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Previous studies have demonstrated an empirical relationship between accumulated R&D expenditures and total factor productivity (TFP), and have shown that the benefits of R&D can spill across countries through trade. This paper extends these analyses to a sample of 15 OECD countries and six Asian countries, Chinese Taipei, India, Indonesia, Korea, Singapore and Thailand. An empirical model is estimated which relates TFP to domestic and foreign R&D activity, TFP catch-up and business cycle variables. Model estimates show that TFP and domestic R&D capital are positively related, and that domestic R&D has a relatively large impact on TFP growth in the NICs and LICs. Country-specific international R&D spillover elasticities are of mixed sign, and no apparent pattern by country group is evident. While this result does not change the earlier qualitative conclusions, it suggests that estimates of sample average R&D spillover elasticities should be cautiously interpreted.

I. INTRODUCTION

Endogenous growth models emphasize innovation and trade as vehicles for technological spillovers that permit developing countries to catch up to industrialized countries. Coe and Helpman (1995) and Engelbrecht (1997) demonstrate an empirical relationship between accumulated R&D expenditures and total factor productivity (TFP), and show that the benefits of R&D can spill across countries through trade. Since open economy endogenous growth models predict convergence only when knowledge spills over perfectly between countries, these findings have implications for countries considering trade liberalization and economic integration policies. However, generalization of the above findings to specific countries is somewhat problematic given that the empirical evidence is for OECD member countries only. While Coe *et al.* (1997) extend their sample and estimate the elasticity of TFP in developing countries with respect to R&D stocks in industrialized countries, they assume that domestic R&D capital is negligible in developing countries. This assumption seems untenable for some of the 'high income' Asian countries considered in their sample, suggesting possible omitted variable bias in estimation results.

This paper examines the role that R&D activity plays in technological progress for a sample of OECD and Asian nations from 1980 to 1995. The study contributes to the received literature by providing the first empirical study of Asian countries using explicit measures of domestic R&D expenditures. An empirical model is estimated which relates TFP to domestic and foreign R&D activity, TFP catch-up and business cycle variables. Model estimates are used to investigate whether the determinants of OECD and G7 TFP growth are similar to those of Chinese Taipei, India, Indonesia, Korea, Singapore and Thailand. The paper is organized as follows. Section II develops the empirical model of TFP and international R&D spillovers, and describes the data used in empirical estimation. Model

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estimates are reported in Section IV. Elasticities of TFP with respect to domestic and international R&D, respectively, are contained therein. Section V presents conclusions.

II. EMPIRICAL MODEL AND DATA

Following Coe and Helpman (1995) and Engelbrecht (1997), the empirical model of TFP is:

$$\log TFP_{it} = \alpha_0 + \alpha_1 \log DRD_{it} + \alpha_2 G7 \log DRD_{it} + \alpha_3 Asia. \log DRD_{it} + \alpha_{4i} Country_i (M/Y)_{it} \log FRD_{it} + \alpha_5 \log CU + \alpha_5 CYC + e_{it} \quad (1)$$

where i is a country index, t indexes the year, DRD is domestic R&D capital stock, *G7* equals one for G7 countries and zero for non-G7 countries, *Asia* equals one for Asian countries (Chinese Taipei, India, Indonesia, Korea, Singapore and Thailand), and zero for non-G7 and Asian countries, (M/Y) is the import to GDP share (a measure of trade openness), $(M/Y)\log FRD$ is import weighted foreign R&D capital, Country equals zero for country $i \neq j$ ($j =$ US) and zero otherwise, CU (catch-up) is country i TFP divided by US TFP, CYC is the growth rate of real GDP, α_1 is the elasticity of TFP with respect to domestic R&D, α_2 is the elasticity of TFP with respect to foreign R&D, and e is a white noise error term.[1] When α_2 is the same for any country group, the foreign R&D elasticity varies in proportion to national import to GDP shares.[2]

The arguments $G7.\log DRD$ and $Asia.\log DRD$ allow the effect of domestic R&D on domestic productivity to differ for G7 and Asian countries, while $(M/Y)\log FRD$ allows foreign R&D capital to affect TFP through trade. When the estimate of the interaction of trade with foreign R&D capital stock is positive, then the effect of foreign R&D on domestic TFP is larger the more open the economy is to foreign trade. The interaction of country with $(M/Y)\log FRD$ captures country-specific effects of trade weighted foreign R&D capital on TFP. When α_{4i} is positive, then the interaction of trade weighted foreign R&D on domestic TFP for country i is larger than country j. A catch-up argument is included in Equation 1 to account for innovation outside of the R&D sector, while the business cycle variable (CYC) captures cyclical variation in productivity growth.

