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SEMI-ENDOGENOUS VERSUS SCHUMPETERIAN GROWTH MODELS: TESTING THE KNOWLEDGE PRODUCTION FUNCTION USING INTERNATIONAL DATA[1]

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Abstract. Using various indicators of innovative activity and product variety in the OECD countries over the past century, this paper tests whether first- and second-generation models of economic growth are consistent with the data over time and across countries. The estimation results give evidence in favour of Schumpeterian models while the semi-endogenous growth theories are not consistent with the data.

JEL Classification: O3, O4
Key words: Schumpeterian growth theory, semi-endogenous growth theory

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1 Introduction

Second-generation endogenous growth models, such as semi-endogenous growth theories and Schumpeterian growth theory, have been used to try to resolve the empirical problems that are associated with first-generation models of economic growth, following Jones' (1995) finding that first-generation endogenous models are inconsistent with empirical evidence for the US. Whereas semi-endogenous growth models relax the assumption of constant returns to knowledge, the Schumpeterian growth theory maintains the assumption from first-generation models of constant returns to knowledge, but assumes that the complexity of new innovations is increasing.

In the semi-endogenous growth models developed by Jones (1995), Kortum (1997), and Segerstrom (1998), a positive growth in R&D inputs is required to maintain sustained growth in total factor productivity (TFP) due to the assumption of diminishing returns to knowledge. The Schumpeterian growth models of Aghion and Howitt (1998), Dinopoulos and Thompson (1998), Howitt (1999), Peretto (1998), and Young (1998) assume that R&D spreads more thinly across product varieties as the economy grows. To ensure sustained TFP growth, R&D has to increase over time to counteract the increasing range of products that lowers the productivity effects of R&D activity.

Several empirical papers have established that the level of TFP is influenced by the R&D *stock* in the OECD countries (Coe and Helpman, 1995, Guellec and de la Potterie, 2004, Del Barrio-Castro *et al*., 2002, Keller, 2002, Lichtenberg and de la Potterie, 1998, Engelbrecht, 1997, Jaffe, 1986, and Park, 1995). However, only a few studies have examined whether second-generation endogenous growth theories can account for the relationship between R&D *expenditure* and TFP. Zachariadis (2004) examines the relationship between TFP growth and the share of R&D expenditure in total income for 10 OECD countries over the period 1971-1995 and finds support for the Schumpeterian hypothesis. Using sectoral data for the US, Zachariadis (2003) finds support for Schumpeterian growth models.

Ha and Howitt (2007) provide probably the first empirical attempt to discriminate between the predictions of the Schumpeterian and the semi-endogenous growth theories. Using aggregate R&D data for the US during the period 1953-2000, they find strong support for the Schumpeterian growth theory, but fail to find empirical support for semi-endogenous growth models, because the growth in R&D inputs has declined significantly since 1953, while TFP growth during the same period has not displayed any downward trend. A problem associated with the studies of Zachariadis (2003, 2004) and Ha and Howitt (2007) is that TFP growth and research intensity have been quite stable over the periods studied and the cross-country variation in the data has not been exploited, thus providing little identifying variation in the data.[4] Furthermore, to the best of my knowledge, studies have not tested whether the second-generation models can account for cross-country variation in the data.

This paper examines whether the second-generation endogenous growth models can explain TFP growth across countries and over time using long historical data and using various indicators of innovative activity and product variety for the OECD countries, while allowing for international technology spillovers in the estimates. Second, in addition to number of employed and income, the stock of trademarks is used as a direct measure of product variety in the tests of Schumpeterian growth models. A key element in Schumpeterian growth theory is the assumption that TFP growth follows the ratio of R&D and product variety, where employment, population, and income are usually used as proxies for the number of products (Ha and Howitt, 2007, Krugman, 1989). Third, patents are used as complements to R&D as indicators of the innovative activity. Patents give the advantage of allowing the estimates to cover the period 1900-2004 for a panel of countries. Fourth, it is tested whether TFP growth is enhanced by the distance to the technological frontier as predicted by Schumpeterian growth theories. In the Schumpeterian models of Howitt (2000), Griffith *et al*. (2003, 2004), and Aghion and Howitt (2006) it is shown that a country at the technology frontier makes incremental improvement of existing leading edge technology while countries behind the technology frontier implements technologies that have been developed elsewhere.

The rest of the paper is organised as follows. Section 2 gives a brief overview of the empirical implications of second-generation models. Section 3 provides a detailed account of data and measurement issues, and Section 4 gives a graphical illustration of the data and discusses whether the models are consistent with the empirical evidence. Empirical testing is undertaken in Sections 5, 6 and 7 and Section 8 concludes the paper.

2 Tests of endogenous growth models

This section outlines the empirical predictions of second-generation models of economic growth.

Consider the homogenous Cobb-Douglas production function:

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

[4] Although Zachariadis (2004) pools the data, he includes fixed-effect dummies, which wipe out any influence of cross-country variation on the parameter estimates.

where Y is output, A is knowledge, K is capital, and L is labour. The growth in knowledge, g_A, is governed by the following function (Ha and Howitt, 2007):

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

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

where Q is product variety, ϕ is returns to scale in knowledge, σ is a duplication parameter, which is zero if all innovations are duplications and 1 if there are no duplicating innovations, β is the coefficient of product proliferation, λ is a research productivity parameter, L is employment or population and X is R&D inputs (semi-endogenous growth models) or the productivity adjusted R&D (Schumpeterian growth models), R&D/A, where the productivity adjustment recognises that innovations are increasing in complexity and, therefore, that there is a tendency for decreasing returns to R&D (Ha and Howitt, 2007). 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, p 408). The ratio between X and Q, henceforth, will be referred to as research intensity. The first-generation endogenous growth theories predict that $\phi = 1$ and $\beta = 0$, Schumpeterian growth models predict that $\phi = 1$ and $\beta = 1$, and semi-endogenous growth models predict that $\phi < 1$ and $\beta = 0$.

Assuming that shocks, e_t, are identically and normally distributed with a mean of zero then Eq. (1) forms the following error-correction model:

$$\ln\left(\frac{\dot{A}_t}{A_t} \right) = \ln \lambda + \sigma \left[\ln X_t - \ln Q_t + \left(\frac{\phi - 1}{\sigma} \right) \ln A_t \right] + e_{1,t}. \tag{2}$$

Under the assumption that $\dot{A}_t / A_t$ is stationary, as found by Ha and Howitt (2007), Zachariadis, (2003), the square bracket term needs to form a cointegrating relationship between the log of A, X and Q. Thus, the second generation endogenous growth theories imply that the terms υ_t and ς_t are stationary:

$$\upsilon_t = \ln X_t + \left(\frac{\phi - 1}{\sigma} \right) \ln A_t \qquad \text{Semi-endogenous growth theory} \tag{3}$$

$$\varsigma_t = \ln X_t - \ln Q_t. \qquad \text{Schumpeterian growth theory} \tag{4}$$

The following cointegration model nests both models:

$$\ln X_t = \mu \ln Q_t + \kappa \ln A_t + e_{2,t}, \tag{5}$$

where $\kappa = (1-\phi)/\sigma$. Schumpeterian theory hypothesises κ = 0 and μ = 1, whereas κ > 0 and μ = 0 under semi-endogenous growth theory and $e_{2,t}$ is a stationary error term. Cointegration estimates of Eq. (3)-(5) have been used by Ha and Howitt (2007) to discriminate between the two theories. Eq. (4) has been estimated by Zachariadis (2003, 2004).

Although cointegration tests of (3)-(5) can satisfy one of, or a combination of, the two growth models, they need not imply that TFP growth is explained by either of the models. Following Eq. (1), the log-linear combinations of the variables *A*, *X*, and *Q* need to explain TFP growth. Thus, cointegration between the variables *A*, *X*, and *Q* is a necessary but not a sufficient condition for either of the models to provide adequate explanations for growth and, for that reason, cannot stand alone as tests of endogenous growth models. Furthermore, the influence on TFP growth of the distance to the technological frontier cannot naturally be tested within a cointegration framework.

The following model of TFP growth complements the cointegration estimates to test whether the predictions of second-generation models are consistent with the data:

$$\Delta \ln A_t = \tau\left(\frac{X_t}{Q_t}\right) + \left(\frac{\sigma}{1-\phi}\right)\Delta \ln X_t + \xi\left(\frac{A_{t-1}^{\max} - A_{t-1}}{A_{t-1}^{\max}}\right) + e_{3,t} \tag{6}$$

where $A^{\max}$ is the leading edge technology and is measured as the highest TFP each year among the countries included in the estimates in this paper. Eq. (6) nests the Schumpeterian theory (from Eq. (1)) extended to allow for gravitation of TFP towards the leading edge technology, and Semi-endogenous theory (from Eq. (3)). Schumpeterian growth theory assumes that $\tau > 0$ and $\xi > 0$ while $\tau = 0$ and $\sigma/(1-\phi) > 0$ is assumed under semi-endogenous growth theory. Zachariadis (2004) estimates Eq. (6), with the second and the third right-hand-side terms restricted to zero, for 10 OECD countries.

The last term in Eq. (6) follows the prediction of the models of Howitt (2000) and Griffith *et al*. (2003, 2004) and the discussion by Aghion and Howitt (2006) in which countries that are behind the technology frontier implement technologies that have been developed elsewhere by actively undertaking R&D. Any country that actively engages in R&D will benefit from technologies that are developed elsewhere and will converge towards the technological frontier. According to Griffith *et al*. (2003) the parameter ξ depends on institutions, government policy, the level of human capital, and openness to trade, among other variables.[5] In the model of Howitt (2000) the last term in Eq. (6) is multiplied by (X/Q) and in the model of Griffith *et al*. (2003) both the last term and the last term multiplied by by (X/Q) explain TFP growth. Due to strong collinearity between the terms $(X/Q)(A^{max} - A)/A^{max}$ and (X/Q) and $(A^{max} - A)/A^{max}$, the inclusion of the term $(X/Q)(A^{max} - A)/A^{ma}$ is considered in the estimates in Section 6.

As the models stand they still leave unanswered the question of how to deal with international technology spillovers. In principle international spillovers should enter the models in the same way as domestic innovative activity does, however, the channel of transmission is less clear-cut. In the endogenous models described in Segerstrom *et al.* (1990) and Grossman and Helpman (1991), the quality of intermediate products imported from abroad positively influences the efficiency of production. The new technology embodied in intermediate products renders them more productive and, consequently, increases the range of products produced and the production efficiency of the host company. This line of reasoning suggests that international technology spill over through the channel of imports.[6] Tests of second-generation models have probably not incorporated import-weighted spillover because its construction is highly time-consuming and requires data that are not readily accessible. Ha and Howitt (2007) and Jones (2002) use the sum of R&D workers in the G5 countries, backward extrapolated in the period 1953-1965. This paper measures international spillovers using import-weighted innovative input, as detailed in the next section. Furthermore, a distance-weighted spillover variable and the international technology spillovers that are independent of trade and distance are considered in Section 6.

3 Data and measurement issues

Data for TFP, X, and product varieties are needed to estimate Eq. (5) and Eq. (6). The data included here are from the following 21 OECD countries (henceforth G21): Canada, the US, Japan, Australia, New Zealand, Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland,

[5] The estimated coefficient of $(A^{max} - A)/A^{max}$, was made conditional on the educational achievement among the labour force, openness and other institutional factors. However, the parameter ξ is assumed to fixed in the empirical estimates below since the parameter estimates of the model, and the significance of the coefficient of and $(A^{max} - A)/A^{max}$, were almost unaffected by allowing the conditioning of ξ.

[6] Following the paper of Coe and Helpman (1995), several papers have established that total factor productivity is significantly, positively related to import weighted R&D *stock* among trade partners (see, for example, Engelbrecht, 1997, Lichtenberg and de la Potterie, 1998, Del Barrio-Castro, 2002, Madsen, 2007, and Madsen, 2008).

Italy, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and the UK. The data sources are detailed in the data appendix. The innovative activity is measured by patents and R&D. The patent data cover the period from 1898 to 2004 and the R&D data cover the period 1965 to 2004 for all countries and go further back for a few of the countries. The data are constructed as follows.

TFP. The TFP data are estimated under the homogeneous Cobb-Douglas technology assumption:

$$A_{it} = Y_{it}/(L_{it}^{\alpha} K_{it}^{1-\alpha}),$$

where α_i is the unweighted average of labour's income share for country *i* and the US, following Wolf (1991). Capital and GDP are measured in purchasing power parity units. Labour's income share is calculated as the economy-wide compensation to employees divided by nominal GDP, where labour's compensation is corrected for imputed payments to the self-employed and the data are calculated as far back in history as income share data are available. This imputation is essential since earnings from self-employment in national accounts are counted as profits, although they should be counted as labour income. To correct for this bias, the average earning per employee, multiplied by the number of self-employed, is added to the compensation to employees. Labour inputs are measured as annual hours worked multiplied by economy-wide employment as opposed to population, to take into account the fact that the labour force participation rate and annual hours worked have changed substantially over time.

R&D and patents. R&D is measured as economy-wide R&D in purchasing power parity units relative to the US. The R&D data are available for the G21 in the period 1965-2004. The R&D data go back further for the following countries, where the numbers in parentheses indicate starting years: US (1920), Japan (1953), Australia (1940), Germany (1870), and Spain (1870). The early R&D data and are constructed from publicly financed R&D data and matched up with the total R&D data for the following countries: Australia (1965), Germany (1948), and Spain (1964), where the numbers in parentheses indicate the years at which industry financed R&D data become available. The omission of R&D expenditures funded by industry in the early data for these countries is unlikely to bias the data significantly. For Germany in 1948, for instance, industry funded R&D was 17% of total R&D and the proportion has increased since then, indicating that the proportion of industry financed R&D in total R&D may have been increasing over time.

Patents are measured as patents applied for or patents granted to residents. Patents applied for by foreign residents are not included in the patent data because they are usually duplicates of domestic patent applications and, furthermore, applications are usually made for the same patent in several countries (OECD, 2003). R&D expenditures are deflated by an unweighted average of average hourly labour costs and the GDP-deflator following the recommendation of Griliches (1984). An alternative R&D deflator is considered in Section 6.

