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LONGEVITY AND TECHNOLOGICAL CHANGE

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We analyze the impact of increasing longevity on technological progress within an overlapping generations research and development (R&D)-based growth framework and test the model's implication on Organization for Economic Co-operation and Development (OECD) data from 1960 to 2011. The central hypothesis is that—by raising the incentives of households to invest in physical capital and in R&D—decreasing mortality positively affects technological progress and productivity growth. The empirical results confirm the theoretical prediction. This implies that the demographic changes we observed in industrialized economies over the last decades were not detrimental to economic prosperity, at least as far as technological progress and productivity growth are concerned.

Keywords: Demographic Change, Longevity, Productivity, Technological Progress, Economic Prosperity

1. INTRODUCTION

Over the last few decades, industrialized countries faced substantial demographic changes. In the Organization for Economic Co-operation and Development (OECD), life expectancy at birth has increased from 67 years in 1960 to 80 years in 2011, while the total fertility rate (TFR) has declined over the same time frame from 3.2 children per woman to 1.8 children per woman [World Bank (2014)].

In addition, the projections of the World Health Organization [WHO (2012)] suggest that in Europe, the proportion of the population aged 65 and above will almost double over the coming decades, increasing from 14% in 2010 to 27% in 2050. These demographic developments have attracted considerable attention not only within the scientific community, but also in the public debate: The Economist (2004) predicts that "Europe's rapid ageing will inflict economic pain"

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and Peterson (1999) even states that aging is a "threat more grave and certain than those posed by chemical weapons, nuclear proliferation, or ethnic strife." Even less alarmist economists and commentators broadly share some substantial concerns: (i) the ongoing increase in the ratio of retirees to the working-age population is expected to undermine the fiscal sustainability of social security systems and pension schemes [see, for example, Gertler (1999), Gruescu (2007), Bloom et al. (2010)]; (ii) savings and investment rates decline when the members of larger, older cohorts retire and start to run down the assets they accumulated in the past [cf. Mankiw and Weil (1989)]; and (iii) population aging might undermine the innovative capacity of a society [cf. Canton et al. (2002), Borghans and ter Well (2002), with the latter summarizing the relevant literature].

We aim to contribute to this debate by explicitly focusing on channel (iii), in particular, by analyzing the extent to which increasing longevity impacts upon technological progress and productivity growth. Our contribution therefore relates most closely to the research and development (R&D)-based growth literature that studies the determinants of technological progress and productivity growth as equilibrium market outcomes resulting from the interaction of utility-maximizing individuals and profit-maximizing firms.[1] To derive an empirically testable theoretical prediction regarding our research question, we therefore simplify the framework used in Prettner (2013) and Kuhn and Prettner (2016a) and propose an R&D-based endogenous economic growth model according to Romer (1990) that is augmented by a demographic structure of overlapping generations in the spirit of Blanchard (1985). It is crucial to mention at this point that all the effects of our theoretical framework would also be present in an overlapping generations version of the semi-endogenous growth model of Jones (1995) during the transition phase [this is shown in detail in Prettner and Trimborn (2016)]. Since the transition phase of calibrated semiendogenous growth models usually lasts many decades (or even centuries), the predictions of the model based upon Romer (1990) and those of a model based upon Jones (1995) would be observationally equivalent for the time span 1960 to 2011 for which we have the data to carry out our empirical analysis.

Our main theoretical prediction is that increasing longevity positively affects technological progress and therefore productivity growth. Intuitively, a decrease in the rate of mortality implies that households live longer and therefore they discount the future less heavily. As a consequence, aggregate savings rise, exerting downward pressure on the long-term market interest rate. Since the expected profits of R&D investments are discounted with the market interest rate, the profitability of R&D rises. This implies that more resources are devoted to R&D activities with a positive impact upon technological progress and productivity growth. The first part of this argument—that population aging is accompanied by an increase in savings and by a declining interest rate—is an established finding in the literature: Krueger and Ludwig (2007) show in an overlapping generations model that the transition toward a longer living population exercises a downward pressure on the rate of return on capital. Analogously, Bloom et al. (2003) demonstrate that a

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higher life expectancy leads to higher saving rates at every age. The second part of our theoretical argument is, in turn, the core mechanism on which the endogenous and the semiendogenous economic growth literature rely.

We empirically test and confirm our theoretical prediction by relying on a panel dataset for 22 OECD countries observed over the period from 1960 to 2011. Our estimates suggest that a 10% decrease in the death rate leads to approximately a 1% increase in the TFP index and a 2.5–2.7% increase in labor productivity. To the extent that the death rate was decreasing at an average annual rate of 1.3% in our OECD sample, it contributed to an annual improvement in TFP by 0.13 percentage points and in labor productivity by 0.33–0.35 percentage points. These results are remarkably robust to the application of different estimation techniques, the introduction of additional control variables, and different ways of expressing the dependent variable, with only small variations in the magnitude of the estimated effect among the different specifications.

Our findings contribute to the ongoing debate on whether an expansion of the individual lifetime horizon has a positive or a negative effect on economic growth. On the one hand, Acemoglu and Johnson (2007, 2014) provide empirical evidence indicating that improvements in life expectancy reduced economic growth as measured in terms of gross domestic product (GDP) per capita and GDP per working age population. This contrasts with the findings of Shastry and Weil (2003), Weil (2007), and Lorentzen et al. (2008), who find that countries with better health conditions and thus greater longevity exhibit faster economic growth. In attempts to clarify this issue, Aghion et al. (2011) and Bloom et al. (2014) provide conceptual and methodological explanations for the results of Acemoglu and Johnson (2007). In particular, they argue that the negative relationship between improved health and economic growth in the period 1960–2000 might be due to the omission of the initial health condition from the estimation. Consequently, the observed significant negative coefficient of life expectancy might not emerge because improvements in the health conditions of the population have a detrimental effect on economic growth, but because countries with better initial health conditions experienced smaller gains in terms of population health over the following decades. Acemoglu and Johnson (2014), in turn, suggest that the results reported by Bloom et al. (2014) are driven by the fact that the inclusion of initial health prevents them from applying a suitable panel data framework. Cervellati and Sunde (2011) identify the presence of nonmonotonic effects in the estimations of Acemoglu and Johnson (2007). In a Malthusian setting (prior to the demographic transition), increasing life expectancy indeed raises population growth and thereby reduces per capita income growth. However, in the modern growth regime (after the demographic transition), increasing life expectancy leads to a more than proportional reduction in fertility and thereby contributes to a slowdown in population growth and a rise in economic growth. By splitting the sample of Acemoglu and Johnson (2007) into pretransitional and posttransitional countries, Cervellati and Sunde (2011) show that the link between life expectancy and economic growth is likely to be negative in the former, and positive in the latter.

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Since we focus on OECD countries, both issues, the convergence of health and the nonlinearities due to different stages in the demographic transition, are much less of a concern. This allows us to apply panel data estimation techniques without including initial health and without splitting the sample to take into account the differential effects of longevity in a pretransitional and in a posttransitional environment. Furthermore, whereas the aforementioned empirical studies focus on the impact of increasing life expectancy on economic growth, we aim to complement the discussion by focusing on the empirical relationship between longevity and an important determinant of long-run economic growth, namely, technological progress. Doing so allows us to abstract from complicated interactions with other mechanisms by which demography affects economic growth directly, such as physical and human capital accumulation, Malthusian dynamics, and changes in dependency ratios.[2] This, of course, also prevents us from concluding that any particular effect of longevity on technological progress will necessarily feed through to economic growth as such. For example, it could very well be the case that the negative effect of rising longevity on the fiscal balance of social security systems and the accompanying increases in social security contributions and/or taxes even overcompensate for the positive effect of increasing longevity on technological progress.

While our paper analyzes the effect of changing longevity, it is also related to the literature on the relation between the age structure of the population and economic growth. Irmen and Litina (2016) find a hump-shaped relation between aging and inventive activity. The positive relation is explained by the awareness that aging requires inventive activity to guarantee current and future living standards, whereas the negative relation is motivated by the tendency of aging societies to lose dynamism. Crespo-Cuaresma et al. (2014) show that prospective aging measures are a better predictor for economic performance than measures based on the chronological age. In a very interesting article, Feyrer (2007) assesses the overall relation between age structure and productivity and finds that having a large cohort of workers in the age group 40–49 is associated with higher productivity. In the conclusions he states: "While emphasizing the importance of demographics, this paper is agnostic as to the mechanisms through which demographic change and productivity are related." [Feyrer (2007, p. 108)]. This is exactly where we want to step in to shed additional light on one particular channel that matters in this regard.

