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R&D AND PRODUCTIVITY GROWTH: EVIDENCE FROM THE UK

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Although the econometric evaluation of R&D has attracted wide interest in many countries, it has not attracted much in the UK. The main objective of this paper is to fill this void, i.e., to estimate the impact of R&D on productivity growth of the UK manufacturing sector. However, there are some additional objectives. Firstly, we estimate the impact of R&D on productivity growth of large and small firms and we discuss a number of theoretical arguments regarding the role of firm size. Secondly, given that the technological infrastructure influences the innovative capacity of a firm, we compare the impact of R&D on productivity growth of high-tech firms with the corresponding impact on productivity growth of low-tech firms. Thirdly, we investigate whether the contribution of R&D to productivity growth has changed over time.

Based on firm-level data (78 firms, 1989–2002), we find that the contribution of R&D is approximately 0.04. Although the R&D-elasticity of large firms (0.044) is higher than the corresponding elasticity of small firms (0.035), the difference is small. In contrast, the R&D-elasticity is considerably high for high-tech sectors (0.11), but statistically insignificant for low-tech sectors. Finally, the investigation of the elasticity of R&D over time revealed an interesting discontinuity showing that although until 1995 the R&D-elasticity was approximately zero, after 1995 it increased dramatically to 0.09. We investigate the potential causes of such non-linearity and we suggest a number of possible explanations.

Keywords: Innovation; Internet; Research and development; Productivity growth

JEL Classification: O3; O52

1 INTRODUCTION

Every manager has the ambition to increase output and cut-down production costs without any additional investment in capital or labor. Economists describe the ambition of 'making more with less' as 'Technical Change' (or simply productivity growth).[1] Higher productivity growth means that more output can be produced from the same amount of input, improving not only firms' profitability but also the standards of living and the wealth of nations. Paradoxically, although firms invested heavily in new technologies, world economy has experienced a continual deceleration of productivity growth (Tab. I). The econometric research that investigates the causes which affect productivity growth has primarily focused on two main factors: (1) technology (e.g., Brynjolfsson and Hitt, 1996) and, (2) R&D (e.g., Griliches and Mairesse, 1984). However, although investments in technology have grown rapidly, spending in R&D, which is

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[1] We can also refer to technical change (A) or productivity growth as total-factor productivity (TFP), multi-factor productivity or residual productivity.

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TABLE I TFP growth rates (%).

	UK	*USA*	*France*	*Germany*	*Japan*
1950–1973	1.30	1.66	3.13	3.98	3.39
1973–1999	1.17	0.43	1.55	1.64	1.18
1989–1999	1.13	0.86	0.61	1.44	0.66
1995–1999	0.88	1.42	0.84	0.97	0.80

Source: Crafts and O'Mahony (2001).

the process that improves technology, has not grown proportionally (see Appendix A, Figs. A1 and A2), leaving economists wondering whether the productivity slowdown is caused by the declining R&D investments.

When the academia realized the important role of R&D for productivity growth, corporate strategy and industrial policy-making, the impact of R&D became a source of debate. However, although the econometric evaluation of R&D has attracted wide interest in many countries (e.g., USA, France and Germany), it has not attracted much in the UK. The main objective of this paper is to fill this void. Using firm-level data (78 firms, 1989–2002), we estimate the impact of R&D on output productivity growth of the UK manufacturing sector. Nevertheless, there are a number of additional objectives. Firstly, we estimate the impact of R&D on productivity growth of large and small firms and we discuss some arguments regarding the role of firm size. Secondly, given that the technological infrastructure influences the innovative capacity of a firm, we compare the impact of R&D on the productivity growth of high-tech firms with the corresponding impact on the productivity growth of low-tech firms.

Thirdly, taking into account that 1990s witnessed major technological transformations that could have changed the productivity of R&D departments (R&D-productivity), we investigate whether the contribution of R&D to productivity growth has changed over time. Given that this investigation revealed an interesting discontinuity in time, we suggest some possible causes of it. The remaining paper is organized as follows. Section 2 reviews the past literature, whereas Section 3 describes the econometric framework of our analysis. Section 4 presents the data and descriptive statistics. Section 5 reports and discusses our findings and Section 6 identifies the limitations of the study. Finally, we draw conclusions and discuss their implications.

2 PAST LITERATURE

Given that there are no any recent literature review papers (the most recent ones are those of Mairesse and Sassenou (1991) and Mairesse and Mohnen (1994)), this section summarizes in Table II the studies that use the same econometric framework as we do, i.e., the cross-sectional studies that estimate the elasticity of output (or labor productivity) with respect to R&D (R&D-elasticity). Although there are pieces of evidence for most of the industrialized countries, the association between R&D and productivity growth at the firm-level is largely unexplored in the UK. The only available study to our knowledge (Wakelin, 2001) uses the rate of return (ROR) method and thus, these findings cannot be compared with the results of our study.[2]

Table II presents a number of cross-sectional studies with the information on R&D-elasticity, examined period, sample and country of study. In summary, these findings confirm that the impact of R&D on productivity growth is positive and statistically significant, whereas the R&D-elasticity usually varies from 0.03 to 0.25. In addition, Table II highlights two major

[2] Wakelin (2001) using a sample of 98 firms and R&D data that cover a 5-year period (1988–1992) found that the ROR to R&D is about 0.28.

TABLE II Cross-sectional studies.

