Quality-adjusted human capital and productivity growth

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QUALITY-ADJUSTED HUMAN CAPITAL AND PRODUCTIVITY GROWTH

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This article examines the influence of quality-adjusted educational attainment on growth and tests whether it facilitates the transfer of technology developed at the frontier for a panel of 60 countries. Using outcomes of pathogen stress as instruments, the results show that quality-adjusted educational attainment and its interaction with distance to the frontier play important roles for growth. (*JEL* I20, O30, O40)

I. INTRODUCTION

Although endogenous growth models predict that human capital is one of the most important sources of economic growth, the macro-level empirical evidence is at best mixed.[1] So far, most studies have concentrated on educational attainment and hence the ambiguous findings may be due to measurement errors as well as large variations in the quality of schooling across countries. The quality of teaching, as measured by internationally comparable test scores, shows staggering cross-country variations among eighth-grade students. While Qatar and Ghana achieve scores in mathematics and science close to 300 in the 2007 Trends in International Mathematics and Science Study (TIMSS), the Western countries score close to 500, indicating large differences between developed and developing countries. The quality of schooling is often inadequate in developing countries due to high teacher and student absentee rates, fewer teaching days a year, rote learning, insufficient teacher qualifications, and the lack of basic resources such as school books, clean classrooms with chairs and tables, and stationery (Pritchett 2004). Furthermore, the high burden of diseases among students in developing countries reduces their attention and concentration in the classroom (Sachs 2001). Thus, even if educational attainment is not that low in many developing countries it may not deliver the desired growth effects because of the poor quality of teaching and the learning environment.

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1. A series of empirical studies find either significantly positive (Barro 1991; Mankiw et al. 1992; Gemmell 1996; Engelbrecht 2002; Madsen 2010), significantly negative (Caselli, Esquivel, and Lefort 1996), insignificant (Knowles and Owen 1995; Pritchett 2001; Radelet et al. 2001; Henderson, Papageorgiou, and Parmeter 2012) or even nonlinear relationships between education levels and growth (Kalaitzidakis et al. 2001). In some studies, the growth rate of human capital is found to have a significant impact on output growth (Krueger 1968; Barro 1991; Mankiw et al. 1992), whereas others cast doubt on this channel and propose that the stock of human capital can better explain variations in output growth (Romer 1990; Benhabib and Spiegel 1994, 2005; Hall and Jones 1999). See Delgado et al. (2013) for an overview of the literature.

ABBREVIATIONS

DALY: Disability-Adjusted Life Year
DTF: Distance to the Frontier
EDR: Estimated Death Rate
GDP: Gross Domestic Product
GMM: Generalized Method of Moments
ICRG: International Country Risk Guide
OLS: Ordinary Least Squares
PCA: Principal Component Analysis
PWT: Penn World Table
TFP: Total Factor Productivity
TIMSS: Trends in International Mathematics and Science Study

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In response to the huge gap in schooling quality, some studies have examined the impact of human capital quality on growth. Using science and mathematics scores on internationally comparable tests as measures of human capital quality, Hanushek and Kimko (2000), Barro (2001), and Hanushek and Woessmann (2008, 2012) find that educational attainment loses significance once educational quality is controlled for in the regressions. However, despite the concern that educational attainment may be endogenous, as highlighted by Bils and Klenow (2000), Vandenbussche, Aghion, and Meghir (2006), and Hanushek and Woessmann (2012), *none* of these studies have catered for potential feedback effects from productivity growth to the quality as well as the quantity of schooling, due to the difficulties associated with finding good instruments. Furthermore, Hanushek and Kimko (2000), Barro (2001), and Hanushek and Woessmann (2008, 2012) have not allowed for the interaction between human capital quality and distance to the frontier—a potentially important issue since human capital is likely to have played a role in facilitating the transfer of technology from the frontier.

Here we argue in favor of using quality-adjusted educational attainment over either the quantity or the quality of education as measures of human capital in growth regressions. Educational attainment measures the number of years of schooling among the adult population, whereas educational quality captures how much they have actually learned in school. Using a nonparametric estimation strategy, Delgado, Henderson, and Parmeter (2013) show that educational attainment is largely ineffective in predicting per capita gross domestic product (GDP) growth rates, suggesting that educational attainment may not adequately measure human capital if the quality dimension of education is omitted in the regressions.

This article contributes to the literature as the first paper that, to the best of our knowledge, explicitly examines the productivity growth effects of quality-adjusted human capital. Furthermore, we investigate the growth effects of the interaction between distance to the frontier and quality-adjusted educational attainment of the adult population under the assumption that human capital enables nonfrontier countries to absorb the technology that is developed at the frontier, in the spirit of Nelson and Phelps (1966) and Vandenbussche et al. (2006). Finally, and most importantly, we introduce a new set of instruments to cater for measurement errors and endogeneity of the quality and quantity of educational attainment. While variables such as public educational expenditures and lagged educational attainment have been used as instruments for educational attainment in the literature (see, e.g., Vandenbussche et al. 2006), they may well be an outcome of growth, and public educational expenditure is more likely to influence the quality than the quantity of teaching since all countries considered here have compulsory schooling. In light of this, we use outcomes of pathogen stress as instruments. As shown below, they are highly correlated with our measure of quality-adjusted educational attainment but uncorrelated with the error term, suggesting that they are strong and valid instruments that satisfy the exclusion restriction assumption.

The next section sets out the theoretical framework and Section III discusses the data, measurement issues, and the instruments used. The empirical results are presented in Section IV and extensions and robustness checks are carried out in Section V. The last section concludes.

II. THEORETICAL FRAMEWORK

The model estimated in this paper is based on the following Nelson and Phelps (1966) model extended by the level of human capital by Benhabib and Spiegel (1994):

(1)
$$(\dot{A}_t/A_t) = \psi h_t + \phi h_t[(\bar{A}_t - A_t)/A_t],\ \phi(0) = 0,$$

where A is technology, $\bar{A}$ is the technological frontier, and h is human capital. Nelson and Phelps (1966) define $\bar{A}$ as the theoretical level of technology, i.e., "*the best-practice level of technology that would prevail if technological diffusion were completely instantaneous*" (p. 71). The philosophy behind the Nelson-Phelps model is intuitive: the further a country is behind the technological frontier, the higher is its growth potential provided that it has a sufficiently high level of human capital, or absorptive capacity, to take advantage of its backwardness.

The importance of education and technological catch-up for growth has also been emphasized in the studies of Henderson and Russell (2005) and Vandenbussche et al. (2006). In particular, using a sophisticated growth accounting approach, Henderson and Russell (2005) decompose productivity growth into technological change, technological catch-up, and capital accumulation. They find that human capital is a significant contributor to productivity growth and that "convergence clubs" formation is induced mainly by efficiency changes associated with technological catch-up. In the theoretical model developed by Vandenbussche et al. (2006), unskilled human capital facilitates imitation or diffusion of existing technology whereas skilled human capital promotes the innovation of new technology. Hence, their model predicts that tertiary education should become increasingly important but primary and secondary education less important for growth as a country moves closer to the technology frontier (see also Ang, Madsen, and Islam 2011). The benefits of technology transfer for growth from the rich to the poor countries, however, have been questioned by Caselli and Coleman (2006). They argue that skilled and unskilled labor are not perfect substitutes and find evidence supporting their proposition that skill premiums play an important part in driving cross-country technological differences. These results imply that poor countries are more efficient than rich countries at using unskilled workers since they have a larger supply of unskilled labor. The presence of a skill premium, therefore, acts as a barrier deterring technology transfer from technologically sophisticated countries to technological laggards.

Benhabib and Spiegel (1994) extend the Nelson-Phelps model to allow for the separate growth effects of human capital since the model has the unwarranted property that it does not account for factors that are responsible for growth in the frontier countries and does not allow human capital to have productivity growth effects independent of the technology adopted from the frontier countries. Note that human capital, h, is unlogged following the *Mincerian* approach in which an additional year of schooling has the same growth effects regardless of the level of education, under the assumption that the returns to an additional year of education are independent of the number of years of education. That is, the growth effects of extending schooling by one year are the same for populations with 1 or 12 years of education. The predictions of this extended model have been supported by the empirical findings of Griffith, Redding, and van Reenen (2004), Benhabib and Spiegel (2005), Vandenbussche et al. (2006), and Madsen, Islam, and Ang (2010), among others.

Although previous attempts have had some success in estimating the extended Nelson-Phelps models, these are not without problems. First, it is not easy to measure human capital and previous studies have predominantly focused on number of years of schooling without accounting for the fact that the quality of schooling varies substantially across countries, as discussed in Section I. Second, the reference frontier country may differ across countries. Most poor countries use production technology that is not developed at the technology frontier (Sachs 2001), and thus the United States may not be the sole technology frontier, as is often assumed in empirical studies. Different advanced countries specialize in different technologies in different sectors. Thus, it is likely that the frontier, in addition to the United States, comprises other technologically sophisticated countries such as other G7 members. For poor countries the reference technology frontier is likely to be found among middle-income countries that have developed technologies particularly suitable for production in low-income countries, as discussed in the following section.

