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Growth, Distance to Frontier and Composition of Human Capital*

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Abstract

We examine the contribution of human capital to economy-wide technological improvements through the two channels of innovation and imitation. We develop a theoretical model showing that skilled labor has a higher growth-enhancing effect closer to the technological frontier under the reasonable assumption that innovation is a relatively more skill-intensive activity than imitation. Also, we provide evidence in favor of this prediction using a panel dataset covering 19 OECD countries between 1960 and 2000 and explain why previous empirical research had found no positive relationship between initial schooling level and subsequent growth in rich countries. In particular, we show that in OECD economies it is crucial to isolate the two separate margins of primary/secondary and tertiary education. Interestingly, the latter type of schooling proves to be a factor of economic divergence.

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1 Introduction

In their recent survey on education and economic growth, Krueger and Lindahl (2001) find that "education [is] statistically significantly and positively associated with subsequent growth only for the countries with the lowest level of education". As these two authors, we view this finding as a puzzle. Why is the relationship between education and growth different in rich countries? More interestingly, why is this relationship insignificant? One plausible reason is that education favors the adoption of new technologies, as noticed by Nelson and Phelps (1966). Since rich countries are closer to the technological frontier, the strength of the catch-up effect with the frontier vanishes with the relative level of development. However, this explanation omits the fact that the source of technological progress is dual. It is the result not only of the adoption of existing technologies but also of pure innovation, especially in technologically advanced economies. Moreover, tasks of imitation and innovation require different types of human capital; in particular, it is reasonable to assume that unskilled human capital is better suited to imitation than to innovation. Taking into account endogenous labor allocation across these two activities, each type of human capital's impact on growth should depend on a country's level of technological development. To solve the puzzle posed by Krueger and Lindahl, we therefore need to focus attention both on an economy's distance to the technological frontier *and* on the composition of its human capital (as much as on its level).[1]

In the theoretical part of the paper, we develop an endogenous growth model, where technological improvements are the result of a combination of innovation and imitation (or adoption), a specification we share with Benhabib and Spiegel (1994) and Acemoglu, Aghion, and Zilibotti (2002). We differ from these two papers by requiring that each of these activities in turn be a combination of

[1] In the paper, we take human capital to be essentially synonymous with education.

high skill and low skill labor. Our main assumption is that innovation makes a relatively more intensive use of skilled labor.[2] We show that the contribution of human capital to productivity growth can be separated into a *level* effect and a *composition* effect. Holding the composition of human capital constant, an increase in its aggregate level is always growth-enhancing. However, holding its level constant, the growth-enhancing properties of human capital depend on both its composition and the distance to the technological frontier. In particular, we show that the growth-enhancing impact of skilled labor increases with a country's proximity to the frontier, where proximity is measured by the ratio between the total factor productivity in the country and the corresponding variable in the US. This complementarity arises because the labor reallocation triggered by a marginal increase in the quantity of skilled labor is larger when the productivity of innovation is higher, and therefore its marginal contribution to growth larger. Conversely, the growth-enhancing impact of unskilled labor decreases with the proximity to the frontier. We also show that the emergence of a technological wave which increases the weight of skilled labor in innovation decreases the strength of this type of labor's impact. This is because when the relative efficiency of skilled labor in innovation increases, more skilled labor is allocated to innovation at a given distance, and therefore less reallocation takes place as the country moves toward the frontier. In the empirical part of the paper, we present evidence in favor of our main theoretical implication using a panel dataset covering 19 OECD countries observed every five years between 1960 and 2000. This finding is robust to alternative definitions of skilled and unskilled human capital and to the use of different education datasets. We deal with problems of endogeneity by allowing for country dummy variables and by instrumenting levels of human capital using lagged public expenditure on ed-

[2] Note that our argument does not require any assumption about the *absolute* intensity of skilled labor in innovation.

ucation. We show the importance of distinguishing between different types of human capital and of endogeneizing their different allocations at different levels of development. In advanced economies, the potential for catching up is very small and so unskilled human capital contributes little to technological improvement. Therefore the relevant margin is not that of total human capital, but that of *skilled* human capital. We show that skilled human capital significantly matters for technological progress and that it is a source of divergence in OECD economies.

Our paper contributes to two different strands of literature. First, it complements previous theoretical and empirical work on the link between the *level* of education and growth.[3] This link was emphasized in the work by Nelson and Phelps (1966), who argued that a more educated labor force would adopt new technologies faster. It was given complementary theoretical support by the new endogenous growth theories (Romer (1990), Aghion and Howitt (1992)) who described human capital as the engine of growth through innovation[4]. Closer to our work, Grossman and Helpman (1991)[5] show that the skill composition of the labor force matters for the amount of innovation in the economy. In particular, they obtain that an increase in the stock of skilled labor is growth-enhancing while an increase in the stock of unskilled labor can be growth-depressing. We go beyond their analysis by studying how the impact of the composition of human capital on growth depends on the distance to the technological frontier.

This technological view of human capital received empirical support in the work of Benhabib and Spiegel (1994), Barro and Sala-i-Martin (1995) and Barro (1998), all of whom showed that both the initial schooling level and its inter-

[3] For an account of the link between human capital *accumulation* and growth, see the recent contributions of Krueger and Lindahl (2001), Bassanini and Scarpetta (2001), Cohen and Soto (2001) and De la Fuente and Domenech (2002). Seminal contributions to this branch of the literature include Lucas (1988) and Mankiw, Romer and Weil (1992).

[4] For further references, see Aghion and Howitt (1998) and Acemoglu (1996, 2002).

[5] See the third section of their Chapter 5.

action with a measure of the technology gap with the frontier were positively associated with subsequent growth.[6] Their work focused on large cross-country datasets and did not address how the effect of different types of education varies with the level of development, which is real focus of our paper.[7]

However, as mentioned at the beginning of this introduction, Krueger and Lindahl (2001) found that the effect of the initial level of education was highly heterogeneous between rich countries (including OECD members), low-income and middle-income countries, and that it was surprisingly not positive in the richest countries of their sample. The possibility that human capital might play a different role at different stages of development has not often been addressed in the literature, despite the theoretical possibilities opened by endogenous growth theories (see in particular Azariadis and Drazen (1990) and more generally the book by Aghion and Howitt (1998)). Apart from Krueger and Lindahl (2001), evidence of heterogeneous effects has been provided by Durlauf and Johnson (1995), and evidence of non-linearities by Kalaitzidakis, Mamuneas, Savvides and Stengos (2001) but was informed by little theoretical analysis. We enrich the existing empirical literature by providing evidence that education has a heterogeneous effect even *among* the OECD group of countries, i.e. that it is crucial to distinguish between the two margins of primary/secondary versus tertiary educational attainment and that the latter type of education is a source of economic divergence.

Bils and Klenow (2000) argued that most of the positive relationship between initial schooling level and subsequent growth in large cross-country datasets reflected reverse causality. While we do not dispute that expected future growth impacts schooling decisions, our use of panel data estimation techniques and

[6] See also Caselli, Esquivel and Lefort (1996) and Desdoigts (2001).

[7] Barro and Sala-i-Martin (1995) and Barro (1998) distinguish between different educational levels and show that only male secondary and tertiary education is related to productivity growth in a cross-country study of around 100 countries.

instrumentation minimize the impact of this reverse channel on our reported estimates. Moreover, as shown by Krueger and Lindahl, there is no positive relationship to explain in OECD countries, at least if one assumes, as Bils and Klenow do, that all types of human capital are perfect substitutes in contributing to productivity improvements. Our empirical analysis shows that this assumption is unwarranted in rich countries.

Second, our paper builds directly on recent work by Acemoglu, Aghion and Zilibotti (2002), henceforth AAZ, on appropriate institutions and economic growth. AAZ analyze an economy where firms undertake both innovation and adoption of technologies from the world technology frontier and study how the selection of high-skill managers depends on the country's distance to the technological frontier. The AAZ model emphasizes the distinction between innovation and imitation as two alternative sources of productivity growth. While imitation allows a firm to catch up with the current world frontier, innovation allows the firm to improve upon its current local technology and thereby to possibly leap-frog the world frontier. Now, what AAZ argue is that the refinancing of old managers encourages long-term investment and imitation, whereas the weeding out of old low-skill managers and the selection of more talented ones, fosters innovation. That selection and innovation become increasingly important as a country moves closer to the technological frontier, simply follows from the fact that catching up with the frontier translates into smaller and smaller technological improvements as a country starts from an initial productivity level that is closer to the frontier productivity. More generally, AAZ argue that growth-maximizing institutions or policies should evolve as a country or sector catches up with the technological frontier. They are comforted in this claim by several pieces of evidence. Using a panel data set of UK firms over the past twenty five years, Aghion, Bloom, Blundell, Griffith and Howitt (2003) show that product market competition enhances innovation in industries where most firms are close to the national technological frontier, and discourages it in industries where some innovating firms are far below the frontier. Aghion, Burgess, Redding and Zilibotti (2003) obtain a similar conclusion when looking at the relationship between innovation and the liberalization of product entry in India. Aghion, Blundell, Griffith and Howitt (2003) show that the threat of entry is more growth-enhancing in UK industries the closer they are to the world technology frontier. AAZ also perform a few empirical exercises of their own. Using a cross-country panel of about 100 non-OECD countries over the 1960-2000 period, they document that a country's growth rate decreases more rapidly as it approaches the world frontier when its openness to trade is low, entry costs are high or its schooling level is low.

The paper is organized as follows. Section 2 develops our model where productivity growth results from imitation and innovation activities, and where each of these two activities requires a different combination of skilled and unskilled workers. In Section 3, we test our main predictions about the marginal effect of skilled human capital on growth as a function of the distance to the frontier and we provide evidence of a technological wave effect. Section 4 tests the robustness of our results. Section 5 concludes. It is followed by a theoretical appendix and empirical annexes containing a complementary empirical analysis.

