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Information and Communication Technologies and Productivity Growth: A Survey of the Literature

Tobias Kretschmer

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INFORMATION AND COMMUNICATION TECHNOLOGIES AND PRODUCTIVITY GROWTH – A SURVEY OF THE LITERATURE

Tobias Kretschmer[1]

ABSTRACT

This paper presents a review of existing studies on dynamic, macroeconomic effects of the ICT on productivity and growth.

RÉSUMÉ

Ce rapport présente un survol des études existantes sur les effets macro-économiques des TIC sur la productivité et la croissance.

[1] Ludwig Maximilians University Munich (t.kretschmer@lmu.de). The views expressed in this paper are those of the author and should not be attributed to the OECD, or its member countries.

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INFORMATION AND COMMUNICATION TECHNOLOGIES AND PRODUCTIVITY GROWTH – A SURVEY OF THE LITERATURE

1. Introduction

The wealth of nations and their economic fortunes are ultimately driven by productivity. More productive workers earn higher wages and experience higher living standards than past generations. Hence, studying the driving forces behind productivity growth is an important question for researchers and policymakers alike. In Europe, it is especially interesting as for much of the recent past it has been lagging behind in many of the relevant measures of economic growth and wellbeing, including productivity.

Post-1995, the United States experienced another acceleration of productivity growth which Europe did not, and most academics and policymakers point to the sizable differences in investment in Information and Communication Technologies (ICT) between the United States and other economic regions as a key reason for this. In particular, much of it originated in industries that produced or used ICT intensively. Given the commonly accepted wisdom that investment in ICT generates economic growth governments initiated policies to foster the adoption of ICT. In the United States for instance, President Obama most recently appealed to lay down broadband lines though the heart of inner cities and rural towns all across America. Such broadband deployment strategies and funding of up to USD 7.2 billion for broadband planning and deployment initiatives in the American Recovery and Reinvestment Act of 2009 indicate that the scepticism regarding the general impact of ICT has vanished. Similar to the United States, Europe set up comparable initiatives: "Europe needs download rates of 30 Mbps for all of its citizens and at least 50% of European households subscribing to internet connections above 100 Mbps by 2020. The Digital Agenda aims to turn this ambition into reality by stimulating investments and proposing a comprehensive radio spectrum plan."

This short paper relies on some of my recent work on the topic. As a review of the existing literature, it is necessarily incomplete and selective. However, there is a general shortage of recent studies that take a methodological approach to screening the literature and, more importantly, presenting the headline findings in a coherent and parsimonious way. This paper is an attempt to do that. While doing so, I hope to point out areas for future research while also summarising what we do know (and what we do not know) about the impact of ICT on economic growth.

Given that even different surveys and meta-analyses arrive at different results as we will see in the following section, this study summarises, organises and compares the divergent empirical results. Particularly, the variation and vastness of existing studies and the resulting abundance of quantifications of the ICT impact make it difficult for policymakers to base decisions on unambiguous and convincing evidence. Further, this study compares both the empirical approaches and their respective results on the growth impact of ICT. To quantify the impact of ICT on productivity growth we classify studies by three different dimensions: *i)* the employed method, where we distinguish non-parametric approaches – primarily growth accounting exercises, and parametric techniques – mainly econometric estimations of production functions; *ii)* the aggregation level: country, industry and firm level; and *iii)* the ICT product/measure: IT (hardware/software), data communication (internet/broadband), telecommunication (mobile), and ICT (in its most extensive definition). We focus on studies in which the dependent variable mainly is represented by productivity or productivity growth although other concepts like output are considered in the literature as well, see *e.g.* Schreyer and Pilat (2001). Not included in this survey are studies on consumer surplus and ICT effects on employment, wages or innovation as well as quality and variety of products. The main findings show that there is a substantial variance in ICT elasticities depending on the methodology employed. While growth accounting exercises show different ICT effects for the United States and Europe, with a lower impact in the latter, econometric estimations provide no significant country differences. Moreover, there is broad evidence that over the last two decades an increase of ICT by 10 % translated into higher productivity growth of 0.5 to 0.6 %.

The remainder of the paper is organised as follows. Section 2 lists and discusses the existing surveys on the topic. Section 3 outlines the general nature of ICT and its ability to serve as a general purpose technology. Section 4 compares different empirical approaches of estimating the effect of ICT on productivity growth, while Section 5 provides an overview of the findings in the published empirical literature. This section also includes a discussion on measurement and identification problems, which typically occur when estimating the impact of ICT on productivity. Finally, Section 6 summarises the key findings of the survey and concludes.

2. Existing surveys of the literature

Besides its productivity enhancing effects, ICT by now has become an integral part of people's everyday lives, including the economic sphere. Hence, ICT has been subject to a plethora of studies on how exactly ICT is changing the economy. While on the one hand this helps illustrate the various aspects of how ICT affects production processes, efficiency and output growth, the abundance of studies also causes confusion arising from a broad literature at different levels of aggregation, studying different ICT products and using different methods. Further, many of the studies have contradictory findings both at the qualitative (*e.g.* finding different answers to the question of whether ICT is a General Purpose Technology) and the quantitative (*e.g.* obtaining different point estimates for the output elasticity of ICT investment) level. The large number of existing studies and findings has triggered a number of reviews as summarised in Table 1.

