

INTERNATIONAL R&D SPILLOVERS THROUGH INFORMATION NETWORKS

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This paper shows that consideration of the role of direct spillovers through information networks is crucial in empirical studies of international R&D spillovers. Data on line penetration rates are used to construct foreign R&D capitals that directly spill over across borders. The conspicuous indirect effects through imports of intermediate goods shown in previous studies diminish considerably when the estimation controls for direct effects. Instead, direct spillovers are strong and significant. In the 1980s, direct effects were stronger than in the 1970s, especially among G7 countries. Indirect effects were insignificant in the 1970s and were significantly negative in the 1980s.

Keywords: International R&D Spillovers, Direct Effects, Networks, Productivity

JEL classification: O30, O47, O57, C23, F01

1. INTRODUCTION

Endogenous growth theory, as represented by Grossman and Helpman (1991) for example, claims that economically motivated R&D activities are the fundamental source of sustained economic growth and that such sustained growth is possible because of the spillovers of R&D results. Such spillover effects exist across countries, which explains the convergence of income *per capita* across countries. Empirical research on R&D spillovers across countries, motivated by endogenous growth theory, was first attempted by Coe and Helpman (1995) (henceforth CH). CH derived an estimating equation on the basis that international trade in intermediate goods is the main channel for R&D spillovers across countries. CH suggested that the influence of country *B*'s R&D capital on the productivity of country *A* is proportional to country *B*'s share of country *A*'s total imports. Thus, a measure of the foreign R&D capital of a given country, embodied in the intermediate goods traded, was constructed as a weighted sum of the R&D capitals of the country's trading partners, with weights given by the bilateral import shares. Furthermore, CH claimed that the influence of such foreign R&D capital is proportional to the country's share of imports in GDP. Having estimated an equation based on these assumptions, CH concluded that the results of R&D investment clearly spill over

through trade in intermediate goods. They further found that the size of these spillover effects depends on two factors. First, importing from a country with a high level of R&D capital raises the productivity of the importing country more than would importing from a country with a low level of R&D capital. Second, a country should benefit more from foreign R&D capital the higher is its share of imports in GDP. In other words, both import composition and the import share affect the size of the spillover effect.

CH's research has been developed by some and criticized by others. Lichtenberg and van Pottelsberghe (1998) pointed out that CH's foreign R&D capital measure is sensitive to potential aggregation biases. Keller (1998), while demonstrating that the explanatory power of a foreign R&D capital measure constructed by using randomly generated weights is also significant, expressed doubts about CH's result that spillover effects across countries depend on import patterns. CH refuted the argument of Keller (1998) in Coe and Hoffmeister (1999). Pedroni (1997, 1999) and Kao and Chiang (1999) proposed methods of testing for cointegration in panel data that were more sophisticated than those used by CH. Müller and Nettekoven (1999) criticized CH's dependence on the fixed-effects model, and showed that using the random-effects model produced very different results. While these criticisms are limited to CH's model, Lichtenberg and van Pottelsberghe (2001) take into account inward and outward foreign direct investments as additional spillover channels. Edmond (2001), claiming that the spillover effect through imports is unclear, takes into account spillovers through exports rather than imports.

This paper builds on previous developments and criticisms of CH, and concentrates on considering an important spillover channel that has been overlooked by previous studies. Spillovers resulting from R&D are essentially spillovers of intangible knowledge or information. International trade in intermediate goods is merely an indirect channel, whereas intangible knowledge or information spills over more directly through various channels. An estimation model that fails to control for such direct spillover effects lacks an important explanatory variable, which implies misspecification of the model and, hence, misleading results.

This paper, based on CH's data and model, examines the role of indirect and direct spillover effects in a model that takes account of such direct spillover effects. It regards physical communications networks as the main channel for the direct spillover of the results of R&D and uses data on rates of phone line penetration to construct measures of foreign R&D capital that spills over directly. Specifically, knowledge or information is assumed to spill over through, for example, the telephone, fax, e-mail, and the Internet. As physical communications networks continue to expand with the rapid growth of the Internet, this research is particularly relevant and current given that many people in a wide range of areas are connected to broader bandwidth networks.

