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R&D AND PRODUCTIVITY: A SURVEY OF ECONOMETRIC STUDIES AT THE FIRM LEVEL

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ABSTRACT

This paper surveys econometric studies investigating the relationship between R&D and productivity at the firm level and assesses the results obtained so far and some of the problems encountered. The findings reviewed fall naturally into three major categories: based on the cross-sectional or time-series dimensions of the data and specified in terms of the elasticity of R&D or the rate of return to R&D.

In view of the problems involved in modelling the effects of R&D on productivity and in measuring the appropriate variables, it is an agreeable surprise that most studies have managed to produce statistically significant and frequently plausible estimates. However, many of the current studies are not fully comparable and their results still leave much to be desired. The task of achieving progress is an arduous one.

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INTRODUCTION: THE ISSUES

A great many economic analyses, such as the pioneering study by R. Solow (1957), and the more recent study by E. Denison (1985), to mention but two of the better-known authors, have demonstrated the central role played by technical progress in economic growth. These studies, which are based primarily on a growth-accounting approach, do not attempt to measure technical progress directly, but treat it as the residual factor accounting for growth. The difficulty in measuring technical progress directly may be explained by the way in which it is actually defined. E. Mansfield, for example, in his book *The Economics of Technological Change* (1968a) considers technical progress as a global phenomenon that encompasses the changes in production techniques as such, as well as the changes in products, and that may also reflect the evolutions in organisational systems and modes of management.

In an attempt to overcome the measurement difficulties inherent in an encompassing definition of technical progress, economists have focused their attention on research and development (R&D), which has been viewed as a relatively clearly defined set of activities contributing both directly and indirectly to changes in techniques and products. However, R&D is but one of many factors of technical change in the broad sense of the term. E. Denison (1985) estimated that R&D accounted for merely 20 per cent of all technical progress. Although R&D contributes only to a modest extent to technical progress and economic growth, it frequently plays a crucial role in corporate strategy and industrial policy at the national level. For statisticians and economists it has the advantage of being quantifiable and measurable through specialised surveys, and thus it can be used to construct indicators that can then be incorporated explicitly in econometric studies and models.

Most econometric studies that attempt to assess the contribution of R&D to economic growth rely on the Cobb-Douglas production function as their basic analytical framework. A measure of R&D capital is then included in the list of explanatory variables in addition to the usual factors of production, that is labour and physical (or tangible) capital (structures and equipment), and, in some formulations, other factors such as materials. The fact that there are no entries in company balance sheets for R&D expenditures which are equivalent to net and gross book values for physical investment clearly raises the problem of obtaining an R&D capital stock estimate at the firm level – and at the sectoral and national levels as well. R&D capital has to be calculated by means of the historical or "perpetual inventory" method, a method which is also commonly used for physical capital. Although practical, this method requires that R&D expenditures be known for a long enough period of time, that appropriate "deflators" be available to derive real R&D values (or "quantities") from the R&D nominal values, and that an estimated rate of depreciation (or obsolescence) be adopted. Thus the equation defining R&D capital is frequently written as follows:

$$K_t = RD_t + (1-\delta)RD_{t-1} + (1-\delta)^2 RD_{t-2} + \ldots = RD_t + (1-\delta)K_{t-1}$$

where K_t is the R&D capital at the end of year t, RD_t the deflated R&D expenditures during year t, and δ the rate of R&D depreciation, which is assumed to be constant.

The problem of estimating R&D capital may be avoided by considering a specification of the Cobb-Douglas function that, while simpler than the usual form, is in principle equivalent. This specification directly relates the rate of total factor productivity growth (computed excluding R&D from the inputs) to R&D intensity, defined as the ratio of R&D expenditures to the value of production or value-added. The coefficient of R&D intensity in this specification may be interpreted as a rate of return to R&D.

* * *

To be precise, the theoretical framework for the studies considered here is the Cobb-Douglas production function, which with three factors can be written as:

$$Q_{it} = A\, e^{\lambda t}\, C_{it}^{\alpha}\, L_{it}^{\beta}\, K_{it}^{\gamma}\, e^{\varepsilon_{it}} \qquad [1]$$

where Q is a measure of output (actual production or sales, or value-added), L a measure of labour (often the number of employees), and C and K are measures of physical and research capital respectively; A denotes a constant; α, β and γ are the elasticities of production with regard to physical capital, labour and R&D capital; λ is the rate of disembodied technical change; ε is the error term for the equation reflecting the effects of unknown factors, approximations and other disturbances; and the indices i and t denote the firm (or the sector) and the period (usually the year) respectively. Within this framework the studies focus mainly on the estimated elasticity γ of R&D capital, as well as its marginal productivity or "rate of return" $\varrho = \partial Q/\partial K = \gamma(Q/K)$.

One advantage to using a Cobb-Douglas function is that it can be estimated as a linear regression if expressed in terms of to the logarithms of variables, either in levels or first differences; this yields the following two equations:

$$q_{it} = a + \lambda t + \alpha c_{it} + \beta l_{it} + \gamma k_{it} + \varepsilon_{it} \qquad [1']$$

$$\Delta q_{it} = \lambda + \alpha \Delta c_{it} + \beta \Delta l_{it} + \gamma \Delta k_{it} + \Delta \varepsilon_{it} \qquad [1'']$$

where x_{it} denotes the logarithm of variable X_{it}, and Δx_{it} the corresponding first difference: $x_{it} - x_{it-1} = \text{Log } X_{it}/X_{it-1}$ which is practically equal, for small variations, to the usual rate of growth of X_{it}: $(X_{it} - X_{it-1})/X_{it-1}$.

In many studies, in order to avoid the measurement of R&D capital stock, authors have been prompted to transform the Cobb-Douglas function by taking the rate of return $\varrho = \gamma(Q/K)$ as the parameter of interest instead of the elasticity $\gamma = \varrho\,(K/Q)$, and by choosing to disregard R&D depreciation, so that $\Delta k = \Delta K/K = RD/K$. The term $\gamma \Delta k_{it}$ expressing the contribution of R&D capital therefore becomes $\varrho(RD/Q)_{it}$, yielding the new equation:

$$\Delta q_{it} = \lambda + \alpha \Delta c_{it} + \beta \Delta l_{it} + \varrho(RD/Q)_{it} + \eta_{it} \qquad [2]$$

which introduces the rate of return ϱ instead of the elasticity γ, and R&D expenditures instead of R&D capital.

In many cases too, authors simplify this equation (as well as the untransformed equations 1′ and 1″) by rewriting them in terms of growth in labour productivity (and growth in physical capital per employee) and by assuming constant returns to scale in the production function ($\alpha + \beta = 1$):

$$\Delta(q-l)_{it} = \lambda + \alpha \Delta(c-l)_{it} + \varrho(RD/Q)_{it} + \eta_{it} \qquad [2']$$

They can go even further by relying on a prior measurement of total factor productivity, that is:

$$\Delta \Pi_{it} = \Delta q_{it} - \bar{\alpha} \Delta c_{it} - \bar{\beta} \Delta l_{it} = \Delta(q-l)_{it} - \alpha \Delta(c-l)_{it}$$

where the elasticity of labour $\bar{\beta}(= 1 - \bar{\alpha})$ is estimated by the share of the costs of labour (wages and related charges) in value-added. They thus estimate the simple regression:

$$\Delta \Pi_{it} = \lambda + \varrho(RD/Q)_{it} + \eta_{it} \qquad [2'']$$

Econometric studies that attempt to estimate the elasticity of R&D or the rate of return to R&D within the framework of the Cobb-Douglas function distinguish themselves not only by the precise specification they adopt, but also by the type of information they use: aggregated macroeconomic or sectoral series on the one hand, and firm data on the other. In the latter case, they also differ by the "dimension of the data" in which the analysis is performed: the longitudinal (or temporal) dimension associated with time-series type estimates, or the transversal (or individual) dimension associated with cross-section type estimates.

* * *

A majority of the early studies to investigate the relationship between R&D and productivity were based on the simplified specification in terms of total factor productivity and R&D intensity[1]. As a general rule, they relied on aggregated series (or small samples of firms). While most recent studies still make use of aggregated series, they vary substantially in content and we felt that it was preferable not to attempt to review them here. Given their differences in terms of scope and level of aggregation, they are difficult to compare and considerable caution must be exercised in bringing together their estimates of rates of return to R&D.

Studies based on an extensive use of firm data are a more recent development, and fortunately the differences between most of them remain relatively slight. Among them, those which are specified directly in terms of the Cobb-Douglas production function with R&D capital are also numerous now. It is these studies relying on firm data whose findings we shall review here. The interest of such a review lies in the comparison of investigations that are relatively similar, despite differing in terms of the country, period and industry considered (as well as in some details of estimation and specification). For an econometrician, they may be seen as a series of different "experiments".

