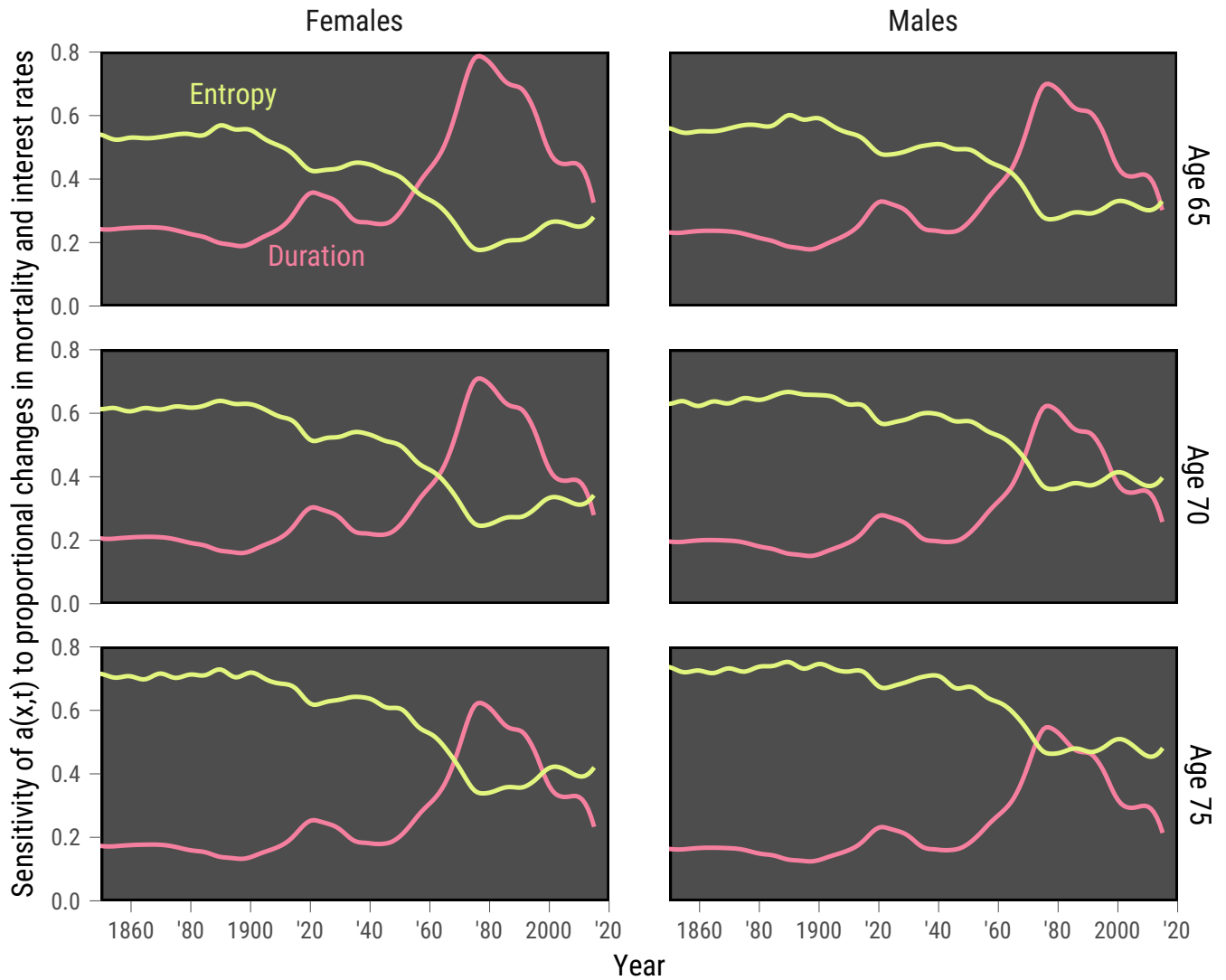


Figure 7: Entropy and modified duration assuming proportional changes calculated at ages 65, 70 and 75. Both sexes, 1841-2018.

