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IMITATION VERSUS INNOVATION IN AN AGING SOCIETY: INTERNATIONAL EVIDENCE SINCE 1870[1]

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Abstract

The budgetary implications of an aging population in the OECD are often considered dire. This study argues that this need not be the case provided that older educated workers are more innovative than their younger counterparts, and that workers with tertiary education stay in the labor force until their 60s. Using a panel of 21 OECD countries over the period 1870-2009, this paper estimates the productivity growth effects of education for different age groups, through the channels of innovation and imitation. The results show that educated workers are highly innovative and that the propensity to innovate increases sharply with age.

JEL Classifications: I20, O30, O40
Key words: productivity growth; human capital; age structure

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1. Introduction

OECD countries are aging fast. The consensus view is that this is likely to act as a strain on future per capita income growth in industrialized countries (OECD, 2006a; Garibaldi et al., 2011). An aging population increases the age dependency ratio, which in turn reduces the tax base and increases government expenditures on pensions and health (OECD, 2006a). Furthermore, it is widely perceived that individuals tend to be more productive at a younger age, as shown by Haltiwanger et al. (1999), among others. Coupled with high resistance towards increasing the pension age, the aging population is considered to be a big threat to the welfare state of the old industrialized countries.

However, as discussed in detail in the next section, aging need not be a drag on productivity growth for the following three reasons. First, since it has become more difficult to innovate after the Second Industrial Revolution, education is increasingly becoming an asset for innovations. Second, cognitive abilities of sufficiently educated people, which are crucial for innovative activity, peak in the later stages of their working life and stabilize thereafter compared to their uneducated counterparts. Third, older workers have some advantages over younger workers due to greater knowledge, based on experience. Thus, provided that older educated workers stay in the labor force, aging need not be a drag on the economy.

Despite the potential large welfare effects of an aging society, very little research, if any, has been undertaken to examine the growth effects of aging for different educational groups at the macroeconomic level. Thus far the discussion has predominantly been centered on the government's balance sheet rather than on innovative activity. However, changes to the government's budget balance will have only one-off effects on income whereas variations in innovative activity will have permanent growth effects if growth is proportional to the level of educational attainment. Since growth rates in the long run override the levels effects, the welfare effects of aging may actually be positive. This depends on the effects of aging on innovative activity, the resources spent on education and whether the pension age is kept constant or is increased along with higher life expectancy.

The objective of this paper is to examine the productivity growth effects of educational attainment among different age groups and educational categories. Previous studies on the relationship between human capital-based absorptive capacity and productivity growth have not considered the productivity effects of different age cohorts and educational groups (see, e.g., Kneller and Stevens, 2006; Vandenbussche et al., 2006). We examine whether the oldest educated age cohort in the labor force contribute more to productivity growth than its younger counterpart and, therefore, whether raising the pension age among educated workers can counterbalance the income drag of increasing old age

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dependency. Using data for 21 OECD countries over the period 1870-2009 and based on the framework of Nelson and Phelps (1966) and Vandenbussche et al. (2006), we test whether the growth effects of human capital through the channels of innovation and imitation differ across age and education.

This paper proceeds as follows. Section 2 discusses the research on cognitive ability and aging. Section 3 presents the baseline empirical estimates. Robustness checks are performed in Section 4, and the last section concludes.

2. Cognitive Ability, Experience, and Aging

The productivity growth effects of aging depend on two counteracting forces. New technology and work organization render some skills obsolete and, therefore, lead to a depreciation of human capital at older ages. However, this may be counterbalanced by the skills and experience required to adapt to the new technology and incorporate it into new products and production processes. Recent studies show that it is becoming increasingly hard to innovate, suggesting that more years of training are required to understand existing technology and develop new technologies based on previous knowledge (Aghion and Howitt, 1998; Jones, 2009, 2010). While inventors before the Second Industrial Revolution during the mid 19th century were often without formal tertiary education, innovative activity has increasingly been undertaken by a highly specialized and educated labor force (Mokyr, 2005; Jones, 2010).

Since productivity growth is driven by technological progress along the balanced growth path, the ability of workers to continue innovating as they age becomes an important issue for the productivity effects of aging and the potential productivity effects of increasing the pension age. The ability to innovate varies with age which, in turn, depends on how fluid and crystallized intelligence develops with aging. Fluid intelligence is the speed at which operations can function whereas crystallized intelligence consists of knowledge acquired over a lifetime due to education and on-the-job training. Medical and psychological research suggests that fluid intelligence peaks at 30-40 years of age and declines thereafter, while crystallized intelligence declines at a much slower rate and may even increase with age (Salthouse, 1985). Salthouse (1985) argues that crystallized intelligence, such as numeracy, among educated workers shows little evidence of decline at older ages.

Experience on the job also tends to improve older compared to younger workers' productivity since the former use more efficient strategies developed through prior learning and experience (Salthouse and Maurer, 1996). Moreover, an older educated workforce is likely to contribute disproportionately to productivity growth through facilitating organizational development. Experienced and knowledgeable workers can provide guidance on how to ameliorate conflict within institutions and improve inter-group

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relations, thereby resulting in higher productivity growth, which may counterbalance decreasing productivity on other fronts (Salthouse and Maurer, 1996).

Research finds that the ability to innovate peaks at around the age of 50 and then plateaus. In particular, Hoisl (2007) finds that the quality of inventions among German inventors peaks between the ages of 45-54 and is fairly stable thereafter. A survey of 9017 European patented inventions in 2003-04 reveals that more than one third of the inventors in the sample were older than 50 (Giuri et al., 2007). Furthermore, Feyrer (2007) shows that an increase in the size of the working population aged 40 to 50 years tends to increase productivity growth. He argues that about one-quarter of income differences between rich and poor nations are attributable to their different demographic structures and that poor countries tend to have low productivity because their workforces are too young. Notwithstanding their findings, these statistics may still understate the role of age and vintage as inventors who have been promoted into senior positions are no longer directly involved in innovative production, although they may still provide input indirectly. Older workers' contribution to productivity growth may also be underestimated due to the time spent on coaching younger workers.

Moreover, studies have consistently found that the risk of dementia in old age is a significant declining function of education (Le Carret et al., 2003). Friedland (1993) suggests that education increases synaptic density and promotes intellectual and creative activity patterns, resulting in a lifelong neural activity that could be physiologically beneficial. Education may be an early cognitive stimulation having a positive influence on cerebral (part of central nerve system) growth and cognition, and is able to provide some resilience to cerebral lesions. Numerous experiential studies suggest that an enriched environment may promote brain development (Le Carret et al. 2003). Importantly, if workers are expected to stay in the labor force for more years their jobs will be more demanding, thus increasing the demand for job training courses. Experiments with rats suggest that stimulating mental activities during post-educational years enhance the effects of education and help to form a cognitive reserve (Le Carret et al., 2003). Furthermore, Hertzog et al. (1999) have shown that intellectually engaging activities in later life act as a buffer against cognitive decline. In a similar vein, Le Carret et al. (2003) find that education is associated with controlled processes and conceptualization abilities.

Finally, there are twice as many successful founders aged over 50 as there are under 25 years old, and twice as many over 60 as under 20, while the highest rate of entrepreneurial activity is among people aged between 55 and 64 and the lowest rate is among the generation of 20 to 34 year olds. Colonel Harland Sanders was in his 60s when he started the Kentucky Fried Chicken chain and Ray Kroc started building the McDonald's franchise system in his 50s (The Economist, 2012). The late Steve Jobs was as

creative in his 50s as he was in his 20s when he started Apple. If these examples and findings can be traced out at the macro level the prospects for an aging society may not be bleak.

3. Empirical Estimates

3.1 Model specification

Endogenous growth theory proposes that growth is driven by the use of better quality technology and more efficient use of resources. Letting productivity growth be a positive function of human capital, technology proximity, and age dependency yields the following regression model:

$$\Delta lnA_{i,t} = \alpha \Delta lnA_{i,t-1} + \beta' \boldsymbol{H}_{i,t-1} + \gamma ln\left(\frac{A_{i,t-1}}{A_{t-1}^{max}}\right) + \delta'\left[\boldsymbol{H}_{i,t-1} ln\left(\frac{A_{i,t-1}}{A_{t-1}^{max}}\right)\right] + \varphi_1 YAG_{i,t}$$

$$+\varphi_2 \Delta YAG_{i,t} + \omega_1 OAG_{i,t} + \omega_2 \Delta OAG_{i,t} + \theta' \boldsymbol{X}_{i,t} + d_t + \varepsilon_{i,t}, \tag{1}$$

where *A* is total factor productivity (*TFP*), labor productivity or per capita GDP, $\frac{A_{i,t-1}}{A_{t-1}^{max}}$ is the proximity to the technology frontier and is measured as the relative productivity gap between country *i* and the technology leader at time *t*, where the leader is chosen as the country having the highest TFP among all countries in the sample at time *t*, $\boldsymbol{H}$ is a vector of human capital decomposed into different educational and age groups, *YAG* and *OAG* are the ratios of young age (0-14) and old age (65+) dependency, respectively, $\boldsymbol{X}$ is a vector of control variables, including trade openness, domestic innovative activity, and international knowledge spillovers, d_t is the time-specific effect, capturing common shocks and world productivity growth or the unobservable individual invariant time effects, and ε_{it} is the stochastic error term. The panel is regressed in 5-year differences in order to filter out the business cycle influences. Human capital, proximity to the frontier and all control variables are measured as the average within the period that is covered by the differences. The growth equation is estimated for a panel of 21 OECD countries covering the period 1870-2009. The data sources are listed in the appendix.