2. DATA

CH derived their estimating equation on the premise that the results of R&D investment spill over across borders through trade in intermediate goods. A measure of a country's foreign R&D capital that spills over through such an indirect channel was constructed by using the import-share-weighted average of domestic R&D capital stocks of its trading partners. This paper uses CH's measure of foreign R&D capital that spills over indirectly through trade in intermediate goods, which is denoted by S_j^{ft} .

$$S_j^{ft} = \sum_{i \neq j} \lambda_{ji} S_i^d. \quad (1)$$

The term λ_{ji} is the bilateral import share of country i from country j and S_i^d is the domestic R&D capital of country i . The main contribution of this paper is that it focuses on the importance of the direct spillover of the results of R&D. A measure of foreign R&D capital that spills over directly is constructed as follows:

$$S_i^{fn} = \sum_{j \neq i} p_i p_j S_j^d. \quad (2)$$

Here, p_i is a scale for the physical communications networks established in country i , for which the number of telephone lines *per capita* taken from the Telecommunications Database of the International Telecommunications Union is used as a proxy. Supposing that the extent of direct spillover effects from country j to country i is influenced by the availability of the two countries' physical communications networks, it is assumed in Equation (2) that the extent of the effect is proportional to the multiple of appropriate scales for the availability of the two countries' networks. That is, $p_j S_j^d$ is the maximum size of the spillover from country j to a foreign country, and the proportion of this that spills over to country i is $p_i p_j S_j^d$.

3. ESTIMATION RESULTS

The main purpose of this paper is to analyse whether the indirect spillover effect, proposed empirically by CH, is significant once the direct spillover effect has been taken into account, and to compare the explanatory power of the direct effect to that of the indirect effect. The basic estimating equation is as follows:

$$\log F_{it} = \alpha_i + \gamma_t + \beta_1 \log S_{it}^d + \beta_2 \log S_{it}^{fn} + \beta_3 m_i \log S_{it}^{ft}. \quad (3)$$

The term m_i is the share of imports in GDP for country i and $\log F_{it}$ is the logarithm of total factor productivity for country i in year t . Data for 22 countries from 1971 to 1990 are used in the estimation. Note that the various variables are clearly trended as usual in total factor productivity studies. It is important to investigate whether the error term is stationary, in which case the variables are cointegrated. Having relied on the test statistics of Levin and Lin (1992, 1993) in testing their model, CH found some ambiguous results. Methods of testing for cointegration in panel data have since improved. In particular, Pedroni (1997, 1999) developed seven test statistics that are based on previous test statistics. Out of the seven statistics, four allow for group-specific dynamics.

Columns (I) and (II) in Table 1 present the estimation results of Equation (3) for the fixed-effects model (hereafter FEM) and the random-effects model (hereafter REM), respectively. Below column (I) are the values for Pedroni's (1997, 1999) seven cointegration test statistics for panel data. With the exception of the panel- ρ and the group- ρ test statistics, these values indicate that the variables are cointegrated. Hence, the estimation results of Equation (3) indicate a long-term relationship between the variables. The two-way model, which takes into account both time and group effects, appears to be superior to the one-way model, which considers only the group effect. Therefore, in estimation, both time and group effects are considered. Although the Hausman test favours the FEM over the REM, the results of two models are not qualitatively different.

