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DOES THE DIGITAL DIVIDE MATTER? THE ROLE OF INFORMATION AND COMMUNICATION TECHNOLOGY IN CROSS-COUNTRY LEVEL AND GROWTH ESTIMATES

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The bulk of information and communication technology is made of weightless, implementable, and infinitely reproducible knowledge products (such as software and databases). These products are transferred by telephone lines, accessed through internet hosts, and processed through personal computers. In this work, the coefficient of the labour augmenting factor in the aggregate production function has been estimated using proxies of variables crucially affecting the diffusion of (non-rival and almost non-excludable) knowledge products. This specification provides interesting answers to some of the open issues in the existing growth literature. The most recent information, though available for a limited period, shows that telephone lines, personal computers, mobile phones, and internet hosts significantly affect levels and growth of income per worker across countries. The result is robust to changes in sample composition, econometric specification, and estimation approach.

Keywords: Cross-country growth; ICT; Mankiw Romer Weil

Jel Classification: O31; O33; O47

1 INTRODUCTION

The empirical literature on the determinants of economic growth has progressively tested the significance of factors contributing to economic growth in addition to the traditional labour and capital inputs. Valuable contributions have assessed, among other things, the role of: human capital (Mankiw, Romer and Weil 1992) (from now on MRW), the government sector (Hall and Jones, 1997), social and political stability (Alesina and Perotti, 1994), corruption (Mauro, 1995), social capital (Knack and Keefer, 1997), financial markets (Pagano, 1977; King and Levine, 1992; Wachtel, 2000), and income inequality (Persson and Tabellini, 1994; Perotti, 1996).[1]

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[1] Durlauf and Quah (1998) survey the empirical literature on growth and list something like 87 different proxies adopted to test the significance of additional factors in standard growth models. None of them is akin to proxies adopted in this paper to measure factors affecting ICT diffusion.

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This literature has left the labour augmenting factor of the aggregate production function unspecified. The impact of technological progress on the differences between rich and poor countries has, therefore, been neglected. This is the outcome of the implicit assumption that knowledge could be incorporated into production methods as if it were a public good, freely available to individuals in all countries (Temple, 1999). This approach does not properly consider the nature of information and communication technology (ICT) and its role on growth. The core of ICT is made by weightless, expansible and infinitely reproducible knowledge products (software and databases). These products create value by increasing labour productivity or by adding value to traditional physical products and services. Knowledge products are almost public goods. Expansibility and infinite reproducibility make them non-rivalrous, and copyright (instead of patent) protection makes them much less excludable than other types of innovations such as new drugs (Quah, 1994). Hence, if ICT consisted only of knowledge products, it should be almost immediately available everywhere, no matter the country in which it has been created. This does not occur though as the immediate diffusion and availability of knowledge products is prevented by some 'bottlenecks'.

For example, it is recognised that the diffusion of the internet in developing countries is precluded by inadequacies of the local loop. Despite the increasing capacity of long-distance (national and international) telephone lines, traditional copper wires at the local level are ineffective when large amounts of data need to be transferred quickly (Mustafa, 2003). This increases the costs associated with the internet in terms of money and time, reducing the economic appeal of the new technology.

It is reasonable to expect that obstacles to the diffusion of information be heterogenous across countries. A natural consequence is that they should affect the dispersion of disembodied technical progress and, in the end, the cross-country levels and growth rates of income. In this paper, we shall consider the following potential bottlenecks: (i) the capacity of the network, (ii) the access of individuals to the network in which knowledge products are immaterially transported and exchanged, and (iii) the availability of terminals which process, implement, and exchange knowledge products over the internet.

Economic freedom and the development of financial markets may affect both ICT propagation and its impact on growth. Insufficient access provision and excessive taxation limit the diffusion of personal computers and internet accesses (Quah, 1994). The liberalisation of the telecommunication sector reduces the costs of accessing the network. Financing projects which improve the capacity of the network and the quality of 'peripherals' is easier in well-developed financial markets.[2]

The cross-country diffusion of ICT is also affected by differences in relative factor-costs. The impact of ICT is different according to the relative abundance of the factors (e.g., skilled labour) more intensively employed by the new technology (Antonelli, 2003).

The omitted consideration of ICT is partially justified by the scarcity of data, but has relevant consequences on the accuracy of growth estimates. If ICT variables are proxies for the diffusion of technology, then, in the case they were omitted, the parameters of the other MRW regressors (labour and investment in physical and human capital) would be biased as long as they are correlated with them (*omitted variable critique*). Moreover, the omitted specification

[2] The relationship between ICT and productivity has long been debated over the past three decades. In 1980s and early 1990s, empirical research generally did not find relevant productivity improvements associated with ICT investment (Bender, 1986; Loveman, 1988; Stokey, 1990; Roach, 1991). This research showed that there was no statistically significant, or even measurable, association between ICT investment and productivity at any level of analysis chosen. More recently, as new data were made available and new methodologies were applied, empirical investigations have found evidence that in the second part of 90s, ICT investment was associated with improvements in productivity, intermediate measures, and economic growth (Brynjolfsson and Hitt, 1996; Sichel, 1997; Lehr and Lichtenberg, 1999; Brynjolfsson and Hitt, 2000; Jorgenson and Stiroh, 2000; Oliner and Sichel, 2002). The same authors find similar evidence in 2001 despite the 2001 downward revision of the US GDP and the recession beginning in March 2001 (Jorgenson *et al.*, 2002; Oliner and Sichel, 2002).

of the labour augmenting technological progress biases cross-sectional regressions on the determinants of per capita income level (*cross-sectional constant critique*). In other words, technological progress cannot be treated as a cross-sectional constant, implicitly attributing the same level of technology to every observation (Islam, 1995; Temple, 1999).[3] The solution of fixed effect panel data (Islam, 1995) is a partial remedy, as it takes into account the unobservable individual country effects.

An alternative approach consists in specifying those factors, like ICT in our example, which are expected to be proxies of the unobserved country effects. The inclusion of ICT variables in the estimate may also avoid that uncontrolled heterogeneity in levels of per capita income induces correlation between the lagged level of per capita income and the error term in the convergence regressions, thereby violating one of the required assumptions for consistency of Ordinary Least Squares (OLS) estimates (*cross-country heterogeneity critique*)[4].

In this paper, we use ICT variables to model the unknown country differences in the diffusion of technology. This approach generates a sharp increase in the explanatory power of cross-sectional estimates of the determinants of levels of income per worker. Therefore, it significantly reduces the effects of the cross-sectional constant and omitted variable critiques. The increased goodness of fit in the Gross Domestic Product (GDP) level regression reduces in turn the effects of the cross-country heterogeneity critique making possible a cross-sectional estimate of convergence in growth rates. The robustness of the main results of the paper (significance of both the initial level and the rate of growth of ICT technology in cross-sectional and growth regressions) is accurately tested. With bootstrap standard errors, we find that it is not affected by departures from the normality assumption for the distribution of the dependent variable and we test its robustness to changes in the composition and weight of sample countries. With generalised 2-stage least squares (G2SLS) panel estimates, we find evidence that the ICT-growth relationship is valid also in shorter sub-periods and is not affected by endogeneity.

The paper is divided into four sections (including Introduction and Conclusions). In the second section, we outline our theoretical hypotheses on the role of ICT variables on aggregate growth. In the third section, we present and comment empirical tests of our hypotheses. Section 4 concludes.

2 THE ICT AUGMENTED MRW MODEL: HYPOTHESES AND ECONOMETRIC SPECIFICATION

In this section, we extend the original MRW model to obtain econometric specifications of the cross-country determinants of level and rate of growth of income that include ICT.

2.1 The Determinants of Cross-Country Differences in Levels and Rates of Convergence of Income

We have argued in the previous section that ICT should improve our ability to explain cross-country difference in levels and growth rates of income. We now provide a simple analytical derivation of the following hypothesis:

Hypothesis 1 Factors affecting ICT diffusion are good proxies for the amount of labour-augmenting technological progress in a MRW growth model.[5]

[3] The only relevant exception may be when regressions are run on regions with a certain degree of technological homogeneity such as US regions in Barro and Sala-I-Martin (1992).

[4] According to Evans (1997), this problem can be neglected when 90–95% of heterogeneity is accounted for.