The paper is structured as follows. Section 2 presents the simplified theoretical framework of R&D-based economic growth with overlapping generations. Section 3 is dedicated to our empirical analysis by means of (dynamic) panel methods. Finally, Section 4 concludes.

2. LONGEVITY AND TECHNOLOGICAL CHANGE: THEORY

2.1. Basic Assumptions

To derive an empirically testable prediction of the impact of longevity on technological progress, we present a simplified version of the overlapping generations

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R&D-based growth model by Prettner (2013) and Kuhn and Prettner (2016a). Note that this theoretical framework mainly serves as a motivation for the empirical analysis in Section 3.

Consider a modern knowledge-based economy with three sectors in the vein of Romer (1990)[3]: final goods production, intermediate goods production, and R&D. Two production factors are used in these sectors: physical capital, $K(t)$, and human capital, $H(t)$. Physical capital is accumulated due to the savings of households and it is used to produce machines in the intermediate goods sector. Aggregate human capital consists of individual human capital, $h(t)$, and raw labor, $L(t)$, such that $H(t) = h(t) \cdot L(t)$. For convenience, we refer to labor employed in the final goods sector as "workers" and to labor employed in the R&D sector as "scientists." Scientists develop the blueprints for machines in the R&D sector, capital and blueprints are used to produce machines in the intermediate goods sector, and workers and machines are used to produce consumption goods in the final goods sector.

In contrast to the representative agent assumption on which the Romer (1990) framework is based, we assume the following demographic structure [see Blanchard (1985), Prettner (2013)]: At each point in time (t), different cohorts that can be distinguished by their date of birth (t_0) are alive. A cohort consists of a measure $L(t_0, t)$ of individuals, each of whom is endowed with h units of human capital and inelastically supplies one unit of labor. Consequently, the population size is equivalent to the size of the labor force. For the sake of analytical tractability, we assume that individuals face a constant risk of death, which we denote by μ and which determines an individual's longevity. Due to the law of large numbers, μ also refers to the fraction of individuals who are dying at each instant. We follow Romer (1990) and assume that the population size stays constant. This implies that the death rate is equal to the *period* fertility rate and that both rates change in lockstep. Consequently, the *cohort* fertility rate and hence households' fertility *decisions* remain unaffected if the mortality rate changes [see Kuhn and Prettner (2016a) for a formal proof].

2.2. Consumption Side

Suppressing time subscripts, we write an individual's discounted stream of lifetime utility as

$$u = \int_{t_0}^{\infty} e^{-(\rho+\mu)(\tau-t_0)} \log(c) d\tau, \tag{1}$$

where c denotes individual consumption of the final good and $\rho > 0$ is the discount rate. Note that the discount rate is augmented by the mortality rate $\mu > 0$ because, as compared to the infinitely lived representative agent setting, somebody who is facing a positive risk of death is less inclined to postpone consumption to the future. Following Yaari (1965), individuals save by investing in actuarial notes of a fair life insurance company. This implies that the assets of those who

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die are redistributed amongst those who survive. Consequently, the evolution of individual physical capital (k) is given by

$$\dot{k} = (r + \mu - \delta)k + \hat{w} - c, \tag{2}$$

where r refers to the capital rental rate that is augmented by the mortality rate μ because of the redistributions of the fair life insurance company, $\delta > 0$ is the depreciation rate, and $\hat{w}$ refers to noninterest income consisting of wage payments and lump-sum distributions of dividends. Utility maximization implies that the optimal consumption path of an individual who belongs to a certain cohort is characterized by the individual Euler equation

$$\frac{\dot{c}}{c} = r - \delta - \rho, \tag{3}$$

stating that consumption growth is positive if and only if the interest rate ($r - \delta$) exceeds the discount rate (ρ). The interpretation is straightforward: Individuals only save if the financial sector (as represented by the life insurance company) is able to offer an interest rate that over-compensates their impatience. Since saving means consuming less today and more in the future, an increase of the saving rate is associated with an increase in consumption growth.

Individuals are heterogeneous with respect to age. Older individuals have had more time to build up positive assets in the past and they are therefore richer and can afford more consumption. Consequently, we have to integrate over all the cohorts alive at time t to obtain the law of motion for aggregate physical capital and aggregate consumption. After carrying out the calculations described in Appendix A, which largely follow Heijdra and van der Ploeg (2002) and Prettner (2013), we arrive at the following expressions:

$$\dot{K} = (r - \delta)K(t) - C(t) + \hat{W}(t), \tag{4}$$

$$\frac{\dot{C}(t)}{C(t)} = r - \rho - \delta - \mu(\rho + \mu)\frac{K(t)}{C(t)}, \tag{5}$$

where we denote aggregate variables by uppercase letters. Note that the term $(\rho + \mu)K(t)/C(t) = [C(t) - c(t,t)L]/C(t)$ is positive and describes the impact of the generational turnover due to the birth and death process on aggregate consumption growth. Intuitively, at each instant, a fraction μ of older and therefore wealthier individuals die and they are replaced by poorer newborns. Since the latter can afford less consumption than the former, the generational turnover slows down *aggregate* consumption growth as compared to *individual* consumption growth.

2.3. Production Side

The production side of the economy closely follows the standard R&D-based growth literature [cf. Romer (1990), Jones (1995)]. The final goods sector produces

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the consumption aggregate with human capital and machines as inputs according to the production function

$$Y = H_Y^{1-\alpha} \int_0^A x_i^{\alpha} di, \tag{6}$$

where Y is output, H_Y refers to human capital employed in final goods production, A is the technological frontier, x_i is the amount of machine i used in final goods production, and $\alpha \in (0, 1)$ is the elasticity of final output with respect to machines. Profit maximization implies the following inverse demand functions for human capital and machines in the final goods sector:

$$w_Y = (1-\alpha)\frac{Y}{H_Y}, \qquad p_i = \alpha H_Y^{1-\alpha} x_i^{\alpha-1}, \tag{7}$$

where w_Y refers to the wage rate per unit of effective labor in the final goods sector and p_i to the prices paid for machines. Note at this stage that we refer to the final good as the numéraire.

The intermediate goods sector is monopolistically competitive because each firm produces one of the blueprint-specific varieties of machines [cf. Dixit and Stiglitz (1977)]. To be able to do so, it has to purchase one blueprint from the R&D sector as fixed input and employ physical capital as a variable production factor. Without loss of generality, we assume that one unit of physical capital can be transformed into one machine, that is, $k_i = x_i$. Free entry into the intermediate goods sector ensures that operating profits are equal to fixed costs in equilibrium such that overall profits are zero. Operating profits are given by

$$\pi_i = p_i k_i - r k_i = \alpha H_Y^{1-\alpha} k_i^{\alpha} - r k_i, \tag{8}$$

and profit maximization of firms yields the price of machines as $p_i = r/\alpha$, where $1/\alpha$ is the markup [cf. Dixit and Stiglitz (1977)]. Note that this holds for all firms, so we can drop the index i in the subsequent analysis.

The R&D sector employs scientists to discover new blueprints according to the production function

$$\dot{A} = \lambda A H_A, \tag{9}$$

where H_A denotes the human capital level of scientists and λ refers to their productivity. Recall that using the alternative specification of Jones (1995) with exponents on A and H_A that are smaller than one would imply similar effects to the ones outlined here during the transition phase [see Prettner and Trimborn (2016)]. Consequently, the prediction that we test empirically over a time frame of approximately 50 years is invariant to whether we base our analysis on the framework of Romer (1990) or on the framework advocated by Jones (1995). There is perfect competition in the research sector such that firms maximize $\pi_A = p_A \lambda A H_A - w_A H_A$, with π_A being the profit of a firm in the R&D sector and p_A representing the price of a blueprint. The first-order condition of the profit

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maximization problem pins down the wage rate per unit of effective labor in the research sector to

$$w_A = p_A \lambda A. \tag{10}$$

2.4. Market Clearing

In an interior equilibrium, the wage rates per unit of effective labor of final goods producers and of scientists have to equalize because of perfect labor mobility. Inserting equation (7) into equation (10) yields the following equilibrium condition:

$$p_A \lambda A = (1-\alpha)\frac{Y}{H_Y}. \tag{11}$$

Firms in the R&D sector charge a price for their blueprints that corresponds to the present value of the operating profits in the intermediate goods sector. The reason is that there is always a potential entrant who is willing to pay that price due to free entry [cf. Romer (1990)]. Consequently, the price of blueprints is $p_A = \int_0^\infty e^{-[R(\tau)-R(t_0)]}\pi \, d\tau$, where the discount rate is the market interest rate $R(t_0) = \int_0^{t_0}[r(s) - \delta] \, ds$. Via the Leibniz rule and the fact that the price of blueprints does not change along a balanced growth path (BGP), we obtain

$$p_A = \frac{\pi}{r-\delta}. \tag{12}$$

Using equation (8), operating profits can be written as $\pi = (1-\alpha)\alpha Y/A$, such that equation (12) becomes $p_A = [(1-\alpha)\alpha Y]/[(r-\delta)A]$. Equation (11) and labor market clearing ($H = H_A + H_Y$) imply that the amounts of human capital employed in the final goods sector and in the R&D sector are, respectively,

$$H_Y = \frac{r-\delta}{\alpha\lambda}, \qquad H_A = H - \frac{r-\delta}{\alpha\lambda}. \tag{13}$$

