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The Aging Society: Is Growth Reverting to Pre-Industrial Levels in the 21st Century?

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Jakob B. Madsen
University of Western Australia
Centre for Applied Macroeconomic Analysis, ANU

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JEL Classification

O00, O10, O30, O40

Address for correspondence:

(E) cama.admin@anu.edu.au

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THE AGING SOCIETY: IS GROWTH REVERTING TO PRE-INDUSTRIAL LEVELS IN THE 21ST CENTURY?[1]

Jakob B. Madsen

Department of Economics, University of Western Australia and CAMA

Abstract. The aging population is expected by many to put an end to the high growth rates experienced in the past century. This paper shows that the aging population and the associated educational and innovative expansion induced by the demographic transition will expand the technology frontier in the 21st century and significantly override the adverse income effects of the aging population. To achieve this, the total income-effects through the channels of innovations, investment, education, and labor force participation are estimated using data over two centuries for 21 OECD countries.

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1. Introduction

In his influential book *The Rise and Fall of American Growth*, Gordon (2016) forwards the thesis that the US and, presumably, the rest of the West have entered a low growth regime and that the high growth experienced in the last one and a half centuries has been a one-time-only event. He argues that the great innovations during the Second Industrial Revolution up until the 1970s will not be repeated in the 21st century and the technology-induced growth decline will be perpetuated by the aging population, which will reduce saving, increase age dependency rates and increase government indebtedness.

Gordon's low growth scenario for the 21st century has been shared by the large amount of literature on the adverse growth effects of aging through saving and age dependency channels (see, for discussion and analysis, Lindh and Malmberg, 1999; Feyrer, 2007; Bloom et al., 2010; Cuaresma et al., 2014; Aiyar and Ebeke, 2016; Acemoglu and Restrepo, 2017; Lutz et al., 2019; Kotschy and Sunde, 2018; Aksoy et al., 2019, Kotschy et al., 2020). Recently, however, the focus has turned to education and innovations. Lutz et al. (2007), Kotschy and Sunde (2018), Kotschy et al. (2020) have put the race

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between education, the age distribution, and the interaction between age distribution and education and their growth effects at the center of the analysis. While Kotschy and Sunde (2018) find that the adverse productivity effects of the age distribution slightly override the positive education-induced growth effects, Lutz et al. (2019) suggest that the age distribution is irrelevant for productivity growth and that education is the overriding factor for the productivity prospects.

As shown by Kotschy and Sunde (2018), Lutz et al. (2019), and Kotschy et al. (2020), the aging population is closely related the educational expansion in the sense that they are outcomes of the same fundamental factors that have driven the fertility transition. The replacement of older and less-educated age cohorts by the more-educated younger age cohorts in the 21st century is an integral part of the aging society since education and aging are joint outcomes of the fertility transition that occurred over the approximate period 1880-1980. Following the quantity-quality framework of Becker (1960), the reduced fertility increased the educational resources available to each child (see also Barro and Becker, 1989; Galor and Weil, 2000; Galor and Moav, 2002; Lagerlöf, 2003, 2006; Doepke, 2004; Strulik and Weisdorf, 2008; Prettner, 2013; Prettner and Trimborn, 2017; Madsen et al., 2020).

The more educated young cohorts have gradually replaced the less educated older working age cohorts over the last century and increased the educational attainment of the working age population – a transition that will first be completed by the mid-21st century if gross enrollment rates stay constant. Furthermore, the significantly increasing share of females with secondary and tertiary education since the 1980s has been, and will continue to be, a significant growth-promoting factor that has been heavily influenced by the fertility transition. Consequently, the educational revolution and the aging population in the OECD countries are outcomes of the same processes and cannot be separated when the economic consequences of aging are analyzed.

To gain insight into the general equilibrium effects of the aging population on income growth, this research estimates the dynamic and interactive effects of the demographic transition on education, innovations, labor force participation, and investment in non-residential fixed capital, using data constructed for 21 advanced countries covering the period 1800-2016. A key aspect of the analysis is the emphasis on the growth effects of education and innovation and the endogenous responses of labor force participation rates, saving, productivity, education and innovation to the changing age distribution of the population and the fertility transition.

More specifically, the paper makes the following contributions to the literature. First, a large annual data set spanning two centuries is constructed for the OECD countries; thus, benefitting from covering the demographic transition in its entirety and, at the same time, it covers significant identifying variations in the age distribution of the population. Furthermore, instruments are used for patent-intensity, interest rates, Tobin's *q*, the credit-GDP ratio, and the change in the age distribution of the population. Second, the following four transmission channels through which the demographic and the educational transition influence future growth rates in the OECD are explicitly considered: Innovations, investment, education, labor productivity, and labor force participation and their endogenous responses to the aging population. Innovations take a much more central role in the analysis than previously by testing how the innovations are affected by the age distribution following the predictions of the recent theoretical literature on technology and aging. Acemoglu and Restrepo (2017), for example, show that aging spurs labor-saving technologies as discussed in more detail below. This result is taken further by showing that the human capital of younger age cohorts entering the labor force exceeds that of the older age cohorts exiting the labor force through innovations.

The paper is organized as follows. The modelling strategy is put into the context of the theoretical literature in Section 2, and the modelling framework is derived in Section 3. The channels through which aging is transmitted to growth are detailed in Section 4, and the identification strategy is discussed in Section 5. The data and the time-path of the key macroeconomic aggregates are analyzed in Sections 6 and 7. The regression results and simulations are presented in Sections 8 and 9. Section 10 concludes.

2. Theoretical literature on endogenous growth and aging

Aging influences per capita output through factor accumulation and technological progress promoted by investment in human capital. Since the dominant source of growth is technological progress, most of the theoretical growth has focused on innovative activity and intertemporal knowledge spillovers. Thus, the implications of changes in mortality and life expectancy impact technological progress driven by education, R&D, and directed technical change, has taken a central role in the theoretical literature on aging (see, e.g., Prettner, 2013; Acemoglu and Restrepo, 2017; Jones, 2022). Most theoretical models predict positive effects of aging on innovations though intertemporal substitution and directed technological change (Gonzalez-Eiras and Niepelt, 2012; Acemoglu and Restrepo, 2017; Gehringer and Prettner, 2019; Irmen, 2017; Sasaki and Hoshida, 2017; Irmen and Litina, 2022), while the calibrations of the models of Aksoy et al. (2019) and Jones (2002, 2022) generate negative aging-effects on innovations.

Based on the same idea as his 2002 paper, Jones (2022), for example, shows that negative population growth combined with a semi-endogenous ideas production function leads to growth rates that converges to zero, simply because the reduction in population growth reduces the number of innovations that are assumed to be a constant proportion to the population. Others suggest that the productivity advances from the Third Industrial Revolution are yet to materialize (see, for example, Cette et al., 2022). Kotschy and Bloom (2023) link TFP growth to productivity growth at the world technology frontier and human capital among other variables. Thus far, there have been only a few attempts to model the growth effects of aging and the models tend to focus on the effects of demographic changes on ideas production.

Incorporating age-specific heterogeneity of individuals into an overlapping generational framework with endogenous fertility and growth, Prettner (2013) shows that aging has positive growth effects because it incentivizes investment R&D through lower interest rates. A decrease in mortality, for example, reduces the turnover of generations, which in turn reduces the market interest rate that is required to sustain growth in aggregate consumption. The lower interest rate increases the discounted profitability of R&D investments and results in increasing R&D. However, the growth effects of the aging population along the balanced growth path depend crucially on the underlying model that describe the growth process. While population aging is, in general, beneficial in the model of Romer (1990), the effect is ambiguous in a semi-endogenous model depending on the relative change between fertility and mortality; a result that is analogous to that of Jones (2022). The reason for the growth effect to be long-lasting is that intertemporal knowledge spillovers are strong in the Romer (1990) model.

Based on an overlapping generations version of the semi-endogenous growth model, Prettner and Trimborn (2017) show that the adverse growth effects of the declining population growth found in the semi-endogenous framework are only applicable to the steady state. In the short- and the medium-run, the growth effects of aging are positive because of an increase in saving, which in turn shifts labor from the production sector into the R&D sector and speeds up fixed investment. While economic growth kicks in almost immediately, the negative population growth effects take a long time to override the growth effects of the declining fertility. Thus, the higher aggregate saving in the short and medium run boost growth, while the negative saving effects dominate in the long run. Their calibrations suggest that the positive growth effects last for several decades.

The empirical framework used in this paper does not have a direct mapping to a coherent theoretical model partly because such a model has not yet been derived. Theoretically, the framework here comes closest to the models of Prettner (2013), Strulik et al. (2013), Prettner and Trimborn (2017) in which declining fertility and increasing longevity feed into growth through increasing investment in physical capital, education, and R&D capital. In these models, growth converges to a lower level along with a slowdown in the population growth because of the moderate intertemporal knowledge spillovers implied by the semi-endogenous growth framework. A temporary growth effect derives from the increasing saving induced by lower fertility and increasing longevity. Saving boosts growth directly as well as indirectly through the channels the channels investigated in this paper, viz education, fixed investment, and investment in R&D, the demographic transition.

3. Modelling framework

The aim of this framework is to identify channels through which aging is channeled through to per capital income growth. This section establishes an extended growth accounting framework in which per capita income is decomposed into the growth contribution of capital, labor intensity, human capital, and R&D. This model captures the direct growth-effects of aging. In the next section, the effects of aging through the channels of investment, education, and labor force participation are identified.

3.1 *Decomposition of growth*

This section decomposes per capita income into its components as a pure growth accounting exercise. First, per capita output is decomposed into labor productivity, labor force participation rate, and the share of population of working age:

$$\frac{Y_t}{Pop_t} \equiv \frac{Y_t}{L_t} \cdot \frac{L_t}{Pop_t^{Wa}} \cdot \frac{Pop_t^{Wa}}{Pop_t} \equiv \frac{Y_t}{L_t} \cdot \frac{L_t}{Pop_t} \equiv \frac{Y_t}{L_t} \cdot LFPOPR_t, \tag{1}$$

where *Y* is output; *L* is employment; Pop^{Wa} is the population of working age; *Pop*: is the population size; *LFPOPR* is the labor force population ratio; i.e., the share of population in the labor force. Here, L/Pop^{WA} and Pop^{WA}/Pop are merged into one term, *LFPOPR*, to allow L/Pop^{WA} to respond endogenously to changes in Pop^{WA}/Pop. This stands in contrast to static growth accounting exercises that treat L/Pop^{WA} as a constant, meaning that the age-induced increase in Pop^{WA}/Pop will automatically reduce the living standard through *LFPOPR*. However, as shown below, *LFPOPR* is only marginally responsive to changes in the age structure, suggesting per capita income will only be marginally affected by the aging population.

Differentiating Eq. (1) yields:

$$g_t^{Y/Pop} = g_t^{Y/L} + g_t^{LFPOPR}, \tag{2}$$

where g^{LFPOPR} is growth in the labor force to population ratio.

To decompose labor productivity into its sources, consider the following homogenous Cobb-Douglas production function:

$$Y_t = A_t K_t^{\alpha} H_t^{1-\beta} T_t^{1-\alpha-\beta}, \tag{3}$$

where Y is output; A is technology; K is capital; T is agricultural land; and H is the quality-adjusted labor intensity, defined as:

$$H = X \cdot L e^{\varphi EA}, \tag{4}$$

where L is raw labor; EA is educational attainment or the average years of education of the labor force; X is annual hours worked; and φ is the returns to education. The functional form of $e^{\varphi EA}$ signifies that returns to one additional year of education are independent of the years of education.

