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How Robust is the R&D – Productivity relationship? Evidence from OECD Countries

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Abstract

We examine the robustness of R&D and productivity relationship in a panel of 16 OECD countries. We control for fifteen productivity determinants predicted by different theoretical models. Following the advances in non-stationary panel data econometrics, we estimate four variants of thirteen specifications. All models appear co-integrated. Results are rigorously scrutinized through extensive bootstrap simulations and sensitivity checks. R&D and human capital emerge robust in all specifications making them universal drivers of productivity across nations. Most other determinants are also significant. Productivity relationships are heterogonous across countries depending on their accumulated stocks of knowledge and human capital.

JEL Classification: F12; F2: O3; O4; C15

Key Words: R&D Capital Stocks; Multifactor Productivity; Heterogeneity; Panel Cointegration; Bootstrap Simulations.

Disclaimer

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1. Introduction

Motivated by the theoretical insights of new growth models, Coe and Helpman (1995, hereafter CH) analyze pooled aggregate data on R&D and productivity for a panel of 21 OECD countries plus Israel over a period of 1971-1990. They report, *inter alia*, that domestic R&D capital and international R&D spillovers significantly explain domestic productivity, which supports knowledge based growth models. CH's work broke tradition with the previous empirical literature – primarily based on firm and/or industry level (micro) data for a single country [1] – and inspired investigations on multicounty macro-panel data.

Ever since, the macro econometric investigations of R&D and productivity have proliferated. This growing literature engages four main issues, namely, channels of international knowledge spillovers, further determinants of productivity (i.e., omitted variables), econometric methodology and cross-country heterogeneity. Research on these issues is not mutually exclusive; a considerable overlap exists in the literature. We set the context by briefly summarizing it.

The bulk of the literature focuses on the potential channels of cross-boarder knowledge spillovers. Typically, total imports (CH; Keller, 1998; Lichtenberg and van Pottelsberghe de la Potterie, 1998 (henceforth LP); Luintel and Khan, 2004), imports of capital goods (Xu and Wang, 1999; Luintel and Khan, 2009), inward and outward FDI stocks and flows (Van Pottelsberghe de la Potterie and Litchenberg, 2001 [henceforth PL]; Lee, 2006; Zhu and Jeon, 2007), information technology (Zhu and Jeon, 2007), bilateral exports (Funk, 2001), and technological proximity between nations (Park, 1995; Guellec and van Pittelsberghe de la Potterie, 2004[henceforth GP]; Lee, 2006) are modeled as potential channels of cross-border knowledge transmission. These channels (ratios) form weights for the alternative measures of foreign knowledge stocks and most of them are found to be significant conduits of international knowledge transmission.

Competing theoretical models predict several determinants of productivity that are external to the sources of knowledge (i.e., beyond measured R&D capital stocks) which makes the robustness of R&D an important issue. We denote the latter collectively as 'non-R&D' determinants of productivity. [2] The literature addresses the robustness issue by augmenting the R&D capital stocks through measures of non-R&D determinants of productivity. To date, measures of human capital and productivity catch-up (Engelbrecht, 1997), import share (Edmond, 2001), business cycle (GP) and institutions (Coe, Helpman and Hoffmaister, 2009) appear to have been used to augment the R&D capital stocks in modeling productivity. However, considering the long list of theoretically proposed determinants (see below), this issue appears somewhat under-researched. [3]

The methodological issue has evolved with the advancement of panel data econometrics. CH applied OLS on pooled (panel) macro data and tested for the stationarity of residuals. Panel co-integration tests were not fully developed at the time. Following recent advances in panel data econometrics, interest in re-examining this issue surged. Some studies have applied up-to-date panel unit root and cointegration tests on CH's data and specifications, while others have investigated new and/or extended dataset employing these methods. Studies in this class include Kao et al. (1999), PL, Edmond (2001), GP, Lee (2006), and Coe, Helpman and Hoffmaister (2009), to name but a few. Overall, they find that productivity and R&D capital stocks are co-integrated and that CH's estimates are plausible despite their usage of OLS. The issue of parameter heterogeneity is recently raised by Luintel and Khan (2004). They show that cross-country parameters of the R&D and productivity relationship differ significantly because countries differ in their accumulated knowledge stocks.

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[1] See, among others, Griliches and Mairesse, 1990; Hall and Mairesse, 1995 and the review by Griliches (1988).

[2] We acknowledge that it is not always convincing to lump all other determinants of productivity except for the three forms of R&D capital stocks as non-R&D determinants. For example, it is hard to segregate ICT from its knowledge content and similar arguments may apply in other cases. However, for the sake of convenience and without any prejudice, we denote them as 'non-R&D' determinants throughout.

[3] Of course, productivity has been separately modelled as a function of a range of other variables like cross-border flow of people (Andersen and Dalgaard, 2006), structural composition of the economy (Moro, 2007) to name but a few. However, our focus here is on those studies that augment R&D capital stocks by other (non-R&D) determinants.

Our main objective is to extend this literature by providing a comprehensive and rigorous characterization of the empirical relationship between domestic productivity, R&D capital stocks and a broad range of theoretically postulated and potentially important non-R&D determinants of productivity. This paper complements as well as extends the existing literature. First, domestic productivity is modeled as a function of three different forms - business, public and foreign - of R&D capital stocks and twelve further non-R&D determinants. The latter are predicted to be potential determinants of productivity by various theoretical models of growth and development (see Section 3). Although this extension does not exhaust all potential non-R&D determinants of productivity, this list is nevertheless wide-ranging and it broadens the empirical literature in a significant way. It offers a rigorous and a wide-ranging examination of the sensitivity of R&D and human capital vis-à-vis the other determinants of productivity.

Second, we model potential cross-country heterogeneity in knowledge-productivity relationships by explicitly modeling the role of the different levels of accumulated R&D stocks and human capital across countries. The idea is to examine whether a high knowledge base country such as the US yields greater productivity benefits than a low knowledge base country like New Zealand.

Third, we model for a new channel of international knowledge transmission. This channel (weight) is the extent of successful bilateral R&D collaboration between countries, which captures the notion that ideas proliferate through collaborative work. The usage of this channel is new to the spillover literature. In addition, we use three other channels well-known in the literature – the bilateral import ratio and the ratios of bilateral inward and outward FDI stocks.

Fourth, we apply the econometrics of non-stationary panel data. In addition, we conduct extensive bootstrap simulations through a moving block bootstrap (MBB) procedure and scrutinize the small sample properties of our results. Finally, we conduct extensive sensitivity analyses vis-à-vis: (i) three (5%, 10% and 15%) depreciation rates for R&D capital stocks; (ii) three (3%, 5% and 8%) depreciation rates for stocks of public infrastructure; (iii) three measures of total factor productivity (TFP); (iv) country size in the sample; and (v) the size of the services sector in the economy. The latter is important because the extant R&D data mainly focuses on manufacturing firms and does not yet offer sufficient coverage to the services sector (Gallacher, Link and Petrusa, 2005). Consequently, it may not fully proxy knowledge stocks of those countries which have a sizable well developed services sector.

The rest of the paper is organized as follows. The following section discusses theoretical issues and empirical specification; data issues are covered in Section 3; econometric issues in Section 4; empirical results in Section 5 and sensitivity tests in Section 6. Section 7 summarizes and concludes.

2. Theoretical issues and empirical specification

The endogenous growth models of Romer (1990a) and the quality ladder models of Grossman and Helpman (1991) and Aghion and Howitts (1992) theorize that innovations drive long-run aggregate productivity and economic growth. Based on these insights, CH specify a basic R&D and productivity relationship as:

$$LogP_{it}^{m} = \alpha_{1i} + \alpha_{1i}^{d} \log S_{it}^{d} + \alpha_{1i}^{f} \log S_{it}^{f} + \varepsilon_{1it}, \qquad (1)$$

(i= 1,…,N; t=1,…, τ_i; and $\Sigma \tau_i = T$).

where "i" indicates the cross-sectional dimension and α_i captures the time-invariant fixed effects. P^m represents multifactor productivity; S^d and S^f denote domestic and foreign R&D capital stocks. Our benchmark model, which is in the spirit of CH, is:

$$LogP_{it}^{m} = \alpha_{2i} + \alpha_{2i}^{b} \log S_{it}^{b} + \alpha_{2i}^{p} \log S_{it}^{p} + \alpha_{2i}^{f} \log S_{it}^{f} + \alpha_{2i}^{h} \log H_{it} + \varepsilon_{2it} \qquad (2)$$

In contrast to CH, we separate out total domestic knowledge stock into business (S_{it}^{b}) and public (S_{it}^{p}) sector knowledge stocks and include the stock of human capital (H) as an additional regressor. The separation of business and public sector knowledge stocks sheds light on the role of the sources of domestic knowledge stocks on productivity. Human capital is a theoretically established and empirically extensively tested determinant of productivity (see, among others, Lucas, 1988 and 1993; Mankiw et. al., 1992; Romer, 1990a, b; Barro and Sala-i-Martin, 2003); therefore, we include it in the benchmark specification.

Theoretically, all three measures of R&D capital stocks exert positive effects on domestic productivity (see among others, CH; Keller, 1998; Nadiri and Mamuneas, 1994; GP). Consequently, we expect positive and significant parameters of all three sources of knowledge stocks a *priori*. The stock of human capital exerts positive effect on productivity and economic growth. This is true for both the exogenous and endogenous growth models. [4]

We augment our benchmark model (equation 2), which already incorporates human capital, by further eleven determinants of productivity, postulated by different theoretical models. The latter include measures of information and communication technology (ICT), the stock of public physical infrastructure (Z), high technology exports (X^{h}), high technology imports (M^{h}), stocks of inward (F^{I}) and outward (F^{O}) foreign direct investment, the relative size of services sector in the economy (SER) and a proxy variable for the business cycle (U). We also use three measures of financial development - private credit ratio (P^{K}), stock market capitalization ratio (S^{MC}) and stock market total value traded ratio (S^{MV}). ICT is viewed as 'general purpose technology' yielding network externalities (Schreyer, 2000) and capital deepening (Basu et al., 2004) both of which boost labor and total factor productivity (TFP). Indeed, ICT is found to have significant effect on aggregate productivity and growth across OECD countries (O' Mahony and Van Ark, 2003 and 2005; Basu *et al.* 2004). Gordon (2000) credits ICT investments for the increase of TFP in the US during the latter half of the 1990s. The Council of Economic Advisors (2001) argues that the late-1990s surge in US labor productivity was mainly confined to ICT intensive industries. Van Ark et al. (2002) report large contribution of ICT on 12 EU countries and the US. However, Basu et al. (op cit.) point out that the short-run (contemporaneous) effect of ICT on TFP may be negative as reorganization and learning processes entail costs. We test for the long-run (cointegrating) relationship, hence expect a positive association between ICT and productivity.

In the models of Arrow and Kurz (1970) and Grossman and Lucas (1974), infrastructure is viewed as an input to the private sector's production function. The 'quality' and the 'size' of public infrastructure augment productivity and growth via cost reductions and/or improved specializations (see Gramlich, 1994 for a survey). On these theoretical grounds, we anticipate a positive effect of infrastructure on productivity.

In learning-by-doing models, access to export markets improves domestic productivity (see, among others, Bernard and Jensen, 1999; Clerides et al., 1998; Eaton and Kortum, 2002). Domestic firms improve their specialization and productivity in providing high product quality required by the foreign markets. However, this effect may be more prominent among technological laggards. In order to capture this learning, by exporting effect, we use the ratio of high technology exports to total exports.