Table 1. Total Factor Productivity Estimation Results 1971-90 440 Observations^a

	Explanatory Variables	(I)	(II)	(III)	(VI)
		FEM	REM	FEM	REM
Estimation Results	$\log S^d$	0.0090 (0.3969)	0.0069 (0.5000)	0.0152 (0.2105)	0.0154 (0.1944)
	$G \log S^d$			0.1377*** (0.0000)	0.1083*** (0.0005)
	$\log S^{fn}$	0.1333*** (0.0000)	0.0740*** (0.0000)	0.1405*** (0.0000)	0.0935*** (0.0000)
	$G \log S^{fn}$			-0.0045 (0.7888)	0.0096 (0.5319)
	$m \log S^{ft}$	-0.0209 (0.6891)	-0.0793* (0.0884)	0.1288** (0.0239)	0.0986* (0.0692)
	$Gm \log S^{ft}$			-0.2199 (0.3102)	-0.3542* (0.0840)
Model Specification	FEM vs. REM (Hausman test ^b)	11.93 (0.0076)		10.54 (0.103608)	
	Two way Vs. One way ^c (χ^2 test)	47.204 (0.00033)		60.075 (0.00000)	
	(F test)	2.360 (0.00115)		3.026 (0.00002)	
Cointegration Tests^d	Panel v-stat	2.16768**			
	Panel ρ -stat	0.04898			
	Panel pp-stat	-2.61964***			
	Panel adf-stat	-3.58985***			
	Group ρ -stat	1.77071			
	Group pp-stat	-2.29087**			
	Group adf-stat	-4.36537***			

^a) The dependent variable is log(total factor productivity), indexed as 1985=1. *, **, *** indicate the parameters that are significant at 10%, 5%, 1% probability level respectively. In parenthesis, p-values are given.

^b) Under the null hypothesis, FEM is no inferior to REM. For details of this test, refer to Hausman (1978)

^c) Under the null hypothesis, two way model allowing both the time and group dummies is better than one way model allowing only the group dummies.

^d) The cointegration tests except Panel v-statistics reject the null hypothesis of no cointegration when test statistics are below -1.64 (10% probability threshold); -1.96(5%), -2.57(1%). For the Panel v-statistics, the test statistics should be greater than 1.64 (10%), 1.96(5%), 2.57(1%) for the rejection. *, **, *** indicate the tests reject the null of no cointegration at 10%, 5%, 1% significance level respectively.

It appears that the direct spillover effect has clear explanatory power whereas both the indirect effect through trade and the effect of domestic R&D capital are not significant. This suggests that CH's evidence of a strong indirect spillover effect might be the result of model misspecification. That is, not taking into account the direct spillover effect, which is necessary and significant for explaining the influence of R&D activities across borders, biases the results. To investigate further, we estimate the following equation, which takes into account the difference between the G7 countries and non-G7 countries.

$$\begin{aligned} \log F_{it} = & \alpha_i + \gamma_t + \beta_1 \log S_{it}^d + \beta_2 G \log S_{it}^d + \beta_3 \log S_{it}^{fn} \\ & + \beta_4 G \log S_{it}^{fn} + \beta_5 m_i \log S_{it}^{fi} + \beta_6 m_i G \log S_{it}^{fi}. \end{aligned} \quad (4)$$

Here, G denotes a dummy variable that represents the G7 countries, and accordingly, β_2 , β_4 and β_6 are parameters that indicate the difference between the G7 countries and non-G7 countries. The estimation results of Equation (4) are presented in columns (III) and (IV) of Table 1, which report results for the FEM and REM, respectively. Again, since the model that takes into account both time and group effects is superior, the two-way model is estimated. Although the results of the Hausman test did not clearly favour the FEM over the REM, it is safe to assume that the FEM is a marginally better model. Both models appear to indicate that the influence of domestic R&D investment on productivity is only significant in the G7 countries. For the R&D spillover effect across countries, only the direct spillover effect is consistently significant. There appears to be no significant difference between the direct spillover effects of the G7 and non-G7 countries. By isolating the effect for the G7 group, the indirect spillover effect through imports becomes significant in both models. The indirect effect is weaker and even becomes negative in the G7 countries, but the deviation from the non-G7 countries is not significant. Nevertheless, this suggests that imports might have a negative effect on the productivity of importing countries among the G7 countries.

Table 2 and Table 3 show the results of estimations undertaken to investigate structural changes between the 1970s and 1980s. What must be pointed out here is that, in the case of the 1980s, tests show that it is desirable not to take into account the time effect. Hence, a one-way model, which does not take into account the time effect, was estimated for both periods.¹ Let us first examine the estimation results for the basic model in Table 2, which does not allow differences between the G7 countries and non-G7 countries.