Inserting H_A from equation (13) into equation (9) and dividing by A yields the growth rate of technology

$$g = \lambda H - \frac{r-\delta}{\alpha}, \tag{14}$$

where the right-hand side still depends on the endogenous interest rate. From the definition of a BGP, we know that $\dot{A}/A = \dot{C}/C = \dot{K}/K = g$. Furthermore, along the BGP, the aggregate Euler equation implies the following relationship between the interest rate on the one hand and economic growth, the rate of depreciation, individual impatience, and the demographic characteristics of the economy on the other:

$$r = g + \rho + \delta + \mu(\rho+\mu)\frac{K}{C}. \tag{15}$$

This relationship can be used to substitute for the interest rate in equation (14). In contrast to a representative agent setting, however, we still have to account for an

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endogenous expression, namely K/C. In so doing, we rewrite the law of motion of aggregate physical capital based upon the economy's resource constraint such that $\dot{K} = Y - C - \delta K$. Dividing by K and using the relation $Y/K = r/\alpha^2$ derived in Appendix A provides the following additional equation that holds along the BGP and that can be used to pin down the relationship of aggregate physical capital to aggregate consumption $\xi := K/C$

$$g = \frac{r}{\alpha^2} - \frac{C}{K} - \delta. \tag{16}$$

The three equations (14)–(16) allow us to solve for the three unknowns g, r, and ξ. The solutions are given by, respectively,

$$g = \frac{\delta - \alpha^2\delta - \alpha\rho - \sqrt{4\alpha^3\mu(\mu+\rho) + [(\alpha-1)(\alpha\delta+\delta+\alpha\lambda H) - \alpha\rho]^2} + \alpha^2\lambda H + \alpha\lambda H}{2\alpha(1+\alpha)},$$

$$r = \frac{(\alpha+1)^2\delta + \sqrt{4\alpha^3\mu(\mu+\rho) + [(\alpha-1)(\alpha\delta+\delta+\alpha\lambda H) - \alpha\rho]^2} + \alpha[(\alpha+1)\lambda H + \rho]}{2(1+\alpha)},$$

$$\xi = \frac{\delta - \alpha^2\delta + \alpha\rho + \sqrt{4\alpha^3\mu(\mu+\rho) + [(\alpha-1)(\alpha\delta+\delta+\alpha\lambda H) - \alpha\rho]^2} - \alpha^2\lambda H + \alpha\lambda H}{2\alpha^2}.$$

We can now state the central theoretical result that we aim to test empirically in Section 3 [cf. Prettner (2013)].

PROPOSITION 1. *Increasing longevity positively affects technological progress and productivity growth.*

Proof. The derivative of the growth rate (g) with respect to mortality (μ) is given by

$$\frac{\partial g}{\partial \mu} = -\frac{\alpha^2(2\mu+\rho)}{(1+\alpha)\sqrt{4\alpha^3\mu(\mu+\rho) + [(\alpha-1)(\alpha\delta+\delta+\alpha\lambda H) - \alpha\rho]^2}}. \tag{17}$$

Since α, μ, ρ, δ, λ, and H are positive and the second term under the square root in the denominator is nonnegative, we are able to conclude that $\partial g/\partial\mu$ is negative. The fact that a rise in longevity is tantamount to a decrease in mortality μ establishes the proof. ■

The intuition for this finding is that a decrease in mortality slows down the turnover of generations. This leads to faster aggregate physical capital accumulation, higher equilibrium savings, and a higher capital to consumption ratio (K/C), which, in turn, reduces the equilibrium interest rate ($r - \delta$).[4] Due to the fact that the future profits of R&D investments are discounted with the equilibrium interest rate, an increase in longevity implies a rise in the profitability of R&D

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investments, which spurs technological progress and productivity growth. Note that the effect of longevity on technological progress neither originates in a strong scale effect nor in a weak scale effect because the size of the workforce L and the aggregate human capital stock H remain constant for a change in μ because of our demographic assumptions (see Section 2.1).

Three points need to be clarified at this stage. We do not claim that our theoretical framework is the one and only possible description of the data-generating process. It rather serves as a guide to organize our thinking with regards to the plausible effect of increasing longevity on technological progress and as a rationale for the corresponding empirical estimations. Of course, in the OECD, many open economies interact with each other and it could be argued that we would need a multicountry open economy model to capture international spillovers and capital flows. However, while there is no reason to believe that the outlined mechanisms would change in case of increasing longevity in all OECD countries as we are currently observing it, the complexity of the framework would increase to the extent that analytical solutions could not be obtained anymore.

Second, it has been argued that the effect of mortality on the interest rate could be ambiguous in a framework with endogenous human capital formation. The reason is that increasing longevity would induce individuals to invest more in education [see, for example, Ben-Porath (1967), Cervellati and Sunde (2013)], which could make human capital relatively abundant as compared to physical capital and therefore result in an increase in the interest rate [cf. Heijdra and Reijnders (2015)]. We think that the long-run decline in the interest rate observed since the 1980s that went hand in hand with an increase in longevity implies that this objection might be less of a concern as far as the mechanism that we outline is concerned. Nevertheless, we control for human capital in some of the econometric specifications below to account for this possibility.

Third, the demographic structure has deliberately been kept simple to guarantee closed-form analytical solutions. In a more realistic setting (i) the population size could grow or shrink and the population growth rate might depend on longevity; (ii) there would be a certain retirement age that could change in line with longevity but it could also stay constant. As far as the first issue is concerned, it has been shown by Prettner (2013) and Prettner and Trimborn (2016) that an increase in longevity has a positive long-run growth effect on technology if the fertility rate stays constant or falls more slowly than mortality. Only in case that fertility falls faster than mortality, it is possible that the long-run rate of technological progress slows down in case of an increase in mortality. Even in this case, however, there would be a short- to medium-run increase in technological progress due to increasing longevity. As far as a fixed retirement age is concerned, Kuhn and Prettner (2016b) show that the positive effect of increasing longevity outlined here is also present in such a framework. However, there is a countervailing effect on technological progress by the accompanying increase in the old-age dependency ratio, which implies that fewer scientists are available and this would tend to reduce the pace of technological progress. The effect of longevity on

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technological progress is therefore a priori ambiguous in case of a fixed retirement age. This further emphasizes the need for empirical investigations on the impact of changing mortality on technological progress. This is what we attempt to provide in the next section.

3. LONGEVITY AND TECHNOLOGICAL CHANGE: EMPIRICAL ANALYSIS

3.1. Data and Variables

Our theoretical model provides a testable hypothesis on how increasing longevity influences technological progress. We assess this theoretical prediction on a dataset that includes 22 OECD countries for which data on the main dependent variable (productivity) are available (see Appendix C for the detailed list of countries). In so doing, we use state-of-the-art methods of dynamic panel data regressions as they are frequently used to assess the steady-state determinants of long-run economic growth [cf. Islam (1995), Caselli et al. (1996), Hauk and Wacziarg (2009)]. By focusing on industrialized economies, we are able to overcome four central obstacles: (i) the problem of strong heterogeneity in the sample, which can be a serious issue for growth regressions [Maddala and Wu (2002), Hineline (2008)][5]; (ii) the problem that demographic change has different implications for growth in a Malthusian regime of stagnation as opposed to a modern growth regime [see Cervellati and Sunde (2011)]; (iii) the issue pointed out by Bloom et al. (2014) that unaccounted health convergence in a heterogeneous sample could be responsible for the finding of spurious effects; and (iv) that less-developed countries do not contribute sufficiently to the advancement of the world technology frontier to warrant their inclusion in the sample [see Jones (2002), Keller (2002), Ha and Howitt (2007)]. We chose the longest time span possible, which resulted in 52 annual observations between 1960 and 2011. We use this data to estimate the model in five-year steps such that we do not base our identification on business-cycle fluctuations.