Imports are conduits of technology diffusion (Grossman and Helpman, 1991; CH; Keller, 1998 and 2004). Countries engaged in imports benefit from international knowledge spillovers. Potentially, technological laggards benefit more than technological leaders. Recent literature emphasizes the importance of trade in differentiated capital goods. We use the ratio of high technology imports to total imports to capture this effect.

FDI is considered to generate technological externalities and raise product market competition, both of which boost productivity and growth. FDI has two facets – foreign firms invest in the domestic economy (inward FDI), and domestic firms invest abroad (outward FDI). Both forms of FDI foster technology diffusion and

[4] Lucas (1993) and Romer (1990b) illustrate the different forms of human capital, e.g., human capital acquired through schooling, learning-by-doing and engaging in trade.

competition (see among others, Lipsey, 2002; Keller and Yeaple, 2009; Griffith et al., 2006). Hence, we expect positive effects of FDI stocks on domestic productivity.

In recent years, the relative importance of services sector in the aggregate output of OECD countries has increased significantly and so have its R&D activities. In the US, R&D performed by the services sector rose from seven percent of total industrial sector R&D in 1970s to 29 percent in 1990. A similar trend is evident across the OECD countries albeit, with mixed magnitudes (see Jankowski, 2001). We control for this phenomenon by: (i) including the relative size of the services sector as one of the regressors in its own right and (ii) re-estimating all the models by controlling for the services sector.

Theoretical models predict that a well-functioning financial sector (banks and capital markets) boosts efficiency of investment, aggregate productivity and economic growth through its multifarious services. In the absence of a financial system, many firms would be constrained to economically inefficient scales (Sirri and Tufano, 1995). A financial system pools multiple savers and investors, improves risk diversification, liquidity and the size of feasible firms. Financial development enhances investment in the high-return projects and accelerates productivity and growth (Bencivenga and Smith, 1991) and induces efficient allocation of capital and faster growth (Greenwood and Jovanovic, 1990).

Further, a financial system enhances corporate control and ensures capital flow to profitable investments (Stiglitz and Weiss, 1983), lowers monitoring and enforcement costs and encourages efficient investment (Diamond, 1984) and eases risk diversification and shifts portfolios towards projects with higher expected returns (Devereux and Smith, 1994). A long list of theoretical models predicts that a well-functioning financial sector contributes to the allocation of resources, productivity and economic growth. On these theoretical grounds, we expect positive effect of financial development indicators on domestic productivity.

Finally, following GP, we capture the business cycle effect on domestic productivity through the rate of employment. Much of the literature predicts a pro-cyclical effect of the business cycle on productivity. Drawing from the preceding discussions, our augmented model for domestic productivity is:

$$LogP_{it}^{m} = \alpha_{3i} + \alpha_{3i}^{b}\log S_{it}^{b} + \alpha_{3i}^{p}\log S_{it}^{p} + \alpha_{3i}^{f}\log S_{it}^{f} + \alpha_{3i}^{h}\log H_{t} + \beta^{'}X_{it} + \varepsilon_{2it} \qquad (3)$$

Where X is a vector containing eleven measures of non-R&D determinants of productivity outlined above and $\beta_{(1x11)}$ is the parameter vector. Equation (3) has 15 covariates excluding the fixed effects. Although these fifteen regressors may not exhaust all the potential productivity determinants available in the literature, they nevertheless represent a wide spectrum of key variables that are arguably sufficient to assess the robustness of R&D and human capital stocks. If knowledge stocks and human capital appear robust vis-à-vis these eleven non-R&D regressors then it is highly likely that they will pass the other such tests. For example, Coe, Helpman and Hoffmaister (2009) report that including institutional factors does not alter the robustness of R&D.

We estimate equation (3) in a dynamic heterogeneous panel framework. The dynamic heterogeneous panel cointegration tests are powerful, and they are robust to cross-country parameter heterogeneity. However, the large number of regressors in equation (3) raises concerns regarding the degrees of freedom and the precision of estimates especially for the application of between dimension panel estimators. Further, in the panel literature, theoretical critical values for cointegration tests are derived and listed for models having at most seven regressors (Pedroni, 1999), which cannot accommodate our specification (model 3). Although suggestive, the derivation of critical values for panel cointegration tests involving more than seven regressors (in fact as many as fifteen in our case) is not trivial and falls outside the scope of this paper. We circumvent this problem in following two ways. First, we sequentially estimate equation (3) by incorporating only one variable of vector X at a time. This gives us twelve models – one benchmark model with four regressors (i.e., excluding the $\beta^{'}X_{it}$ part), and the remaining eleven augmented models with five regressors each (i.e., using one regressor at a time from the vector X). Second, we jointly use all the regressors contained in vector X through the method of principal components.

Countries show considerable differences in their accumulated stocks of R&D and human capital across the sample countries (see Table 1). The US dominates in the ownership of knowledge stocks and the pool of scientists working in the R&D sector. Likewise, important cross-country heterogeneity is evident in the levels and growth rates of productivity. In our sample, the average annual growth rate of domestic productivity ranges between a minimum of 0.6 percent (Canada) to a maximum of 3.2 percent (Ireland); the sample mean is 1.1 percent. This gives rise to an interesting testable proposition of whether countries with high magnitudes of accumulated knowledge and human capital stocks yield higher productivity gains. If the evidence were affirmative then countries with a smaller knowledge stock and less human capital would benefit by opting for policies that augment their stocks of knowledge and human capital. A formal test of this hypothesis requires specifications that directly allow for the cross-country differences in knowledge and human capital stocks. Our specifications, which capture this spirit, are:

$$LogP_{it}^{m} = \alpha_{4i} + \alpha_{4i}^{b}\log(S_{it}^{b} * \bar{S}_{i}^{b}) + \alpha_{4i}^{p}\log(S_{it}^{p} * \bar{S}_{i}^{b}) + \alpha_{4i}^{f}\log(S_{it}^{f} * \bar{S}_{i}^{b}) + \alpha_{4i}^{h}\log(H_{it} * \bar{S}_{i}^{b}) + \varepsilon_{4it} \quad (4)$$

$$LogP_{it}^{m} = \alpha_{5i} + \alpha_{5i}^{b}\log(S_{it}^{b} * \bar{S}_{i}^{p}) + \alpha_{5i}^{p}\log(S_{it}^{p} * \bar{S}_{i}^{p}) + \alpha_{5i}^{f}\log(S_{it}^{f} * \bar{S}_{i}^{p}) + \alpha_{5i}^{h}\log(H_{it} * \bar{S}_{i}^{p}) + \varepsilon_{5it} \quad (5)$$

$$LogP_{it}^{m} = \alpha_{6i} + \alpha_{6i}^{b}\log(S_{it}^{b} * \bar{H}_{i}) + \alpha_{6i}^{p}\log(S_{it}^{p} * \bar{H}_{i}) + \alpha_{6i}^{f}\log(S_{it}^{f} * \bar{H}_{i}) + \alpha_{6i}^{h}\log(H_{it} * \bar{H}_{i}) + \varepsilon_{6it} \quad (6)$$

where, $\bar{S}_{i}^{b} = T_{i}^{-1}\sum_{t=1}^{T_i} S_{it}^{b}$; $\bar{S}_{i}^{p} = T_{i}^{-1}\sum_{t=1}^{T_i} S_{it}^{p}$; and $\bar{H}_{i} = T_{i}^{-1}\sum_{t=1}^{T_i} H_{i,t}$.

In equation 4, we interact all the covariates of our benchmark model - S_{it}^{b} , S_{it}^{p} , S_{it}^{f} and H_{it} - by country-specific mean levels of business sector R&D capital stock.[5] A positive and significant α_{4i}^{b} implies that countries with a large stock of accumulated business sector R&D capital experience bigger productivity gains and vice versa. To illustrate this point, assume that two sample countries (A & B) in the panel have mean business sector knowledge stocks of $\bar{S}_{A}^{b}$ and $\bar{S}_{B}^{b}$, respectively, such that $\bar{S}_{A}^{b} > \bar{S}_{B}^{b}$. From equation (4), this yields a point elasticity of $\alpha_{4i}^{b} * \bar{S}_{A}^{b}$ for country A and $\alpha_{4i}^{b} * \bar{S}_{B}^{b}$ for country B, necessitating higher point elasticity for country A due to its larger accumulated knowledge stock. These specifications make important revelations on whether high knowledge base countries like US or Germany tend to see more productivity gains compared to low knowledge base ones like Greece or Spain. Positive and significant α_{4i}^{p} , α_{4i}^{f} and α_{4i}^{h} imply that business sector R&D capital complements public and foreign R&D capital stocks and human capital respectively in augmenting productivity. In equations (5) and (6), the benchmark model is interacted by country-specific mean levels of public sector R&D capital stock ($\bar{S}_{i}^{p}$) and human capital ($\bar{H}_{i}$), respectively, and their parameters are to be interpreted correspondingly. [6]

3. Data

We analyze 16 OECD countries (see Table 1). We assemble data on three measures of productivity (the dependent variable) and 15 regressors discussed in Section 2. Data frequency is annual for a period of 23 years (1982-2004). We have a balanced panel of 368 observations. Data appendix lists all the data series and their sources and computations. In Figure 1, we report bar charts of multifactor productivity, business and public sector R&D capital stocks and the stocks of inward FDI. Data exhibit large differences across the sample countries. Domestic productivity growth rates range between 0.6 percent (Canada) to 3.2 percent

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[5] It is often argued that R&D intensity measures capture the cross-country differences in R&D activities. However, Khan and Luintel (2006) illustrate that intensity measures fail to capture the full extent of disparity in R&D activities across sample countries. Hence, we use mean levels of S_{it}^{b} , S_{it}^{p} and H_{it} to capture the cross-country heterogeneity.

[6] In models (4) through (6) only interacted covariates appear. This is because we employ between dimension dynamic heterogeneous panel estimator, which precludes the joint use of the level and the interacted covariates due to perfect collinearity. Our specifications capture the within country variations and are similar in spirit to Beck and Levine (2002). Luintel et al., (2008) elaborate on the alternative specifications involving interacted covariates.

(Ireland) which is a difference of over five folds. There are huge differences in accumulated business and public sector knowledge stocks across the OECD countries; the US completely dominates. Such cross-country differences are also evident amongst the non-R&D determinants of productivity. Since it is not feasible to provide bar charts for all the variables due to limited space, we report summary statistics of some of the key variables in Table 1.

Table 1 shows important differences in the growth rates of productivity and their determinants across the sample OECD countries. The productivity of the US and the UK grew by around 1.3 percent during the sample period, while Japan, Germany and France experienced somewhat higher growth rates of 1.6 percent or so. The sample mean of business sector R&D intensity (business sector R&D expenditure to GDP ratio) is 1.6 percent but it ranges from a minimum of 0.1 percent (Greece) to a maximum of 2.3 percent (Sweden). Likewise, the intensity of public sector R&D ranges from a minimum of 0.3 percent (Greece) to a maximum of 0.9 percent (Sweden); the sample mean is 0.7 percent. The stock of human capital, measured by average years of schooling, is lowest in Spain (7.6 years) and highest in the US (12.6 years). Foreign R&D capital stocks, public infrastructure, high technology exports and imports, FDI, ICT also exhibit sharp cross-country differences whereas financial development, proxied here by stock market capitalization, appears to be relatively smooth across countries.

