Macroeconomic Dynamics, 2013, Page 1 of 37. Printed in the United States of America.
doi:10.1017/S1365100513000229

WHAT DRIVES IDEAS PRODUCTION ACROSS THE WORLD?

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The ideas production function is at the heart of endogenous growth theory. Using data for Europe, its offshoots, and the Asian Tiger economies over the period from 1870 to 2010, this paper provides direct estimates of an ideas production function that explicitly distinguishes between the first- and second-generation endogenous growth models while allowing for human capital and international knowledge spillovers through various channels. The estimates show strong intertemporal and cross-country knowledge spillovers, provide robust support for Schumpeterian growth theory, and suggest that human capital and some channels of international knowledge spillover are influential for ideas production.

Keywords: Ideas Production, Schumpeterian Growth Models, International Knowledge Transmission

1. INTRODUCTION

The ideas production function is at the heart of endogenous and unified theories of economic growth. In these theories, productivity growth is the result of technological progress, which in turn is a function of the production of new ideas. Broadly speaking, ideas are produced by a combination of conscious R&D efforts and intertemporal knowledge spillovers. The ideas production function gives important insights into the role of the knowledge production sector as an engine of growth, the growth effects of R&D, duplication effects of R&D effort, R&D productivity, the presence of product proliferation, and intertemporal and spatial knowledge spillovers.

Using a unique data set covering 26 countries over the period from 1870 to 2010, this paper provides direct estimates of the ideas production function to discriminate between various endogenous growth theories and to provide some insights into cross-country knowledge spillovers. Measured in terms of domestic patent applications, the country sample in this paper produced 93.4% of the world's innovations during the period 2000–2006, suggesting that the sample includes

Helpful comments and suggestions from two referees are much appreciated. We also gratefully acknowledge financial support from the Australian Research Council (James Ang & Jakob Madsen: DP120103026; Jakob Madsen: DP110101871). Address correspondence to: James B. Ang, Department of Economics, Monash University, 900 Dandenong Road, Caulfield East, Vic 3145, Australia; e-mail: James.Ang@monash.edu.

 1365-1005/13

almost all the world's ideas production [see the Data Appendix (Appendix B) for data sources].

The estimates explicitly distinguish between the predictions of the first-generation endogenous growth models of Romer (1990) and Aghion and Howitt (1992) and the two leading second-generation growth models, i.e., the semi-endogenous growth model of Segerstrom (1998) and the Schumpeterian growth models of Aghion and Howitt (1998), Peretto (1998), Howitt (1999) and Peretto and Smulders (2002), while allowing for various channels of knowledge transmission and human capital. As such, the estimates not only give insight into the creation and international transmission of ideas but also shed some light on the functional form of the ideas production function.

In spite of its importance, little is known about the functional form of ideas production. The empirical papers of Ha and Howitt (2007), Madsen (2008b), Madsen et al. (2010), and Venturini (2012) have tested the implications of the ideas production function and used the results to differentiate between various first- and second-generation models of growth. However, these studies do not directly examine whether there are constant returns to the knowledge stock in ideas production, measure ideas production by total factor productivity (TFP) or by labor productivity, do not test the relationship between ideas production and innovative activity, and do not pay specific attention to the spillover effects. One of the problems associated with TFP and labor productivity estimates is that they are only indirect measures of ideas production and are, as such, subject to potential measurement errors. Griliches (1979) has demonstrated that productivity accounts are strongly biased and that productivity cannot be measured in many sectors of the economy. Aghion and Howitt (1998, pp. 442–447) show formally that TFP and GDP growth rates are significantly underestimated because quality improvements are hard to incorporate into national accounts.[1] Furthermore, TFP is influenced by factors that may be unrelated to ideas production, such as factor utilization, efficiency of production, and sectoral change.

More importantly, some productivity-based tests of endogenous growth theories rely on the assumption that economies are in their steady state. The long time span of transitional dynamics and the fact that economies are constantly exposed to shocks render the parameter estimates in these regressions potentially biased. Because transitional dynamics move toward infinity as the scale parameter approaches one, economies are likely to be constantly outside their steady state. The ideas production function, in contrast, holds regardless of whether an economy is in its steady state or transiting between steady states. Thus, the ideas production function is an ideal testing ground to discriminate between various endogenous growth theories, to uncover factors that determine the production of ideas and how ideas flow between countries.

Direct estimates of the ideas production function are sparse. The studies of Porter and Stern (2000), Ulku (2007a, 2007b), and Ang and Madsen (2011) are among the few papers that have estimated an ideas production function. However, Porter and Stern (2000) do not allow for product proliferation effects as predicted by the Schumpeterian growth models, cover only a short sample period (1973–1993/2000), omit human capital influences, consider only foreign patents filed in the United States, and allow for only limited cross-country ideas spillovers. Furthermore, their study is troubled by the finding of constant or increasing returns to knowledge. Because they do not allow for proliferation effects in R&D, these results imply that productivity is growing proportionally with the number of R&D workers—a prediction that contradicts the empirical evidence [see, e.g., Jones (1995)].

The studies of Ulku (2007a, 2007b) and Ang and Madsen (2011) both allow for proliferation effects in the ideas production function; however, they consider only a limited sample, pay little attention to international knowledge spillovers, and use only domestic patents [Ang and Madsen (2011)] or patents to nonresidents in the United States [Ulku (2007a, 2007b)]. Moreover, the role of educational attainment is not considered by Ang and Madsen (2011). Whereas Ulku (2007a) uses patent applications for four manufacturing sectors in 17 OECD countries in the United States over the period 1981–1997, Ulku (2007b) considers patent applications filed by 41 countries over the period 1981–1997, and Ang and Madsen (2011) provide estimates for six Asian countries over the period 1953–2006.

This paper makes three contributions to the literature. First, it is the first study to use long historical data covering the period 1870–2010, during which increases in per capita income were substantially higher than in the entire period of human history prior to 1870. The use of long historical data on patent applications for 26 countries not only enables us to estimate the panel with five-year intervals but also enhances the efficiency of the estimates by allowing for the cross-country correlation in the residuals. Furthermore, the long time series data cover important milestones in history, such as two industrial revolutions, two economic depressions, and two world wars, thus supplying plenty of identifying variations in the data while allowing for large medium-term movements in innovation. Second, the influences of human capital and international knowledge transmission on ideas production through various channels are examined. The channels of knowledge spillover considered are imports, geographic distance, patent flows, no particular channel, and distance to the frontier.

Third, long historical data for patents granted to foreign residents in the following three industrial powerhouses since the beginning of the Second Industrial Revolution in 1870 are used: the United States, the United Kingdom, and Germany. Although the United States has been the technology leader in terms of number of patent applications during the period 1870–2010, the United Kingdom and Germany each accounted for almost half as many domestic patents as the United States before WWII. Taken together the United States, the United Kingdom and Germany accounted for 88% (76%) of the domestic patent applications in the 26 sample countries used here in 1870 (1950) and, as such, were the world's technological powerhouses up to 1950. Although the United States, the United Kingdom, and Germany are still among the world's most innovative countries, their share of the 26 countries' domestic patent applications has decreased somewhat to 37% in 2010 because of a surge in innovative activity among the Asian Miracle economies, particularly China, Japan, Korea, and Taiwan.[2]

The paper proceeds as follows. The next section outlines and discusses the implications of the ideas production function. Section 3 formulates the empirical specification for testing the validity of each ideas production function as implied by different innovation-driven endogenous growth models. The results are presented in Section 4 and robustness checks are presented in Section 5. The last section concludes the paper.

2. THE IDEAS PRODUCTION FUNCTION

In endogenous growth models, TFP growth is driven by technological progress, which is in turn generated by the production of new ideas. Consider the homogenous Cobb–Douglas production function,

$$Y = AK^{\pi} L^{1-\pi}, \quad (1)$$

where Y is output, A is the stock of ideas or knowledge, K is capital, L is labor, and π is capital's income share. Technological progress is governed by the following closed-economy ideas production function [see, e.g., Ha and Howitt (2007); Madsen (2008b)]:[3]

$$\dot{A} = \lambda \left(\frac{X}{Q^{\beta}} \right)^{\sigma} A^{\phi}; \quad 0 < \sigma \leq 1, \phi \leq 1, \quad (2)$$

where $\dot{A}$ is new ideas, λ is a research productivity parameter, X is R&D effort, Q is product variety, σ is a duplication parameter (which is zero if all innovations are duplications and 1 if there are no duplicate innovations), A is the domestic knowledge stock, ϕ is returns to scale in knowledge, and β is the parameter of product proliferation. The ratio between X and Q, henceforth, will be referred to as research intensity.

The key distinction between various endogenous growth models lies in the values of ϕ and β. In the first-generation endogenous growth models of Romer (1990), Grossman and Helpman (1991), and Aghion and Howitt (1992), TFP growth is positively related to the levels of R&D. The result is an outcome of the assumption of constant-returns-to-knowledge scale effects in ideas production ($\phi = 1$) and the absence of product proliferation effects ($\beta = 0$). The semiendogenous growth model of Segerstrom (1998) abandons the scale effects in ideas production by assuming diminishing returns to the stock of R&D knowledge ($\phi < 1$) and the absence of product proliferation effects ($\beta = 0$). Thus, R&D has to increase continuously to sustain positive TFP growth.

The Schumpeterian growth models of Aghion and Howitt (1998), Peretto (1998), Howitt (1999), and Peretto and Smulders (2002) maintain the assumption of constant returns to the stock of knowledge ($\phi = 1$) and the presence of product proliferation as the economy expands ($\beta > 0$). Thus, growth can still be sustained if R&D remains at a fixed proportion of the number of product lines, which is in turn proportional to the size of the population along the balanced growth path. Consequently, to ensure sustained growth in knowledge, R&D has to increase over time to counteract the increasing range and complexity of products, which lower the productivity effects of R&D activity.

The following ideas production function extends equation (2) by allowing for educational attainment, international technology spillovers through the world knowledge stock, and distance to the frontier:

$$\dot{A} = \lambda \left(\frac{X}{Q^{\beta}} \right)^{\sigma} A^{\phi} (\theta \cdot \text{sch})^{\tau} e^{\nu \Delta \ln(\theta \cdot \text{sch})} (A^{\text{w}})^{\psi - \alpha} e^{\kappa \text{DTF}} (S^{\text{im}})^{\xi} \left(\frac{M}{Y} \right), \qquad \textbf{(3)}$$

where θ is the rate of return to schooling; sch is educational attainment, defined as the average years of schooling of the adult population; A^{w} is the world's knowledge stock (excluding the country in question); DTF is distance to the frontier; S^{im} is knowledge spillovers through the channel of imports; and M/Y is the average propensity to import, where M is nominal imports and Y is nominal GDP. Knowledge spillovers consist of a domestic component (A) and foreign components (A^{w}, S^{im}, and DTF), under the assumption that a country can tap into both the domestic and the foreign knowledge stock.