In his meta-analysis, Stiroh (2005) summarises the effects of ICT on productivity and output by estimating them econometrically. He shows that the inclusion of fixed effects or estimation in first differences tends to lower the estimated ICT elasticity, while more aggregated data or utilisation of more recent data revisions tends to raise it. According to Brynjolfsson and Yang (1996), who surveyed more than 150 studies, there were neither robust findings on the link between IT and productivity during the 1980s and early 1990s, nor was it possible to measure this accurately due to lack of data and use of inadequate analytical methods.

By contrast, Melville *et al.* (2004) conclude that IT investments indeed provide value, but the impact of IT spending depends on levels of complementary resources, competitive climate, and the general macroeconomic environment. Moreover, synergies between technical and human IT resources only provide short-lived competitive advantage. In their survey on broadband and its contributions to economic growth Holt and Jamison (2009) suggest that broadband has had a positive impact overall, but the quantitative impact could not be measured with great precision. The review by Oz (2005) highlights the challenges researchers face and proposes a simple theory to explain the diminishing contribution of IT.

Table 1. Overview over existing surveys of the ICT literature

Study	**Method**	**Results**
Brynjolfsson and Yang (1996)	Written survey based on over 150 studies.	Discusses explanations for the productivity paradox, measuring the IT output link was practically impossible due to lack of data and use of inadequate analytical methods.
Brynjolfsson and Hitt (2000)	Literature survey on how IT is linked to higher productivity and organisational transformation, based mainly of firm-level studies.	IT performance depends of complementary institutional investments and these investments lead to improvements in intangible aspects. These factors are not well captured by traditional macroeconomic measurement approaches hence the Solow Paradox.
Baily (2012)	Summarises growth accounting and case study evidence and asses other indicators of structural change.	IT is an important, but not the only cause of the productivity resurgence in the 1990s. Competition and globalisation were the further basic drivers.
Dedrick *et al.* (2003)	Written survey on 19 firm level and 15 country level studies between 1987-2002.	Productivity paradox refuted, wide range of IT investments among different organisations can be explained by complementary investments in organisational capital.
Melville *et al.* (2004)	Develop a model of IT business value added on resource based view to review the literature.	IT investments provide value, but impact depends on level of complementarity resources, competitive climate, general macroeconomic environment. Synergies between technical and human IT resources yield competitive advantage.
Stiroh (2005)	Meta analysis (20 studies from 1994-2002).	Study characteristics explain about 35%% of the saturation in the IT elasticities. Median elasticity at 0.046.
Draca *et al.* (2006)	Survey micro and macro literature.	Macro studies meanwhile show evidence of ICT impact. In micro studies the effect is larger than the neo-classical contribution would expect, which is due to organisational complements.
Holt and Jamison (2009)	Literature survey on broadband studies.	Broadband has positive impact, but cannot be measured with any precision.

3. Is ICT a general purpose technology?

It is often argued that ICT is a "special" technology in the sense that it affects a multitude of sectors and economic activities, and most importantly makes other sectors more productive. That is, a narrow definition of ICT investment would not capture the true impact of ICT on the economy. Rather, ICT is often considered a general purpose technology (GPT).

The idea of ICT representing a GPT is based on concepts associated with ICT investments going beyond the notion of conventional capital equipment and being more of an "enabling technology" (Jovanovic and Rousseau, 2005). This may be especially true as knowledge has become qualitatively and quantitatively more important to economic activities. ICT facilitates communication and the creation of new knowledge through more efficient processes of collaboration and information processing. In firms, this property of ICT can often be observed. Faster information processing might allow firms to think of new ways of communication with suppliers or arranging distribution systems. Processes can be reorganised and streamlined, which allows for a reduction in capital needs through better utilisation of equipment and reduction in inventories or space requirements. Increased communication reduces co-ordination costs and the number of supervisors required. More timely and widespread transfer of information enable better decision making and reduces labour costs (Arvanitis and Loukis, 2009; Atrostic *et al.*, 2002; Gilchrist *et al.*, 2001). Lower communication and replication costs let businesses innovate by offering new products (Brynjolfsson and Saunders, 2010).

Scholars interested in transaction costs consider communication technologies as lowering the fixed costs of acquiring information and the variable costs of participating in markets (Norton, 1992; Leff, 1984), thus initiating a shift towards market-based solutions. In these examples, the productivity enhancing effects of ICT previously mentioned are associated with spillovers. Spillovers constitute positive externalities and lead to excess rates of social return over private rates of investment eventually affecting many sectors in the economy (Jaffe *et al.*, 1993). The notion of new ideas or techniques that influence the economy on a broad basis was first published by Bresnahan and Trajtenberg (1995), who coined the phrase of GPTs. The main characteristics of a GPT are the following:

i) applicability across a broad range of uses – "pervasiveness";

ii) wide scope for improvement, experimentation and elaboration, continuously falling costs – "improvement"; and

iii) facilitating further product and process innovations – "innovation spawning".

Although the concept of spillovers is intuitively appealing, in practice it can take a long time to fully transform business processes to reap the full benefits of GPTs (David, 1990; David and Wright, 1999).