To illustrate the time profile of our data series we plot P^m, S^b, S^p and S^f in Figure 2. The plotted foreign R&D capital stock is derived using the bilateral R&D cooperation coefficients as weights. All plots show an upward trend throughout the sample period, suggesting that they are probably non-stationary unit root processes. We confirm this through panel unit root tests in section 5. The time profiles of these plots are also representative of other variables that are not reported here for space reasons.

4. Econometric Issues

Individual series of multicounty macro-panel are widely reported to be unit root processes. This requires the application of panel unit root and cointegration tests in empirical scrutiny. These tests exhibit better power properties than the conventional time series tests when sample size is moderate. Further, panel estimators of cointegrating vectors are super-consistent and robust to endogeneity, measurement errors and dynamic heterogeneity (Pedroni, 1999).

A number of panel unit root tests are proposed in the literature. Hlouskova and Wagner (2006) provide a comparative study of some of these tests through extensive Monte Carlo simulations. We implement a number of these panel unit root tests and, given the robustness of our results, only report that of Im, Pesaran and Sin (2003; hereafter IPS), Fisher-ADF (Maddala and WU, 1999) and Hadri (2000). The IPS test tests the null of unit root for each cross-sectional unit in the panel against the alternative that a fraction of cross-sections may contain a unit root. We choose IPS test due to its generality, as it allows for the heterogeneity of: (i) persistence; (ii) dynamics; and (iii) error variance across groups. Further, it is a more general test than those that maintain stationarity across all groups under the alternative hypothesis.

The Fisher-ADF test, proposed by Maddala and Wu (1999), combines the p-values of each unit root test conducted on individual member of the panel. They show that under the null of a unit root for all N cross-sections, the quantity: $\sum_{i=1}^{N}\log(\pi_i)$ is asymptotically χ^2_{2N}; where π_i is the p-value of unit root test on the ith variable of the ith panel member. Hardi's panel unit root test tests the null of stationarity against the alternative of unit root assuming a common persistence parameter across cross-sections. Although, Hlouskosva and Wagner (2006) report that Hadri's test suffers from significant size distortion in the presence of autocorrelations, we nevertheless employ it, because it tests different null and alternative hypotheses compared to the earlier two tests. Hadri also derives autocorrelation and heteroskedasticity consistent LM tests under the null of stationarity across all cross-sections.

Pedroni (1999) proposes seven residual-based tests of panel cointegration. Four of them are within-dimension tests that assume homogeneous cointegrating vectors across all panel members. The remaining three are between-dimension tests (referred to as group mean statistics), which allow heterogeneity of cointegrating vectors across all panel members. The distinction between these two sets of tests is crucial because incorrect imposition of homogeneous cointegrating parameters would lead to the non-rejection of the null of non-cointegration even when the variables are cointegrated (Pedroni, 1999, p. 656). Given the heterogeneity in productivity levels and factors determining them, we have no reason to believe that the cointegrating vectors across our panel of countries are homogeneous. Further, the between-dimension estimators exhibit lower size distortions than the within-dimension estimators (Pedroni, 2000). We therefore opt for the between-dimension tests. Of the three between-dimension panel cointegration tests, the group t-statistic is the most powerful (Pedroni, 2004). We report the group t-statistic and the group ρ -statistic derived by Pedroni (1999).[7] A point to note is that these panel cointegration tests do not address the issues of normalization and multi-cointegration. However, we have an established normalization in mind, which originates in the seminal work of CH and we aim to extend this literature.[8]

Following Pedroni (1999 and 2001), we estimate the cointegrating parameters through Fully Modified OLS (FMOLS). Under this approach, the panel cointegrating vectors are essentially the average of the country-by-country time series estimates. Hence, the (small) size is a potential issue, which we address through bootstrap simulations. The integrated and cointegrated properties of our data and models preclude us from treating estimated residuals as i.i.d. (identical independently distributed) processes. Consequently, the standard i.i.d. resampling schemes cannot be applied for bootstrap exercises. Instead, the Moving Block Bootstrap (MBB) procedure, proposed by Knunsch (1989) and Liu and Singh (1992), preserves such data structure and hence suitable. Further, Goncalves and White (2005) show that MBB procedures could be applied to processes with substantial memory (known as near epoch dependent process).

A brief sketch of the MBB procedure is as follows. Consider a series $\{X_{Tt}:t=1,...,T\}$; let ℓ be a block length such that $B_{t,\ell}=\{X_{Tt,}X_{Tt+1},...,X_{Tt+\ell-1}\}$ is a the block of ℓ consecutive observations starting at X_{Tt}. The MBB draws b blocks randomly with replacement from the set of overlapping blocks $\{B_{1,\ell},...,B_{T-\ell+1,\ell}\}$ where $T=b\ell$. Letting $I_{T1},...,I_{Tb}$ as i.i.d. random variables distributed uniformly over $\{0,....,T-\ell\}$, we have $\{X^{*}_{Tt}=Z_{T,\tau_{nt}},t=1,...,T\}$, where τ_{nt} defines a random array $\tau_{nt}\equiv\{I_{T1}+1,....,I_{T1}+\ell,....,I_{Tb}+1,....,I_{Tb}+\ell\}$. We estimate ℓ by setting it equal to the highest order of the significant residual autocorrelation.

The residual resampling draws on the time dimension of the panel in order to match it with the nature of Pedroni's (2001) Panel FMOLS approach.[9] We generate 1000 bootstrapped samples of residuals and through our regression equation, 1000 endogenous variables. We then compute 1000 parameter vectors for each model through the FMOLS regressions on these pseudo-samples. The mean and the median values of the simulated parameters and their distributions are derived. We also compute the empirical p-values for the estimated regression coefficients.

5. Empirical Results

Table 2 reports the results of IPS, ADF-Fisher and Hadri panel unit root tests. The first two columns of results test the null of unit root for each member in the panel against the alternative that a fraction of cross-section may contain unit root. Neither test rejects the null at any conventional significance level (10-percent or better) for any of the data series in the panel. The Hadri test, which tests the null of stationarity, rejects the

[7] For brevity, we do not outline these test statistics but they are detailed in Pedroni (1999). Alternative panel cointegration tests proposed by Kao (1999), Kao, Chiang and Chen (1999) and McCoskey and Kao(1998) all assume homogeneous cointegrating vectors across the panel members hence are less appealing at the present context.

[8] The issue of multi-cointegration is an interesting proposition to be pursued in future work.

[9] As stated above, Pedroni's panel estimates are essentially the mean of the country-specific FMOLS estimates of Philips and Hansen (1990).

null for all series in the panel at very high levels of precision. Reported results pertain to the specifications that include country-specific intercepts. However, the results are robust to changes in deterministic components (inclusion of constants and linear trends or otherwise). All individual series in the panel are stationary at first differences. [10] The overall message from these tests is that all individual data series in the panel are unit root processes.

Table 3 reports the results of cointegration tests and bootstrap summary statistics. The first half of the table contains the results of those empirical models that use bilateral import weighted foreign R&D capital stocks (S^{fm}) computed at a 15% depreciation rate. The stock of public infrastructure (Z) used is based on a 3.0 percent depreciation rate, but results remain qualitatively the same at alternative depreciation rates (see Section 7). Panel A shows the results for the benchmark model (equation 2). Both the group ρ-statistic and the group t-statistic firmly reject the null of non-cointegration at very high levels of precision implying that domestic productivity, three forms of R&D capital and human capital stocks are cointegrated in the panel. All the cointegrating parameters of the benchmark model are positive and highly significant, which confirms to theoretical priors. Both the asymptotic and the bootstrap p-values uphold the precisions of the estimated parameters. The point elasticity of public sector R&D capital stock appears bigger than that of the business and foreign sector R&D capital stocks. Human capital shows point elasticity similar to that of the public sector R&D.

The mean values of the simulated parameters confirm the positive effects of the sources of knowledge and human capital on domestic productivity. They are close to the regression estimates for the three forms of knowledge stocks, suggesting that the small sample bias may not be a serious problem vis-à-vis these parameter estimates.

However, for human capital, the mean value of the simulated parameter appears quite high compared to the regression coefficient, indicating a downward bias in the regression estimate. Such discrepancy between the regression estimates and the mean values of small sample parameter distributions - which is apparent in other specifications as well - highlights the importance of health checks through bootstrap simulations. Overall, our findings of significant positive effects from the three forms of knowledge stocks and human capital on domestic productivity are consistent with the existing literature (see, among others, CH; Engelbrecht, 1997).

Panel B contains the results of the augmented models. Each column of Panel B is obtained by augmenting the benchmark model through the regressor listed in the respective column. For example, the ICT column contains results when the benchmark model is augmented by the ICT variable. In the last column, the weighted principal component (WPC) that summarizes all the eleven non-R&D regressors listed in Panel B augments the benchmark model. We compute eigenvectors from data on all these eleven regressors for each country in the panel. The WPC is the weighted sum of all the eigenvectors that cumulatively explain total (100%) variation in the data; the proportion of total variation explained by each eigenvector is the respective weight.

Results reveal that all augmented models are cointegrated – both test statistics are highly significant and reject the null of panel non-cointegration. Thus, cointegration is evident under all three specifications - the benchmark model, the individually augmented eleven models and the model jointly augmented by the WPC. These results are symptomatic of a long-run equilibrium relationship between domestic productivity and its fifteen determinants postulated by different theoretical models.

How well do the non-R&D determinants of productivity fare? Of the eleven covariates, seven – information and communication technology, public infrastructure, stocks of inward and outward FDI, two measures of financial development (S^{MC} and S^{MV}) and the services sector of the economy – appear positive and significant when judged from empirical p-values. Asymptotic p-values show ICT and SER as insignificant

[10] We do not report the results of panel unit root tests on the first differenced data, but the results are available on request.

and Z as marginal (significant at 9.95 only). The remaining four regression estimates – coefficients of high technology export and import ratios, private sector credit ratio and the proxy of business cycle – appear negative. However, the mean values of simulated parameters show that all regressors except for the high technology export and import ratios and the business cycle proxy are positive. The mean values of the simulated parameters associated with high technology export and import ratios are very small. The business cycle proxy variable appears counter cyclical which does not confirm to *a priori* expectation. The bootstrap results show some evidence of asymmetric upper and lower bounds with respect to a few parameters. Some mean and median values of the simulated parameters also differ. Overall, parameter distributions appear largely symmetric. The last column reports the joint effect of all the eleven covariates listed in panel B summarized by a weighted principal components (WPC), is positive and significant. The parameter of WPC shows a very high precision and indicates symmetric distribution.

How robust are R&D and human capital stocks? The results of benchmark model are extremely robust to every single augmentation. The coefficient of business sector R&D ranges between a minimum of 0.017 and a maximum of 0.174 but always remains positive and significant across all twelve augmentations. Likewise, the parameters of public sector R&D range between 0.071 and 0.284, those of foreign R&D between 0.010 and 0.057, and those of human capital between 0.045 and 0.439, and all remain positive and statistically significant. Thus, the three forms of R&D capital stocks and human capital appear robust to a wide spectrum of productivity determinants. This robustness holds irrespective of whether the other regressors are modeled individually or jointly through the summary measure of WPC.

The second half of Table 3 reports the results of the empirical models that use bilateral R&D collaboration weighted foreign R&D capital stocks (S^{fc}). To our knowledge, this channel remains unexplored in examining international knowledge spillover vis-à-vis domestic productivity. As before, group ρ -statistic and group t-statistic both reject the null of non-cointegration across all specifications. The benchmark model and all the twelve augmented models are cointegrated.

