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# LONGEVITY-INDUCED VERTICAL INNOVATION AND THE TRADEOFF BETWEEN LIFE AND GROWTH

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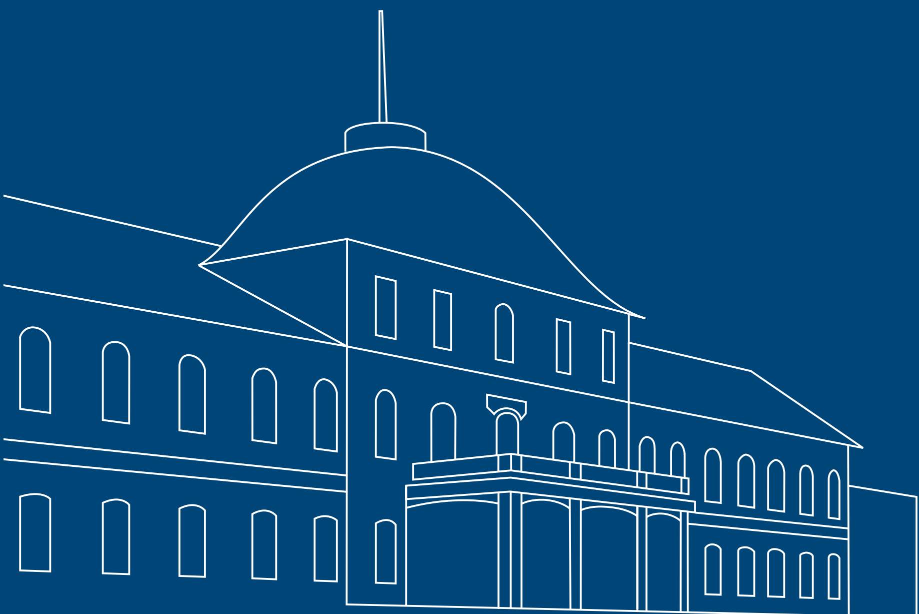

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**Abstract**

We analyze the economic growth effects of rising longevity in a framework of endogenous growth driven by quality-improving innovations. We show that a rise in longevity raises savings and thereby reduces the market interest rate. Since the monopoly profits generated by a successful innovation are discounted by the endogenous market interest rate, this raises the net present value of innovations, which, in turn, fosters R&D. The associated increase in the employment of scientists leads to faster technological progress and a higher long-run economic growth rate. From a welfare perspective, we show that the direct effect of an increase in life expectancy on lifetime utility is much larger than the indirect effect of the induced higher consumption due to faster economic growth. Consequently, the debate on rising health care expenditures should not predominantly be based on the growth effects of health care.

**JEL classification:** J11, J17, O31, O41.

**Keywords:** Long-run growth, vertical innovation, increasing life expectancy, welfare effects of changing longevity, size of health-care sectors.

# 1 Introduction

While there are deep-rooted concerns on the negative economic consequences of population aging in the public debate (see, for example, The Economist, 2011a,b), a negative effect on economic growth is not yet visible empirically (Acemoglu and Restrepo, 2017). One of the reasons might be that increasing longevity, which is one of the two causes of population aging, has positive side effects that work so as to raise economic growth. For example, individuals save more if they expect a longer life in order to be able to sustain their living standards in a prolonged retirement period (Bloom et al., 2003, 2007, 2010). Another channel is that increasing longevity leads to a longer working life such that the incentives to invest in education are higher, which in turn raises labor productivity and thereby economic growth (Cervellati and Sunde, 2013; Strulik and Werner, 2016). In general, despite the earlier work of Acemoglu and Johnson (2007) who found a negative causal effect of increasing life expectancy on economic growth, the more recent empirical evidence suggests that the increase in life expectancy over the last decades by itself has been a driver of economic growth in industrialized countries (Lorentzen et al., 2008; Cervellati and Sunde, 2011; Aghion et al., 2011; Bloom et al., 2014; Gehringer and Prettner, 2017).