As our main choice of the dependent variable, we use the total factor productivity (TFP) index as proxied by the Solow residual. The index is provided by the European Commission's Directorate General for Economic and Financial Affairs (DG ECFIN) in its AMECO database for macroeconomic analysis.[6] Although in our view TFP reflects in the most accurate way the concept of technological progress to which we refer, it is not fully free of concerns. For that reason, we apply two robustness checks. First, we replace the TFP variable with labor productivity as measured by real GDP per employee {calculated as the ratio $rgdpe/emp$, with both series obtained from the Penn World Tables (PWT), version 8.0 [Feenstra et al. (2013)]}. Second, following Irmen and Litina (2016), we use a patent count variable as an alternative proxy for technological progress.[7] Specifically, we calculate the ratio $patent/population$, where $patent$ refers to the number

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of patent applications by residents provided by the World Intellectual Property Organization.[8]

Our most important explanatory variable is the death rate taken from the World Development Indicators database [World Bank (2014)]. This variable reflects the parameter μ of our theoretical model most precisely and its inverse is a reasonable approximation of longevity.

Irrespective of the fact that the parameter estimate of the influence of the death rate on productivity is robust against the omitted variable bias because of our dynamic specification, we include further explanatory variables that have been argued to constitute important determinants of productivity: trade openness [TO from the PWT, version 7.1 Heston et al. (2012)], human capital $\{HC$, which has been newly included in the PWT, version 8.0 [Feenstra et al. (2013)] and is expressed in terms of a human capital index, based on years of schooling—following Barro and Lee (2013)—and returns to education—as in Psacharopoulos (1994)$\}$, and the capital-to-output ratio [K, obtained based on data from the PWT, version 7.1]. Regarding this last variable, although capital is considered among the standard production factors that partly explain growth in income per capita and its direct effect is therefore removed by a growth accounting procedure, we want to account for possible indirect influences that the capital intensity might have on productivity development.

To capture the long-run influence in the underlying relationships better, we use data on TFP in five-year intervals, starting in 1960 in our baseline estimations. To the rest of the variables, we apply a transformation into five-year nonoverlapping averages, again starting in 1960, to overcome the concerns with regard to cyclical influences and to average out the noisy observations that are typical of annual data. This notwithstanding, in our robustness checks, we apply alternative five-year transformations of our original data to rule out the possibility that a particular data transformation procedure could have influenced our results.

3.2. Empirical Specification

Following our theoretical model, we test whether increasing longevity has positively affected technological progress in our sample of OECD countries. As our preferred specification, we use a dynamic framework that fully accounts for the countries' unobserved heterogeneity. The advantage of this specification is twofold. From an econometric point of view, we account for the strong persistence of the productivity variable, which requires a necessary AR(1) check. From a conceptual point of view, the specification including the lagged values of productivity permits us to account for the path-dependent nature of productivity development.

To this end, we specify our empirical model in dynamic form as follows:

$$\ln(\mathrm{TFP}_{i,t}) = \beta_1 + \beta_2 \ln(\mathrm{TFP}_{i,t-1}) + \beta_3 \ln(\mu_{i,t}) + \beta_4' \mathbf{Z}_{i,t} + \theta_i + \tau_t + \epsilon_{i,t},$$

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where $\text{TFP}_{i,t}$ is the TFP index in country i at time t, $\text{TFP}_{i,t-1}$ is its lagged value, $\mu_{i,t}$ refers to the death rate, $\mathbf{Z}_{i,t}$ is the vector of control variables, β_4' is a row vector of the corresponding coefficients to be estimated, θ_i and τ_t control for country-specific and time-specific fixed effects, respectively, and, finally, $\epsilon_{i,t}$ is the idiosyncratic error term. Despite the fact that our dynamic model theoretically eliminates the omitted variable bias, we still control for important country-specific characteristics that display some variability over time and that potentially influence the productivity dynamics. First, we control for the degree of international openness to trade to take into account the possibility that competition from abroad might raise the efforts of firms in the home country to increase their productivity [Bernard et al. (2006)]. More generally, international trade could affect the overall efficiency of an economy by enhancing specialization and by enabling access to new markets with new and advanced technologies [Grossman and Helpman (1991)]. Second, we include human capital to capture the fact that better educated scientists are more productive in developing new ideas as expressed in equation (9) and also argued by Strulik et al. (2013) or, more broadly, that a better educated workforce instigates the adoption of more efficient production techniques.[9] Third, as mentioned above, we control for the indirect contribution to productivity growth coming from producing with a higher capital intensity.[10]

3.3. Econometric Method

The inclusion of the lagged-dependent variable on the right-hand side of the specification in equation (18) potentially generates endogeneity. This renders the estimation results from standard methods, in particular, fixed-effects estimation, biased [Nickell (1981)]. As a valid solution, Generalized Method of Moments (GMM) estimation has been suggested.[11] This method, however, is only asymptotically efficient for samples with a small time dimension (small T) and a large cross-section dimension (large N). Consequently, it is not suited to our sample consisting of 22 countries observed over 52 years. A method proposed to deal with dynamic panel data and with endogeneity issues in cases in which the standard GMM framework cannot be applied efficiently is the corrected least-square dummy variable (LSDVC) estimator proposed by Kiviet (1995) and Judson and Owen (1999) and extended by Bruno (2005b) to allow for application in the case of an unbalanced panel such as the one used in the present study. This estimator has been shown to outperform other consistent estimators, such as standard GMM estimators, in Monte Carlo simulations based on small samples [see Bun and Kiviet (2003)].

To provide a better illustration of the method, suppose that we have an AR(1) autoregressive panel data model with observations that can be collected over time and across individuals. Such a model can be written as

$$y = \alpha \mathbf{X} + \zeta \mathbf{D} + \omega, \tag{18}$$

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where y is the vector of individual time-specific observations of the dependent variable, $\mathbf{X}$ is the matrix of explanatory variables, including the lagged-dependent variable, α refers to the corresponding vector of coefficients, $\mathbf{D}$ is the matrix of individual dummies, ζ represents the corresponding vector of individual effects, and ω is the idiosyncratic error term. The (uncorrected) LSDV estimator is then given by

$$\eta_{\text{LSDV}} = (\mathbf{X'AX})^{-1}\mathbf{X'A}y, \tag{19}$$

where $\mathbf{A}$ is the transformation matrix wiping out the individual effects. This estimator is not consistent when the lagged-dependent variable enters the specification. Bun and Kiviet (2003) derive the analytical form of the bias as

$$E(\eta_{\text{LSDV}} - \eta) = c_1(T)^{-1} + c_2(N^{-1}T^{-1}) + c_3(N^{-1}T^{-2}) + O(N^{-2}T^{-2}), \tag{20}$$

with the analytical expressions for $c_1(T)^{-1}$, $c_2(N^{-1}T^{-1})$, and $c_3(N^{-1}T^{-2})$ as described by Bun and Kiviet (2003, p. 147). Based on this estimation bias, Bun and Kiviet (2003) and Bruno (2005a) consider its three possible nested approximations, extended to the first (B_1), the first two (B_2), and the first three (B_3) terms of equation (20).[12] Given that B_3 is the most comprehensive and accurate approximation of the bias, we correct for it, such that our LSDVC estimator is given by

$$\text{LSDVC} = \text{LSDV} - B_3. \tag{21}$$

The correction procedure implies that, as a first approximation, the estimation has to be performed with a standard estimator that is consistent. There are three possible variants, namely the Anderson and Hsiao (1982), the Arellano and Bond (1991), and the Blundell and Bond (1998) estimators, which are, however, asymptotically equivalent. In our estimation procedure, we opt for correction with the Blundell and Bond (1998) initial estimator. As a final improvement to the standard estimation procedure, we bootstrap our standard errors. In so doing, we overcome the issue that the estimated standard errors are poor approximations in small samples, implying unreliable t-statistics.

