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The path of R&D efficiency over time

Pilar Beneito [a,b,*], María Engracia Rochina-Barrachina [a], Amparo Sanchis [a]

[a] University of Valencia and ERI-CES, Spain
[b] University of Valencia (Spain) and ERI-CES, Facultad de Economía, Departamento de Análisis Económico, Avda. de los Naranjos s/n, 46022 Valencia, Spain

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ABSTRACT

In this paper we investigate the pattern of R&D efficiency in terms of the number of product innovations achieved by firms over time. Using a panel dataset of Spanish manufacturing firms for the period 1990–2006, we follow the innovative performance of R&D active firms and observe that innovation rates change over firms' R&D histories. To explain these facts we propose a model that explicitly acknowledges the twofold composition of firms' R&D expenditures, comprising spending on both physical capital for R&D projects and payments to researchers. We regard this latter component of R&D as a source for dynamic returns to firms' R&D investments. Consequently firms' innovation outcomes clearly depend on how long they have been investing in R&D and also on whether there have been any interruptions in the temporal sequence of R&D activities. Our results suggest that R&D activities exhibit dynamic returns that are positive but at a decreasing rate, and that interruptions in R&D engagement reduce R&D efficiency.

1. Introduction

Measuring the returns to R&D has undoubtedly been a major issue in innovation economics since the seminal work of Griliches (1958). A primary concern has been how to measure the way in which knowledge accumulates over time. It has proved most difficult to construct acceptable measures of R&D capital stocks, which are to be later introduced into production functions or market value functions (Griliches et al., 1991), to estimate R&D returns. Empirical research about how to construct a stock measure derived from the flows of firms' R&D investments has focused on the measurement of depreciation rates of knowledge capital, still a central concern in the measurement of the returns to R&D (Hall, 2010). Griliches and subsequent researchers used a conventional declining balance formula (the perpetual inventory method) for the construction of knowledge or R&D capital, in a similar form to that used with ordinary investment and capital in production theory.

It is somewhat surprising how a close analogy between ordinary physical capital and knowledge capital has been taken as given when applying that methodology to the flow of R&D investments, when, in fact, they differ in quite fundamental aspects.[1] One of the most prominent differences is that, unlike ordinary capital investments, firms' R&D expenditures involve both the purchase of capital goods in the classical sense (machinery, equipment and so on) and spending on R&D labour. Schankerman (1981) stressed that the inclusion of spending on labour, capital and materials within R&D flows could introduce a problem of double counting in production functions (to the extent that these inputs are already included within the values of ordinary capital, labour and materials) that could bias the estimation of R&D returns. However, this diverse nature of R&D spending also implies that there are at least two different concepts of capital accumulation embodied in the R&D capital stock, one corresponding to physical capital and another one corresponding to human capital. How the efficiency of these two components evolves over time is probably very difficult to address and identify empirically. However, it seems sensible to consider that, whereas the rate of efficiency of R&D physical capital probably decays over time because of physical deterioration and obsolescence, the rate of

* Corresponding author at: University of Valencia (Spain) and *ERI-CES*, Facultad de Economía, Departamento de Análisis Económico, Avda. de los Naranjos s/n, 46022 Valencia, Spain.
E-mail address: pilar.beneito@uv.es (P. Beneito).

[1] As argued by Boulding (1966) and Pakes and Schankerman (1984), among others, the different nature of (traditional) physical capital and knowledge capital determines the definition of the rate of decay in productivity (or depreciation) corresponding to each case. They point out that the rate of decay of knowledge does not obey the laws of physical deterioration in the same way as traditional capital, and that the appropriate definition of "depreciation" in the case of knowledge capital has to do with the decay of the market valuation of the output of knowledge (i.e., the decline in the appropriable revenues from R&D).

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efficiency of R&D workers could in fact increase over time as knowledge may grow with cumulative experience. The rationale behind such an observation is well grounded in the vast literature on *learning-by-doing*, firstly developed to explain the evolution of productivity advance over the lifetime of the firm. This line of the literature starting with the pioneer empirical studies of Wright (1936) or Hirsch (1956), gave rise to the concept of "*learning curves*" or "*progress ratios*", and the theoretical contributions of Arrow (1962) or Rosen (1972), among others.

More recently, authors like Benkard (2000, 2004) and Besanko et al. (2010) have revisited the learning-by-doing hypothesis within production theory, emphasising that not only cumulative experience but also *organizational forgetting* is essential to explain the dynamics in the industry. According to these authors, the decrease in marginal costs of production arising from experience might be undone by organizational forgetting due to labour turnover, periods of inactivity or failures to institutionalize tacit knowledge. Besanko et al. (2010) argue that organizational forgetting, which has been largely ignored by the theoretical literature, may lessen the market dominance promoted by learning (Dasgupta and Stiglitz, 1988), thus equalizing differences between firms and making improvements from learning-by-doing more transitory.

