DEMOGRAPHIC CHANGE, TECHNOLOGICAL ADVANCES, AND GROWTH

A CROSS-COUNTRY ANALYSIS

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CONTENTS

TABLES AND FIGURES

TABLES

FIGURES

ABSTRACT

This paper revisits the impact of population aging on economic growth. In order to understand the impact of population aging on economic growth, it is important to consider the changes in the entire age distribution of demography. Our empirical analysis indicates that a change in age distribution that increases the proportion of older people while reducing the working-age population lowers economic growth. We also investigate the effect of technological advances on the relation between population aging and economic growth, using four plausible proxies of technological advancement: life expectancy, labor productivity, automation, and total factor productivity. We find that increasing life expectancy and labor productivity benefit old age groups as they likely help older age groups contribute more positively to future growth. More automation also helps improve productivity of old age groups but in a different way. When robot density increases, old age groups become less disadvantaged compared to the young. Lastly, technological adoption enhances the growth contribution of productive age groups from the 30s to 60s when one compares low with high total factor productivity scenarios.

Keywords: demographic change, growth, labor productivity, life expectancy, robotics

JEL codes: J11, J24, O33, O47, O57

I. INTRODUCTION

Population aging presents major policy challenges in many countries in Asia and across the world. But no consensus has emerged yet about the impact on economic growth of this demographic trend. On one hand, some studies emphasize the negative effects. Lee and Shin (2019), Cooley and Henriksen (2018), and Aksoy et al. (2018) find that population aging lowers gross domestic product (GDP) growth per capita, particularly in advanced countries. Using the variation in the rate of population aging across US states during 1980–2010, Maestas, Mullen, and Powell (2016) estimate the impact of state-level population aging on state output per capita growth and find a significant negative effect. On the other hand, Bloom, Canning, and Finlay (2008) argue that no substantial negative effect of population aging on economic growth occurs. Acemoglu and Restrepo (2017a and 2017b) further show that population aging actually leads to higher economic growth.

While there are a number of channels through which aging affects growth, one prominent channel is technological progress. Yet here, too, there are mixed findings. Jones (2010) provides evidence that older people are less innovative, which suggests that technological progress is lower in "older" economies. Derrien, Kecskés, and Nguyen (2018) confirm Jones' finding based on the age structure of the local labor force across states in the United States (US) and its influence on corporate innovation. Using an Organisation for Economic Co-operation and Development (OECD) country sample, Aksoy et al. (2018) find middle-aged workers (ages 40–49) have a strong positive impact on innovative activities. Wasiluk (2014) also argues that firms with a higher share of elderly workers update their technology less often and prefer older, cheaper technologies because they are reluctant to train their workers for new technologies due to their shorter expected work life. Engbom (2017) develops a model following the empirical evidence that an aging US labor force has led to a significant decline in firm and worker dynamics, which drives less creative destruction. Basso and Jimeno (2019) also emphasize a trade-off between innovation and automation that leads population aging to cause lower growth in GDP per capita. According to their model, while aging boosts automation, as automation crowds out innovation, ~~that~~ automation itself cannot boost growth. However, Acemoglu and Restrepo (2017b) present the opposite result. According to their theoretical model and empirical evidence, aging, by encouraging more active adoption of automation technology, promotes growth.

Another related issue, on which studies only start to emerge, is the effect of technological advances on the relation between aging and growth. ADB (2018) explores the possibility that technological advances in automation and artificial intelligence, by supplementing and complementing old workers, reduce the negative effects of aging. It argues that such technological innovation may transform work and the workplace so that senior workers are encouraged to participate more in the labor market and even become more productive. For example, automation makes the same task less demanding manually and physically and hence the workplace becomes more friendly to old workers.

This paper revisits the issue of an aging population's impact on growth of GDP per capita. Following the approach by Acemoglu and Restrepo (2017b) which define aging as the ratio of the population above 50 years old to the population between 20 and 49, we confirm their empirical result using a panel dataset that a rise in the ratio is positively associated with higher growth. However, we also find that a rise in working-age population share, population ages 15–64, as a percentage of total population, leads to higher growth. These conflicting results are explained by Lee and Shin (2019), who show that increasing old-age population share—population over 64 as a percentage of total population—may coincide with an increasing working-age population share at the beginning stage of aging, which makes the results difficult to interpret if they are used as a regressor individually. While Acemoglu and Restrepo (2017b) did not use old-age population share *per se*, the ratio they used is almost identical to it. These results provide an important lesson: it is essential to consider the entire age distribution to understand the impact of demographic change on growth. Following the methodology of Fair and Dominguez (1991), we empirically investigate the effect of aging based on the entire age distribution of a population. Our results indicate that old and young population shares are negatively associated with growth, and only the working-age population share is positively associated.

We also empirically investigate the effect of technological advancement on the relation between demographic change and growth. We examine four proxies to capture technological advancement. First, we consider life expectancy, which represents technological improvement in providing health care and hence increasing life span. The second proxy is labor productivity, which more broadly captures any technological advancement associated with labor productivity increases. Third, we use robot density to measure technological progress more narrowly by the degree of automation. Last, total factor productivity (TFP), a widely known measure reflecting development of production and process technologies, is also used as a proxy. We interact these four proxies with the entire age distribution of population to examine how technological advancement alters the impact of demographic change on GDP per capita growth. We find that as life expectancy increases from 50 to 80, the range of age groups that have a positive impact on future growth becomes wider to include older age groups. Labor productivity enhancement also causes older age groups to contribute more positively to future growth, with a subtle difference. Labor productivity enhancement moves the range of age groups that have positive impacts toward older age groups, which implies that very young age groups no longer contribute positively to future growth. More automation does not move the range of age groups that have positive impacts on economic growth. However, higher robot density also favors an old population in the sense that old age groups become less disadvantageous relative to peak age groups as the difference in their contribution to economic growth shrinks. Finally, technological adoption enhances the growth contribution of productive age groups from the 30s to 60s when one compares low (-0.5) to high (0.5) TFP scenarios (expressed in logs).

The rest of the paper is organized as follows. In the next section, we investigate the impact of population aging on growth. Section III lays out our empirical framework, which allows us to consider the entire age distribution of population in examining the impact of demographic change on growth and to report baseline empirical findings. Section IV discusses various technological advancements that influence the impact of demographic change on GDP per capita growth. Section V concludes.

II. IMPACT OF POPULATION AGING ON GROWTH

National account data on GDP at constant prices in local currency unit (real GDP using national accounts [RGDP^{NA}]) is collected from the Penn World Table version 9.0.[1] We divide real GDP by total population to obtain real GDP per capita and calculate its growth rate. To derive the age distribution of population, we rely on the United Nations World Population Prospects 2017, which reports population by 5-year age groups.

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[1] Penn World Table (PWT) 9.0 reports five types of real GDP, but it recommends RGDP^{NA} for studies on cross-country growth rates. The latest year available for PWT 9.0 is 2014. We think that Acemoglu and Restrepo (2017b) also used the same GDP data for their empirical analyses.

As a proxy for aging, Acemoglu and Restrepo (2017b) use the ratio of population above 50 to population between 20 and 49. They regress the growth rate of GDP per capita from 1990 to 2015 on the change in the ratio during the same period for each whole country (for 169 countries) and for OECD countries only (35 countries). To avoid an endogeneity issue, they also report instrumental variable (IV) regression results by using birth rates as instruments. While the evidence is weaker for OECD countries, they generally find strong evidence that aging is positively associated with growth.

While the empirical analysis by Acemoglu and Restrepo (2017b) is based on cross-sectional data of the growth rate during 25 years, we try to replicate their findings using panel data with 5-year intervals, since we will use the same data format for the rest of the paper. As is common in the literature, we minimize the influence of business cycle fluctuations by calculating 5-year growth rates. We divide the entire period of 1965–2015 into 10 5-year subperiods: period 1 (1965–1970), period 2 (1970–1975), period 3 (1975–1980), period 4 (1980–1985), period 5 (1985–1990), period 6 (1990–1995), period 7 (1995–2000), period 8 (2000–2005), period 9 (2005–2010), and period 10 (2010–2014).[2] We then calculate the average growth rate of GDP per capita for each 5-year subperiod.

Table 1 reports summary statistics for the variables used in the paper. The left panel reports summary statistics for the whole sample; the right panel reports summary statistics for countries with robot stock data greater than zero. The sample size reduces to about one-tenth as we remove countries without robot stock data. The mean 5-year GDP per capita growth of the whole sample is 1.8%, while it is 2.4% in the robot-data sample. Initial GDP and life expectancy are higher in the robot-data sample as it includes more recent periods.

Table 1: Summary Statistics

	Whole Sample				Robot-Data Sample			
Variables	Count	Mean	Min	Max	Count	Mean	Min	Max
5-year GDP per capita growth	1,613	0.018	−0.253	0.258	188	0.022	−0.1	0.086
5-year change in the ratio of old to young workers	1,910	0.002	−0.026	0.052	188	0.013	−0.003	0.032
5-year change in the working-age population share	1,549	0.17	−1.38	2.04	184	0.03	−0.69	1.40
Log of initial GDP per capita	1,613	1.75	−1.86	7.96	188	3.05	0.70	4.54
Life expectancy	1,544	63.5	23.6	83.1	184	76	62.6	83.1
Log labor productivity	1,440	9.69	6.18	15.37	188	10.78	8.58	11.95
Log of robot stock					188	6.42	−0.42	12.84
Employment (millions)	1,440	14	0	781.4	188	36.5	0.2	781.4
Log robot density					188	4.31	−2.47	8.66

GDP = gross domestic product.
Note: See Appendix for the definition and source of the variables.
Source: Authors' calculations.

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[2] For the 10th subperiod, we calculate the growth rate from 2010 to 2014 as the GDP data end in 2014.

In Table 2, columns 1–5 report pooled ordinary least squares (OLS) regression results that replicate Acemoglu and Restrepo (2017a) as closely as possible. Column 1 shows a raw correlation between the 5-year growth rate of GDP per capita and the 5-year change in the ratio of population above 50 to population between 20 and 49, that is, the aging measure used by Acemoglu and Restrepo (2017b). We find strong evidence of a positive correlation between them. Column 2 includes log initial GDP per capita for each subperiod as an additional regressor, while column 3 also adds the initial aging to regressors. Column 4 also includes a set of dummies for World Bank "regions" as regressors to allow for differential trends by regions.[3] Despite these additional controls, the coefficient of the 5-year change in the ratio is still statistically significant at the 1% level. Following Acemoglu and Restrepo (2017b), we also report IV regression results in column 5 by using lagged birth rates as instruments.[4] Again, we still find the coefficient of interest statistically significant at the 1% level.

One advantage of using panel data is that we can eliminate unobserved country fixed effects. Columns 6 and 7 report panel regression results with country fixed effects and IV panel regression results with country fixed effects, respectively. Including country fixed effects hardly changes the evidence that the growth rate of GDP per capita is positively associated with the change in aging. Finally, in columns 8 and 9, we report panel regression results with country fixed effects and IV panel regression results with country fixed effects, respectively, for OECD countries. As Acemoglu and Restrepo (2017b) note, we have much weaker results for OECD countries: the coefficient of interest is positive and statistically significant at the 10% only in column 8 and is negative and statistically significant at 10% in column 9.