Combining Eqs. (3) and (4) and differentiating yields the labor productivity growth rate, $g^{Y/L}$:

$$g_t^{Y/L} = \frac{1}{1-\alpha} g_t^A + \frac{\alpha}{1-\alpha} g_t^{K/Y} + \frac{(1-\beta)\psi}{1-\alpha} \Delta EA_t + \frac{1-\beta}{1-\alpha} g_t^X - \frac{1-\beta-\alpha}{1-\alpha} g_t^L, \tag{5}$$

where g^A is the total factor productivity (TFP) growth rate; and $g^{K/Y}$ is the growth rate in the capital-output ratio, g^X is the growth in annual hours worked. The last term in Eq. (5) is the population growth drag due to diminishing returns introduced by land as a fixed factor of production.

The capital stock can be converted to a flow variable from the equation:

$$K_t = \frac{I_t}{g^I + \delta}, \tag{6}$$

where g^I is the long-run investment growth rate, and δ is the depreciation rate.

Assuming that the TFP growth is proportional to the share of the population that is employed in the research sector, $S^{R\&D}$, then the time-differential of Eqs. (2), (4) and (5) can be combined to yield the per capita income growth:

$$g_t^{Y/Pop} = \frac{\mu}{1-\alpha} \ln S_t^{R\&D} + \frac{\alpha}{1-\alpha} g_t^{I/Y} + \frac{(1-\beta)\psi}{1-\alpha} \Delta EA_t + \frac{1-\beta}{1-\alpha} g_t^X - \frac{1-\beta-\alpha}{1-\alpha} g_t^L, \tag{7}$$

where μ is a constant.

Eq. (7) is reminiscent of a standard growth accounting equation in which per capita income growth is decomposed into the growth in fixed and human capital, technology, hours worked, and labor force participation rate. This method, however, is not useful here because we need to find a mapping between innovation and productivity and the direct productivity effects of the age distribution. Furthermore, the hours worked elasticity of productivity need not reflect factors shares given by the $(1-\beta)-(1-\alpha)$ ratio but could well be lower than that due to diminishing returns to working hours.

Eq. (7) shows the approximate determinants of growth. The effects of aging for each variable in this model are estimated in the next sections to find the total growth effect. The model illustrates why reduced form productivity growth regressions, where productivity is regressed on the age structure, will not reveal the full effects of aging. First, innovations have growth effects while the other variables have level effects on productivity; effects that are very difficult to disentangle in reduced form productivity models. Second, the relevant determinants of each explanatory variable in Eq. (7) are rarely controlled for in reduced form regressions and, if included, these controls are likely to interact with other variables in the regression because the reduced form regression often lacks a level-growth distinction; thus, giving biased parameter estimates. Third, since the level of education is determined by the economic conditions, including the contemporaneous and expected age structure that prevailed at the time at which the workers did their education, it will take up to 58 years before the full effects of the changing age structure on education are borne out – effects that simply cannot be captured in reduced form regressions, particularly because population dynamics interact with cohort effects. Since, as shown below, innovations are conditioned on an educated labor force, the length and dynamic effects of education will be further compounded.

Two features of Eq. (7) are worth noting: First, since $(1-\alpha)^{-1} > 1$, technological progress magnifies growth more than proportionally to its direct effect, as technological progress induces capital deepening by increasing the returns to investment projects. Second, capital indicated by an increasing *I-Y* ratio, has a modest impact on growth since the share of *net* productive investment (net non-residential investment) in total income has only been 3.4% on average over the period 1800-2018. This suggests that age-induced saving effects on growth are small relative to other growth promoting effects of g^h, g^A and g^{LFPOR}. If one focuses on total gross savings, then α would, on average, have been 15% over the period 1800-2016, and more than 20% since WWII; highlighting the importance of focusing on net non-residential investment instead of gross saving rates.

3.1 Stochastic specification of labor productivity

The stochastic counterpart of Eq. (7), extended to allow for the influence of the change in the age distribution of the population on productivity is:

$$\Delta \ln(Y/L)_{it} = \lambda_0 + \lambda_1 \ln(Pat/L)_{it} + \lambda_2 \Delta h_{it}^{Tot} + \lambda_3 \Delta \ln X_{it} + \lambda_4 \beta_{it} \Delta \ln L_{it} + \lambda_5 \Delta (I^{NR}/Y)_{it} + \vartheta_j \Delta \ln Age_{it}^{j} + CD + TD + \varepsilon_{1,it}, \quad (8)$$

$j \epsilon$ 0-14, 15-24, 25-34, 35-44, 45-54, 55-64, 65+,

where *Y* is real GDP; *Pat* is the number of patent applications of residents; β_t is the agricultural share in total income; h^{Tot} is educational attainment, computed as the weighted average of educational attainment at the primary, secondary, and tertiary levels, where the weights are based on years of schooling at each level (7-5-5); I^{NR} is net non-residential investment; *TD* and *CD* are time and country dummies; and Age^j is the share of population in age cohort *j*; and ε is a stochastic error term. The model is estimated in five-year non-overlapping differences to filter out the influence of the business cycle and other short-term shocks and because most of the pre-WWII labor force data is not available at annual frequencies. The five-year differences are divided by five to ease the interpretation of the coefficients of research intensity. Finally, Age_{it}^{j} is included in the model to test for the direct productivity effects of the age structure that have not been captured by the other regressors.

The innovative activity is proxied by patent intensity, *Pat/L*, following the findings of the empirical growth literature (see, e.g., Ha and Howitt, 2007, Ulku; 2007; Madsen, 2008, 2010; Venturini, 2012a; Venturini and Minniti, 2017). As stressed in the endogenous growth literature, R&D may be indirectly affected by aging through reduced fertility. Jones (2002, 2022), for example, argues that growth in the 21st century may be impaired by declining population growth. Provided that the number of R&D workers is kept in a fixed proportion to population, it follows from semi-endogenous growth models that the declining population growth in the 21st century will reduce productivity growth proportionally. While the declining population growth has no or little impact on productivity growth in standard Schumpeterian models as long as the number of researchers is kept as a constant proportion to population, Peretto's (2018) '4G' Schumpeterian growth model predicts that a decrease in the rate of population growth temporarily slows the ability for product proliferation to respond to non-linearities for product improvement, thus increasing the average innovation productivity.

Technological progress is determined by the R&D that is implied by the following ideas production function (Peretto, 1998; Dinopoulos and Thompson, 1998; Peretto and Smulders, 2002; Dinopoulos and Waldo, 2005; Ha and Howitt, 2007; Venturini, 2012a, b; Madsen and Ang, 2016):

$$\dot{A} = \lambda\left(\frac{R\&D}{Q}\right)^{\sigma} A^{\phi}, \qquad 0 < \sigma \leq 1,\ \phi \leq 1$$

$Q \propto L^{\beta}$ in steady state,

or

$$g^{A} = \left(\frac{\dot{A}}{A}\right) = \lambda\left(\frac{R\&D}{Q}\right)^{\sigma} A^{\phi-1}, \tag{9}$$

where *R&D* is the population involved in R&D activities; Q is product variety; λ is a research productivity parameter; σ is a duplication parameter (0 if all innovations are duplications and 1 if there are no duplicating innovations); ϕ is returns to scale of knowledge; and β is the coefficient of product proliferation. Research intensity, $R\&D/Q$, has permanent growth effects if there are scale effects in ideas production, i.e., $\phi = 1$. For $\phi < 1$ the growth effects of research intensity are temporary.

This ideas production function extends the first-generation knowledge production function to allow for product proliferation and decreasing returns to knowledge stock, as highlighted in the second-generation models of economic growth; viz Schumpeterian and semi-endogenous growth models (see Aghion and Howitt, 1998; Peretto, 1998; Ha and Howitt, 2007). Following the Schumpeterian paradigm, where $\beta > 0$ and $\phi = 1$, *R&D* is divided by product varieties, *Q*, in the (*R&D*/*Q*)-term as R&D spreads more thinly across the variety of products as the economy grows. Following the results of Ha and Howitt (2007), Madsen (2008), and Venturini (2012a, b), β and ϕ are set to one.

Measuring the research intensity, *R&D/Q*, by educational attainment at the secondary and tertiary levels, Eq. (9) reduces to:

$$g^{A} = \left(\frac{\dot{A}}{A}\right) = \mu(h^{ST})^{\sigma}, \tag{10}$$

where μ is a research productivity parameter. This model shows that technological progress and growth are driven by innovative activity and that growth remains positive as long as h^{ST} is positive.

The model given by Eq. (10) follows the predictions of standard endogenous growth models in which the R&D of the firm depends on the discounted returns to investment in R&D, where expected returns depend on the pool of qualified researchers that enhances the expected returns to innovation as captured by the h^{ST} term. Educational attainment at higher levels is an important determinant of innovative activity because education is a prerequisite for understanding the processes involved in creating techniques and templates that push out the technology frontier and, more broadly, a better educated workforce is required for the adoption of more efficient production techniques (Strulik et al., 2013). As stressed by Freeman (1995), technical change is not dependent on R&D only, but also on other related activities, such as education, training, production engineering, design, quality control, feedback loops from the market, and the interactions with the market and related firms, e.g., sub-contractors, suppliers of materials and services. These factors are directly or indirectly conditional on an educated labor force and, according to Freeman (1995), are not captured by R&D expenditure in regressions in which R&D is the only explanatory variable. The computer revolution, for example, is emphasized by Freeman (1995) as an example of the importance of organizational and managerial change in the innovative process – factors that are excluded from the R&D statistics.

Furthermore, during the second half of the 19th century, inventors typically had a secondary or a tertiary degree (Meisenzahl and Mokyr, 2012; Gibbons, 2016; Madsen and Murtin, 2017). In his survey for the US in 1953, Schmookler (1957) finds that more than 50% of innovators had a tertiary education, while almost 6% had only primary education. For the post-1960 period, Wang (2010) and Becker (2013) find tertiary education to be the principal determinant of R&D and that the typical inventor had a tertiary degree. Higher education links diverse areas of knowledge and enables problem solving that leads to knowledge breakthroughs and expands knowledge in ways that may be of economic and technological importance. Estimating a VAR model for Germany over the period 1855-1913, Grupp et al. (2005) find a highly significant relationship between patents and the lagged share of the population enrolled in tertiary education and conclude that tertiary education Granger causes innovation.

4. Transmission channels

This section outlines the stochastic specification of the models of research intensity, education, labor force population ratio and investment rate, while allowing the outcome variables to depend on the age structure. The models are estimated for the OECD countries over the periods 1820-2016, 1870-2016, and, in some instances, 1950-2016.

4.1 Innovative activity

Assuming that research productivity, μ, depends on access to finance and the age distribution, Eq. (10) is stochastically specified as:

$$\ln(Pat/L)_{it} = \alpha_0 + \alpha_1 \ln h_{it}^{ST} + \alpha_2 \ln FD_{it} + \alpha_j \ln Age_{it}^{j} + CD + TD + \varepsilon_{2,it}, \quad (11)$$

$j \in$ 0-14, 15-24, 25-34, 35-44, 45-54, 55-64, 65+,

where h^{ST} is the sum of secondary and tertiary educational attainment of the working age population; and *FD* is financial development, measured as the share of credit to the non-financial private sector divided by nominal GDP. The real interest rate on long-term government bonds was included in the initial regressions; however, it was consistently insignificant and, therefore, omitted from the model. The coefficients of Age^j are normalized to deviations from their mean.