[5] In the following empirical analysis, we compare estimates of the MRW base case with those augmented for ICT variables. Hence, in the case our hypothesis is rejected, we may discriminate between two alternatives: (i) the

Consider a standard MRW production function with physical and human capital:

$$Y_t = F[K_t, H_t, A_t L_t] = K_t^{\alpha} H_t^{\beta} (A_t L_t)^{1-\alpha-\beta} \tag{1}$$

where H is the stock of human capital, L and K are the two traditional labour and physical capital inputs, A is labour-augmenting technical progress, and $\alpha \in (0, 1-\beta)$, $\beta \in (0, 1)$. Physical and human capital follow the standard laws of motion.

$$\dot{K}_t = s_k Y_t - \delta K_t \tag{2}$$

and

$$\dot{H}_t = s_h Y_t - \delta H_t \tag{3}$$

where s_k and s_h are the fractions of income invested in physical and human capital, respectively. δ is the depreciation rate assumed equal for both types of capital. The exogenous growth of the labour input is expressed as:

$$L_t = L_0 \mathrm{e}^{nt} \tag{4}$$

where n and L_0 are the rate of growth and the initial stock of labour, respectively. Differently from MRW, we model labour augmenting technological progress by assuming that most of it is proxied by weightless, infinitely reproducible, knowledge products (software and databases). However, we assume that knowledge products are able to enhance technical progress only if made easily accessible to a large number of individuals. The access to the network, the capacity of the network, and the availability of peripherals which process and exchange knowledge products, thus determine the diffusion of knowledge products. We define ICT as the set of intermediate goods that encourage the diffusion of knowledge products. A simple way to capture the relationship among ICT, knowledge products, and technical progress is to specify the dynamics of technical progress as:

$$A_t = A_{\mathrm{KP}(t)} A_{\mathrm{ICT}(t)} \tag{5}$$

with $A_t = A_0 \mathrm{e}^{gt}$, $A_{\mathrm{KP}(t)} = A_{\mathrm{KP}(0)} \mathrm{e}^{g^t_{\mathrm{KP}}}$, and $A_{\mathrm{ICT}(t)} = A_{\mathrm{ICT}(0)} \mathrm{e}^{g^t_{\mathrm{ICT}}} (g \equiv g_{\mathrm{KP}} + g_{\mathrm{ICT}}) \cdot A_{\mathrm{ICT}}$ is a measure of the stock of ICT factors and g_{ICT} its rate of growth. A_{KP} is the contribution to technological progress of the stock of weightless infinitely reproducible knowledge products and g_{KP} denotes its rate of growth. As shown in Appendix A, the assumptions made in this section imply the following linear relationship between log-income (per labour unit) and its determinants:

$$\begin{aligned} \ln\left(\frac{Y}{L}\right) &= c + \ln A_{\mathrm{ICT}(0)} + g^t_{\mathrm{ICT}} + \frac{\alpha}{1-\alpha-\beta}[\ln s_k - \ln(n+g+\delta)] \\ &\quad + \frac{\beta}{1-\alpha-\beta}[\ln s_h - \ln(n+g+\delta)] \end{aligned} \tag{6}$$

where $c \equiv \ln A_{\mathrm{KP}(0)} + g^t_{\mathrm{KP}(0)}$ is the quasi-public good component of knowledge products and is therefore assumed to be a constant across countries. The difference with the traditional MRW specification is that we reinterpret the intercept and we add two variables to the determinants of ln (Y/L), representing the log of the stock of ICT at the initial period and its rate of growth per time unit. The ICT variables enter in our specification through the labour augmenting term

base case equation fits the data and therefore ICT variables are bad proxies for technical progress; (ii) the base case equation does not fit the data and therefore the hypothesis is rejected because the (MRW) model in which conditional convergence is led by human capital is rejected in our sample period.

which was treated as a cross-sectional constant in the original MRW work.[6] Note also that cross-country differences in the steady state level of per capita income do not depend only on the levelling of population growth and broad capital investment rates. They are also affected by both the initial stock and the growth rate of ICT. A further difference in this equation is that the country specific rate of technology growth plus depreciation ($g + \delta$ in all previous models) is no more treated as fixed and equal to 0.05 for all countries (a rather heroic assumption).[7] In our specification, it varies being crucially influenced by the measured country specific growth rates of ICT.

We also consider the implications of our model for cross-country convergence. In Appendix A, we obtain the following relationship among the changes in income, the determinants of the steady state, and the initial level of income:

$$\begin{aligned}\ln\frac{Y_t}{L_t} - \ln\frac{Y_0}{L_0} = {} & c' + g^t_{\mathrm{ICT}} + (1 - \mathrm{e}^{-\lambda t})A_{\mathrm{ICT}(0)} \\ & + (1 - \mathrm{e}^{-\lambda t})\frac{\alpha}{1-\alpha-\beta}\ln s_k + (1 - \mathrm{e}^{-\lambda t})\frac{\beta}{1-\alpha-\beta}\ln s_h \\ & - (1 - \mathrm{e}^{-\lambda t})\frac{\alpha+\beta}{1-\alpha-\beta}\ln(n+g+\delta) - (1 - \mathrm{e}^{-\lambda t})\ln\frac{Y_0}{L_0}, \qquad (7)\end{aligned}$$

where $c' = g^t_{\mathrm{KP}} + (1\mathrm{e})^{-\lambda t}\ln A_{\mathrm{KP}}(0)$.

Again, the difference with the traditional MRW approach is in the interpretation of the common intercept (which now incorporates the worldwide diffusion of quasi-public knowledge products) and in the fact that convergence may be prevented by differences in both the initial stocks of ICT and/or their rates of growth.

3 EVIDENCE

3.1 The Database and Descriptive Statistics

Variables for our empirical analysis are taken from two sources: the World Bank's World Development Indicators database and Penn World Tables. The dependent variable Y/L is the gross domestic product per working-age person converted into international dollars using purchasing power parity rates,[8] L is the number of people who can be economically active (population aged between 15 and 64). s_k is gross domestic investment over GDP.[9] s_h is a proxy for human capital investment. When data are available, we prefer to use average schooling years of the working population to gross enrolment ratios in our estimates. This is because current enrolment ratios represent the investment of future and not current workers and, even if we lag this variable, it is very difficult to relate it exactly with the human capital investment

[6] Of course, alternative specifications could be acceptable as well. For instance, one might argue that ICT is a production factor and should be treated like physical and human capital. The advantage of our approach is that it takes into account the interactions between the (rival) ICT and the quasi-public component of technological progress.

[7] This is the approach followed by Solow (1956), Mankiw *et al.* (1992), and Islam (1995) among many others.

[8] An international dollar has the same purchasing power over GDP as US dollar in the United States.

[9] As an alternative to WB gross domestic investment to GDP we use the equivalent value provided by World Penn Tables. These data are the result of a UN project which tries to create time–space consistent and comparable information for different countries. To do so it uses survey information on prices of identical capital goods in different countries and perpetual inventory methods to compare replacement values of capital goods. In this way, it tries to reduce at a minimum distortions arising from differences in quality and market structure of capital goods across countries. For a detailed discussion of the methodology and of the critical issues of PWTs (Heston and Summers, 1991).

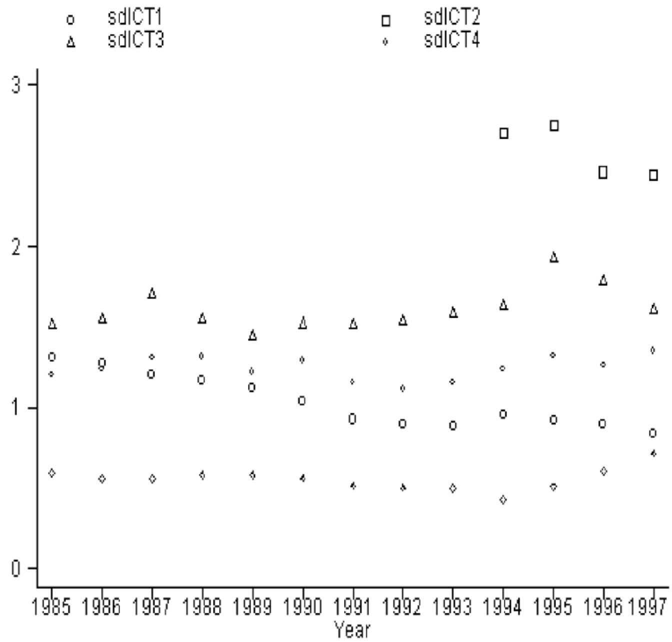

FIGURE 1 Sigma convergence of ICT indicators (standard deviation to mean ratios). sdICT1: standard deviation/mean ratio of main telephone lines per 1000 people; sdICT2: standard deviation/mean ratio of internet hosts (or the number of computers with active IP addresses connected to the internet) per 10,000 people; sdICT3: standard deviation/mean ratio of mobile phones (per 1000 people). sdICT4: standard deviation/mean ratio of personal computers (per 1000 people). The last symbol represents sdICT (composite index): unweighted average of ICT1, ICT2, ICT3, and ICT4.

