Empirical Economics manuscript No.
(will be inserted by the editor)

An empirical note on international R&D spillovers

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May 12, 2012

Abstract Whether international R&D spillovers are global and trade–related is still a debated issue. By adopting two specifications that nest models previously estimated in the literature, we test the hypothesis that international R&D spillovers are global and trade–unrelated for a sample of OECD countries over the period 1971–2004. In particular, via a randomization exercise, we reject the null hypothesis of a "global pool of technology" and show that there are partitions of countries associated with relatively strong/weak knowledge spillovers. Then, we estimate a nonlinear specification that includes simultaneously geographical distance and international trade among the determinants of domestic TFP. We find robust evidence that both factors affect how foreign knowledge impacts on the domestic productivity of each recipient country.

Keywords International R&D spillovers · International technology diffusion · Localized knowledge spillovers · Total Factor Productivity

JEL Classification C23; F01; O30; O47.

1 Introduction

Several theoretical contributions in the strand of the literature focusing on endogenous growth (e.g. Grossman and Helpman 1991; Rivera-Batiz and Romer 1991; Aghion and Howitt 1992; Eaton and Kortum 1999; Howitt 2000) suggest that foreign R&D activities can improve domestic Total Factor Productivity (TFP) because

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knowledge can spill over into foreign countries through a range of theoretically plausible channels.

At one extreme of this range, knowledge is disembodied and moves freely across nations: accordingly, knowledge spillovers are global and independent from "physical" exchanges of goods and services of any kind. At the opposite extreme, foreign knowledge spillovers are both localized, in the sense that they are negatively affected by distance, and trade–related, because closely associated with existing international trade relationships.

Localized, trade–related spillovers can materialize if foreign knowledge affects domestic productivity when embodied in traded intermediate goods and services. The first way in which this can happen is under the form of rent–spillovers (Griliches 1979; Jaffe 1986), that occur when the market prices of the imported innovations do not fully reflect the productivity increase they generate. Another possible channel is via the (partly sequential) process of: 1) using the foreign technology; ii) learning the technology *per se*; iii) imitating the technology, iv) improving the technology (Keller 2004). These knowledge spillovers are clearly trade–related and necessarily geographically localized, since the increase in transport costs makes international trade volumes decrease with distance.

There could be localized trade–related spillovers also when, although knowledge is not strictly embodied in the traded goods, the above mentioned process of learning and imitation is enhanced by international trade. For instance, trade might increase international economic interactions and this in turn makes it easier to catch up with the foreign technology.

Trade–unrelated knowledge spillovers, on the contrary, are those produced by the "diffusion of ideas" (Eaton and Kortum 1996), with no underlying international market transactions. This process of knowledge diffusion does not characterize only the global spillovers mentioned above. The more important the role played in the diffusion of ideas by factors such as face–to–face contacts and interactions, commonalities of habits and cultural similarities, the more geographically localized the trade–unrelated spillovers are, given that these factors tend to decrease with distance (Eaton and Kortum 1999; Keller 2004).

At the empirical level, what channels of knowledge diffusion are at work remains an open issue and existing results in the literature are mixed. This is particularly true for the trade–related channel: while there is solid evidence in the literature about learning associated with international trade and investment activities at the micro level, the impact of foreign knowledge on domestic productivity at the macro level remains highly controversial.

On the one hand, a number of studies following the seminal work by Coe and Helpman (1995)—showing that the import–weighted sum of foreign R&D stocks is positively associated with domestic TFP—find that international knowledge spillovers are localized and trade flows do have a role in shaping them (see, e.g., Engelbrecht 1997; Xu and Wang 1999; Keller 2002; Lejour and Nahuis 2005; Lumenga-Neso et al. 2005; Franco et al. 2011). On the other hand, Keller (1998) shows that the simple sum of the foreign R&D stock performs better than the import–weighted sum used in Coe and Helpman (1995), thereby suggesting that spillovers are global and trade–independent. Moreover, Klenow and Rodriguez-Clare (2005) maintain that extremely localized spillovers are at odds with the catch–up process occurred in the last few decades in many developing countries.

Notwithstanding further research on the issue undertaken in more recent years (see, for instance, Busse and Groizard 2008; Coe et al. 2009), these contrasting hypotheses (i.e., global knowledge diffusion versus localized and trade–dependent knowledge diffusion) have not yet been tested one against the other by means of nested empirical specifications. Thus, whether R&D spillovers are global or not and, in the case of a negative answer, to what extent the impact of foreign knowledge on domestic TFP depends on international trade remain open empirical questions.

In this paper, we address these issues by means of new empirical specifications that nest the alternative hypotheses under investigation. We improve on previous studies that focus on nonnested alternative models and, hence, fail to provide conclusive results about their relative performance. The sequence of nested tests we propose allows first to test the hypothesis of global spillovers and, subsequently, to assess the relative impact of trade and distance on the diffusion process of knowledge. This procedural approach allows to account for the various rationalizations of knowledge spillovers identified, as discussed above, in the theoretical literature. To facilitate the comparison of our results with previous findings, we estimate both the baseline non–nested models and our nested specifications by using the same dataset recently compiled by Coe et al. (2009).

In a nutshell, our results suggest that knowledge spillovers are not global but, rather, localized. Moreover, we show that, even accounting for a distance–related decay in the diffusion of knowledge, spillovers are significantly related to trade.