We aim to contribute to this debate by elaborating on the theoretical mechanism by which increasing longevity affects economic growth in modern knowledge-based economies. In these economies, the standard neoclassical type of growth model in terms of which the debate on the effects of increasing life expectancy is usually framed (Solow, 1956; Cass, 1965; Diamond, 1965) are not suitable because long-run growth in these economies is driven by endogenous technological progress and not by physical capital accumulation (Romer, 1990; Jones, 1995; Strulik et al., 2013). While there has been some progress in the analysis of the effects of increasing longevity on horizontal innovation, i.e., the introduction of new products (see, for example, Prettner, 2013; Prettner and Trimborn, 2016; Hashimoto and Tabata, 2016), we are not aware of a comparable study that is based on vertical innovations, i.e., quality-improvements of existing products. Closing this gap in the literature is important because i) due to the different mechanism by which growth is generated in the vertical innovation framework, the way increasing longevity affects economic growth might be different, ii) the welfare implications could be different because in the vertical innovation framework, there is a Schumpeterian creative destruction effect to the extent that a new innovation drives the old incumbent out of business. Consequently, long-run growth might be too high from a social point of view within this setting.

Despite that endogenous and semi-endogenous growth models with vertical innovations (Grossman and Helpman, 1991; Aghion and Howitt, 1992; Segerström, 1998) analyze the economic growth effects of changing population size and changing population growth, they do not examine the consequences of changing longevity. The reason is that a single representative individual who lives forever makes all the relevant economic decisions in these models. We introduce an overlapping generations structure that allows for the analysis of changing life expectancy into the model proposed by Aghion and Howitt (1992), which has been simplified subsequently by Aghion and Howitt (1999, 2005, 2009). The basic mechanism in this framework is that research activities randomly lead to quality-improving innovations. The more researchers an economy employs and the more productive these researchers are in generating innovations, the higher is the probability that a new innovation occurs in a given time period. A quality-improving innovation raises the productivity of intermediate goods in producing the final consumption good. Consequently, a higher probability of innovations raises long-run economic growth.

We introduce age-specific heterogeneity into this setting by assuming a demographic structure with three overlapping generations in discrete time, childhood, adulthood, and retirement. Individuals face an exogenously given survival probability from adulthood to retirement. Varying this parameter allows us to analyze the effects of changing longevity. If longevity increases, the economy saves more at the aggregate level, which reduces the market interest rate. This is an important difference to Aghion and Howitt (1992), who assume a constant and exogenous interest rate. Since innovators discount the future expected profits of an innovation by the market interest rate, this raises the net present value of an innovation, which, in turn, raises the incentive to come up with a quality-improving new idea. To raise the probability of a successful quality-improvement, R&D firms hire additional researchers, which raises the innovation rate and in turn productivity growth.

We apply the resulting framework to decompose the welfare effects of increasing longevity into two separate effects. The direct effect is that higher life expectancy allows individuals to enjoy consumption over a longer expected time period. The indirect effect is that the increase in life expectancy induces innovation, which in turn raises growth of aggregate output and consumption. We show that the direct welfare effect is much higher than the indirect welfare effect based on induced economic growth. This result is consistent with the literature that shows that raising investments in the health sector of an economy beyond the growth-maximizing point – such that the additional resources channeled toward the health sector even reduce economic growth – can be Pareto improving (Kuhn and Prettner, 2016). Furthermore, we show that the relative importance of the direct welfare effect increases with economic development. This is in turn consistent with Hall and Jones (2007) who show that, as the economy develops, it is optimal to invest an ever larger share of aggregate income in better health.

The paper is organized as follows. In Section 2 we introduce the overlapping generations structure that we implement into a standard model of vertical innovations. In Section 3 we derive our main analytical results with respect to the growth effects of increasing life expectancy and the numerical results with respect to the welfare decomposition into the direct effect and the indirect effect. In Section 4 we summarize and draw some lessons from a policy perspective.

# 2 The model

## 2.1 Consumption side

Consider an overlapping generations economy with single-sex individuals living for three time periods: childhood, adulthood, and retirement. Childhood lasts for 20 years, adulthood for 40 years, and the phase of retirement can last for 40 years after which an individual dies for sure. Consequently, the maximum achievable life span is 100 years. However, there is a survival probability from adulthood to retirement which determines the overall life expectancy. Children face no economic decisions and fulfill their consumption needs via parental expenditures. The single-sex adult individual consumes, saves for retirement, works for the wage rate $w_t$, and gives birth to one child such that the cohort size stays constant. We assume that parents give birth to children in the middle of the adulthood period such the children enter adulthood at the time when adults enter retirement. Retirees only consume out of the savings accumulated as adults (see Samuelson, 1958; Diamond, 1965, for the corresponding consumption-savings decision of adults).

