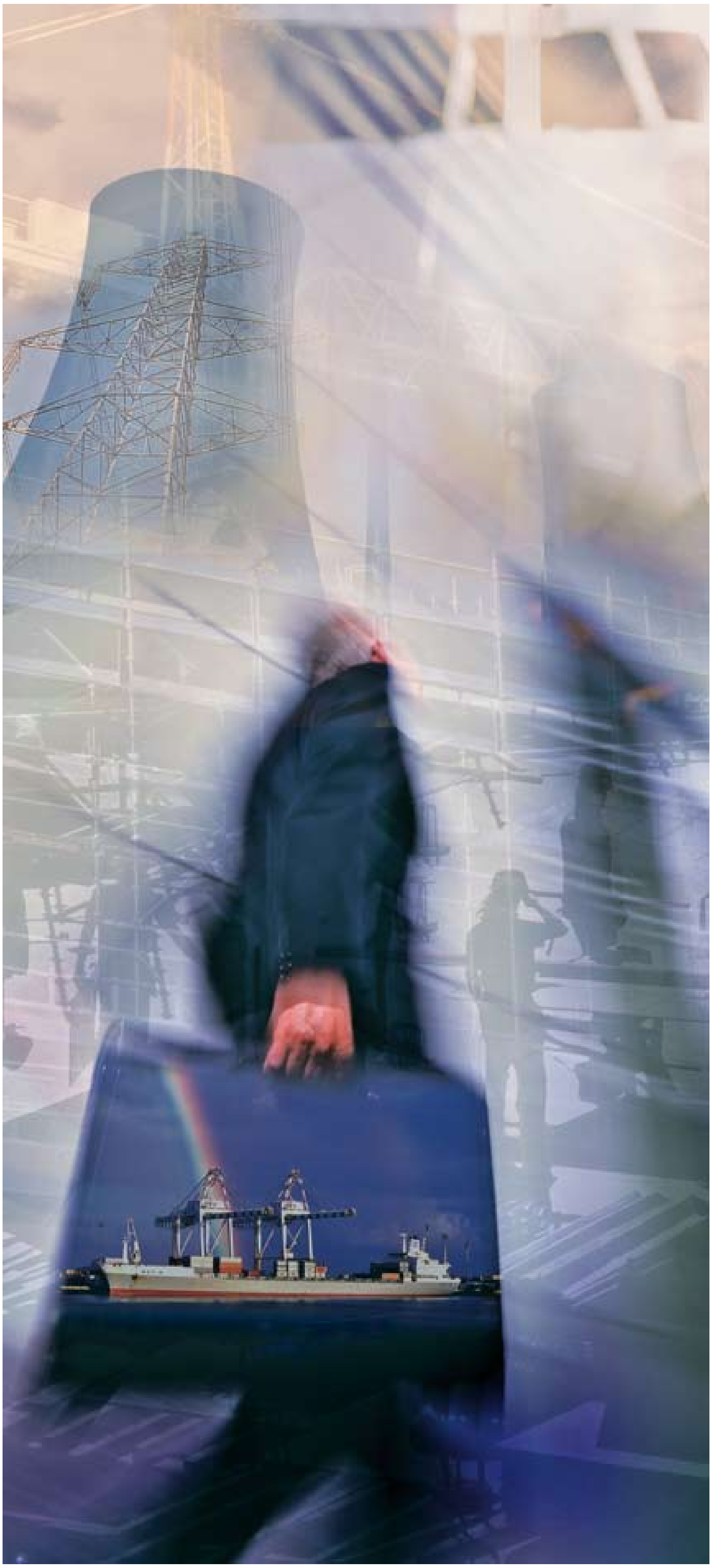

Queensland

The Economic Society of Australia Inc.

Proceedings of the 37th Australian Conference of Economists

Papers delivered at ACE 08

30th September to 4th October 2008
Gold Coast Queensland Australia

ISBN 978-0-9591806-4-0

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The Paper following forms part of - *Proceedings of the 37th Australian Conference of Economists*
ISBN 978-0-9591806-4-0

Human Capital and Growth

Jakob B. Madsen[1]

Abstract. Using a new data set for human capital for 16 industrialized countries over the period from 1870 to 2006 this paper examines the extent to which productivity growth can be explained by educational achievement, educational knowledge spillovers through the channel of imports, and the interaction between educational achievement and the distance to the world technology frontier. The estimates show that educational attainment influences growth through the channel of imports and through the distance to the frontier. Educational attainment by itself only has temporary growth effects.

JEL Classification: O30, O40
Key words: human capital, patents, distance to the frontier, spillovers

Human capital plays a central role in models of economic growth in models of Nelson and Phelps (1966), Lucas (1988), Mankiw, Romer and Weil (1992), Aghion and Howitt (1998), Galor and Weil (1999, 2000), Jones (2002, 2003 – in Phelps), Aghion, Boustan, Hoxby and Vandenbussche (2005), Galor (2005), and Vandenbussche, Aghion, and Meghir (2006). While growth is a result of capital accumulation in the models of Weil and Romer (1992) and Lucas (1988), it is particularly the interaction between education and the distance to the technology frontier that drive growth in the models of Nelson and Phelps (1966), Aghion, Boustan, Hoxby and Vandenbussche (2005), and Vandenbussche, Aghion, and Meghir (2006). In the unified theories of Galor and Weil (1999, 2000) human capital played the key role in transforming the west European economies and their offshoots from the post-Malthusian regime into a modern growth regime due to the joint effect of skill-capital complementarily and the positive spillovers from education.

Empirically, however, it has been difficult to find a robust relationship between growth and educational attainment, where educational attainment is defined as average years of schooling of the population in the labour force (Pritchett, 2001, 2005). Furthermore, the estimates are highly sensitive to human capital measurement, model specification, and country sample (Benhabib and Spiegel, 1994, 2005, Pritchett, 2001, 2005, de la Fuente and Domenech, 2006). More importantly Pritchett argues "there can be no 'growth' effect of schooling levels" (2005, title to Section IIA). Pritchett observes that growth rates have not increased significantly over the past century in the

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[1] Department of Economics, Monash University, FRU and EPRU, University of Copenhagen, and CAMA, Australian National University. Helpful comments and suggestions from participants at seminars at Melbourne University and Monash University and financial support from the Australian Research Council are gratefully acknowledged. Christian Eriksen Stassen and Morten Engberg Jensen provided excellent research assistance.

OECD countries while secondary school enrolment rates have increased 25 fold during the same period. Thus, while there may potentially be a positive cross-country relationship between educational achievement and the level or the growth in productivity it appears that there is no reason to expect human capital to have played a pivotal role in the history of growth. It is also widely agreed among economic historians that human capital did not play an important role for growth during the first industrial revolution in the latter part of the 18th century (Galor, 2005).

This brings us back to the question of factors that have been responsible for the strong growth performance among most OECD countries over the past one and a half century. The evidence of Madsen (2007 JIE, 2008 JEG) suggest that post WWII growth among the OECD countries has to a large extent been driven by R&D and technology spillovers through the channel of imports. However, the level and the growth in R&D among the industrialized countries from the start of the second industrial revolution up to WWII were probably too low to account for the all growth. The scant evidence on R&D suggests that the ratio of R&D and income was very low before WWII (Madsen, 2007 EL). We therefore, have a growth paradox unless education affected growth during the period from 1870 to WWII. The question is how. Three possibilities are investigated in this paper: that there is a non-linear relationship between growth and educational attainment, that education has been interacting with other variables, that human capital spillovers among countries have been influential for growth, and that educational achievement has only temporary growth effects as argued by Mankiw, Romer and Weil (1992) and Jones (2002).

To address these questions this papers uses a unique new *annual* dataset for human capital for 16 industrialized countries over the period from 1870 to 2006 and uses recent developments within endogenous growth theory to address the Pritchett critique. The long historical data are not only ideal to address Pritchett's critique and the growth paradox. It also overcomes cross-country comparison problems of schooling surveys, on which estimates of human capital are based on. Since fixed effects are suppressed in the estimates in this paper the parameter estimates are driven by time-variation in the data. This stands in contrast to almost all other studies in which most the variation in the data are driven by the cross-section variation in the data. Furthermore, human capital data cover the transitional period from the Post-Malthusian Epoch to the Modern Growth Regime during around 1900, in which human capital has potentially played a key role during the transition (Galor and Weil, 1999, 2000, Galor, 2005).