In the case of spillover effects from ICT, its capacity to serve as a GPT is reflected in the dramatic ICT price decreases leading to a substitution of ICT equipment for less productive assets (Jorgenson, 2005). Generally, the focus of GPT-related ICT studies has been on the price of computers and embedded semi-conductors as the foundation of ICT innovations and it is often thought to originate with improvements in tangible hardware equipment, often described by Moore's Law (Moore, 1965).

Regarding the surge in United States productivity during the period of the New Economy, a broad consensus attributes strong IT investment to be the main driving force, where much of it originated in the ICT-producing sectors. Nevertheless, there is at least some indication that efficiency gains from implementation of more productive investment equipment were not limited to the production sectors only, but spilled over to industries that heavily used these new technologies as well. This became most relevant during the second surge of the United States economy post-2000, which was much more broad based

(Stiroh and Botsch, 2007). It is particularly this latter characteristic that makes ICT likely to be a GPT, since computers and related ICT equipment are expected to be utilised in most sectors of the economy eventually as digitisation continues.

Although it might be reasonable to claim that productivity gains from ICT can be found all around daily business life, quantifying the effect of spillovers from ICT is difficult, especially as these effects are hard to isolate. Thus, this survey will also provide a closer look on how spillovers of ICT work and the current status of the existing empirical evidence.

4. Comparing the empirical approaches

Growth accounting

There are different econometric approaches to assess the impact of ICT on productivity growth which can be classified as either parametric or non-parametric techniques. A well-established representative of the latter is the method of growth accounting, based on the seminal paper by Robert Solow on technical change and the aggregate production function (Solow, 1957), and which discussed in Barro (1999) and Aghion and Howitt (2007).

Generally, non-parametric approaches employ properties of the economic theory of production to determine empirical measures of the parametres of a production function by constructing economically defined index numbers. A prerequisite for an exact identification of the parametres is the validity of neoclassical assumptions like the possibility to represent production processes by production functions, which may be separable by different inputs, competitive factor markets (price takers) and efficient producer behaviour (profit/cost maximisation/minimisation). In parametric techniques, econometric methods are applied to estimate the parametres of a production function directly. These parametric approaches will be discussed in detail in the subsequent section.

Growth accounting exercises provide a well-established tool to examine how much of a country's or industry's growth in output can be explained by growth in inputs, especially by growth in different types of capital input. Steady advances in productivity measurement of input factors over the last decades nowadays enable researchers to distinguish between appropriately measured ICT and non-ICT capital based on national statistics (OECD, 2001). A number of researchers developed growth accounting into a well-tested approach to quantify the ICT contribution to economic and productivity growth (Jorgenson *et al.*, 2005b; Jorgenson and Timmer, 2011; van Ark *et al.*, 2003; Inklaar *et al.*, 2005; Timmer and van Ark, 2005; Inklaar *et al.*, 2007).

The strength and intuitive appeal of the methodology lies in its relatively easy determination of the sources of output and productivity growth according to a well-designed and consistent economic framework. Nevertheless, it does not allow for uncovering causal relationships. Also, the strong assumptions underlying the theoretical framework ultimately affect the interpretation of productivity and technology measures.

To construct an index that measures the contribution of combined inputs, the growth rates of the input factors (*i.e.* capital and labour) have to be weighted appropriately. Following production theory and simplifying assumptions, factor income shares are generally used as weights. These income shares approximate production elasticities, *i.e.* for labour for example, the shares resemble the share of labour compensation in total costs. Similar to output elasticities in econometric estimations of production functions, these elasticities are interpreted as the effect of a 1 % change in a specific input on output growth. Starting with a Cobb-Douglas production function with ICT and non-ICT capital and labour as inputs and a residual A, the function can be log-linearised and differenced and ultimately divided by hours worked on both hand sides to generate a feasible growth accounting equation in exponential growth rates:

$$\Delta \ln y = \bar{v}_{K_{NIT}} \Delta \ln k_{NIT} + \bar{v}_{K_{IT}} \Delta \ln k_{IT} + \bar{v}_L \Delta \ln L_Q + \overline{w}_{NIT} \ln A_{NIT} + \overline{w}_{IT} \ln A_{IT} \quad (1)$$

where, $\Delta\ln y$ resembles labour productivity growth (output per hour worked), $\Delta\ln k_{NIT}$ is non-ICT capital deepening (non-ICT capital input per hour worked), $\Delta\ln k_{IT}$ is ICT capital deepening (ICT capital input per hour worked), and $\Delta\ln L_Q$ represents labour quality growth (growth in labour composition).

The contributions to labour productivity growth are derived by weighting each of the factor growth rates by their respective weights v (two-period averages), which correspond to the revenue share of each factor in total output. Given the assumptions of perfect competition and constant returns to scale these input shares of capital provide an exact measure of the elasticity.