Age dependency rates are only included in the per capita income growth regressions because age dependency does not directly affect TFP and labor productivities as these estimates are based on hours worked and not on the size of the population. An increase in age dependency rates should lower per capita income because the population outside the workforce does not contribute to production. Although accounting identities predict that age dependency rates are equally a drag on per capita income they are subdivided into old and young age dependency rates since the focus of this paper is on the productivity growth effects of aging.

The productivity growth effects of education are divided into three educational groups (primary, secondary, and tertiary) and three age groups (20-34, 35-49, and 50-64). The coefficients of these groups reflect their social returns and their relative sizes. Human capital is assumed to influence productivity growth by increasing the efficiency of production, innovative activity and the ability to adapt technologies that are developed elsewhere (Nelson and Phelps, 1966; Vandenbussche et al., 2006). In the model developed by Vandenbussche *et al.* (2006), workers with primary or secondary education facilitate imitation or diffusion of existing technology, whereas workers with tertiary education promote the innovation of new technology. Their theoretical model proposes that tertiary education should become increasingly important for productivity growth as a country moves closer to the technology frontier, whereas primary and secondary education become less important. These effects are captured by the level of human capital and the interaction between human capital and proximity to the frontier.

In particular, the model of Vandenbussche et al. (2006) predicts that the coefficient of the interaction between human capital and proximity to the frontier depends on whether the workers are high skilled (tertiary education) or low skilled (primary and secondary education). For high skilled workers the coefficient is predicted to be positive because they innovate, but for low skilled workers, negative because the growth effects of imitation decrease as the economy approaches the technology frontier. Thus, the growth-enhancing impact of skilled labor increases with a country's proximity to the frontier. Conversely, the growth-enhancing impact of unskilled workers decreases as a country catches up with the technology frontier. Growth is assumed to be negatively related to proximity to the frontier because the effective costs of adaption of new technologies are inversely related to the technological distance (Dowrick and Nguyen, 1989).

However, the effects of the interaction terms may not follow the predictions of the model of Vandenbussche et al. (2006). The seminal model of Nelson and Phelps (1966) lumps all groups of educational attainment together and predicts that the impact of the interaction between the average years of schooling among the working age population and proximity to the technology frontier is negative under the assumption that education facilitates the adaptation of technologies developed at the world frontier.[2] Thus, the Nelson-Phelps model predicts the coefficients of the interaction terms to be the same

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[2] Related to that Cohen and Levinthal (1989) argue that in addition to pursuing new process and product innovation, firms invest in R&D to exploit externally available information. Since the focus of the model of Vandenbussche et al., 2006) is on human capital the empirical implications of their model may well be different from that of Cohen and Levinthal (1989) in that human capital creates techniques and processes that are quite different from that of technological progress created by R&D. R&D is directed towards the creation of new processes, better technology and higher quality products while investment in human capital is channeled towards increasing knowledge of a particular field.

for all groups of educational achievement. Which model is the best description of the OECD experience is an empirical question addressed in this paper.

Finally, trade openness, domestic innovative activity, and international knowledge spillovers through the channel of imports are included as control variables. Growth is assumed to be positively related to openness because increased openness to international trade implies lower tariff and other trade barriers, greater specialization and a greater potential to acquire knowledge embedded in imported goods (Madsen, 2009). Domestic innovative activity is measured as research intensity, which is defined as the ratio of the number of patent applications by domestic residents to employment, following the prediction of Schumpeterian growth theory. Accordingly, innovative activity (patenting) is divided by product variety (employment) because the effectiveness of R&D is diluted due to the proliferation of products as the economy expands. The predictions of other endogenous growth models are not included because they are inconsistent with empirical evidence (see, e.g., Madsen, 2008; Madsen et al., 2010; Ang and Madsen, 2011). International knowledge spillovers are assumed to enhance productivity due to the improved quality and product variety of imported intermediate products (Keller, 2004; Madsen, 2007; Ang and Madsen, 2012).

3.2 Data

As mentioned above, productivity is measured as TFP, labor productivity and output per capita. Two measures of TFP are used in the regressions: a conventional measure with Hicks-neutral technological progress (in the robustness section) and one with disembodied technological progress (default regressions). The former is measured as economy-wide TFP data and is based on the two-factor homogenous Cobb-Douglas production technology with Hicks-neutral technical change as follows: $Y_{it} = A_{it}K_{it}^{\alpha}L_{it}^{1-\alpha}$, where Y_{it} is real output for country i at time t, A_{it} is TFP, K_{it} is total capital stock, L_{it} is the number of hours worked, and α is capital's income share. Thus, TFP is computed as:

$$A_{it} = Y_{it}/(K_{it}^{\alpha}L_{it}^{1-\alpha}), \tag{2}$$

where $(1 - \alpha)$ is computed as the unweighted average of labor's income share in country i and the US. Labor's income share for each country is in turn estimated as the average during the period for which data are available (for details, see Madsen, 2010). Labor is measured by economy-wide employment multiplied by annual hours worked.

The second TFP measure allows for embodied technological progress following the seminal contribution of Solow (1960), which is extended by Greenwood et al. (1997) (see also Hercowitz, 1998). According to the embodiment hypothesis, new technology is predominantly embodied in new, more efficient types of capital resources, particularly equipment and machinery (Greenwood et al. (1997). Consequently, the embodiment and disembodiment effects can be distinguished by considering efficiency capital as an additional factor in the Cobb-Douglas production function with Hicks-neutral technological progress as follows:

$$Y_{it} = A_{it}^E \left(\widetilde{K}_{it}^{eq} + K_{it}^{st} \right)^{\alpha} L_{it}^{(1-\alpha)}, \tag{3}$$

Where A_{it}^E is disembodied technological progress, $\widetilde{K}_{it}^{eq}$ is capital stock of equipment in efficiency units, and K_{it}^{st} is capital stock of structures.

Relative prices of consumer and investment goods are used to capture embodied technological progress following the approach of Greenwood et al. (1997). They argue that technological progress makes new equipment less expensive than old equipment in efficiency units, *ceteris paribus*. Computers are examples of equipment that has become substantially cheaper in efficiency units over time and they have increased the efficiency of production due to embodied technological progress. Since significant quality improvements do not occur in the consumer goods producing sector, embodied technological progress increases the relative prices of consumption goods, assuming that costs have changed by the same proportion in the two sectors. Accordingly, embodied technological progress, proxied by relative prices, is incorporated into the efficiency capital stock using the inventory perpetual method as follows:

$$\widetilde{K}_{i,t}^{eq} = (1 - \delta)\widetilde{K}_{i,t-1}^{eq} + I_{i,t}^{eq} \left(1 + \frac{P_{i,t}^{cpi}}{P_{i,t}^{meq}} \right), \tag{4}$$

where δ is the depreciation rate, $I_{i,t}^{eq}$ is gross investment in equipment and machinery, $P_{i,t}^{cpi}$ is the consumer price index and $P_{i,t}^{eq}$ is the price deflator for equipment and machinery. Thus, disembodied TFP is computed as:

$$A_{it}^E = Y_{it}\left[\left(\widetilde{K}_{it}^{eq} + K_{it}^{st} \right)^{\alpha} L_{it}^{(1-\alpha)} \right]^{-1}. \tag{5}$$

Although this adjustment appears to be straight forward, it is incredibly difficult to obtain price deflator data for equipment and machinery investment back to 1870 and the effect of embodied technological progress may not have been sufficiently captured in the calculation of historical investment deflators. In particular, hedonic pricing is usually required to capture the quality improvements of investment in equipment and machinery (see Greenwood et al., 1997). National statistical agencies have increasingly improved investment deflators in the post-WWII period and this is reflected in a significant increase in consumer prices relative to prices of equipment machinery. However, information about the construction of investment deflators before WWII is rarely available and the relative prices of consumer goods have not shown the consistent increases that we would expect. Furthermore, there are large measurement errors that have to be adjusted for during periods of high inflation and hyperinflation. These considerations suggest that the estimates of investment-induced technological progress are not as reliable as we would like them to be.