	Author(s)	*Country*	*Covered period*	*Sample*	*R&D-elasticity*	$R^2(SE)$
US	Minasian (1969)	US	1948–1957	17 chemical firms	0.26 (0.03)	0.98
	Griliches (1980)	US	1963	883 manufacturing firms	0.07 (0.01)	0.92 (0.33)
	Schankerman (1981)	US	1963	110 chemical firms	0.16 (0.04)	0.91 (0.36)
	Griliches and Mairesse (1984)	US	1966–1977	133 mainly manufacturing firms	0.054 (0.111)	0.52
	Griliches (1986)	US	1967	386 firms	0.11	n.a
			1972	491 firms	0.11	n.a.
			1977	491firms	0.09	n.a
	Jaffe (1986)	US	1973 and 1979	432 firms	0.2 (0.05)	0.44 (0.35)
	Hall (1993)	US	1964–1990	Up to 1,600 firms in four sub-periods	0.032 (0.002)	0.96 (0.37)
	Adams and Jaffe (1996)	US	1974–1988	80 chemicals/1,400 plants	0.08 (n.a)	0.41
	Mairesse and Hall (1996)	US	1981–1989	6521 observations	0.24 (0.012)	0.82 (0.85)
Europe	Dilling-Hansen *et al.* (1999)	Denmark	1995	110 observations	0.08 (0.0251)	0.88
	Cuneo and Mairesse (1984)	France	1972–1977	182 firms	0.20 (0.01)	0.52 (0.268)
	Mairesse and Hall (1996)	France	1981–1989	6,282 observations	0.09 (0.006)	0.86 (0.5)
	Mairesse and Cuneo (1985)	France	1974 and 1979	296 firms	0.16 (0.02)	0.96 (0.236)
	Hall and Mairesse (1995)	France	1980–1987	197 manufacturing firms (long sample)	0.25 (0.01)	0.99 (0.34)
			1980–1987	340 manufacturing firms (large sample)	0.2 (0.01)	0.99 (0.37)
	Harhoff (1998)	Germany	1979–1989	443 manufacturing firms	0.136 (0.01)	0.46 (0.34)
Asia	Sassenou (1988)	Japan	1976	394 firms	0.10 (0.01)	0.20 (0.349)
	Wang and Tsai (2003)	Taiwan	1994–2000	136 firms	0.19 (0.03)	0.35

Note: Values in the parentheses are the standard error of R&D variable. SE, standard error of the regression.

research gaps: (i) the lack of R&D studies in the UK and (ii) the majority of studies are based on data from the mid-1960s to the late 1980s, leaving the 1990s and the early 2000s relatively unexplored. Hence, although past findings imply that the contribution of R&D to productivity growth decreased during the 1990s (Hall, 1993), we do not know whether this picture changed during the 1990s and early 2000s.

3 THE FRAMEWORK

This paper employs the well-known and extensively used Cobb–Douglas framework.[3] Using the ordinary least squares (OLS) method and the cross-sectional dimension of the data

[3] For a detailed description of this framework, see Mairesse and Sassenou (1991).

(the so-called 'total' regression), we estimate an extended Cobb–Douglas production function where output (Q) is correlated with three inputs: capital (K), labor (L) and R&D-capital stock (R). The form after accounting for time (t) and firm (i) differences is

$$Q_{it} = Ae^{\lambda t} K_{it}^{\alpha} L_{it}^{\beta} R_{it}^{\gamma} e^{\varepsilon_{it}} \tag{1}$$

or by transforming Eq. (1) in logarithmic form

$$q_{it} = \mathrm{a} + \lambda t + ak_{it} + \beta l_{it} + \gamma r_{it} + \varepsilon_{it}, \tag{2}$$

where lower case letters denote the logs of the variables, α, β, and γ are the elasticities of output with respect to ordinary capital, labor and R&D-capital stock, respectively, a is a constant, t is a time trend, λ captures the disembodied technical change and ε_{it} is the error term. Following Hall and Mairesse (1995), however, in the actual estimation, we replace the time trend λt by time dummies capturing the differences between years. Additional dummies are included to account for the industry effects. We also re-estimate Eq. (2) after dividing our sample into four sectors, small/large firms, high/low-tech firms and two time sub-periods.

By imposing constant returns to scale (CRS), Eq. (2) can be transformed into an alternative model. By assuming that factor elasticities $\mu = \alpha + \beta + \gamma$ equal unity, the model is written as

$$(q_{it} - l_{it}) = \mathrm{a} + \lambda t + a(k_{it} - l_{it}) + \gamma(r_{it} - l_{it}) + (\mu - 1)l_{it} + \varepsilon_{it}. \tag{3}$$

Of course, the CRS assumption can be rejected only if the coefficient of labor ($\mu - 1$) is different from zero. The advantage of using this simplified model is that the multicollinearity problem is reduced (due to fewer explanatory variables). However, given that we want to examine different sub-samples (e.g., high/low-tech, small/large firms) whose returns to scale probably vary, we prefer to use Eq. (2) and, as Thomas (1993) argues, not to force our data into a pattern they do not fit.

Regarding the R&D-capital stock, following Griliches (1979), we estimate it with the usual way, i.e., we rely on the concept that the R&D-capital stock R_{it} of firm i at time t depends on the cumulative past R&D expenditure (RD)

$$R_{it} = \mathrm{RD}_{it} + \mathrm{RD}_{i(t-1)} + \mathrm{RD}_{i(t-2)} + \cdots \tag{4}$$

However, past research, as any other type of capital, depreciates and becomes less valuable, primarily, because new knowledge replaces the previous one and a percentage of the R&D-capital stock is diffused, used and thus neutralized by other firms. For that reason, a weighting factor δ is introduced to account for the declining usefulness and convert the gross research to net

$$R_{it} = \mathrm{RD}_{it} + \sum_{1}^{k} (1-\delta)^k \mathrm{RD}_{i(t-k)}. \tag{5}$$

The term k represents the lagged year while the geometrically declining depreciation δ is set to 15% per year, as usual.

4 THE VARIABLES, DATA AND DESCRIPTIVE STATISTICS

This section provides a description of the data and briefly explains how the variables of the study are constructed. The estimation of the impact of R&D on productivity growth requires a panel data set. For this purpose, 205 UK manufacturing firms (the majority of them listed in London stock exchange) were examined and data for their sales, capital, labor and R&D expenditure were collected. From the raw data, we constructed several variables. A record of output at constant prices was computed by deflating the total sales of each firm (for additional information on the variables construction and deflators, see Table BI, Appendix B).

For the construction of capital and labor records, we adopted the concept of flowing capital services (see Jorgenson, 1963). This framework suggests that capital input must be a measure of 'productive stock', implying that its efficiency declines, as it gets older. By ignoring the so-called 'wear and tear' effect of the capital stock, we overstate it and thus, its contribution to productivity is underestimated. Therefore, the appropriate measure is not the capital but the services flowing from it. Using this concept and a proxy used by Griliches (1980), capital input is estimated as the deflated depreciation of gross capital plus 8% of the deflated net fixed capital stock.[4]

Similarly, in an attempt to estimate the usefulness of labor and to capture its heterogeneity (e.g., different effort, skills and education), labor input is defined as the number of employees multiplied by their deflated salary and benefits, i.e., the costs of labor. Both capital and labor variables are corrected for double counting. The R&D-capital stock is estimated using Eq. (5). The figures of R&D expenditures are deflated using three different deflators (see Appendix B). We calculate the initial R&D-capital stock (year 1989) by assuming a pre-sample growth rate of R&D expenditure of 8% per year (Hall, 1990). Therefore, the initial R&D-capital stock is 4.35 times the spending of R&D in 1989 $\{1/(0.15 + 0.08) = 4.35\}$. The missing R&D-points (not more than 3) were interpolated using the average growth rate of the nearest years.