The paper seeks to accommodate Pritchett's critique in the following ways. First, human capital needs not be normalised by population of working age as is usually done in empirical estimates on growth and human capital. The Schumpeterian growth theories of Howitt (1999), Peretto (1998), and Young (1998) suggest that human capital should be normalized by employment or, in some events, by income (see for example Aghion and Howitt, 1998, p 339, Cannon, 2000, and Madsen, 2008 JEG). The idea behind Schumpeterian models is that the inventive production of human capital spreads more thinly across product varieties as the economy grows. To ensure sustained productivity growth, human capital has to increase over time along with the range of product lines to counteract the increasing range of products that lowers the average productivity of R&D activity. In steady state the growth in human capital must follow employment or population growth rates. Since the ratio of employment and population has varied substantially over time employment is likely to be a better normalizing variable than population of working age.

Second, changing educational achievement may only have temporary growth effects as predicted by the Solow growth model (Mankiw, Romer and Weil, 1992) and, more recently, by the semi-endogenous growth models of Jones (2002). Third, non-linear effects of educational achievement on growth are allowed for in the estimates. Earnings growth is often assumed to be a decreasing function of years of schooling (see for example Hall and Jones, 1999, Baier *et al*., 2006). This suggests that growth should be proportional to educational achievement in a non-linear fashion.

The estimates are extended to allow for the interaction between educational achievement and distance to the technology frontier, as predicted by the model of Nelson and Phelps (1966), and to allow for transmission of educational attainment through the channel of imports. These variables are important control variables to complement the excess smoothness of educational attainment relative to growth. Several studies have shown that trade is an important channel through which R&D transmits internationally (Coe and Helpman, 1995, Madsen, 2007 JIE, 2008 SJE). Following the logic of these studies imports of knowledge are in this paper measured as the educational attainment capital that is embodied in imports of goods. Furthermore, following Schumpeterian growth theories the estimates are extended to allow for research lead growth in the post-war period.

The empirical estimates give important insight into the anatomy of growth in the industrialized world since the second industrialized revolution, international transmission of educational knowledge, and the knowledge production function that could form the basis for further development within endogenous growth theory. While human capital played an important role during and immediately after the second industrialized revolution R&D has been important impetus for growth in the post-WWII period and will continue to be that in the future while human capital is unlikely to contribute much to growth in the future.

The paper is organized as follows. The next section examines human capital models, Section 3 addresses measurement issues and the empirical estimates are presented in Section 4.

2 The nexus between growth and human capital

Consider the extended Nelson-Phelps growth model:

$$\frac{\dot{A}_t}{A_t} = g\left(\frac{H}{Q}\right)_t + \phi\left(\frac{H}{Q}\right)_t \left[\frac{\overline{A}_{t-1} - A_t - 1}{A_{t-1}}\right], \qquad \phi(0) = 0, \qquad (1)$$

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

where A is technology, $\overline{A}$ is the world technological frontier, H is human capital, β is the coefficient of product proliferation, L is the labour force, and Q is product variety. Human capital is the sum of educational resources in the economy. Human capital intensity, (X/Q), is usually measured as educational attainment. The $g(H/Q)$-term is omitted in the Nelson-Phelps framework while the second right-hand-side term is omitted and β=0 in the model of Lucas (1988). Nelson and Phelps define $\overline{A}$ as the theoretical level of technology, i.e. "the best practice level of technology that would prevail if technological diffusion was completely instantaneous," (1966, p 71).

The philosophy behind the Nelson-Phelps model is intuitive and simple: the further a country is behind the technological frontier the higher is its growth potential provided that it has a sufficiently high level of human capital, or absorptive capacity, to take advantage of its backwardness. The technology that has been created at the technological frontier can be used by an educated labour force in an off-frontier country to create new technologies in their own country. The Nelson-Phelps model is of partial nature in that it does not explain the factors that are responsible for growth in the frontier countries. Furthermore, the model does not allow for the possibility that off-frontier countries develop new products and production methods independently of the technology developed elsewhere. To overcome this deficiency Benhabib and Spiegel (1994) extended the Phelps-Nelson model to allow for the growth effects of educational achievement, which is represented by the first right-hand-side term in Equation (1).

While the Nelson-Phelps model was developed more than 40 years ago and extended by Benhabib and Spiegel (1994) 15 years ago it has first recently been shown by Young (1998) that knowledge needs to be normalised to allow for the increasing number of product varieties as the labour force is increasing following the Schumpeterian paradigm. As the number of products or product lines increase as the economy is growing innovations affect a smaller proportion of the economy and, therefore, has a smaller proportional effects on the aggregate stock of knowledge (Aghion and Howitt, 1998, p 417). This normalization is partly an attempt to accommodate the critique by Jones (1995) of first-generation endogenous growth models. Jones pointed out that the strong increase in the number of R&D workers in the G5 countries has failed to increase the US productivity growth rate in the post-WWII period. This stands in contrast to the predictions of first generation models of growth in which productivity growth is proportional to the number of R&D workers.

The reasoning behind the normalization of human capital in Schumpeterian models is that an increasingly educated labour force increases the variety as well as the quality of products. While product variety does not affect the level of income in Schumpeterian models product quality does. Assuming that the number of products is assumed to grow at the same rate as employment it follows that growth is proportional to the ratio of human capital and employment.[2]

Furthermore, it took 25 years before it was shown by Howitt (2000) that the interaction between human capital intensity and distance to the world technology frontier is consistent with steady-state properties of the Schumpeterian growth model. Howitt (2000) shows that growth is a positive function of the interaction between research intensity and the distance to the technology frontier. The reasoning follows the seminal hypothesis of Gerschenkron that backward countries possessing an educated labour force would be able to take advantage of the technology developed elsewhere.

There are various ways of measuring X/Q. X/Q is usually, if not always, measured as educational attainment, while the earlier literature used school enrolment rates as proxies for X/Q. Nelson and Phelps write that (X/Q) "is some index of educational attainment" (1966, p 72), which appears to suggest that X/Q needs not exactly be measured by educational attainment. Now, since growth is stationary, as found by Ho and Howitt (2007), H and Q must form a cointegrated relationship; otherwise the extended Nelson-Phelps model does not have a balanced growth path (see Howitt, 2000, for a proof). Thus, the disturbance term, v, in the following cointegration relationship must be stationary:

$$lnX_t = lnQ_t + v_t. \quad (2)$$

Following from this the first step is to examine whether X and Q form a cointegrated relationship for various measures of X. This will ensure that a balanced growth path exists and that X is normalized with the appropriate variable.

As discussed in the introduction Equation (1) is unlikely to account for growth in a historical perspective because gross enrolment rates have increased markedly over the past century while productivity growth rates have not (Pritchett, 2005). While most individuals had some form of formal education in the 19th century the school attendance rate and particularly the number of schooldays within a year were extremely low by today's standard. Ljungberg and Nilsson (2005)

[2] Alternatively, Jones (2003) argues that educational attainment should be considered as a flow variable equivalent to the investment ratio.

estimate that the school year consisted of 36 days in Sweden in 1812 and 60 days in 1860, which cover the years over which the largest fraction of the labour force in 1870 did their schooling.

While the distance-to-frontier-term in the model may alleviate the Pritchett critique for countries that back in time were far from the technology frontier the model may not be able to explain growth among the frontier countries and countries that have been close to the frontier over the past one or two centuries. One way to overcome this problem is to allow for other conditional variables. However, conditioning variables that are usually highlighted in endogenous growth models, such as R&D intensity and import of knowledge have also been increasing over time and, therefore, do not resolve the problem (see Madsen, 2007 JIE). Consequently, other steps need to be taken to counter the growth-effects of increasing educational attainment.