Financial development is important for R&D because R&D projects require large outlays that can first be recouped after a long gestation period. The difficulties associated with forecasting future cash flows derived from R&D projects make it very difficult to secure external finance. If the firm has no access to credit, risk-averse entrepreneurs may devote fewer resources to R&D to avoid potential illiquidity. Gorodnichenko and Schnitzer (2013), for example, show theoretically and empirically that firms' decisions to invest in R&D are adversely affected by financial frictions that increase the cost of external finance.

The relative magnitudes of the coefficients of the share of population in various age cohorts, ς_j, signify the importance of the age structure for patenting activity. The influence of the age structure on innovations has been somewhat controversial in the literature. The model predictions of aging go from positive (Ang and Madsen, 2015; Acemoglu and Restrepo, 2017; Gehringer and Prettner, 2019; Irmen, 2017; Baldanzi et al., 2019; Sasaki and Hoshida, 2017; Irmen and Litina, 2022) to negative (Aksoy et al., 2019). Acemoglu and Restrepo (2017) suggest that, in response to aging, technical change will be directed towards rapid adoption of automation technologies. In a similar view, the model of Irmen and Litina (2022) predicts that aging societies will implement institutions and policies that foster inventive activity. Gehringer and Prettner (2019) and Irmen (2017) stress intertemporal optimization as a growth promotor: Anticipating a longer life, households discount the future more heavily; thus, exerting downward pressure on required asset returns, which in turn increases the present value of investment in R&D. Finally, Dalgaard and Kreiner (2003) show that, if the common assumption of a unit elasticity of substitution between technology and effective labor is relaxed, a decline in the effective labor force could be replaced by new technology if the substitution between technology and effective labor is larger than one.

4.2 Education

Since educational attainment, like fixed capital, is a stock variable derived from past enrollment in education, the essential variables to be explained are flows measured as enrollment rates, which can subsequently be transformed to educational attainment. Gross enrollment rates, GERs, at secondary and tertiary levels are explained by the following model:

$$\ln GER_{it}^{ST} = \kappa_0 + \kappa_1 \ln Lexp_{it} + \kappa_2 \ln FD_{it} + \kappa_j \ln Age_{it}^{j} + CD + TD + \varepsilon_{3,it}, \tag{12}$$

where GER^{ST} is the average gross enrollment rates at the secondary and tertiary levels (fraction of population of the relevant schooling age that is enrolled in secondary and tertiary education).

GERs are positive functions of life expectancy because rational individuals will invest more in education to enhance earnings for consumption over a longer life in response to a longer expected life (Zhang and Zhang, 2005). Similarly, as shown by Cervellati and Sunde (2005), the increasing life expectancy in the West has been an important contributor to its productivity advances through human capital investment, perpetuated by generational educational effects. Furthermore, the mechanism of Gehringer and Prettner (2019), Baldanzi et al. (2019) and Irmen (2017) in which increasing life expectancy increases the discounted value of R&D through lower required returns must apply equally to investment in education. GERs may also be positively affected by an aging population because more private and public resources are invested in education as the population ages as a precautionary measure to counter potential adverse income effects (Gonzalez-Eiras and Niepelt, 2012).

Financial development affects the schooling decision in the same way as investment: Financially constrained students are refrained from investing in education because they lack sufficient financial resources to pay for their living and schooling fees (Lochner and Monge-Naranjo, 2012). This applies, in particular, to secondary and tertiary education for which tuition fees and for forced living away from home render these forms of education expensive.

4.3 Investment and saving

The following life-cycle investment and saving models are estimated:

$$ln(I^N/Y)_{it} = \gamma_0 + \gamma_1 R_{it} + \gamma_2 \ln FD_{it} + \gamma_j \ln Age_{it}^j + CD + TD + \varepsilon_{6,it}, \quad (13)$$

$$ln(I^N/Y)_{it} = \varrho_0 + \varrho_1 q_{it} + \varrho_j \ln Age_{it}^j + CD + TD + \varepsilon_{7,it}, \quad (14)$$

$$ln(S^N/Y)_{it} = \iota_0 + \iota_1 R_{it} + \iota_2 \ln Lexp_{it} + \iota_3 \ln FD_{it} + \iota_j \ln Age_{it}^j + CD + TD + \varepsilon_{8,it}, \quad (15)$$

where I^N/Y is the net non-residential investment-GDP ratio; S^N/Y is the net saving rate; q is Tobin's q, *FD* is the credit to the non-banking private sector in total GDP; and *R* is the nominal interest rate on a long- term government bond.

Life expectancy is expected to affect saving positively since rational individuals will save more for old-age consumption the longer they expect to live (Zhang and Zhang, 2005). Two investment models are estimated. Eq. (15) is a simple model in which the investment ratio is explained by the interest rate and the credit availability, while Eq. (16) is a theory-consistent model in which the investment ratio is explained by Tobin's q. As has been stressed for a long time in the literature on financial development, savings may be curbed by financial underdevelopment because it increases the spread between borrowing and lending rates and curbs access to high return investment opportunities, such as pension schemes, and investment in domestic and foreign stocks (see, e.g. McKinnon, 1973). Conversely, easy access to credit may curb saving (see, e.g., Carroll et al., 2019).

4.4 Labor force participation rate

The following models are estimated to check for the effects of the population age distribution on the labor force participation rate, *LFPR*, and the labor force population ratio, *LFPOPR*:

$$\text{Ln}\, LFPR_{it} = \beta_0 + \beta_j \ln Age_{it}^j + CD + TD + \varepsilon_{4,it}, \quad (16)$$

$$\text{Ln}\, LFPOPR_{it} = \beta_0 + \beta_j \ln Age_{it}^j + CD + TD + \varepsilon_{5,it}, \quad (17)$$

where, in Eq. (14), *LFPOPR* is the dependent variable instead of the labor force participation rate conventionally defined because we are interested in the response in the labor force to changes in the age structure of the population.

The models are very simple; however, variables predicted by the optimizing female labor force participation model of Bloom et al. (2009), such as fertility and infant mortality, are omitted because they are insignificant. Similarly, life expectancy at birth is insignificant. The capital-labor ratio, which is also included in the model of Bloom et al. (2009), is omitted from the model here because, unlike the labor force participation rate, it is not a bounded variable.

A priori, we would expect the old age dependency to influence the labor force participation rate positively for two reasons. First, following from the life-cycle model of consumption, an unexpected increase in the old-age life expectancy will give workers an incentive to remain longer in the labor force to keep the level of consumption constant over their life cycle. Second, the age at which the population is eligible for an age pension may be endogenous to the share of population that is older than 65, Age^{65+}. The OECD (2012), for example, states that increases in retirement ages are underway or planned in 28 out of the 34 OECD countries. If the coefficient of Age^{65+} is sufficiently high, the net effect of an increase in Age^{65+} on the government's budget may be positive.

5. Identification

The key drivers of growth in this framework, viz innovation, education, and financial development, may be significantly influenced by economic development and consequently may bias the OLS estimates. Instruments for education, innovations, financial development, Tobin's *q*, the growth in the population distribution, and interest rates are used to deal with endogeneity. Separate identification strategies are used for education, the financial variables (interest rates, Tobin' *q*, and financial development), and the growth in the distribution of population-shares on ages. Although widely practiced, instruments cannot be directly used for education because educational attainment is a pre-determined stock variable consisting of individuals that did their education up to 58 years prior to time *t*. Thus, the decision to enroll in education was determined by circumstances at the time at which they did their education, suggesting that educational attainment needs to be created from instrumented gross enrollment rates, GER. The financial variables are instrumented using a combination of exchange regime, the degree of capital mobility, and financial variables in the anchoring countries as suggested by Jordà et al. (2015). Since the identification procedure for education is rather involved and lengthy, the identification strategy and IV results for education are relegated to the online Appendix.

5.1 Monetary and financial conditions

The identification strategy for interest rates, *R*, Tobin's *q*, and financial development, *FD*, are based on the policy trilemma, which states that a country cannot simultaneously pursue the three mutually incompatible policy goals of fixed exchange rates, capital mobility, and monetary policy autonomy (Obstfeld et al., 2005). Under perfect capital mobility and floating exchange rates, for example, *R* and *FD* are determined by monetary policies of anchor countries, dominated by the US, the UK, France, and Germany to varying degrees depending on the period considered. Conversely, monetary policies cannot be controlled domestically under fixed exchange rates and perfect capital mobility but are governed by the monetary policies of the anchor countries. This was best demonstrated under the height of gold and silver standard regimes, 1821-1913, during which the international capital market was highly integrated, leaving the authorities with little room for maneuvering. The fixed exchange regime with highly mobile capital came to an end at the outbreak of WWI, and apart from a few short stints, it took half a century before the fixed exchange rate regimes and a reasonably high degree of capital mobility were reinstated. Since the breakdown of the Bretton Woods fixed exchange rate system in 1973, the exchange rates have mostly been anchored against a base currency in the countries considered here.

Based on the trilemma paradigm, the instruments using the financial and monetary conditions of the anchor countries are created as follows:

$$FD_{it}^{F} = \sum_{A} CC_{it} ER_{it} A_{it} FD_{t}^{A}, \quad (18)$$

and

$$R_{it}^{F} = \sum_{A} CC_{it} ER_{it} A_{it} R_{t}^{A}, \quad (19)$$

and

$$q_{it}^{F} = \sum_{A} CC_{it} ER_{it} A_{it} q_{t}^{A}, \quad (20)$$

where A_{it} is a 0-1 binary variable taking the value of 1 for the anchor country of country *i* at time *t*, $A \epsilon \{USA, UK, Ger, Fra\}$; the superscripts *F* and *A* stand for foreign influence and anchor country; FD_{it} is financial development, measured as the share of credit to the non-financial private sector in total GDP; *CCi* is the degree of capital control in country *i*, $0 \leq CC_{it} \leq 1$, where 1 stands for perfect capital mobility and 0 for total capital immobility; ER_i is country *i*'s exchange regime, $0 \leq ER_{it} \leq 1$, where 0 stands for floating, 1 for fixed and in-between is the degree to which the exchange rate of country *i* is pegged to that of the anchor country; *R* is a nominal long-term interest rate; *q* is Tobin's *q;* and Ψ and Ω are constants. Note that the summation Σ_A is only over one anchor country at a time. The values attached to CC_{it} and ER_{it} under different regimes are based on national and international sources as detailed in the online Appendix. Under fixed exchange rates and perfect capital mobility, FD^F, for example, collapses to $FD_{it}^{F} = \sum_{A} A_{it} \cdot FD_{t}^{A}$, and to $FD_{it}^{F} = 0$ under a pure floating exchange rate regime regardless of the degree of capital mobility.

Eqs. (18)-(20) can be used to form the instruments for *FD*, *R*, *q* and patent intensity. However, since foreign instruments are zero under floating exchange rates or capital immobility, the instruments need to be complemented with internal instruments to cover the periods of no or only partial foreign influence. Using contract-intensive money, *CIM*, as internal instruments, I arrive at the following first-stage regressions:

$$\ln FD_{it} = \Psi_0 \, FD_{it}^{F} + \Psi_1 \ln CIM_{it} + \zeta \boldsymbol{V}_{it} + CD + TD + \varepsilon_{7,it}, \quad (21)$$

$$R_{it} = \Omega \, R_{it}^{F} + \zeta \boldsymbol{W}_{it} + \ln CIM_{it} + CD + TD + \varepsilon_{8,it}„ \quad (22)$$

$$\ln q_{it} = \Lambda_0 \, q_{it}^{F} + \Lambda_1 \ln CIM_{it} + \zeta \boldsymbol{Y}_{it} + CD + TD + \varepsilon_{9,it}, \quad (23)$$

$$\ln(Pat/L)_{it} = \Phi_1 \, R_{it}^{F} + \Upsilon \ln \, FD_{it}^{F} + \Phi_1 \ln CIM_{it} + \zeta \boldsymbol{Z}_{it} + CD + TD + \varepsilon_{10,it}, \quad (24)$$

where ***V***, ***W***, ***Y***, and ***Z*** are vectors of the exogenous regressors in the structural models.