In tests of the Schumpeterian growth theories, X is usually measured as R&D/A, where R&D is divided by A to allow for diminishing returns to R&D, following the evidence reported by Kortum (1993), amongst others, of a declining ratio of patents and R&D for the US (Ha and Howitt, 2007). Patents overcome the scaling problems by directly measuring the innovative output and the benefits from distinguishing between patents filed by residents and non-residents, which enables one to distinguish between ideas that are outcomes of domestic and foreign R&D activity, respectively.

An additional advantage of using patents as opposed to R&D, as indicators of innovative activity, is that informal R&D is patented. Bound *et al*. (1984) find that small firms patent proportionally more than large firms despite large firms having a disproportionally higher share of R&D, which suggests that patents are more inclusive measures of the innovative activity than R&D expenditure. However, when more than 100 years of data are considered, it is important that the patent counts are comparable over time, i.e. that the propensity to patent and the average value of patents are constant. Unfortunately, there is not much research done in this area. Mansfield (1986) finds little change in the propensity to patent patentable innovations over time in the US. However, Pakes and Griliches (1980) argue that patents are flawed measures of the innovation activity and that the impact of patents varies substantially across patents. Based on their empirical estimates Pakes and Griliches (1980) argue that the relationship between patents and research activity across firms is strong but less so over time. The problem associated with measuring the innovative activity by patents is that not all innovations are patented. Furthermore, Griliches (1990) finds indirect evidence of increasing costs of patenting over time. Finally, Coballero and Jaffe (1993) find that the average value of patents, measured by patent citations, has been changing over time. Therefore, the propensity to patent and the average value of patents may have changed over time. To check the robustness of the results that are based on historical data the slope coefficients are allowed to vary over time and estimates using long historical R&D data for four countries are undertaken in Section 6.

Product varieties. Product variety in Schumpeterian growth models are usually measured by employment (Aghion and Howitt, 1998, Chapter 12, Ha and Howitt, 2007), whereas Krugman (1989) uses GDP as a measure of product variety in the context of international trade. This paper uses the stock of trademarks, GDP, and employment as measures of product variety. The stock of trademarks is probably a better measure of the range of products than income and labour inputs. The stock of trademarks is a particularly good measure of product variety if the number of products produced under the same trade mark is relatively constant over time. Trademarks are converted to the stock of product variety based on the perpetual inventory method using a 20% depreciation rate following the practice of tax departments.

The biggest potential problem associated with the use of trademarks as a measure of product variety is that not all new products are registered as trademarks and that not all trademarks represent genuinely new products. In any event, Gao and Hitt (2004) argues that trademarks represent non-trivial product differentiation. Based on estimates using a large panel of US firms, Gao and Hitt (2004) find that trademarks contain information about product differentiation that is not included in other measures of product variety. These findings suggest that trademarks are adequate measures of product varieties.

Research intensity. The following normalisations of R&D and patents are used as measures of research intensity:

$$\left(\frac{X}{Q}\right)_A = \frac{R\&D}{Y}, \quad (7a) \qquad \left(\frac{X}{Q}\right)_B = \frac{R\&D}{A \cdot L}, \quad (7b)$$

$$\left(\frac{X}{Q}\right)_C = \frac{R\&D}{A \cdot S^{TM}}, \quad (7c) \qquad \left(\frac{X}{Q}\right)_D = \frac{Pat}{L}, \quad (7d)$$

$$\left(\frac{X}{Q}\right)_E = \frac{Pat}{S^{TM}}, \quad (7e)$$

where Pat is the number of domestic patent applications, L is economy-wide employment, S^{TM} is the stock of new trademarks, and R&D is total real R&D. The normalisation given by (7a) follows Zachariadis (2003, 2004) and Ha and Howitt (2007), and the normalization given by (7b) follows Ha and Howitt (2007). R&D is divided by A in (7b) and (7c) to allow for the increasing complexity that is associated with the production of new innovations. The two last measures of research intensity are not divided by TFP because patents are measured as research output.

International technology spillovers. Spillovers through the channel of imports of intermediate products that contain new technology from country *j* to country *i* are computed from the following weighting scheme:

$$\left(\frac{X}{Q}\right)_{it}^{f} = \sum_{j=1}^{21} \frac{m_{ijt}}{m_{it}} \left(\frac{X}{Q}\right)_{jt}^{d}, \qquad i \neq j \qquad \text{Schumpeterian growth theory}$$

$$X_{it}^{f} = \sum_{j=1}^{21} \frac{m_{ijt}}{m_{it}} \tilde{X}_{jt}^{d}, \qquad i \neq j \qquad \text{Semi-endogenous growth theory}$$

where m_{ij} is country *i*'s imports of high technological products from country *j*, m_i is country *i*'s total import of high technological products, the superscripts *d* and *f* stand for domestic and foreign, and $\tilde{X}_j$ is an index of innovative activity, which is equal to one in 1995 for each individual country to ensure that large countries do not have a higher weight in the index than smaller countries. In other words, $100 of imports of high-tech products have the same impact on domestic productivity regardless of whether they are imported from the US or from Denmark. The following SITC classifications for high technological products are used before WWII: Chemicals and related products (SITC Section 5), machinery and transport equipment (SITC Section 7), and professional and scientific instruments (SITC Section 8.7). Total bilateral trade is used before WWII since bilateral trade on various classifications are not available. An advantage of using high technological products, in addition to the fact that technology is transmitted through trade in technological products, is that they are much more representative of intermediate products, which, according to the Coe and Helpman (1995) hypothesis, are the transmitters of technology.

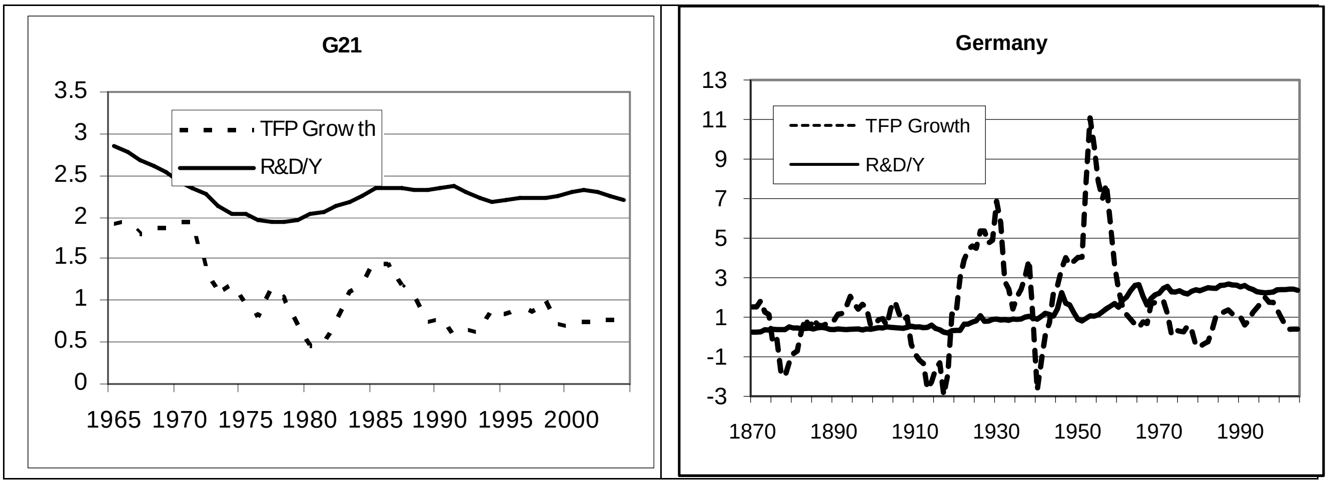
4 Are the theories consistent with the data?

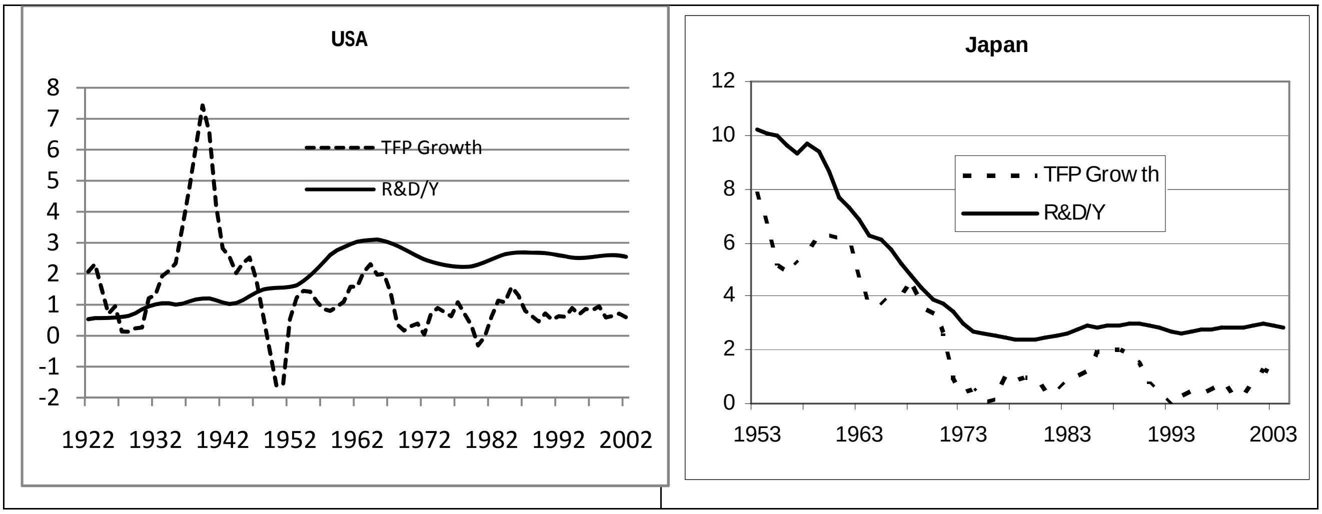
This section presents informal evidence of whether the predictions of the theories are consistent with the data.

4.1 Schumpeterian growth theory

The Schumpeterian growth theory predicts that TFP growth varies proportionally with research intensity, X/Q. Figure 1 displays the ratio of R&D and GDP and TFP growth rates for the G21, Germany, Japan, and the US, noting that different deflators are used for R&D and GDP as discussed in the previous section. For the G21 countries, the TFP growth and research intensity have both been relatively constant over the period 1965 to 2004, which is consistent with the predictions of Schumpeterian growth models. Considering earlier periods, there is no clear positive relationship between research intensity and TFP growth. Germany had half the R&D intensity in the period 1870-1960 compared to the post-1960 period, while TFP growth was at least as high before 1960 as it was after. R&D intensity was significantly lower in the US before 1953 than after, while TFP growth, on average, was higher before 1953 than after. The pronounced cycle in TFP growth in the 1930s and 1940s in the US renders it difficult to distinguish the trend from the cycle and may have blurred the relationship between TFP growth and research intensity. Japan experienced both exceptionally high TFP growth and high research intensity in the period 1953-1973, which is consistent with the predictions of Schumpeterian growth theory. Overall, the time-series evidence is largely, but not entirely, consistent with Schumpeterian growth theory.

Figure 1. The ratio of R&D and income and TFP growth.

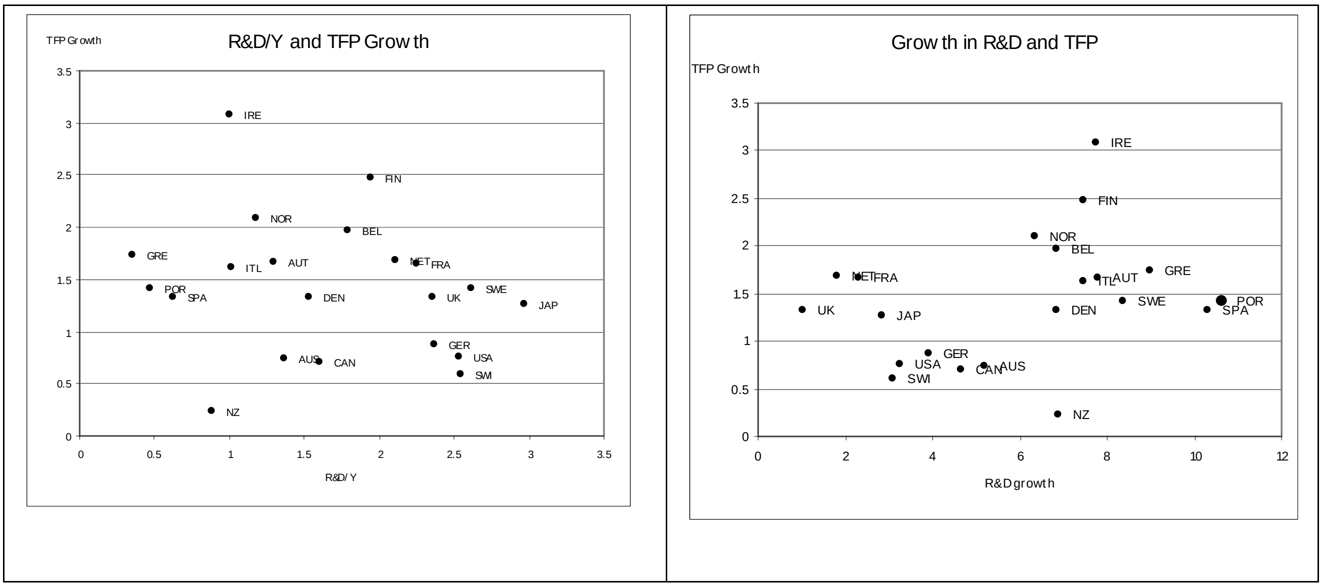




Notes. The TFP growth rates are based on 5-year centred moving averages of annual growth rates. 2003 and 2004 TFP growth rates are set equal to the growth rate in 2002. For Germany and the US, the TFP growth rates over the period 1911-1960 and 1922-1960 are based on 11-year centred moving averages. The averages for the G21 countries are weighted by GDP at PPP.