Seeking to overcome the Pritchett critique Equation (1) is extended as follows:

$$\frac{\dot{A}_t}{A_t} = \alpha_1 h_t^d + \alpha_2 \left(h_t^d\right)^2 + \alpha_3 h_t^f + \alpha_4 \Delta h_t^d + \alpha_5 h_t^d \left[\frac{\overline{A}_{t-1} - A_{t-1}}{A_{t-1}}\right], \tag{3}$$

where h is human capital intensity, H/Q, α_i's are constants, and the superscripts d and f stand for domestic and foreign. Δh_t^f was initially included in the estimates, however, it was omitted since it was insignificant in all the estimates. This equation accommodates the predictions of Schumpeterian growth theory, non-linear growth effects of educational attainment, and knowledge spillovers through the channel of imports. The model of Benhabib and Spiegel (1994) and Schumpeterian growth theories assume that $\alpha_4 = 0$ and $(\alpha_1, \alpha_3, \alpha_5) > 0$ (Madsen, 2008 JEG). Consequently, a constant level of human capital intensity keeps the rate of innovative activity, and thus productivity growth, constant in Schumpeterian models along a balanced growth path. The variable Δh_t^d is included in the estimates to allow educational intensity to have only temporary effects on growth. Note that this variable is not directly related to semi-endogenous growth theory, which predicts that $\Delta \ln H_t^d$ is the relevant variable for productivity growth (see for example Jones, 2002). Instead, product proliferation is allowed for, following Schumpeterian growth theory, however, scale effects are absent following semi-endogenous growth theories. Product proliferation is allows for in all the estimates below since the estimated coefficient of $\Delta \ln H_t^d$ was either negative or had low significance levels.

The $\alpha_2 \left(h_t^d\right)^2$-term allows for non-linear effects, where $\alpha_2 < 0$ if human capital intensity affects growth at a decreasing rate. Hall and Jones (1999) and Baier *et al.* (2006), for example, assume that earnings increase 13.4% for each additional year of schooling the first four years, 10.1% for the next four years and 6.8% thereafter.

The h^f-terms allow for imports of technology following the predictions of some of the endogenous growth models described in Grossman and Helpman (1991) in which TFP depends on the horizontally and vertically differentiated intermediate inputs. According to these models an increasing variety of intermediate inputs increases the economy-wide efficiency of production and the quality of intermediate input in final production. Vertically integrated intermediate products come in different qualities and the effectiveness of an intermediate input in final production is positively related to the number of times the input has been improved. Common for both vertically and horizontally differentiated intermediate inputs is that they are predominantly explained by cumulative human capital. Thus, TFP is a positive function of the stock of human capital. This line of reasoning, while allowing for product proliferation that is present in Schumpeterian models, suggests that the innovative activity of a country depends on its own educational achievement and the human capital embodied in imported intermediate inputs. Thus, technology is transmitted internationally by the import-weighted human capital intensity. Interaction effects between human capital intensity and h^f were also allowed for in initial estimates; however, the coefficient estimates turned out to be less significant and, consequently, not considered in the rest of the paper.

3 Measurement

Measurement of human capital, TFP, distance to the world technological frontier and knowledge spillovers through the channel of imports are discussed in this sub-section. Data sources are relegated to the data appendix. The following 16 countries over the period from 1870 to 2006 are included in the data set: Canada, the US, Japan, Australia, Belgium, Denmark, Finland, France, Germany, Italy, the Netherlands, Norway, Spain, Sweden, Switzerland, and the UK. These countries will be referred to as the G16.

3.1 Educational attainment

Estimating human capital back in history is a momentous task. Many census surveys back in history do not contain educational attainment and the educational classifications in the surveys that report educational attainment, vary substantially over time. Even recent surveys in the OECD countries change their educational classifications significantly over time (de la Fuente and Domenech, 2006). Furthermore, census surveys were only undertaken approximately every ten year before WWII. Thus, census surveys are not suitable to construct human capital in a historical context. An alternative to census surveys is the perpetual inventory method in which school enrolment data are accumulated while allowing for depreciation. The perpetual inventory method is for example used by Lau *et al.* (1991) and Nehru *et al*. (1995). The problem associated with the perpetual inventory method is that survival rates and immigration flows are difficult to adequately deal with and that schooling classifications may change over time (Pritchett, 2005). If emigration is ignored human capital will be underestimated in countries that have experienced large immigration waves, such as Australia, New Zealand, Canada and the US, and overestimated for the European countries that have experienced large emigration waves over the past 137 years, particularly Ireland. Furthermore, educational achievement will be upward biased when survival rates are not allowed for – particularly during the 19th century when the life expectancy was well below 50 years of age and not much above 30 years of age in the beginning of the 19th century (Galor, 2005).

To overcome the data problems associated with survival and emigration a modified perpetual method is used in this paper. The method is based on the gross enrolment rate (GER), where GER 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 school enrolment is estimated for each age cohort. Educational attainment in one particular year is then estimated as the average of the educational attainment for each age cohort that is in the labour force. 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 for the countries considered in this study back to the 19th century. 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 its first year of primary schooling in 1861.

The advantage of using GER is that the estimates of educational attainment are not biased by migration and by assumptions about survival rates that may not hold. The only data that are required in addition to school enrolment is population distributed on age groups so that the GER rate can be transformed to educational attainment for all age groups in the labour force. Population data on age groups are generally available from 1860 to 1940 from the census surveys on 10 year intervals. Annual data become available after circa 1940. The data are interpolated between these years based on the following method. In the period 1860 to 1870, for example, the fraction of the population in each age cohort is geometrically interpolated between 1820 and 1830 and multiplied by the total population. Over the period 1812-1860 the population for different age cohorts is extrapolated back using total population and the distribution of population on age cohorts for the first year population on age groups are available. In the estimates it is implicitly assumed that the educational attainment among emigrants is the same as the achievement among the labour force in the country from which they emigrate and to which they immigrate to.

Finally, the data are adjusted for the length of the school year and attendance rates. Attendance rates are available for Canada, Australia, and the US over the period from circa 1850 up to the 1960s. The post-1960 attendance rates are set equal to attendance rates that prevailed in the mid 1960 since attendance rates have been stable from the 1940s onwards. Attendance rates for Sweden are used before 1850. The average of attendance rates for Canada, Australia and the US are used for all countries, which is not likely to be a strong assumption since attendance rates for these three countries moved quite closely. The estimates of the length of the school year in Sweden by Ljungberg and Nilsson (2005) are used for all countries since I was not able to find similar data for other countries.

Following Hall and Jones (1999) the following measure of human capital was also tried in the initial regressions:

$$H = H_0 \exp\,(\varphi_0 P + \varphi_1 S + \varphi_2 T + \lambda_0 E + \lambda_1 E^2$$

where *P* is number of years of primary schooling, *S* is the number of years of secondary schooling, *T* is the number of years of territory schooling, and *E* is years of experience (years in the workforce). The following parameters are used: $\varphi_0 = 0.134$, $\varphi_1 = 0.101$, $\varphi_2 = 0.068$, λ_0=0.0495, and $\lambda_1 = -0.0007$. This measure was not used in the regressions presented below because it lowered the overall performance of the regressions without overturning the results.

3.2 Productivity and world technological frontier

Productivity is measured by output per hour worked and TFP. Output per hour worked is used as a complement to TFP in the estimates as a double check on the reliability of the estimates. In any event, TFP and output per capita grow at the same rate along a balanced growth path. TFP has the advantage over labour productivity that it allows for transitional dynamics while labour productivity does not. Conversely, labour productivity is not affected by measurement errors in capital stock. The capital stock is, particularly, measured by an error during and after the world wars during which a significant part of the capital stock was destructed in Germany, Japan, Belgium, France, and the UK. It is, therefore, not clear whether labour productivity or TFP is the best measure of technology.