Contract intensive money is used as the sole external control variable in Eqs. (21)-(24) and is measured as (*M*2-*M*0)/*M*2, where *M*2 is broad money and *H*0 is high-powered money. Clague *et al.* (1999) suggest contract-intensive-money as a powerful proxy for third-party contract enforcement because it shows the extent to which the public trusts the banks as intermediaries for money transactions and storage of money as measured by deposits as a share of high-powered money. In economies with excellent third-party contract enforcement, credit and deposit money will be the preferred store of money and medium of exchange over cash money because they are safe, efficient, in most cases, pay interest, and enable the tracking of credit history and thereby better enable banks' to screen borrowers. If, by contrast, contracts are *not* enforced by the government, 1) the safety of money in financial institutions is not guaranteed; 2) repayment of loans cannot be taken for granted;

3) lenders do not have the any security rights to mortgage assets if a borrower defaults; and 4) credit is usually obtained through saving and family connections (Clague *et al*., 1999). In these cases, cash will be the preferred medium of exchange over credit.

Finally, as instruments for the age distribution, the one period (5-year) lagged growth in the share of the population in various age cohorts in the productivity growth model following Kotschy and Sunde (2018) and Kotschy and Bloom (2023). This IV strategy is not used in the fixed effects regressions because the lagged age distribution may potentially be correlated with the lagged unobserved confounders. If such a correlation is present, the instruments worsen the endogeneity bias, and the likelihood of a type 1 error is almost one as shown by Wang and Bellemare (2019).

6. Data

The models are estimated for the following 21 OECD countries, mostly covering the period 1820-2016: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Ireland, Italy, the Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, the UK and the US. Japan is excluded from the estimates presented in Tables 1 and 2 below because financial development could not be estimated with reasonable accuracy and was heavily distorted by the hyperinflation during the later part of WWII. The data sources are mostly national sources as detailed in the Data Appendix.

Since estimates of Tobin's q are limited, except for the US, the method suggested by Barro (1990) is employed. Accordingly, Tobin's q is estimated as the residual from regressing the log of real share prices on a linear time-trend. This approach is consistent with the q-theory of investment in which q fluctuates around a constant level but adjusts quickly towards the long-run equilibrium under perfect competition, while the speed of adjustment towards equilibrium is tardier under imperfect competition, as shown by Kerspien and Madsen (2024). Regressing Tobin's q based on Barro's approach on the direct estimates of Tobin's q by Wright (2004) for the US over the period 1900-2018, Kerspien and Madsen (2024) arrive at a correlation coefficient between the two series of 0.89 (levels) and 0.92 (logs); thus, giving credibility to Barro's approach.

Net non-residential investment, I^{NR}, is computed as $I_t^{NR} = \Delta K_t^{ME} + \Delta K_t^{BC} + \Delta K_t^{IPP}$, where K^{ME} is machinery and equipment capital stock; K^{BC} is non-residential buildings and construction capital stock; and K^{IPP} is intellectual property products stock (R&D, trademarks, art work, marketing, software, databases, etc.) where capital stock is based on the perpetual inventory method using depreciation rates of 3% (non-residential buildings and construction), 17% (machinery and equipment); and 25% (intellectual property products). Investment in intellectual property products is first available from circa 1970 depending on the country in question and is backdated using expenditure on tertiary education and other R&D expenses as detailed in the online Appendix. The itemization of investment and capital stock is crucial since the increasing share of total investment in machinery, equipment, and intellectual property products over the past two centuries has pulled the average depreciation rate on non-residential capital stock up by several percentage points. The net saving rate is estimated as the gross saving rate, S/Y^N minus the ratio of real depreciation and real income. The gross saving rate is estimated as the sum of total investment and the current account on the balance of payment divided by nominal GDP. The real depreciation of fixed capital is estimated as $I_t^{Gross} - (I_t^{NR} + \Delta K_t^{Res})$, where I^{Gross} is total gross investment in fixed prices and K^{Res} is real residential capital stock.

The labor force population ratio, *LFPOPR*, is estimated as $LFPOPR = L/[(1-U)Pop]$, where U is the unemployment rate in decimal points; and *Pop* is the population. Employment data for the 19th century is based mostly on census surveys and missing data are backdated to 1800 using the population of working age. Though the 20th century employment data are mostly on annual frequencies, the employment rate (employment divided by the population of working age) is relatively constant over the period 1930-1940, despite the marked increase in unemployment during the Great Depression, suggesting that the employment data have been interpolated between 1930-1940 in some of the source material. To allow for the decreasing employment during the Depression, the *LFPOPR* is interpolated between 1930 and 1940 and employment is backed out from the equation $LFPOPR = L/[(1-U)Pop^{WA}]$, where Pop^{WA} is the population of working age. Finally, in countries for which the unemployment rate is not available back to 1800, it is estimated as a linear transformation of the deviation of the log of per capita from a time-trend derived from regression analysis.

The data on age-dependent labor force participation rates is derived from population censuses and labor force surveys. The population census data are typically available at 10-year intervals, while the labor force surveys are predominantly conducted in one-year intervals. Since the data are often presented as absolute numbers in each age cohort, age dependent population data are used to derive the participation rates on ages. The quality of the employment data is not high compared to the other data used in this paper because definitions of labor force attachment have changed over time and vary across countries before WWII and even after. Exclusion of unemployment and females working on farms from the labor force statistics in the early data, for example, is an obvious bias (see the online Appendix for a discussion of data and data availability in years).

Educational attainment is estimated from historical gross enrollment rates based on the method derived by Madsen (2014) in which educational attainment is derived by summing over the population at each age multiplied by the GERs for the years in which they did their education. The educational attainment and GERs for Australia, Canada, New Zealand and the US are adjusted for immigrants' education since a large fraction of the work force was born overseas, particularly before WWI. In Australia in 1800, for example, almost the entire non-aboriginal working population was born in Britain, suggesting that education in Britain is the correct measure of education in Australia in 1800 under the assumption that the immigrants' education matched that of the average British population. Furthermore, since Sydney University, as the first university in Australia, was founded in 1850, the share of Australia's working age population with a university degree taken in Australia would first converge to the share of the working population born in Australia in the late 19th century. It is, therefore, vital to account for immigrants' education in the estimates for the high immigration countries, i.e., Australia, Canada, New Zealand, and the United States. The approach taken here is to multiply the educational attainment, or GERs, of the country of birth, j, by the share of the population of country i that is born in country j. For example, since 81% of the population in Australia in 1818 was born in the UK (excl. Ireland, which was a part of the UK in 1818), the educational attainment of the UK weighs 81% in the educational attainment in Australia. On average, 31 countries are used to construct the immigration-adjusted educational attainment for these high-immigration countries. The countries are listed in the online Appendix.

Tertiary student enrollment back to the early 19th century is based on detailed national sources and university calendars to form educational attainment starting from 1820 using national sources and, particularly, information on students' enrollment in each individual university before national statistical agencies started collecting nation-wide data – typically starting from the late 19th century (see online Data Appendix, for sources and details). This data extension is a marked improvement over the data constructions of Madsen (2010, 2014) and, particularly, Morrisson and Murtin (2009), where the data is based almost entirely on Mitchell (2008) and, in most cases, retropolated/interpolated throughout the 19th century (noting that enrollment data for 1812 are required to construct full working age labor force educational attainment starting from 1870). Retropolating the enrollment data based on growth rates during the first years for which data are available often leads to a projected enrollment path that is markedly different from the actual path; thus, resulting in large measurement errors for education in these studies. Consequently, literacy data are used for retropolation.

7. Graphical analysis, 1800-2100

Figure 1 displays the share of the population of working age as an average for the OECD countries over the period 1800-2100, where the post-2016 projections are from United Nations (2017). The share of the population of working age fluctuates around an average of 62% over the period 1800-2050, peaks at 67% in 2010, and, according to the UN's predictions, is expected to decline to 57% by 2050, corresponding to a 15% decline relative to the 2010-peak. If the steady-state value of 62% is used instead as the reference level, then the expected decline shrinks to 8% - approximately half of the figure when 2010 is used as the reference year. Thus, approximately half of the 15% decline in labor force participation over the period 2010-2050 represents a gravitation towards the long run equilibrium. The high plateau that prevailed in the period 1980-2010 was mainly a result of the demographic transition: The fertility transition over the period 1880-1980 first reduced the fraction of the population below the age of 15 and, subsequently, has resulted in an increase in the share of the population of working. The 62% long-run average should arguably be used as a benchmark to infer the economic implications of the aging society as opposed the 67% peak reached in 2010.

Figure 1. ***Pop*^{WA}*/Pop*, OECD. (2017-2100: UN Projections)**

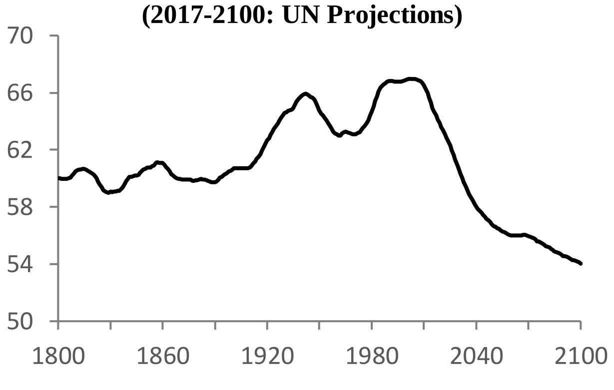
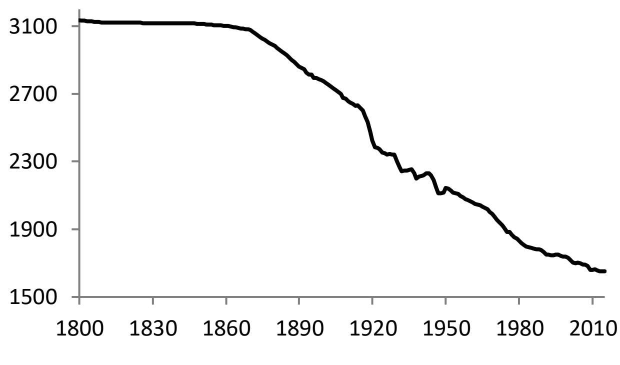


Figure 2. Annual Hours Worked, OECD



The increasing share of the population of working age over the period 1910-1944 may have contributed to the declining annual working hours per employee experienced over the 20th century (Figure 2). Since 1870, the annual hours worked have declined by 50%, suggesting that this is potentially a larger source of variation in labor inputs than the share of the population of working age and that the income effects of the aging population could be neutralized by increasing the hours worked to the level that prevailed a few decades ago, providing that the income effects of the two sources of labor inputs are the same.