The first two additional terms in Eq. (3) allow for the production of ideas by educated workers, following the Schumpeterian model of Vandenbussche et al. (2006), in which TFP growth is proportional to educational attainment. This differs from the model of Romer (1990), in which the ideas production of educated people is limited to those who are employed in the R&D sector. The assumption of Romer (1990) that educated people employed outside the R&D sector do not add to ideas production is probably realistic from the perspective that his model was developed to explain growth in the post-WWII period; however, because our estimates start in 1870 and formal R&D was rarely undertaken before WWII, it is possible that educated people not engaged in R&D activity may also have contributed to ideas production for the whole period considered here.

The baseline model allows for four variables of international knowledge spillovers. First, the world knowledge stock, A^{w}, influences ideas production independent of any particular channel of transmission; thus, all countries in the world can tap into the world knowledge stock, because it is freely available to every country. However, A^{w} need not affect ideas production of the individual country positively, as argued by Porter and Stern (2000). On one hand, the larger is the world's knowledge stock, the more opportunities there are for innovators in individual countries to expand on the ideas that are already developed elsewhere—an effect that is captured by the ψ term. On the other hand, international knowledge raises the bar at which ideas are new to the world—an effect that is captured by the α term. Porter and Stern (2000) find that the negative bar effect outweighs the positive spillover effect.

Second, the knowledge spillovers through the channel of imports have often been found to be an effective channel of knowledge spillovers in productivity regressions [see, e.g., Coe and Helpman (1995); Coe et al. (2009)]. This channel of transmission is based on the foundations in many endogenous growth models, in which better-quality intermediate products enhance the quality of final production. Consequently, intermediate products that embody imports of knowledge enhance productivity. Whether this effect also works for ideas production is unclear. If the theory developed to support the spillover channel discussed in Grossman and Helpman (1991) is correct, we would expect innovative production in a country to increase along with increasing stocks of knowledge in the foreign countries from which it imports. There are several mechanisms through which this could occur. For example, imports of high-tech hardware are often a precondition for innovations in medicine, physics, biotechnology, nanotechnology, and chemistry. Furthermore, international expert knowledge, which is predominantly measured as imports of services, is often used in the process of developing new products.

Third, the DTF term captures knowledge transmission across borders through the geographical location of a country and the frontier, as emphasized by Gerschenkron (1952), Dowrick and Gemmell (1991), and Howitt (2000). The further a country is from the technology frontier, the lower are the effective costs of innovation and the higher is the production of new ideas.

The average propensity to import, *M/Y*, is included as the fourth spillover variable in the model to capture globalization waves and their influence on international flows of ideas—an effect that may be potentially important in the regressions in which foreign patents are used. The two globalization waves experienced since 1870 are captured by this openness variable. The first globalization wave, which started in 1870, came to an abrupt halt at the outbreak of WWI. After a long globalization contraction during the interwar period and WWII, globalization started to recover toward the end of the 1960s and has since gained momentum, particularly from the mid-1990s up to the outbreak of the Global Financial Crisis in 2007. Because globalization waves are associated with movements of people across borders, increasing cross-border interaction, and increasing foreign direct investments, it is likely that innovations will be positively related to M/Y as a proxy for globalization.

There are three channels through which globalization can potentially enhance ideas production. First, Gorodnichenko et al. (2010) find that emerging market economies benefit from globalization through the vertical transfer of capability from foreign to domestic firms. Second, globalization may impact positively on innovation through enhanced competition induced by the exposure of domestic firms to more advanced practices and technologies. Finally, enhanced competition may provide incentives for the improved organization of production and greater cost efficiency based on the threat of potential entrance of foreign firms [Gorodnichenko et al. (2010)].

3. ESTIMATION MODEL

3.1. Empirical Specification

Taking logs of equation (3) yields the following general stochastic specification, which nests the first-generation, semiendogenous, and Schumpeterian growth models:

$$\ln \dot{A}_{it} = \alpha_0 + \alpha_1 \ln X_{it} + \alpha_2 \ln Q_{it} + \alpha_3 \ln A_{it} + \alpha_4 \ln(\theta_i \mathrm{sch}_{it}) + \alpha_5 \Delta \ln(\theta_i \mathrm{sch}_{it}) + \alpha_6 \ln A^{\mathrm{w}}_{it} + \alpha_7 \ln DTF_{it} + \alpha_8 \ln S^{\mathrm{im}}_{it} + \alpha_9 \ln \left(\frac{M}{Y}\right)_{it} + \varepsilon_{it}, \tag{4}$$

where Δ is a five-year difference operator and ε is a stochastic error term. $\dot{A}$ is measured by the number of patents applied for by domestic residents; X is measured by real R&D expenditures; Q is measured by real GDP, following Ha and Howitt (2007) and Madsen (2008b); A is measured as the stock of patent applications by domestic residents; sch is measured as the average number of years of schooling among the population of working age; θ is measured as the microeconomic estimated rate of return to schooling for each country, using the estimates of Psacharopoulos and Patrinos (2004); A^{w} is measured as the sum of the patents stock of all countries in the sample excluding the country under consideration; DTF is distance to the frontier and is defined as $(A^{\max} - A)/A$, where $A^{\max}$ is the knowledge stock at the technology frontier, i.e., the United States before 1971 and Japan thereafter; S^{im} is international knowledge spillovers through the import channel; and *M/Y* is import intensity. The first-generation endogenous growth models predict $\alpha_1 > 0$, $\alpha_2 = 0$, and $\alpha_3 = 1$, and semiendogenous growth models predict $\alpha_1 > 0$, $\alpha_2 = 0$, and $0 < \alpha_3 < 1$, whereas Schumpeterian growth models predict $\alpha_1 > 0$, $\alpha_2 < 0$, and $\alpha_3 = 1$.

The level data are measured in five-year averages over the time period that the five-year differences span. The data are measured at five-year intervals to filter out erratic and cyclical fluctuations in patents and to allow adjustment to take place within the five-year period that is covered in the panel. The model is estimated using a FGLS estimator that allows cross-country residual correlation, and the standard errors are heteroskedasticity-consistent, derived using White's procedure. We have not used cointegration regression techniques in the baseline regressions because the dependent variable is found to be stationary, as shown in Table A.1 in Appendix A. Although based on established procedures, these results cannot be taken as providing conclusive evidence on the order of integration of the variables, given that there are many alternative types of unit root test procedures available in the literature with varying degrees of power that may provide different predictions. Hence, to ensure that the estimates are not biased because of the conclusion of our unit root tests, the panel vector error-correction and first-difference estimators are also used in the robustness section under the assumption that the dependent variable contains a unit root.

3.2. Data

Patents applied for by domestic residents, as well as patents granted to nonresidents, in the United States, the United Kingdom, and Germany distributed on countries of residence for 26 countries over the period from 1870 to 2010 are used in the regressions. The sample includes Australia, Austria, Belgium, Canada, China, Denmark, Finland, France, Germany, Greece, India, Ireland, Italy, Japan, Korea, Netherlands, New Zealand, Norway, Portugal, Singapore, Spain, Sweden, Switzerland, Taiwan, the United Kingdom, and the United States.[4] The data sources are listed in Appendix B. The country sample is dictated by the availability of R&D data over a sufficiently long time span. The U.S. sample consists of these 26 countries excluding the United States, whereas patents granted in the United Kingdom and Germany to residents of China, India, Korea, Singapore, and Taiwan are relegated to the "other countries" group in the official statistics and therefore are excluded from these samples.

Patents applied for abroad by residents are not used in the baseline regressions because they are predominantly duplicates of domestic patents. There are important reasons that patents applied for are used in the sample with domestic patents, whereas patents granted are used in the sample containing foreign patents in the United States, the United Kingdom, and Germany. Patents applied for are used in the domestic patent sample, as they are better measures of innovative activity than patents granted for international comparisons, particularly because the granting frequency varies substantially across countries and over time [see Griliches (1990)]. Dernis et al. (2001) find that the time between filing and granting or rejecting the patent varies between two and ten years and differs across countries.

Patents granted to nonresidents are used instead of patents applied for by nonresidents in this sample because the cross-country variation in granting frequency is not an issue when only one destination country is considered. More importantly, patents applied for by foreign residents have recently lost some of their value as indicators of innovative production following the introduction of the Patent Cooperation Treaty (PCT) in the early 1980s. The PCT gives an option that allows a patent application to remain open to present in the future [Dernis et al. (2001)]. Using patents granted statistics overcomes this deficiency.

Although foreign patents granted in the United States, the United Kingdom, and Germany benefit from being processed in a consistent manner and, as such, are not subject to cross-country variations in laws, practices, application fees, and processing time, domestic patents are used in the baseline regressions for two reasons. First, only the most commercially promising patents are filed internationally after one year, because patents filed by domestic residents are protected by member countries of the World Intellectual Property Organization (WIPO). Because foreign patents are, in most cases, inventions made in research laboratories of multinational companies and applied for by company headquarters [OECD (2009, p. 127)] it follows that countries that do not have multinational companies operating in the United States, the United Kingdom, and Germany will file only a fraction of their patents in these countries.

The proportion of patents granted to foreign residents in the United States, the United Kingdom, and Germany was around 10% in 1939, which is approximately the middle of the sample. Foreign patents granted in the United States as a percentage of patents granted to residents in their country of residence were 55.1% for Canadian residents, 11.4% on average for European residents (unweighted), and 0.9% for the Asian residents (unweighted) in 1939. The overall average was 11.6% (unweighted) and 7.2% (weighted). The overall weighted average was 7.1% for patents granted to nonresidents in the United Kingdom in 1939. The corresponding number was 2.9% for Germany in 1939; however, this number is atypical because of the Nazi regime's nationalist policies and was close to the U.S. and U.K. fractions by being 8.9% in 1932. These fractions suggest that caution needs to be applied when drawing conclusions based on foreign patents filed in the major markets.

Second, following the enactment of the Patent Cooperation Treaty (PCT), which has been in force since 1978, the owner of a patent has the option of postponing fees and translation costs for up to 30 months after the priority filing [OECD (2003, p. 53)]. Because the PCT procedure provides an intermediate step between the priority application and filing for patents abroad, the timing between conducting domestic R&D and the filing of a foreign patent will vary from patent to patent, thus rendering estimates of the ideas production function potentially unstable over time. Given that the use of the PCT increased substantially during the 1980s [Madsen (2008a)], the time lag between R&D activity and the filing of patents abroad has been increasing gradually during this transitional period and has rendered the time lag between R&D activity and international patenting particularly unstable.

Knowledge spillovers through the channel of imports, S^{im}, are constructed as follows, following the approach of Lichtenberg and van Pottelsberghe de la Potterie (1998):

$$S_{it}^{\text{im}} = \sum_{j=1}^{26} \left(\frac{M_{ijt}}{Y_{jt}} \right) S_{jt}, \quad i \neq j, \tag{5}$$

where subscript i refers to the recipient country; subscript j refers to the country that provides the technology; and M_{ijt}/Y_{jt} is the propensity of country j to export high-technology products to country i. Finally, the perpetual inventory method with a depreciation rate of 15% for R&D expenditure is used to compute the knowledge stock, and the initial knowledge stock is computed as R&D expenditure in 1870 divided by the depreciation rate and the average annual geometric growth rate in R&D expenditure over the period from 1870 to 2010.

4. EMPIRICAL RESULTS

Results using domestic patents applied for and patents granted to nonresidents in the United States, the United Kingdom, and Germany are presented in this section. First we consider domestic patents.