The financial reports of 205 firms gathered over a 14-year period, 1989–2002, from Datastream and firms' web-sites. There is a particular reason why our data start in 1989. In that year, a revised Statement of Standard Accounting Practice (SSAP 13, revised) was introduced in the UK. The revised SSAP 13, by recommending that firms of a certain size should separately report their R&D expenditure, had a positive impact on the extent to which firms disclose their R&D expenditure (Stoneman and Toivanen, 2001). Indeed, our attempt to collect data before 1989 revealed that only one third of those firms reported their R&D expenditures. However, although accounting rules suggest that a firm should report its R&D expenditure, there is no law to force them and thus, the reporting of R&D remains to some extent voluntary (Stoneman and Toivanen, 2001).

As a result, 89 firms of our sample reported zero R&D expenditure. Contrary to other studies (e.g., Wakelin, 2001) which included firms with zero R&D spending, we excluded them from our sample. As was noted earlier, many firms that invest in R&D may never report it (we discuss the issue of disclosure in Section 6). Therefore, believing that we might distort our sample by including these firms, we preferred to eliminate them. The sectoral analysis of the remaining 116 firms is presented in the right column of Table III (initial sample). From that sample, we eliminated 31 firms because four or more R&D-points were missing and seven more firms from sectors like paper, plastic and textiles.

As a result, our final restricted-sample of 78 firms (1092 observations) is exclusively composed of six various sectors (the two-digit 1980 SIC (Standard Industrial Classification) classification is given in the parentheses): chemicals (25), mechanicals (32), electrical/electronics (33, 34), metals (22, 31), motor parts (35) and transportation (36) (see Tab. III, left column).[5] Note that the R&D intensity of the initial sample (2.2%) is very close to the corresponding intensity of the final sample (2.3%). Nevertheless, it is much lower than that of other studies

[4] The record of capital services, however, is not so different from the net fixed capital stock.

[5] Diversified firms with activities in more than one sector were included in their closest sector according to their sales.

TABLE III Sectoral analysis of the sample.

Sector	SIC(80) industry classification	Final sample: No. of Firms	Final sample: R&D/ sales (%)	Initial sample: No. of firms	Initial sample: R&D/ sales (%)
Chemicals	25	12	3.3	16	3.2
Mechanical machinery	32	22	1.0	28	1.0
Office and data machinery	33	6	3.3	12	3.4
Electrical and electronic machinery	34	19	3.3	25	3.2
Metal manufacturing	22	7	0.9	7	0.9
Other metal goods	31	5	0.8	4	0.8
Motor vehicles and parts	35	4	2.6	7	2.5
Other transportation	36	3	5.4	5	5.2
Non-metallic manufacturing	24	0	–	3	0.7
Textiles	43	0	–	1	0.8
Footwear and clothing	45	0	–	2	0.7
Paper	47	0	–	2	0.6
Rubber and plastics	48	0	–	4	1.3
Total		78	2.3	116	2.2

which is approximately 3.8% (Griliches and Mairesse, 1983; Griliches and Mairesse, 1984). Although we could have a larger sample for a shorter time-period, a ‘long’ sample is essential for our aim to investigate whether the contribution of R&D to productivity growth has changed over time. In addition, given that the 14-year period captures both recessions and revivals of the UK economy, a ‘long’ sample safeguards against any ‘business cycle’ bias.

In 2002, the private R&D investments of the entire UK manufacturing sector were about £10.1 billion. The 78 firms of our sample account for £2 billion and thus, approximately 20% of the total. However, the industries that our sample represents (chemical, mechanical, electrical/electronics, metals and transportation) invested about £6.3 billion which means that our sample accounts for about one third of the total R&D expenditures of the specific industries. Although selectivity is still a problem, this is the cost we pay for having a ‘long’ sample.

The sample includes 37 high-tech firms (48% of the whole sample), whereas the remaining 41 firms belong in low-tech industries. Contrary to other studies that focus on large firms, our sample includes both large and small firms. Table BII (see Appendix B) presents a set of descriptive statistics not only for the whole sample but also for the high- and low-tech firms, for the small and large firms and for the two time sub-periods (1989–1995 and 1996–2002). As usual, the high-tech firms are more R&D-intensive (3.3%) as compared with low-tech firms (1.4%), whereas the R&D-intensity between small and large firms is approximately the same. Finally, note that firms of our sample became less R&D-intensive over time (2.4% in A' period *vs.* 2.2% in B' period).

5 FINDINGS AND DISCUSSION

5.1 Basic Results

The basic estimates are presented in Table IV. These results are obtained from the cross-sectional dimension of the data and to be precise they are the ‘total’ estimates without imposing the CRS assumption. These findings confirm the positive and statistically significant impact of R&D on productivity growth (at 1% level of significance). Given that our sample focuses on six

TABLE IV Cross-sectional estimates, 78 firms, 1989–2002.

	Capital	*Labor*	*R&D*	*R^2(SE)*	*R&D/sales (%)*
Without dummies	0.13	0.84	0.0394	0.97	–
	(0.015)	(0.017)	(0.008)	(0.27)	
Time dummies	0.13	0.84	0.0373	0.97	–
	(0.016)	(0.018)	(0.008)	(0.27)	
Industry dummies	0.10	0.87	0.0395	0.97	–
	(0.016)	(0.018)	(0.008)	(0.27)	
Time and industry dummies	0.10	0.87	0.0363	0.97	–
	(0.016)	(0.018)	(0.008)	(0.27)	
Chemicals	0.24	0.69	0.0503**	0.98	3.3
(168 observations)	(0.041)	(0.049)	(0.024)	(0.21)	
Mechanical machinery	0.15	0.78	0.0615	0.96	1.0
(308 observations)	(0.032)	(0.033)	(0.015)	(0.24)	
Electrical and electronics	0.07	0.82	0.152	0.96	3.3
(350 observations)	(0.032)	(0.037)	(0.018)	(0.29)	
Other[a]	0.10	0.99	−0.091	0.97	1.9
(266 observations)	(0.024)	(0.029)	(0.015)	(0.25)	

Note: *Insignificant, **5% level of significance, and ***10% level of significance. If not otherwise stated with the asterisk symbol, the level of significance is 1%. SE, standard error of the regression.
[a]The Other group includes the sectors of metal manufacturing, motor parts and transportation.

manufacturing industries, we cannot claim that it represents the whole manufacturing sector. However, given that approximately 50% of it are high-tech firms, there is no any downward (or upward) bias coming from the inclusion of 'too many' low-tech (or high-tech) firms.