3.4. Results

The results for the main model as described above are reported in Table 1. Three different methods are implemented, pooled OLS (columns 1–3), pooled IV regressions with the lagged death rate as an instrument for longevity (columns 4–6), and, finally, the corrected LSDV estimator (columns 7–9). The comparison between the methods allows us to perform a better assessment of the direction and the extent of the bias (i) by not accounting for possible endogeneity of the covariates, (ii) by not controlling for unobserved time-invariant country characteristics, and (iii) by excluding the dynamic effects of the dependent variable. Overall, the significance

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TABLE 1. Baseline results

	POLS (1)	POLS (2)	POLS (3)	IV (4)	IV (5)	IV (6)	LSDVC (7)	LSDVC (8)	LSDVC (9)
lagged TFP							0.741	0.739	0.722
							(0.049)***	(0.050)***	(0.052)***
μ	−0.129	−0.128	−0.122	−0.167	−0.165	−0.129	−0.173	−0.106	−0.124
	(0.056)**	(0.057)**	(0.051)**	(0.058)***	(0.060)**	(0.056)**	(0.037)***	(0.038)***	(0.043)***
TO	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	(0.000)	(0.000)	(0.000)*	(0.000)**	(0.000)**	(0.000)**	(0.000)***	(0.000)***	(0.000)***
HC		0.000	−0.000		0.000	0.000		0.001	0.001
		(0.001)	(0.000)		(0.001)	(0.001)		(0.001)	(0.001)
K			0.030			0.028			−0.011
			(0.008)***			(0.009)***			(0.011)
N	225	225	225	206	206	206	204	204	204
Country fe	No	No	No	No	No	No	Yes	Yes	Yes
Time fe	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.825	0.823	0.817	0.771	0.769	0.770	0.945	0.941	0.960

Note: One asterisk refers to significance at the 10% level, two asterisks refer to significance at the 5% level, and three asterisks refer to significance at the 1% level. POLS, IV and LSDVC refer to pooled OLS, pooled IV, and corrected least squares dummy variable estimations. In the IV estimations, the covariates at time t are instrumented with their one-period lags. Hausman test has been implemented to test the IV model versus fixed effects estimations. In all cases, the test was in favor of the IV model. The standard errors are reported in parenthesis. The bias correction has been initialized by the Blundell–Bond estimator. For definitions of the variables, see Table C.1 in Appendix C.

of the coefficient of the lagged-dependent variable in columns 7–9 provides strong support for a dynamic specification.

In the first columns referring to each method, we start with a parsimonious specification, considering only the death rate and trade openness (in addition to the lagged-dependent variable in the case of the LSDVC method). These two factors are significant across almost all the methods, specifications, and robustness checks. In the subsequent columns, we add other explanatory variables one by one. This permits us to detect how the basic results are affected by enlarging the set of covariates. The results show that there is some small variation in the *magnitude* but not in the *sign* of the estimated coefficients due to the inclusion of further variables.

Generally, there is a significantly negative effect of the death rate on TFP, which confirms our theoretical findings. As the death rate declined steadily over the years considered in our sample, it contributed to the observed rise in TFP. More precisely, according to the dynamic specification, a 10% decrease in the death rate brought about an increase of around 1% in TFP. The effect estimated according to the static specifications is slightly higher (1.3%–1.7%), but it is known to be susceptible to endogeneity issues and to the omitted variable bias. Note that we instrument for contemporaneous mortality by lagged mortality in the IV specification, which leads to a slightly more pronounced negative effect of mortality on productivity growth in most specifications.

In addition to the death rate, trade openness positively influenced TFP across all the specifications supporting the view that openness to international goods and services markets raises competition, which induces firms to increase their productivity. This result is in line with the previous literature explicitly investigating the impact of trade openness on TFP [see Miller and Upadhyay (2000), Gehringer (2013), the latter of which contains recent evidence from a sample of developed countries]. Regarding other explanatory variables, human capital did not have any significant impact on TFP, which is consistent with the previous literature [cf. Miller and Upadhyay (2000)]. In a comprehensive investigation, Pritchett (2001) provides three reasons for no (or even a negative) association between increases in human capital and growth in productivity. First, a greater demand for a better educated workforce could have come in part from "socially wasteful or counterproductive activities" [Pritchett (2001, p. 368)]. Second, by expanding the supply of educated labor in case of a stagnating demand for it, the rate of return on education could fall. The third explanation is that the quality of schooling could be low such that there is no positive contribution of education on skills upgrading and productivity. For the capital-to-output ratio, the results are mixed. The coefficient estimates are negative but insignificant under the LSDVC method, whereas they are almost always significantly positive under the static methods. Since the LSDVC estimator is the preferred method, we conclude that we do not find indirect effects of capital deepening on productivity growth.

Based on additional estimations, we want to corroborate the results from the baseline model. To this end, we first replace our dependent variable TFP with a

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labor productivity measure, expressed in terms of output per employee. The results are reported in Table 2 and confirm that the established relationship between the death rate and productivity is valid not only for TFP but also for labor productivity. It is also worth noting that the magnitude of the effect is stronger for labor productivity than for TFP. The explanation is that a lower death rate implies a better health condition of workers, which raises their productivity directly, while it does not have any direct impact on the productivity of physical capital. For the other explanatory variables, we could broadly confirm the results obtained previously.

In the next robustness check, we replace TFP with a patent count measure, expressed as the share of patent applications at the World Intellectual Property Organisation per thousand inhabitants. This alternative measure for technological progress is useful to check the general validity of our approach, but there are also drawbacks. Indeed, productivity measures based on patents suffer from limitations because patents refer to innovative outcomes officially registered at a patent office. Given that patent application and maintenance procedures tend to be very costly and the associated idea has to be published, innovators might not always register their patentable innovation and prefer to keep their ideas secret instead. In addition, some firms might apply and hold patents with the purpose of blocking other firms from using these patents and/or with the purpose of extracting license fees from other firms that have to use these patents. This, of course, implies that an increase in the number of patents does not, by itself, raise productivity. Finally, patent counts are not available for early time periods in our sample, which reduces the number of observations. This notwithstanding, we run our basic specifications with the patent count variable instead of TFP. Doing so generally confirms the results from out baseline model from a qualitative point of view (Table 3).

The second set of robustness checks refers to the possible influence of the recent financial and economic crisis. As the data description showed, the evolution of productivity was affected by the crisis. This could potentially have repercussions for the underlying relationships that we estimated. We therefore exclude the last observation from our sample (corresponding to the years 2008–2011) and report the results in Table 4. The direction of the influence of the death rate remains the same as in the baseline estimations. The magnitude of the influence, however, is slightly higher, by approximately 0.03 percentage points. This suggest that the years of the crisis were associated with sluggish productivity growth, despite the ongoing increase in longevity.

Finally, we assess the sensitivity of our results in response to a modification of the averaging procedure with respect to our TFP measure. To obtain the results displayed in Table 5, we used five-year nonoverlapping averages instead of the TFP series in five-year intervals. Qualitatively, in terms of the sign and the significance of the coefficient estimates, the results are robust to this different measurement of productivity. However, the coefficient estimates are slightly closer to zero.

Altogether our results are consistent with empirical cross-country growth regressions in which the growth rate of per capita GDP is, inter alia, explained by

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TABLE 2. Estimation results with labor productivity as the dependent variable

	POLS (1)	POLS (2)	POLS (3)	IV (4)	IV (5)	IV (6)	LSDVC (7)	LSDVC (8)	LSDVC (9)
lagged LP							0.827	0.829	0.799
							(0.034)***	(0.035)***	(0.037)***
μ	−0.394	−0.362	−0.101	−0.691	−0.657	−0.253	−0.254	−0.254	−0.189
	(0.105)***	(0.106)***	(0.111)	(0.127)***	(0.129)***	(0.134)*	(0.062)***	(0.064)***	(0.076)**
TO	0.003	0.003	0.004	0.002	0.002	0.003	0.000	0.000	0.001
	(0.001)***	(0.001)***	(0.001)***	(0.001)**	(0.001)**	(0.001)***	(0.001)	(0.001)	(0.001)
HC		0.003	0.002		0.001	0.001		0.000	−0.000
		(0.003)	(0.003)		(0.003)	(0.003)		(0.002)	(0.001)
K			0.129			0.141			0.030
			(0.021)***			(0.025)***			(0.018)
N	262	262	239	238	238	215	238	238	238
Country fe	No	No	No	No	No	No	No	No	No
Time fe	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.621	0.633	0.587	0.505	0.516	0.483	0.962	0.962	0.830

Note: One asterisk refers to significance at the 10% level, two asterisks refer to significance at the 5% level, and three asterisks refer to significance at the 1% level. POLS, IV and LSDVC refer to pooled OLS, pooled IV, and corrected least squares dummy variable estimations. In the IV estimations, the covariates at time t are instrumented with their one-period lags. Hausman test has been implemented to test the IV model versus fixed effects estimations. In all cases, the test was in favor of the IV model. The standard errors are reported in parenthesis. The bias correction has been initialized by the Blundell–Bond estimator. For definitions of the variables, see Table C.1 in Appendix C.