Turning to cross-sectional evidence, the left graph in Figure 2 plots the average R&D intensity, measured as the ratio of R&D and GDP, over the period 1965-2004 against the average TFP growth over the same period. The long averages filter out cyclical fluctuations and, to a large extent, also the transitional dynamics. The scatter plot shows that there is no relationship between TFP growth and research intensity, even if Ireland is removed from the sample.

Figure 2. R&D and TFP growth.



Notes. The figures are averages over the period 1965-2004. The following regressions apply: $\Delta \ln TFP = \underset{(5.76)}{1.48} - \underset{(1.17)}{0.08}\frac{R\&D}{Y} + \underset{(10.7)}{1.68} D^{IRE}$ and $\Delta \ln TFP = \underset{(4.37)}{1.01} + \underset{(1.89)}{0.07}\Delta \ln R\&D$, where the numbers in parentheses are *t*-statistics and D^{IRE} is a dummy variable for Ireland. The standard errors are based on White's heteroscedasticity consistent covariance matrix.

How can this result be settled with the time-series evidence showing a relatively stable positive relationship between TFP growth and research intensity? One possibility is that the R&D data are not internationally comparable. Although there are small cross-country differences in the coverage of R&D activities, attempts at harmonizing by UNESCO and the OECD in the early 1960s have rendered the R&D data internationally comparable (Godin, 2005). It is, therefore, unlikely that the lack of cross-comparison in the R&D expenditures can explain the discrepancy between the cross-country and time-series evidence. Another possibility is that the covariance between TFP growth and research intensity in the time-series data is predominantly driven by the business cycle and transitional dynamics. While some co-variation between TFP growth and research intensity on cyclical frequencies in the G21 data can be observed in Figure 1, the pre-1965 evidence for the US, Japan, and Germany indicates that this may not be the case. Finally, the cross-sectional evidence may be subject to an omitted variable bias because human capital and the distance to the frontier are not allowed for in the estimates. However, allowing average years of schooling among the adult population and the distance to the frontier does not change the results. The estimated coefficient of research intensity remains insignificant when the average years of schooling among the adult population and the distance to the frontier are allowed for in the estimates.[7] Overall, it appears that Schumpeterian growth theory cannot adequately account for the cross-country variation in TFP growth.

4.2 Semi-endogenous growth theory

Semi-endogenous growth theory assumes that real R&D and TFP grow proportionally. Time-series evidence of R&D and TFP growth rates are presented in Figure 3. For the G21 countries, it is difficult to find any systematic relationship between growth in real R&D and TFP growth, particularly because of the pro-cyclicality of both R&D and TFP growth. Considering Germany, there is a positive relationship between the rates of growth in R&D and TFP. The high TFP growth

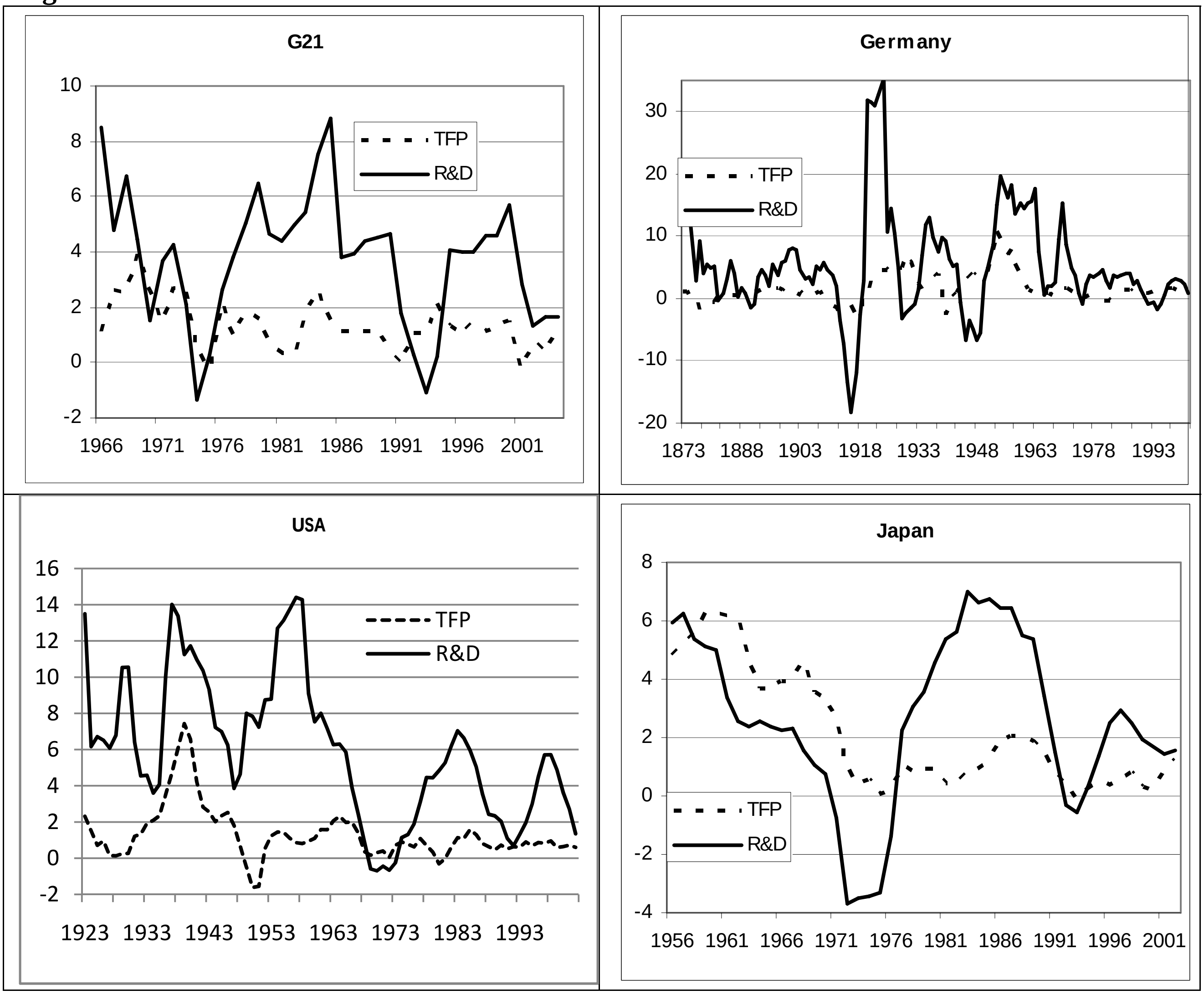
[7] Including average years of schooling among the adult population in the period 1971 to 1998, on average, denoted by HC, and the distance to the frontier yields the following estimates:

$$\Delta \ln A = \underset{(3.58)}{3.88} + \underset{(0.86)}{0.18}\left(\frac{R\,\&\,D}{Y}\right) - \underset{(2.33)}{0.27}\,HC - \underset{(1.08)}{0.34}\,D^{IRE} - \underset{(0.04)}{0.03}\left(\frac{R\,\&\,D}{Y}\right)\left(\frac{A^{\max} - A}{A^{\max}}\right),$$

where the data on human capital are from De la Fuente and Doménech (2006). Whereas *A* and (R&D/*Y*) are measured as averages over the 1965-2004 period the last term is measured in 1965. The estimates are insensitive to exclusion of (R&D/*Y*) from the last term.

periods of 1920-1940 and 1950-1960 are positively related to high growth in real R&D, whereas growth in R&D and TFP were both low in the surrounding periods. For the US, there is a positive relationship between growth in TFP and growth in R&D. Finally, there is a positive relationship between growth in R&D and growth in TFP in Japan, however, the relationship is not strong. Overall the graphical evidence gives some support for semi-endogenous growth theory.

Figure 3. Growth in TFP and R&D.



Considering the long-run relationship between TFP growth and R&D growth in the right-hand-side of Figure 2, there is a slight positive relationship between the two variables. This suggests that semi-endogenous growth theory has some promise in accounting for the cross-country variation in TFP growth.

5 Empirical estimates

5.1 Stochastic specification

Based on the discussion in Section 2, the following models are estimated:

$$\ln A_{it} = \alpha_{0,i} + \alpha_1 \ln Q_{it}^d + \alpha_2 \ln X_{it}^d + \alpha_3 \ln Q_{it}^f + \alpha_4 \ln X_{it}^f + \varepsilon_{1,it}, \qquad (8)$$

$$\ln X_{it}^d = \gamma_{0,i} + \gamma_1 \ln Q_{it}^d + \varepsilon_{2,it}, \qquad (9)$$

$$\Delta \ln A_{it} = \beta_{0,i} + \beta_1 \Delta \ln X_{it}^d + \beta_2 \Delta \ln X_{it}^f + \beta_3 \ln(X/Q)_{it}^d + \beta_4 \ln(X/Q)_{it}^f + \beta_5 \left(\frac{Y_{t-1}^{\max} - Y_{i,t-1}}{Y_{t-1}^{\max}} \right) + \varepsilon_{3,it}, \qquad (10)$$

where the subscript *i* signifies country *i* and, as noted above, the superscripts *d* and *f* stand for domestic and foreign, and ε is a stochastic error term. Eq. (8) is the cointegration model given by Eq. (5), Eq. (9) is the cointegration model given by Eq. (4), and Eq. (10) is the stochastic counterpart of Eq. (6). As mentioned in the previous section it is important to keep in mind that Eq. (8) and Eq. (9) are conditional on stationarity of TFP growth.[8]

Eq. (8) tests the semi-endogenous growth model extended to allow for research proliferation. The semi-endogenous growth model predicts that $\alpha_2, \alpha_4 > 0$, $\alpha_1 = \alpha_3 = 0$, and that the error term is stationary. Eq. (9) tests Schumpeterian growth theory, which predicts that $\gamma_1 = 1$ and that the error term is stationary. Eq. (10) nests both second-generation models of endogenous growth while allowing for international spillover effects. Schumpeterian growth theory predicts that $\beta_1 = \beta_2 = 0$ and $\beta_3, \beta_4, \beta_5 > 0$ whereas semi-endogenous growth theory predicts that $\beta_3 = \beta_4 = 0$ and $\beta_1, \beta_2 > 0$. Eq. (10) is estimated in 5, 10, and 20-year differences, as opposed to one-year differences, to reduce the influence on the estimates of the business cycle and transitional dynamics. Since TFP growth and research intensity may be pro-cyclical, a positive correlation between the variables may be driven by the business cycle and transitional dynamics and not by a genuine structural relationship between the variables. The research intensity variables are measured as the average within the period that is covered by the differences. The higher frequency estimates (5 and 10-year differences) yield more efficient estimates that the low frequency estimates, however, the parameter estimates may be influenced more by transitional dynamics. The significant change in sectoral composition in the post-war period, as identified by Schon (2000) for Sweden, may have pushed the economies away from their steady state over prolonged periods. The estimates in 20-year differences are, therefore, an important supplement to the 5 and 10-year difference estimates.

[8] See, for example, Zachariadis (2004), who finds that TFP is stationary for all ten OECD countries in his sample.

5.2 Estimation method

Eq. (8) and Eq. (9) are estimated using the dynamic least squares estimator of Stock and Watson (1993), where the first-differences of one-period lags and leads and concurrent values of the explanatory variables are included as additional regressors to capture the dynamic path around the long-run equilibrium. The advantage of using this estimator over the OLS estimator is that it possesses an asymptotic normal distribution and, therefore, the associated standard errors allow for valid calculations of *t*-tests, and that, in contrast to the OLS estimator, yields unbiased coefficient estimates in panels (Kao and Chiang, 2000). The Dickey-Fuller test for panel cointegration suggested by Kao (1999) is used to test for cointegration. Equation (10) is estimated using OLS.

5.3 Estimation results

Cointegration estimates

The results of estimating the cointegration models Eq. (8) and Eq. (9) are presented in Table 1. R&D is used for X in the estimates displayed in the upper part of the table and the models are estimated for the G21 countries in the period from 1966 to 2003. The estimates of the semi-endogenous growth model in the top left quadrant show that the logs of TFP and R&D are not cointegrated. When $A \cdot L$, Y, or $A \cdot S^{TM}$ are included as regressors to allow for product proliferation, the variables form a cointegrating relationship only in the case in which $A \cdot S^{TM}$ is included as an additional regressor and the estimated coefficients of R&D are insignificant in two of the three cases. These results suggest that semi-endogenous growth theory is not consistent with the long-run evidence when R&D is used as a measure of the innovative activity. This result is consistent with the findings of Ha and Howitt (2007) for the US.

The estimates in the top right quadrant give some support to Schumpeterian growth theory. R&D is cointegrated with Y, $A \cdot S^{TM}$, and $A \cdot L$ at the 5% significance level. The estimated coefficients of Y, $A \cdot S^{TM}$ and $A \cdot L$ are highly significantly different from zero, however, they are also significantly different from one at conventional significance levels, which is inconsistent with the predictions of Schumpeterian growth theory. However, since the estimated coefficients of Y, $A \cdot S^{TM}$ and $A \cdot L$ are both higher and lower than one suggests that the trend in product variety may not have been entirely captured by the Y, $A \cdot S^{TM}$ and $A \cdot L$ variables and, therefore, that the deviation of the coefficients from unity cannot strictly be used as evidence against Schumpeterian theory.

In the lower half of Table 1, research activity is measured as patents by residents (granted and applications). The estimated period is extended back to 1900, which, due to data availability, reduces the number of countries to 14 (the country sample is detailed in the notes to Table 1). Consider first the tests of semi-endogenous theory in the lower left-hand side of the table. The tests do not give support for semi-endogenous growth theory. The estimated coefficients of patents are insignificant at conventional significance levels, except in the estimates where proliferation variables are excluded from the estimates. However, the null hypothesis of no cointegration cannot be rejected unless proliferation variables are included in the estimates.

The tests in the right-hand-side middle part in Table 1 give strong support for Schumpeterian growth theory. Patents and the proliferation variables are cointegrated in all estimates and the estimated coefficients of the proliferation variables are all significant at conventional significance levels, regardless of whether the innovative activity is measured by patents granted or patents applied for. The estimated coefficients are again sensitive to the measurement of X. The estimated coefficients of employment are close to 1, as predicted by the Schumpeterian growth theory, whereas the estimated coefficients of Y and the stock of trademarks are significantly below one.

