Do we need top PISA scores for innovation and growth?[1]

Martin Zagler and Cristiana Zanzottera[2]

1 Introduction

In recent years it has become more and more clear that education, knowledge and human capital constitute a key element of modern economies both from an individual and from an aggregate point of view.

Developed economies have to concentrate on skill intensive industries in order to defend their leading position in the world economy. In this context information and knowledge are the crucial inputs and outputs of nearly all economic processes and subsequently economic growth.

The available empirical evidence suggests that the importance of human capital as an input has grown over time as production processes have become increasingly knowledge intensive. Knowledge is in fact replacing physical capital as the main engine of economic growth. Today, relatively few occupations involve only mechanical or physical tasks and a large and growing fraction of jobs are related to the processing of information or require the application of specialized knowledge and skills to the production of increasingly sophisticated goods and services. In particular in research and development activities (R & D) more and more

[1] The authors would like to thank the participants of the "Knowledge Economy Conference" in Reutlingen, in particular Maurizio Baussola, and Klaus Vondra for helpful comments.

[2] Correspondence: Martin Zagler, Wirtschaftsuniversität Wien, Augasse 2-6, A-1090 Vienna, Austria. Homepage: http://www.wu-wien.ac.at/inst/vw1/zagler Email: martin.zagler@wu-wien.ac.at

knowledge is applied, and depends on formal scientific results. These R & D activities are therefore increasingly skill intensive.

Employees with greater problem-solving and communications abilities should perform better than their less skilled counterparts at any task that requires more than the routine application of physical labor. Moreover these highly skilled workers should also learn faster, should be able to operate more sophisticated technologies that place greater demands on their capacities and can be expected to be more productive than unskilled workers for any given production process. A more educated labor force will also be able to achieve faster productivity growth acting as innovators on the market both through gradual improvements in existing production processes and through the adoption and development of more advanced technologies. The latter effect should be significant in the most qualified segment of the skill distribution, that is among the best students, who will most likely go on to become innovators.

There exists a vast literature on the role of education both from a microeconomic and from a macroeconomic point of view. The microeconomic analysis, on the one hand, has been merely concentrated on the estimation of private returns to investments in education; on the other hand the macroeconomic analysis has typically considered the relation between education and growth.

The microeconomic analysis on the private returns of education dates back to the late 1950s. In more than 40 years of research many surveys have been written in order to establish general patterns. The micro labor literature has produced several estimates of the monetary return to education considering that variability in workers schooling attainment was generated by some exogenous force (like for example peculiarities in compulsory schooling laws). Results of the empirical research have shown that the rate of return to education varies significantly in response to various influencing factors, however the average estimate of this rate for developed economies generally ranges from 5% to 10% (Wilson, 2001).

The macroeconomic research on education and growth on the other hand has generally investigated whether the level of schooling in a cross section of countries is related to the countries level of GDP growth rate. There appears to be no consensus on the role of education in the explanation of economic growth, and few authors find a significant contribution of human capital for economic growth. These difficulties of empirical estimations are mainly due to the poor quality of data existing on education, even for the OECD countries.

Both in the micro and in the macro literature empirical tests using human capital have been generally measured “quantitatively” using other a stock variable, such as the average years of education or a flow variable as the school enrollment rate. The use of years of schooling or other quantitative measures for education is widespread as these variables are easily available and collected by most of the countries. It is however widely recognized that school attainment or school enrollment will be at best an imperfect proxy for the true stock of human capital and that this generates a measurement error problem that will cause the statistical results of empirical tests to understate the strength of the connection between human capital and wages or productivity.

So far in fact much of the research in the micro and macroeconomics of education has focused just on school attainment with no consideration of quality differences or of other sources of learning as per example influence of the family environment. The use of these quantitative measures for education however ignores some important “qualitative” aspects: a year of schooling in a school located in a developing country is not the same in terms of “quality” as a year of schooling in a school located in a developed country. It is nowadays well acknowledge that the amount of human capital created by one year of schooling depends largely on the quality of the educational system in which it takes place, on the efficiency of the education system, on the quality of teaching and on the quality of the educational infrastructure.

Moreover the formation of knowledge of an individual derives not only from years one has spent in schooling but also from the contribution of families, peers, and others environmental elements. On the contrary, the use of years of schooling as a measure for knowledge implicitly assumes that all skills and human capital formation of an individual come from formal schooling. That is why, when estimating the effect of education on economic growth, it is really important to measure properly how much students have learned while in school, rather than to count how long students have sat in school.

When all these above mentioned aspects are not considered, relevant distortions in the understanding of the relationship between education and economic outcomes arise. First, important differences between education and skills on the one hand and individual earnings on the other hand are not outlined. Second, the interpersonal distribution of incomes across societies is not well understood. Third, an important element of the effect of education and the accumulation of knowledge on economic growth is missed.

In the light of the above mentioned considerations, the majority of the existing literature on education and growth has two important limitations: it only provides precise quantitative estimates of some of the benefits from human capital and it has relied almost exclusively on measures of the quantity of formal schooling ignoring the measurement of the skill and competencies of the individual that are the important variable in affecting productivity and growth.

Recently however a literature has emerged that suggests that the quality of education may be just as important for productivity as its quantity (see Hanushek and Wößmann, 2007). We agree with this point of view and, in developing our paper we have take into account all the aspects above mentioned, in an attempt to specify a growth regression in which human capital is measured by quality, in particular the average score reached by the best students in certain specific subjects as stated in the OECD PISA survey. The use of the score reached by students gives a magnitude of the cognitive knowledge of the individuals that affects the development and the economic growth.

We think that the contribution of our paper, with respect to the recent existing literature using a quality measure for education, is that we use not only the average scores of the students but also the score of the best 5% of the student population in order to understand whether it is the performance of the best students that boost the economic results and not only the average performance, as suggested by the above presented argument that the best students will contribute to the innovation process.

We give empirical evidence, to our knowledge so far unexploited, for theories of innovation and growth suggesting that it is the skill level of the excellent students that matter for economic growth. We agree on the fact that economic growth needs innovators, and innovators are generally the more skilled persons in the society, i.e. the individuals that reached higher scores when tested for their cognitive skills.

The paper will be structured as follows: first we will assess the micro- and macroeconomic theoretical framework of the economics of education. Then we review the existing empirical work analyzing the relationship between education or knowledge and wages, productivity and growth. We then present our theoretical hypotheses and empirical evidence. We conclude with some policy indications.

2 Theory on education

Today it is well understood that education and human capital play a crucial role for the welfare of countries and the performance of their economies, especially in advanced countries with their increasingly knowledge-based economies.