of current workers (Woßmann, 2003). As a proxy of average schooling years, we use 10-year data calculated by Barro and Lee (2001). Barro and Lee apply the same methodology based on census and survey data on educational attainment levels.[10] In order to measure factors reducing ICT bottlenecks, we consider four different proxies: (i) the number of main telephone lines per 1,000 inhabitants;[11] (ii) internet hosts (per 10,000 people) or the number of computers with active Internet Protocol (IP) addresses connected to the internet (per 10,000) people; (iii) mobile phones (per 1,000 people); and (iv) personal computers (per 1,000 people).[12] Simple statistics of sigma convergence clearly confirm that ICT indicators are far from being freely available public goods as the variability in the spread of ICT across countries is extremely high and persistent (Fig. 1). On average, for the entire observation period, it is higher when we consider internet hosts, i.e., the latest ICT innovation. The cross-country standard deviation of such variable is two and a half its mean whereas, when we consider telephone lines, the standard deviation becomes much closer to the mean.

Table I provide the list of countries included in the sample. For each country, we display the level of the ICT variable in the first and last available year. We have data for 115 countries from 1983 if we just consider the spread of telephone lines, whereas we can rely on much less countries and more limited time, if we consider the other three ICT indicators. For this

[10] We are grateful to a referee for his/her suggestions about the best proxy for human capital.

[11] Telephone mainlines are telephone lines connecting a customer's equipment to the public switched telephone network. Data are presented per 1,000 people for the entire country.

[12] As all these factors are expected to ease the diffusion and processing of knowledge products, a qualitative measure of their 'power' (i.e., the processing capacity of PCs) would improve the accuracy of our proxies. Unfortunately, this information is not available for long time periods and across the countries observed in our sample.

Table I. Data appendix.

Id	ICT variables county	Telephone mainlines (per 1,000 people) First year		Last year		Internet hosts (per 10,000 people) First year		Last year		Mobile phones (per 1,000 people) First year		Last year		Personal computers (per 1,000 people) First year		Last year	
1	Algeria	1965	6.0	1997	47.5	1994	0.004	1997	0.011	1990	0.019	1997	0.508	1990	0.996	1997	4.200
2	Angola	1960	1.3	1997	5.3	1994	0.000	1997	0.015	1993	0.107	1997	0.608	1997	0.700	1997	0.700
3	Argentina	1960	44.3	1997	191.0	1994	0.368	1997	5.321	1989	0.072	1997	56.303	1988	4.430	1997	39.216
4	Australia	1960	148.0	1997	505.0	1994	90.037	1997	381.828	1987	0.271	1997	264.324	1988	103.030	1997	362.162
5	Austria	1960	60.8	1997	492.0	1994	34.002	1997	108.283	1985	1.291	1997	143.742	1988	39.474	1997	210.657
6	Bangladesh	1977	0.9	1996	2.6	1994	0.000	1996	0.000	1992	0.002	1995	0.021			–	
7	Barbados	1960	30.0	1997	404.0	1994	0.000	1997	0.755	1991	1.884	1997	29.888	1995	57.471	1995	57.471
8	Belgium	1960	85.1	1997	468.0	1994	17.250	1997	84.511	1986	0.385	1997	95.490	1988	50.556	1997	235.294
9	Benin	1960	0.9	1997	6.3	1994	0.000	1997	0.022	1995	0.192	1997	0.752	1995	0.547	1997	0.900
10	Bolivia	1980	25.2	1997	68.8	1994	0.000	1997	0.693	1991	0.074	1997	14.929	–	–	–	
11	Botswana	1970	7.3	1997	56.0	1994	0.000	1997	1.553	1995	0.000	1996	0.000	1994	6.993	1996	13.400
12	Brazil	1975	20.3	1997	107.0	1994	0.383	1997	4.196	1990	0.005	1997	27.500	1988	1.786	1997	26.250
13	Burkina Faso	1970	0.2	1997	3.2	1994	0.000	1997	0.046	1995	0.000	1997	0.135	1990	0.113	1997	0.700
14	Burundi	1965	0.4	1997	2.5	1994	0.000	1997	0.012	1993	0.061	1997	0.100	–	–	–	
15	Cameroon	1960	0.5	1997	5.3	1994	0.000	1997	0.054	1994	0.124	1997	0.302	1990	1.304	1995	1.504
16	Canada	1960	278.4	1997	609.0	1994	63.728	1997	227.928	1985	0.463	1997	138.900	1980	4.065	1997	270.627
17	Cape Verde	1960	0.9	1997	81.8	1994	0.000	1997	0.399	1995	0.000	1997	0.049	–	–	–	
18	Cent. Afr. Rep.	1978	1.1	1997	2.8	1994	0.000	1997	0.018	1995	0.013	1997	0.200	–	–	–	
19	Chad	1965	0.4	1997	1.1	1994	0.000	1995	0.000	1995	0.000	1997	0.000	–	–	–	
20	Chile	1960	17.3	1997	180.0	1994	2.181	1997	13.109	1989	0.376	1997	28.082	1988	4.688	1997	54.110
21	China	1975	1.8	1997	55.7	1994	0.005	1997	0.209	1987	0.001	1997	10.476	1988	0.268	1997	5.952
22	Colombia	1960	17.2	1997	148.0	1994	0.327	1997	1.724	1994	2.516	1997	34.807	1992	9.581	1997	33.425
23	Comoros	1970	1.1	1997	8.4	1994	0.000	1995	2.656	1995	0.000	1997	0.000	1970	0.000	1995	0.266
24	Costa Rica	1970	23.1	1997	169.0	1994	2.440	1997	12.295	1992	1.003	1997	18.559	–	–	–	
25	Denmark	1960	182.0	1997	633.0	1994	35.396	1997	259.278	1982	1.406	1997	272.727	1988	58.480	1997	360.200
26	Dominican Rep.	1980	19.0	1997	87.5	1994	0.000	1997	0.031	1990	0.442	1997	16.049	–	–	–	
27	Ecuador	1965	9.3	1997	75.2	1994	0.290	1997	0.903	1994	1.598	1997	13.445	1991	1.905	1995	13.043
28	Egypt Arab Rep.	1960	7.9	1997	55.6	1994	0.027	1997	0.314	1987	0.052	1997	0.116	1994	3.368	1997	7.300
29	El Salvador	1965	4.0	1996	56.1	1994	0.000	1997	0.337	1993	0.302	1997	6.779	–	–	–	
30	Ethiopia	1960	0.3	1997	2.6	1994	0.000	1997	0.000	1995	0.000	1997	0.000	–	–	–	
31	Fiji	1960	13.1	1997	91.9	1994	0.065	1997	0.000	1994	1.438	1997	6.658	–	–	–	
32	Finland	1960	96.6	1997	556.0	1994	133.847	1997	653.631	1982	0.549	1997	417.476	1990	100.000	1997	310.680
33	France	1960	48.0	1997	575.0	1994	14.447	1997	49.840	1986	0.163	1997	99.487	1988	55.258	1997	174.359
34	Ghana	1965	2.2	1997	5.7	1994	0.000	1997	0.153	1992	0.025	1997	1.200	1983	0.000	1997	1.600
35	Greece	1960	21.8	1997	516.0	1994	3.381	1997	18.733	1993	4.615	1997	89.333	1988	12.000	1997	44.762
36	Guatemala	1960	4.4	1997	40.8	1994	0.000	1997	0.839	1990	0.033	1997	6.114	1993	1.047	1995	3.006

(*continued*)

