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Abstract. Semi-endogenous models and, to some extent, also Schumpeterian models are based on the assumption of diminishing returns to R&D. This paper shows that the null hypothesis of constant returns to R&D cannot be rejected for the OECD countries.

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Key words: Returns to R&D, endogenous growth theory.

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1 Introduction

Semi-endogenous models of economic growth have been motivated by graphical evidence of a decline in R&D productivity in the USA (Kortum, 1993, Griliches, 1990, 1994, and Manchlup, 1962) and in the UK, Germany and France over the period 1970-1990 (Everson, 1993). Schumpeterian theories of endogenous growth have, to some extent, also been motivated by diminishing returns to R&D by assuming that innovations are spread over a larger variety of products and, therefore, that there is a tendency for decreasing returns to R&D (Aghion and Howitt, 1998, Ha and Howitt, 2005).

One may, however, question the general validity of diminishing returns to R&D because R&D productivity has picked up in the OECD countries since the mid 1980s and some industrialised countries have even experienced increasing returns to R&D over the whole period for which data are available. Using new historical data sets, this paper shows that the null hypothesis of constant returns to R&D cannot be rejected.

2 Returns to R&D in endogenous growth models

Consider the homogenous Cobb-Douglas production function:

$$Y = AK^{\alpha}L^{1-\alpha}$$

where Y is output, A is knowledge, K is capital and L is labour. The growth in knowledge is governed by the following function:

$$g_A = \frac{\dot{A}}{A} = \lambda \left(\frac{X}{Q} \right)^{\sigma} A^{\phi-1}, \qquad 0 < \phi \leq 1,\ \lambda > 0 \qquad (1)$$

$$Q \propto L^{\beta} \text{ in steady state,}$$

where Q is product variety and $X = R\&D \cdot A^{\gamma}$, where γ is a fixed parameter which takes the value of 0 in semi-endogenous models and -1 in Schumpeterian models. The productivity adjustment of R&D in Schumpeterian models allows for the possibility that innovations are increasing in complexity (Aghion and Howitt, 1998, Ha and Howitt, 2005). Product variety, Q, is usually measured by employment or population, as each worker is assumed to have the same propensity to imitate (Aghion and Howitt, 1998). The first generation endogenous growth theories predict $\phi = 1$

and $\beta = 0$, Schumpeterian models predict $\phi = 1$ and $\beta = 1$, while semi-endogenous growth models predict $\phi < 1$ and $\beta = 0$.

The Schumpeterian models by Aghion and Howitt (1998), Dinopoulos and Thompson (1998), Howitt (1999), and Peretto (1998) maintain the assumption from the first generation endogenous growth models of constant returns to knowledge, $\phi = 1$, however, the output-effects of knowledge are diluted by dividing R&D by *A*. In the semi-endogenous models by Jones (1995), Kortum (1997), and Segerstrom (1998) an increasing growth in R&D inputs is required to maintain a sustained TFP growth due to the assumption of diminishing returns to knowledge.

The returns to R&D in the second generation models of endogenous growth are as follows. Setting σ = 1 (1) can be written as:[2]

$$\frac{\dot{A}}{R\,\&\,D} = \lambda L^{-\beta} A^{\phi+\gamma}. \qquad (2)$$

Schumpeterian theory assumes that $\phi + \gamma = 1 - 1 = 0$ and $\beta = 1$, which implies that the $\dot{A}$/R&D decreases over time as the variety of goods, measured by *L*, increases. In other words R&D has to increase over time to maintain a constant TFP growth because R&D is spread over an increasing range of products. Semi-endogenous theory assumes that $0 < \phi + \gamma = \phi < 1$ and $\beta = 0$, which implies that $\dot{A}$/R&D decreases over time because of diminishing returns to R&D.