The labor force participation rate, *LFPR*, and the labor force to population ratio, *LFPOPR*, are displayed in Figure 3, where *LFPOPR* is *adjusted* upwards to have the same mean as the *LFPR*. While the *LFPR* has fluctuated at slow-moving frequencies around a relatively constant level over the past two centuries, the *LFPOPR* has fluctuated around an upward trend and, consequently, has resulted in a convergence between *LFPR* and the *unadjusted LFPOPR* (note that the *LFPOPR* is adjusted upward relative to the *LFPR* in Figure 3 and, therefore, disguises the convergence of *LFPOPR* towards the *LFPR*). This result suggests that the share of the population outside working age has responded endogenously to the increasing old age dependency. This informal evidence supports the discussion above that *LFPOPR* is the key variable that needs to be explained, not the *LFPR* when the welfare effects of the changing demographic structure are analyzed.

Figure 3. Labor Force Participation Rates, OECD

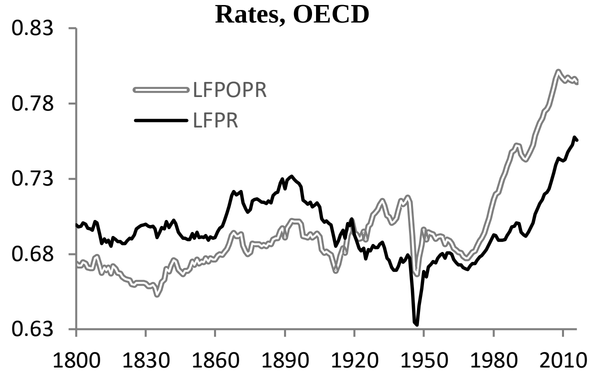
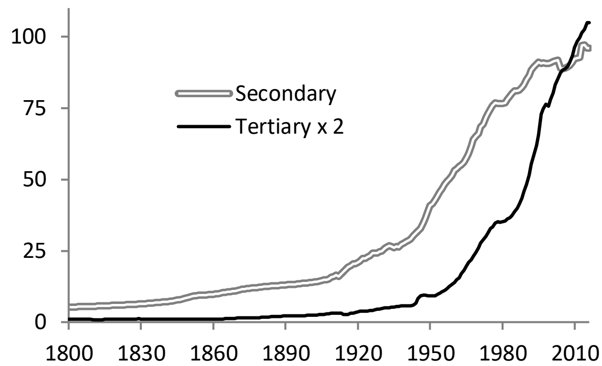


Figure 4. Gross Enrollment Rates, %



Notes. Figure 3: *LFPOPR* (labor force population ratio) is adjusted to have the same mean as *LFPR* (labor force participation rate). Figure 4: Tertiary GERs are multiplied by a factor of two.

Gross enrollment rates, GERs, at the secondary and tertiary levels are displayed in Figure 4, where tertiary GERs are multiplied by a factor of 2. GERs at the secondary levels rose steeply over most of the 20th century and reached a level close to 100% in 2010. GERs at the tertiary level have followed the small time-profile as that of the secondary level; however, with a 25-50-year time lag. Today almost half of the 18-22 age cohort is enrolled in tertiary education; a share that is likely to increase in the future along with the aging population as shown in the regression analysis below.

Figure 5 shows the log of educational attainment at secondary and tertiary levels over the period 1800-2100, where the path over the period 2017-2100 is simulated under the conservative assumption that GERs at secondary and tertiary levels remain constant at their 2016 levels throughout the rest of the 21st century and using the population age distribution projected by United Nations (2017). Under this scenario, the 2016 educational attainment at the secondary and tertiary levels would increase by 13% and 41%, to be at their approximate steady states by 2060. As shown below, this increase would be a significant boost to growth, directly, through factor accumulation and, indirectly, through R&D.

Figure 5. Educational Attainment, OECD (logs)

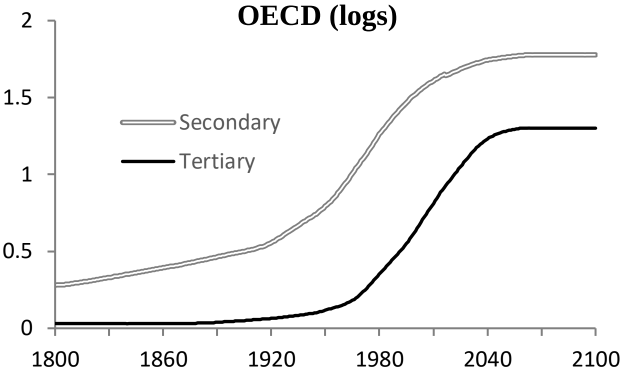
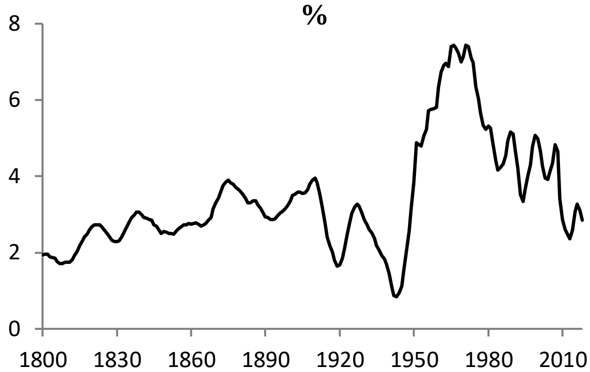


Figure 6. Net Non-Res. Inv-GDP Ratio, %



Notes. Figure 5: Educational attainment over the period 2017-2100 is simulated under the assumption that GERs at secondary and tertiary levels stay constant at their 2016 levels. The population age distribution in the post-2016 period is based on the projections of the United Nations (2017). Figure 6: The I^{NR}-Y ratio is measured as a 9-year centered moving average before 1960.

Finally, net non-residential investment, displayed in Figure 6, has fluctuated around a mean of 3.4% over the period 1800-2018 despite an increasing gross saving rate over the same period (not shown).[2] The increasing gap between net investment and gross saving has been driven mainly by increasing capital-output ratios and depreciation rates that have been increasing along with an increasing share of investment in products with high depreciation rates, such as machinery, equipment, and intellectual property products. Since the Global Financial Crises (GFC), net investment has been at a low of 3%, which may be an outcome of unfavorable investment opportunities, as stressed by the secular stagnation hypothesis (Gordon, 2015), perhaps coupled with high returns to investment in real estate.

8. Regression results

This section presents estimates of innovations, GERs, the labor force population ratio, and per capita income growth over the periods 1820-2016, 1870-2016, and, for the labor force estimates, 1950-2016 and 1980-2016, where the 1870 starting year is dictated by the first year at which the instrumented educational attainment is available, noting that the 64-age cohort started their education at the age of 6. Furthermore, the quality of the data increases significantly around 1870. Estimates over the period 1900-2016 are presented in the accompanying working paper by Madsen (2024). The coefficients of Age^j, are normalized to have a mean of zero across all age cohorts in all regressions because it is the change in relative distribution, as opposed to the level, of the age structure that is relevant for assessing the effects on the outcome variables of changes in the age structure. Correspondingly, the associated t-ratios are tests of the null hypotheses that the coefficients of each age-cohort are equal to the mean of the coefficients of all age cohorts.

The model is estimated using the cross-sectionally heteroscedastic and time-wise autoregressive estimator of Kmenta (1971), which allows for contemporary cross-country correlation

[2] The Dicky-Fuller test for unit root of the non-residential net-investment ratio over the period 1870-2016 for 21 OECD countries, yields a coefficient of -0.39(t = 27.0), suggesting strong mean-reverting properties in the data. Country fixed effects are included in the regression.

between the error terms, which is similar to the seemingly unrelated regression (SUR) principle. This estimator caters for unobserved endogenous effects (Egger, 2001) and yields more efficient parameter estimates than the FE-OLS estimator. To be feasible, the number of time periods must exceed the number of cross-sectional units and the panel must be balanced. Feasible least squares are applied to address heteroscedasticity and serial correlation.

8.1 First-stage regressions

The generic first-stage regression results (Eqs. (21)- (24)) are presented in Table 1. The share of population on age cohorts are included in all regressions, but note that the Tobin's q regression starts 50 years later than the other regressions because of data availability. The other confounders that are specific to the individual regression results are not shown to preserve space and because the F-tests for excluded instruments are almost identical to the ones presented in Table 1. The coefficients of the instruments are all statistically significant except for one case, they all have the expected signs, and the F-tests for excluded instruments are all well above the level that is required to satisfy the relevance criteria.

Table 1. First-stage regressions (Eqs. (21)-(24)).

	1	**2**	**3**	**4**
	R_{it}	$\ln FD_{it}$	$\ln(Pat/L)_{it}$	$\ln q_{it}$
R_{it}^F	0.24(5.87)***		-0.08(3.76)***	
$\ln FD_{it}^F$		0.29(5.82)***	0.42(9.07)***	
$\ln q_{it}^F$				0.08(6.04)***
CIM_{it}^F	-1.46(5.47)***	0.09(3.42)***	0.52(13.2)***	0.03(1.06)
Est. Period	1820-2016	1820-2016	1820-2016	1870-2016
Obs.	3940	3940	3940	3087
***F*-test**	29.8***	25.7***	92.7***	19.0***

Notes: Absolute t-statistics are in parentheses and are based on heteroscedasticity and serial correlation robust standard errors. Time and country dummies are included in all regressions. Japan is excluded from all the estimates. F-test is an F-test for excluded instruments. The superscript "F" stands for financial and monetary conditions of the anchor country; R is the interest rate of a long-term government bond; FD is financial development (credit-GDP ratio); q is Tobin's q; and CIM is contact-intensive money. The shares of population by age cohorts are included in all regressions. *** = significant at 1%; ** = significant at 5%; * = significant at 10%.

8.2 Second-stage regressions

8.2.1 Innovative activity

Estimates of the innovation model are presented in the first five columns in Table 2. The significance of the coefficients of financial development are surprisingly low. However, the coefficients of FD are significantly positive when R&D-intensity, measured as the ratio of R&D expenditure and income, is the dependent variable as shown in the accompanying working paper by Madsen (2024). The coefficients of secondary and tertiary education are highly significantly positive in all five regressions and, as expected, the coefficients of tertiary education in columns (4) and (5) are approximately twice the size of their combined secondary and tertiary educational counterparts. The coefficients of education remain highly significant when education is instrumented as shown in the online Appendix. Finally, the coefficients of education are significantly lower in the estimates over the period 1870-

2016 than those of 1820-2016. The decline after 1870 may be because of declining productivity of R&D workers as identified by Madsen et al. (2024).

Table 2. Determinants of innovation, education, and labor force (Eq. (11)-(14)).

