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R&D AND PRODUCTIVITY GROWTH: PANEL DATA ANALYSIS OF 16 OECD COUNTRIES

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INTRODUCTION

The recent acceleration of multifactor productivity (MFP) in several OECD Member countries, after two decades of slow growth, is often explained by a surge in the pace of technical change. That is consistent with both economic theory and anecdotal evidence. Economic theory (Solow, 1957; Romer, 1990) points to technical change as the major source of productivity growth in the long run. Anecdotal evidence suggests that new technology (especially information technology) has substantially contributed to recent improvement in the productivity of firms.[1]

This study presents estimates of the contribution of technical change to MFP growth in major OECD countries over the 1980-98 period. It contributes to the existing literature in this field of analysis in two ways. First the major sources of new technology are taken into account simultaneously: domestic business R&D, public R&D and foreign business R&D. Second, an attempt is made to differentiate across countries the impact of the three sources of knowledge on output growth. The results are intended to provide insights into the following:

- The contribution of business generated technology to productivity growth.
- The importance of foreign flows of technology ("international spillovers") as compared with domestic technology.
- The contribution of government and university research to productivity growth.
- The role of absorptive capabilities of firms for technology coming from public and foreign sources.
- How the impact of the various sources of new technology has evolved over time.
- Which country-specific factors influence the effect of these various sources of technology.

The analysis is performed at the aggregate (macroeconomic) level for 16 OECD countries over the period 1980-98 using annual data. This study complements a previous work published by the OECD (Bassanini *et al.*, 2000) which took into account more factors of productivity growth (*e.g.* human capital) but did not investigate in detail the effects of technology on MFP. Results from these two studies are consistent with each other.

Research and development, resulting in new goods, new processes and new knowledge, is a major source of technical change. As defined by the *Frascati Manual* (OECD, 1993, p. 29), R&D "comprise creative work undertaken on a systematic basis in order to increase the stock of knowledge and the use of this stock of knowledge to devise new applications". There are different types of R&D, however, and the effect of R&D on productivity may work through various channels. In order to capture the links between R&D and productivity it is necessary to take these aspects into account. R&D is not the only source of new technology: in modern, industrial economies, other activities, such as learning by doing or design are conducted in most cases on the basis of new technology coming out of R&D (*e.g.* changes in the organisation of business related to the use of information and communication technology). The relationship between R&D and innovation is a complex, non-linear one. However, it is recognised also that it is difficult for substantial advances in technology to occur without work undertaken on a systematic basis (even serendipity tends to develop in such a context), and R&D is a good indicator of this broader phenomenon.

R&D performed by business results in new goods and services, in higher quality of output and in new production processes. These are factors of productivity growth at the firm level and at the macroeconomic level. The effect of business R&D on productivity has been investigated in many empirical studies, performed at all aggregation levels – business units, firm, industry and country levels – and for many countries (especially the United States). All these studies reach the conclusion that R&D matters, the estimated output elasticity with respect to business R&D varying from 10 per cent to 30 per cent (see a survey of the literature by Nadiri, 1993). This large variation is mainly due to the fact that studies differ in terms of the econometric specification, data sources, number of economic units, measurement methods for R&D and economic performance, and periods under study. Business performed R&D may be funded by business itself or by government (Guellec and van Pottelsberghe, 1999 and 2001*b*): it might be that business R&D has a different effect on productivity depending on its source of funds (which affects the research agenda and the incentive structure).

Government and university research have a direct effect on scientific knowledge and public missions, they generate basic knowledge. In many cases the effect of government research on productivity is not measured, either because it is indirect[2] or because its results are not integrated in existing measures of GDP (health-related research allows to improve length and quality of life, which are not taken into account in GDP measures). Basic research performed mainly by universities enhances the stock of knowledge of the society. New knowledge is not considered as an output in the current system of national accounts (contrary to physical investment and software for instance), and as such it is not included in GDP measures: hence the direct outcome of basic research is overlooked. However, basic research may open new opportunities to business research, which in turn affects productivity.

It is therefore not surprising that there have been very few studies of the effects of public research on productivity. Only some components of public research have been used in empirical frameworks. For instance, Adams (1990) finds that fundamental stocks of knowledge, proxied by accumulated academic scientific papers, significantly contributed to productivity growth in US manufacturing industries. Another example is provided by Poole and Bernard (1992) for military innovations in Canada, who present evidence that a defence-related stock of innovation has a negative and significant effect on the total factor productivity growth of four industries over the period 1961-85.

Foreign knowledge (knowledge generated in other countries) is a third source of new technology for any national economy. There are many ways for technology to cross borders, as knowledge coming out of a given country's research is used by another country's enterprises. Companies can buy patents, licences or know-how from foreign firms, they can observe competition (*e.g.* reverse engineering), they can hire foreign scientists and engineers, they can interact with foreign competitors who invested in their country (foreign direct investment), read the scientific and technological literature, or have direct contacts with foreign engineers in conferences or fairs. The impact of foreign-produced knowledge on a country's productivity may depend on the capacity of the recipient country to digest such knowledge, to make efficient use of it, which requires in turn this country to have sufficient technological activity of its own. This is traditionally labelled as the "absorptive capacity" of an economy.