Without the inclusion of dummy variables, the coefficients of ordinary capital and labor are 0.13 and 0.84, respectively, whereas the R&D-elasticity is approximately 0.04, i.e., when firms increase by 1% their R&D-capital, output is increased by 0.04%. Although the estimated R&D-elasticity is lower than those of the studies we reviewed earlier (e.g., Griliches, 1980; Harhoff, 1998; Mairesse and Hall, 1996), this might be the result of the relatively low R&D-intensity of our sample (2.3%). The low R&D-elasticity can also be justified by the fact that we measure output using sales. As Mairesse and Hall (1996) found that the use of sales can bias the estimates downwards (they found the R&D-elasticity attenuated from 0.16 to 0.09 when sales (and not value added) were used).

When we included time and industry dummies, the estimated R&D-elasticity became 0.0373 and 0.0395, respectively. The fact that the inclusion of the industry dummy does not decrease the R&D-elasticity but it slightly increases, it is surprising and not consistent with the majority of studies. However, analogous phenomena have been observed in studies that use sales instead of value added (e.g., Harhoff, 1998). This phenomenon may also explain the argument of Mairesse and Sassenou (1991) that industry dummies might not be representative proxies of the real omitted variables and thus, they might increase (and not decrease) the biases. Taking into account that several firms of our sample are diversified, this argument sounds quite plausible.

Given that our calculations are based on the least-squares method, a number of econometric assumptions are required in order to confirm that these findings are unbiased and robust. For that reason, we carried out a number of tests to check for normality, heteroscedasticity and autocorrelation. No evidence of such problems has been found (see Appendix C). In Appendix C, we also examine whether our estimates are stable to changes in variable definitions. We tried different depreciation rates for R&D-capital and another definition for capital stock. We found that our estimates are considerably stable.

The estimates of the upper part of Table IV are computed under the assumption that all sectors of the economy experience a similar production function. However, taking into account that production techniques vary across industries, this assumption seems to be implausible. For that reason, we divide our sample into four different industries and we investigate which of them experienced higher returns to R&D. The lower part of Table IV presents the results for the chemical, mechanical, electrical and electronics and 'other' industries.[6] Although the sample is small to be divided, given that the majority of firms belong to only three industries, a number of interesting observations can be noted.

The R&D coefficient varies from −0.09 for sectors such as metal to about 0.15 for 'electrical and electronics', suggesting that R&D is more important for the UK electrical and electronics manufacturers. It must be noted, however, that we do not know whether the negative R&D-elasticity of the fourth group is 'real' or simply resulted from the aggregation of heterogeneous industries. In addition, due to the small number of firms that each industry contains, the 'noise' was increased and this fact is reflected in the higher standard errors. The high R&D-elasticity of electrical and electronics industry was expected and it can merely be justified by the high R&D-intensity of the specific industry and by the short life cycle of products. In contrast, we did not expect such a low R&D-elasticity for the chemical industry (0.05). However, the relatively low elasticity may explain why so many chemical and pharmaceutical firms complained in 1990s that the European patent-law cannot adequately protect their research findings.

5.2 Firm Size and High *vs*. Low-Tech Firms

According to Schumpeter (1950), larger firms are more able to innovate and improve their productivity. In order to investigate this hypothesis, we divided our data set into two sub-samples (small and large firms), the R&D-intensities of which are approximately the same.[7] Table V presents the estimates. The scale factor varies from 0.95 (large firms) to 1.02 (small firms) and is highly consistent with theory showing that although economies of scale do exist, they tend to disappear as the scale increases.[8] Although the R&D-elasticity of large firms appears to be higher (0.044) than that of small firms (0.035), the difference is small. Our findings are consistent with those of other studies (e.g., Link, 1981; Lichtenberg and Siegel, 1991) which found that the R&D coefficient is only slightly higher for large firms. We should note, however, that there are also many pieces of evidence showing that the return to R&D is not associated with firm size (Griliches, 1980; Wang and Tsai, 2003).

Although there are not many pieces of econometric evidence, there is a plethora of theoretical arguments that explain why R&D-elasticity of larger firms should be higher. For instance, large firms afford to invest not only in applied but also in basic research, which has greater ROR (Griliches, 1986). In addition, large firms are favored from the economies of scale, i.e., their large-scale production allows them to apply the results of R&D to more products and processes and thus, spread the cost (Cohen and Klepper, 1996). Another reason may be the lower cost of funding (as large firms can fund R&D projects using their own money or obtain loans more readily and at preferential rates to small firms). Furthermore, larger firms in order to satisfy the requirements of international clients tend to be more decentralized, with geographically dispersed departments and business units. Hence, they can capture broader knowledge and innovations from several countries and scientists.

Nevertheless, other arguments support that R&D-productivity is negatively connected to firm size. For instance, coordination and communication for decentralized firms is difficult, costly and time consuming, while the infrequent face-to-face contact slows down the

[6] Note that the 'Other' group includes the industries of metal manufacturing, motor parts and transportation.

[7] The small-firm sample contains companies whose average sales were less that £200 million per year, whereas the remaining firms were included in the large-firm sample.

[8] Scale factor is the sum of the capital, labor and R&D coefficients.

TABLE V Large *vs.* small firms and high-*vs.* low-tech firms.

	Capital	*Labor*	*R&D*	R^2*(SE)*
Large firms	0.16	0.75	0.044	0.94
(546 observations)	(0.023)	(0.028)	(0.011)	(0.28)
Small firms	0.12	0.87	0.035	0.90
(546 observations)	(0.021)	(0.027)	(0.012)	(0.26)
High-tech firms	0.14	0.77	0.11	0.97
(518 observations)	(0.024)	(0.029)	(0.015)	(0.28)
Low-tech firms	0.12	0.88	−0.01*	0.97
(574 observations)	(0.02)	(0.02)	(0.011)	(0.26)

Note: *Insignificant, **5% level of significance, and ***10% level of significance. If not otherwise stated with the asterisk symbol, the level of significance is 1%. SE, standard error of the regression.

knowledge-creation process. However, the returns to R&D may be related not only to firm size but also to other factors such as ownership. Small firms tend to be privately owned and thus, their strategy and management are considerably different as compared with those of large firms. As Mansfield (1984) finds, the strategy of large firms focuses on large and long-term projects but not on risky ones. Nevertheless, Dilling-Hansen *et al.* (1999) find that ownership plays only a minor role.