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
	$\ln(Pat/L)_{it}$	$\ln(Pat/L)_{it}$	$\ln(Pat/L)_{it}$	$\ln(Pat/L)_{it}$	$\ln(Pat/L)_{it}$	$\ln GER_{it}^{ST}$	$\ln GER_{it}^{ST}$	$\ln GER_{it}^{T}$
h_{it}^{ST}	0.78*** (11.3)	0.75*** (15.1)	0.35*** (8.45)					
h_{it}^{T}				1.53*** (12.9)	0.86*** (8.56)			
$\ln FD_{it}$	0.12*** (2.83)	0.02 (1.58)	0.02 (0.88)	0.03** (2.08)	0.02 (1.00)	0.10*** (11.8)	0.05*** (5.03)	0.27*** (13.0)
$\ln Lexp_{it}$						0.06*** (3.37)	0.10*** (3.91)	0.22*** (5.15)
$\ln Age_{it}^{0-14}$	-1.88*** (3.15)	-2.43*** (5.86)	-1.44*** (3.38)	-3.23*** (8.70)	-1.72*** (4.27)	-1.64*** (13.0)	-1.52*** (10.1)	-1.23*** (6.82)
$\ln Age_{it}^{15-24}$	-0.72* (1.88)	-0.70** (2.37)	-051* (1.77)	-1.00*** (3.62)	-0.61** (2.16)	-0.82*** (10.3)	-0.86*** (8.88)	-1.04*** (8.36)
$\ln Age_{it}^{25-34}$	-0.29 (0.78)	-0.30 (0.93)	-0.81 (0.11)	-0.42 (1.37)	0.09 (0.30)	0.08 (1.15)	0.03 (0.32)	0.07 (0.56)
$\ln Age_{it}^{35-44}$	0.11 (0.29)	-0.02 (0.07)	0.17 (0.54)	-0.03 (0.09)	0.14 (0.47)	0.25*** (3.44)	0.16 (1.55)	0.21* (1.66)
$\ln Age_{it}^{45-54}$	0.65* (1.79)	0.68** (2.19)	0.21 (0.73)	0.94*** (3.08)	0.25 (0.86)	0.70** (9.71)	0.49*** (5.21)	0.63*** (5.46)
$\ln Age_{it}^{55-64}$	0.89*** (3.26)	1.07*** (4.51)	0.61*** (2.71)	1.29*** (5.50)	0.67*** (3.00)	0.79*** (13.6)	0.76*** (10.8)	0.35*** (3.71)
$\ln Age_{it}^{65+}$	1.27*** (5.81)	1.69*** (9.12)	0.85*** (4.30)	2.48*** (13.9)	1.17*** (6.00)	0.81*** (16.7)	0.94*** (15.5)	1.15*** (13.5)
Est. Period	1820-2016	1820-2016	1870-2016	1820-2016	1870-2016	1820-2016	1870-2016	1870-2016
Estimator	IV-SUR	FE-SUR	FE-SUR	FE-SUR	FE-SUR	IV-SUR	IV-SUR	IV-SUR
Instrumented	FD_{it}	–	-	-	–	FD_{it}	FD_{it}	FD_{it}
Obs.	3940	3940	2940	3940	2940	3940	2940	2940

Notes: Absolute *t*-statistics are in parentheses and are based on heteroscedasticity and serial correlation robust standard errors. The pooled SUR estimator is used in all regressions. Time and country dummies are included in all regressions. The coefficients of Age^j are standardized to have a mean of zero and their associated *t*-ratios are tests of the null hypotheses that the coefficients are equal to the mean of the coefficients of the age structure. Japan is excluded from all the estimates. h^{ST} is educational attainment at secondary and tertiary levels; h^T is educational attainment at the tertiary level; *Lexp* is life expectancy at birth; *FD* is financial development (credit-GDP ratio); *LFPOPR* is the share of the total population that is in the labor force; *LFPR* is the labor force participation rate; and Age^j is the share of population in the *j*'th age cohort. The employment data are adjusted for the Great Depression (see text). *** = significant at 1%; ** = significant at 5%; * = significant at 10%.

Turning to the age structure of the population in the innovation regressions, the coefficients of the 0-24-year age cohorts are significantly negative, close to zero in the 25-44-year age cohort, and highly significantly positive and increasing with age for the 45+ age cohorts. A 10% increase in the share of the population aged 65+ at the expense of the 0-24 age cohort is, on average, associated with a 30% [(1.455+1.5475)*10] increase in research intensity. This result is consistent with that of Feyrer (2007) who finds marked positive effects on TFP of increasing the age dependency rates, suggesting that an aging population should have positive output effects.

This positive innovation effect probably cannot be solely attributed to older workers having a relatively higher innovative activity but rather reflects precautionary initiatives to counter the potential adverse effects of aging through various channels, such as directed technological change, institutional improvements, intertemporal substitution etc., as advocated by Acemoglu and Restrepo (2017), Gehringer and Prettner (2019), Irmen (2017), Sasaki and Hoshida (2017), and Irmen and Litina (2022). Acemoglu and Restrepo (2017), for example, argue that aging is associated with a more rapid adoption of automation technologies, and they find that the countries that have experienced the most rapid aging have also grown the most in recent decades. In the same vein, Geheringer and Prettner (2019) hypothesize that reduced mortality rates enhance productivity by raising the incentives for households to invest in physical capital and R&D. In support for their hypothesis, they find that TFP is a decreasing function of mortality for a large panel of countries.

8.2.2 Gross enrollment rates

The IV-SUR GER^{ST} and GER^{T} regressions are presented in columns (6)-(8) in Table 2. Consistent with the results of Cervellati and Sunde (2005), the coefficients of life expectancy are significantly positive. The increase in life expectancy of 17% over the period 1960-2016, has contributed to a 1.7% (3.7%) increase in GER^{ST} (GER^{T}) based on the post-1870 estimates in columns (7) and (8). Although these effects are modest, they will nevertheless contribute to growth over the next decades as the highly educated young age cohorts replace the lower-educated workers that exit the labor force.

Turning to the age structure, the coefficients are steeply increasing in age; from an average of -0.48 for $Age^{0\text{-}14}$ to +0.97 for Age^{65+} (or -1.77 for $Age^{0\text{-}14}$ to +1.07 for Age^{65+} based on the FE-SUR estimates as reported in online Appendix Table A2). Thus, a mean-preserving 15% increase in the share of the population aged 65+ and a corresponding decrease in the share of the population in the 0-14-year age cohort is, on average for all three regressions, associated with a 22% increase in GER^{ST}/GER^{T}. Using the coefficient estimates of the Solow growth model of Mankiw et al. (1992), this increase is associated with a parallel 22% increase in per capita income along the balanced growth path. These results give support to the hypothesis that the investment in secondary and tertiary education increases as the society is aging as a precautionary measure to counter potential adverse income effects of the aging population, such as the expected income decline after retirement (Gonzalez-Eiras and Niepelt, 2012). More importantly, the increasing aging is associated with directed technological change, institutional improvements, intertemporal substitution etc. as discussed above.

Table 3. Parameter estimates of the investment and saving functions (Eqs. (13)-(15)).

	1	**2**	**3**	**4**	**5**	**7**	**6**	**8**	**9**
	$\ln(I^{NR}/Y)_{it}$	$\ln(I^{NR}/Y)_{it}$	$\ln(I^{NR}/Y)_{it}$	$\ln(I^{NR}/Y)_{it}$	$\ln(I^{NR}/Y)_{it}$	$\ln(S^{NR}/Y)_{it}$	$\ln(S^{NR}/Y)_{it}$	$\ln(S^{NR}/Y)_{it}$	$\ln(S^{NR}/Y)_{it}$
$\ln \boldsymbol{q_{it}}$					0.37*** (3.19)				
$\ln \boldsymbol{R_{it}}$	0.04 (0.85)	-0.01 (0.78)	0.13*** (2.90)	0.12*** (5.94)		-0.01** (2.09)	-0.002** (2.18)	-0.01*** (3.16)	0.004 (1.42)
$\ln \boldsymbol{FD_{it}}$	0.37*** (4.83)	0.02 (0.58)	0.34*** (3.65)	-0.08 (1.17)		0.01** (2.42)	-0.01*** (3.47)	0.02*** (2.67)	0.03*** (3.79)
$\ln \boldsymbol{Lexp_{it}}$	-0.27 (1.17)	0.26 (1.24)	0.17 (0.17)	0.38** (2.56)		0.014** (1.97)	0.12*** (5.00)	0.01 (0.33)	0.002 (0.17)
$\ln \boldsymbol{Age_{it}^{0-14}}$	-0.28 (0.58)	-1.64*** (4.01)	0.24 (0.59)	0.37 (0.37)	-0.26 (0.82)	0.01 (0.23)	-0.07** (2.49)	-0.05 (1.39)	0.10* [illegible]
$\ln \boldsymbol{Age_{it}^{15-24}}$	-0.10 (0.29)	-0.88*** (2.71)	0.46*** (1.55)	0.26 (0.74)	0.09 (0.31)	0.09*** (3.67)	0.11*** (4.38)	0.07*** (2.75)	0.05 [illegible]
$\ln \boldsymbol{Age_{it}^{25-34}}$	0.53 (1.32)	0.20 (0.50)	0.56 (1.63)	0.55* (1.69)	0.40 (1.16)	-0.06** (2.31)	0.02 (074)	-0.05 (1.49)	-0.05 [illegible]
$\ln \boldsymbol{Age_{it}^{35-44}}$	1.15*** (2.70)	0.66 (1.60)	1.09*** (2.95)	0.34 (1.14)	0.57 (1.53)	0.10*** (3.94)	0.11*** (3.28)	0.05 (1.60)	-0.01 [illegible]
$\ln \boldsymbol{Age_{it}^{45-54}}$	0.79* (1.81)	0.54 (1.26)	-0.46 (1.27)	-1.18*** (4.45)	-0.78** (2.17)	-0.03 (0.98)	0.05 (1.61)	0.02 (0.72)	-0.01 [illegible]
$\ln \boldsymbol{Age_{it}^{55-64}}$	-0.43 (1.11)	-0.94*** (2.75)	0.11 (0.36)	-0.93*** (4.09)	0.27 (0.95)	-0.02 (0.95)	0.02 (0.98)	0.02 (0.64)	-0.06** [illegible]
$\ln \boldsymbol{Age_{it}^{65+}}$	1.39* (1.65)	0.25 (1.18)	0.15 (0.73)	0.75** (2.03)	-0.29 (1.53)	-0.09*** (5.43)	0.05 (0.30)	-0.07*** (3.56)	-0.03 [illegible]

Est. Period	1820-2016	1820-2016	1870-2016	1950-2016	1870-2016	1820-2016	1870-2016	1870-2016	1950-2016
	IV-SUR	**SUR**	**IV-SUR**	**IV-SUR**	**IV-SUR**	**IV-SUR**	**SUR**	**IV-SUR**	**IV-SUR**
Instrumented	$R\&FD_{it}$	-	$R\&FD_{it}$	$R\&FD_{it}$	q_{it}	$R\&FD_{it}$		$R\&FD_{it}$	$R\&FD_{it}$
Obs.	3940	3940	2940	1340	3940	3940	2940	2940	1340

Notes: See notes to Table 2. *R* is the interest rate of long-term government bonds; and *q* is Tobin's *q*.

8.2.3 Investment and saving

The results of estimating the net investment and net saving models are presented in Table 3. The coefficients of the interest rate are insignificant in the investment models but significantly negative in the saving models, suggesting that the income effect is overridden by the substitution effect in saving. The coefficients of financial development are significantly positive in half of cases; the coefficient of Tobin's *q* is significantly positive in the regression in column (5); and the coefficients of life expectancy are significantly positive in three of the nine cases.

Turning to the coefficients of the age structure, the coefficients of the 35-44 age cohort tend to be positive, while they tend to be negative for the 55-64 age cohort. For the 65+ age cohort, the coefficients are significantly positive for investment in two of the five cases and significantly negative in two of the four cases for saving. The finding of slightly adverse effects of aging on saving is consistent with the life-cycle hypothesis of consumption and with the calibrations of the overlapping generation model of Börsch-Supan et al. (2006). The findings of some positive net investment effects for the 65+ age cohort is consistent with the productivity growth results, which are discussed in detail below.

