R&D, Human Capital and International Technology Spillovers: A Cross-country Analysis

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Abstract

This paper is based on recent developments in the theory of innovation-driven growth that emphasize both the importance of R&D efforts — domestic as well as foreign — for explaining national productivity, and the complementarity between R&D and human capital investments. Estimates of specifications, in growth terms and in level terms, on a cross-section of OECD countries from the early 1960s to the early 1990s lend strong support to this thesis. The data show a significant influence of both domestic and foreign R&D. Moreover, there is clearly a net positive impact of human capital. The level and growth rate of human capital are shown to affect productivity growth and there is evidence of interaction with the catch-up process.

Keywords: R&D; human capital; spillovers; productivity

JEL classification: O33; O47

I. Introduction

Recent contributions to the literature on endogenous growth have emphasized the importance of both domestic R&D efforts and international technology spillovers in explaining national productivity growth. Some theoretical work has also stressed the complementarity between R&D and human capital investments. The relevant empirical literature is still in its infancy, however. In this paper, we attempt to shed new light on these issues in a cross-country analysis of 21 OECD countries, using alternate specifications and estimation methods. We begin by considering equations that relate long-run total factor productivity (TFP) growth to domestic and foreign R&D intensity. These equations are then expanded to include the rate of growth or the level of human capital. They are each time estimated on a cross-section of average data over the period 1961–1991. A cointegration analysis is then performed on equations in level terms. These equations respectively relate the log of TFP to the logs of the stocks of domestic and foreign capital, and to the same variables and the log of human capital. The

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cointegrating equations and the corresponding error correction models are estimated on a panel of pooled annual time series for the same countries over the period 1965–1991.

The paper is organized as follows: Section II contains a theoretical justification for the empirical specifications; Section III presents the data; the estimates are reported in Section IV and Section V concludes. The sources and definitions of the data are described in the appendix.

II. Theory

Recent developments in theoretical growth economics have emphasized the importance of commercially oriented R&D efforts as an engine of growth. Models have been constructed which predict that labour productivity and TFP are positively related to the stock of domestic R&D capital; see Romer (1990), Grossman and Helpman (1991, Chs. 3, 4 and 5), and Aghion and Howitt (1992). A characteristic feature of these models is that they assume the existence of knowledge spillover effects that are strong enough to allow R&D costs to remain constant in terms of goods. A given level of R&D effort will in this case suffice to generate sustained TFP growth.

A logical consequence of these models is that, given the level of R&D effort, a process of opening up and integrating formerly closed economies will tend to raise their rates of growth. Flows of ideas will now take on a more international character; see Rivera-Batiz and Romer (1991). Taking into account the limits to integration, open economy models were constructed which assume technological leader–follower relationships; see Grossman and Helpman (1991, Chs. 11 and 12), Segerstrom (1991) and Barro and Sala-i-Martin (1995, Ch. 8). They concentrate on international trade as a channel for technology spillovers. It is assumed that while final goods are perfectly tradable across countries, intermediate goods are only partly so and require mastering and adaptation. Since imitation is easier than innovation, these models imply transitional dynamics characterized by conditional convergence through technical diffusion.

One shortcoming of innovation-driven growth models is that they do not adequately take into account the role of human capital, which is at most viewed as an input in the research process. These models fail to accord adequate consideration to the need for a sufficiently qualified labour force, capable of working with the new technologies created by innovation efforts. Redding (1996) attempted to remedy this weakness by proposing a model that emphasizes the complementarity between R&D efforts by firms and investment in human capital. Its steady-state rate of growth is determined by both the rate of investment in R&D and the rate of human capital accumulation. The main line of reasoning can easily be extended to the case of imitation in an open economy context.
The empirical study reported here was conducted by first considering specifications that include R&D-related variables and then extending these to allow for human capital as a separate factor. The general form of the basic relations in level terms can be expressed as:

\[ TFP = f(RS_d, RS_f, (H)) \]  

where \( RS_d \) and \( RS_f \) denote domestic and foreign R&D capital stock and \( H \) is human capital. Foreign R&D capital is defined as a weighted average of the domestic R&D capital stocks of the other OECD countries covered, where the weights reflect the degree of technological closeness. For reasons of data availability, we used weights based on bilateral import shares. To the extent that parts of imports consist of intermediate and investment goods used by firms in downstream sectors, our weighting scheme implies that we partially capture what Griliches (1992) has called embodied "rent" spillovers. Since these imports, as well as those of consumer goods, may incorporate foreign knowledge accessible through reverse engineering, and since trade can be taken as an indicator of the degree of interaction between the countries involved, our measure of foreign R&D capital also captures pure knowledge spillovers.\(^1\)