III. EMPIRICAL FRAMEWORK

Extending the model given by Equation (1) to allow for control variables yields the following specification that will be estimated for a panel of 60 countries in the period 1970–2010:

(2)
$$g_i^A = \alpha + \beta_1(\Phi\cdot H)_i + \beta_2(\Phi\cdot H)_i \times \mathrm{DTF}_{i,1970} + \gamma' C_i + \varepsilon_i,$$

where g^A is total factor productivity (TFP) growth; Φ is the quality of education measured in various ways as discussed below; H is educational attainment among adults aged 25 years and above; DTF is distance to the frontier, which is measured at the start of the sample period in 1970, following the literature (see, e.g., Benhabib and Spiegel 1994); C is a vector of control variables; and ε is a stochastic error term.

The following control variables are included in the regressions: trade openness (exports plus imports divided by GDP), the ratio of foreign direct investment inflow to GDP, the rates of consumer price inflation, and the investment ratio (gross capital formation over GDP). Trade openness is assumed to influence growth positively in the literature under the assumption that open economies have a more outward-oriented policy.[2] Foreign direct investment is assumed to be growth-enhancing because it embodies new technology, know-how, and knowledge. Inflation retards growth because it is often an indication of macroeconomic mismanagement.

The investment ratio is included in the regression as it is found by Levine and Renelt (1992) to be the most robust determinant of growth among a large set of growth variables. The investment ratio can influence growth through the production function or through productivity externalities. In the neoclassical growth model, the investment ratio has growth effects as long as the economy is on its transitional growth trajectory, as is often assumed in empirical studies. Investment has permanent growth effects if there are positive externalities to investment and provided that there are scale effects in ideas production. Scale effects in ideas production are implicitly assumed in Equation (2) in the sense that human capital is assumed to have permanent as opposed to temporary growth effects.

A. Estimation Method and Instruments

The instrumental variable technique is used to deal with potential endogeneity and measurement errors for the quality-adjusted educational attainment measure and its interaction with distance to the frontier.[3] Educational attainment is measured with errors since it does not allow for differences in student and teacher attendance rates and the number of school days per year across countries and time periods, in addition to the usual errors associated with census surveys, on which most of the educational attainment data are based. de la Fuente and Doménech (2006), for example, find large errors in the census data on educational attainment for OECD countries that, supposedly, have data of much better quality than developing countries. Moreover, the quality of schooling is subject to measurement errors because most of the measures used here do not allow for the fact that the average cognitive abilities among children entering the schooling system differ across countries (Eppig, Fincher, and Thornhill 2010).

Bils and Klenow (2000) argue that schooling is endogenous because the returns to investment in schooling depend positively on the expected productivity growth rates, which in turn depend on the contemporaneous and historical growth rates. The quality of education may also be endogenous since the resources available for teaching are likely to depend positively on economic growth. Governments are likely to cut budgets for education expenditure in periods of low or negative growth following the shrinking growth or direct reductions in tax revenues. However, since it is hard to reduce school enrolment numbers due to the provision of free-of-charge education and compulsory schooling requirements, the resources available to each student are likely to shrink during periods of low, decreasing, or negative growth.

The following instruments are used for quality-adjusted educational attainment and its interaction with DTF: (1) disability-adjusted life years lost per 100,000 population (DALY) due to communicable, maternal, perinatal, and nutritional diseases and (2) estimated death rates due to communicable, maternal, perinatal, and nutritional diseases per 100,000 population (EDR).

DALY measures the number of years lost due to ill-health, disability, or early death and is calculated as the sum of reduced life expectancy relative to the Japanese life expectancy and the years of quality life lost due to disability and poor health. We use DALY due to communicable, maternal, perinatal, and nutritional diseases as an instrument, thus excluding DALY due to noncommunicable diseases such as cancer, cardiovascular diseases, and injuries—factors that are unlikely to influence school performance since they most often happen much later in life. DALY due to communicable, maternal, perinatal, and nutritional diseases serves as a good instrument for the quality of learning and teaching because infectious and parasitic diseases impair the ability to learn, reduce students' attention and concentration in the classroom, and increase student and teaching absenteeism. Moreover, DALY is a good instrument for educational attainment because it is influential for life expectancy and individuals who are expected to live longer are likely to invest more in schooling than those with a shorter life expectancy because the returns from investment in schooling are spread over a longer

2. Pritchett (1996) finds that different measures of outward orientation capture different dimensions of the trade regime and, therefore, sometimes give conflicting results. Since trade regime is not the focus of this article, we do not investigate this matter further.

3. We use the generalized method of moments (GMM) in the instrumental variable estimation. A key advantage of the IV-GMM estimator over the commonly used IV-2SLS approach is that the former is more efficient in the presence of heteroskedasticity. This is our preferred method since under the strict assumption of no heteroskedasticity, the IV-GMM estimator is asymptotically no worse than the IV-2SLS estimator (Baum, Schaffer, and Stillman 2003).

life span. Bils and Klenow (2000) show formally that there is a one-to-one relationship between the optimal years of schooling and years of expected life.

DALY due to communicable, maternal, perinatal, and nutritional diseases is not likely to be influenced by growth because they are, essentially, driven by pathogen stress. Guernier, Hochberg, and Guégan (2004) show that pathogen stress is determined by ecology and that parasitic and infectious diseases are particularly widespread in the tropics. Helminth (all kinds of parasitic worms) and vector-borne diseases, for example, are much more widespread in the tropics than the temperate zones and these diseases are responsible for the high DALY in the tropical countries (Sachs 2001).

Finally, deaths due to communicable, maternal, perinatal, and nutritional diseases are used as instruments for quality-adjusted educational attainment for the same reasons as DALY. These two instruments are highly correlated since they have a large overlap. The main difference between them is that nonfatal diseases, such as helminth morbidity, affect DALY but are rarely fatal. Malaria, as a major parasitic disease, is not always terminal for infected people who have gained immunity (Sachs 2001). Thus, malaria and helminth are two major diseases that show up more strongly in DALYs than in EDRs and, at the same time, are influential for school children's and school teachers' attendance rates and concentration at school (Sachs 2001). Finally, EDR has the advantage over DALY in that it is not measured with nearly as large an error as DALY since there is a large judgmental component associated with the measurement of DALY.

B. Data and Measurement Issues

The variables used to estimate Equation (2) are constructed as follows.[4] TFP is recovered from the following aggregate production function: $Y = AK^{\alpha}(HL)^{1-\alpha}$, where Y is the real GDP; K, the real physical capital stock; L, the total labor force; H, the quantity of schooling; and α, the share of capital in total output. TFP (A) is thus measured as $y/k^{\alpha}H^{1-\alpha}$, where y is the output per worker (Y/L), and k is the capital per worker (K/L). Quantity of schooling, H is computed as: $\exp(\theta \cdot \text{SCH})$, where SCH is the educational attainment, defined as the average years of schooling among the population aged 15 years and above, and θ is the returns to schooling, which is usually set at 0.07 in the literature (see, e.g., Jones 2002). However, in light of the previous findings of Psacharopoulos and Patrinos (2004) and Henderson, Polachek, and Wang (2011) that these returns vary significantly across countries, we follow their approach and allow the returns to schooling to vary across countries using the estimates of Bils and Klenow (2000) and Psacharopoulos and Patrinos (2004). The dataset of Barro and Lee (2010) is used for educational attainment because it has the broadest coverage for the available data on educational attainment, noting that this latest version of their dataset has accommodated the problems in their previous one (i.e., Barro and Lee 2001) highlighted by Cohen and Soto (2007). The results are almost identical if alternative datasets are used (see Appendix A).

Capital's income share (α) is allowed to vary across countries. Most of our estimates for α are extracted from Gollin (2002) and Caselli and Feyrer (2007), where preference is given to the latter for overlapping countries. The missing values of α are measured as the predicted values from regressing capital income shares on real per capita GDP for available countries.[5] Capital stock is constructed using the perpetual inventory method with a 5% rate of depreciation, following Bosworth and Collins (2003). The initial capital stock is estimated as $I_0/(\delta + g)$, where I_0 is the initial real investment, δ, the rate of depreciation, and g, the steady-state rate of investment growth.

Two educational quality composite indicators, namely output and input, are derived based on the method of principal component analysis. The results presented throughout the article are based on the educational quality output measure. Analyses that involve the educational quality input measure are relegated to the robustness section. The principal component analysis is an approach that is often used to reduce a large set of correlated variables into a smaller set of uncorrelated variables, known as principal components. The first principal component is chosen as it is able to account for most of the variation

4. These data can be downloaded at http://jakobmadsen.net/data-archive-6/.

5. Regressing capital income share on real per capita income across countries gave a constant coefficient of 0.297367 and a slope coefficient of −0.0000071. The correlation coefficient is −0.72. Income shares for the following countries are estimated using per capita income: Argentina, Brazil, Bulgaria, Cameroon, China, Cyprus, the Dominican Republic, Germany, Iceland, Indonesia, Iran, Kenya, Malawi, Mali, Mauritania, Senegal, Syria, Thailand, Togo, Turkey, Uganda, and Zimbabwe.

in the data and, therefore, captures most of the information from the different measures capturing various aspects of educational quality.