The residual A in equation (1) is called Total Factor Productivity (TFP) or Solow residual, and it exhibits positive growth rates whenever the growth rate of the volume of output rises faster than the growth rate of all combined inputs. Rather than an interpretation of the residual as pure technological change, TFP resembles a host of unobserved factors that affect the improvement in overall efficiency of how output is produced (Schreyer, 2001). Thereby, TFP does not capture the effects of technological change on growth which are already measured by quality improvements of capital and labour and which are referred to as embodied technological change (Jorgenson, 1966). In fact, TFP represents all those technological improvements that are not directly captured by quality changes and thus represents so-called disembodied technological change. However, Aghion and Howitt (2007) argue on innovation embodied in capital that "it is hard to separate the influence of capital accumulation from the influence of innovation". In fact, because the precise quality-adjusted real price decrease is difficult to assess and national income accountants tend to be very careful regarding any data manipulation, the typical adjustments are too cautious resulting in too low TFP in upstream markets and vice versa for downstream industries.

Reverting to equation (1) residual growth is separated into TFP growth from non-ICT intensive sectors and ICT-intensive sectors. Consequently, industry TFP growth rates are weighted with their share of industry output of non-ICT intensive and ICT-intensive sectors in total output, respectively. ICT-intensive sectors usually comprise ICT-producing and ICT-using sectors, whereas ICT-using sectors are often derived from an industry taxonomy that classifies sectors according to their IT capital shares (*i.e.*, for example, nominal IT capital as a share of total capital) being above some kind of threshold (*e.g.* the median of all industries) (Stiroh, 2002b, 2006; Jorgenson *et al.*, 2005b; Baily and Lawrence, 2001; Bosworth and Triplett, 2004). Non-ICT intensive industries are determined as the residual.

The impact of ICT in the neoclassical growth accounting framework is theoretically based on the idea that an increase in ICT capital deepening (*i.e.* more ICT investment per employed labour input) is triggered by rapidly falling IT prices. This was especially the case during the New Economy, which led to an increase in the rental price of ICT equipment. In addition, rental prices of ICT are affected by rapid depreciation, which raises rental costs of ICT relative to other assets. Hence, ICT capital must have larger marginal products to cover the high rental prices than other capital assets. The key critique of the growth accounting method is in not explicitly accounting for the underlying causes of growth. Rather, it allows for the quantification of the proximate sources of growth in a systematic and consistent neoclassical framework. But in its most original form the framework does not consider a number of specific growth drivers including adjustment costs, variable factor utilisation, deviations from perfect competition and constant returns to scale, outsourcing and offshoring, management expertise, or intangibles that are omitted from official data accounts (Oliner *et al.*, 2007).

More recent generations of growth accountants try to overcome these conceptually hurdles. On the notion of ICT being a GPT, the neoclassical assumptions of the growth accounting framework do not provide accelerations in TFP growth outside the ICT production sector. The fall in input prices implies substitution between inputs of different marginal products, but it does not consider spillover effects and shifts of production functions of other sectors. These spillover effects would be what by definition characterises the nature of GPTs.

Productivity estimations

The econometric approach of estimating the production equation avoids postulating the relationship of production elasticities and income shares that implies perfect competition and may not correspond to reality. In contrast the estimation procedure is used to determine whether a variable is a significant factor in productivity growth. The regression equation like the growth accounting equation is derived from the Cobb-Douglas Function and is estimated as (see Brynjolfsson and Hitt, 1995; Brynjolfsson *et al.*, 2003):

$$\ln Q_{it} = \beta_1 \ln C_{it} + \beta_2 \ln K_{it} + \beta_3 \ln L_{it} + controls + \varepsilon_{it} \quad (2)$$

where Q is output, which in many firm level and industry level studies is measured as value added. In country studies though the GDP measure as a gross output measure prevails. C is the ICT capital, K the capital stock of non ICT goods and L the labour input.

The overwhelming majority of the production functions are estimated with panel data. Here, i stands for the observational unit, *i.e.* either country, industry or firm, t represents the time period, most commonly measured in years. The most commonly used control variables in addition to time dummies are industry, region and age controls in firm level studies. Some studies control for the observational unit in fixed effect models to capture any time-invariant idiosyncratic productivity effect.

The coefficient β_1 is the IT elasticity and corresponds to the v_{kIT} calculated from national accounts in growth accounting. The benefit of the estimation is that the IT effect is tested statistically instead of postulated as in the growth accounting exercise.

However, due to endogeneity issues, this causal test also has limitations. The main concern is that ICT investment is not exogenous but the decision is linked to output and productivity. To this date no real exogenous experiment is known that explains ICT investment, therefore most studies resort to econometric techniques to conduct robustness checks and assess causality. For firm studies it is most common to exploit the panel nature of the data by using dynamic panel data models to instrument ICT with lagged values, often with an Arellano-Bond System GMM estimator (as applied by Brynjolfsson and Hitt, 1995; Hempell, 2005b; Tambe and Hitt, 2011). Another possibility is the use of the time series behaviour of other inputs to make corrections for estimates of capital coefficients with the Levinsohn-Petrin (LP) estimator (as applied by Tambe and Hitt, 2011). Several country studies build structural models to explicitly estimate the different simultaneous influences in three or four simultaneous equations (Koutroumpis, 2009; Röller and Waverman, 2001). Finally, an alternative approach was adopted in Czernich *et al.* (2011), who estimate the degree of broadband penetration by means of a first stage diffusion equation, thus making use of the time variation of broadband penetration while avoiding problems of reverse causality through use of an exogenous instrument.