A few studies, such as by Coe and Helpman (1995), OECD (1997) and van Pottelsberghe and Lichtenberg (2001), have estimated the effect of foreign R&D on productivity. This is done by regressing multi factor productivity (MFP) on a stock of domestic R&D and a stock of foreign R&D. Coe and Helpman find that domestic R&D contributes significantly to productivity growth and that this impact is substantially higher for the G7 than for other developed countries. In addition, foreign R&D has a significant impact on MFP growth. Lichtenberg and van Pottelsberghe (1998) show that foreign R&D can affect domestic performances through both imports and outward foreign direct investment (through technology sourcing and learning practices).

THE MODEL AND DATA

Based on the above framework, we estimate the contribution of technical change to productivity growth. We distinguish the various sources of technical change: domestic, foreign, and public sources. We also take into account business-cycle effects that strongly influence productivity in the short run. The model on which the estimated equation is based is a simple Cobb-Douglas production function.

$$MFP_{it} = \exp\left[\phi_i + \varphi_t + \mu_{it}\right]\ BRD_{it-1}^{\beta_{rd}} \cdot\ FRD_{it-1}^{\beta_{frd}} \cdot PRD_{it-2}^{\beta_{prd}} \cdot\ U_{it}^{\sigma_U} \cdot G^{\sigma_G} \qquad (1)$$

The variables (for country *i* and time *t*) are defined as follows.

MFP is an index of total factor productivity of industry. MFP has been computed in the usual way (OECD, 2001), as the ratio of the domestic product of industry on the weighted sum of the quantity of labour and fixed capital stock, the weights being the annual labour cost share and the capital cost share, respectively (under assumptions of perfect competition and constant return to scale). The series comes from the OECD National Accounts database.

BRD is the domestic business R&D capital stock. It has been computed using the perpetual inventory method from total intramural business R&D expenditures, in constant 1990 GDP prices and US PPPs. The depreciation rate is 15 per cent (sensibility analysis shows that the results of the regressions do not change significantly with the chosen depreciation rate). The series come from the OECD Main Science and Technology Indicators.

FRD is the foreign R&D capital stock, which is the weighted sum of the domestic business R&D capital stocks of the 15 other countries of the panel. The weights correspond to the bilateral technological proximity between countries (see Appendix 1). The underlying assumptions are two-fold: first, technology circulates directly, with no need for exchange of goods as a vector (although this may help). This assumption differs from that of Coe and Helpman (1995), who measure foreign capital stock for any country as the sum of other countries' R&D capital stock *weighted by the foreign trade structure of the country*. However, our assumption is consistent with available evidence on the circulation of knowledge across borders.[3] The second assumption is that a country will benefit more from foreign knowledge relating to the same technology fields it works on than from knowledge in other fields.

PRD is total public R&D capital stock, which comprises R&D expenditures performed in the higher education sector and in the government sector (public laboratories). The depreciation rate is 15 per cent (again, sensitivity analysis shows that the results of the regressions do not change significantly with the chosen depreciation rate). Since these R&D activities are not performed by the business sectors, we expect a longer delay before they affect business productivity and therefore include them in the model with a two-year lag.

A range of control variables is included in all the regressions. U is intended to capture the business cycle effect: it is equal to 1 minus the unemployment rate. This should be a better proxy than the usually applied rate of utilisation of capital, which applies to manufacturing industries only (which account for about 20 per cent of GDP in OECD countries). In the context of this study, it is also better than the output gap, as the calculation of the output gap relies on certain assumptions on MFP growth: by using it, we would be faced with simultaneity problems (if MFP is the same on both sides of the equation) or inconsistency (if two different MFPs are used on the two sides of the equation). G is a dummy equal to 1 for Germany in 1991, and 0 otherwise; in order to take into account the exogenous shock of the German unification. ϕ_i are country dummies which allow country-specific framework conditions that might affect long-term growth. φ_t are time dummies which take into account exogenous technical change and exogenous shocks that are common to several countries, such as changes in exchange rates.

The basic equation we estimate, adapted from (1) is an error correction model (ECM), which allows separating short-term from long-term effects. The long-term (stationary) form of the model expressed in logarithmic form is as follows:

$$LMFP_{it} = \beta_{brd}\ LBRD_{it-1} + \beta_{frd}\ LFRD_{it-1} + \beta_{prd}\ LPRD_{it-2} + \sigma_U\ LU_{it} + \sigma_G\ G + \phi_i + \varphi_t + \mu_{it} \qquad (1')$$

Which translates into the following error correction model (ECM):

$$\begin{aligned}\Delta MFP_{it} = {} & \lambda\ \Delta MFP_{it-1} + \alpha_{brd}\ \Delta BRD_{it-1} + \alpha_{frd}\ \Delta FRD_{it-1} + \alpha_{prd}\ \Delta PRD_{it-2} + \eta\ LMFP_{it-2} \\ & + \beta_{brd}\ LBRD_{it-2} + \beta_{frd}\ LFRD_{it-2} + \beta_{prd}\ LPRD_{it-3} + \sigma_U\ \Delta U_{it} + \sigma_G \cdot G + \phi_i + \varphi_t + \mu_{it}\end{aligned} \qquad (2)$$

Where Δ represents the first logarithmic difference and L the natural logarithm. In this equation, the long-term elasticity of output with respect to, say business R&D (LBRD), is $[-\beta_{RD} / \eta]$.

The parameters that are to be estimated are assumed to be constant across countries and over time; they are defined as follows:

- β_{brd} The elasticity of MFP with respect to domestic business R&D.
- β_{frd} The elasticity of MFP with respect to foreign business R&D.
- β_{prd} The elasticity of MFP with respect to public R&D.
- σ_U The elasticity of MFP with respect to the capacity utilisation rate.
- σ_G The impact of the German unification on MFP in Germany.