Human capital is measured as the fraction of the working age population for the age groups 20-34, 35-49, and 50-64 having primary (*PRI*), secondary (*SEC*) and tertiary (*TER*) education. It is estimated using the gross enrolment rate (*GER*), which is defined as the fraction of the population in a certain age cohort that is enrolled at a certain educational level. The *GER* for primary, secondary and tertiary education is estimated for each age cohort. School enrolment data are available on primary (6-11 years of age), secondary (12-17 years of age) and tertiary (18-22 years of age) levels since the 19th century for the countries considered in this study. For some countries the data are extrapolated backward to ensure that primary school enrolment is available from 1812. In 1870, for example, the oldest cohort in the labor force (64 years of age) did their first year of primary schooling in 1812, while the youngest cohort (15 years of age) did their first year of primary schooling in 1861. The data are adjusted for the length of the school year and school attendance rates.

International knowledge spillovers through the channel of imports (*IKS*) are measured following the formula suggested by Lichtenberg and van Pottelsberghe de la Potterie (1998), and extended by Madsen (2007) as follows:

$$IKS_{it} = \sum_{j=1}^{21} \left[\frac{m_{ijt}^f + (1-\delta)m_{ij,t-1}^s}{y_{jt}^f + (1-\delta)y_{ij,t-1}^s} \right] PI_{jt}^d, \qquad i = 1,2,\dots,21; t = 1870 - 2009 \tag{6}$$

where m_{ijt} is country i's imports from the exporting country j at time t; y_{jt} is exporter j's GDP at time t; PI_{jt}^d is exporter j's patent intensity (number of patent applications over employment) at time t, that is, it is

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the patent intensity of the 21 OECD countries considered in this study; m^f and m^s are the "flow" and "stock" of nominal imports, respectively; and y^f and y^s are the "flow" and "stock" of nominal GDP, respectively. The initial values of m^s and y^s are estimated, respectively, as $m^s_{i,1870} = m^f_{i,1870}/(g^m_i + \delta)$ and $y^s_{i,1870} = y^f_{i,1870}/(g^y_i + \delta)$, where g^m and g^y are the average annual growth rates of m^f and y^f for each country over the period 1870-2009. Unlike Lichtenberg and van Pottelsberghe de la Potterie (1998), the stock rather than the flow measure is used here since it is less subject to temporary shocks in import penetration. A cyclical reduction in imports will dramatically reduce the values of international knowledge spillovers although this does not necessarily imply that international knowledge has been lost in the process, given that imported high-tech equipment is a not short-lived physical asset. The stock measure overcomes this deficiency (Madsen, 2007).

Trade openness is measured as the ratio of imports to GDP. Age dependency is captured by two measures: the young age dependency ratio (the number of people under 15 as a proportion of the total population) and the old age dependency ratio (the number of people over 64 as a proportion of the total population).

[Insert Table 1 here]

The summary statistics for the key variables are presented in Table 1. The average educational attainment is lower for the older than the younger age cohort because educational attainment has been increasing during the sample period. The TFP, labor productivity and per capita GDP growth rates appear high because they are measured in 5-year periods. On an annual basis they are only 1.5, 2.6 and 2.2 percent, respectively. The labor productivity growth rates are higher than the TFP growth rates because TFP-induced capital accumulation increases labor productivity growth rates. Finally, the labor productivity rates exceed the per capita growth rates because of a significant reduction in annual hours worked during the period 1870-2009 while the labor force participation rates, on average, have only increased modestly over the sample period.

3. 3 Estimation Method

The model is estimated using the system GMM estimator. Under certain assumptions and moments conditions, Arellano and Bover (1995) and Blundell and Bond (1998) propose the use of a system GMM estimator that combines the regression in first differences with an additional regression in

levels using suitable instruments to produce more consistent and efficient estimates. Accordingly, past levels of the regressors are used as instruments for current differences in the first-differenced regression whereas past changes of the regressors are used as instruments for future levels in the regression involving level variables. These are internal instruments which are generated based on some transformation of the existing variables that may not be truly exogenous. However, it would be a very challenging task to find suitable external instruments for different levels of educational attainment going as far back as 1870. Furthermore, the feedback effects from growth to educational attainment is likely to be minuscule since educational attainment is determined from schooling decisions from up to 58 years before. Potential endogeneity is, therefore, dealt with using the system GMM estimator of Arellano and Bover (1995) and Blundell and Bond (1998) without incorporating any additional external instruments. This estimator is shown to be the preferred approach for estimation of empirical growth models due to its superior ability in exploiting stationarity restrictions (see Bond et al., 2001).

Two identification tests are presented to check the validity of the instruments, as suggested by Arellano and Bond (1991), Arellano and Bover (1995) and Blundell and Bond (1998). The first is a Sargan's test of over-identifying restrictions, which tests the overall validity of the instruments. The second test checks for second order serial correlation (i.e., AR(2)) in the first-differenced error term. Support for the use of this approach is found since the null hypotheses could not be rejected in any of the regression models below.

3.4 Core results

Table 2 presents the results for the dynamic panel growth regressions. The coefficients of the time dummies are not reported in the table to conserve space. The estimates show that neither primary nor secondary education has a direct positive growth effect, whereas almost all the coefficients of tertiary education are significantly positive. This is consistent with the results of Luca et al. (2009) that the age profile of cognitive skills is heavily influenced by the level of education. Thus, these findings suggest that to get into a permanent growth path through education a country has to invest in tertiary education. This, however, may not hold for the poorest countries whose poor quality of education may prevent investment in education from delivering its desired growth effects.

[Insert Table 2 here]

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Regarding the age-specific educational growth effects, older workers with tertiary education are markedly more productive than their younger counterparts. The coefficients of tertiary education are nearly twice as large for the oldest compared to the youngest age cohort. This effect is amplified by a factor of approximately three if it is taken into account that educational attainment among the younger age cohort is on average almost three times as large as the older age cohort in the sample period (see Table 1). Increasing the fraction of the working age population in the 50-64 age group with tertiary education by ten percentage points would increase the TFP growth rates by $0.31 x 0.464 = 0.14$ percentage points annually, provided the productivity effects from the interaction between education and the distance to the frontier are held constant. This number seems minuscule. However, assuming that the real interest rate is higher than the TFP growth rate by two percent, the present value of TFP would increase by 376 percent, which is a significant gain.[3]

Turning to the interaction terms, the interaction between secondary education and proximity to the frontier are significantly negative in most cases while the interaction term for primary education is significantly negative in only a third of the cases, and the absolute values of the coefficients are substantially smaller than the former. These results make intuitive sense in that workers with secondary education have the better skills to adapt the technologies developed at the frontier compared to individuals with only primary education. Furthermore, there is also some evidence to suggest that this relationship strengthens with age, suggesting that the older age cohorts with a secondary education in the work force are better at adopting frontier technologies than their younger counterparts.

The coefficients of the interaction between tertiary education and proximity to the frontier, however, are found to have a larger significant positive impact on growth in nearly all cases. The absolute magnitude of the coefficients on the tertiary interaction term increases steeply with age, signifying the increasing importance of seniority for innovation as the country moves toward the frontier. Coupled with the finding of a significant direct positive effect of tertiary education, this provides strong evidence in support of the hypothesis that skilled human capital facilitates innovative invention and technological improvements as countries move closer to the technological leader. Given that such an effect is found to be strongest among older workers, it appears that more experienced, educated and technically trained

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[3] The present value of TFP is given by $PV = A_0 \int_0^\infty e^{(g-r)t} dt = \frac{A_0}{r-g}$, A_0 is initial TFP, where r is the real interest rate and g is the TFP growth rate. If the latter is increased permanently by 0.14 percentage points then the present value would be $PV_1 = \frac{A_0}{r-(g+0.0014)}$ and the gain would be $PV_1 - PV_0 = \frac{A_0}{r-(g+0.0014)} - \frac{A_0}{r-g} = A_0 \cdot \frac{0.0014}{(r-g-0.0014)(r-g)}$.

older workers contribute disproportionately to growth in economies close to the frontier. Thus, older workers are not only better at imitating they are also more capable of innovating.