The output indicator of the quality of education consists of the following indicators: nonrepetition rates at the primary and secondary levels, test scores in mathematics, science and reading at the primary and secondary levels, and the number of universities per worker listed in the ARWU's top 500 rankings. Nonrepetition rates capture the quality of teaching in the sense that students who do not meet the national standards will be required to repeat classes. Test scores capture the quality of teaching directly by measuring student capabilities. Hanushek and Kimko (2000) and Hanushek and Woessmann (2008) advocate test scores as the preferred measures over other quality indicators of education such as teacher-pupil ratio and per capita expenditure on education. The shortcoming of the scoring measures is that the cognitive abilities of students entering school are influenced by parents' stimulation of children during their upbringing, which in turn is likely to vary substantially across countries (Hanushek and Woessmann 2012). It is well known that parents with fewer children spend more resources on stimulating children than parents with more children (Galor and Weil 2000).

University ranking is used as a proxy for the quality of teaching because high ranking universities require high entrance qualification scores, which can only be satisfied in countries with good quality teaching. Furthermore, countries with good universities tend to produce high quality teachers. The Shanghai Jiao Tong University's *Academic Ranking of World Universities* is used here. By ranking the top 500 universities it provides information for a substantially larger sample of countries than any other international university ranking system. Its ranking indicators include alumni and staff winning Nobel Prizes and Field Medals, highly cited researchers, articles published in *Nature and Science*, articles indexed in major citation indices (e.g., the Science Citation Index-Expanded and Social Science Citation Index), and the per capita academic performance of an institution.

Following Card and Krueger (1992), Lee and Barro (2001), and Sequeira and Robalo (2008), we use the teacher-pupil ratio at the primary and secondary levels and the ratio of real public educational expenditure per student to real per capita GDP at the primary, secondary, and tertiary levels as the input measures of educational quality. These indicators reflect the quality of schooling through resources allocated to each student. They vary substantially across countries and, as expected, their values appear to be low in many developing countries. The shortcoming of these measures is that they do not measure some important dimensions of the quality of teaching, such as learning to think independently, problem solving, lateral and creative thinking, and the caliber of teachers.

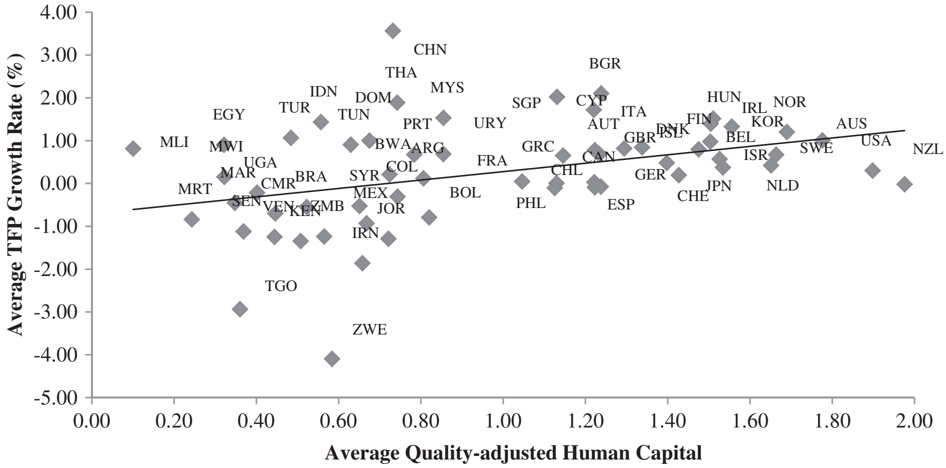
The scatter plots for the quality-adjusted human capital measure ($\Phi \cdot H$) against the growth rate and level of TFP are presented in Figures 1 and 2, respectively. The graphs show that the level as well as the growth in TFP is positively related to $\Phi \cdot H$. The relationship between level of TFP and ($\Phi \cdot H$) is particularly strong.

In Figure 1, Togo, Zimbabwe and, to some extent, China appear to be outliers. It is, however, well known that Zimbabwe's recent poor growth performance has been affected by macroeconomic mismanagement and, thus, is unrelated to ($\Phi \cdot H$). China's TFP growth has been higher than justified by ($\Phi \cdot H$) because the surge in innovative activity and savings has been highly influential for its growth experience (Young 2003; Ang and Madsen 2011, 2013). Togo's decline, which started around 1977, has predominantly been caused by plummeting prices of its main earnings: cotton (50%), coffee (87%), and cocoa (72%) where the numbers in parentheses are the decline in the real market prices of these commodities over the period from 1977 to 2010 (see Harvey et al. 2010). Thus, the outlier status of Togo, Zimbabwe, and China is not evidence against the human capital hypothesis, but rather a reflection of the fact that other factors have also had a forceful influence on growth rates for these countries. Overall, the figures suggest a strong positive relationship between productivity and ($\Phi \cdot H$).

DTF for country i is measured as $(\text{TFP}^{\text{leaders}} - \text{TFP}^{i})/\text{TFP}^{\text{leaders}}$ in 1970. In contrast to most other empirical studies, we do not use the United States as the sole technology leader because many rich countries also adopt technologies developed in frontier countries outside the United States. Furthermore, poor countries generally do not make use of the frontier technology, but rather often adopt lower level technologies that are developed and used in middle-income countries (Masters and McMillan 2001; Quah 1996; Sachs 2001). In this context, it is important to note that agriculture is

FIGURE 1

Average Quality-Adjusted Human Capital ($\Phi \cdot H$) vs. Average TFP Growth (1970–2010)



Note: Φ is measured by five schooling output variables, including (1) the rates of nonrepetition; (2) test scores in mathematics; (3) test scores in science; (4) test scores in reading; and (5) number of universities per million workers listed in ARWU's top 500 ranking. See Appendix B for sources.

the most significant production sector in many developing countries and, therefore, that the transfer of agricultural technology such as agricultural machinery and new plant varieties are more important for aggregate economic outcomes than transfers of manufacturing technology for these countries. Since high-yielding crops developed in the temperate zones cannot generally be adapted to tropical climates, and vice versa (Sachs 2001), the technology leader among developing tropical countries is more likely to be located in the tropical or sub-tropical zone.

The approach used here to differentiate the reference technology leader is consistent with the "twin peaks" proposition of Quah (1996), who argues that countries tend to polarize into twin peaks of rich and poor, thus converging toward their own convergence clubs. Using advanced econometric techniques Bianchi (1997), Henderson, Parmeter, and Russell (2008), and Pittau, Zelli, and Johnson (2010) find evidence in favor of the presence of polarization and clubs formation in the distribution of income across countries as hypothesized by Quah (1996). Moreover, Masters and McMillan (2001) find that temperate countries have converged to high levels of income while tropical countries have converged toward income levels associated with economic scale and the extent of the market.

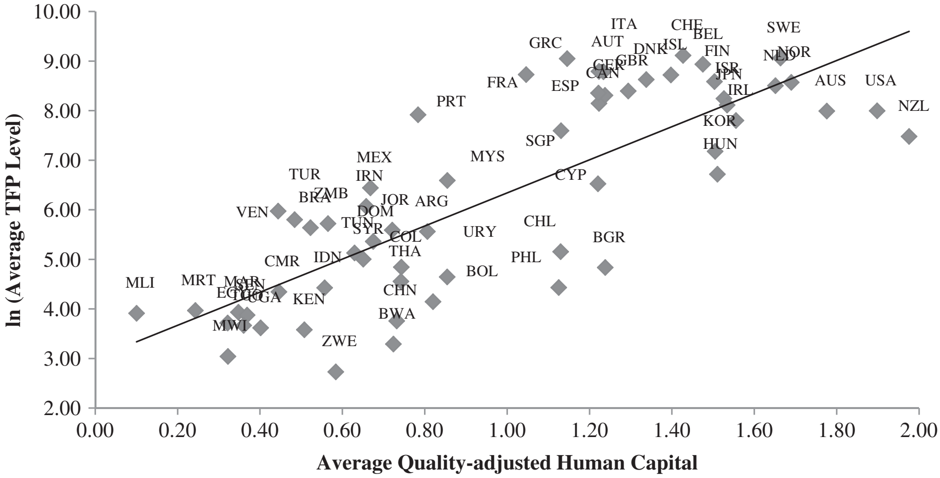
Following this discussion, the total sample of 60 countries is split into two groups of 30, one with the higher and the other the lower per capita GDPs in 2010, under the assumption that the two have different technology leaders. An alternative classification based on income data in 1970 is used as a sensitivity check in Section V. The technological leaders for the high income group consist of the G7 countries (Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States), which are the major technology-producing countries in the world. Brazil, Bulgaria, the Dominican Republic, Mexico, and Turkey, which are all in the low-income group in per capita GDP terms, are used as the reference technology frontier group for the low-income countries. These five nonoil and noncommodity-based countries are also those with the highest TFP levels over the entire sample period (using the latest TFP data yields the same ranking) in the low-income group.