3 Data and measurement issues

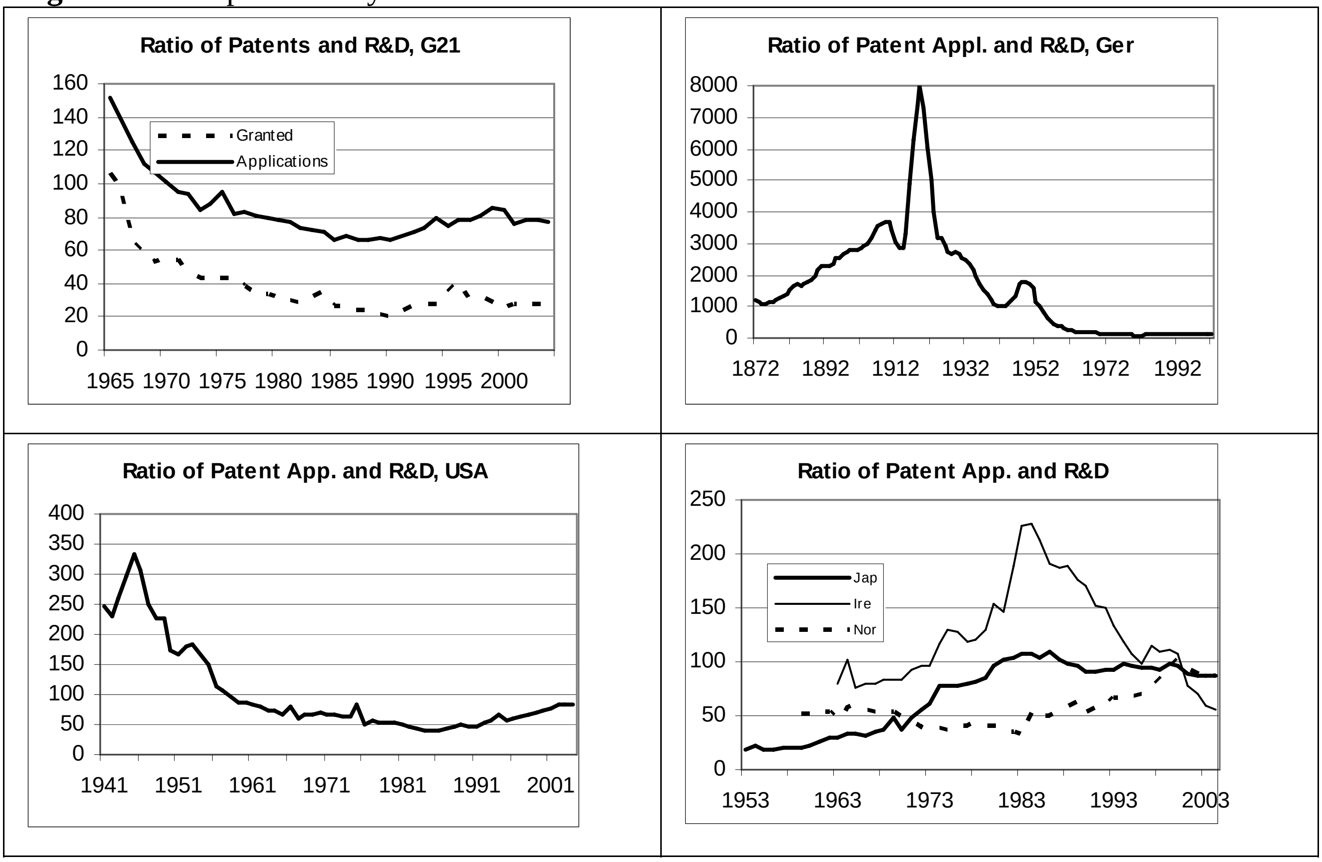
The ratio $\dot{A}$/R&D is measured as the ratio of patents and total real R&D expenditures. The data cover the following 21 OECD countries (henceforth G21) over the period 1965-2004: Canada, the US, Japan, Australia, New Zealand, Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the UK. The data go back further for the following countries, where the numbers in parentheses indicate starting year: USA (1941), Japan (1953), Germany (1870), and the Netherlands (1959). The German pre-1948 R&D data are constructed from publicly financed R&D data and multiplied by a constant to match up to the total R&D data in 1948. The omission of R&D funded by industry before 1948 is unlikely to bias the data significantly. In 1948 industry funded R&D was 17% of total R&D in Germany and the fraction has increased significantly since then, indicating that

[2] The parameter σ is usually restricted to one in empirical applications. See for instance Zachariadis (2004).

industry financed R&D was probably relatively low back in history. R&D is deflated by an unweighted average of the GDP deflator and hourly labour costs following Griliches (1984). The data sources are detailed in the data appendix.