The purpose of this paper therefore is to carry out a survey of studies of R&D and productivity and to help in providing an assessment of the results obtained so far and the problems encountered. The scope of this survey is strictly circumscribed. We restrict ourselves to econometric studies at the firm level, which are based on measurements of firms' R&D efforts and proceed explicitly from an analysis expressed in terms of production functions[2]. Thus we leave aside the many studies based primarily on aggregated information and statistics (even at a detailed industry level). We also limit our survey to studies concerning manufacturing industries, whether it be a particular industry or the group of industries frequently referred to as the "scientific sectors" (those investing most heavily in R&D), or manufacturing as a whole. We therefore do not review studies addressing agriculture[3]. We similarly disregard analyses, usually in the form of monographs, of the profitability and productivity of a given research programme or cluster of innovations. We also exclude the relatively numerous studies which attempt to exploit patent data (or those which try to use direct information on innovations)[4]. We also do not consider the still relatively small number of econometric studies specified in terms of a cost function, that is to say the relationship between R&D and costs (dual to that between R&D and productivity)[5]. Finally, we are not concerned in this paper with investigations into other important aspects of R&D such as analysis of its determinants (size of firms, market structure, technological prospects and opportunities, for example) or analysis of the links between research, patents and innovations, or indeed studies addressing the issues of organisation and evaluation of research.

Even within the area we have chosen to focus on, our choice of studies has been governed by our concern that studies should be readily comparable. Despite their interest, we do not give details about estimates that try to take account of the heterogeneity of R&D by making a distinction between basic and applied research or publicly and privately financed research; nor do we consider estimates that attempt to assess the indirect impact of R&D embodied in equipment (or materials) or that attempt to shed light on the interfirm or intersectoral effects of spillovers, which arise from the different opportunities to appropriate knowledge and the various ways in which it is diffused[6]. Despite our efforts to achieve comprehensive coverage of the field that we have well delineated, there clearly may be a fair number of papers that will have escaped our notice, particularly among those that have not been published in English. It is probable too, as is (unfortunately) often the case with applied research, that many investigations yielding negative or inconclusive results have not been reported in published works. Such considerations need to be borne in mind when contemplating any review of the empirical literature in a particular field.

The findings that we review fall naturally into three major categories, according to the cross-sectional or time-series dimensions of the data on which they are based, and according to the type of econometric specification, whether in terms of the R&D elasticity or the rate of return to R&D, upon which they rely. In the first section of the paper, we describe the cross-section type estimates of R&D elasticity, and in the second section the corresponding time-series type estimates. In the third section we give the rates of return to R&D estimates obtained from specifications that relate the growth in labour productivity, or total factor productivity, directly to R&D intensity. In each section we have attempted to present all the estimates together in the form of summary tables. In a sense these tables provide the basic contribution of our survey. Our comments cannot provide a sufficient account of each study, and for a better appraisal readers should consult the original papers[7].

I. CROSS-SECTIONAL ESTIMATES OF RESEARCH ELASTICITY

The "cross-section estimates" of the relationship between R&D and productivity come from studies based on firm panel data, where they are to be found alongside "time-series estimates" which we shall discuss next[8]. They are obtained from regressions that directly express (in terms of logarithms) the Cobb-Douglas function with an R&D capital stock measure (equation 1'). These estimates are, to be precise, cross-section estimates in the proper sense, that is they correspond to regressions carried out on the variables in levels for a given year (i.e. x_{it}, in logarithms, for a fixed t). They are also estimates corresponding to so-called "between" regressions which are based on a "mean cross section", that is to say which are performed on the individual firm means of variables over several years (i.e. $x_{i.} = 1/T \Sigma_{t=1}^{T} x_{it}$). In a less obvious way, they are also estimates of so-called "total" regressions obtained from all firm-year observations by means of the usual least squares method (i.e. x_{it}). The total estimates are generally very close to the "between" estimates. Indeed, in the breakdown of the total variability (of the variables in levels), the share of the between (or between firm or individual) variability is much larger than that of the within (or within firm or temporal) variability[9]. The estimates that we refer to as cross-sectional estimates are therefore those based primarily on the information provided by the individual differences between firms in the levels of variables, as opposed to those we refer to as time-series estimates which relate solely to the individual changes in variables (regardless of their levels).

Table 1 summarises the main cross-sectional estimates of the R&D elasticity γ that we compile. Where we give no indication of the area of investigation, the estimates are based on samples of firms (doing R&D) pertaining to manufacturing as a whole. We also give estimates, where available, for the "scientific sectors" alone, which as a rule cover chemicals, drugs, electrical and electronic equipment (including office and data processing equipment), and scientific instruments.

To our knowledge, the first three studies to use panel data to estimate R&D elasticity within the framework of a Cobb-Douglas function with R&D capital were those by Mansfield (1965), Minasian (1969) and Griliches (1980)[10]. Mansfield's study, which is based on a sample of 10 chemical and petroleum US firms over the period 1946-62 (and on aggregated industrial series as well) is not really comparable to the other studies, with respect to its formulation and its estimation method. It was difficult for this reason to bring his results together with the other estimations that we present[11]. Minasian's study is performed on a sample of 17 chemical US firms over the period 1948-57. With sound intuition (but also some confusion, given that the econometrics of panel data were still at a very early stage), Minasian compares estimates derived from total regressions (of the cross-section type) with time-series estimates of so-called "within" regressions (see following section). The first estimates, unlike the second ones, result in a statistically very significant and high R&D elasticity of 0.26. Griliches' results are obtained from a very large sample of industrial firms based on the match of the 1958 and 1963 Census of Manufactures statistics with the National Science Foundation R&D annual survey. The author notes with some surprise that the cross-section estimates (for the 883 firms in his sample for 1963) appear to be reasonable and confirm the order of magnitude of the time-series estimates. He perceives in this consistency between the two types of estimates a significant indication of their validity, since they were likely (a priori) to be affected by biases of various origins. R&D elasticity amounts to 0.07 for manufacturing as a whole, but with quite differing values by industry, ranging, for example, from 0.03 in electrical equipment to 0.12 in chemical and petroleum.

Following the lead given by Griliches, a number of other researchers: Schankerman (1981), Griliches & Mairesse (1984), Griliches (1986) and Jaffe (1986) for the United States, Cuneo & Mairesse (1984) and Mairesse & Cuneo (1985) for

Table 1 Cross-sectional estimates of research elasticity

	Sample		Details of specification	R&D elasticity	Log(C/L)	Log(L)	R^2 (SE)
Minasian (1969)	United states 17 firms Chemicals 1948-57		Total estimate	0.26 (0.03)	0.36 (0.03)	–0.00 (n.a.)	0.98 (n.a.)
Griliches (1980)	United states 883 firms 1963 Cross-section		Industry dummies	0.07 (0.01)	0.42 (0.02)	–0.14 (n.a.)	0.92 (0.330)
Schankerman (1981)	United states 110 firms Chemicals and oil 1963 Cross-section			0.10 (0.04)	n.a.	n.a.	0.90 (0.372)
			Corrected data	0.16 (0.04)	n.a.	n.a.	0.91 (0.359)
Griliches Mairesse (1984)	United states 1966-77	133 firms	Total estimate	0.05 (0.01)	0.33 (0.01)	–0.03 (0.01)	0.52 (0.307)
		77 firms Scientific sectors	Total estimate	0.18 (0.01)	0.25 (0.01)	–0.05 (0.01)	0.60 (0.247)
Cuneo Mairesse (1984)	France 1972-77	182 firms	Total estimate Corrected data	0.20 (0.01)	0.22 (0.01)	–0.02 (0.01)	0.52 (0.268)
		98 firms Scientific sectors	Total estimate Corrected data	0.21 (0.01)	0.24 (0.02)	–0.00 (0.01)	0.49 (0.281)
			Total estimate	0.11 (0.01)	0.27 (0.02)	–	0.41 (0.272)
Mairesse Cuneo (1985)	France 296 firms Scientific sectors Average year 1974 and 79		Corrected data	0.16 (0.02)	0.25 (0.02)	–0.01 (n.a.)	0.96 (0.236)
			Corrected data Industry dummies Skill variables	0.10 (0.02)	0.16 (0.02)	–0.02 (n.a.)	0.98 (0.196)
Griliches (1986)	United states 491 firms	1972 Cross-section	Industry dum. Corrected labour variable	0.11 (0.02)	0.25 (0.04)	–0.17 (n.a.)	n.a. (0.309)
		1977 Cross-section	Industry dum. Corrected labour variable	0.09 (0.02)	0.29 (0.03)	–0.10 (n.a.)	n.a. (0.290)

Table 1 (*continued*)

Cross-sectional estimates of research elasticity

	Sample		Details of specification	R&D elasticity	Log(C/L)	Log(L)	R^2 (SE)
Jaffe (*a*) (1986)	United states 432 firms 1973 and 1979		Profits Total estimate	0.20 (0.05)	0.56 (0.02)	–	0.44 (3.46)
Sassenou (1988)	Japan 1976 Cross-section	394 firms		0.10 (0.01)	0.14 (0.03)	–0.04 (0.01)	0.20 (0.349)
		112 firms Scientific sectors		0.16 (0.03)	0.42 (0.03)	–0.05 (0.03)	0.45 (0.305)
			R&D spillover variable	0.08 (0.03)	0.27 (0.08)	0.02 (0.03)	0.58 (0.268)
			Industry dummies	0.07 (0.02)	0.28 (0.08)	0.00 (0.03)	0.58 (0.268)

n.a. = not available.