IV. EMPIRICAL RESULTS

Table 1 presents the estimates of Equation (2) where the quality of education is measured by the first principal component of our output measures, teaching quality. Consider first the ordinary least squares (OLS) estimates in column (1). Consistent with the predictions of

FIGURE 2

Average Quality-Adjusted Human Capital ($\Phi \cdot H$) vs. Average TFP Level (1970–2010)



Note: Φ is measured by five schooling output variables, including (1) the rates of nonrepetition; (2) test scores in mathematics; (3) test scores in science; (4) test scores in reading; and (5) number of universities per million workers listed in ARWU's top 500 ranking. See Appendix B for sources.

the extended Nelson and Phelps (1966) model, the coefficients of quality-adjusted human capital ($\Phi \cdot H$) and its interaction with the technology gap ($\Phi \cdot H \times$DTF) are both found to be highly significant and have the right sign. Consequently, quality-adjusted educational attainment has both direct growth effects through the $\Phi \cdot H$-term and indirect growth effects through facilitating the adoption of technologies developed by the reference frontier countries. A nonfrontier country will continue to benefit from the technologies developed by the frontier countries until it eventually catches up. In steady state, a nonfrontier country will grow at a rate that is determined by the weighted average of quality-adjusted educational attainment and the productivity growth rate of the frontier countries.

The parameter estimates are almost unaltered when control variables are included in the regressions (column (2)). Among them, the investment ratio and the inflation rate are statistically significant and of the right signs and these results prevail in all remaining regressions in Table 1. Since the output effects of capital accumulation are already accounted for in the TFP estimates, the significance of the investment ratio suggests that there are positive productivity externalities to investment or that the economies have not yet converged to their steady state following a shock to the investment ratio. Inflation suppresses productivity growth, indicating that macroeconomic mismanagement is growth abating. Finally, the effects of foreign direct investment inflow and openness to international trade are insignificant in all regressions.

Different combinations of instruments are used for quality-adjusted educational attainment and its interaction with the initial DTF in the regressions in columns (3)–(5). The Wu-Hausman tests reject the null hypothesis of exogeneity of quality-adjusted human capital at conventional significance levels, suggesting that the instrumental variable technique is appropriate. The F-tests of excluded instruments in the first-round regressions exceed 18 in all cases, suggesting that the instruments are sufficiently correlated with quality-adjusted educational attainment and its interaction with DTF to serve as good instruments.

Consider the regression in column (3) in which quality-adjusted educational attainment and its interaction with DTF are instrumented using EDR and their interactions with DTF as instruments. In line with the OLS results, quality-adjusted educational attainment and its interaction with DTF are found to be significantly positive determinants of productivity growth. This finding remains unchanged when EDR is replaced with DALY (column (4)) or when DALY is added as an additional

TABLE 1
TFP Growth and Quality-Adjusted Human Capital

	(1) Basic model (OLS)	(2) Add controls (OLS)	(3) IV = EDR (IV-GMM)	(4) IV = DALY (IV-GMM)	(5) IV = EDR, DALY (IV-GMM)
$\Phi_i \cdot H_i$	0.010***	0.007**	0.018***	0.015***	0.013***
	(3.375)	(2.587)	(7.123)	(5.592)	(6.372)
$\Phi_i \cdot H_i \times \text{DTF}_{i,1970}$	0.004**	0.005***	0.005***	0.011***	0.005***
	(2.497)	(2.738)	(3.077)	(3.938)	(3.305)
$\text{Investment}_i/\text{GDP}_i$		0.031	0.035**	0.035**	0.034***
		(1.296)	(2.489)	(2.579)	(3.294)
Inflation_i		−0.005***	−0.003**	−0.005***	−0.004***
		(−4.242)	(−2.657)	(−3.757)	(−3.429)
FDI $\text{Inflows}_i/\text{GDP}_i$		0.241**	0.108	0.166*	0.112
		(2.049)	(1.239)	(1.826)	(1.386)
Trade openness_i		−0.007	−0.004	−0.005	−0.002
		(−1.245)	(−0.840)	(−1.116)	(−0.544)
No. of observations	60	60	60	60	60
R^2	0.199	0.461	0.308	0.274	0.407
			Diagnostic tests for IV-GMM (columns (3)–(5))		
Hansen test (p value)			0.207	0.170	0.251
C-test ($\Phi_i \cdot H_i$) instruments (p value)			0.363	0.366	0.879
C-test ($\Phi_i \cdot H_i \times \text{DTF}_{i,1970}$) instruments ($p$ value)			0.400	0.338	0.202
Endogeneity-test (p value)			0.010	0.009	0.027
1st-stage F-statistic ($\Phi_i \cdot H_i$)			21.961	19.560	29.662
1st-stage F-statistic ($\Phi_i \cdot H_i \times \text{DTF}_{i,1970}$)			24.430	12.061	45.430
1st-stage R^2 ($\Phi_i \cdot H_i$)			0.671	0.678	0.838
1st-stage R^2 ($\Phi_i \cdot H_i \times \text{DTF}_{i,1970}$)			0.837	0.700	0.904

Notes: The dependent variable is the average growth rate of TFP over the period 1970-2010. H is the quantity of schooling measured by average years of schooling for the population aged 15 and over and Φ, the quality of schooling measured by the first principal component of the rates of nonrepetition at the primary and secondary levels; test scores in mathematics, science, and reading at the primary and secondary levels; and the number of universities listed in the ARWU's top 500 rankings per million workers. Initial distance to frontier (DTF_{1970}) is the TFP gap in 1970 between the technological leaders and the country under consideration. The G7 countries are the technology leaders for the 30 countries with the higher income levels, whereas Brazil, Bulgaria, the Dominican Republic, Mexico, and Turkey are the technology leaders for the 30 countries with the lower incomes in 2010. The IV-GMM estimates in columns (3)–(5) use the estimated death rates per 100,000 population by causes (communicable, maternal, perinatal, and nutritional conditions) (EDR), the estimated disability-adjusted life years per 100,000 population by causes (communicable, maternal, perinatal, and nutritional conditions) (DALY), and their interaction with DTF_{1970} as instruments. The Hansen test is a test of overidentifying restrictions that checks the validity of the instruments where the null hypothesis is that the instruments are not correlated with the residuals from the structural estimates. The C-test is the difference-in-Hansen test that examines the exogeneity of the instrument subsets under the null hypothesis that the subsets of instruments are exogenous. The null hypothesis under the endogeneity test is that the specified endogenous variables can be treated as exogenous. An intercept is included in the regressions but not reported. The numbers in parentheses are t-statistics and are based on robust standard errors.

*Significant at 10%; **significant at 5%; and ***significant at 1%.

instrument (column (5)). Finally, the estimated coefficients are higher in the IV than the OLS estimates, pointing toward an attenuation bias introduced by measurement errors.

Overall, our results are largely consistent with the results of Hanushek and Woessmann (2012), who find that the quality of education is a significant contributor to GDP growth. A remarkable feature of our results is that quality-adjusted educational attainment has permanent growth effects; that is, the economies will keep growing as long as quality-adjusted human capital exceeds a certain level that is determined by the negative constant term. This implies that there are scale effects in ideas production and that knowledge creation overcomes the force of diminishing returns to the factors of production. Economies will experience permanent growth effects from investment in quality-adjusted educational attainment. These results go beyond the predictions of the human capital-based extended Solow growth model and semi-endogenous growth models in which human capital has only transitory growth effects.