The findings that the coefficient of the interaction terms are positive for tertiary education but negative for primary and secondary education are consistent with the model of Vandenbussche et al. (2006) but inconsistent with the predictions of the Nelson and Phelps (1966) model in which the interaction between education at all levels and proximity (distance) to the frontier are expected to have negative (positive) effects on growth. They are also in line with the empirical results of Vandenbussche et al. (2006) and Ang et al. (2011), but incompatible with Bartel and Lichtenberg (1987) who find that highly educated workers have a comparative advantage with respect to learning and implementing new technologies developed elsewhere. This evidence is in favour of their hypothesis based on derived labor demand functions using data for 61 US manufacturing industries. The conflicting results may reflect that cross-country data are used in this paper and in the estimates of Vandenbussche et al. (2006) and Ang et al. (2011) whereas Bartel and Lichtenberg (1987) base their evidence on industrial data.

The coefficients of proximity to the frontier are negative and highly significant in all nine cases, which is consistent with the findings of Dowrick and Nguyen (1989) and the predication that the effective costs of innovations are smaller the further away the country is from the frontier. Trade openness is mainly found to have negative growth effects whereas there is some positive effect of international knowledge transmission via the imports channel. The finding of a negative growth effect of trade openness seems counterintuitive, but is consistent with previous studies using long historical data (see, e.g., Vamvakidis, 2002).

Finally, the coefficients of old age as well as young age dependency rates are negative and are mostly significant, which is consistent with the fact that income is spread over more people as the age dependency rates increase. The negative effect on growth is found to be significantly larger for old-age dependency.

While our results suggest that old age dependents in the economy act as a drag on income growth, this negative impact is more than offset by the growth effects of older well-educated workers who remain in the workforce. Our estimates in column (3c) in Table 2 imply that the average old-age dependency ratio would have to be increased by at least 45 percent, holding other effects constant, for this positive growth effect of an older educated workforce to be counterbalanced. Although continued increases in human longevity imply that the number of elderly dependents as a share of those of working age will rise steeply in the OCED over the next few decades, this estimate is based on the simplifying assumptions that

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the ratio of the working age population for the 50-64 age group having tertiary education and the labor force participation rates among elderly workers remain constant in the future.

4. Robustness Checks

Five robustness checks are undertaken in this sub-section by: 1) providing estimates for the post WWII sample period; 2) regressing the model using innovative activity as the dependent variable instead of productivity growth; 3) estimating the full model which encompasses all age group specific human capital variables; 4) providing estimates in which time-dummies are excluded from the regressions; and 5) separating the embodied and disembodied technological progress in the regression models.

4.1 Post WWII regressions

The post WWII estimates will reveal whether the growth effects of aging and schooling have changed relative to the period before 1946. Furthermore, the post WWII data of educational attainment and embodied technological progress are of better quality than the earlier data because school enrollment data going as far back as 1812 were not available for all countries. The regression results of the post WWII estimates are displayed in Table 3. Due to a much smaller sample the coefficients are slightly less significant than those reported in Table 2. However, the key results still prevail. Tertiary education still has significant positive direct and indirect growth effects and the strength of the relationship increases even more sharply with age than the results described above, using the full sample period. This result is consistent with the finding in the literature that the complexity of innovation has been increasing over time (Aghion and Howitt 1998; The Economist, 2012), therefore giving an advantage to educated workers in the older age cohort.

[Insert Table 3 here]

Specifically, the coefficients of the interaction between tertiary education and proximity to the technology frontier are significantly positive in five of the nine cases, which is consistent with the regressions in Table 2. Although there is some weak effect of primary education, secondary education still has no positive direct growth effects. The coefficients of the interaction between secondary education and proximity to the frontier are negative and statistically significant in five of the cases, thus reinforcing the finding above that individuals with secondary education adapt the technologies that are developed at

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the frontier. Finally, the old age as well as the young age dependency ratio has a negative effect on per capita income. Overall, the results are broadly consistent with those reported in Table 2.

4.2 Innovations

Table 4 reports estimates of Eq. (1) using innovative activity as the dependent variable, where innovative activity is measured as patent applications divided by the stock of patents, which in turn is constructed based on the inventory perpetual method. The coefficients of secondary education are either insignificant or significantly negative at the 10 percent level whereas the coefficients of primary education are positive and significant only for the old age cohort. Consistent with the above findings, coefficients of the interaction between secondary education and proximity to the frontier are significant and negative, and this relationship strengthens with age.

[Insert Table 4 here]

Turning to tertiary education, the coefficients of tertiary education are positive and statistically significant in five of the six cases and again increase steeply with age. In line with our baseline results, the coefficients of the interaction between tertiary education and proximity to the frontier are significant in four cases and their magnitude also steeply increases with age. Thus, these results suggest that ideas production is an important channel through which the older educated cohorts in the labor force influence productivity growth.

4.3 Encompassing model regressions

Table 5 displays the estimates in which all human capital variables and their interaction with proximity to the frontier are entered simultaneously in the regressions. By doing so, this exercise sheds some light into the relative contributions of each age group specific variable to growth. Although the direct effect of tertiary education loses significance, probably due to the excessive number of explanatory variables, its indirect effect on growth remains, remarkably, statistically significant for the older age group. The coefficients of the interaction between the age group 50-64 with tertiary education and proximity to the frontier are very precisely estimated at the one percent level, corroborating the conclusions above.

[Insert Table 5 here]

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4.4 Excluding time dummies

Time dummies have been included in all the regressions above. Therefore, these estimates may have been affected by the interaction between the time dummies and the included regressors or may have captured time effects from variables that show the same cross-country time profile. However, excluding time dummies from the regressions, as reported in Table 6, does not alter the principal results. The coefficients of tertiary education remain mostly significant and continue to rise steeply with age. The interaction terms also maintain their signs and significance: secondary schooling is important for imitation of products and processes developed at the frontier while the tertiary educated labor force is innovating. Furthermore, growth remains significantly positively related to distance to the frontier. The only major difference between the results in Table 6 compared to the results above is that age dependency rates are no longer significantly negative, suggesting that they may not have as strong a negative effect on per capita income as predicted by accounting identities or that their variations may not have been sufficiently large for identifying any systematic effect.

[Insert Table 6 here]

4.5 Separating embodied and disembodied technological progress

The TFP regressions have thus far been based on TFP estimates in which embodied technological progress has been catered for. The dependent variable in the regressions in columns (1a) to (1c) in Table 7 is based on the conventional TFP growth rates in which no adjustment for embodied technological progress has been made. The results are remarkably consistent with those found previously: the coefficients of tertiary education as well as its interaction with proximity to the frontier are all significant and increasing with age.

[Insert Table 7 here]

Embodied technological progress, measured as TFP minus TFP adjusted for embodied technological progress, is included as an additional regressor in columns (2a) to (2c) in Table 7. The dependent variable is the TFP growth adjusted for embodied technological progress (the default measure). The coefficients of the educational variables and their interactions with proximity to the frontier are largely consistent with the previous estimates. The coefficients of embodied technological progress are

found to be statistically insignificant. However, this does not mean that embodied technological progress has been an unimportant driver for technological progress, but rather, it highlights some measurement issues. As discussed previously, efficiency gains are unlikely to have been properly incorporated into the investment deflator for equipment and machinery during most of the estimation period. Also measuring the CPI in periods of high inflation is difficult. Both of these factors may have rendered the estimates of embodied technological progress inaccurate.

5. Conclusion

The estimates in this paper showed that the productivity growth effects of older workers with tertiary education are substantially higher than those of their younger counterparts. Furthermore, secondary schooling was found to be a significant determinant of imitation of products and processes developed at the frontier countries and the strength of the adaption of frontier technology sharply increases with the age of the labor force. The results were robust to inclusion of control variables, consideration of a more recent sample period, whether time dummies are included in the regressions, and whether the dependent variable is measured by growth in total factor productivity, labor productivity, per capita income or the rate of patenting. Thus, although individuals pull per capita income down when they retire, workers with tertiary education will more than compensate for the health and pension expenses during their later years in the labor force.

Although workers in most European countries are trying to defend their "right" to retire early there are signs that labor force participation rates among older workers are rising. An increasing trend in labor force participation rates among older workers has been observed in a number of OECD countries over the period 1984-2004 (OECD, 2006b). This trend has continued even during the recent global financial crisis where employment growth for workers over the age of 54 has increased by nearly 2 percent in OECD countries (OECD, 2010). The fact that workers over the age of 50 with a tertiary education contribute substantially to productivity growth suggests that an increase in the pension age among workers with tertiary education can potentially have a large positive productivity effect. Thus, society can actually gain from aging provided that workers with tertiary education stay in the labor force just a little bit longer than they currently do. Since life expectancy at birth has almost doubled over the last century while the retirement age has remained almost unaltered, it seems reasonable to ask for a few more years of contribution to the economy.