¹ It appears that the qualitative results for the 1970s remain unchanged whether or not the time effect is considered, while those for the 1980s do not. Therefore, estimating in this way, which is consistent for both periods, does produce the same qualitative results as would estimating a two-way model for the 1970s and a one-way model for the 1980s.

Table 2. Structural Changes between 70's and 80's: without G7 Dummy Variables^a

		FEM		REM	
		70's	80's	70's	80's
Estimation Results	$\log S^d$	0.0235 (0.2424)	0.0268 (0.1660)	0.0192 (0.2951)	0.0203 (0.2872)
	$\log S^{fn}$	0.0661*** (0.0000)	0.0928*** (0.0000)	0.0673*** (0.0000)	0.0977*** (0.0000)
	$m \log S^{ft}$	-0.0657 (0.4996)	-0.1330*** (0.0087)	-0.0510 (0.5649)	-0.1642*** (0.0002)
Structural change	F-test	19.9482 (0.00000)			
Model Specification	FEM vs. REM (Hausman test)	5.93 (0.11486)	4.18 (0.24233)		
	Two way Vs. One way (χ^2 test)	38.130 (0.00002)	7.225 (0.61373)		
	(F test)	3.911 (0.00014)	0.690 (0.71748)		

^a) The dependent variable is $\log(\text{total factor productivity})$, indexed as 1985=1. *, **, *** indicate the parameters that are significant at 10%, 5%, 1% probability level respectively. In parenthesis, p -values are given.

In both the REM and the FEM, the direct spillover effect appears to be significant during both periods, with the effect being stronger in the 1980s than in the 1970s. By contrast, the indirect spillover effect through trade has no explanatory power for the 1970s and has a negative effect in the 1980s. The influence of domestic R&D capital strengthens in the 1980s, but does not appear to be significant. An F-test indicates significant structural change between the 1970s and 1980s.

The estimation results based on the introduction of the G7 dummy are shown in Table 3. In this case, the Hausman test clearly indicates that the REM is superior to the FEM. First, in the case of the direct spillover effect, there appears to be no significant difference between the G7 and non-G7 countries in the 1970s. In the 1980s, there was a significant increase in the direct spillover effect for non-G7 countries. However, given an even bigger increase for the G7 countries, the gap between the G7 and non-G7 countries appears to have widened. While the indirect spillover effect for both the G7 and non-G7 countries appears to be insignificant in the 1970s, the effect is distinctly negative for the G7 and non-G7 groups in the 1980s. The effect appears to be much more negative for the G7 countries. While domestic R&D capital has much more explanatory power for the G7 group than for the non-G7 group in the 1970s, there is no significant difference in the 1980s.

Table 3. Structural Changes between 70's and 80's: with G7 Dummy Variables^a

		FEM		REM	
		70's	80's	70's	80's
Estimation Results	$\log S^d$	0.0399* (0.0943)	0.0428** (0.0412)	0.0367* (0.0950)	0.0358* (0.0822)
	$G \log S^d$	0.1369** (0.0480)	0.0131 (0.8091)	0.1262** (0.0382)	0.0175 (0.7450)
	$\log S^{fn}$	0.0419*** (0.0060)	0.0731*** (0.0000)	0.0422*** (0.0034)	0.0786*** (0.0000)
	$G \log S^{fn}$	0.0019 (0.9354)	0.0716** (0.0164)	0.0048 (0.8252)	0.0682** (0.0198)
	$m \log S^{fi}$	0.0770 (0.4976)	-0.1040** (0.0330)	0.1114 (0.2881)	-0.1381*** (-0.0016)
	$Gm \log S^{fi}$	0.0719 (0.8627)	-0.8277*** (0.0077)	-0.0415 (0.9034)	-0.8115*** (-0.0073)
Structural change	F-test	19.9482 (0.00000)			
Model Specification	FEM vs. REM (Hausman test)			1.29 (0.9723)	7.70 (0.26183)
	Two way Vs. One way (χ^2 test)	41.708 (0.00000)	8.023 (0.53184)		
	(F test)	4.244 (0.00005)	0.755 (0.65791)		

^{a)} The dependent variable is $\log(\text{total factor productivity})$, indexed as 1985=1. *, **, *** indicate the parameters that are significant at 10%, 5%, 1% probability level respectively. In parenthesis, p -values are given.