Previously economists considered education as a merely consumption good i.e. a good that is consumed by individuals like any other good and that does not enter in a production transforming process. It was considered that individuals receive education only for their personal utility and choose to invest in subjects they like and not on subjects that could enter in an efficient way in production function of a firm. Education was then not considered a saleable good. This evidence was also a worrying matters for Adam Smith, who asked to "…have those public endowments directed the course of education towards objects more useful, both to the individual and to the public, than those to which it would naturally have gone of its own accord?".

Neither Malthus nor the neoclassical approach to growth pays much attention to human capital in specifying their production function. Traditional neoclassical models in fact focused almost exclusively on the accumulation of physical capital (equipment and structures) rather then considering also education as a relevant factor in a production process.

Only the advent of the human capital theoretical models has attributed increasing importance to the accumulation of human capital and productive knowledge and to the interaction between these two factors. Education, i.e. human capital, was not anymore considered as a mere consumption good but as part of a production process exactly as physical capital. The analysis of the demand for education, mainly driven by the human capital approach, has been pioneered by Gary Becker, Jacob Mincer and Theodore Schultz.

Human capital theory states that education may serve to enhance human capital. Education viewed as an investment yields powerful insights: the more one learns the more productive one can be (Becker, 1985).

2.1 Microeconomic theory

In human capital theory education is an investment of current resources, the opportunity cost of the time involved as well as any direct costs, in exchange for future returns.

The benchmark model for the development of the empirical estimation of these returns to education is the key relationship specified by Mincer (1974).

The typical human capital theory (Becker, 1964) assumes that the level of education is chosen to maximize expected present value of the stream of future incomes up to the retirement, considering the costs of education. From this specification derives the so called internal rate of return. So an individual would invest in years of schooling till when the internal rate of return is greater than the market rate of interest.

The empirical approximation of the human capital theoretical framework is the familiar functional form of the earnings equation known as the Mincerian equation. In this equation the earnings for an individual are a function of her schooling, her experience, a set of variables assumed to affect earnings and a disturbance term representing other forces which may not be explicitly measured, assumed independent of schooling and other variables. Mincer shows that, under certain conditions (i.e. no direct cost of education), the coefficient of the schooling variable can be considered the private financial return to schooling because it represents the proportionate effect on wages of an increment to schooling. This parameter is generally known as the Mincerian return to schooling (or the schooling wage premium or the gross return to schooling).

Within the human capital theory framework the microeconomic theory of the life cycle that analyzes the earning profile of individuals with different levels of education has been developed (McMahon, 1998; Mincer, 1997). These human capital models explain positive effects of years of education and training on earnings, employment and labor market participations. They also explain why earning growth against age but at a decreasing rate: for two groups high school leavers and graduates the spread of income should be very high among the young, narrow as the educated eventually graduate from college and then wide again (Mincer, 1997). These models have been used also to estimate a rate of return to education. The rate estimated is the one that equalizes the net present value of the costs of education to its benefits where the costs are the earnings forgone during the studies and the costs for necessary learning inputs and the benefits are the discounted earnings premia for those with educational qualifications over those without it.

Education and then human capital (the accumulation of education) depend however on an individual's ability or prior attainment. The life cycle models presented should be adjusted considering the selection for education of the more able. It yields a wage function that depends on ability and cognitive attainment (Moll, 1998).

The Mincerian earnings function, as above already said, is the general equation that specifies the individuals return of education however it does not permit distinction between supply and demand influences on education and earnings premia and does not analyze the effect of directed technological change on wage premia. This latter should be considered for the analysis and development of policy.

Acemoglu (1998) investigated the long run effect of the role of technologies and the changes in demand and supply of high skilled and low skilled workers. Starting from the evidence that in the United States the college wage premium has been increasing since 1979, the author has stated that this happened because of worker's skills and firm's production being complementary. The technologies can be used within more enterprises at low marginal costs, so if school enrollments increase, the number of highly skilled workers and subsequently the market for these technologies increases. An increase in the supply of high skilled workers will reduce in the short run their college wage premium; however, in the long run, an increase in the firm's demand for highly skilled workers due to the expansion of the markets using technologies will lead to an increase in the college wage premium. This long run effect suggests that the flexibility of highly skilled workers to new industrial technologies is important and that the economy's capital stock will affect the demand for highly educated labor. This directed technological change may also highlight the different human capital requirements across countries and then clarify the "brain drain" migration patterns.

Human capitalists often argue that, even if human capital framework is consistent with the empirical results, it does not capture the true direction of causality between knowledge and growth. The theory of signalling highlights for example that the education may only provide a signal to employers of the applicant's abilities and may not actually increase the productivity of the individual. From an individual point of view, whether education is only a screen other a productive factor, has no impact on the choice of educational investment: the individual will invest in schooling up to the point where the present value of additional education is equal to the cost of its acquisition. However at the individual level there could be different implications for the connection between schooling and growth: education in fact can be considered only as a normal consumption good and so, like any other consumption good, an increase in wealth will lead to an increase of the consumption of education. Increase incomes are associated with higher schooling attainment as the simple results of income effect. For example Bowles (1972) found that 52% of the variation in level of schooling can be explained by the family background variables. This reaffirms the theory that views education as consumption good: schoolings increase an individual's wealth only by the consumption value of the good, since it is a non saleable asset on the market.

Important critiques to the human capital models (even when is largely recognized their role for understanding the paths of earnings of individuals) are the following: they can be extended only under the assumption of specific conditions; they require that the wage is equal to the marginal product, an assumption which needs formal substantiation.

2.2 Microeconomic evidence

The hypothesis that human capital is a key determinant of productivity has been a central topic within the academic literature. At a microeconomic level labor economists have long analyzed the impact of schooling and skills on individual wages and other labor market outcomes.

The usual specification for the microeconomic test is a production function (typically the Mincerian wage regression described above) that relates wages to schooling. The use of wages as dependent variables is due to the fact that the wage is the most important consequence of higher levels of formal education and moreover the wage is often seen as reflecting marginal labor productivity implying that the link between formal schooling and wages can be used to analyze the productivity effects of formal schooling.

All authors have faced similar difficulties in correctly estimating the relationship between wages and schooling due to the fact that other elements (i.e. family background and ability) differentiate individuals with high and low levels of schooling. As these characteristics are difficult to measure, empirical tests try to identify the percentage increase in wages implied by additional formal education holding other observable characteristics (like family background and ability) constant. However, when these variables are omitted, the effect of formal schooling on wages can be overestimated. Another problem in estimating the percentage increase in wages implied by additional formal education is that individual schooling is often collected with error implying that least-squares results understate the effect of formal schooling on wages.