Table I. *Continued.*

Id	ICT variables county	Telephone mainlines (per 1,000 people) First year		Last year		Internet hosts (per 10,000 people) First year		Last year		Mobile phones (per 1,000 people) First year		Last year		Personal computers (per 1,000 people) First year		Last year	
37	Guinea	1960	0.6	1997	2.5	1994	0.003	1997	0.003	1993	0.006	1997	0.377	1994	0.054	1997	0.344
38	Guinea-Bissau	1960	0.5	1997	6.8	1994	0.000	1997	0.088	1995	0.000	1997	0.000	–	–		
39	Haiti	1981	3.6	1997	8.0	1994	0.000	1997	0.000	1995	0.000	1997	0.000	–	–	–	
40	Honduras	1975	5.6	1997	36.8	1994	0.000	1997	0.986	1995	0.000	1997	2.271	–	–	–	
41	Hong Kong China	1960	25.7	1997	565.0	1994	20.591	1997	74.839	1984	0.186	1997	343.077	1988	25.688	1997	230.769
42	Hungary	1960	24.3	1997	304.0	1994	6.627	1997	33.302	1990	0.255	1997	69.314	1988	8.286	1997	49.020
43	Iceland	1960	187.5	1997	617.0	1994	169.551	1997	521.481	1986	10.864	1997	241.544	1990	39.063	1995	205.224
44	India	1960	0.7	1997	18.6	1994	0.004	1997	0.050	1995	0.083	1997	0.924	1988	0.185	1997	2.094
45	Indonesia	1960	0.8	1997	24.7	1994	0.009	1997	0.542	1984	0.011	1997	4.557	1988	0.581	1997	7.960
46	Ireland	1960	39.0	1997	411.0	1994	15.281	1997	90.224	1985	0.085	1997	146.027	1990	106.286	1997	241.300
47	Israel	1960	30.6	1997	450.0	1994	22.645	1997	104.764	1990	3.207	1997	282.572	1988	44.346	1997	186.125
48	Italy	1960	60.9	1997	447.0	1994	4.951	1997	36.849	1985	0.112	1997	204.100	1986	9.353	1997	113.043
49	Ivory Coast	1960	0.9	1997	9.3	1994	0.000	1997	0.175	1995	0.000	1997	2.353	1996	1.351	1997	3.268
50	Jamaica	1960	12.2	1996	140.0	1994	0.308	1997	1.366	1991	1.059	1996	21.667	1994	3.457	1996	4.563
51	Japan	1960	38.9	1997	479.0	1994	7.731	1997	75.794	1981	0.113	1997	303.968	1985	17.355	1997	202.381
52	Jordan	1960	13.7	1997	69.7	1994	0.000	1997	0.383	1990	0.338	1995	2.114	1994	5.769	1997	8.700
53	Kenya	1965	2.8	1997	8.1	1994	0.000	1997	0.160	1992	0.044	1997	0.162	1990	0.348	1997	2.300
54	Korea, Rep.	1965	7.7	1997	444.0	1994	4.020	1997	28.782	1986	0.172	1997	150.217	1988	11.190	1997	150.652
55	Luxembourg	1960	116.1	1997	669.0	1994	12.525	1997	91.435	1985	0.109	1997	160.766	1996	375.303	1996	375.303
56	Madagascar	1965	1.5	1997	2.7	1994	0.000	1997	0.029	1994	0.021	1997	0.300	1997	1.300	1997	1.300
57	Malawi	1965	0.9	1997	4.0	1994	0.000	1997	0.000	1995	0.039	1996	0.366	–	–	–	
58	Malaysia	1960	5.8	1997	195.0	1994	0.815	1997	18.707	1986	0.675	1997	113.364	1988	4.142	1997	46.083
59	Mali	1960	0.3	1997	2.0	1994	0.000	1997	0.028	1995	0.000	1997	0.247	1995	0.278	1997	0.600
60	Malta	1960	29.7	1997	498.0	1994	0.000	1997	20.933	1991	6.333	1997	47.074	1990	14.045	1995	80.645
61	Mauritania	1970	0.4	1997	5.4	1994	0.000	1997	0.000	1995	0.000	1997	0.000	1996	5.319	1996	5.319
62	Mauritius	1960	9.1	1997	195.0	1994	0.000	1997	1.838	1990	2.075	1997	32.456	1987	0.456	1997	78.947
63	Mexico	1960	9.7	1997	96.0	1994	0.720	1997	3.735	1988	0.018	1997	18.154	1988	4.469	1997	37.344
64	Morocco	1960	6.7	1997	49.9	1994	0.000	1997	0.325	1987	0.003	1997	2.709	1993	1.149	1997	2.545
65	Mozambique	1960	1.2	1997	3.6	1994	0.000	1997	0.026	1995	0.000	1997	0.137	1996	0.843	1997	1.600
66	Myanmar	1960	0.5	1997	4.6	1994	0.000	1997	0.001	1993	0.015	1997	0.183	–	–	–	
67	Namibia	1981	31.1	1997	58.0	1994	0.000	1997	2.157	1995	2.258	1997	7.764	1996	12.658	1997	18.600
68	Nepal	1975	0.5	1997	7.7	1994	0.000	1997	0.074	1995	0.000	1997	0.000	–	–	–	
69	Netherlands	1960	90.8	1997	564.0	1994	55.807	1997	218.851	1985	0.331	1997	109.554	1988	50.676	1997	280.255
70	New Zealand	1960	225.9	1997	486.0	1994	87.193	1997	413.927	1987	0.738	1997	149.077	1991	96.802	1997	263.852
71	Nicaragua	1970	8.2	1997	29.3	1994	0.114	1997	1.589	1993	0.079	1997	1.818	–	–	–	
72	Niger	1960	0.2	1997	1.6	1994	0.000	1997	0.035	1995	0.000	1997	0.010	1997	0.200	1997	0.200
73	Nigeria	1960	0.4	1996	3.5	1994	0.000	1997	0.001	1993	0.086	1995	0.117	1993	3.810	1997	5.100