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DATA APPENDIX

(A) EDUCATIONAL ATTAINMENT

For the construction of educational attainment data, it is assumed that the length of primary schooling is six years (6-11 years of age), secondary schooling is six years (12-17 years of age) and tertiary schooling is five years (18-22 years of age). The average years of tertiary education among the population of working age, for example, is computed using the following formula:

$$Ea_t^{Ter} = \frac{2}{5}\left[\frac{1}{10}GER_{j=20,t-1} + \frac{2}{10}GER_{j=20,t-2} + \frac{2}{10}GER_{j=20,t-3} + \frac{2}{10}GER_{j=20,t-4} + \frac{2}{10}GER_{j=20,t-5} + \frac{1}{10}GER_{j=20,t-6}\right]$$

$$+ \sum_{j=20}^{60}\left[\frac{1}{25}GER_{t-j+14} + \frac{2}{25}GER_{t-j+15} + \frac{3}{25}GER_{t-j+16} + \frac{4}{25}GER_{t-j+17} + \frac{5}{25}GER_{t-j+18} + \frac{4}{25}GER_{t-j+19}\right.$$

$$\left. + \frac{3}{25}GER_{t-j+20} + \frac{2}{25}GER_{t-j+21} + \frac{1}{25}GER_{t-j+22}\right]$$

$$j = (20, 25, \ldots, 60) \in 20-24, 25-29, \ldots, 60-64,$$
$$t = 1870, 1871, \ldots, 2009,$$

where GER_j is the gross enrolment rate in age cohort j, which is defined as the ratio of enrolled students and the population in age cohort j. Note that the fractions in the squared brackets sum to one. The weights 1/25, 2/25 etc. are the fraction of students in each age cohort that were enrolled in the periods t–46, t-45 etc., where the divisor of 25 equals the average length of the tertiary degree in years of 5 (a fifth of the degree is taken in one year) multiplied by the number of age groups contained in each age cohort (there are 5 age groups in each cohort). In 1870, for example, only the individuals at the age of 64 in the 60-64 age cohort could be enrolled as students in 1824, while both the individuals at the age of 64 and 63 were enrolled in 1825, and therefore multiplied by 2, etc. In 1828 all individuals in the 60-64 cohort, who did a tertiary degree, were enrolled as students and GER is, therefore, multiplied by 5. Considering the first squared bracket, in which the 20-24 age cohort is considered, only individuals of the ages of 23 and 24, who were enrolled as students have a degree. Thus, the squared bracket needs to be multiplied by 2/5 and GER is divided by 10, which is the number of years in the first cohort (20-24) multiplied by the two year groups that can potentially take a degree. Data for population in various age groups are typically available every ten years before WWII and available on an annual basis thereafter. The data are interpolated between the census dates for the years in which data are not available and scaled up so the sum of all cohorts sum to the mid-year population which is available on an annual basis for all years. For some countries the data are extrapolated backward to ensure that primary school enrolment is available from 1812. In 1870, for example, the oldest cohort in the labour force (64 years of age) did their first year of primary schooling in 1812, while the youngest cohort (15 years of age) did their first year of primary schooling in 1861.

The following data sources are used: B. R. Mitchell, 1975, *European Historical Statistics 1750-1975*, Macmillan: London, B. R. Mitchell, 1983, *International Historical Statistics: Americas and Australasia*, London: Macmillan, Authur S Banks, 1971, *Cross-Polity Time-Series Data*, Cambridge, MA: MIT Press, P. Flora, F. Kraus, and W. Phenning, 1987, *State, Economy, and Society in Western Europe* 1815-1975, Macmillan: London, OECD's Global Education Digest CD-Rom, 2005, Table C2:"Enrolment by ISCED level", EUROSTAT, F. H. Leacy (ed.), 1983, *Historical Statistics of Canada*, Statistics Canada: Ottawa. Lindert, Peter (homepage) "Lindert data CUP book, Primary Enroll's 1830-1930, Student Enrollment Rates in. Primary Schools, Selected Countries, 1830-1930", Appendix Table A1 and *Statistisk Centralbyraa*, Statistics Norway, Historical Statistics.

(B) CONSUMER PRICE INDEX

General Note: The principal data source is the OECD.Stat's Consumer Prices (Main Economic Indicators) (http://stats.oecd.org/index.aspx?), accessed on 29/07/2012. The data are backdated by splicing figures from different sources as mentioned below:

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(C) **INVESTMENT PRICE DEFLATOR**

General Note: The principal data source is the OECD.Stat's Fixed Capital Formation (http://stats.oecd.org/index.aspx?), accessed on 29/07/2012. Investment deflator is calculated as the ratio of nominal to real investment in equipment and machinery in million national currencies. The data are backdated by splicing figures from different sources as mentioned below:

Australia, 1861-1958 Mitchell, B. R., 2007. *International Historical Statistics:* Africa, Asia and Oceania, 1750-2005. 5th Ed. Palgrave Macmillan, New York; 1959-2010 OECD.Stat, **Austria**, 1870-1912 Schulze, Max-Stephan, 1996. *Engineering and Economic Growth, The Development of Austria-Hungary's Machine-Building Industry in the Late Nineteenth Century*; 1913-1963 Kausel, A., Nemeth, N. and Seidel, H. 1965. *Osterreichs Volkseinkommen, 1913 bis 1963, Monatsberichte des*

Osterreichischen Institutes fur Wirtschaftsforschung, 14th Sonderheft; 1964-1975 OECD National Accounts; *1976-2011* OECD.Stat, **Belgium**, 1890-1994 Meerteen Michelangelo Van, 2003. *Capital Formation in Belgium, 1900-1995*, Leiven University Press; 1995-2011 OECD.Stat, **Canada**, 1847-1925 Investment Deflator of the US; 1926-1970 Historical Statistics of Canada; 1971-2010 OECD.Stat, **Denmark**, 1844-1929 Hansen, Svend Aage,1974. *Okonomisk Vaekst I Danmark, Bind ii: 1914-1970*, Akademisk Forlag, Kobenhavn; 1930-1950 *Danmarks Nationalprodukt 1870-1950*, Kobenhavn, 1958; 1951-1979 *OECD National Accounts*; 1980-2011 OECD.Stat, **Finland**, 1860-1974 Hjerppe, Riitta, 1989. *The Finnish Economy 1860-1985: Growth and Structural Change*, Bank of Finland; 1975-2011 OECD.Stat, **France**, 1896-1938 Dubois, P., 1975. *French Economic Growth*, Stanford University Press; 1939-1950 GDP Deflator; 1951-2005 *OECD National Accounts*; 2006-2011 Total Investment Deflator, OECD.Stat, **Germany**, 1838-1959 Hoffman, W. G., 1965. *Das Wachstum der deutschen wirtschaft seit der mitte des 19 jahrhunderts*; 1960-1979 *OECD National Accounts*; 1980-2010 OECD.Stat, **Greece**, 1858-1959 (GDP Deflator of Greece × Investment Deflator/GDP Deflator of Spain); 1960-1994 Total Investment Deflator, OECD.Stat; 1995-2011 OECD.Stat, **Ireland**, 1953-1979 Mitchell, B. R., 2007. *International Historical Statistics: Europe, 1750-2005*. 6th Ed. Palgrave Macmillan, New York; 1980-1994 *OECD National Accounts*; 1995-2010 OECD.Stat, **Italy**, 1861-1955 Istituto centrale di statistica (1958), *sommario di statistiche, storiche Italiane 1861-1955*, Roma; 1956-1969 *OECD National Accounts*; 1970-2011 OECD.Stat, **Japan**, 1885-1970 Ohkawa, Kazushi and Meissner, Larry, 1979. *Patterns of Japanese Economic Development, A Quantitative Appraisal*, New Haven and Yale University press, London; 1971-1979 *OECD National Accounts*; 1980-2010 OECD.Stat, **Luxembourg**, 1913-1994 (GDP Deflator of Luxembourg × Investment Deflator/GDP Deflator of Belgium); 1995-2011 OECD.Stat, **Netherlands**, 1800-1913 Albers, R. M., 2002. *Machinery Investment and Economic Growth, The Dynamics of Dutch Development 1800-1913*, Amsterdam: Aksant; 1914-1979 Rijks Universiteit Groningen, 2001. *Tweehonderd Jaar Statistiek in Tijdreeksen, 1800-1999*, Centraal Bureau Voor de Statistiek; 1980-2011 OECD.Stat, **New Zealand**, 1860-1870 & 1901-1909 GDP Deflator of New Zealand; 1871-1900 Dowie, J. A., 1966. The Course and Character of Capital Formation in New Zealand-1871-1900, *New Zealand Economic Papers*, 1(1): 38-58; 1910-1964 Francis T.W., 1968. Capital Formation in New Zeland Manufacturing Industries 1910-1964, Technical Paper No. 6, Agricultural Economics Research Unit, Lincoln College; 1965-1986 *OECD National Accounts*; 1987-2006 OECD.Stat, 2007-2010 Investment Deflator of Australia, **Norway**, 1865-1960 Bjerke, Juul, 1966. *Trends in Norwegian Economy 1865-1960*, Oslo: Statistics Norway; 1961-1969 *OECD National Accounts*; 1970-2011 OECD.Stat, **Portugal**, 1870-1969 (GDP Deflator of Portugal × Investment Deflator/GDP Deflator of Spain); 1970-1987 Total Investment Deflator, OECD.Stat; 1988-2011 OECD.Stat, **Spain**, 1850-1958 Prados de la Escosura, L., 2003. *El progreso económico de España, 1850-2000*. Madrid: Fundación BBVA; 1959-1999 *OECD National Accounts*; 2000-2010 OECD.Stat, **Sweden**, 1800-1992 Edvinsson, Rodney, 2005. Growth, Accumulation, Crisis: With New Macroeconomic Data for Sweden 1800-2000, Doctoral Thesis, Department of Economic History Stockholm University; 1993-2011 OECD.Stat, **Switzerland**, 1870-1989 Ritzmann-Blickenstorfer, Heiner, 1996. *Historical Statistics of Switzerland*; 1990-2010 OECD.Stat, **United Kingdom**, 1851-1979 Mitchell, B. R., 1988. *British Historical Statistics*, Cambridge University Press; 1980-2011 OECD.Stat, **United States**, 1847-1924 Public Utility Deflator of the US, Goldsmith, Raymond W., 1955. *a study of Savings in United States*, Greenwood Press , NY; 1925-1969 *Historical Statistics of USA*, 1970-2010 OECD.Stat.