Table 1. Cointegration estimates (Eq. (8) and Eq. (9)).

Semi-endogenous	**Schumpeterian**
Estimation Period: 1966-2003	**Estimation Period: 1966-2003**
$\ln A_t = \underset{(9.38)}{0.28} \ln R\&D_t \quad z = -0.89[0.18]$	$\ln R\&D_t = \underset{(11.5)}{1.78} \ln(A \cdot L)_t \quad z = -3.10[0.00]$
$\ln A_t = \underset{(0.81)}{0.04} \ln R\&D_t + \underset{(5.46)}{0.52} \ln(A \cdot L)_t \quad z = -0.71[0.23]$	$\ln R\&D_t = \underset{(11.6)}{1.40} \ln Y_t \quad z = -3.43[0.00]$
$\ln A_t = \underset{(0.73)}{0.04} \ln R\&D_t + \underset{(4.26)}{0.41} \ln Y_t \quad z = -0.84[0.20]$	$\ln R\&D_t = \underset{(6.18)}{0.60} \ln(A \cdot S^{TM})_t \quad z = -1.95[0.02]$
$\ln A_t = \underset{(3.34)}{0.16} \ln R\&D_t + \underset{(3.12)}{0.11} \ln(A \cdot S_t^{TM}) \quad z = -3.88[0.00]$	
Estimation Period: 1900-2003	**Estimation Period: 1900-2003**
$\ln A_t = \underset{(2.77)}{0.45} \ln Pat_t^a \quad z = 1.07[0.86]$	$\ln Pat_t^a = \underset{(5.24)}{1.10} \ln L_t \quad z = -4.73[0.00]$
$\ln A_t = \underset{(0.17)}{0.01} \ln Pat_t^a + \underset{(0.39)}{0.08} \ln L_t - \underset{(0.43)}{0.02} \ln Pat_t^{im,a} + \underset{(5.10)}{1.34} \ln L_t^{im} \quad z = -3.75[0.01]$	$\ln Pat_t^a = \underset{(5.98)}{0.42} \ln Y_t \quad z = -5.87[0.00]$
$\ln A_t = -\underset{(1.78)}{0.07} \ln Pat_t^a + \underset{(3.12)}{0.54} \ln Y_t - \underset{(0.53)}{0.02} \ln Pat_t^{im,a} - \underset{(0.52)}{0.05} \ln Y_t^{im} \quad z = -2.33[0.01]$	$\ln Pat_t^a = \underset{(4.95)}{0.39} \ln S_t^{TM} \quad z = -5.24[0.00]$
$\ln A_t = -\underset{(0.71)}{0.04} \ln Pat_t^a + \underset{(2.41)}{0.14} \ln S_t^{TM} - \underset{(2.23)}{0.10} \ln Pat_t^{im,a} + \underset{(3.39)}{0.27} \ln S_t^{im,TM} \quad z = -3.97[0.00]$	$\ln Pat_t^g = \underset{(3.75)}{0.76} \ln L_t \quad z = -23.45[0.00]$
$\ln A_t = \underset{(1.10)}{0.22} \ln Pat_t^g \quad z = -0.75[0.22]$	$\ln Pat_t^g = \underset{(4.16)}{0.29} \ln Y_t \quad z = -24.67[0.00]$
$\ln A_t = \underset{(0.34)}{0.01} \ln Pat_t^g + \underset{(0.47)}{0.10} \ln L_t - \underset{(2.43)}{0.13} \ln Pat_t^{im,g} + \underset{(4.05)}{1.05} \ln L_t^{im} \quad z = -4.95[0.00]$	$\ln Pat_t^g = \underset{(3.20)}{0.23} \ln S_t^{TM} \quad z = -23.30[0.00]$

$\ln A_t = \underset{(1.35)}{-0.04}\ln Pat_t^g + \underset{(6.07)}{0.50}\ln Y_t - \underset{(0.29)}{0.01}\ln Pat_t^{im,g} - \underset{(0.20)}{0.02}\ln Y_t^{im}$ $\quad z = -2.33[0.01]$	**No fixed effect dummies**
$\ln A_t = \underset{(0.86)}{0.05}\ln Pat_t^g + \underset{(2.39)}{0.17}\ln S_t^{TM} - \underset{(1.40)}{0.14}\ln Pat_t^{im,g} + \underset{(1.46)}{0.20}\ln S_t^{im,TM}$ $\quad z = -3.81[0.00]$	$\ln Pat_t^a = \underset{(6.93)}{1.03}\ln L_t \quad z = +0.73[0.77]$
No fixed effect dummies	$\ln Pat_t^g = \underset{(9.67)}{1.01}\ln L_t \quad z = -9.75[0.00]$
$\ln A_t = \underset{(0.68)}{0.08}\ln Pat_t^a \quad z = +2.18[0.99]$	$\ln Pat_t^g = \underset{(1.74)}{0.51}\ln Y_t \quad z = -2.25[0.01]$
$\ln A_t = \underset{(0.46)}{0.06}\ln Pat_t^g \quad z = +2.10[0.97]$	$\ln Pat_t^g = \underset{(3.60)}{0.70}\ln S_t^{TM} \quad z = +1.78[0.96]$

Notes. The numbers in parentheses are *t*-statistics and the numbers in square brackets are *p*-values. Constant terms and fixed-effect dummies are included in the estimates but not shown. The estimates include, as additional variables, one-period lags and leads and concurrent values of the explanatory variables in first-differences. The *t*-statistics associated with the estimates are corrected for autocorrelation following Stock and Watson (1993). The *z* statistic is Kao's (1999) panel Dickey-Fuller test for cointegration, distributed as $N(0,1)$ under the null hypothesis of no cointegration. The G21 countries are included in the estimates in the period 1966-2003 and the following countries are included in the estimates covering the period 1900-2003: Canada, the US, Japan, Belgium, Denmark, France, Germany, Italy, the Netherlands, Norway, Spain, Sweden, Switzerland, and the UK. Pat^g = number of patents granted, and Pat^a = number of patents applied for.

Thus far, the parameter estimates have been driven entirely by the time-series path of the data, because the effects on the parameter estimates of the cross-country variations in the data have been removed by the fixed-effect dummies. Estimates without fixed-effect dummies, therefore, constitute powerful tests of the theories, because the cross-country variance in the data is higher than the within country variance in the data. Removing the fixed-effect dummies from the regressions yields the estimates in the last rows in Table 1. Only the key estimates are presented to preserve space. In the semi-endogenous growth models the estimated coefficients of patents are insignificant and the null hypothesis of unit roots in the residuals cannot be rejected. Turning to the estimates for Schumpeterian theory, the estimated coefficients in three of the four cases are highly significant and the variables are cointegrated in half of the cases. These results suggest that Schumpeterian theory is able to account for at least some of the cross-country variation in the data.

Panel estimates

The results of estimating the TFP growth model given by Eq. (10) are presented in Tables 2, 3 and 4. The estimates in 5 and 10-year differences are limited to the period 1965-2004 because of a large noise-to-signal ratio in both TFP and patent growth rates prior to 1965, particularly, during and immediately after the two world wars and during the depressions in the early 1920s and the 1930s, that blurs the relationship between the dependent and the independent variables.

Table 2. Parameter estimates of Eq. (10) in 5-year differences.

$\frac{X}{Q}$	$\frac{R\&D}{TFP \cdot S^{TM}}$	$\frac{R\&D}{Y}$	$\frac{R\&D}{TFP \cdot L}$	$\frac{Pat^a}{S^{TM}}$	Pat^a / L	Pat^g / S^{TM}	Pat^g / L
$\Delta \ln X^d$	0.029(2.17)	0027(2.00)	0.026(1.88)	0.015(1.35)	0.013(1.17)	-0.002(0.39)	-0.001(0.29)
$\Delta \ln X^f$	0.028(0.74)	0.046(1.18)	0.037(0.92)	-0.025(0.58)	-0.002(0.36)	-0.018(1.04)	-0.016(0.97)
$(X/Q)^d$	0.035(8.70)	0.031(9.15)	0.001(0.94)	0.057(2.98)	0.019(1.32)	0.014(0.65)	0.023(1.23)
$(X/Q)^f$	0.120(2.98)	3.126(1.64)	3.37(1.72)	0.198(2.63)	0.017(3.09)	0.301(3.30)	0.306(3.37)
DTF	0.227(4.89)	0.286(5.40)	0.306(5.48)	0.250(4.87)	0.276(5.86)	0.266(5.70)	0.265(5.74)
R^2	0.56	0.54	0.51	0.52	0.52	0.52	0.52

Notes. DTF = $(A^{max} - A_i)/A^{max}$. Estimation period 1970-2004. The period 2000-2004 is used for the last observation. Research intensity is measured as the average intensity in the interval over which the 5-year differences have been taken. The *t*-statistics in parentheses are based on White's heteroscedasticity consistent covariance matrix. Pat^g = number of patents granted, and Pat^a = number of patents applied for.

Consider first the estimates over the period 1965-2004 in Tables 2 and 3. For semi-endogenous growth theory, the estimated coefficients of the growth in domestic innovative activity are statistically significant in some of the estimates. The estimated elasticities of the growth in R&D are in the neighborhood of 0.05. This suggests significant excess social returns to investment in R&D noting that the estimated elasticities of domestic research activity are *excess* social returns to domestic R&D and patenting and not the total effects of the innovative activity on output, since R&D expenditures are already included in capital and labour and, therefore, in the estimates of TFP. The estimated coefficients of the growth in imports of technology are predominantly insignificant in the 5 and 10-year difference estimates but mostly significant in the estimates in 20-year differences, which suggests that the growth in the imports of technology have significant positive long-term effects on TFP growth but that the short-term effects may either be negligible or blurred by transitional dynamics and cyclical influences.

Table 3. Parameter estimates of Eq. (10) in 10-year and 20-year differences.

	10-Year Differences			20-Year Differences			
$\frac{X}{Q}$	$\frac{R\&D}{TFP \cdot S^{TM}}$	$\frac{R\&D}{Y}$	$\frac{Pat^a}{S^{TM}}$	$\frac{R\&D}{TFP \cdot S^{TM}}$	$\frac{R\&D}{Y}$	$\frac{Pat^a}{S^{TM}}$	$\frac{R\&D}{TFP \cdot S^{TM}}$ No CD
$\boldsymbol{\Delta lnX^d}$	0.004(1.83)	-0.004(0.4)	0.015(0.75)	0.103(3.17)	0.082(3.81)	0.07(3.73)	0.020(0.51)
$\boldsymbol{\Delta lnX^f}$	0.028(0.70)	0.123(2.96)	0.011(0.35)	0.201(2.56)	0.754(7.18)	0.064(1.80)	0.097(0.79)
$(X/Q)^d$	0.008(12.9)	0.007(11.4)	0.071(3.20)	0.115(3.18)	0.027(7.59)	-0.127(1.6)	-0.008(4.5)
$(X/Q)^f$	0.226(3.22)	12.5(4.07)	0.443(3.47)	0.634(4.98)	74.5(6.77)	0.077(0.27)	0.367(1.48)
DTF	0.439(5.86)	0.560(7.42)	0.473(6.26)	0.075(0.45)	0.552(8.69)	0.528(3.77)	0.616(6.26)
R^2	0.75	0.77	0.72	0.89	0.95	0.91	0.55

Note. See notes to Table 2.

Turning to Schumpeterian theory, the estimated coefficients of domestic research intensity are statistically highly significant in almost all of the estimates where the innovative activity is measured by R&D, regardless of whether the estimates are in 5, 10 or 20 year differences. The coefficient estimates are less significant in the estimates where the innovative activity is measured by patents, regardless of whether the innovative activity is measured by patents applied for or by patents granted. Only a third of the coefficient estimates are significant at conventional significance levels. The estimated coefficients of the spillover variables are highly significant, regardless of whether the innovative activity is measured by R&D or patents and regardless of whether the estimates are in 5, 10 or 20-year differences. This result gives strong support to the Schumpeterian theories because the theory suggests that growth is related to (X/Q) regardless of the source of innovation.

Removing the country dummies from the 20-year difference estimates yields the estimates in the last column in Table 3. The estimated coefficients of the growth in domestic and the foreign innovative activity are insignificant and the estimated coefficient of (X/Q) has a sign opposite to the predictions of Schumpeterian theory. The results are robust to the measurement of X and Q and the length of the first differences (the results are not shown). These results are consistent with the scatter plot in Figure 2, which shows the absence of any relationship between TFP growth and the research intensity.

What explains the conflict between the time-series and the cross country evidence for Schumpeterian theory? The conflict could be caused by cross-country measurement errors. However, the measurement errors need not lower the covariance between the research intensity and TFP growth – they may increase the covariance. Furthermore, since the results are insensitive to whether the innovative activity is measured by R&D, patents applied for, or patents granted, there is a low likelihood that the parameter estimates have been driven by errors-in-variables. Another possibility is that adequate measures of product varieties are not available. The innovative activity normalised by employment, income, TFP, or stock of trademarks may well proxy the time-path, but not the level of product variety to such an extent that the cross-country variations in measured research intensities are unrelated to true research intensities. Another possibility is that the Schumpeterian theory cannot adequately account for growth.

Table 4. Parameter estimates of Eq. (10) in 20-year differences. 1905-2004.

	Pat^a / L	Pat^a / S^{TM}	Pat^g / S^{TM}	Pat^g / L	Pat^a / L	Pat^a / S^{TM}	Pat^g / L
$\Delta \ln X^d$	0.098(1.56)	0.089(1.37)	0.046(0.98)	0.048(1.04)	0.050(0.92)	0.054(0.94)	0.022(0.72)

$\Delta \ln X^f$	0.042(1.38)	0.036(1.13)	0.063(3.61)	0.072(4.30)	0.056(1.72)	0.048(1.44)	0.086(4.20)
$(X/Q)^d$	0.094(2.29)	-0.02(0.99)	-0.01(0.63)	0.242(2.84)	0.056(1.65)	0.017(0.88)	0.157(2.29)
$(X/Q)^f$	0.682(2.69)	0.642(2.44)	-0.02(4.76)	-0.02(5.26)	0.468(1.89)	0.491(1.79)	-0.013(4.59)
DTF	0.826(6.00)	0.810(5.61)	1.000(5.75)	1.00(5.87)	0.517(4.20)	0.493(3.91)	0.609(4.47)
CD	Yes	Yes	Yes	Yes	No	No	No
R^2	0.37	0.35	0.42	0.45	0.26	0.24	0.35

Notes. See notes to Table 2. CD = country dummies.