In summary, although there are several reasons why R&D-elasticity between small and large firms should vary, the empirical findings of our and previous studies do not support these arguments. However, there is a possibility that all these findings (including ours) are seriously biased. The sample-selection biases may be different for the two samples, e.g., small firms that report their R&D expenditure may be success stories. If this assumption holds and the 'small' sample includes only successful firms then the real R&D-elasticity of the small firms could be much lower than our estimates.

Furthermore, in order to investigate whether R&D investments contribute more to the output of high-tech firms (e.g., electronics and chemicals) or low-tech firms (e.g., metal manufacturing), we divided our sample into two sub-samples. The lower part of Table V presents the findings. R&D-elasticity of high-tech firms is 0.11 but statistically insignificant for low-tech firms. These findings are exactly the same as those of Verspagen (1995) at the industry level of the UK (Verspagen finds that the R&D-elasticity of high-tech sectors is 0.11 but insignificant for low-tech sectors). They are also consistent with the findings of firm-level studies for other countries. Griliches and Mairesse (1984) find that the R&D-elasticity of high-tech US sectors is 0.22, whereas the corresponding elasticity of low-tech sectors is negative. Harhoff (1998) reports similar findings for Germany (0.16 instead of 0.09), whereas Wang and Tsai (2003) find analogous results for Japan (0.30 instead of 0.07).

The R&D-intensity of high-tech firms is 3.3%, whereas the corresponding intensity of low-tech firms is 1.4% . This difference can be explained from the fact that the life cycle of high-tech products such as semiconductors is short (Iansiti and West, 1997). However, the long life cycle of low-tech products does not justify their zero or even negative R&D-elasticity. Given that the life cycle of these products is long, there is no need to continually develop new products giving the opportunity to firms to invest in process R&D and bring the production costs down. The lower production costs can allow firms to decrease the selling prices and thus, increase sales. However, if this argument holds, then why does their R&D-elasticity appear to be so low? One possibility may be that the reduction of selling prices is not analogous to the reduction of production costs. In such case, the impact of R&D is reflected not only in sales but also in profits.

Regarding the high-tech firms of the sample, their high R&D-elasticity can be justified by several arguments. One explanation is related to the phenomenon of spillovers, i.e., as high-tech firms belong in R&D-intensive sectors, they can 'steal' knowledge from a larger knowledge-pool. Additionally, the innovative labor of these firms may be more able to acquire and exploit external knowledge and thus, to increase the absorptive capacity of a firm. Another way to explain these findings is the concept of 'dynamic capabilities'. According to this concept, product development mechanisms guide the evolution of dynamic capabilities which promote innovation by providing a dynamic environment of knowledge-creation (Eisenhardt and Martin, 2000). Finally, given that the high-tech firms possess a better infrastructure and understanding of technologies (see Kessler, 2003), they may be more capable of integrating new technologies in the existing processes and further increase their innovative capacity.

5.3 Exploring Potential Time Patterns

The contribution of R&D to productivity growth in 1960s and 1970s was stable (Griliches, 1986). In contrast, this contribution decreased dramatically in the 1980s (Hall, 1993). However, for several reasons (e.g., the revolution of information and communication technologies), this picture might be different in 1990s and in the early 2000s. In order to investigate the impact of R&D on productivity growth over time, we divided the main sample into two time sub-periods (1989–1995 and 1996–2002) and we re-estimated the elasticity of R&D. The findings are quite striking (see Table VI). The R&D-elasticity (all firms) for the first time-period (1989–1995) was 0.011 but statistically insignificant. In contrast, in the second time-period R&D-elasticity was amplified to 0.07.

The discrepancy between high-and low-tech firms is even greater. During 1989–1995, the R&D-elasticity of high-tech firms was 0.08 and negative (−0.03) for the low-tech firms. The R&D-elasticity in the second time-period was higher for both the groups. Specifically, for the high-tech sector it increased from 0.08 to 0.14, whereas the corresponding elasticity of the low-tech sector improved slightly from −0.03 to 0.0 (but still not positive). Motivated by this discontinuity in time, we investigated a number of factors which could have improved the R&D-productivity after 1995.

TABLE VI Elasticities of two time-periods.

	Capital	*Labor*	*R&D*	R^2*(SE)*
A′ time-period (1989–1995)				
All firms	0.13	0.85	0.012*	0.96
(546 observations)	(0.026)	(0.027)	(0.011)	(0.28)
High-tech firms	0.15	0.77	0.082	0.97
(259 observations)	(0.036)	(0.043)	(0.019)	(0.27)
Low-tech firms	0.14	0.87	−0.03***	0.96
(287 observations)	(0.037)	(0.038)	(0.017)	(0.29)
B′ time-period (1995–2002)				
All firms	0.12	0.83	0.0702	0.97
(546 observations)	(0.019)	(0.023)	(0.012)	(0.26)
High-tech firms	0.12	0.77	0.143	0.97
(259 observations)	(0.033)	(0.042)	(0.023)	(0.28)
Low-tech firms	0.12	0.87	0	0.98
(287 observations)	(0.022)	(0.027)		(0.23)

Note: *Insignificant, **5% level of significance, and ***10% level of significance. If not otherwise stated with the asterisk symbol, the level of significance is 1%. SE, standard error of the regression.

Firstly, the increase of R&D-elasticity could be fueled by a sudden increase of R&D investments in the second time-period. We investigated this scenario and we rejected it since the R&D-intensity of our sample has not been increased after 1995 but decreased from 2.4% to 2.2% (which is contradictory with the fact that R&D-elasticity increased dramatically after 1995). An additional explanation for such increase could be the lower cost of funding (e.g., the falling interest rates). However, in that case the elasticity of ordinary capital stock (which was found to be stable) should have also been increased in the second time-period.

Secondly, a reason for such discontinuity could also be a macroeconomic change (such as the oil shock of 1973). This explanation seems to be possible, since 1993 the size of market increased considerably (this year the agreement for the unification of Europe took place). After the unification, firms could reach larger number of customers, increase their sales and benefit from factors such as the economies of scale. Although the average sales per year started to increase after 1994, this increment is not large enough to explain the dramatic change of R&D-elasticity (was approximately 20% during the last 7 years). Another cause that could have boosted R&D-elasticity is the acceleration of productivity growth. However, we should also reject this argument since (as we can observe in Tab. I) productivity growth rate after 1995 has not been increased but decreased (from 1.38% to 0.88%).