TABLE 1. Baseline parameter estimates of equation (4) using domestic patent applications

(Dep. var. $= \ln \dot{A}_{it}$)	(1) Basic model	(2) Restricted (first-generation) model	(3) Add human capital variables	(4) Add open economy measures	(5) Full model
$\ln X_{it}$	0.012***	0.002	0.009***	0.031***	0.021***
	(0.001)	(0.001)	(0.002)	(0.002)	(0.002)
$\ln Q_{it}$	−0.013***		−0.037***	−0.019***	−0.035***
	(0.002)		(0.002)	(0.002)	(0.003)
$\ln A_{it}$	0.983***	0.983***	0.999***	0.985***	1.004***
	(0.001)	(0.001)	(0.002)	(0.001)	(0.001)
$\ln(\theta_i \text{sch}_{it})$			0.011		0.011
			(0.007)		(0.007)
$\Delta \ln(\theta_i \text{sch}_{it})$			0.007***		0.003***
			(0.001)		(0.000)
$\ln A^{\text{w}}_{it}$				−0.119***	−0.100***
				(0.006)	(0.006)
DTF_{it}				0.128***	0.096***
				(0.006)	(0.012)
$\ln S^{\text{im}}_{it}$				0.016***	0.004***
				(0.002)	(0.001)
$\ln(M/Y)_{it}$				0.010***	0.038***
				(0.003)	(0.003)
Intercept	−1.341***	−1.433***	−1.236***	0.076	0.036
	(0.018)	(0.012)	(0.020)	(0.075)	(0.075)
Observations	728	728	728	728	728
Countries	26	26	26	26	26
Durbin–Watson	1.879	1.889	1.935	1.902	1.973

Notes: The estimates are derived from a feasible generalized least-squares (FGLS) estimator that accounts for both cross-section heteroskedasticity and contemporaneous correlation. The data are measured in five-year nonoverlapping intervals. Figures in parentheses are White's robust standard errors. The dependent variable is the logs of number of domestic patents applied for by residents. The model is estimated in five-year intervals over the period from 1875 to 2010. Country and time dummies are included in the estimation but not reported. Figures in parentheses are White's robust standard errors.
***, **, and * 1%, 5%, and 10% levels of significance.

4.1. Domestic Patenting

The results of regressing the restricted and unrestricted versions of equation (4) using patents applied for by residents are presented in Table 1. We begin from the simple closed-economy model [logs of equation (2)] in the first column, sequentially add other explanatory variables, and end up with a complete, unrestricted model in the last column. The Durbin–Watson tests indicate the absence of first-order serial correlation in all regressions, underscoring that the t-statistics are not inflated by positive serial correlation in the residuals.

The estimated coefficient of the domestic knowledge stock, ($\ln A$), in the regression in the first column is highly significant, with an elasticity of 0.98, which is very close to one, as predicted by the first-generation endogenous growth models and the Schumpeterian models. The coefficient of R&D is positive and highly significant and the coefficient of product proliferation is significantly negative, as predicted by Schumpeterian growth theory, but inconsistent with the first-generation and semiendogenous-growth theories. Excluding the product variety variable, $\ln Q$, from the regression (second column) renders the coefficient of R&D insignificant at most conventional significance levels. The key insight of this result is that the predictions of first-generation and semiendogenous growth models do not hold when proliferation effects are not allowed for in the ideas production function.

Adding the levels of and growth in educational attainment to the regression model (third column) does not alter the basic results in the first column—the scale parameter remains close to one and the product proliferation parameter follows the predictions of Schumpeterian growth models. The coefficient of the change in the logs of educational attainment is positive and significant, whereas that of the levels of educational attainment is insignificant at conventional significance levels. This result is consistent with the model of Lucas (1988) but inconsistent with that of Romer (1990), in which the growth in ideas is proportional to the levels of human capital.

The result indicating that education has only temporary effects on ideas production makes sense from the perspective that only a fraction of educated people are employed to innovate, and this fraction is predominantly counted as R&D workers in national statistics. In fact, education is a means of understanding and using the technology that has been generated in the past, whereas the purpose of R&D is to move the technology frontier and to adapt new technologies that have been developed elsewhere. Education may affect innovations by improving the environment in which R&D workers are employed. However, it is not clear a priori to what extent the growth effects of education are permanent, and although the results in Table 1 indicate only temporary growth effects of educational attainment, some of the robustness tests that follow indicate permanent growth effects.

Spillover variables are added to the regressions in the last two columns in Table 1. The world stock of knowledge is estimated to have a significant negative effect, whereas all other spillover variables are found to exert a significant positive influence on ideas production. From this it can be inferred that international knowledge spillovers through imports, distance to the frontier, and trade openness all play a significant role in stimulating ideas production, but not the knowledge that is freely available worldwide. The significance of the coefficients of DTF indicates that backward countries in the sample can use the knowledge stock at the frontier to develop new ideas. The negative role of the world stock of knowledge is consistent with the findings of Porter and Stern (2000) and indicate that the negative raising-the-bar effects overpower the positive spillover effects and therefore decrease the ability of a country to produce new-to-the-world technologies.

Sizes of the positive coefficients of ln Q are very close to those of negative coefficients of ln$X$ in all regressions, suggesting that the product proliferation parameter, β in equations (2) and (3), is estimated to be very close to one. The finding that product proliferation neutralizes increasing R&D activity as the economy is growing has two main implications: the productivity growth rate is not proportional to R&D, and growth is independent of the size of the population. That growth is independent of the size of the domestic population in the modern growth regime (i.e., after the Second Industrial Revolution in most European countries and their offshoots) is consistent with the fact that economic growth rates have not been very high in countries with high population growth rates. In fact, although the population has increased about tenfold in the United States, Australia, Canada, and New Zealand since 1870, their economic growth rates have not been higher than in the rest of the countries, which have experienced an approximately twofold increase in their populations.

Common to all the regressions is the finding of approximately constant returns to the knowledge stock, i.e., $\phi \sim 1$. This result is consistent with the findings of Ulku (2007a, 2007b), Braun et al. (2008), Madsen (2008b), and Ang and Madsen (2011). However, it is possible that this finding reflects different stages of innovations instead of permanent effects. Furthermore, the results may have been driven partly by the use of domestic patents that are subject to different laws and rules across countries, which could give rise to biased estimates. The next subsection investigates this possibility.

4.2. Nonresident Patenting

Thus far we have pooled the domestic patent data under the assumption that patent processing practices are the same across countries. However, the quality of patents may vary across countries, because patent applications are subject to different laws and rules and processing speeds, and this opens up the possibility that the coefficients of research intensity may be higher in countries with lax patenting laws than countries with strict patenting laws. To overcome this problem, patents granted to nonresidents in the United States, the United Kingdom, and Germany are used instead of domestic patents in this subsection. The results are presented in Table 2.

Consider first the basic results in columns (1), (3), and (5), in which patenting activity is regressed on R&D, product variety, and the stock of knowledge for patents granted in the United States, the United Kingdom, and Germany. As before, the coefficients of the knowledge stock are close to one, indicating strong intertemporal knowledge spillovers. The coefficients of ln X and ln Q are, again, highly significant, which is consistent with the predictions of Schumpeterian growth theory in that they are of approximately the same magnitude, but opposite sign. The coefficients of R&D are approximately the same as in the regressions

TABLE 2. Parameter estimates of equation (4) using patents granted in the United States, the United Kingdom, and Germany to nonresidents

(Dep. var. $= \ln \dot{A}_{it}$)	(1) Basic model (U.S.)	(2) Full model (U.S.)	(3) Basic model (U.K.)	(4) Full model (U.K.)	(5) Basic model (Germany)	(6) Full model (Germany)
$\ln X_{it}$	0.105***	0.070***	0.012***	0.008**	0.015**	0.033***
	(0.004)	(0.004)	(0.003)	(0.004)	(0.007)	(0.007)
$\ln Q_{it}$	−0.180***	−0.137***	−0.011**	−0.019**	−0.286***	−0.051***
	(0.004)	(0.006)	(0.005)	(0.008)	(0.020)	(0.008)
$\ln A_{it}$	0.869***	0.864***	1.008***	0.992***	1.056***	1.043***
	(0.004)	(0.004)	(0.003)	(0.009)	(0.008)	(0.009)
$\ln(\theta_i \text{sch}_{it})$		−0.063***		0.007		0.028**
		(0.004)		(0.012)		(0.012)
$\Delta \ln(\theta_i \text{sch}_{it})$		−0.020***		0.002***		0.003***
		(0.001)		(0.001)		(0.001)
$\ln A^{\text{w}}_{it}$		0.116***		−0.016*		−0.311***
		(0.009)		(0.009)		(0.017)
DTF_{it}		−1.154***		−0.021		0.214***
		(0.095)		(0.040)		(0.023)
$\ln S^{\text{im}}_{it}$		−0.046***		0.040***		0.025***
		(0.003)		(0.005)		(0.006)
$\ln(M/Y)_{it}$		0.081***		−0.038***		0.007**
		(0.005)		(0.003)		(0.004)
Intercept	0.881***	0.969***	−1.494***	−1.378***	1.561***	0.759***
	(0.035)	(0.168)	(0.045)	(0.085)	(0.209)	(0.144)
Observations	700	700	560	560	560	560
Countries	25	25	20	20	20	20
Durbin–Watson	1.848	1.877	1.907	1.810	1.848	1.916

Notes: The estimates are derived from a feasible generalized least-squares (FGLS) estimator that accounts for both cross-section heteroskedasticity and contemporaneous correlation. The dependent variable is the log of the number of patents granted to foreign residents in the United States, the United Kingdom, and Germany, respectively. The data are measured in five-year nonoverlapping intervals. The model is estimated over the period from 1875 to 2010. Figures in parentheses are White's robust standard errors. Country and time dummies are included in the regressions but not reported, to conserve space. A^{w} is estimated as the sum of foreign patents granted to nonresidents in the United States, the United Kingdom, and Germany, respectively.
***, **, and * 1%, 5%, and 10% levels of significance.

for domestic patents in Table 1 for the United Kingdom and Germany; however, they are substantially larger in the U.S. regressions. This result, however, needs not imply that the number of duplicate ideas is lower in the United States than in other markets. The variation in the duplication parameters across countries reflects the fact that the propensity of innovators in country i to file a patent in the United States, conditional on a given domestic research intensity, is higher in the United States than in the United Kingdom and Germany.

The signs and significance of coefficients of the control variables vary substantially across the samples. Growth in education has a positive effect on patents granted in the United Kingdom and Germany, but a negative effect on patenting in the United States. Similarly, the levels of educational attainment have a negative effect on patents granted in the United States to nonresidents, whereas the effect is positive for Germany. The negative schooling coefficients for the United States may reflect the fact that $\ln(\theta_i \text{sch}_{it})$ is relatively highly correlated with $\ln A^{\text{w}}_{it}$, with a correlation coefficient of 0.68. Among the spillover variables in the U.S. sample, A^{w} and M/Y are found to have positive effects, whereas DTF and S^{im} are found to exert a negative influence. Almost the opposite results hold true for the U.K. and German samples. These results suggest that one needs to be cautious in using patents granted in foreign countries in estimating the ideas production function, because they are only a small fraction of domestic patents, as shown in the data section, and therefore do not capture the full effects of the innovative process. In this context it is important to note that the ratios of patents of country i applied for in country j (where $j =$ the United States, the United Kingdom, or Germany) to domestic patents (diffusion rates) vary substantially across countries over time. These variations are likely to bias the coefficient estimates of the control variables, and therefore it is difficult to make meaningful interpretations of them.