The results of estimating Eq. (10) in 20-year differences over the period from 1905 to 2004 are shown in Table 4. The results are consistent with the results in Tables 2 and 3. The estimated coefficients of growth in the domestic innovative activity are statistically insignificant at conventional significance levels in all cases, while the estimated coefficients of research intensity are significant at conventional levels in three of the seven cases; thus giving some support for Schumpeterian growth theory. The estimated coefficients of imported research intensity are insignificant in three of the seven cases. This result is likely to reflect the powerful movements in propensities to import during the world wars and the Great Depression (see Madsen, 2007, for discussion of this aspect).

Finally, the estimated coefficients of the distance to the frontier are both statistically and economically highly significant in all estimates in Tables 2, 3 and 4. This result is consistent with the argument of Aghion and Howitt (2006) that the further behind the technological frontier a country is the stronger is, its growth potential provided that the right institutions are set in place and that R&D is undertaken.

6. Sensitivity analysis

This section examines the sensitivity of the results to measurement in the innovative activity, R&D deflators, international technology spillovers, the interactions between distance to the frontier and research intensity, interactions with trade partners that is conditional on the propensity to import, allowance of structural breaks.

6.1 Long R&D data

As discussed in the previous section, the propensity to patent and the average real value of a patent may have changed over the past 100 years. To investigate whether the second generation models of endogenous growth are consistent with the data in the very long run, historical R&D data are used to estimate Eq. (8) and Eq. (9) for the four countries for which data are available over at least 65 years. These countries are USA, Australia, Germany and Spain. Note that the quality of the data suffers from the fact that private R&D is not included in the total R&D data for the entire estimation periods for Australia, Germany and Spain.

Table 5. Tests of Schumpeterian theory for individual countries (Eq. (9)).

Regressor	$\ln{(L \cdot A)}$	$\ln{(Y)}$	$\ln{(S^{TM} \cdot A)}$	R^2	ADF	Est. Per.
USA	1.79(8.04)			0.95	-3.18	1922-2003
		1.56(7.77)		0.95	-3.05	1922-2003
			1.10(1.56)	0.80	-1.28	1922-2003
Australia	1.94(6.54)			0.82	-3.47	1942-2003
		1.40(11.0)		0.84	-3.46	1942-2003
			0.89(7.78)	0.86	-2.65	1942-2003
Germany	2.01(27.9)			0.95	-3.18	1872-2003
		1.66(20.4)		0.95	-3.05	1872-2003
			0.33(0.63)	0.80	-1.28	1872-2003
Spain	3.77(27.5)			0.88	-2.62	1872-2003
		2.52(26.1)		0.87	-2.46	1872-2003
			0.48(21.4)	0.52	-3.14	1872-2003

Notes. The dependent variable is the log of real R&D. Constants have been included in the estimates but not shown here. The ADF tests contain one lag, no constant and no trend. The critical value of the ADF tests is -3.04 at the 10% level.

The tests of Schumpeterian growth theory are presented in Table 5. The ADF tests indicate that the variables are cointegrated in more than half of the estimates, at the 10% level. The coefficient estimates are mostly highly significant and fairly consistent with Schumpeterian theory. Overall the results give evidence in favour of Schumpeterian theory.

The results of testing semi-endogenous theory are presented in Table 6. Consider first the rows in which the log of TFP is regressed only on the log of real R&D. The estimated coefficients of the log of R&D are highly significant, however, the variables are only cointegrated for half of the countries. Including $\ln{(L \cdot A)}$, $\ln(Y)$ and $\ln{(S^{TM} \cdot A)}$ as additional regressors renders the variables cointegrated at the 10% level in 11 of the 12 cases. Furthermore, the estimated coefficients of the log of R&D are, in most cases, rendered insignificant by the addition of the product dilution variables. These results are consistent with the results in Table 1 and are evidence against semi-endogenous growth theory.

Table 6. Tests of semi-endogenous theory for individual countries (Equation (8)).

Regressor	$\ln{(R\&D)}$	$\ln{(L \cdot A)}$	$\ln{(Y)}$	$\ln{(S^{TM} \cdot A)}$	R^2	ADF
USA	0.23(11.2)				0.91	-4.06
	0.05(0.68)	0.32(2.24)			0.96	-3.17
	0.13(1.30)		0.16(1.03)		0.94	-3.15
	0.19(3.93)			0.04(0.67)	0.92	-4.06
Australia	0.11(4.96)				0.77	-2.67
	-0.02(2.80)	0.30(24.0)			0.99	-6.21

	-0.04(3.62)		0.24(17.9)		0.98	-5.27
	-0.03(1.29)			0.15(7.11)	0.96	-3.92
Germany	0.32(22.7)				0.94	-5.15
	0.07(0.45)	0.52(1.70)			0.96	-3.82
	0.18(1.45)		0.24(1.15)		0.96	-4.21
	0.34(18.5)			-0.01(1.58)	0.94	-5.36
Spain	0.15(4.45)				0.79	-1.92
	-0.06(0.60)	0.89(2.21)			0.99	-3.22
	-0.04(0.49)		0.58(2.21)		0.99	-3.22
	0.11(2.29)			0.03(1.05)	0.84	-1.73

Notes. The dependent variable is the log of TFP. The estimation periods are the same as the ones indicated in Table 5. The critical ADF values, at the 10% level, are -3.04 in the estimates that contain one regressor and -3.45 in the estimates containing two regressors.

6.2 Distance to the technological frontier

The Schumpeterian theory predicts that TFP growth is positively affected by the distance to the technological frontier. In the model of Howitt (2000) TFP growth is positively related to $(X/Q)(A^{\max} - A)/A^{\max}$, while TFP growth is positively related to both $(X/Q)(A^{\max} - A)/A^{\max}$ and $(A^{\max} - A)/A^{\max}$ in the Schumpeterian models of Griffith *et al*. (2003, 2004). The term $(X_{t-1}/Q_{t-1})(A_{t-1}^{\max} - A_{t-1})/A_{t-1}^{\max}$ is added to the estimates of Eq. (10) in this sub-section. The variable is measured in the beginning of the estimation period over which the first differences are taken.

Table 7. Parameter estimates of Eq. (10) augmented with $(X/Q)(A^{\max} - A)/A^{\max}$ in 5-year differences, 1965-2004.

$\frac{X}{Q}$	$\frac{R\&D}{TFP \cdot S^{TM}}$	$\frac{R\&D}{Y}$	$\frac{R\&D}{TFP \cdot L}$	$\frac{Pat^{a}}{S^{TM}}$	Pat^{a}/L	Pat^{g}/S^{TM}	Pat^{g}/L
$\Delta \ln X^{d}$	0.029(2.16)	0028(2.00)	0.028(2.05)	0.015(1.35)	0.008(0.71)	0.000(0.21)	0.001(0.14)
$\Delta \ln X^{f}$	0.030(0.77)	0.047(1.18)	0.051(1.28)	-0.025(0.58)	-0.002(0.02)	-0.016(0.95)	-0.015(0.96)
$(X/Q)^{d}$	0.007(3.11)	0.009(1.32)	-0.001(2.39)	0.062(1.15)	0.046(2.65)	0.004(0.19)	0.005(0.24)
$(X/Q)^{f}$	0.115(2.71)	3.117(1.62)	3.335(1.72)	0.198(2.63)	0.266(3.08)	0.291(3.24)	0.284(3.17)
DTF	0.228(4.94)	0.286(5.41)	0.284(5.36)	0.250(4.65)	0.327(3.07)	0.227(4.31)	0.243(5.23)
CDTF	0.001(0.60)	-0.001(0.30)	0.003(7.48)	-0.016(0.15)	-0.010(1.92)	0.118(2.35)	0.061(4.23)
R^2	0.56	0.54	0.54	0.52	0.52	0.54	0.54

Notes. See notes to Table 2. $CDTF = (X/Q)\left((A^{\max} - A_i)/A^{\max}\right)$.

The results of estimating the model in 5, 10 and 20-year differences are presented in Tables 7, 8 and 9. The parameter estimates are quite similar to the estimates in the previous section except for the parameter estimates of research intensity. The significance of the estimated coefficients of domestic research intensity and the distance to the frontier is reduced slightly by the addition of

$(X/Q)(A^{\max} - A)/A^{\max}$ as a regressor. This reduction is not surprising given that there is a high correlation between (*X*/*Q*) and (*X*/*Q*) $(A^{\max} - A)/A^{\max}$, as discussed above. The estimated coefficients of $(X/Q)(A^{\max} - A)/A^{\max}$ are positive and significant at conventional significance levels in less than 20% of all cases, which suggests that growth is, to some extent, driven by the interaction between absorptive capacity and the unconditional distance to the frontier, $(A^{\max} - A)/A^{\max}$, however, the results are sensitive to model specification and the measurement of innovative activity and the measurement of product variety.[9]

Table 8. Parameter estimates of Eq. (10) augmented with $(X/Q)(A^{\max} - A)/A^{\max}$ in 10-year and 20-year differences, 1965-2004.

	10-Year Differences			20-Year Differences			
$\frac{X}{Q}$	$\frac{R\&D}{TFP \cdot S^{TM}}$	$\frac{R\&D}{Y}$	$\frac{Pat^a}{S^{TM}}$	$\frac{R\&D}{TFP \cdot S^{TM}}$	$\frac{R\&D}{Y}$	$\frac{Pat^a}{S^{TM}}$	$\frac{R\&D}{TFP \cdot S^{TM}}$ No CD
$\Delta \ln X^d$	0.004(1.83)	0.000(0.44)	0.014(0.76)	0.091(1.94)	0.087(4.61)	-0.08(4.03)	0.020(0.50)
$\Delta \ln X^f$	0.028(0.68)	0.125(2.96)	0.010(0.29)	0.139(1.24)	0.774(7.36)	0.149(3.96)	0.096(0.78)
$(X/Q)^d$	0.008(4.73)	0.004(1.81)	0.010(1.41)	0.064(1.34)	4.27(2.14)	-0.89(3.32)	-0.01(2.79)
$(X/Q)^f$	0.225(3.08)	12.5(4.09)	0.444(3.46)	0.441(1.34)	73.8(6.76)	-0.01(0.06)	0.376(1.46)
DTF	0.439(5.89)	0.559(7.38)	0.481(0.41)	0.226(1.39)	0.608(11.2)	0.231(1.33)	0.619(6.27)
CDTF	0.000(0.13)	0.002(1.21)	-0.07(0.41)	-0.00(0.55)	-0.94(2.13)	1.093(3.13)	-0.00(0.83)
R^2	0.75	0.77	0.90	0.90	0.85	0.93	0.55

Note. See notes to Tables 2 and 7.

Table 9. Parameter estimates of Eq. (10) augmented with $(X/Q)(A^{\max} - A)/A^{\max}$ in 20-year differences. 1905-2004.

	Pat^a/L	Pat^a/S^{TM}	Pat^g/S^{TM}	Pat^g/L	Pat^a/L	Pat^a/S^{TM}	Pat^g/L
$\Delta \ln X^d$	0.061(0.99)	0.092(1.40)	0.049(1.02)	0.043(0.88)	0.037(0.67)	0.058(1.01)	0.016(0.49)
$\Delta \ln X^f$	0.004(0.12)	0.040(1.20)	0.064(3.58)	0.068(3.58)	0.046(1.42)	0.051(1.53)	0.083(3.84)
$(X/Q)^d$	0.199(3.15)	-0.03(1.82)	-0.02(1.14)	0.273(2.26)	0.093(1.46)	0.001(0.10)	0.196(1.81)
$(X/Q)^f$	0.494(1.84)	0.659(2.48)	-0.02(4.78)	-0.018(4.76)	0.413(1.65)	0.513(3.72)	-0.01(4.36)
DTF	1.15(6.16)	0.796(5.62)	1.000(5.66)	1.008(5.48)	0.600(3.35)	0.477(3.72)	0.638(3.98)
CDTF	-0.34(2.66)	0.024(0.69)	0.028(1.00)	-0.11(0.46)	-0.11(0.85)	0.041(1.62)	-0.10(0.49)
CD	Yes	Yes	Yes	Yes	No	No	No
R^2	0.40	0.34	0.42	0.45	0.26	0.24	0.35

[9] If the growth in TFP is regressed on $(X/Q)(A^{\max} - A)/A^{\max}$ as the only regressor together with country dummies, the estimated coefficient of $(X/Q)(A^{\max} - A)/A^{\max}$ becomes highly significant in most estimates and with the expected sign. This suggests that mulicolinearity has played an important role in the estimates above.

Note. See notes to Table 2 and 7.

6.3 R&D deflators

R&D deflators are not published on a consistent basis for the OECD countries. If research intensity is measured by the ratio of nominal R&D and nominal GDP, as is often done in empirical studies, it is implicitly assumed that the GDP-deflator applies to R&D. However, the studies of Mansfield (1984), OECD (1979) and Dougherty *et* al. (2003) show R&D inputs consist of labour, intermediate goods, and investment in buildings and equipment. Unfortunately, these studies use a combination of deflators that are not available for most countries and for the whole period covered in this study. Furthermore, their deflators we in most cases approximations. Griliches (1984) finds a very close relationship between an unweighted combination of labour costs and the GDP deflator and the R&D deflator estimated for the US by Mansfield (1984). This recommendation has been followed in the empirical estimates in Section 5 and in the literature on international technology spillovers.

This sub-section tests whether the results obtained in Section 5 are sensitive to an alternative R&D deflator, which is estimated as an average of the total labour cost deflator (45%), the GDP deflator (45%), the deflator for investment in machinery and equipment (5%), and the deflator for investment in buildings and structures (5%), where the numbers in parentheses signify the weight. These weights come close to the weights that are often used in the literature (see for instance OECD, 1979, and Dougherty *et al*., 2003).