Interpretation of these elasticities should take into account the fact that the explained variable is not GDP but MFP. That means that we capture only the spillover effects of R&D, not the total effect on output growth (which includes also the direct effect on private return). This concerns especially business R&D: part of the private resources devoted to R&D (labour and capital) are already reflected in the calculation of MFP, as they are included in the economy's stock of capital and pool of labour. Hence, if the social return to R&D is equal to its private return, and if the private return to R&D is equal to its output share (and if the assumptions underlying the calculation of MFP hold, notably perfect competition and constant returns to scale at the aggregate level) then the elasticity of MFP with respect to domestic business R&D should equal zero. A positive elasticity would signal the existence of spillovers.

Foreign business R&D is partly paid for by domestic business users, in the form of international payments for technology transfers (patents, licences and know-how contracts). However, such payments are relatively small in most countries (less than 0.4 per cent of GDP on average in OECD, including payments for software which are not taken into account directly in this analysis) and probably cover only a small fraction of all the benefits that accrue to users: the international market for technology is still very incomplete. Being treated by national accounts as intermediate consumption, payments for technology, be it to domestic or to foreign suppliers, are not accounted for as such in GDP, hence in MFP. For instance, increased payments for foreign technology will not impact *directly* on the level of GDP, as it is not considered as value added. Hence, the effects we will capture are only spillovers, the portion of the benefits for which users do not pay. In general, business users do not fully compensate government for the benefits from public R&D. Hence, most of its effect on business activity is spillovers.

As a consequence, this model captures most of the effect of public and foreign R&D but only the excess private return added to the public effect of business R&D. A further caveat is that the assumptions used for calculating MFP may not hold totally: increasing returns to scale and imperfect competition are often associated with R&D (*e.g.* Romer, 1990). If that is the case, the MFP index that we explain is subject to measurement errors that might be correlated with the right-hand-side variables. In order to mitigate this problem, we conducted estimates with instrumental variables.

We now look at some descriptive statistics. Table 1 reports compound annual growth rates for all the variables and countries, over the 1980-98 period. MFP growth ranges from 0.3 per cent a year in Germany to 3.4 per cent in Ireland. Most countries, however, are very close to 1 per cent a year (ten countries are between 0.9 per cent and 1.4 per cent). MFP growth, as well as R&D growth, is high for Ireland as this country has been catching up over this period. Business R&D (capital stock) growth ranges from 1.9 per cent (United Kingdom) to 8.9 per cent (Finland) and even 10.8 per cent for Ireland, with most countries around 4 per cent to 7 per cent. In most countries the growth of business R&D has been higher in the 1980s than in the 1990s (see Guellec and Ioannidis, 1999, for an analysis of the "levelling off" of R&D). Foreign R&D growth rates fluctuated around 4 per cent for all countries except Ireland where it was about 7 per cent a year, on average. In most coun-

Table 1. **Descriptive statistics: average annual growth rates, 1980-98**
Per cent

Country	Business R&D capital stock	Foreign R&D capital stock	Public R&D capital stock	MFP growth
AUT	7.50	3.80	3.69	0.84
BEL	4.07	4.19	2.11	1.34
CAN	6.71	3.84	2.46	0.69
DNK	7.08	3.41	4.23	1.02
FIN	8.86	5.11	5.86	2.60
FRA	3.80	4.10	3.45	1.05
GER	3.62	3.71	2.41	0.30
IRL	10.76	7.15	3.35	3.39
ITA	4.83	3.92	4.18	1.08
JPN	6.31	3.56	3.71	0.94
NLD	2.66	4.27	2.68	1.05
NOR	5.41	4.34	3.32	1.08
ESP	4.40	4.41	1.95	1.38
SWE	5.79	4.27	4.25	1.20
GBR	1.90	4.21	1.83	1.03
USA	3.66	4.47	2.04	0.94

tries, the growth of public performed R&D was much lower than that of business R&D over this period. It ranges from 1.9 per cent (United Kingdom) to 6.6 per cent (Finland), with most countries reporting around 1.8 per cent to 5.9 per cent. The major reasons for that are the end of the cold war (reduced defence spending) and strained budgetary conditions in many countries, as well as intensified efforts of business in this area.

Simple analysis of correlation between the average growth rates (1980-98) of these variables is reported in Table 2. MFP is quite highly correlated with business R&D and with foreign R&D, which are the two variables expected to have the more direct relationships. It is also positively correlated with public R&D, although the relationship is weaker. Business R&D is well correlated with the other two R&D variables. Foreign R&D is not correlated with public R&D and there is no reason to expect such a relationship. The positive correlation between foreign and business R&D can be explained as follows: foreign R&D is a weighted average of

Table 2. **Correlation matrix between average annual growth rates for 16 countries, 1980-98**

	Business R&D	Foreign R&D	Public R&D
MFP	0.675	0.909	0.383
Public R&D	0.622	0.094	
Foreign R&D	0.528		

other countries' R&D, with the weights reflecting technological proximity. As a country expands its R&D expenditures, it is likely to broaden the range of technologies it covers, thus increasing its correlation with other countries' specialisation. Such a mechanism applies especially to countries starting from a relatively low technological level, where the range of technologies covered is quite limited (Ireland is a case in point).