2 Theoretical framework

2.1 Economic environment

We consider a world consisting of a finite number of economies, each of which is composed of intermediate entrepreneurs and a size 1 population of workers. We abstract from international trade[8]. Workers have heterogeneous human capital endowments so that in aggregate an economy is endowed with S highly educated

[8] The implications of international trade and labor mobility are beyond the scope of this paper. They will be considered in future work.

(”skilled”) and U less educated (”unskilled”) units of labor given exogenously and constant over time. In what follows, we shall formulate the model in terms of units of labor rather than workers. This will permit the aggregation of the labor input of workers with heterogeneous schooling attainment hence allowing heterogeneous individual productivities. At the end of this section we shall draw attention to the special case where units of labor and workers coincide.

Time is discrete and all agents live for one period only. In the following analysis, we shall be primarily interested in the effect of an exogenous increase in the skilled labor endowment S on productivity growth in economies at different distances from the technological frontier. In every period and in any particular country, final output y is produced competitively using a continuum of mass 1 of intermediate inputs according to the following Cobb-Douglas production function:

$$y_t = \int_0^1 A_{i,t}^{1-\alpha} x_{i,t}^{\alpha} di \tag{1}$$

where $\alpha \in (0,1)$, $A_{i,t}$ is the productivity in sector i and $x_{i,t}$ is the flow of intermediate good i used in final production at time t. Given that the final good sector is competitive, the price of each intermediate input is equal to its marginal product, so that by the first order condition with respect to intermediate good i we have:

$$p_{i,t} = \frac{\partial y_t}{\partial x_{i,t}} = \alpha A_{i,t}^{1-\alpha} x_{i,t}^{\alpha-1}$$

In each intermediate sector i, one intermediate producer can produce good i with productivity $A_{i,t}$, using final good as capital according to a one-for-one technology. This productivity level will in turn be endogeneized in the next subsection. The local monopolist chooses $x_{i,t}$ so as to solve:

$$\max_{x_{i,t}} (p_{i,t} x_{i,t} - x_{i,t})$$

which yields the equilibrium demand for input i:

$$x_{i,t} = \alpha^{\frac{2}{1-\alpha}} A_{i,t}$$

The corresponding monopoly profit in intermediate sector i is then simply equal to:

$$\pi_{i,t} = (p_{i,t} - 1)x_{i,t} = \delta\pi_{i,t} = \delta A_{i,t} \qquad (2)$$

where $\delta \equiv (\frac{1}{\alpha} - 1)\alpha^{\frac{2}{1-\alpha}}$.

2.2 Dynamics of productivity

At the initial stage of each period, firm i decides upon technology choice. A technology improvement results from a combination between: (i) imitation activities aimed at adopting the world frontier technologies; (ii) innovation upon the local technological frontier. Both activities use unskilled and skilled labor as inputs. The dynamics of technology in sector i can be captured using a general positive function F increasing in its arguments:

$$A_{i,t} = A_{i,t-1} + F(\bar{A}_{t-1} - A_{t-1}, A_{t-1}, u_{m,i,t}, s_{m,i,t}, u_{n,i,t}, s_{n,i,t})$$

where $\bar{A}_{t-1}$ is the world productivity frontier at time $t-1$, A_{t-1} is the country's productivity frontier at the end of period $t-1$, $u_{m,i,t}$ (resp. $s_{m,i,t}$) is the amount of unskilled (resp. skilled) labor input used in imitation in sector i at time t, $u_{n,i,t}$ (resp. $s_{n,i,t}$) is the amount of unskilled (resp. skilled) units of labor used by sector i in innovation at time t.

In line with the recent literature on endogenous growth, and in particular following Benhabib and Spiegel (1994) and Acemoglu, Aghion and Zilibotti (2002), we characterize technological progress as a linear function of imitation and innovation. We shall thus assume[9]:

[9] Benhabib and Spiegel (1994) do not distinguish between different types of human capital

$$A_{i,t} = A_{i,t-1} + \lambda[u_{m,i,t}{}^{\sigma} s_{m,i,t}^{1-\sigma}(\bar{A}_{t-1} - A_{t-1}) + \gamma u_{n,i,t}^{\phi} s_{n,i,t}^{1-\phi} A_{t-1}] \quad (3)$$

where σ (resp. ϕ) is the elasticity of unskilled labor in imitation (resp. innovation), $\gamma > 0$ measures the relative efficiency of innovation compared to imitation in generating productivity growth, and $\lambda > 0$ measures the efficiency of the overall process of technological improvement.

To reflect the higher intensity of skilled labor in innovation than in imitation, we make the following assumption:

(A1) *The elasticity of skilled labor is higher in innovation activities than in imitation activities, i.e.* $\phi < \sigma$.

Conversely, the elasticity of unskilled labor is higher in imitation than in innovation.

2.3 Analytical results

Let $w_{u,t}\bar{A}_{t-1}$ (resp. $w_{s,t}\bar{A}_{t-1}$) denote the wage of unskilled (resp. skilled) labor. The total labor cost of productivity improvement by intermediate firm i at time t is then equal to:

$$W_{i,t} = [w_{u,t}(u_{m,i,t} + u_{n,i,t}) + w_{s,t}(s_{m,i,t} + s_{n,i,t})]\bar{A}_{t-1}$$

Using (2) together with the fact that entrepreneurs live for one period only and thus maximize current profit net of labor costs, each intermediate good producer i at date t will choose $(u_{m,i,t}, u_{n,i,t}, s_{m,i,t}, s_{n,i,t})$ to solve the following

and write

$$A_{i,t} - A_{i,t-1} = c(H_i)(\bar{A}_{t-1} - A_{t-1}) + g(H_i)A_{t-1}$$

where H is the total amount of human capital, while Acemoglu, Aghion and Zilibotti (2002) do not focus on human capital and write

$$A_{i,t} = s_{i,t}(\eta\bar{A}_{t-1} + \gamma_{i,t}A_{t-1})$$

where $s_{i,t}$ is project size, η is a constant and $\gamma_{i,t}$ is managerial skill.

program:

$$\max_{u_{m,i,t},u_{n,i,t},s_{m,i,t},s_{n,i,t}} \lambda\delta[u_{m,i,t}{}^{\sigma}s_{m,i,t}^{1-\sigma}(1-a_{t-1})+\gamma u_{n,i,t}^{\phi}s_{n,i,t}^{1-\phi}a_{t-1}]\bar{A}_{t-1}-W_{i,t}$$

where $a_{t-1} \equiv A_{t-1}/\bar{A}_{t-1}$ is an inverse measure of the country's distance to the world frontier at $t-1$.

Given that:

(1) all intermediate firms face the same maximization program, so that in equilibrium:

$$\begin{aligned} u_{m,i,t} &\equiv u_{m,t}; \\ s_{m,i,t} &\equiv s_{m,t}; \\ u_{n,i,t} &\equiv u_{n,t}; \\ s_{n,i,t} &\equiv s_{n,t}; \end{aligned}$$

(2) there is a mass 1 of intermediate firms, so that the labor market equilibrium writes:

$$\begin{aligned} S &= s_{m,t}+s_{n,t}; \\ U &= u_{m,t}+u_{n,t}; \end{aligned}$$

we obtain the following two first order conditions for an interior solution, which express that the marginal productivity of each type of labor is equalized across activities (time indices are omitted for simplicity):

$$\sigma u_m^{\sigma-1}s_m^{1-\sigma}(1-a)=\gamma\phi(U-u_m)^{\phi-1}(S-s_m)^{1-\phi}a \tag{4}$$

and

$$(1-\sigma)u_m^{\sigma}s_m^{-\sigma}(1-a)=\gamma(1-\phi)(U-u_m)^{\phi}(S-s_m)^{-\phi}a \tag{5}$$

Dividing across equations, we obtain:

$$\sigma(1-\phi)s_m(U-u_m)=(1-\sigma)\phi u_m(S-s_m) \tag{6}$$

We can rewrite this equality as:

$$\psi \frac{u_n}{s_n} = \frac{u_m}{s_m} \tag{7}$$

where $\psi \equiv \frac{\sigma(1-\phi)}{(1-\sigma)\phi} > 1$ given (A1).

The above equation shows that the ratios of unskilled to skilled employment are proportional across activities. Interestingly, this implies that their comparative statics with respect to U, S and a will be the same.

From equation (6), we can easily get u_m as a function of s_m:

$$u_m = \frac{\psi U s_m}{S + (\psi - 1)s_m} \tag{8}$$

Substituting (8) in (4), we obtain

$$(\psi - 1)s_m = h(a)U - S \tag{9}$$

where

$$h(a) \equiv \left(\frac{(1-\sigma)\psi^{\sigma}(1-a)}{(1-\phi)\gamma a}\right)^{\frac{1}{\sigma-\phi}}$$

is a decreasing function of a. For an interior solution to obtain, s_m and s_n cannot exceed S. These conditions can be re-expressed using (9), and we state the outcome in the following lemma:

Lemma 1 *An interior solution obtains if and only if*

$$\frac{h(a)}{\psi} \leq \frac{S}{U} \leq h(a) \tag{10}$$

The lemma expresses a condition on relative factor endowments for an interior solution to obtain. Given factor endowments, if a country is too far away from the frontier, i.e. if a is too small, it will employ all its resources in imitation. On the opposite, if it is too close to the frontier, it will specialize in innovation. It is only for intermediate values of a that it will pursue both imitation and innovation. Another way to look at the lemma is to hold a constant, and describe what happens when factor endowments vary. If the country is relatively abundant in skilled (resp. unskilled) labor, it will tend to specialize in innovation (resp. imitation).

Our model lets itself be analyzed in a fashion similar to a two-factor two-sector Heckscher-Ohlin model of international trade, and we shall pursue the analogy in what follows for expositional purposes. From (8) and (9), we can easily express the relative factor intensities in the two activities:

$$\frac{u_m}{s_m} = \frac{\psi}{h(a)} \tag{11}$$

$$\frac{u_n}{s_n} = \frac{1}{h(a)} \tag{12}$$

These factor intensities are independent of total factor endowments. We can therefore use the diagram of Figure 1 to explore further the properties of the model. The horizontal axis measures quantities of unskilled labor, while the vertical axis measures quantities of skilled labor. A corner solution with full specialization in imitation is obtained below the (M) line, and a corner solution with full specialization in innovation is obtained above the (N) line. These two lines are drawn using condition (10). When the endowment point E is inside the cone, the economy is diversified between imitation and innovation. The line segment OA represents the vector or labor resources devoted to innovation, and OB that devoted to imitation.