We conceptualize an adult's remaining lifetime utility ($u_t$) by means of a logarithmic utility function that ensures analytical tractability. This function is given by

$$u_t = \ln(c_{1,t}) + \phi\beta \ln(c_{2,t+1}), \tag{1}$$

where $c_{1,t}$ is the consumption of an adult at time $t$, $c_{2,t+1}$ refers to consumption in retirement at time $t+1$, $0 < \phi < 1$ is the survival probability between adulthood and retirement[1], and $0 < \beta < 1$ is the discount factor. Following Blanchard (1985) and Yaari (1965), there are perfect and fair annuity markets such that individuals

[1]For similar treatments of the survival probability in the overlapping generations literature, see, for example, Blackburn and Cipriani (2002), Chakraborty (2004), and Zhang and Zhang (2005).

insure themselves against the risk of dying with positive assets. Thanks to the annuity market, all savings are intermediated through mutual funds. At the end of the first period, every individual deposits her savings with a mutual fund, which buys assets in the form of shares of firms, yielding a gross return of $(1 + r_{t+1})/\phi$. In this expression, $r_{t+1}$ is the real rate of return on savings and it is equivalent to the dividend yield plus the valuation gain of the investment. The budget constraints of adults and retirees are therefore given by

$$c_{1,t} + s_t = w_t, \tag{2}$$

$$c_{2,t+1} = \frac{1 + r_{t+1}}{\phi} \cdot s_t, \tag{3}$$

where consumption as adult plus savings for retirement ($s_t$) cannot exceed wage income in the first period of life [equation (2)] and consumption of retirees that survived from adulthood to retirement is given by the savings carried over from adulthood plus the return earned by investing in the annuity market [equation (3)]. Combining the budget constraints, the lifetime budget constraint is obtained as

$$c_{1,t} + \phi \frac{c_{2,t+1}}{1 + r_{t+1}} = w_t. \tag{4}$$

From the first-order conditions, the individual Euler Equation follows as

$$\frac{c_{2,t+1}}{c_{1,t}} = (1 + r_{t+1})\,\beta. \tag{5}$$

Notice that the survival probability drops out of the individual Euler Equation because of the fully insured mortality risk. Since the birth rate is assumed to be equal to the replacement rate, the relative cohort size between adults and retirees is only influenced by the survival probability to the extent that $N_{2,t+1} = \phi N_{1,t}$. Defining aggregate consumption of adults and of retirees by $C_{1,t} = c_{1,t}N_{1,t}$ and $C_{2,t+1} = c_{2,t+1}N_{2,t+1}$, respectively, aggregation yields $c_{2,t+1}N_{2,t+1} = (1+r_{t+1})\beta c_{1,t}\phi N_{1,t}$. From this expression, the "aggregate" Euler equation follows immediately as

$$\frac{C_{2,t+1}}{C_{1,t}} = (1 + r_{t+1})\,\beta\phi. \tag{6}$$

We notice that aggregate consumption growth rises with the survival probability, i.e., $\partial(C_{2,t+1}/C_{1,t})/\partial\phi > 0$. The economic intuition is straightforward: the introduction of lifetime uncertainty induces individuals to reduce their propensity to save. Therefore, aggregate savings are smaller, which reduces aggregate consumption growth. In the individual Euler equation, this negative effect on consumption growth exists as well but it is exactly offset by the additional transfers by the life insurance company from the individuals who die between adulthood and retirement. Consequently, the death process only slows down the growth of aggregate consumption.

## 2.2 Production side

The production side of the economy is a simplified version of the production side of the Schumpeterian growth model as developed by Aghion and Howitt (1992) and further elaborated upon in Aghion and Howitt (2005, 1999). There are three sectors, the final goods sector, the intermediate goods sector, and the R&D sector. The aggregate final good is produced under perfect competition using the intermediate good as input. The intermediate good is in turn produced by a monopoly in the intermediate goods sector, with a one-to-one technology out of labor. The monopolist owns the patent of the most recent quality-improving innovation developed in the R&D sector. When the next quality-improving innovation occurs, the incumbent is driven out of business and loses the monopoly rents. Since firms in the intermediate goods sector earn a positive profit stream due to monopolistic competition (as long as they are in the position of being the incumbent), the firms have positive value and their shares are sold via the mutual funds to the households in the economy. We abstract from physical capital such that these shares represent the only savings vehicle. Introducing physical capital would complicate the model substantially without changing the main mechanisms.[2]