–: This mark in column Log(L) indicates that the regression is estimated under the assumption of constant returns to scale, and this does not include the term in Log(L).

a) The profit equation given for this study is not strictly comparable to the productivity equations in other studies; the labour variable is omitted and the physical capital variable is Log(C) [instead of Log(C/L)].

R^2: The R^2 are not always comparable among studies, depending on whether the estimated regression is specified in terms of output, labour productivity or total factor productivity.

SE: Estimated standard error of the regression.

France, and Sassenou (1988) for Japan, have also considered the estimates of R&D elasticity obtained in the cross-sectional dimension. Their findings provide a fairly remarkable confirmation of the role of R&D capital as a statistically highly significant factor contributing to productivity differences among firms. The estimated elasticities γ range on average from 0.05 to 0.20, and are significantly higher for the scientific sectors than for other manufacturing industries. Thus Griliches & Mairesse (1984) obtain an elasticity of 0.18 for firms from the scientific sectors in their sample, and an elasticity equal to virtually zero for firms in the other industries (the average estimate for all firms amounting to 0.05).

The estimates of Schankerman (1981) and Cuneo & Mairesse (1984) (as well as those of Mairesse & Cuneo, 1985), are based on data, for which corrections for R&D double counting could be made. Thus the number of researchers is subtracted from the total number of employees and physical capital devoted to R&D laboratories is deducted from total physical capital, whereas materials used up in R&D

activities are reincorporated in the measure of value-added. The lack of such corrections tends to produce a downward bias in estimates of R&D elasticity, a bias that can be quite marked in the cross-sectional estimates. This observation is clearly borne out by the results for the chemicals and petroleum industry in the United States and for the scientific sectors in France, where the cross-sectional estimates amount to 0.16 with corrections instead of 0.10 in the first case, and 0.21 instead of 0.11 in the second.

In his 1986 paper updating his 1980 study, Griliches has information on the share of total R&D expenditures devoted to basic research and on that of privately financed research, and he introduces these two indicators of R&D mix into the basic model as additional variables. In this new study, Griliches finds estimates of the R&D elasticity γ that are comparable to his previous estimates (slightly higher) and that are again close in both the cross-sectional and the time dimensions. However, as in other studies addressing these points (notably Mansfield, 1980), he finds a very high premium for basic research that tends to indicate that it is, on the whole, more productive than applied research and development. He also estimates a significant (although smaller) mix effect for privately financed research, implying that company funds are allocated to research projects that are on the whole more profitable, or less risky, than the projects financed by public funds.

The criticism that is most frequently levelled at cross-sectional estimates is that they may be biased due to the omission of variables characterising firms or industries. Under certain assumptions, these biases could lead to an overestimation of the true value of the elasticity of R&D capital γ (as well as that of physical capital α). Authors generally guard against biases due to the omission of industry characteristics by introducing industry dummy variables into their regressions (thereby taking account of so-called "industry effects"). In so doing, the mean differences between industry are wiped out, and the resulting estimates are solely based on between firms, but within industry, differences. It may be observed, in fact, that in studies that present estimates obtained with and without industry dummies, the former can be significantly lower than the latter. Interpreting these differences simply in terms of an omitted variable bias and giving preference to a specification that includes industry dummies may pose problems, however, as shown by some of the considerations suggested by Mairesse & Cuneo (1985) and Sassenou (1988) (and also Mairesse & Sassenou, 1989). Industry effects may indeed be more or less satisfactory substitutes for the "true" variables that have been omitted, and may thus result in changing the sign and in increasing (rather than decreasing) the biases in the estimates of R&D elasticity (and other parameters of interest in the production function).

Thus Mairesse & Cuneo (1985) introduce skill variables into their regressions (in the form of the share of engineers, technicians, skilled workers, etc., in the total number of employees, as well as the breakdown into males and females). The inclusion of these supplementary variables has an impact that goes beyond that of industry dummies, resulting in a decrease in the elasticity of R&D capital γ for the scientific sectors in France of the order of 0.16 to 0.10, and a similar decrease in the elasticity of physical capital α of approximately 0.25 to 0.16. This reduction naturally reflects the fact that firms which are more capital-intensive and invest more in R&D tend to employ a more highly skilled workforce. Care needs to be exercised in drawing conclusions from this correlation, however, in that the question here is whether capital and skill composition are to be considered as either substitutable or complementary factors. In the first case, the formulation of a Cobb-Douglas function (within the limits of its approximation) is satisfactory, and the lower estimates of the elasticities of research capital and physical capital are indeed those that should be considered. In the second case, skill variables ought not be introduced into the regressions and the higher values are those that should be adopted. One can nonetheless conclude that augmenting the research capital or the physical capital is not *in itself* sufficient to bring about an effective increase in a firm's productivity; it has to be accompanied by an increase in labour skills, and doubtless other conditions would have to be satisfied too.

Instead of industry dummy variables, Sassenou (1988) introduces a variable for the industry R&D intensity into some of his regressions. This variable is calculated for a firm as the ratio of the total R&D capital of other firms in the same industry to the total number of employees. The presence of this variable is virtually equivalent to including the industry dummies; it yields the same decrease in the estimated R&D elasticity and the same improvement in the quality of fit. Its coefficient is statistically significant and may be interpreted as an expression of the spillover effects, on one firm in a given industry, of the research programmes pursued by the other firms in the same industry. The order of magnitude observed appears to be fairly reasonable, since it indicates that the external impact of R&D (on the productivity of other firms in the same sector) would be of the order of 10 per cent of its internal effect. Mairesse & Sassenou (1989), using data from the same sample for France as Mairesse & Cuneo (1985), find estimates that are quite comparable to the Sassenou results for Japan. The industry effects may thus reflect, at least in part, R&D spillovers, which vary from one industry to another. They may similarly reflect scientific and technical opportunity factors, which account for greater fecondity of R&D in some industries than in others.

In order to assess the importance of R&D diffusion and spillover effects, Jaffe (1986) constructs a measure for an external R&D capital stock (or "spillover pool"), which is not based simply on which industry firms belong to, but rather on "technological proximity". Technological proximity is itself determined using the distribution by classes of the patents granted to firms. Jaffe considers a three-equation model aiming to "explain" the number of patent applications, the profits and the stock-market value of firms. The equation for profits (measured in terms of gross operating income) is not really comparable to the production (or productivity) equations used in the other studies; it is, in fact, derived from them by considering that labour is not exogenous but determined simultaneously with production. Regarding the internal elasticity of R&D capital γ, the estimates are of the order of 0.20 (approximately a third of the elasticity of physical capital) and compatible with those obtained by Griliches (1986) from a similar sample.

* * *

By going one step further, it is possible with panel data to safeguard against not only the omission of industry characteristics, but also the omission of firm characteristics (which are assumed to be permanent or to vary only slowly over time). All that is required in this respect is the inclusion of dummy variables for each firm (and not only for each industry) in the regressions. This method is equivalent to leaving out the mean differences between firms, and taking into account only the within firm differences in estimating parameters of interest. The estimates that we shall now consider are of this type; they were obtained in the same studies as the cross-sectional estimates we have just described and are therefore directly comparable with them.

II. TIME-SERIES ESTIMATES OF RESEARCH ELASTICITY

The main time-series estimates in studies based directly on the Cobb-Douglas function with an R&D capital stock measure are summarised in Table 2. This set of studies is the same as that in Table 1[12]. Unlike the cross-sectional estimates, however, the time-series estimates for the scientific sectors alone are not significantly different from those obtained for the other manufacturing industries (in studies in which such estimates are available); accordingly, we have only given the estimates relating to the full samples in Table 2.

