Education and ageing

SUMMARY

This paper investigates the consequences of population ageing and of changes in the education composition of the population for macroeconomic performance. Estimation results from a theoretically founded empirical framework show that ageing as well as the education composition of the population influence economic performance. The estimates and simulations based on population projections and different counterfactual scenarios show that population ageing will have a substantial negative consequence for macroeconomic performance in many countries in the years to come. The results also suggest that education expansions tend to offset the negative effects, but that the extent to which they compensate the ageing effects differs vastly across countries. The simulations illustrate the heterogeneity in the effects of population ageing on economic performance across countries, depending on their current age and education composition. The estimates provide a method to quantify the increase in education that is required to offset the negative consequences of population ageing. Counterfactual changes in labour force participation and productivity required to neutralise ageing are found to be substantial.

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Can education compensate the effect of population ageing on macroeconomic performance?

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1. INTRODUCTION

Population ageing is one of the most important economic and social challenges in the twenty-first century. With increasing life expectancy and falling fertility, the populations

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of most countries grow older, resulting in substantial shifts in the age composition of workforce and population at large. At the same time, the demographic transition and the associated shift in the age distribution imply substantial changes in the aggregate stock of human capital as well as its age distribution, as relatively large cohorts with low or moderate levels of formal education are replaced by relatively small cohorts with high levels of formal education.

This can be illustrated by changes in the age structure of populations over long time periods. Panel (a) of Figure 1 plots the age structure in the world and in high-income (OECD) countries in 1950 and 2010. Evidently, not only the size of the world population has changed over this period but, in particular, also the age composition. Whereas in a global perspective the population has increased rather uniformly across all ages, with a slowdown only visible for the youngest cohorts below 20 years of age, ageing is much more pronounced among the high-income countries. However, even within the group of high-income countries, there are substantial differences in the demographic dynamics. Panel (b) of Figure 1 plots the corresponding patterns for Germany, the United Kingdom, and France in 1950 and 2010. In Germany, the age composition of the population is most uneven, with the consequence of a stronger ageing momentum than in the United Kingdom and, in particular, in France, where the age composition is fairly uniform at ages below 65 years.

These demographic changes have important consequences for productivity and human capital. The shift in the age composition has implications for the informal, experience-related human capital embodied in the population. This follows from the empirically well-documented age-experience profile from life-cycle models of human capital (Ben-Porath, 1967). At the same time, populations differ greatly in their formal education attainment, both across age groups and across countries. Younger cohorts typically exhibit much higher levels of schooling and formal training. Figure 2 documents the secular increase in the share of high-skilled over the period 1950–2010 for high-income (OECD) and non-OECD countries in Panel (a), as well as for three developed countries, Germany, the United Kingdom, and France, in Panel (b).

Although these forceful demographic dynamics can be expected to have major implications for macroeconomic performance, the joint effects of population ageing and of changes in the human capital endowment for macroeconomic performance are still not well understood. Whereas the economic consequences of ageing and of changes in human capital have been investigated in isolation, their interactions have been largely neglected in the existing literature.

This paper addresses three questions that remain open in light of the existing literature: How do population ageing and the contemporaneous changes in aggregate human capital affect macroeconomic performance? Can investment in education offset the (potentially negative) effects of population ageing? And, finally, what are the corresponding prospects of future economic development?

Using data from a cross-country panel of more than 130 countries for the period 1950–2010, we investigate empirically how changes in the age structure of the workforce

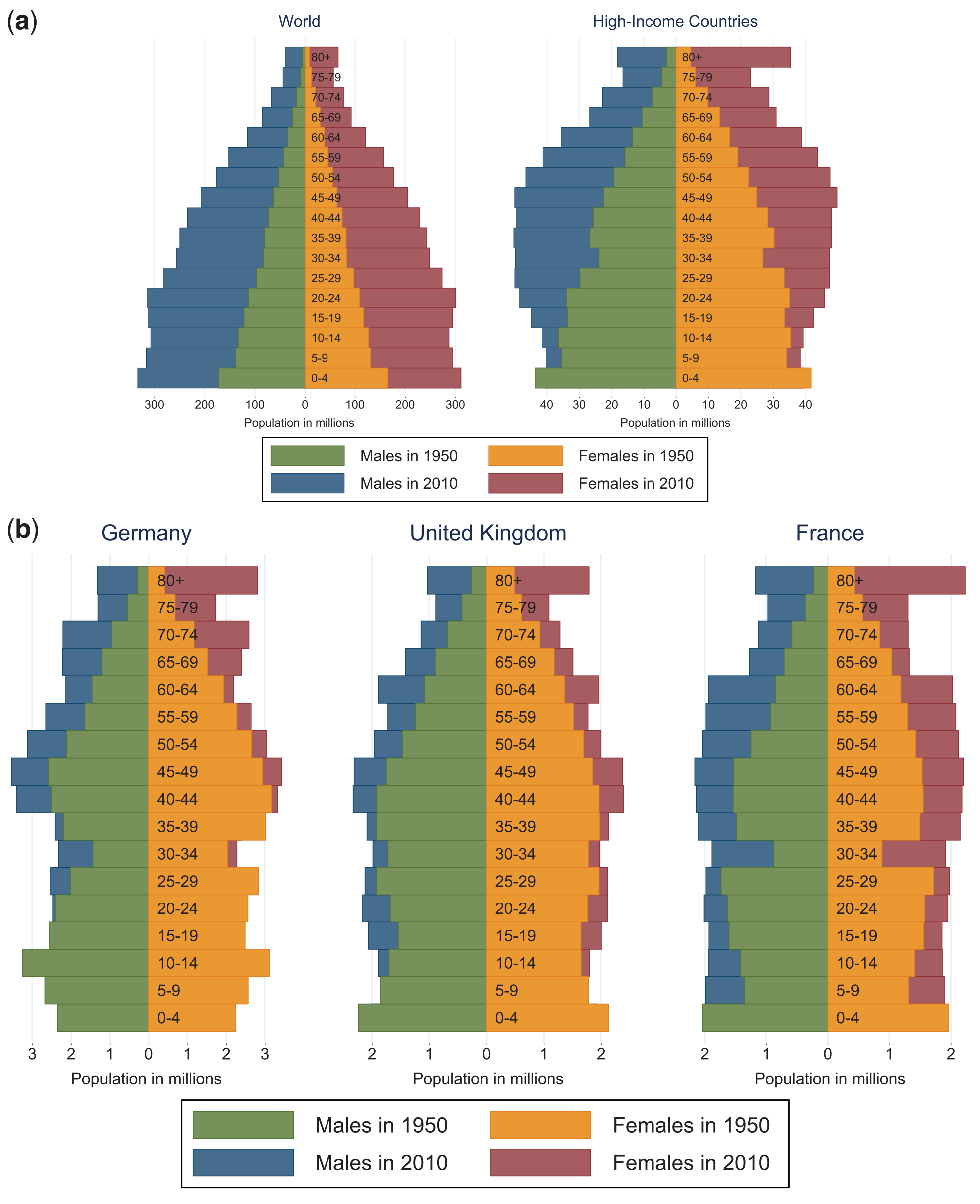

Figure 1. Population dynamics – selected regions

(a) World and High-Income Countries

(b) Germany, United Kingdom, and France

Source: United Nations (2015).

and in the distribution of human capital affect macroeconomic performance in terms of levels and growth rates. The investigation is based on an extended empirical development accounting model that encompasses the empirical frameworks used in the existing literature and that allows estimating the distinct effects of ageing and human capital.

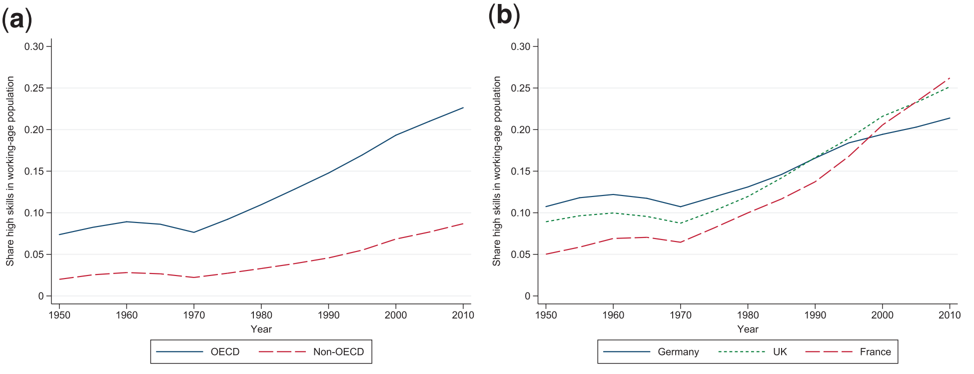

Figure 2. Dynamics of educational attainment

(a) OECD and Non-OECD Countries

(b) Germany, United Kingdom, and France

These estimates can be used for a detailed analysis of the relative importance of ageing and human capital dynamics for the projected development paths of countries around the world until 2050, and for a quantitative assessment of different scenarios of ageing and education acquisition.

The analysis proceeds in three steps. The first step sets the stage by restricting the analysis to the effects of population ageing and of changes in the aggregate human capital endowment for macroeconomic performance in isolation from each other, thereby replicating the existing evidence in the literature. The estimation results reveal that changes in the age composition of the workforce significantly affect economic performance. The estimates mirror the well-known hump-shaped individual productivity patterns from micro studies, with the largest positive effects being associated with prime working ages and smaller effects for young and old population segments. Likewise, the levels and dynamics in aggregate human capital are shown to affect economic performance independently from the demographic structure.

In the second step, the empirical analysis explicitly considers the interactions between ageing and changes in the skill composition. This analysis complements and extends the existing literature, which, with few exceptions, has largely been restricted to focusing either on population ageing or changes in the human capital endowment in isolation. The results reveal that population ageing has substantial implications on economic performance even when accounting for changes in the education composition, and that the demographic structure of the workforce and education both jointly affect economic performance. Moreover, the demographic structure affects economic performance nonmonotonically, implying heterogeneous prospective development paths conditional on the extent of demographic change. At the same time, there is little evidence for eroding productivity of human capital attained in terms of formal education in older cohorts.

In the third and final step of the analysis, the estimation results are used to conduct quantitative exercises that shed light on the relative importance of the changes in the age and in the skill composition of the workforce that occur as a consequence of the ongoing process of population ageing. In particular, based on the empirical estimates, macroeconomic performance is projected under several alternative scenarios that use the projected changes in age composition and education. These projections are compared to counterfactual scenarios that fix the age composition or human capital at current levels. According to these quantitative exercises, ageing and a slowdown in education attainment will dampen economic performance particularly in developed economies, where ageing is especially pronounced and the population has already attained fairly high levels of education throughout all age cohorts. Investment in education turns out to be a powerful force in compensating the negative consequences of population ageing. However, the results also suggest that even enhanced investments in education are unlikely to completely offset the effects of population ageing in the countries that face the greatest pressure of population ageing. In contrast, for economies with a relatively stable demographic structure, ageing is projected to have rather neutral effects on macroeconomic performance, while the projected increase in human capital implies a positive prospective performance.

Furthermore, the results provide an estimate of the elasticity of substitution between the age composition and the human capital endowment of a country. This elasticity provides new insights into the change in the distribution of human capital that is needed in order to offset the effects of changes in the age composition of the workforce. The quantitative estimate for this elasticity suggests that ageing-related shifts in the composition of the population require substantial increases in the education of young cohorts.

This paper contributes to the literature in multiple ways. Several contributions in macro-development have focused on the consequences of ageing by focusing on the implications of variation in the young- and old-age dependency ratio for the demographic dividend (Bloom and Williamson, 1998; Bloom *et al.*, 2003), and, more recently, Aiyar *et al.* (2016), and Acemoglu and Restrepo (2017) for productivity and technical change. Other contributions have analysed the effects of ageing and skills on growth. Feyrer (2007) finds that the age composition of the workforce affects macroeconomic performance, mainly through total factor productivity (TFP). Maestas *et al.* (2016) use variation in ageing across US states over the period 1980–2010 to estimate the growth effect of ageing and find a substantial negative effect. However, these studies only indirectly account for the changes in human capital and its age composition. In contrast, Cuaresma *et al.* (2014) investigate the joint effect of skills and ageing. Instead of conducting a cohort-based analysis that accounts for the distribution of skills and ageing as we do in this paper, they look at the role of labour force participation and dependency ratios. In contrast, Sunde and Vischer (2015) show that human capital affects output growth through the productivity of production factors and the potential to innovate (Lucas, 1988; Aghion and Howitt, 1992), or to adopt and diffuse new technologies (Nelson and Phelps, 1966). The approach taken in this paper incorporates these different contributions into a single coherent framework. This allows investigating the relative importance of changes in the age composition and in the skill composition of the population, shedding light on the robustness of earlier results. Thereby, we provide a systematic investigation and decomposition of ageing effects through shifts in the demographic composition and changes in the human capital distribution, which is missing in the existing literature. The findings indeed point to interactions between population ageing and changes in the human capital composition, suggesting that restricting attention to only one dimension delivers an incomplete picture.

To our knowledge, the only two papers that go in a similar direction are by Lindh and Malmberg (1999) and Cuaresma *et al.* (2016). However, the analysis by Lindh and Malmberg (1999) is confined to using cross-country data for OECD countries, whereas Cuaresma *et al.* (2016) focus on European countries. Our analysis is based on a theoretically founded empirical framework that encompasses frameworks used previously and presents estimation and projection results for a long panel data set for more than 130 countries. Moreover, the estimates presented below contribute by allowing to conduct counterfactual simulations of economic performance under alternative scenarios of ageing, human capital dynamics, labour force participation, and productivity. Another novelty are the estimates for an upper bound of the semi-elasticity between changes in the age structure and changes in human capital, as well as of changes in labour force participation and productivity improvements, which are required to offset the macroeconomic consequences of the changes in the age composition in the most favourable case.