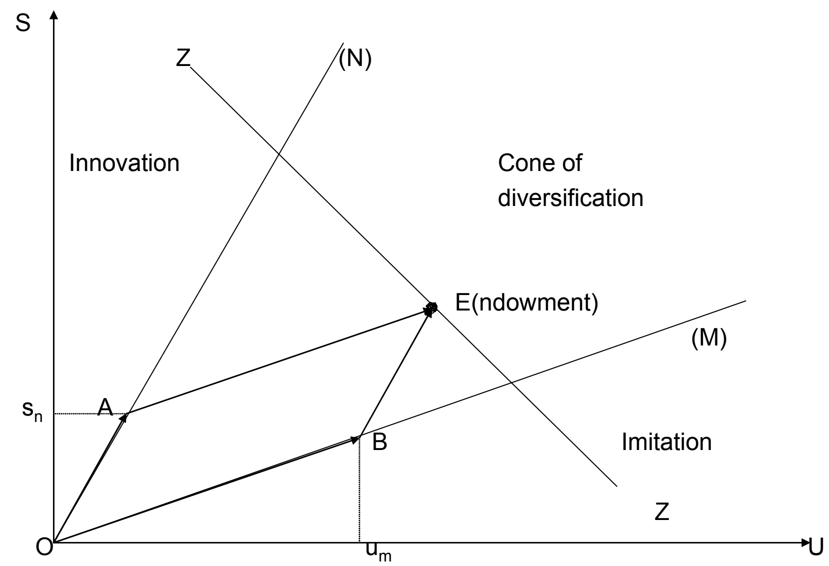


Figure 1

Moving the endowment point along the 45 degree line (ZZ), we vary the human capital composition of the economy while maintaining its aggregate level constant. When the economy becomes relatively richer in skilled labor, employment of both factors increases in innovation and decreases in imitation. The opposite happens when the composition of human capital tilts more toward unskilled human capital. When a increases, both the (M) and the (N) lines rotate clockwise, and this implies that both types of labor are reallocated from imitation to innovation.

When we shift the (ZZ) line out, inducing a proportional increase in both factors, employment of each skill category increases proportionally in each activity. Some of these results can be summarized in the following lemma:

Lemma 2 *When both imitation and innovation are performed in equilibrium, the optimal amount of skilled and unskilled labor employed in imitation is increasing (resp. decreasing) in the total number of unskilled (resp. skilled) units of labor U (resp. S), and decreasing in the distance to the frontier a.*

Consider the first claim of the lemma. When U increases, the amount of unskilled labor employed in imitation increases proportionally more than that employed in innovation (since $\sigma > \phi$), therefore the marginal productivity of skilled labor increases more in imitation than in innovation, which attracts skilled labor into imitation. Because there is less skilled labor in innovation, the productivity of unskilled labor decreases in innovation and so even more unskilled labor goes to imitation. In the end, employment of both categories of labor in imitation has increased, and has decreased in innovation, despite the initial increase in the unskilled labor force. The opposite happens when S increases: employment decreases in imitation and increases in innovation, regardless of the skill category. We therefore get a results analogous to the famous Rybczynski theorem of international trade.[10]

Now, the intuition for the second claim, can be summarized as follows. Far below the technological frontier, when the catch-up effect of imitation is sufficiently high, it pays more for intermediate firms to employ both types of labor in imitation; however, the closer the economy moves to the frontier, the more profitable it becomes to increase employment in innovation, which in turn explains why s_m (as well as u_m) is a decreasing function of a.

The existence of corner solutions is an artifact of our assumption of perfect substitutability between imitation and innovation. This assumption was only made for analytical tractability. In practice, it is very likely that imitation

[10] The Rybczynski theorem states that if endowment in one factor rises (falls) in one country, and if output prices remain the same, then the output of the sector that uses that factor more intensively will rise (fall) while the output of the other sector will fall (rise). Grossman and Helpman (1991, chap.5) obtain a result similar to ours in an economy with two sectors, where innovations can occur only in the more skill-intensive of the two (the 'high technology sector').

and innovation have some degree of complementarity. In Appendix 1, we show that when the elasticity of substitution between the two activities is strictly lower than one, we can rule out corner solutions. Moreover, for an elasticity of substitution sufficiently close to one, the content of our main result (Proposition 1) below is unaffected. In the remaining part of the paper, we shall thus focus the analysis on the interior solution, which embodies the mechanism that is economically relevant for us. We can now turn our attention to the effect of changes in the skilled labor supply on the equilibrium growth rate.

This rate at date t is equal to

$$g_t = \int_0^1 \frac{A_{i,t} - A_{t-1}}{A_{t-1}} di$$

Thus, by substituting for the equilibrium value of s_m in equation (3) we obtain:

Lemma 3 *The growth rate of the economy is given by:*

$$g/\gamma\lambda = \phi h(a)^{1-\phi} U + (1-\phi) h(a)^{-\phi} S \tag{13}$$

which can be rewritten as:

$$g/\gamma\lambda = [\phi h(a)^{1-\phi} \frac{U}{U+S} + (1-\phi) h(a)^{-\phi} \frac{S}{U+S}](U+S)$$

It is now straightforward to see that human capital has two effects on growth. First there is a positive *level* effect: increasing the aggregate amount of human capital $U + S$, holding its distribution constant, is always growth-enhancing in this economy. What is more interesting is the *composition* effect: the growth-enhancing impact of the two types of human capital vary in opposite directions as a function of the distance to the frontier a.

More specifically, we can now establish the main result of our theoretical section:

Proposition 1 *Under assumption (A1), a marginal increase in the stock of skilled human capital enhances productivity growth all the more the economy is* *closer to the world technological frontier. Correspondingly, a marginal increase in the stock of unskilled human capital enhances productivity growth all the more the economy is further away from the technological frontier.*

Proof. The result follows directly from equation (13) since $h(a)$ is a decreasing function of $h(a)$. ■

In words, an increase in the supply of skilled labor S attracts both types of labor into innovation for reasons already spelled out in Lemma 2. This in turn implies that the innovation component of productivity growth will increase at the expense of the imitation component. That the positive effect on innovation dominates the negative effect on imitation all the more the economy is closer to the frontier in turn results from the fact that the factor intensities u_m/s_m and u_n/s_n are proportional and increasing in a. This means that the amount of unskilled labor employed in innovation u_n is increasing faster than the amount of skilled labor employed in innovation s_n, and that the amount of unskilled labor employed in imitation u_m is decreasing slower than the amount of skilled labor employed in imitation s_m when the economy approaches the frontier. Indeed a more indirect but more intuitive way of deriving the result is to use the proportionality of the factor intensities captured in equation (7) to write the growth rate as

$$g/\lambda = (\frac{u_n}{s_n})^{\phi}[\psi^{\sigma}(\frac{u_n}{s_n})^{\sigma-\phi}s_m(\frac{1-a}{a}) + \gamma s_n]$$

which, using equation (12), we can rewrite

$$g/\gamma\lambda = (\frac{u_n}{s_n})^{\phi}[\frac{(1-\phi)}{(1-\sigma)}s_m + s_n]$$

The first term on the right hand side is the factor intensity u_n/s_n which we know depends (positively) only on a. From equation (9), the derivative of the term in the bracket with respect to S is a strictly positive constant. The intuition for the effect of an increase of the stock of unskilled human capital U is exactly similar.

Finally, consider the effect of skill biased technological change modelled as an increase in the elasticity of skilled labor in innovation (i.e. a reduction in ϕ). The following Proposition summarizes our findings.

Proposition 2 *Under Assumption (A1), the extent to which proximity to the frontier positively affects the impact of a marginal increase of skilled labor on the rate of productivity growth decreases with the elasticity of skilled labor in innovation when* $a > \frac{1}{1+\gamma}$.

Proof. From (13), we can write

$$\frac{\partial^2 g}{\partial a \partial S} = \frac{\lambda}{a^2}\left(\frac{1-\phi}{\sigma-\phi}\right)\left[\phi\left(\frac{\sigma^\sigma(1-\sigma)^{(1-\sigma)}}{\phi^\sigma(1-\phi)^{(1-\sigma)}}\right)^{\frac{-\phi}{\sigma-\phi}}\right]\left(\frac{\gamma a}{1-a}\right)^{\frac{\sigma}{\sigma-\phi}}$$

Computing the derivative of this expression with respect to ϕ is cumbersome. Instead, we resort to numerical simulation. For all values of σ, the expression in brackets on the right hand side is increasing in $\phi < \sigma$. Therefore the whole right hand side is increasing in ϕ whenever $\frac{\gamma a}{1-a} > 1$. ■

The intuition behind the corollary is that when innovation activities are sufficiently skilled labor intensive relative to imitation activities, even a country that is far from the frontier allocates most of its skilled labor resources to innovation; therefore, the flow of skilled workers from imitation to innovation as the country moves closer to the frontier, also becomes smaller.

2.4 Answering the Krueger and Lindahl puzzle

We are now well equipped to offer an explanation to the Krueger and Lindahl puzzle. In OECD economies, the total amount of human capital (in our notations $U + S$) is not a sufficient statistic to predict the growth rate of the economy, because at a given distance to the frontier, U and S have different marginal effects on the growth rate (keeping $U+S$ constant). We illustrate the consequences of this simple observation through the following example.