74	Norway	1960	126.8	1997	621.0	1994	111.43	1997	474.635	1981	0.407	1997	380.700	1991	145.54	1997	360.800
75	Pakistan	1960	1.3	1997	18.5	1994	0.000	1997	0.075	1990	0.018	1997	0.797	1990	1.339	1996	4.478
76	Panama	1978	59.6	1997	134.0	1994	0.066	1997	1.434	1995	0.000	1997	6.250	–	–	–	
77	Papua New Guin.	1965	1.9	1996	10.6	1994	0.000	1997	0.176	1995	0.000	1996	0.693	–	–	–	
78	Paraguay	1960	4.6	1997	42.8	1994	0.000	1997	0.470	1992	0.332	1997	16.600	–	–	–	
79	Peru	1965	7.2	1997	67.5	1994	0.073	1997	2.671	1990	0.076	1997	17.869	1995	5.957	1997	12.300
80	Philippines	1965	2.5	1997	29.0	1994	0.050	1997	0.586	1991	0.557	1997	17.687	1988	2.058	1997	13.600
81	Poland	1960	18.1	1997	194.0	1994	2.796	1997	11.225	1992	0.057	1997	22.145	1988	3.968	1997	36.176
82	Portugal	1960	11.5	1997	402.0	1994	5.100	1997	18.247	1989	0.284	1997	151.911	1988	14.344	1997	74.447
83	Puerto Rico	1975	81.1	1997	351.0	1994	0.222	1997	0.298	1987	1.153	1996	45.187	–	–	–	
84	Qatar	1960	13.3	1997	249.0	1994	0.000	1997	4.787	1990	7.856	1997	76.450	1994	46.555	1996	62.724
85	Reunion	1970	18.2	1997	351.0	1994	0.000	1997	0.000	1991	4.484	1997	39.673	–	–	–	
86	Romania	1965	16.0	1997	167.0	1994	0.230	1997	2.659	1993	0.035	1997	8.900	1990	0.431	1997	8.900
87	Rwanda	1960	0.4	1996	2.7	1994	0.000	1997	0.008	1995	0.000	1997	0.000	–	–	–	
88	Senegal	1960	2.9	1997	13.2	1994	0.000	1997	0.313	1994	0.012	1997	0.792	1981	0.002	1997	11.400
89	Seychelles	1965	4.9	1996	196.0	1994	0.000	1997	4.508	1995	4.329	1996	15.132	–	–	–	
90	Sierra Leo.	1965	1.1	1997	3.9	1994	0.000	1997	0.000	1995	0.000	1997	0.000	–	–	–	
91	Singapore	1960	22.7	1997	543.0	1994	15.631	1997	195.502	1988	3.789	1997	273.400	1988	42.105	1997	399.500
92	Solomon Islands	1982	6.1	1997	19.3	1994	0.000	1997	0.050	1994	0.393	1997	1.629	–	–	–	
93	Somalia	1960	0.3	1996	1.5	1994	0.000	1995	0.000	1995	0.000	1997	0.000	–	–	–	
94	South Afr.	1960	37.3	1997	107.0	1994	6.693	1997	28.932	1989	0.107	1997	36.951	1988	4.144	1997	41.570
95	Spain	1960	42.1	1997	403.0	1994	7.053	1997	30.980	1986	0.044	1997	110.433	1988	17.857	1997	122.137
96	Sri Lanka	1960	2.3	1997	17.0	1994	0.000	1997	0.329	1990	0.059	1997	6.183	1990	0.176	1997	4.086
97	Sudan	1960	1.5	1997	4.0	1994	0.000	1997	0.001	1995	0.000	1997	0.136	1994	0.195	1997	1.147
98	Suriname	1975	28.8	1997	146.0	1994	0.000	1997	0.000	1993	2.609	1997	9.359	–	–	–	
99	Swaziland	1970	5.9	1996	24.0	1994	0.000	1997	2.504	1995	0.000	1997	0.000	–	–	–	
100	Sweden	1960	279.3	1997	679.0	1994	84.741	1997	321.464	1981	2.452	1997	358.192	1988	59.242	1997	350.282
101	Switzerland	1960	203.4	1997	661.0	1994	67.597	1997	208.843	1987	0.827	1997	146.685	1988	52.317	1997	394.922
102	Syrian A. R.	1960	8.5	1997	87.7	1994	0.000	1997	0.000	1995	0.000	1997	0.000	1994	0.362	1997	1.700
103	Tanzania	1960	0.7	1997	3.3	1994	0.000	1997	0.020	1994	0.013	1997	0.641	1997	1.600	1997	1.600
104	Thailand	1960	1.4	1997	80.0	1994	0.294	1997	2.111	1986	0.016	1997	33.003	1988	1.842	1997	19.802
105	Togo	1960	0.7	1997	5.8	1994	0.000	1997	0.014	1995	0.000	1997	0.694	1995	3.623	1997	5.787
106	Trinidad & To.	1965	24.7	1997	190.0	1994	0.000	1997	3.236	1991	0.361	1997	13.594	1991	4.237	1995	20.000
107	Tunisia	1960	6.2	1997	70.1	1994	0.061	1997	0.016	1987	0.030	1997	0.821	1990	2.602	1997	8.574
108	Turkey	1960	6.4	1997	250.0	1994	0.308	1997	3.602	1986	0.007	1997	25.596	1988	2.235	1997	20.668
109	Uganda	1965	1.2	1997	2.4	1994	0.000	1997	0.013	1995	0.091	1997	0.240	1995	0.518	1997	1.400
110	Un. Kingdom	1960	96.1	1997	540.0	1994	38.713	1997	148.834	1985	0.883	1997	151.300	1985	37.102	1997	242.373
111	United States	1960	272.7	1997	644.0	1994	121.80	1997	442.013	1984	0.386	1997	206.343	1981	9.217	1997	406.716
112	Uruguay	1965	52.7	1997	232.0	1994	0.543	1997	3.135	1992	0.546	1997	45.732	1995	21.944	1995	21.944
113	Venezuela	1965	19.5	1997	116.0	1994	0.247	1997	2.054	1988	0.098	1997	46.121	1988	5.435	1997	36.638
114	Yemen, Rep.	1980	2.0	1997	13.3	1994	0.000	1996	0.001	1992	0.124	1996	0.554	1997	1.200	1997	1.200
115	Zambia	1965	4.7	1996	9.4	1994	0.087	1997	0.270	1995	0.165	1996	0.329	–	–	–	
116	Zimbabwe	1975	13.2	1997	17.2	1994	0.017	1997	0.237	1995	0.000	1997	0.900	1990	0.202	1997	9.000

reason, we define a composite indicator which is an unweighed average of each of the four normalised ICT indicators (when available). For each estimation, the list of countries included in the sample is reported in Table III.

The number of countries included in the regressions also changes according to the availability of data when we use average schooling years rather than school enrolment ratios to account for human capital investment.

Finally, the interested reader will find in Table III descriptive statistics for the dependent variables for all subsamples used in the cross-section regressions. The descriptive evidence suggests that the dependent variable is not, in general, normally distributed. This fact, neglected by the existing literature, should be taken into account when running regressions in levels and rates of growth.

3.2 Cross-Section Estimates – Levels

In this section, we discuss cross-section estimates of the parameters in Eq. (6).[13]

Table IV compares results from the standard MRW model with the model specified in Eq. (6) using different ICT indicators.[14]

The traditional MRW estimate is compared with two specifications in which ICT indicators are, respectively, computed using the composite index (averaging the four ICT indicators) and the first ICT proxy (number of main telephone lines per 1,000 inhabitants). In the first three columns, we use a school enrolment proxy of human capital, whereas in the second three columns we more conveniently adopt the average schooling years of the working population to measure human capital. To prevent our results from depending on differences in sample size, we fix a constant number of countries for these estimates (79 in the estimates with the enrolment ratio and 65 in the estimates with average schooling years, respectively).[15] Countries are included on the basis of data availability. The estimation period is recent and relatively short (1991–1997).

Our results show that both $A_{\mathrm{ICT}(0)}$ and g_{ICT} are always strongly significant and with the expected sign. Their introduction significantly improves the overall goodness of fit. The model explains almost 90% of the cross-sectional heterogeneity when ICT is proxied by the composite index. Our estimates indicate an elasticity range from 0.2 to 0.6 of the starting period stock of ICT variables ($A_{\mathrm{ICT}(0)}$), suggesting that a 10% higher stock of ICT variables at the beginning of the sample period corresponds to 2–6% higher level of per capita GDP.

Inspection of the implied factor shares shows that they are not substantially changed when we add ICT variables to the traditional MRW specification. Specifically, the human capital share is in the ranges calculated by MRW for the US, or slightly above when we use average schooling years of the working population as proxy of the investment in human capital.[16] The implied share for physical capital is quite low but consistent with empirical evidence on its decline in recent times and with its substitutability relationship with ICT technology. In the same original MRW estimates the physical capital factor share drops from 0.41 in the overall sample to 0.14 in the Organisation for Economic Cooperation and Development (OECD)

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[13] We alternatively perform estimates considering either population in working age or ILO labour force as labour inputs. The ILO labour force includes the armed forces, the unemployed, and first-time job-seekers, but excludes homemakers and other unpaid caregivers and workers in the informal sector. Results are unchanged under the two different specifications and only those considering the first option are provided here.

[14] Equation (6) imposes equality between the coefficient of $\log(n + g + \delta)$ and the sum of the coefficients of $\log s_h$ and $\log s_h$. Running regressions in which this restriction is removed does not provide substantially different results. Evidence is available from the authors.

[15] We are grateful to a referee for pointing out this potential problem in previous estimates.

[16] According to MRW, who compare minimum wage to average manufacturing wage in the US, the human capital factor share should be between $1/2$ and $1/3$.

Table III. Individual countries included in the cross-section and panel regressions.