TFP is measured as $A = Y/(L^{\alpha} K^{1-\alpha})$, where *Y* is GDP, *L* is labour measured by employment times number of hours worked per year, *K* is non-residential capital stock, α is the unweighted average of labour's income share for country *i* and the US, following Wolf (1991). Capital and GDP are measured in purchasing power parity units. Labour's income share is calculated as the economy-wide compensation to employees divided by nominal GDP, where labour's compensation is corrected for imputed payments to the self-employed and the data are calculated as far back in history as income share data are available. This imputation is essential since earnings from self-employment in national accounts are counted as profits, although they should be counted as labour income. To correct for this bias, the average earning per employee, multiplied by the number of self-employed, is added to the compensation to employees. Labour inputs are measured as annual hours worked multiplied by economy-wide employment as opposed to population, to take into account the fact that the labour force participation rate and annual hours worked have changed substantially over time.

The world technology frontier, $\bar{A}$, is measured as the maximum TFP of the US and the UK under the assumption that small countries cannot represent the world technology frontier. Ireland, for example, has climbed to the top of the world TFP league tables over the past couple of decades. However, Irish economy is too small to represent the world technological frontier.

3.3 International knowledge spillovers

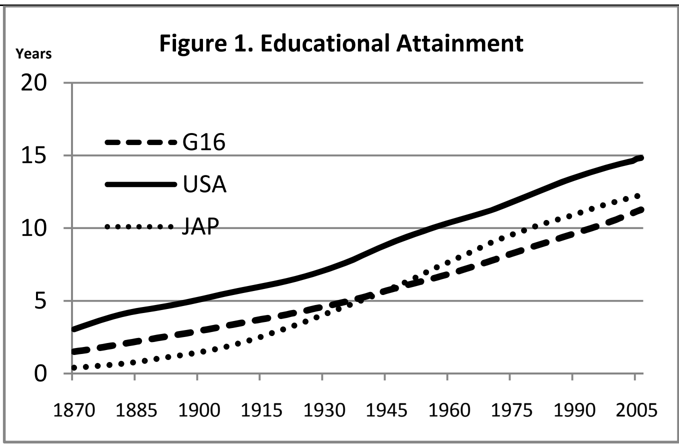
Educational knowledge spillovers through the channel of imports of intermediate products that contain new technology from country *j* to country *i* are computed from the following weighting scheme:

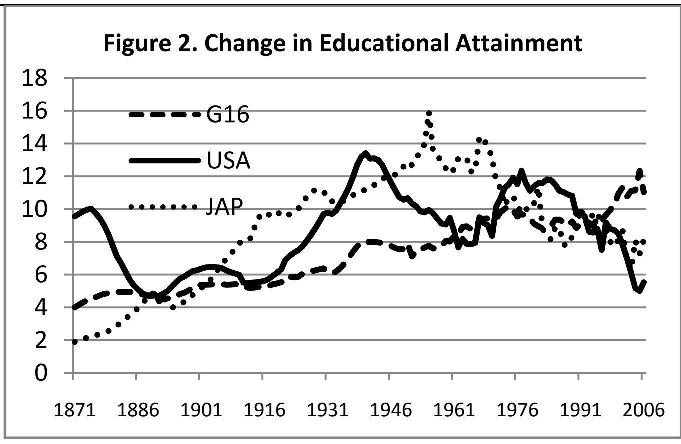
$$h_{it}^{f} = \sum_{j=1}^{21} \left(\frac{M_{ijt}}{Y_{jt}^{n}} \right) h_{jt} , \qquad i \neq j .$$

where M_{ijt} is nominal imports of goods from country *j* to country *i*, Y_j^n is nominal income of country *j* and *h* is human capital intensity measured as educational attainment because scaling variables other than population of working age are available for all of the 21 countries used in the index. Coe and Helpman (1995) also use bilateral import weights, however, they use the economy-wide stock of R&D knowledge while educational attainment is used here. The 21 countries are the 16 countries used in this paper plus New Zealand, Austria, Greece, Ireland, and Portugal.

4 Graphical evidence

Figure 1 shows a graduate increase in the average educational attainment for the G16 countries, where the population of working age is used as weights, over the entire data period. The educational attainment is also displayed for Japan and the US. Japan started out as the country among the G16 countries with the lowest level of educational attainment. It overtook G16 at the end of WWII following a surge in educational attainment from 1905. The US population of working age, on the other hand, has always been in the lead in terms of educational achievement. In relative terms G16 has converged to the US but diverged in absolute terms.





Notes. G16 is a weighted average of the G16 countries where population of working age are used as weights. The G16 countries consist of the following countries: Canada, the US, Japan, Australia, Belgium, Denmark, Finland, France, Germany, Italy, the Netherlands, Norway, Spain, Sweden, Switzerland, and the UK. The change in educational attainment in Figure 2 is multiplied by 100.

The level of educational attainment in Figure 1 highlights Pritchett's (2005) critique. Educational attainment has increased gradually over the years while productivity growth has only increased slightly (productivity growth is not shown). Furthermore, the productivity growth rate increased less in the US than in the G16 countries on average and in Japan over the past 137 years although it has had the highest educational attainment over the entire period. This informal evidence suggests that productivity growth is unlikely to be linearly related to educational attainment over time and across countries.

Although educational attainment has been increasing over the whole period its absolute change has fluctuated substantially over the years for Japan and the US (Figure 2). The US, particularly, has experienced marked movements in the change in educational attainment over time while Japan experienced an almost uninterrupted increase up to 1970 and a decline since. The G16 countries on average, has experienced an upward trend in growth up to the mid 1970s, after which the growth has stabilized on a relatively constant level.

5 Empirical estimates

5.1 Relationship between *X* and *Q*

Before the growth models are estimates it is determined whether X and Q form a cointegrated relationship and which variables best represents Q. As argued in Section 3 X and Q must form a cointegrated relationship to render the productivity growth rate stationary. The following equation is estimated using annual data over the period from 1870 to 2006:

$$lnX_{it} = \beta_i lnQ_{it} + CD + \varepsilon_t, \quad (4)$$

where CD is country dummies, ε is a stochastic error term, and β_i is the proliferation elasticity which is allowed to vary across countries. Q is measured by real GDP, employment and the population of working age.

The results of estimating Equation (4) are shown in Table 1. The *t*-statistics reported in Table 1 are modified to account for serial correlation in the residuals and they can be compared to tabulated *t*-statistics.[3] Note that the *t*-statistics are valid only if the variables are cointegrated. The variables are cointegrated in the case where Q is measured by employment at the 3% significance level. The log of X and the log of Q are not cointegrated at any reasonable significance level when Q is measured by income or population of working age. The conclusion from these estimates is, therefore, that employment is likely to be the best normalizing variable for human capital.

Table 1. Parameter estimates of Equation (4).

	Income	Employment	Working age pop
Canada	0.82(8.92)	1.65(14.9)	1.66(17.9)
USA	0.80(7.46)	1.61(12.5)	1.74(15.0)
Japan	0.90(10.1)	3.72(17.1)	3.01(20.9)
Australia	0.98(8.87)	1.67(15.1)	1.67(18.2)
Belgium	0.83(5.06)	1.84(8.56)	3.02(10.4)
Denmark	0.91(7.10)	2.11(11.8)	2.64(14.3)
Finland	1.33(12.3)	4.49(21.2)	5.02(25.5)
France	0.63(4.36)	3.53(7.13)	3.91(8.65)
Germany	0.69(5.54)	2.30(9.56)	2.12(11.6)
Italy	0.92(7.10)	6.20(12.4)	3.78(15.0)
Netherlands	0.87(7.24)	1.89(12.3)	1.98(14.8)
Norway	0.64(5.72)	1.93(9.7)	2.37(11.6)
Spain	1.12(9.76)	4.17(17.6)	3.76(21.0)
Sweden	0.63(5.70)	2.04(9.5)	2.98(11.4)
Switzerland	0.67(5.25)	1.76(8.8)	2.13(10.7)
UK	1.13(10.6)	3.98(18.1)	3.65(21.7)
Kao	3.29(1.00)	-1.89(0.03)	4.58(1.00)

Notes: dependent variable is the log of human capital. Estimation period 1870-2006. The numbers in parentheses are t-statistics. Kao is Kao's (1999) the Dickey-Fuller test for panel cointegration.