ESTIMATION RESULTS

We run estimates (see Table 3) of the error correction model (2).[4] Different ranges of estimates were conducted for checking robustness: one constraining the short-term parameters to be the same for all countries; another allowing short-term parameters to vary across countries; SURE and 3SLS procedures have been used; and the model has been estimated over different sub-periods.[5] There are no significant differences between the parameters estimated with these various techniques, denoting the robustness of our estimates. Lags for the long-term relationships have been set at two years for business and foreign R&D, and three years for public R&D. The choice has been made by testing different lags and choosing those delivering the most significant results. The longer lag for public R&D is consistent with the view that it is more basic than business R&D, and takes more time to affect productivity. Anyway in an ECM, in which long-term coefficients reflect relationships *in level*, the choice of lags is not as important as in other types of models. For detecting possible outliers, and the robustness of the results with respect to the sample of countries, the model was estimated on 16 sub-samples of 15 countries, which means that each country was dropped in turn. The figures reported in Appendix 3 further support the robustness of our estimates. In all cases the coefficients remain significantly different from zero.

The long-term elasticity of MFP with respect to business R&D is 0.13 (Table 3, column 1).[6] Such an elasticity is quite in line with estimates reported in the literature (Nadiri, 1993), although it is in the low range. As the direct impact of business R&D on output is at least already partly accounted for in MFP, this positive coefficient must capture mainly spillovers and possibly extra return (coming in addition to normal remuneration of capital and labour) arising from R&D. It should be compared with the ratio of business R&D on business GDP (around 2 per cent in the OECD over the 1980s and 1990s). The social return to business R&D therefore is much higher than the "normal private return" (reflected in the income share of R&D).

Crossing the elasticity of business R&D with a time trend (Table 5, column 6) shows that there has been a growing impact of business R&D on MFP over time (an increase of about 0.005 a year). This finding confirms the impression given by

Table 3. **Multi-factor productivity estimation results, error correction model**

Dependent variable ΔMFP		80-98	80-98	80-98	80-96	84-98
		3SLS	SURE	SURE	3SLS	3SLS
Regressions		1	2	3	4	5
Multi-factor productivity growth (t-1)	ΔMFP	–0.396*	–0.088*		–0.419*	–0.370*
		(–7.81)	(–3.41)		(–13.17)	(–30.20)
Business R&D growth (t-1)	ΔBRD	–0.024	–0.019	–0.010	–0.046*	0.024*
		(–1.12)	(–1.13)	(–0.72)	(–2.43)	(2.78)
Foreign R&D growth (t-1)	ΔFRD	0.055*	0.069*	0.042*	0.044*	0.125*
		(2.93)	(4.14)	(2.40)	(2.94)	(20.34)
Public R&D growth (t-2)	ΔPRD	0.091	0.067*	0.041	0.073*	0.125*
		(2.66)	(2.32)	(1.54)	(2.23)	(8.96)
MFP level (t-2)	LMFP	–0.205*	–0.181*	–0.162*	–0.211*	–0.192*
		(–11.20)	(–13.04)	(–10.88)	(–13.19)	(–29.47)
Business R&D (t-2)	LBRD	0.027*	0.024*	0.024*	0.029*	0.022*
		(5.28)	(5.17)	(5.52)	(5.82)	(6.11)
Foreign R&D (t-2)	LFRD	0.094*	0.079*	0.067*	0.090*	0.127*
		(7.74)	(7.83)	(6.67)	(8.32)	(26.85)
Public R&D (t-3)	LPRD	0.035*	0.028*	0.029*	0.025*	0.035*
		(5.12)	(4.20)	(4.70)	(4.34)	(16.28)
Control variables						
Employment rate growth (t)	ΔU	0.380*	0.372*	0.338*	0.376*	0.378*
		(8.95)	(11.05)	(9.44)	(10.17)	(39.41)
German unification dummy (t)	G	–0.100*	–0.096*	–0.097*	–0.099*	–0.094*
		(–20.78)	(–28.63)	(–26.94)	(–23.30)	(–52.81)
Country-specific short-term effects		No	No	Yes	No	No
Number of countries		16	16	16	16	16
Adjusted R-squared		0.501	0.477	0.477	0.525	0.505
Nunber of observations		302	302	302	272	238

Notes: Panel data, 16 countries, 1980-98. All regressions include country-specific intercepts (within estimates) and time dummies. The SURE estimation method (seemingly unrelated regression equations) corrects for the contemporaneous correlation of the error term across countries and the 3SLS method (three-stage least squares) corrects for the presence of the lagged endogenous variable among the right-hand side variables. * indicates the parameters that are significant at a 5 per cent probability threshold.
The instrumental variables for the 3SLS (three-stage least squares) estimates are all the exogenous variables (including dummies) and the endogenous variables (lagged two years).
The long-term coefficients as mentioned in the main text are obtained as follows (in accordance with the error correction model as developed in the section on estimation results): For variable X (X = BRD, FRD or PRD), divide the estimated coefficient for LX by the opposite of estimated coefficient for LMFP in the same regression. For instance, in the first regression (column 1), the long-term coefficient for business R&D is: 0.024/0.180 = 0.13.

business reporting that R&D is an increasingly important activity for firms in the knowledge-based economy: when firms in most OECD countries are now at the technological frontier (after several decades of catching up), keeping pace with competition implies not only to build physical capacities, but increasingly to innovate (OECD, 2000).