The cointegrating parameters associated with business and public sector R&D capital stocks and the human capital appear positive and significant, which confirms the earlier results. The regression coefficient of international knowledge spillover appears negative and insignificant asymptotically; however, this is overturned by bootstrap results, as the mean and the median values of simulated parameters are both positive. The bootstrap results confirm bilateral R&D collaboration as a conduit of international knowledge transmission.

As before, the results of the benchmark model are robust to all augmentations. Of the eleven non-R&D regressors, all but two have positive and statistically significant cointegrating parameters. The exceptions are the high technology import ratio and the services sector, which have negative coefficients. However, the mean and median values of simulated parameters are negative for three of the non-R&D determinants (namely, M^h , SM^v and U); the services sector appears positive. Overall, the distributions of simulated parameters echo the same message discussed above.

Tables 4 reports results that use inward and outward FDI weighted foreign R&D capital stocks, respectively, with a 15% depreciation rate. Results in the upper half, pertaining to inward FDI weighted foreign R&D capital stocks (S^{fI}), show that the benchmark model and all the augmented models are cointegrated. Results are consistent with the earlier findings that international knowledge travels through inward foreign direct investment as well. All parameters of the benchmark model are positive and significant, echoing the findings reported earlier. Their simulated mean and median values are all positive and are very close in magnitudes. Of the eleven non-R&D determinants, the regression coefficients (cointegrating parameters) are positive and significant for all except the private credit- -to-GDP ratio (P^K) and services sector (SER). However, the mean value of the bootstrap parameters is positive for all except the import ratios and employment rate.

As above, the majority of non-R&D determinants appear to exert positive effect on productivity. This is further supported by the results of the last column – a positive and statistically significant joint effect of all the eleven regressors captured by the WPC. The upper and lower bounds of simulated parameters show very few cases of asymmetry. The lower half of the results is obtained from the models that use outward FDI-weighted foreign R&D capital stock (S^{fO}). The benchmark model and the entire set of augmented models are cointegrated. Judging by their bootstrapped p-values, all the cointegrating parameters are positive and statistically significant for the benchmark model. In panel B, regression coefficients of all but two regressors (P^K and U) are positive and statistically significant. The mean values of simulated parameters are positive for all but M^h and U . Essentially, the results are similar to those in the upper half. Outward FDI is yet another conduit of cross-border knowledge spillovers.

Overall, results of Tables 3 and 4 reveal that (i) the three forms of R&D capital stocks and human capital are robust in explaining domestic productivity; and (ii) a large number of other determinants proposed by competing theoretical models are also significant and confirm to the theoretical predictions. Judging by the mean values of our bootstrap parameters, information and communication technology, public infrastructure, stocks of inward and outward FDI, services sector and two measures of financial sector development (P^K and SM^C) show positive effect in all specifications. The ratios of high technology exports and stock market value traded are also positive in most (three out of four) specifications. Interestingly, the high technology import ratio appears with a small but negative coefficient across all specifications. Theoretically, imports are viewed as conduits of technology diffusion. This is captured by the bilateral import ratios weighted foreign R&D capital stocks, which is significantly positive. Therefore, this small (near zero) negative coefficient of import ratio may suggest that imports have no productivity role beyond knowledge diffusion. The employment rate (U), contrary to GP's findings, shows counter cyclical effect on productivity indicating that it may not be a robust proxy for the business cycle.

Table 5 reports the results of models (4) through (6). They test if countries with high accumulated knowledge and human capital stocks experience greater productivity gains. The interacted covariates capture cross-country heterogeneity due to diversity in accumulated stocks.

The coefficients of interacted covariates, namely, $S^b * \overline{S}^b$, $S^p * \overline{S}^p$ and $H * \overline{H}$ are all positive and significant which confirms that countries in possession of large knowledge and human capital stocks tend to benefit from high productivity gains. The coefficients of all the cross-product regressors – $S^p * \overline{S}^b$, $S^{fm} * \overline{S}^b$, $H * \overline{S}^b$; $S^b * \overline{S}^p$, $S^{fm} * \overline{S}^p$, $H * \overline{S}^p$; and $S^b * \overline{H}$, $S^{fm} * \overline{H}$, $S^{fm} * \overline{H}$ – are also positive and significant, indicating that the three sources of knowledge and human capital are complementary in augmenting productivity, although the magnitudes appear to be rather small. The central tendency of simulated parameters appears positive in all cases. The results, especially the bootstrap mean values of the parameters, are qualitatively similar across the both measures of foreign knowledge stocks.

6. Sensitivity Analyses

All the results reported thus far are based on the R&D capital stocks computed at 15 percent depreciation rate. Our first sensitivity tests examine if our results are susceptible to variations in depreciation rates. We re-estimate all the models by using R&D capital stocks measured at 10 and 5 percent depreciation rates and find that the results are robust to these variations. Table A1 reports results based on a 10 percent depreciation rate. Results pertaining to FDI weighted foreign R&D capital stocks and a 5 percent depreciation rate are not reported to conserve space but are available on request.

Results of mean interacted models (Table 5), which reveal that higher levels of accumulated knowledge and human capital stocks yield greater productivity gains, are also robust to the use of 10 and 5 percent depreciation rates. Table A2 reports results estimated at a 10 percent depreciation rate. Results obtained by using a five percent depreciation rates are qualitatively similar but are not reported to conserve space.

Second, we assess the sensitivity of our results to alternative measures of total factor productivity. We re-estimate all specifications by employing further two measures of productivity, namely, the total factor productivity measure by the European Commission and our own calculation following the well-known Solow residual approach (see data appendix). Table A3 reports results obtained from the use of these alternative productivity measures; again, results are robust.

Third, we examine whether our results are affected by the size of countries in the sample. We re-estimated all models by dropping one country at a time from the sample. These results, reported in Table A4, appear robust to variations in the size of sample countries.

Fourth, we control for the services sector by directly including the relative size of the services sector in all the regressions reported in Tables 3 and 4 except for the SER column. Controlling for the services sector does not alter the reported results qualitatively. Finally, we use stocks of public infrastructure computed at eight percent and five percent depreciation rates and find that the reported results remain qualitatively similar throughout these changes. For brevity, we do not report these two sets of results but they are available on request. Overall, our main results are robust to a range of sensitivity tests.

7. Summary and Conclusion

We empirically examine the robustness of sources of knowledge and human capital in driving productivity in a panel of 16 OECD countries. We allow for fifteen theoretical determinants (regressors) of productivity. They include three forms (business, public and foreign) of R&D capital stocks, human capital and further eleven determinants of productivity. The latter, which we term 'non-R&D' determinants of productivity, include information and communication technology (ICT), public infrastructure (Z), high technology exports (X^h) and imports (M^h) ratios, ratios of inward (F^I) and outward (F^O) FDI stocks, the relative size of the services sector (SER), three measures of banking and capital market developments and a proxy of business cycle (U). We estimate their individual as well as joint effects on productivity.

We specify thirteen basic specifications. They comprise of one benchmark model (which includes three forms of R&D and human capital as regressors), eleven individually augmented models (where the benchmark model is augmented by one of the non-R&D determinants at a time), and one general model that augments the benchmark model using the joint variations of all the eleven non-R&D determinants. The joint variation (effect) is captured through a weighted principal component. We estimate four variants of these thirteen basic specifications. The four variants capture the four channels of international knowledge transmissions used as weights to compute the four alternative measures of foreign R&D capital stocks. These weights are the ratios of bilateral capital imports, bilateral R&D collaborations and bilateral inward and outward FDI stocks. Thus, we estimate fifty-two empirical models to assess the robustness of R&D and human capital stocks with respect to their productivity effects.

It is well known that a huge disparity exists in the ownership of R&D and human capital across OECD (sample) countries. For example, the US dominates in terms of the ownership of world knowledge stocks. We, therefore, directly test if varying levels of knowledge and human capital stocks across nations lead to cross-country heterogeneity in productivity relationships (productivity parameters). These hypotheses are tested through mean interacted empirical models.

We carry out panel unit root and cointegration tests to estimate the long-run relationships between domestic productivity and its determinants. The small-sample validity of the estimated cointegrating vectors is scrutinized through the Moving Block Bootstrap (MBB) procedure. We find that all variables in the panel are individually integrated (unit root) processes. All thirteen specifications and their four variants each (fifty-two models) are cointegrated which is indicative of a long-run equilibrium relationship between domestic productivity and its fifteen determinants postulated by different theoretical models.

The three forms of R&D capital stocks and human capital remain robust in explaining productivity; their parameters remain positive and statistically significant throughout all augmentations. Most of the eleven non-R&D regressors also have a positive and significant effect. In particular, information and communication technology, public infrastructure, inward and outward FDI stocks, services sector of the economy, high technology exports and financial deepening appear as the main non-R&D determinants of productivity. Import ratio appears to affect productivity only as a conduit of knowledge spillovers. However, the joint effect of all the non R&D determinants modeled through the weighted principal components appears to be positive and significant in all specifications. All four conduits of international knowledge transmission are also statistically significant.

We find that countries with greater accumulated knowledge and human capital stocks tend to see greater productivity gains than those that have smaller knowledge and human capital bases. Our findings imply that countries like the US and Germany achieve higher productivity gains from their pool of R&D stocks and human capital than countries such as Spain and New Zealand. We also find that the three sources of knowledge stocks and human capital are complementary in increasing productivity.

Finite sample concerns of our estimated parameters are addressed through extensive bootstrap simulations. Our results pass a battery of sensitivity tests vis-à-vis depreciation rates for R&D capital and public infrastructure, alternative measures of total factor productivity, country size and the relative size of the services sector in the economy. To conclude, the sources of knowledge and human capital can be considered robust determinants of domestic productivity across nations, yet a range of other factors also play important role in explaining productivity.

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Data Appendix

Data on multi-factor productivity (P^{m}), obtained from OECD (2008), are measured as the difference between log of output minus a weighted average of the log of labour and capital inputs. Labour and capital inputs are respectively measured as the total hours worked and capital services (OECD, 2008). German data are available from 1991 only; we extrapolated the pre-1991 data using the growth rate of the TFP series obtained from Timmer, Ypma and Van Ark (2003). However, dropping Germany from the sample does not change our results (see Section 6). Two further measures of TFP are used for robustness. The first one is our own measure of TFP (P^{a}) calculated as: log P^{a} = log GDP – 0.3 log K – 0.7 log L; where K is the total net physical capital stock and L is the total employment level. The second measure of TFP (P^{ec}) is published by the European Commission which uses average real unit labour cost to compute labour input.