The final good is denoted by $Y_t$ and produced according to the production function

$$Y_t = A_t x_t^{\alpha}, \tag{7}$$

where $A_t$ refers to the productivity of the intermediate good in producing the final good, $x_t$ is the intermediate good produced by the monopolist, and $0 < \alpha < 1$ is the elasticity of output with respect to intermediate inputs. Innovations are tantamount to the introduction of a new variety of the single intermediate good with a higher quality that replaces the previous one. The new intermediate good increases the productivity $A_t$ by a constant factor $\gamma > 1$ such that

$$A_{i+1} = \gamma \cdot A_i. \tag{8}$$

where $i$ refers to the number of innovations that have occurred until now (Aghion

[2]For a framework of horizontal innovation with increasing longevity in which both types of assets, physical capital and shares of intermediate goods producers are available, see Prettner (2013).

and Howitt, 1992).

The intermediate good is produced by using the amount $x_t$ of the production factor labor as denoted by $L$ because of the one-for-one technology according to which one unit of labor produces one unit of the intermediate good. Labor is also used in the research sector, with the amount being denoted by $n_t$. Consequently, the labor market clearing condition is

$$L = x_t + n_t. \tag{9}$$

Given employment $n_t$ in the research sector, the arrival of innovations follows a random Poisson arrival rate $\lambda \cdot n_t$, where $\lambda > 0$ denotes the productivity of researchers. This means that more researchers and a higher productivity of these researchers both increase the probability of a successful innovation in a given period. The firm that succeeds to obtain the newest innovation from the R&D sector monopolizes the intermediate goods sector until it is replaced by the next innovator. Employment of researchers can be calculated with the help of the no-arbitrage condition

$$w_i = \lambda V_{i+1}, \tag{10}$$

where $w_i$ refers to the wage of the researchers and $V_{i+1}$ to the discounted expected payoff of innovation $i+1$. The no-arbitrage condition states that the investment of the research firm in terms of the wage bill for scientists has to equal the expected discounted payoff of an innovation in terms of a quality improvement and the associated monopoly rents over the period in which the innovator will be the new incumbent. The value of $V_{i+1}$ is in turn determined by the no-arbitrage equation for the investments of households given by

$$rV_{i+1} = \pi_{i+1} - \lambda n_{i+1} V_{i+1}. \tag{11}$$

The left-hand side is the income earned on an investment of the amount $V_{i+1}$ at the risk free interest rate $r$, while the right-hand side consists of the monopoly profits due to owning the incumbent firm minus the expected loss that occurs when the incumbent is driven out of business by a new quality-improving innovation. While in Aghion and Howitt (1999) the interest rate is exogenously given, in our overlapping generations framework the "aggregate" Euler equation determines the real interest rate. Hence, we endogenize the interest rate, which is particularly important when analyzing the growth effects of increasing life expectancy.

From Equation (11), we obtain

$$V_{i+1} = \frac{\pi_{i+1}}{r + \lambda n_{i+1}}.$$

It is straightforward that $\partial V_{i+1}/\partial n_{i+1} < 0$, i.e., if more researchers are employed in the R&D sector, the probability of the next innovation is larger, which implies lower monopoly profits because an incumbent can expect to be replaced earlier. The incumbent innovator determines optimal output $x_i$ by maximizing

$$\pi_i = p_i(x_i)x_i - w_i x_i \tag{12}$$

with respect to the choice of $x_i$. This choice in turn determines the profits $\pi_i$. Given perfect competition in the final good sector, $p_i(x_i) = A_i \alpha x_i^{\alpha-1}$ is the inverse demand function for intermediates. The maximization of profits then yields

$$x_i = \left(\frac{\alpha^2 A_i}{w_i}\right)^{1/(1-\alpha)}. \tag{13}$$

Substituting $p_i(x_i)$ into Equation (12), we obtain

$$\pi_i = \left(\frac{1}{\alpha} - 1\right) w_i x_i = A_i \frac{1-\alpha}{\alpha} \omega_i x_i = A_i \tilde{\pi}, \tag{14}$$

where $\omega_i = w_i/A_i$ is the productivity-adjusted wage rate and $\tilde{\pi} = (1-\alpha)\omega x/\alpha$. Exploiting the new definition of profits in Equation (14) and dividing both sides of Equation (10) by $A_i$ acknowledging that $A_{i+1}/A_i = \gamma$ from Equation (8), we can rewrite the no-arbitrage condition as

$$\omega_i = \lambda \frac{\gamma \tilde{\pi}\left(\omega_{i+1}\right)}{r + \lambda n_{i+1}}. \tag{15}$$