Consider two economies X and Y at the same distance to the frontier a. X is endowed with more human capital in aggregate ($U_X + S_X > U_Y + S_Y$) but Y has more skilled human capital, i.e. $\Delta U \equiv U_X - U_Y > -\Delta S \equiv -S_X + S_Y > 0$. Calling g_X and g_Y the respective growth rates of these economies, we obtain from (13):

$$g_X - g_Y = [\phi h(a)^{1-\phi} \Delta U + (1-\phi) h(a)^{-\phi} \Delta S]$$

This equation in turn implies:

$$g_X - g_Y < 0 \iff h(a) < -\frac{1-\phi}{\phi} \frac{\Delta S}{\Delta U}$$

The above inequality is satisfied when the composition effect is sufficiently large to overcome the level effect. In that case, a regression of the growth rate on the aggregate amount of human capital $U + S$ would return a negative coefficient.

2.5 Particular case: fractions

One special case of the general formulation above is obtained by endowing each worker in the economy with only one unit of labor, whether skilled or unskilled. Then S (resp. U) simply describes the *fraction* of the labor force that is skilled (resp. unskilled). As we assume a total population of mass 1, this interpretation imposes that $U + S = 1$. Therefore only the composition effect of human capital on growth remains. We focus on this special case because this specification will be tested in the empirical section. We are now left with only one human capital variable to describe the state of the economy. Replacing U by $(1 - S)$, the growth rate (see Proposition 1) becomes a sole function of S, the fraction of skilled workers:

$$g/\lambda = \gamma\phi h(a)^{1-\phi}(1-S) + \gamma(1-\phi)h(a)^{-\phi}S$$

Now a marginal increase of the skilled labor stock is going to have an ambiguous effect on the growth rate. Indeed, far from the frontier, it is unskilled labor that is the prime driver of growth, and an increase in S will be growth enhancing only if the induced amount of innovation is enough to compensate for the loss in imitation, as can be seen in the following formula (remember that $h(a)$ is positive and decreasing in a):

$$\frac{1}{\lambda}\frac{\partial g}{\partial S} = -\gamma\phi h(a)^{1-\phi} + \gamma(1-\phi)h(a)^{-\phi}$$

However, the complementarity between S and a is now stronger than in the general case. On top of the effect already described in the previous subsection, an increase in the fraction of skilled workers will now reduce the amount of unskilled labor available in the economy hence depressing the marginal productivity of skilled labor in imitation. This accelerates the reallocation of skilled labor toward innovation as the economy approaches the frontier. Therefore Proposition 1 holds even more strongly in the case where we define the skilled human capital stock as the fraction of skilled workers in the economy.

2.6 Summarizing our main theoretical predictions

Two main implications emerge from our analysis in this section:

(P1) The growth-enhancing effect of a marginal increase in the stock of skilled human capital is stronger the closer the economy is to the technological frontier.

(P2) This complementarity between proximity to the frontier and stock of skilled human capital is weakened by the occurrence of a technological wave which increases the elasticity of skilled labor in innovation.

In the next Section, we shall confront these two implications with a panel dataset on educational achievement and productivity growth in OECD countries.

3 Empirical analysis

As seen in section 2, when the stock of skilled human capital is assumed to be the skilled fraction of the labor force, two effects instead of one generate a complementarity between skilled human capital and the proximity to the frontier. Provided there is enough homogeneity within each human capital category, this assumption should therefore make it more difficult to reject our implication (P1). Moreover, the model in which we consider this specific formulation of (P1) contains fewer parameters. It is less demanding on the data, requires less instruments and so should facilitate identification. After describing our dataset, we consider (P1) in a first specification with fractions then in a second specification where skilled and unskilled human capital can vary independently. In this second specification, we also consider (P2).

3.1 Data description and empirical procedure

We combine five different sources to construct our panel dataset covering 19 OECD countries between 1960 and 2000. First, we use GDP and investment data from the Penn World Tables 6.1 compiled by Heston et al (2002). The dataset provides yearly data on output and investment from 1950 to 2000 for a large number of countries. However, it does not include a measure of the capital stock and we construct this variable using a classic perpetual inventory method assuming a depreciation rate of 6%, a usual assumption in the literature. To construct a measure of the capital stock in 1949, we use the following formula:

$$K_{1949} = \frac{I_{1950}}{g + .06}$$

where I_{1950} is investment in 1950 and g is the growth rate of output between 1950 and 1960. This formula corresponds to the value of the capital stock in the steady state of a neoclassical growth model with a depreciation rate of 6% and an exogenous growth rate of g. Since our econometric analysis starts in 1960, most of the error on this initial value of the capital stock has disappeared from the measure of the capital stock we actually use. Without any information on the share of residential capital in the total capital stock, we work with the total stock.

We then construct total factor productivity defined as output per adult minus capital per adult times the capital share[11]. Output per adult is constructed by dividing total GDP by the size of the population aged between 15 and 64, taken from the World Development Indicators (2002)- our second data source. Given the absence of a comprehensive panel dataset on labor shares, we take them to be constant across countries and equal to .7.[12] Then we define proximity to the technological frontier as the ratio of a country's tfp level to that of the US.

Given the long-lasting debate on the quality of schooling attainment data (see Krueger and Lindahl (2001), Cohen and Soto (2001) and De la Fuente and Domenech (2002)), we present results using two education datasets, those of Barro and Lee (2000) -henceforth BL- and De la Fuente and Domenech (2002) - henceforth DD. Both give the distribution of the population across schooling attainment levels and a number of years corresponding to each level at five

[11] Our results are not affected when we use output per worker instead. This means that they are not driven by changes in the labor supply. Similarly, our results are not qualitatively affected if we use GDP per adult or labor productivity instead of tfp.

[12] Gollin (1998) builds a cross-country dataset on labor shares, where most values are between .65 and .8. We do not use these numbers because they would lead to implausible tfp levels. For instance, Greece and the US would have about the same tfp level over the period we study. We believe .7 is a reasonable average for OECD economies. Other authors in the literature, in particular Topel (1999) and Bernanke and Gurkaynak (2001) have also used a constant labor share in their analysis.

year intervals. BL has seven categories, while DD has six.[13] BL covers over 100 countries between 1960 and 2000 and each of its categories is associated with the same number of years, regardless of the country. BL's population of reference is adults between 15 and 64 years old. DD covers 21 OECD countries between 1960 and 1995, and has a small amount of cross-country heterogeneity with respect to the number of years in each category. DD's population of reference is adults aged between 25 and 64.

Finally, we rely on Unesco's Statistical Yearbook (1999) to obtain data on public expenditures on all levels of education between 1950 and 1990.[14] Our sample of countries is obtained by taking the intersection of all five datasets, which leaves us with 19 OECD countries.[15]

Table I provides some descriptive statistics of the main variables of interest. The proximity variable has a mean of .74 and a minimum value of .42. The fraction variable has a mean value of .13. Mean years of primary/secondary education are somewhat higher in DD than in BL (9.1 versus 7.6). The same is true for mean years of tertiary education (.41 versus .38).

[13] BL' s categories are: no schooling, some primary, complete primary, some secondary, complete secondary, some tertiary, complete tertiary. DD's are: illiterate, primary, lower secondary, upper secondary, lower tertiary, upper tertiary.

[14] The 1999 Yearbook provides public expenditure data between 1970 and 1990. We construct the early part of the series by working backward through previous Yearbooks.

[15] They are: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Greece, Ireland, Italy, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom, United States.

TABLE I
DESCRIPTIVE STATISTICS

	Mean	Std. Dev.	Min	p10	p25	p75	p90	Max
Proximity	0.74	0.126	0.417	0.57	0.64	0.8	0.88	1
P/S-expend. /capita	658	307	54.2	228	433	867	1020	1400
T-expend./capita	164	118	6.05	29.2	66	234	340	559
Education								
Barro Lee								
Fraction	0.13	0.1	0.01	0.026	0.05	0.16	0.23	0.5
Mean years P/S	7.6	1.6	2.6	5.4	6.4	8.6	9.2	11
Mean years T	0.38	0.27	0.026	0.064	0.135	0.457	0.666	1.34
De La Fuente Domenech								
Fraction	0.13	0.096	0.015	0.041	0.063	0.18	0.25	0.48
Mean years P/S	9.1	1.98	4.3	5.87	7.8	10.7	11.4	12.2
Mean years T	0.41	0.29	0.052	0.13	0.2	0.55	0.73	1.6

Source: Heston et al. (2002), Barro and Lee (2000), De la Fuente et Domenech (2002), Unesco (1999).
Proximity is the ratio of a country's total productivity level to that of the US. Primary/Secondary and Tertiary expenditures per capita are expressed in dollars. Fraction is the percentage of the adult population with at least some tertiary education
Data are for the period 1960-1995.

A main difficulty in conducting our empirical analysis has been to deal with the endogeneity of educational attainment, a problem acutely emphasized in the paper by Bils and Klenow (2000). Finding an exogenous source of variation in the skill composition of the labor force of 20 countries is a challenging task. One might think of using education reforms as a possible instrument,[16] but it is unclear whether reforms are exogenous enough and more importantly it is difficult to assess their quantitative impact as well as the timing of their effective implementation. We also could possibly use election results, assuming that left-wing governments would favor education more than their right-wing counterparts.[17] However, this variable turns out to be a rather poor instrument. In the end, we shall focus the analysis on lagged public education expenditures

[16] We thank Guy Neave for guiding us through the opaque landscape of higher education reforms in industrialized countries.

[17] We are grateful to Jim Snyder for providing us with data on election results.

as our main instrument[18], which after all summarizes both the true impact of educational reforms and the political arbitrage of governments, irrespective of their ideological biases.

3.2 First specification: Fractions

In this specification, our measure of the skilled human capital stock is the fraction of people having studied above high school, which corresponds to the union of the top two categories of the BL and DD datasets.