The research output is measured as patents applied for by domestic residents. Patents granted are less useful than patent applications for international comparisons because the granting frequency varies substantially across countries (Griliches, 1990). Patents granted are only used for illustration in the graph for the G21 countries below. Patents applied for abroad by residents are excluded from the data because they are predominantly duplicates of domestic patent applications (OECD, 2003). Patents are usually first applied for domestically and if the patent is granted, the patentee files one or several patent applications abroad (OECD, 2003). The same patentable item is, consequently, counted multiple times if foreign patents are added to domestic patents.

Figure 1. R&D productivity.



Notes: Weighted average of the G21 countries, where the weights are GDP at purchasing power parities (PPP). R&D is measured as USD R&D expenditure in PPP units. A 5-year centred moving average is taken for Germany.

The top left-hand-side of Figure 1 shows that the ratio of patents applied for and R&D for the G21 countries declined substantially during the period 1965-1985 and has since increased to reach a level in 2004 that prevailed in the second half of the 1970s. The ratio of patents granted and R&D for the G21 countries shows the same path (top left). The US R&D productivity was decreasing in the period 1941 to 1988 and has been increasing since then and in 2004 is on the level that prevailed in the early 1960s, which suggests constant returns to R&D in the US in the period 1960-2004.

The time-profile of the German R&D productivity in the top right-hand-side of Figure 1 is instructive. It increased over the period 1870-1921, declined from 1921 to the mid 1960s, from which period it fluctuates around a relatively constant level. From this time-profile it appears that R&D productivity swings over time on low frequencies and that there is no clear sign of diminishing returns to R&D in the long run, particularly if it is taken into account that informal or unrecorded R&D activity has been diminishing over time. Schmookler (1957) finds that most of the innovative activity back in time in the USA was an informal activity undertaken by individuals and, as such, was not accounted for as R&D expenditures in the statistics, and that the fraction of inventions by individuals has been diminishing over time. Therefore, the declining R&D productivity over the very long run for Germany is probably aggravated.

This path for Germany is consistent with the time-series evidence by Machlup's (1962) in the period 1870-1950 for the USA, and consistent with Griliches' (1994) finding of declining R&D productivity in the period 1920-1990 in the USA. Note, however, that the definition of R&D workers in Manchup's (1962) data, which are based on Schmookler's (1954) data, is non-standard. Schmookler's definition of technological workers includes, among several other professions, managers, bricklayers, plumbers, blacksmiths, designers, painters, builders, tailors, and photographers. These professions would not be considered as R&D workers in the definitions used by the OECD and UNESCO.

The last of the figures (bottom right-hand-side) shows R&D productivity for countries that have not followed the inverted hump shape of the other G21 countries. Japanese R&D productivity increased during the period 1953-1985 and has since stabilised at a constant level. Norwegian R&D productivity has remained almost constant over the period 1965-1990, after which it has doubled. Finally, R&D productivity has been hump shaped in Ireland and is today almost at the same level as in 1965. Overall the figures suggest that R&D productivity shows low-frequency movements and that there is no clear evidence of decreasing or increasing returns to R&D.

4 Empirical tests

As shown in Section 2 the two second-generation models imply that $\dot{A}$/R&D decreases over time. This section tests the hypothesis that $\dot{A}$/R&D is stationary and, therefore, unrelated to Q and A. Denoting patents by Pat, yields the following equation defined under the hypothesis of stationarity:

$$\frac{Pat}{R\&D} = \varepsilon_t , \qquad (3)$$

where ε is an error term that is stationary under the hypotheses of the absence of diminishing returns to R&D or that R&D is spread over a larger variety of goods. Comparing of (2) and (3) it follows that ε is only stationary if $\phi + \gamma = \beta = 0$.

Table 1. Tests for unit roots.