Table 4. **Long-term elasticities of output with respect to R&D variables**

	Business R&D	Foreign R&D	Public R&D
Long-term elasticities	0.132	0.459	0.171

Further estimates allow the identification conditions that enhance or reduce this elasticity (Table 5, column 1). A country's business R&D intensity (the ratio of business R&D expenses on business GDP) has a positive effect on the elasticity of business R&D: a further percentage point in a country's R&D intensity increases its elasticity by 0.003 to 0.004. This finding points to some kind of increasing returns from investment in research. By spending more on R&D, businesses in a country are able to reap internal economies of scale, to set up networks, to benefit from each other's discoveries. It also denotes an improved ability to absorb the domestic knowledge generated by other firms and/or industries.

The share of government funding has a negative effect on the elasticity of business R&D, although it is small (Table 5, column 1). However, only the defence-related part of public funding has a significant negative effect on MFP (Table 5, column 2). Only four or five OECD countries have a substantial defence R&D budget and might be concerned by this problem. Actually, public funding with a civilian objective has a (weak) positive effect on the elasticity of business R&D. As this elasticity mainly captures spillovers, this might indicate that government funding is fairly successful in enhancing business R&D with higher social return. This is all the more possible as part of government funding of civilian business R&D is related to health or the environment, with no direct impact on measured MFP.

The long-term elasticity of foreign R&D on productivity is in the range of 0.45 to 0.5. This figure may seem surprisingly high, as this is essentially low-cost technology for the economy (the direct cost of absorbing new technology *when the domestic conditions are right* must be substantially lower than the cost of inventing it, which is the *raison d'être* for technology transfers). Estimates by Coe and Helpman (1995), although lower, are in the same order of magnitude: 0.29. This is high also as compared with the elasticity of domestic R&D reported above, leading to the conclusion that for any one country, other countries' R&D matter more than domestic R&D for the purpose of productivity growth, provided that the country has the capacity to absorb technology from abroad. This result is consistent with the fact that the domestic social return on R&D is higher than the private one: if technology spillovers occur within countries, there is no reason for it to stop at the border, and international spillovers should occur. As any country is small as compared with the whole OECD (or: the share of any country in new knowledge

Table 5. **Multi-factor productivity estimation results: error correction model and interactions**

Dependent variable		ΔMFP 1980-98					
Regressions		1	2	3	4	5	6
Multi-factor productivity level (t-2)	LMFP	–0.193*	–0.208*	–0.206*	–0.210*	–0.241*	–0.214*
		(–9.74)	(–9.45)	(–11.68)	(–11.66)	(–13.28)	(–10.60)
Business R&D (t-2)	LBRD	0.020*	0.017*	0.026*	0.019*	0.018*	0.016*
		(3.65)	(2.94)	(5.25)	(3.78)	(3.27)	(2.91)
R&D intensity (IRD) * LBRD (t-2)		0.044*	0.067*				
		(2.96)	(4.49)				
Share of public funding * LBRD (t-2)		–0.002*					
		(–2.17)					
Defence share of public funding * LBRD (t-2)			–0.011*				
			(–4.83)				
Civilian share of public funding * LBRD (t-2)			0.003*				
			(2.17)				
Trend * LBRD (t-2)							0.001*
							(2.79)
Foreign R&D (t-2)	LFRD	0.088*	0.096*	0.159*	0.092*	0.107*	0.080*
		(7.42)	(7.56)	(4.63)	(7.51)	(7.94)	(5.71)
Log (average DPI) * LFRD (t-2)				–0.003*			
				(–2.09)			
IRD * LFRD (t-2)					0.395*		
					(4.34)		
Trend * LFRD (t-2)							0.001
							(0.93)
Public R&D (t-3)	LPRD	0.033*	0.032*	0.026*	0.024*	0.039*	0.041*
		(4.83)	(4.45)	(3.71)	(3.92)	(4.30)	(5.80)
Business R&D intensity * LPRD (t-3)						0.049*	
						(4.30)	
Defence as a percentage of GBOARD * LPRD (t-3)						–0.003*	
						(–3.65)	
Higher education as a percentage of public * LPRD (t-3)						0.004*	
						(4.19)	
Trend * LPRD (t-3)							–0.001*
							(–3.80)
Adjusted R-squared		0.519	0.532	0.508	0.513	0.538	0.502
Nunber of observations		302	297	302	302	298	302

Note: Panel data, 16 countries, 1980-98. All regressions include country-specific intercepts (within estimates) and time dummies, the short-term parameters and control variables are not reported for the sake of space. The 3SLS method (three-stage least squares) corrects for the possible simultaneity of the left-hand-side variable and certain of the right-hand-side variables. * indicates the parameters that are significant at a 5 per cent probability threshold.

generated by the 16-country panel is small), the benefits from other countries may dwarf those arising from domestic technology.[7]

A first straightforward deduction from this interpretation is that the impact of foreign spillovers on productivity should be larger for small countries than for large ones (the world abroad is even more important for smaller countries than for larger ones). The number of researchers is lower the smaller a country is. Hence the probability that the colleagues with whom you interact are located abroad is higher when you are from a small country. This is confirmed in Guellec and van Pottelsberghe (2001*a*), who use patent data for showing that smaller countries have a higher share of their inventions that involve co-operation with other countries (as opposed to inventions made by domestic inventors only). This size effect might be compensated by specialisation, as researchers interact mainly with colleagues *working in a related scientific field*: a small but highly specialised country may be as intensive as larger ones in the fields it covers, but the number of fields it covers may be lower ("specialisation effect"). We tested the "size effect" hypothesis by interacting foreign R&D with an indicator of size for each country: the average over the 1980-98 period of (log) GDP (results are reported in Table 5, column 3). The negative and significant parameter confirms that smaller countries do benefit more from foreign R&D than larger ones, although the effect is quite small. Hence, the "specialisation effect" also is strong, although it does not entirely cancel out the size effect. In addition to previous findings that R&D is more internationalised in smaller countries, the present study shows that smaller countries also benefit more, in terms of productivity, from such internationalisation.