To be consistent, we rewrite the labor market clearing condition in terms of the productivity-adjusted wage rate

$$L = n_i + \left(\frac{\alpha^2}{\omega_i}\right)^{\frac{1}{1-\alpha}}. \tag{16}$$

The production function, Equation (7), can be reformulated as $Y_i = A_i \left(L - n_i\right)^{\alpha}$ by exploiting the labor market clearing condition. This implies that

$$Y_{i+1} = \gamma Y_i, \tag{17}$$

meaning that output grows at the rate $\gamma - 1$ for each innovation that occurs. Since the time between two innovations is random, we compute the average growth rate of the economy over time by relying on the relation

$$\ln Y_{t+1} = \ln Y_t + \ln \gamma \cdot \epsilon_t, \tag{18}$$

where $\epsilon_t$ is the number of innovations between time $t$ and time $t+1$. The number of innovations is Poisson distributed with the parameter $\lambda \cdot n$ describing the average number of innovations by time step. Computing the expectation of Equation (18), we get the average growth rate of the economy, $g_t$, as

$$g_t = E\left(\ln Y_{t+1} - \ln Y_t\right) = \lambda \cdot n_t \cdot \ln \gamma. \tag{19}$$

Note that this is also the growth rate of per capita GDP at the steady state because we assume that fertility is at the replacement rate.

## 2.3 The balanced growth path

Along the balanced growth path, all markets clear and the common long-run growth rate of technology and output is constant. The endogenous consumption-savings decision of individuals affects the real interest rate and, as obvious from Equation (15), exerts an influence on the demand for research, which affects the number of scientists and thereby the frequency of quality-improving innovations. This in turn determines the growth rate of the economy. Along the balanced growth path, the time dimension is not relevant because the growth rate is constant such that we suppress the time index and the innovation index from now on. The model dynamics along the balanced growth path are summarized by the following four-dimensional system of equations:

$$g_C = (1+r)\beta\phi - 1, \tag{20}$$

$$g_Y = \lambda n \cdot \ln(\gamma), \tag{21}$$

$$1 = \frac{\lambda\gamma(1-\alpha)\left(L-n\right)}{\alpha(r+\lambda n)}, \tag{22}$$

$$L = n + \left(\frac{\alpha^2}{\omega}\right)^{\frac{1}{1-\alpha}}. \tag{23}$$

Along the balanced growth path, aggregate consumption grows at the same rate as aggregate output such that $g_C = g_Y$ as referred to in Equations (20) and (21). Assuming a sufficiently high $\lambda$ ensures that innovations arrive with a high probability within one period. Recalling that we have an overlapping generations framework in which a time period lasts for approximately 40 years, it is reasonable that many innovations occur within one period on average. Equation (22) can be derived by plugging the flow of profits $\tilde{\pi} = (1-\alpha)\omega x/\alpha = (1-\alpha)\omega\,(L-n)\,/\alpha$ into the no-arbitrage condition and Equation (23) is the labor market clearing condition.

Using Equations (20)-(23), we solve for the four unknowns $g = g_C = g_Y$, $r$, $n$, and $\omega$. The associated long-run growth rate of the economy boils down to

$$g = \max\left\{\frac{\ln(\gamma)\{\alpha + \beta\phi[(\alpha-1)\gamma\lambda L - \alpha]\}}{\beta\phi[\alpha(\gamma-1)-\gamma] - \alpha\ln(\gamma)}, 0\right\}. \tag{24}$$

Note that the first expression within the curly brackets is typically positive as long as the product of $\beta$, $\phi$, $\gamma$, $\lambda$, and $L$ is not too low. However, there is the possibility that research incentives are too low to sustain a positive growth rate, for example, if the productivity of researchers, $\lambda$, is close to zero. Since employment of researchers and with it the long-run growth rate of the economy cannot become negative, we have the lower bound of zero on the long-run growth rate as reflected in the formulation of Equation (24). In this case, the economy would be in a corner solution associated with long-run stagnation.