The Cobb-Douglas functional form is fairly restrictive with assumptions such as a substitution elasticity among its inputs being equal to one and homotheticity, which indicates that the relative demands for the inputs are independent of the level of output. Therefore other more flexible functions have been proposed for estimation (Berndt, 1991; Mefford, 1986). The constant elasticity of substitution or CES function allows, as the name suggests, for other values of the elasticity of substitution among its inputs and adds the term $\theta[\ln K - \ln L]^2$ to the Cobb-Douglas production function. The translog function allows for non-homotheticity and adds the quadratic terms and the interacted term of all inputs to the function. A number of firm-level IT studies consider the more flexible translog function in addition to the Cobb-Douglas function (*e.g.* Brynjolfsson and Hitt, 1995; Dewan and Min, 1997; Hempell, 2005a).

5. Summary of existing results

For an overview of the existing research, Table 2 lists the most cited articles for every field of research, where a field is determined by the aggregation level and the ICT good at the focus of the study. As the rate of the Google Citation Index indicates, the most active fields were firm level studies of IT on productivity and country studies on the ICT effect. The two studies cited in the latter field (ICT-country) are both growth accounting studies, while the most cited IT-firm and communication-country studies are productivity estimations. The newest field is the study of broadband on productivity, while to date no firm-level studies on voice-communication or industry studies on broadband exist.

Table 2. Overview of the most cited studies

ICT measure	***Aggregation level***		
	Firm	**Industry**	**Country**
Telco		Greenstein and Spiller (1995) Correa (2006)	Röller and Waiverman (2001) Hardy (1980)
Broadband	Grimes and Ren (2009)		Lehr *et al.* (200)
IT	Bresnahan *et al.* (2002) Brynjolfsson (1996)	Siegel and Griliches (1991) Stiroh (1998)	Gordon (2000) Jorgenson and Stiroh (1999)
ICT	Bertschek and Kaiser (2004) Hempell (2005b)	Stiroh (2002a) Morrison (1997)	Olmer and Sichel (2000) Jorgenson (2001)

Growth accounting studies

One important indicator that most growth accounting studies report and therefore can be easily compared is the contribution of ICT to labour productivity in per cent. It is calculated by adding up the effect of ICT capital deepening and TFP growth in the ICT producing industry. These two summands terms reflect a contribution of investments in ICT regardless of an additional eventual existence of spillover effects. Adding up these two growth rates (in percentage points) and dividing it by labour productivity growth gives us the ICT contribution for the neoclassical assumptions discussed above. The results from major studies on the United States and the European Union are reported in Table 3. The contribution of ICT was the lowest in Europe before 1995 at only 17% of productivity growth, the peak contribution was over 70% in the United States in the five years between 1995-2000.

Table 3. Overview of ICT contribution to labour productivity form growth accounting studies

	EU		USA	
	in %	**Source**	**in %**	**Source**
1990-1995	17%	van Ark *et al.* (2002)	36%	Jorgenson (2001)
1995-2000	42%	van Ark *et al.* (2002)	73%	Jorgenson *et al.* (2008), Oliner *et al.* (2007)
2000-2005	45%	van Ark and Inklaar (2005)	43%	Jorgenson *et al.* (2008), Oliner *et al.* (2007)
2003-2007	31%	European Commission (2010)		

The basic storyline resulting for the United States from the Growth Accounting studies is that after its productivity slowdown in the pre-1995 period, when productivity growth fell behind European levels, the United States experienced a productivity resurgence. In the period from 1995-2000 the United States show high investments in IT and experience large productivity growth. IT capital represents 1.1 percentage points of the 4.8% output growth during 1996-1999 and 40% of the TFP growth was happening in IT producing sectors. The resurgence was hence strongly driven by the IT producing sector (Oliner *et al.*, 1994).

Although Jorgenson (2005) recognises the role of IT, admitting that the productivity growth rates are by far the highest in ICT production, he concludes that the overall contribution is limited due to the low shares of this sector in the aggregate economy. But even under the neoclassical assumptions ICT accounted for 60% of the labour productivity growth rate. After 2000 ICT investment and productivity slowed, but remained strong compared to the pre-1995 period. Reduced TFP growth in ICT producing industries was partly offset by a rise of TFP in IT using industries, especially services (Jorgenson, 2007). Therefore the United States experienced continued growth due to IT, albeit smaller than in the preceding decade. Alternative explanations for post-2000 TFP growth were technological progress outside the IT sector and cyclical dynamics which led to more cautious hiring and increased competitive pressure (Gordon, 2003; Oliner *et al.*, 2007).

The European Union, on the other hand, since 1995, shows lower productivity and lower IT investments, and the differential to the United States has increased through the early 2000s (van Ark and Inklaar, 2005). Though the percentage of ICT contribution in the 2000-2005 period is of similar magnitudes as in the US, this is due to the substantially lower productivity growth rate. This was labeled the “Atlantic divide” by Timmer *et al.* (2003), who emphasise that IT is only one factor explaining lower productivity. Daveri (2002) confirms that a part of the EU-US gap can be attributed to new technologies. Shares of ICT in total investment are approximately half to two thirds of United States levels, though of course large variations within the EU exist. TFP growth is also consistently lower in the European Union (van Ark *et al.*, 2003). Explanations for the productivity differential post-2000 are seen in the smaller contribution of market services, in particular retail and finances (van Ark *et al.*, 2008) mainly due to missing efficiency gains and less because of different ICT investment levels (Inklaar *et al.*, 2008). Still, the explanation of the gap is not the missing ICT production sector, as Colecchia and Schreyer (2002) find by comparing OECD countries. Australia is an example for a country with strong TFP growth in ICT using industries but no important ICT producing sector.