While the results in Table 2 suggest that population aging is positively associated with growth, particularly when we use the whole country sample, Lee and Shin (2019) recently point out that an increasing old-age population share does not necessarily coincide with a decreasing working-age population share if the youth-age population share decreases at a higher rate.[5] In fact, in most non-OECD countries, where a demographic shift is still in the early stages, as the old-age population share increases, the working-age population share increases as well. It is therefore difficult to interpret the results in Table 2, since only a variable related to the old-age population share, but not the working-age population share, is included as a regressor.

The above problem is also illustrated in Table 3, where we include only the change in the working-age population share as a regressor. Table 3 is the same as Table 2 except that the change in the working-age population share is used instead of the change in the ratio of the population above 50 to the population between 20 and 49. Again, at least for non-OECD countries, we find that the coefficient of the change in the working-age population share is positive and statistically significant, suggesting that an increase in the working-age population is also positively associated with growth.[6]

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[3] Following Acemoglu and Restrepo (2017b), the regions are Latin America, East Asia, South Asia, Africa, North Africa and Middle East, Eastern Europe and Central Asia, and developed countries.

[4] Since Acemoglu and Restrepo (2017b) used birth rates for the 1960, 1965, 1970, 1975, and 1980 cohorts for the 1990–2015, we use 3-, 4- and 5-year period lags as instruments.

[5] Old-age population, working-age population, and youth-age population shares follow the definition provided by the World Development Indicators that are, respectively, the population ages 65 and above, population ages 15–64, and population ages 0–14 as a percentage of total population.

[6] This statement is true except for the results reported in column 7.

Table 2: Impact of Aging on Gross Domestic Product Per Capita Growth

	Dependent Variable: 5-Year GDP Per Capita Growth								
Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Change in aging in 5 years	0.599***	0.816***	0.725***	0.570***	3.132***	1.159***	2.839***	0.278*	–3.758*
	[0.142]	[0.167]	[0.170]	[0.167]	[0.570]	[0.270]	[0.435]	[0.143]	[1.996]
Log initial GDP per capita		–0.004***	–0.005***	–0.007***	–0.009***	–0.027***	–0.038***	–0.023***	0.026
		[0.001]	[0.001]	[0.001]	[0.002]	[0.004]	[0.004]	[0.004]	[0.025]
Initial aging			0.017**	0.011	–0.038***	–0.045**	–0.091***	–0.028*	–0.006
			[0.007]	[0.010]	[0.013]	[0.019]	[0.023]	[0.016]	[0.028]
Pooled regression	√	√	√	√	√				
Fixed effects						√	√	√	√
Area dummy				√	√				
IV regression					√		√		√
OECD countries								√	√
First-stage F-stat (IV reg)					48.23		85.35		3.139
Sargen-Hansen Stat (IV reg)					0.007		0.0001		0.0421
Observations	1,547	1,547	1,547	1,538	1,280	1,547	1,288	323	323
R-squared	0.012	0.023	0.027	0.070	–0.081	0.109	0.054	0.220	–1.270
Number of countries						170	170	35	35

GDP = gross domestic product, IV = instrumental variable, OECD = Organisation for Economic Co-operation and Development, OLS = ordinary least squares.

Notes: We estimate the impact of aging on 5-year real GDP per capita growth for all countries (columns 1–7) and OECD countries (columns 8 and 9). The entire sample period of 1965–2014 is divided into 10 5-year subperiods. Note that the 10th subperiod is 4 years (2010–2014) due to the data availability in the Penn World Table 9.0. Following Acemoglu and Restrepo (2017b), aging is defined as the 5-year change in the ratio of the population above 50 years old to the population between 20 and 49. Columns 1–5 present pooled OLS estimates and columns 6–9, panel estimates with country fixed effects. Columns 4 and 5 include a set of dummies for World Bank “regions” as regressors. Columns 5, 7, and 9 report instrumental variable estimates in which we instrument aging using the birth rates in 3-, 4- and 5-period lags. Numbers in brackets are robust standard errors and ***, **, and * denote the significance levels of 1%, 5%, and 10%, respectively.

Source: Authors’ calculations.

Table 3: Impact of Working-Age Population Share on Gross Domestic Product Per Capita Growth

	Dependent Variable: 5-Year GDP Per Capita Growth								
Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Change in aging in working-age population in 5 years	0.016***	0.017***	0.024***	0.019***	0.024	0.011**	−0.068***	0.005	−0.028**
	[0.004]	[0.003]	[0.004]	[0.004]	[0.028]	[0.004]	[0.024]	[0.006]	[0.012]
Log initial GDP per capita		−0.002**	−0.006***	−0.007***	−0.005***	−0.022***	−0.024***	−0.019***	−0.028***
		[0.001]	[0.001]	[0.001]	[0.002]	[0.003]	[0.003]	[0.004]	[0.006]
Initial aging in working-age population			0.043***	0.036***	0.032	−0.010	−0.114***	−0.022	−0.032
			[0.007]	[0.011]	[0.028]	[0.020]	[0.040]	[0.019]	[0.023]
Pooled regression	√	√	√	√	√				
Fixed effects						√	√	√	√
Area dummy				√	√				
IV regression					√		√		√
OECD countries								√	√
First-stage F-stat (IV reg)					4.996		15.05		31.86
Sargen-Hansen Stat (IV reg)					0.000		0.000		0.699
Observations	1,549	1,549	1,537	1,528	1,272	1,537	1,280	323	265
R-squared	0.017	0.022	0.046	0.078	0.083	0.082	−0.276	0.216	−0.030
Number of countries						169	169	35	35

GDP = gross domestic product, IV = instrumental variables, OECD = Organisation for Economic Co-operation and Development, OLS = ordinary least squares.

Notes: We estimate the impact of the working-age population share (population ages 15–64 as a percentage of total population) on 5-year real GDP per capita growth for all countries (columns 1–7) and OECD countries (columns 8 and 9). The entire sample period of 1965–2014 is divided into 10 5-year subperiods. Note that the 10th subperiod is 4 years (2010–2014) due to the data availability in the Penn World Table 9.0. Columns 1–5 present pooled OLS estimates and columns 6–9, panel estimates with country fixed effects. Columns 4 and 5 include a set of dummies for World Bank "regions" as regressors. Columns 5, 7, and 9 report instrumental variable estimates in which we instrument aging using the birth rates in 3-, 4-, and 5-period lags. Numbers in brackets are robust standard errors and ***, **, and * denote the significance levels of 1%, 5%, and 10%, respectively.

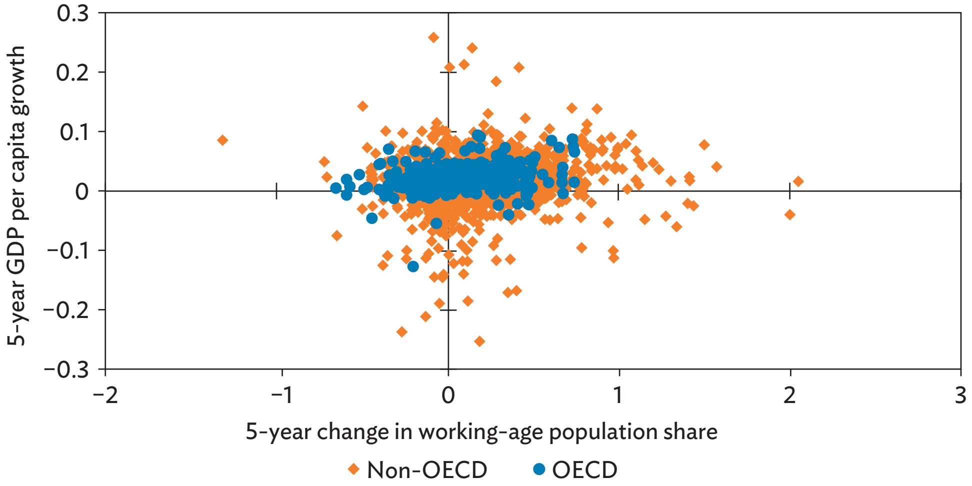
Source: Authors' calculations.

Figures 1 and 2 also graphically show the unconditional correlations reported in column (1) of Tables 2 and 3, respectively. In fact, the positive correlation is more visible in Figure 2, that is, for the correlation between the 5-year change in the working-age population share and the 5-year GDP per capita growth.

Figure 1: 5-Year Gross Domestic Product Per Capita Growth and Change in Aging

GDP = gross domestic product, OECD = Organisation for Economic Co-operation and Development.
Note: Following Acemoglu and Restrepo (2017b), aging is defined as the 5-year change in the ratio of the population above 50 years (thus, old) to the population between 20 and 49 (young).
Source: Authors' calculations.

Figure 2: 5-Year Gross Domestic Product Growth Per Capita and Change in Working-Age Population Share



GDP = gross domestic product, OECD = Organisation for Economic Co-operation and Development
Note: Aging is defined as the 5-year change in the working-age population share.
Source: Authors' calculations.

Tables 2 and 3, and Figures 1 and 2 suggest that the change in the ratio of the population above 50 to the population between 20 and 49 may not be an appropriate measure of aging. If the impact of aging mainly comes through a shortage in the working-age population, directly looking at the change in the working-age population share would be more desirable. An even better measure would be to consider the whole age distribution of the population. The next section examines how our view on the impact of aging changes if we utilize the information on the whole age distribution of the population.

III. IMPACT OF DEMOGRAPHIC CHANGE ON GROWTH

Fair and Dominguez (1991) proposed one way to consider the whole age distribution of the population. Suppose that the population for country i at time t is divided into J age-groups and the share of each group is represented by $\mathrm{p1}_{it}, \mathrm{p2}_{it}, \dots, \mathrm{pJ}_{it}$. Then the impact of the whole distribution on y_{it} can be estimated from the following equation:

$$y_{it} = \lambda + X_{it}\beta + \alpha_1 \mathrm{p1}_{it} + \alpha_2 \mathrm{p2}_{it} + \cdots + \alpha_J \mathrm{pJ}_{it} + u_{it} \tag{1}$$

where λ is a constant term, X_{it} is a ($1\times k$) vector of other explanatory variables, β is a ($k\times1$) vector of coefficients, α_j is age-group j's coefficient, and u_{it} is the error term. Since the sum of pj_{it} over j=1,2,...,J is equal to 1 and a constant term is included, a restriction must be imposed on α_j. Following Fair and Dominguez (1991), the sum of age-group coefficients is restricted to equal to zero: $\sum_{j=1}^{J} \alpha_j = 0$. As one adopts finer classification of age groups, the number of coefficients to estimate also increases. Fair and Dominguez (1991), to avoid this problem, imposed a second restriction that the age-group coefficients lie on a second-order polynomial. We extend their approach and restrict that they lie on a third-order polynomial: $\alpha_j = \gamma_0 + \gamma_1 j + \gamma_2 j^2 + \gamma_3 j^3$. In this way, the number of coefficients to estimate is substantially lowered. We can easily show that the final equation is reduced to the following:[7]

$$y_{it} = \lambda + X_{it}\beta + \gamma_1 D1_{it} + \gamma_2 D2_{it} + \gamma_3 D3_{it} + u_{it} \tag{2}$$

where $D1_{it} = \sum_{j=1}^{J} j \cdot pj_{it} - \frac{1}{J}\sum_{j=1}^{J} j$, $D2_{it} = \sum_{j=1}^{J} j^2 \cdot pj_{it} - \frac{1}{J}\sum_{j=1}^{J} j^2$, and $D3_{it} = \sum_{j=1}^{J} j^3 \cdot pj_{it} - \frac{1}{J}\sum_{j=1}^{J} j^3$. By estimating equation (2), we can recover the coefficients, α_j, in equation (1).