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TABLE 3. Estimation results with patents per thousand inhabitants as the dependent variable

	POLS (1)	POLS (2)	POLS (3)	IV (4)	IV (5)	IV (6)	LSDVC (7)	LSDVC (8)	LSDVC (9)
lagged patent							1.061	1.075	1.048
							(0.027)***	(0.029)***	(0.027)***
μ	−0.511	−0.342	0.086	−1.045	−0.869	−0.342	−0.544	−0.550	−0.328
	(0.186)***	(0.178)*	(0.210)	(0.241)***	(0.239)***	(0.283)	(0.095)***	(0.092)***	(0.108)***
TO	−0.003	−0.002	−0.001	−0.005	−0.004	−0.003	−0.000	−0.000	−0.000
	(0.002)	(0.002)	(0.002)	(0.002)***	(0.002)**	(0.002)	(0.001)	(0.001)	(0.001)
HC		0.028	0.025		0.023	0.021		−0.004	−0.005
		(0.005)***	(0.005)***		(0.006)***	(0.007)***		(0.003)	(0.003)
K			0.155			0.225			0.090
			(0.039)***			(0.050)***			(0.028)***
N	239	239	232	231	231	210	212	212	212
Country fe	No	No	No	No	No	No	No	No	No
Time fe	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.115	0.092	0.173	0.116	0.117	0.210	0.916	0.963	0.955

Note: One asterisk refers to significance at the 10% level, two asterisks refer to significance at the 5% level, and three asterisks refer to significance at the 1% level. POLS, IV and LSDVC refer to pooled OLS, pooled IV, and corrected least squares dummy variable estimations. In the IV estimations, the covariates at time t are instrumented with their one-period lags. Hausman test has been implemented to test the IV model versus fixed effects estimations. In all cases, the test was in favor of the IV model. The standard errors are reported in parenthesis. The bias correction has been initialized by the Blundell–Bond estimator. For definitions of the variables, see Table C.1 in Appendix C.

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TABLE 4. Estimation results excluding the crisis

	POLS (1)	POLS (2)	POLS (3)	IV (4)	IV (5)	IV (6)	LSDVC (7)	LSDVC (8)	LSDVC (9)
lagged TFP							0.740	0.740	0.730
							(0.043)***	(0.045)***	(0.044)***
μ	−0.147	−0.149	−0.143	−0.182	−0.181	−0.141	−0.138	−0.142	−0.137
	(0.062)**	(0.063)**	(0.057)**	(0.066)***	(0.068)***	(0.063)**	(0.058)**	(0.059)**	(0.061)**
TO	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	(0.000)	(0.000)	(0.000)**	(0.000)	(0.000)*	(0.000)**	(0.000)**	(0.000)**	(0.000)**
HC		−0.000	0.000		0.000	0.001		0.002	0.002
		(0.002)	(0.001)		(0.002)	(0.001)		(0.001)	(0.001)
K			0.037			0.032			0.002
			(0.009)***			(0.010)***			(0.012)
N	203	203	185	184	184	166	182	182	182
Country fe	No	No	No	No	No	No	No	No	No
Time fe	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.812	0.811	0.801	0.753	0.752	0.749	0.942	0.934	0.968

Note: One asterisk refers to significance at the 10% level, two asterisks refer to significance at the 5% level, and three asterisks refer to significance at the 1% level. POLS, IV and LSDVC refer to pooled OLS, pooled IV, and corrected least squares dummy variable estimations. In the IV estimations, the covariates at time t are instrumented with their one-period lags. Hausman test has been implemented to test the IV model versus fixed effects estimations. In all cases, the test was in favor of the IV model. The standard errors are reported in parenthesis. The bias correction has been initialized by the Blundell–Bond estimator. For definitions of the variables, see Table C.1 in Appendix C.

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TABLE 5. Robustness check on data averaging method

	POLS (1)	POLS (2)	POLS (3)	IV (4)	IV (5)	IV (6)	LSDVC (7)	LSDVC (8)	LSDVC (9)
lagged TFP							0.786	0.787	0.810
							(0.038)***	(0.046)***	(0.045)***
μ	−0.132	−0.130	−0.121	−0.169	−0.163	−0.132	−0.093	−0.081	−0.121
	(0.051)***	(0.052)**	(0.048)**	(0.054)***	(0.055)***	(0.052)**	(0.042)**	(0.046)*	(0.046)***
TO	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	(0.000)**	(0.000)**	(0.000)***	(0.000)***	(0.000)***	(0.000)***	(0.000)***	(0.000)***	(0.000)**
HC		0.000	0.001		0.001	0.001		0.001	0.002
		(0.001)	(0.001)		(0.001)	(0.001)		(0.001)	(0.001)*
K			0.026			0.023			−0.026
			(0.008)***			(0.008)***			(0.008)***
N	227	227	209	208	208	190	184	206	206
Country fe	No	No	No	No	No	No	No	No	No
Time fe	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.808	0.808	0.794	0.747	0.743	0.743	0.966	0.961	0.947

Note: One asterisk refers to significance at the 10% level, two asterisks refer to significance at the 5% level, and three asterisks refer to significance at the 1% level. POLS, IV and LSDVC refer to pooled OLS, pooled IV, and corrected least squares dummy variable estimations. In the IV estimations, the covariates at time t are instrumented with their one-period lags. Hausman test has been implemented to test the IV model versus fixed effects estimations. In all cases, the test was in favor of the IV model. The standard errors are reported in parenthesis. The bias correction has been initialized by the Blundell–Bond estimator. For definitions of the variables, see Table C.1 in Appendix C.

life expectancy [Sachs and Warner (1997), Sala-i-Martin (1997), Sala-i-Martin et al. (2004)].

4. CONCLUSIONS

The theoretical predictions of an R&D-based endogenous growth model with overlapping generations suggest a positive relationship between longevity and technological change, which, in turn, determines productivity. This is due to the fact that a longer lifetime horizon renders investments in physical capital, the payoffs of which accrue in the future, more lucrative. Consequently, agents substitute savings for consumption, which reduces the market interest rate. This, in turn, raises the present value of R&D investments, which fosters technological progress and thereby productivity growth. The implications of the model are confirmed empirically based on estimations of dynamic panel data models using a sample of 22 OECD countries observed over 52 years. Our baseline estimates suggest that a 10% decrease in the death rate leads to approximately a 1% increase in the TFP index and a 2.5–2.7% increase in labor productivity. Since the death rate was decreasing at an average annual rate of 1.3% in our sample, it contributed to an annual increase in TFP by 0.13 percentage points and in labor productivity by 0.33–0.35 percentage points. The positive effect of increasing longevity is remarkably robust to different estimation techniques, the use of additional control variables, and different methods of measuring productivity.

Overall, this outcome suggests that some aspects of aging exert a positive effect on technological progress and hence on economic growth. However, there are many more channels—not explicitly investigated in this paper—through which demographic changes impact upon economic well being in general (e.g., changing dependency ratios, changing patterns of human capital accumulation, and influences on the fiscal balance of social security systems, which, in turn, have repercussions on governmental investments and/or governmental taxation). A promising avenue for future research would thus be to assess the quantitative importance of the different channels and to use the results to estimate the overall impact of demographic change on economic growth.

NOTES

1. See, for example, Romer (1990), Grossman and Helpman (1991), Aghion and Howitt (1992), Jones (1995), Kortum (1997), Peretto (1998), Segerström (1998), Young (1998), Howitt (1999), Funke and Strulik (2000), Strulik (2005), Bucci (2008, 2013), Strulik et al. (2013), Chu et al. (2013), Grossmann et al. (2013), Bucci and Raurich (2017), Prettner and Strulik (2017), and many others. Note that in frameworks with diminishing returns to capital, the effects of population aging on per capita output growth can only be transient [see Solow (1956), Cass (1965), Diamond (1965), Koopmans (1965), Gruescu (2007)]. For studies that analyze the effects of demographic change outside the R&D-based growth literature, see, for example, de la Croix and Licandro (1999, 2013), Reinhart (1999), Boucekkine et al. (2002, 2003), Kalemli-Ozcan (2002, 2003), Zhang and Zhang (2005), Heijdra and Mierau (2010, 2011, 2012), and Heijdra et al. (2014). For two recent interesting contributions regarding

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the theoretical effects of aging in a framework with directed technical change, see Heer and Irmen (2014) and Irmen (2017).

2. See, for instance, Brezis and Dos Santos Ferreira (2016) for an analysis of endogenous fertility and Diene et al. (2016) for a study of human capital accumulation.

3. As already mentioned in the introduction, using a semiendogenous growth model in the vein of Jones (1995) would lead to similar results during the transition toward the long-run balanced growth path [see Prettner and Trimborn (2016)]. Taking into account that we have data from 1960 to 2011 and that transition phases of semiendogenous growth models usually last several decades, such a model would lead to predictions that are observationally equivalent to the predictions of the model that we use.

4. For a similar effect, see Bloom et al. (2003) and Krueger and Ludwig (2007).

5. We also address the concerns regarding cross-country heterogeneity by controlling for country-specific fixed effects [cf. Lindh and Malmberg (1999)].