# 3 Results

## 3.1 Growth effects

Since we are interested in the effects of rising life expectancy on long-run economic growth, we analyze the effect of the survival probability, $\phi$, on the long-run balanced growth rate. A higher survival probability implies a higher life expectancy and also a higher average age in the economy, such that an increase in $\phi$ is tantamount to population aging. We can state the following proposition.

**Proposition 1.** *The long-run growth rate, $g$, increases in response to a higher survival probability, $\phi$.*

*Proof.* The partial derivative of the growth rate with respect to the survival probability is given by

$$\frac{\partial g}{\partial \phi} = \frac{\alpha\beta\ln(\gamma)\{\alpha+\gamma-\alpha\gamma+\ln(\gamma)[\alpha-(\alpha-1)\gamma\lambda L]\}}{[\beta\phi(\alpha+\gamma-\alpha\gamma)+\alpha\ln(\gamma)]^2}. \tag{25}$$

The denominator of this expression is always positive. Taking into account that $0 < \alpha < 1$, the numerator is also always positive such that the survival probability

$\phi$ has a strictly positive effect on the long-run growth rate of the economy.

□

The economic intuition for this finding is that an increase in life expectancy reduces the generational turnover and therefore raises aggregate savings. Given the higher savings, the mutual funds can invest more into the shares of intermediate goods companies which raises the demand for new innovations. This in turn leads to a higher employment level in the research sector such that the probability of successful innovations within each period increases. As a consequence, the long-run growth rate of aggregate consumption and aggregate output rise.

Interestingly, since higher savings imply a decrease in the interest rate, individual consumption growth decreases. This is due to the perfectly insured risk of death: a change in the survival probability does not affect individual consumption growth directly but only indirectly via the reduction in the interest rate. A lower interest rate implies that individual consumption growth decreases. On the aggregate level, however, there are two opposing effects. An increase in $\phi$ has a direct positive effect on aggregate consumption growth because of the reduction in the generational turnover effect, whereas the decrease in the interest rate has an indirect negative effect on aggregate consumption growth. The negative indirect effect of a lower interest rate, $r$, will always be overcompensated by the positive direct effect of a higher survival rate, $\phi$. Otherwise, aggregate savings would not rise and the interest rate would not decrease to start with. Altogether, therefore, aggregate consumption growth increases with the survival probability. Consequently, a rising survival probability reduces the wedge between individual consumption growth and aggregate consumption growth. In the limit of $\phi = 1$, inspection of the individual and the "aggregate" Euler equation shows that they are the same. In this case, we would be back in the standard formulation of an overlapping generations model.

Inspecting the long-run growth rate $g$ in Equation (24), shows that the effects of $\beta$, $\lambda$, and $L$ are positive, while the effect of $\alpha$ is negative. These results are the same as expected and in line with the literature. The effect of $\gamma$ is ambiguous, but for a reasonably high $\gamma$, it is positive because the monopolist enjoys higher rents, which eventually increases the incentives to invest in research. The negative relationship for low values of $\gamma$ is caused by $n$ becoming negative, which is, however, ruled out for economic reasons.

In Figure 1, we show the relationship between the growth rate $g$ and the survival probability $\phi$ for the following values of the parameters. We assume that the size of the workforce is $L = 161$ million persons, approximately the size of the workforce in the United States. The choice of the discount factor $\beta = 0.1$ corresponds to a yearly