Table 4 reports the estimation results of equation (2) where the dependent variable, y_{it}, is 5-year average growth rate of GDP per capita and X_{it} includes only the initial real GDP per capita for each 5-year subperiod.[8] Before the estimation, we removed outliers.[9] As reported by the United

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[7] See Higgins (1998), appendix, for the derivation of equation (2) when the age-group coefficients lie on a third-order polynomial.

[8] Because the initial GDP per capita is included as a regressor, if we include country fixed effects, normally a dynamic panel specification is preferred. However, we do not estimate a dynamic panel specification, since we use a different measure of GDP for the initial GDP per capita. While the GDP per capita to calculate the growth rate used for the dependent variable is based on national accounts ($\mathrm{RGDP}^{\mathrm{NA}}$), the initial GDP per capita is measured based on the output-side real GDP at chained purchasing power parity ($\mathrm{RGDP}^{\mathrm{O}}$) that is more appropriate to compare real GDP per capita across countries for different years.

[9] We removed observations with 5-year annual average growth rate less than -5% or over 15% since these extreme growth rates are not explained by purely economic fundamentals. We also removed extremely young countries with old dependency rates less than 4%.

Nations World Population Prospects 2017, the population distribution is denoted by 17 $(= J)$ 5-year age groups: (0,4); (5,9);...;(80 and over). While we used the change in the ratio of the population above 50 to the population between 20 and 49 as a regressor in section II, we measure $D1_{it}, D2_{it}$ and $D3_{it}$ at the initial year of each 5-year subperiod. There are two reasons for this. First, unlike the ratio, it is not easy to calculate the change in the whole distribution. Second, the distribution in some sense already captures the difference. For example, if we ignore death, population belonging to the age group (0,4) will belong to the next age group (5,9) in 5 years, and the difference in the share of each age group can be easily inferred from the distribution.

Table 4: Impact of Age Distribution on Gross Domestic Product Per Capita Growth

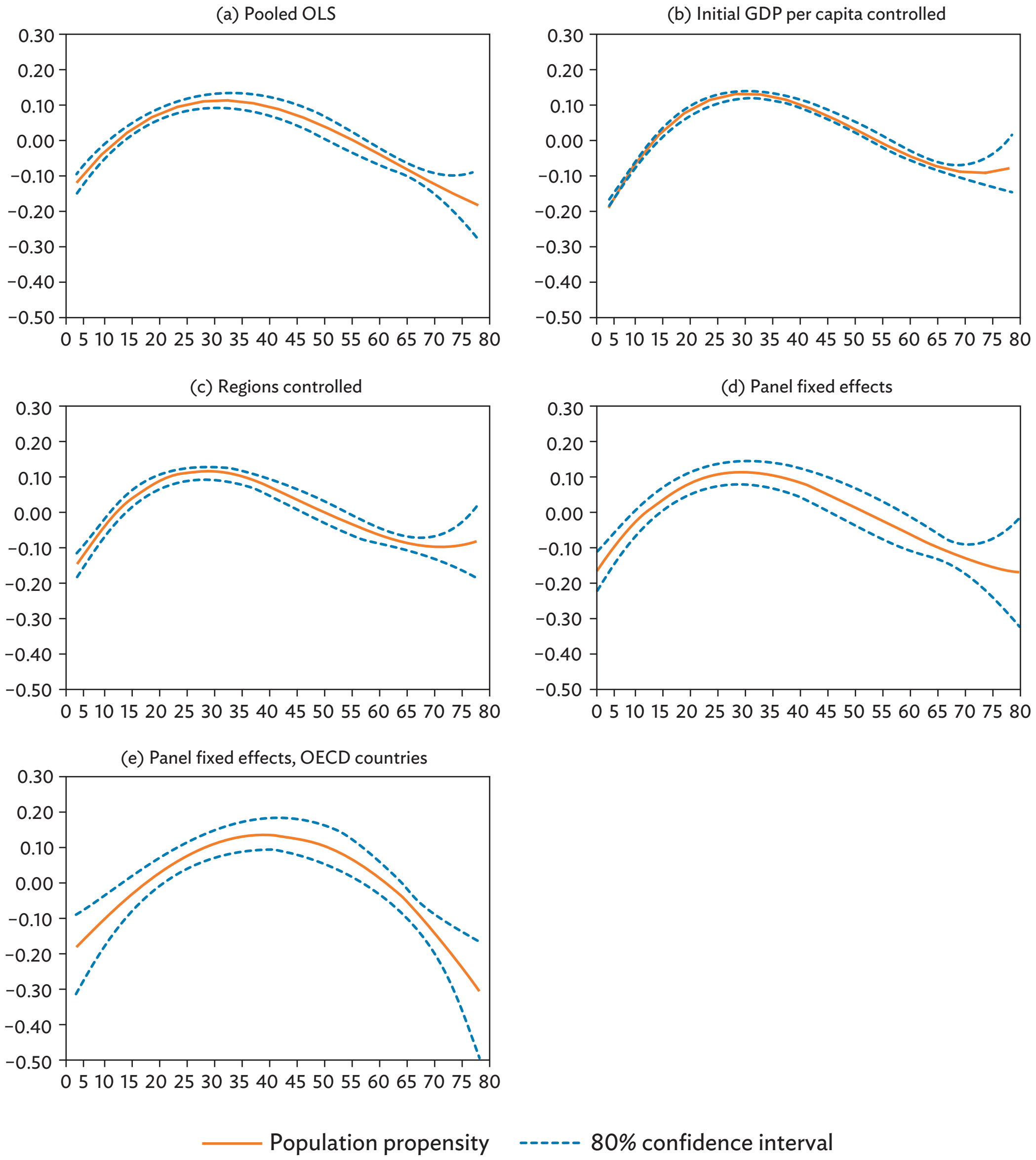
	Dependent Variable: 5-Year GDP Per Capita Growth				
Variables	(1)	(2)	(3)	(4)	(5)
Log initial GDP per capita		−0.006***	−0.006***	−0.019***	−0.032***
		[0.001]	[0.001]	[0.004]	[0.006]
$D1$	0.110***	0.170***	0.147***	0.139***	0.099
	[0.029]	[0.032]	[0.031]	[0.045]	[0.068]
$D2$	−0.011**	−0.019***	−0.017***	−0.015**	−0.005
	[0.005]	[0.005]	[0.005]	[0.007]	[0.009]
$D3$	0.000	0.001***	0.001***	0.000	−0.000
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Pooled regression	√	√	√		
Fixed effects				√	√
Area dummy			√		
OECD countries					√
Observations	1,454	1,454	1,445	1,454	321
R-squared	0.065	0.089	0.127	0.100	0.347
p-value of joint test	0.000	0.000	0.000	0.000	0.004
Number of countries	167	167	167	167	35

GDP = gross domestic product, OECD = Organisation for Economic Co-operation and Development, OLS = ordinary least squares.
Notes: We estimate the impact of age distribution on 5-year real GDP per capita growth for all countries (columns 1–4) and OECD countries (column 5). The entire sample period of 1965–2014 is divided into 10 5-year subperiods. Note that the 10th subperiod is 4 years (2010–2014) due to the data availability in the Penn World Table 9.0. Columns 1–3 present pooled OLS estimates and columns 4 and 5, panel estimates with country fixed effects. Column 3 includes a set of dummies for World Bank "regions" as regressors. D1, D2, and D3 are transformation variables of the age distribution by assuming that the age-group coefficients lie on a third-order polynomial. Numbers in brackets are robust standard errors and ***, **, and * denote the significance levels of 1%, 5%, and 10%, respectively. P-value is for the joint hypothesis that the coefficients of D1, D2, and D3 are all zero.
Source: Authors' calculations.

In Table 4, columns 1–3 report the pooled OLS regression results of estimating equation (2). In column 1, we do not include the initial GDP per capita as a regressor. We include the initial GDP per capita in column 2 and both the initial GDP per capita and the region dummies in column 3. In these pooled OLS regressions, the coefficients of $D1, D2,$ and $D3$ are highly significant and the p-value of the joint hypothesis that all three coefficients are zero is rejected at less than 1% level. The panel regression results with country fixed effects are reported in column 4 (all countries) and column 5 (OECD countries only). Again, the individual coefficients of $D1$ and $D2$ are highly significant in column 4 and while the individual coefficients of $D1, D2,$ and $D3$ are not statistically significant, the p-value of the joint hypothesis that all three coefficients are zero is 0.02 in column 5. These results strongly support that the initial age distribution is closely associated with future growth.

Figure 3 illustrates α_j $(j = 1, \ldots 17)$ retrieved from the transformation: $\alpha_j = \gamma_0 + \gamma_1 j + \gamma_2 j^2 + \gamma_3 j^3$. Note that γ_1, γ_2, and γ_3 are from Table 4 and γ_0 is from the restriction that the sum of α_j $(j = 1, \ldots 17)$ is equal to zero. Figure 3 presents five figures with 80% confidence intervals corresponding to the five columns in Table 4.

Figure 3: Age-Group Coefficients for 5-Year Gross Domestic Product Per Capita Growth



GDP = gross domestic product, OECD = Organisation for Economic Co-operation and Development, OLS = ordinary least squares.
Notes: On the horizontal axis, 0 represents the age group (0,4); 5 represents the age group (5,9); and so on. The five figures are derived from the five columns reported in Table 4. The solid line denotes age-group coefficients that lie on a third-order polynomial and the dashed lines, 80% confidence intervals.
Source: Authors' calculations.

In the figure, 0 represents the age group (0,4); 5 represents the age group (5,9); and so on. While there are some differences across different specifications, one common feature for the first four figures is that age groups between 15 and 40 (or 45) contribute positively to future growth, and age groups below 10 and above 60, negatively.[10] Another interesting feature is that the confidence interval for very old age groups is large, indicating that their contribution is not precisely estimated. In contrast, the last figure, for OECD countries only, shows a wider range of age groups between 20 and 65 that contribute positively to future growth. In all cases, age-group coefficients take an inverted-U shape, indicating that age groups in the middle contribute most to economic growth.

In Table 5, we estimate equation (2) for different subsample periods. We include the initial GDP per capita as regressors. Columns 1 and 2 cover periods 1–4, columns 3 and 4, periods 5–8, and columns 5 and 6, periods 7–10. The odd columns report pooled OLS estimates and the even columns, panel regression estimates with country fixed effects. The coefficients of $\mathrm{D1}$, $\mathrm{D2}$, and $\mathrm{D3}$ are all statistically significant individually in columns 3–5 and jointly in all columns.