(D) OTHERS

For data sources of TFP, patents, imports, employment, knowledge spillovers see Madsen (2008).

Table 1: Descriptive statistics (1870-2009)

Variable	Mean	Std. Dev.	Min	Max
TFP growth (disembodied)	0.074	0.145	-0.496	1.047
TFP growth (conventional)	0.077	0.145	-0.503	1.046
Labor productivity growth	0.128	0.157	-0.476	1.082
Per capita GDP growth	0.112	0.165	-0.564	1.246
PRI (age 20-34)	0.782	0.369	0.006	1.545
PRI (age 35-49)	0.687	0.387	0.002	1.477
PRI (age 50-64)	0.588	0.392	0.001	1.422
SEC (age 20-34)	0.237	0.286	0.001	1.347
SEC (age 35-49)	0.161	0.227	0.000	1.251
SEC (age 50-64)	0.101	0.160	0.000	1.057
TER (age 20-34)	0.085	0.137	0.001	1.138
TER (age 35-49)	0.057	0.089	0.001	0.659
TER (age 50-64)	0.031	0.047	0.000	0.350
$\ln(A_{it}/A_t^{max})$	-0.735	0.507	-2.593	0.000
Old age dependency	0.089	0.040	0.017	0.212
Young age dependency	0.275	0.064	0.137	0.425

Notes: the variables are expressed in five-year differences or averages. The TFP measure is the default TFP measure in which embodied technological progress is incorporated into the estimates. The total number of observations is 588. *PRI* (20-34) is the years of primary education attained by population in the age group of 20 to 34 and so forth. The following 21 OECD countries are included: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Japan, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, the UK and the US.

Table 2: System GMM growth estimates by age group

	(1a)	(1b)	(1c)	(2a)	(2b)	(2c)	(3a)	(3b)	(3c)
	20-34	35-49	50-64	20-34	35-49	50-64	20-34	35-49	50-64
	(1) TFP growth			(2) Labor productivity growth			(3) GDP per capita growth		
$PRI_{i,t-1}$	-0.081	-0.038	-0.016	-0.064	-0.056	0.011	-0.059	0.022	0.048
	(0.269)	(0.497)	(0.689)	(0.420)	(0.360)	(0.818)	(0.561)	(0.691)	(0.466)
$SEC_{i,t-1}$	-0.092	-0.156*	-0.157+	-0.074	-0.167*	-0.219#	-0.046	-0.223+	-0.236#
	(0.242)	(0.100)	(0.045)	(0.207)	(0.052)	(0.001)	(0.571)	(0.031)	(0.009)
$TER_{i,t-1}$	0.361#	0.439+	0.464+	0.312#	0.470#	0.647#	0.324+	0.450	0.484*
	(0.000)	(0.013)	(0.012)	(0.001)	(0.002)	(0.004)	(0.039)	(0.108)	(0.067)
$\ln(A_i/A^{max})_{t-1}$	-0.044+	-0.048*	-0.084#	-0.041*	-0.076+	-0.072#	-0.037*	-0.073#	-0.138#
	(0.022)	(0.097)	(0.001)	(0.055)	(0.014)	(0.005)	(0.068)	(0.002)	(0.001)
$PRI_{i,t-1}\times$ $\ln(A_i/A^{max})_{t-1}$	-0.056	-0.093#	-0.120#	-0.094	-0.054	-0.089	-0.127*	-0.052	-0.098
	(0.343)	(0.003)	(0.000)	(0.137)	(0.286)	(0.115)	(0.059)	(0.419)	(0.210)
$SEC_{i,t-1}\times$ $\ln(A_i/A^{max})_{t-1}$	-0.505#	-0.546	-0.301	-0.431+	-0.604	-0.772*	-0.413*	-0.768*	-0.938+
	(0.009)	(0.145)	(0.396)	(0.025)	(0.117)	(0.077)	(0.060)	(0.051)	(0.021)
$TER_{i,t-1}\times$ $\ln(A_i/A^{max})_{t-1}$	0.707*	1.150*	1.308#	0.721+	1.324+	2.036#	0.446	1.157	1.535#
	(0.095)	(0.097)	(0.001)	(0.050)	(0.046)	(0.000)	(0.258)	(0.301)	(0.007)
Imports / GDP	-0.251+	-0.172	-0.204+	-0.166	-0.218	-0.158	-0.320+	-0.311#	-0.430#
	(0.014)	(0.139)	(0.036)	(0.167)	(0.110)	(0.101)	(0.042)	(0.002)	(0.002)
Patent app. / Employment	0.028	0.013	0.016	0.025	0.023	-0.006	0.018	0.010	-0.006
	(0.146)	(0.383)	(0.320)	(0.210)	(0.184)	(0.784)	(0.484)	(0.551)	(0.653)
Int. knowledge spillovers	0.069	0.084*	0.096+	0.107+	0.109+	0.120+	0.128+	0.136+	0.143#
	(0.114)	(0.068)	(0.025)	(0.022)	(0.025)	(0.035)	(0.012)	(0.022)	(0.009)
Young age dependency							-0.584*	-0.434	-0.642+
							(0.064)	(0.157)	(0.021)
Δ Young age dependency							-0.133	-0.188	-0.113
							(0.860)	(0.795)	(0.881)
Old age dependency							-1.268+	-1.165+	-2.129#
							(0.019)	(0.036)	(0.001)
Δ Old age dependency							0.009	0.499	0.840
							(0.995)	(0.691)	(0.532)
Observations	567	567	567	567	567	567	567	567	567
No. of countries	21	21	21	21	21	21	21	21	21
AR(2) (p-val)	0.952	0.982	0.992	0.480	0.557	0.151	0.619	0.920	0.705
Sargan (p-val)	0.914	0.971	0.884	0.923	0.921	0.993	0.185	0.971	0.561

Notes: the dependent variables (ΔlnA) are total factor productivity growth (columns (1)), labor productivity growth (columns (2)), and per capita GDP growth (columns (3)). A constant, time dummies and a lagged dependent variable are included in all regressions but are not reported to conserve space. Robust standard errors are used in the estimation. The number of instruments has been truncated using the "collapse" command in STATA. Figures in the parentheses indicate *p*-values. #, + and * denote 1%, 5% and 10% levels of significance, respectively.