5.3.1 The Role of the Internet

Another noteworthy reason that could have improved the contribution of R&D to productivity growth is the Internet. Although the econometric analysis of the association between R&D and the Internet is difficult and possibly requires an entire paper in order to investigate it, we would like to discuss a number of important issues. The Internet and the informational changes accompanying it, transformed the traditional way R&D individuals acquire external knowledge, communicate, and the general way of doing R&D (Mitchell, 2000). However, their role is disregarded by past studies. For instance, the spillover literature investigates the role of the external knowledge but it does not focus on the medium by which R&D departments acquire and then disseminate knowledge.

The Internet has improved the process of knowledge accumulation and made information retrieval easier (Antonelli *et al.*, 2000; Baujard *et al.*, 1998). It can reduce the cost of accessing, searching, retrieving and storing the required knowledge by providing low-cost sources such as e-books and journals, forums (discussion groups), newsgroups (e-mailing messages) and e-conferences. It does not only decrease the cost but also the time devoted to access, search, retrieve and store the required knowledge. In a similar way, by accessing larger number of knowledge sources, R&D departments can increase the quality of products as they can collect more knowledge, create more technological components and examine more possible versions of the final product.

The Internet can also facilitate better communication, i.e., improve the dimensions of quantity and quality of communication. It can improve R&D-productivity by decreasing the costs and the time R&D teams spend to communicate and to coordinate with other teams, departments and organizations. Ghosh (1998) found that the Internet can provide services inexpensively by allowing easy and direct links to anyone, whereas Howe *et al.*, (2000) argue that the Internet by providing easy access to people, data and documents has allowed firms to shorten the development cycles and achieve lead-time reductions. However, the Internet does not only provide fast-and low-cost communication but also it facilitates better communication which is an important element for triggering the creation of knowledge (Nonaka and Takeuchi, 1995). By providing channels that did not exist before, it circulates ideas, distributes information and transfers knowledge (Kessler, 2003).

In summary, the Internet affects the way of doing R&D in two main ways: (1) by offering in less time and at lower cost more knowledge to R&D departments and (2) by providing to R&D teams, departments and associate organizations with low-cost, fast and efficient communicational tools. The above arguments match perfectly the concept of absorptive capacity. According to Cohen and Levinthal (1990), absorptive capacity is the ability of a firm to capture external information, assimilate it, and apply it to the ongoing projects. As they argue, the three main factors that influence absorptive capacity are: (1) the firm's prior related knowledge, (2) the firm's interface with the external sources of knowledge and (3) the firm's ability to transfer knowledge within and across departments. We argue that although the Internet cannot affect the first factor (which is mainly connected to the firm's previous investments in R&D), it can dramatically influence the remaining two.

The second factor refers to the acquisition of knowledge and to the elements which increase a firm's ability to access the external environment and knowledge sources. However, this ability is limited. The ease (or difficulty) of accessing them depends on the mediums (or external channels) that a firm uses to reach them. We argue that the Internet improves the interaction of firm with the external environment (1) by improving the already established external channels and (2) by providing channels which did not exist before. In addition, the Internet can affect the third main factor of absorptive capacity. This factor refers to the internal dissemination of the knowledge acquired from external sources and thus, to the ability of a firm to exploit this knowledge (Cohen and Levinthal, 1990). The success of R&D-process requires not only the efficient collaboration of R&D individuals and R&D teams but also other departments such as marketing and production (Mansfield, 1968). The ease (or difficulty) of communicating with one another depends on the internal channels, i.e., the linkages between the different subunits of firm. We argue that the Internet can improve the established internal channels and also provide new ones. It does not only enhance communication but also it gives the opportunity to individuals to reach members of the firm which could not be reached previously. A vivid example is that of virtual teams which although their members are in dispersed geographical places, can collaborate from a distance.

The correlation between the Internet and R&D has not hitherto been explored econometrically and thus, the formal evidence whether the Internet caused such discontinuity in time is lacking. A proxy to represent the available online scientific and non-scientific knowledge (e.g., information for the commercial trends and demographics) may be the online web sites per year, whereas a proxy that reflects the links that the Internet provides (i.e., how many individuals, firms, institutions and universities can communicate) may be the number of Internet hosts (i.e., the registered computers with IP address). To observe in detail any potential time pattern in data, we estimated the elasticity of R&D for each year starting from 1989 to 2002. Table VII presents the results along with statistics for the number of web sites and hosts.

The first column of Table VII reveals a distinct pattern over time. Until 1995 the R&D-elasticity was zero or very close to zero, after 1995 it increased dramatically up to approximately 0.09 (in 2000) and decreased to 0.065 (in 2002). The second and third columns present statistics for the Internet. Although the commercial use of the Internet started in 1993, before 1995 the number of web sites and hosts was negligible. However, after 1995 the number of web sites and hosts has started to increase and the Internet has become a respectable source of knowledge and an important tool for communication. As was noted earlier, the possible causes of the discontinuity in time may be several. However, we can observe in Table VII that R&D-elasticity matches the growth of web sites and hosts, i.e., R&D-elasticity started to increase in 1995 (when the number of web sites and hosts started to increase), whereas the slightly decrease of the R&D-elasticity in 2001 and 2002 may be associated with the problem

TABLE VII R&D and the role of the Internet.

Year	*R&D-elasticity*	*Online web sites*	*Internet hosts*
1989	−0.016	–	159,000
1990	−0.01	–	376,000
1991	0.011	–	727,000
1992	0.026	–	1,313,000
1993	0.018	623	2,217,000
1994	0.017	10,022	5,846,000
1995	0.041	100,000	14,352,000
1996	0.034	603,367	21,819,000
1997	0.044	1,681,868	29,670,000
1998	0.075	3,689,227	43,230,000
1999	0.087	9,560,866	72,398,092
2000	0.087	25,675,581	109,574,429
2001	0.073	36,276,252	147,344,723
2002	0.065	35,114,000	171,638,297

Source: Zacon Group LLC.

of dot.coms in 2000. Thus, further investigation of the relationship between the Internet and R&D should be particularly interesting.