6. The full database is available at `http://ec.europa.eu/economy_finance/db_indicators/ameco/index_en.htm`. The country specific developments in TFP ad in labour productivity are shown in Figure B.1 in Appendix B.

7. We are grateful to an anonymous referee for suggesting this robustness check.

8. See WIPO online database at `http://ipstats.wipo.int/ipstatv2/index.htm`.

9. TFP growth is usually constructed by subtracting the contribution of physical capital accumulation and of human capital accumulation from per capita GDP growth. Given that this is done accurately, endogenous growth theory nevertheless implies that TFP growth itself depends on the stock of human capital because purposeful R&D is driven by well-educated scientists [cf. Romer (1990)].

10. In our first specification, we include neither the human capital nor the capital stock variable. The reason is that these variables enter the production function directly and, thus, their direct influence is in principle accounted for in the construction of the TFP indicator. This notwithstanding, it is plausible to expect that physical capital and human capital would influence efficiency indirectly. The influence here is a priori unclear, depending on the quality of the stock of existing physical capital and the abilities of the labor force, and remains a purely econometric issue. There is a second reason for the exclusion of these variables from the first specification, namely the potential collinearity between them and the openness variable, so first we want to assess the impact of openness on productivity separately from the other possible factors.

11. See Arellano and Bond (1991) and Blundell and Bond (1998) for the pioneering contributions on the difference and system GMM methodologies, respectively.

12. Precisely, $B_1 = c_1(T)^{-1}$, $B_2 = B_1 = c_2(N^{-1}T^{-1})$, and $B_3 = B_2 = c_3(N^{-1}T^{-2})$.

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APPENDIX A: DERIVATIONS

A.1. THE INDIVIDUAL OPTIMIZATION PROBLEM

The current-value Hamiltonian is

$$\mathcal{H} = \log(c) + \lambda\left[(r + \mu - \delta)k + \hat{w} - c\right].$$

The necessary first-order conditions (FOCs) for the optimal evolution of individual consumption are as follows:

$$\frac{\partial \mathcal{H}}{\partial c} = \frac{1}{c} - \lambda \stackrel{!}{=} 0 \Leftrightarrow \frac{1}{c} = \lambda \tag{A.1}$$

$$\frac{\partial \mathcal{H}}{\partial k} = (r + \mu - \delta)\lambda \stackrel{!}{=} (\rho + \mu)\lambda - \dot{\lambda} \Leftrightarrow \dot{\lambda} = (\rho + \delta - r)\lambda. \tag{A.2}$$

Taking the time derivative of equation (A.1) and plugging it into equation (A.2) yields

$$\frac{\dot{c}}{c} = r - \rho - \delta.$$

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A.2. AGGREGATION

To obtain the evolution of aggregate physical capital and consumption, we apply the following aggregation rules [cf. Blanchard (1985), Heijdra and van der Ploeg (2002), Prettner (2013)]:

$$K(t) \equiv \int_{-\infty}^{t} k(t_0,t)L(t_0,t)dt_0, \tag{A.3}$$

$$C(t) \equiv \int_{-\infty}^{t} c(t_0,t)L(t_0,t)dt_0, \tag{A.4}$$

where we denote aggregate variables by uppercase letters. Taking our demographic assumptions into account, we have

$$C(t) \equiv \mu L \int_{-\infty}^{t} c(t_0,t)e^{\mu(t_0-t)}dt_0, \tag{A.5}$$

$$K(t) \equiv \mu L \int_{-\infty}^{t} k(t_0,t)e^{\mu(t_0-t)}dt_0 \tag{A.6}$$

because, in the case of a constant population size (L), each cohort is of size $\mu L e^{\mu(t_0-t)}$ at time $t > t_0$. Consequently, $\int_{-\infty}^{t} \mu L e^{\mu(t_0-t)}dt_0 = L$ holds for the total population and, due to our assumption of an inelastic unitary labor supply, for the size of the workforce as well. Following Heijdra and van der Ploeg (2002) and differentiating equations (A.5) and (A.6) with respect to time yields

$$\begin{aligned}\dot{C}(t) &= \mu L\left[\int_{-\infty}^{t} \dot{c}(t_0,t)e^{\mu(t_0-t)}dt_0 - \mu\int_{-\infty}^{t} c(t_0,t)e^{\mu(t_0-t)}dt_0\right] + \mu L c(t,t) - 0\\ &= \mu L c(t,t) - \mu C(t) + \mu L\int_{-\infty}^{t} \dot{c}(t_0,t)e^{-\mu(t-t_0)}dt_0,\end{aligned} \tag{A.7}$$

$$\begin{aligned}\dot{K}(t) &= \mu L\left[\int_{-\infty}^{t} \dot{k}(t_0,t)e^{\mu(t_0-t)}dt_0 - \mu\int_{-\infty}^{t} k(t_0,t)e^{\mu(t_0-t)}dt_0\right] + \mu L k(t,t) - 0\\ &= \mu L k(t,t) - \mu K(t) + \mu L\int_{-\infty}^{t} \dot{k}(t_0,t)e^{-\mu(t-t_0)}dt_0.\end{aligned} \tag{A.8}$$

From equation (2), it follows that

$$\begin{aligned}\dot{K}(t) &= -\mu K(t) + \mu L\int_{-\infty}^{t} \left[(r+\mu-\delta)k(t_0,t) + \hat{w}(t) - c(t_0,t)\right]e^{-\mu(t-t_0)}dt_0\\ &= -\mu K(t) + (r+\mu-\delta)\mu L\int_{-\infty}^{t} k(t_0,t)e^{-\mu(t-t_0)}dt_0\\ &\quad - \mu L\int_{-\infty}^{t} c(t_0,t)e^{-\mu(t-t_0)}dt_0 + L\left(\frac{\mu\hat{w}e^{-\mu(t-t_0)}}{\mu}\right)_{-\infty}^{t}\\ &= (r-\delta)K(t) - C(t) + \hat{W}(t).\end{aligned}$$

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The individual optimization problem can be reformulated as

$$\max_{c(t_0,\tau)} U = \int_t^\infty e^{(\rho+\mu)(t-\tau)} \log[c(t_0,\tau)]d\tau$$
$$s.t. \quad k(t_0,t) + \int_t^\infty \hat{w}(\tau)e^{-R^A(t,\tau)}d\tau = \int_t^\infty c(t_0,\tau)e^{-R^A(t,\tau)}d\tau, \tag{A.9}$$

where $R^A(t,\tau) = \int_t^\tau (r(s) + \mu - \delta)ds$. The FOC is

$$\frac{1}{c(t_0,\tau)} e^{(\rho+\mu)(t-\tau)} = \lambda(t)e^{-R^A(t,\tau)}.$$

In period $\tau = t$, the FOC pins down to

$$c(t_0,t) = \frac{1}{\lambda(t)}.$$

Therefore, we can write

$$\frac{1}{c(t_0,\tau)} e^{(\rho+\mu)(t-\tau)} = \frac{1}{c(t_0,t)} e^{-R^A(t,\tau)}$$
$$c(t_0,t)e^{(\rho+\mu)(t-\tau)} = c(t_0,\tau)e^{-R^A(t,\tau)}.$$

Integrating and using equation (A.9) yields

$$\int_t^\infty c(t_0,t)e^{(\rho+\mu)(t-\tau)}d\tau = \int_t^\infty c(t_0,\tau)e^{-R^A(t,\tau)}d\tau$$
$$\frac{c(t_0,t)}{\rho+\mu}\left[-e^{(\rho+\mu)(t-\tau)}\right]_t^\infty = k(t_0,t) + \underbrace{\int_t^\infty \hat{w}(\tau)e^{-R^A(t,\tau)}d\tau}_{hw(t)}$$
$$\Rightarrow c(t_0,t) = (\rho+\mu)\left[k(t_0,t) + hw(t)\right], \tag{A.10}$$

where $hw(t)$ refers to human wealth, that is, noninterest wealth, of individuals. Human wealth does not depend on the date of birth because productivity and lump-sum transfers are age independent. Aggregate consumption is

$$C(t) \equiv \mu N \int_{-\infty}^t c(t_0,t)e^{\mu(t_0-t)}dt_0$$
$$= \mu N \int_{-\infty}^t e^{\mu(t_0-t)}(\rho+\mu)\left[k(t_0,t) + hw(t)\right]dt_0$$
$$= (\rho+\mu)\left[K(t) + HW(t)\right], \tag{A.11}$$

where $HW(t)$ refers to aggregate human wealth. Note that $k(t,t) = 0$ because there are no bequests such that newborns do not own physical capital. Therefore,

$$c(t,t) = (\rho+\mu)hw(t) \tag{A.12}$$

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holds for each newborn. Putting equations (3), (A.7), (A.11), and (A.12) together yields

$$\begin{aligned}\dot{C}(t) &= \mu(\rho+\mu)HW(t) - \mu(\rho+\mu)\left[K(t)+HW(t)\right] \\ &\quad + \mu N\int_{-\infty}^{t}(r-\rho-\delta)c(t_0,t)e^{-\mu(t-t_0)}dt_0 \\ &= \mu(\rho+\mu)HW(t) - \mu(\rho+\mu)\left[K(t)+HW(t)\right] + (r-\rho-\delta)C(t) \\ \Rightarrow \frac{\dot{C}(t)}{C(t)} &= r-\rho-\delta+\frac{\mu(\rho+\mu)HW(t)-\mu(\rho+\mu)\left[K(t)+HW(t)\right]}{C(t)} \\ &= r-\rho-\delta-\mu(\rho+\mu)\frac{K(t)}{C(t)} \\ &= r-\rho-\delta-\mu\underbrace{\frac{C(t)-c(t,t)L}{C(t)}}_{\in(0,1)}.\end{aligned}$$