The analysis is also related to, and complementing, microeconometric work on age–education decompositions of labour earnings. Work by Card and Lemieux (2001) has used models with imperfect substitution between similarly educated workers in different age groups to study the dynamics of the college wage premium. More recent work by Acemoglu and Autor (2011) and Autor and Dorn (2013) shows for census data and tasks how skill-biased technological progress and changes in the supply of skill levels across cohorts has led to wage polarisation in the United States. Vandenberghe (2017) investigates whether a better educated and more experienced workforce contributes to the recent rise in TFP. Our estimation and projection results complement these studies by providing novel insights into the consequences of population ageing and demographic change. In analogy to the approach popularised by Card and Lemieux (2001) and applied by Fitzenberger and Kohn (2006), we develop a decomposition that allows estimating elasticities of substitution between demographic ageing and changes in the education structure. Our empirical findings also complement recent evidence for the effect of ageing on productivity and wages. For instance, Göbel and Zwick (2013) find that productivity among employees is highest around 50 and only find modest declines in the productivity at older ages, while Börsch-Supan and Weiss (2016) find that there are (almost) no negative ageing effects on productivity for production line workers before age 60 years. Complementing this, Mahlberg *et al.* (2013) find little evidence between productivity or wages at the firm level and the share of older employees in that firm. The findings for the aggregate level presented in this paper deliver macroeconomic age profiles that are consistent with these findings.

The quantitative analysis sheds new light on the potential implications of ageing and education dynamics for growth. Recent work by Acemoglu and Restrepo (2017) suggests that directed technical change and a rapid adoption of automation technologies might provide a countervailing force to the negative growth effects of population ageing, particularly in countries that undergo more pronounced demographic changes. Our findings allow quantifying how large, ceteris paribus, the productivity improvements of directed technical change would have to be in different countries in order to fully offset the effects of population ageing and the associated education dynamics.

The remainder of this paper is structured as follows. Section 2 presents our methodology and empirical framework. A data description is provided in Section 3. Section 4 provides estimation results and Section 5 presents the implications of these estimation results for future economic performance, using different scenarios of ageing and education projections. Section 6 concludes.

2. METHODOLOGY

The analysis is based on an aggregate production framework that underlies the standard development accounting model as in Benhabib and Spiegel (1994) and Hall and Jones (1999). Output Y is produced as a function of TFP A, physical capital K, and human capital H of the form:

$$Y_{it} = A_{it} K_{it}^{\alpha} H_{it}^{1-\alpha}. \tag{1}$$

Subscripts i and t denote cross-sectional units (countries) and time units (five-year intervals). Dividing by the labour force (working-age population), L_{it}, delivers the output per worker in intensive form

$$y_{it} = \frac{Y_{it}}{L_{it}} = A_{it} k_{it}^{\alpha} \left(\frac{H_{it}}{L_{it}} \right)^{1-\alpha}$$

with $k_{it} = \frac{K_{it}}{L_{it}}$ being capital per worker.

The aggregate stock of human capital H_{it}, is a function of human capital per worker h_{it} and the overall quality of the labour force Q_{it} as a function of the demographic structure of the workforce and cohort-specific productivity parameters. Quality of the labour force is assumed to be a simple size-weighted average

$$H_{it} := h_{it} Q_{it} = h_{it} \left[\pi_1 L_{it}^1 + \cdots + \pi_k L_{it}^{J} \right], \tag{2}$$

where $L_{it}^1, \ldots, L_{it}^{J}$ denote the labour force of each age cohort in the workforce and $\pi_1, \ldots, \pi_{J}$ the respective productivity of each group. Age-related productivity differences can be related to differences in physical strength, or, more likely, correspond to differences in human capital that is acquired on the job in terms of experience. This is consistent with standard models of human capital acquisition over the life cycle (Ben-Porath, 1967). Moreover, this specification implies that productivity-adjusted labour shares of different age groups are perfectly substitutable, and in the empirical analysis, relative productivity differences across age groups will be estimated and held fixed across countries. This allows us to study the effects of changing supplies of labour in different age (and skill) groups while fixing their relative efficiency.[1] The aggregate human capital stock per worker is thus given by

$$\frac{H_{it}}{L_{it}} = h_{it}\left[\left(\frac{1}{L_{it}}\right)\sum_{j=1}^{J}\pi_j L_{it}^j\right] = h_{it}\left[\sum_{j=1}^{J}\pi_j\frac{L_{it}^j}{L_{it}}\right] = h_{it}\left[\sum_{j=1}^{J}\pi_j S_{it}^j\right]$$

with S^j denoting the share of each age cohort in the total labour force such that $\sum_{j=1}^{J} S_{it}^j = 1$. In order to avoid multicollinearity in the empirical model, a reference category S_{it}^{r} is chosen so that ?

$$\frac{H_{it}}{L_{it}} = h_{it}\pi_{\mathrm{r}}\left[S_{it}^{\mathrm{r}} + \sum_{j\neq \mathrm{r}}\frac{\pi_j}{\pi_{\mathrm{r}}}S_{it}^j\right] = h_{it}\pi_{\mathrm{r}}\left[(1-\sum_{j\neq \mathrm{r}}S_{it}^j) + \sum_{j\neq \mathrm{r}}\frac{\pi_j}{\pi_{\mathrm{r}}}S_{it}^j\right].$$

The aggregate human capital stock per worker is then given by

$$\frac{H_{it}}{L_{it}} = h_{it}\pi_{\mathrm{r}}\left[1 + \sum_{j\neq \mathrm{r}}\lambda^j S_{it}^j\right], \tag{3}$$

with $\lambda^j := \frac{\pi_j}{\pi_{\mathrm{r}}} - 1$ denoting the difference in relative productivity between an age cohort j and the reference category. Inserting the expression for the human capital stock per worker in Equation (3) into the production function in Equation (1) and taking logs yields

1 Analysing the simple case with substitution elasticity of one between physical and human capital and perfect substitution across age cohorts has the advantage of a straightforward derivation of a linear estimation framework. Moreover, the case of perfect substitution appears to be conservative in the present setting; see, for example, the discussion by Caselli and Ciccone (2018). Alternatively, one could model the quality of the labour force more flexibly using a general constant elasticity of substitution (CES) form as in similar settings applied to different contexts; see, for example, Sato (1967), Hellerstein and Neumark (1995), Card and Lemieux (2001), or more recently, Vandenberghe (2017). The CES specification would allow for more flexible substitution patterns between age groups. This assumption is inessential, however, and could be relaxed by working with a CES specification and conducting estimates using a non-linear estimation model.

$$\ln(y_{it}) = \ln(A_{it}) + \alpha \ln(k_{it}) + (1-\alpha)\ln\left(\frac{H_{it}}{L_{it}}\right)$$
$$= \ln(A_{it}) + \alpha \ln(k_{it}) + (1-\alpha)[\ln(h_{it}) + \ln(\pi_{\mathrm{r}})] + (1-\alpha)\ln(1 + \sum_{j\neq \mathrm{r}} \lambda^j S^j_{it}).$$

The last term in parentheses can be expected to be close to unity, since the term for productivity ratios λ^j and the share of each age cohort in the total workforce is close to zero for a sufficiently large number of age groups, and correspondingly also their product. Hence, the last term in logarithms can reasonably be approximated by

$$\ln\left(1 + \sum_{j\neq \mathrm{r}} \lambda^j S^j_{it}\right) \approx \sum_{j\neq \mathrm{r}} \lambda^j S^j_{it}. \tag{4}$$

Human capital per worker $\mathrm{h_{it}}$ is assumed to be a function of an individual worker's skills which can either be high or low. Correspondingly, each skill group is assigned a skill-specific productivity $\{\pi_{\mathrm{h}}, \pi_{\mathrm{l}}\}$. Averaging over the entire economy, human capital per worker is thus the weighted average of the shares of each skill group $\{S^h_{it},\ 1 - S^h_{it}\}$ multiplied by the respective productivity, or formally

$$h_{it} = \pi_{\mathrm{h}} S^h_{it} + \pi_{\mathrm{l}}(1 - S^h_{it}). \tag{5}$$

Taking logs and choosing the low skill group as reference, this expression can be rearranged to

$$\ln(h_{it}) = \ln\left[\pi_{\mathrm{l}}\left(1 + \left(\frac{\pi_{\mathrm{h}}}{\pi_{\mathrm{l}}} - 1\right) S^h_{it}\right)\right],$$

which, using the same arguments as before, can be approximated by

$$\ln(h_{it}) = \ln(\pi_{\mathrm{l}}) + \ln(1 + \lambda^h S^h_{it}) \approx \ln(\pi_{\mathrm{l}}) + \lambda^h S^h_{it} \tag{6}$$

with $\lambda^h := \frac{\pi_{\mathrm{h}}}{\pi_{\mathrm{l}}} - 1$ denoting the difference in relative productivity between high-skilled and low-skilled workers. Log output is thus given by

$$\ln(y_{it}) \approx c + \ln(A_{it}) + \alpha \ln(k_{it}) + (1-\alpha)\lambda^h S^h_{it} + (1-\alpha)\sum_{j\neq \mathrm{r}} \lambda^j S^j_{it}, \tag{7}$$

where $c = (1-\alpha)[\ln(\pi_{\mathrm{l}}) + \ln(\pi_{\mathrm{r}})]$ is a (potentially country-specific) constant. By taking first differences, the model is expressed in terms of growth rates:

$$\Delta\ln(y_{it}) \approx \Delta\ln(A_{it}) + \alpha\Delta\ln(k_{it}) + (1-\alpha)\lambda^h\Delta S_{it}^h + (1-\alpha)\left[\sum_{j\neq r}\lambda^j\Delta S_{it}^j\right]. \quad (8)$$

Because, in practice, TFP is not observed, we model a country's TFP as being determined by three components: An exogenous time trend ζ_t, which represents freely available technology from the world technological frontier in a given period t, allowing for a technology diffusion process across countries; the past level of output, which, by definition, comprises past TFP; and an idiosyncratic error component ϵ_{it}, which serves as the error term for the empirical framework. This modelling assumption for TFP is motivated by the strong correlation between initial productivity, reflected by output per worker, and subsequent growth rates (see, e.g., Baumol, 1986).[2] Lagged output per worker therefore introduces persistence in the availability of technology within countries into the levels specification. This persistence may for example reflect capital-embodied technology that has been accumulated over time. Consequently, we posit that

$$\ln(A_{it}) = \zeta_t + \gamma\ln(y_{it-1}) + \epsilon_{it}. \quad (9)$$

Moreover, this specification implies a further straightforward extension of our estimation framework to long-run productivity differences across countries along other dimensions that might enter Equation (9) as additional control variables (e.g., institutions).

Therefore, the empirical model which is used to estimate the effect of the demographic structure of the workforce and the distribution of skills on output is given by

$$\ln(y_{it}) = \gamma\ln(y_{it-1}) + \alpha\ln(k_{it}) + (1-\alpha)\lambda^h S_{it}^h + (1-\alpha)\left[\sum_{j\neq r}\lambda^j S_{it}^j\right] + c_i + \zeta_t + \epsilon_{it}, \quad (10)$$

where c_i allows for country-specific constants. The model in levels is estimated with the within-transformation to remove the country-specific-fixed effects.

In terms of dynamics, we assume that TFP growth of a country is determined by four components: An exogenous time trend τ_t, which represents growth of freely available technology at the world technological frontier in a given period t, allowing for a technology diffusion process across countries; the economy's share of high skills in period $t-1$, which may facilitate the diffusion and adoption of already existing technologies (Nelson and Phelps, 1966) or foster novel innovation (Aghion and Howitt, 1992; Romer, 1990);

2 In an earlier version of this paper, we also included lagged skills in the levels equation. However, the respective variable was always insignificant in the empirical application and did not quantitatively change the overall effect of skills on output. Hence, the variable has been dropped from the specification.

the past level of output, which, by definition, comprises past TFP; and an idiosyncratic error component u_{it} serving as the error term for the empirical framework.

Consequently, the growth rate of TFP is assumed to take the form

$$\Delta\ln(A_{it}) = \tau_t + \theta S^h_{it-1} + \psi\ln(y_{it-1}) + u_{it}. \qquad (11)$$

This modelling of technological progress again accommodates for the strong correlation between initial productivity and subsequent growth (Baumol, 1986) and has been widely applied in models that study economic growth in general or the demographic dividend in particular (Fagerberg, 1994; Dowrick and Rogers, 2002; Bloom *et al.*, 2004; Cuaresma et al., 2014). Specifically, this modelling assumption implies conditional convergence in productivity across countries. In contrast to other models of conditional convergence such as Mankiw *et al.* (1992), however, this modelling of TFP growth allows for long-run differences in productivity even after the diffusion process is complete. Such differences may enter the estimation model through other variables in Equation (11). Correspondingly, the estimation equation in growth rates is given by

$$\begin{aligned}\Delta\ln(y_{it}) &= \psi\ln(y_{it-1}) + \alpha\Delta\ln(k_{it}) \\ &\quad +(1-\alpha)\lambda^h\Delta S^h_{it} + \theta S^h_{it-1} + (1-\alpha)\left[\sum_{j\neq r}\lambda^j\Delta S^j_{it}\right] + \tau_t + u_{it}.\end{aligned} \qquad (12)$$

Estimating the model in terms of growth rates also accommodates for the possibility of a unit root in the error term, if income follows a random-walk. Correspondingly, the series will be stationary. As will become clear below, coefficient estimates do not differ substantially between both models, but, unsurprisingly, the levels model is more efficient and explains a larger fraction of the variation. Results for both versions of the model are reported in Section 4.

This specification of the estimation framework is very flexible and can be adjusted to obtain the regression models of important other contributions of the literature. For example, the estimation model of Feyrer (2007) is obtained by assuming human capital to be the exponential of a piece-wise linear function of human capital savings and imposing no further assumptions on the structure of TFP growth apart from a common time trend across. Given this set of assumptions, the effect of the demographic structure is contained by TFP.

The specification of Cuaresma *et al.* (2014) can be obtained under the following assumptions: human capital per worker takes an exponential form as described above; GDP is expressed in terms of per capita instead of per worker terms, and the demographic structure of the workforce is neglected. In this case, the demographic structure enters output through the labour force participation rate and the share of the working-age population in the total population.

Finally, the specification of Sunde and Vischer (2015) is derived by assuming that human capital enters both, productivity and output, in logarithms instead of shares.

Further control variables can be included by extending either the TFP residual by lagged level controls or the output by additional terms as a multiplicative or exponential function.

3. DATA

Data for output and physical capital are from Penn World Tables by Feenstra *et al.* (2015). The main dependent variables are log output per worker and the corresponding growth rate. In robustness analysis, we also use output per capita.