5.2 Productivity growth regressions

The following stochastic counterpart of Equation (3) is estimated for the 16 countries listed in table 1 over the period from 1870 to 2006:

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3 The following method is used to calculate the *t*-tests. As proved by Hamilton (1994, Section 19.3):

$$\chi_T^2 \xrightarrow{p} (\tilde{\lambda}_{11}^2 / s_{NT}^2) \cdot \chi^2(m),$$

where m is the number of restrictions, $\tilde{\lambda}_{11}^2$ is the serial-correlation consistent standard error of the DOLS estimates of (1), s_{NT}^2 is the standard error of the DOLS estimates of Equation (4) and NT is the total number of observations in the estimates of Equation (4). This result establishes that the OLS *t*-statistics need to be multiplied by a consistent estimate of $(\tilde{\lambda}_{11}^2 / s_{NT}^2)^{1/2}$ and the resulting statistics can be compared with standard *t* tables. A consistent estimate of $\tilde{\lambda}_{11}^2$ is obtained from $\tilde{\lambda}_{11}^2 = \hat{\sigma}_1 / (1 - \hat{\rho}_1 - \hat{\rho}_2)$, where ρ_i is estimated from the OLS regression $\hat{e}_{it} = \hat{\rho}_1 \hat{e}_{i,t-1} + \hat{\rho}_2 \hat{e}_{i,t-2} + v_{it}$ and $\hat{\sigma}_1 = (NT-2)^{-1} \sum_{i=1}^{16} \sum_{t=3}^{T} \hat{v}_t^2$, where T is the number of observations for each country.

$$\Delta \ln A_{it} = \lambda_0 + \lambda_1 h_{it}^d + \lambda_2 \left(hi_t^d\right)^2 + \lambda_3 h_{it}^f + \lambda_4 \Delta h_{it}^d + \lambda_5 h_{it}^d \left[\frac{\overline{A}_{t-1} - A_{i,t-1}}{A_{i,t-1}}\right] + TD + e_{it} \quad (5)$$

where TD is time-dummies, e is a stochastic error term and Δ is a five-year or ten-year first difference operator. The data are measured in five-year or in ten-year intervals to filter out business cycle influences and, to some extent, also transitional dynamics. The distance to the frontier term is measured in the first year of the time interval that the first differences span and h is measured as the annualized average during the period over which the first differences span. The distance to the frontier is indicated by DTF in the tables below.

To gain efficiency and to correct for serial correlation and heteroscedasticity, the covariance matrix is weighted by the correlation of the disturbance terms using the variance-covariance structure as follows:

$$\mathrm{E}\{\varepsilon_{it}^2\} = \sigma_i^2, \quad \mathrm{i} = 1, 2, \ldots N,$$
$$\mathrm{E}\{\varepsilon_{it}, \varepsilon_{jt}\} = \sigma_{ij}, \quad i \neq j,$$
$$\varepsilon_{it} = \rho\varepsilon_{i,t-1} + v_{it}$$

where σ_i^2 is the variance of the disturbance terms for country $i = 1, 2, \ldots N$, σ_{ij} is the covariance of the disturbance terms across countries i and j, ε is the disturbance term and v is an *iid* disturbance term. The variance σ_i^2 is assumed to be constant over time but to vary across countries and the error terms are assumed to be mutually correlated across countries, σ_{ij}, as random shocks are likely to impact all countries at the same time. The parameters σ_i^2, ρ and σ_{ij} are estimated using feasible generalized least squares. The correlation between the error terms, σ_{ij}, is *only* allowed for in the 5-year difference estimates. The time-period is too short in the 10-year difference estimates to allow for the mutual correlation between the error terms.

The results of estimating Equation (5) are shown in Tables 2 and 3. The statistical significance of the coefficient estimates are lower for the 10-year difference (Table 3) estimates than the 5-year difference estimates (Table 2) because the number of observations is too low to allow for cross-country correlation between the residuals. The squared educational attainment terms are omitted in the estimates in the first four columns of the table for comparison with estimates in the literature. The estimated coefficients of the level of human capital intensity are either insignificant or negative. The results are unchanged if human capital is normalized by income or by population of working age (the results are not shown). These results are consistent with Pritchett's (2005) critique and a large body of the empirical literature.

Table 2. Restricted and unrestricted parameter estimates of Equation (5) in 5-year differences.

	1	2	3	4	5	6	7	8
LHS	ΔlnTFP	ΔlnTFP	Δln(Y/L)	Δln(Y/L)	ΔlnTFP	ΔlnTFP	Δln(Y/L)	Δln(Y/L)
Δh^d	0.18 (7.08)	0.21 (8.15)	0.43 (15.1)	0.47 (16.7)	0.16 (6.40)	0.20 (7.70)	0.44 (15.1)	0.48 (17.0)
h^d	-0.001 (1.36)	-0.001 (1.63)	-0.002 (2.43)	-0.003 (3.56)	-0.006 (3.14)	-0.014 (2.00)	0.002 (0.85)	0.005 (1.85)
$(h^d)^2$					0.0002 (2.92)	0.0001 (1.47)	-0.0002 (1.92)	-0.0004 (3.40)
h^d*DTF$_{t-1}$	0.009 (13.9)	0.010 (14.0)	0.012 (20.6)	0.012 (18.2)	0.010 (12.9)	0.010 (13.2)	0.010 (15.9)	0.011 (16.2)
h^f	0.027 (5.02)	0.048 (7.12)	0.048 (11.1)	0.093 (9.95)	0.029 (5.38)	0.050 (7.29)	0.050 (7.22)	0.087 (9.77)
TD	Y	N	Y	N	Y	N	Y	N
DW	1.97	1.99	1.95	1.99	1.97	1.98	1.99	2.00
R^2(Buse)	0.93	0.57	0.96	0.71	0.94	0.57	0.96	0.72

Notes. The numbers in parentheses are absolute *t*-statistics. Educational attainment is normalized by employment. The following years are included in the estimates: 1975, 1880, 1890, 1895, 1900, 1905, 1910, 1915, 1920, 1925, 1930, 1935, 1940, 1951, 1956, 1961, 1966, 1971, 1976, 1981, 1986, 1991, 1996, 2001, and 2006. DTF = distance to frontier. The TD row indicates whether time-dummies are included, Y = yes, N = no. DW = Durbin-Watson test for first-order serial correlation. R^2(Buse) = Buse's multiple correlation coefficient.

Non-linear effects are allowed for in the estimates in columns 5-8. Consider first the estimates in columns five and six in Table 2 in which the growth in TFP is the dependent variable. The estimated coefficients of the level of human capital intensity are negative while they are positive for squared human capital intensity. The productivity growth effects of education are negative up to a level of education of 30 years and positive thereafter. Considering the estimates in which labour productivity is the dependent variable in Table 2 human capital intensity affects growth positively and at a declining rate at a low level of education. The growth is negative when schooling length is in excess of approximately 12 years. However, the statistical significance of the estimated coefficients is generally low. Furthermore, the estimated coefficients of the level and the squared human capital intensity are insignificant at any conventional significance level in the 10-year difference estimates in Table 3. The latter results reinforce the conclusion from the five-year difference estimates that the level of human capital intensity appears not to have been influential for growth in the G16 countries over the past 137 years.

However, the estimated coefficients of changes in human capital intensity are highly significant in both the 5-year and the 10-year difference estimates. The estimated coefficient of the change in human capital intensity is in the vicinity of 0.2 in the estimates where the growth in TFP is the dependent variable and around 0.4 when growth in labour productivity is used as dependent variable. The coefficient is probably highest in the estimates with labour productivity growth as the dependent variable because human capital intensity interacts with capital deepening. An increase in human capital intensity, for example, increases the marginal productivity of capital, which through the channel of Tobin's *q*, triggers a capital deepening process. Assuming that the coefficient estimates of 0.2 are probably the more unbiased of the two the approximate ten year increase in human capital intensity over the past 137 years in the G16 countries has contributed to an 160% increase in TFP during the same time-span. This suggests that the increasing human capital intensity over the past 137 years, in insulation, has been an important factor behind the productivity advances in the industrialized countries. Since the cost of education is only a small fraction of GDP the money on education appears to have been well spent.