Domestic business sector R&D capital stocks (S^{b}) are calculated from the research and development expenditure of the business sector (E_{b}^{RD}), using the perpetual inventory method. The initial stock, S_{0}^{b} **,** is calculated as:

$$S_{0}^{b} = \frac{E_{b,0}^{RD}}{g + \delta} \quad \text{(A1)}$$

where δ denotes the depreciation rate, g is the average annual growth rate of E_{b}^{RD} over the sample, and $E_{b,o}^{RD}$ is the initial value of E_{b}^{RD} . This method of computing capital stocks requires making assumptions about the average life of capital stocks and depreciation rates, which do not always capture the complexity of different types of capital assets and different depreciation rates affecting them. The issues of taxes on capital assets and price of capital further complicate the matter. However, this method is widely used in the literature on the grounds of cost and convenience, and we do the same. All R&D capital stocks are computed using 15, 10 and 5 percent depreciation rates. The public sector R&D expenditure (E_{p}^{RD}) is the total R&D expenditure of the government and higher education sectors. Public sector R&D capital stocks (S^{p}) are generated from the public sector R&D expenditure (E_{p}^{RD}), applying the same approach as in equation A1. Due to the lack of R&D deflators, R&D expenditures are converted to constant prices by the GDP deflators. The initial capital stocks, S_{o}^{b} and S_{0}^{p} , are generated for the earliest year for which R&D expenditure data are available (their availability ranges from late sixties to early eighties). We compute four different measures of foreign R&D capital stocks using bilateral imports, bilateral R&D collaborations and stocks of bilateral inward and outward FDI as weights. The import ratio-weighted foreign R&D capital stock (S^{fm}) is:

$$S_{i,t}^{fm} = \sum_{j=1}^{N-i} (M_{ij,t} / Y_{j,t}) * S_{j,t}^{b} \quad \text{(A2)}$$

where, Y_{j} denotes the GDP of country j and M_{ij} is the imports of country i from country j; throughout, 't' denotes time subscript. We use bilateral capital import ratio which include chemicals and related products (SITC 5), manufactured goods classified chiefly by material (SITC 6), machinery and transport equipment (SITC 7) and miscellaneous manufactured articles (SITC 8). Agro industries and raw materials (SITC 0-4) are excluded. The bilateral R&D collaboration weighted foreign knowledge stock (S^{fc}) is:

$$S_{i,t}^{fc} = \sum_{j=1}^{N-i} (PC_{ij,t} / TP_{i,t}) * S_{j,t}^{b} \quad \text{(A3)}$$

where TP_{i} is country i's total patent applications and PC_{ij} is its joint patent applications with countries J, both made at the EPO. Data on patent applications are obtained from the EPO. We compute 15X23 matrixes of bilateral patent cooperation coefficient for each sample country. Likewise, foreign R&D capital stocks based on inward (S^{fI}) and outward (S^{fO}) FDI stocks are computed as:

$$S_{i,t}^{fI} = \sum_{j=1}^{N-i} (FDI_{ij,t} / K_{j,t}) * S_{j,t}^{b} \quad \text{(A4)}$$

$$S_{i,t}^{fO} = \sum_{j=1}^{N-i} (FDO_{ij,t} / K_{j,t}) * S_{j,t}^{b} \quad \text{(A5)}$$

where K_j is country J's capital stock, generated from non-resident fixed capital formation using the perpetual inventory method at 8.0 percent depreciation rate. FDI_{ij} is country i's FDI stock originating from country j; FDO_{ij} is country J's FDI stocks originating from country i. Data are expressed in constant 2000 price using GDP deflator (PL). The relevant weights for all the foreign knowledge stocks are computed using three-year moving averages to avoid yearly fluctuations. Human capital (H) is proxied by the average years of schooling of 25-64 age group. Bassanini and Scarpetta (2002) kindly provided data for the period until 2000; we extrapolate the last four observations. We acknowledge that this is only a rough measure of human capital but we do not have any suitable alternative measures. Data on Information and communication technology investment (ICT) consist of non-resident investment in hardware, communications equipment and software. They are expressed as a percentage of GDP. High technology exports (X^h) and imports (M^h) are expressed as a percentage of total exports and imports, respectively. We follow OECD's (2007) definitions which include: pharmaceuticals (ISIC.2423); office, accounting and computing machinery (ISIC.30); radio, TV and communications equipment (ISIC.32); medical, precision and optical instruments (ISIC.33) and aircraft and spacecraft (ISIC.353) as high technology items of trade. Service sector (SER) is measured as the value added of the service sector relative to GDP. The service sector consists of ISIC Rev.3 industries from 50 to 90. Following GP, the proxy for business cycle is 1 minus the unemployment rate (U).

Stocks of public infrastructure (Z) is generated from government's fixed capital formation (I^{gov}) using perpetual inventory method (equation (A1)). I^{gov} is converted to constant 2000 PPP US dollars using the fixed capital formation deflator. Measures of Z based on 3, 5 and 8 percent depreciation rates are generated. Data on stocks of inward (F^I) and outward (F^O) FDIs are published by the UNCTAD in current US dollars. They are converted to constant PPP dollars, using GDP deflator and PPP exchange rates. Banking sector development is proxied by the ratio of private sector credit by deposit money banks and other financial institutions to GDP (P^K). Two measures of capital market development are the stock market capitalization to GDP ratio (S^{MC}) and the stock market total value traded to GDP ratio (S^{MV}). They are well known measures of financial sector development (see Beck and Levine, 2002; Luintel et al., 2008).

Source OECD: GDP. Multifactor Productivity. R&D Expenditure. ICT. High Technology Exports and Imports. Total Exports and Imports. Service Sector Value Added. Bilateral Imports. Patent Applications. GDP Deflator. Employment Level. Unemployment Rate. PPP Exchange Rate. Government Fixed Capital Formation (GFCF). GFCF Deflator. Non-Resident Fixed Capital Formation.

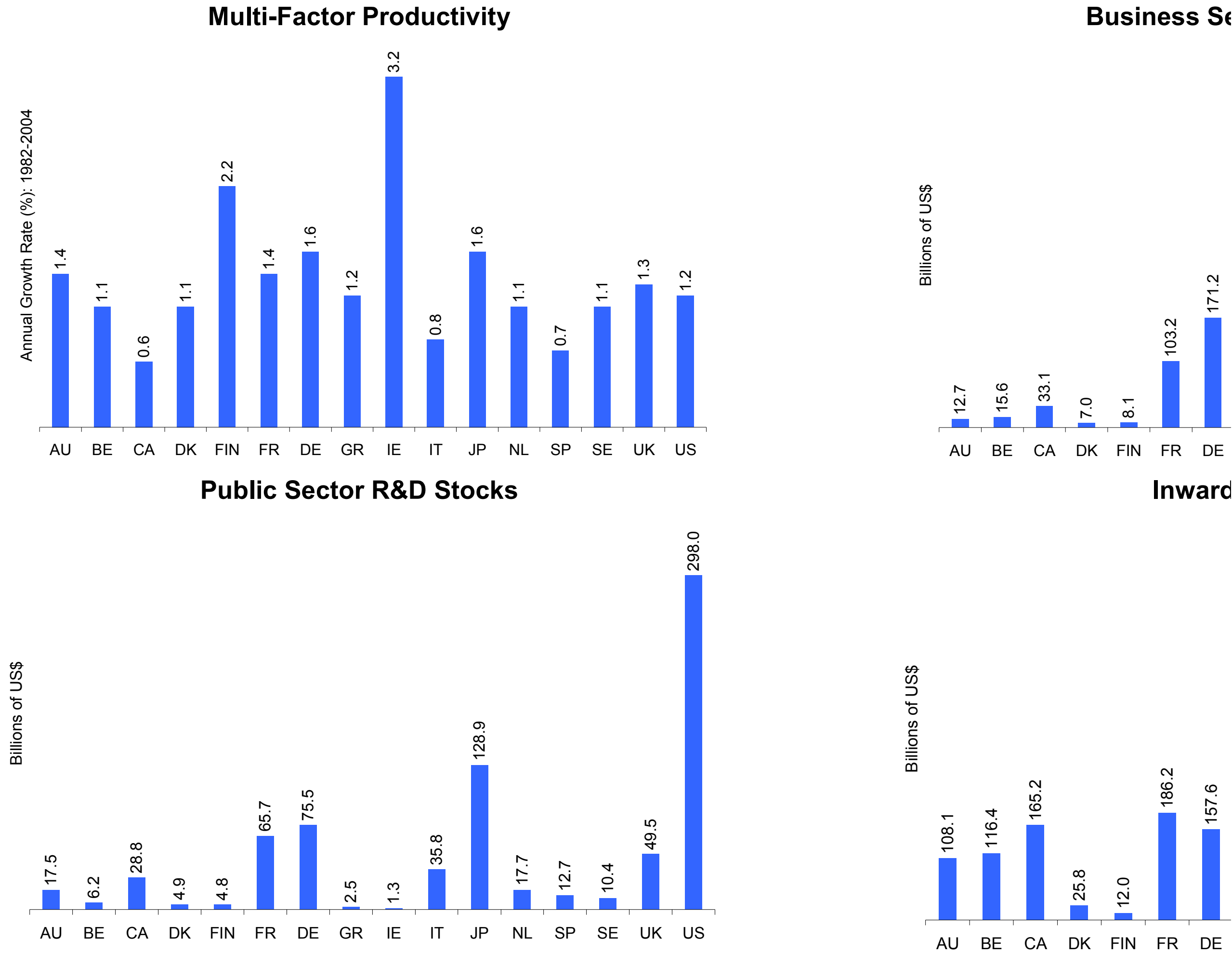
Source World Bank: Private Sector Credit by Deposit Money Banks and other Financial Institutions to GDP. Stock Market Capitalization to GDP. Stock Market Total Value Traded to GDP.

Source European Commission: Total Factor Productivity and Capital Stocks.

Source UNCTAD: Stocks of Total Inward and Outward Foreign Direct Investment.

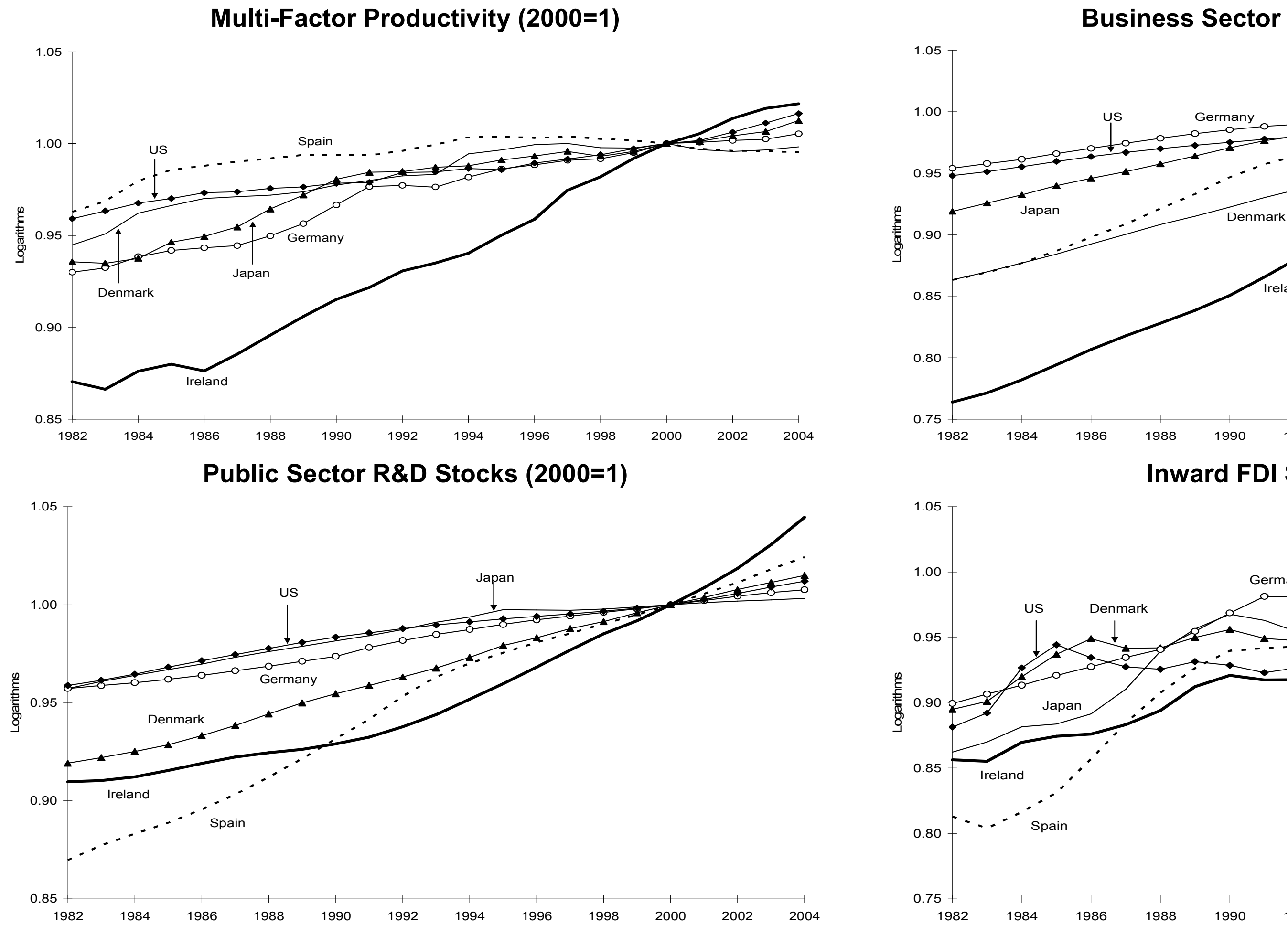
Source Bassanini and Scarpetta (2002): Human Capital.