**III. Data**

Details about the data sources and construction of the data are provided in the Appendix. Here, we only highlight some features of the data. As shown in Table 1, the rate of growth of TFP, \( \Delta tfp \), was on average positive over the period 1965–1991 in all countries except New Zealand. However, this rate was, not uniform across countries or over time. Ireland and Italy experienced the strongest growth, whereas there was no growth at all in New Zealand. Figure 1 plots the log of TFP, \( tfp \), for 10 of the countries and shows that they exhibit substantial fluctuations.

The average rate of growth of domestic R&D capital stock, \( \Delta rs_d \), was clearly more important over the same period. Again, there were substantial differences among countries. The countries with the fastest growth, Greece and Spain, had a very low beginning-of-period stock of R&D capital.

\[^1\]This is all the more the case since, as indicated in the Appendix, our measure of foreign R&D is based on bilateral import weights with respect to a representative year, rather than on yearly changing import weights. This approach was chosen because the latter show highly erratic short-term fluctuations which, as demonstrated by Keller (1998), are ill supported by the data. Yearly changing weights are, in principle, better justified if the purpose is to concentrate exclusively on embodied "rent" spillovers.

Table 1. Summary statistics

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<th></th>
<th>Δtfp</th>
<th>Δrs\textsuperscript{d}</th>
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**Mean**

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<th>Q\textsubscript{1964}\textsuperscript{b}</th>
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<td>without US</td>
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</table>

**Coefficient of variation**\textsuperscript{c}

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<th>RIf</th>
<th>Δh</th>
<th>H\textsubscript{1964}\textsuperscript{a}</th>
<th>Q\textsubscript{1964}\textsuperscript{b}</th>
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<td>0.22</td>
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<td>without US</td>
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<td>0.68</td>
<td>0.12</td>
<td>0.66</td>
<td>0.32</td>
<td>0.62</td>
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</tbody>
</table>

Notes:

\textsuperscript{a} Years of schooling.

\textsuperscript{b} In percent of the US.

\textsuperscript{c} Standard deviation divided by mean. Variables in levels are expressed in uppercase letters and their log in lowercase letters, whereas variables in lowercase letters preceded by Δ stand for their rate of change. Refer to the main text for variable definitions and to the Appendix for data sources.

Although varying among countries, the evolution of the log of $RS^d$, $rs^d$, over time was more regular in this case, as can be seen from Figure 2.

The rates of growth of foreign R&D capital, $Δrs^f$, were much more uniform across countries. In this case, only one country, the US, stood out as having a much higher rate. This is clearly depicted by the evolution of the log of $RS^f$, $rs^f$, over time in Figure 3. This reflects the fact that even though the US had a below-average rate of growth for domestic R&D capital, the size of its stock of R&D capital give the US a dominant weight in the measure of foreign R&D capital of the other countries.

Fig. 1. Total factor productivity (logarithms); period: 1965–1991

Fig. 2. Domestic R&D capital (logarithms); period: 1965–1991

The domestic R&D intensity of a country, $R{\bar{I}}^d$, is defined as the proportion of its R&D expenditure over business-sector GDP, and the foreign R&D intensity, $R{\bar{I}}^f$, is defined as the import-weighted average of the domestic R&D intensities of the country's trade partners. Once again, domestic R&D
intensity shows a clearly greater variation across countries than foreign R&D intensity. The foreign R&D intensity of the US is smaller, however, than that of the other countries. This reflects the fact that, most often, domestic R&D intensity remains, smaller in the other countries than in the US, despite their increasing R&D efforts.