The last two lines contain equivalent expressions for the aggregate Euler equation that differs from the individual Euler equation by the term $-\mu\left[C(t)-c(t,t)L\right]/C(t)$ that is due to the generational turnover induced by birth and death.

A.3. OPERATING PROFITS OF INTERMEDIATE GOODS PRODUCERS

Profits of intermediate goods producers can be obtained via equation (8) as

$$\pi = \frac{r}{\alpha}x - rx = (1-\alpha)\alpha\frac{Y}{A}.$$

A.4. HUMAN CAPITAL EMPLOYMENT IN BOTH SECTORS

We determine the fraction of human capital employed in the final goods sector and in the R&D sector by using equation (11)

$$\begin{aligned}p_A\lambda A &= (1-\alpha)\frac{Y}{H_Y} \\ \Leftrightarrow H_Y &= \frac{r-\delta}{\alpha\lambda} \\ \Rightarrow H_A &= H-\frac{r-\delta}{\alpha\lambda},\end{aligned}$$

where the last line follows from $H = H_A + H_Y$.

A.5. PRODUCTION PER CAPITAL UNIT

Production per physical capital unit can be expressed as a function of the interest rate and the elasticity of final output with respect to machines of type i:

$$r = \alpha p = \alpha^2\frac{Y}{K} \Rightarrow \frac{Y}{K} = \frac{r}{\alpha^2}. \tag{A.13}$$

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APPENDIX B: DEVELOPMENT OF COUNTRY-SPECIFIC TFP AND LABOR PRODUCTIVITY

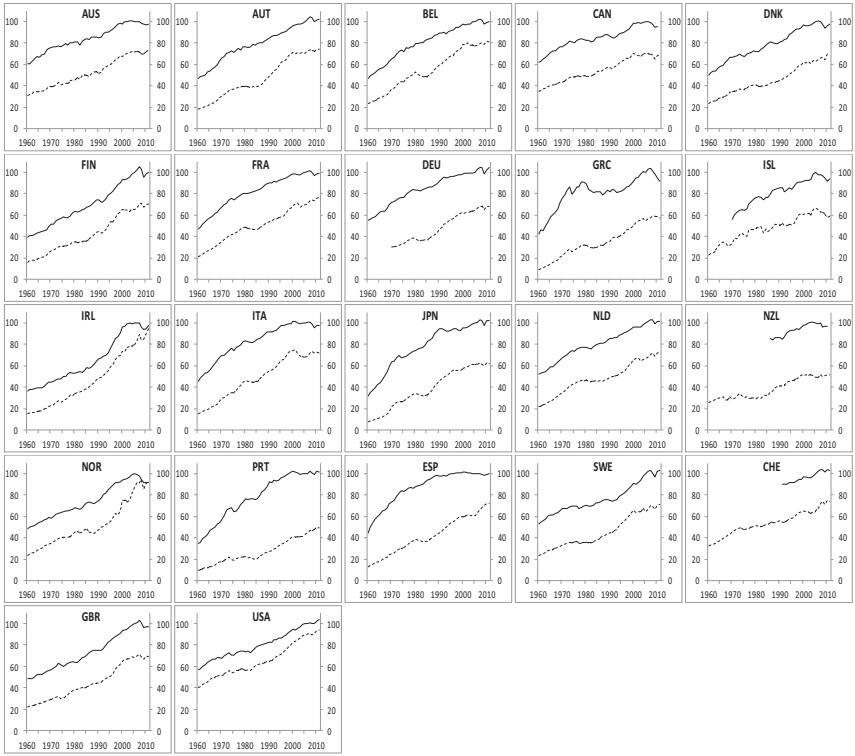


FIGURE B.1. Development of country-specific TFP (solid lines) and labor productivity (dotted lines) for the countries included in the sample. TFP is an index (2005=100) and is represented by the solid line on the left axis. Labor productivity is represented by the dotted line and is defined as real GDP per person employed, in thousand of 2005 US dollars. It is represented on the right axis. The sample is composed by 22 OECD countries: AUS—Australia; AUT—Austria; BEL—Belgium; CAN—Canada; CHE—Switzerland; DEU—Germany; DNK—Denmark; ESP—Spain; FIN—Finland; FRA—France; GBR—United Kingdom; GRC—Greece; IRL—Ireland; ISL—Island; ITA—Italy; JPN—Japan; NLD—Netherlands; NOR—Norway; NZL—New Zealand; PRT—Portugal; SWE—Sweden; USA—United States. Ameco macroeconomic database.

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APPENDIX C: DATA

The list of countries included in our sample is the following: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, the United Kingdom, and the United States. Data on TFP start in 1970 for Iceland, in 1986 for New Zealand, and in 1991 for Switzerland. Table C.1 contains a description of the variables, their abbreviations, and the data sources.

TABLE C.1. Variables and their sources

Variable	Definition	Source
TFP	Total factor productivity index, 2005=100, computed as a residual from a standard Cobb–Douglas production function	Ameco
LP	Labor productivity, given by the GDP at constant 2005 and PPP adjusted prices (*rgdpe*) over total employment (*emp*)	PWT, 8.0
μ	crude death rate	WDI
TO	Trade openness at constant 2005 prices, obtained as the share of the sum of imports and exports over GDP (*openk*)	PWT, 7.1
HC	Human capital index, based on years of schooling and returns to education	PWT, 8.0
K	Capital-to-output ratio, calculated as a share of capital stock at constant 2005 prices in mil. US dollars (*rkna*) over real GDP at constant 2005 prices in mil. US dollars (*rgdpna*)	PWT, 8.0

APPENDIX D: DESCRIPTIVE STATISTICS

Tables D.1 and D.2 provide some useful information regarding the descriptive statistics and pair-wise correlations between the variables. Among the most important variables of interest, average TFP was equal to 80.1, ranging from a minimum of 31.9 (Japan in 1960) to a maximum of 105.6 (Finland in 2007). Correspondingly, the average level of labor productivity was equal to around 46,000 of constant (2005) PPP adjusted US-Dollars, with a minimum of 3,900 US-Dollars (Korea in 1962) to a maximum of 95,000 US-Dollars (Ireland in 2011). The average death rate in our sample was equal to 9.1 per thousand midyear population. This means that in a population of 1 million, a death rate of 9.1 would imply 9,100 deaths per year. The minimum value of the death rate was observed in Korea in 2006 and amounted to 5.0, whereas the maximum death rate of 14.4 was registered again in Korea in 1960. From the correlation matrix, it emerges that the death rate is negatively (although weakly) correlated with all the other explanatory variables, with the exception of trade openness.

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TABLE D.1. Descriptive statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
TFP	1075	80.1	16.8	31.9	105.6
LP	1238	45804.3	18083.8	3865.5	94716.5
patent	1238	0.340	0.494	0.008	3.056
μ	1248	9.1	1.8	5.0	14.4
TO	1214	48.2	28.8	4.1	172.4
HC	1248	2.7	0.4	1.5	3.6
K	1248	2.960	0.659	1.342	4.448

TABLE D.2. Correlation matrix

	TFP	LP	*patent*	μ	TO	HC	K
TFP	1						
LP	0.801	1					
patent	0.099	0.045	1				
μ	−0.2948	−0.2771	−0.1486	1			
TO	0.4509	0.5792	−0.2397	0.0200	1		
HC	0.5837	0.7116	0.2326	−0.4423	0.2193	1	
K	0.2695	0.2445	0.3865	−0.0445	−0.3069	0.2667	1

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