Figure 1: Multi-Factor Productivity and R&D Capital Stocks



Note: R&D and FDI data are in constant PPP$ and 1982-2004 mean values. Country codes: Australia (AU), Belgium (BE), France (FR), Germany (DE), Greece (GR), Ireland (IE), Italy (IT), Japan (JP), Netherlands (NL), Spain (SP), Sweden (SE), Unite

Figure 2: Trend in Multi-Factor Productivity and R&D Capital Stocks



For visual ease of cross-country comparisons these plots are normalized at 2000=1.

Table 1: Descriptive Statistics (1982-2004 mean value)

	MFP[1]	Business R&D [2,3]		Public R&D [2,4]		Foreign R&D [2]	Human Capital[5]	Public Infrastructure [2, 6]		High-Technolog	
	Growth Rate	Expenditure [Intensity]	Stocks	Expenditure [Intensity]	Stocks	Stocks	Stocks	Expenditure [Intensity]	Stocks	Imports Intensity	Exp Inter
AU	1.4	2.8 [0.7]	12.7	3.1 [0.8]	17.5	2.6	11.9	9.3 [2.4]	181.9	21.6	
BE	1.1	2.8 [1.2]	15.6	1.1 [0.5]	6.2	6.8	10.2	4.9 [2.2]	96.4	10.8	
CA	0.6	6.7 [0.9]	33.1	5.2 [0.7]	28.8	11.5	12.7	17.1 [2.4]	242.5	17.2	
DK	1.1	1.5 [1.1]	7.0	0.9 [0.7]	4.9	2.0	11.1	2.3 [1.7]	42.1	14.4	
FIN	2.2	1.8 [1.5]	8.1	0.9 [0.8]	4.8	1.4	10.8	3.6 [3.3]	57.7	16.6	
FR	1.4	18.2 [1.3]	103.2	11.2 [0.8]	65.7	11.1	10.4	41.4 [3.0]	656.4	16.4	
DE	1.6	29.9 [1.7]	171.2	13.0 [0.7]	75.5	13.5	12.4	36.9 [2.2]	652.8	16.9	
GR	1.2	0.2 [0.1]	0.9	0.5 [0.3]	2.5	1.0	9.3	5.1 [3.3]	73.0	10.7	
IE	3.2	0.5 [0.6]	2.3	0.3 [0.4]	1.3	1.7	9.7	2.7 [3.9]	39.7	28.7	
IT	0.8	7.5 [0.6]	43.2	6.5 [0.5]	35.8	7.8	8.6	38.3 [3.0]	596.2	13.8	
JP	1.6	58.0 [2.0]	305.6	21.9 [0.8]	128.9	6.2	11.6	202.5 [7.1]	3157.1	14.6	
NL	1.1	3.8 [1.0]	22.0	3.0 [0.8]	17.7	6.6	11.2	11.4 [3.1]	204.1	19.8	
SP	0.7	2.9 [0.4]	14.0	2.6 [0.4]	12.7	4.9	7.6	24.8 [3.6]	317.1	14.1	
SE	1.1	4.8 [2.3]	24.6	1.9 [0.9]	10.4	2.8	11.2	6.1 [3.0]	109.9	17.2	
UK	1.3	16.5 [1.3]	100.7	8.1 [0.7]	49.5	11.9	11.2	18.9 [1.5]	350.0	20.7	
US	1.2	145.8 [1.9]	809.0	52.2 [0.7]	298.0	24.3	12.6	253.6 [3.2]	3570.7	20.0	
Mean	1.3	19.0 [1.6]	104.6	8.3 [0.7]	47.5	7.3	10.8	42.4 [3.5]	646.7	17.4	

1. Average annual growth rate of multi-factor productivity. 2. Billion constant (2000) PPP US dollars. 3. Intensity (business secto (public sector R&D expenditure as a % of GDP). 5. Human capital, proxied by the average years of schooling of the population g stocks of public physical capital stock and its intensity is defined as public infrastructure expenditure as a % of GDP. 7. Hig exports (imports). 8. ICT investment to GDP ratio. 9. Financial development, proxied by stock market capitalization to GDP ratio.

Country codes: Australia (AU), Belgium (BE), Canada (CA), Denmark (DK), Finland (FIN), France (FR), Germany (DE), Gre Netherlands (NL), Spain (SP), Sweden (SE), United Kingdom (UK) and United States (US).

Table 2: Panel Unit Root Tests			
	IPS [W-Stat]	ADF-Fisher [Chi-Square]	Hadri [Consistent Z-stat]
P^m	3.915 [1.000]	26.575 [0.738]	12.848 [0.000]
H	6.980 [1.000]	15.367 [0.994]	13.571 [0.000]
S^b	-0.081 [0.468]	35.084 [0.324]	13.493 [0.000]
S^p	3.776 [0.999]	16.865 [0.987]	13.672 [0.000]
S^{fc}	0.670 [0.749]	40.569 [0.142]	13.373 [0.000]
S^{fI}	2.038 [0.979]	14.797 [0.991]	12.413 [0.000]
S^{fO}	0.407 [0.657]	29.98 [0.467]	12.054 [0.000]
S^{fm}	1.055 [0.854]	24.358 [0.831]	12.565 [0.000]
ICT	-0.387 [0.350]	32.666 [.434]	7.921 [0.000]
F^I	5.188 [1.000]	10.790 [0.999]	11.848 [0.000]
F^O	5.070 [1.000]	9.950 [0.999]	12.233 [0.000]
M^h	-0.341 [0.367]	35.032 [0.3262]	12.506 [0.000]
X^h	1.779 [0.962]	26.263 [0.752]	11.370 [0.000]
SER	1.453 [0.927]	22.209 [0.902]	12.216 [0.000]
Z	6.143 [1.000]	12.650 [0.999]	13.093 [0.000]
P^K	1.912 [0.972]	28.247 [0.657]	8.084 [0.000]
S^{MC}	1.544 [0.939]	17.655 [0.964]	7.964 [0.000]
S^{MV}	1.410 [0.921]	21.084 [0.885]	8.277 [0.000]
U	-0.076 [0.469]	25.795 [0.773]	5.887 [0.000]
P^a	2.965 [0.999]	20.275 [0.946]	13.049 [0.000]
P^{ec}	2.197 [0.986]	27.738 [0.682]	13.034 [0.000]

Sample [1982-2004]. Exogenous variables: Individual effects. For the IPS and Fisher-ADF tests, the maximum lag length of 3 is set and equation-specific lag lengths are chosen through Schwarz information criteria. W-Stat is the standardized $\overline{t}_{NT}$ test of IPS. ADF Fisher tests are χ^2 (32) distributed. Altering the lag lengths does not change the qualitative nature of the results. The Hadri test is computed using Newey-West bandwidth selection and Bartlett kernel; the reported test statistic is heteroskedasticity consistent Z-statistic. Results of Hadri tests are robust to homoscedasticity and/or serial correlation in the error term.

Panel cointegration tests and the FMOLS estimates of cointegrating parameters

	Panel A				Panel B											
	Results based on bilateral imports weighted foreign R&D stocks (S^{fm}).															
	S^b	S^p	S^{fm}	H	ICT	X^h	M^h	Z	F^I	F^O	P^K	S^{MC}	S^{MV}	U	SER	
tistic	0.010				0.000	0.000	0.000	0.001	0.001	0.000	0.001	0.001	0.002	0.001	0.001	
istic	0.000				0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.0
	0.089	0.193	0.043	0.197	1.141	-0.102	-0.069	0.049	0.024	0.041	-0.041	0.002	0.006	-0.170	0.227	
	(0.000)	(0.000)	(0.000)	(0.000)	(0.368)	(0.000)	(0.000)	(0.099)	(0.000)	(0.000)	(0.000)	(0.005)	(0.000)	(0.000)	(0.162)	(
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.004]	[0.004]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.004]	[0.000]	[
	0.121	0.115	0.004	0.303	0.315	-0.008	-0.006	0.151	0.004	0.006	0.002	0.001	0.001	-0.114	0.085	
	-0.067	-0.137	-0.042	-0.709	-2.744	-0.511	-0.392	-0.382	-0.027	-0.030	-0.097	-0.042	-0.036	-0.830	-0.614	-
	0.309	0.374	0.048	1.297	2.469	0.509	0.354	0.662	0.041	0.038	0.101	0.037	0.034	0.587	0.847	
	0.104	0.119	0.004	0.268	-0.420	-0.009	-0.004	0.230	0.002	0.004	0.006	-0.001	0.003	0.027	0.155	
	Results based on bilateral R&D collaboration weighted foreign R&D stocks (S^{fc})															
	S^b	S^p	S^{fc}	H	ICT	X^h	M^h	Z	F^I	F^O	P^K	S^{MC}	S^{MV}	U	SER	
istic	0.001				0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
stic	0.000				0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.115	0.000	
	0.133	0.188	-0.013	0.246	0.750	0.142	-0.089	0.259	0.019	0.046	0.003	0.030	0.022	0.154	-0.364	
	(0.000)	(0.000)	(0.120)	(0.009)	(0.001)	(0.436)	(0.004)	(0.001)	(0.000)	(0.000)	(0.014)	(0.000)	(0.000)	(0.085)	(0.000)	(
	[0.000]	[0.000]	[0.002]	[0.000]	[0.000]	[0.000]	[0.002]	[0.000]	[0.000]	[0.000]	[0.002]	[0.000]	[0.000]	[0.000]	[0.002]	[
	0.098	0.114	0.010	0.269	0.324	0.024	-0.043	0.190	0.004	0.004	0.002	0.001	-0.002	-0.098	0.071	
	-0.108	-0.126	-0.043	-0.727	-2.695	-0.527	-0.448	-0.305	-0.031	-0.032	-0.117	-0.045	-0.046	-0.756	-0.582	-
	0.286	0.364	0.061	1.366	2.120	0.447	0.328	0.695	0.039	0.040	0.109	0.041	0.039	0.545	0.725	
	0.098	0.144	0.012	0.325	0.466	-0.070	-0.028	0.187	0.007	0.005	-0.007	-0.001	-0.002	-0.033	0.045	