Table 4 and Table 5 report the estimated elasticity of each country's productivity with respect to the G7 countries' R&D capitals. The estimation results for Equation (4) based on the two-way FEM, which proved to be the superior model, were used to obtain these elasticities. For these computations, parameters that were not significant at 10% significance level were set equal to zero. Therefore, each elasticity was calculated on the basis that there is no difference between the G7 and non-G7 countries in terms of estimated values for both direct and indirect spillover effects. Table 4 shows the elasticity of productivity increase through the indirect spillover effect and Table 5 shows the elasticity of productivity increase through the direct spillover effect.

First, the change in the productivity of country A that is due to a 1% increase in the R&D capital of country i through the indirect spillover channel is calculated using the following equation:

$$\delta_{Ai} = \hat{\beta}_5 \cdot m_A \frac{\lambda_{Ai} S_i^d}{S_A^{fn}} = \hat{\beta}_5 \cdot m_A \frac{\lambda_{Ai} S_i^d}{\sum_{j \neq A} \lambda_{Aj} S_j^d}. \quad (5)$$

The average elasticity, which is weighted by GDP, was calculated for the G7 countries and for all countries. According to Table 4, a 1% increase in the R&D capital of the US raises the productivity of other countries by an average of 0.014% through the indirect spillover channel. The corresponding figure for Japan is 0.0022%. Since the R&D capital of the US is four times that of Japan, the effectiveness of spillovers of Japan's R&D capital through the indirect channel seems small relative to that of the US. A change in the R&D capital of the US and Japan appears to affect other G7 countries and non-G7 countries to a similar degree. However, in the case of Germany, the effect on all countries (0.0017%) is much greater than the effect on the G7 countries (0.0011%). The same is true for the UK and France.

Similarly, the change in the productivity of country A that is due to a 1% increase in the R&D capital of country i through the direct spillover channel is calculated using the following equation:

$$\rho_{Ai} = \hat{\beta}_3 \cdot \frac{P_A P_i S_i^d}{S_A^{fn}} = \hat{\beta}_3 \cdot \frac{P_A P_i S_i^d}{\sum_{j \neq A} P_A P_j S_j^d}. \quad (6)$$

Using the average elasticity from Table 5, it is found that while a 1% increase in the R&D capital of the US raises the productivity of other countries by an average of 0.15% through the direct spillover channel, a 1% increase in the R&D capital of Japan increases it by 0.05%. Taking into account the relative size of Japan's R&D capital, it is more effective in terms of spillovers through the direct channel.

The last row in Table 5 reports the overall elasticity for the G7 countries, which includes both direct and indirect international spillover effects as well as effects on domestic productivity. For this, in accordance with t-test results, it is assumed that each country's R&D capital affects domestic productivity only in the G7 countries. A 1% increase in US R&D capital raises its own productivity and that of other countries by an average of 0.23%. Corresponding figures for Japan and Germany are 0.11% and 0.067%, respectively.

Table 4. Elasticity of Productivity Increase through Indirect Spillover Channel 1990^a