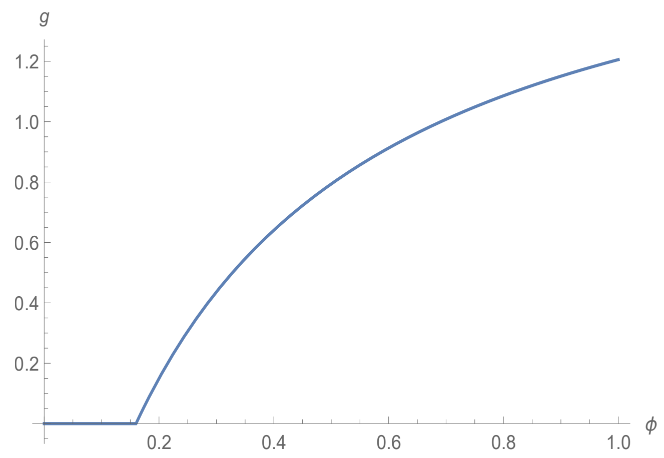


Figure 1: Survival probability and the long-run growth rate

discount rate of approximately 6%, the size of $\gamma = 1.1$ implies that every successful quality improvement increases productivity by 10%. The survival probability $\phi$ is set such that life expectancy corresponds to the value in the United States of 78.75 years (World Bank, 2016). Finally, we set the productivity of scientists to $\lambda = 0.0000001737$ to fit the implied growth rate of the model to the actual aggregate growth rate of the United States economy over 40 years. The low value of $\lambda$ makes intuitively sense because, in reality, the probability of one single scientist to come up with a quality-improving innovation of an order of magnitude corresponding to 10% is rather low.

As described above, we observe a strictly positive effect of the survival probability $\phi$ on the long-run growth rate $g$. Notice that the effect of the survival probability on economic growth is concave such that the positive effect of an increase in the survival probability is high for a low level of the survival probability, whereas the converse holds true for a high level of the survival probability. For very low values of $\phi$, i.e., for a very low life expectancy, the number of scientists and the economic growth rate could turn negative. While this can be explained by the same logic as above, the outcome is not meaningful in an economic sense such that, in this case, the economy is trapped in the stagnation equilibrium with no employment in the research sector and a growth rate of zero.

## 3.2 Welfare effects

We have shown that increases in longevity positively impact on long-run economic growth. It is clear that in our overlapping generations economy, higher economic growth is related to higher welfare at the individual as well as at the aggregate level. Keeping that in mind, the welfare gains can be disentangled into two separate effects:

(1) Increases in longevity positively impact on the savings rate, which raises productivity and thus the growth rate of the economy. In the long run, this increases consumption and therefore welfare.

(2) Individuals do not only derive utility from the higher consumption induced by the effect of higher life expectancy on economic growth but also from the direct effect of living longer.

Considering these two channels, it is interesting to analyze the relative importance of each channel depending on the health status of the inhabitants of an economy (measured by $\phi$) and depending on how developed an economy already is (measured by the level of technology $A_t$). We do so by comparing how an increase in longevity of 1 year, i.e., an increase in $\phi$ of 0.025, impacts on the relative importance of productivity gains for the gains in overall welfare. In so doing, we isolate the welfare effect of an increase in longevity by calculating the welfare derived from higher consumption due to higher productivity, given a *counterfactually unchanged* survival probability. Then we calculate the welfare effect of an increase in longevity as the share of the total increase in welfare that is due to an increase in longevity. We perform these calculations depending on

a) initial life expectancy ($\phi$),

b) the development stage of the economy ($A_t$).

The result is illustrated in Figure 2. In this case $\phi$ refers to the initial survival probability, such that life expectancy is 60 years at $\phi = 0$ and 100 years at $\phi = 1$. The welfare share refers to the share of welfare increases due to increases in productivity after life expectancy has increased by 1 year. It is apparent that higher initial life expectancy implies a lower relative importance of increases in productivity for individual welfare gains. Put differently, for economies with an already high life expectancy, a further increase in $\phi$ mostly increases welfare because of additional utility derived from living longer. Additional utility gains derived from higher consumption become less important. The same logic applies to the comparison in case of different development stages. The more developed an economy is, the less important are productivity gains for increases in welfare.[3] This result contains a very plausible

[3]The values of $A$ correspond to wage rates in the range of $5,000$\$ to $50,000$\$, indicating the different welfare shares from developing countries to developed countries.