To be precise, the time-series estimates may be obtained from the "within" regressions, that is those performed on the deviations of the variables from their individual firm means (i.e. $x_{it} - x_{i.}$), which is equivalent to introducing firm dummy variables into the regressions based on the non-transformed observations (x_{it}). They may also be the estimates from the regressions performed on the first differences (i.e. $\Delta x_{it} = x_{it} - x_{it-1}$), that is approximately the yearly growth rate, if the variables are in logarithms ($x_{it} = \text{Log } X_{it}$). This is in fact another way to eliminate possible biases resulting from the omission of firm effects. The regressions may also use long differences, for example, from the first to the last year of the study period. These long differences correspond (approximately) to the growth rates over the period for variables expressed as logarithms. Preference is occasionally given to the average differences, or mean yearly growth rates, resulting from division by the number of years T in the period. This has no effects on the elasticity estimates as such but divides the estimated standard errors of the regressions disturbances by $\sqrt{T}$. Considering the long differences, or rates of growth over a

Table 2

Time-series estimates of research elasticity

	Sample	Details of specification	R&D elasticity	Log(C/L)	Log(L)	R^2 (SE)
Minasian (1969)	United States 17 firms Chemicals 1948-57	Within estimate	0.08 (0.07)	0.17 (0.08)	0.07 (n.a.)	0.99 (n.a.)
Griliches (1980)	United States 883 firms 1957-65	Average growth rate Industry dummies	0.08 (0.01)	(*a*)	-	0.11 (0.056)
Griliches Mairesse (1983)	United States and France 343 + 185 firms 1973-78	Average growth rate	0.02 (0.03)	0.17 (0.04)	-	n.a. (0.043)
Griliches Mairesse (1984)	United States 133 firms 1966-77	Within estimate	0.16 (0.02)	0.18 (0.02)	-	0.44 (0.141)
			0.09 (0.02)	0.16 (0.02)	-0.12 (0.02)	0.61 (0.139)
Cuneo Mairesse (1984)	France 182 firms 1972-77	Within estimate Corrected data	0.11 (0.04)	0.33 (0.05)	-	0.17 (0.147)
			0.05 (0.04)	0.25 (0.05)	-0.23 (0.06)	0.18 (0.146)
Mairesse Cuneo (1985)	France 390 firms 1974 and 79	Growth between extreme years	0.02 (0.10)	0.09 (0.08)	-0.16 (n.a.)	0.29 (0.129)
Griliches (1986)	United States 652 firms 1966-77	Average growth rate Industry dummies	0.12 (0.02)	-	-	n.a. (0.031)
Jaffe (*b*) (1986)	United States 432 firms 1973 and 79	Profits Growth between extreme years	0.10 (0.30)	-0.22 (0.06)	-	0.10 (0.450)

Table 2 (*continued*)

Time-series estimates of research elasticity

	Sample	Details of specification	R&D elasticity	Log(C/L)	Log(L)	R^2 (SE)
Sassenou (1988)	Japan 394 firms 1973-81	Within estimate	-0.01 (0.01)	-0.10 (0.03)	-	0.63 (0.182)
			-0.02 (0.01)	-0.14 (0.03)	-0.11 (0.03)	0.63 (0.182)
		Annual growth rate	0.02 (0.02)	-0.18 (0.03)	-	0.01 (0.179)
			-0.02 (0.02)	-0.32 (0.03)	-0.41 (0.05)	0.03 (0.179)
		Average growth rate	0.04 (0.04)	0.16 (0.04)	-	0.01 (0.045)
			0.04 (0.04)	0.17 (0.08)	0.05 (0.08)	0.01 (0.045)

n.a. = not available.

–: This mark in column Log(L) indicates that the regression is estimated under the assumption of constant returns to scale, and this does not include the term in Log(L).

a) The elasticity of labour is not estimated in the regression, but is taken to be equal to the share of the cost of labour.

b) The profit equation given for this study is not strictly comparable to the productivity equations in other studies; the labour variable is omitted and the physical capital variable is Log(C) [instead of Log (C/L)].

R^2: The R^2 are not always comparable among studies, depending on whether the estimated regression is specified in terms of output, labour productivity or total factor productivity.

SE: Estimated standard error of the regression.

specific period, rather than the first differences, or yearly growth rates, may have the advantage of reducing some of the potential biases, as we shall indicate later on.

The numbers given in Table 2 show that the time-series estimates of the R&D elasticity γ, as well as the estimates of the physical capital elasticity α, generally tend to be lower than the corresponding cross-sectional estimates. This phenomenon may be attenuated, to a certain extent, by imposing *a priori* constant returns to scale. It becomes more apparent if this constraint is relaxed, implying estimated returns to scale which are sharply decreasing (whereas the cross-sectional estimates of returns to scale are constant or weakly decreasing).

These trends are clearly apparent in the results found for France by Cuneo & Mairesse (1984) and Mairesse & Cuneo (1985); they may also be seen in the results for the United States obtained by Minasian (1969) (except for the returns to scale estimate), Griliches & Mairesse (1984) (except for the R&D elasticity estimate) and

Jaffe (1986), and are particularly striking in the results for Japan obtained by Sassenou (1988) (except for the returns to scale estimated from the regression on mean growth rates). The only exceptions would seem to be the results of Griliches (1980 and 1986), and indeed the author is pleased to find that his cross-sectional and time-series data more or less match. These two studies, however, only report the time-series estimates found when imposing the labour elasticity to be equal to the share of labour costs in value-added. There is therefore a risk that the estimates of R&D elasticity would deteriorate in the absence of this constraint (as in the other studies if constant returns to scale are not imposed).

Indeed, if the results obtained for the United States in the studies by Griliches and by Griliches & Mairesse (1984) are not taken into account, the time-series estimates for R&D elasticity found in the other studies do not differ significantly from zero (at least without imposing constant returns to scale). This is true of the studies for France by Cuneo & Mairesse (1984) and Mairesse & Cuneo (1985), and in the study for Japan by Sassenou (1988). It is also true of the two studies for the United States by Minasian (1969) and Jaffe (1986), and also the study by Griliches & Mairesse (1983), in which the authors consider jointly their two samples of US and French firms. The time-series estimates of the elasticity of physical capital themselves seem to be very low (and even statistically insignificant in the studies by Mairesse & Cuneo, 1985, and Sassenou, 1988, for the regressions "within" and in terms of yearly growth rates)[13].

The fact that there are significant disparities between estimates arising from the cross-sectional and the time-series dimensions is a common feature of panel data econometrics. The standard view in these cases is to give preference to the time-series estimates (generally the "within-firm" estimates), given that, as we have indicated, they are not affected by the biases caused by the omission of firm effects (which would be correlated with the main variables of interest). This view seems to be open to question, however, when the time-series estimates are poor and highly unlikely in comparison with better looking cross-sectional ones. There are in fact many reasons why time-series estimates may themselves be biased and lack robustness. These reasons have been discussed by Griliches & Mairesse (1984) and by Mairesse & Cuneo (1985) (and also in a slightly different context by Mairesse, 1978, as concerns the estimation of the elasticity of physical capital and that of the coefficient of capital-embodied technical progress: like the elasticity of R&D capital, this latter coefficient cannot easily be estimated, one reason being that they are both parameters whose order of magnitude is *a priori* small)[14].

One reason for the lack of robustness of the time-series estimates noted by Griliches & Mairesse is the collinearity of physical and R&D capital with time. If a time trend for disembodied technical change is not included in the production function, the estimates of the elasticity of physical capital, and also R&D capital, tend to be substantially higher. One way to solve this problem is to assume that returns to scale are constant and to base the estimates of labour and physical capital elasticities on the share of labour costs in value added and its complement to unity. This is standard practice in the analyses explaining total factor productivity directly on the basis of R&D capital alone (rather than output or labour productivity on the basis of other factors as well).

The presence of significant biases in time-series estimates may have other causes too. Biases may result from random measurement errors in variables (errors that are both weakly correlated with the "true" value of variables and much less "auto-correlated" over time than the variables themselves). They may also arise from an inadequate specification of lags occurring in the relationship between productivity and its factors (and which in principle are taken into account in the Cobb-Douglas function through the measurements of the stocks of physical capital and research capital, in the form of weighted sums of past investments in equipment and R&D). Likewise (and this is the possibility stressed by Griliches & Mairesse and Mairesse & Cuneo) they may be generated by the omission of variables reflecting short term adjustments to business cycle fluctuations by the firm, such as hours of work and capacity utilisation. One point that these various biases have in common is that they may be relatively minor for cross-sectional estimates on the levels of variables, but are likely to be magnified in time-series estimates based on changes in these variables. Such biases tend also to be higher if the changes are measured over shorter periods of time. Estimates based on first differences, or yearly growth rates, are more likely to be seriously affected than estimates based on long differences, or growth rates over several years. This is one of the arguments that is frequently advanced for giving the latter preference among the various time-series estimates.