8.2.4 Labor force participation

Consider first the regressions in columns (1) and (2) in Table 4 in which the labor force share of the total population, *LFPOPR*, is the dependent variable. This is the key model of the labor force estimates because it shows the extent to which the population in the labor force, and hence per capita income, is affected by the age distribution of the population. The estimation periods are restricted to1950-2016 and 1980-2016 because 1) the labor force statistics data is often only available with long time intervals before WWII; 2) the dependency of the labor market attachment on ages is likely to have changed in the wake of the structural change from agriculture to services and manufacturing; and 3) the historical female labor force participation rates were severely underestimated in some countries (Humphries and Sarasúa, 2012). The coefficients of the 55+ age cohorts and the 0-44 age cohorts are, on average, close to zero regardless of whether the estimation period is 1950-2016 or 1980-2016), suggesting that *LFPOPR* is not significantly affected by aging; statistically or economically. A one percentage increase in the population share in the 55+ age cohort at the expense of the pre-55 age cohort is associated with a decline in *LFPOPR* of 2.0% (-1.0%) with a statistical significance of $p = 0.08$ ($p = 0.25$) based on the estimates over the period 1950-2016 (1980-2016).

Considering the regression in column (3) in Table 4 in which the labor force participation rate is the dependent variable and the estimation period is 1870-2016, the participation rate is hardly influenced by the age distribution. However, when the estimation period is 1950-2016 (column (4)), the coefficients of the population shares in the 35-64 age cohorts are significantly negative and significantly positive for the 65+ age cohort. Using the estimates in column (4), the 15% increase in Age^{65+} at the expense of $Age^{15\text{-}64}$ over the 21st century, as projected by the UN (2017), will result in a

6.3% decrease in *LFPR*, approximately, and, consequently, in a 6% decline in per capita income. This stands in sharp contrast to the standard accounting exercises in which labor market participation rates are independent of the age distribution. With fixed labor force participation rates, the UN-projected 15% increase in Age^{65+} at the expense of $Age^{15\text{-}54}$ over the 21st century would result in a 15% decline in per capita GDP, an effect that has often been used in the public debate as a warning of the adverse effects of the aging society (see, without endorsement, Bloom et al., 2024).

Overall, the estimates suggest that, as the society ages, workers stay longer in the labor force and the labor force participation rate of almost any working age cohort increases. The finding that the share of the population in the labor force, *LFPOPR*, is only little affected by the age structure of the population suggests that the tax revenue is approximately independent of the age structure of the population provided that average earnings are not affected by the changing age structure of the labor force. Though aging is likely to increase the pressure on public health systems, the estimates nevertheless show that the pressure on public finances are mitigated by the endogenous labor force participation response to the increasing share of the population in the 65+ age cohort.

Table 4. Labor force and income and labor productivity growth (Eqs. (8), (16) & (17)).

	1	2	3	4	5	6	7	8	9	10
Dep. Var.	$\ln LFPOPR_i$	$\ln LFPOPR_i$	$\ln LFPR_{it}$	$\ln LFPR_{it}$	$\ln LFPR_{it}$	$\Delta \ln (Y/L)_{it}$	$\Delta \ln (Y/L)_{it}$	$\Delta \ln (Y/Pop^{WA})_{it}$	$\Delta \ln (Y/Pop)_{it}$	$\Delta\ln (Y/L)_{it}$
$\ln(Pat/L)_{it}$						0.015*** (9.13)	0.004*** (6.48)	0.012*** (7.09)	0.012*** (6.44)	
$\Delta \ln h_{it}^{Tot}$						0.021*** (3.85)	0.018*** (3.10)	0.015*** (2.57)	0.016*** (2.57)	
$\Delta\ln X_{it}$						0.213*** (4.77)	0.208*** (4.33)	0.275*** (6.57)	0.275*** (6.37)	
$\beta_{it}\Delta \ln L_{it}$						- 0.855*** (10.9)	- 0.923*** (11.2)	- 0.502*** (5.75)	- 0.513*** (6.00)	
$\Delta (I^{NR}/Y)_{it}$						0.530*** (13.3)	0.543*** (14.0)	0.669*** (15.7)	0.673*** (15.9)	
$\Delta \ln Age_{it}^{0-14}$	[illegible]*** (3.54)	[illegible]*** [illegible]	[illegible]*** (2.87)	(0.37)	[illegible]** (1.95)	-0.005 (0.05)	0.007 (0.06)	-0.116 (1.14)	- 0.284*** (2.84)	0.049 (0.49)
$\Delta\ln Age_{it}^{15-24}$	[illegible]** (2.28)	[illegible]	[illegible] (0.64)	(0.13)	[illegible]*** (2.98)	- 0.229*** (3.38)	- 0.295*** (4.39)	-0.205*** (3.23)	- 0.163*** (2.68)	- 0.231*** (3.33)
$\Delta\ln Age_{it}^{25-34}$	[illegible]*** (3.25)	[illegible]*** [illegible]	[illegible] (1.41)	(0.00)	(1.40)	-0.048 (0.84)	-0.041 (0.72)	-0.040 (0.71)	0.008 (1.38)	-0.014 (0.18)
$\Delta\ln Age_{it}^{35-44}$	(0.92)	[illegible]*** [illegible]	[illegible]* (1.68)	[illegible]*** (0.34)	[illegible]	-0.020 (0.36)	-0.031 (0.52)	-0.043 (0.79)	0.004 (0.08)	-0.074 (1.31)
$\Delta\ln Age_{it}^{45-54}$	(0.02)	[illegible]*** [illegible]	(0.23)	[illegible]*** (3.49)	(1.11)	0.171*** (3.32)	0.139*** (2.63)	0.118** (2.37)	0.159*** (3,44)	0.091* (1.81)
$\Delta\ln Age_{it}^{55-64}$	[illegible]** (2.39)	[illegible]	[illegible] (1.22)	[illegible]*** (5.71)	[illegible]*** (4.46)	0.046 (1.16)	0.118*** (2.93)	0.042 (1/05)	0.095*** (2.57)	0.045 (1.17)
$\Delta \ln Age_{it}^{65+}$	(1.10)	[illegible]	[illegible]* (1.65)	[illegible]*** (5.35)	[illegible]*** (5.06)	0.083** (2.24)	0.118*** (2.93)	0.242*** (6.40)	0.116*** (3.34)	0.135*** (3.67)
Est. Period	1950-2016	1980-2016	1870-2016	1950-2016	1980-2016	1820-2016	1820-2016	1820-2016	1820-2016	1820-2016
Obs.	1340	777	2940	1340	777	840	800	840	840	840
Estimator	FE-SUR	FE-SUR	FE-SUR	FE-SUR	FE-SUR	FE-SUR	IV-SUR	FE-SUR	FE-SUR	FE-SUR
# Countries	21	21	21	21	21	21	20	21	21	21
Instrumented	-	-	-	-	-	-	Pat/L; Age			

Notes: The pooled SUR estimator is used. The parameter estimates are corrected for cross-country heterogeneity and serial-correlation. The productivity models in columns (6)-(10) are in 5-year non-overlapping intervals and the 5-year differences are annualized. Country and time fixed effects are included in all regressions. *Pat*/*L* is the ratio of residents' patent applications and employment; h^{Tot} is total educational attainment; *X* is annual hours worked by the average worker; $\beta_{it}\Delta \ln L_{it}$ is the population growth drag; I^{NR}/Y is the share of net non-residential investment in real GDP; and Age^j is the share of the population in the *j*'th age cohort. The employment data are adjusted for the Great Depression (see text). *** = significant at 1%; *** = significant at 5%; *** = significant at 10%.

8.2.5 Productivity growth regressions

Productivity growth regressions estimated in non-overlapping 5-year differences are presented in Table 4. The dependent variable is output per worker in columns (6)-(7), income per working age population in column (8), and per capita income in column (9). The coefficients of patent intensity, educational attainment at all levels of the population of working age, h^{Tot}, annual hours worked, the investment ratio and the population growth drag are all significant at the 1% level and have the expected signs. The coefficients of research intensity are twice as high in the FE-SUR than the IV-SUR regressions, suggesting positive feedback from economic development to innovation. Despite this feedback, the coefficients of innovation in the IV-regressions remain highly significantly positive determinants of economic growth. The importance of the positive effects of the level of research intensity is that labor productivity will continue to grow in the future for any (positive) value of research intensity and that the *steady state* growth rate will remain unaltered in the 21st if the innovative activity remains constant at its present level. Since research-intensity is a positive function of aging, directly and indirectly through education, the growth implications of the aging society will ensure that the R&D-induced growth will not diminish in the 21st century.

The coefficients of annual hours worked are, on average, 0.25, implying that the almost 50% reduction in annual hours worked since 1870 has contributed to a 13% reduction in output per worker over the same period under the assumption that $\alpha = \beta$ (see Eq. (5)). Although the coefficient of working hours is likely to be downward biased because the increasing share of professionals in the labor force whose long working hours are not accounted for in the statistics, it is likely to be well below one because of fatigue associated with long hours. Consequently, expansions of annual working hours may not be the most effective response to counter the direct productivity effects of the aging population, which again, highlights the problems associated with policy recommendations based on simple growth accounting models in which the output elasticity of hours worked is equal to one.

Though significantly positive, the educational elasticity of growth, h^{Tot}, is on average 0.06 (the coefficient of educational attainment multiplied by the sample mean of educational attainment) in the labor productivity regressions, which is below the conventional estimates of approximately 0.17 (Cohen and Soto, 2007; Madsen and Murtin, 2017), suggesting that the coefficients of educational attainment in Table 3 are at least not likely to be upward biased. The coefficients of education are significantly higher in the labor productivity than in the income per working population and income per capita regressions, suggesting that the labor force participation rates are increasing functions of the educational attainment. This result makes sense because the opportunity costs of dropping out of the labor force is higher for the educated than the uneducated.

The coefficients of the population growth drag are on average 0.90 in the labor productivity regressions in columns (6) and (7), suggesting significantly negative impact of population growth on productivity growth through diminishing returns introduced by land as a fixed factor of production. While the population growth-drag significantly contributed to the relatively low productivity growth rates before WWII, its effect has diminished significantly along with the agricultural decline. Finally, the coefficients of the net investment rates are statistically highly significant at around 0.6, which is consistent with the predictions of the Solow model in which the coefficient of the net investment rate is given by $\alpha/(1-\alpha) \cong 0.5$.

Next, consider the coefficients of the age cohorts. The coefficients of the population shares in the 45-65 age cohort are, on average, 0.12 and 0.18 for the 65+ age cohort, suggesting that the direct productivity effects of aging are significantly positive. A 15% increase in the Age^{65+} age cohort relative to that of the working age population is associated with a 3.8% increase in productivity. Consistent with the abundant empirical evidence on the earnings profile over the life cycle, productivity is steeply increasing with age until it peaks at the $Age^{45\text{-}55}$; a cycle that is often attributed to learning-by-doing and on the job training (Mincer, 1997). The regressions here show that the 65+ age cohort promotes productivity relative to the average of the other age cohorts, particularly the population below the age of 45. Although these results may be surprising, they are, nevertheless, consistent with Feyrer's (2007) results. Feyrer (2007) finds that the population outside working age is contributing significantly more to productivity than any of the working age cohorts; thus, giving even stronger evidence than the results in Table 3 against the conventional wisdom that aging reduces productivity.

The findings of positive productivity effects of aging need not imply that older people are more productive than their younger counterparts. Rather, these results reflect endogenous productivity-enhancing responses to aging. Acemoglu and Restrepo (2017), for example, find that countries experiencing more rapid aging have grown more in recent decades, and they show theoretically, that their finding reflects the faster adoption of automation technologies in countries undergoing more pronounced demographic changes – effects that are unlikely to be captured by the conditioning variables in the regressions in Table 3. Furthermore, Bellettini and Ceroni (1999) show that a pay-as-you-go social security system may give taxpayers incentives to support growth-oriented policies, such as investment in infrastructure and public education. At the same time, higher longevity increases the political support for public investment in education and infrastructure as a precautionary measure to counter potential adverse income effects of the aging population (Gonzalez-Eiras and Niepelt, 2012). Finally, unobserved compensating productivity advances may be at play, potentially through self-selection: the most productive workers stay in the workforce beyond retirement age, while workers with comparatively lower productivity are, for financial reasons, forced to remain in the labor force until they reach retirement age.