One drawback of the parameter estimates presented in Table 1 is that one cannot read

TABLE 2
Partial Derivatives of TFP Growth with Respect to Quality or Quantity of Education

$(\partial g^A/\partial\Phi)$ or $(\partial g^A/\partial H)$	DTF = 0 (1)	DTF = 0.30 (2)	DTF = 0.50 (3)	DTF = 0.90 (4)
Φ or $H = 0.2$	0.26	0.29	0.31	0.35
Φ or $H = 0.4$	0.52	0.58	0.62	0.70
Φ or $H = 0.6$	0.78	0.87	0.93	1.05
Φ or $H = 0.8$	1.04	1.16	1.24	1.40
Φ or $H = 1.0$	1.30	1.45	1.55	1.75

Notes: Column (1) shows only the estimated direct effects (i.e., DTF = 0) on TFP growth for a change in Φ or H, whereas the remaining columns report both the estimated direct and indirect effects of Φ or H on TFP growth. The partial derivatives in column (1) are obtained by multiplying $\hat{\beta}_1$ by the assumed values of H or Φ. Columns (2)–(4) add these direct effects to the indirect ones, which are obtained by multiplying $\hat{\beta}_2$ by the assumed values of H or Φ and DTF. $\hat{\beta}_1$ and $\hat{\beta}_2$ are estimated parameters for quality-adjusted human capital and its interaction with the technology gap, respectively, obtained from our benchmark regression in column (5) of Table 1. H and Φ are scaled to a range between 0 and 1 to ease interpretation. DTF = 0.30 refers to a country with a TFP that is 70% of the reference frontier country, DTF = 0.50 refers to a country with a TFP of half the reference frontier country, and DFT = 0.90 refers to the country that has a TFP that is 10% of the reference frontier country.

the economic significance of the coefficients of quality-adjusted educational attainment and its interaction with DTF. To ease the interpretation of the parameter estimates, Table 2 shows the implied growth effects of changes in the quality or quantity of human capital from the baseline regression (column (5) of Table 1). Note that H and Φ are each normalized to be in the interval between 0 and 1. Consider column (1), which shows the partial derivatives of TFP growth with respect to quality (Φ) or quantity (H) of education without considering their absorptive capacity (i.e., DTF is set to zero). Suppose an average country that has accumulated 0.6 units of educational attainment (H = 0.6) experiences an improvement in the quality of teaching ($\Delta\Phi$) by 0.5 units, then its TFP growth rate is predicted to increase by 0.39% points. The same result applies to a country with $\Phi = 0.6$ that experiences an increase in H by 0.5 units. These results are plausible in the sense that a marked increase in the quality or quantity of human capital is required to gain a permanently higher productivity growth rate of 0.39% points.

The growth effects of the interaction between quality-adjusted educational attainment and DTF are displayed in the next three columns in Table 2. For the average country (H or Φ = 0.6) that has half of the TFP of the reference leader country, its productivity growth rate will increase by 0.47% points following an increase in Φ or H by 0.5. This growth effect is plausible. However, for a poor country that is very distant from the frontier (DTF = 0.9) and which has an H or Φ of 0.2, the effects of increasing Φ or H by 0.5 is a mere 0.18% points gain in growth, which shows that being distant from the reference frontier is not a sufficient condition for benefitting from transfers of technologies developed at the frontier.

Finally, following from the multiplicative nature of H and Φ in the computation of quality-adjusted educational attainment and its interaction with DTF, the growth effects of increases in either H or Φ are increasing functions of Φ and H, respectively. Thus, the returns from enhancing human capital are highest in highly educated societies—an issue we will elaborate on in the extensions and robustness tests in the next section. This result may not seem plausible in light of the standard assumption of diminishing returns to factors of production. However, looking at the test scores across countries, these results do make sense. Since test scores are progressive in design it is much harder to improve the scores from 500 to 600 than from 100 to 200 in the PISA tests. Similarly, lower grade teaching is much less intensive than higher grade teaching. Hence, the results following from the multiplicative nature of H and Φ are quite plausible.

V. EXTENSIONS AND ROBUSTNESS TESTS

Thus far the results have been based on certain output-related measures of quality of teaching, growth rates over a relatively short time span, the extended Nelson-Phelps model, cross-sectional data, a certain technology frontier reference group, and a multiplicative relationship between H and Φ. Furthermore, innovations and institutional quality and unobserved regional heterogeneity have not been controlled for in the regressions. These considerations are catered for in this section. Following the benchmark model in the last column of Table 1, DALY and EDR are used as instruments in all regressions below. Moreover, except for the regression based on the Mankiw-Romer-Weil model, all control variables are included in the regression.

A. Using Input Measures of Quality

To ensure that our results are not driven by the choice of educational quality measures, the quality of human capital is also measured as the first principal component of two input measures, namely the teacher-pupil ratio at the primary and secondary levels and the ratio of real public educational expenditure per student to real per capita GDP at the primary, secondary, and tertiary levels, to provide a sensitivity check of the results. As shown in column (1) in Table 3, the coefficients of quality-adjusted educational attainment and its interaction with DTF are both significant and of the right sign. These results are consistent with our baseline results.

B. Alternative Measures of Educational Quality

The regressions in columns (2) and (3) in Table 3 use the data of Hanushek and Kimko (2000) and Hanushek and Woessmann (2012) as alternative measures of educational quality. Their data are constructed using test scores in mathematics and science. The coefficients of quality-adjusted educational attainment and its interaction with DTF remain significant—a result that reinforces the findings above that the results are not very sensitive to the measurement of schooling quality and that quality-adjusted educational attainment is a good measure of human capital.

C. Functional Relationship Between Quality and Quantity

A multiplicative relationship between the quality and quantity of schooling has been assumed in the previous analyses. This implies that the growth effect of Φ is positively related to H and, hence, that the highest growth effect of quality will be achieved for high values of educational attainment. Measuring the interaction between quality and quantity, instead, by $\ln(\Phi{\cdot}H)$ yields insignificant coefficients of quality-adjusted human capital (results are not shown), suggesting that the growth effects of a change in Φ are not inversely related to H or vice versa. The following alternative functional forms are considered in columns (4)–(6) in Table 3: Φe^{H}, $e^{\Phi}H$, and $e^{\Phi}e^{H}$. The coefficients of quality-adjusted educational attainment are all significant at conventional levels. From the baseline regressions and the results in this subsection, it can be concluded that the growth effects of Φ (H) are unambiguously increasing functions of H (Φ). What the best exact functional form is, however, cannot be determined from the relatively small sample used here.

D. Individual Effect of Education Quantity

To assess the importance of adjusting for its quality, human capital is measured as the quantity of human capital (H). The results, which are reported in column (7) in Table 3, show that in this case the coefficient of human capital quantity is only significant at the 10% level; thus much less precisely estimated than the case where it is adjusted for educational quality. Moreover, its interaction with distance to the frontier loses significance at conventional significance levels. These results give support to our approach that it is essential to account for the quality of education in the assessment of the effects of human capital on productivity growth.

E. The Mankiw-Romer-Weil Model

The estimates have so far been based on the extended Nelson-Phelps model. We consider below a slightly modified model of Mankiw, Romer, and Weil (1992) to investigate whether the results are robust to the neoclassical specification. Specifically, production is given as:

$$Y_{it} = K_{it}^{\alpha} e_{it}^{\beta\Phi H} (AL)_{it}^{1-\alpha-\beta} \tag{3}$$

The above equation differs from the production function of Mankiw et al. (1992) only to the extent that we adjust human capital for quality and assume that the returns to one additional year of schooling is independent of the existing years of schooling. Incorporating Equation (3) into the model of Mankiw et al. (1992) yields the following dynamic growth model:

$$\begin{aligned} g_i^{Y/L} = {} & (1 - e^{-\lambda t})[1/(1-\alpha-\beta)][\alpha \ln(I/Y)_i \\ & + \beta(\Phi{\cdot}H)_i - (\alpha+\beta)\ln(n+g+\delta)_i] \\ & - (1 - e^{-\lambda t})\ln(Y/L)_{1970} \end{aligned} \tag{4}$$

where λ is the speed of convergence toward steady state; $g_i^{Y/L}$, the average growth rate of real GDP per worker over the period 1970–2010; $(Y/L)_{1970}$, the initial income per worker; (I/Y), the investment ratio; n, the population growth rate; g, the rate of technological progress; and δ, the rate of depreciation. Equation (4) is the standard dynamic Solow model in which growth is positively related to investment and human capital in the transitional

TABLE 3
Alternative Human Capital Measures and Specifications

	(1) $h=\Phi\cdot H$, where Φ is input measures	(2) $h=\Phi\cdot H$, where Φ is labor force quality (Hanushek and Kimko 2000)	(3) $h=\Phi\cdot H$, where Φ is cognitive data (Hanushek and Woessmann 2012)	(4) $h=\Phi\cdot e^H$	(5) $h=e^{\Phi}\cdot H$	(6) $h=e^{\Phi}\cdot e^H$	(7) $h=H$	(8) Mankiw-Romer-Weil model	(9) Mankiw-Romer-Weil model (restricted)
h	0.049*** (6.013)	0.031*** (6.311)	0.028*** (5.303)	0.006*** (7.105)	0.003*** (6.308)	0.002*** (6.793)	0.013* (1.909)	0.008** (2.474)	
$h-\ln(n+g+\delta)$									0.006** (2.400)
$h\times DTF$	0.019*** (3.199)	0.012*** (3.753)	0.009*** (3.675)	0.002*** (3.163)	0.001*** (3.043)	0.001*** (2.854)	0.006 (1.587)	0.006*** (4.759)	0.004** (2.307)
$\ln(Y/L)_{1970}$								−0.005*** (−2.884)	−0.008*** (−4.890)
$\ln(I/Y)$								0.021*** (5.476)	
$\ln(I/Y)-\ln(n+g+\delta)$									0.003 (0.918)
$\ln(n+g+\delta)$								−0.006*** (−4.122)	
No. of observations	60	53	47	60	60	60	60	58	58
R^2	0.344	0.472	0.485	0.465	0.380	0.391	0.484	0.338	0.184
Diagnostic Tests									
Hansen test (p value)	0.172	0.225	0.279	0.172	0.303	0.264	0.112	0.195	0.151
C-test (h) (p value)	0.569	0.825	0.578	0.215	0.880	0.584	0.450	0.429	0.578
C-test ($h\times$DTF) (p value)	0.502	0.484	0.268	0.134	0.277	0.320	0.388	0.225	0.272
Endogeneity-test (p value)	0.039	0.083	0.095	0.021	0.017	0.013	0.094	0.886	0.160
1st-stage F-statistic (h)	11.362	24.910	13.249	13.742	20.351	17.045	26.039	14.012	13.041
1st-stage F-statistic ($h\times$DTF)	28.260	25.672	96.590	87.971	29.443	50.391	8.667	43.341	26.234
1st-stage R^2 (h)	0.665	0.834	0.776	0.745	0.812	0.794	0.768	0.846	0.835
1st-stage R^2($h\times\cdot$DTF)	0.903	0.904	0.937	0.917	0.881	0.900	0.787	0.917	0.930