The aim of this paper is to investigate whether the efficiency of firms' R&D investments in terms of product innovations depends upon the length of time firms have been undertaking R&D activities. We also explore whether periods of interruption in R&D activities may undo accumulated learning, and thus affect firms' rates of innovation. We acknowledge the twofold composition of R&D investment, embodying both physical capital and human capital, and assume that, as firms engage in R&D in a continuous way, two effects may be at work: on the one hand, R&D physical capital may follow the classical assumptions of depreciation and its corresponding replacement with new R&D spending; on the other hand, R&D investment related to human capital provides the firm with a potential source of increasing efficiency of R&D investments over time. This second effect is based on the notion that with higher R&D experience firms may become more efficient in obtaining innovations from a given level of R&D investment. This effect is probably more relevant in shaping the evolution of firms' R&D returns, and this is the main focus of this paper.

The dataset used in this paper is drawn from the *Encuesta sobre Estrategias Empresariales* (ESEE, henceforth) for 1990–2006. This is an annual survey carried out by *Fundación SEPI* (a Spanish government agency), which is representative of Spanish manufacturing firms and provides detailed information at the firm level on a broad number of issues, including innovation activities.

We specify an innovation production function augmented to include the temporal sequence of R&D investments. In particular, we assume that firms obtain product innovations from their R&D investment at a rate that depends on how long they have been investing in R&D. Firms may invest in R&D on a continual basis or they may interrupt their R&D activities for a given number of years. We explore whether the interruption in R&D, that is, periods of R&D inactivity between R&D spells, affects the rate of achievement in innovation outcomes. The underlying assumption is that acquired knowledge may depreciate during R&D interruptions. This also suggests a type of *dynamic return* that is endogenous to the firm arising from its own accumulated R&D experience. This source of improvement over time differs from that affecting the quality of R&D capital or the qualification of R&D workers available to all firms, and takes place with the passage of time *per se*.[2]

Our paper is an attempt to better characterise the knowledge production function by introducing a new source of firm heterogeneity arising from the temporal sequence of R&D investments. It is not our aim in this paper to measure the private returns to R&D within a production function or market value approach but, instead, to measure the efficiency of R&D in terms of achieved product innovations. Pakes and Shankerman (1984) emphasized that the decay of revenues accruing to industrially produced knowledge, determining the private rates of return to R&D, arises from the reduction in the market valuation of innovations rather than in the productivity of knowledge. This amounts to saying that, depending on the approach used, the relevant dynamics to consider differ: *how the market value of an innovation changes over time* is the relevant question when estimating private returns to R&D, whereas *how the efficiency of R&D in achieving innovations changes over time* is more pertinent when estimating innovation success rates.

The issue addressed in this paper has direct implications both for empirical and for theoretical research in R&D economics. First, it concerns the analysis of the depreciation of R&D capital. Since the depreciation rate of an asset depends on its path of efficiency over time, if the efficiency of R&D investments differs among firms with different R&D sequences, then a common depreciation rate across firms does not exist.[3] The idea that a constant depreciation rate across firms may not be a reasonable assumption when constructing R&D stocks has been recently stressed by authors such as Hall (2010). Second, it has also implications for measuring the private rate of return to investment in research. In the model of Pakes and Schankerman (1984), for instance, the private return on each dollar of research depends negatively on the mean *gestation lag*, defined as "*the average time between the outlay of an R&D dollar and the beginning of the associated revenue stream*" (pp. 82). If firms accumulate experience managing R&D projects as time goes on, one should expect a reduction in these gestation lags and a corresponding rise in the private returns to R&D.

Another implication of firms' R&D efficiency changing over time is related to the optimum path of accumulation of R&D capital. Rosen (1972), for instance, in his theoretical model of learning by experience in production, established that the marginal cost of knowledge is its discounted future marginal product, adjusted for the fact that greater knowledge reduces future learning costs. If this kind of dynamic internal economies also exists in the production of innovations, then the optimality of any additional R&D effort has to be evaluated in terms of its contribution to current innovations as well as to the capacity of innovating more and better in the future. Conversely, the losses from interrupting R&D activity exceed the innovations that could have been achieved during the interruption, and include, also, the losses derived from a lower probability to innovate in the future.

To anticipate our results, we obtain that the number of years of R&D engagement has a positive effect on expected innovation outcomes, that is, R&D investments exhibit dynamic returns due to a process of learning taking place with the passage of time. These dynamic returns are positive but decreasing over time, possibly because of exhaustion of innovation opportunities. In addition, we find that interruptions of R&D activities may reduce R&D efficiency, probably due to an organizational forgetting effect. However, we also observe spillover effects between firms' R&D spells since, if the interruption of R&D activity is relatively short, firms resuming R&D activities seem to achieve innovation rates that exceed those of their initial years of R&D activities. Thus, our findings provide evidence in support of both learning and organizational forgetting effects in R&D engagement.

The rest of the paper is organized as follows. Section 2 reports the data and some descriptive statistics and presents some empirical evidence on the time evolution of R&D efficiency over time. In Section 3 we present a model that is consistent with our theoretical considerations and accommodates the descriptive facts observed in our data. In Section 4 the empirical implications of the model are tested using econometric techniques and, finally, Section 5 concludes.

[2] To give an example, although two firms investing today in R&D may have access to higher quality R&D capital or better-qualified R&D workers than twenty years ago, the firm with a longer R&D history is likely to achieve higher rates of innovation success from its current investment.

[3] See Hulten and Wykoff (1996) for a discussion on the correspondence between different efficiency functions and the resulting paths of depreciation of an asset.