Annual data for 1980 through 1995 are collected by country group: G7 (Canada, France, Germany, Italy, Japan, United Kingdom and the US); Non-G7 (Australia, Denmark, Finland, Ireland, Netherlands, Norway, Spain, and Sweden); Asia newly industrialized (NICs) (Chinese Taipei, Korea and Singapore); and Asia low income (LICs) (India, Indonesia and Thailand). R&D capital stocks are calculated using the perpetual inventory method with a depreciation rate fixed at 5%. Foreign R&D capital stocks are obtained by weighting the average of domestic R&D capital stock by the twenty most important trading partners bilateral import shares. TFP series are calculated by:

$$TFP = \frac{Y}{K^{1-\beta} L^{\beta}} \quad (2)$$

where Y is GDP, K is capital stock, L is labour force and β is the labour share of output.[3]

Table 1. *TFP summary statistics 1980–1995*

Country	Mean	St dev	Growth (%)
G7			
Canada	0.973	0.038	−0.6
France	1.031	0.040	0.5
Germany	1.148	0.216	2.7
Italy	1.026	0.034	0.3
Japan	1.024	0.045	0.3
UK	0.999	0.043	0.3
US	0.989	0.023	0.2
G7 Average	*1.027*	*0.063*	*0.5*
Non-G7			
Australia	0.995	0.024	0.2
Denmark	0.991	0.050	1.1
Finland	0.967	0.062	−0.7
Ireland	1.096	0.138	2.5
Netherlands	1.004	0.017	−0.2
Norway	1.005	0.064	1.4
Spain	1.029	0.032	−0.1
Sweden	0.950	0.055	−1.0
Non-G7 Average	*1.004*	*0.055*	*0.4*
NICs			
Chinese Taipei	1.697	0.743	8.5
Korea	1.138	0.213	4.0
Singapore	1.174	0.152	2.4
NIV Average	*1.336*	*0.370*	*5.0*
LICs			
India	1.073	0.121	2.4
Indonesia	1.0987	0.134	2.4
Thailand	1.243	0.313	4.9
LIC Average	*1.138*	*0.189*	*3.2*

Note: 1980 = 1.
Source. IMF (1997), International Labour Office (ILO; 1991, 1993, 1995), SORC (1996, 1997), Summers and Heston (1991) World Bank (1997).

[1] Engelbrecht (1997) argues that Coe and Helpman's (1995, 1997) results present a potentially misleading picture of the beneficial role of international R&D spillovers because country-specific spillover estimates are obtained by multiplying the parameter estimate common to all countries by country-specific import levels. He obtains country specific spillover estimates by interacting country dummies with foreign R&D capital.

[2] Import weighting captures the role international trade plays in the transmission of international R&D, and is analogous to using technological distance to gauge spillover intensity.

[3] Capital stock data are obtained from Summers and Heston (1991) as capital stock per worker in 1985 international prices. Series are complete for 1980 to 1992, except for Chinese Taipei, Indonesia, Korea and Singapore. The perpetual inventory method is used to interpolate missing data points. Gross domestic fixed investment data is obtained from the World Bank (1997) and depreciated at the constant rate of 15% (Griliches, 1990).

Means, standard deviations and growth rates for TFP and R&D are reported in Table 1 and Table 2, respectively. Chinese Taipei had the highest rate of TFP growth for the entire sample at 8.5% per annum (p.a.), while Thailand has the highest TFP growth rate, 4.9% p.a., among LICs. TFP growth in the NICs and LICs is substantially higher than G7 and non-G7 country groups. Of the OECD countries, Germany (2.7% p.a.) and Ireland (2.5% p.a.) had relatively high TFP growth rates over the sample period. Table 2 shows that NICs had the highest growth rate in domestic R&D capital stock of all country groups at 14.7% p.a. Korean domestic R&D capital stock growth is the strongest (18.5% p.a.), followed by Chinese Taipei (15.3% p.a.) and Singapore (10.4% p.a.). The LICs experience is mixed with strong domestic R&D capital stock growth in India (8.9% p.a.) and Thailand (7.9% p.a.), whilst Indonesia had the weakest growth for the entire sample (1% p.a.). Non-G7 countries (5.2% p.a.) experience higher growth in domestic R&D capital stock than G7 countries (3.9% p.a.). Ireland and Finland had relatively high rates of domestic R&D growth, whilst UK domestic R&D growth is the second smallest for the sample at 1.2% p.a.