Although the average rates of growth of human capital, $\Delta h$, are positive in every case, they show a substantial variation across countries. A comparison with the level of human capital at the beginning of the period, $H_{1964}$, indicates that the countries with the strongest rates of growth, Portugal and Austria, are those with low initial levels of human capital. This is not always the case, however, for the other countries with strong growth rates. Figure 4 shows that the evolution of the log of human capital, $h$, over time is also far from regular. It should be kept in mind, however, that errors of measurement may magnify the fluctuations.

Finally, the beginning-of-period level of labour productivity, $Q_{1964}$, shows a large variation across countries, with the US by far the most productive. A comparison with the $\Delta tfp$ column suggests that, in accordance with the catch-up hypothesis, countries with an initially low level of productivity tend, on average, to grow at a faster rate. This relation appears far from uniform, however, suggesting that other variables have actively contributed to TFP growth.

IV. Estimates

Estimation of long-run relationships between productivity and R&D and human capital can be carried out using specifications in growth terms or in level terms, and by applying various econometric techniques. Each of these procedures has its own advantages and disadvantages and may lead to different results. An attempt was therefore made to obtain a more reliable picture by applying some of the most appropriate methods and by comparing the respective results.

**Long-run Average Growth Equations**

We began by estimating long-run growth equations in a traditional manner, concentrating on an R&D-driven equation. A specification in growth terms is easily obtained by logarithmic differentiation of a multiplicative form of the basic relation (1) in Section II. A major advantage of a specification in growth terms is that it makes it possible, by a simple transformation, to relate the growth of TFP, $\Delta tfp$, to the domestic and foreign R&D intensities, $RI^d$ and $RI^f$, respectively rather than to the growth rates of the stocks of domestic and foreign capital. The coefficients of the R&D intensity variables provide measures of the corresponding social rates of return on domestic and foreign R&D expenditure in terms of domestic income. This allows us to use
the readily available data on gross R&D expenditure, thereby avoiding the always delicate estimation of R&D capital stock.

The equation is extended to include a constant term to account for possible exogenous trendmatic influences on productivity. This has most often been justified by the existence of at least some exogenous disembodied technical progress. Moreover, as seen from the summary statistics in Table 1, it is also useful to include the initial level of labour productivity as a variable in order to capture a catch-up effect.²

This equation was estimated on a cross-section of average values of TFP growth and R&D intensity variables for the business sector of 21 OECD countries over the entire period of investigation, 1961–1991. Averaging out the variables over time has the practical advantage of eliminating most of the noise attributable to short-term errors of measurement and cyclical behaviour of the data. Estimation was performed by ordinary least squares (OLS) and the results are presented on line (i) of Table 2.

The coefficients of the R&D intensity variables and of the catch-up term are of the expected sign and statistically significant at the 5 per cent level. The coefficient of domestic R&D intensity indicates an important social rate of return on domestic R&D expenditure and is of the same order of magnitude as found by Gittleman and Wolff (1995) for their sample of industrial market economies. As regards foreign R&D intensity, we find a substantially stronger influence. The significance of the catch-up term itself can be viewed as mainly reflecting a conditional convergence effect through technical diffusion. It may, however, also partly reflect convergence through capital accumulation under conditions of decreasing returns on capital. The significance of the constant term, C, implies that there are other trendmatic influences on productivity growth not captured by the variables included.

In view of the fact that the larger economies have advantages of scale for conducting domestic R&D efforts, they are likely to take up most technical leader positions, even though they may also be followers of one another. More significant domestic scale effects, due to larger technical diffusion between firms, also imply that R&D efforts in large countries are likely to have a stronger influence on TFP. Accordingly, their elasticity of TFP with respect to domestic R&D capital can be expected to be stronger. In order to assess whether this also translates into a higher average social rate of return on domestic R&D expenditure, we interacted the \( R^d \) variable with a dummy, \( G7 \), which takes the value 1 for the seven largest economies and 0