Notes: DALY and EDR are used as instruments for quality-adjusted educational attainment (h) and its interaction with DTF. Except for columns (8) and (9) where the Mankiw et al. (1992) model is used, all regressions include trade openness, FDI inflows/GDP, the inflation rate and the investment ratio as control variables. For columns (8) and (9), n is the population growth rate; g, the rate of technological progress, δ, the depreciation rate, and ($g+\delta$) is assumed to be 5%, following Mankiw et al. (1992).

*Significant at 10%; **significant at 5%; and ***significant at 1%.

path from one steady state to the other while population growth hampers economic growth through capital dilution.

Allowing for the interaction between human capital and DTF (note that the results are almost unaltered if the interaction term is omitted from the regressions) yields the following unrestricted counterpart of Equation (4)

$$(5)\quad g_i^{Y/L} = a + b_1(\Phi\cdot H)_i + b_2(\Phi\cdot H)_i \times \mathrm{DTF}_{i,1970} + b_3 \ln(Y/L)_{1970} + b_4 \ln(I/Y)_i + b_5 \ln(n + g + \delta)_i + \varepsilon_i$$

where $(g + \delta)$ is assumed to be 5%, following Mankiw et al. (1992).

Column (8) in Table 3 presents the results for regressing the above equation without imposing any restrictions. It is evident that the estimates are consistent with the extended Nelson-Phelps growth model in which quality-adjusted educational attainment and its interaction with DTF are the important drivers of growth. Furthermore, the coefficients of the investment ratio and initial income are both significant and of the right sign, indicating that income is converging toward its steady state and that the variations in investment have positive growth effects.

A problem associated with the unrestricted regression of Equation (5), however, is that the coefficients cannot be held up against the theoretical predictions of Equation (4) because the model is not identified. To identify the parameters of the Solow growth model we need to impose the restriction of constant returns to scale. Doing so yields the results in the last column of Table 3. Unfortunately, the restriction of constant returns to scale (i.e., $b_1 + b_4 = b_5$) is strongly rejected at the conventional significance levels (F (1, 52) = 12.53, $p = .0009$). Thus, the parameter estimates of the restricted model need to be taken with a pinch of salt. Recovering the scale coefficients from the estimates in the last column of Table 3 using Equation (4) yields $\alpha = .21$ and $\beta = .79$, which are quite plausible, thus giving support to the Solow growth model extended to allow for quality-adjusted human capital and its interaction with DTF.

F. Panel Data Estimates

So far we have only exploited the cross-sectional variations in the data, following the common practice in the literature. Consequently, the variations identified are only between countries but not across time. To address this concern, the model is also estimated in 20-year differences using a fixed effect panel estimator, and an IV-GMM panel estimator as well as the system GMM dynamic panel estimator. The results reported in columns (1)–(3) in Table 4 suggest that our previous findings prevail, in that both quality-adjusted human capital and its interaction with the technology gap are significant determinants of productivity growth.

G. Long Historical Growth Rates

An issue that plagues almost all cross-country growth regressions is that the growth rates typically span a period of 30–40 years from 1960, but such a short period may not be representative of the growth histories of the countries involved in the regressions. Countries go through long phases of low and high growth. Many South American nations and the Philippines, for example, had comparatively high growth rates before World War II, but lost momentum thereafter. Most of the Asian miracle economies, by contrast, experienced dismal growth rates up until the mid-20th century and subsequently experienced spectacular growth rates. Unfortunately, we cannot overcome this problem by measuring the dependent variable in levels since the theory says that quality-adjusted educational attainment influences growth rates and not the level of income. To overcome this problem, the per capita growth rates over the period 1820–2008 are used as the dependent variable—a variable that captures the essentials of modern growth history, noting that per capita income was close to the subsistence level for almost all the countries in the world around 1820. Although quality-adjusted educational attainment in the period 1970–2008 may not have been representative for the entire period 1820–2008, a lot of the variation in the regressors is driven by DALY and EDR as instruments and it is not unreasonable to assume that the ranking of these variables between countries has been relatively constant over time.

The estimation results of these long regressions are displayed in column (4) in Table 4. The coefficients of quality-adjusted human capital and its interaction with DTF are remarkably significant, suggesting that per capita income growth in the poor countries over the past two centuries has been impaired by insufficient quality-adjusted educational attainment. Since education in turn has been influenced by

TABLE 4
Further Robustness Checks

	(1) Panel fixed effects (20-year interval)	(2) Panel IV-GMM (20-year interval)	(3) System GMM (20-year interval)	(4) y = GDP growth rate (1820–2008)	(5) Add POLITY	(6) Add scientific journals	(7) Alternative DTF (based on 1970 income data)	(8) Include regional dummies	(9) TFP calculated using $\Phi \cdot H$ as an input (return from H is used)	(10) TFP calculated using $\Phi \cdot H$ as an input (return from H is NOT used)
h	0.146**	0.276***	0.263***	0.007***	0.013***	0.016***	0.015***	0.011***	0.011***	0.010***
	(2.323)	(5.365)	(3.468)	(4.283)	(3.010)	(3.910)	(5.232)	(2.811)	(5.411)	(5.121)
$h \times DTF$	0.085**	0.118***	0.114***	0.002**	0.005***	0.006**	0.005***	0.003**	0.006***	0.009***
	(2.080)	(3.396)	(2.714)	(2.068)	(3.062)	(2.540)	(2.830)	(2.067)	(3.408)	(4.629)
Non-OECD East Asia & the Pacific								0.012***		
								(2.744)		
Latin America & the Caribbean								−0.004		
								(−0.893)		
Sub-Saharan Africa								−0.012***		
								(−3.931)		
High income OECD								−0.006		
								(−1.495)		
POLITY					−0.001					
					(−0.186)					
Scientific journals/labor						−0.005				
						(−1.315)				
No. of observations	120	120	120	58	60	60	60	60	60	60
R^2	0.489	0.295	—	0.310	0.405	0.433	0.303	0.581	0.391	0.526
Diagnostic Tests										
Hansen test (p value)	—	0.417	0.165	0.615	0.192	0.196	0.235	0.322	0.246	0.282
C-test (h) (p value)	—	0.861	0.141	0.295	0.786	0.179	0.158	0.725	0.849	0.775
C-test ($h \times$DTF) (p value)	—	0.452	0.277	0.777	0.151	0.112	0.299	0.368	0.180	0.149
Endogeneity-test (p value)	—	0.000	—	0.073	0.061	0.063	0.021	0.0921	0.023	0.092
1st-stage F-statistic (h)	—	31.624	—	26.572	15.182	11.420	24.601	18.601	24.321	28.290
1st-stage F-statistic ($h \times$DTF)	—	26.581	—	7.603	32.061	20.953	16.035	27.280	38.330	38.353
1st-stage R^2 (h)	—	0.812	—	0.838	0.853	0.844	0.700	0.876	0.828	0.828
1st-stage R^2 ($h \times$DTF)	—	0.864	—	0.874	0.904	0.852	0.801	0.943	0.893	0.859

Notes: DALY and EDR are used as instruments for quality-adjusted educational attainment (h) and its interaction with DTF. All regressions include trade openness, FDI inflows/GDP, the inflation rate, and the investment ratio as control variables. In column (7), Brazil, Chile, the Dominican Republic, Malaysia, and Turkey are chosen to be the technology leaders for the 30 countries with the lower incomes in 1970 in our sample. The number of instruments used in the system GMM estimation is 34 (column (3)).

*Significant at 10%; **significant at 5%; and ***significant at 1%.

pathogen stress that has resulted in a large number of years lost due to ill-health, disability, and early death, the results here give insight into a potential channel through which geography influences growth and why tropical countries tend to be the poorest in the world.