III. MODEL ESTIMATES

Equation 1 is estimated using Kmenta's GLS cross-sectional heteroscedastic and time-wise autoregressive model. Foreign R&D capital are weighted by a one period lagged import to GDP share to allow for non-instantaneous transmission of foreign R&D spillovers (Engelbrecht, 1997). A dummy variable (GR) is included to account for the reunification of Germany (GR equals one for $i =$ Germany and $t > 1989$, and zero otherwise). Regression results are reported in Table 3.

Model estimates show that TFP catch-up is negative, indicating that TFP across the sample converges toward US TFP. The business cycle variable (CYC) is significant, indicating a positive relationship between macroeconomic activity and productivity growth. Domestic R&D has a positive effect on TFP, and the impact is higher in Asian countries. Nine of the 21 foreign R&D coefficients are significant, indicating spillovers from foreign R&D through trade.

TFP elasticities with respect to domestic R&D capital stock, and country-specific TFP elasticities for international R&D spillovers, are listed in Table 4. All elasticities have plausible magnitudes, lying in absolute value between zero and one. The elasticity of TFP for domestic R&D in the NICs and LICs is approximately six times the size of the corresponding elasticity for OECD countries. On average, 1% increases in domestic R&D capital stock raises Asian and OECD output by 0.3% and 0.05%, respectively. A joint F-test shows that seven of the eleven significant R&D spillover elasticities are positive.[4] Chinese Taipei, France, Germany, Indonesia, Ireland, Japan and Thailand record positive spillovers, while negative spillovers are found for Canada, Finland, Korea and Sweden.

Table 2. *R&D summary statistics 1980 to 1995*

	Domestic R&D			Foreign R&D		
Country	Mean	St dev	Growth (%)	Mean	St dev	Growth (%)
G7						
Canada	1.191	0.307	5.5	1.105	0.174	3.2
France	1.105	0.177	3.4	1.134	0.171	2.5
Germany	1.087	0.136	2.5	1.151	0.211	3.6
Italy	1.206	0.316	5.4	1.045	0.083	1.7
Japan	1.182	0.293	5.4	1.098	0.174	3.0
UK	1.043	0.063	1.2	1.123	0.216	3.7
US	1.124	0.203	3.7	1.132	0.237	4.5
G7 Average	*1.134*	*0.214*	*3.9*	*1.113*	*0.181*	*3.2*
Non-G7						
Australia	1.210	0.298	5.1	1.119	0.189	3.3
Denmark	1.192	0.311	5.6	1.084	0.136	2.2
Finland	1.235	0.369	6.3	1.130	0.180	3.3
Ireland	1.230	0.382	7.1	1.060	0.223	5.3
Netherlands	1.113	0.172	3.2	1.091	0.142	2.8
Norway	1.170	0.257	4.6	1.147	0.165	2.4
Spain	1.239	0.351	5.7	0.949	0.071	−0.3
Sweden	1.126	0.210	3.9	1.073	0.156	2.0
Non-G7 Average	*1.189*	*0.294*	*5.2*	*1.082*	*0.158*	*2.6*
NICs						
Chinese Taipei	1.731	1.101	15.3	1.097	0.183	15.3
Korea	2.150	1.563	18.5	1.141	0.180	18.4
Singapore	1.408	0.684	10.4	1.102	0.176	10.5
NIC Average	*1.763*	*1.116*	*14.7*	*1.113*	*0.180*	*14.7*
LICs						
India	1.367	0.555	8.9	1.100	0.165	3.2
Indonesia	0.992	0.045	1.0	0.980	0.137	3.0
Thailand	1.062	0.279	7.9	1.159	0.174	3.2
LIC Average	*1.140*	*0.293*	*5.9*	*1.080*	*0.158*	*3.1*

Note: 1980 = 1.
Source. Coe and Helpman (1995), IMF (1984, 1990, 1996, 1997), Indonesian Ministry of Industry and Trade (1997), ILO (1991, 1993, 1995), Korean Ministry of Science and Technology (1997), National Science and Technology Board (1996), OECD (1996, 1997), SORC (1982, 1996, 1997), Thai Office of Policy and Planning (1997), UNESCO (various issues), World Bank (1997).[5]

[4] Country-specific international R&D spillover elasticities are obtained by adding country-specific foreign R&D estimates to the US foreign R&D estimate.

[5] Some R&D expenditure series are not complete for the period 1980 to 1995. To complete these series an equation is estimated regressing the logarithms of real R&D on real output and investment to interpolate missing values (Coe and Helpman, 1995). R&D data are deflated by the rule:

$$PR = 0.5P + 0.5W \quad (3)$$

where PR is an R&D deflator, P is a GDP price deflator and W is the average wage.