5. EXTENSIONS AND ROBUSTNESS CHECKS

To gain deeper insight into ideas production and to check the robustness of the results in the previous section, this part (1) considers alternative channels of international knowledge spillovers; (2) allows for different depreciation rates for the knowledge stock; (3) subdivides the full sample into Asian and European economies; (4) normalizes distance to the frontier and world stock of knowledge; and (5) considers different time aggregations of the data.

5.1. Alternative Channels of International Knowledge Spillover

We have, thus far, paid only limited attention to international knowledge spillovers. However, productivity-based growth estimates indicate that international knowledge spillovers are influential for productivity. For instance, the studies of Coe and Helpman (1995), Madsen (2007), Braun et al. (2008), and Ang and Madsen (2013) find that foreign knowledge is more important than domestic knowledge for domestic productivity, highlighting the importance of international technology transmission for productivity advances. Furthermore, Braun et al. (2008) find that U.S. R&D Granger-causes Japanese TFP even controlling for Japanese R&D.

The following alternative channels of knowledge transmission and different functional forms of foreign knowledge are considered in this subsection:

Geographic channel:

$$S_{it}^{\mathrm{geo}} = \sum_{j=1}^{26} \left(1 - \frac{D_{ij}^{\mathrm{geo}}}{D_{\max}^{\mathrm{geo}}}\right) S_{jt}, \quad \mathbf{(6)}$$

Import channel (semiendogenous):

$$S_{it}^{\mathrm{im(semi)}} = \sum_{j=1}^{26} \left(\frac{M_{ijt}}{Y_{jt}}\right) X_{jt}, \quad \mathbf{(7)}$$

Import channel (Schumpeterian):

$$S_{it}^{\mathrm{im(sch)}} = \sum_{j=1}^{26} \left(\frac{M_{ijt}}{Y_{jt}}\right) \left(\frac{X}{Q}\right)_{jt}, \quad \mathbf{(8)}$$

Import channel (Asia only):

$$S_{it}^{\mathrm{im(Asia)}} = \sum_{\tau=1}^{6} \left(\frac{M_{i\tau t}}{Y_{\tau t}}\right) S_{\tau t}, \quad \mathbf{(9)}$$

Import channel (Europe only):

$$S_{it}^{\mathrm{im(Europe)}} = \sum_{\upsilon=1}^{20} \left(\frac{M_{i\upsilon t}}{Y_{\upsilon t}}\right) S_{\upsilon t}, \quad \mathbf{(10)}$$

Patent channel:

$$S_{it}^{\mathrm{pat}} = \sum_{j=1}^{26} \left(\frac{Pat_{ijt}}{TP_{it}}\right) A_{jt}, \quad \mathbf{(11)}$$

where, in all cases, $i \neq j$. S^{geo} [equation (6)] is knowledge spillovers through geographic proximity, D_{ij}^{geo} is the geographic distance between city i and city j, $D_{\max}^{\mathrm{geo}}$ is the maximum distance between any two cities in the whole sample, and S_{jt} is R&D stock in country j. $S^{\mathrm{im(semi)}}$ [equation (7)] is R&D expenditure spillovers through the channel of imports following the predictions of semiendogenous growth models and X_{jt} is real R&D expenditure in foreign country j. $S^{\mathrm{im(sch)}}$ [equation (8)] is research intensity spillovers through the channel of imports following the predictions of Schumpeterian growth models and $(X/Q)_{jt}$ is research intensity in foreign country j. $S^{\mathrm{im(Asia)}}$ [equation (9)] is knowledge stock spillovers from the Asian countries through the channel of imports, where the Asian countries include China, India, Japan, Korea, Singapore, and Taiwan. $S^{\mathrm{im(Europe)}}$ [equation (10)] is knowledge stock spillovers from the European countries and their offshoots (all 26 countries minus the 6 Asian countries) through the channel of imports. S^{pat} [equation (11)] is patent applications spillovers from country j to country i, Pat_{ijt} is the number of patent applications filed in country i by residents from country j, and TP_{it} is the total patent applications in country i filed by foreign residents.

Knowledge spillovers through geographic proximity, as indicated in equation (6), may be important channels of knowledge transmission, because countries with similar growth and income experiences are clustered in geographically concentrated areas such as East Asia, South Asia, Southeast Asia, North America, Western Europe, Africa, and South America. These geographically concentrated groups of countries often have close trade links, similar cultures, and high movement of labor across borders. The importance of geographical distance between trade partners has been highlighted in the trade and growth literature by Grossman (1998) and Keller (2002), among others. Grossman (1998) argues that geographic distance between two trade partners captures not only transport costs but also unfamiliarity or informational barriers. Keller (2002) suggests that with closer proximity people are more able to create knowledge through interaction and adopt and assimilate knowledge that has been developed elsewhere. Geographical proximity allows technological knowledge to be transmitted through informal contacts, such as conferences, speeches, visits, and seminars. Keller (2002) shows that knowledge spillovers are positively related to geographic proximity. Bottazzi and Peri (2003) examine the technology spillovers between European regions and find evidence that spillovers tend to cluster geographically.

Equations (7) and (8) allow for R&D and R&D intensity spillovers as opposed to knowledge stock spillovers through imports following the predictions of semiendogenous and Schumpeterian growth theories. R&D may be transmitted directly, as innovative activity of one country may diffuse directly to another country through collaboration and personal interactions as it sharpens the competitive environment in the race to be the most innovative firm or country. In equations (9) and (10) knowledge spillovers are split into two groups: the six Asian countries and the European countries and their offshoots.

Finally, equation (11) uses the flow of patents applied for by residents of country j to the recipient country i as a weight for knowledge spillovers. The weights used for Japan, for instance, are based on the number of Chinese patents applied for in Japan weighted by their share of the total number of patent applications by nonresidents in Japan. The weights are not fixed but are allowed to change from one year to the next. This spillover mechanism directly measures where ideas are flowing, and it is quite possible that country i benefits more from knowledge spillovers from country j_a than from country j_b because country j_a exchanges more ideas with innovators in country i than in country j_b.

The results of including the new spillover variables sequentially and jointly in the regressions are presented in Table 3. The results are revealing in that they show which channel is operative for knowledge transmission and which is not. Considering the coefficients of the flow of R&D and R&D intensity through the channel of imports, the coefficient of $S^{\mathrm{im(semi)}}$ is positive and significant and this follows the predictions of semiendogenous growth theory; however, the coefficient of $S^{\mathrm{im(sch)}}$ is significant but negative. These results suggest the absence of proliferation effects when R&D is transmitted internationally.

TABLE 3. Further analysis on international knowledge spillovers and ideas production

(Dep. var. $= \ln \dot{A}_{it}$)	(1) Semi vs. Schumpeter	(2) Asia vs. Europe	(3) Geographic proximity	(4) Patent flows channel	(5) No specific channel	(6) Horserace for all channels
$\ln X_{it}$	0.043***	0.005***	0.017***	0.028***	0.021***	0.012***
	(0.002)	(0.002)	(0.001)	(0.001)	(0.002)	(0.002)
$\ln Q_{it}$	−0.028***	−0.011***	−0.017***	−0.028***	−0.018***	−0.014***
	(0.003)	(0.003)	(0.002)	(0.003)	(0.002)	(0.003)
$\ln A_{it}$	0.982***	0.998***	0.988***	0.984***	0.987***	0.988***
	(0.001)	(0.002)	(0.001)	(0.002)	(0.001)	(0.002)
$\ln(\theta_i \text{sch}_{it})$	0.038***	0.012	0.002***	−0.004	0.013	0.010
	(0.009)	(0.008)	(0.007)	(0.011)	(0.008)	(0.008)
$\Delta \ln(\theta_i \text{sch}_{it})$	0.007***	0.004***	0.008***	0.008***	0.008***	0.006***
	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)
$\ln A_{it}^{\text{w}}$	−0.121***	−0.105***	0.001***	−0.080***	0.007	−0.070***
	(0.009)	(0.009)	(0.007)	(0.007)	(0.010)	(0.004)
DTF_{it}	0.116***	0.115***	0.029***	0.031***	0.016	0.107***
	(0.015)	(0.013)	(0.009)	(0.012)	(0.011)	(0.011)
$\ln S_{it}^{\text{im(semi)}}$	0.042***					
	(0.004)					
$\ln S_{it}^{\text{im(sch)}}$	−0.064***					
	(0.006)					
$\ln S_{it}^{\text{im(Asia)}}$		0.007**				
		(0.003)				
$\ln S_{it}^{\text{im(Europe)}}$		0.004***				
		(0.001)				
$\ln S_{it}^{\text{im}}$						0.017***
						(0.003)
$\ln S_{it}^{\text{geo}}$			−0.031***			−0.208***
			(0.003)			(0.008)
$\ln S_{it}^{\text{pat}}$				0.022***		0.010***
				(0.001)		(0.001)
$\ln S_{it}^{\text{w}}$					−0.039***	0.185***
					(0.003)	(0.006)
$\ln(M/Y)_{it}$	0.005	0.049***	0.008***	−0.004	0.008***	−0.008**
	(0.003)	(0.004)	(0.002)	(0.003)	(0.003)	(0.003)
Intercept	−0.440***	−0.141	−1.071*	−0.309***	−1.026***	−0.513***
	(0.115)	(0.102)	(0.071)	(0.093)	(0.101)	(0.057)
Observations	728	728	728	728	728	728
Countries	26	26	26	26	26	26
Durbin–Watson	1.904	1.953	1.888	1.887	1.901	1.898

Notes: The estimates are derived from a feasible generalized least-squares (FGLS) estimator that accounts for both cross-section heteroskedasticity and contemporaneous correlation. The dependent variable is the logs of number of domestic patents applied for by residents. The model is estimated in five-year nonoverlapping intervals over the period from 1875 to 2010. Country and time dummies are included in the estimates but not reported. Figures in parentheses are White's robust standard errors. The Durbin–Watson tests do not suggest any evidence of serial correlation at the 5% level of significance.

***, **, and * 1%, 5%, and 10% levels of significance.

When the import channel is decomposed into Asian and European countries, the regression in column (2) shows that the results are robust to this consideration and that knowledge in Asia as well as Europe stimulates ideas production worldwide. The coefficient of S_{it}^{geo} is significant but negative [column (3)], whereas positive spillover effects are found to operate through the direct transmission of patents, S_{it}^{pat} [column (4)]. In column (5), the effect of foreign R&D stock, without going through any specific channel, is found to be negative and significant, but the reverse is found when knowledge spillovers through all channels, including the import channel used in the baseline model, are included. This result suggests that the findings of Porter and Stern (2000) of a raising-bar effect that overpowers the positive spillover effects are not that robust. Finally, DTF and trade openness are significant positive determinants of ideas production in most cases.