Despite the rigid growth accounting framework, the results differ. Reasons for these different numbers can be using different output measures, as these can rely on the product side only or can be averaged over income and product accounts. Further different approaches include or exclude the farm sector, consumer durables and owner-occupied housing from inputs and outputs (Baily, 2002), and which products are included in the ICT measure, different price deflators and different start and end dates. However, generally the basic picture of capital deepening and TFP growth among the studies show a similar pattern.

Another important distinguishing feature is consideration of intangible capital. Marrano *et al.* (2009) treat spending on knowledge-type investments (economic competencies, innovative property, computerised information, *i.e.* mainly software) as investments and find that thereby value added rises considerably, labour productivity grows, while TFP is overstated. This finding of the lower TFP impact is confirmed by Oliner *et al.* (2007), who also control for intangible assets. But they also find that IT is a substantial contributor to labour productivity after 2000, even after accounting for factor utilisation, adjustment costs and intangible asset accumulation.

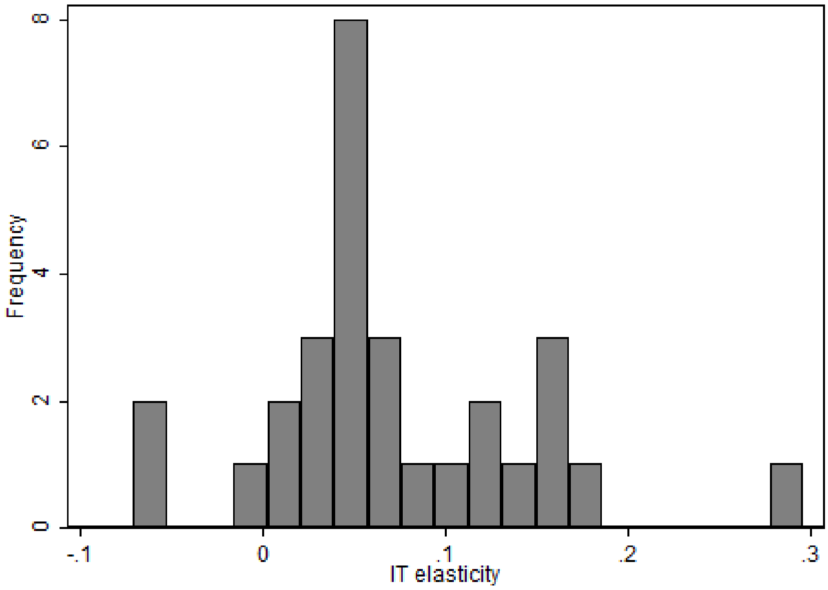
Results from productivity estimations

Early studies could not find evidence of ICT having a significant impact on productivity (Berndt and Morrison, 1995; Brynjolfsson, 1996; Loveman, 1994). This was explained *ex post* mainly with the amount of IT capital being too small for its effect to be detected in large scale studies (Schreyer, 2001). However, later on an increasing number of studies confirmed a positive and significant effect on productivity (Bertschek and Kaiser, 2004; Black and Lynch, 2004; Bloom *et al.*, 2010; Brynjolfsson and Hitt, 2003; O'Mahony and Vecchi, 2005; Röller and Waverman, 2001).

To compare the elasticities, a rigorous search procedure was conducted to avoid biases of a simple snowball literature search. Therefore first, a keyword search combining ICT, Computers, Internet, Broadband, (Mobile) Telecommunication, Information Technology each with Economic Growth and Productivity was conducted for the relevant academic journals. To avoid publication bias, the same keyword search was repeated with sharing sites for working papers. In the next step within the selected studies that had estimated an elasticity, one estimate was chosen according to the following criteria: *i)* the estimation with the most general sample (*i.e.* total industry instead of manufacturing only), *ii)* the most conservative estimate regarding possible endogeneity biases (Instrumental variable estimation before fixed effects before simple OLS), and *iii)* for comparability reasons, we chose the most simple model regarding further control variables.

The result of the procedure can be seen in Figures 1 and 2. Note that the majority of studies was conducted with United States data. Though from a growth accounting perspective ICT investments play a much larger role in the US, from the analyzed elasticities there seem to be no geographical differences in IT elasticity. We therefore do not separate the studies by geographic origin.

Figure 1. Histogram of estimated elasticities



The histogram in Figure 1 shows a clustering of estimated elasticities around the value of 0.05-0.06, with some notable outliers of either highly positive or even negative output elasticities.

When looking at the time trend of the data based on the average year of the data used for the estimation a positive time trend can be found, as illustrated in Figure 2. Other analyses according to aggregation level, region or ICT measure did not show any significant differences across any of these dimensions.