A second straightforward deduction from the interpretation above is that the higher the R&D intensity of a country, the more it should benefit from foreign R&D. We tested this hypothesis by interacting foreign R&D with business R&D intensity for each country.[8] The results presented in column 4 show that the impact of domestic R&D intensity on the elasticity of foreign R&D is positive and significant: a 0.1 per cent difference in R&D intensity between two countries generates a spread of about 0.002 between their elasticities. If firms from a country want to take full advantage from international spillovers, they have to spend on R&D: the free rider approach clearly does not work. It is clear that any firm intending to adopt or improve the knowledge generated by other firms or public institutions (be they domestic or foreign) will have to invest in "imitative" or "adaptive" research activities. This argument is forcefully stated by Geroski (1995) and has some empirical validation. For instance, the econometric studies of Cohen and Levinthal (1989) and Branstetter and Sakakibara (1998) illustrate that a firm's own R&D activity enhances its absorptive capacity of R&D results generated by other firms. Furthermore, the survey results of Mansfield (1981) show that imitation costs on average are about 65 per cent of the original innovation costs. Finally, the interaction of foreign R&D with a time trend (Table 5, column 6) shows that there is no significant increase over time in the elasticity of foreign R&D.

The long-term elasticity of government and university-performed research on productivity is around 0.17. This is much higher than the ratio of public-performed research on business GDP (0.7 per cent to 0.9 per cent in the 1980s and 1990s in OECD), which tends to show that overall public R&D is very valuable to the economy.[9] The elasticity of public research is higher when the business R&D intensity of the economy is higher: this shows the importance of the business sector being able to seize opportunities raised by public research. Therefore, part of the effect of public research on productivity is indirect, flowing through the use of its discoveries by the business sector. Stronger links between public and private research, which governments in most OECD countries are trying to build, should enhance this effect.

The elasticity of public R&D is positively affected by the share of universities (as opposed to government laboratories) in public research (Table 5, column 5). This may point to the fact that much government performed R&D is aimed at public missions that do not impact directly on productivity (health, environment), whereas universities are providing the basic knowledge that is used in later stages by industry to perform technological innovation. This is confirmed by the negative effect of the share of defence in public R&D budgets, as it is not the main purpose of defence R&D to increase productivity. Another possible explanation for the higher impact of university research has to do with the way funds are allocated: in most OECD countries, at least part of funds for university research are allocated on a project basis, whereas government laboratories have an institutional funding. The former allows more reactivity to changing technological priorities than the latter (dropping technological lines which turn out to offer little opportunities, switching to promising areas), and may have a bigger impact on productivity. More case studies would be necessary to substantiate this assumption. Finally, the trend of the elasticity of public research over time is negative. This is at odds with trends in business and foreign research. This is also surprising, as the share of defence, which has a negative impact, has tended to decrease over time. One explanation may be that in many countries the public research sector has been slow to engage in new technology areas, especially ICT, which have spurred MFP growth in the recent years. This lack of flexibility could have contributed to the decreasing impact of public research on productivity.

The two control variables (for the business cycle and for German unification) are of the expected sign and are significant. The employment rate has a large and positive impact on productivity growth, which confirms previous findings that productivity is essentially pro-cyclical. The German unification dummy takes account of the sharp drop in average productivity in Germany following the 1990 events.

TENTATIVE POLICY CONCLUSIONS

One must be careful in drawing policy conclusions from such an exercise, which is performed at a very aggregated level and shows only OECD-wide averages over almost two decades: any policy lesson should then be confirmed by more detailed and country-level studies. Overall, the study points to the importance of technology for economic growth, be it developed by business, by the public sector or coming from foreign sources. It also shows the strong interactions between the various channels and sources of technology, which underline the necessity for government of having a broad and coherent policy approach:

- *Doing R&D is important for productivity and economic growth*. Business R&D has high spillover effects, it enhances the ability of the business sector to absorb technology coming from abroad or from government and university performed research. The social return on business R&D is then higher than its private return, which is a possible justification for some sort of government support to business R&D.
- *Governments should provide appropriate funding of R&D performed in the public sector, in particular the higher education sector, which has a substantial impact on economic growth in the long run*. The lower impact of research performed in government laboratories compared with research performed in the higher education sector points to the need for reviewing the way research is funded in the government sector (in relation to the way the research agenda is set and performance is monitored). However, as these institutional arrangements differ substantially across countries, country-specific studies would be needed for drawing more robust conclusions.
- *The effect of public performed R&D on productivity depends on the intensity of the business R&D effort*. Actually, business research develops technologies that in many cases have been first explored by the public research. It is therefore important that government provide the right framework for encouraging solid relationships between public and private research, so that knowledge flows more easily between the two sectors.
- *Governments should ensure the openness of their country to foreign technology, through flows of goods, of people or of ideas, and ensure that firms have the absorptive capabilities needed for making the best of foreign technology*. As countries that spend more on R&D also take more advantage of foreign technology, free riding (*i.e.* by waiting for other countries to develop the new technology and just trying to imitate when it is ready) would be ineffective.