Table 5: Impact of Age Distribution on Gross Domestic Product Per Capita Growth by Period

	Dependent Variable: 5-Year GDP Per Capita Growth					
	(1)	(2)	(3)	(4)	(5)	(6)
	Periods 1–4		Periods 5–8		Periods 7–10	
Variables	OLS	FE	OLS	FE	OLS	FE
Log initial GDP per capita	−0.000	−0.052***	−0.011***	−0.039***	−0.014***	−0.021***
	[0.002]	[0.007]	[0.002]	[0.009]	[0.002]	[0.006]
D1	0.151**	0.170*	0.328***	0.416***	0.193***	0.188*
	[0.069]	[0.095]	[0.051]	[0.098]	[0.047]	[0.099]
D2	−0.018*	−0.011	−0.040***	−0.054***	−0.020***	−0.017
	[0.011]	[0.015]	[0.008]	[0.016]	[0.007]	[0.015]
D3	0.001	−0.000	0.001***	0.002***	0.001**	0.000
	[0.000]	[0.001]	[0.000]	[0.001]	[0.000]	[0.001]
Observations	522	522	603	603	650	650
R-squared	0.049	0.211	0.199	0.193	0.185	0.120
p-value of joint test	0.001	0.000	0.000	0.000	0.000	0.000
Number of countries	167	142	167	167	166	166

FE = fixed effects, GDP = gross domestic product, OLS = ordinary least squares.
Notes: We estimate the impact of age distribution on 5-year real GDP per capita growth for all countries for periods 1–4 (columns 1 and 2), periods 5–8 (columns 3 and 4), and periods 7–10 (columns 5 and 6). Columns 1, 3, and 5 present pooled OLS estimates and columns 2, 4, and 6, panel estimates with country fixed effects. D1, D2, and D3 are transformation variables of the age distribution by assuming that the age-group coefficients lie on a third-order polynomial. Numbers in brackets are robust standard errors and ***, **, and * denote the significance levels of 1%, 5%, and 10%, respectively. p-value is for the joint hypothesis that the coefficients of D1, D2, and D3 are all zero.
Source: Authors' calculations.

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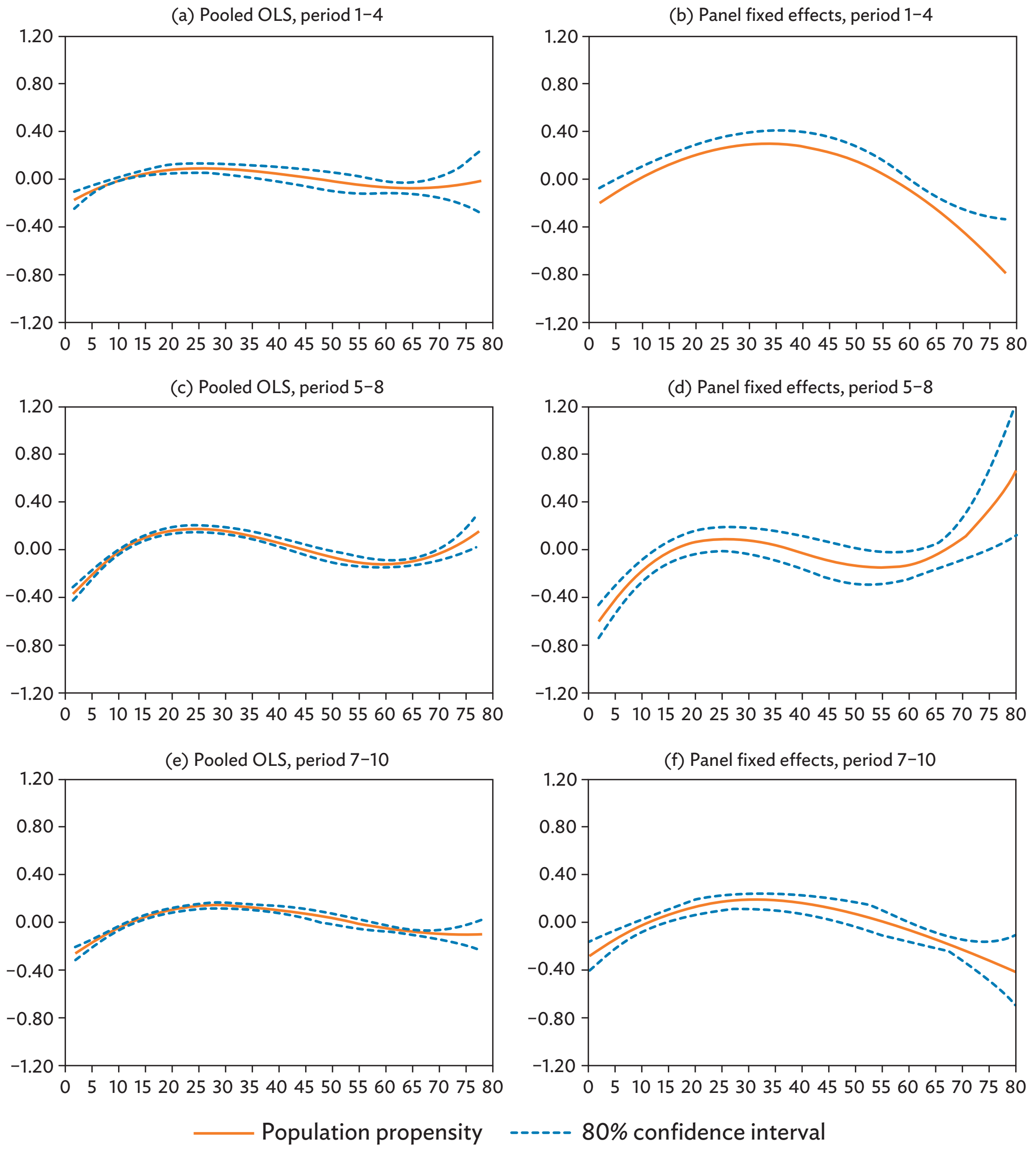
[10] Note that we normalize the sum of the coefficients to be equal to zero. Hence, whether the contribution is positive or negative should be interpreted to mean that the level of the growth rate is appropriately adjusted by the constant term. Recently Aksoy et al. (2018) also show that, based on a panel vector autoregression of 21 OECD economies, young and old dependents have a negative impact, while workers contribute positively to medium-run growth trends. Lindh and Malmberg (1999), by dividing population into four age groups—(15–29), (30–49), (50–64), and (65 and over)—and using their shares directly as regressors, find that the 50–64 age group contributes positively to growth, and the group above 65, negatively.

In Figure 4, we illustrate graphically the age-group coefficients. In the left panel, we plot age-group coefficients derived from pooled OLS estimates and in the right panel, we plot those derived from panel regression estimates. In both panels, while there is some peculiar pattern that for very old age groups in the middle periods 5–8, the estimates are not precise for those groups. While differences exist in the age-group coefficients across periods, overall, the age-group coefficients exhibit an inverted-U shape.

Figure 4: Age-Group Coefficients for 5-Year Gross Domestic Product Per Capita Growth by Periods



OLS = ordinary least squares.
Notes: On the horizontal axis, 0 represents the age group (0,4); 5 represents the age group (5,9); and so on. The six figures are derived from the six columns reported in Table 5. The solid ine denotes age-group coefficients that lie on a third-order polynomial and the dashed lines, 80% confidence intervals.
Source: Authors' calculations.

IV. TECHNOLOGICAL ADVANCEMENTS AND THE IMPACT OF AGING ON GROWTH

In the previous section, we found that, in general, age-group coefficients follow an inverted-U shape. Our findings thus suggest that demographic change that increases old-age population share and decreases working-age population share lowers future growth. However, as suggested in Table 5, the shape of age coefficients changes over time and is expected to be influenced by several other factors.

In this section, we consider four proxies of technological advancement and examine each variable's influence on the impact of population aging on growth. The first proxy is life expectancy, which represents technological improvement in providing better health care to increase life span. In Table 6, we report the estimation results when we add the interaction term between life expectancy and age-group distribution to the regressors, maintaining the restriction that age-group coefficients lie on a third-order polynomial. Column 1 reports pooled OLS regression results and column 2, panel regression results with country fixed effects.

In column 1, every individual coefficient is statistically significant at the conventional level and both joint hypotheses that all three individual coefficients of $D1$, $D2$, and $D3$ are zero and that those of their interaction terms are all zero are rejected at the 1% level. In column 2, individual coefficients are less precisely estimated and only the joint hypothesis that all three individual coefficients of $D1$, $D2$, and $D3$ are zero is rejected at the 10% level.

Table 6: Increasing Life Expectancy and Impact of Age Distribution on Gross Domestic Product Per Capita Growth

	Dependent Variable: 5-Year GDP Per Capita Growth	
Variables	(1) Pooling	(2) Fixed Effects
Log initial GDP per capita	−0.008***	−0.021***
	[0.001]	[0.004]
Life expectancy	−0.003***	−0.001
	[0.001]	[0.001]
$D1$	0.567***	0.612**
	[0.200]	[0.307]
$D2$	−0.081***	−0.078*
	[0.031]	[0.047]
$D3$	0.003***	0.003
	[0.001]	[0.002]
Interaction ($D1$ x Life expectancy)	−0.007**	−0.008*
	[0.003]	[0.005]
Interaction ($D2$ x Life expectancy)	0.001**	0.001
	[0.000]	[0.001]
Interaction ($D3$ x Life expectancy)	−0.000***	−0.000
	[0.000]	[0.000]

continued on next page

Table 6 *continued*

	Dependent Variable: 5-year GDP Per Capita Growth	
Variables	(1) Pooling	(2) Fixed Effects
Observations	1,439	1,439
R-squared	0.129	0.115
p-value of joint test: Level terms	0.000	0.074
p-value of joint test: Interaction terms	0.000	0.131
Number of countries	165	165

GDP = gross domestic product.
Notes: We estimate the impact of age distribution on 5-year real GDP per capita growth for all countries. The entire sample period of 1965–2014 is divided into 10 5-year subperiods. Note that the 10th subperiod is 4 years (2010–2014) due to the data availability in the Penn World Table 9.0. D1, D2, and D3 are transformation variables of the age distribution by assuming that the age-group coefficients lie on a third-order polynomial. Numbers in brackets are robust standard errors and ***, **, and * denote the significance levels of 1%, 5%, and 10%, respectively. p-values are for the joint hypotheses that the coefficients of D1, D2, and D3 are all zero and the coefficients of their interactions with life expectancy.
Source: Authors' calculations.

In Figure 5, we illustrate how age-group coefficients change as life expectancy increases from 50 to 80. As reported in Table 1, the mean, minimum, and maximum of life expectancy in the sample is 63.5, 23.6, and 83.1, respectively. Figure 5.A is based on the estimation results of column 1 in Table 6, which is obtained from the pooled OLS estimations with the restriction that the age-group coefficients follow a third-order polynomial. If we ignore the extremely old age groups for which the coefficients are not precisely estimated, as life expectancy increases, the range of age groups that contribute to economic growth cover older-age population. When life expectancy is 50, the positive range is between 15 and 50; but as life expectancy increases to 80, the positive range becomes wider and even the coefficients of groups age 70 and above are positive.