Common to these results is the fact that trade plays a very special role in knowledge spillovers, as signified by the coefficients of the direction of patent flows, openness, and knowledge spillovers through the channel of imports. Because companies tend to patent in their largest markets, S_{it}^{pat} implies, to some extent, a potential trade–ideas relationship. In other words, idea flows follow trade flows or trade flows follow idea flows. The importance of this result is that the growth effects of trade are conditional on the R&D and the knowledge stock among the countries from which the country in question imports.

Considering the nonspillover variables, the results are consistent with the baseline regression results in Table 1. The coefficients of the growth in education are consistently positive and significant, whereas the coefficients of the level of education are insignificant in all cases but one. Furthermore, the regression results are consistent with the predictions of Schumpeterian models.

5.2. Time Aggregation

Regressions using annual data and 20-year nonoverlapping intervals are presented in the first two columns in Table 4. The key results are very similar to the baseline regression results in Table 1 in that the coefficients of the knowledge stock remains close to one, the coefficients of $\ln X$ and $\ln Q$ remain highly significant and have the expected signs, and the growth in human capital remains significantly positive. Regarding the coefficients of $\ln A^{\text{w}}$, DTF, and $\ln S^{\text{im}}$, only the coefficients of $\ln S^{\text{im}}$ are marginally significant, suggesting that the effects of knowledge spillovers on ideas production are not as robust as those of domestic R&D and the knowledge stock. However, the low significance of the control variables may reflect the low efficiency in 20-year interval estimates and a low signal-to-noise ratio in the annual data.

5.3. The Returns to the Knowledge Stock and Depreciation Rates

One of the key controversies in the endogenous growth literature is whether there are constant returns to the knowledge stock in ideas production. The assumption

TABLE 4. Robustness checks

(Dep. var. $= \ln \dot{A}_{it}$)	(1) Annual interval	(2) 20-year interval	(3) 5% dep. rate on A	(4) 25% dep. rate on A	(5) Use regional leader for DTF	(6) Normalize DTF and A^{w}	(7) Panel VECM	(8) Post-WWII	(9) Allow for AR(1) errors	(10) Lagged regressors	(11) 1st-diff.
$\ln X_{it}$	0.032***	0.027***	0.016***	0.020***	0.024***	0.020***	0.015***	0.054***	0.026***	0.050***	0.024***
	(0.005)	(0.009)	(0.004)	(0.002)	(0.002)	(0.002)	(0.004)	(0.020)	(0.002)	(0.006)	(0.001)
$\ln Q_{it}$	−0.021***	−0.032***	−0.054***	−0.073***	−0.039***	−0.036***	−0.014***	−0.055**	−0.011**	−0.024***	−0.027***
	(0.004)	(0.011)	(0.012)	(0.004)	(0.002)	(0.002)	(0.005)	(0.022)	(0.005)	(0.006)	(0.008)
$\ln A_{it}$	0.981***	0.988***	1.035***	1.023***	1.004***	1.004***	0.999***	0.996***	0.990***	0.942***	1.087***
	(0.002)	(0.008)	(0.006)	(0.003)	(0.001)	(0.001)	(0.002)	(0.009)	(0.002)	(0.003)	(0.007)
$\ln(\theta_i \mathrm{sch}_{it})$	0.006	−0.014	0.052**	0.092***	0.004***	0.010***	−0.012	−0.025	−0.013	0.086***	0.145***
	(0.010)	(0.045)	(0.025)	(0.014)	(0.006)	(0.007)	(0.008)	(0.053)	(0.012)	(0.012)	(0.021)
$\Delta \ln(\theta_i \mathrm{sch}_{it})$	0.018***	0.003***	0.001	0.010***	0.004***	0.003***	0.003	0.002***	0.002***	0.022***	−0.001***
	(0.005)	(0.001)	(0.001)	(0.001)	(0.000)	(0.000)	(0.004)	(0.001)	(0.000)	(0.001)	(0.000)
$\ln A^{\mathrm{w}}_{it}$	0.026	0.124	−0.593***	−0.685***	−0.094***	−0.198**	−0.044***	−0.202***	−0.107***	−0.301***	0.235***
	(0.084)	(0.228)	(0.022)	(0.006)	(0.005)	(0.012)	(0.011)	(0.046)	(0.013)	(0.013)	(0.054)
DTF_{it}	0.006	−0.042	0.184***	0.252***	0.047**	0.068***	0.029	0.184**	0.103***	0.372***	0.009

Table 4. Continued

(Dep. var. $= \ln \dot{A}_{it}$)	(1) Annual interval	(2) 20-year interval	(3) 5% dep. rate on A	(4) 25% dep. rate on A	(5) Use regional leader for DTF	(6) Normalize DTF and A^{w}	(7) Panel VECM	(8) Post-WWII	(9) Allow for AR(1) errors	(10) Lagged regressors	(11) 1st-diff.
	(0.057)	(0.175)	(0.049)	(0.016)	(0.018)	(0.009)	(0.027)	(0.079)	(0.020)	(0.018)	(0.027)
$\ln S_{it}^{im}$	0.003	0.021*	−0.006	0.009***	0.003***	0.004***	0.005**	0.042***	0.008**	0.037***	−0.002
	(0.002)	(0.011)	(0.005)	(0.002)	(0.002)	(0.001)	(0.003)	(0.016)	(0.004)	(0.004)	(0.001)
$\ln(M/Y)_{it}$	0.011***	−0.004	0.148***	0.127***	0.038***	0.039***	−0.001	0.071**	0.031***	−0.033***	0.081***
	(0.004)	(0.015)	(0.009)	(0.004)	(0.003)	(0.003)	(0.004)	(0.033)	(0.006)	(0.008)	(0.005)
Intercept	−1.934	−2.778	5.227***	5.427***	0.014*	0.898	−1.296***	1.323**	−0.106	2.883***	−0.064***
	(1.264)	(2.699)	(0.264)	(0.105)	(0.075)	(0.130)	(0.134)	(0.532)	(0.155)	(0.185)	(0.013)
Estimation period	1871 −2010	1890 −2010	1875 −2010	1875 −2010	1875 −2010	1875 −2010	1875 −2010	1875 −2010	1875 −2010	1880– 2010	1880 −2010
Observations	3666	182	728	728	728	728	728	338	728	702	702
Countries	26	26	26	26	26	26	26	26	26	26	26

Notes: The estimates are derived from a feasible generalized least-squares (FGLS) estimator that accounts for both cross-section heteroskedasticity and contemporaneous correlation unless otherwise specified. The dependent variable is the number of domestic patents applied for by residents (logs). The data are measured in nonoverlapping five-year intervals. Country and time dummies are included in the regressions but not reported. Figures in parentheses are White's robust standard errors. In column (5) the United States is treated as the regional leader for the European countries and their offshoots, whereas Japan is used as the regional leader for the Asian countries in the estimates of the DTF. The components of A^{w} and DTF are normalized by $K^{\pi} L^{1-\pi}$ in the regression in column (6), where π is set to 0.3. All regressors, except $\ln\theta_i sch_{it}$, are treated as endogenous in the panel VECM in column (7). The post-WWII estimates in column (8) cover the period 1945–2010. All regressors are lagged one period (five years) in the regression in column (10). Except for column (3), no evidence of serial correlation is detected at the 5% level of significance (results not reported). In this case, AR(1)-correction is allowed for in the panel estimation.

***, **, and * 1%, 5%, and 10% levels of significance.

of constant returns to the knowledge stock in ideas production is often regarded as arbitrary and as being a knife-edge assumption [see, e.g., Solow (1994)]. However, Peretto (1998) argues that this assumption is based on firm theoretical foundations and, as such, is not a knife-edge assumption. To investigate whether the estimated coefficient of ϕ, to some extent, has been driven by the assumption of a knowledge stock depreciation rate of 15%, the calculation of the stock of knowledge is based on 5% and 25% depreciation rates in the regressions in columns (3) and (4) in Table 4. These depreciation rates span those estimated in the literature. Pakes and Schankerman (1984), for example, estimate the depreciation rate to be 25%, whereas Caballero and Jaffe (1993) estimate it to be 7%.

The results are remarkably insensitive to the choice of depreciation rate [columns (3) and (4) in Table 4]. There is no clear pattern of relationship between the coefficient of ln A and the depreciation rates used. The coefficients of ln A are slightly higher than those in the baseline regressions in Table 1, and hence the size of the coefficients of ϕ is not systematically related to the choice of depreciation rates. Thus, the estimates of ϕ found in the baseline regressions have not been driven by the choice of depreciation rate. Finally, the control variables are mostly highly significant and carry the same signs as in the baseline regressions.

5.4. Basing Distance to the Frontier on Regional Leaders

We have so far followed the literature by having the same technology leader for each country. However, different regions or cultures may have different technological leaders. In the regression in column (5) in Table 4, the United States is used as the reference leader for European countries and their offshoots, whereas Japan is the technological leader for Asian countries in constructing the DTF measure. The overall results from the baseline regressions remain largely intact. However, the economic and statistical significance of the coefficient of DTF is lower than in the baseline regressions, suggesting that the United States and not Japan is probably the technology frontier for Asian countries.

5.5. Normalizing World Stock of Knowledge and Distance to the Frontier

A relevant question is whether proliferation effects should also be allowed for in the measures of the world stock of knowledge and distance to the frontier. As A^{w} and DTF have not been normalized in the preceding estimates, it follows that they are increasing with factor accumulation, under the assumption that the propensity to patent is constant for labor and capital. Following the logic of constructing a TFP measure, the components of A^{w} and DTF are normalized by $K^{\pi}L^{1-\pi}$, where K is measured as nonresidential capital, L is measured as employment times annual hours worked, and π is set to 0.3, following the convention in the literature. The results, which are presented in column (6) in Table 4, are qualitatively consistent with the baseline regressions.

5.6. Endogeneity and Stationarity

Guided by the unit root tests in Appendix A showing that the dependent variable is stationary, the ideas production function has thus far been estimated in levels. Furthermore, all regressors have been treated as exogenous. To allow for the possibility that the underlying variables are endogenous and nonstationary, equation (4) is estimated using a panel VECM estimator. In this case, except for the growth in education, all regressors are assumed to be endogenous and contain a unit root. The results are presented in column (7) in Table 4. The coefficients of $\ln X$, $\ln Q$, and $\ln A$ are highly significant and have the right signs, reinforcing the results found earlier. The control variables are less significant than they are in the baseline regressions. Despite this, the coefficients of knowledge spillovers through the channel of imports and the world stock of knowledge remain significant and have signs consistent with the baseline regressions.

5.7. Post–World War II Period Estimates

The post-WWII period estimates are presented in column (8) in Table 4 to check the stability of the parameter estimates against the estimation period. The results are remarkably similar to the baseline results. Again there is strong support for Schumpeterian growth theory. Furthermore, the growth in human capital, knowledge spillovers through the channel of imports, distance to the frontier, and openness remain significant positive determinants of ideas production. Among the key parameters, the only difference between the baseline results and the post-WWII regressions is that the coefficient of research intensity, $\ln(X/Q)$, is higher in the post-WWII estimates than in the baseline regressions, implying that the efficiency of R&D has increased over time—a result that makes sense because R&D was not undertaken systematically by private firms before WWII to a large extent, but mostly by government institutions. Furthermore, the coefficient of research intensity is likely to be biased downward before WWII because the R&D data presumably were measured less precisely before WWII than after. In all cases, the similarity of the parameter estimates in the baseline regressions and the post-WWII estimates give credence to the generality of the ideas production function and the view that ideas are created in approximately the same way today as they were during the Second Industrial Revolution.