3.2.1 The empirical specification and estimation

We consider the following empirical specification for TFP growth:

$$g_{j,t} = \alpha_{0,j} + \alpha_1 a_{j,t-1} + \alpha_2 f_{j,t-1} + \alpha_3 a_{j,t-1} * f_{j,t-1} + \epsilon_{j,t} \qquad (14)$$

where $g_{j,t} = \log A_{j,t} - \log A_{j,t-1}$, $A_{j,t}$ being TFP in country j at period t, $a_{j,t-1} \equiv \log A_{j,t-1} - \log \bar{A}_{t-1}$ is the log of the proximity to the total factor productivity frontier in the previous period (note that this last variable is a *negative* number) and $f_{j,t-1}$ is the fraction of the population with higher education in the previous period. We always include time dummies, and $\alpha_{0,j}$ reflects country dummies which control for unobserved permanent differences in TFP growth that may exist among OECD countries. In addition to the fixed country effects we also allow for the possibility that the shocks $\epsilon_{j,t}$ are an MA(1). Since the period of observation is every five year, which is dictated by the availability of education data, this is quite a lot of persistence allowed for. As a result, we treat all right hand side variables as endogenous. Our instruments are the log of the proximity lagged two periods ($a_{j,t-2}$), expenditure on tertiary education per capita lagged two periods and the interaction of these instruments, together with country dummies and time dummies. In order to assess the explanatory power of our

[18] Using lagged values of educational attainment yields comparable results.

instruments we carry out a rank test which tests on the three reduced forms.[19] Finally the standard errors we report allow for serial correlation (cluster effects by country) and heteroskedasticity.

3.2.2 Estimation results

The reduced forms The reduced forms for the models we estimate are presented in Table II. In each of the three reduced forms we include a set of time dummies and a set of country dummies. Over and above these we also include the log of the proximity to the frontier lagged twice (i.e. 10 years before)[20], tertiary education expenditure lagged twice and the interaction of these two instruments.

In the first reduced form for proximity all the three instruments, that are excluded from the TFP growth regression are highly significant. In the second reduced form for the proportion of skilled adults (see the second column) we find that lagged education expenditure is very significant. The interaction coefficient indicates that lagged expenditure is more important in determining the proportion of skilled adults for countries close to the frontier. Finally, in the reduced form for the interaction of proximity to the frontier and education (see the third column), the expenditure variable and lagged distance matter when interacted together. Thus overall we see that our instruments have explanatory power. To see whether jointly the rank test would reject a rank less than three we implemented the Robin and Smith (1995) rank test which gave a p-value of 7% (see Table IIIa, column [4]) for reduced forms based on the BL data[21]. This indicates that the instruments have a strong explanatory power across all reduced forms. Similar results are obtained for the reduced form based on the

[19] If the instruments have sufficient explanatory power the rank of the coefficient matrix of the three reduced forms would be three.

[20] The choice of lagging twice is the result of the arbitrage between getting a sufficiently distant variable to eliminate as much endogeneity as possible and not going too far back in time to preserve a reasonable number of observations for the empirical analysis.

[21] To implement the test, we carry out a block bootstrap with 1000 replications.

DD data set (see the fourth and fifth columns), and the overall rank test here has a p-value of 20%. However in some specifications we add more restrictions, which aid at identification.

TABLE II
REDUCED FORMS (FRACTION SPECIFICATION)

		BL		DD	
	Proximity	**Fraction**	**Prox*Frac**	**Fraction**	**Prox*Frac**
Lagged Proximity	0.620	-0.005	0.000	-0.099	0.032
	(.081)***	(.052)	(.021)	(.039)**	(.017)*
Lagged T-expend./capita	-0.38	0.42	0.002	0.44	-0.018
	(.13)***	(.084)***	(.033)	(.06)***	(.03)
Lagged Prox*T-expend.	-1.00	0.63	0.35	1.20	0.13
	(.39)**	(.25)**	(.1)***	(.18)***	(.08)
R2	0.95	0.94	0.87	0.97	0.89
Number of observations	122	122	122	118	118

Note: standard errors in parentheses. Time and country dummies not reported. A test for the joint significance of the time dummies yields a p-value of 0. The same is true for country dummies. Tertiary expenditures are in thousand dollars.
One, two and three * indicate significance at the 10, 5 and 1% level respectively.

The estimation method we will be using is Instrumental Variables on within groups, since we take out the country effects. It is well known that within groups is biased in panels with a low time dimension (see Nickell, 1981). However, the time dimension here is large covering the period from 1960 to 2000. Moreover, in our view using the first difference estimator would lead to much greater biases because the instruments are not capable of predicting the first difference in the education and distance. However, as we have shown, the instruments' predictive ability for education and distance, even conditional on country effects is quite decent. In this context we believe the within estimator to be most appropriate.

The Estimates We start our discussion of the BL estimates by presenting a pure level regression, i.e. without interaction terms (see Table IIIa, column [1]). The sign changes from a negative education effect on growth to a positive one when the country effects are included but no effect is in any way significant. The effect of lagged distance on growth is negative implying tfp convergence not mediated by education but, again, this effect is not very significant.

In column [3] of Table IIIa, we estimate our model including the interaction effect between proximity and the proportion of adults with tertiary education, but excluding country dummies. There indeed we find that the interaction between our education measure and proximity is positive, signifying that adults with tertiary education are more important for growth in economies closer to the frontier. The other side of this is that for countries with higher levels of skilled workers the lagged effect of proximity to the frontier on growth is less negative. It is even positive when the fraction of skilled adults is above .21. Importantly, very similar results are obtained when we use the DD data set (see column [3] of Table IIIb). However, these results although consistent with our original hypothesis have the unappealing implication that for countries with a tfp level more than 16% below that of the US, the impact of higher education is negative on growth (see the value of the variable 'proximity threshold' in the Table). This level is quite high since it implies that in year 2000, only two countries would benefit from having a more skilled population.

TABLE IIIa
TFP GROWTH EQUATION (FRACTIONS BL)

	[1]	[2]	[3]	[4]	[5]
Proximity	-0.071	-0.222	-0.16	-0.05	-0.35
	(.05)	(.161)	(.045)***	(1.06)	(.057)***
Fraction	-0.048	0.49	0.125	1.54	0.386
	(.084)	(1.9)	(.058)**	(4.1)	(.13)***
Proximity*Fraction	-	-	0.78	-1.88	1.46
			(.2)***	(11.2)	(.35)***
Country dummies	No	Yes	No	Yes	Groups
p-value country dummies	-	-	-	0	-
Proximity threshold	-	-	-0.160	-	-0.264
			(.062)	-	(.051)
Rank test (p value)	-	-	-	7%	-
Number of observations	122	122	122	122	122

Note : standard errors in parentheses. Time dummies not reported. In column [5], countries are grouped in the following way:
Group 1: Belgium, France, Italy, Netherlands; Group2: The four Scandinavian countries, Austria, UK, Switzerland; Group3: Canada, US;
Group 4: Australia, New Zealand; Group 5: Portugal, Spain; Group 6: Greece; Group 7: Ireland.
Proximity is the log ratio of a country's tfp to the technological frontier's tfp (hence it is a negative number).
Proximity threshold indicates the value of Proximity above which Fraction is growth-enhancing. One, two and three * indicate significance at the 10, 5 and 1% level respectively.

We now allow for country dummies, reflecting unobservable influences on growth. The results are presented in column [4]. The country dummies are jointly significant with a p-value of 0. The results are far too imprecise to draw any firm conclusions. To improve on this we group countries based on geographical proximity and/or institutional proximity at the beginning of the sample period.[22] The results are very encouraging in this respect. Indeed the coefficient values are consistent with the theory and they imply that all countries with a productivity above 73% that of the frontier (see column [5]) benefit by the presence of skilled adults. The implication is also that in economies in the top

[22]We form the following groups: Group 1: Belgium, France, Italy, Netherlands, who are all founding members of the European Union since the Treaty of Rome signed in 1957; Group 2: The four Scandinavian countries, Austria, UK, Switzerland, who belong to the European Free Trade Association (Finland became an associated member in 1961 only); Group 3: Canada, US; Group 4: Australia, New Zealand; Group 5: Portugal, Spain; Group 6: Greece; Group 7: Ireland. The restrictions implied by combining the dummies are acceptable with a p-value of 95%.

10% of the skill distribution, which includes four countries in 2000, proximity to the frontier has a positive effect on subsequent growth.

Very similar conclusions can be drawn when we use the DD data, where we impose the same groups as in the BL data set. The coefficients obtained using the DD data set are of comparable precision and the threshold for a positive impact of tertiary education on growth is lower at 60% of the frontier. The results are therefore consistent with each other and confirm our original implication (P). Most and maybe all OECD countries would benefit from having a larger fraction of skilled workers in 2000, according to our estimates.

TABLE IIIb
TFP GROWTH EQUATION (FRACTIONS DD)

	[1]	[2]	[3]	[4]	[5]
Proximity	-0.093	-0.222	-0.17	-2.5	-0.34
	(.05)*	(.14)	(.044)***	(23)	(.067)***
Fraction	6.00E-05	0.2	0.136	-3.1	0.486
	(.08)	(1.1)	(.064)**	(37)	(.15)***
Proximity*Fraction	-	-	0.649	25	1.21
			(.27)**	(252)	(.31)***
Country dummies	No	Yes	No	Yes	Groups
p-value country dummies	-	-	-	0	-
Proximity threshold	-	-	-0.210	-	-0.402
			(.11)	-	(.04)
Rank test (p value)	-	-	-	20%	-
Number of observations	118	118	118	118	118

Note : standard errors in parentheses. Time dummies not reported. In column [5], countries are grouped in the following way:
Group 1: Belgium, France, Italy, Netherlands; Group2: The four Scandinavian countries, Austria, UK, Switzerland; Group3: Canada, US;
Group 4: Australia, New Zealand; Group 5: Portugal, Spain; Group 6: Greece; Group 7: Ireland.
Proximity is the log ratio of a country's tfp to the technological frontier's tfp (hence it is a negative number).
Proximity threshold indicates the value of Proximity above which Fraction is growth-enhancing. One, two and three * indicate significance at the 10, 5 and 1% level respectively.