ıated equation is $LogP^m_{it} = \alpha_{3i} + \alpha^b_{3i}\log S^b_{it} + \alpha^p_{3i}\log S^p_{it} + \alpha^f_{3i}\log S^f_{it} + \alpha^h_{3i}\log H_t + \beta' X_{it} + \varepsilon_{3it}$. The vector X∈ (ICT , SER , Z , X^h , M
, S^{MC} , S^{MV} , U , WPC); all in logs. The depreciation rates for S^f_{it} and Z are 15% and 3%, respectively. Panel A reports the results of benchma
cludes the $\beta' X_{it}$ bit from the estimating equation. In panel B, each column reports results of augmented model; e.g., column ICT augments the be
the ICT variable. The group ρ - and group t-statistics are panel cointegration tests due to Pedroni (1999). β -vector is the FMOLS esti
ting parameters; μ and M^D are the mean and median values of bootstrap parameters; U^B and L^B are their upper and lower bounds. 1000
rs are computed. (.) are asymptotic p-values and [.] are bootstrap p-values. For details on variables see notes to Table 4.

able 4: Panel Cointegration Tests and FMOLS Estimates of Cointegrating Parameters

	Panel A				Panel B											
	Results based on bilateral inward FDI weighted foreign R&D stocks (S^{fI})															
	S^b	S^p	S^{fI}	H	ICT	X^h	M^h	Z	F^I	F^O	P^K	S^{MC}	S^{MV}	U	SER	WP
ɔ $- statistic$	0.001				0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.00
$- statistic$	0.022				0.000	0.000	0.001	0.000	0.019	0.013	0.000	0.000	0.000	0.003	0.000	0.00
ꞵ	0.093	0.171	0.001	0.388	1.463	0.164	0.064	0.165	0.026	0.040	-0.065	0.021	0.010	0.009	-0.051	0.0
	(0.000)	(0.000)	(0.262)	(0.002)	(0.000)	(0.001)	(0.002)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.016)	(0.040)	(0.00
	[0.000]	[0.000]	[0.002]	[0.000]	[0.000]	[0.004]	[0.004]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.004]	[0.004]	[0.00
ι	0.104	0.123	0.001	0.374	0.145	0.013	-0.002	0.172	0.007	0.004	0.001	0.002	0.000	-0.065	0.041	0.0
ɜ	-0.114	-0.165	-0.033	-0.843	-2.302	-0.612	-0.369	-0.451	-0.028	-0.027	-0.124	-0.033	-0.039	-0.656	-0.677	-0.0
B	0.324	0.427	0.035	1.603	2.489	0.579	0.433	0.736	0.043	0.041	0.099	0.037	0.041	0.592	0.675	0.0
ID	0.119	0.123	0.001	0.371	-0.113	0.113	0.016	0.192	0.007	0.002	0.009	0.001	0.001	-0.082	0.097	0.0
	Results based on bilateral outward FDI-weighted foreign R&D stocks (S^{fO})															
	S^b	S^p	S^{fO}	H	ICT	X^h	M^h	Z	F^I	F^O	P^K	S^{MC}	S^{MV}	U	SER	WP
ɔ $- statistic$	0.000				0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000
$- statistic$	0.022				0.002	0.000	0.002	0.000	0.014	0.076	0.000	0.000	0.000	0.004	0.000	0.00
ꞵ	0.071	0.161	0.005	0.665	1.723	0.007	0.026	0.196	0.022	0.047	-0.065	0.028	0.012	-0.066	0.030	0.0
	(0.000)	(0.000)	(0.427)	(0.000)	(0.000)	(0.000)	(0.000)	(0.017)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.212)	(0.011)	(0.00
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.004]	[0.004]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.004]	[0.004]	[0.00
ι	0.106	0.128	0.002	0.320	0.143	0.003	-0.021	0.200	0.005	0.005	0.007	0.003	0.003	-0.019	0.035	0.0
ɜ	-0.107	-0.148	-0.036	-0.871	-2.402	-0.545	-0.454	-0.363	-0.029	-0.030	-0.101	-0.031	-0.039	-0.685	-0.638	-0.0
B	0.314	0.398	0.035	1.404	2.611	0.525	0.366	0.740	0.039	0.042	0.122	0.043	0.043	0.653	0.748	0.0
ID	0.117	0.121	0.003	0.213	-0.025	-0.011	-0.053	0.185	-0.001	0.007	0.004	0.007	0.003	0.032	0.127	0.0

he variables are: S^b = business sector R&D capital stock; S^p =public sector R&D capital stock; H = human capital; ICT =information ar ɔmmunication technology; X^h =ratio of high technology exports to total exports; M^h =ratio of high technology imports to total imports; Z = publ ɲysical infrastructure; F^I = stock of inward FDI; F^O = stock of outward FDI; P^K = ratio of private sector credit by deposit money banks and oth ɲancial institutions to GDP; S^{MC} = stock market capitalization to GDP ratio; S^{MV} =stock market total value traded to GDP ratio; U =1-unemployme ɩte; SER =value added of the services sector relative to GDP; WPC = weighted principal component. For other definitions please refer to the end note f Table 3.

Table 5: FMOLS Estimates of Mean Interacted Specifications

	Panel A				Panel B				Panel C			
	Estimation based on bilateral imports weighted foreign R&D stocks (S^{fm}).											
	$S^b_{it}*\bar{S}^b_i$	$S^p_{it}*\bar{S}^b_i$	$S^{fm}_{it}*\bar{S}^b_i$	$H_{it}*\bar{S}^b_i$	$S^b_{it}*\bar{S}^p_i$	$S^p_{it}*\bar{S}^p_i$	$S^{fm}_{it}*\bar{S}^p_i$	$H_{it}*\bar{S}^p_i$	$S^b_{it}*\bar{H}_i$	$S^p_{it}*\bar{H}_i$	$S^{fm}_{it}*\bar{H}_i$	$H_{it}*\bar{H}_i$
β	0.008	0.021	0.005	0.009	0.009	0.021	0.005	0.014	0.039	0.080	0.018	0.071
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
μ	0.012	0.013	0.000	0.026	0.013	0.012	0.000	0.025	0.051	0.051	0.001	0.118
L^B	-0.007	-0.012	-0.005	-0.079	-0.007	-0.014	-0.005	-0.088	-0.034	-0.051	-0.021	-0.334
U^B	0.030	0.038	0.006	0.134	0.030	0.038	0.006	0.142	0.131	0.159	0.023	0.567
M^D	0.010	0.013	0.001	0.021	0.013	0.009	0.000	0.028	0.048	0.047	-0.001	0.116
	Estimation based on bilateral R&D collaboration weighted foreign R&D stocks (S^{fc})											
	$S^b_{it}*\bar{S}^b_i$	$S^p_{it}*\bar{S}^b_i$	$S^{fc}_{it}*\bar{S}^b_i$	$H_{it}*\bar{S}^b_i$	$S^b_{it}*\bar{S}^p_i$	$S^p_{it}*\bar{S}^p_i$	$S^{fc}_{it}*\bar{S}^p_i$	$H_{it}*\bar{S}^p_i$	$S^b_{it}*\bar{H}_i$	$S^p_{it}*\bar{H}_i$	$S^{fc}_{it}*\bar{H}_i$	$H_{it}*\bar{H}_i$
β	0.013	0.019	-0.001	0.026	0.013	0.019	-0.001	0.031	0.057	0.078	-0.005	0.098
	(0.000)	(0.000)	(0.120)	(0.009)	(0.000)	(0.000)	(0.120)	(0.009)	(0.000)	(0.000)	(0.120)	(0.009)
	[0.000]	[0.000]	[0.002]	[0.000]	[0.000]	[0.000]	[0.002]	[0.000]	[0.000]	[0.000]	[0.002]	[0.000]
μ	0.010	0.012	0.001	0.027	0.010	0.013	0.001	0.027	0.041	0.049	0.004	0.114
L^B	-0.009	-0.014	-0.004	-0.078	-0.011	-0.015	-0.004	-0.078	-0.042	-0.056	-0.016	-0.316
U^B	0.030	0.038	0.006	0.133	0.030	0.038	0.006	0.133	0.125	0.158	0.025	0.537
M^D	0.008	0.011	0.001	0.035	0.010	0.011	0.001	0.019	0.041	0.049	0.002	0.144

Panels A, B and C report estimated results of models (4), (5) and (6) in the text, respectively. S^b and S^p respectively denote the domestic business and private sector R&D capital stocks. H denotes human capital stocks. $\bar{S}^b_i = T_i^{-1}\sum_{t=1}^{T} S^b_{it}$; $\bar{S}^p_i = T_i^{-1}\sum_{t=1}^{T} S^p_{it}$; and $\bar{H}_i = T_i^{-1}\sum_{t=1}^{T} H_{i,t}$. Variables mnemonics are defined in the notes to Table 4.

able A1: Panel cointegration tests and FMOLS estimates of the cointegrating parameter: R&D capital stocks at 10% epreciation rate.

	Panel A				Panel B											
Results based on bilateral imports weighted foreign R&D stocks (S^{fm}).																
	S^b	S^p	S^{fm}	H	ICT	X^h	M^h	Z	F^I	F^O	P^K	S^{MC}	S^{MV}	U	SER	WPC
ɔ $-statistic$	0.008				0.000	0.000	0.000	0.001	0.001	0.000	0.000	0.001	0.001	0.001	0.001	0.00
· $-statistic$	0.000				0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.00
ɜ	0.019	0.258	0.041	0.208	1.594	-0.109	-0.102	-0.107	0.020	0.034	-0.037	0.015	0.024	-0.149	0.115	0.03
	(0.002)	(0.000)	(0.000)	(0.000)	(0.043)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.003)	(0.000)	(0.000)	(0.000)	(0.128)	(0.00
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.002]	[0.002]	[0.002]	[0.000]	[0.000]	[0.002]	[0.000]	[0.000]	[0.002]	[0.002]	[0.00
ι	0.060	0.199	0.000	0.215	0.304	-0.031	-0.031	0.059	0.003	0.004	0.002	0.001	0.002	-0.056	0.017	0.00
ɜ	-0.205	-0.151	-0.051	-0.950	-2.861	-0.576	-0.401	-0.600	-0.033	-0.030	-0.118	-0.041	-0.038	-0.778	-0.731	-0.03
B	0.320	0.548	0.048	1.334	2.230	0.530	0.327	0.653	0.036	0.036	0.115	0.039	0.039	0.629	0.743	0.03
D	0.091	0.204	0.000	0.267	-0.302	-0.046	-0.059	0.138	0.003	0.002	0.009	-0.001	-0.001	-0.089	0.065	0.00
Results based on bilateral R&D collaboration weighted foreign R&D stocks (S^{fc})																
	S^b	S^p	S^{fc}	H	ICT	X^h	M^h	Z	F^I	F^O	P^K	S^{MC}	S^{MV}	U	SER	WPC
ɔ $-statistic$	0.001				0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.00
· $-statistic$	0.001				0.000	0.000	0.000	0.000	0.004	0.012	0.000	0.000	0.000	0.220	0.000	0.00
ɜ	0.047	0.309	-0.018	0.123	1.097	0.074	-0.130	0.025	0.015	0.033	0.000	0.027	0.024	0.255	-0.563	0.03
	(0.002)	(0.000)	(0.002)	(0.054)	(0.000)	(0.103)	(0.000)	(0.248)	(0.000)	(0.000)	(0.160)	(0.000)	(0.000)	(0.252)	(0.000)	(0.00
	[0.000]	[0.000]	[0.002]	[0.000]	[0.000]	[0.000]	[0.002]	[0.002]	[0.000]	[0.000]	[0.002]	[0.000]	[0.000]	[0.000]	[0.000]	[0.00
ι	0.074	0.175	0.003	0.188	0.223	0.004	-0.039	0.049	0.002	0.004	0.001	0.001	-0.001	-0.038	0.003	0.00
ɜ	-0.188	-0.212	-0.051	-0.864	-2.441	-0.497	-0.432	-0.508	-0.031	-0.030	-0.119	-0.039	-0.041	-0.647	-0.616	-0.03
B	0.345	0.524	0.053	1.279	1.867	0.527	0.343	0.620	0.039	0.038	0.121	0.035	0.039	0.592	0.705	0.04
D	0.095	0.197	0.000	0.166	-0.622	-0.039	0.020	0.086	0.002	0.003	-0.005	-0.002	0.000	0.034	-0.096	0.00

or all definitions, please refer to the end notes of Tables 3 and 4.