Another source of bias that Griliches & Mairesse (1984), followed by Cuneo & Mairesse (1984), and Sassenou (1988), paid particular attention to is the simultaneity regarding production and employment decisions which cast doubt on the hypothesis of exogeneity of the labour variable in estimating the production function. Assuming that firms determine jointly output and employment in order to maximise their profits in the short term for predetermined stocks of physical and research capital, the authors formulate what they refer to as a system of "semi-reduced form equations"[15]. This system may be written as follows using the notation described in the introduction:

$$\begin{aligned} \Delta q_{it} &= \alpha/(1-\beta)\Delta c_{it} + \gamma/(1-\beta)\Delta k_{it} + e_{it} \\ \Delta l_{it} &= \alpha/(1-\beta)\Delta c_{it} + \gamma/(1-\beta)\Delta k_{it} + v_{it} \end{aligned} \qquad [3]$$

This system yields an estimate (which is in principle free from simultaneity bias) not of the R&D capital elasticity γ itself, but rather of the value of $\gamma/(1-\beta)$, or its magnitude relative to that of the physical capital elasticity α.

The time-series estimates obtained from the semi-reduced form equations considered separately and jointly (imposing the equality between their coefficients) are given in Table 3. These estimates are perhaps slightly better than those

Table 3

Time-series estimates of the relative importance of research elasticity with regard to that of physical capital (semi-reduced form equations)

	Sample	Equations	Log K	Log C	System R^2
Griliches Mairesse (1984)	United States 133 firms Within 1966-67	Sales	0.26 (0.03)	0.41 (0.02)	0.56
		Labour	0.29 (0.03)	0.40 (0.02)	
		Constrained system	0.28 (0.03)	0.40 (0.02)	0.56
Cuneo Mairesse (1984)	France 98 firms Scientific sectors Within 1972-73	Value added	0.20 (0.06)	0.31 (0.06)	0.30
		Labour	0.13 (0.04)	0.35 (0.04)	
		Constrained system	0.15 (0.03)	0.34 (0.04)	0.30
Sassenou (1988)	Japan 394 firms Within 1973-81	Value added	0.03 (0.01)	0.28 (0.03)	0.54
		Labour	0.05 (0.00)	0.40 (0.01)	
		Constrained system	0.05 (0.00)	0.40 (0.01)	0.54
	Japan 394 firms Annual growth rate 1973-81	Value added	0.01 (0.01)	-0.21 (0.04)	0.03
		Labour	0.04 (0.01)	0.11 (0.01)	
		Constrained system	0.04 (0.01)	0.11 (0.01)	0.01
	Japan 394 firms Average growth rate 1973-81	Value added	0.09 (0.04)	0.64 (0.03)	0.31
		Labour	0.05 (0.02)	0.56 (0.03)	
		Constrained system	0.05 (0.02)	0.56 (0.03)	0.31

obtained by estimating the production function directly. It is confirmed that the coefficients in the two equations are more or less equal (for the United States and France); it can also be noted that if such equality is imposed, the labour equation "dominates" the production equation in the estimation of the constrained system. The results indicate that the size of the R&D elasticity is about half of the physical capital elasticity in the United States and France, but to merely 10 per cent in Japan. However, the coefficient for physical capital itself $\alpha/(1-\beta)$ seems very low. The hypothesis of constant returns to scale would suggest that the sum of capital coefficients $(\alpha+\gamma)/(1-\beta)$ should in fact be close to unity. As Griliches & Mairesse indicate, it is also possible to challenge the hypothesis of perfect competition on which the derivation of the semi-reduced form is based. Whatever the reasons may be, however, there is no escaping the fact that the "phenomenon of declining returns" affects the system of "semi-reduced form equations" as much as it does the production function itself in the case of time-series estimates[16].

* * *

The results of the different studies, despite providing overall confirmation that there is a significant relationship between R&D and productivity, nonetheless reveal sharp disparities between the cross-sectional estimates based on more or less permanent differences between firms, and the time-series estimates which only rely on the changes within firms. The estimates of "returns to R&D" that we shall now examine represent a compromise between the cross-sectional and time-series estimates of R&D elasticity. This approach, however, has its own problems.

III. ESTIMATES OF RATES OF RETURN TO RESEARCH

Studies that attempt to estimate the rate of return to R&D directly on the basis of individual firm data are both more numerous and more varied than the ones we have just reviewed. As we stressed in our introduction, although these studies explicitly use the same conceptual framework as the previous ones, their formulation differs, relating directly the growth rates for labour productivity, or total factor productivity, to R&D intensity. The productivity growth rates are generally calculated over a period of several years, whereas R&D intensity, measured as the ratio of R&D expenditure to sales or value-added, is often considered at the beginning of the period. However, insofar as this ratio is relatively stable for most firms, timing inconsistency matters little in practice[17].

The transformed model thus establishes a direct relation between *changes* in productivity and *levels* of R&D intensity (and not, as previously, between variables in changes for time-series estimates, on the one hand, and variables in levels for cross-sectional estimates on the other). This is due to a subtle shift in the specification, to which Griliches & Mairesse (1990) in particular have drawn attention. Whereas the original production function assumes that the elasticity γ of R&D capital is constant, the transformed model assumes that the marginal productivity or rate of return to R&D, $\varrho = \gamma(Q/K)$ is the constant parameter. Thus the transformed model with a R&D intensity variable does not strictly correspond to the Cobb-Douglas production function with R&D capital. The fact that a (marginal) propensity coefficient such as ϱ, rather than a (marginal) elasticity such as γ , has to be estimated nonetheless poses serious practical problems that are worth stressing, before we attempt to compare the estimates gathered in Table 4.

The price that unfortunately must be paid for the simplicity of the new formulation is the dependency that it creates between the order of magnitude of the estimated rate of return ϱ and the precise definition of R&D intensity. Depending upon the study, R&D expenditures can vary in terms of scope and detail, and above all may be divided by the value of sales or value added. In principle, this choice should match the corresponding choice involved in measuring labour productivity or total factor productivity. In practice, however, this need not be the case, insofar as the use of either sales or value added as a basis for computing productivity growth rates has little effect on the final result. The computed growth rates would be identical were materials to vary in strict proportion to output (and were variations in stocks to be negligible). Assuming then that the corresponding measures of R&D intensity are strongly correlated across firms, which is probably the case, it follows that the corresponding estimates of ϱ should vary more or less in inverse proportion to them. These estimates may therefore be two or even three times as high, depending upon whether R&D intensity is measured with respect to value added or sales (since value added represents a third to a half of sales in manufacturing firms). Particular attention therefore needs to be paid to the R&D intensity indicator that is used when comparing estimates of the rate of return to R&D ϱ obtained from different studies. Estimates of the R&D elasticity γ do not present such drawbacks, and in this respect they may be more directly and more safely compared.

In fact the problem is deeper than might appear at first sight, and it affects the interpretation of the rate of return to R&D actually being estimated. In particular, the estimated rate is in most cases viewed as a "gross" rate of return. Consequently, a "net" rate of return will have to be calculated if an appropriate comparison is to be made between, for example, the profitability of research capital and that of physical capital; to do so, the rate of depreciation (or obsolescence) δ of R&D must be subtracted: $\varrho_{net} = \varrho_{gross} - \delta$. Contrary to what one might hope for, the problem of the assessment of R&D depreciation posed by the measurement of the stock of R&D capital cannot really be avoided. The values proposed for the rate of depreciation of R&D δ are generally high, of a magnitude which might be considered an excellent rate of return. Thus, in their studies, Griliches & Mairesse adopt a rate of 15 per cent for δ[18]. Given such high orders of magnitude, estimates of the net rate of return are particularly sensitive to uncertainty over the value of