Eq. (6) with 79 countries	*Eq. (6) with 65 countries*	*Eq. (7) with 92 countries*	*Eq. (7) with 73 countries*	*Panel Eq. (7) with 80 countries*
Algeria	Algeria	Algeria	Algeria	Algeria
Angola	Argentina	Angola	Argentina	Angola
Argentina	Australia	Argentina	Australia	Argentina
Australia	Belgium	Australia	Austria	Australia
Belgium	Benin	Austria	Bangladesh	Austria
Benin	Bolivia	Bangladesh	Belgium	Belgium
Bolivia	Botswana	Belgium	Benin	Benin
Botswana	Brazil	Benin	Botswana	Botswana
Brazil	Cameroon	Bolivia	Brazil	Brazil
Burkina Faso	Canada	Botswana	Cameroon	Burkina Faso
Burundi	Chile	Brazil	Canada	Cameroon
Cameroon	China	Burkina Faso	Chile	Canada
Canada	Colombia	Burundi	China	Chile
Centr. Afr. Rep.	Costa Rica	Cameroon	Colombia	China
Chad	Denmark	Canada	Costa Rica	Colombia
Chile	Dominican Rep.	Centr. Afr. Rep.	Denmark	Denmark
China	Ecuador	Chad	Dominican Rep.	Ecuador
Colombia	Egypt	Chile	Ecuador	Egypt
Costa Rica	Arab Rep Finland	China	El Salvador	Arab Rep.
Denmark	France	Colombia	Finland	Finland
Dominican Rep.	Ghana	Costa Rica	France	France
Ecuador	Greece	Denmark	Ghana	Ghana
Egypt	Guatemala	Dominican Rep.	Greece	Greece
Ethiopia	Honduras	Ecuador	Guatemala	Guatemala
Finland	Hong Kong	Egypt	Haiti	Guinea
France	China	Arab Rep.	Honduras	Hong Kong
Ghana	Hungary	El Salvador	Hong Kong	China
Greece	India	Ethiopia	China	Hungary
Guatemala	Indonesia	Finland	Hungary	Iceland
Guinea	Ireland	France	India	India
Honduras	Italy	Ghana	Indonesia	Indonesia
Hong Kong	Kenya	Greece	Ireland	Ireland
Hungary	Korea Rep.	Guatemala	Israel	Israel
India	Malaysia	Guinea	Italy	Italy
Indonesia	Mauritania	Haiti	Jamaica	Jamaica
Ireland	Mauritius	Honduras	Japan	Japan
Italy	Mexico	Hong Kong	Jordan	Jordan
Kenya	Nepal	China	Kenya	Kenya
Korea	Netherlands	Hungary	Korea	Korea
Madagascar	New Zealand	India	Rep. Malaysia	Luxembourg
Malaysia	Norway	Indonesia	Mauritius	Madagascar
Mali	Pakistan	Ireland	Mexico	Malaysia
Mauritania	Peru	Israel	Nepal	Mali
Mauritius	Poland	Italy	Netherlands	Malta
Mexico	Portugal	Jamaica	New Zealand	Mauritania
Morocco	Senegal	Japan	Norway	Mauritius
Mozambique	Singapore	Jordan	Pakistan	Mexico
Namibia	South Africa	Kenya	Paraguay	Morocco
Nepal	Sri Lanka	Korea Rep.	Peru	Mozambique
Netherlands	Sweden	Madagascar	Philippines	Namibia
New Zealand	Switzerland	Malawi	Poland	Netherlands
Niger	Syrian Arab Rep.	Malaysia	Portugal	New Zealand
Norway	Tanzania	Mali	Romania	Niger
Pakistan	Thailand	Malta	Senegal	Nigeria
Peru	Togo	Mauritania	Singapore	Norway
Poland	Trinidad & Tob.	Mauritius	South Africa	Pakistan
Portugal	Tunisia	Mexico	Spain	Peru
Senegal	Turkey	Morocco	Sri Lanka	Philippines
Sierra Leone	Uganda	Mozambique	Sudan	Poland
Singapore	United Kingdom	Namibia	Swaziland	Portugal
South Africa	United States	Nepal	Sweden	Romania
Sri Lanka	Uruguay	Netherlands	Switzerland	Senegal
Sweden	Venezuela	New Zealand	Syrian Arab Rep.	Singapore
Switzerland	Yemen	Niger	Thailand	South Africa
Syrian Arab Rep.	Rep. Zambia	Nigeria	Togo	Spain

(*continued*)

Table II. *Continued.*

Eq. (6) with 79 countries	*Eq. (6) with 65 countries*	*Eq. (7) with 92 countries*	*Eq. (7) with 73 countries*	*Panel Eq. (7) with 80 countries*
Tanzania	Zimbabwe	Norway	Trinidad & Tob.	Sri Lanka
Thailand		Pakistan	Tunisia	Sweden
Togo		Paraguay	Turkey	Switzerland
Trinidad & Tob.		Peru	Uganda	Syrian Rep.
Tunisia		Phillippines	United Kingdom	Tanzania
Turkey		Poland	United States	Thailand
Uganda		Portugal	Uruguay	Togo
United Kingdom		Romania	Venezuela	Trinidad & Tob.
United States		Rwanda	Zambia	Tunisia
Uruguay		Senegal	Zimbabwe	Turkey
Venezuela		Sierra Leone		Uganda
Yemen		Singapore		United Kingdom
Zambia		South Africa		United States
Zimbabwe		Spain		Uruguay
		Sri Lanka		Venezuela
		Swaziland		Yemen Rep.
		Sweden		Zimbabwe
		Switzerland		
		Syrian Arab Rep.		
		Tanzania		
		Thailand		
		Togo		
		Trinidad & Tob.		
		Tunisia		
		Turkey		
		Uganda		
		United Kingdom		
		United States		
		Uruguay		
		Yemen		
		Rep. Zambia		
		Zimbabwe		

Table III. Descriptive statistics.

Variable	*GDP 1997*	*GDP 1997*	*ΔGDP 1985–1997*	*ΔGDP 1985–1997*
Countries	65	79	73	92
Estimate	*Table* IV	*Table* IV	*Table* VII	*Table* VII
Percentile				
1	7.024	6.692	−0.093	−0.173
10	7.815	7.455	0.242	0.152
20	8.123	7.823	0.355	0.322
30	8.551	8.106	0.427	0.406
40	8.987	8.552	0.498	0.485
50	9.259	9.015	0.551	0.525
60	9.535	9.267	0.590	0.581
70	9.866	9.594	0.640	0.630
80	10.335	10.299	0.745	0.676
90	10.446	10.425	0.918	0.906
99	10.699	10.699	1.303	1.303
Mean	9.200	8.927	0.552	0.552
St. dev.	0.983	1.102	0.267	0.267
Shapiro–Wilk Test	2.324	2.533	0.837	0.444
Prob > z	0.010	0.005	0.201	0.328

Notes: Table reports descriptive statistics and normality tests for the dependent variables used in the cross-section regressions (Tabs. IV and VII). ΔGDP is the log difference of GDP in 2 years considered. Differences in the number of countries included in each regression depend on the availability of data on average schooling years of working population.

Table IV. Cross-section regressions with and without ICT indicators: levels.

	Estimation Period 1991–1997					
	s_h = *Tertiary school enrolment ratio*			s_h = *Average schooling years of working population*		
Variable	*MRW-type estimate*	*Equation (6) ICT1*	*Equation (6) ICT composite index*	*MRW-type estimate*	*Equation (6) ICT1*	*Equation (6) ICT composite index*
$\ln s_k - \ln(g + n + \delta)$	0.44*	0.392*	0.268*	0.42*	0.409*	0.276*
	[4.39]	[4.42]	[2.95]	[3.23]	[3.3]	[2.28]
$\ln s_h - \ln(g + n + \delta)$	0.482*	0.531*	0.423*	1.002*	0.954*	0.633*
	[9.78]	[11.7]	[8.87]	[6.98]	[6.77]	[4.02]
g_{ICT}		0.319**	0.584*		0.33*	0.74*
		[2.83]	[4.12]		[2.03]	[3.69]
$\ln A_{\mathrm{ICT}}(0)$		0.272*	0.583*		0.197*	0.517*
		[4.76]	[5.39]		[2.8]	[3.81]
Constant	4.375*	3.043*	5.159*	2.597*	1.908*	4.579*
	[11.69]	[6.94]	[12.78]	[5.66]	[3.32]	[6.53]
R^2	0.843	0.88	0.892	0.784	0.812	0.839
α	0.23	0.20	0.15	0.17	0.17	0.14
β	0.25	0.28	0.25	0.41	0.40	0.33
Countries	79	79	79	65	65	65

Notes: Table reports result on the estimation of Eq. (6). In the second, third, fifth, and sixth column the standard MRW approach is augmented with ICT variables. ICT1: main telephone lines per 1,000 people. ICT composite index: unweighed average of ICT1, ICT2, ICT3, and ICT4 where ICT2 is the number of computers with active IP addresses connected to the internet) per 10,000 people, ICT3 is the number of mobile phones (per 1,000 people). ICT4 is the number of personal computers (per 1,000 people). g is $g_{\mathrm{ICT}} + g_{\mathrm{KP}}$, where g_{ICT} is the growth rate of the selected ICT variable, and g_{KP} is assumed constant across countries. The proxy used for s_h is indicated in the column header. s_k is Summers–Heston corrected investment to GDP ratio. s_h, s_k, and $g_{\mathrm{ICT}}t$ are calculated as estimation period averages, while the dependent variable takes the value at the end of the period. T-stats are reported in square brackets. We use the percentile and bias corrected approach with 2,000 replications. See Table II for the list of countries included in each regression.
*95% significance with bootstrap standard errors.
**90% significance with bootstrap standard errors.

sample. This change may be explained in the light of our results given the higher contribution of ICT technology to output in the first group of countries. Further support for this hypothesis comes from Jorgenson and Stiroh (2000). They document the dramatic decrease in the selling and rental price of computers in the USA, paralleled by an increase in the same prices for physical capital between 1990 and 1996, and ascribe part of the change in the relative contribution to growth of the two types of capital to high firms and households elasticity of substitution between the inputs.[17]

The re-estimation of the model with bootstrap standard errors shows that the significance of the ICT variables remains strong for all the considered indicators and robust to changes in the composition of sample countries.[18]

[17] The same shift in technological patterns induced by the ICT revolution seems to be an autonomous cause of substitution between ICT and physical capital as ICT investment modifies the trade-off between scale and scope economies. The literature finds that ICT investment fosters the change from a Fordist to a flexible, less-capital intensive, network productive model (see the discussion on the introduction of CAD/CAM technology in Milgrom and Roberts (1990)) in which products and processes are more frequently adapted to satisfy consumers' taste for variety (Barua *et al.*, 1995; Becchetti *et al.*, 2003).