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²Preliminary hypothesis tests confirmed that the coefficients of labour and physical capital used in the construction of the TFP variable do not significantly differ from their average income shares and add up to unity, implying constant returns to scale with respect to the traditional factors. There is thus no need to add labour and physical capital growth terms to our TFP growth equation.
Table 2. The influence of R&D intensity and human capital on total factor productivity growth in the business sector: growth equations estimated on averages over period, 1961–1991 (21 OECD countries)

<table>
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<tr>
<th>Right-hand-side variables</th>
<th>Regression statistics</th>
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<td>Adj $R^2$</td>
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<td>$RI^d$</td>
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<td>$q_{1960}$</td>
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</table>

Notes: The equations are estimated by ordinary least squares. The absolute values of the t-statistics are in parentheses underneath. Refer to the main text for variable definitions and to the appendix for data sources and construction.
for the others, in equation (ii). Its coefficient is found to be insignificant, however, suggesting that there is no such difference in social rates of return between large and small economies.

Equations (iii) and (iv) add human capital growth, $\Delta h$, to equations (i) and (ii). Its coefficient is found to be positive but statistically insignificant. The main effect is to reduce the constant term somewhat and make it non-significant. It can be argued, however, that the level of human capital also matters, since the introduction of new technology, or of more advanced foreign technology, may require a certain level of skills. Even strong human capital investments may not suffice if that level is not met. As suggested by Nelson and Phelps (1966), the catch-up term should therefore be interacted with the level of human capital; see also Benhabib and Siegel (1994) in this regard. Since the transitional dynamics are likely to be affected mainly by the initial skill level, we interacted the catch-up term in equations (v) and (vi) with the beginning-of-period level of human capital, $H_{1960}$.

The results indicate that the coefficients both of this human capital variable and this variable interacted with the catch-up term are of the expected sign and statistically significant. Moreover, the statistical fit of the regressions is vastly improved. The coefficients of the R&D intensity variables are reduced somewhat (by about 20-30 percent compared with equations (i) and (ii)), but this does not affect their statistical significance. The main effect appears to be that the influence of the constant term in the regressions totally eliminate. This would imply that, when due account is taken of the effects of human capital as well as of domestic and foreign R&D efforts, there remains no evidence of exogenous trendmatic influences on productivity growth.

Cointegrating Equations and Error Correction Models

Although averaging out the variables over time has the practical advantage of eliminating most of the noise due to short-term errors of measurement, the price of doing so is a considerable loss of information. Another procedure for estimating long-run relationships between TFP and R&D is to use a panel of pooled annual time series. This avoids the loss of information resulting from averaging. Since, as seen from the figures, the data exhibit a clear stochastic trend, we sought to estimate equations that are cointegrated. In principle, this allows us to exploit the relevant information about shared trends that is embodied in the data.

We concentrate first on equations that relate the log of TFP, $t fp$, to the logs of domestic and of foreign R&D capital, $rs^d$ and $rs^f$, respectively, and then extend these to include the log of human capital, $h$. The equations include country-specific intercept terms aimed at capturing country-specific fixed
effects not caught by the variables used. Such effects can be explained by the influence of institutional variables which change only slowly over time.

We complete this part of our analysis by estimating parsimonious error correction models (ECM) corresponding to the cointegrating equations. These models provide information on the short-term dynamics. They are obtained by differencing the respective variables of the corresponding cointegrating equations, allowing for delayed responses and augmented to include their estimated lagged residuals. In order to allow for the dynamics in the ECM, we shortened the period of investigation for our cointegration analysis by a few years to cover the period 1965–1991.

Actual implementation of the cointegration estimation procedure entails first confirming that the data are indeed non-stationary. We therefore applied two unit root tests for panel data proposed by Levin and Lin (1992) and Im et al. (1997), respectively. The first is an augmented Dickey–Fuller (ADF) test based on a model with common slopes but allowing for country-specific intercepts. The second is an average ADF test derived from the individual ADF tests performed for each country separately. It thereby also allows for slope heterogeneity. The results confirmed each time that the data are non-stationary.