3.3 Second specification: Years

We now turn to a specification where we allow the stocks of unskilled and skilled labor to vary independently. To that end, we group the top two categories (corresponding to adults educated above high school) of both education datasets. There are seven categories in BL, so we define the following variables:

$$YearsT \equiv (p_6 + p_7)n_6 + p_7 n_7$$

and

$$YearsPS \equiv \sum_{i=1}^{5} \left(\sum_{j=i}^{7} p_i \right) n_i$$

where p_i is the fraction of the population in category of schooling attainment i and n_i is the number of extra years of education which an individual in category i has accumulated over an individual in category $(i-1)$. We have $(n_1, n_2, n_3, n_4, n_5, n_6, n_7) = (0, 3, 3, 3, 3, 2, 2)$. The variable $YearsT$ (resp. $YearsPS$) represents the number of years of tertiary (resp. primary/secondary) education of the average adult in the population. With these assumptions, a college graduate contributes 12 years to $YearsPS$ and 4 years to $YearsT$. We construct similar variables from the DD data, working with six categories instead of seven.

3.3.1 The empirical specification and estimation

We use a similar specification to (14):

$$\begin{aligned} g_{j,t} &= \beta_{0,j} + \beta_1 a_{j,t-1} + \beta_2 YearsPS_{j,t-1} + \beta_3 YearsT_{j,t-1} \\ &\quad + \beta_4 a_{j,t-1} * YearsPS_{j,t-1} + \beta_5 a_{j,t-1} * YearsT_{j,t-1} + \epsilon'_{j,t} \qquad (15) \end{aligned}$$

where $g_{j,t} = \log A_{j,t} - \log A_{j,t-1}$ is the growth rate is country j between $t-1$ and t, $a_{j,t-1} = \log A_{j,t-1} - \log \bar{A}_{t-1}$ is the log of the proximity to the frontier. Note, again, that this last variable is a *negative* number. $YearsPS_{j,t-1}$ and $YearsT_{j,t-1}$ are defined as above. Again, we include time and country dummies. To estimate the model we use as instruments for the two measures of education the log of the lagged expenditures per capita on primary/secondary and on tertiary levels of education respectively. The reduced forms for these results are presented in Tables A2a and A2b in Appendix 2.

We begin our discussion by presenting a regression similar to that of Krueger and Lindahl (see their section 4.2). They find that for rich countries, growth is negatively associated with the initial stock of human capital. Our specification is slightly different from theirs, and we basically find no direct effect of education on TFP growth when we do not include country dummies, whether we use the BL data or the DD data (column 1 of Tables IVa and IVb). When we include country dummies, primary and secondary education still have no effect, while tertiary education has a positive although insignificant effect in BL and DD.

Looking straight at column 5 of Table IVa where we include dummies for the group of countries identified earlier we see that there is a very strong, positive and significant interaction effect between the tertiary years of education and proximity to the frontier. By contrast the years of primary/secondary have a negative interaction with the proximity to the frontier, implying that given the level of tertiary education more primary/secondary educated individuals are decreasingly contributing to growth when a country approaches the frontier. However this effect is not significant. These two results are consistent with our theoretical analysis and offer support to our implication (P1). Almost all OECD countries benefit from tertiary education according to the BL data since the threshold above which tertiary education has a growth-enhancing effect is at 30% below the frontier.[23] The results for the DD data set are again in broad agreement to those obtained based on the BL data.

[23] In assessing the impact of education on growth, it is important ot remember that the primary/secondary education level is 10 to 20 times larger than the tertiary one.

TABLE IVa
TFP GROWTH EQUATION (YEARS I BL)

	[1]	[2]	[3]	[4]	[5]	[6]
Proximity	-0.079	-0.248	-0.072	-0.42	-0.225	-0.09
	(.075)	(.148)	(.17)	(.26)	(12)*	(.2)
YearsPS	0.0013	0.003	-0.0012	0.02	-0.004	-0.029
	(.007)	(.044)	(.015)	(.05)	(.015)	(.02)
YearsPS post1985	-	-	-	-	-	0.015
						(.012)
YearsT	-0.018	0.138	0.087	0.11	0.183	0.418
	(.035)	(.13)	(.075)	(.18)	(.11)	(.18)**
YearsT post1985	-	-	-	-	-	-0.113
						(.124)
Proximity*YearsPS	-	-	-0.029	0.017	-0.026	-0.053
			(.035)	(.043)	(.03)	(.045)
Prox*yearsPS post1985	-	-	-	-	-	-0.039
						(.038)
Proximity*YearsT	-	-	0.5	0.265	0.61	1.2
			(.2)**	(.41)	(.28)**	(.58)*
Prox*YearsT post1985	-	-	-	-		-0.167
						(.5)
Country dummies	No	Yes	No	Yes	Groups	Groups
Proximity threshold	-	-	-0.174	-0.415	-0.300	-0.348
			(.09)	(.79)	(.05)	(.046)
Threshold post 1985	-	-	-	-	-	-0.295
						(.06)
Rank Test (p value)	-	-	-	21%	-	-
Number of observations	122	122	122	122	122	122

Note : standard errors in parentheses. Time dummies not reportes. In columns [5] and [6], countries are grouped in the following way:
Group 1: Belgium, France, Italy, Netherlands; Group2: The four Scandinavian countries, Austria, UK, Switzerland; Group3: Canada, US;
Group 4: Australia, New Zealand; Group 5: Portugal, Spain; Group 6: Greece; Group 7: Ireland.
Proximity is the log ratio of a country's tfp to the technological frontier's tfp (hence it is a negative number).
Proximity threshold indicates the value of Proximity above which Fraction is growth-enhancing. One, two and three * indicate significance at the 10, 5 and 1% level respectively.

In the final column of Table IVa we consider our implication (P2) and attempt to test whether the occurrence of the IT revolution had any impact on the relationship between education and growth. To achieve this we interact all our education variables and their interaction with the proximity to the frontier with a post 1985 dummy. We also include corresponding interactions with this time dummy in the instrument set[24].

One sees that before 1985 there was a very strong frontier effect and that higher education had a growth enhancing impact above a proximity threshold at 35% below the frontier. However, after 1985 the strength of the frontier effect declined in both BL and DD, although the estimates of this decline are

[24] The instruments now include the proximity lagged two periods, the log of expenditure on primary/secondary education lagged two periods, the log of expenditure on tertiary education lagged two periods, the interaction of the first and second instruments, the interaction of the first and third instruments, plus these last four instruments times a post-1985 dummy. In total, we therefore have 9 instruments.

imprecise. In any case, the frontier effect before 1985 is about twice as strong as that measured for the average of the sample period. Qualitatively similar results obtain if we look for a break in 1980 or 1990. This finding is compatible with an increase in the relative elasticity of skilled labor in innovation as shown in our Proposition 2.

The evidence presented in this subsection offers strong empirical support to our theoretical implication (P1): holding unskilled human capital constant, skilled human capital has a higher growth-enhancing effect closer to the technological frontier.

TABLE IVb
TFP GROWTH EQUATION (YEARS I DD)

	[1]	[2]	[3]	[4]	[5]	[6]
Proximity	-0.08	-0.21	0.2	-0.31	-0.14	-0.25
	(.06)	(.14)	(.12)	(.34)	(.12)	(.11)**
YearsPS	-0.0021	0.004	-0.019	0.04	-0.0086	-0.003
	(.005)	(.12)	(.006)**	(.14)	(.007)	(.0086)
YearsPS post1985	-	-	-	-	-	-0.01
						(.007)
YearsT	0.007	0.11	0.135	0.17	0.19	0.296
	(.022)	(.18)	(.021)***	(.18)	(.08)**	(.093)***
YearsT post1985	-	-	-	-	-	-0.09
						(.095)
Prox*YearsPS	-	-	-0.065	-0.001	-0.022	-0.024
			(.015)***	(.075)	(.019)	(.024)
Prox*YearsPS post1985	-	-	-	-	-	0.015
						(.042)
Prox*YearsT	-	-	0.623	0.4	0.53	1.08
			(.12)***	(.85)	(.2)**	(.38)**
Prox*YearsT post1985	-	-	-	-		-0.74
						(.57)
Country dummies	No	Yes	No	Yes	Groups	Groups
Proximity threshold	-	-	-0.217	-0.425	-0.358	-0.274
			(.032)	(.79)	(.16)	(.052)
Threshold post 1985	-	-	-	-	-	-0.606
						(.43)
Rank Test (p value)	-	-	-	28%	-	-
Number of observations	118	118	118	118	118	118

Note : standard errors in parentheses. Time dummies not reportes. In columns [5] and [6], countries are grouped in the following way:
Group 1: Belgium, France, Italy, Netherlands; Group2: The four Scandinavian countries, Austria, UK, Switzerland; Group3: Canada, US;
Group 4: Australia, New Zealand; Group 5: Portugal, Spain; Group 6: Greece; Group 7: Ireland.
Proximity is the log ratio of a country's tfp to the technological frontier's tfp (hence it is a negative number).
Proximity threshold indicates the value of Proximity above which Fraction is growth-enhancing. One, two and three * indicate significance at the 10, 5 and 1% level respectively.

4 Robustness of the empirical results

We now check the robustness of our empirical results in two directions. First, we show that a specification using different skilled and unskilled capital stocks based on an alternative possible definition of skilled labor still yields support to our implications (P1) and (P2). Second, we show that the association we find between skilled human capital and growth, especially close to the technological frontier is not due to a higher rate of human capital accumulation in countries richly endowed with skilled human capital.

4.1 Alternative definition of skilled and unskilled labor

An alternative possibility to define mean years of skilled and unskilled education would be to consider that all years of education of a skilled individual should count as skilled units of labor. In a sense, this specification (which we call Years II) is intermediate between our preferred years specification (called Year I) presented above and the fractions specification. It is more extreme because it implies that one year of higher education is enough to transform 12 years of 'unskilled' education into 12 years of 'skilled' education. To proceed, we define the following variables from the BL data:

$$YearsS \equiv p_6 \sum_{j=0}^{6} n_j + p_7 \sum_{j=0}^{7} n_j$$

and

$$YearsU \equiv \sum_{i=1}^{5} \left(\sum_{j=1}^{i} n_j \right) p_i$$

where again p_i is the fraction of the population in category of schooling attainment i and n_i is the number of extra years of education which an individual in category i has accumulated over an individual in category $(i-1)$. The variable $YearsS$ (resp. $YearsU$) represents the number of years of skilled (resp. unskilled) education of the average adult in the population. With these assumptions, a college graduate contributes 16 years to $YearsS$ and 0 years to $YearsU$. We again construct similar variables from the DD data.