Philips-Peron test.				Augmented Dickey Fuller			
Can	-43.2	Itl	-22.3	Can	-3.58	Itl	-10.06
USA	-55.2	Net	-33.6	USA	-3.32	Net	-3.24
Jap	-32.6	Nor	-44.7	Jap	-2.40	Nor	-2.89
Aus	-44.3	Por	-24.4	Aus	-2.02	Por	-4.01
NZ	-50.4	Spa	-42.2	NZ	-2.63	Spa	-6.70
Aut	-30.0	Swe	-21.1	Aut	-3.18	Swe	-3.97
Bel	-21.7	Swz	-20.1	Bel	-20.16	Swz	-2.01
Den	-24.6	UK	-49.2	Den	-4.93	UK	-4.94
Fin	-39.4	USA (1941)	-51.2	Fin	-4.51	USA (1941)	-5.14
Fra	-42.8	Jap (1953)	-42.6	Fra	-2.86	Jap (1953)	-2.83
Ger	-32.9	Ger (1870)	-114.6	Ger	-7.40	Ger (1870)	-3.43
Gre	-50.2	Net (1959)	-42.1	Gre	-3.07	Net (1959)	-13.55
Ire	-32.4			Ire	-3.08		

Notes. Estimated over the period 1966-2004 except for the countries where the dates in the parentheses indicate the starting year, and where the end year is 2004. Philips-Peron test: The critical values are -14.1 at the 5% level and -20.6 are the 1% level. The Newey-West method is used to remove the serial correlation from the residuals and the length of the truncation lag is the order of the highest significant lag order from the autocorrelation function. ADF: A constant but no trend is included in the tests. The critical values are -2.86 at the 5% level and -3.43 are the 1% level

Table 1 reports the Phillips-Perron (Phillips, 1987, and Perron, 1988) and ADF tests for unit roots for the individual countries over the period 1966-2004 or longer for the countries for which data are available before 1965 (starting year is indicated in the parentheses). The Philips-Peron tests reject the null hypothesis of unit root for all countries at conventional significance levels and the ADF tests reject the null hypothesis of unit root for almost all countries except for four countries at the 5% significance level. To increase the power of the unit root tests the panel unit root test suggested by Pesaran (2006), which is denoted CIPS test, is used to test whether Pat/R&D is stationary. The test belongs to the family of second-generation panel unit root tests where cross-sectional dependence and serial correlation in the residuals are allowed for. The CIPS test takes the value of -3.11, with a critical value of -2.38 at the 1 percent level, which suggests that the null hypothesis that Pat/R&D contains a unit root is strongly rejected for the panel. Overall, the tests indicate that the null hypothesis of non-constant returns to R&D is easily rejected.

5 Concluding remarks

The empirical results of the paper show that the hypothesis of constant returns to R&D cannot be rejected for 21 industrialised countries and, therefore, challenge the conventional wisdom of diminishing returns to R&D or that R&D is diluted due to an increasing variety of products as the economy grows. The statistical results were supported by graphical evidence which showed that diminishing returns to R&D have been limited to some countries and certain periods in history, particularly the 1960s. The results imply that the assumptions underlying Semi-endogenous growth theories cannot be maintained and that Schumpeterian theories have to relax the assumption that R&D is spread over an increasing range of goods as the economy is growing to be consistent with the empirical evidence.

DATA APPENDIX

Patents. World Intellectual Property Organisation. **R&D.** OECD, *Main Science and Technology Indicators*, OECD, Paris, OECD Archive (OECD-DSTI/EAS), National Science Foundation, Statistics Netherlands, and UN Statistical Yearbook. Japan. Historical Statistics of Japan, Statistics Bureau and Statistical Research and Training Institute, Ministry of Internal Affairs and Communication. USA. 1941-52: Machlup (1962). Germany. 1870-1948: Frank R. Pfetsch, 1985, Datenhandbuch zur Wissenschaftsentwicklung, Koln: Zentrum fur Historische Socialforschung. 1948-1965: Wissenschaftsausgaben der Wirtschaft 1964, Beitrag des Stifterverbandes zum internationalen Statischen Jahr, 1967. **GDP deflator**. Nominal GDP divided by real GDP, OECD, *National Accounts Vol. 2* (*NA*). **Wages**. Compensation to employees divided by economy-wide employment, (*NA*).

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