To solve the first of the above mentioned difficulties empirical economists have estimated the effect of schooling on wages using data on twins. This approach is because twins are more similar in many dimensions (as family background) than two randomly chosen individuals and there should be fewer problems in estimating the effect of formal schooling on wages using least-squares techniques that omit other relevant characteristics.

The second type of difficulties, i.e. the measurement error of schooling data, has been faced using non-standard statistical technique called instrumental-variable estimation. The instrumental variable approach implies the use of an additional variable, the instrument (usually i.e. institutional changes affecting school leaving age), that affects years of schooling but is not correlated with omitted determinants of wages or the measurement error of individual schooling. The estimation is developed in two steps: firstly is obtained an estimation of the effect of the instrument on schooling and secondly on wages, then the estimation of the effect of formal schooling on wages is obtained by dividing the latter by the former.

More in general all the contributions to the empirical literature have come to a common result: higher levels of education are accompanied by higher wages, lower unemployment probabilities, and higher labor force participation rates.

An important field of the microeconomic empirical research (that could be linked also to the macro economic results) regards the impact of technological change on the demand for human capital and on the wage differentials between low and high skilled workers.

A first theoretical hypothesis consider that highly educated workers have a comparative advantage in adjusting to new technologies and developing them, then the diffusion of these new technologies increase the demand for high human capital workers relative to low human capital workers. In case of mismatch between demand and supply for these skills (i.e. the demand for high skill workers is higher than the supply), the Mincerian return to schooling increases. Another theoretical hypothesis regarding the link between new technologies and demand for better educated workers considers that new technologies introduced in the last few decades are skill biased: firms, holding output and relative prices constant, increase the demand for human capital in the production process because the new technologies replace labour-intensive tasks and are complementary to high human capital workers.

Katz and Murphy (1992) have explained the empirical evidence on the educational wages differentials found for the United States in the 1970s and 1980s (i.e. a decrease of the return of schooling during the 1970s and an increase during the 1980s) starting from the basic idea that the increase in the supply of high human capital workers dominated demand growth during the 1970s, reducing the Mincerian return to schooling, and that on the contrary during the 1980s the increase in the demand for high human capital workers dominated supply growth, raising the schooling wage premium. Similar evidence has been found for Europe by Denny, Harmon and Lydon (2001) even if with a shift on time (i.e. in the 1970s and 1980s return to schooling decrease and started again to increase only in the 1990s).

On the analysis of development of new technologies and education, an interesting finding from Doms, Dunne and Troske (1997) shows that the presence of human capital is a prerequisite for the implementation of new technologies. The authors analyze a cross section of United States's plants in different points of time, and they conclude not only that better technologies are accompanied by a higher demand for human capital but also that the plants that adopt new technologies show higher proportion of high human capital workers even before the advent of the new technologies.

Together with the evidence on the positive impact of new technologies on the increasing demand for high skilled workers there are also some studies that examine the exact mechanisms that lead to this result at a firm level arguing that organizational change (the decentralization of authority, the delayering of managerial functions) plays a key role (e.g. Dunne, Haltiwanger and Troske, 1996; Machin and Van Reenen, 1998; Caroli and Van Reenen (1999)). In particular Caroli and Van Reenen (1999), using a panel of British and French plants, have found that these changes in organizational practice reduce the demand for low human capital workers and lead to greater productivity growth (especially in establishments with higher average levels of human capital).

Finally, other specifications of the empirical earnings equations take into consideration the direct cost of each year of schooling, differing from the Mincerian equation. Through this specification is it possible to measure: the private rate of return to education (that relates the resources invested by those obtaining education, i.e. the opportunity cost as well as direct cost of education); and the social rate of return to education (including the public cost of education in the estimation). Empirical evidence on Europe shows that the private return of a tertiary education for men in Europe is on average more than 12 %: UK has the highest data (17.3 %) and Italy the lowest (6.5 %). Social rates of return are generally somewhat lower than private (the social rate of return of a tertiary education for men is on average around 2 percentage points lower than the private).

2.3 Macroeconomic theory

Macroeconomists in general and growth theorists in particular have long considered the formation of human capital an important issue. It has come to the centre of attention with the emergence of endogenous growth theory, which delivered two hypotheses that explain changes in the capacity frontier of an economy.

Paul Romer found that given non decreasing returns to scale with respect to reproducible factors of production, the capital accumulation process needs not cease, hence an economy may grow without bounds (Romer, 1986).

Lucas (1988) proposed a production function with three arguments, human capital, labour, and the economies (or at least the industries) average stock of human capital. This technology exhibits constant returns to scale with respect to firm specific factors of production, namely human capital and labour, and with respect to reproducible factors of production, namely human capital and the average stock of human capital. As firms have an incentive to invest in human capital, they also augment the economy wide stock of human capital, thus they induce a non declining marginal product of human capital for any level of economic activity. Given an interest rate below the marginal product of human capital, the economy may grow without bound.

Both models assume a homogenous input (physical and human capital), which is against the intuition that more of the same knowledge can improve productivity, just like more of the same capital goods has beneficial spillovers to other producers, when it should be the variety and diversity of inputs that trigger these effects.

This evidently unpleasant characteristic of the above mentioned growth model triggered a second wave of endogenous growth models, due to Romer (1990), Grossman and Helpman (1991), and Aghion and Howitt (1992). Basically, all three variants operate through the same channel. Splitting the labour force into two groups, labelled workers and innovators for convenience, one group can produce an ever improved consumption good, whilst the other can permanently innovate new or better products or production processes, thus triggering a long-run permanent growth process.

These models differ in several ways from the first class of models. First, instead of human capital, they focus on research and development as the engine of growth. Second, instead of perfect competition, they are based on monopolistic competition, which enables providers of innovations and inventions with a possibility to receive a rent for the research and development efforts. Third, they no longer build upon non decreasing returns with respect to reproducible factors. Innovation is therefore individualized as the key engine to economic growth. It is our belief that these models downplay the role of human capital too much, as innovators certainly require a lot of specialized skills to become successful, skills which the will accumulate during the formative years in the educational process.

2.4 Macroeconomic evidence

Human capital is well acknowledged as relevant in the new growth theory developed in the recent years. The general theoretical framework for analysing the relationship between human capital and growth stated that individuals' knowledge and skills directly raise productivity and strengthen an economy's ability to develop and to adopt new technologies.