TABLE Va
TFP GROWTH EQUATION (YEARS II BL)

	[1]	[2]	[3]	[4]	[5]	[6]
Proximity	-0.08	-0.23	-0.11	-0.41	-0.22	-0.008
	(.076)	(.17)	(.13)	(.28)	(.13)	(.23)
YearsU	0.0012	-0.0005	0.0008	0.018	-0.005	-0.037
	(.007)	(.046)	(.01)	(.055)	(.01)	(.024)
YearsU post1985	-	-	-	-	-	0.015
						(.011)
YearsS	-0.0022	0.028	0.015	0.037	0.034	0.069
	(.007)	(.036)	(.007)*	(.027)	(.014)**	(.035)*
YearsS post1985	-	-	-	-	-	-0.009
						(.022)
Prox*YearsU	-	-	-0.02	0.018	-0.028	-0.07
			(.03)	(.04)	(.03)	(.055)
Prox*YearsU post1985	-	-	-	-	-	-0.043
						(.042)
Prox*YearsS	-	-	0.067	0.063	0.11	0.256
			(.019)***	(.06)	(.04)**	(.127)*
Prox*YearsS post1985	-	-	-	-	-	-0.096
						(.098)
Country dummies	No	Yes	No	Yes	Groups	Groups
Proximity threshold	-	-	-0.224	-0.587	-0.309	-0.270
			(.065)	(.63)	(.2)	(.037)
Threshold post 1985	-	-	-	-	-	-0.375
						(.034)
Number of observations	122	122	122	122	122	122

Note : standard errors in parentheses. Time dummies not reportes. In columns [5] and [6], countries are grouped in the following way:
Group 1: Belgium, France, Italy, Netherlands; Group2: The four Scandinavian countries, Austria, UK, Switzerland; Group3: Canada, US;
Group 4: Australia, New Zealand; Group 5: Portugal, Spain; Group 6: Greece; Group 7: Ireland.
Proximity is the log ratio of a country's tfp to the technological frontier's tfp (hence it is a negative number).
Proximity threshold indicates the value of Proximity above which Fraction is growth-enhancing. One, two and three * indicate significance at the 10, 5 and 1% level respectively.

Results are broadly similar to those obtained in our preferred specification. The only noticeable difference is that coefficients on tertiary education are now much smaller, reflecting the fact that the impact of a marginal individual on the skilled human capital stock is about seven times larger (his contribution is indeed 14 years instead of 2).

We still do not observe any significant effect of education in a pure level regression (see columns [1] and [2] of Tables Va-b). The estimate for $YearsS$ is large but not significant in a regression with country dummies. When introducing interaction terms between education and proximity to the frontier (see column [5]) we find again a significant positive frontier effect for skilled human capital, and a negative one for unskilled human capital. The frontier effect (i.e. the positive slope) is a little larger in BL than in DD. Finally, there is again some evidence that the frontier effect was stronger before 1985 than after in both datasets.

TABLE Vb
TFP GROWTH EQUATION (YEARS II DD)

	[1]	[2]	[3]	[4]	[5]	[6]
Proximity	-0.078	-0.21	0.22	-0.31	-0.06	-0.12
	(.06)	(.15)	(.15)	(.36)	(.12)	(.1)
YearsU	-0.002	0.026	-0.019	0.04	-0.015	-0.0168
	(.005)	(.13)	(.007)**	(.13)	(.0065)**	(.007)**
YearsU post1985	-	-	-	-	-	-0.01
						(.008)
YearsS	-0.0012	0.055	0.014	0.0686	0.032	0.068
	(.006)	(.14)	(.006)**	(13)	(.0127)**	(.02)***
YearsS post1985	-	-	-	-	-	-0.017
						(.017)
Prox*YearsU	-	-	-0.069	0.0016	-0.035	-0.04
			(.017)***	(.064)	(.019)*	(.023)
Prox*YearsU post1985	-	-	-	-	-	-0.018
						(.035)
Prox*YearsS	-	-	0.08	0.06	0.088	0.23
			(.024)***	(.22)	(.029)***	(.075)***
Prox*YearsS post1985	-	-	-	-	-	-0.126
						(.08)
Country dummies	No	Yes	No	Yes	Groups	Groups
Threshold	-	-	-0.175	-	-0.364	-0.296
			(.06)	-	(.19)	(.046)
Threshold post 1985	-	-	-	-	-	-0.490
						(.1)
Number of observations	118	118	118	118	118	118

Note : standard errors in parentheses. Time dummies not reportes. In columns [5] and [6], countries are grouped in the following way:
Group 1: Belgium, France, Italy, Netherlands; Group2: The four Scandinavian countries, Austria, UK, Switzerland; Group3: Canada, US;
Group 4: Australia, New Zealand; Group 5: Portugal, Spain; Group 6: Greece; Group 7: Ireland.
Proximity is the log ratio of a country's tfp to the technological frontier's tfp (hence it is a negative number).
Proximity threshold indicates the value of Proximity above which Fraction is growth-enhancing. One, two and three * indicate significance at the 10, 5 and 1% level respectively.

4.2 Accumulation and Level of Human Capital

Our specification in years (15) excluded human capital accumulation as a right hand side variable. We were forced to make this choice for lack of a proper instrument for this variable. One might argue however that the initial level of education could be positively related to subsequent accumulation of human capital and therefore to total factor productivity growth. This could arise for instance if the initial level of education served as a proxy for the capacity of the education system.

To check that our main result is not driven by this phenomenon, we report in Table VI the outcome of the following IV regression[25]:

$$\begin{aligned}\Delta n_{j,t} &= \gamma_{0,j} + \gamma_1 a_{j,t-1} + \gamma_2 YearsPS_{j,t-1} + \gamma_3 YearsT_{j,t-1} \\ &\quad + \beta_4 a_{j,t-1} * YearsPS_{j,t-1} + \beta_5 a_{j,t-1} * YearsT_{j,t-1} + \epsilon^{''}_{j,t}\end{aligned}$$

where $\Delta n_{j,t} \equiv (YearsPS_{j,t} + YearsT_{j,t} - YearsPS_{j,t-1} - YearsT_{j,t-1})$ is the accumulation of years of education of the average adult between $t-1$ and t. We also include time dummies and group of country dummies. We use the same instruments as in Section 3.2. The first column reports results obtained with the BL data, and the second results obtained with DD. Inspection of the regression outcomes reveals no significant effect[26] and we conclude that accumulation is unlikely to be the driver of our main result.

[25] We allow again for cluster effects by country.

[26] A test of joint significance of the four education variables returns a p-value of 77% for BL data, a marginal 4% for DD data.

TABLE VI
ACCUMULATION EQUATION (YEARS)

	BL	DD
Proximity	0.42	0.97
	(1.7)	(.58)
YearsPS	-0.016	-0.075
	(.178)	(.047)
YearsT	0.158	0.14
	(.9)	(.32)
Proximity*YearsPS	-0.13	-0.076
	(.27)	(.08)
Proximity*yearsT	0.41	-0.615
	(1.8)	(.81)
Country dummies	Groups	Groups
Number of observations	122	99

Note: standard errors in parentheses. Time and group of country dummies not reported.
One, two and three * indicate significance at the 10, 5 and 1% level respectively.

5 Conclusion

Technological progress is a dual phenomenon which makes a different use of labor inputs at different levels of development. Far from the technological frontier, imitation of technologies is the main engine of total factor productivity growth. As a country gets closer to the frontier, it relies more and more on innovation, which implies reallocating labor from one activity to the other. Using an endogenous growth model, we demonstrate that this reallocation process can create a complementarity between skilled labor and proximity to the frontier. We use this theoretical insight to revisit the empirical relationship between schooling level and growth in rich countries, which previous research had found to be slightly negative. Using a panel of 19 OECD countries between 1960 and 2000, we obtain two main results. First, the growth-enhancing margin in OECD countries is that of *skilled* human capital rather than that of total human capital. Second, skilled human capital has a stronger growth-enhancing effect in economies which are closer to the technological frontier.

Our model is stylized and could be enriched in several dimensions. First, we have taken the skill composition of the labor force to be exogenous. A further step would be to endogeneize it by modeling explicitly schooling decisions and by allowing for cross-country migrations. The current research by Aghion-Boustan-Hoxby-Vandenbussche (2004) on Education, Migration, and Growth across US states, is a first attempt in that direction[27]. Our empirical estimates in this paper can be used to derive policy prescriptions on the optimal composition of education spending in developed countries[28], however endogenizing educational achievement would make this objective more rigorously reachable. Second, for simplicity we abstracted from international trade considerations. Developing a dynamic Ricardian model around the core idea presented in this paper would make it possible to study cross-sectoral allocation of skilled and unskilled labor in a context of international specialization. Such analysis would certainly yield further insights on the relationship between distance to frontier, composition of human capital and economic growth.

6 Appendix 1: An extension of the model

In Section 2, we assume that productivity improvements result from the addition of two separate components, imitation and innovation. This specification bears the underlying assumption of the activities being perfect substitutes. Yet, one might think that technological progress necessitates a combination of imitation

[27] Focusing on the US States, that paper is able to both use a finer set of instruments and construct more precise measures of educational achievement.

[28] See for example Sapir (2003), which builds on the present paper to argue that EU countries should invest more in higher education in order to reduce the productivity growth deficit vis-à-vis the US. Currently, EU countries invest 1.1% of their GDP in higher education, compared to 3% in the US.

and innovation, i.e. that these activities are not perfect substitutes. In this appendix, we show first that for an elasticity of substitution strictly smaller than one the solution to the problem is always interior for $0 < a < 1$. Second, we show by means of a numerical simulation that for an elasticity of substitution sufficiently close to one, Proposition 1 still holds.