Table 10. Cointegration estimates (Eq. (8) and Eq. (9)) using an alternative R&D deflator.

Semi-endogenous	Schumpeterian
Estimation Period: 1966-2003	**Estimation Period: 1966-2003**
$\ln A_t = \underset{(9.36)}{0.27} \ln R\&D_t \quad z = -1.10[0.13]$	$\ln R\&D_t = \underset{(11.4)}{1.75} \ln(A \cdot L)_t \quad z = -2.91[0.00]$
$\ln A_t = \underset{(0.82)}{0.04} \ln R\&D_t + \underset{(5.29)}{0.51} \ln(A \cdot L)_t \quad z = -0.86[0.20]$	$\ln R\&D_t = \underset{(12.2)}{1.47} \ln Y_t \quad z = -3.12[0.00]$
$\ln A_t = \underset{(0.71)}{0.04} \ln R\&D_t + \underset{(4.11)}{0.41} \ln Y_t \quad z = -0.90[0.18]$	$\ln R\&D_t = \underset{(6.44)}{0.63} \ln(A \cdot S^{TM})_t \quad z = -1.82[0.03]$
$\ln A_t = \underset{(3.33)}{0.16} \ln R\&D_t + \underset{(2.90)}{0.11} \ln(A \cdot S_t^{TM}) \quad z = -3.89[0.00]$	

Notes. See notes to Table 1. R&D is deflated by GDP deflator (45%), total labour cost deflator (45%), the deflator for investment in machinery and equipment (5%) and the deflator for investment in non-residential buildings and structures (5%).

Table 11. Parameter estimates of (10) in 5-year differences.

$\frac{X}{Q}$	$\frac{R\&D}{TFP \cdot S^{TM}}$	$\frac{R\&D}{Y}$	$\frac{R\&D}{TFP \cdot L}$
	Imp wgt	**Imp wgt**	**Imp wgt**

$\Delta \ln X^{d}$	0.029(2.16)	0.026(1.91)	0.026(1.90)
$\Delta \ln X^{f}$	0.027(0.72)	0.0.37(0.93)	0.036(0.90)
$(X/Q)^{d}$	0.009(6.91)	0.454(0.47)	0.000(0.41)
$(X/Q)^{f}$	0.112(3.03)	3.387(1.69)	3.445(1.75)
DTF	0.226(4.87)	0.312(5.52)	0.305(5.47)
R^2	0.56	0.51	0.51

Notes. See notes to Table 2. R&D is deflated by GDP deflator (45%), total labour cost deflator (45%), deflator for investment in machinery and equipment (5%) and deflator for investment in non-residential buildings and structures (5%).

The results of estimating Eq. (8) and Eq. (9) based on the alternative deflator are shown in Table 10. The results are almost identical to the estimates in Table 1. The results give evidence in favour of the Schumpeterian theory but give only little evidence in favour of Semi-endogenous growth for the reasons given in the discussion of the results in Table 1 in Section 5.3. The results of estimating Eq. (10), with the alternative R&D deflator are shown in Table 11. Compared to the estimates in Table 2 the multiple correlation coefficients are reduced substantially by the use of the alternative deflator, which, by itself, suggests that the alternative deflator is of lower quality than the one used in Section 5. The significance of the coefficient estimates has also been reduced by the use of the alternative deflator, otherwise, the conclusion that was reached in Section 5 remains.

6.4 Different spillover mechanisms

Until now it has been assumed that technology is transmitted internationally through the channel of imports. In this section it is investigated whether the results change by allowing technology to be transmitted by geographical proximity and transmitted by other means independent of geographical proximity and trade of goods. Referring to the economic geography literature on agglomeration, Keller (2002) shows that geographic distance works as an impediment to international technological spillovers. Through geographical proximity technological knowledge can be transmitted by informal contacts, such as conferences, speeches and seminars. Finally, the models of Parente and Prescott (1994), one of the models considered by Rivera-Batiz and Romer (1991) and in some of the models discussed in Grossman and Helpman (1991) show that ideas travel internationally, independently of trade of goods because telecommunications, the Internet, books, magazines and other means of communication render technology, which is developed in one market, globally available. Technology that is globally available, and can unconditionally be used by all countries, will favour convergence. However, if technology transmissions are geographically limited in scope convergence may never take place and we may experience converge clusters. The two measures of international spillovers of technological activity are measured as follows.

The world innovative activity is measured as follows:

$$\left(\frac{X}{Q}\right)^f_{it} = \sum_{j=1}^{21} \frac{Y_{jt}}{Y_{Wt}} \left(\frac{X}{Q}\right)^d_{jt}, \qquad i \neq j \quad \text{Schumpeterian growth theory} \qquad (11)$$

$$X^f_{it} = \sum_{j=1}^{21} X^d_{jt}, \qquad i \neq j \quad \text{Semi-endogenous growth theory} \qquad (12)$$

where Eq. (11) measures foreign research intensity as the weighted sum of country *j*'s research intensity, $j \in G21$, $i \neq j$, where Y_W is the sum of GDP in the G21 countries at purchasing power parities (PPP). Eq. (12) measures foreign innovative activity as the sum of patents or real R&D at PPP. X^f and $(X/Q)^f$ differ across countries only to the extent that their own X^f and $(X/Q)^f$ are not included in the estimates.

Technology spillovers by geographical distance are measured as follows:

$$\left(\frac{X}{Q}\right)^f_{it} = \sum_{j=1}^{21} \sqrt{Dis_{ij}} \left(\frac{X}{Q}\right)^d_{jt}, \qquad i \neq j \quad \text{Schumpeterian growth theory} \qquad (13)$$

$$X^f_{it} = \sum_{j=1}^{21} \sqrt{Dis_{ij}}\, X^d_{jt}, \qquad i \neq j \quad \text{Semi-endogenous growth theory} \qquad (14)$$

where Dis is the distance between capital cities from Haveman (2000). The square root of distance is taken under the assumption that absolute changes in distances are proportionally more influential for technology spillovers on short than on long distances. Compared to estimates based on distance only, the measured based on the squared root of distance gave better results in terms of R^2 and Akaike's information criterion.

Table 12. Parameter estimates of Eq. (10) in 5-year differences where the spillover variables are based on world-wide spillovers (Eq. (11) and Eq. (12)).

$\frac{X}{Q}$	$\frac{R\&D}{TFP \cdot S^{TM}}$	$\frac{R\&D}{Y}$	$\frac{R\&D}{TFP \cdot L}$	Pat^a / S^{TM}	Pat^a / L	Pat^g / S^{TM}	Pat^g / L
$\Delta \ln X^d$	0.028(2.08)	0.026(1.98)	0.028(2.06)	0.015(1.43)	0.016(1.45)	-0.002(0.81)	-0.002(0.49)
$\Delta \ln X^f$	0.004(0.11)	0.013(0.38)	-0.014(0.40)	0.086(2.03)	0.085(2.03)	0.018(1.04)	0.032(1.23)
$(X/Q)^d$	0.029(7.82)	0.033(6.48)	0.001(0.89)	0.028(1.68)	0.011(0.98)	0.032(1.22)	0.009(0.46)
$(X/Q)^f$	1.967(1.35)	0.055(3.23)	3.174(1.57)	0.122(4.10)	0.134(4.68)	0.002(3.31)	0.002(3.36)

DTF	0.263(5.01)	0.201(4.15)	0.301(1.58)	0.190(3.77)	0.199(4.27)	0.216(4.06)	0.226(4.72)
R^2	0.54	0.56	0.51	0.55	0.55	0.52	0.52

Notes. See notes to Table 2.

Consider first the estimates using world-wide technology spillovers. The estimation results in 5-year differences are presented in Table 12. The parameter estimates of growth in the domestic and foreign innovative activity and the domestic and foreign research intensity are almost the same as the estimates using trade-based spillovers as reported in Table 2.

Finally, consider the estimates based on distance-weighted technology spillovers. The estimation results in 5-year differences are presented in Table 13. The parameter estimates of growth in the domestic innovative activity and the domestic research intensity are almost the same as the estimates using trade-based spillovers as reported in Table 2. The estimated coefficients of growth in the foreign innovative activity and the foreign research intensity are slightly more significant than their counterparts reported in Table 2, which suggests that geographical proximity is as least an important international channel of technology transmission than the trade-based transmission.

Table 13. Parameter estimates of (10) in 5-year differences where the spillover variables are based on distance-weighted spillovers (Eq. (13) and Eq. (14)).

$\frac{X}{Q}$	$\frac{R\&D}{TFP \cdot S^{TM}}$ **Imp wgt**	$\frac{R\&D}{Y}$ **Imp wgt**	$\frac{R\&D}{TFP \cdot L}$ **Imp wgt**	Pat^a / S^{TM} **Imp wgt**	Pat^a / L **Imp wgt**	Pat^g / S^{TM} **Imp wgt**	Pat^g / L **Imp wgt**
$\Delta \ln X^d$	0.029(2.18)	0.033(2.31)	0.031(2.29)	0.017(1.57)	0.009(0.74)	-0.001(0.39)	0.000(0.68)
$\Delta \ln X^f$	0.029(0.76)	0.250(2.54)	0.235(2.44)	0.106(3.51)	0.102(3.15)	0.070(2.83)	0.000(0.04)
$(X/Q)^d$	0.008(10.7)	0.993(9.92)	0.001(1.35)	0.057(3.02)	-0.041(1.34)	0.032(1.72)	0.008(0.33)
$(X/Q)^f$	0.117(2.91)	10.04(4.64)	9.58(4.42)	0.534(4.41)	0.182(1.48)	0.941(4.16)	0.087(0.80)
DTF	0.227(4.91)	0.290(4.94)	0.273(4.82)	0.244(4.59)	0.274(5.49)	0.206(4.15)	0.308(5.74)
R^2	0.56	0.56	0.56	0.55	0.53	0.54	0.49

Note. See notes to Table 2.

Overall the results in sub-section suggest 1) that the innovative activity is transmitted internationally globally and locally through geographical proximity and world-wide independently of trade in goods and geographical proximity; and 2) that the tests of Schumpeterian versus semi-endogenous theory are insensitive as to the channel of international transmission of technology.

6.5 Multiplying imports of technology with the propensity to import

In the seminal paper of Coe and Helpman (1995) the influence on TFP of knowledge transmission through the channel of imports is conditional on the propensity to import. Modifying Eq. (8) and (10) to allow for foreign variables that are conditional on the propensity to imports, yields the equations:

$$\ln A_{it} = \alpha_{0,i} + \alpha_1 \ln Q_{it}^d + \alpha_2 \ln X_{it}^d + \alpha_3 im_{it} \ln Q_{it}^f + \alpha_4 im_{it} \ln X_{it}^f + \varepsilon_{4,it}, \tag{15}$$

$$\begin{aligned}\Delta \ln A_{it} &= \beta_{0,i} + \beta_1 \Delta \ln X_{it}^d + \beta_2 im_{it} \Delta \ln X_{it}^f + \beta_3 im_{it} \ln(X/Q)_{it}^d \\ &\quad + \beta_4 \ln(X/Q)_{it}^f + \beta_5 \left(\frac{Y_{t-1}^{\max} - Y_{i,t-1}}{Y_{t-1}^{\max}} \right) + \varepsilon_{5,it},\end{aligned} \tag{16}$$

where *im* is the propensity to import, which is measured as imports of goods divided by nominal GDP. Eq. (16) is only estimated in 5-year differences. Note that Eq. (15) tests only semi-endogenous growth theories while Eq. (16) is a test for semi-endogenous growth theories as well as a test for Schumpeterian theories.

Table 14. Cointegration estimates (Eq. (15)).

$\ln A_t = \underset{(2.26)}{0.09}\ln Pat_t^a - \underset{(0.05)}{0.01}\ln L_t - \underset{(0.43)}{0.31} im_t \ln Pat_t^{im,a} - im_t \underset{(0.34)}{0.13}\ln L_t^{im} \qquad z=-6.77[0.00]$
$\ln A_t = -\underset{(1.82)}{0.08}\ln Pat_t^a + \underset{(5.46)}{0.54}\ln Y_t - \underset{(0.16)}{0.02} im_t \ln Pat_t^{im,a} + \underset{(0.62)}{0.06} im_t \ln Y_t^{im} \qquad z=-1.97[0.02]$
$\ln A_t = \underset{(1.90)}{0.08}\ln Pat_t^a + \underset{(1.26)}{0.05}\ln S_t^{TM} - \underset{(4.23)}{0.27} im_t \ln Pat_t^{im,a} - \underset{(0.15)}{0.02} im_t \ln S_t^{im,TM} \qquad z=-6.79[0.00]$
$\ln A_t = \underset{(1.29)}{0.04}\ln Pat_t^g - \underset{(0.08)}{0.12}\ln L_t - \underset{(6.56)}{0.55} im_t \ln Pat_t^{im,g} - \underset{(0.49)}{0.17} im_t \ln L_t^{im} \qquad z=-6.42[0.00]$
$\ln A_t = -\underset{(1.35)}{0.04}\ln Pat_t^g + \underset{(11.5)}{0.47}\ln Y_t - \underset{(0.22)}{0.01} im_t \ln Pat_t^{im,g} + \underset{(0.62)}{0.05} im_t \ln Y_t^{im} \qquad z=-3.54[0.00]$
$\ln A_t = \underset{(0.98)}{0.05}\ln Pat_t^g + \underset{(3.13)}{0.20}\ln S_t^{TM} - \underset{(3.17)}{0.23} im_t \ln Pat_t^{im,g} + \underset{(0.81)}{0.17} im_t \ln S_t^{im,TM} \qquad z=-3.82[0.00]$

Note. See notes to Table 1.

The results of estimating Eq. (15) are presented in Table 14. The results have not changed much compared to the estimates in Table 1 where the foreign variables have not conditional on the propensity to import. The estimated coefficients of patents are still mostly insignificant or of the wrong sign, suggesting that there is still no support for semi-endogenous growth theory when interactions with trade partners are conditional on the propensity to import.