[18] Bootstrapping provides an alternative way of estimating standard errors which does not rely on any priori given distributional form (Efron, 1979; Efron and Stein, 1981; Efron and Tibshirani, 1986). More specifically, in each trial of the bootstrapping procedure we draw with replacement N observations from the N observation dataset (therefore in each trials some countries may have higher weight and other countries may not be included in the sample). We perform 2000 trials and for each of them we compute the coefficient magnitude. The estimate of the standard error of that statistics then depends on the variability of the estimate in the different trials. In this sense, bootstrapping measures the sensitivity of the result to changes in composition of the sample.

3.3 Panel Estimates – Levels

The use of a cross-sectional regression to estimate the determinants of levels of per capita income has been strongly criticised by Islam (1995). His argument is that the labour augmenting A-factor in the aggregate production function represents country specific preferences and technological factors. It is, therefore, not possible to assume that it is absorbed in the intercept and therefore constant across countries (cross-sectional constant critique). Our estimates partially overcome the problem by specifying the technological variable. On the other hand, we take into account the reasonable possibility that some additional country specific variables (deep fundamentals such as ethos or governance parameters such as economic freedom) are omitted. We consider a panel estimate of Eq. (6) in which fixed effects capture all additional country specific variables.

The fixed effect is preferred to the random effect approach as the second implies the assumption of independence between the regressors and the disturbance term.

The advantage of this approach is that it retains more degrees of freedom and we are, therefore, able to estimate the model also with individual ICT indicators, which have not been used in cross-sectional estimates for the reduced number of observations (ICT3, mobile phones per 1,000 people and ICT4, personal computers per 1,000 people). The disadvantage is that we do not have yearly data for schooling years of the working population and we, therefore, have to replace the variable with school enrolment ratios.

Fixed effect panel results on yearly data (1985–1997) confirm the robustness of the significance of the technological variable (Tab. V). Our results are a direct answer to Islam (1995) interpretation of country specific fixed effects in its MRW-type panel estimate. In his specification, country specific technology effects are significantly and positively correlated with GDP growth rates and human capital. Our results show that ICT variables are positive and significant. Their inclusion improves goodness of fit and reduces the joint significance of the fixed effects (Tab. V). Thus, they are formally (in the model) and substantially (in the data) a

Table V. Fixed effects panel regressions: levels.

	Estimation period 1985–1997				
Variable	*MRW-type*	*ICT1*	*ICT3*	*ICT4*	*ICT index*
$\ln s_k - \ln(g+n+\delta)$	0.192	0.176	0.079	0.146	0.097
	[4.92*]	[4.55*]	[2.41*]	[5.28*]	[3.12*]
$\ln s_h - \ln(g+n+\delta)$	0.219	0.203	0.043	0.035	0.086
	[8.34*]	[7.76*]	[2.02*]	[1.65]	[3.87*]
$\ln A_{\mathrm{ICT}}$		0.117	0.061	0.138	0.226
		[5.12*]	[18.34*]	[18.77*]	[15.1*]
Constant	7.12	6.747	8.636	7.917	8.43
	[31.81*]	[29.16*]	[44.07*]	[48.55*]	[43.41*]
R^2 (within groups)	0.261	0.311	0.654	0.635	0.566
R^2 (between groups)	0.196	0.189	0.762	0.858	0.852
R^2 (overall)	0.168	0.176	0.695	0.853	0.849
Obs.	60.71	50.35	190.38	199.22	143.14
F-test	274.93	270.01	279.84	158.01	96.57
F-test $u_i = 0$	426	418	381	426	426
Countries	80	80	76	80	80

Notes: Table reports result on the estimation of Eq. (6) using fixed effects panel regression on yearly data. The dependent variable is the log GDP per working-age person. ICT1 is main telephone lines per 1,000 people. ICT3 is the number of mobile phones (per 1,000 people). ICT4 is the number of personal computers (per 1,000 people). ICT composite index: unweighed average of ICT1, ICT2, ICT3, and ICT4 where ICT2 is the number of computers with active IP addresses connected to the internet) per 10,000 people. g is $g_{\mathrm{ICT}} + g_{\mathrm{KP}}$, where g_{ICT} is the growth rate of the selected ICT variable and g_{KP} is assumed constant across countries. s_h is tertiary school gross enrolment ratio. s_k is Summers–Heston corrected investment to GDP ratio. T-stats are reported in square brackets. See Table II for the list of countries.
*95% significance.

relevant part of the fixed effects measured by Islam (1995). To this respect, the goodness of fit is higher both in terms of within and between group significance, but especially remarkable when we consider between group significance.

This type of estimate may generate an endogeneity problem since the contribution of ICT is no longer split into the two components of initial levels and rates of growth and is, therefore, not completely lagged with respect to the dependent variable. To overcome the problem, we use the G2SLS methodology which combines fixed effect panel estimates with instrumental variables.[19] We use two-to-four-periods lagged values of ICT indicators as instruments.[20] Results show that ICT variables are still significant (Tab. VI). The ICT elasticity in panel estimates is smaller (between 0.07 and 0.35) than the corresponding elasticity in cross-sectional estimates.

Persistence of cross-country differences in the ICT indicators, as documented in Figure 1, suggests that lagged values of ICT indicators are strongly related to the current values. This is an essential requirement for instrumental variables. However, if income levels are strongly autocorrelated, our instruments risk to violate the orthogonality condition with the error term. This problem has no immediate solution as it is hard to contemplate a set of variables that, being related to ICT, do not incur in the same problem.[21]

3.4 Cross-Section Estimates – Growth Rates

The reduced interval for which we have ICT data limits our analysis to short-medium term convergence and prevents us to estimate convergence on the basis of panel data. Nonetheless, as the best specification of Eq. (6) explains almost 90% of the observed cross-sectional heterogeneity our attempt at estimating convergence with a cross-sectional estimate is not severely affected by the cross-country heterogeneity critique (Evans, 1997). Our results are roughly in line with the existing literature and with our theoretical predictions formulated in the previous section. Table VII shows that our ICT-growth model performs better than the MRW model in 90s. The effect of ICT on growth is quantitatively smaller than that on levels, displaying 0.9–0.13 elasticity (a 10% higher stock of ICT variables at the beginning of the sample period corresponds to 0.9–1.3% additional rate of growth in the considered period).

Short-run convergence does not appear to be conditional only to investments in physical and human capitals, it also depends on ICT investments.[22] If we arbitrarily set $(n + \delta + g)$ equal to 0.05 for all countries, our implied λ is larger than that in MRW and lower than that in Solow (1956) and Islam (1995).

Convergence is also slightly stronger when we introduce ICT variables. In interpreting our result on faster convergence, it is necessary to warn that we are working on a reduced and almost non-overlapping sample period with respect to MRW (1985–1997 against 1960–1985). In this period, convergence looks faster when it is conditional on variables relevant for our model.

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[19] Our decision to use G2SLS instead of GMM hinges on a recent result of Erickson (2001) showing that 'The main advantage of GMM is its well-known covariance matrix formula rather than its efficiency with respect to 2SLS... the difference between GMM and 2SLS estimates is likely to be small.' Therefore, the difference between the two approaches is only in the computational simplicity of the variance–covariance matrix.

[20] This estimation would require five consecutive observations on any ICT indicator for each country. To prevent the number of countries from falling dramatically, we include in the regression any country that meets the requirement for at least one specific ICT indicator.

[21] We thank a referee for suggesting a discussion of this potential problem.

[22] The lack of significance of the coefficient of human capital is a well-known result in the literature. Islam (1995) argues that the positive cross-sectional effect of human capital is likely to be outweighed by the negative temporal effect (higher levels of investment in human capital do not produce positive changes in growth).

Table VI. Fixed effects panel G2SLS regressions: levels.