6 LIMITATIONS OF THE STUDY

This section discusses the limitations and problems of this study. Given that past literature (e.g., Mairesse and Sassenou, 1991) has reported many of these limitations, we initially briefly report them and we then focus on the accounting treatment of R&D which has not attracted much interest. The main limitations and problems are (1) the sales may not capture the immeasurable improvements of output such as better quality or increased product variety. Although one might expect that a new or improved product would be reflected in a firm's sales, it may not because it is neutralized by the new or improved competitors' products. In addition, the price of products may change due to the business cycle and market concentration, (2) although the use of labor costs solves to some extent the problem of employees' heterogeneity, this solution rests on the assumptions (a) that employees get paid fairly depending on their productivity and (b) that the average salary across industries is similar, assumptions that may not be plausible in the real world, (3) R&D expenditure can only represent the formal research effort. However, the scientific knowledge is also determined by many other sources of knowledge, i.e., informal research, patent licenses, the knowledge produced from 'learning by doing' and the knowledge that spills over from universities and other firms, (4) although we use firm-level data, a degree of aggregation still remains. Large firms are nationals or multinationals owning many smaller firms or operating in different states and countries across which many parameters vary, (5) given that many firms are diversified and produce a variety of products or they change their main field of business over time, one may end-up aggregating dissimilar firms, (6) R&D is in itself aggregated (in terms of composition). Reported R&D expenditure is the sum of different R&D activities, e.g., basic and applied R&D, product and process R&D, short-term and long-term projects, small and large projects (Mansfield, 1984) and (7) There are no appropriate R&D deflators.

Besides the limitations and the problems that mentioned earlier, we would like to discuss the problems related to the quality of data and the accounting treatment of R&D. Given that these data are collected from firms' financial statements, the accounting treatment of R&D

expenditures determines the quality of data. For instance, the Financial Accounting Standards Board (USA), the Accounting Standards Board (UK) and the International Accounting Standards Committee suggest a different treatment for R&D expenditures. The source of a main distortion is the fact that R&D expenditure can be regarded either as an asset or as an expense. In the first case, it is capitalized and only a percentage of the expenditure is reported, whereas in the latter case the total R&D expenditure is reported at the end of each financial year (Nixon, 1997).

An additional problem is that of 'disclosure'. A firm has to decide (a) whether to disclose its R&D expenditure and (b) how much it should report. As was noted earlier, the reporting of R&D remains to some extent voluntary engendering some potential selectivity biases. Past literature (e.g., Dye, 1986) suggests three major factors that affect the decision of a firm with respect to the reporting of R&D: (1) the impact of R&D expenditure on its market value (e.g., a firm whose R&D spending did not lead to successful patents may not report it in an effort to cover up the unsuccessful investment), (2) the costs of identifying and reporting such expenditures and (3) the strategic impact (e.g., high R&D expenditure may alarm competitors).

However, there are more reasons that affect this decision. A firm might under- or over-report its R&D spending depending on the tax regulations or government subsidies policy. In other cases, R&D is outsourced and thus, the accounting treatment may vary. Additionally, the number of other firms in the industry which already report their R&D expenditure might influence the decision of firm. However, Stoneman and Toivanen (2001) found no evidence to support this argument. Nevertheless, their study indicates that large firms are more likely to report their R&D expenditures. For instance, R&D effort in small firms is merely informal research which may be mixed with other activities (e.g., the production department may improve a product or develop a better production process) and thus, it is never reported. Kleinknecht (1987) found that although the Dutch official data indicated that the 91% of R&D is done by large firms, the real figure was 77%.

7 CONCLUSION

This paper estimates the impact of R&D on productivity growth of a country and a time-period which are largely unexplored. Based on firm-level data of the UK manufacturing sector (1989–2002, 1092 observations), we calculate that the R&D-elasticity is 4% . We also offer a discussion concerning the role of firm size and the role of technology (high- *vs.* low-tech sectors). The econometric examination of those arguments gave results which are consistent with the findings of past studies, i.e., although the firm size has only a small impact on R&D-elasticity (0.035 for small firms and 0.044 for large ones), the role of technology is very important (0.11 for high-tech firms and insignificant for low-tech ones). In addition, we investigate whether the contribution of R&D to productivity growth has changed over time. This examination revealed an interesting non-linearity showing that although until 1995 the R&D-elasticity was approximately zero, after 1995 it increased dramatically to 0.09. We investigate some potential causes of such discontinuity and we suggest a number of possible explanations.

This paper can be of value for both policy-making and scholarly knowledge. Given that the correlation between R&D and productivity growth is largely unexplored in the UK, our findings confirm to firms' managers and to policy makers the significant impact of R&D on productivity growth (especially for high-tech sectors). We should be very careful, however, when we interpret the findings regarding the low-tech sector. The approximately zero (or even negative) R&D-elasticity does not imply that these firms should not invest in R&D. As was argued earlier, R&D might have a greater impact on their profitability and lower impact on their sales.

In addition, given that there is no much research to illuminate how the Internet can increase the absorptive capacity of a firm, this study may serve as a possible basis for further investigation. Our discussion regarding the impact of the Internet on R&D should be of particular interest to researchers in the tradition of the spillovers literature. We believe that this is a major gap that econometric research should fill. As was noted earlier, the channels by which R&D departments acquire and then circulate knowledge are very important for the knowledge-creation mechanism and the innovative capacity of a firm. Therefore, further investigation of the role of such channels should be particularly useful to the R&D research field.

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Zacon Group LLC, Hobbes' Internet Timeline, Online Internet Statistics. Available at www.zakongroup.com

APPENDIX A

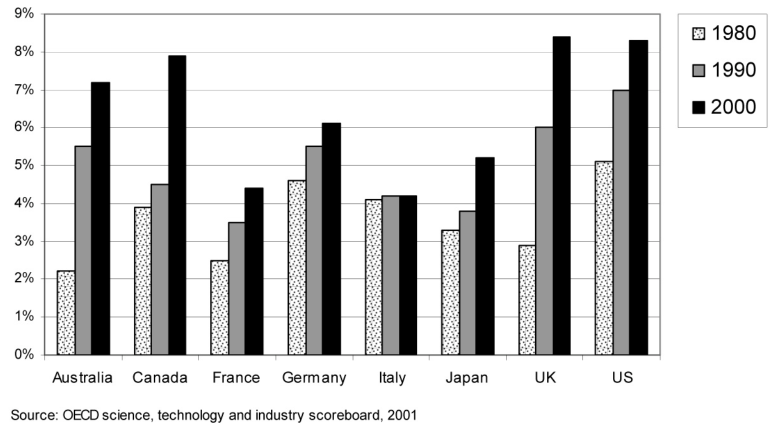

FIGURE A1 Percentage share of IT investments in total investment.