A simple empirical specification of this theoretical relation introduces the stock of human capital in the standard production function that relates aggregate output to the stocks of productive inputs, employment and physical capital, and to an index of technical efficiency or total factor productivity. The impact of education on growth so identified is known as *level effect*, having the stock of human capital a direct impact on the level of output.

Another alternative approach involves the inclusion of human capital as a determinant of the rate of technological progress through the specification of a technical progress function that may include as additional arguments variables related to R & D investment and the gap between each country and the world technological frontier. The impact of education on growth is here defined as *rate effect* because the human capital affects the growth rate of output through the total factor productivity.

The rich empirical evidence underlines that the contribution of human capital to aggregate productivity growth is important, although uncertainty remains about its exact magnitude, because of various econometric problems that complicate the interpretation of the empirical results. Different empirical analyses have in fact yield to different econometric results, and sometimes the "education" variable enters in the regressions with the "wrong" sign. A general explanation of the weakness of the results could be due to the poor quality of data used for the education variable.

Whatever is then the approach used, the empirical results suffer from noise due to the poor quality of data on education used, i.e. inconsistencies in the primary data used to construct the dataset on cross-country educational attainment. In general an underestimation of the human capital coefficient occurs, because the noise generates a mismatch between the variability of the stock of human capital and the level of productivity.

A general result is that, all other things being equal, an additional year of average school attainment increases the level of aggregate productivity by around 5 % on impact and by a further 5 % in the long run. This second effect reflects the contribution of human capital to technological progress, i.e. to the development and adoption of new technologies and to the continued improvement of existing production processes.

Numerous empirical papers have analysed the relation between growth and education defining specific ad hoc growth equations. In these growth equations have been introduced some indicators of human capital in a convergence equation in which the growth rate of real output over a given period is explained in terms of the initial level of income per capita and other variables motivated by informal theoretical considerations.

The independent variables used in these regressions include the initial level of per capita income, different indices of human capital at the beginning of the period and the rates of investment and population (or labour force) growth. Landau (1983), Baumol, Batey, Blackman, and Wolf (1989) and Barro (1991) find that the coefficient of initial human capital is positive and highly significant.

In all the papers cited above the introduction of a human capital variable is due to the need of capturing the impact of the rate of innovation and technology on the growth. Due to the lack of comparable data on the average educational attainment of the labour force for a sufficient number of countries, generally the authors use flow variables (enrolment rates) as proxies for the educational level. Although all of them use lagged enrolment rates, these could be highly correlated with investment in human capital over the sample period, not allowing for a clear discrimination *level and rate effects*. Kyriacou (1991) constructs an estimate of the average stock of human capital, i.e. the average years of schooling of the labour force, which he includes in convergence regressions with results qualitatively similar to those discussed above.

The results of the different studies using the ad hoc growth equation are generally supportive of the view that human capital has a positive effect on growth. The pattern of results for the schooling indicators (enrolment rate or average years of schooling) is generally consistent with the existence of some sort of positive growth effect and suggests also that an increase in educational attainment helps to speed up convergence between economies, for example by facilitating the adoption of foreign technologies.

Different contributions of Barro and Lee (1994) outlined that the average number of years of male secondary schooling enters the growth equation with a positive and significant coefficient. This variable behaves better than the corresponding flow variable: the secondary enrolment rate is not significant. Also the number of years of university education, which is added as a regressor in another equation is not significant. Most of these findings are replicated by Barro and Sala i Martin (1995). In their equation the change in the years of male secondary schooling is not significant but on the other hand there are indications that educational expenditure matters and that human capital fasts convergence.

The studies above mentioned have two types of problems: they do not allow disentangling of the *level* and the *rate effect* of education on growth and they show puzzling results about the growth effects of female schooling (i.e. the coefficient of female educational variables is often negative and sometimes significant).

An influential paper that has used a different approach from the one previously described is the one of Mankiw, Romer and Weil (1992). The authors have defined a structural convergence equation using cross-sectional data for the period 1960-1985. Their equation relates the log output per capita with the average rates of investment in physical and human capital over the relevant period, the rate of depreciation, which is assumed to be the same for both types of capital, the rate of technical progress and the rate of working-age population growth. The authors have found that average rates of investment in physical and human capital enter in the equation with the right positive sign. This paper was extremely influential, because with a simple extension of the standard neoclassical model (i.e. broadening of the relevant concept of capital in order to include the accumulated investment in education) they provide a satisfactory description of the process of growth and of the evolution of the regional (or national) income distribution.

The Mankiw, Romer and Weil (1992) paper was the starting point of a series of empirical studies (De la Fuente, 1998; Vasudeva and Chien, 1997) that have tried to test the robustness of the results using different econometric techniques and better data. All these studies lead to similar results on the relevance of human capital for growth.

However other studies have found different results when the outlier countries (i.e. the countries with greater residuals) are not included in the regression. The exclusion of these countries results in a non significant coefficient for human capital (Temple, 1998).

Moreover Hamilton and Monteagudo (1998) find that Mankiw, Romer and Weil schooling indicator loses its significance when their model is used to try to explain changes in growth performance across decades. Hamilton and Monteagudo re-estimate the Mankiw, Romer and Weil model in first differences (the difference between average values for 1960–70 and 1975–85) finding that the estimate of the schooling variable is actually negative.

A third group of papers has examined the growth effects of human capital through the estimation of aggregate production functions (Kyriacou, 1991; Benhabib and Spiegel, 1994). These authors estimate a Cobb-Douglas production function using a single cross-section of growth rates computed over a long period. Pritchett (1999) makes a similar exercise after constructing a 'Mincerian' stock of human capital using microeconometric estimates of the returns to schooling parameter and data from both Barro and Lee (1993) and Nehru, Swanson and Dubey (1995). These studies find that the coefficient of the human capital variable is either non-significant or negative also after a number of changes in the specification, such as the inclusion of regional dummies or initial income per capita to control for a technological catch-up effect.

In this context some interesting papers have analyzed the interaction between education and technological diffusion underlining the *rate effect* of human capital. They have found a positive *rate effect* that seems to work at least in part through the role of education in facilitating the absorption of foreign technologies. Following the work of Nelson and Phelps (1966) and Romer (1989), Kyriacou (1991) argues that the level of education should be included in a growth equation as a determinant of the rate of technological progress. Benhabib and Spiegel (1994) follow a similar approach and extend the model to allow for technological diffusion and rate effects from human capital finding that the log of the stock of human capital and the log of initial income per capita income, interpreted as a proxy for the initial level of technical efficiency, are both significant and have the expected signs (positive the first and negative the second).