Data for the demographic structure are taken from different sources. The primary source of information about the working-age population for age cohorts in five-year intervals from 15 to 69 years as well as for human capital and the corresponding projections is the IIASA–VID database by Lutz *et al.* (2007).[3] We define age cohorts of the workforce as cohort shares of the total working-age population in brackets 15–19 (below 20), 20–24, 25–29, 30–34, 35–39, 40–44, 45–49, 55–59, 60–64, and 65–69 (65+). This reflects the potential workforce of a cohort in a given period in the estimation; that is, we refrain from an adjustment for hours worked or employment shares to avoid endogeneity problems that might bias the estimates. In some specifications, the cohorts are collapsed to ten-year intervals in order to reduce the number of parameters to be estimated. The microeconometric evidence on age-productivity profiles discussed in the 'Introduction' section indicates that the cohort 50–54 represents the most productive cohort. In light of this finding, we take this cohort as the reference group. Different classifications do not affect the results qualitatively. An alternative data source for population counts and human capital by age is Barro and Lee (2013). For this data set, no population projections are available, which is the reason for using the IIASA–VID data as baseline. Alternative population counts and projections as well as young- and old-age dependency ratios are obtained from the United Nations World Population Prospects.[4] Data on life expectancy are obtained from the World Development Indicators provided by the World Bank.[5]

Human capital per worker is proxied by the share of high- and low-skilled individuals in the working-age population. The share of low-skilled workers is defined as the sum of the respective shares of individuals with either no formal education, or primary or secondary schooling only. Correspondingly, the share of high-skilled corresponds to those workers who have received formal tertiary education or equivalent vocational skills. The respective shares are taken from the IIASA–VID database by Lutz *et al.* (2007). As described in Section 2, the share of high-skilled human capital is chosen as reference

3 The IIASA–VID projection data are available at http://www.iiasa.ac.at/web/home/research/researchPrograms/WorldPopulation/Projections_2014.html.

4 Data from UN World Population Prospects are from the 2015 Revision and available at https://esa.un.org/unpd/wpp/Download/Standard/Population/.

5 The data can be retrieved at databank.worldbank.org/wdi.

category. Data are available for up to 139 countries in five-year intervals from 1960 to 2010 (13 time periods in total). Online Appendix Table A1 reports the descriptive statistics.

In the projection analysis, we also make use of data for hours and labour market participation provided by the International Labour Organization (2011).[6] In addition, we use projections for hours and labour market participation for 26 European countries that have been constructed recently by Fürnkranz-Prskawetz *et al.* (2016).

4. ESTIMATION RESULTS

This section reports the estimation results regarding the effect of the age structure and the distribution of skills on economic performance. In the first step, both effects are investigated in isolation, thereby reproducing the analysis conducted in the existing literature. In the second step, we provide evidence for a model that combines both dimensions. The section ends with results from robustness checks and alternative estimation frameworks.

The empirical models are estimated either in levels as in Equation (10) or first differences as proposed in Equation (12). Lagged levels of output per worker and the share of high-skilled workers in the population enter all estimation models in levels to control for convergence dynamics of output and technological diffusion. If not stated otherwise, specifications are estimated for a baseline panel of 120 countries in five-year intervals for the time period 1950–2010.[7]

4.1. Demographic structure

Estimation results for the effect of the age structure of the workforce on output are reported in Column (1) of Table 1 for the model in levels. The reference age group in the levels model is the cohort aged 50–54 years. The results are obtained from a specification of the estimation framework with country-fixed effects, period-fixed effects, and controls for lagged output per worker and capital per worker.

The results reveal that all coefficients for the cohort-specific workforce shares are negative and significant. Therefore, shifting population mass out of the reference cohort 50–54 into another cohort implies a negative effect on output. This effect is particularly pronounced for a relative increase of the population group aged 60–64 years, revealing a negative effect due to population ageing. An increase in the population share of this cohort by one percentage point at the cost of the reference group of age 50–54 implies a decrease in output per worker of roughly 5.5%. Population shifts of such size are no

6 The data can be obtained online at https://www.ilo.org/ilostat.

7 The robustness material contains results for 139 countries when using alternative data sources.

Table 1. Effects of ageing and education on economic performance: levels model

	Demography (1)	Skills (2)	Demography and Skills (3)	Bias correction (4)	Demography instrumented (5)	Skills instrumented (6)	Both instrumented (7)
Share <20	−3.84***		−3.06**	−3.05**	−3.64***	−2.09*	−2.53**
	(1.22)		(1.21)	(1.31)	(1.21)	(1.20)	(1.18)
Share 20–24	−2.37**		−1.84*	−1.82	−3.23**	−1.16	−2.58*
	(1.10)		(1.10)	(1.41)	(1.37)	(1.11)	(1.36)
Share 25–29	−3.56**		−3.12**	−3.18*	−2.77*	−2.58*	−2.30
	(1.42)		(1.39)	(1.65)	(1.47)	(1.32)	(1.41)
Share 30–34	−3.06**		−2.74**	−2.74*	−3.96***	−2.33*	−3.61**
	(1.27)		(1.25)	(1.65)	(1.43)	(1.21)	(1.41)
Share 35–39	−4.01***		−3.71**	−3.63**	−2.97*	−3.33**	−2.49*
	(1.44)		(1.43)	(1.74)	(1.57)	(1.39)	(1.51)
Share 40–44	−1.53		−1.35	−1.37	−1.87	−1.12	−1.81
	(1.32)		(1.29)	(1.47)	(1.41)	(1.26)	(1.39)
Share 45–49	−3.19**		−3.07**	−3.31	−3.98**	−2.92**	−3.89**
	(1.43)		(1.41)	(2.14)	(1.55)	(1.37)	(1.51)
Share 55–59	−4.66**		−4.37**	−4.76**	−4.40**	−4.00**	−4.16**
	(1.85)		(1.81)	(2.14)	(1.82)	(1.74)	(1.77)
Share 60–64	−5.48***		−5.50***	−5.96***	−6.06***	−5.53***	−6.33***
	(1.37)		(1.34)	(1.69)	(1.50)	(1.30)	(1.48)
Share 65+	−3.06*		−3.24**	−3.35**	−4.21***	−3.47**	−4.22**
	(1.58)		(1.55)	(1.64)	(1.62)	(1.56)	(1.68)
Share high-skill		0.97***	1.08***	0.85**	0.84**	2.45***	2.35***
		(0.34)	(0.40)	(0.33)	(0.41)	(0.76)	(0.77)
Output p.w. (t–1)	0.50***	0.48***	0.48***	0.59***	0.48***	0.46***	0.46***
	(0.04)	(0.05)	(0.05)	(0.04)	(0.05)	(0.05)	(0.05)
Capital p.w.	0.32***	0.33***	0.33***	0.29***	0.33***	0.35***	0.34***
	(0.05)	(0.04)	(0.05)	(0.02)	(0.05)	(0.05)	(0.05)
Cohort shares (p-value)	0.01		0.01	0.00	0.01	0.00	0.00
Skill share (p-value)		0.00	0.01	0.01	0.04	0.00	0.00
First-stage F-statistic					13.3	27.9	4.5
Hansen test (p-value)					–	0.25	0.28
Countries	120	120	120	120	120	120	120
Observations	1,098	1,098	1,098	1,053	1,098	1,098	1,098
R^2	0.86	0.86	0.87		0.87	0.86	0.86

Notes: This table reports results for demographic and human capital data by IIASA-VID (Lutz *et al.*, 2007). The dependent variable is log output per worker. All regressions include country-specific fixed and time effects. Lagged output p.w. and capital p.w., measured in logarithms, are included as controls in all specifications. Column (4) corrects for the dynamic-panel bias using the Bruno (2005) estimator. The p-value for a Wald test whether coefficients of workforce shares (proxied by the working-age population) or high-skill shares are jointly different from zero are reported. Instruments are shifted age cohorts in Column (5), the lagged shares of high skills of cohorts at the edge of the working-age population in Column (6), and a combination of both in Column (7). See Online Appendix Figure A3 for an illustration. First-stage F-statistic reports the first-stage Kleibergen-Paap rk Wald F-statistic. Hansen test p-values refer to the robust overidentifying restriction test. Standard errors are clustered at the country level. Asterisks indicate significance levels.
*$p < 0.1$. **$p < 0.05$. ***$p < 0.01$.

exception in the data. Across all workforce shares, around 25% of all out-shifts of a cohort are roughly equal to a unit percentage point shift or even larger. The same pattern holds for 25% of all in-shifts into a cohort. Furthermore, the estimated negative point estimates are largest for the age cohorts that are either at the very beginning or at the end of their work lives. These patterns are consistent with estimates from disaggregate data mentioned in the 'Introduction' section, which suggest that productivity is high for individuals around age 50 years, when they have acquired sufficient work experience and on-the-job training. In particular, the results are also in line with a hump-shaped pattern as predicted by standard human capital theory over the life cycle (Ben-Porath, 1967): For middle-aged cohorts, additional productivity gains become smaller as the marginal return from more experience decreases and ultimately declines to zero as the benefits of additional education investments deteriorate with the lower amortization period. At some point, the depreciation rate of human capital outweighs additional gains by experience such that individual productivity decreases in many cases towards the end of the work life. Taken together, the results largely confirm earlier micro-level findings on the effects of population ageing (e.g., Göbel and Zwick, 2013). Moreover, the joint Wald test on the coefficients of all workforce shares confirms that the overall demographic structure plays a significant role for output.

Table 2 Column (1) contains the corresponding results for the model in (log) differences. To be consistent with the levels model, the differences model uses the change in the age cohort aged 50–54 years as reference category. The results essentially replicate those obtained for the levels model qualitatively and quantitatively. In particular, the age pattern and the importance of heterogeneity in the effect of changes in the age composition of the workforce on output growth are very similar. The results also show that the estimated coefficient for lagged output per worker is positive and smaller than one in the levels model, and negative in the model in differences, providing evidence for the usual conditional convergence patterns.[8] The estimated values for the capital income share α is 0.32 for the specification in Column (1) of Table 1 and 0.40 for the specification in Column (1) of Table 2.

The results in the differences specification closely resemble the empirical specifications estimated by Feyrer (2007) and reproduce his results for a different data set.[9]

4.2. Human capital and distribution of skills

As a next step, the analysis focuses on the role of the effect of human capital and the distribution of skills on economic performance. Column (2) of Table 1 presents the corresponding estimates for a specification that only includes the share of high-skilled in addition to lagged output and capital per worker. The point estimate of the share of individuals with high-skilled human capital is positive and highly significant. A one

8 The bias in coefficient estimates in specifications with lagged dependent variable and fixed effects should be moderate in a relatively long panel with 13 time periods, see Nickell (1981) and Judson and Owen (1999); see also the discussion in Section 4.4.

9 In particular, Feyrer (2007) also finds point estimates that are negative relative to the relatively most productive age cohort. The point estimates are qualitatively very similar to the results for empirical specification proposed in this paper and quantitatively slightly smaller.

Table 2. Effects of ageing and education on economic performance: differences model

	Demography (1)	Skills (2)	Demography and skills (3)	Bias correction (4)	Demography instrumented (5)	Skills instrumented (6)	Both instrumented (7)
Δ Share <20	−3.68***		−2.83**	−1.24	−4.23***	−3.35***	−5.22***
	(1.16)		(1.19)	(1.13)	(1.36)	(1.26)	(1.81)
Δ Share 20–24	−3.03***		−2.05**	−1.35	−4.03***	−2.54**	−4.91***
	(1.01)		(1.02)	(0.98)	(1.27)	(1.12)	(1.48)
Δ Share 25–29	−3.47***		−2.78**	−1.70	−4.34***	−3.12***	−4.91***
	(1.15)		(1.15)	(1.13)	(1.51)	(1.20)	(1.74)
Δ Share 30–34	−3.92***		−3.41***	−2.48**	−4.10**	−3.15***	−4.20**
	(1.13)		(1.14)	(1.15)	(1.76)	(1.11)	(1.89)
Δ Share 35–39	−4.97***		−4.58***	−3.75***	−4.44***	−4.89***	−4.29***
	(1.22)		(1.23)	(1.20)	(1.50)	(1.37)	(1.56)
Δ Share 40–44	−2.56**		−2.33**	−1.12	−2.70**	−2.36**	−2.60**
	(1.10)		(1.06)	(0.94)	(1.16)	(1.11)	(1.21)
Δ Share 45–49	−3.08***		−2.93***	−1.60*	−4.09***	−2.92***	−4.21***
	(1.12)		(1.09)	(0.94)	(1.19)	(1.09)	(1.24)
Δ Share 55–59	−2.35**		−2.17**	−1.01	−2.65***	−2.28**	−3.13***
	(0.96)		(0.95)	(0.97)	(1.01)	(1.00)	(1.12)
Δ Share 60–64	−5.26***		−5.14***	−3.08***	−5.63***	−5.29***	−6.25***
	(1.20)		(1.20)	(1.06)	(1.41)	(1.29)	(1.57)
Δ Share 65+	−6.61***		−6.22***	−1.71	−6.32***	−6.49***	−6.93***
	(1.67)		(1.64)	(1.43)	(1.80)	(1.70)	(1.99)
Δ Share high-skill		2.68**	3.30***	1.21	1.87	0.64	−3.09
		(1.07)	(1.15)	(0.87)	(1.16)	(4.23)	(4.75)
Share high-skill (*t*–1)		0.67***	0.55**	0.42***	0.55*	0.71*	0.83**
		(0.24)	(0.25)	(0.15)	(0.33)	(0.37)	(0.41)
Output p.w. (*t*–1)	−0.21***	−0.24***	−0.23***	−0.02***	−0.24***	−0.24***	−0.23***
	(0.03)	(0.03)	(0.03)	(0.01)	(0.03)	(0.03)	(0.03)
Δ Capital p.w.	0.40***	0.39***	0.41***	0.43***	0.40***	0.41***	0.40***
	(0.06)	(0.06)	(0.06)	(0.05)	(0.06)	(0.06)	(0.06)
Cohort shares (*p*-value)	0.01		0.01	0.01	0.00	0.00	0.00
Skills shares (*p*-value)		0.00	0.00	0.00	0.05	0.01	0.11
First-stage *F*-statistic					8.5	52.1	5.9
AR(2) test (*p*-value)				0.65			
Hansen test (*p*-value)				0.33	—	0.45	0.50
Countries	120	120	120	120	120	120	120
Observations	1,098	1,098	1,098	978	1,053	1,053	1,053
R^2	0.42	0.39	0.43		0.42	0.43	0.40

Notes: This table reports results for demographic and human capital data by IIASA-VID (Lutz *et al.*, 2007). The dependent variable is the log difference in output per worker. All regressions include country-specific fixed and time effects. Lagged output p.w. and capital p.w., measured in logarithms, are included as controls in all specifications. Column (4) corrects for the dynamic-panel bias using the system GMM estimator by Arellano and Bover (1995) and Blundell and Bond (1998). The *p*-value for a Wald test whether coefficients of workforce shares (proxied by the working-age population) or high-skill shares are jointly different from zero are reported. Instruments are shifted age cohorts in Column (5), the lagged shares of high skills of cohorts at the edge of the working-age population in Column (6), and a combination of both in Column (7). See Online Appendix Figure A3 for an illustration. First-stage *F*-statistic reports the first-stage Kleibergen-Paap rk Wald *F*-statistic. Hansen test *p*-values refer to the robust overidentifying restriction test. For system GMM, also the *p*-values of the AR(2) test are reported. Standard errors are clustered at the country level. Asterisks indicate significance levels.
$^*p < 0.1$. $^{**}p < 0.05$. $^{***}p < 0.01$.

percentage point increase in the share of high skilled of in an economy is accompanied by an increase in output of 0.97%.