Table 4

Estimates of rates of return to research

	Sample		Details of specification	Rate of return to R&D	Log (C/L)	R^2 (SE)
Minasian (1962)	United States 18 firms Chemicals 1947-57		Total productivity Value added	0.25 (0.04)	–	0.67 (n.a.)
Mansfield (1980)	United States 16 firms Chemicals and petroleum 1960-76		Total productivity Value added	0.27 (0.07)	–	0.49 (n.a.)
Link (1981)	United States 1971-76	174 firms	Total productivity Value added	–0.00 (0.03)	–	0.00 (n.a.)
		33 firms Chemicals		0.07 (0.03)	–	0.14 (n.a.)
		34 firms Machinery		0.05 (0.07)	–	0.02 (n.a.)
		19 firms Transport equipment		0.15 (0.21)	–	0.03 (n.a.)
Link (1983)	United States 302 firms 1975-79		Totalproductivity Sales	0.06 (0.04)	–	0.34 (n.a.)
Griliches Mairesse (1983)	United States and France 343 + 185 firms 1973-78		Sales	0.28 (0.06)	0.17 (0.03)	n.a. (0.042)
			Sales Industry dummies	0.12 (0.06)	0.17 (0.03)	n.a. (0.040)
Odagiri (1983)	Japan 370 firms 1969-81	Scientific sectors	Total productivity Sales	0.26 (0.10)	–	0.04 (n.a.)
		Other sectors		–0.47 (0.29)	–	0.01 (n.a.)
Clark Griliches (1984)	924 business units 1971-80		Sales Industry dummies	0.18 (0.05)	0.25 (0.01)	0.59 (0.111)
			Total productivity Sales Industry dummies	0.20 (0.05)	–	0.15 (0.113)

Table 4 (*continued*)
Estimates of rates of return to research

	Sample		Details of specification	Rate of return to R&D	Log (C/L)	R^2 (SE)
Odagiri Iwata (1986)	Japan 135 firms 1966-73		Total productivity Value added	0.20 (0.11)	–	0.01 (n.a.)
			Total productivity Value added Industry dummies	0.17 (0.13)	–	0.22 (n.a.)
	Japan 168 firms 1974-82		Total productivity Value added	0.17 (0.06)	–	0.05 (n.a.)
			Total productivity Value added Industry dummies	0.11 (0.06)	–	0.58 (n.a.)
Sassenou (1988)	Japan 394 firms 1973-81		Sales	0.69 (0.19)	0.17 (0.08)	0.04 (0.051)
			Value added	0.22 (0.11)	0.18 (0.08)	0.02 (0.051)
			Value added Industry dummies	–0.02 (0.07)	0.17 (0.05)	0.65 (0.030)
			Value added Industry dummies Free returns	–0.04 (0.07)	0.13 (0.05)	0.66 (0.030)
Goto Suzuki (1989)	Japan 1976-84	13 firms Drugs	Total productivity Value added	0.42 (0.12)	–	0.80 (n.a.)
			Total productivity R&D capital	0.23 (0.13)	–	0.76 (n.a.)
		5 firms Electrical machinery	Total productivity Value added	0.22 (0.09)	–	0.58 (n.a.)
			Total productivity R&D capital	0.53 (0.18)	–	0.62 (n.a.)
Lichtenberg Siegel (1989)	United States 5240 firms 1972-85		Total productivity Sales Industry dummies	0.13 (0.02)	–	0.03 (n.a.)
Fecher (1989)	Belgium 292 firms 1981-83		Total productivity Sales Industry dummies	0.04 (0.04)	–	0.02 (n.a.)

Table 4 (*end*)

Estimates of rates of return to research

	Sample	Details of specification	Rate of return to R&D	Log (C/L)	R^2 (SE)
Griliches Mairesse (1990)	United States 525 firms 1973-80	Sales	0.41 (0.09)	0.15 (0.03)	0.07 (0.037)
		Sales Industry dummies	0.27 (0.10)	0.16 (0.03)	0.25 (0.033)
		Sales Industry dummies Free returns	0.25 (0.10)	0.11 (0.03)	0.27 (0.033)
	Japan 406 firms 1973-80	Sales	0.56 (0.23)	0.40 (0.07)	0.09 (0.044)
		Sales Industry dummies	0.30 (0.21)	0.31 (0.05)	0.50 (0.033)
		Sales Industry dummies Free returns	0.20 (0.21)	0.24 (0.05)	0.53 (0.032)

n.a. = not available.

R^2: The R^2 are not always comparable among studies, depending on whether the estimated regression is specified in terms of output, labour productivity or total factor productivity.

SE: Estimated standard error of the regression.

Free return: Indicates that the returns to scale are not constrained to be constant, which is the case in the absence of such mention.

Sales or Value added: Indicates that the R&D intensity variable is computed as a ratio of R&D expenditures to sales or to value added respectively. This choice is consistent with the measurement of the productivity variable, which may be computed on the basis of sales or value added. The only exceptions are the estimates given for the first regression of Sassenou (1988) (see the table at Sassenou, row "sales"); in this regression the productivity measure is based on value added while the R&D intensity ratio is computed on the basis of sales.

the rate of depreciation[19]. In contrast, it can be shown that estimates of the R&D elasticity γ are robust with regard to the choice of rates of depreciation used for the construction of R&D capital[20].

The meaning of the rate of return to R&D ϱ is also subject to further ambiguity when the estimates are based on variables for labour productivity and physical capital (or for total factor productivity) which are not corrected for R&D double-counting. This is generally the case, and authors who are aware of the problem tend to interpret the estimated rate of return to R&D as though it were *in excess* of the normal rate of return to physical capital[21]. In other words, if the (net) marginal productivity of investment in research was equal to that of investment in equipment, we should expect the estimate of ϱ to be equal to zero (or to the difference between the rate of depreciation of research capital and that of physical capital, i.e. of the order of 5 to 10 per cent). This interpretation, however, lacks a solid basis, particularly with regard to estimates based on productivity changes. It is plausible that these changes remain extremely close regardless of whether they are measured on the basis of raw data or with data corrected for R&D double-counting; thus it is by no means obvious that what is estimated is the rate of excess return rather than the actual rate of economic return itself, or some intermediate value. It should be noted that, unlike the previous problems, this particular difficulty also affects the precise interpretation that should be made of the estimates of the R&D elasticity γ[22].

A final difficulty in interpreting the rate of return to R&D, and similarly R&D elasticity, is related to the distinction between "private" and "social" rates of return. Estimates based on firm data are sometimes considered to correspond to the private rate of return, whereas those obtained from aggregate data (at the industry level, for example) are seen as relating to the social rate of return[23]. Such an interpretation is clearly not robust in practice. If only because of complex problems of aggregation, it is by no means sure that estimates at the aggregate level take proper account of the spillover effects which make the social return to research higher than the private return alone. Moreover, firms' research efforts tend to vary largely according to the industry, and consequently estimates based on firm data may reflect, to an uncertain degree (particularly in the absence of industry dummy variables), a social return to research as much as a private return. As we mentioned with regard to some studies that have pursued this line of investigation, the production function should include a measure of an "external R&D capital stock" (calculated, for example, as the sum of the internal R&D capital stocks of firms either within the same industry or "technologically close"), in addition to the internal R&D capital stock variable. It would then be possible (in principle) to estimate the spillover effects, and to assess separately the private and social returns to research. In this respect, one should note that the rate of depreciation of external R&D capital is probably lower than that of internal R&D capital (some authors go so far as to assume that it is either zero or very low).

Given the factors that can adversely affect the comparability and interpretation of estimates of the rates of return to R&D ϱ, we should therefore expect to find widely varying numbers. This is borne out by the estimates given in Table 4, which lists the results of thirteen studies, ranging from a paper (which as far as we know is the earliest) published by Minasian in 1962, and covering 18 firms in the chemical industry, to a recent study by Lichtenberg & Siegel (1989) covering 5 240 manufacturing firms[24]. However, there is no evidence of the large discrepancies that one might expect to find between studies in which R&D intensity is measured with respect to sales and those in which it is measured with regard to value-added. The estimates of the rate of return ϱ found for the former (Link, 1983; Odagiri, 1983; Clark & Griliches, 1984; Griliches & Mairesse, 1983 and 1990; and Lichtenberg &

Siegel, 1989) are not really any higher than those found for the latter. The first two regressions by Sassenou (1988) that we have reproduced nonetheless confirm that the problem does exist and that it may indeed be serious. While these two regressions differ only by the fact that R&D intensity is measured relatively to sales in the first instance and value-added in the second, they yield estimates of ϱ ranging from 0.69 for the former to 0.22 for the latter.

Moreover the results obtained by Goto & Suzuki (1989) show that the estimates of the rates of return to R&D can be greatly affected when a measure of R&D intensity corrected for depreciation (and therefore computed as the ratio of the change in the R&D capital stock to output: $\Delta K/K = (RD - \delta K)/Q$) is used instead of an uncorrected intensity measure (as in the other studies). Actually the estimated rate of return is found to be 0.23 in the first case as against 0.42 in the second case for the sample of firms in the drug industry, and 0.53 as against 0.22 for that in electrical machinery. As we have pointed out (and explained in footnote 19) the interpretation of such discrepancies between the estimates in terms of a net rate of return versus a gross rate of return does not hold. If this interpretation seems plausible for the sample of pharmaceutical firms, it is not for the sample in electrical machinery. Nor is it in the case of the estimates found by Goto & Suzuki in five other industries (which are not reproduced in Table 4).