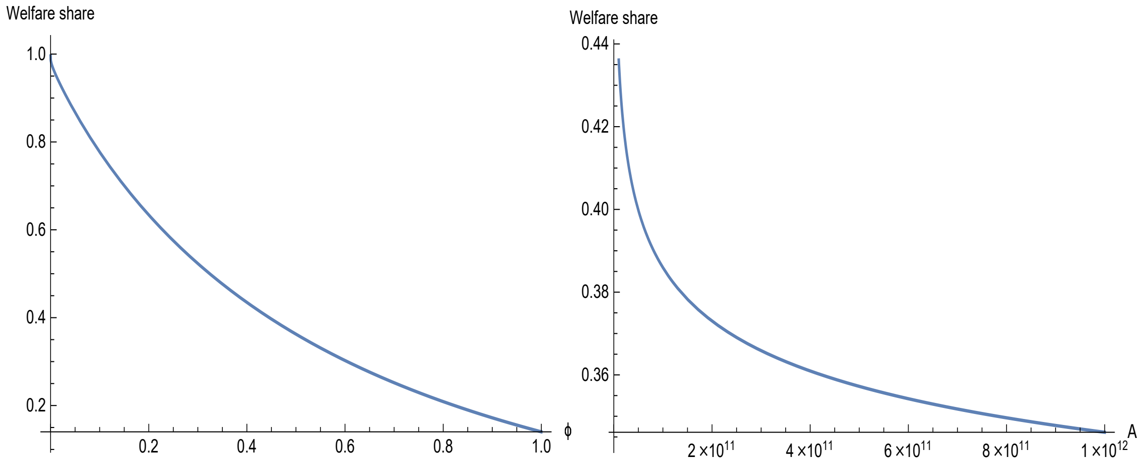


Figure 2: Relative share of productivity gains for gains in welfare

logic: in order to enjoy their welfare longer, individuals in well-developed economies prefer increases in life expectancy over increases in productivity. We summarize this in the following remark.

**Remark 1.** *Increases in life expectancy primarily raise welfare because individuals live longer. The resulting improvements in productivity become less important the better the health status of the inhabitants of an economy and the more developed an economy is.*

To make this intuition clearer, Table 1 contains a numerical example. We adjust the parameters in this exercise such that they correspond to the observed values for the United States, which corresponds to the actual welfare shares. We then conduct a comparative static analysis by separately decreasing the initial life expectancy by 10 years, the wage rate by $10,000$$ and the size of the work force by 20 million, ceteris paribus. This allows us to understand how different parameter values impact on the importance of the welfare share of productivity.

The results confirm the relationships explained in Figure 2. High initial life expectancy as well as high initial productivity imply that the increase in welfare triggered by an increase in life expectancy is predominantly due to the welfare derived from living longer. Furthermore, it is surprising that the development stage does not change the picture by much – even though a negative relationship with the welfare share of productivity gains can be observed. Even for less developed economies, the welfare share of longevity gains exceeds the one of productivity gains. The same weak relationship holds true for the size of the work force, $L$, because of the scale effect in the R&D sector.

| | Productivity share | Longevity share |
|---|---|---|
| Actual parameter values | 38.36% | 61.64% |
| Initial life expectancy reduced by 10 years | 60.79% | 39.21% |
| Yearly wage rate per worker reduced by $10,000$$ | 38.76% | 61.24% |
| Size of the work force reduced by 20 million | 38.96% | 61.04% |

Table 1: Decomposition of additional utility for an increase in life expectancy of 1 year

**Remark 2.** *Even for early stages of development, the higher growth rate of the economy that is induced by the rise in longevity, is less important for welfare gains than the actual utility gain derived from living longer in the first place.*

Altogether, the results are clear and straightforward. The welfare gains of additional growth that is induced by living longer are much smaller than the direct welfare gains of living longer. This is fully consistent with the results of Kuhn and Prettner (2016) who show that an increase of the health sector beyond the growth-maximizing size is actually a Pareto improvement. In other words, choosing the size of the health care sector solely by considering its economic growth effect crucially misses the point because it disregards the large direct welfare effects of higher life expectancy. Furthermore, we have shown that the relative welfare gain that is due to living longer increases with the level of development of an economy. This is fully in line with the result of Hall and Jones (2007) who show that an increase in the share of resources devoted to health care is the optimal outcome in the course of economic development.

# 4 Conclusions

We introduce a demographic structure with three overlapping generations, childhood, adulthood, and retirement into an endogenous growth model based on vertical innovations, i.e., quality improvements of intermediate goods. in this setting, individuals face an exogenously given survival probability from adulthood to retirement, which determines the life expectancy in the economy. We show that increasing longevity by means of a rise in the exogenous survival probability leads to higher aggregate savings, which raises the demand for innovation. This in turn leads to higher employment in the R&D sector, faster technological progress and higher long-run economic growth.

We also assess the welfare effects of rising longevity and decompose the effect into the direct welfare effect of living longer, and the indirect consumption effect of the higher induced economic growth rate. We show that the direct welfare effects are much larger than the indirect welfare effects. Furthermore, the relative importance of the direct welfare effect increases with economic development. Both of these results are consistent with the literature and they emphasize that focusing solely on the growth effects of any health care reform misses a crucial point.

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