Table 15. Parameter estimates of Eq. (16) in 5-year differences.

$\frac{X}{Q}$	$\frac{R\&D}{TFP \cdot S^{TM}}$	$\frac{R\&D}{Y}$	$\frac{R\&D}{TFP \cdot L}$	$\frac{Pat^a}{S^{TM}}$	Pat^a / L	Pat^g / S^{TM}	Pat^g / L
$\Delta \ln X^d$	0.031(2.27)	0028(2.15)	0.025(1.9)	0.015(1.40)	0.013(1.23)	-0.002(0.52)	-0.018(0.44)
$\boldsymbol{\Delta im \cdot lnX^f}$	0.006(0.04)	0.211(1.34)	0.196(1.22)	-0.044(0.67)	-0.019(0.29)	-0.027(0.59)	-0.025(0.55)
$(X/Q)^d$	0.008(7.00)	0.007(10.6)	0.001(1.34)	0.057(2.90)	0.017(1.31)	0.011(0.42)	0.021(0.99)
$im(X/Q)^f$	0.128(1.37)	-11.7(2.31)	-10.4(2.03)	0.204(2.64)	0.267(2.92)	0.608(0.95)	0.647(1.03)
DTF	0.251(5.41)	0.238(4.65)	0.263(4.74)	0.242(4.59)	0.275(5.81)	0.291(6.35)	0.292(6.41)
R^2	0.54	0.55	0.52	0.52	0.53	0.50	0.50

Note. See notes to Table 2.

Considering the estimates of Eq. (16) in Table 15 the coefficients of growth in the innovative activity and research intensity are quite similar to the estimates reported in Table 2. Thus the conclusions regarding Schumpeterian versus semi-endogenous growth theories obtained in Section 5 remain. The coefficient of $\Delta im \cdot lnX^f$ is rendered statistically insignificant in all cases and the estimated coefficient of $im(X/Q)^f$ is significantly negative in two cases. Finally, the estimated coefficients of distance to the frontier remain highly significant.

6.6 Allowing for changing slope coefficients

Thus far the estimated coefficients have been assumed to be constant over the whole estimation period. However, in the cointegration estimates covering the period from 1900 to 2003 the slope coefficients may not be constant over time because of measurement errors, omitted variables or because the models are inadequate. Of particular concern is that the value of each patent count and the propensity to patent may have changed over time. To investigate these issues the slope coefficients are allowed to vary in Equations (8) and (9) in the following three periods: 1900-1913, 1914-1944, and 1945-2003. Economic relationships may have changed in the period 1914-1945 due to two world wars, the Great Depression, the 1921 depression and the high inflation period following WWI. Furthermore, the period from 1913 to 1945 is likely to be a period in which the variables are measured with errors.

To allow for the changing slope coefficient, Equations (8) and (9) are augmented with the variables $X \cdot D00-13$ and $X \cdot D45-03$, where X is a vector of all the independent variables in the model (excluding the deterministic variables), D00-13 is a dummy variable taking the value of one before 1913 and zero elsewhere, and D45-03 is a dummy variable taking the value of 1 over the period from 1945 to 2003 and zero elsewhere. The joint significance of the *X*-variables is reported in Table 16.

Considering first the tests of Schumpeterian theories, which are displayed in the upper half of Table 16, the results are almost unaltered compared to the results in Table 1, in which slope constancy are imposed on the coefficient estimates. However, the estimates in which the fixed effect dummies are excluded, give more support for the Schumpeterian model than the estimates in Table 1. Furthermore, in none of the cases are the estimated coefficients of the *X*-variables significantly differently from zero, which suggests that the joint hypothesis of structural stability and constancy in the propensity to patent and constancy of the average value of patents, cannot be rejected at conventional significance levels.

The tests of semi-endogenous growth theories are displayed in the lower half of Table 16. In the estimates in which patent counts is the only explanatory variable the joint null hypothesis of structural stability and constancy of the propensity to patent and constancy of the average value of patents, is rejected at any conventional significance level. Furthermore, the estimated coefficients of patents remain insignificant in all these estimates. In the other estimates where proliferation variables are included in the models the estimates are structurally stable in the sense that the null hypothesis of structural stability cannot be rejected at the 5% levels. Moreover, the null hypothesis of no cointegration cannot be rejected at conventional significance levels.

In summary the estimation results in Table 16 reinforce the conclusion reached in Section 5 that Schumpeterian theories are predominantly consistent with the data while the Semi-endogenous growth models are not, when the slope coefficients are allowed to change over time. The extent to which the propensity to patent and the average value of a patent has changed over time cannot be revealed from the estimates in Table 16. However, the finding that the conclusion in Section 5.3 has not changed significantly when the slope coefficients are allowed to change over time gives some indication that the results in Section 5.3 have not been driven by changing propensity to patent and changing average values of patents and errors-in-variables.

Table 16. Cointegration estimates (Eq. (8) and Eq. (9)) with changing slope coefficients.

Schumpeterian
$\ln Pat_t^a = \underset{(0.21)}{0.81} \ln L_t \quad z = -5.18[0.00] \quad \chi^2(2) = 2.8$
$\ln Pat_t^a = \underset{(4.14)}{0.54} \ln Y_t \quad z = -8.22[0.00] \quad \chi^2(2) = 3.6$
$\ln Pat_t^a = \underset{(2.23)}{0.27} \ln S_t^{TM} \quad z = -5.63[0.00] \quad \chi^2(2) = 1.8$

$\ln Pat_t^g = \underset{(1.23)}{0.43} \ln L_t \quad z = -24.30[0.00] \quad \chi^2(2) = 3.1$
$\ln Pat_t^g = \underset{(2.71)}{0.38} \ln Y_t \quad z = -25.80[0.00] \quad \chi^2(2) = 3.1$
$\ln Pat_t^g = \underset{(0.56)}{0.06} \ln S_t^{TM} \quad z = -24.80[0.00] \quad \chi^2(2) = 4.2$
No fixed effect dummies
$\ln Pat_t^a = \underset{(6.37)}{1.02} \ln L_t \quad z = +0.63[0.73] \quad \chi^2(2) = 1.28$
$\ln Pat_t^g = \underset{(9.23)}{1.03} \ln L_t \quad z = -9.93[0.00] \quad \chi^2(2) = 1.3$
$\ln Pat_t^g = \underset{(1.91)}{0.70} \ln Y_t \quad z = -2.91[0.00] \quad \chi^2(2) = 2.4$
$\ln Pat_t^g = \underset{(3.58)}{0.67} \ln S_t^{TM} \quad z = -3.89[0.00] \quad \chi^2(2) = 2.2$
Semi-endogenous
$\ln A_t = \underset{(1.72)}{0.13} \ln Pat_t^a \quad z = -5.07[0.00] \quad \chi^2(2) = 17.4$
$\ln A_t = \underset{(0.36)}{0.03} \ln Pat_t^a + \underset{(0.89)}{0.16} \ln L_t + \underset{(0.29)}{0.06} \ln Pat_t^{im,a} + \underset{(1.17)}{0.56} \ln L_t^{im} \quad z = -5.40[0.01] \quad \chi^2(8) = 6.26$
$\ln A_t = -\underset{(1.72)}{0.09} \ln Pat_t^a + \underset{(5.98)}{0.57} \ln Y_t - \underset{(0.65)}{0.07} \ln Pat_t^{im,a} + \underset{(0.75)}{0.12} \ln Y_t^{im} \quad z = -3.90[0.00] \quad \chi^2(8) = 13.4$
$\ln A_t = \underset{(0.71)}{0.05} \ln Pat_t^a + \underset{(1.05)}{0.07} \ln S_t^{TM} + \underset{(0.13)}{0.03} \ln Pat_t^{im,a} + \underset{(0.82)}{0.34} \ln S_t^{im,TM} \quad z = -5.63[0.00] \quad \chi^2(8) = 7.5$
$\ln A_t = \underset{(0.06)}{0.00} \ln Pat_t^g \quad z = -5.82[0.00] \quad \chi^2(2) = 19.4$
$\ln A_t = \underset{(0.11)}{0.01} \ln Pat_t^g + \underset{(0.88)}{0.06} \ln L_t - \underset{(0.20)}{0.03} \ln Pat_t^{im,g} + \underset{(1.33)}{0.64} \ln L_t^{im} \quad z = -5.43[0.00] \quad \chi^2(8) = 5.6$
$\ln A_t = -\underset{(0.46)}{0.04} \ln Pat_t^g + \underset{(6.87)}{0.50} \ln Y_t - \underset{(0.25)}{0.01} \ln Pat_t^{im,g} - \underset{(0.24)}{0.02} \ln Y_t^{im} \quad z = -6.34[0.00] \quad \chi^2(8) = 5.8$
$\ln A_t = \underset{(0.49)}{0.02} \ln Pat_t^g + \underset{(1.43)}{0.08} \ln S_t^{TM} - \underset{(0.62)}{0.10} \ln Pat_t^{im,g} + \underset{(0.29)}{0.03} \ln S_t^{im,TM} \quad z = -7.31[0.00] \quad \chi^2(8) = 12.7$
No fixed effect dummies
$\ln A_t = -\underset{(0.30)}{0.01} \ln Pat_t^a \quad z = -2.63[0.00] \quad \chi^2(2) = 16.3$
$\ln A_t = -\underset{(0.58)}{0.02} \ln Pat_t^g \quad z = -2.63[0.00] \quad \chi^2(2) = 16.0$

Notes. See notes to Table 1. $\chi^2(k)$ is a Wald test for the null hypothesis that the estimated coefficients of the *X* variables are zero and is distributed as a Chi-square under the null hypothesis. The *X*-variables composes of $X \cdot D00-13$ and $X \cdot D45-03$ where *X* is a vector of all the independent variables in the model (excluding the deterministic variables), *D*00-13 is a dummy variable taking the value of one before 1913 and zero elsewhere, and *D*45-03 is a dummy variable taking the value of 1 over the period from 1945 to 2003 and zero elsewhere.

7 Causality and endogeneity

Thus far it has been assumed that the explanatory variables are exogenous. However, it cannot be ruled out that there is a significant feedback from TFP growth to innovative activity due to a

Tobin's q effect, as discussed in the next paragraph. To ensure that the results in the previous section are not subject to a simultaneity bias, this section undertakes Granger causality tests and uses instruments for innovative activity to examine further the endogeneity and simultaneity issues. In any event, it should be kept in mind that Granger causality tests only yield information about precedence and that the instrumental variable method is well-known for giving misleading results when the instruments are weak (Nelson and Startz, 1990).

There is a potential two-way relationship between the domestic innovative activity and TFP growth through the channel of Tobin's q. The price of a stock and, therefore, Tobin's q are, under the assumption of perfect competition in the labour and goods markets and Cobb-Douglas technology, are given by:[10]

$$q = \frac{MP_K}{\rho} = \frac{\alpha(Y/K)}{\rho},$$

where ρ is the required stock returns and MP_K is the actual marginal productivity of capital, which, for simplicity, is set equal to the expected marginal productivity of capital.[11] A technological innovation increases A and, consequently, MP_K and Tobin's q, which in turn initiates a capital deepening process. The capital deepening continues until Tobin's q is back to its steady state level under the assumption of diminishing returns to capital. Since capital stock includes both tangibles and intangibles in the Tobin's q model, the capital deepening also involves investment in R&D. This establishes a feed-back effect from TFP to R&D investment.

7.1 Granger causality tests

Using annual data, the following Granger causality test is undertaken:

$$\Delta Z_{i,t} = a_0 + a_1 \Delta Z_{i,t-1} + a_2 \Delta Z_{i,t-2} + a_3 \Delta Y_{i,t-1} + a_4 \Delta Y_{i,t-2} + \varepsilon_{4,it},$$

where Z is the *lnA* and Y is the technology indicator in the first round regression. In the second round regression, the Z is the technology indicator and Y is the *lnA*. The estimates are pooled across the G21 countries to gain efficiency.

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[10] For stock prices to be equal to Tobin's q, stock prices must be measured in real terms and all earnings have to be paid out as dividends.

[11] For a formal derivation of this valuation model and a discussion of the relationship between Tobin's q and stock prices, see Madsen and Davis (2006). Madsen and Davis (2006) also formally show the relationship between investment in R&D, TFP growth, and Tobin's q.

To gain further efficiency in the estimates, the covariance matrix is weighted by the correlation of the disturbance terms using the variance-covariance structure as follows:

$$E\{\varepsilon_{it}^2\} = \sigma_i^2, \quad i = 1, 2,... N,$$
$$E\{\varepsilon_{it},\varepsilon_{jt}\} = \sigma_{ij}, \quad i \neq j,$$

where σ_i^2 is the variance of the disturbance terms for country i = 1, 2,... N, σ_{ij} is the covariance of the disturbance terms across countries i and j, and ε is the disturbance term. The variance σ_i^2 is assumed to be constant over time but to vary across countries and the error terms are assumed to be mutually correlated across countries, σ_{ij}, as random shocks are likely to impact all countries at the same time. The parameters σ_i^2 and σ_{ij} are estimated using feasible generalized least squares.

The test results are presented in Table 14. The first column shows the results of regressing TFP growth on the growth rate in the innovative activity following the predictions of semi-endogenous growth theory. The estimates show that none of the estimated coefficients of the variables for the domestic innovative activity are statistically significant at conventional significance levels. These results are, to a large extent, consistent with the estimation results in the previous sections. The estimates in the second colomn show that TFP does not precede any of the technology variables and that the estimated coefficients of TFP growth are only significant when the estimated coefficients are negative.

Table 17. Granger causality tests.