Column (2) of Table 2 presents the corresponding results for a specification in differences. This specification also accounts for the possibility that, conceptually, human capital influences output (growth) through two channels. First, changes in the share of skills account for composition effects of productions factors, which can be accrued to the complementarity of human and physical capital in standard growth models (Solow, 1956; Lucas, 1988). Second, the accumulation of human capital may alleviate the diffusion and adoption of already existing technologies (Nelson and Phelps, 1966) or spur innovation as in the endogenous growth literature (Romer, 1990; Aghion and Howitt, 1992). Not accounting for both channels might lead to a potential bias in the estimates due to the omission of one relevant channel from the estimation, as indicated by the results of Sunde and Vischer (2015). The results provide evidence supporting the specification with both levels and changes of human capital, as suggested by the work of Sunde and Vischer (2015). Both point estimates of levels and changes in the share of high-skilled human capital are positive and individually and jointly significant.[10]

Quantitatively, the results imply that a one percentage point larger share of skilled workers in the economy is accompanied by a 0.67% increase in growth of output per worker over a five-year period. In light of the literature, this effect works through innovation as well as diffusion and adoption of new technologies. Growth of one percentage point in the share of high-skilled implies an increase in the growth rate of 2.68% over five years. The coefficient for lagged output per worker takes negative values for the differences model, indicating conditional convergence, and the coefficient of the capital income share is similar to the previous results.

4.3. Considering demographics and skills in combination

While the results so far have successfully reproduced the findings in the existing literature, the specifications have considered the demographic structure and the influence of human capital in isolation. However, in view of the possibility that the age structure and the human capital composition of the population are correlated and both influence

10 The specification of the model in levels, which follows from Equation (10), does not contain a term involving the change in the share of high-skilled in the population, because this term emerges from the dynamics of TFP. In unreported estimations, we nevertheless included changes in the share of high-skilled individuals in the specification of the empirical model of the levels estimation to estimate a symmetric empirical specification in both levels and differences and obtain directly comparable estimates of the coefficients of interest. Moreover, this specification provides a natural specification test, because the coefficient of the change in the skill share is hypothesised to be zero in light of the theoretical model (10). The findings suggest that the coefficient is indeed not significantly different from zero in an extended version of the specification in Column (2) of Table 1, which indirectly supports the empirical model. The estimation results are qualitatively and quantitatively almost identical when estimating a specification of the levels model that does additionally include the change in the share skilled, see Online Appendix Table A2 for details.

macroeconomic performance, the estimates might suffer from omitted-variable bias. In order to investigate this possibility and potential interactions, we now proceed to estimate more comprehensive models that account for both the demographic structure of the workforce and the distribution of skills in the population.

Columns (3) of Tables 1 and 2 present the estimation results for such an extended specification. The coefficient estimates for the age structure and human capital are qualitatively similar, indicating that both dimensions affect macroeconomic performance. In the levels model, the skill pattern appears to exhibit slightly smaller coefficient estimates than in the specification without human capital, while the human capital effect is slightly larger than in the specification without controlling for the age structure. The same is true for the differences model, with the exception of the effect of the share of high-skilled individuals in levels, whose coefficient is also slightly smaller than in Column (2).

Figure 3 provides a graphical representation of the estimates of the coefficients for the different age shares obtained with (a) the levels model and (b) the model in differences. Panels (c) and (d) reproduce the respective productivity profiles for an alternative specification using ten-year instead of five-year age cohorts. The graphs illustrate that the age-related coefficients are somewhat smaller in absolute terms for the differences model but otherwise very comparable. Hence, an increase in the share of a specific age cohort relative to the 50- to 54-year-olds leads to a reduction in output. Moreover, the skill distribution positively affects macroeconomic performance through its level and change, which is consistent with the innovation and adoption of technology as well as the composition of production factors. Most importantly, demographic structure of the workforce and human capital both jointly affect output. Therefore, both channels are conceptually relevant for themselves even if they interact substantially.

4.4. Alternative estimation and identification strategies

The estimation results presented so far, in particular in the levels specification, were based on a two-way-fixed effects estimator with a lagged dependent variable (log output per worker) as additional regressor. Consequently, the coefficient estimates, in particular for the lagged dependent variable might be biased, see Nickell (1981). To investigate whether this might be an issue for the coefficients of interest, Columns (4) of Tables 1 and 2 present the corresponding results obtained with an estimator that corrects for the potential bias in dynamic panels.[11] The estimation results are qualitatively and quantitatively very similar for the levels model, whereas they reflect some quantitative differences in the differences specification. Alternative estimation results obtained with a levels

11 In the levels model the bias correction is implemented via the corrected fixed effects estimator of Bruno (2005). To be internally consistent with the theoretical model outlined in Section 2, the bias correction in the differences model is performed using the system GMM estimator of Arellano and Bover (1995) and Blundell and Bond (1998).

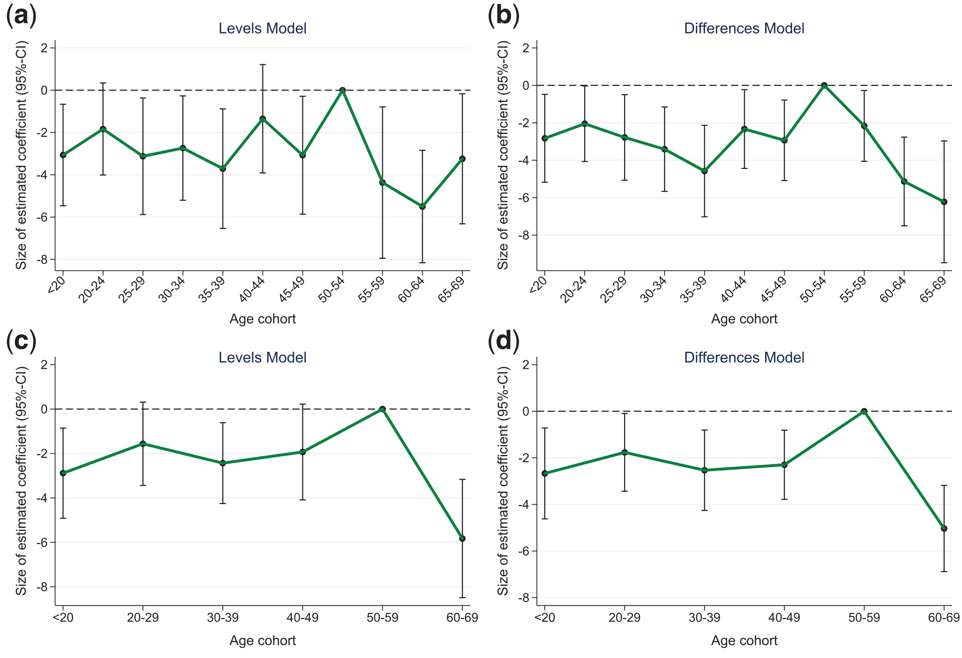

Figure 3. Macro productivity profiles

(a) Five-year cohorts (Table 1, Column 3)

(b) Five-year cohorts (Table 2, Column 3)

(c) Ten-year cohorts (Table A7, Column 3)

(d) Ten-year cohorts (Table A8, Column 3)

model without lagged dependent variable also deliver qualitatively similar results.[12] The simulation results shown below will be based mainly on the levels model.

Another potential concern is identification and endogeneity. The identification of the coefficients for ageing and human capital so far was based on the implicit assumption that the current workforce (in terms of age structure and skill composition) is the result of fertility and education decisions in the past. Controlling for past income, capital, and country-specific intercepts related to productivity and other time-invariant factors account for country-specific differences in economic performance that might influence, or correlate with, the age and skill composition. Additionally, the results implicitly correspond to an intention-to-treat interpretation, where population shares reflect the potential size of the workforce of each age cohort, instead of accounting for the actual

12 See Online Appendix Table A3. Due to the omission of the lagged dependent variable, the human capital variable picks up some of the persistence, with the consequence of slightly larger coefficient estimates for human capital obtained with this specification. In the following, we restrict attention to the model with lagged dependent variable, which delivers results for the role of human capital that are more conservative in this respect.

workforce, which might be affected by endogenous labour supply decisions at the extensive or intensive margin, and thus give rise to endogeneity concerns. The estimates thus implicitly assume changes in the workforce be arguably exogenous given the lagged dependent variable, country-fixed effects, and period-fixed effects. The finding of similar results in the levels and differences models is reassuring in this regard since similar estimates for the respective coefficients are obtained despite the use of alternative variation for identification.

Nonetheless, in order to probe further into potential identification problems caused by unobserved variables that correlate with the factors of production and thus lead to problems of endogeneity bias, we present the results from three alternative identification approaches based on instrumental variables (IVs).

A first alternative way to obtain identification is to exploit the fact that the demographic structure of the working-age population follows very stable and predictable dynamics. Concretely, a cohort of individuals aged 40 years at a particular point in time will be of age 50 years ten years later. The same is approximately true for the age composition, because the relative sizes of cohorts of different ages are unlikely to change over time and thus provide valuable predictors over long periods of time. Simultaneously, however, lagged age shares satisfy the exclusion restriction of an instrument, which stipulates that they must be unrelated to unobserved factors driving macroeconomic performance some decades into the future. Hence, demographic dynamics lend themselves naturally to an IVs approach in the present setting of panel data.

On the basis of these considerations, the IV strategy exploits the fact that the relative size of particular cohorts at some point in time predicts these cohorts' size in the future. At the same time, it is unaffected by economic performance in the future and thus exogenous for the purpose of the estimation framework applied here. For a given country-period-cohort cell, this is plausibly the case, in particular, once conditioning on the lagged dependent variable and country-fixed effects. The share of the working-age population of a particular cohort, for instance the 25- to 29-year-olds in 1990, is instrumented using the respective share of this cohort in 1985, when it was the cohort of 20- to 24-year-olds, using the corresponding lag structure. Additional identification is obtained by exploiting that the shares of the youngest cohorts of working-age adults are instrumented by shares of cohorts that were not even in the labour force, and by using cohorts that have already left the labour force when the outcome variables are realized. Panels (a) and (b) of Online Appendix Figure A3 illustrate this identification strategy.[13]

Columns (5) of Tables 1 and 2 present the second-stage results from two-stage least squares (2SLS) estimations using this instrumentation strategy for the age shares in the corresponding specifications (in levels or differences). The first stage is sufficiently strong, as indicated by the respective *F*-statistics. The coefficients in the outcome equation

13 Moreover, the figure illustrates that this IVs approach can be applied regardless of whether the data are coded in five-year or than ten-year cohorts.

closely resemble those obtained from standard panel estimation techniques, however. In particular, the overall patterns remain unchanged.

A similar identification strategy can be applied to the share of high-skilled individuals (or its change). The logic here is that the formal (tertiary or vocational) education attained by a given cohort is unlikely to change over the range of five or ten years. At the same time, using the lagged shares provides variation that is less likely to be affected by (or correlated with) contemporaneous macroeconomic performance, conditional on the full set of controls. The variation in the share of high-skilled over the course of five or ten years primarily depends on the education of young individuals entering the labour force and of the old individuals leaving the labour force. We therefore use the lagged skill shares in these respective age cohorts as instruments. The logic of this identification approach is illustrated in Panels (c) and (d) of Online Appendix Figure A3.[14] Columns (6) of Tables 1 and 2 present the corresponding results for the second stage of the 2SLS framework applied to human capital. Again, the first stage is strong as expected. The estimates for the outcome equation are qualitatively identical and quantitatively somewhat larger for human capital than those obtained with the baseline estimation approach, whereas the coefficient estimates for the age shares are somewhat smaller.[15] Again, this suggests that endogeneity bias appears not to be a serious concern for the qualitative patterns.

Columns (7) of Tables 1 and 2 present the corresponding results for the second stage of the 2SLS framework applied to both the age structure and human capital. Again, the overall pattern is very similar.

4.5. Robustness and further results

In order to investigate the robustness of these results, we conducted several additional checks.

A first robustness check concerns the estimation of the same model using an alternative data set for the age composition and human capital endowment provided by Barro and Lee (2013). The corresponding results reveal very similar estimation results.[16]

14 Notice that this additional instrumentation strategy provides the possibility of conducting overidentification tests, as there are more instruments than instrumented variables.

15 One potential caveat with the instrumentation approach of human capital could be that the education composition of the share of the young entering the labour force might reflect anticipated macroeconomic performance, and thus pose a potential problem of endogeneity, while this is unlikely for the cohort leaving the labour force. In additional robustness checks, we therefore applied an alternative identification that only uses the education composition of the cohort that exits the labour force, paralleling the approach popularized by Acemoglu and Johnson (2007) by implicitly assuming that all newly entering cohorts are high skilled. The results are qualitatively similar, see Online Appendix Table A4.