All the papers above mentioned show different results on the impact of education on growth. A number of recent papers argue that the negative results found in the earlier literature reported above can be attributed to low data quality and the resulting measurement error bias. Some authors have then tried to construct ad hoc new datasets in order to obtain more consistent estimation. Krueger and Lindahl (2001) argue that Benhabib and Spiegel's (1994) failure to find significant level effects of the human capital variable can be attributed to the almost complete lack of signal in the schooling variable they use. De la Fuente and Doménech (2000, 2001), Cohen and Soto (2001) and Bassanini and Scarpetta (2001) have constructed new data sets that appear to have higher signal to noise ratios than those used in the earlier literature. These authors find clear evidence of level effects of the human capital variable. De la Fuente and Doménech examine the sensitivity of the results to the quality of the human capital data by re-estimating several specifications with three different data sets: their own, and those constructed by Barro and Lee (1996) and Nehru, Swanson and Dubey (1995). The pattern of results that emerges for the different human capital data sets is consistent with the authors' hypothesis about the importance of educational data quality for growth estimates.

An interesting evolution of the macroeconomic empirical evidence is related to some recent contribution of Vandenbussche, Aghion and Meghir (2004) and of Aghion, Boustan, Hoxby and Vandenbussche (2005) that encounter in a sense our hypothesis that human capital does not affect innovation and imitation uniformly, outlining that for growth, especially in developed countries, the average level of education of the population does not matter. Within this literature is considered important to have a certain percentage of population with a higher level education or better, a population with a high performance in cognitive skill, i.e. the so called innovators of a society. These authors claim that primary and secondary education produce imitators, whereas tertiary education produces innovators. This means that in countries that move towards the technological frontier the tertiary education should become more important for growth compared to primary and secondary education. Vandenbussche, Aghion and Meghir confront this prediction with cross-country panel evidence on higher education, distance to frontier and productivity growth. They use a panel dataset of 22 OECD Countries over the period 1960-2000 and run a regression relating a country's growth rate over a five year period with the country closeness to the technological frontier and the fraction of the working age population with some higher education. The authors find a statistically significant coefficient for the human capital variable and for the interaction variable between the distance to the technological frontier and the educational variable indicating that education matters more when a country is closer to the frontier. They tested also the impact of an additional year of schooling of higher education finding that it is more important to expand year of higher education close to the technological frontier.

The authors of the other paper, Aghion, Boustan, Hoxby and Vandenbussche (2005), test the same hypothesis on cross United States data instead of cross-country data. They take the fact that when using cross-region data the educational policy should affect migration across regions more than it affects migration across countries into account. They specify a regression that considers the impact of migration on the interaction between closeness to the technological frontier and higher education, finding that investing in higher education in a country that is far from the technological frontier would contribute to growth in countries near the frontier, as the newly skilled workers would emigrate to a frontier country where productivity and wages are higher.

A novel field of macroeconomic empirical research considers the educational quality rather than educational level (quantity of years of schooling) as the best proxy for the investment in human capital and for the analysis of its relation with growth.

These studies complement the standard schooling indicators with some measure of quality taking into account the fact that other variables, such as the quality of the national educational system, educational expenditures and determinants of school quality, or direct measures of skills, such as scores in standardised international achievement tests, have an impact on human capital accumulation.

Dessus (1999) argues that the impact on productivity of an additional year of schooling should vary across countries depending on the quality of the education system. He uses data covering the period 1960–90 for a sample of 83 countries to estimate a variant of the Mankiw, Romer and Weil model (written in terms of the stock of human capital) with fixed country effects and a varying parameter specification that makes the coefficient of human capital a function of some indicator of the average quality of schooling. The results of this paper are generally supportive of the view that human capital elasticities do indeed differ across countries and are responsive to expenditure variables.

Some studies have examined the correlation between growth performance and standardised achievement measures. A paper by Lee and Lee (1995) has used science scores from tests administered by the International Association for the Evaluation of Educational Achievement (IEA) in the early 1970s as a proxy for initial human capital. The correlation between test scores and growth rate of GDP per worker is positive and significant even when the authors control for alternative human capital indicators such as the primary or secondary enrolment rates or the average years of schooling of the adult population. Moreover all these latter variables tend to lose their significance when the score variable is included as a regressor.

Barro (2000) confirms Lee and Lee's findings on the significance of test scores but finds that, in some but not all specifications, years of schooling continue to be significant when both variables are entered simultaneously in the growth equation.

On the same line Hanushek and Kimko (2000) construct an indicator of labour force quality for a sample of 31 countries using their scores in a number of international achievement tests in mathematics and science. The indicator is then included as a regressor in a growth equation with results that are qualitatively similar to those of Lee and Lee (1995).

Hanuschek and Wößmann (2007) have recently analyzed the relation between education measured as the average country score and growth. They have constructed a dataset starting with a measure of the quality of education that is a simple average of the mathematics and science scores over all the international tests made so far. After controlling for the initial level of GDP per capita and for years of schooling, the test-score measure features a statistically significant effect on the growth in real GDP per capita in 1960-2000. According to this specification, test scores that are larger by one standard deviation (measured at the student level across all OECD countries in PISA) are associated with an average annual growth rate in GDP per capita that is two percentage points higher over the whole 40-year period.

Our paper extends the above cited recent empirical research. Our novel approach is to combine the idea of using a qualitative measure for education (see Dessus, 1999; Hanushek and Kimko, 2000) with the idea that what matters for growth is the educational level (measured in cognitive skills) of the higher educated and not the average level of education of the population (Vandenbussche, Aghion and Meghir, 2004). In this respect, this paper is a clear improvement of the literature.

3 Theoretical Considerations

Whilst the empirical literature has shown that there is little evidence for a quantitative channel from human capital accumulation to economic growth, we claim that there is an important indirect channel from human capital formation to innovation and further to economic growth. We argue that the key to economic growth are innovations. Innovations require innovators, a sound institutional setting, correct incentives for innovators and innovative firms, and a beneficial macroeconomic environment.

It has become common knowledge that economic growth, at least for countries at or close to the global technological frontier, can only prevail if innovations in products or production processes, that can generate more output with the some amount of resources, take place. Several aspects are important to generate innovations. One element certainly is innovators. These innovators are different from other economic agents not only by their ability to generate good ideas, but also by their willingness to bear risk and their devotion to provide effort. Whereas policy can do little about the creativity of innovators (except for education, as discussed below), it can do a lot to alter the incentives to bear risk and devote effort.