	U.S.	Japan	Germany	France	Italy	U.K	Canada
U.S.		0.002923	0.000522	0.000181	0.000068	0.000324	0.000324
Japan	0.013712		0.000428	0.000174	0.000048	0.000179	0.000073
Germany	0.007955	0.001669		0.001394	0.000418	0.001027	0.000027
France	0.007023	0.000938	0.002978		0.000468	0.000929	0.000020
Italy	0.004575	0.000483	0.002995	0.001368		0.000579	0.000019
U.K.	0.011853	0.001537	0.002928	0.001044	0.000259		0.000059
Canada	0.062457	0.001683	0.000442	0.000159	0.000063	0.000460	
	Average elasticity of foreign R&D capital embodied in imports flow among G7 countries						
	0.014537	0.002209	0.001094	0.000459	0.000146	0.000443	0.000186
Aus'lia	0.017908	0.004010	0.000843	0.000216	0.000107	0.000766	0.000057
Austria	0.005394	0.001835	0.010929	0.000727	0.000594	0.000532	0.000021
Belgium	0.015004	0.001873	0.013101	0.005476	0.000626	0.003709	0.000066
Denmark	0.008052	0.001127	0.004480	0.000656	0.000210	0.001187	0.000019
Finland	0.006582	0.001902	0.003040	0.000489	0.000216	0.000973	0.000027
Greece	0.004383	0.002087	0.004341	0.000976	0.000860	0.001069	0.000018
Ireland	0.031295	0.002834	0.002871	0.000885	0.000229	0.011475	0.000045
Israel	0.035844	0.001350	0.003656	0.000901	0.000519	0.002502	0.000041
Nether.	0.017558	0.001577	0.009073	0.001772	0.000340	0.002371	0.000048
N.Z.	0.014781	0.004173	0.000644	0.000151	0.000074	0.001143	0.000054
Norway	0.011273	0.001470	0.003246	0.000574	0.000204	0.001674	0.000103
Portugal	0.007807	0.001346	0.004235	0.002253	0.000707	0.001846	0.000044
Spain	0.008175	0.001078	0.002241	0.001368	0.000419	0.000835	0.000013
Sweden	0.009544	0.001771	0.003924	0.000688	0.000214	0.001338	0.000028
Switz.	0.008769	0.001554	0.007750	0.001653	0.000620	0.001096	0.000017
	Average elasticity of foreign R&D capital embodied in imports flow						
	0.014002	0.002167	0.001701	0.000596	0.000183	0.000613	0.000164

^a) Estimated elasticity of productivity increase through the indirect spillover channel in the row country with respect to the increase of R&D capital stock in the column country. Based on the estimation result of column (III) of Table 1. Averages are calculated using GDP weights.

Table 5. Elasticity of Productivity Increase through Direct Spillover Channel 1990^a

	U.S	Japan	Germany	France	Italy	U.K.	Canada
U.S.		0.06886	0.04647	0.03437	0.01080	0.03926	0.01060
Japan	0.06875		0.00937	0.00693	0.00218	0.00791	0.00214
Germany	0.21608	0.04362		0.02177	0.00684	0.02487	0.00672
France	0.21815	0.04404	0.02972		0.00691	0.02511	0.00678
Italy	0.18064	0.03647	0.02461	0.01820		0.02079	0.00561
U.K.	0.16526	0.03336	0.02252	0.01665	0.00523		0.00514
Canada	0.05442	0.01099	0.00741	0.00548	0.00172	0.00626	
	Average elasticity of foreign R&D capital directly spilled over among G7 countries						
	0.143852	0.054794	0.032790	0.024187	0.007693	0.028113	0.007686
	Average elasticity of foreign and domestic R&D capital among G7 countries						
	0.148469	0.07014	0.043319	0.033098	0.017221	0.036599	0.013864
Aus'lia	0.08749	0.01766	0.01192	0.00882	0.00277	0.01007	0.00272
Austria	0.19577	0.03952	0.02668	0.01973	0.00620	0.02253	0.00608
Belgium	0.20408	0.04120	0.02781	0.02056	0.00646	0.02349	0.00634
Denmark	0.26550	0.05360	0.03618	0.02675	0.00841	0.03056	0.00825
Finland	0.24302	0.04906	0.03311	0.02449	0.00770	0.02797	0.00755
Greece	0.21592	0.04359	0.02942	0.02176	0.00684	0.02485	0.00671
Ireland	0.07764	0.01567	0.01058	0.00782	0.00246	0.00894	0.00241
Israel	0.09552	0.01929	0.01302	0.00962	0.00303	0.01100	0.00297
Nether.	0.18453	0.03725	0.02514	0.01859	0.00584	0.02124	0.00573
N.Z.	0.11376	0.02297	0.01550	0.01146	0.00360	0.01310	0.00354
Norway	0.24029	0.04851	0.03274	0.02421	0.00761	0.02766	0.00747
Portugal	0.14126	0.02852	0.01925	0.01423	0.00447	0.01626	0.00439
Spain	0.11616	0.02345	0.01583	0.01170	0.00368	0.01337	0.00361
Sweden	0.29671	0.05990	0.04043	0.02990	0.00940	0.03415	0.00922
Switz.	0.24846	0.05016	0.03385	0.02503	0.00787	0.02860	0.00772
	Average elasticity of foreign R&D capital directly spilled over						
	0.151431	0.051600	0.031423	0.023200	0.007370	0.026914	0.007356
	Average elasticity of foreign and domestic R&D capital						
	0.234887	0.108021	0.068685	0.052259	0.022365	0.059133	0.019585