5.8. Allowing for Serial Correlations, Lags, and First Differencing

Although the Durbin–Watson tests in Table 1 show that the null hypothesis of no first-order serial correlation cannot be rejected at conventional levels, the estimator used in the regression in column (9) in Table 4 still allows an AR(1) error structure as a safety check. The results remain almost unaltered from the baseline regressions, suggesting that the statistical significance of the coefficients in the baseline regressions has not been inflated by positive serial correlations in the residuals.

So far it has been assumed that ideas production is driven by its determinants within the five-year data intervals in the baseline regressions. However, ideas take some time to develop and extensive R&D over a prolonged period is sometimes required before the R&D bears fruit. To allow for the possibility of some lagged responses and to deal with potential endogeneity, the regressors are lagged by one period (five years) in the regression in column (10) in Table 4. The results give two important insights. First, the product proliferation effect still prevails, as does the positive R&D effect. Furthermore, the coefficient of the knowledge stock is 0.94, which is significantly lower than in the baseline and other regressions, indicating that R&D intensity has very persistent effects. The estimated coefficient of $\ln A$ is likely to be below one because its influence on ideas production within the first five years is not accounted for in the regression. Second, the coefficients of growth in human capital, world stock of knowledge, knowledge spillovers through the channel of imports, and distance to the frontier are all significant and have signs consistent with the baseline regressions, suggesting that the results are robust when the regressors are lagged one period.

To deal with potential unit roots in the data that may result in serial correlations in the residuals, first-differenced estimates are presented in column (11) in Table 4. The support for Schumpeterian growth theory is still maintained; however, the sign of the coefficients of educational attainment are opposite to those of the baseline regressions, in that ideas production is now positively and significantly related to the level of educational attainment and negatively related to the growth in educational attainment. The latter result may reflect the inappropriateness of estimating in first differences or a weak and inconsistent level effect from education to ideas production.

5.9. Asia versus Europe

This section explores the possibility that the shape of the ideas production function differs between mature economies and those that may be in their transitional phase toward steady states. As highlighted in the Introduction, transitional dynamics does not affect the estimates of ideas production. However, the estimates can shed light on whether the shape of ideas production change as an economy goes through different phases of development. To investigate this issue the sample is divided into the Asian group (China, India, Japan, Korea, Singapore, and Taiwan) and the non-Asian group (the rest). The results are reported in Table 5.

Five features of the estimates are worth highlighting. First, the coefficients of the stock of knowledge are slightly below one for the Asian as well as for the non-Asian countries. Second, the coefficients of product proliferation are significantly negative and the coefficients of R&D are significantly positive, as predicted by Schumpeterian growth theory. Third, the coefficient of R&D is either of the wrong sign and significant or insignificant if product variety is *not* allowed for [columns (2) and (5)], again stressing the importance of allowing for proliferation effects.

TABLE 5. Europe versus the Asian Tigers

(Dep. var. $= \ln \dot{A}_{it}$)	(1) Basic model (Europe)	(2) Restricted model (Europe)	(3) Full model (Europe)	(4) Basic model (Asia)	(5) Restricted model (Asia)	(6) Full model (Asia)
$\ln X_{it}$	0.016***	−0.008**	0.016***	0.057**	0.011	0.094**
	(0.002)	(0.003)	(0.004)	(0.026)	(0.016)	(0.038)
$\ln Q_{it}$	−0.066***		−0.033***	−0.065**		−0.088**
	(0.007)		(0.012)	(0.032)		(0.042)
$\ln A_{it}$	0.971***	0.964***	0.978***	0.980***	0.981***	0.986***
	(0.004)	(0.004)	(0.004)	(0.009)	(0.010)	(0.015)
$\ln(\theta_i \mathrm{sch}_{it})$			−0.009			−0.046
			(0.013)			(0.094)
$\Delta \ln(\theta_i \mathrm{sch}_{it})$			0.001			−0.003
			(0.001)			(0.002)
$\ln A^{\mathrm{w}}_{it}$			−0.058***			−0.040
			(0.018)			(0.107)
DTF_{it}			0.267***			0.130
			(0.023)			(0.194)
$\ln S^{\mathrm{im}}_{it}$			0.011**			−0.015
			(0.005)			(0.015)
$\ln(M/Y)_{it}$			−0.024**			0.078**
			(0.011)			(0.039)
Intercept	−0.796***	−1.365***	−0.838***	−0.801***	−1.377***	−0.102
	(0.053)	(0.015)	(0.268)	(0.291)	(0.094)	(1.446)
Observations	560	560	560	168	168	168
Countries	20	20	20	6	6	6

Notes: The estimates are derived from a feasible generalized least-squares (FGLS) estimator that accounts for both cross-section heteroskedasticity and contemporaneous correlation in the residuals. The dependent variable is the logs of the number of domestic patents applied for by residents. The variables are measured in five-year intervals. The model is estimated over the period from 1875 to 2010. Country and time dummies are included in the regressions but not reported. Figures in parentheses are White's robust standard errors. Some evidence of serial correlation is detected at the 5% level of significance for the estimations involving only the Asian countries [columns (4) to (6)]. In those cases, AR(1) corrections have been allowed for in the panel estimates. "Europe" refers to the European countries and their offshoots.
***, **, and * 1%, 5%, and 10% levels of significance.

Fourth, the coefficients of R&D are substantially larger for the Asian countries than for the non-Asian countries, suggesting that replications of new products are more widespread among the mature economies than among that are growing strongly or that the productivity of R&D is higher for the Asian than for the non-Asian countries. This result is perhaps surprising in that transitional economies are often thought to have a high propensity to imitate, whereas the mature economies have high innovation propensities. Clearly, this is not the case, and the results here instead suggest that the social returns to R&D are approximately five times higher for transitional economies than for mature economies.

Fifth, spillover effects are surprisingly dissimilar between the two country groups. Although DTF and knowledge spillovers through the channel of imports are highly influential for growth in the non-Asian group, both variables are insignificant for the Asian group. Openness, in contrast, is positive and significant for the Asian economies, but the reverse is found for the non-Asian economies, confirming the view that openness among the Asian economies has been a positive factor behind their prosperity.

Overall, the regression results suggest that although the predictions of Schumpeterian endogenous growth models are consistent with the evidence for the two country groups, there are important differences between the ways in which external factors influence ideas production. Remarkably, international knowledge spillovers have not been nearly as important for the Asian Tiger economies as they have been for the mature non-Asian economies. From this it is tempting to conclude that the Asian Tiger economies have *not* been tapping into the ideas produced in the frontier countries and that their successes have, to a large extent, been driven by internal knowledge creation. However, this conclusion may be too hasty. It is quite plausible that technology has been transmitted to the Asian Tiger economies through channels that have not been considered here, which may also explain why the coefficient of domestic R&D is significantly higher for Asia than for the non-Asian economies.

One potential channel of foreign knowledge transmission not considered in the regressions is foreign direct investment (FDI), given that the Asian countries have experienced a large inflow of FDI over the past few decades. FDI enhances productivity directly through the provision of advanced technology and sharpened competition in the local market. The recent findings by Ang and Madsen (2013) indeed indicate that foreign knowledge has been transmitted through the channel of inward FDI in the Asian miracle economies since the 1950s. Unfortunately, the absence of long historical data for FDI prevents us from investigating its role as a source of international knowledge spillovers here.

5.10. Human Capital and Innovations

The preceding regressions have generally shown that the growth in human capital is a significant positive determinant of growth. Although mostly insignificant, the coefficients of the levels of human capital were significantly positive in a few instances, suggesting that it is worth investigating further the role played by human capital in the innovative process. Instead of allowing the returns to schooling, θ, to vary across countries it is fixed at 7%, following the estimates of Bils and Klenow (2000), in the regression in the first column in Table 6. The coefficient of the growth in educational attainment remains positive and significant, whereas the coefficient of the levels of educational attainment is significantly negative. Because a negative coefficient of human capital is counterintuitive, these results underscore the importance of allowing the returns to schooling to vary across countries. The other coefficient estimates remain consistent with the baseline regression results.

TABLE 6. Further analyses on human capital and ideas production

(Dep. var. $= \ln \dot{A}_{it}$)	(1) Fixed returns on education (7%)	(2) Quality-adjusted education	(3) Alternative data set (Morrisson & Murtin)	(4) Human capital unlogged
$\ln X_{it}$	0.030***	0.019***	0.021***	0.023***
	(0.002)	(0.001)	(0.002)	(0.001)
$\ln Q_{it}$	−0.028***	−0.035***	−0.039***	−0.015***
	(0.003)	(0.003)	(0.002)	(0.002)
$\ln A_{it}$	0.990***	1.002***	1.004***	0.983***
	(0.001)	(0.001)	(0.001)	(0.001)
$\ln(\theta_i \text{sch}_{it})$	−0.019**	0.030***	0.028***	0.147***
	(0.009)	(0.007)	(0.006)	(0.014)
$\Delta \ln(\theta_i \text{sch}_{it})$	0.007***	0.004***	0.003***	0.741***
	(0.000)	(0.000)	(0.000)	(0.047)
$\ln A^{w}_{it}$	−0.076***	−0.107***	−0.106***	−0.143***
	(0.008)	(0.005)	(0.006)	(0.005)
DTF_{it}	0.061***	0.099***	0.106***	0.214***
	(0.012)	(0.011)	(0.011)	(0.006)
$\ln S^{\text{im}}_{it}$	0.008***	0.005***	0.005***	0.017***
	(0.002)	(0.001)	(0.001)	(0.002)
$\ln(M/Y)_{it}$	0.011***	0.036***	0.036***	0.002
	(0.003)	(0.003)	(0.003)	(0.002)
Intercept	−0.393***	−0.035*	0.154**	0.211***
	(0.084)	(0.051)	(0.070)	(0.060)
Observations	728	728	728	728
Countries	26	26	26	26

Notes: The estimates are derived from a feasible generalized least-squares (FGLS) estimator that accounts for both cross-section heteroskedasticity and contemporaneous correlation. The dependent variable is the logs of the number of domestic patents applied for by residents. The variables are measured in five-year intervals. Estimation period: 1875–2010. Country and time dummies are included in the regressions but not reported. Educational attainment is multiplied by PISA scores in column (2). Figures in parentheses are White's robust standard errors. No evidence of serial correlation is detected at the 5% level of significance.
***, ** and * 1%, 5%, and 10% levels of significance.