Table A2: FMOLS estimates of the mean interacted specifications: R&D capital stocks at 10% depreciation rate.												
	Panel A				**Panel B**				**Panel C**			
Estimation based on bilateral imports weighted foreign R&D stocks (S^{fm}).												
	$S_{it}^{b} * \overline{S}_{i}^{b}$	$S_{it}^{p} * \overline{S}_{i}^{b}$	$S_{it}^{fm} * \overline{S}_{i}^{b}$	$H_{it} * \overline{S}_{i}^{b}$	$S_{it}^{b} * \overline{S}_{i}^{p}$	$S_{it}^{p} * \overline{S}_{i}^{p}$	$S_{it}^{fm} * \overline{S}_{i}^{p}$	$H_{it} * \overline{S}_{i}^{p}$	$S_{it}^{b} * \overline{H}_{i}$	$S_{it}^{p} * \overline{H}_{i}$	$S_{it}^{fm} * \overline{H}_{i}$	$H_{it} * \overline{H}_{i}$
β	0.001	0.028	0.004	0.010	0.001	0.027	0.004	0.014	0.010	0.108	0.017	0.074
	(0.002)	(0.000)	(0.000)	(0.000)	(0.002)	(0.000)	(0.000)	(0.000)	(0.002)	(0.000)	(0.000)	(0.000)
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
μ	0.006	0.019	0.000	0.022	0.006	0.019	0.000	0.020	0.024	0.085	0.000	0.100
L^{B}	-0.022	-0.014	-0.005	-0.091	-0.021	-0.016	-0.005	-0.092	-0.098	-0.073	-0.021	-0.327
U^{B}	0.031	0.055	0.005	0.138	0.031	0.054	0.005	0.120	0.142	0.244	0.022	0.609
M^{D}	0.006	0.015	0.001	0.029	0.008	0.019	0.000	0.023	0.007	0.095	0.002	0.086
Estimation based on bilateral R&D collaboration weighted foreign R&D stocks (S^{fc})												
	$S_{it}^{b} * \overline{S}_{i}^{b}$	$S_{it}^{p} * \overline{S}_{i}^{b}$	$S_{it}^{fc} * \overline{S}_{i}^{b}$	$H_{it} * \overline{S}_{i}^{b}$	$S_{it}^{b} * \overline{S}_{i}^{p}$	$S_{it}^{p} * \overline{S}_{i}^{p}$	$S_{it}^{fc} * \overline{S}_{i}^{p}$	$H_{it} * \overline{S}_{i}^{p}$	$S_{it}^{b} * \overline{H}_{i}$	$S_{it}^{p} * \overline{H}_{i}$	$S_{it}^{fc} * \overline{H}_{i}$	$H_{it} * \overline{H}_{i}$
β	0.005	0.030	-0.001	0.010	0.005	0.029	-0.001	0.014	0.021	0.129	-0.007	0.043
	(0.002)	(0.000)	(0.002)	(0.054)	(0.002)	(0.000)	(0.002)	(0.054)	(0.002)	(0.000)	(0.002)	(0.054)
	[0.000	[0.000	[0.002	[0.000	[0.000	[0.000	[0.002	[0.000	[0.000	[0.000	[0.002	[0.000]
μ	0.007	0.017	0.000	0.017	0.007	0.017	0.000	0.015	0.028	0.076	0.002	0.080
L^{B}	-0.019	-0.017	-0.005	-0.082	-0.019	-0.019	-0.005	-0.089	-0.086	-0.089	-0.020	-0.395
U^{B}	0.033	0.054	0.005	0.118	0.031	0.051	0.005	0.126	0.149	0.239	0.024	0.578
M^{D}	0.007	0.019	0.000	0.011	0.008	0.020	0.000	0.018	0.030	0.081	0.001	0.086
For definitions please refer to the end notes of Table 5.												

Table A3: : FMOLS estimates of the cointegrating parameter based on alternative measures of TFP

	Panel A				Panel B											
Results based on our own measure of TFP (P^a).																
	S^b	S^p	S^{fm}	H	ICT	X^h	M^h	Z	F^I	F^O	P^K	S^{MC}	S^{MV}	U	SER	WPC
β	0.150	0.051	0.055	0.336	1.874	0.056	-0.031	-0.138	0.028	0.035	-0.039	0.034	0.028	-0.024	-0.200	0.050
	(0.000)	(0.000)	(0.000)	(0.021)	(0.000)	(0.001)	(0.007)	(0.433)	(0.000)	(0.000)	(0.044)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.002]	[0.002]	[0.002]	[0.000]	[0.000]	[0.002]	[0.000]	[0.000]	[0.002]	[0.002]	[0.000]
μ	0.105	0.126	0.004	0.240	0.314	-0.014	-0.025	0.170	0.003	0.004	0.004	0.000	0.000	-0.107	0.082	0.004
L^B	-0.073	-0.120	-0.039	-0.813	-2.912	-0.543	-0.372	-0.350	-0.032	-0.033	-0.106	-0.035	-0.036	-0.758	-0.613	-0.036
U^B	0.283	0.383	0.051	1.364	2.148	0.474	0.329	0.701	0.035	0.038	0.115	0.035	0.036	0.490	0.752	0.041
M^D	0.105	0.126	0.007	0.377	-0.127	0.039	-0.024	0.169	0.002	0.005	0.007	0.002	0.000	0.062	0.051	0.004
Results based on the European Commission's data on TFP (P^{ec}).																
	S^b	S^p	S^{fm}	H	ICT	X^h	M^h	Z	F^I	F^O	P^K	S^{MC}	S^{MV}	U	SER	WPC
β	0.121	0.068	0.069	0.298	1.108	0.017	-0.068	-0.074	0.026	0.036	-0.067	0.025	0.022	-0.128	-0.168	0.050
	(0.000)	(0.000)	(0.000)	(0.000)	(0.005)	(0.012)	(0.030)	(0.115)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.002]	[0.002]	[0.002]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.002]	[0.002]	[0.000]
μ	0.103	0.130	0.005	0.290	0.311	-0.027	-0.020	0.172	0.004	0.004	0.007	0.001	-0.001	-0.098	0.077	0.004
L^B	-0.084	-0.129	-0.042	-0.890	-2.857	-0.500	-0.410	-0.307	-0.029	-0.032	-0.111	-0.032	-0.036	-0.846	-0.567	-0.031
U^B	0.281	0.373	0.049	1.362	2.057	0.418	0.317	0.694	0.038	0.039	0.129	0.033	0.034	0.533	0.677	0.040
M^D	0.105	0.119	0.005	0.308	-0.536	-0.007	-0.042	0.166	0.001	0.002	0.005	0.004	-0.003	-0.045	0.097	0.003

All the reported models are cointegrated. Panel cointegration tests with these alternative measures of total factor productivity appear close to those reported in Tables 3 and 4. To economise on the size of the table we do not report the results of cointegration tests. Data on P^{ec} are directly available from the European Commission. We compute P^a as: log P^a = log GDP – 0.3 log K – 0.7 log L; where K is the total net physical capital stock and L is the total employment level. For other definitions, please refer to the notes to Table 3. For variable mnemonics see Table 4.

Table A4: Panel Cointegration Tests and FMOLS Estimates of the Cointegrating Parameter

	Panel A					Panel B									
	S^b	S^p	S^{fm}	H	ICT	X^h	M^h	Z	F^I	F^O	S^{MC}	S^{MV}	U	SER	WPC
Australia*	0.105	0.152	0.047	0.284	1.356	0.012	-0.052	0.011	0.028	0.043	0.011	0.010	-0.183	0.317	0.046
Belgium*	0.081	0.196	0.053	0.186	1.248	-0.075	-0.038	0.020	0.025	0.043	0.011	0.015	-0.174	0.238	0.045
Canada*	0.097	0.222	0.046	-0.033	1.608	-0.049	-0.034	0.091	0.019	0.029	0.009	0.014	-0.195	0.288	0.035
Denmark*	0.129	0.136	0.036	0.212	0.799	-0.036	-0.073	0.050	0.027	0.043	0.019	0.021	-0.164	0.152	0.047
Finland*	0.085	0.208	0.043	0.146	1.331	-0.114	-0.079	0.070	0.024	0.045	0.012	0.016	-0.156	0.282	0.045
France*	0.075	0.214	0.038	0.185	1.148	-0.100	-0.065	0.033	0.025	0.044	0.012	0.016	-0.186	0.240	0.045
Germany*	0.105	0.176	0.037	0.170	1.206	-0.103	-0.059	0.062	0.025	0.043	0.013	0.017	-0.177	0.196	0.045
Greece*	0.081	0.187	0.042	0.372	0.577	-0.204	-0.083	-0.041	0.023	0.039	0.008	0.015	-0.193	0.347	0.042
Ireland*	0.086	0.195	0.033	0.183	1.347	-0.093	-0.049	0.061	0.027	0.044	n.a.	n.a.	-0.166	0.218	0.047
Italy*	0.063	0.237	0.046	0.144	0.346	-0.189	-0.151	0.074	0.025	0.040	0.005	0.010	-0.111	0.134	0.044
Japan*	0.068	0.222	0.042	0.226	1.387	-0.050	-0.041	0.073	0.021	0.040	0.013	0.016	-0.250	0.232	0.038
Netherlands*	0.091	0.176	0.048	0.237	1.221	-0.126	-0.098	0.037	0.024	0.042	0.011	0.016	-0.146	0.253	0.044
Spain*	0.099	0.184	0.044	0.271	0.667	-0.195	-0.168	0.016	0.017	0.041	0.004	0.015	-0.122	0.097	0.041
Sweden*	0.069	0.225	0.046	0.231	1.399	-0.079	-0.024	0.081	0.023	0.044	0.016	0.017	-0.202	0.241	0.044
United Kingdom*	0.099	0.156	0.047	0.193	1.207	-0.120	-0.069	0.076	0.022	0.041	0.011	0.014	-0.188	0.176	0.043
United States*	0.085	0.200	0.045	0.143	1.406	-0.111	-0.030	0.075	0.035	0.037	0.010	0.017	-0.103	0.227	0.041

Note: * indicates exclusion of the country from the sample while computing these results. For example, Australia* denotes exclusion of Australia from the sample while estimating the results of the first row. The same structure applies for the results in other rows. All specifications are cointegrated. Again, to save space, we do not report these sixteen set of panel cointegration tests. Greece does not have data on S^{MC} and S^{MV}.