The coefficient estimates of the level and the changes in human capital intensity suggest the absence of scale effects in ideas production and, therefore, that there is diminishing returns to domestic educational knowledge stock. It is important to note that these results do not give credence to semi-endogenous growth as they are usually presented. Product proliferation is allowed for in the estimates of h^d, while semi-endogenous growth theory normally assumes that $\Delta \ln H_t^d$, and not $\Delta \ln h_t^d$, is the relevant variable in explaining growth (Jones, 2002). It is interesting, however, $\Delta \ln h_t^d$ is the relevant variable in the not very well-known paper of Jones (2003) (the working paper version of this paper was written in 1996).

The estimated coefficients of the interaction between human capital intensity and the distance to the frontier are statistically and economically highly significant in all the estimates in the tables. In fact the estimated coefficients of $h_t^d\left[\overline{A}_{t-1} - A_{t-1}\right]/A_{t-1}$ are in the narrow range of 0.009-0.012 in estimates in five year estimates and in the range of 0.015-0.018 in the ten-year difference estimates. Dividing these numbers by five and ten to find the approximate annual effect of human capital intensity shows that a country that is 10% below the technology frontier and with a human capital intensity of five years of schooling the distance term contributes to an 0.1% productivity increases every year on average. This result suggests that the interaction between human capital intensity and the distance to the frontier has a significant effect on growth on countries that are below the technology frontier. This interaction between education and the distance to the technology frontier would particularly have been influential for growth in Japan and Finland before WWII.

Table 3. Restricted and unrestricted parameter estimates of Equation (5) in 10-year differences.

	1	2	3	4	5	6	7	8
LHS	ΔlnTFP	ΔlnTFP	Δln(Y/L)	Δln(Y/L)	ΔlnTFP	ΔlnTFP	Δln(Y/L)	Δln(Y/L)
Δh^d	0.13 (2.23)	0.16 (2.95)	0.25 (3.51)	0.36 (4.49)	0.11 (1.77)	0.17 (2.77)	0.27 (3.56)	0.40 (4.73)
h^d	-0.002 (0.61)	0.000 (0.01)	-0.005 (1.55)	-0.003 (1.06)	-0.006 (0.90)	0.001 (0.12)	0.001 (0.14)	0.011 (1.18)
$(h^d)^2$					0.0002 (0.73)	0.0000 (0.12)	-0.0003 (0.77)	-0.0006 (1.62)
h^d*DTF$_{t-1}$	0.014 (8.10)	0.015 (8.30)	0.018 (7.72)	0.018 (7.18)	0.014 (7.97)	0.015 (7.84)	0.017 (7.25)	0.016 (6.09)
h^f	0.044 (1.96)	0.072 (3.53)	0.096 (3.37)	0.143 (5.08)	0.045 (1.97)	0.071 (3.33)	0.093 (3.29)	0.013 (4.45)
TD	Y	N	Y	N	Y	N	Y	N
DW	1.92	1.97	1.89	1.85	1.93	1.98	1.90	1.87

R2(Buse)	0.73	0.67	0.82	0.72	0.73	0.67	0.82	0.73

Note. See notes to Table 2.

The estimated coefficients of international spillovers of educational attainment are economically and statistically highly significant in almost all the estimates. The estimated coefficients of h^f are in all instances positive and statistically significant at the 5% level. These results suggest that there are strong positive externalities to educational attainment through the channel of trade. The higher is the propensity to import the higher is the growth effects from a given level of educational attainment among trade partners. Moreover, the more educated is the labour force among exporting countries the higher is the growth potential of the importing country. Thus, a country can positively increase its growth rate by importing intermediate goods that have a large embodiment of human capital. These results are, in some sense, stronger than the results in the literature on technology spillovers through the channel of imports. In this literature the *level* of productivity is a positive function of the trade-weighted imported stock of knowledge (see for example Coe and Helpman, 1995, and Madsen, 2007). A increase in the stock of knowledge among trade partners will bring the domestic level of TFP up to a higher level. Once the new balanced growth path has been reached there are no more growth effects from imports of knowledge in these models. In the estimates in this paper, however, imports of educational achievement have permanent growth effects.

The result that foreign but not domestic human capital intensity has permanent growth effects is puzzling. There are the following possible explanations for this. The estimates of Madsen (2007, 2008 SJE) show that patent knowledge spillovers through the channel of imports are significantly more important for TFP than domestic patent knowledge stock. This result may apply to both the innovative activity and human capital. Furthermore, knowledge slipovers through the channel of imports may not be a general law but be limited to a certain period in history. A possible story is that human capital intensity has been important for growth during and after the second industrial revolution but not thereafter. Human capital played a key role during the transition to the modern growth regime around the turn of the 20th century in the models of Galor and Weil (1999, 2000) and Galor (2005), which is consistent to the estimates in this section. In the post WWII period research intensity appears to have been the engine of growth in the industrialised countries (Ha and Howitt, 2007, Madsen, 2008). I now turn to the importance of human capital for growth in the post WWII period.

6 Robustness checks

This section checks the robustness of the results in the previous section to two alternative data set on human capital, non-linearity and to estimation period. The estimation results are presented in Table 4 below. The estimates are in fin-year differences and time-dummies are included in all estimates. Consider first the estimates in columns 1 and 2 in which the data of Bassanini and Scarpetta (2001) for educational achievement are used. The estimated coefficients of educational achievement in levels and in differences are all negative and, in one instance, statistically significant. Including squared educational attainment does not change the results (results not shown). The interaction between educational attainment and the distance to the frontier remains highly significant while educational knowledge slipovers through the channel of imports is statistically insignificant at conventional significance levels. As will be discussed shortly the latter result is not because other data for educational attainment has been used appears to a post WWII phenomenon. The estimates in columns 5 and 6 in which the data of de la Fuente and Dominique (2006) are used are quite similar to the estimates displayed in columns 1 and 2. This result is not so surprising given that both data sets are based on an improved Barro-Lee data set. The data of Bassanini and Scarpetta (2001) is based on earlier data of de la Fuente and Dominique (2006) and is extrapolated 10 years using educational data.[4]

- Mention the low DW statistics

The estimates in columns 3 and 4 use the same data as the estimates in Table 2 except that the country sample has been extended to 21 countries. The estimates are insensitive to whether data are used for 16 or 21 countries. The estimation period spans from 1956 to 2006. In terms of economic and statistical significance the estimates are quite similar to the estimates in Table 2 with the exception that the estimated coefficients of educational knowledge spillovers through the channel of imports are insignificant. This result is consistent with the estimation results in columns 1, 2, 5 and 6, and, as such, suggests that there is strong evidence that educational knowledge spillovers through the channel of imports has not contributed to growth in the post-WWII period. The growth effect has been limited to the pre-WWII period. This result is also more consistent with the result that the level of human capital intensity alone has not been a significant contributor to growth over the period from 1870 to 2006.

Table 4. Parameter estimates of Equations (5) and (6) in 5-year differences.

	1	2	3	4	5	6	7	8
LHS	ΔlnTFP	Δln(Y/L)	ΔlnTFP	Δln(Y/L)	ΔlnTFP	Δln(Y/L)	ΔlnTFP	Δln(Y/L)
Δh^d	-0.027	-0.024	0.150	0.40	-0.007	-0.015	0.162	0.40

[4] Based on equations based on transitional dynamics of the Solow model Bassanini and Scarpetta (2001) find that educational attainment positively influences growth on the transitional path. Using the production function approach de la Fuente and Dominique (2006) find that the labour productivity elasticity of educational attainment significantly exceeds its share of income.