Semi-endogenous growth models			Schumpeterian growth models		
X variable	*A* on LHS	*A* on RHS	*X* variable	*A* on LHS	*A* on RHS
$\Delta \ln(pat^a)^d$	-0.42	-2.52	$(pat^a / S^{TM})^d$	3.08	-0.14
$\Delta \ln(pat^g)^d$	-0.58	-2.50	$(pat^a / L)^d$	0.00	-1.55
$\Delta \ln(R\&D)^d$	0.15	-0.15	$(pat^a / Y)^d$	1.34	-2.11
			$(R\&D / A \cdot S^{TM})^d$	3.36	0.54
			$(R\&D / A \cdot L)^d$	1.07	-1.60
			$(R\&D / Y)^d$	3.37	-0.84
$\Delta \ln(R\&D)^f$	-0.47	-2.42	$(R\&D / A \cdot S^{TM})^f$	3.88	-0.28
$\Delta \ln(pat^a)^f$	2.60	-0.63	$(pat^a / S^{TM})^f$	2.76	0.80
$\Delta \ln(pat^g)^f$	3.02	-0.60	$(pat^a / L)^f$	3.50	0.46
			$(R\&D / Y)^f$	1.62	-2.43

Notes. The numbers are *t*-tests of the null hypothesis that the coefficients of the lagged *X*-variables are jointly zero. Estimation period 1969-2004. All G21 countries are included in the estimates. Two lags are included in the estimates.

Turning to Schumpeterian growth theories, the tests presented in the third and fourth columns in Table 17 show that both domestic and foreign research intensities are significant predictors of TFP growth, whereas TFP does not precede research intensity, regardless of how research intensity is measured. Only in the case where employment is the denominator of the research intensity variable is there no evidence that research intensity precedes TFP growth, which is consistent with the results in the previous section that working hours may, in some instances, be a less useful proxy for product variety. These results are strongly in favour of the Schumpeterian growth theory of growth and suggest that very little, if any, of the research intensity is driven by TFP growth. If some of the research intensity is driven by TFP growth, it should have been revealed by the Granger causality tests, since the Tobin's *q* model predicts that R&D takes time to adjust to innovations in TFP due to convex adjustment costs.

A remarkable result is that foreign research intensity and, to some extent also the growth in international research activity, is highly significant in explaining TFP growth. This result highlights the importance of international spillover effects and, at the same time, reinforces the finding above that foreign research intensity, particularly, is an important engine of TFP growth.

7.2 Instrument variable estimates

The instrumental variable (IV) method is difficult to apply to Eq. (10), because only weak instruments are available in the estimates in 10 and 20 year differences. The IV estimates, therefore, are undertaken only for the 5-year difference estimates. The following instruments are used to represent innovative activity: one period lag of the innovative activity (i.e. one period lag of all endogenous variables in each equation), time-dummies, and contemporaneous and one period lag of dividend yield the *ex post* real interest rate (nominal interest rate minus contemporaneous consumer price inflation). Dividend yield, which is the ratio of dividends and stock prices, and the real interest rate are used as discount factors for the expected returns to R&D, thus being important for the R&D decision. An increase in the real cost of capital, for example, implies that the future reward from current-period R&D investment is discounted at a higher rate and, therefore, lowers the present value of the returns from R&D investment.

Table 18. Instrument variable estimates of Eq. (10) in 5-year differences.

$\frac{X}{Q}$	$\frac{R\&D}{TFP \cdot S^{TM}}$	$\frac{R\&D}{Y}$	Pat^a / S^{TM}	Pat^g / S^{TM}
$\Delta \ln X^d$	-0.016(0.04)	0.042(0.27)	-0.003(0.09)	-0.008(0.69)
$\Delta \ln X^f$	-0.031(0.24)	-0.046(0.42)	-0.018(0.46)	0.009(0.19)
$(X/Q)^d$	-0.001(2.12)	-0.001(0.42)	0.016(3.28)	0.001(0.37)
$(X/Q)^f$	0.020(1.16)	-0.772(1.01)	0.020(0.74)	0.022(0.94)
Sargan	6.22	7.77	8.16	9.87
R^2	0.43	0.42	0.43	0.42

Notes. See notes to Table 2. Estimation period: 1970-2004. Import weighted spillovers are used. The following instruments are used: One period lags of innovative activity, time-dummies, and contemporaneous and one period lags of the *ex post* real bond rate and dividend yield. Sargan = Sagan's test of overidentifying restrictions and is distributed as $\chi^2(8)$ under the null hypothesis of instrument validity.

The results of estimating Eq. (10) using the IV method are shown in Table 18. Only the key estimates are presented. The instruments are adequate. The Sargan tests do not reject the null hypothesis instrument validity (the critical value of $\chi^2(8)$ at the 1% level is 20.09). Second, the R^2 in the first round regressions are, on average, 0.67, which suggests that the instruments are relatively highly correlated with the endogenous variables.

The estimated coefficients of domestic R&D growth and growth in domestic patents are statistically insignificant at conventional significance levels in all the estimates. The estimated coefficient of the ratio of patents applied for and trade mark capital stock (third column) is quite significant, whereas the other estimated coefficients of domestic research intensity are statistically insignificant. Overall, the IV estimation results in Table 18 are less favourable to the Schumpeterian growth model than are the OLS estimates, however, they do not overturn the OLS results.

8 Concluding remarks

Using various model specifications and estimators, this paper has examined whether second-generation growth models can account for TFP growth for the OECD countries over time and across countries. The tests show that semi-endogenous growth theories cannot adequately account for the level and the growth in TFP over time and across countries. The Schumpeterian growth theory is, to a large extent, consistent with the time-series evidence: 1) domestic and foreign research intensities are, to a large extent, able to account for TFP growth; 2) research intensities Granger-cause TFP, and 3) the innovative activity and product variety are cointegrated. Furthermore, it was shown that TFP growth is positively related to the distance to the frontier, which is also consistent with the predictions of Schumpeterian growth theory. Finally, the paper found that TFP growth is enhanced by international technology spillover effects through the channel of imports of intermediate goods, through the channel of geographical proximity and through channels that are independent of trade and geographical proximity. More importantly, it was found that research intensity spillovers consistently influenced TFP growth, while the spillovers of growth in the innovative activity had mixed effects on TFP growth; thus giving further support to Schumpeterian growth theory.

The cross-country evidence was less favourable for the Schumpeterian growth theory than the time-series evidence. The discrepancy between the time-series and the cross-section evidence for the Schumpeterian growth model is a challenge to the Schumpeterian growth theory, to theories that seek to explain cross-country income differences, and to measurement, particularly the variety of goods. Even trademarks, which are probably the closest one can come to measuring the variety of goods, may not completely approximate new goods, and old goods may not disappear by a fixed 20% depreciation rate.

Another empirical challenge ahead is to confront the theories with very long historical evidence, and particularly to investigate whether endogenous growth theories can explain the transition from stagnation in growth to positive growth rates that took place in many European countries around 200 years ago (Galor, 2005). This requires data on innovative activity that go back much further than the century of data used in this study.

DATA APPENDIX

Patents and trademarks. Patents are measured as domestic patents applied for whereas trademarks are measured as foreign plus domestic trademarks applied for, where foreign patents are included because trademarks decomposed into domestic and foreign trademarks are not readily available for many countries back in history. The following sources are used. Federico, P J, 1964, "Historical Patent Statistics 1791-1961," *Journal of the Patent Office Society*, 46, 89-171, World Intellectual Property Organisation, 100 Years of Industrial Property Statistics," WIPO Publication No. 876, and World Intellectual Property Organisation, Annual Patent Statistics, http://www.wipo.int/ipstats/en/statistics/patents. National sources are used in the past two years. A complete list of sources is available from the author. USA. Department of Commerce, 1975, *Historical Statistics of the United States: Colonial Times to 1970*, Bureau of the Census: Washington DC. France. M Lévy-Leboyer and F Bourguignon, 1985, *The French Economy in the Nineteenth Century*, Cambridge: Cambridge University Press. Norway. Bjørn L Basberg, 1984, "Patenter og teknologisk endring I Norge 1840-1980. En metodediskusjon om patentdata anvendt som teknologi-indikator," Mimeo, Institutt for Økonomisk Historie, Norges Handelshøyskole, Bergen. UK. B. R. Mitchell, 1962, *Abstract in British Historical Statistics*, Cambridge: Cambridge University Press.

Capital stock of equipment and non-residential structures. The perpetual inventory method is used with the following depreciation rates. 17.6% for Machinery and equipment, and 3% for non-residential buildings and structures. The stock of capital is initially set to the Solow model steady state value of $I_t/(\delta + g)$, where I is investment, δ is the depreciation rate and g is the growth in investment during the period from 1870 to 2004. The post 1960 data are from OECD, *National Accounts, Vol. II,* Paris, *(NA)*. Before 1960 the following sources are used for the countries at which historical data are available**.** Canada. 1870-1900: Both types of investment are assumed to follow total non-residential investment in nominal prices deflated by the CPI. 1901-1925: 5-year average disaggregated into 1-year intervals using total non-residential investment deflated by CPI. Source: F. H. Leacy (ed.), 1983, *Historical Statistics of Canada*, Statistics Canada: Ottawa. United States. Angus Maddison, 1995, *Explaining the Economic Performance of Nations*, Edward Elgar. Japan: 1885-1988: A Maddison (1995) *op cit.*, Backdated to 1870 using the growth rate in total investment from Maddison (1995) *op cit*. 25.7% war damage to the 1945 capital stock is incorporated into the capital stock following Maddison (1995) *op cit*. Australia: 1863-1902: C. Clark, 1970, "Net Capital Stock," *Economic Record*, pp. 449-466. 1903-1950: M. W. Butlin, 1977, *A Preliminary Annual Database 1900/01 to 1973/74*, Research Discussion Paper 7701, Reserve Bank of Australia: Sydney. Belgium. M. van Meerten, 2003, *Capital Formation in Belgium, 1900-1995*, Leuven: Leuven University Press. Before 1900: The ratio of investment and GDP in 1900 multiplied by real GDP is used backdate the data to 1870. War damage correction: WWI. 15.5% of 1913 GDP spread out evenly between the years 1914-1917. WWII 7.1% spread out evenly on the years 1943-45. The correction for war damage follows van Meerteen, 2003, (see his footnote no. 39). Denmark. 1870-1950: K. Bjerke and Nils Ussing, 1958, *Studier Over Danmarks Nationalprodukt 1870-1950*, G. E. C. Gads Forlag: København. Finland. R. Hjerppe, 1989, *The Finnish Economy, 1860-1985*, Helsinki: Bank of Finland, Government Printing Centre. France. 1856-1895. Total investment deflated by industry prices. E. Chadeau, 1989, *l'Economie Nationale Aux XIX et XX Siecles*, Paris: Presses de l'Ecole normale Superieure. 1896-1914 and 1921-1938. J-J Carre P. Dubois and E. Malinvaud, 1975, *French Economic Growth*, Stanford: Stanford University Press. 1914-1921 and 1939-1949. Crude steel production adjusted. Liesner *op. cit.* War damage of 2% is assumed each year over the periods 1914-17 and 1942-1945 following Maddison, 1995, *op cit*. Germany. W. Kirner, 1968, *Zeitreihen fur das Anlagevermogen der Wirtschaftsbereiche in der Bundesreplublik Deutschland*, Deutsches Institut fur Wirtschaftsforschnung, Duncker & Humbolt: Berlin. The data are adjusted for war damage in the source. Non-residential buildings and structures 1850-1949. The following categories are added together: Land und Forstwirtschaft, Energiewirtschaft, Bergbau, Grundstoff- und Productionguter-industrie, Investeringsguterindustrie, Verbrauchenguterindustrie, Nahrings- und Genussmittel-industrie, Industrie Kleinbetr. und Handwerk, Baugewerbe, Handel, Eisenbahnen, Schifffahrt, Ubringer Verkehr, Nachr. ubermittlg, Kreditintitutionen und Vers. gew., Wohnungsvermietung, Sonst. Dienstleist., Strassen und

Brukken, Wasser strassen und Hafen, and Ubrige staatl. Bereiche. Machinery and equipment 1926-1949. The same categories are added together as for investment in non-residential buildings and structures. 1870-1925: Scaled investment in machinery and equipment for Denmark, using the average over the period 1926-1930 as scaling factor. Italy. Instituto Centrale di Statistica, 1976, *Statistiche Storiche Dell'Italia 1861-1975*. Residential building investment is included in investment in buildings. Only 10-year averages are available before 1945. The data are uniformly distributed within the 10-year intervals. Netherlands. 1800-1913: J-P Smits, E Horlings, and J L van Zanden, 2000, *Dutch GNP and its Components, 1800-1913*, Groningen, http://www.eco.rug.nl/ggdc/PUB/dutchgnp.pdf. The general investment deflator is used as deflator. 1913-60: Central Bureau voor de Statistiek, 2001, *Tweehondred Jaar Statistiek in Tijdreeksen, 1800-1999*, Centraal Bureau voor de Statistiek, Voorburg. 10% war damage is evenly spread out over the years 1943-1945. Norway. Statistisk Sentralbyraa, 1968, *Nasjonalregnskap*, Oslo. 1865-1930: The investment data are derived from capital stock and official depreciation rates using the following formulae for buildings and equipment, respectively: $I_t^{eq} = K_t^{eq} - K_{t-1}^{eq}(1-0.15)$ and $I_t^{st} = K_t^{st} - K_{t-1}^{st}(1-0.02)$. 1930-1949: The data are interpolated from 1940 to 1945 using the algorithm which is suggested by V. Gomez and A. Maravall, 1994, “Estimation Prediction and Interpolation for Nonstationary Series with the Kalman Filter,” *Journal of the American Statistical Association*, 89, 611-624. The general investment price deflator is used to adjust the *pre* 1940 data which are in 1938 prices, whereas the *post* 1945 data are in 1955 prices. Spain. A. Carrearas (ed), 1989, Estsdisticas Historicas De Espana, Madrid: Fundacion Banco Exterior. 1850-1960: The growth rate in total investment is used to backdate investment in structures and machinery, respectively. Sweden. 1861-1949. O. Krantz and C. A. Nilsson, 1975, *Swedish National Product 1861-1970*, C. W. K. Gleerup. Investment in buildings include residential investment. Switzerland. Ritzmann-Blickenstorfer, 1996, *Historical Statistics of Switzerland*, Zurich: Chronos. The growth rate in total investment is used to backdate the data from 1922. UK. Maddison ,1995, *op cit*. An annual 3.5% war damage is corrected for in the estimates during the 1943-45 period.

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