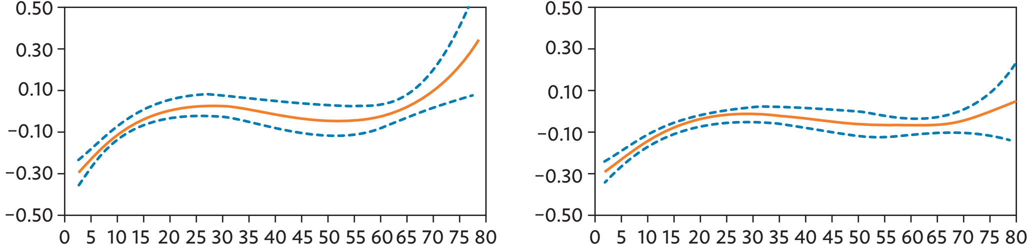
Hence, we conclude that increasing life expectancy enables even older people to more positively contribute to future growth. Generally, we obtain consistent results in Figure 5.B, which is based on the estimation results of column 2 in Table 6, obtained from the panel fixed effects estimation.

Our second proxy for technological progress is labor productivity, which is supposed to capture any technological advancement associated with labor productivity increases. We calculate labor productivity from dividing output-side real GDP at chained purchasing power parities by the number of people engaged, obtained from the Penn World Table 9.0. Again, Table 7 presents regression results that include interaction terms between log labor productivity and age distribution variables in third-order polynomial. In Table 7, both individually and jointly, the coefficients of the levels and interaction terms are highly significant in both pooled OLS and panel fixed effects estimations. Hence the age-group coefficients are affected as labor productivity changes.

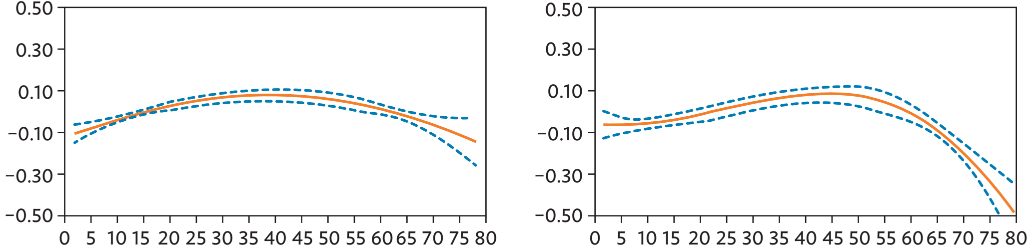
Figure 5: Increasing Life Expectancy and Age-Group Coefficients

A. Pooled OLS regression

(a) Life expectancy = 50 years (b) Life expectancy = 60 years

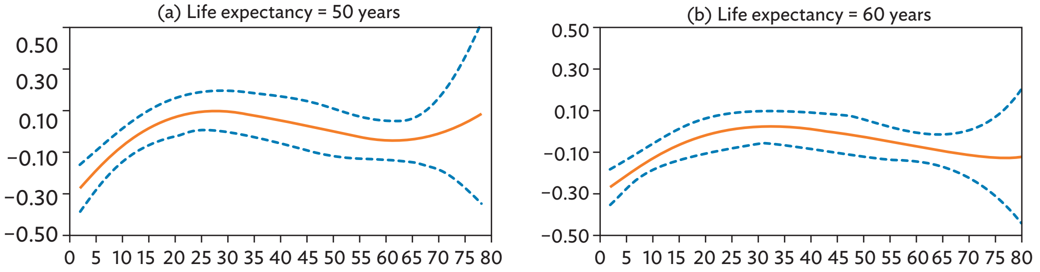


(c) Life expectancy = 70 years (d) Life expectancy = 80 years

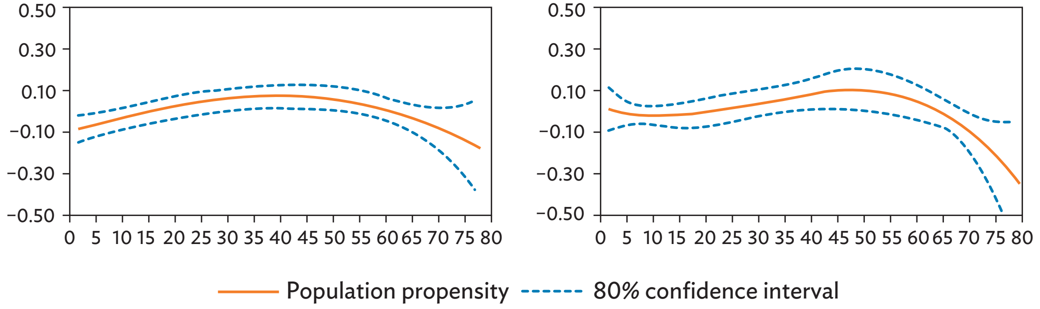


B. Panel fixed effects regression

(a) Life expectancy = 50 years (b) Life expectancy = 60 years



(c) Life expectancy = 70 years (d) Life expectancy = 80 years



OLS = ordinary least squares.

Notes: On the horizontal axis, 0 represents the age group (0,4); 5 represents the age group (5,9); and so on. Figures in panels A and B assume that the age-group coefficients lie on a third-order polynomial that are derived from columns 1 and 2 in Table 6, respectively, with life expectancy varying from 50 to 80. The solid line denotes age-group coefficients that lie on a third-order polynomial and the dashed lines, 80% confidence intervals.

Source: Authors' calculations.

Table 7: Increasing Labor Productivity and Impact of Age Distribution on Gross Domestic Product Per Capita Growth

	Dependent Variable: 5-Year GDP Per Capita Growth	
Variables	(1) Pooling	(2) Fixed Effects
Log initial GDP per capita	−0.005	−0.053***
	[0.004]	[0.012]
Labor productivity	−0.021***	0.016
	[0.007]	[0.018]
$\mathrm{D1}$	1.672***	2.355***
	[0.269]	[0.404]
$\mathrm{D2}$	−0.230***	−0.324***
	[0.042]	[0.066]
$\mathrm{D3}$	0.009***	0.012***
	[0.002]	[0.003]
Interaction ($\mathrm{D1}$ x Labor productivity)	−0.158***	−0.226***
	[0.028]	[0.040]
Interaction ($\mathrm{D2}$ x Labor productivity)	0.022***	0.032***
	[0.004]	[0.007]
Interaction ($\mathrm{D3}$ x Labor productivity)	−0.001***	−0.001***
	[0.000]	[0.000]
Observations	1,324	1,324
R-squared	0.158	0.161
p-value of joint test: Level terms	0.000	0.000
p-value of joint test: Interaction terms	0.000	0.000
Number of countries	167	167

GDP = gross domestic product.

Notes: We estimate the impact of age distribution on 5-year real GDP per capita growth for all countries. The entire sample period of 1965–2014 is divided into 10 5-year subperiods. Note that the 10th subperiod is 4 years (2010–2014) due to the data availability in the Penn World Table 9.0. Column 1 presents pooled OLS estimates and column 2, panel estimates with country fixed effects. $\mathrm{D1}$, $\mathrm{D2}$, and $\mathrm{D3}$ are transformation variables of the age distribution by assuming that the age-group coefficients lie on a third-order polynomial. Numbers in brackets are robust standard errors and ***, **, and * denote the significance levels of 1%, 5%, and 10%, respectively. p-values are for the joint hypotheses that the coefficients of $\mathrm{D1}$, $\mathrm{D2}$, and $\mathrm{D3}$ are all zero and the coefficients of their interactions with labor productivity.

Source: Authors' calculations.

In Figure 6, we illustrate how age-group coefficients change as the log labor productivity increases from 8.5 to 11.5.[11] Figure 6.A is based on the estimation results of column 1 in Table 7, running pooled OLS regressions. Again, if we ignore the extremely old age groups for which the coefficients are not precisely estimated, increasing labor productivity moves the positive range of the coefficients toward older age groups. For example, when log labor productivity is 8.5, the positive range is between 10 and 45, and when it increases to 11.5, the positive range moves between 30 and 70. In Figure 6.B, which is based on the estimation results of column 2 in Table 7, as the log labor productivity increases from 8.5 to 11.5, the positive range moves from the age groups between 10 and 45 to the age groups between 30 and 70. Overall, our evidence indicates that increasing labor productivity favors older generations and disfavors the younger.

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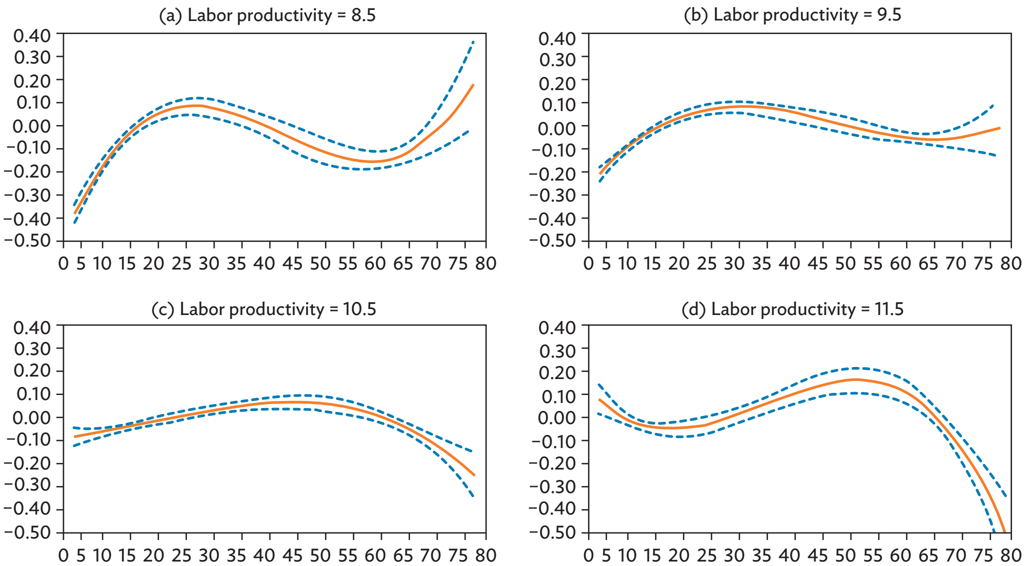
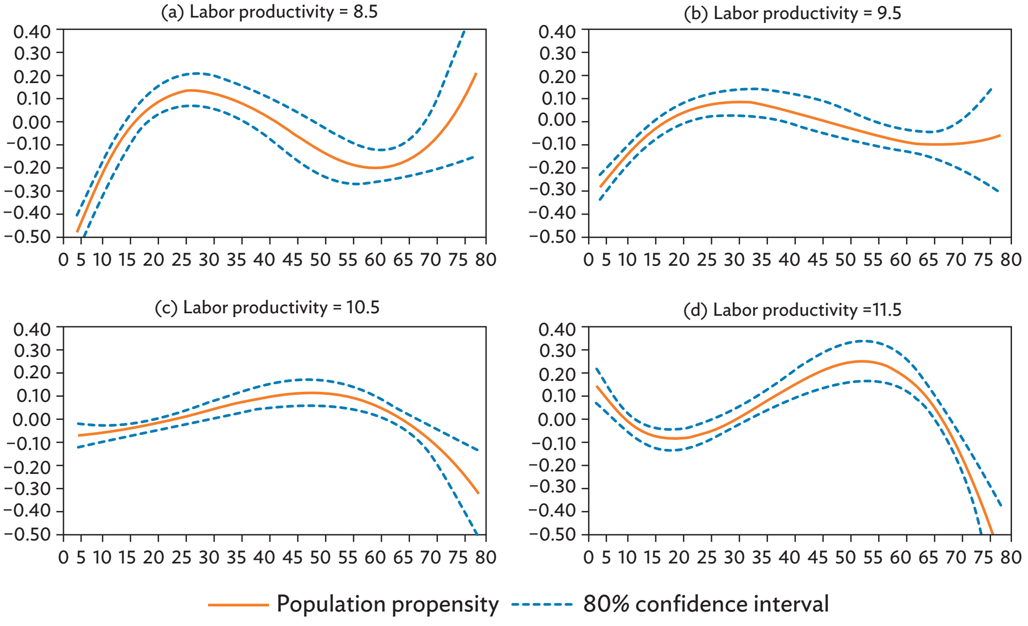
[11] In Table 1, the mean, minimum, and maximum of the log labor productivity in the sample is 9.7, 6.2, and 15.4, respectively. If we remove the outliers, it varies in the range of 8 and 12.