Human capital has thus far been measured as years of schooling without paying attention to the quality of schooling. Educational attainment is multiplied by PISA (Programme for International Student Assessment) scores as a measure of the quality of education in the regression in column (2) in Table 6. These are average scores of students' performance in reading, mathematics, and science. Unfortunately, data on PISA scores are not available before 2000 and we are not aware of any comparable data on quality of education going back far enough. Therefore, data before 2000 are assumed to be constant under the assumption that changes in the quality of teaching were fairly limited over the last century. The results are consistent with the baseline results, except that the level of human capital is now found to have a significant positive effect. These results prevail when the Morrisson and Murtin (2009) educational data are used and when human capital is unlogged [columns (3) and (4), respectively]. The finding of a significant positive effect of the levels of human capital on ideas production in the last three regressions in Table 6 contradicts most of the previous results and shows that the extent to which education has permanent growth effects is unclear.

6. CONCLUDING REMARKS

Using data for a sample of countries that produce more than 90% of the world's ideas, this paper has provided direct estimates of the ideas production function over the past 140 years, while allowing for the influence of human capital and several channels of knowledge spillovers, namely the world knowledge stock, distance to the frontier, imports, geographic distance, and the flows of patents between countries. Domestic patents as well as patents granted in the United States, the United Kingdom, and Germany to nonresidents residing in 20 or 25 countries were used in the regressions.

The estimates gave important insights into the generation of ideas and the implications for endogenous growth theory. The results provided evidence in favor of Schumpeterian growth models on two counts. First, we found consistently strong intertemporal knowledge spillovers, and the coefficients of the knowledge stock were consistently very close to one. Second, we found significant proliferation effects, and population-induced expansions in R&D were neutralized by a proportional increase in product variety. In other words, it is research intensity and not real R&D expenditure that is essential for productivity growth. These results applied to domestic patents as well as patents granted to nonresidents in the United States, the United Kingdom, and Germany and imply that ideas production and therefore productivity is growing at a constant rate in a steady state with constant research intensity. The results were robust to different time aggregation, provision of dynamic structure in the specification, decomposing the sample into Asian and European economies, using first-differenced estimates, allowing for endogeneity, allowing for normalization effects, and considering alternative depreciation rates for knowledge stock.

The estimates gave evidence of strong knowledge spillover through the channels of imports, distance to the technology frontier, and direct knowledge flow through foreign patenting. These results show that the interaction of innovators with the outside world enhances the production of ideas, and that the value of interacting with the outside world is increasing with the stock of knowledge among the partners the domestic innovators are interacting with. Furthermore, the ability to create ideas is likely to be a positive function of distance to the frontier, because the effective costs of creating viable new ideas in an underdeveloped market are higher than those in countries close to or at the technology frontier. Geographic proximity and the world stock of knowledge, however, did not have positive effects on ideas production; on the contrary, the world stock of knowledge had, in the majority of cases, significant negative effects on ideas production, which is consistent with the proposition and findings of Porter and Stern (2000) that the increasing world stock of knowledge increases the requirements for domestic innovators to enter the world market with a new innovation.

NOTES

1. There are many sources of measurement errors in productivity data. First, statistical agencies tend to be quite slow at including new products in their price deflators, and therefore do not capture many innovations in the early stages of their cycles [Griliches (1979)]. Second, levels and changes in productivity cannot be measured in many sectors of the economy. The productivity effects of R&D in government and most private services, including health, defense, and space, are not measured. Third, output and capital stock contain well-known errors beyond those related to measurement of technology, particularly for developing countries. When schooling is allowed for in the TFP estimates, Pritchett (2006) finds TFP to be negative on the average in Africa, the Middle East, and Latin America, indicating serious measurement problems. Fourth, TFP estimates may be biased by the underlying assumptions relating to estimates of labor's income share, the assumption of returns to scale, and the fact that estimated factor shares are influenced by rent and may not reflect relative marginal productivities [Hall (1988)]. Fifth, growth in labor productivity and TFP are occasionally negative, even if they are measured in long differences to filter out business cycle influences, thus preventing the ideas production function from being estimated in log-linear form.

2. We initially considered Japan in the sample because of its geographic location in the East Asian region. However, its market for foreign patents was far too tiny for it to be considered as an innovative powerhouse before 1950. In 1939, which represents the mid-sample year, the weighted percentage of patents applied for in terms of domestic patents was only 1.4%. In 1932, before the build-up of war machinery, this number was similar at 1.5%.

3. The implicit assumption here is that productivity is driven by R&D. This is an approximately valid assumption. Braun and Nakajima (2009), for example, find that growth in R&D capital accounts for 75% of the GNP growth rate.

4. The variance–covariance matrix for patent applications by domestic residents for 26 countries is presented in Table A.2.

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APPENDIX A

A.1. PANEL UNIT ROOT TESTS

The integration properties of the underlying variables are examined using several panel unit root tests, including those of Levin et al. (2002) and Im et al. (2003) and the Fisher-type tests using the ADF and PP tests of Maddala and Wu (1999) and Choi (2001), respectively. The results reported in Table A.1 show that the dependent variable $\ln \mathring{A}_{it}$ follows a stationary process. Results for the regressors are mixed; they are either stationary or integrated at order one.

TABLE A.1. Panel unit root tests

Variable	Levin et al. (2002)	Im et al. (2003)	Maddala and Wu (1999)	Choi (2001)	Conclusion
$\ln \dot{A}_{it}$	$I(0)$	$I(0)$	$I(0)$	$I(0)$	$I(0)$
$\ln X_{it}$	$I(1)$	$I(1)$	$I(1)$	$I(1)$	$I(1)$
$\ln Q_{it}$	$I(1)$	$I(1)$	$I(1)$	$I(1)$	$I(1)$
$\ln A_{it}$	$I(0)$	$I(0)$	$I(0)$	$I(0)$	$I(0)$
$\ln(\theta_i \mathrm{sch}_{it})$	$I(1)$	$I(1)$	$I(0)$	$I(0)$	$I(0)/I(1)$
$\Delta \ln(\theta_i \mathrm{sch}_{it})$	$I(0)$	$I(0)$	$I(0)$	$I(0)$	$I(0)$
$\ln A^{\mathrm{w}}_{it}$	$I(0)$	$I(0)$	$I(0)$	$I(1)$	$I(0)/I(1)$
DTF_{it}	$I(1)$	$I(1)$	$I(0)$	$I(1)$	$I(0)/I(1)$
$\ln S^{\mathrm{im}}_{it}$	$I(1)$	$I(1)$	$I(1)$	$I(1)$	$I(1)$
$\ln(M/Y)_{it}$	$I(1)$	$I(0)$	$I(0)$	$I(1)$	$I(0)/I(1)$

Notes: A trend term is included in the estimates that involve the levels of the variables but not the differenced variables. The unit root tests are based on a 5% decision rule.

A.2. COVARIANCE OF (LOGS) PATENT APPLICATIONS BETWEEN COUNTRIES

TABLE A.2. Variance–covariance matrix for patent applications by domestic residents ($\ln \dot{A}_{it}$)

	Canada	USA	Australia	New Zealand	Austria	Belgium	Denmark	Finland	France	Germany	Greece	Ireland	Italy	Netherlands	Norway	Portugal	Spain	Sweden	Switzerland	UK	China	India	Japan	Korea	Singapore	Taiwan
Canada	0.6																									
USA	0.4	0.3																								
Australia	0.5	0.3	0.8																							
New Zealand	0.8	0.5	0.9	1.3																						
Austria	0.1	0.1	0.1	0.1	0.2																					
Belgium	0.2	0.1	0.4	0.5	0.0	0.5																				
Denmark	0.7	0.5	0.8	1.2	0.1	0.4	1.1																			
Finland	1.4	1.0	1.6	2.2	0.2	0.7	2.1	4.3																		
France	0.4	0.3	0.4	0.5	0.1	0.2	0.5	1.1	0.3																	
Germany	0.5	0.4	0.7	0.9	0.0	0.3	0.9	1.7	0.4	0.7																
Greece	1.8	1.3	2.3	2.7	0.4	0.5	2.7	5.8	1.6	2.3	10.4															
Ireland	1.8	1.4	1.9	2.5	0.3	0.4	2.4	5.3	1.4	2.0	8.4	7.8														
Italy	0.8	0.6	1.0	1.4	0.1	0.4	1.3	2.6	0.7	1.1	3.7	3.1	1.7													
Netherlands	1.2	0.9	1.5	1.9	0.2	0.5	1.9	3.8	1.0	1.6	5.9	5.0	2.4	3.7												
Norway	1.0	0.7	1.3	1.7	0.1	0.6	1.6	3.0	0.8	1.3	4.1	3.5	1.9	2.8	2.4											
Portugal	1.3	0.8	1.6	2.1	0.2	0.9	1.9	3.7	0.9	1.5	4.8	4.2	2.3	3.3	2.8	3.6										
Spain	0.7	0.4	0.8	1.1	0.1	0.4	1.0	1.9	0.5	0.8	2.5	2.2	1.2	1.7	1.4	1.8	1.0									
Sweden	0.6	0.4	0.9	1.1	0.1	0.4	1.1	2.2	0.5	0.9	3.2	2.6	1.4	2.1	1.6	1.9	1.0	1.2								
Switzerland	0.6	0.4	0.9	1.1	0.1	0.5	1.1	2.1	0.5	0.9	2.9	2.3	1.3	2.0	1.6	1.9	1.0	1.2	1.3							
UK	0.3	0.2	0.4	0.6	0.0	0.3	0.5	1.0	0.3	0.4	1.2	1.1	0.6	0.8	0.8	0.9	0.5	0.5	0.5	0.3						
China	4.1	3.3	4.0	5.3	1.3	0.2	5.2	12.4	3.3	4.3	19.7	18.2	7.2	11.7	7.6	9.4	4.8	5.8	4.9	2.2	46.9					
India	1.0	0.8	1.0	1.4	0.2	0.2	1.4	3.0	0.8	1.1	4.2	4.0	1.8	2.7	1.9	2.4	1.2	1.4	1.3	0.6	10.1	2.4				
Japan	1.9	1.3	1.9	2.6	0.4	0.6	2.4	5.4	1.4	1.9	7.7	7.3	3.1	4.9	3.6	4.4	2.2	2.6	2.3	1.1	17.8	4.0	7.5			
Korea	2.0	1.7	1.7	2.6	0.5	0.1	2.5	5.8	1.5	2.1	9.0	8.4	3.4	5.5	3.7	4.5	2.3	2.7	2.2	1.0	21.8	4.8	8.2	10.6		
Singapore	3.0	2.4	2.7	3.8	0.8	0.1	3.8	8.7	2.3	3.1	13.5	12.7	5.1	8.2	5.4	6.6	3.4	4.0	3.4	1.5	32.8	7.1	12.4	15.7	23.4	
Taiwan	2.5	2.0	2.4	3.2	0.8	0.1	3.1	7.5	2.0	2.5	11.8	11.1	4.2	7.0	4.5	5.5	2.8	3.4	2.9	1.3	28.7	6.1	10.9	13.3	19.9	17.7

APPENDIX B

B.1. GDP AND EMPLOYMENT

The following sources were used to obtain GDP for Asia:

China: China Statistical Yearbook (various issues) and *Comprehensive Statistical Data and Materials on 50 Years of New China,* Beijing: China Statistics Press..
India: National Account Statistics (various issues) and Penn World Table 6.2..
Japan: Japan Statistical Yearbook (various issues).
Korea: Korea Statistical Yearbook (various issues).
Singapore: Yearbook of Statistics Singapore (various issues).
Taiwan: Taiwan Statistical Data Book (various issues).