While estimating the level equations by ordinary least squares (OLS), two tests of cointegration were performed by testing for the presence of a unit root in the residuals. The first entailed again applying the Levin–Lin test as such, and the second involved applying a comparable test proposed by Kao (1997), which corrects for nuisance effects. In addition, we applied a third cointegration test, proposed by McCoskey and Kao (1997), which allows for slope heterogeneity in the cointegrating equations. This test is comparable to Im’s average ADF unit root test; here, it is derived from the residual-based ADF tests performed for the countries separately.

The standardized test statistics of these cointegration tests are reported in Table 3, behind the OLS estimates of the cointegrating equations. In each instance they were shown to have an asymptotic standard normal distribution. Their small sample critical values have been inferred by Monte Carlo methods. For the number of observations considered in this study, the critical values at a 5 percent level of significance are −1.780 for the Levin–Lin test and −1.768 for the Kao test. In the case of the McCoskey and Kao test, the estimated size distortions are negligible, so that the asymptotic critical value of −1.645 can be safely used. In every instance, the results indicate conclusively that the null hypothesis of no cointegration is rejected in favour of the alternative of cointegration.

We prefer to present both since Kao (1997) has also shown that although the power of his test is slightly superior to that of the Levin–Lin test, the latter proves to be more robust to changes in the underlying data-generation process.

Table 3. The influence of R&D and human capital on TFP in the business sector: cointegrating equations estimated on pooled annual time series 1965–1991 (21 OECD countries, 567 = 21 × 27 obs.)

<table>
<thead>
<tr>
<th>Right-hand-side variables</th>
<th>Cointegration tests</th>
<th>Regression statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>rs^d</td>
<td>G7-rs^d</td>
</tr>
<tr>
<td>(i) OLS</td>
<td>0.091</td>
<td>0.220</td>
</tr>
<tr>
<td>(i) DOLS</td>
<td>0.106</td>
<td>0.253</td>
</tr>
<tr>
<td></td>
<td>(3.464)</td>
<td>(2.836)</td>
</tr>
<tr>
<td>(ii) OLS</td>
<td>0.090</td>
<td>0.092</td>
</tr>
<tr>
<td>(ii) DOLS</td>
<td>0.103</td>
<td>0.085</td>
</tr>
<tr>
<td></td>
<td>(3.494)</td>
<td>(2.529)</td>
</tr>
<tr>
<td>(iii) OLS</td>
<td>0.080</td>
<td>0.190</td>
</tr>
<tr>
<td>(iii) DOLS</td>
<td>0.096</td>
<td>0.215</td>
</tr>
<tr>
<td></td>
<td>(3.092)</td>
<td>(2.400)</td>
</tr>
<tr>
<td>(iv) OLS</td>
<td>0.077</td>
<td>0.098</td>
</tr>
<tr>
<td>(iv) DOLS</td>
<td>0.091</td>
<td>0.092</td>
</tr>
<tr>
<td></td>
<td>(3.059)</td>
<td>(2.666)</td>
</tr>
</tbody>
</table>

Notes: OLS and DOLS denote ordinary least squares and dynamic ordinary least squares estimates of the cointegrating equations, respectively. The (country-specific) intercept terms are not shown. The absolute value of the t-statistics of the DOLS estimates are in parentheses underneath. The DOLS estimates are based on a regression that includes the explanatory variables as well as concurrent and (one-period) lagged and lead values of the first difference of these variables. The standard errors underlying the t-tests are computed from a (White) heteroscedastic and (first-order) autocorrelation consistent variance-covariance matrix. The correction for autocorrelation was performed by taking a moving average of the error autocovariances using the Bartlett kernel. The number of terms in the moving average was determined by Andrews’s optimal bandwidth value and was chosen to be four.

LL stands for Levin and Lin’s standardized augmented Dickey–Fuller (ADF) test applied on the residuals of the cointegrating equation and K denotes Kao’s comparable test which corrects for nuisance effects. MK stands for McCoskey and Kao’s standardized average ADF test obtained from the corresponding country-specific residual-based ADF tests.