NOTES

1. The role of information and communication technology in recent growth has been investigated in Schreyer (2000).
2. The most direct and visible effect of research in defence is to capture resources that could be devoted to more economically productive use, although defence may contribute to supporting the institutional framework that is conducive to technical change, something which escapes from direct measurement.
3. Eaton and Kortum (1999) show that, except for small countries very near the source of information, trade is not the major conduit for the spread of new technology. Their results suggest that benefits from innovation spread primarily through the transmission of ideas themselves, rather than through the export of goods embodying them.
4. We also performed static regressions, in log-level, and in growth rate, in order to check the robustness of the results from the ECM: results are reported in Appendix 2. They support results of the dynamic model presented below.
5. SURE: seemingly unrelated regression, allows to control for contemporaneous shocks affecting the 16 countries. 3SLS (three-stage least squares) allows to control for contemporaneous shocks and for the presence of the lagged dependent variable among the right-hand-side variables. Hence, 3SLS controls for potential simultaneity biases, due to the possible influence of the dependent variable on certain of the right-hand side variables. Instruments for the 3SLS regressions are all the right-hand-side variables (including dummies) and the left-hand-side variable lagged two years.
6. The derivation of long-term elasticities (as reported in the text and in Table 4) from the estimated coefficients (as reported in Tables 3 and 5) is detailed in note 3 of Table 3.
7. A simple thought experiment helps realising the importance of world technology for any particular country: imagine that all countries suddenly disappear, except for one, left untouched; this country would have then to rely exclusively on its own research for advancing its technology. One can easily imagine how dramatic the slowdown in productivity growth would be in this country. In a way, certain countries were in a such a situation (think for instance of Albania until a decade ago), with highly visible effects on their technology span and productivity level.
8. When we introduce simultaneously the average size and R&D intensity (both interacting with foreign R&D), size is not significant any more. We decided to introduce them separately into the model for two reasons. First, it seems that there is a correlation between size and R&D intensity among the countries included in the present analysis. This does not mean that small countries are in general more R&D intensive than large ones (a systematic negative relationship between size and R&D intensity). This is the case with our sample of countries because the small countries for which all the data

were available are generally intensive in R&D (*e.g.* Sweden, Finland, the Netherlands). To state it another way, there is a tendency for small countries with low R&D intensity not to have as much data available as large countries with low R&D intensity. Hence, the latter were included in our sample, whereas the former were excluded. The second reason is more technical. The R&D intensity variable varies across countries and over time, whereas the size variable (average GDP over the 1980-98 period) is fixed over time (this choice was made in order to avoid endogeneity of the right-hand-side variable). Therefore the former variable has a much higher variance, which "secures" its significance as compared with the latter variable.

9. In the absence of spillovers, the elasticity of any factor (which reflects its marginal productivity) should be equal to its income share.

Appendix 1

CALCULATION AND DATA SOURCES OF THE TECHNOLOGICAL VARIABLES

R&D capital stocks

R&D capital stocks are calculated following the perpetual inventory method. The stock at time *t* is equal to the new investment at time *t* plus the stock at time *t*-1 minus depreciation:

$$R_t = r_t + (1-\delta)R_{t-1} \tag{A1.1}$$

$$R_t = r_t + (1-\delta)r_{t-1} + (1-\delta)^2 r_{t-2} + (1-\delta)^3 r_{t-3} + \ldots \tag{A1.2}$$

To construct the initial stock we assume a constant annual rate of growth of the past investments,

$$R_t = r_t + (1-\delta)\lambda r_t + (1-\delta)^2 \lambda^2 r_t + (1-\delta)^3 \lambda^3 r_t + \ldots \tag{A1.3}$$

$$R_t = \frac{r_t}{1-\lambda(1-\delta)} \tag{A1.4}$$

where

R_t = R&D capital stock at time t.

r_t = R&D investment at time t.

δ = Depreciation rate (constant over time).

$\lambda = \frac{1}{1+\eta}$ and η is the mean annual rate of growth rt.

The same formula has been used to calculate the business R&D capital stock (BRD) and the public R&D capital stock (PRD).

Foreign R&D capital stock

FRD is the foreign R&D capital stock calculated as the weighted sum of the domestic R&D capital stocks of 15 industrialised countries, the weights being the technological proximity between pairs of countries. The technological proximity is computed as in Jaffe (1986, 1988) using patents granted by the USPTO:

$$FRD_i = \sum_{j \neq i} \omega_{ij}^{M3} \cdot BRD_j \qquad i,j = 1, \ldots, 16 \text{ industrialised countries.} \qquad \text{(A1.5)}$$

$$\omega_{ij} = \frac{F_i \, F_j^{\prime}}{F_{ij} \, F_{ji}} \qquad F_i = \left| \frac{P_i^{TC1}}{\sum_{z=1}^{50} P_i^{PCz}} \qquad \frac{P_i^{TC50}}{\sum_{z=1}^{50} P_i^{PCz}} \right|$$

F_i is the frequency distribution across 50 technological classes of patent granted by the USPTO to country *i*. The weight that are used (ω^{M3}) to compute the foreign R&D capital stock are a three-year moving average of ω.