H. Controlling for Institutional Quality and Innovations

The quality of institutions and per worker publications of scientific and technical journal articles are included as additional control variables in the regressions in columns (5) and (6), respectively, to address the critique of Bosworth and Collins (2003) and Chen and Luoh (2010). They find that the quality of teaching becomes insignificant for growth once institutions and scientific journal publications are allowed for. The quality of institutions is measured by the POLITY index, which consists of a number of authority characteristic component variables, including regulation of chief executive recruitment, competitiveness of executive recruitment, openness of executive recruitment, executive constraints, regulation of participation, and competitiveness of participation. The POLITY index, which has a scale ranging between −10 (strongly autocratic) and +10 (strongly democratic), differs from the index used by Bosworth and Collins (2003), who use the International Country Risk Guide (ICRG) institutional quality data. These data are not used here because they are only available from 1984 (see Knack and Keefer 1995), whereas the POLITY data cover the whole sample period considered here. However, the principal results remain unaltered if data from the ICRG are used (the results are not shown). Scientific journal publications are measured as the number of scientific and engineering articles published in physics, biology, chemistry, mathematics, clinical medicine, biomedical research, engineering and technology, and earth and space sciences.

As is evident from the regressions in columns (5) and (6), the principal findings in this article are robust to the inclusion of POLITY and scientific or technical journals per worker, thus overcoming the Bosworth and Collins (2003) and Chen and Luoh (2010) critique. The results prevail if both variables are included in the same specification. The coefficients of quality-adjusted educational attainment and its interaction with DTF are statistically significant in both cases. The coefficients of POLITY and scientific journals per worker are insignificant. This need not mean that these variables are unimportant for prosperity. The quality of institutions has been found to be an important determinant of the *level* of per capita income and is rarely used in growth regressions (see, e.g., Acemoglu, Johnson, and Robinson 2001; Hall and Jones 1999). Thus, the quality of institutions may have been important for historical growth rates but not the growth rates in the period 1970–2010. The insignificance of the coefficient of scientific journals may reflect the fact that (1) scientific journals may not be good proxies for innovative activity because they do not measure the research activity that is undertaken in the private sector and (2) scientific journals are predominantly published in the Anglo-Saxon countries.

I. Using an Alternative Distance to the Frontier Measure

Our results may be sensitive to the selection of leaders and to the classification of countries between the two groups. For example, it is possible that Brazil, Bulgaria, the Dominican Republic, Mexico, and Turkey that we chose as leaders for the low-income group, could have been converging to the G7 leaders. To ensure that the results are not driven by the classifying of the countries using income data in 2010, we reclassify the countries based on income in 1970 and select only five leaders. In this case, the chosen leader countries in the developing group are Brazil, Chile, the Dominican Republic, Malaysia, and Turkey. Column (7) in Table 4 shows that our results still hold even if this alternative classification based on initial income is used.

J. Including Regional Dummies

Next, we include several regional dummies to ensure that the relationship between quality-adjusted education and TFP growth that we have found so far is not affected by the correlation between education and some unobserved heterogeneous effects. Following the approach of Temple (1998) and Temple and Woessmann (2006), regional dummies for sub-Saharan Africa, non-OECD East Asia and the Pacific, Latin America and the Caribbean, and the high-income OECD countries are included in the regression in column (8) in Table 4. The results we have obtained so far remain largely unchanged when these regional dummies are included in the regression. This result is more robust than that found by Hanushek and Woessmann (2012) in which the size of their schooling quality coefficient reduces somewhat when regional dummies are added to the specification. Thus, our results are not subject to the critique of Temple (1998), who shows that the positive effect of schooling on growth found in Mankiw et al. (1992) disappears once regional fixed effects are controlled for. Instead, our results are consistent with Temple and Woessmann (2006), whose results are also robust to the inclusion of regional dummies.

K. Considering Alternative Measures of TFP

The quality of schooling has so far not been used as an input in our calculation of the TFP measure since we do not have estimated returns for educational quality. The omission of education quality may affect the measurement of TFP and the distance to the frontier variable and therefore bias our results. To cater for the role of schooling quality we assume that the returns to Φ are the same as the returns to H. Furthermore, it is also assumed that the returns to Φ and H are constant across countries. Columns (9) and (10) in Table 4 report the estimates. As is evident, our principal results are not driven by these considerations.

L. Effects of Each Level of Educational Attainment on Growth

Thus far we have used total educational attainment and one composite measure of the quality of teaching. Educational attainment is disaggregated into primary, secondary, and tertiary education in the regressions in Table 5. The test scores at grade 4 are used as teaching quality measures for primary education, the test scores at grade 8 are used for secondary schooling, and university rankings are used for the quality of teaching at the tertiary level. Each level of education is entered separately into each individual regression because the common sample in some cases is only 20 observations when mathematics, science, and reading are considered jointly.

The regressions show that quality-adjusted educational attainment and its interaction with DTF at any educational level are statistically significant determinants of growth. Considering the different dimensions of teaching quality it is notable that the growth effects of reading skill scores are no lower than the growth effects of scores in mathematics and science. This result is remarkable because scores in mathematics and science are often considered to be essential for growth (Hanushek and Kimko 2000; Hanushek and Woessmann 2008), presumably because productivity growth, in steady state, is driven by product and process innovations that are outcomes of R&D activities done by researchers with a background in science or engineering. There are two reasons why reading skills are influential for growth. First, scores in science, mathematics, and reading are highly correlated. Thus, we would expect the growth outcome to be quite similar for the three score dimensions.

Second, reading scores are essential for communication and coordination. Poor reading skills may result in a breakdown of coordination and the more people involved in an interlinked production process with bad reading and communication skills, the more likely it is that a production breakdown will occur. As shown by Kremer (1993), skill complementarities are important in producing O-Ring forms of fragile, delicate output. Small differences in worker skills may cause marked differences in cross-country productivities because weak links in the production process can have large macro effects. Kremer (1993) begins with a seemingly obvious point: looking around at common forms of rich-country economic output, he notes that often one small error in the production process can drastically destroy the value of the final output. After all, in an O-Ring world, lower worker quality means multiplicative increases in errors across the spectrum of production.

Considering the coefficients of quality-adjusted primary, secondary, and tertiary education, the coefficients are approximately the same across levels of education, thus supporting the *Mincerian*-type earning functions in which the returns to education are the same for all its levels. Hence, it is not the logs but the levels of education that are relevant in growth regressions. The coefficients of the interaction terms are 0.001–0.002 for primary education, 0.002–0.007 for secondary education, and 0.042 for tertiary education, implying that they are increasing functions of the levels of quality-adjusted education. This result is intuitive in the sense that workers with better quality and higher levels of education are more able to use and develop the technology that is developed at the frontier countries than otherwise.

VI. CONCLUDING REMARKS

Empirically it has been difficult to find a positive relationship between educational attainment

TABLE 5
The Composition of Quality-Adjusted Human Capital

Φ =	(1a) PRI PCA	(1b) PRI Mathematics score	(1c) PRI Science score	(1d) PRI Reading score	(1e) PRI Nonrepetition rate	(2a) SEC PCA	(2b) SEC Mathematics score	(2c) SEC Science score	(2d) SEC Reading score	(2e) SEC Nonrepetition rate	(3) TER Uni rank
$\Phi \cdot H$	0.003***	0.006***	0.005***	0.006***	0.004***	0.003***	0.005***	0.006***	0.003**	0.005***	0.048***
	(6.076)	(9.605)	(5.251)	(7.862)	(5.796)	(5.724)	(2.795)	(3.270)	(2.246)	(5.290)	(3.951)
$\Phi \cdot H \times \text{DTF}_{1970}$	0.001**	0.001**	0.002**	0.001**	0.001***	0.002***	0.004***	0.007***	0.002***	0.003***	0.042**
	(2.569)	(2.646)	(2.303)	(2.249)	(3.177)	(3.620)	(3.212)	(3.819)	(2.844)	(3.835)	(2.157)
No. of observations	60	46	37	47	60	60	46	46	40	60	60
R^2	0.413	0.380	0.293	0.593	0.462	0.324	0.376	0.251	0.554	0.325	0.107
Diagnostic Tests											
Hansen test (p value)	0.201	0.549	0.420	0.205	0.132	0.182	0.216	0.192	0.380	0.228	0.155
C-test ($\Phi \cdot H$) (p value)	0.776	0.782	0.435	0.283	0.607	0.822	0.572	0.312	0.495	0.861	0.530
C-test ($\Phi \cdot H \times$DTF) (p value)	0.271	0.318	0.627	0.226	0.203	0.480	0.405	0.226	0.322	0.166	0.177
Endogeneity-test (p value)	0.042	0.015	0.053	0.074	0.295	0.002	0.083	0.097	0.017	0.004	0.020
1st-stage F-statistic ($\Phi \cdot H$)	10.211	84.113	36.301	46.302	24.731	21.881	14.021	11.141	15.720	24.932	14.850
1st-stage F-statistic ($\Phi \cdot H \times$DTF)	76.460	92.531	19.120	9.462	110.123	24.211	31.240	10.074	31.282	36.001	11.051
1st-stage R^2 ($\Phi \cdot H$)	0.771	0.823	0.753	0.774	0.745	0.781	0.625	0.655	0.777	0.755	0.404
1st-stage R^2 ($\Phi \cdot H \times$DTF)	0.902	0.876	0.774	0.795	0.915	0.854	0.828	0.775	0.892	0.883	0.559

Notes: PRI, SEC, and TER indicate primary, secondary, and tertiary level of education, respectively. DALY and EDR are used as instruments for quality-adjusted educational attainment and its interaction with DTF. The human capital variables are normalized to the range of 0 and 1. All regressions include trade openness, FDI inflows/GDP, the inflation rate, and the investment ratio as control variables.