	Estimation period 1985–1997			
Variable	*ICT1*	*ICT3*	*ICT4*	*ICT index*
$\ln s_k - \ln(g+n+\delta)$	0.117	0.201	0.193	0.107
	[3.99]*	[5.63]*	[6.00]*	[4.74]*
$\ln s_h - \ln(g+n+\delta)$	0.486	0.097	0.091	0.444
	[8.98]*	[2.01]*	[1.8]**	[9.81]*
$\ln A_{\mathrm{ICT}}$	0.347	0.094	0.217	0.089
	[6.44]*	[14.47]*	[15.09]*	[1.52]
Constant	3.548	7.597	7.048	5.533
	[7.61]*	[19.86]*	[19.14]*	[17.37]*
R^2 (within groups)	0.730	0.795	0.791	0.218
R^2 (between groups)	0.622	0.744	0.907	0.848
R^2 (overall)	0.632	0.725	0.896	0.840
F-test (overall)	46.72	174.36	164.61	44.05
F-test ($u_i = 0$)	148.15	254.07	160.75	89.25
σ_u	0.707	0.511	0.365	0.520
σ_e	0.083	0.042	0.035	0.074
Obs.	390	196	181	443
Countries	85	51	51	94

Notes: Table reports results on the estimation of Eq. (6) using G2SLS panel regression on yearly data. The dependent variable is the log GDP per working-age person. ICT1 is main telephone lines per 1000 people. ICT3 is the number of mobile phones (per 1000 people). ICT4 is the number of personal computers (per 1000 people). ICT composite index: unweighed average of ICT1, ICT2, ICT3, and ICT4 where ICT2 is the number of computers with active IP addresses connected to the internet) per 10,000 people. g is $g_{\mathrm{ICT}} + g_{\mathrm{KP}}$, where g_{ICT} is the growth rate of the selected ICT variable and g_{KP} is assumed constant across countries. s_h is secondary school gross enrolment ratio. s_k is Summers–Heston corrected investment to GDP ratio. T-stats are reported in square brackets. $\ln A_{\mathrm{ICT}(t)}$ and is instrumented with $\ln A_{\mathrm{ICT}(t-2)}$, $\ln A_{\mathrm{ICT}(t-3)}$, and $\ln A_{\mathrm{ICT}(t-4)}$.
*95% significance.
**90% significance.

Table VII. Cross-section regressions with and without ICT indicators: growth rates.

	Estimation period 1985–1997			
	s_h = Tertiary school enrolment ratio		*s_h = Average schooling years of working population*	
Variable	*MRW-type estimate*	*Eq. 7 with ICT composite index*	*MRW-type estimate*	*Eq. 7 with ICT composite index*
$\ln s_k - \ln(g+n+\delta)$	0.418**	0.322**	0.395**	0.225**
	[5.46]	[4.5]	[3.73]	[2.29]
$\ln s_h - \ln(g+n+\delta)$	0.084*	0.022	0.098	0.016
	[2.36]	[0.6]	[1.13]	[0.21]
g_{ICT}		0.115**		0.174**
		[4.84]		[5.16]
$\ln A_{\mathrm{ICT}(0)}$		0.092**		0.135**
		[3.84]		[2.76]
$\ln Y/L_{1985}$	−0.150**	−0.242**	−0.115	−0.311**
	[−3.08]	[−4.73]	[−2.14]	[−3.57]
Constant	−0.990**	0.738	−1.137**	1.955
	[−2.08]	[1.21]	[−2.04]	[1.85]
R^2	0.395	0.533	0.286	0.489
Impliedλ	0.025	0.033	0.025	0.038
Countries	92	92	73	73

Notes: Table reports results on the estimation of Eq. (7). The dependent variable is the log difference of GDP per working-age person (1985–1997). See Table II for the list of countries included in each regression.
*99% significance.
**90% significance.

Sensitivity analysis shows that our results are confirmed even when we use bootstrap standard errors (considering either the composite ICT index or the PC diffusion variable as proxies of ICT). Moreover, they are robust to the inclusion of three by three combinations of all additional variables used in Levine and Renelt (1992) with several different qualitative indicators relating to institutions and macroeconomic policies (omitted).

4 SUMMARY AND CONCLUSIONS

The technological revolution originated by the progressive convergence of software and telecommunications and fostered by the progress of digital technology is dramatically changing the world. This revolution has sharply reduced transportation costs, deeply modified geographical patterns of productive factors across the world and significantly increased the productivity of human capital. We believe that ICT mainly consists of a core of reproducible and implementable knowledge incorporated in quasi-public 'knowledge products' such as software and database libraries, which would be accessible to everyone in a frictionless world. However, we argue that possible frictions are represented by capacity and access to the network and by the availability of efficient terminal nodes, which allow to process, exchange, and reproduce these knowledge products. Domestic growth is thus likely to be affected by the quality of telephone lines and by the number of personal computers, mobile phones, and internet hosts. These factors are expected to reduce or remove bottlenecks which may limit the diffusion of technological knowledge.

The empirical literature on growth has so far neglected this phenomenon for lack of available information or under the theoretical assumption that technology is a public good which can be easily incorporated without costs into domestic aggregate production functions. Our empirical evidence demonstrates that this is not the case. Even though for a more limited time span than in traditional empirical analyses, our results support the theoretical prediction of a significant role of ICT diffusion in explaining levels and rates of growth of income per worker. They also show that the ICT factor is an additional crucial determinant of convergence. These findings are robust to changes in specification, sample composition, and estimation approach. Our conclusion is that the ICT factors contribute to explaining conditional convergence. It bridges the gap between pessimistic concerns that cross-country differences in income are structural and are going to persist, and optimistic views believing that those who lag behind will be able to catch up. By collecting additional information on ICT diffusion in the next years, we will be able to know whether ICT contribution to growth is an empirical regularity.

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A APPENDIX

Formal Derivation of Equations (6) and (7)

By rewriting the production function in terms of output per efficiency units as $y = k^{\alpha}h^{\beta}$, we can obtain the two standard growth equations:

$$\dot{k}_t = s_k y_t - (n + g + \delta)k_t \tag{A1}$$

$$\dot{h}_t = s_h y_t - (n + g + \delta)h_t \tag{A2}$$

where $g = g_{\mathrm{ICT}} + g_{\mathrm{KP}}$. If we set the growth of physical and human capitals equal to zero in the steady state we find:

$$k^* = \left(\frac{s_k^{1-\beta} s_h^{\beta}}{n + g + \delta}\right)^{1/(1-\alpha-\beta)} \tag{A3}$$

$$h^* = \left(\frac{s_k^{\alpha} s_h^{1-\alpha}}{n + g + \delta}\right)^{1/(1-\alpha-\beta)} \tag{A4}$$

The production function is:

$$\frac{Y}{L} = Af(k^*, h^*) = A_{\mathrm{KP}(0)} e^{g_{\mathrm{KP}}^{t}} A_{\mathrm{ICT}(0)} e^{g_{\mathrm{ICT}}^{t}} (k^*)^{\alpha} (h^*)^{\beta} \tag{A5}$$

By replacing h^* and k^* into the production function and taking logs we obtain Eq. (6).

Under Hypothesis 1, it is possible to show that, in the proximity of the balanced growth path, y converges to y^* at the rate $(1 - \alpha - \beta)(n + g + \delta) \equiv \lambda$. This implies that:

$$\frac{d \ln y_t}{dt} = -\lambda[\ln y_t - \ln y^*] \tag{A6}$$

Solving the previous equation yields:

$$\ln y_t - \ln y^* = \mathrm{e}^{-\lambda t}[\ln y_0 - \ln y^*] \tag{A7}$$

If we add $\ln(y^*) - \ln(y_0)$ to both sides we obtain an equation for the rate of growth:

$$\ln y_t - \ln y_0 = -(1 - \mathrm{e}^{-\lambda t})[\ln y_0 - \ln y^*] \tag{A8}$$

Replacing $\ln y^*$ with our solution we get:

$$\begin{aligned} \ln y_t - \ln y_0 = {} & (1 - \mathrm{e}^{-\lambda t})\frac{\alpha}{1-\alpha-\beta}\ln s_k + (1 - \mathrm{e}^{-\lambda t})\frac{\beta}{1-\alpha-\beta}\ln s_h \\ & - \ln(1 - \mathrm{e}^{-\lambda t})\frac{\alpha+\beta}{1-\alpha-\beta}\ln(n + g + \delta) - (1 - \mathrm{e}^{-\lambda t})\ln y_0 \end{aligned} \tag{A9}$$

which implies Eq. (7).