Figure 2. Time trend of estimated elasticities

(Note: Size of the bubble indicates number of observations in the study)

The time trend is positive and significant and suggests that the output elasticity of ICT investment increases over time and is now approaching 1. This trend is confirmed by Tambe and Hitt (2010) in a study with data from 1987-2006. They measure the marginal product of IT spending to be higher from 2000-2006 than in any previous period, suggesting that firms may have been continuing to develop new, valuable IT-enabled business process innovations.

The problem of endogeneity is potentially especially important in productivity regressions. Interestingly, some studies show a evidence larger IT effect with IV estimations (Brynjolfsson, 1996; Brynjolfsson and Hitt, 2000). Tambe and Hitt (2010) find that GMM estimators accounting for endogeneity are only about 10% lower than unadjusted estimates, suggesting that the effects of endogeneity on IT productivity estimates are rather small. Similarly, Bloom *et al.* (2010) find no qualitatively different results on their IT elasticity when conducting robustness checks with System-GMM and Olley-Pakes estimations to control for possible endogeneity. Conversely, Hempell (2005a) finds that controlling for endogeneity attenuates the ICT coefficient significantly. There is therefore no clear consensus on the issue of endogeneity in ICT productivity regressions.

Including fixed effects to obtain a more conservative estimate of the ICT impact on productivity is useful because it controls for any persistent, firm-specific components of IT returns as well as any firm-specific, time-invariant benefits of IT. In the study of Brynjolfsson and Hitt (1995) the fixed effects estimations show an ICT effect that is 50% lower. Other studies have confirmed this downward adjustment when controlling for firm-specific effects (McGuckin and Stiroh, 2002; Stiroh, 1998).

Other studies stress the importance of organisational complements for IT productivity. Bresnahan *et al.* (2002) argue that firm-level changes materialise through a three way cluster of complementarity. IT use is more likely to be effective with a higher quality of service/output mix, decentralised decision making and skilled workers. Similarly, Black and Lynch (2001) show the importance of workplace organisation for IT productivity. Interestingly, the greater the proportion of non-managerial workers who use computers, the higher is plant productivity. By contrast, the proportion of managers who use computers is not significant. This suggests that the usage of IT at mid to low level workers has a decisive impact on firm performance. Crespi *et al.* (2007) show that including organisational capital reduces IT returns which implies the complementarity. In contrast to these findings the study by Bertschek and Kaiser (2004) finds that the individual output elasticities of ICT investment do not differ significantly between firms with or without workplace reorganisation.

Another discussion revolves around the existence of a threshold value, which has been especially prevalent in the communication technology literature. Röller and Waverman (2001) state that there is only a significant relationship between telecommunication and growth if services reach a certain threshold which is near universal levels. Similarly, Dewan and Kraemer (2000) find no significant relationship for the subsample of developing countries, nor do Shiu and Lam (2008) for China except in affluent regions. Gruber and Koutroumpis (2010) show that the growth contribution of mobile telecommunication is (significantly) lower for low-penetration countries than for high-penetration countries. We can therefore conclude that non-constant returns to scale exist, at least for communication technologies.

Evidence for the GPT hypothesis

This section discusses whether the GPT hypothesis passes empirical testing. Jorgenson and Stiroh (1999) do not find spillovers and argue that the rewards are large because of the swift pace of technical change in the production of computers and the rapid deployment of IT equipment through substitution (Jorgenson *et al.*, 2008). Oz (2005) argues that excess IT returns may have been accrued in its early days (when IT, especially software was hard to measure), but today a firm without PCs will simply not survive as IT has become a mature and ubiquitous technology. Gordon (2000), based on growth accounting figures, finds that the productivity resurgence was driven by ICT production and can only be seen in the sector of manufacturing durable goods. For the remaining 88 % of the economy, the New Economy's effects on productivity growth are surprisingly absent, and capital deepening has been remarkably unproductive. Therefore no structural acceleration throughout the economy in productivity during 1995-9 took place, and the pervasiveness of the technology is absent, which is constituent for a GPT. In later work, Gordon (2003) adds that the investment in IT has been largely exaggerated.

One important characteristic of a GPT is its pervasiveness. Despite large variation in ICT intensity regarding the adoption in households and labeled the digital divide (for explanations of different demand structures see Savage and Waldman (2009)), Jovanovic and Rousseau (2005) show that households adopted electricity about as rapidly as they are adopting the PC and that such disparities are not unique for digital technologies.

At the business level, ICT investments made up constantly more than 20% of overall investments in the 1990s in the United States, and above 15% in the United Kingdom (Colecchia and Schreyer, 2002). In fact Triplett and Bosworth (2006) argue that the only real change over time is that IT capital is much larger than it once was and therefore not surprisingly contributes more to recent growth than it did in earlier periods. Even though ICT investment levels vary greatly among sectors, the ICT phenomena is not confined to a narrow sector and has a broad range of applications, *e.g.* transport, health services or banking. Concluding, investments have been huge, application is widespread, though full diffusion in every firm or every household is still far from complete.

Regarding spillovers, for communication technologies the network effects are straightforward. Most studies just simply state this as a basic premise of telecommunication (Hardy, 1980; Le, 1984) or for broadband (Majumdar *et al.*, 2009). But for ICT in general or more specifically computerisation, the existence of spillovers through network effects or other channels is not that obvious. Vertical spillovers (across vertically related industries) would imply that TFP growth must be evident also in the ICT using industries. A number of studies tackle this question. Table 5 presents an overview of the main approaches to empirically assess the GPT hypothesis and lists the studies that applied the approaches according to their main outcome – support of the GPT hypothesis or not.