*Significant at 10%; **significant at 5%; and ***significant at 1%. See also notes to Table 1.

and growth (Delgado et al. 2013). In this article, we argue that one reason for the absence of a robust relationship between growth and educational attainment is that educational attainment measures only the quantity dimension of human capital and, as such, suppresses the quality dimension of educational attainment. To overcome this deficiency, we measure human capital as quality-adjusted educational attainment. Furthermore, in contrast to almost all other studies, we use instruments for quality-adjusted schooling, acknowledging that educational attainment is likely to be particularly endogenous in cross-sectional studies since the resources that are available for the quality as well as the quantity of schooling depend on past and current growth rates. Furthermore, the returns to education depend on expected growth rates. Deaths and life years lost due to communicable diseases were used as instruments because they were highly correlated with quality-adjusted educational attainment and because they were likely to satisfy the identifying restriction that the disease environment influences growth through quality-adjusted education.

The results gave consistent support for the hypothesis that quality-adjusted human capital and its interaction with the technology gap are essential for growth. The results are robust to different combinations of instruments, different measures of the quantity and quality of human capital, inclusion of control variables, alternative estimation periods, inclusion of regional dummies, alternative measures of productivity, and different model specifications. Furthermore, we found that the social returns to the quality (quantity) of schooling are increasing functions of the quantity (quality) of schooling and this relationship is robust to variations in the functional relationship between quality and quantity in the regressions. The significance of this result is that the returns to investing in quality teaching are highest in the countries with the longest years of education, thus suggesting that it is difficult for countries with low education to overcome their development trap.

APPENDIX A

Alternative Measures of Educational Attainment

The results in the main body of the paper are based on the educational attainment data of Barro and Lee (2010). The results in Table A1 are based on the following alternative data sources on educational attainment: Baier, Dwyer, and Tamura (2006), Cohen and Soto (2007) and Lutz et al. (2007). Furthermore, Barro and Lee's (2010) data on educational attainment for the population aged 25 years and above are considered, noting that the data used in the main text refer to the population aged 15 years and above. In terms of significance and the size of the coefficients, the results are very similar to the baseline results in column (5) of Table 1. These results reinforce the results in the main text that quality-adjusted educational attainment and its interaction with distance to the frontier are significant determinants of productivity growth.

APPENDIX B

Sources of Data

TFP: K, L, and Y are calculated from the 7.0 version of the Penn World Table (see http://pwt.econ.upenn.edu/php_site/pwt_index.php). Capital stock is computed using the perpetual inventory method with a 5% rate of depreciation. The initial capital stock is estimated as $I_0/(\delta + g)$, where I_0 is the initial real investment and g the steady-state rate of investment growth. PWT 7.0 data are available till 2009 and therefore, required data for final year (2010) have been spliced with available data in the 2011 World Development Indicators online database

(see http://databank.worldbank.org/ddp/home.do?Step=12&id=4&CNO=2).

H: "*Quantity of human capital* (H)" is measured by the average years of schooling for the population aged 15 or 25 years and above. It is compiled from four different sources: (1) Barro and Lee (2010) (see http://www.barrolee.com/), (2) Cohen and Soto (2007) (see http://soto.iae-csic.org/Data.htm), (3) Lutz et al. (2007) (see http://www.iiasa.ac.at/Research/POP/edu07/index.html?sb=11), and (4) Baier et al. (2006) (see http://www.jerrydwyer.com/growth/index.html). Lutz et al. (2007) and Baier et al. (2006) school attainment data are available till 2000 and hence those schooling data are extrapolated from 2001 to 2010.

Φ: "*Quality of human capital* (Φ)" is measured by two schooling input and five schooling output variables. The input variables include: (1) teacher-pupil ratio and (2) real public educational expenditure per student/real per capita GDP. The output variables consist of (1) the rates of nonrepetition, (2) test scores in mathematics, (3) test scores in science, (4) test scores in reading, and (5) number of universities per million workers listed in ARWU's top 500 ranking. Data on educational input and output variables except university ranking are compiled from Lee and Barro (2001) for 1970–1990. Those data have been extended by Altinok and Murseli (2007) from 1991 to 1999. Data from 2000 to 2010 have been compiled from UNESCO Institute for Statistics (see http://stats.uis.unesco.org/unesco/tableviewer/document.aspx?ReportId=143); Institute of Education Sciences for TIMSS (see http://nces.ed.gov/timss/); and PISA database (see http://pisa2009.acer.edu.au/multidim.php). ARWU's top 500 ranking universities' data are obtained from "Academic Ranking of World Universities (ARWU)" (2003–2010) published by the Shanghai Jiao Tong University (see http://www.arwu.org).

Control Variables: Data on "*the rate of inflation*" (measured as the growth rate of CPI), "*trade openness*" (measured as the sum of total exports and imports over GDP), "*the ratio of FDI inflows to GDP*," and "*scientific and technical journal articles*" from 1970 to 2010 are taken from

TABLE A1
Alternative Measures of Educational Attainment

H is measured using sources from:	(1) Barro and Lee (2010), ≥ 25 years	(2) Cohen and Soto (2007), ≥ 15 years	(3) Cohen and Soto (2007), ≥ 25 years	(4) Lutz et al. (2007), ≥ 15 years	(5) Lutz et al. (2007), ≥ 25 years	(6) Baier et al. (2006), ≥ 15 years
$\Phi \cdot H$	0.013***	0.007***	0.007***	0.013***	0.013***	0.013***
	(6.299)	(3.543)	(3.500)	(5.419)	(5.390)	(7.523)
$\Phi \cdot H \times$DTF	0.005***	0.005***	0.005***	0.005***	0.005***	0.007***
	(3.168)	(3.080)	(2.938)	(3.074)	(2.961)	(3.552)
No. of observations	60	55	55	54	54	59
R-squared	0.403	0.469	0.463	0.388	0.381	0.447
Diagnostic Tests						
Hansen test (p value)	0.246	0.149	0.145	0.253	0.246	0.256
C-test ($\Phi \cdot H$) instruments (p value)	0.882	0.369	0.393	0.636	0.637	0.483
C-test ($\Phi \cdot H \times$DTF) instruments (p value)	0.193	0.172	0.163	0.140	0.125	0.112
Endogeneity-test (p value)	0.028	0.077	0.093	0.047	0.042	0.028
1st-stage F-statistic ($\Phi \cdot H$)	23.331	46.034	46.711	22.682	20.101	29.861
1st-stage F-statistic ($\Phi \cdot H \times$DTF)	32.660	31.871	24.720	53.490	40.310	58.170
1st-stage R^2 ($\Phi \cdot H$)	0.839	0.880	0.881	0.793	0.784	0.859
1st-stage R^2 ($\Phi \cdot H \times$DTF)	0.896	0.896	0.890	0.899	0.890	0.896

Note: Baier et al. (2006) do not provide data on average years of schooling for population aged 15 years and over. Φ is the quality of human capital measured by PCA extracted educational output. DALY and EDR are used as instruments for quality-adjusted educational attainment and its interaction with DTF. All regressions include trade openness, FDI inflows/GDP, inflation rate and investment ratio as control variables.

*Significant at 10%; **Significant at 5%; and ***Significant at 1%. See also notes in Table 1.

the 2011 World Development Indicators online database (see http://databank.worldbank.org/ddp/home.do?Step=12&id=4&CNO=2). Data on "the ratio of investment to GDP" are compiled from the 7.0 version of the Penn World Table (PWT 7.0) (see http://pwt.econ.upenn.edu/php_site/pwt_index.php). *POLITY* data are obtained from the "Polity IV project" of the University of Maryland (see http://www.systemicpeace.org/polity/polity4.htm).

Instrumental Variables: Data on "*the estimated death rates per 100,000 population (EDR)*" and "*the disability-adjusted life years per 100,000 population (DALY)*" have been collected from the World Health Organization's Global Health Observatory Data Repository (see http://apps.who.int/ghodata/). These data are available for 2002 and 2004 and thus their average values have been considered in the empirical estimation.

Other Variables: Data on "*Per Capita GDP*" (1990 International Geary-Khamis dollars) over the period 1820–2008 are collected from Statistics on World Population, GDP and Per Capita GDP, 1-2008 AD available at Angus Maddison's homepage (see http://www.ggdc.net/MADDISON/oriindex.htm).

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