Appendix 2

REGRESSIONS IN LOG-LEVELS

Robustness of regressions of the ECM can be assessed by estimating regressions in log-levels – according to equation (1'). As such a model misses the dynamics of the linkages between the variables, the purpose is primarily to look for simple, static relationships. Results are reported in Table A1. In columns 1 to 5 we progressively extend the range of variables in the regression (variables of interest and control variables). The estimated coefficients for all variables of interest are of the expected sign and are significant. The coefficient for business R&D is reduced as new variables are introduced into the regression. It drops from 0.2 to 0.1 when all variables are there. The coefficient for foreign R&D is 0.4, which may look high; explanations for that are reported in the main text. Column 6 reports regression results in growth rate (or first logarithmic difference), which can be seen as a test of robustness of the estimated parameters and specification. The coefficient associated with business R&D is not substantially different from the estimation in log-levels. The coefficient for foreign R&D is still significant, but it is much lower than in the regression in levels: this may reflect a dynamic adjustment that is different for this variable. The impact of public R&D is no longer significant. These estimates in growth rate capture short-term variation from a long-term equilibrium relationship. This non-significant estimated parameter may reflect the fact that public research has essentially a long-term impact on MFP growth.

Table A1. **Multi-factor productivity estimation results, in log-levels**

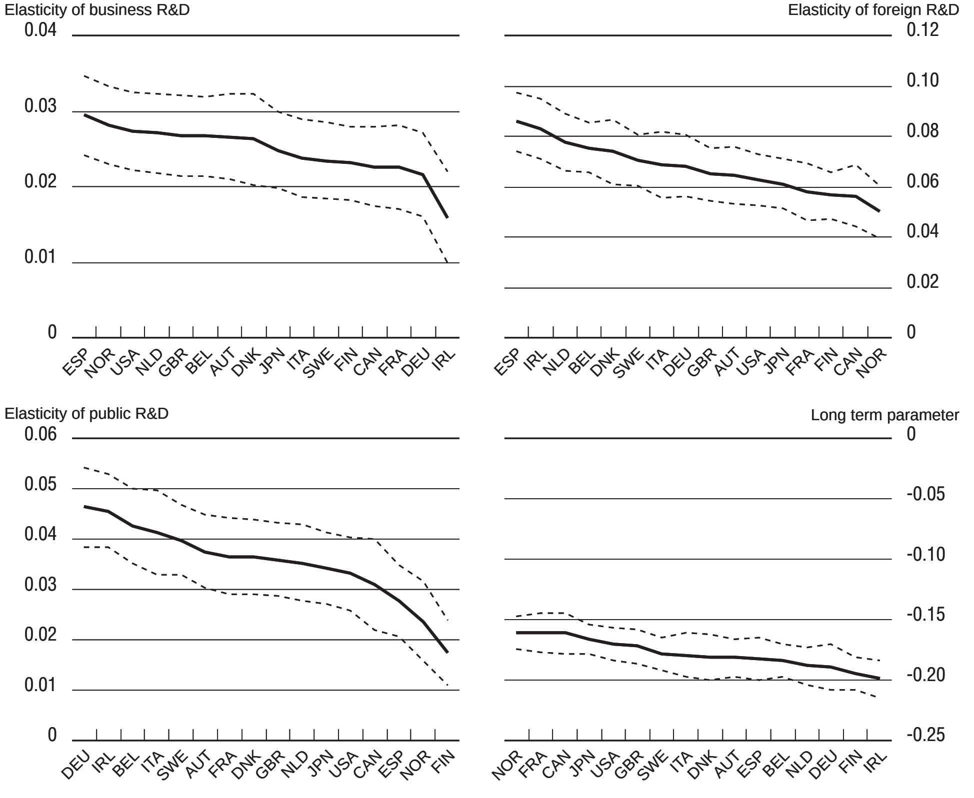
Dependent variable		LMFP	LMFP	LMFP	LMFP	LMFP	ΔMFP
Regressions		1	2		4	5	6
Business R&D (t-1)	LBRD	0.208*	0.168*		0.127*	0.104*	0.087*
		(150.8)	(72.2)		(74.27)	(48.11)	(7.11)
Foreign R&D (t-1)	LFRD				0.385*	0.410*	0.049*
					(42.39)	(35.64)	(3.01)
Public R&D (t-2)	LPRD					0.083*	0.015
						(11.76)	(0.77)
Control variables							
Employment rate growth (t)	ΔU	1.382*	1.448*		1.156*	1.295*	0.143*
		(53.21)	(39.03)		(36.96)	(38.98)	(3.76)
German unification dummy (t)	G	–0.076*	–0.078*		–0.074*	–0.075*	–0.099*
		(–20.40)	(–20.66)		(–27.29)	(–26.74)	(–26.58)
Country dummies		Yes	Yes		Yes	Yes	no
Time dummies		No	Yes		Yes	Yes	Yes
Adjusted R-squared		0.839	0.835		0.892	0.896	0.274

Note: Panel data, 16 countries, 1980-98, 302 observations. All regressions include country-specific intercepts (within estimates) and time dummies. The estimation method is SURE (seemingly unrelated regression equations) that corrects for the contemporaneous correlation of the error term across countries. * indicates the parameters that are significant at a 5 per cent probability threshold.

Appendix 3

STABILITY OF THE ESTIMATED PARAMETERS

The following four figures illustrate the stability of the estimated parameters of equation (2) when one out of the 16 countries is withdrawn from the panel.



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