Clearly there are many other factors besides the definition and measurement of R&D intensity that may result in disparities among the estimated rates of return. Table 4 shows that certain differences in the regressions specification may be responsible for significant deviations in the estimates: whether or not the regressions include industry dummies; whether they relate total factor productivity or labour productivity to research intensity (in the latter instance Table 4 gives also the estimates of the physical capital elasticity α); whether or not they impose constant returns to scale.

Thus it may be observed that the introduction of industry dummies tends to reduce the estimated rate of return to R&D. This effect, which we have already encountered with regard to the cross-sectional estimates of the R&D elasticity γ, poses the same problem of interpretation. While the productivity gains achieved in the various industries probably depend to a large extent on their research efforts, in particular through the associated spillover, diffusion and appropriability phenomena, they also depend on other specific factors. The industry effects are only a reflection of the combined result of these influences without allowing one to distinguish among them.

If in a sense the inclusion of industry dummies in the regressions may go too far, on the other hand, it may also take only partial account of industry heterogeneity. Even though all the studies reviewed here concern manufacturing firms in developed countries, the industry composition of the samples may be quite variable and may represent an additional factor contributing to the discrepancies between estimates. This point is clearly illustrated in the estimates given for

Link (1981). This author is one of the few to have published results that were on the whole negative; however, he finds somewhat more encouraging estimates for three industries: chemicals, machinery and transportation equipment. The same is true of the estimates produced by Odagiri (1983), who obtains a positive and statistically significant rate of return for the scientific sectors only. Similar findings are also confirmed by many other results from the studies reviewed, which could not be summarised in Table 4[25].

It may also be noted that the estimates of the elasticity of physical capital are often relatively low and (doubtless) lower than the capital share in value added which is used to weight the contribution of physical capital in the calculation of total factor productivity. To the extent that firms which invest the most in equipment tend to be also those investing actively in terms of R&D (resulting in a significant correlation between the growth of physical capital and R&D intensity), the estimates of the rate of return to R&D might be expected to be lower for regressions relating to total factor productivity than for those relating to labour productivity. This observation does not show up clearly in the results presented, however. In contrast, the estimates obtained with free returns to scale, which are given for Sassenou (1988) and Griliches & Mairesse (1990), seem to confirm the tendency already shown for the time-series estimates of the R&D elasticity γ. They indicate a slight fall in the rate of return ϱ and in the elasticity of physical capital α[26].

Finally, contrary to what is commonly supposed, the choice of an indicator for labour productivity (or total factor productivity), constructed on the basis of a measure of production or sales rather than on the basis of a measure of value added, may be quite important (irrespective of the way in which R&D intensity is calculated). In periods such as those marked by the first and second oil shocks, changes in production and materials, and consequently in value-added, often diverge to a certain extent, and these changes may themselves be more or less closely related to firms' investment in equipment or even to their R&D efforts. Comparison of the results obtained for Japan by Sassenou (1988), with those obtained by Griliches & Mairesse (1990), would seem to suggest a problem of this type. The samples used by these authors are practically identical and the periods studied differ merely by a single year. However, due to problems of comparability with the data available for their US sample, Griliches & Mairesse used sales as a measure of production, whereas Sassenou chose to use value added. While the estimated rates of return to R&D ϱ do not differ significantly for comparable definitions of R&D intensity in the two studies, the estimated elasticity of physical capital α, in contrast, varies by a factor of up to two. Given the speed at which the physical capital of Japanese firms has grown, this is clearly a substantial disparity that merits in itself further investigation[27].

* * *

There are therefore many reasons for the wide range of estimates of the rate of economic return to R&D ρ for firms, and on the whole these results are far from being truly comparable. Nonetheless, most of the studies confirm that a relationship exists between productivity and R&D. In accepting the orders of magnitude found for the estimates, many authors even consider that R&D expenditures represent an especially productive investment for firms, with a rate of return that is at least equal to, if not higher than that of investment in equipment. Careful comparison of the studies, however, reveals a number of problems. It shows that, apart from their diversity, estimates also lack robustness; and their precise interpretation in terms of rates of return is itself extremely problematic. Contrary to what one might have hoped for, the simplest *a priori* approach formulated in terms of a "return to research" does not provide better results than those obtained from an approach formulated in terms of "elasticity of research" that explicitly requires a measure of R&D capital stock. The disparities and uncertainties affecting the time-series estimates of R&D elasticity γ are even exacerbated somewhat. Some of these problems may of course be ascribed to the nature of R&D as a factor of production. Many others, however, are more general and certainly tend to aggravate the ones which are specific to R&D. On the methodological side they involve panel-data econometrics, and on the application side they relate to the econometrics of production. As we have emphasised, the difficulties affect the estimates of physical capital elasticity and returns to scale just as well as the estimates of the elasticity or returns to research.

IV. AN INEVITABLE CONCLUSION: RESEARCH IS NOT EASY

The comments we have made and the partial conclusions we have drawn throughout this overview of econometric studies at the firm level, have frequently been critical and in some cases negative. Should our overall conclusion be one of pessimism, therefore, and does this mean that econometric studies fail to demonstrate that a significant link exists between R&D and productivity? Clearly the answer to both these questions is no.

The phenomena that econometricians attempt to summarise by relatively simple relationships are usually highly complex ones; this is particularly true with respect to R&D activities and their effects on productivity. R&D effects are intrinsically uncertain, they often occur with long lags, they may vary significantly from one firm or sector to another and change over time. They may also be hidden by the effects of other factors of production and productivity which occur simultaneously and may largely dominate them. In view of this situation, not to mention the formidable problems involved in measuring variables and in obtaining high-quality data, it is understandably difficult to establish a statistical relationship, such as a production function, between R&D and productivity. It is therefore an agreeable surprise to discover that most studies have managed to produce statistically significant and frequently plausible estimates of the elasticity of R&D or the rate of return to R&D.

However, the issue at stake is not so much the question of whether or not a relationship exists between R&D and productivity. Individual case studies and other factual knowledge in the field, as well as the fact that firms do indeed undertake research, leave little room for doubt on this score. The crux of the matter is whether or not econometric studies can characterise such a relationship in a satisfactory and useful manner. Parameters such as the elasticity of R&D or the rate of return to R&D, and indeed the production function itself, should simply be seen as abstract constructs designed to summarise and quantify approximately major phenomena, or certain important aspects of them. Attempts to model the production function and to estimate such parameters should allow us to unravel the threads of these phenomena, despite their complexity, and thereby permit us to analyse some of their mechanisms or predict some of their consequences.

The question, if it is posed in such a way, calls for an answer, which in our opinion should be qualified. First, the results of current studies still leave much to be desired; second, although there is much progress one would look for, the task of achieving such progress seems to be an extremely arduous one. As we have said earlier, it is rare for econometric analyses, even restricted to those based on firm data, to be fully comparable with each other; their results often lack robustness and comparison of different studies reveals inconsistencies and problems of interpretation about which we have no firm conclusions nor good explanations. While a fairly clear picture of the qualitative significance of R&D effects on productivity emerges from the gathering of the different studies, the way in which these effects can be characterised remains crude and imprecise. The range of estimates is especially wide; but one cannot be sure whether the differences between them are real and a result, for example, of differences in the period, industry or country considered, or simply a reflection of the peculiarities of the individual studies.

Many improvements should be made and much progress sought for if we are to overcome such inadequacies and move closer to solving the problems. To conclude our discussion, we shall first briefly indicate three important orientations for productivity studies in general, and then we shall mention three more specific directions of investigations relating directly to the analysis of R&D effects. These lines of research merit continued encouragement, considering their importance to our knowledge, and the difficulties in pursuing them.

The first general objective of research efforts must be to improve the data and, in particular, to be able to account more fully for quality effects in the measurement of output and input prices and quantities. This is clearly a crucial matter in order to make a better assessment of the R&D effects, which often result in product innovations. The second general objective concerns the need to take account of heterogeneity and variability in the analysis and modelling of firm behaviour. It is important to get a better understanding of the diversity of firms individual situations and of the evolutions of these situations over time, and to try to account for such diversity (at least up to a certain point) in terms of certain general characteristics. These characteristics can be internal to the individual firm or specific to their environment, be of a technical or financial nature, depend on the overall economic situation or that of the industry or the region, be related to the market structure or form of competition, etc. We have already dealt with the third general orientation which concerns a central issue of panel data econometrics: trying to reconcile the time-series and cross-sectional type estimates. This reconciliation calls not only for the availability of variables that are less subject to measurement errors, but also the development of more satisfactory models, notably by improving the dynamic specification of the interaction between variables and the modelling of short-term adjustments.