16 See Online Appendix Tables A5 and A6 for detailed estimation results and Online Appendix Figure A4 for the corresponding estimated age-productivity profiles.

A second robustness check concerns the possibility of overfitting and multicollinearity by using data at the level of five-year age cohorts. Estimation results obtained with data for ten-year age cohorts deliver qualitatively and quantitatively similar results for the effects of the age structure of the population, and even slightly larger coefficient estimates for human capital.[17] The same holds when restricting the specification to only four or three age cohorts.[18]

As third robustness check, we considered an alternative coding of the human capital composition by considering the average years of schooling, while allowing for a more flexible specification. The results confirm the previous findings, both regarding the age profile as well as regarding the relevance of the share of high-skilled individuals with at least secondary education.[19]

.Another robustness check refers to the use of income (output) per capita instead of output per worker as a variable of main interest. While output per worker captures the notion of productivity and macroeconomic performance from the perspective of the production process, income per capita might be seen as more relevant from a policy perspective. The results are essentially the same for income per capita.[20]

Results obtained with an extended specification that also accounts for the age-related change in skills by incorporating cohort-specific information on the share of skilled individuals are also similar. In particular, these estimates only provide weak evidence for differences in the effect of the share of high-skilled individuals across different age cohorts when controlling for cohort-specific skill shares. At the same time, the qualitative and quantitative results for the effects of the demographic age structure as such remain largely unaffected.[21]

To some extent, these findings shed new light on the results of Cuaresma *et al.* (2014), who conclude, based on an analysis that uses a comparable data set, that the demographic dividend is mostly the byproduct of increases in education. Whereas Cuaresma *et al.* (2014) do not specifically control for the cohort-based demographic structure but instead for labour force participation and the relative size of the working-age population to total population (i.e., the inverse of the dependency ratio), the findings here suggest

17 Detailed results are reported in Online Appendix Tables A7 and A8. Panels (c) and (d) of Figure 3 show the corresponding productivity profiles obtained with ten-year panel data.

18 See Online Appendix Figure A5.

19 Detailed results can be found in Online Appendix Table A9.

20 Notice that the estimation equation for income per capita can also be directly derived from the conceptual framework. This requires defining the sizes of the age groups as shares of the total population (rather than of the working-age population) and controlling for the (young- and old-age) dependency ratio. The respective results are displayed in Online Appendix Table A10. The corresponding productivity profiles are displayed in Online Appendix Figure A6.

21 See the results in Online Appendix Tables A11 and A12 for details.

that the age structure might have an independent effect from the human capital endowment.[22]

Instead of considering the age composition of the workforce, the previous literature has focused on the old-age dependency ratio. Additional results suggest that adding the dependency ratio as well as the size of the working-age population (in logs or in absolute numbers) as further control variables leaves the results essentially unaffected.[23] This suggests that the role of ageing for macroeconomic performance does not predominantly work through population size or the share of elderly but through the age composition of the workforce. Consequently, a main economic implication of low fertility in the aftermath of the demographic transition appears to be population ageing rather than a shrinking (or reduced growth) of the population at large. This issue will be discussed in more detail in the simulations below.

Controlling for life expectancy also leaves the main results unaffected.[24] Using average years of schooling instead of the population share with a high-skilled education delivers similar results for the role of the age structure but no significant effect for human capital in terms of average years of schooling.[25] This result potentially reflects the fact that skill shares provide a more appropriate measure of the skill endowment than the use of average years of schooling.[26]

Note that controlling for the dependency ratio, the size of the working-age population, and life expectancy at birth accounts for variation in fertility, health, and longevity across countries and over time. Controlling for these variables might lead to endogeneity concerns, if economic development unfolds a feedback mechanism on either of these dimensions in the long run and, at the same time, the corresponding variables correlate with the age structure or with education. If selection on observables is informative for selection on unobservables, the stability of parameter estimates across specifications with additional controls suggests that the bias is limited.[27] Hence, it is reassuring that including further control variables does not considerably affect the quantitative and qualitative results compared with our baseline specification.

22 Moreover, the analysis of Cuaresma *et al.* (2014) accounts for variation in labour force participation rates, which might be driven partly by cyclical phenomena instead of long-run trends, imposing problems for identification. As indicated before, the effects of the demographic structure presented here correspond to intention-to-treat effects, which are likely to provide a lower bound of the actual effect under the assumption of relatively stable participation patterns.

23 See Online Appendix Tables A13–A15 for detailed results.

24 See Online Appendix Table A16 for details.

25 See Online Appendix Table A17 for details.

26 See, for example, Hanushek and Woessmann (2012).

27 Moreover, the coefficient estimates across the different specifications are very similar, while the variation explained is fairly comparable, indicating that selection and endogeneity concerns should be limited, following arguments in the spirit of Altonji *et al.* (2005) and Oster (2017).

4.6. Education to counteract the effects of ageing?

Instead of relying on qualitative assessments of the implications of population ageing and education dynamics, the estimation framework and the corresponding estimates also allow to go one step further in the quantification of the increase in education that is needed to offset the effects of population on economic performance. In particular, the framework provides the possibility to estimate an elasticity of substitution between changes in the age structure and changes in the human capital structure of the economy that is needed to keep output per worker constant. An upper bound for this skills-ageing elasticity in the levels model is given by

$$\eta^j_{\max} = \frac{(1-\hat{\alpha})\hat{\lambda}^j}{(1-\hat{\alpha})\hat{\lambda}^h} = \frac{\hat{\lambda}^j}{\hat{\lambda}^h} < 0. \tag{13}$$

In the differences model, the elasticity takes the form

$$\eta^j_{\max} = \frac{(1-\hat{\alpha})\hat{\lambda}^j}{(1-\hat{\alpha})\hat{\lambda}^h + \hat{\theta}} < 0. \tag{14}$$

The corresponding parameters are the structural estimates of the empirical model in Equation (10) or (12). Because the elasticity depends on the level of schooling in the previous period and changes in the current skill distribution, an increase in the share of skills in the same period can only work through the composition channel (i.e., the denominator is $(1-\hat{\alpha})\hat{\lambda}^h$ in this case). In the following period, the skills-ageing elasticity is given by the expression in Equation (13) corrected for additional changes in the distribution of skills, which are again weighted by $(1-\hat{\alpha})\hat{\lambda}^h$. Since the denominator is positive and the cohort effects of the demographic structure are negative as long as the most productive cohort is chosen as reference group, the elasticity will always exhibit a negative sign. Hence, the elasticity is largest, when the denominator is maximized. This is the case when the share of high-skilled workers in the population increases over at least two consecutive periods and no human capital is lost due to retirement or emigration in the working-age population. Consequently, η^j cannot be greater than the expression stated in Equation (13). In fact, it is lower whenever the gains in human capital are eroded. Thus, $\eta^j_{\max}$ represents an upper bound for the skills-ageing elasticity. Moreover, this upper bound has a natural interpretation in that it is the most favourable scenario under which negative feedback from changes in the demographic structure on output can be compensated.

The elasticity can be computed for each age group. For example, suppose an ageing society, where a large fraction of the workforce (the baby boomer cohorts) shift out of the most productive group of the 50- to 54-year-olds into the less productive group of the 60- to 64-year-olds. Columns (3) of Tables 1 and 2 then provide upper bounds for the skills-ageing elasticity of $\eta^{60-64}_{\max} = -\frac{5.50}{1.08} \approx -5.09$ and $\eta^{60-64}_{\max} = -\frac{5.14}{3.30+0.55} \approx -1.34$. Assuming constant returns to schooling, the share of high-skill workers would thus have to increase by 1.34–5.09 percentage points in order to offset a one percentage point shift out of the cohort 50–54 into the cohort 60–64. However, because schooling takes place mostly at a young age, it is unrealistic to increase the human capital of older workers by more than a small extent. Changes in the skill distribution must therefore come mostly through young cohorts. This is particularly problematic if young cohorts are small in size relative to the cohorts approaching retirement, such as in the case of the baby boomer generation. Therefore, even in the presence of large human capital increases, the demographic structure unfolds a forceful effect on macroeconomic performance. This may also be one of the reasons why large-scale extensions of schooling in developing countries in the context of the demographic transition (and the decline in fertility) were not associated by a strong development boost.[28]

However, as discussed in Section 4.5, a richer specification that considers the education composition of different age cohorts of the working-age population (age 15–69 years) delivers little evidence for a strong and systematic role of the skill distribution across age groups for output. The corresponding estimates are insignificant in most cases. Also, the Wald test for joint significance of the estimated parameter sets fails to reject that estimates are jointly different from zero in many cases.[29] Hence, we find little evidence for the obsolescence of high-skilled education embodied in older generations.

5. IMPLICATIONS FOR FUTURE ECONOMIC PERFORMANCE

By and large, the estimation results reveal a relevant role of demographic dynamics in terms of ageing as well as in terms of changes in the human capital embodied in the working population, for economic development. At the same time, the heterogeneity across subsamples indicates that ageing might not affect all countries in the same way. In particular, countries with a relatively old population, and with an ongoing ageing process, appear to be affected most by the adverse effects of ageing.

In order to obtain a more coherent picture of these patterns, and gain some understanding of the relative importance of human capital in offsetting the effects of population ageing, this section presents the results of simulations of economic performance based on the baseline estimates of the previous section, and several alternative scenarios regarding ageing and human capital dynamics.

28 Another reason may be that schooling quality is generally low. For more information see, for example, Hanushek and Woessmann (2008).

29 In order to further test whether there might be an interplay between the demographic structure of the workforce and the distribution of skills, interacted models can be estimated. This allows to test the null hypothesis whether the effect of the demographic structure is stronger (or weaker) the larger the share of high-skilled workers in the population is. However, there is only weak evidence that this is the case (results not shown).

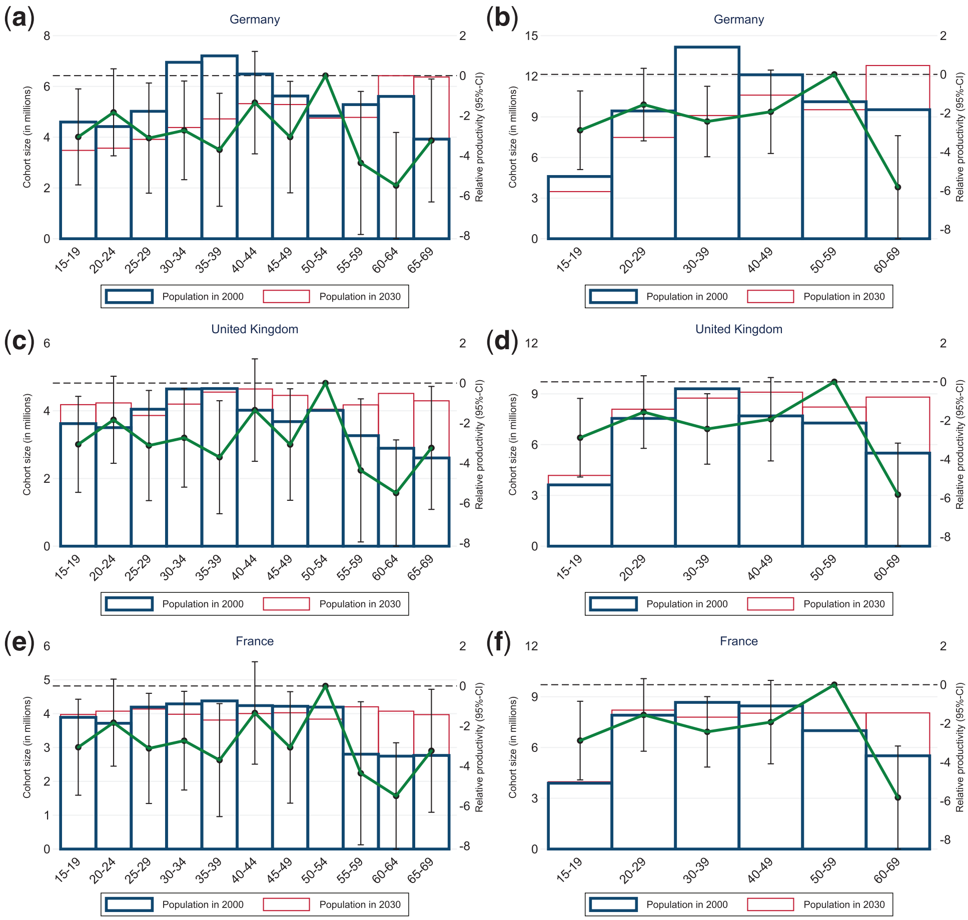

Figure 4. Macro productivity profiles and demographic change for selected countries

(a) Germany (five-years cohorts)

(b) Germany (ten-year cohorts)

(c) United Kingdom (five-years cohorts)

(d) United Kingdom (ten-year cohorts)

(e) France (five-years cohorts)

(f) France (ten-year cohorts)

5.1. Projecting the effects of ageing and education on future performance

While ageing appears to be a process that is hard, if not impossible, to influence in the short and medium run, the skill composition of the population is a possible dimension through which policy might try to influence the economic prospects of a country. This raises the question about the relative importance of population ageing and changes in the skill composition, and about the likely scenarios faced by countries with different age and skill compositions of their populations.

To illustrate the usefulness of the methodology developed in this paper for addressing these questions, consider Figure 4, which contrasts the coefficient estimates for the age structure obtained with specifications for five-year and ten-year age cohorts, with the projected change in the age structure for Germany, the United Kingdom, and France. Taking the age-profile of coefficients as a stable world average, the predicted economic performance will differ only because of heterogeneous ageing patterns across countries. This is illustrated by the different age structures in Germany, the United Kingdom, and France. Similarly, one can use projections of the human capital composition for the two countries to compute the predicted performance due to the changes in this dimension.

In the following, we use the estimates to conduct counterfactual experiments to infer the relative importance of ageing and changes in the skill composition of the population for future economic development. To this end, we use available projections of the prospective age and skill composition of the population. These projections can be conducted under several scenarios. The baseline scenario is to use the estimates to obtain an estimate of output per worker (or its growth rate) by inserting population projections in terms of age and skill structure and compute output as in Equation (10) over the period over which projections for age structure and skill composition are available. This scenario uses all information about the evolution of the economy and thus provides a best practice projection.