Although the OLS estimates of a cointegrating equation can – as is well known – be shown to be “super consistent”, they have the drawback that their distribution is generally non-standard, so that no inference can be drawn about their significance. Thus, we also used an alternative estimation procedure: Stock and Watson’s (1993) dynamic ordinary least squares (DOLS) method which, in principle, overcomes this disadvantage. The DOLS estimates can be shown to possess an asymptotic normal distribution and the corresponding standard errors allow the valid calculation of t-tests.

Table 3 presents the estimates of the cointegrating equations. The esti-
mates by OLS and DOLS are found to be remarkably close and the $t$-values of the latter show the respective coefficients to be statistically significant. The estimates of equations (i) and (ii) show a high elasticity of TFP with respect to domestic R&D capital and, in conformity with the long-term average growth equations, a substantially higher elasticity of TFP with respect to foreign R&D capital. The inclusion of a $G7$ domestic R&D capital interaction variable in equation (ii) improves the statistical fit of the regression. Its coefficient is found to be statistically significant and its order of magnitude would imply that the elasticity of TFP with respect to domestic R&D capital is, on average, about twice as large in the $G7$ countries as compared to the smaller OECD countries.  

The inclusion of the log of human capital, $h$, in equations (iii) and (iv) improves the statistical fit. Its coefficient is found to be statistically significant and implies a substantial elasticity. The effect is once again to reduce somewhat the coefficients of the R&D capital terms (now by about 15–20 percent compared to equations (i) and (ii)) without, however, affecting their statistical significance.

Although unreported here, appropriate Wald tests on the intercepts of the DOLS equations conclusively accepted the hypothesis of the existence of country-specific intercepts against the alternative of a common intercept. This accords with our assumption of a likely net direct influence on productivity of institutional variables which vary across countries. Interestingly enough, a comparison with the estimates of the corresponding equations having a common intercept indicated that the inclusion of country-specific intercepts did not reduce the coefficients of the R&D and human capital variables. This implicitly confirms the robustness of our estimates.

Table 4 reports the estimates of the error correction models corresponding to the cointegrating equations estimated by OLS. The equations easily pass the diagnostic tests for the non-existence of serial correlation in the residuals. There are, however, some problems of heteroscedasticity. We therefore used White’s heteroscedastic-consistent standard errors for computing the $t$-values.

The term comprising the lagged residuals of the cointegrating equation, $RES_{t-1}$, represents the error correction term. In each instance its coefficient is found to be significantly smaller than zero and thereby clearly implies
Table 4. Error correction models estimated on pooled annual time series, 1966–1991 (21 OECD countries, 546 = 21 × 26 obs.)

<table>
<thead>
<tr>
<th>Right-hand-side variables</th>
<th>Regression statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta tf_{t-1}$</td>
<td>$\Delta rs_{t-1}^d$</td>
</tr>
<tr>
<td>(i)</td>
<td>0.135</td>
</tr>
<tr>
<td>(2.919)</td>
<td>(3.212)</td>
</tr>
<tr>
<td>(ii)</td>
<td>0.134</td>
</tr>
<tr>
<td>(2.886)</td>
<td>(3.090)</td>
</tr>
<tr>
<td>(iii)</td>
<td>0.126</td>
</tr>
<tr>
<td>(2.771)</td>
<td>(2.954)</td>
</tr>
<tr>
<td>(iv)</td>
<td>0.125</td>
</tr>
<tr>
<td>(2.736)</td>
<td>(2.815)</td>
</tr>
</tbody>
</table>

Notes: The error correction models (ECM) correspond to the cointegration equations estimated by OLS in Table 3 and are themselves estimated by OLS. The estimation was originally performed while allowing for up to four lag periods. The statistically non-significant terms were then eliminated, starting from the least significant. The absolute value of the t-statistics based on White’s heteroscedastic consistent standard errors are shown in parentheses underneath the parameter estimates.

LM1 and LM4 stand for the Lagrange multiplier tests for first- and fourth-order serial correlation, respectively. Their statistics are asymptotically distributed as chi-square variates with 1 and 4 degrees of freedom, $\chi^2_1$ and $\chi^2_4$, respectively. BP denotes the Breusch–Pagan test for heteroscedasticity. Its statistic is asymptotically distributed as a $\chi^2_m$ variate, where $m$ corresponds to the number of regressors.