	(1.49)	(1.24)	(2.78)	(6.64)	(0.29)	(0.43)	(5.92)	(13.5)
h^d	-0.004 (1.42)	-0.012 (4.36)	0.003 (0.92)	-0.001 (0.34)	-0.038 (3.48)	-0.071 (4.13)	-0.003 (1.34)	0.003 (1.62)
$(h^d)^2$			-0.0001 (0.61)	0.0000 (0.10)			0.0001 (1.00)	-0.0003 (2.59)
h^d*DTF$_{t-1}$	0.015 (4.06)	0.016 (4.32)	0.010 (8.59)	0.011 (7.61)	0.015 (6.69)	0.017 (5.59)	0.014 (9.72)	0.018 (9.95)
h^f	0.009 (0.17)	0.091 (1.50)	-0.031 (0.74)	0.024 (0.37)	0.012 (0.30)	-0.015 (0.20)	0.012 (2.33)	0.031 (5.43)
σ_{ij}	N	N	Y	Y	N	N	Y	Y
N	105	105	252	252	126	126	520	520
DW	1.41	1.33	1.88	1.86	1.56	1.98	1.94	1.95
R2(Buse)	0.74	0.87	0.80	0.86	0.88	0.89	0.95	0.97

Note. See notes to Table 2. The following 21 OECD countries are included in the estimates: Canada, the US, Japan, Australia, New Zealand, Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and the UK. Time-dummies are included in all the estimates. The column σ_{ij} indicates whether (Y) or not (N) cross-country correlation in the residuals is allowed for. N = number of observations.
Columns 1 and 2. The data are from Bassanini and Scarpetta (2001) over the period 1978-1998.
Column 3 and 4. The data set is from this paper over the period 1956-2006.
Columns 5 and 6. The data are from de la Fuente and Dominique (2006) over the period 1965-1990.
Columns 7 and 8. Equation (6) estimated over the period 1875-2006 (see notes to Table 2). 1946 is omitted.

- Argue that the non-linear model (that estimates which club a country is converging to) of Benhabib and Spiegel (2005) is not estimated – the purpose of their exercise is to identify convergence clubs. "If technology is of the logistic type, countries with educational levels that are too low will get behind and we may observe the phenomenon of "convergence clubs"" (p 943).

The estimates in the last two columns in Table 4 estimate the following model suggested by Benhabib and Spiegel (2005):

$$\Delta \ln A_{it} = \varphi_0 + \varphi_1 h_{it}^d + \varphi_2 \left(hi_t^d\right)^2 + \varphi_3 h_{it}^f + \varphi_4 \Delta h_{it}^d + \varphi_5 h_{it}^d \left[\frac{A_{i,t-1}}{\bar{A}_{t-1}}\right]\left[\frac{\bar{A}_{t-1} - A_{i,t-1}}{A_{i,t-1}}\right] + TD + \varepsilon_{it} \qquad (6)$$

Where ε is a stochastic error term.
This model is similar in the spirit of a logistic model of technology diffusion.

7 Ideas production function and the anatomy of growth

The estimates in Section 5 pointed toward permanent growth effects of foreign human capital intensity. While imports of technology have permanent growth effects the interaction between human capital intensity and the distance to the frontier influence growth until the technological frontier has been reached, which may take long.

The anatomy of growth during the period 1870 to 2006 can be summarized as follows. It was first during the second industrialized revolution around 1870 that the industrialized countries entered the modern growth regime (Galor, 2005). School enrolment, attendance rates, and the length of the school year increased markedly during the period from 1870 to WWI and contributed to an increasing number of individuals with an education entering the labour force. Increasing trade combined with an increasing educational attainment contributed significantly to growth during that period. Furthermore, the large cross-country discrepancies between TFP levels back in 1870 gave the most backward countries a large chance to converge to the frontier countries provided that there were able and willing to expand the educational achievement among new entrants to the labour market. Overall, human capital was a key contributing factor to economic success from the onset of the second industrial revolution to WWI. Since formal R&D was low during that period (Madsen, 2007 EL, 2008 JEG) the growth effects coming from formal R&D was low. The increase in productivity growth during and shortly after the second industrial revolution contributed to higher standard of living in terms of per capita output. The marked decline in fertility at the end of the 19th century contributed further to increasing per capita income growth (Galor, 2005).

Growing human capital intensity has continued to play an important role for growth in the post-WWII period. Furthermore, convergence to the technology frontier was also an important impetus to growth in the intermediate post-WWII period until the 1970s during which most countries had almost converged to the technology frontier. International human capital spillovers through the channel of imports appear not to have played a role in the post-WWII period. Since educational attainment cannot continue to grow all these factors point toward low productivity growth for the rest of this century. This is also the conclusion reached by Jones (2002). However, the evidence by Ha and Howitt (2007) and Madsen (2008 JEG) suggest that economies will continue to grow proportionally with R&D intensity (the ratio of R&D expenditure and income for instance). Furthermore, Madsen (2008, JEG) found that there are significant spillover effects of R&D intensity through the channel of imports. What all this suggests is that knowledge spillover of human capital intensity has been overtaken by formal R&D spillovers.

Adding research intensity to the estimates of Equation (5) following the predictions of Schumpeterian theory of economic growth, yield the estimates in Table 5.[5] Research intensity is measured as real R&D expenditures divided by real GDP (see Ha and Howitt, 2007, and Madsen, 2008). R&D expenditures are deflated by an unweighted average of the GDP-deflator and hourly compensation to employees. Compared to the estimates in columns 3 and 4 in Table 4 the inclusion of R&D intensity does not affect the parameter estimates of the variables included in Equation (5).

[5] Semi-endogenous growth theory predicts that productivity growth is positively related to the change in real R&D. The estimated coefficient of the change in real R&D was initially included in the estimates, however, it was omitted since it was insignificant.

The estimated coefficient of R&D intensity is statistically significant in all the estimates at the one percentage level. The estimates are quite insensitive to whether time-dummies are included in the estimates. Deleting the statistically insignificant variables yield the estimates in columns 3 and 4. The estimates indicate that productivity growth in the post-1970 period has been significantly driven by changes in human capital intensity, the interaction between human capital intensity and the distance to the frontier, and research intensity. Imports of human capital intensity has played has not played a role in the post-WWII estimates.

Table 5. Parameter estimates of research-intensity-extended Equation (5) in 5-year differences.

	1	2	3	4	5	6	7	8
LHS	ΔlnTFP	Δln(Y/L)	ΔlnTFP	Δln(Y/L)				
Δh^d	0.119 (2.16)	0.364 (5.79)	0.249 (4.23)	0.548 (7.27)				
h^d	-0.006 (0.93)	-0.014 (1.75)						
$(h^d)^2$	0.000 (0.30)	0.000 (0.52)						
h^d*DTF_{t-1}	0.013 (6.56)	0.014 (6.46)	0.015 (6.43)	0.017 (5.79)				
h^f	-0.083 (1.58)	-0.197 (3.03)						
R&D/Y	0.0060 (5.08)	0.0098 (3.37)	0.0065 (3.76)	0.011 (2.61)				
σ_{ij}	N	N	N	N				
N	168	168	168	168				
DW	1.80	1.58	1.60	1.40				
R2(Buse)	0.85	0.89	0.79	0.83				

Note. See notes to Tables 2 and 4. Fixed effect dummies are included in the estimates. Time-dummies are not included in the estimates. Estimation period 1971-2006. The 21 countries considered in Table 4 are included in the estimates.

Why has human capital spillovers through the channel of imports been important factors of productivity growth before WWII but not after? A possibility is that the R&D activity was of informal nature before WWII and undertaken by educated people. In the post-1960s period, which is covered by the estimates in Table 5, education needs no longer be a sufficient condition for improvement of goods that can be imported by other countries and used in the production process to enhance the level and growth in productivity. The casual observer will notice that shop assistants, receptionists and secretaries have university degrees and, as such, do no use their degree to enhance productivity. R&D on the other hand, is vital for quality improvements and has taken over from human capital as the important factor behind productivity enhancement and international technology spillovers.

This suggests that once all countries have caught up to the frontier country, which has almost been completed by now, and the human capital intensity stops increasing growth is driven by research intensity. Provided that countries continue to allocate a constant fraction of its resources to R&D the trend growth rate in the economy will remain constant.