As a consistency check for this methodology, we conducted two in-sample prediction experiments. First, we used the estimates obtained from the entire sample 1950–2000 to project economic performance until 2010, based on the actual observations for the changes in the age structure and in the skill share between 2000 and 2010. The results suggest that the model is able to track development rather well, with the exception that unpredictable events such as the global financial crisis of 2007/2008 imply deviations of the model projections from the actual data.[30] Second, we estimated the model on the full sample of countries over the period 1950–2010, but excluding data for France and Germany for the period 1970–2010, and then used these estimates applying the same methodology as in the main analysis to project log GDP per worker for France and Germany for the leave-out period 1970–2010. These estimates demonstrate the model's ability to project economic development even over long periods exclusively relying on demographic variation.[31]

As a first alternative scenario, we use only the projection for the human capital structure but keep the age composition of the population constant. In other words, this corresponds to a simulation that stops the ageing process and keeps the population at its current status quo in terms of age composition. Conceptually, this corresponds to the (deliberately extreme and unrealistic) counterfactual assumption of a stable population ('constant demographic structure').

30 See Online Appendix Figure A7, where the economic performance of non-OECD countries is matched well, whereas the projection of economic performance is too benevolent for OECD countries, which have been affected more by the global financial crisis up to 2010.

31 See Online Appendix Figure A8.

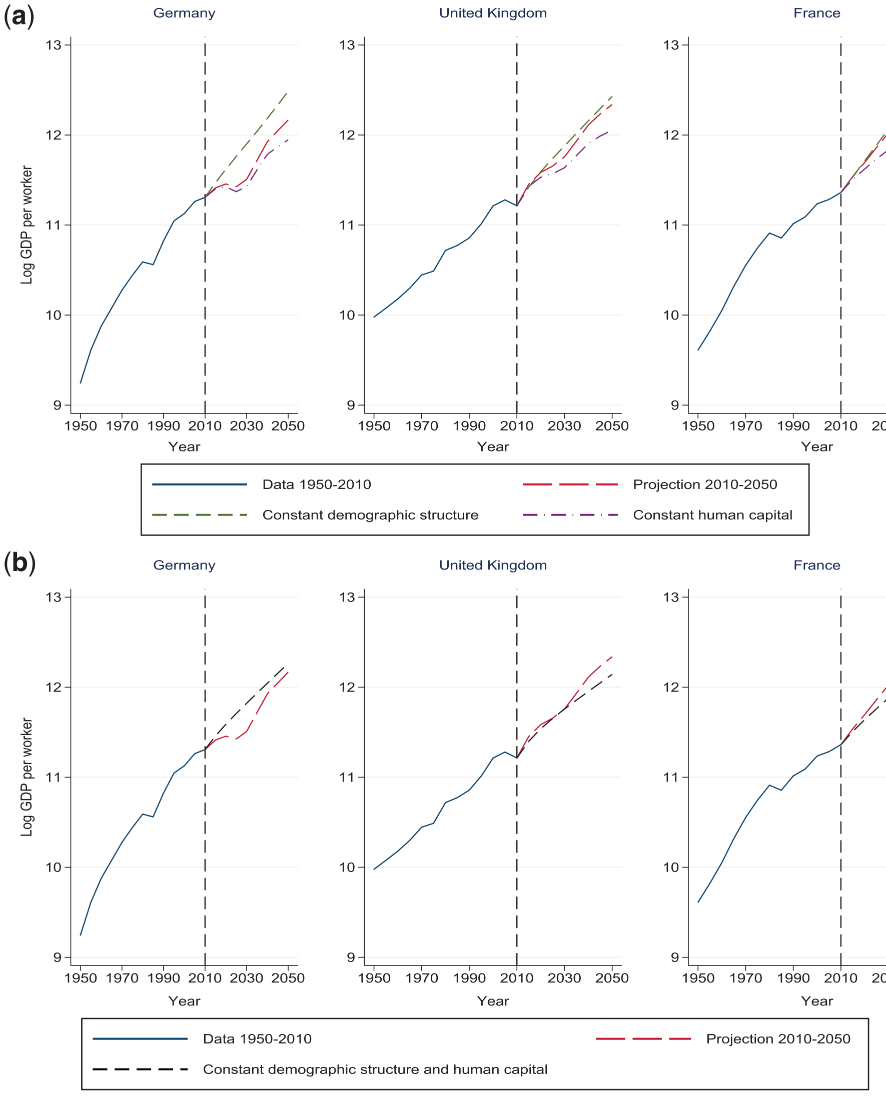

Figure 5. Projections under different scenarios

(a) Selected Countries: Germany, United Kingdom, and France

(b) Aging vs. Human Capital Accumulation

As a second alternative scenario, we simulate the model using the available population projections for the dynamics of the age structure but keep the composition of human capital in the population constant at the present levels. This corresponds to a scenario that evaluates the consequences of ageing in isolation while keeping human capital constant ('constant human capital'). The reference year for both counterfactual exercises is 2010.

In the following, we use Germany, the United Kingdom, and France as prime examples of developed economies that differ in terms of the speed of population ageing. All three countries have comparable income levels and experienced roughly comparable patterns of economic development in the past. As Figure 1 shows, however, the three countries have different age structures of their population and correspondingly face different dynamics of population ageing in the future. Moreover, the trajectories of educational attainment differ across these two countries as shown in Figure 2.[32] Using the same set of coefficient estimates from the empirical analysis for the three countries, we can therefore provide comparable simulations that allow us to identify the implications of the projected ageing and human capital dynamics for future development.

Figure 5 presents the corresponding projection results for the different scenarios for Germany, the United Kingdom, and France. For all three countries, the simulated performance using the available projections for ageing and human capital suggests a dampened economic performance in the decades to come. The predicted slow-down is more pronounced for Germany than for the United Kingdom and France. Obviously, these projections are based on strong assumptions and should not be confused with forecasts of output growth, because important components like capital accumulation, depreciation, etc. are not adequately modelled in these simulations but held constant at their 2010 levels.[33] Nevertheless, they are useful as a benchmark for comparing the projections to the counterfactual simulations that freeze the demographic structure or the human capital distribution at their respective current shapes. When considering a constant age structure ('constant demographic structure'), the projection of the economic performance in the three countries is more positive than in the baseline projection, implying a negative effect of population ageing. However, the difference between the best projection and this counterfactual projection is substantially more different in the case of Germany, which faces more pronounced population ageing than the United Kingdom and France. Alternatively, keeping the human capital structure unchanged ('constant human capital') implies a moderately dampened economic development in Germany, whereas the development in the United Kingdom and France is affected more negatively by this scenario. While in Germany, freezing the skill share at its current level has relatively minor implications, in particular in the near future, a continued upskilling of the population in the United Kingdom and France seems to be a major factor for future development. Taken together, the results predict that in Germany population ageing is a powerful dampening force for economic performance that is likely to unfold its effects in the future, whereas the effect of changes in the education composition has rather limited power, because the population is already very skilled and young cohorts are small in size. In contrast, in the United Kingdom, and even more so in France, ageing poses less

32 The same applies for education projections, see Online Appendix Figure A9.

33 Below, we turn to alternative simulation scenarios that also incorporate capital projections and alternative scenarios for education attainment.

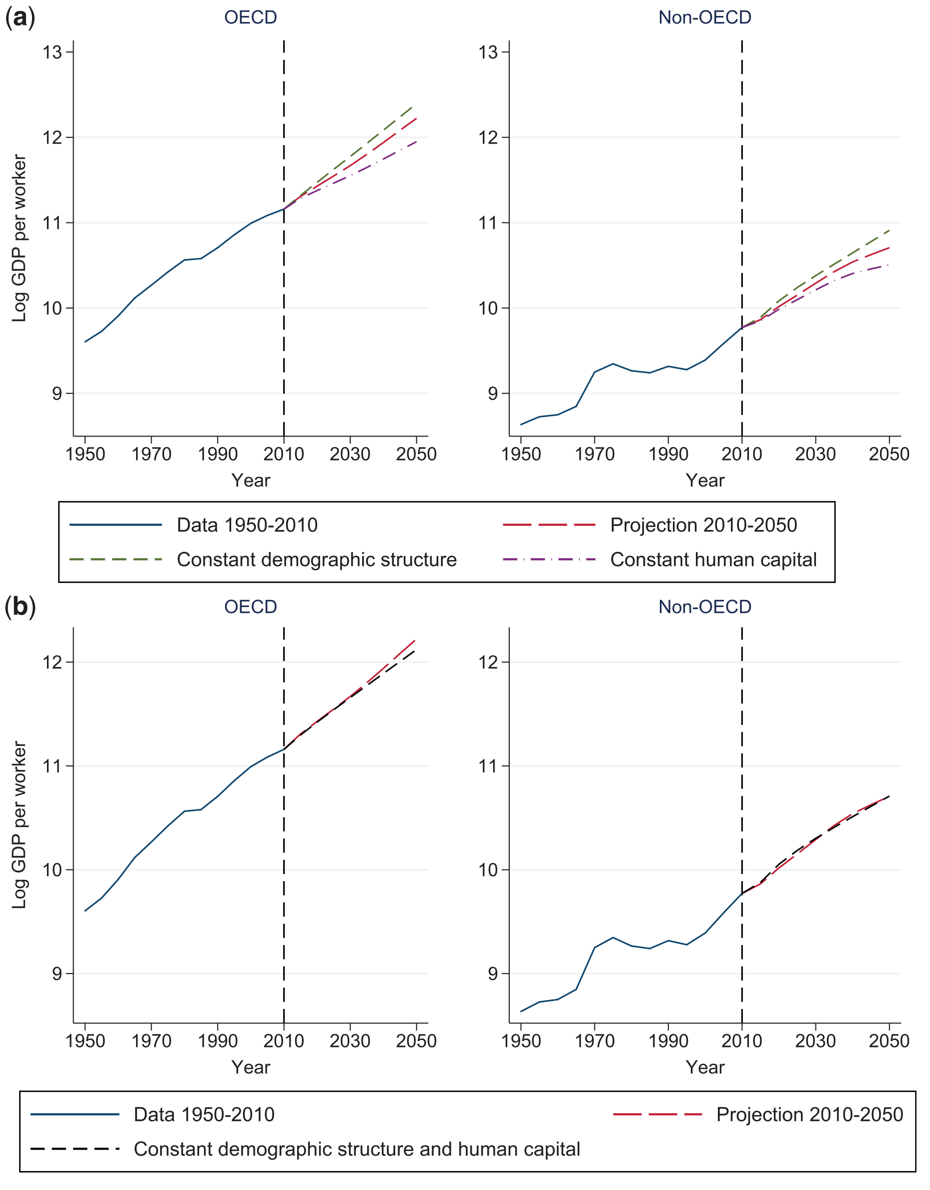

Figure 6. Projections under different scenarios

(a) Developed vs. Developing Economies

(b) Aging vs. Human Capital Accumulation

of a problem, whereas a failure to keep pace with the projected education attainment might impose substantial negative effects on development. This relative difference between ageing and education is illustrated in Panel (b) of Figure 5, which compares the predicted dynamics of output per worker using the projections for demography and human capital to the counterfactual with both distributions frozen at their current shapes: Germany is predicted to exhibit a lower performance than under the counterfactual status quo, whereas the United Kingdom and France will develop faster. Part of this is due to the greater leverage for human capital implied by the different demographic structure. Greater ageing pressure also limits the scope for human capital, which is embodied in the young but small cohorts, to compensate the direct effects of ageing. Similarly, heterogeneous results are obtained for other developed economies such as the United States and Japan.[34]

One noteworthy aspect in this context is that specifications without a control for the lagged development deliver somewhat larger effects for human capital. Correspondingly, projections obtained with these specifications deliver a somewhat more benign scenario, with greater scope for human capital in compensating the effects of population ageing for countries that face substantial population ageing but have a rather skilled population.[35]

Figure 6 presents the corresponding results for OECD and non-OECD countries. Again, the benchmark projections deliver a rather pessimistic outlook about economic performance in both samples. Freezing the age structure at its current level implies faster development in the OECD countries, suggesting that ageing will be a major impediment for economic performance in the future. A potentially more surprising result is that ageing appears to have a similar negative effect on economic development in non-OECD countries, as evidenced by the simulation that keeps the age structure constant ('constant demographic structure'). The positive trajectory is mainly due to improvements in the skill composition of the population. Conducting the alternative scenario with constant skill structure but incorporating the demographic ageing process reveals a worse performance for OECD and non-OECD countries compared with the baseline scenario.[36] This result highlights the importance of increasing human capital in the process of the demographic transition and the corresponding ageing of the population in developing countries. The results are striking in showing the potential of human capital to counteract negative implications of ageing, particularly when there is substantial scope for improvements in the education attainment of the population, as in less developed countries.

In countries with high fertility rates and a relatively young population, such as many African countries, population ageing might even exert a positive effect: Because ageing allows for the acquisition of more experience, it implies greater incentives to acquire more formal human capital. The key impediment for development in these countries

34 See Online Appendix Figure A10.

35 See Online Appendix Figure A11 for details.

36 Online Appendix Figure A9 illustrates the education projections that are neglected in this scenario. Alternative scenarios comprise constant enrollment rates, see the discussion below.

appears to be a slow-down in the accumulation of human capital. Simulations illustrate this for Niger, Nigeria, Uganda, and Mali.[37]

5.2. Sensitivity and alternative scenarios

The projection results are robust to changes in the specification of the estimation equation or the use of income per capita rather than income per worker.[38] Moreover, if based on the empirical results of the IVs approach (Table 1, Column 7), the projection results remain qualitatively unchanged with education showing a slightly more promising quantitative role for future development.[39]

Obviously, the quantitative dimension of the projections obtained with the different simulation scenarios are subject to a number of potentially restrictive and unrealistic assumptions. First, the alternative scenarios, in particular the assumption of a constant age structure as if the population were stable in its current form ('constant demographic structure'), were deliberately extreme. It should be clear that such a scenario is not only unrealistic but also inconsistent in terms of the implied demographic dynamics of non-stable populations. It should therefore be seen as an illustrative thought experiment, rather than a realistic (or even in some way implementable) possibility with normative character. A less extreme way to construct counterfactual scenarios in this context is to make alternative assumptions about vital rates. Such scenarios would fix fertility, or mortality, or both, at their 2010 levels—instead of fixing the age shares—and then compare the implied ageing dynamics with the actually projected ones. The problem with these scenarios is that the resulting patterns of population ageing differ only very mildly compared with the available projections.[40] This reflects the well-known difficulty for any policy aiming at vital rates to change the momentum of population ageing. On the contrary, such scenarios camouflage the true extent of the consequences of ageing for economic performance, as they imply differences in the age structure that are too minor to provide substantially new insights. We therefore view the alternative scenarios studied here as more illustrative.