Table 5. Overview of the studies testing the GPT hypothesis

Method	GPT hypothesis confirmed	GPT hypothesis refused
Industry study	Stiroh (2002b) Baily and Lawrence (2001) Bosworth and Triplett (2003)	
TFP regression with lagged ICT variable as explanatory	Brynjolfsson and Hitt (2003) Basu *et al.* (2003) Basu and Fernald (2007) Greenan and Mairesse (2000)	Stiroh (2002a) van Ark and Inklaar (2005) Wolff (2002) Inklaar *et al.* (2008)
Comparing with other GPTs of the past	Crafts (2002) Jovanovic and Rousseau (2005)	Gordon (2000)
Excess return	Brynjolfsson and Hitt (2003) Lichtenberg (1995) Gilchgrist *et al.* (2001) O'Mahony and Vecchi (2005) Venturini (2009)	Stiroh (2005)

In an industry study, Stiroh (2002b) shows with a difference-in-difference methodology that industries that are above the median in their information technology intensity have about 2 percentage points larger acceleration in labour productivity after 1995 than other industries. He evaluates this evidence for showing that the IT phenomena was widespread because the productivity surge was not only limited to the ICT production sector and cannot be explained by cyclical factors only. Stiroh makes no judgement regarding the spillover property of ICT, but instead states that the strong and robust correlation between IT intensity and the subsequent productivity acceleration implies that there may be a deeper relationship between IT investment and productivity growth.

Similarly, Baily and Lawrence (2001) find substantial acceleration in labour productivity outside the computer sector with a labour productivity measure (gross domestic income per employee) that incorporates both capital deepening and TFP growth and interprets his findings as some support for the GPT hypothesis. Bosworth and Triplett (2003) calculate the labour productivity and TFP by industry and find that the accelerating productivity in the service sector plays a crucial part in the productivity resurgence post-1995 and states that these industries are intensive users of ICT and thereby gives some evidence of usage of ICT and TFP growth. In a later study, Bosworth and Triplett (2007) confirm that non-ICT-producing sectors saw a sizeable acceleration in TFP, especially in the service industries in the 2000s, whereas TFP growth in ICT-producing sectors in fact declined in the 2000s compared to its golden era in the 1990s. Descriptive studies therefore indicate that ICT triggers innovation in the ICT using sector. All of these studies have been conducted with United States data.

However, hard evidence for spillovers could be found if ICT use or investments have a positive significant effect on TFP. As mentioned, TFP is a sign for innovation in an industry. The corresponding equation regresses ICT investment on TFP. But finding a positive effect has to be interpreted with great care, as it may be explained by true spillovers, *i.e.* due to fundamental improvements in the production process as a consequence of investing in ICT, or due to mismeasurement, which would falsely interpret TFP growth as spillovers. Firstly, TFP is very prone to mismeasurement. Secondly, organisational or other forms of intangible capital are not measured and therefore not all inputs are observed correctly. As investment in organisational capital is correlated to ICT, without accounting for complementary investments in the equation the ICT effect is biased. Of course the huge complementary investments in the form of intangible capital are also an indication for a GPT, but regarding the TFP regressions this clearly leads to an overstatement. Thirdly, for externalities to materialise takes time, therefore TFP should rise in ICT-using industries with a lag. In fact contemporaneous investments in ICT may be associated with lower TFP as resources are diverted to reorganisation and learning (Basu *et al.*, 2003). But the exact timing is unknown and no theory is available to determine which exact positive lag would prove the existence of true spillovers, which may lead to an atheoretical process of datamining until a significant lag is found. Finally, the problem of endogeneity is exacerbated as the dependent variable (TFP) is constructed through the explanatory variable, ICT capital (Draca *et al.*, 2006).

6. Key conclusions

This paper gives an overview of the vast empirical literature on ICT and productivity and highlights the main numerical results and the methodological differences. Overall the empirical studies demonstrate that ICT is a massive story not only ostensibly in everyday lives but very ostensibly in the productivity statistics as well. The evidence further indicates that the productivity effect is not only significant and positive, but also increasing over time. Of course having a significant effect does not mean that low performers can increase productivity by simply increasing ICT investment. ICT has to be embedded in complementary organisational investments.

Regarding the GPT hypothesis we find strong indication but no final evidence. However, interestingly most positive evidence was found for United States data, and it is more difficult to find evidence in Europe. Therefore a better understanding of how spillovers work with ICT might help bridge the gap, especially since many questions regarding possible externalities remain unanswered: do management ideas and knowledge on ICT diffuse among firms? How can this knowledge best be transferred? Which time lag is needed for spillovers to materialise? Moreover, while the GPT property of ICT is widely discussed and empirically tested, it has not been tested explicitly for broadband, even though this seems to be the main target of policy agendas.

Of course, the endogeneity issue also still remains unsolved. Thanks to the existence of computerisation, the possibilities to empirically investigate these questions have improved greatly. This should help to continue to empirically observe how exactly ICT is changing the economy.

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