Figure 6: Increasing Labor Productivity and Age-Group Coefficients

A. Pooled OLS regression



B. Panel fixed effects regression



OLS = ordinary least squares.

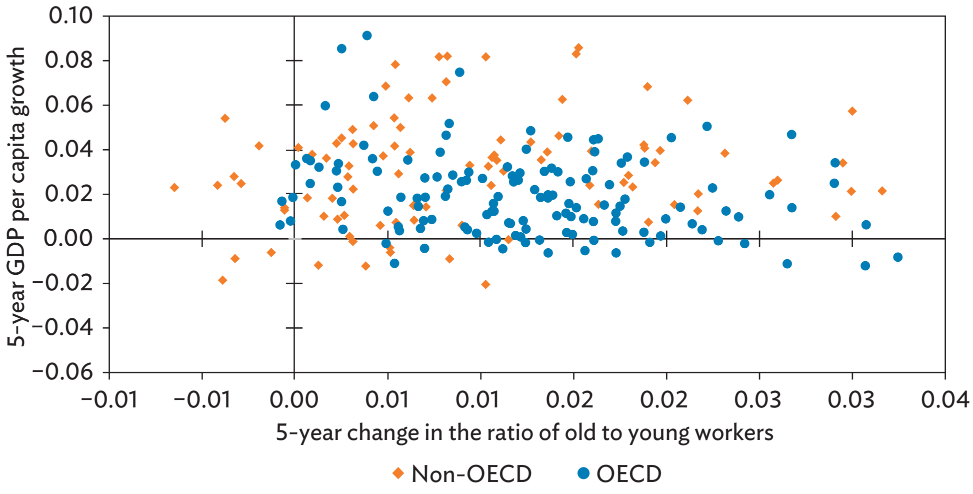
Notes: On the horizontal axis, 0 represents the age group (0,4); 5 represents the age group (5,9); and so on. Figures in panels A and B assume that the age-group coefficients lie on a third-order polynomial that are derived from columns 1 and 2 in Table 7, respectively, with log labor productivity varying from 6 to 15. The solid line denotes age-group coefficients that lie on a third-order polynomial and the dashed lines, 80% confidence intervals.

Source: Authors' calculations.

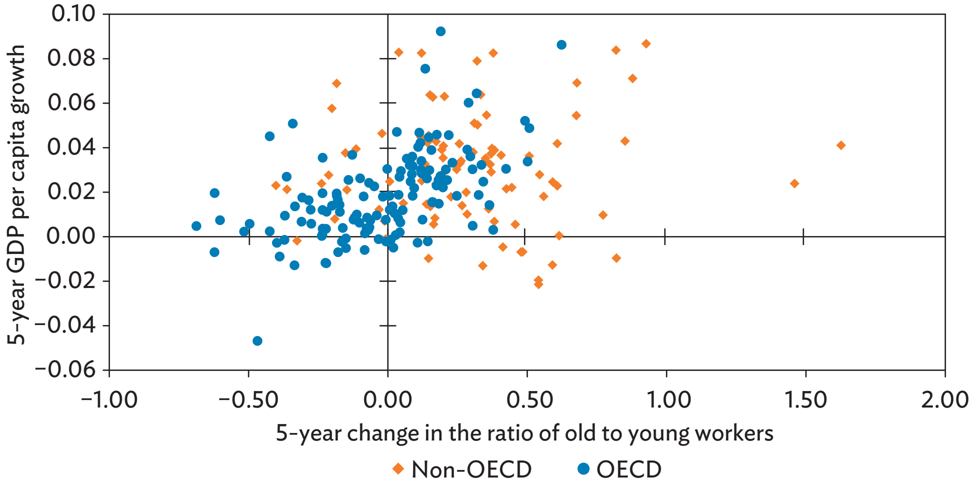
The third proxy, robot density, measures technological progress more narrowly by the degree of automation. Robot density is defined as the stock of robots per million workers. One problem with using robot density is that the sample shrinks substantially, since the robot data are available for limited countries and for a limited time span. To see if the baseline findings persist, we present the raw correlation between 5-year GDP per capita growth and change in aging (as per Acemoglu and Restrepo 2017b) in Figure 7.A and between 5-year GDP per capita growth and change in the working-age share in Figure 7.B. OECD countries are denoted by circles and non-OECD countries, by diamonds. As before, we see more clear positive correlation in Figure 7.B.

Figure 7: Correlations for a Robot Data Subsample

A. 5-year GDP per capita growth and change in aging



B. 5-year GDP per capita growth and change in working-age share



GDP = gross domestic product, OECD = Organisation for Economic Co-operation and Development.
Notes: The sample is restricted to the observation for which robot data are available. Following Acemoglu and Restrepo (2017b), aging in 7.A is defined as the 5-year change in the ratio of the population above 50 years old to the population between 20 and 49, while in 7.B, it is defined as the 5-year change in the working-age population share.
Source: Authors' calculations.

Table 8 also replicates Table 4 using the robot data sample.[12] In Table 8, not only the individual coefficients of age distribution, $D1$, $D2$, and $D3$, are generally statistically significant, the p-value of the joint hypothesis that all three coefficients are equal to zero is quite small, ranging from 0 to 0.06 depending on the specifications.

Table 8: Impact of Age Distribution on Gross Domestic Product Per Capita Growth: Robot Data Subsample

	Dependent Variable: 5-Year GDP Per Capita Growth				
Variables	(1)	(2)	(3)	(4)	(5)
Log initial GDP per capita		−0.013***	−0.011***	−0.048***	−0.075***
		[0.002]	[0.002]	[0.011]	[0.016]
$D1$	0.153	0.223***	0.229***	0.338***	0.224**
	[0.093]	[0.083]	[0.086]	[0.117]	[0.094]
$D2$	−0.014	−0.023**	−0.024**	−0.030*	−0.023*
	[0.013]	[0.012]	[0.012]	[0.018]	[0.012]
$D3$	0.000	0.001	0.001	0.001	0.001
	[0.001]	[0.000]	[0.000]	[0.001]	[0.000]
Pooled regression	√	√	√		
Fixed effects				√	√
Area dummy			√		
OECD countries					√
Observations	273	273	273	273	136
R-squared	0.160	0.290	0.307	0.284	0.528
p-value of joint test	0.000	0.000	0.000	0.000	0.058
Number of countries	69	69	69	69	34

GDP = gross domestic product, OECD = Organisation for Economic Co-operation and Development.
Notes: We estimate the impact of age distribution on 5-year real GDP per capita growth for all countries (columns 1–4) and OECD countries (column 5) for the sample period for which the robot data are available. The entire sample period of 1995–2014 is divided into 10 5-year subperiods. Note that the last subperiod is 4 years (2010–2014) due to the data availability in the Penn World Table 9.0. Columns 1–3 present pooled OLS estimates and columns 4 and 5, panel estimates with country fixed effects. Column 3 includes a set of dummies for World Bank "regions" as regressors. $D1$, $D2$, and $D3$ are transformation variables of the age distribution by assuming that the age-group coefficients lie on a third-order polynomial. Numbers in brackets are robust standard errors and ***, **, and * denote the significance levels of 1%, 5%, and 10%, respectively. p-value is for the joint hypothesis that the coefficients of $D1$, $D2$, and $D3$ are all zero.
Source: Authors' calculations.

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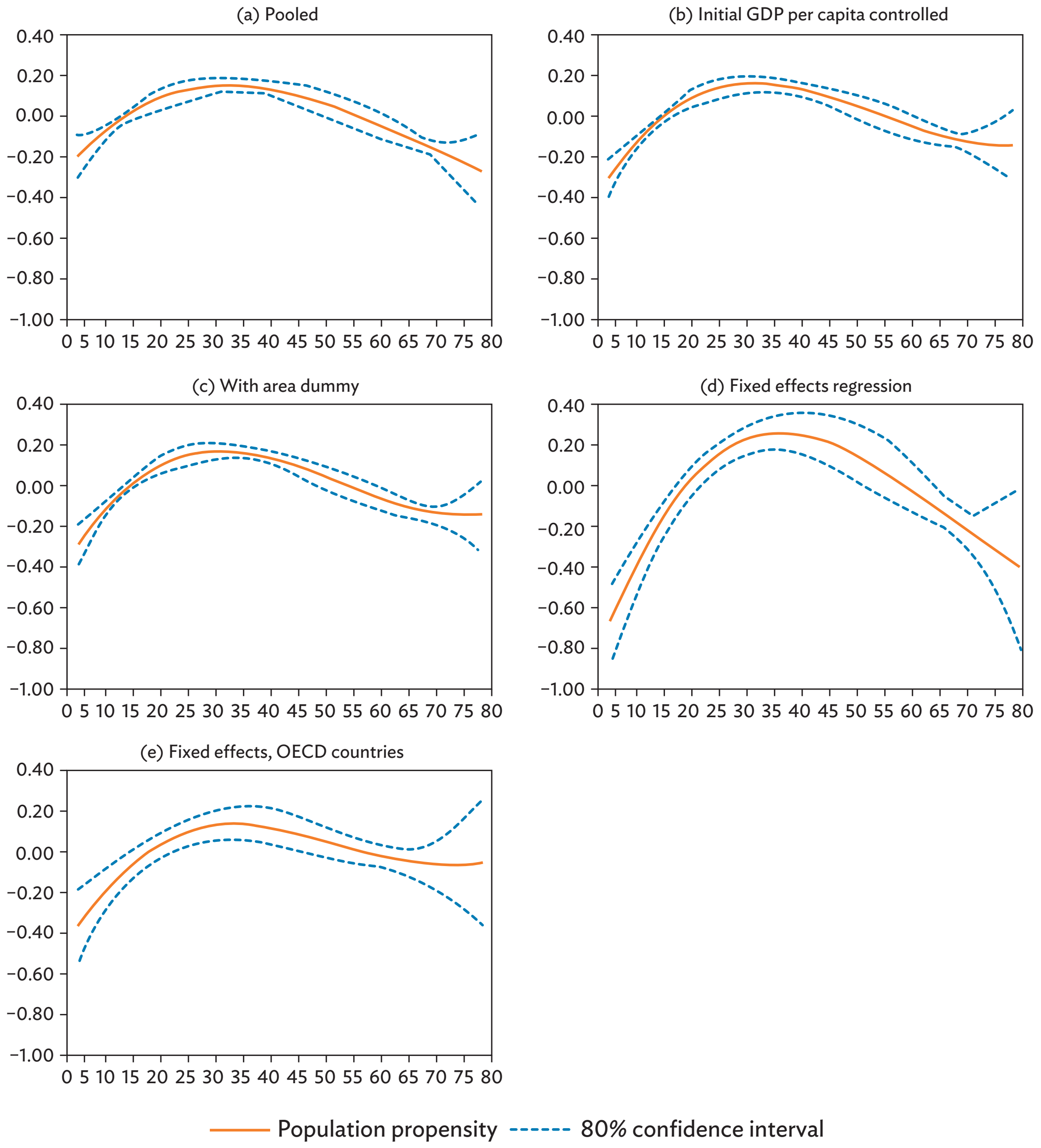
[12] Since most countries in the sample belong to the OECD, we do not report separate regression results for OECD countries.