Second, the simulations are based on the assumption of physical capital following the average growth trend over the period 1950–2010. This assumption is clearly counterfactual, but it allows us to focus on the demographic aspects while remaining agnostic about the implications for savings and capital accumulation. An alternative is to specify

37 See Online Appendix Figure A12.

38 To illustrate this, Online Appendix Figures A13–A15 present the corresponding projections for a coarser specification of age groups as well as for income per capita instead of output per worker for selected countries and county groups. Online Appendix Figures A16 and A17 show the corresponding projections when accounting for the size of the working-age population.

39 Online Appendix Table A18 presents the corresponding projections for Germany, France, and OECD and non-OECD countries.

40 This is illustrated in Online Appendix Figure A19.

an auxiliary equation for the accumulation of physical capital per worker as a function of past output, past levels of physical and human capital, and the age structure of the population, along the line of the estimation framework for output. Such an auxiliary equation can be estimated and the coefficient estimates can be used to project physical capital under alternative scenarios, and in a second step output. The results from such a refined methodology leave the main results, in particular related to the relative importance of ageing and human capital dynamics in different countries unaffected.[41]

Third, the simulations are obtained under the assumption of stable coefficients over time and across countries, as well as a constant growth trend. These assumptions allow for a comparable simulation across all countries, thereby providing the possibility to identify differences in economic performance that are due to projections in the demographic domain (the age structure) and projections in the domain of human capital, while holding other factors, such as structural parameters of relative productivity, constant. This delivers qualitative results that are internally consistent. To investigate the robustness of the findings with respect to less restrictive assumptions about parameter stability, we also conducted the same counterfactual projections based on estimation results obtained for the sample period 1990–2010 instead of the entire sample period 1950–2010. The results of these projections are qualitatively very similar.[42]

Finally, the combination of estimation and projection analysis is subject to the criticism of not explicitly accounting for behavioural adjustments and mechanisms that underlie the population projections, and potential equilibrium effects, like fertility. In our view, the purpose of this paper is not so much about identifying point estimates but about making the point that, holding structural parameters fixed, the imminent and unrelenting demographic dynamics of the coming decades will have first-order effects on macroeconomic performance. The methodology is suited to address this issue, and the sensitivity analysis shown in this section indicates that the result is robust to various scenarios that should account for the scope of such behavioural

41 Online Appendix Figure A20 compares the projection scenarios for exogenous and endogenous capital. The simulation results suggest that capital accumulation is reduced in developed countries as a consequence of ageing, whereas the differences are less pronounced in low-income countries. This is consistent with the results from computable general equilibrium models that predict a negative effect of ageing populations on capital formation, see, for example, Sanchez-Romero (2013). However, these estimates are based on the implicit and counterfactual assumption of closed economies without access to international capital markets. See Börsch-Supan *et al.* (2006) and Domeij and Floden (2006) for quantitative and empirical studies on the implications of population ageing for international capital flows.

42 See Online Appendix Figures A21 and A22. In order to test the assumption of parameter stability, we conducted a second robustness check by estimating an even more flexible version of the model that allows the age-group-specific parameters to vary by decade. While the unreported results show some variability in the coefficients over time, there is no systematic variation in the age-specific productivity coefficients relative to the coefficient obtained for 2010. We view this as further a supportive evidence for the validity of our baseline specification.

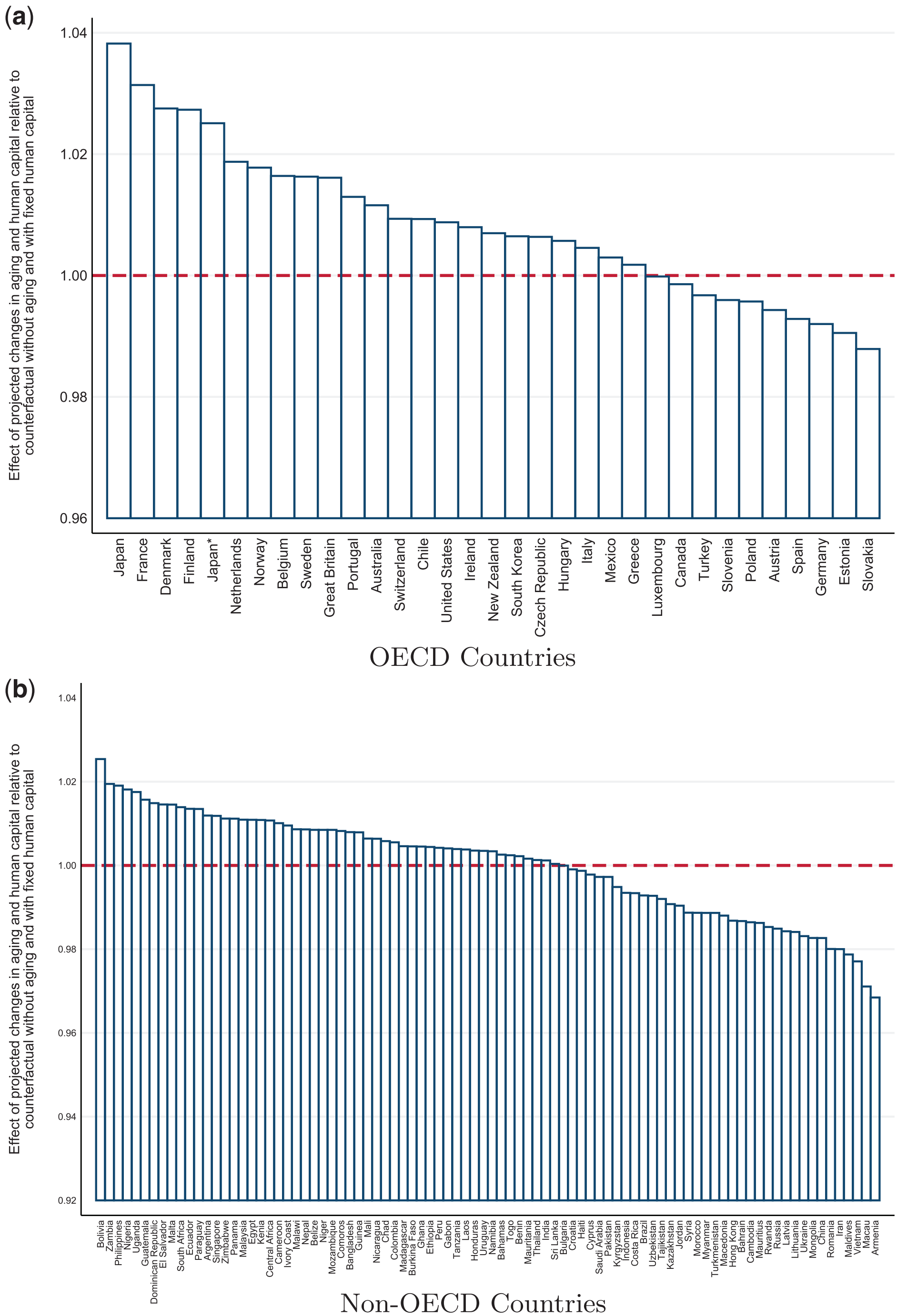

Figure 7. Projected performance relative to the counterfactual status quo

adjustments. However, a structural analysis of behavioural adjustments is beyond the scope of this paper.

Overall, the projection results suggest that the implications of population ageing on economic performance differ across countries with different age compositions and human capital projections. We therefore proceed by investigating this issue in more detail.

5.3. The role of the contemporaneous age composition

After having established how population ageing and the contemporaneous changes in aggregate human capital affect macroeconomic performance and how this influences the prospects of future economic development, we return to the question whether investment in education can potentially offset the effects of population ageing. Using the simulation methodology, we focus on which countries are predicted to suffer most from population ageing, measured in terms of economic performance. We then contrast the positive impact of human capital acquisition to the predicted negative effect of ageing, allowing us to quantify whether the former is large enough to offset the latter.

Using similar counterfactual experiments as in the previous section, one can simulate the effect of projected changes in the age and human capital structure of a country and compare it to a counterfactual scenario where both the age and human capital structures are fixed at their current (2010) levels. Figure 7 provides a plot of the predicted performance of OECD and non-OECD countries relative to the counterfactual status quo. Countries with a young population that are projected to further increase their share of skilled individuals, such as France, are predicted to exhibit a substantially better performance than they would absent population ageing and continued skill acquisition. On the other end of the spectrum, countries like Germany, but also Austria, Spain, Estonia, or Slovakia, that face substantial population ageing with populations that do not have much scope for further upskilling, are likely to do worse than under the counterfactual status quo. Similar patterns can be observed for non-OECD countries.

These predicted effects are mainly due to the differences in the scope for further acquisition of human capital at the aggregate level. This is illustrated by a decomposition, in which the contribution of the projected ageing of the population to predicted economic performance is isolated from the contribution of the projected change in human capital.[43]

Returning to the estimation framework, additional results confirm these insights by revealing heterogeneity in the effects when splitting the sample into subsamples with different levels of economic or demographic development. In particular, the results reveal stronger effects of changes in the age structure on economic performance in non-OECD

43 See Online Appendix Figures A23 and A24 for the respective graphs.

than in OECD countries.[44] This finding could indicate that the ageing process is less pronounced once the demographic transition is completed. Alternatively, this finding could indicate that the adoption of technologies allows rich economies to insulate themselves from the negative effects of ageing on average, as suggested by Acemoglu and Restrepo (2017). In contrast, poorer countries in which the process of population ageing sets in with force might experience particularly adverse effects on their economic performance. This finding is also consistent with the finding that population ageing has a more pronounced effect on societies with a large share of young people when considering a sample split.

A more direct way of testing this conjecture is by investigating the stability of coefficients for samples split in terms of the observation period, or in terms of the relative age of the population. When considering estimates separately for the period before and after 1990, the results reveal that the importance of population ageing appears to have increased in recent decades. Concretely, the effects are stronger when considering a subsample for the period after 1990.[45] When splitting the sample into countries with old populations versus countries with young populations relative to the median of the young age dependency ratio, one obtains large and negative effects of the age structure in the 'old' countries but large and positive effects of the age structure for the group of 'young' countries.[46] This is consistent with the patterns obtained from the simulation shown in Figure 7. Ageing is predominantly a problem for economic development in countries with an unfavourable age composition (such as Germany, and many Eastern European and Asian countries), whereas countries with a young population are standing to gain from the projected ageing and education patterns (such as France, or many countries in Africa).[47]

5.4. The scope for adjustment

We conclude the analysis by investigating several alternative margins besides additional investments in education along which the ageing effect might be counteracted. A key dimension in this respect is the intensity with which human capital, and labour in general, is supplied. Given the primary role of education, we conducted additional projections for alternative education scenarios. Specifically, in addition to the 'general education

44 See Online Appendix Table A18 for details.

45 See Online Appendix Tables A19 and A20 for details.

46 See Online Appendix Table A21.

47 Interestingly, also countries with a rather old and well-educated population, such as Japan, are projected to gain from the future dynamics. This is partly due to the fact that they already underwent substantial shifts in the age distribution in the past and stand to face a 'pause' in the coming decades. For this reason, we report also a scenario Japan* where the demographic structure has been fixed in the year 2000 instead of 2010. In other countries, the development is projected to be positive due to considerable immigration that is projected to stabilize the age distribution, as, for example, in Switzerland.

trend' that represents our baseline, we conducted projections under a 'fast enrollment' scenario representing the most optimistic enrollment dynamics conceived by the IIASA–VID projections, a 'constant enrollment ratio' scenario, which keeps the ratio of the respective age cohorts constant, as well as a 'constant enrollment number' scenario, which keeps the total number of enrolled constant. Irrespective of the scenario, we find very little sensitivity of our results.[48]

To explore whether the decline in the relative supply of labour by young cohorts due to population ageing could be neutralised by an increased labour force participation, in particular by women, or by longer work weeks, we proceed in three steps. First, we provide an assessment of the scope of adjustment along this dimension by comparing the effective labour supply of the different age groups in 2010 to the projected levels in 2050. The effective labour supply in 2010 is computed by using the same information about the age structure of the workforce as in the estimates and combining it with data about the absolute size of the workforce and information about age-specific labour force participation at the extensive and intensive margin provided by the International Labour Organization (2011).[49] For 2050, we use the IIASA–VID projection for the working-age population and assume that age-specific labour force participation and hours worked by women attain the same level as for men in the 2010 ILO data. This allows us to construct several alternative scenarios compared with the (implicit) assumption of constant female labour force participation and hours worked in the results presented so far. In particular, we compare the baseline projection as before, which assumes constant labour force participation at the extensive and intensive margin, to three alternative scenarios: a projection that also accounts for changes in female labour force participation, for changes in hours, and for changes in both, until 2050. When comparing the magnitudes relative to the projected effects of ageing for the size of the workforce of each age group, these increases appear rather moderate. In particular, these projections indicate that the overall patterns of ageing will at most be moderated but not completely neutralised.[50]

In a second step, we make use of novel age projections of labour force participation constructed by Fürnkranz-Prskawetz *et al.* (2016) for 26 European countries to project the macroeconomic performance of these countries using the baseline estimates obtained from the age structure of the working-age population. In particular, using the 2010 data on labour force participation, we construct an index for the labour force participation that takes a value of 100 for each age group in 2010, and compute the relative change up to 2050 using the projection data by Fürnkranz-Prskawetz *et al.* (2016). The projection results document that ageing remains a substantial impediment for economic

48 See Online Appendix Figure A25.

49 The data are available at https://www.ilo.org/ilostat.

50 This is illustrated in Online Appendix Figures A26 and A27, where we plot the labour supply in terms of the total weekly hours worked by the different age groups as of 2010 and the projected change under the different scenarios until 2050, for Germany, France, and OECD and non-OECD countries. Notice that the data and projections average over men and women.

development for most countries.[51] A drawback of this analysis is that it relies on estimates that do not incorporate information about labour force participation but that only rely on the age structure of the working-age population. This reduced form approach helps avoiding endogeneity problems related to labour force participation, but it introduces a slight methodological inconsistency.