Refer to the main text for variable definitions and to the Appendix for data sources and construction.
convergence towards the cointegrating relation. This conforms with the earlier evidence of cointegration obtained by means of the residual-based unit root tests.

Although the estimation was originally performed while allowing for up to four lag periods, the strong multicollinearity between the lagged and concurrent terms of the dynamic variables made their estimates imprecise and most often non-significant. As seen from Table 4, elimination of the non-significant terms leaves only one term remaining for each variable. The estimates suggest that, each time, there is a one-period lagged response of productivity growth to the R&D variables. Moreover, there is evidence of a significant one-period lagged dependent variable. This may indicate the presence of a Koyck-type dynamic adjustment process over and above these lags.5

Comparison with Earlier Studies

Our results improve on earlier comparable findings by Coe and Helpman (1995), who concentrated on the relation between TFP and domestic and foreign R&D. Since they used OLS, they were unable to perform tests of significance on the parameters of the cointegrating equations. Further, by considering a shorter sample period starting in the 1970s, they were unable to present unambiguous tests of cointegration. Compared to our estimates of equations (i) and (ii) in Table 3, their results tend to underestimate the effect of foreign R&D. This is not surprising since international technology spillovers are likely to have been especially strong during the "golden years" period until 1973, which is far better represented in our sample. Moreover, their use of highly erratic, actual yearly changing import weights, rather than weights with respect to a representative year, introduces noise in their foreign R&D variable and causes a downward bias in its estimated coefficient. The same holds for the more disaggregate panel data estimates by Verspagen (1997), who estimated intersectoral as well as international spillovers. Verspagen also used OLS and yearly changing import weights in the construction of his foreign R&D variable, and he considered an even shorter sample period.

None of these studies included a human capital variable. As a result, their estimated R&D coefficients are bound to suffer from an upward bias. To our

5In order to assess the extent to which the short-term dynamics is affected by business cycle noise, we re-estimated the error correction models while including several measures of domestic and foreign cyclical output variation. The main effect was a slight reduction in the coefficient of the lagged dependent variable. Although it would imply somewhat shorter dynamics, the implied elasticities of TFP with respect to the R&D variables and human capital were thereby left largely unaffected.
knowledge, only one study analysing the productivity impact of domestic and foreign R&D has included such a variable. This study is due to Engelbrecht (1997) and it consisted mainly in extending Coe and Helpman’s (1995) estimates in this regard. It thereby suffers from the same econometric weaknesses, exacerbated by the fact that his estimation period is even shorter. Compared to our own results, Engelbrecht’s inclusion of a human capital variable has a stronger negative impact on the coefficient of foreign R&D capital. This is most likely due to the presence of more significant errors of measurement in the measure of human capital used.6

Our study may thus be seen to contribute to the literature by virtue of its more comprehensive approach using alternate model specifications and more appropriate econometric methods and sample periods. This makes it possible to better identify not only significant domestic and foreign R&D influences on TFP, but also a separate significant human capital influence. The question remains, however, as to whether the size of the estimates is realistic.

It has been argued by Barro and Sala-i-Martin (1995, Ch. 10) that the finding of substantial R&D regression coefficients may in part be explained by a simultaneity bias, due to a reverse linkage caused by a positive response of R&D spending to growth opportunities. Moreover, some individuals may conceive at least part of their educational efforts as non-investment in nature (for the pleasure of studying, for example), rather than as an investment. Thus, educational efforts may to some extent be income determined.

The latter problem is avoided in our study, by considering the level of school attainment of the working-age population, which is predetermined with a substantial lag by earlier educational efforts. In the case of R&D, however, there may be some reverse causality. A way to check this is to perform exogeneity tests on the error correction models and on their corresponding marginal processes. Although not reported here, the results of such tests indicated that the hypothesis of strong exogeneity of the R&D variables could not be rejected.