7.1 Ideas production

The estimates in the previous section showed that while human capital intensity has only temporary growth effect R&D intensity has permanent growth effects. Conventional knowledge production functions tend to lump human capital and R&D capital together. The following knowledge production function has been used to encompass traditional and recent growth theories (Ha and Howitt, 2007, Madsen, 2008):

$$g_A = \frac{\dot{A}}{A} = \lambda \left(\frac{X}{Q} \right)^{\sigma} A^{\phi - 1}, \qquad 0 < \sigma \leq 1, \ \phi \leq 1$$

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

where Q is product variety, ϕ is returns to scale in knowledge, σ is a duplication parameter, which is zero if all innovations are duplications and 1 if there are no duplicating innovations, β is the coefficient of product proliferation, λ is a research productivity parameter, L is employment or population and X is R&D inputs (semi-endogenous growth models) or the productivity adjusted R&D (Schumpeterian growth models), R&D/A, where the productivity adjustment recognises that innovations are increasing in complexity and, therefore, that there is a tendency for decreasing returns to R&D. The first-generation endogenous growth theories (Romer, 1990, Grossman and Helpman, 1991, Aghion and Howitt, 1992) predict that $\phi = 1$ and $\beta = 0$, Schumpeterian growth models predict that $\phi = 1$ and $\beta = 1$, and semi-endogenous growth models predict that $\phi < 1$ and $\beta = 0$.

To incorporate the results of this paper knowledge production needs to be decomposed into R&D knowledge and human capital knowledge. Productivity is a geometric average of human capital stock and R&D knowledge stock. The interaction between human capital intensity and the distance to the frontier can be straightforwardly incorporated into the ideas production function (see Howitt, 2000), however, this term is omitted to make the exposition as simple as possible. Thus, productivity growth is a weighted average of the growth in human capital stock and the growth in knowledge stock:

$$g_A = \frac{\dot{A}}{A} = dln(B^{\alpha} C^{1-\alpha}) \tag{7}$$

where B refers is human capital stock, C is R&D knowledge stock, and α is a parameter that needs not be fixed over time. R&D knowledge stock can consist of formulas, blueprints and templates that have been developed in the past such as the dynamo. As such it is an outcome of accumulation of knowledge that is an outcome of R&D activities. Human capital stock consists of knowledge that has been created by educational activity such as the ability to organise society, the establishment of social capital such as lower crime rates, ability to communicate, able to interact with other individuals on an organisational level, etc.

The growth in knowledge is given by

$$\frac{\dot{B}}{B} = \lambda_B \left(\frac{X_B}{Q_B}\right)^{\sigma_B} B^{(\phi_B - 1)} \qquad 0 < \sigma_B \leq 1, \quad \phi_B \leq 1 \tag{8}$$

$$\frac{\dot{C}}{C} = \lambda_C \left(\frac{X_C}{Q_C}\right)^{\sigma_C} C^{(\phi_C - 1)} \qquad 0 < \sigma_C \leq 1, \quad \phi_C \leq 1 \tag{9}$$

$(Q_A, Q_B) \propto L^{\beta}$ in steady state,

The empirical estimates suggest the absence of scale effects for the stock of human capital and scale effects for the stock of R&D knowledge and that β = 1 for both the stock of human capital and for R&D stock of knowledge. Thus the R&D-induced productivity growth is given by:

$$\frac{\dot{C}}{C} = \lambda_C \left(\frac{X_C}{Q_C}\right)^{\sigma_C}. \tag{10}$$

The human capital growth-induced growth effects are more indirect. Since ln $(\dot{B}/B)$ is stationary X_B, Q_B and B form the following cointegration relationship:

$$lnB = \frac{\sigma_B}{1-\phi_C} ln\left(\frac{X_B}{Q_B}\right) + e$$

where e is a stochastic error term. Differentiating yields:

$$\frac{\dot{B}}{B} = dlnB = \frac{\sigma_B}{1-\phi_C} dln\left(\frac{X_B}{Q_B}\right) + de. \tag{11}$$

Nesting Equations (10) and (11) yields the growth equation arrived at in the previous section where productivity growth is a linear function of the level of R&D intensity and the change in human capital intensity. The only difference between Equation (10) and (11) and the estimated equations is that the log of intensities are taken here but not in the empirical estimates.

8 Concluding remarks

This paper has found that human capital intensity alone cannot significantly explain growth regardless of whether productivity is measured as TFP or as output per hour worked and whether non-linear effects in human capital intensity are allowed for. The results are consistent with the argument by Pritchett (2005) that growth has not increased over the past century in the OECD countries while educational attainment has increased markedly.

Human capital intensity, however, has significant growth effects if it is allowed to interact with the distance to the frontier. The interaction between human capital intensity and the distance to the frontier is highly influential for growth and robust to inclusion of variables, choice of dependent variable, and the length of the first differences. This result suggests that a country can catch up to the technology frontier if it invests sufficiently in human capital. This, of course, requires that proper institutions are in place as highlighted in the literature (Gerschenkron, 1952, Howitt, 2000). All countries considered in this paper meet the criterion of having appropriate institutions throughout the whole period.

Human capital intensity spillovers through the channel of imports have also been highly influential for growth in the pre-WWII period. This implies that countries will continue growing as long as they trade with other nations. For a constant level of human capital intensity, or educational achievement, and constant propensity to import a country will experience a permanent positive growth rate. Furthermore, as long as a country is below the technological frontier human capital intensity will continue to have positive growth effects. Since most countries in this study have first recently converged to the technology frontier, the interaction between human capital intensity and the distance to the frontier has been influential for the growth in these countries during most of the past 137 years.

The results have important implications for knowledge production and endogenous growth models. First, human capital intensity has robust and significant temporary growth effects but not permanent growth effects. Thus, there are not scale effects from educational knowledge. Second, there are constant returns to R&D knowledge production, while the number of product lines increases along the growth path and dilutes the productivity effects of R&D activity. Thus, as long as the fraction of the labour force in R&D remains constant the economy will continue to grow. Third, following from the last two points, endogenous growth theories have tended not to distinguish between educational achievement and R&D. This study suggests that this distinction needs to be sharp. Giving a larger proportion of the population education needs not increase the production of knowledge....

An important result is that the ideas production function needs to be of dual nature.

Data appendix

Bilateral propensity to import, output per hour worked and TFP see J B Madsen 2007, "Technology Spillover through Trade and TFP Convergence: 135 Years of Evidence for the OECD Countries," *Journal of International Economics*, 72, 464-480.

R&D intensity. See J B Madsen, 2008b, "Semi-Endogenous Models versus Schumpeterian Theory: International Evidence over a Century," *Journal of Economic Growth,* 13, 1-26.

Educational attainment. 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 territory education among the population of working age, for example, is computed using the following formula:

$$Ea_t^{Ter} = \frac{2}{5}\left[\frac{1}{10}GER_{j=20,t-1} + \frac{2}{10}GER_{j=20,t-2} + \frac{2}{10}GER_{j=20,t-3} + \frac{2}{10}GER_{j=20,t-4} + \frac{2}{10}GER_{j=20,t-5} + \frac{1}{10}GER_{j=20,t-6}\right]$$
$$+ \sum_{j=20}^{60}\left[\frac{1}{25}GER_{t-j+14} + \frac{2}{25}GER_{t-j+15} + \frac{3}{25}GER_{t-j+16} + \frac{4}{25}GER_{t-j+17} + \frac{5}{25}GER_{t-j+18} + \frac{4}{25}GER_{t-j+19}\right.$$
$$\left. + \frac{3}{25}GER_{t-j+20} + \frac{2}{25}GER_{t-j+21} + \frac{1}{25}GER_{t-j+22}\right]$$

$$j = (20, 25, \ldots, 60) \in 20-24, 25-29, \ldots, 60-64,$$
$$t = 1870, 1871, \ldots, 2006,$$

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. is 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 1925, and therefore multiplied by 2, etc. In 1828 all individuals in the 60-64 cohort, which 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, that 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 its 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, www.econ.ucdavis.edu/faculty/fzlinder/Lindert%20data%20CUP%20book/App._T._A1__**primary**_enrol.xls and Statistisk Centralbyraa, Statistics Norway, Historical Statistics.

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