We now contemplate the more general productivity growth function:

$$A_{i,t} = A_{i,t-1} + \lambda[({u_{m,i,t}}^{\sigma} s_{m,i,t}^{1-\sigma})^{\rho}(\bar{A}_{t-1} - A_{t-1})^{\rho} + \gamma(u_{n,i,t}^{\phi} s_{n,i,t}^{1-\phi})^{\rho} A_{t-1}^{\rho}]^{1/\rho} \quad (16)$$

where $\rho \in [0, 1]$ measures the substitutability between imitation and innovation activities in generating productivity growth and other variables and parameters are the same as in (3).

First order conditions are now:

$$\sigma s_m^{\rho(1-\sigma)}(1-a)^{\rho} u_m^{\sigma\rho-1} = \gamma\phi s_n^{\rho(1-\phi)} a^{\rho} u_n^{\phi\rho-1} \quad (17)$$

and

$$(1-\sigma)u_m^{\rho\sigma}(1-a)^{\rho} s_m^{(1-\sigma)\rho-1} = \gamma(1-\phi)u_n^{\rho\phi} a^{\rho} s_n^{(1-\phi)\rho-1} \quad (18)$$

Dividing across equations, we find again (6), and so:

$$\psi\frac{u_n}{s_n} = \frac{u_m}{s_m}$$

and

$$u_m = \frac{\psi U s_m}{S + (\psi - 1)s_m}$$

Replacing in (17), we get:

$$[\frac{\sigma(1-a)^{\rho}}{\phi a^{\rho}}\psi^{\sigma\rho-1}U^{\rho(\sigma-\phi)}]^{\frac{1}{\rho-1}} s_m[S + (\psi-1)s_m]^{\frac{\rho}{1-\rho}(\sigma-\rho)} = S - s_m$$

This equation makes it clear that when $\rho < 1$, we can rule out corner solutions. Indeed as s_m goes to zero, the left hand side goes to zero, while the right hand side goes to S. Conversely, when s_m goes to S, the right hand side goes to zero while the left hand side does not. This guaranties that if a solution exists, it has to be an interior solution.

The above equation cannot be solved analytically. However, whenever $\frac{\rho}{1-\rho}(\sigma-\rho)$ is a strictly positive integer, i.e. for $\rho = \frac{N}{N+\sigma-\phi}$ (where $N \in \mathbb{N}^{+}$), it is a polynomial equation, thus allowing the application of numerical simulation. We do so for the arbitrary vector of parameters $(\lambda, \gamma, \sigma, \phi, N, U) = (1, 1, .8, .2, 2, 1)$. This choice of parameters is without loss of generality. Figure 2a plots the growth rate as a function of proximity to the frontier on the horizontal axis (we let proximity vary between .4 and .98) and the stock of skilled human capital on the vertical axis (we let it vary between 0.02 and .9). Figure 2b plots the derivative of the growth rate with respect to proximity, and Figure 2c the cross-derivative of the growth rate with respect to proximity and skilled human capital. On this last figure, the black (resp. white) area represents the domain where the cross-derivative is positive (resp. negative) and we observe that in the domain close to the frontier, Proposition 1 indeed holds.

FIGURE 2a: GROWTH RATE

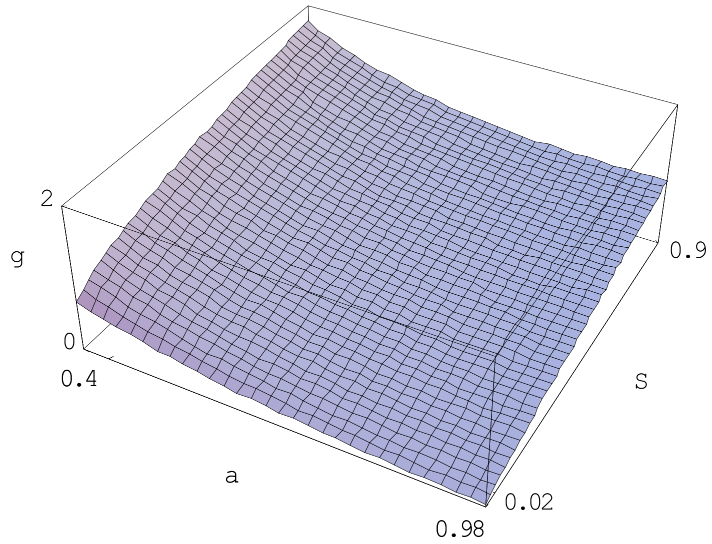


FIGURE 2b: $\frac{dg}{da}$

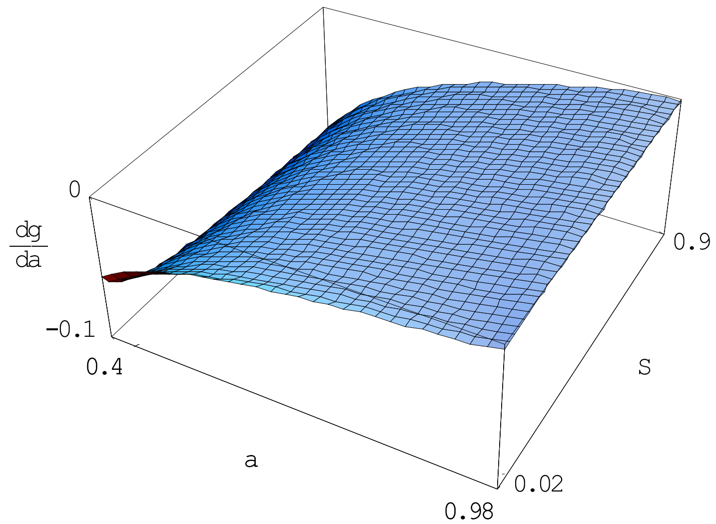
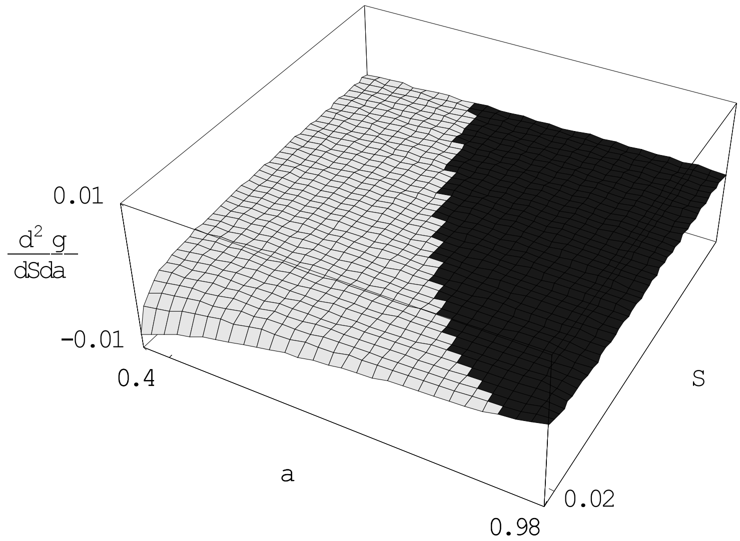


FIGURE 2c: $\frac{d^2 g}{dSda}$



7 Appendix 2: Additional Tables

TABLE A2a
REDUCED FORM (YEARS I BL)

	Proximity	YearsPS	YearsT	Prox*YPS	Prox*YT
Lagged proximity	0.1	5.7	0.59	-7.7	-0.34
	(.33)	(4.8)	(.56)	(2.6)***	(.21)
Lagged PS-exp./capita	0.091	-0.98	-0.26	1.35	0.08
	(.06)	(.9)	(.13)*	(.54)**	(.048)
Lagged T-exp./capita	-0.1	0.77	0.12	-0.89	-0.019
	(.029)***	(.5)	(.07)	(.27)***	(.023)
Lagged Prox*PS-exp/capita	0.25	-1.1	-0.27	3.1	0.067
	(.1)**	(1.7)	(.21)	(.76)***	(.07)
Lagged Prox*T-exp/capita	-0.24	0.66	0.29	-1.7	0.017
	(.06)***	(1)	(.18)**	(.52)***	(.054)
R2	0.95	0.91	0.94	0.89	0.87
Number of observations	122	122	122	122	122

Note: standard errors in parentheses. Time and country dummies not reported. All independent variables are in logs. Expenditures are in dollars.
A test for the joint significance of country dummies yields a p-value of 0. The same is true for time dummies.
One, two and three * indicate significance at the 10, 5 and 1% level respectively.

TABLE A2b
REDUCED FORM (YEARS I DD)

	Proximity	YearsPS	YearsT	Prox*YPS	Prox*YT
Lagged Proximity	0.1	-1.49	0.94	-5.5	-0.44
	(.33)	(3.55)	(.81)	(3.8)	(.3)
Lagged PS-exp./capita	0.091	0.39	-0.37	1.3	0.1
	(.06)	(.72)	(.175)**	(.75)*	(.067)
Lagged T-exp./capita	-0.1	-0.01	0.21	-0.92	-0.045
	(.029)***	(.36)	(.11)*	(.38)**	(.031)
Lagged Prox*PS-exp/capita	0.25	0.67	-0.51	3.3	0.14
	(.1)**	(1.04)	(.3)	(1.2)**	(.1)
Lagged Prox*T-exp./capita	-0.24	-0.49	0.53	-2.15	-0.06
	(.06)***	(.64)	(.23)**	(.83)**	(.08)
R2	0.95	0.99	0.96	0.9	0.88
Number of observations	118	118	118	118	118

Note: standard errors in parentheses. Time and country dummies not reported. All independent variables are in logs.
A test for the joint significance of country dummies yields a p-value of 0. The same is true for time dummies.
One, two and three * indicate significance at the 10, 5 and 1% level respectively.

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