It would thus appear that the evidence of high regression coefficients of the R&D variables cannot be explained by simultaneity bias. In fact, it is interesting to note that the size of the estimated elasticities presented in Tables 3 and 4 are still quite modest when viewed in the light of the new theoretical growth literature. If anything, they are more likely to be biased downwards due to the presence of errors of measurement in the R&D, human capital and TFP variables.

6Engelbrecht uses Barro and Lee’s human capital stock data, as we do. But, whereas we predict the missing data on the basis of previous school enrolment rates – as explained in the Appendix – he does so simply by linear interpolation and thereby obtains an artificially smooth series that is more collinear with the foreign R&D capital variable.

V. Conclusions

Recent developments in the theory of innovation-driven growth have emphasized the importance of both domestic R&D efforts and international technology spillovers for explaining national productivity growth. Some theoretical work has also stressed the complementarity between firm R&D efforts and human capital investments, making it possible to attain a sufficiently qualified labour force, capable of operating with new or more advanced foreign technologies. Owing to advantages of scale, large economies can be expected to assume most technological leader positions. Because of their size, they can be presumed to benefit from more substantial domestic technology spillover effects. The productivity impact of their own R&D efforts is thus likely to be more significant than in the case of smaller economies, which benefit more from foreign technology spillovers.

In our cross-country analysis for the OECD over a period from the early 1960s to the early 1990s, strong evidence was presented in support of these predictions. Cross-section estimates of long-term average growth equations as well as panel estimates of cointegrating equations in level terms and corresponding dynamic error correction models showed that both R&D and human capital exercise a significant influence on TFP. In the case of R&D, there was evidence of a significant impact of both domestic and foreign R&D. The impact of domestic R&D was found to be relatively more important in the G7 economies than in the smaller economies. In the case of human capital, the results indicate that both its level and its rate of increase matter for explaining productivity growth. Moreover, there is explicit evidence of significant interaction between the level of human capital and the catch-up process.

Appendix. Definition of Variables and Sources of Data

Total factor productivity is defined as $\text{TFP} = Y/(K^\beta L^{1-\beta})$ where $Y$ is value added at factor costs in constant prices in the business sector, $K$ is the stock of business sector capital in constant prices, $L$ is employment in the business sector, and $\beta$ and $1 - \beta$ are the average income shares of capital and labour over the period of investigation. All variables are constructed as indices with $1985 = 1$. The data are from the OECD Business Sector Database.

Domestic R&D intensity, $RId$, is defined as the proportion of real domestic R&D expenditures in the business sector over the business sector value added at constant prices. Nominal R&D expenditures are based on the total gross expenditure on R&D in the business sector series from the OECD Science and Technology Statistics. Real R&D expenditures were obtained by deflating nominal expenditures by an R&D price index, $prd$, defined as:

$$prd = 0.5p + 0.5w$$
where \( p \) is the implicit deflator of business sector value added and \( w \) is an index of average business sector wages. The missing early data on R&D expenditures for some countries were predicted on the basis of a regression of real R&D expenditures on investment (all in logarithms) and a time trend. The domestic R&D capital stocks, \( RS_d \), were calculated from domestic real R&D expenditures by means of the perpetual inventory method while assuming a depreciation rate of 5 percent.

For each of the 21 countries the foreign R&D intensity, \( RIf \), is defined as a bilateral import-share weighted average of the domestic R&D intensities of the country’s 20 trading partners. In a similar way, the foreign R&D capital stock, \( RS_f \), is defined as a bilateral import-share weighted average of the domestic R&D capital stocks of the country’s 20 trading partners, expressed in dollars at purchasing power parity exchange rates. We used bilateral import shares with respect to a representative year, since these are far better supported by the data than actual yearly changing import shares, which are affected by highly erratic short-term fluctuations. The bilateral import shares are from 1990 and were derived from the IMF Direction of Trade.

Finally, the human capital data refer to average educational attainment rates as measured by the average years of schooling of the total population aged over 25. They were obtained from Barro and Lee’s databank, as described in Barro and Lee (1993). The missing years were predicted on the basis of regressions between these school attainment rates and the gross secondary enrolment ratios five years earlier. The gross secondary school enrolment ratios were obtained from the UNESCO Statistical Yearbook.

References

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