Data before 1953 are spliced with the Maddison (2008) GDP data. Employment and hours worked data for China, India, Korea, Singapore and Taiwan over the period 1953–2006 are taken from Madsen and Ang (2009). The data series are updated to 2010 using the same sources listed therein. To obtain estimates before 1953, the series are extrapolated backward to 1870 using the geometric average growth rate over the period for which data are available.

For other OECD countries, see Madsen (2008b).

B.2. CAPITAL STOCK

The construction of physical capital stock involves (i) nonresidential buildings and structures and (ii) machinery and equipment. A depreciation rate of 3% is assumed for the former and 17% for the latter. Investment data from the earliest available years have been used to generate the initial stock. The initial physical capital stock is obtained using the same procedure as patent stock (see Section B.7). The breakdown of investment series for China is available only from 1981. They have been backdated using the total investment series. The following sources have been used to obtain investment data:

China: China Statistical Yearbook (various issues) and *Comprehensive Statistical Data and Materials on 50 Years of New China,* Beijing: China Statistics Press.
India: National Account Statistics (various issues).
Japan: Madsen (2008b). 25.7% war damage has been applied to the 1945 capital stock.
Korea: Timmer and Ark (2000) and Korea Statistical Yearbook (various issues). All pre-1953 investment data have been discounted by 40% to account for war damage.
Singapore: Yearbook of Statistics Singapore (various issues).
Taiwan: Timmer and Ark (2000) and Taiwan Statistical Data Book (various issues).

The data series are updated to 2010 using the same sources listed therein. To obtain estimates before 1953, the series are extrapolated backward to 1870 using the geometric average growth rate over the period for which data are available. Data for other OECD countries are taken from Madsen (2008b). All data are expressed in constant 1995 dollars valued at PPP.

B.3. GEOGRAPHIC DISTANCE

Data on the distances between capital cities are obtained from the following source: http://www.macalester.edu/research/economics/page/haveman/trade.resources/Data/Gravity/dist.txt.

B.4. EDUCATIONAL ATTAINMENT

The data are available on an annual basis from 1870 to 2010 from Madsen (2010) for all countries except China, India, Korea, Singapore, and Taiwan. The data for educational attainment for China, India, Korea, Singapore, and Taiwan are from Barro and Lee (2010) over the period 1950–2010 and are extrapolated backward to 1870 using the geometric average growth rate over the period for which data are available. The data, which are available only for every five years to 2010, are interpolated to get annual series in the robustness check analysis using annual estimates.

B.5. PISA SCORES

These are average Programme for International Student Assessment scores of students' performance in reading, mathematics, and science. Data are only available since 2000. For the period before 2000, the series are assumed to be constant under the assumption that changes in the quality of teaching have been fairly limited over the last century. *Source:* Hanushek and Woessmann (2010).

B.6. R&D EXPENDITURE

Most countries in our sample do not have R&D data before 1965. In this case, a reference group that includes only countries for which data are available before 1965 was created. This group includes only Germany and Spain from 1870 to 1919. The United States and Australia are added to the group from 1919 and 1940 onward, respectively. Missing data for the European countries and Japan are then spliced using the average R&D intensity (real R&D expenditure/real GDP) values of this reference group under the assumption that R&D intensity grew more or less at the same rate within the OECD and Japan up to 1965. Real R&D expenditure data are then recovered by multiplying the estimated R&D intensity values by real GDP. Data since 1965 for these countries are obtained from OECD Main Science and Technology Indicators, the OECD Archive (OECD/DSTI/EAS), the National Science Foundation, and Statistics Netherlands. Earlier year data are obtained from the following sources:

United States: 1921–1952. Terleckyj, Nestor E. 1963 *Research and Development: Its Growth and Composition.* National Industries Conference Board Studies in Business Economics, No. 82. New York: The Board. 1953–2010. National Science Foundation.

Japan: Historical Statistics of Japan, Statistics Bureau and Statistical Research and Training, Institute, Ministry of Internal Affairs and Communication (http://www.stat.go.jp/english/data/chouki/index.htm).

Australia: 1940–1964. Table ES 249–257. In Vamplew, W. (1987). *Australian Historical Statistics*. Broadway, New South Wales: Fairfax, Syme and Weldon Associates.

Netherlands: 1959–1972. Statistics Netherlands. Contact: Ferry Lapré at infoservice@cbs.nl. Germany. 1870–1970. Pfetsch, F.R. (1985). *Datenhandbuch zur Wissenschaftsentwicklung*. Cologne: Zentrum für historische Socialforschung.

Spain: 1870–1970. Aracil, J. and J. L. Peinado, 1976, "Classification funcional de los gastos del estado (1850–1965)," in Valentin Fernandez Acha (ed.), *Datos Basicos para la Historia Financiera de Espana (1850–1975)*. Madrid: Instituto de Estudios Fiscales.

Real R&D expenditure data for China, India, Korea, Singapore, and Taiwan over the period 1953–2006 are taken from Ang and Madsen (2011). The data series are updated to 2010 using the same sources listed in Ang and Madsen (2011). To obtain estimates for the missing data, R&D intensity data since 1953 for these countries are spliced with the R&D intensity data of Japan before 1953. Real R&D expenditure is then obtained by multiplying the estimated intensity ratio with real output.

B.7. DOMESTIC PATENTS AND DOMESTIC PATENT STOCK

See Madsen (2008a) for sources (the same sources are used for Asia). Patent stock is constructed using the perpetual inventory method. The initial patent stock is obtained by using the Solow model steady state value of $A_0/(\delta+g)$, where A_0 is initial patent applications, δ is the rate of depreciation (assumed to be 15%), and g is the growth rate in patent applications over the period for which patent applications data are first available to 2010.

B.8. FOREIGN PATENT APPLICATIONS

The years in parentheses are the initial years.

United States (1870): Department of Commerce, op cit..

Japan (1885): Japanese Government, 2000, *Japanese Patent Statistics: 1884–1993*, Tokyo: The Patent Office.

Australia (1870): Wray Vamplew (ed.), 1987, *Australian Historical Statistics*, Broadway, New South Wales: Fairfax, Syme & Weldon Associates.

New Zealand (1870): G. T. Bloomfield, 1984, *New Zealand: A Handbook of Historical Statistics*, Boston: G. K. Hall & Co.

Germany (1883): W. Kirner, op cit.

Switzerland (1888): H. Ritzmann-Blickenstorfer, op cit..

United Kingdom (1870): B. R. Mitchell, 1988, *British Historical Statistics*, Cambridge, UK: Cambridge University Press.

Canada (1883), *Austria* (1889), *Belgium* (1883), *Denmark* (1994), *Finland* (1920), *France* (1885), *Greece* (1923), *Ireland* (1927), *Italy* (1884), *Luxembourg* (1921), *Netherlands* (1912), *Norway* (1886), *Portugal* (1886), *Spain* (1886), and *Sweden* (1885): Obtained from World Intellectual Property Organisation, *Industrial Property Statistics*, Geneva: World Intellectual Property Organisation. Updated using U.S. Patent and Trademark Office, Information Products Division, Technology Assessment and Forecast Branch, Washington, DC 20231, and *Industrial Property Statistics*, Geneva: World Intellectual Property Organisation.

Nominal R&D expenditure is deflated using an unweighted average of the economywide value-added price deflator and hourly earnings, following Coe and Helpman (1995), to express it in real terms. The price deflator is obtained from the same domestic sources as *Y* and *L,* described previously. Hourly earnings data for Japan are compiled from *Japan Statistical Yearbook* (various issues) and for all other countries from the *Yearbook of Labour Statistics*, Geneva: International Labour Office and other domestic sources described in the preceding.

B.9. FOREIGN PATENT APPLICATIONS AND PATENTS GRANTED

Canada: Canada Yearbook, Statistics Canada. "Blatt für Patent-, Muster- und Zeichenwesen mit Urheberrechts-Teil." Federico, P.J. (1964), "Historical Patent Statistics 1791–1961," *Journal of the Patent Office Society*, 46, 89–171.

United States: U.S. Department of Commerce, Patent and Trademark Office (1977). Technology Assessment and Forecast: Seventh Report, pp. 196–200, for 1883–1952. Dosi, G., K. Pavitt, and L. Soete (1990), *The Economics of Technical Change and International Trade*, New York: Harvester Wheatsheaf. Federico, P.J. (1964), op. cit.

Japan: The Department of Finance, *23rd Financial and Economic Annual of Japan*, Government Printing Office, Tokyo. Various issues, "Blatt für Patent-, Muster- und Zeichenwesen mit Urheberrechts-Teil." Federico, P.J. (1964), op. cit.

Australia: Data supplied by the Australian Patent Office and Federico, P.J. (1964), op. cit.

Austria: Statistisches Jahrbuch für die Republik Österreich.

Belgium: Federico, P.J. (1964), op. cit. and WIPO.

Denmark: Danmarks Statistik, Statistisk Årbog.

Finland: Annuaire statistiques de Finlande and *Statistisk Årsbok för Finland.*

France: Annuaire statistique de la France and "Blatt für Patent-, Muster- und Zeichenwesen mit Urheberrechts-Teil."

Germany: "Blatt für Patent-, Muster- und Zeichenwesen mit Urheberrechts-Teil" and *Statistisches Jahrbuch Für die Bundesrepublik Deutschland.*

Ireland: Saorstat Eireann, Statistical Abstract.

Italy: "Blatt für Patent-, Muster- und Zeichenwesen, mit Urheberrechts-Teil," *Annuario Statistico*, and Federico, P.J. (1964), *op cit*.

Netherlands: "Blatt für Patent-, Muster- und Zeichenwesen mit Urheberrechts-Teil" and *Jaarcifers voor Nederland*.

Norway: "Statistiske opplysninger vedkommende Patentvæsenet i Norge" (1886–1933). "Norsk tidende for det industrielle rettsvern" (1939–1970). 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, "Patentstyret—Styret for det industrielle rettsvern."

Spain: WIPO.

Sweden: Statistisk Årsbok för Sverige

Switzerland: Ritzmann-Blickenstorfer (1996), op. cit.

United Kingdom: The data were kindly provided by Scott Tilbury, the Patent Office.

General note: Where data for patents granted are not available, the missing data are filled in by interpolation using patent applications data. This was done by first calculating the average percentage of applications approved using total figures for patent applications and patents granted. This rate is assumed to apply for all countries. The second step involves multiplying the acceptance rate by the total number of applications submitted in year N for country i. Where the interpolated total for all countries for each year was significantly different from the actual total, the acceptance rate was adjusted to ensure that the values match. This was particularly necessary to smooth out the jumps between actual and interpolated data. Data for total applications and those granted were obtained from the WIPO database (http://www.wipo.int/portal/index.html.en), accessed 7/9/2012. The data were backdated and updated beyond actual or interpolated data by decomposing the total number of patents granted for each year using the average of the patents granted for the first or last five-year period, respectively. This method was used to update, backdate, and fill in the missing data for patent applications.