Table 3: System GMM growth estimates by age group (post WWII: 1946-2009)

	(1a)	(1b)	(1c)	(2a)	(2b)	(2c)	(3a)	(3b)	(3c)
	20-34	35-49	50-64	20-34	35-49	50-64	20-34	35-49	50-64
	(1) TFP growth			(2) Labor productivity growth			(3) GDP per capita growth		
$PRI_{i,t-1}$	0.040	0.047	0.065	0.050	0.039	0.097	0.198+	0.238*	0.287+
	(0.552)	(0.256)	(0.424)	(0.653)	(0.680)	(0.443)	(0.043)	(0.087)	(0.034)
$SEC_{i,t-1}$	-0.080+	-0.120+	-0.136+	-0.077	-0.123	-0.218*	-0.084	-0.232#	-0.287+
	(0.034)	(0.021)	(0.044)	(0.114)	(0.132)	(0.089)	(0.107)	(0.004)	(0.027)
$TER_{i,t-1}$	0.140+	0.245#	0.402#	0.226#	0.359#	0.637#	0.130	0.316*	0.516*
	(0.035)	(0.005)	(0.002)	(0.009)	(0.001)	(0.002)	(0.273)	(0.084)	(0.097)
$\ln(A_i/A^{max})_{t-1}$	-0.133	-0.139#	-0.176+	-0.180	-0.172*	-0.266+	-0.237*	-0.261*	-0.305+
	(0.161)	(0.007)	(0.017)	(0.239)	(0.065)	(0.015)	(0.090)	(0.059)	(0.011)
$PRI_{i,t-1}\times$	-0.006	-0.010	-0.028	-0.020	-0.043	0.032	0.104	0.095	0.133
$\ln(A_i/A^{max})_{t-1}$	(0.946)	(0.862)	(0.749)	(0.889)	(0.686)	(0.833)	(0.404)	(0.465)	(0.310)
$SEC_{i,t-1}\times$	-0.169*	-0.369#	-0.545+	-0.292	-0.493	-0.937	-0.304	-0.737+	-1.240*
$\ln(A_i/A^{max})_{t-1}$	(0.076)	(0.007)	(0.036)	(0.202)	(0.109)	(0.134)	(0.197)	(0.045)	(0.099)
$TER_{i,t-1}\times$	0.252	0.553*	1.661+	0.576+	0.955*	2.529+	-0.031	0.866	1.261
$\ln(A_i/A^{max})_{t-1}$	(0.243)	(0.081)	(0.024)	(0.039)	(0.076)	(0.038)	(0.942)	(0.289)	(0.547)
Imports /	0.582	-0.243	0.722	-2.095	-4.276	-1.344	0.177	-0.475	-4.480
GDP	(0.906)	(0.966)	(0.904)	(0.740)	(0.566)	(0.877)	(0.980)	(0.962)	(0.728)
Patent app. /	0.009	0.003	0.002	0.009	0.002	0.003	-0.002	-0.003	-0.030
Employment	(0.293)	(0.725)	(0.871)	(0.198)	(0.806)	(0.839)	(0.749)	(0.773)	(0.267)
Int. knowledge	-0.008	0.004	-0.001	0.012	0.034	0.023	0.090	0.101	0.073
spillovers	(0.855)	(0.930)	(0.991)	(0.832)	(0.599)	(0.741)	(0.441)	(0.428)	(0.618)
Young age							-0.704*	-0.551	-0.595
dependency							(0.081)	(0.136)	(0.138)
Δ Young age							-1.802#	-1.734#	-1.551+
dependency							(0.007)	(0.007)	(0.018)
Old age							-0.845	-1.079	-1.055
dependency							(0.129)	(0.117)	(0.224)
Δ Old age							-1.928#	-1.653+	-1.316
dependency							(0.007)	(0.011)	(0.130)

Notes: the dependent variables (ΔlnA) are total factor productivity growth (columns (1)), labor productivity growth (columns (2)), and per capita GDP growth (columns (3)). A constant, time dummies and a lagged dependent variable are included in all regressions but are not reported to conserve space. Robust standard errors are used in the estimation. The number of instruments has been truncated using the "collapse" command in STATA. The total number of countries included is 21 and the total number of observations in each regression is 252. Figures in the parentheses indicate p-values. #, + and * denote 1%, 5% and 10% levels of significance, respectively.

Table 4: System GMM ideas production estimates using patenting activity as the dependent variable

	(1a)	(1b)	(1c)	(2a)	(2b)	(2c)
	20-34	35-49	50-64	20-34	35-49	50-64
	(1) excluding age dependency			(2) including age dependency		
$PRI_{i,t-1}$	0.009	0.099	0.302#	-0.025	0.036	0.325#
	(0.911)	(0.229)	(0.006)	(0.815)	(0.620)	(0.009)
$SEC_{i,t-1}$	-0.115	-0.172	-0.414*	-0.097	-0.143	-0.395*
	(0.423)	(0.132)	(0.063)	(0.424)	(0.153)	(0.072)
$TER_{i,t-1}$	0.249	0.442+	1.231+	0.447#	0.636#	1.260*
	(0.332)	(0.026)	(0.048)	(0.007)	(0.003)	(0.069)
$\ln(A_i/A^{max})_{t-1}$	-0.125*	-0.103#	-0.225#	-0.051	0.002	-0.192+
	(0.059)	(0.005)	(0.001)	(0.416)	(0.973)	(0.017)
$PRI_{i,t-1} \times \ln(A_i/A^{max})_{t-1}$	0.204	0.069	0.339*	0.024	-0.031	0.220
	(0.112)	(0.449)	(0.058)	(0.844)	(0.699)	(0.199)
$SEC_{i,t-1} \times \ln(A_i/A^{max})_{t-1}$	-0.912+	-0.899#	-1.567*	-0.727+	-0.930#	-1.859*
	(0.025)	(0.009)	(0.085)	(0.015)	(0.006)	(0.054)
$TER_{i,t-1} \times \ln(A_i/A^{max})_{t-1}$	0.153	1.549+	2.404+	0.544	1.755#	3.202#
	(0.851)	(0.017)	(0.033)	(0.312)	(0.005)	(0.004)
Imports / GDP	-0.853+	-0.548*	-1.813#	-0.779+	-0.641*	-1.764#
	(0.012)	(0.050)	(0.000)	(0.013)	(0.084)	(0.000)
Patent app. / Employment	0.060	0.022	0.024	0.044	-0.012	-0.016
	(0.114)	(0.222)	(0.228)	(0.205)	(0.734)	(0.677)
Int. knowledge spillovers	0.011	0.076	0.084	0.047	0.043	0.103
	(0.838)	(0.158)	(0.250)	(0.364)	(0.528)	(0.282)
Young age dependency				0.782	0.783	0.961
				(0.145)	(0.168)	(0.167)
Δ Young age dependency				1.075	1.258	0.627
				(0.169)	(0.119)	(0.491)
Old age dependency				0.881	0.394	0.167
				(0.318)	(0.660)	(0.883)
Δ Old age dependency				0.028	1.069	0.511
				(0.982)	(0.501)	(0.656)

Notes: the dependent variable is the ratio of the number of patent applications to the stock of patent applications. A constant, time dummies and a lagged dependent variable are included in all regressions but are not reported to conserve space. Robust standard errors are used in the estimation. The number of instruments has been truncated using the "collapse" command in STATA. The total number of countries included is 21 and the total number of observations in each regression is 567. Figures in the parentheses indicate *p*-values. #, + and * denote 1%, 5% and 10% levels of significance, respectively.

Table 5: Growth estimates with all age groups and levels of educational attainment

	(1) TFP growth	(2) Labor productivity growth	(3) GDP per capita growth
$PRI_{i,t-1}$ (20-34)	-0.108	-0.099	-0.168
$PRI_{i,t-1}$ (35-49)	0.244	0.239	0.289+
$PRI_{i,t-1}$ (50-64)	-0.090	-0.084	-0.109
$SEC_{i,t-1}$ (20-34)	0.139	0.093	0.189
$SEC_{i,t-1}$ (35-49)	-0.398	-0.255	-0.241
$SEC_{i,t-1}$ (50-64)	0.087	-0.052	-0.199
$TER_{i,t-1}$ (20-34)	-0.018	-0.127	-0.045
$TER_{i,t-1}$ (35-49)	0.273	0.487	0.157
$TER_{i,t-1}$ (50-64)	0.176	0.157	0.218
$\ln(A_i/A^{max})_{t-1}$	-0.209#	-0.185#	-0.183#
$PRI_{i,t-1}$ (20-34) $\times \ln(A_i/A^{max})_{t-1}$	-0.234	-0.336*	-0.404+
$PRI_{i,t-1}$ (35-49) $\times \ln(A_i/A^{max})_{t-1}$	0.465	0.500	0.602+
$PRI_{i,t-1}$ (50-64) $\times \ln(A_i/A^{max})_{t-1}$	-0.231	-0.167	-0.260
$SEC_{i,t-1}$ (20-34) $\times \ln(A_i/A^{max})_{t-1}$	0.144	-0.044	0.325
$SEC_{i,t-1}$ (35-49) $\times \ln(A_i/A^{max})_{t-1}$	-0.969	-0.354	-0.671
$SEC_{i,t-1}$ (50-64) $\times \ln(A_i/A^{max})_{t-1}$	0.859	0.001	0.270
$TER_{i,t-1}$ (20-34) $\times \ln(A_i/A^{max})_{t-1}$	-1.236	-1.450	-1.195
$TER_{i,t-1}$ (35-49) $\times \ln(A_i/A^{max})_{t-1}$	0.724	1.235	0.289
$TER_{i,t-1}$ (50-64) $\times \ln(A_i/A^{max})_{t-1}$	3.619#	3.635#	3.450#
Imports / GDP	-0.370#	-0.270*	-0.498#
Patent app. / Employment	0.037*	0.022	0.032
Knowledge spillovers	0.101+	0.132+	0.149#
Young age dependency			-0.741+
Δ Young age dependency			0.032
Old age dependency			-2.297#
Δ Old age dependency			0.258

Notes: the dependent variables (ΔlnA) are total factor productivity growth (column (1)), labor productivity growth (column (2)), and per capita GDP growth (column (3)). A constant, time dummies and a lagged dependent variable are included in all regressions but are not reported to conserve space. Robust standard errors are used in the estimation. The number of instruments has been truncated using the "collapse" command in STATA. The total number of countries included is 21 and the total number of observations in each regression is 567. The *p*-values are not reported here due to space constraints. #, + and * denote 1%, 5% and 10% levels of significance, respectively.