Figure 8 illustrates the age-group coefficients based on Table 8. They show quite consistent results with those in Figure 3. Overall, the evidence indicates that our baseline results, that the age coefficients take an inverted-U shape, persist even in the robot data sample.

Figure 8: Age-Group Coefficients for 5-Year Gross Domestic Product Per Capita Growth: A Robot Data Subsample



GDP = gross domestic product, OECD = Organisation for Economic Co-operation and Development.
Notes: The sample is restricted to the observation for which robot data are available. In the horizontal axis, 0 represents the age group (0,4); 5 represents the age group (5,9); and so on. The five figures are derived from the five columns reported in Table 8. The solid line denotes age-group coefficients that lie on a third-order polynomial and the dashed lines, 80% confidence intervals.
Source: Authors' calculations.

Table 9 presents regression results for third-order polynomial approximations when we add interaction terms between log robot density and age distribution variables. Both in columns 1 and 2, which report pooled OLS estimations and panel estimation with country fixed effects, only the joint hypothesis that all three coefficients of $D1$, $D2$, and $D3$ are zero is statistically significant at the 10% level.

Table 9: Increasing Robot Density and Impact of Age Distribution on Gross Domestic Product Per Capita Growth

	Dependent Variable: 5-Year GDP Per Capita Growth	
Variables	(1) Pooling	(2) Fixed Effects
Log initial GDP per capita	−0.011***	−0.038***
	[0.003]	[0.012]
$D1$	0.197	0.572
	[0.224]	[0.351]
$D2$	−0.017	−0.067
	[0.032]	[0.054]
$D3$	0.000	0.002
	[0.001]	[0.002]
Log robot density	0.002	−0.000
	[0.003]	[0.012]
Interaction ($D1$ x Log robot density)	−0.002	−0.053
	[0.037]	[0.059]
Interaction ($D2$ x Log robot density)	−0.000	0.006
	[0.005]	[0.008]
Interaction ($D3$ x Log robot density)	0.000	−0.000
	[0.000]	[0.000]
Observations	183	183
R-squared	0.442	0.402
p-value of joint test: Level terms	0.060	0.094
p-value of joint test: Interaction terms	0.846	0.600
Number of countries	65	65

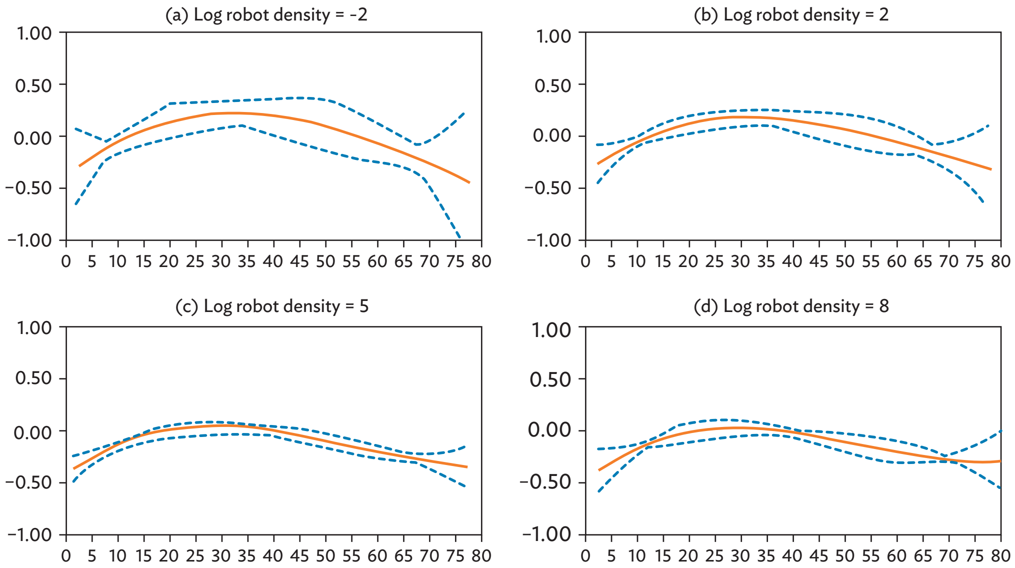
GDP = gross domestic product.

Notes: We estimate the impact of age distribution on 5-year real GDP per capita growth for all countries. The entire sample period of 1995–2014 for which the robot data are available is divided into 10 5-year subperiods. Note that the last subperiod is 4 years (2010–2014) due to the data availability in the Penn World Table 9.0. Column 1 presents pooled OLS estimates and column 2, panel estimates with country fixed effects. $D1$, $D2$, and $D3$ are transformation variables of the age distribution by assuming that the age-group coefficients lie on a third-order polynomial. Numbers in brackets are robust standard errors and ***, **, and * denote the significance levels of 1%, 5%, and 10%, respectively. p-values are for the joint hypotheses that the coefficients of $D1$, $D2$, and $D3$ are all zero and the coefficients of their interactions with robot density.

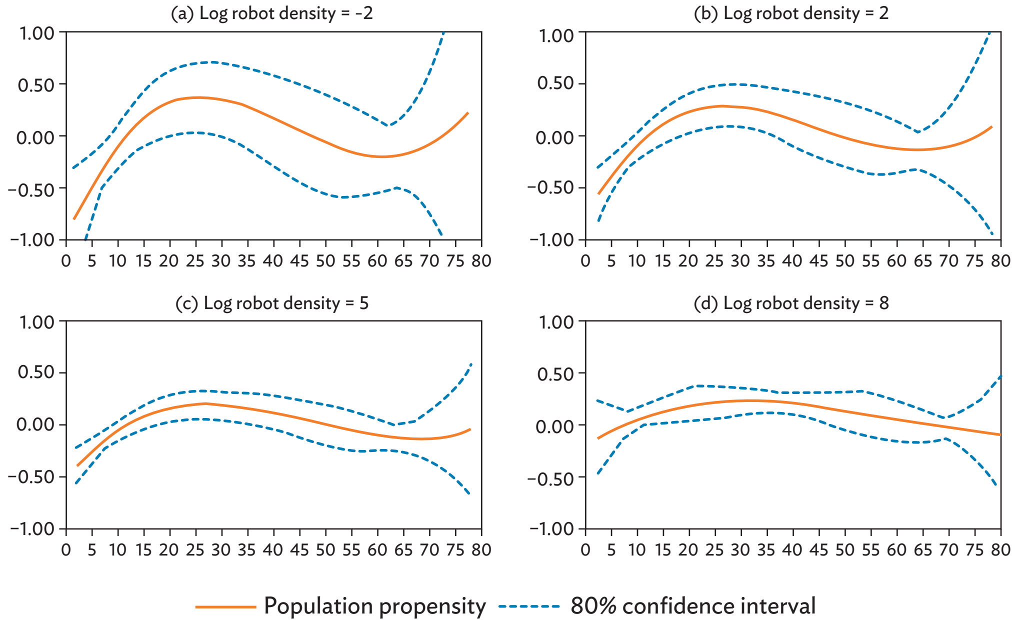
Source: Authors' calculations.

Figure 9: Increasing Robot Density and Age-Group Coefficients

A. Pooled OLS regression



B. Panel fixed effects regression



OLS = ordinary least squares.
Notes: In the horizontal axis, 0 represents the age group (0,4); 5 represents the age group (5,9); and so on. Figures in panels A and B assume that the age-group coefficients lie on a third-order polynomial that are derived from columns 1 and 2 in Table 9, respectively, with log robot density varying from 0 to 13. The solid line denotes age-group coefficients that lie on a third-order polynomial and the dashed lines, 80% confidence intervals.
Source: Authors' calculations.

Figure 9 illustrates age-group coefficients derived from Table 9. Interestingly, in this case, we do not see any evidence that the positive range moves as the log robot density increases from −2 to 8.[13] For example, in Figure 9.A, the positive range is between 10 and 55 when the log robot density is −2 and it stays the same when the log robot density increases to 5. Even when the log robot density further increases to 8, the positive range is between 10 and 50. In Figure 9.B, which is obtained from panel regressions, we obtain similar results. The positive range is between 15 and 50 when the log robot density is −2 and it changes to the 15–55 range when the log robot density increases to 8.

However, there are changes in the age coefficients in other dimensions. Both the maximum and the minimum values of age coefficients decrease in absolute value as the log robot density increases. For example, in Figure 9.A, when the log robot density is −2, the maximum coefficient is 0.23 at the age groups 30–34 and 35–39 and the minimum coefficient is −0.42 at the age group 85 and over. In contrast, when the log robot density increases to 8, the maximum coefficient is 0.14 for the age groups 25–29 and 30–34 and the minimum coefficient is −0.13 for the age group 80–84. Hence the difference in contribution to economic growth between peak age groups and old age groups is much smaller when the log robot density is higher. In Figure 9.B, which is from panel regressions, the maximum and the minimum coefficients are 0.37 at age group 25–30 and −0.35 at age group 5–9, respectively, when the log robot density is −2. The corresponding coefficients are 0.13 at age group 30–34 and −0.18 at age group 0–4, respectively, when the log robot density increases to 8. When we compare the age coefficient of age group 60–64, the oldest of the regularly defined working-age population, it is −0.20 when the log robot density is −2 but −0.04 when the log robot density increases to 8. Overall, our estimation results indicate that more robot adoption favors old age groups by reducing the difference between peak age groups and old age groups in their contribution to economic growth.

TFP is our final proxy for technological progress, which is regarded as a critical element explaining economic growth, although measuring it and deriving cross-country comparable information remains a challenge due to data availability and reliability. For this exercise, we use calculated TFP levels, expressed as relative value to the US, reported from the Penn World Table version 9.1, instead of the 9.0 version considering the observed anomalies in the latter version documented by İmrohoroğlu and Üngör (2016). Like the third proxy, the exercise using TFP is also estimated in a smaller number of countries, largely dependent on data availability. Table 10 presents regression results interacting the log of TFP and age distribution variables following a third-order polynomial. The joint hypothesis that all three coefficients of $D1$, $D2$, and $D3$ are zero is rejected in the pooled OLS regression while the joint test on the coefficients of three interaction terms (D x TFP) is rejected in the panel regression.