^a) Estimated elasticity of productivity increase through the direct spillover channel in the row country with respect to the increase of R&D capital stock in the column country. Based on the estimation result of column (III) of Table 1. Averages are calculated using GDP weights.

4. CONCLUSION

R&D investment generates spillover effects not only across firms and industries, but also across countries. The extent to which one country's R&D influences the productivity of other countries is an important determinant of convergence of *per capita* income across countries and the speed of the convergence in the process of globalization. The empirical research for measuring such spillover effects of R&D investment across countries began with Coe and Helpman (1995), which has generated much subsequent research. However, the fact that intangible knowledge and information, the final products of R&D investment, spill over directly through various channels, including physical communications networks, has been overlooked by this research. The main proposition of this paper is that the estimated indirect spillover effect through trade can be biased when the direct spillover effect is not taken into account. Hence, this paper estimates a model that considers the direct spillover effect through physical communications networks as well as the indirect spillover effect through intermediate goods imports. This model was used to re-examine the conspicuous indirect spillover effect obtained by CH, and to evaluate the significance and magnitude of the direct spillover effect.

Many meaningful results emerge from the estimation using numerous model specifications. While the direct spillover effect appeared to be consistently significant and strong, the indirect spillover effect through trade, which was found conspicuous in CH, appeared to be insignificant or negative. Examining the difference between the G7 and non-G7 groups, no significant difference appears in the estimated parameters for the direct spillover effects. The indirect effect is weaker and even becomes negative in the G7 countries, but the deviation from the non-G7 countries is not significant, either. The effect of a country's R&D capital on its productivity appeared to be significant only for the G7 group. The estimation results also provided evidence of significant structural change between the 1970s and 1980s. The direct spillover effect for both the G7 and non-G7 groups increased in the 1980s and the increase was larger for the G7 group. The indirect spillover effect was not significant in the G7 and non-G7 groups in the 1970s, but became significantly negative in the 1980s. This tendency is more apparent among the G7 countries. The effect on its own productivity appears to be greater for the G7 group than for the non-G7 group in the 1970s, but the difference became insignificant in the 1980s due to the diminishing magnitude of the effect in the G7 group.

Putting these results together, it can be said that consideration of direct spillovers of knowledge and information across countries through various channels, including physical communications networks, is very important in research on R&D spillover effects across countries. Models that do not consider direct spillover effects might bias the magnitude and direction of the spillover effect through other channels.

However, the proxy for the direct spillover effect used in this study lacks detail due to data limitations. For example, it may be desirable to consider telecommunications expenditure and line quality, in addition to line penetration rates. Further, it will be

useful for future research to develop a proxy that takes into account the spillovers through other direct channels such as direct visits and publications such as academic journals, in addition to physical communications networks. In particular, the new phenomenon of the explosive growth of the Internet in recent years is not reflected in this paper. This will be a useful subject for research when sufficient panel data have accumulated from the mid 1990s, which marks the start of the Internet boom.

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Manuscript received November, 2004; final revision received March, 2005.