Table 6: System GMM growth estimates without time dummies

	(1a)	(1b)	(1c)	(2a)	(2b)	(2c)	(3a)	(3b)	(3c)
	<u>20-34</u>	<u>35-49</u>	<u>50-64</u>	<u>20-34</u>	<u>35-49</u>	<u>50-64</u>	<u>20-34</u>	<u>35-49</u>	<u>50-64</u>
	(1) TFP growth			(2) Labor productivity growth			(3) GDP per capita growth		
$PRI_{i,t-1}$	0.087	0.157+	0.248+	0.100	0.223+	0.249+	0.268+	0.234#	0.405#
	(0.256)	(0.036)	(0.019)	(0.197)	(0.021)	(0.039)	(0.016)	(0.009)	(0.001)
$SEC_{i,t-1}$	-0.096	-0.286+	-0.482#	-0.086	-0.279+	-0.497#	-0.064	-0.360#	-0.736#
	(0.300)	(0.018)	(0.007)	(0.292)	(0.025)	(0.010)	(0.399)	(0.002)	(0.005)
$TER_{i,t-1}$	0.124	0.368+	0.609+	0.093	0.215*	0.595*	-0.102	0.413*	0.828+
	(0.246)	(0.017)	(0.029)	(0.369)	(0.091)	(0.069)	(0.366)	(0.097)	(0.040)
$\ln(A_i/A^{max})_{t-1}$	-0.140#	-0.195#	-0.296#	-0.128+	-0.265#	-0.292#	-0.199*	-0.199#	-0.394#
	(0.007)	(0.000)	(0.000)	(0.011)	(0.000)	(0.001)	(0.066)	(0.005)	(0.000)
$PRI_{i,t-1}\times$ $\ln(A_i/A^{max})_{t-1}$	0.013	0.072	0.185*	-0.016	0.168*	0.147	0.103	0.177*	0.405+
	(0.880)	(0.362)	(0.062)	(0.857)	(0.099)	(0.201)	(0.522)	(0.088)	(0.021)
$SEC_{i,t-1}\times$ $\ln(A_i/A^{max})_{t-1}$	-0.620#	-1.134#	-1.592#	-0.689#	-1.256#	-1.949#	-0.338	-1.305#	-2.785#
	(0.005)	(0.003)	(0.002)	(0.003)	(0.001)	(0.002)	(0.128)	(0.001)	(0.000)
$TER_{i,t-1}\times$ $\ln(A_i/A^{max})_{t-1}$	0.901+	1.727+	3.501#	1.008+	1.446*	3.519#	-0.068	1.857	6.386#
	(0.046)	(0.011)	(0.000)	(0.035)	(0.067)	(0.001)	(0.880)	(0.144)	(0.000)
Imports / GDP	-0.207+	-0.224*	-0.432#	-0.137	-0.340#	-0.401#	-0.134	-0.325#	-0.631#
	(0.024)	(0.063)	(0.001)	(0.235)	(0.006)	(0.005)	(0.334)	(0.001)	(0.003)
Patent app. / Employment	0.041	0.038	0.051*	0.034	0.063*	0.045	0.021	0.023	0.038
	(0.134)	(0.150)	(0.059)	(0.252)	(0.078)	(0.136)	(0.600)	(0.451)	(0.418)
Int. knowledge spillovers	0.134#	0.182#	0.210#	0.151#	0.212#	0.226#	0.208#	0.244#	0.285#
	(0.002)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)
Young age dependency							-0.045	0.181	0.473
							(0.911)	(0.567)	(0.291)
Δ Young age dependency							1.036*	0.899	0.605
							(0.054)	(0.121)	(0.289)
Old age dependency							-0.261	0.136	0.728
							(0.769)	(0.855)	(0.508)
Δ Old age dependency							1.142	1.350	0.952
							(0.433)	(0.358)	(0.594)

Notes: the dependent variables (ΔlnA) are total factor productivity growth (columns (1)), labor productivity growth (columns (2)), and per capita GDP growth (columns (3)). A constant and a lagged dependent variable are included in all regressions but are not reported to conserve space. Robust standard errors are used in the estimation. The number of instruments has been truncated using the "collapse" command in STATA. The total number of countries included is 21 and the total number of observations in each regression is 567. Figures in the parentheses indicate *p*-values. #, + and * denote 1%, 5% and 10% levels of significance, respectively.

Table 7: Robustness checks for the adjustment of embodied technological progress

	(1a)	(1b)	(1c)	(2a)	(2b)	(2c)
	20-34	35-49	50-64	20-34	35-49	50-64
				(2) disembodied TFP growth with		
	(1) conventional TFP growth			embodied technological progress as an		
				additional regressor		
$PRI_{i,t-1}$	-0.087	-0.035	-0.015	-0.081	-0.030	-0.017
	(0.266)	(0.534)	(0.699)	(0.276)	(0.589)	(0.678)
$SEC_{i,t-1}$	-0.083	-0.162*	-0.159*	-0.095	-0.166*	-0.163+
	(0.304)	(0.091)	(0.051)	(0.256)	(0.081)	(0.040)
$TER_{i,t-1}$	0.381#	0.488#	0.513#	0.368#	0.451#	0.491#
	(0.000)	(0.009)	(0.006)	(0.001)	(0.008)	(0.003)
$\ln(A_i/A^{max})_{t-1}$	-0.044+	-0.045	-0.086#	-0.044+	-0.051*	-0.083#
	(0.026)	(0.122)	(0.001)	(0.019)	(0.068)	(0.001)
$PRI_{i,t-1}\times$	-0.058	-0.094#	-0.119#	-0.055	-0.091#	-0.121#
$\ln(A_i/A^{max})_{t-1}$	(0.341)	(0.006)	(0.001)	(0.358)	(0.005)	(0.000)
$SEC_{i,t-1}\times$	-0.515#	-0.642	-0.335	-0.519#	-0.589*	-0.295
$\ln(A_i/A^{max})_{t-1}$	(0.009)	(0.120)	(0.361)	(0.007)	(0.099)	(0.389)
$TER_{i,t-1}\times$	0.715*	1.353*	1.374#	0.739*	1.198*	1.326#
$\ln(A_i/A^{max})_{t-1}$	(0.088)	(0.083)	(0.001)	(0.083)	(0.064)	(0.000)
Imports /	-0.261+	-0.161	-0.208+	-0.258#	-0.174	-0.210+
GDP	(0.014)	(0.126)	(0.037)	(0.007)	(0.102)	(0.026)
Patent app. /	0.030	0.011	0.016	0.028	0.013	0.015
Employment	(0.149)	(0.422)	(0.315)	(0.159)	(0.415)	(0.339)
Int. knowledge	0.070	0.086*	0.096+	0.069	0.087*	0.095+
spillovers	(0.120)	(0.070)	(0.026)	(0.114)	(0.059)	(0.026)
Embodied				-1.998	-1.754	-2.576
technological progress				(0.780)	(0.802)	(0.707)

Notes: the dependent variables are conventional TFP growth (columns (1)) and disembodied TFP growth (columns (2)). Embodied technological progress is measured as conventional TFP minus TFP adjusted for embodied technological progress. A constant and a lagged dependent variable are included in all regressions but are not reported to conserve space. Robust standard errors are used in the estimation. The number of instruments has been truncated using the "collapse" command in STATA. The total number of countries included is 21 and the total number of observations in each regression is 567. Figures in the parentheses indicate *p*-values. #, + and * denote 1%, 5% and 10% levels of significance, respectively.