Table 3. *TFP model estimates*

Independent variable	I Coefficient	I Std. error	II Coefficient	II Std. error
Intercept	−0.006[a]	0.002	−0.033[a]	0.002
TFP catch-up	−0.014[a]	0.005	−0.015[a]	−0.005
Business cycle	0.263[a]	0.024	0.262[a]	0.024
Germany Dummy			0.028	0.024
Domestic R&D	0.055[b]	0.025	0.057[b]	0.025
Domestic R&D Asia	0.248[a]	0.047	0.247[a]	0.048
Domestic R&D G7	−0.005	0.037	−0.005	0.037
Foreign R&D US	−0.094	0.378	−0.103	0.361
Foreign R&D Canada	−0.876[b]	0.382	−0.870[b]	0.361
Foreign R&D France	0.861[b]	0.363	0.870[b]	0.347
Foreign R&D Germany	3.506[a]	0.830	3.070[a]	0.896
Foreign R&D Italy	0.593	0.449	0.592	0.435
Foreign R&D Japan	1.501[b]	0.592	1.514[a]	0.577
Foreign R&D UK	0.060	0.440	0.073	0.425
Foreign R&D Australia	−0.257	0.505	−0.257	0.486
Foreign R&D Denmark	0.108	0.426	0.123	0.411
Foreign R&D Finland	−1.131[b]	0.477	−1.120[b]	0.462
Foreign R&D Ireland	0.508	0.404	0.511	0.389
Foreign R&D Netherlands	−0.010	0.397	0.001	0.382
Foreign R&D Norway	0.206	0.468	0.231	0.454
Foreign R&D Spain	−0.197	0.564	−0.188	0.555
Foreign R&D Sweden	−1.015[b]	0.508	−1.027[b]	0.490
Foreign R&D Chinese Taipei	1.987[a]	0.727	1.992[a]	0.723
Foreign R&D Korea	−1.492	0.782	−1.487	0.780
Foreign R&D Singapore	0.055	0.389	0.065	0.373
Foreign R&D India	−0.840	1.338	−0.831	1.353
Foreign R&D Indonesia	1.950[a]	0.558	1.987[a]	0.551
Foreign R&D Thailand	2.124[a]	0.569	2.128[a]	0.561

Note: a, b, c denote estimates are significant at 1%, 5% and 10% respectively.

Table 4. *TFP elasticities with respect to R&D*

Country/group	I	II
Domestic R&D		
G7	+0.052	+0.050
Non-G7	+0.057	+0.055[b]
NICs and LICs	+0.304	+0.303[a]
Foreign R&D		
G7		
Canada	−0.970	−0.973
France	+0.767	+0.767
Germany	+3.412	+2.967
Italy	+0.499	+0.489
Japan	+1.407	+1.411
UK	−0.034	−0.030
US	−0.084	−0. 013
Non-G7		
Australia	−0.351	−0.360
Denmark	+0.014	+0.020
Finland	−1.225	−1.223
Ireland	+0.414	+0.408
Netherlands	+0.104	−0.102
Norway	+0.112	+0.128
Spain	−0.291	−0.291
Sweden	−1.109	−1.130
NICs		
Chinese Taipei	+1.893	+1.889
Korea	−1.586	−1.590
Singapore	−0.039	−0.038
LICs		
India	−0.934	−0.934
Indonesia	+1.856	+1.883
Thailand	+2.021	+2.025

V. CONCLUSIONS

This study examines the role R&D plays in technological progress for a sample of OECD and Asian countries. Model estimates show TFP tends toward the US value, and the TFP growth path is pro-cyclical TFP and domestic R&D capital growth are positively related. Domestic R&D has a relatively large impact on TFP growth in the NICs and LICs, which suggests that it is not appropriate to assume that the role of domestic R&D capital is negligible in developing countries. Following Engelbrecht (1997), country-specific spillover estimates are obtained by interacting country dummies with foreign R&D capital. Mixed signs for country-specific international R&D spillover elasticities are reported. Chinese Taipei, France, Germany, Indonesia, Ireland, Japan and Thailand have positive spillovers, whilst Canada, Finland, Korea and Sweden have negative spillovers. No apparent pattern by country group is evident. This finding supports Engebrech's (1997) conclusion that estimates of sample average R&D spillover elasticities should be cautiously interpreted.

Finally, future research must develop appropriate measures of domestic R&D capital for non-OECD countries. Alternative transmission mechanisms for international R&D spillovers, such as education and training received abroad, telecommunications and foreign direct investment, should also be considered.

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