Considering more specifically R&D studies, the first line of investigation that we want to mention requires a knowledge of R&D expenditure, broken down into their various components, over long periods and preferably at the firm level. It seems indeed important to develop further the studies that attempt to take into account the wide variety of R&D activities and the different lags between these activities and their results, and that generally attempt to improve the measurement of R&D capital. The second line of investigation is the modelling of the various forms of R&D spillover between firms and sectors; this is a crucial aspect in the analysis of R&D effects, and it is necessary to pursue further and deeper the initial work that has been done in this area. The third direction of investigation is that of the analysis of the interrelations between the conception and implementation of R&D projects and their actual or anticipated outcomes (in other words the study of the endogeneity of R&D expenditures). Such analysis relate more generally to that of the simultaneity between firms research decisions and their other important decisions, notably as regards production, employment and equipment[28].

One advantage of the econometric studies which we have reviewed in this paper is that they attempt to use information and to model firm behaviour at the microeconomic level; clearly, however, they are not the only type of study capable of contributing to our knowledge of R&D issues. The major lines of research that we have just mentioned are also applicable to other types of econometric investigation, such as work which is based on aggregate data (preferably at the level of detailed classifications) or which attempts to make use of the information on innovations contained in patent data or obtained from special surveys. This is also true of studies expressed in terms of cost functions or in terms of systems of factor demand equations; there are still relatively few such studies including R&D as a factor of production, and they are not really comparable; however, they do offer scope for much refinement and are potentially fruitful.

Whatever progress we may expect to make in the future, the econometric methods do have their own limitations. They need to be supplemented and cross-fertilised by individual case studies. Well designed and rigorously executed case studies can provide detailed descriptions and in-depth knowledge of complex phenomena. Far too often, however, the proponents of statistical and econometric methods and the advocates of the case study approach do not acknowledge each others work. It is easily understandable that in many respects the collaboration between the two camps would be extremely uncomfortable; however, despite the obstacles, one would think that such collaboration would be fruitful, indeed essential, in a field such as R&D economics. Thus, to paraphrase a comment attributed to Georges Stigler, but without any ironical intent, could we say that "The plural of case study is statistics[29]"?

NOTES

1. See Griliches (1973), and also Griliches (1979), for references to the earliest studies following this approach, as well as for an analysis of their results and some of the problems that they raise.
2. Many studies based on firm data that are surveyed here have been carried out by Griliches and various co-authors, or have been written following his lead.
3. See Evenson (1989) for a summary of studies in this area.
4. See Griliches (1990a) for a review of the problems raised by the use of patent data.
5. In a recent paper partly based on our own survey, Mohnen (1990) gives an extensive review of studies of R&D and productivity using both aggregate and firm data. Mohnen also describes the few studies, mostly of recent date, framed in terms of cost functions. See also for another synthesis, the Bureau of Labor Statistics (1989) publication.
6. See Griliches (1990b) and Mohnen (1991) for an overview of results on R&D spillovers.
7. We ask our readers forgiveness for commenting at greater length on papers in which we have ourselves collaborated on and which are therefore more familiar to us.
8. The one exception is the study by Schankerman (1981) which only presents cross sectional estimates for six major industries in the United States for the year 1963. This study, however, does in fact use panel data from Griliches (1980). In Table 1 of our paper, we give only Schankerman's results for the "chemicals and petroleum" industry; his estimates for the other industries are similar.
9. On this point, see Mairesse (1988) for example.
10. Mansfield's study can be found also in Mansfield (1968b). Minasian had already used the same sample in Minasian (1962), but within an analysis in terms of the rate of return to R&D. Griliches study was performed several years before its publication.
11. Mansfield (1965) provides estimates of the rates of return to R&D separately by firms and under various assumptions, that mainly concern the orders of magnitude of the rates of disembodied and capital-embodied technical progress. These estimates vary greatly, but are on the whole compatible with the estimates (also quite variable) that are shown in Table 4.
12. There are, however, two exceptions: Schankerman (1981), who only provides cross-sectional estimates, and Griliches & Mairesse (1983) who give estimates based only on growth rates from their US and French firms samples.
13. As an extreme case, the elasticity of physical capital in Jaffe's (1986) profit equation based on growth rates is actually negative.
14. See also Mairesse (1988 and 1990) regarding the question of divergences between production function estimates in the cross-sectional and time-series dimensions.

15. It is these very assumptions that lead to the equation in terms of profits used by Jaffe (1986); such a profit equation could be added to the two "semi-reduced form equations" for output and labour. See also Siu (1984).

16. The cross-sectional R&D estimates of the system of semi-reduced form equations (which confirm the importance of R&D capital) yield results that are more satisfactory in this case too, with returns to scale closer to one. This is what can be seen from the total estimates given by the authors in their studies (but not reproduced here). This is also illustrated by the total estimate of Jaffe's (1986) profit equation given in Table 1 (specially by contrast with the estimate on rates of growth shown in Table 2).

17. In this regard see, for example, Scherer (1982).

18. In this regard, see also Pakes & Schankerman (1984), and Shankerman & Pakes (1985).

19. As a general rule, the shift from a Cobb-Douglas form with an R&D capital stock measure K to one with an R&D intensity variable (RD/Q) not only admits that the constant parameter of interest is no longer the elasticity γ, but the rate of return ρ, it also assumes that the rate of depreciation of research δ is negligible or low. If this should not prove to be the case, then the estimate of ρ may in fact be strongly biased. The variable of gross R&D intensity RD/Q replaces the true variable $(RD-\delta K)/Q$, with the result that the least squares estimate $\hat{\rho} = (1-\delta b)$, where b is the coefficient of regression of (K/Q) over RD/Q. If it is assumed that R&D expenditures grow at a constant rate g, then $b = 1/(g + \delta)$ and $\hat{\rho} = (1 - \delta/(\delta + g))$. Therefore the estimated $\hat{\rho}$ will differ only slightly from the true ρ if δ is low with respect to g; on the other hand, if g is zero, then the estimated $\hat{\rho}$ is also zero: $\hat{\rho} = 0$.

20. The reason for this is similar to the one we just mentioned. One can see also the estimates given in the annex to Griliches & Mairesse (1984), which are based on R&D capital measures calculated according to different rates of depreciation. One can make also an argument similar to that given in the preceding footnote, assuming that the deflated R&D expenditures (RD) grow at a constant rate g. If δ is the rate of depreciation used to calculate the R&D capital stock K, the latter will be equal to $RD/(g + \delta)$. If instead of being equal to δ, the rate of depreciation is φ, then the R&D capital stock must be multiplied in the proportion of $(g + \delta)/(g + \varphi)$. The marginal productivity of capital $\rho = \gamma(Q/K)$ is itself divided in the same proportion. The estimated R&D elasticity γ, however, remains unchanged (since the relative change in the R&D capital stock $\Delta K/K$ is the same for a given research effort).

21. See, for example, Griliches (1980).

22. In this regard, see Schankerman (1981) and the annex to Cuneo & Mairesse (1984), which shows that the interpretation in terms of excess return, or excess elasticity, is likely to be valid for the cross-sectional estimates on productivity levels (but it is not for the time-series estimates on productivity changes).

23. On this point, see also Griliches (1980).

24. The study by Griliches & Mairesse published in 1990 is in fact a revised version of a study that has been available since 1985 in the form of a National Bureau of Economic Research working paper.

25. Thus the estimate of a slightly positive (and not significant) rate of return to R&D by Fecher (1989) for the Belgian manufacturing industry corresponds to the two following estimates: one of +0.05 (with an estimated standard deviation of 0.04) for the scientific sectors and another of −0.16 (with an estimated standard deviation of 0.22) for the other industries.

26. As in the previous results, the estimated returns to scale are decreasing: −0.14 for Japan in the Sassenou study, and −0.08 and −0.24 for the United States and Japan in the Griliches and Mairesse one.

27. The various complementary results obtained by Sassenou (1988), confirm the fact that the problem exists, but fail to offer any real solution.
28. This analysis may also concern the entry, exit or merger decisions of the firms and may thus be linked to problems regarding the representativeness and selection of the samples used in the studies.
29. The quotation attributed to Georges Stigler is: "The plural of anecdote is data."

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