Whereas little can be done to create innovators, incentives can be set so that more people with the potential will actually pursue innovative activities. An important basis for innovation is certainly a sound educational base. However, most innovations are not the result of a sound general education, but result from very specialized education that very few universities can provide.

And clearly, we claim that the ability to innovate is correlated with the individual's skills. Whereas human capital theories suggest that it is the average skill level that determines economic growth, theories of innovation and growth suggest that it is the skill level of the excellent students that matter for economic growth. And this gives us a testable hypothesis which we will pursue in the following chapter.

4 Evidence

In the following, we present our empirical evidence on the theoretical considerations described above. After briefly discussing the methodology and the data we show the results from our econometrical exercise.

4.1 Methodology

In order to test our hypothesis, we have run conventional cross sectional growth equations with human capital variables as explanatory variables. The dependent variable is the average annual growth rate between 1960 and 2006 for a selection of 39 countries. We control for convergence by including the initial level of GDP in 1960 for all countries. We then test whether knowledge of best 5% of the student population, taken from OECD PISA test, can indeed explain economic growth. Significance of this regressor would imply that there is some evidence that a highly skilled group of innovators will make a difference for the innovative and growth capabilities of a country. These innovators may require a large group of qualified people to implement their innovations. Hanushek and Wößmann (2007) have used the number of individuals above a threshold level of test scores to control for this effect. We will follow their approach. Given that we only have the average test results for the median student and the 95% percentile student, we linearly approximate the quantity of students q above a test score of $s*$ (*Size* variable) by

$$q_i = 50 + 45(s_i^{95} - s*)/((s_i^{95} - s_i^{50}),$$

where s^{95} and s^{50} are the score of the median and 95 percentile, respectively[3]. This will give a quantitative measure of the size of the educated workforce. We set $s*$ at a score equal to the integer below the lowest 95 percentile score of the sample. This implies that the educated workforce will be at 5% for the country with the lowest 95 percentile score, and larger for all other countries. This is a rather strict definition for the educated workforce, but results do not change significantly if we reduce the threshold value for $s*$.

[3] Note that the inclusion of both the median and the 95 percentile score in our approximation of size impedes us from using the median score separately.

Finally, in order to control for the conventional measure of years of schooling we have included the average years of schooling y at age 15 and age 25 into the regression, both individually and as an interaction term with the size of the educated population. The latter should give a measure in the quantitative and qualitative dimension of the workforce. The regression therefore reads,

$$g = \alpha + \beta GDP_i^{60} + \gamma s_i^{95} + \delta q_i + \varepsilon y_i + u_i \,,$$

where u is a standard error term. We expect a positive sign on all variables except initial GDP, which should be negative according to the convergence hypothesis. Note that there is a well known endogeneity issue involved, as rich countries may be tempted to spend more on education. The literature agrees that this would be identified by a positive relation between the level of GDP and the years of schooling (Hanushek and Wößmann, 2007). We should therefore expect a different sign on β and ε. A negative or insignificant relation would be evidence that the endogeneity problem is not important.

4.2 The Data

In order to run the growth equation above specified we have, has already said, composed a dataset including variables for a selection of 39 countries for which the OECD PISA test 2003 scores on mathematic, problem solving and science were available.

The final dataset includes the following data: GDP in 1960 in purchasing power parities and the GDP growth rate 1960-2006 from the Ameco Database; average years of schooling from the Barro and Lee database on educational attainment; average scores in mathematics, problem solving and science from the OECD PISA test 2003; score of the 95 percentile student in mathematics, problem solving and science from the OECD PISA test 2003.

The GDP growth rate has been computed for all the countries included in the OECD PISA dataset using the series available from the Ameco Database.

The GDP initial level 1960 was available from the Ameco Database. When the series started from a later year than 1960 (i.e. for the Eastern

European Countries) we have calculated the initial GDP level discounting the first GDP value we had for the country using the average growth level for the OECD and non OECD Countries in the period 1960-2006.

We have collected and used data on average years of schooling from the Barro and Lee database on educational attainment for the population 15 years old and more and for the population 25 years old and more.

The use of a "qualitative" measure for the human capital variable, the OECD PISA score, is coherent with all the considerations above described in the introduction.

4.3 Results

We ran regressions for the economic growth rate per employee[4] using the 95 percentile PISA test scores for mathematics, problem solving and science separately, and applying three different specifications. We use initial GDP in 1960 in all specifications, to control for convergence. In the first and second specification, we include the size of the educated workforce. In the first specification, we include the traditional variable of years of schooling for the population above the age of 25, whereas in the second specification we use years of schooling for the population above the age of 15. The latter may be biased downwards as schooling may be continuing beyond the age of 15. This is a particularly a problem in our case, where we focus on excellent students, which may proceed for another 10 years in the educational system.

In the third specification, we interact the years of schooling of the population above 15 with the size of the educated workforce in order to obtain a measure of the quantitative and qualitative dimension of the workforce.

[4] Using economic growth per capita instead does not change the results in any significant manner, so we refrain from reporting the results here.

Table 1: The impact of top math scores on economic growth

	(1)	(2)	(3)
Initial GDP	**-0.010**	**-0.010**	**-0.011**
	(-3.59)	(-3.68)	(-3.99)
95 percentile (math)	**0.135**	**0.125**	**0.127**
	(2.58)	(2.35)	(2.32)
Size	-0.004	-0.005	
	(-1.12)	(-1.23)	
Years of schooling (25)	-0.008		
	(-0.71)		
Years of schooling (15)		-0.003	
		(-0.23)	
Size x Years (15)			-0.003
			(-1.21)
Constant	**-0.735**	**-0.681**	-0.700
	(-2.26)	(-2.06)	(-2.01)
R^2	34.8	34.0	33.6

Source: own estimations. All variables except for the growth rates are in logs. Values in parenthesis are t-statistics. Variables that are statistically significant at the 5% level are in bold.

The results reported in table 1 are quite remarkable. We obtain the usual coefficient for initial GDP, which is negative and significant, implying that the convergence hypothesis holds. We also get a significant measure for the 95 percentile PISA math test score, implying that excellent students in mathematics will foster economic growth, potentially through their innovative capacities. We find that a ten percent increase in the PISA test score of the 95 percentile will increase the growth rate of the economy by more than one percent. This implies that if we can improve education of the top 5 percent of the student population consistently by ten percent, we will have a GDP of 1.35 percent higher after a generation.

Surprisingly, the size of the educated workforce matters little for economic growth. The coefficient shows a negative sign, but it is statistically insignificant. This implies that innovators can reap the benefits of their skills irrespective of the workforce they are working with.