In a third step, we therefore re-estimate the model using information on the effective labour force and, hence, effective human capital supply, by incorporating age-specific differences in the intensive margin for the period 1980–2010 for which respective age-structured data are available from the ILO (International Labour Organization, 2011). In this context, it is worth noting that most of the respective variation is driven by female labour force participation. Based on these estimates, we then project macroeconomic performance using the workforce projections by Lutz *et al.* (2007) and by Fürnkranz-Prskawetz *et al.* (2016). The descriptive statistics indicate that the age structure of the working-age population and of the workforce is rather similar.[52] Consistently, the estimation results do not differ substantially from the baseline estimates and deliver the same qualitative results.[53] Correspondingly, the projections incorporating age-specific labour force participation patterns do not deliver substantially different results. In particular, ageing remains to exert a major negative effect on macroeconomic performance, whereas human capital is only able to offset this effect partially.[54] Overall, the results from these three exercises suggest that the incorporation of age-specific projections for labour force participation and hours worked does not greatly affect the conclusions regarding the effects of ageing and skills for future macroeconomic performance.

Another margin of adjustment is a potential shift in the age-profile of productivity. Whether in the future the productivity will peak at younger or older ages is an open question. Given the ongoing improvements of health status and labour force attachment of older cohorts in the workforce, and the observation of a stable experience premium that has led to the conjecture of experience-biased technical change (Caselli, 2015), one might expect that the most productive age range might shift from age 50–54 to older ages.[55] To account for this possibility, we replicated the projections by shifting the estimated productivity profile by one age group (i.e., considering ages 55–59 years as the most productive group instead of ages 50–54 years). The corresponding results reveal a

51 See Online Appendix Figure A28.

52 In particular for age groups above 20 years, see Online Appendix Table A1 for details.

53 Online Appendix Table A22 contains the corresponding estimation results.

54 Online Appendix Figure A29 provides a direct comparison of the projections obtained with the baseline methodology and with estimates that incorporate variation in labour force participation for the 26 EU countries for which labour force projections are available. Online Appendix Figure A30 plots the respective projections for Germany and France.

55 Complementing this, research productivity as measured by scientific breakthroughs has shifted to older ages (Jones and Weinberg, 2011). However, there is also evidence that suggests that new technologies such as ICT might shift the productivity peak to younger years (Falck *et al.*, 2016). In the present context, a shift to younger years would reinforce the effects of ageing.

modified projection of the consequences of population ageing compared with the baseline in the sense that the negative effects of population ageing in countries like Germany are delayed.[56]

Finally, the methodology allows us to address the question regarding the scope for technical change or productivity improvements to offset the effects of ageing. Recent work has suggested that directed technical change might provide a countervailing force to the negative growth effects of population ageing (Acemoglu and Restrepo, 2017). Likewise, improvements in the quality of human capital have been shown to affect macroeconomic performance across states (Hanushek *et al.*, 2017). To investigate this issue, we conduct another counterfactual exercise and compute the extent of skill-biased technical change or quality improvement, in the form of an increase in the relative productivity of high-skilled to low-skilled workers, λ^h, that is needed to offset the effect of population ageing until 2050. The results of this exercise replicate the previous findings about which countries are expected to suffer or gain from population ageing, but this time the estimates provide a quantitative interpretation in terms of productivity. In particular, the relative productivity of high-skilled workers would have to increase by more than two-fold to counteract the effects of population ageing in countries that are affected negatively by population ageing, such as Germany.[57]

6. CONCLUSION

This study presents novel evidence regarding the role of the demographic structure of the workforce and the distribution of skills for aggregate economic performance. On the basis of an extended development accounting model, we derive a flexible empirical framework that can accommodate empirical models previously used in the literature. In particular, assuming that the quality of the labour force depends on the demographic structure allows incorporating workforce demographics into the production function and provides a coherent framework to evaluate the implications of population ageing and education dynamics for future economic development.

The estimation results show that changes in the age structure of the working-age population have a strong effect on output, even when controlling for human capital. At the same time, the evidence suggests that the stock of human capital embodied in the population has a positive effect on economic performance, conditional on the age structure of the population. The effects of ageing in terms of changing relative sizes of the different age cohorts mirror productivity profiles that have been found earlier in terms of hump-shaped productivity patterns over the age dimension. Consequently, the results show that population ageing in old societies reduces the future growth potential. The estimates suggest that human capital can help to compensate for these ageing pressures and

56 See Online Appendix Figures A31–A33 for details.
57 See Online Appendix Figure A34 for details.

deliver an upper bound for the elasticity between the age structure and the distribution of skills. This elasticity allows gauging the change in the distribution of skills that is required to offset the negative effects of ageing of the workforce. The quantitative estimates of this elasticity predict that shifts out of the most productive age cohort into older and less productive age groups can be offset by higher investment in schooling. However, these offsetting effects might not be sufficient to fully compensate for ageing, particularly in developed countries. Nevertheless, the results suggest that a continued expansion of education is crucial for future macroeconomic performance.

The results are also useful to infer the relative importance of ageing and human capital accumulation for macroeconomic performance by ways of projections on the basis of different scenarios of population ageing and human capital dynamics. Projections of future economic development predict that ageing will play an important role by slowing down economic development in developed and less developed countries. Ageing is, hence, not a problem of the developed world only. There is substantial heterogeneity in the projected macroeconomic performance as a result of differential population ageing patterns across countries. This heterogeneity emerges through the heterogeneous productivity but also as a consequence of the implications for the scope of human capital in compensating this effect. In fact, the projections reveal a central role of human capital in ameliorating the negative consequences of ageing. This is particularly the case in countries that are yet underdeveloped in terms of human capital endowments and that have considerable potential for an increase in the human capital endowment of the still largely low-skilled population. The scope of human capital improvements for compensating the consequences of population ageing appears more limited in economies that age faster. However, the findings make clear that without further improvements in the skill composition of the workforce in these countries, the consequences of population ageing will be much more dramatic. Additional projections suggest that increased female labour force participation or longer work hours will be unlikely to neutralise these effects or replace human capital. Moreover, skill-biased technical change will have to be substantial to counteract these developments.

We would like to end with a word of caution. The main purpose of this paper is not about making accurate predictions; the future will certainly look different than in our projections. Rather, the contribution of this paper lies in providing new evidence for the close connections between ageing and the supply of human capital, as well as their implications for macroeconomic performance, with the aim of raising the awareness of the profession, and of policymakers, regarding this link. Overall, the results are consistent with an important role of long-run demographic dynamics for future economic development, pointing towards the possibility of more stagnant development in the future. In this sense, the results complement recent findings by Cervellati *et al.* (2017). In our view, these issues do not receive adequate attention by researchers and policymakers.

Discussion

Pietro Biroli

University of Zurich

I find this paper by R.K. and U.S. to have four strong qualities: it is comprehensive, robust, relevant, and honest. If I had to identify some potential improvements, I would suggest a model that can shed light on the cross-country difference in the estimated parameters, and advocate for a more optimistic description of the results.

Let me address all of its strengths. First, the authors manage to comprehensively describe and connect demographic, educational, and economic trends of 130 countries spanning a period of 60 years. As common in this literature – mostly due to data limitations – some new, small, or low-income countries are missing, and the trends that shaped this world before 1950 cannot be included. Still, the empirical strategy captures countries and periods with very different cultural and institutional backgrounds, undergoing the first and the second demographic transition (as shown in Figure 1), more than quadrupling of the educational attainment (as shown in Figure 2), and subject to secular changes in economic growth. The authors cleverly leverage the momentum of both ageing and education that has been thoroughly described and forecasted by demographers, and pit one against the other into a dynamic economic model that includes capital investments and total factor productivity. The model is relatively simple, yet flexible enough to nests several specification widely used in the literature.

Second, the empirical analysis proves to be robust across several dimensions. As shown in the different columns of the tables, the authors consider various estimation strategies, addressing potential bias and endogeneity, both in levels and in first differences. Although none of these strategies have a bulletproof identification, and they all might suffer from misspecification of the underlying model, it is reassuring that the broad patterns are similar across the different specifications. Their analysis shows remarkable changes in productivity by age, and highlights the importance of focusing on skills and education.

Third, their analysis focuses on a very relevant policy question: what can our current population structure tell us about future economic performance? While changes in fertility or mortality might be too slow or too small to be used as a policy lever to impact macroeconomic performance, investments in skills and education could prove to be an important public expense. Indeed, the authors show that in many countries the negative macroeconomic impact of an aging population can be counterbalanced by its changing skill composition. Another important demographic channel subject to policy influence that could impact future economic growth would be migration. However, unlike aging and education, migration could be more volatile, and less determined by the current demographic stock.

Finally, this paper is honestly written. The authors are careful in stating the shortcomings of their approach, clear about the uncertainty of their predictions ('The main purpose of this paper is not about making accurate predictions; the future will certainly look different than in our projections'), and forthcoming regarding the potential limitations of their estimates and identification strategy.

In terms of potential improvements, first of all I would suggest to construct a model that takes seriously the underlying difference in the estimated parameters over time and across countries. For simplicity, the current model assumes constant structural parameters for the labour share α, the persistence of output γ, and the productivity ratios λ^j. However, a significant difference in coefficients jumps out of the heterogeneity Tables A18 and A19 in the Online Appendix, both when splitting the sample before and after 1990, and when looking at OECD versus non-OECD countries. In future work, one could either estimate the distribution of these coefficients – for example, by estimating a random coefficient-model – or even better try to micro-found these differences. For example, observable changes in culture and institutions across time and space could be used as determinants for the differences in these structural coefficients.

Finally, I believe that a more optimistic outlook can be warranted by looking at the projections of macroeconomic performance: Figure 6b shows that the projections of log GDP per worker for both OECD and non-OECD countries look no worse than the counterfactual with constant demographic structure and human capital. Figure 6a shows that the projections are slightly worse than a counterfactual with constant demographic structure, but much better than one with constant human capital. Finally, Figure 7 shows that most countries in the world have a projected performance that is *above* the counterfactual status quo. In other words, past investments in skills and human capital did manage, at least on average, to buffer the negative consequences of an ageing population.

Francesco Drago

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This is an important work analysing the relationship between population ageing, human capital, and economic performance. This topic is of enormous importance given the trends in life expectancy and fertility in the most developed countries. Life expectancy has risen by 2–3 years a decade in the last two centuries and will continue to rise so in the next decades, while in several countries fertility started to fall. These patterns lead to population ageing and pose important challenges for the economic performance of the countries mostly affected by shifts in the age composition. The age structure of a country is potentially important for its economic performance for several reasons. Among the most important ones, substantial shifts in the age composition of workforce impact participation rates in the labor market. Second, different age groups may have different productivity impacting the total factor productivity and the accumulation of human capital.

The paper addresses two separate questions. First, what is the impact of age structure and skill composition of the workforce on economic performance. Second, to which extent education can counteract the negative effect of ageing on economic performance. The paper assembles a dataset on age structure and socio-economic variables covering 132 countries between 1960 and 2010. The answer to the first question confirms previous findings – qualitatively and quantitatively – in the literature. Namely, age composition negatively impact GDP per capita while human capital tends to increase it. Using these results, the authors assess by how much human capital should increase to offset a one percentage point shift out of one cohort (say 50–54) into the next one (60–64). Effectively, the increase in human capital needed to offset the effect of ageing is large and somehow unrealistic for old cohorts (e.g., share of high skilled should increase between 1 and 5 percentage points depending on specification) in response to a 1 percentage point shift out of the 50–54 to the 60–64 cohort. The usefulness of this approach is that we can draw implications for future performance on different countries. Unlike France or United Kingdom, in Germany, for example, ageing will be an important limiting force to development in the next decades given its current level of fertility, the relatively high skilled workforce, and small young cohorts that limit the scope of investments in human capital.

From the methodological point of view, the empirical analysis exploits the panel structure of the data allowing to control for country-specific trends, country-fixed characteristics, common shocks, and many other observable time-variant variables. The analysis is very careful in estimating the effect of ageing and human capital and addresses the potential threats to identification with a number of robustness checks that add credibility to the results.

The paper has the merit to raise the awareness of economists and policy makers of the consequences of population ageing on development. At the same time, it indicates that investments in human capital can only partially offset the impact of ageing. The projections in the paper are sensible in the medium run over which we can reasonably ignore important behavioural adjustments. Indeed, the authors analyse different scenarios over the next 30 years. With a more optimistic view, it is not obvious that in the very long-run the picture will be identical to the one projected in the medium run. Important changes in fertility rates, different migration patterns, and investments in human capital not simply captured by our current standard variables may counteract the effect of population ageing on macroeconomic performance.

Panel discussion

Fadi Hassan wondered why the decline in productivity for individuals older than 55 years is happening. He also suggested it would be important to discuss the within-country effects of population ageing and changes in the education composition of the population. Brian Burgoon mentioned that the treatment of investment and education in the paper is very generic, while Tito Boeri maintained that age-productivity profiles might be education-specific as the micro literature suggests.

Luigi Guiso argued that population ageing can be driven by either fertility or life expectancy and, as a result, it is essential to separate these two components as they have different implications. Andrea Ichino said the hump-shaped productivity patterns could simply be explained by one generation being more productive than the rest. He also suggested that the authors make more within-sample predictions to test how reliable the simulations are. Finally, he maintained that the paper over-emphasizes the causal effect of education on productivity and wondered if there is an excess of education across advanced economies, or what the role of technological progress or automation may be in counteracting the effects of population ageing.

Replying to comments and questions, U.S. first clarified that the purpose of this paper is not to make forecasts but simply to examine what are the potential forces at play and, using a coherent framework, show by how much ageing might affect output performance. He also agreed that examining the effects within countries is an interesting idea, but that goes beyond the scope of this paper. Finally, U.S. said they can do more within-sample predictions as a robustness test and, regarding education-specific age profiles, clarified that they do not find significant differences in the age profiles by education at the macro level.

SUPPLEMENTARY DATA

Supplementary data are available at *Economic Policy* online.

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