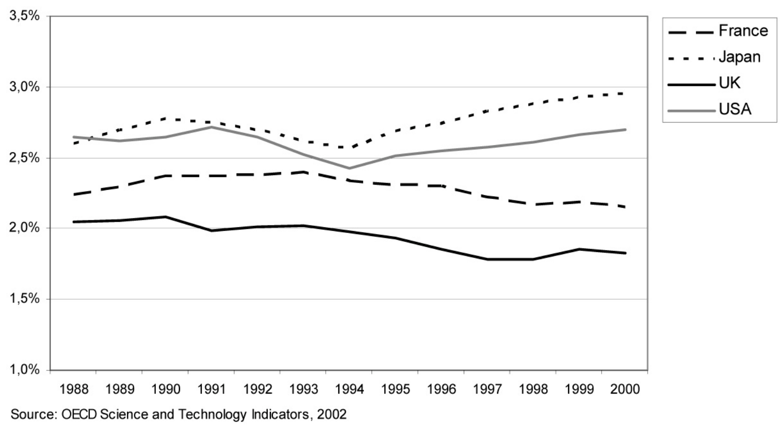

FIGURE A2 Gross R&D expenditure as percentage of GDP (Gross Domestic Product).

APPENDIX B: CONSTRUCTION OF THE VARIABLES AND DESCRIPTIVE STATISTICS

TABLE BI Variables construction and deflators.

Variable	*Definition*	*Deflators*
Output (Q)	The total sales of firms deflated by a two-digit manufacturing price index.	Industry specific two-digit output deflators (from the UK office of national statistics).
Ordinary capital stock (K)	Depreciation of gross capital stock converted to constant prices and 8% of the deflated net fixed capital stock. This record is corrected for double counting by subtracting the capital devoted to R&D department from the ordinary capital.	Fixed investment deflator (from the UK office of national statistics).
Labor (L)	The number employees multiplied by their salary and benefits, i.e., labor costs. This record was then deflated and adjusted for double counting.	Deflator for labor compensation (from the UK office of national statistics).
R&D-capital stock (R)	The knowledge stock for each firm was computed using Eq. (5). The geometrically declining depreciation was set to 15% per year. The initial knowledge stock (year 1989) was computed by assuming a pre-sample growth rate of R&D expenditure of 8% per year. Thus, the initial knowledge stock is 4.35 times the spending of R&D in 1989 $\{1/(0.15 + 0.08) = 4.35\}$.	Data from the UK office of national statistics indicate that 11% of firms' R&D expenditure is devoted to capital, 41% to labor and 48% to materials. For that reason, the 11% of firms' R&D expenditure was deflated using a fixed investment deflator, the 41% was deflated using the compensation deflator, whereas the remaining 48% was deflated using a 'materials' deflator.

TABLE BII Descriptive statistics – Median and mean final sample 78 firms 1989–2002 after deflation.

		Sales	*Capital services*	*Labor services*	*R&D-capital*	*R&D-sales*
Whole sample	Median	140,450	29,730	33,150	11,730	2.3
(1092 observations)	Mean	669,350	205,863	151,832	93,252	
High-tech firms	Median	110,335	20,680	24,800	12,400	3.3
(518-observations)	Mean	705,696	235,278	143,772	124,913	
Low-tech firms	Median	209,472	42,610	58,240	11,376	1.4
(574 observations)	Mean	636,544	179,319	159,106	64,682	
Small Firms	Median	49,700	11,250	12,770	4,320	2.35
(546 observations)	Mean	66,118	17,549	16,054	8,081	
Large Firms	Median	540,925	109,050	144,860	32,100	2.25
(546 observations)	Mean	1,272,575	394,177	287,611	178,425	
A′ time-period	Median	122,800	25,090	29,970	8,837	2.4
(1989–1995)	Mean	611,578	187,969	143,269	86,933	
B′ time-period	Median	159,446	35,324	35,211	15,530	2.2
(1996-2002)	Mean	727,116	223,758	160,396	99,573	

Note: All the monetary values above are in £1,000 (year 2002).

APPENDIX C: EXAMINATION OF THE ECONOMETRIC ASSUMPTIONS AND SENSITIVITY ANALYSIS

Given that our calculations are based on the least squares method, a number of econometric assumptions should be tested in order to confirm that these estimates are unbiased and consistent. The first important assumption is that of 'normality'. We initially estimated skewness (S) and kurtosis (K) of the OLS residuals and we then conducted a Jarque and Bera (JB) test.[9] We found that the residuals are normally distributed. The distribution was further examined by plotting the disturbances which were observed to have a normal (Gaussian) distribution confirming the result of the JB test. The second required assumption of homoscedasticity, i.e., the assumption that the residual variances must be equal over the sample was tested using a version of the 'white' heteroscedasticity test (Koenker, 1981).[10] We found no evidence of heteroscedasticity. Finally, using the Breusch–Godfrey test, we investigated whether there is a correlation between disturbances and no evidence of autocorrelation was found.[11]

However, our study still suffers from the inescapable problem of 'simultaneity' which besets the studies that use the Cobb–Douglas framework. The disturbance must not be correlated with the inputs otherwise, the estimated elasticity will be biased. In such cases, as the inputs are not exogenously determined, it is likely that the function estimates the impact of output on R&D expenditure rather than the opposite (the so-called 'reversed causality' problem). Although methods such as the two stage least squares can sometimes deal with the simultaneity problem, if there is no simultaneity, then these estimates remain consistent but they are not efficient (Gujarati, 1995).

Finally, we investigated the robustness of our estimates by changing the definitions of our variables. To test the sensitivity of the estimated R&D-elasticity to different depreciation rates, we re-calculated the regression using the rates of 10% and 20% (instead of 15%). When the depreciation was set to 10% the R&D coefficient decreased from 0.0394 to 0.0380, whereas it was slightly increased to 0.0407 when the rate of 20% was used. Another parameter that could affect the results is a misspecification of the 'capital stock' variable. Using an alternative definition for capital (instead of the 'capital services' defined in Section 4, the net capital stock), we re-calculated the elasticity of R&D and found that it remained approximately the same.

[9] For more details on the test, see Bera and Jarque (1981).

[10] Note that this version of the white heteroscedasticity test is calculated using Microfit. It initially calculates the regression of the squared residuals on the squared fitted values and then, it tests whether the squared fitted values in this regression are statistically significant. For more details, see Koenker (1981).

[11] For more details on the test, see Breusch and Godfrey (1981).