There is no significant impact of the years of schooling variables, which is due to the inclusion of PISA test scores in the regression. This implies that it is not the quantity of time students spend in school, but the quality of time that matters for economic growth consistently with our theoretical hypothesis and other empirical evidence above cited. Note that the estimated coefficient, though insignificant, even shows the opposite sign, implying that augmenting the years of schooling without improving the quality of education is counterproductive. Finally, we find no impact of the interaction term of the size of the educated workforce on economic growth.

Table 2: The impact of top problem solving scores on economic growth

	(4)	(5)	(6)
Initial GDP	**-0.010**	**-0.011**	**-0.011**
	(-3.73)	(-3.82)	(-4.17)
95 percentile (problem solving)	**0.147**	**0.137**	**0.123**
	(2.92)	(2.61)	(2.52)
Size	-0.005	-0.005	
	(-1.32)	(-1.43)	
Years of schooling (25)	-0.011		
	(-1.05)		
Years of schooling (15)		-0.008	
		(-0.57)	
Size x Years (15)			-0.003
			(-1.29)
Constant	**-0.803**	**-0.744**	**-0.665**
	(-2.60)	(-2.33)	(-2.18)
R^2	37.4	36.0	34.6

Source: own estimations. All variables except for the growth rates are in logs. Values in parenthesis are t-statistics. Variables that are statistically significant at the 5% level are in bold.

The results reported in table 2 for problem solving scores are similar to the ones obtained in table 1 when math scores are considered. The coefficient for initial GDP is negative (signalling once again that the convergence hypothesis holds) and of the same magnitude of the one found for math scores.

The impact of the 95 percentile PISA problem solving test score is still positive and significant. A ten percent increase in the PISA test score of the 95 percentile will increase the growth rate of the economy by almost 1.5 percent signalling also in this case that the best students are expected to be the future innovators of the economy.
Similar results as the one obtained in table 1 are found also regarding the impact of the size of the educated workforce (negative and non significant) and for the impact of the years of schooling (negative and non significant). Finally, we find again no impact of the interaction term of the size of the educated workforce on economic growth.

Table 3: The impact of top science scores on economic growth

	(7)	(8)	(9)
Initial GDP	**-0.009**	**-0.010**	**-0.010**
	(-3.46)	(-3.54)	(-3.96)
95 percentile (science)	**0.156**	**0.140**	**0.121**
	(2.64)	(2.32)	(2.18)
Size	-0.004	-0.005	
	(-1.03)	(-1.04)	
Years of schooling (25)	-0.012		
	(-1.08)		
Years of schooling (15)		-0.007	
		(-0.54)	
Size x Years (15)			-0.003
			(-0.88)
Constant	**-0.876**	**-0.775**	-0.668
	(-2.36)	(-2.07)	(-1.87)
R^2	35.8	34.2	33.0

Source: own estimations. All variables except for the growth rates are in logs. Values in parenthesis are t-statistics. Variables that are statistically significant at the 5% level are in bold.

The theoretical hypotheses are confirmed also through the results reported in table 3 when the science scores are considered and for all the three specification of the growth function adopted. The convergence hypothesis for the initial GDP also holds in this case. It is once again confirmed that the best educated students count in order to improve the growth of the economy. The PISA test score coefficient for science is the highest among the three scores tested. A ten percent increase in the PISA test score of the 95 percentile will increase the growth rate of the economy by more than 1.5 percent. Also in this case there is no significant impact of the years of schooling variable on the growth rate of the economy and of the size of the educated population. And once again the interaction term of the size of the educated workforce on economic growth does not have a significant impact.

5 Policy Recommendations

The results we have reviewed and found in this paper suggest that educational quality may be just as important as quantity, if not more so, as a determinant of productivity. This raises the policy question of what may be done to improve the quality of education systems. This requires an improvement in teaching techniques and curriculum design, accompanied by higher educational expenditure, as more resources may (but not necessarily will) translate into more and better teachers and into improved facilities.

More in details the above analysis gives way to several straightforward policy recommendations, particularly concerning education policy. It seems obvious to concentrate on the educational attainments of the most qualified students, and try to encourage them to contribute to the innovative capacity of the economy. In particular, countries should improve the basis for accumulation of human capital for scientific research. Since much of this capital derives from research itself, policy should strengthen the existing link between higher education and private and public research. Moreover, education and training should be extended to ensure that the technical and scientific personnel are available to allow new technologies to be developed and adopted. Finally, actions to improve educational outcomes, both by reviewing teaching programmes and methods and by increasing expenditure, if necessary, should be implemented.

Economic growth is no ends, but a means to ensure social welfare. And apart from average income, distribution is important for welfare. One would hope that the growth dividend gets divided fairly among various income groups. However, whilst it may be intrinsically consistent to support the highly skilled in order to foster economic growth, as modern arguments suggest, this has negative distributional consequences. If all workers are paid their marginal productivity, than investing into the skills of high-potential individuals, as suggested by theory and the evidence presented here, implies increasing their wage earning potential even further. Whilst one can argue that the distribution which the market induces, where everybody gets paid her marginal product, is fair, this can no longer be valid when policy specifically interferes to change marginal productivities. Financing investments into the highly skilled should therefore not be (tax) financed by the general population, but instead paid for by the recipients of the qualification. In this respect, the US system of educating the highly skilled seems fairer. There, every student pays her own tuition, which can easily add up to 50.000 US$. It is true that highly skilled individuals receive a relatively higher wage than the unskilled (and the skill bias is more pronounced in the US). But in part, the higher skill premium is used to finance the private educational expenditures. Reproducing the elitist educational system of the US implies that one should also be willing to reproduce their mode of financing.