The non-deterministic conditional variables are omitted in the regression in the last column in Table 4. The coefficients of the age structure are close to those of the baseline regressions in the first two columns, suggesting the effects of the age structure through the channels of the conditional variables are not picked up by reduced form estimates and, therefore, that reduced form productivity regressions are not likely to reveal the general equilibrium economic effects of aging.

9. Counterfactual growth simulations for the 21st century

This section simulates the steady state general equilibrium income effects of the increasing share of the population over 55 at the expense of the population below the age of 55 using the age distribution predicted by the United Nations (2017) for the 21st century. The conditional variables, such as the interest rate, GERs, and financial development, are assumed to remain constant for the rest of this century. The income implications of the changing demographics are decomposed into growth and level effects.

9.1 Level effects

The per capita income level effects of aging in steady state are derived from Eqs. (8), (12), and (15) and the estimated coefficients are from Table 2, columns (1) and (6), Table 3, column (1), and Table 4, columns (1) and (6):

$$\left.\frac{d\ln(Y/L)}{d\ln Age^{55+}}\right|_{\frac{I^N}{Y}} = \frac{\partial\ln(Y/L)}{\partial\ln(I^N/Y)}\cdot\frac{\partial\ln(I^N/Y)}{\partial\, ln\, Age^{55+}} =>$$

$$d\ln(Y/L) = \hat{\lambda}_5(\hat{\gamma}_{55+} - \hat{\gamma}_{0-54})\, d\ln Age^{55+} = -0.14\, d\ln Age^{55+}, \tag{24}$$

$$\left.\frac{d\ln(Y/L)}{d\ln Age^{55+}}\right|_{LFPOPR} = \frac{\partial\ln(Y/L)}{\partial\ln LFPOPR}\cdot\frac{\partial\ln LFPOPR}{\partial\, ln\, Age^{55+}} =>$$

$$d\ln(Y/L) = (\hat{\beta}_{55+} - \hat{\beta}_{0-54})\, d\ln Age^{55+} = -0.02\, d\ln Age^{55+}, \tag{25}$$

$$\left.\frac{d\ln(Y/L)}{d\ln Age^{55+}}\right|_{GER^{ST}} = \frac{\partial\ln(Y/L)}{\partial\ln h^{Tot}}\cdot\frac{\partial\ln h^{Tot}}{\partial\ln h^{ST}}\cdot\frac{\partial\ln h^{ST}}{\partial\ln GER^{ST}}\cdot\frac{\partial\ln GER^{ST}}{\partial\, ln\, Age^{65+}} =>$$

$$d\ln(Y/L) = \hat{\lambda}_2\cdot 0.5(\hat{\kappa}_{55+} - \hat{\kappa}_{0-54})\, d\ln Age^{55+} = 0.03\ \ d\ln Age^{55+}, \tag{26}$$

$$\left.\frac{d\ln(Y/L)}{d\ln Lexp}\right|_{GER^{ST}} = \frac{\partial\ln(Y/L)}{\partial\ln h^{Tot}}\cdot\frac{\partial\ln h^{Tot}}{\partial\ln h^{ST}}\cdot\frac{\partial\ln h^{ST}}{\partial\ln GER^{ST}}\cdot\frac{\partial\ln GER^{ST}}{\partial\, ln\, \text{Lexp}} =>$$

$$d\ln(Y/L) = \hat{\lambda}_2\cdot 0.5\cdot\hat{\kappa}_2\, d\ln Lexp = 0.0006\, d\ln Lexp, \tag{27}$$

$$\left.\frac{d\ln(Y/L)}{d\ln Age^{55+}}\right|_{Y/L} = \frac{\partial\ln(Y/L)}{\partial\, ln\, Age^{55+}} => d\ln(Y/L) = (\hat{\vartheta}_{55+} - \hat{\vartheta}_{0-54})\, d\ln Age^{55+} = -0.01\, d\ln Age^{55+}, \tag{28}$$

where $d\ln Age^{55+}$ signifies a one percent increase in the share of the population over 55 at the expense of the population below the age of 55.

The sum of the coefficients over the level effects (Eqs. (24)-(28)), yields a total of -0.14, suggesting that the 9.6% (5.1%) increase in Age^{55+} (Age^{65+}) cohort over the 21st century is associated with a per capita income contraction of 1.3% (0.7%). As the younger more educated age cohorts replace the older less educated cohorts that exit the labor force reduces the age-induced income level contraction to 0.9% (0.3%) in steady state, suggesting that the income level effect of aging is marginal.

9.2 *Growth effects*

The total growth effects in steady state from aging are derived from Eqs. (8), (10), and (11) as follows:

$$d\, g_{Y/L}\big|_{Pat/L} + d\, g_{Y/L}\big|_{h^{ST}} = \frac{\partial\, g_{Y/L}}{\partial\ln(Pat/L)}\left[\frac{\partial\ln(Pat/L)}{\partial\ln h^{ST}}\cdot\frac{\partial\ln h^{ST}}{d\ln GER^{ST}}\cdot\frac{\partial\ln GER^{ST}}{\partial\, ln\, Age^{55+}}\, d\ln Age^{55+} + \frac{\partial\ln(Pat/L)}{\partial\, ln\, Age^{55+}} + \frac{\partial\ln(Pat/L)}{\partial\, ln\, h^{ST}}\, d\ln h^{ST}\right]$$

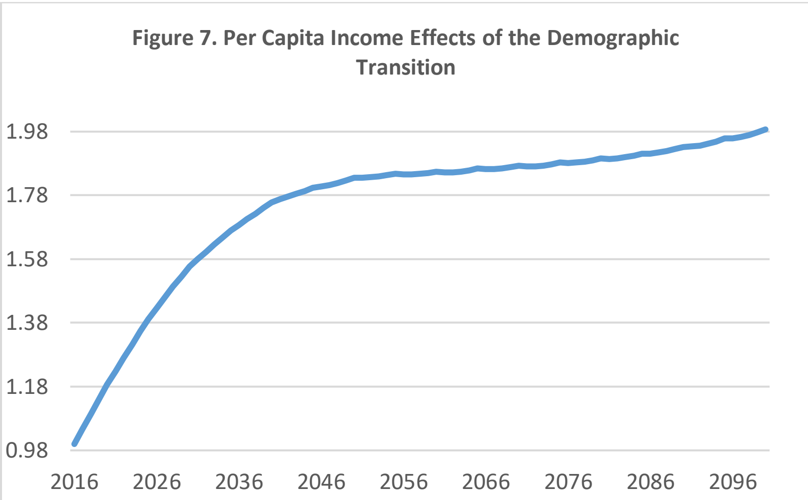
$$=> d\, g_{Y/L} = \hat{\lambda}_1\left[\hat{\alpha}_1\{(\hat{\kappa}_{55+} - \hat{\kappa}_{0-64}) + (\hat{\alpha}_{55+} - \hat{\alpha}_{0-54})\}\, d\ln Age^{55+} + \hat{\alpha}_1\, d\ln h^{ST}\right] =>$$

$$d\, g_{Y/L} = = 0.098\, d\ln Age^{55+} + 0.00117\cdot d\ln h^{ST}, \tag{29}$$

where the coefficient estimates are from the first column in each of Tables 1-3. Since Eq. (29) is the change in growth, it is not possible to predict the growth scenario for the 21st century. Instead, it is possible to simulate the contribution of aging and education to the growth that would otherwise have been experienced after 2016 had the educational attainment and the age structure been constant at the level that prevailed in 2016; a scenario I am now turning to.

9.3 Total income effects

Figure 7 shows the total per capita income effects of the increasing old age dependency, the increasing life expectancy, and the educational 'replacement effects', in which the younger age cohorts with secondary and tertiary education gradually replace the older age cohorts that exit the labor force. Income increases steeply up until the mid-21st century; an increase that is predominantly driven by the increasing educational attainment as evidenced in Figure 2. Educational attainment flattens out after the mid-21st century and the modest increase in per capita income is driven by a moderate increase in the average age of the population. By 2100, per capita income has increased by almost 100% since 2016. The principal driver of growth up until the mid-21st century is essentially higher tertiary education that provides permanent growth effects through research intensity. Note that 2100 does not represent a steady state equilibrium because the age-dependency rate is, according to UN's projections in Figure 1, above its long-run equilibrium. Thus, the share of the population of working age will increase in the 22nd century as the economies move toward their steady state and the income effects will, to some extent, be reversed in the 22nd century.



Notes: The graph shows the simulated contribution of the demographic transition to the per capita income path.

10 Concluding remarks

The growth implications of aging have predominantly been suggested to be negative and sometimes even alarmingly so. To take an extreme example, Peterson (1999) paints a bleak picture of the future by arguing that, "Global aging could trigger a crisis that engulfs the world economy. This crisis may even threaten democracy itself" (Peterson, 1999, p. 55). This paper has shown that such predictions are based on a factor accumulation framework in which endogenous responses to aging, the lagged fertility effects of education, and endogenous growth effects are omitted from the analysis. In this paper, I have extended the literature in three dimensions, all of which more than counter the negative growth effects of the demographic transition on investment: 1) by showing that fertility transition-induced increase in enrollments into higher education has positive growth payoffs in the future; 2) by bringing ideas production and higher education into the center of the analysis; and 3) by allowing for the endogenous responses of education, innovative activity, investment, and labor force participation to the age structure of the population.

Allowing for these effects, the analysis gives five main insights that are relevant for the growth prospects of the OECD in the 21st century. First, even if gross enrollment rates in secondary and tertiary education are kept constant at their current levels, educational attainment will continue to increase over the next few decades as the more educated age cohorts replace the older ones in the labor force, which will consequently promote productivity. Second, the increased educational attainment will promote innovations as the share of potential R&D workers in the population increases. Third, the increase in the labor force participation (LFP) rate of the younger female age cohorts will ensure an increasing overall LFP rate in the future, as they replace older female age cohorts with lower LFP rates. Fourth, the aging population is associated with increasing innovative activity, probably not because older individuals are more innovative than their younger counterparts, but because precautionary measures are taken to counter the potential adverse effects of aging through various channels, such as directed technological change, institutional improvements, intertemporal substitution etc. Fifth, as the society ages, workers stay longer in the labor force and the labor force participation rates of the working age cohort increases so that the share of the labor force in the total population stays constant despite the aging.

Simulating the general equilibrium income effects of the demographic transition, based on the UN's (2017) projections for the population age distribution and life expectancy for the rest of the 21st century and simulations of the educational attainment under the assumption of constant gross enrollment rates in secondary and tertiary education, suggests that per capita income will increase approximately 100% more over the period 2016-2021 more than otherwise had the educational attainment, life expectancy, and age distribution remained at their 2016 levels throughout the rest of the century. The principal driver of growth up until the mid-21st century is essentially higher tertiary education that provides permanent growth effects through research intensity. The question is whether the increasing tertiary educational attainment will continue to push the technology frontier forward to the same extent as in the past as the share of graduates at the lower tail of the ability distribution grows along with the increasing share of the labor force with a tertiary education. While this is probably true for males, most of the increase in tertiary education over the past few decades has been females catching up to those of males, thus countering some of the dilution effect from increasing male enrollment.

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