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[13] As Table 1 reports, the mean, minimum, and maximum of the log robot density in the sample is 4.3, −2.5, and 8.7, respectively.

Table 10: Increasing Total Factor Productivity and Impact of Age Distribution on Gross Domestic Product Per Capita Growth

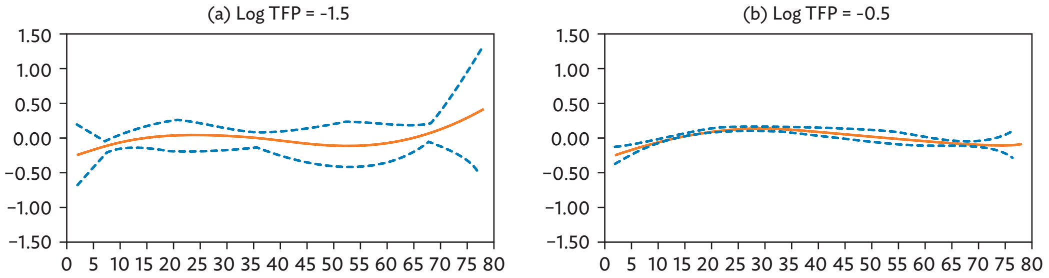
	Dependent Variable: 5-Year GDP Per Capita Growth	
Variables	(1) Pooling	(2) Fixed Effects
Log initial GDP per capita	−0.011***	−0.030**
	[0.003]	[0.014]
D1	0.171	0.072
	[0.164]	[0.236]
D2	−0.014	0.007
	[0.023]	[0.032]
D3	0.000	−0.001
	[0.001]	[0.001]
Log TFP	−0.046*	−0.141***
	[0.026]	[0.047]
Interaction (D1 x Log TFP)	−0.023	−0.559*
	[0.349]	[0.296]
Interaction (D2 x Log TFP)	0.009	0.086*
	[0.051]	[0.043]
Interaction (D3 x Log TFP)	−0.001	−0.004**
	[0.002]	[0.002]
Observations	252	252
R-squared	0.286	0.343
p-value of joint test: Level terms	0.000	0.102
p-value of joint test: Interaction terms	0.187	0.027
Number of countries		63

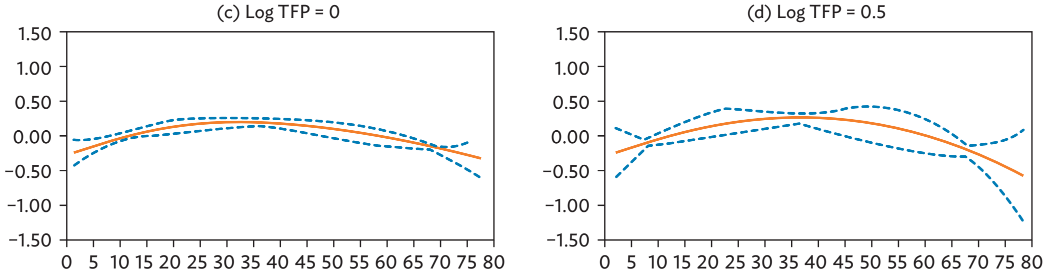
GDP = gross domestic product, TFP = total factor productivity.
Notes: We estimate the impact of age distribution on 5-year real GDP per capita growth for all countries. The entire sample period of 1995–2014 for which the robot data are available is divided into 10 5-year subperiods. Note that the last subperiod is 4 years (2010–2014) due to the data availability in the Penn World Table 9.0. Column 1 presents pooled OLS estimates and column 2, panel estimates with country fixed effects. D1, D2, and D3 are transformation variables of the age distribution by assuming that the age-group coefficients lie on a third-order polynomial. Numbers in brackets are robust standard errors and ***, **, and * denote the significance levels of 1%, 5%, and 10%, respectively. p-values are for the joint hypotheses that the coefficients of D1, D2, and D3 are all zero and the coefficients of their interactions with robot density.
Source: Authors' calculations.

Figure 10 draws a similar picture of the relative economic growth contribution by age group across different levels of TFP. The degree of technological adoption of a country proxied by TFP also seems to affect the way age cohorts contribute to growth, with the magnitude of the effect substantially larger than for longer life expectancy.

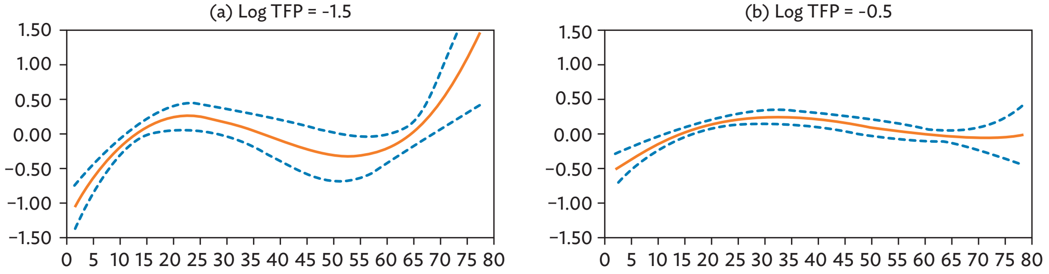
Figure 10: Increasing Total Factor Productivity and Age-Group Coefficients

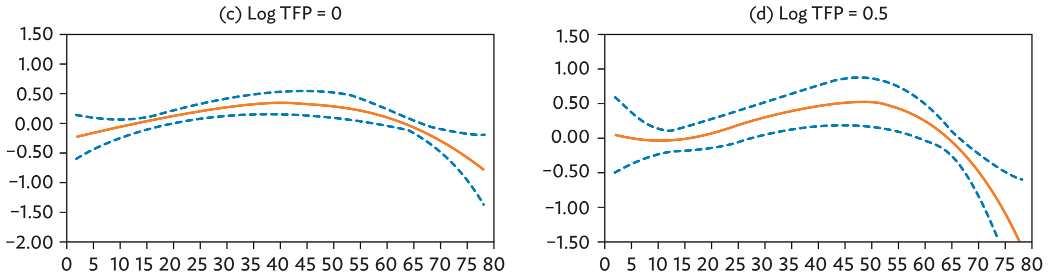
A. Pooled OLS regression





B. Panel fixed effects regression





OLS = ordinary least squares, TFP = total factor productivity.

Notes: On the horizontal axis, 0 represents the age group (0,4); 5 represents the age group (5,9); and so on. Figures in panels A and B assume that the age-group coefficients lie on a third-order polynomial that are derived from columns 1 and 2 in Table 10, respectively. The solid line denotes age-group coefficients that lie on a third-order polynomial and the dashed lines, 80% confidence intervals.

Source: Authors' calculations.

Using the fixed effects regression results in Column 2 of Table 10, when comparing the scenarios of low TFP (in log) at −0.5 and high TFP at 0.5, a large difference can be clearly seen in the growth contribution of the productive age groups from the 30s to 60s. A percentage increase of cohorts among these age groups to relative growth can be one to 20 times larger in countries with high technology adoption than in low adoption economies, with more benefits accruing for the older age cohort. The relative growth contribution under high TFP scenario for the age cohort of 55–59 is 20.4 times as large, and 1.3 times for the age cohort of 30–34. Similar to longer life expectancy scenario, the high-TFP scenario extends the productive years by 5 years. At the same time, delay is observed in younger threshold age to become a positive contributor by the same margin, indicating that more years of education are needed in the high-TFP scenario for youth to be productive.

V. CONCLUSION

This paper revisits the impact of population aging on economic growth. We find that to understand the impact of population aging on economic growth, it is important to consider potential effects of the demographic change in the whole range of age distribution. Our empirical analyses suggest that a change in age distribution that increases the share of older people and decreases the working-age population reduces economic growth.

We also investigate the effect of technological advances on the relation between population aging and economic growth. We examine four proxies of broad technological advancements: life expectancy, labor productivity, automation, and TFP. We find that increasing life expectancy and labor productivity favor old age groups allowing older age groups to contribute more positively to future growth. More automation also favors old age groups, but in a different way. When robot density increases, old age groups become less disadvantaged, as the difference between peak age groups and old age groups in their contribution to economic growth is reduced. Technological adoption, acting through TFP, enhances the growth contribution of productive age groups from the 30s to 60s.

The findings offer some important policy insights. Public health policies to increase the average life expectancy help the elderly population continue to make valuable contributions to the economy. Therefore, positive implications of extended life expectancy on productivity and economic growth should be taken into account in the assessment of the overall fiscal impacts of age-related spending. Automation, particularly robots in manufacturing, is also seen to help older workers maintain the level of their economic contributions compared to the most productive age group. However, in order to leverage this potential, policies need to encourage companies to adopt automation to augment human tasks and support workers' training for making better use of robots. Finally, the findings confirm the importance of improving TFP (that comes with technological advances) in workers' contributions to growth. In order to improve TFP, policy priorities should be to (i) promote investment in information and communication technology and research and development, (ii) accelerate labor market reforms for efficiency and flexibility, and (iii) strengthen education and training to boost the skills and productivity of workers.

APPENDIX

Definitions of Variables and Data Sources

Variables	Description and Construction	Data Source
Real GDP (national account), 1960–2014	Real GDP at constant 2011 national prices (in 2011 US dollars)	Penn World Table 9.0
Real GDP (output side), 1960–2014	Output-side real GDP at chained PPPs (in 2011 US dollars)	Penn World Table 9.0
Population, 1960–2014	Total population	Penn World Table 9.0
Population employed, 1960–2014	Number of people engaged in employment (millions)	Penn World Table 9.0
Population by age group, 1950–2015	Total population (both sexes combined) by 5-year age group	United Nations Department of Economic and Social Affairs (UN DESA), Population Division. 2017. *World Population Prospects: The 2017 Revision*
Number of births, 1950–2015	Number of births in 5 years, divided by five, both sexes combined	UN DESA, Population Division. 2017. *World Population Prospects: The 2017 Revision*
Life expectancy, 1950–2015	Life expectancy at birth, both sexes combined (years)	UN DESA, Population Division. 2017. *World Population Prospects: The 2017 Revision*
Robot stock data, 1993–2015	Operational stock of industrial robots at the end of the year, IFR	International Federation of Robots. 2014. *World Robotics Industrial Robots*
Region dummies	A series of dummies indicating region classification according to the World Bank	World Bank list of economies (June 2017)
OECD dummy	A dummy of OECD member countries	

GDP = gross domestic product, IFR = International Federation of Robotics, OECD = Organisation for Economic Co-operation and Development, PPP = purchasing power parity, US = United States.
Source: Authors' compilation.

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Demographic Change, Technological Advances, and Growth

A Cross-Country Analysis

This paper revisits the impact of population aging on economic growth and explores how technological advancement affects this relationship. The empirical analysis suggests that a growing share of older people combined with a shrinking working-age population lowers economic growth. The paper also finds that technological advancement and adoption help older cohorts contribute more to growth. Increased life expectancy and labor productivity also help older age-groups contribute to growth, while higher robot density narrows the difference between older and younger people's contributions to growth. Improved total factor productivity enhances the growth contribution of people aged 50 and above.

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