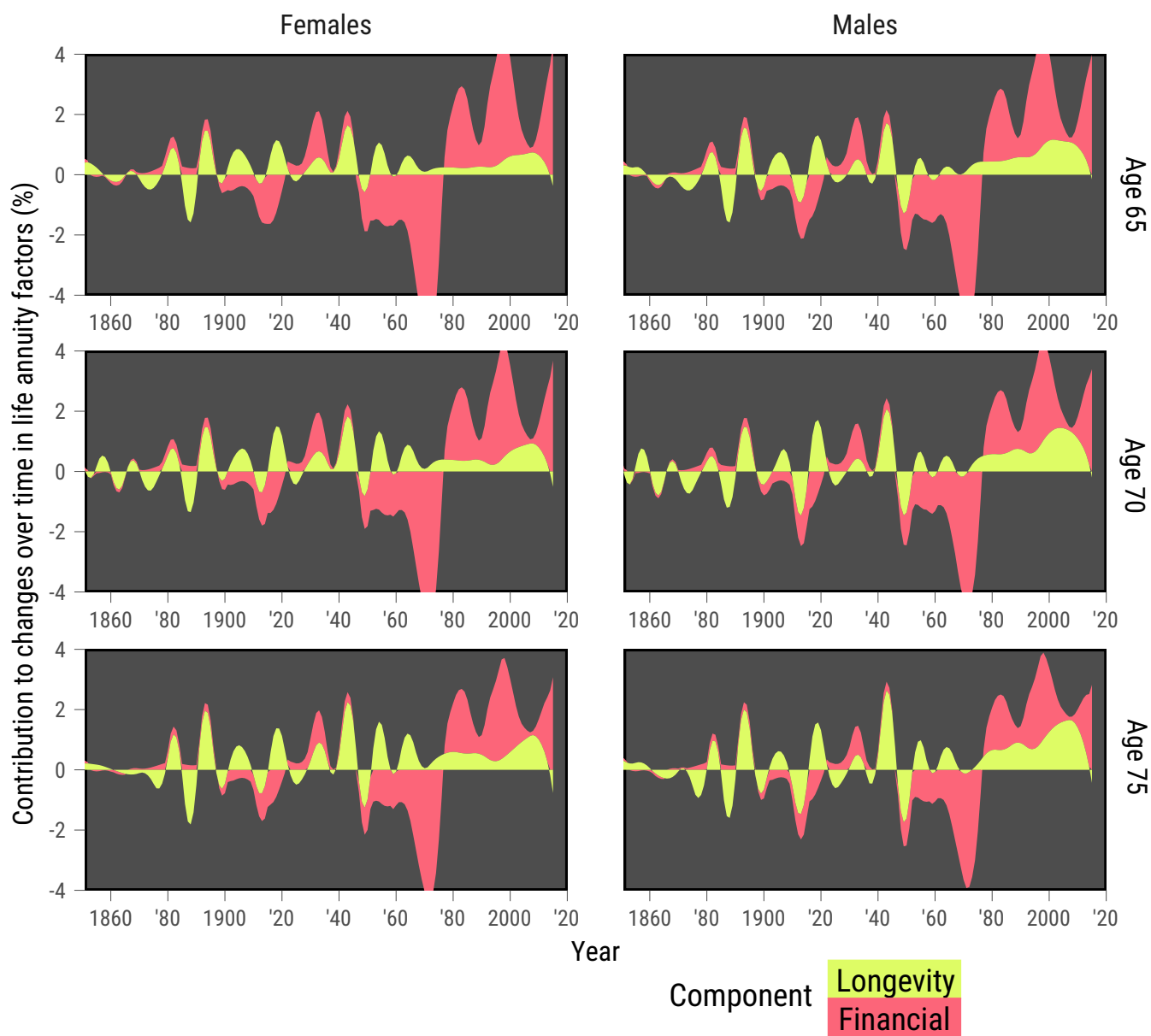


Figure 8: *Decomposition of changes over time in life annuity factors calculated at ages 65, 70 and 75. Both sexes, 1841-2018.*