References

Acemoglu, D. (1998): Why do new technologies complement skills? Direct technical change and wage inequality, in Quarterly Journal of Economics, Vol. 113(4), S. 1055-1089

Aghion, P., Howitt, P. (1992): A Model of Growth through Creative Destruction, in Econometrica Vol. 60, S. 323-351

Aghion, P., Boustan, L., Hoxby, C., Vandenbussche, J. (2005): Exploiting States Mistakes to Evaluate the Impact of Higher Education on Growth, Working paper, Harvard

Barro, R. (1991): Economic growth in a cross-section of countries, in Quarterly Journal of Economics Vol. CVI (2), S. 407-443

Barro, R., Lee, J. W. (1993): International comparisons of educational attainment’, in Journal of Monetary Economics Vol. 32, S. 363-394

Barro, R., Lee, J. W. (1994): Sources of economic growth, Carnegie-Rochester Conference Series on Public Policy, Vol. 40, S. 1-46

Barro, R., Sala i Martin, X. (1995): Economic growth, McGraw-Hill, New York

Barro, R., Lee, J. W. (1996): International measures of schooling years and schooling quality, in American Economic Review Papers and Proceedings Vol. 86(2), S. 218-223

Barro, R. (2000): Education and economic growth, Mimeo, Harvard University

Bassanini, A., Scarpetta, S. (2001): Does human capital matter for growth in OECD countries? Evidence from pooled mean-group estimates, OECD Economics Department Working Paper Nr. 282

Baumol, W., Batey Blackman, S. A., Wolf, E. (1989): Productivity and American leadership: the long view, MIT Press

Becker, G.S. (1964): Human Capital, A theoretical and empirical analysis, with special reference to education, Columbia University Press, New York

Becker, G.S. (1985): Human Capital, Effort and the Sexual Division of Labour, in Journal of Labour Economics, Vol. 3(1), S. 33-58

Benhabib, J., Spiegel, M. (1994): The role of human capital in economic development: evidence from aggregate cross-country data, in Journal of Monetary Economics Vol. 34, S. 143-173

Bowles, S. (1972): Schooling and Inequality from Generation to Generation, in Journal of Political Economy, S. 219-251

Caroli, E., Van Reenen, J. (1999): Organisation, skills and technology: evidence from a panel of British and French establishments, Institute for Fiscal Studies, Working Paper Series Nr. 99/23, London

Cohen, D., Soto, M. (2001): Growth and human capital: good data, good results, CEPR Discussion Paper Nr. 3025

De la Fuente, A. (1998): Convergence equations and income dynamics: the sources of OECD convergence, 1970–95, CEPR Discussion Paper Nr. 1794

De la Fuente, A., Doménech, R. (2000): Human capital in growth regressions: How much difference does data quality make?, Economics Department Working Paper Nr. 262, OECD

De la Fuente, A., Doménech, R. (2001): Schooling data, technological diffusion and the neoclassical model, in American Economic Review, Papers and Proceedings Vol. 91(2), S. 323-327

Denny, K., Harmon, C., Lydon, R. (2001): Cross-country evidence in the returns to education: patterns and explanations, Mimeo

Dessus, S. (1999): Human capital and growth: the recovered role of educational systems, Mimeo, the World Bank

Doms, M., Dunne, T., Troske, K. (1997): Workers, wages and technology, in Quarterly Journal of Economics, Vol. 112(1), S. 253-290

Dunne, T., Haltiwanger, J., Troske, K. (1996): Technology and jobs: secular changes and cyclical dynamics, NBER Working Paper Nr. 5656, Cambridge, MA

Grossman, G. M., Helpman, E. (1991): Innovation and Growth in the Global Economy, The MIT Press, Cambridge and London

Hamilton, J., Monteagudo, J. (1998): The augmented Solow model and the productivity slowdown, in Journal of Monetary Economics Vol. 42, S. 495-509

Hanushek, E., Kimko, D. (2000): Schooling, labourforce quality and the growth of nations, in American Economic Review Vol. 90(5), S. 1184-1208

Hanushek, E.A., Wößmann, L. (2007): The Role of Education Quality in Economic Growth, World Bank Policy Research Working Paper Nr. 4122

Katz, L., Murphy, K. (1992): Changes in relative wages. 1963–1987: supply and demand factors, in Quarterly Journal of Economics, Vol. 107(1), S. 35-78

Krueger, A., Lindahl, M. (2001): Education for growth: Why and for whom?, in Journal of Economic Literature XXXIX, S. 1101-1136

Kyriacou, G. (1991): Level and growth effects of human capital: a cross-country study of the convergence hypothesis, Mimeo, New York University

Landau, D. (1983): Government expenditure and economic growth: a cross-country study, in Southern Economic Journal, S. 783-792

Lee, D. W., Lee, T. H. (1995): Human capital and economic growth - Tests based on the international evaluation of educational achievement, in Economics Letters 47, S. 219-225

Lucas, R. (1988): On the mechanics of economic development, in Journal of Monetary Economics, Vol. 22, S. 3-42

Machin, S., Van Reenen, J. (1998): Technology and changes in skill structure: evidence from seven OECD countries, in Quarterly Journal of Economics Vol. 113(4), S. 1215-1244

Mankiw, G., Romer, D., Weil, D. (1992): A contribution to the empirics of economic growth, in Quarterly Journal of Economics, S. 407-437

McMahon, W. (1998): Conceptual framework for the analysis of the social benefits of lifelong learning, in Education Economics, Vol. 6(3), S. 309-346

Mincer, J. (1974): Schooling, Experience and Earnings, Columbia University Press, New York

Mincer, J. (1997): The Production of Human Capital and the Life Cycle of Earnings: Variation on a Theme, in Journal of Labor Economics, Vol. 15(1), S. 26-47

Moll, P.G., (1998): Primary Schooling, Cognitive Skills and Wages in South Africa, in Economica New Series, Vol. 65, Nr. 258, S. 263-284

Nehru, V., Swanson, E., Dubey, A. (1995): A new database on human capital stocks in developing and industrial countries: sources, methodology and results, in Journal of Development Economics, Vol. 46, S. 379-401

Nelson, R., Phelps, E. (1966): Investment in humans, technological diffusion, and economic growth, in American Economic Review, S. 69-82

Pritchett, L. (1999): Where has all the education gone?, Mimeo, the World Bank

Romer, P. M. (1986): Increasing Returns and Long Run Growth, in Journal of Political Economy Vol. 94, S. 1002-1037

Romer, P. (1989): Human capital and growth: theory and evidence, NBER Working Paper Nr. 3173

Romer, P. M. (1990): Endogenous Technological Change, in Journal of Political Economy, Vol. 98 (5), S. 71-102

Smith, A. (1776): An enquiry into the Nature and causes of the wealth of nations

Temple, J. (1998): Robustness tests of the augmented Solow model, in Journal of Applied Econometrics Vol.13, S. 361-375

Vandenbussche, J., Aghion, P., Meghir, C. (2004): Growth, Distance to Frontier and the Composition of Human Capital, Working paper, Harvard-UCL

Vasudeva, N. R., Chien, I. S. (1997): The empirics of economic growth for OECD countries: some new findings, in Economics Letters Vol. 55, S. 425-429

Wilson, K. (2001): The Determinants of Educational Attainment: Modelling and Estimating the Human Capital Model and Education Production Functions, in Southern Economic Journal, Vol. 67(3), S. 518-551