The paper proceeds as follows. In Section 2, we put forward a randomization exercise to test the hypothesis that R&D spillovers are truly global, and therefore trade–independent and non–localized. Having rejected such hypothesis, in Section 3 we analyze the distinct roles of distance and trade, and consider the possibility that geographical proximity, with its impact on both trade and knowledge spillovers, is the actual determinant of R&D spillovers. Section 4 concludes summing up the main results and drawing some policy implications.

2 A simple test of the global pool hypothesis

To assess the impact of foreign knowledge on domestic productivity, Coe and Helpman (1995) propose the following specification:

$$\log F_{it} = \alpha_i + \beta^d \log S^d_{it} + \beta^f \log S^f_{CHit} + \epsilon_{it} \tag{1}$$

where the log of the TFP of country i at time t (F_{it}) is regressed against a country dummy (α_i), the log of domestic R&D capital stock (S^d_{it}) and the log of foreign R&D stock of country i (S^f_{CHit}). The latter is calculated as an import–weighted sum of the domestic R&D stock of the other countries ($S^f_{CHit} = \sum_j \frac{m_{ijt}}{\sum_j m_{ijt}} S^d_{jt}$ where m_{ijt} is the import of country i from country j at time t). Using macroeconomic data for 21 OECD countries plus Israel over the 1971–1990 time period, the authors find that trade–weighted foreign R&D stock positively impacts on domestic TFP. It is worth noticing that, notwithstanding some limitations singled out in subsequent works in the literature, Coe and Helpman's empirical framework still represents the workhorse of the macro–level empirical research on the impact of foreign knowledge on domestic productivity.[1]

Keller (1998) challenges these findings and re–estimates the equation after substituting the import–weighted sum of R&D stock with the simple sum of the rest of the world stock of R&D ($S^f_{Kit} = \sum_{j \neq i} S^d_{jt}$). Keller's specification can thus be written as:

$$\log F_{it} = \alpha_i + \beta^d \log S^d_{it} + \beta^f \log S^f_{Kit} + \epsilon_{it} \quad (2)$$

He shows that this specification gives rise to a point estimate of the TFP elasticity with respect to the foreign R&D as high as in Coe and Helpman (1995), with a better fitness of the regression. On this basis, he concludes that "the composition of imports of a country plays no particular role in estimating a positive and significant impact from foreign R&D on domestic productivity levels" (1998, p.1479).[2] Somehow at the risk of overstating Keller's conclusions, this statement can be considered equivalent to a hypothesis of a "global pool" of technology.

In Table 1, we report the estimates for the specifications proposed by Coe and Helpman (1995) and Keller (1998), to which we add human capital (H_{it}) among the regressors as in Engelbrecht (1997). To maintain the comparability of these results with Keller (1998) and Coe and Helpman (1995) while extending the dataset to larger and more recent data, we test these competing hypotheses on a sample of 24 OECD countries over the period 1971–2004, using the data on R&D stock, human capital and TFP indexes from Coe et al. (2009).[3]

In addition, to fully exploit the cointegrating properties of the series, we calculate panel dynamic OLS (DOLS) estimates with individual fixed effects, where leads and lags of first differenced independent variables are added to the original equation so as to obtain coefficient estimates with better limiting distribution properties (for details see Kao et al. 1999). As suggested by Nelson and Sul (2003) and discussed in Coe et al. (2009), employing panel DOLS allows to exploit, on the one hand, the commonalities across countries (given the limited time–series observations), and, on the other hand, the superconsistency of the estimates under cointegration. Panel DOLS estimators are not only superior to OLS and fully modified OLS estimators in terms of mean biases (as shown by Kao and Chiang 2000), but also computationally simpler.

Fixed effects can account for time–invariant, country–specific unobserved factors. Accordingly, while the cointegrating vector is homogeneous across countries, unobserved heterogeneity is allowed through individual specific fixed effects.[4]

[1] On the problems entailed by this specification see Lichtenberg and van Pottelsberghe de la Potterie (1998) and Coe et al. (2009). Some econometric issues are instead addressed by Kao et al. (1999) and Edmond (2001).

[2] Keller (1998) also "randomizes" Coe and Helpman's (1995) measure by creating a weighted sum of the foreign R&D stocks with random weights and finds similar results. However, Coe and Hoffmaister (1999) show that such weights were not truly random, but simple averages of the actual data with a random component. Funny enough, in this section we randomize the randomizer.

[3] Countries are: Australia, Austria, Belgium–Luxembourg, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Israel, Italy, Japan, Korea, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, UK, US. The panel is balanced. For a discussion of data sources, definitions, descriptive statistics and plots, we refer to Coe et al. (2009).

[4] Although fixed effects capture some of the heterogeneity characterizing the series, it could be argued (Nelson and Sul 2003) that panel DOLS build on the extreme assumption of

Table 1 Panel DOLS estimates with country–fixed effects. Equations (1) and (2)

	(1)	(2)
$\log H$	0.7106***	0.6080***
	(0.0920)	(0.1050)
$\log S^d$	0.0608**	0.0663**
	(0.0249)	(0.0251)
$\log S^f_{CH}$	0.1264***	
	(0.0298)	
$\log S^f_K$		0.1072***
		(0.0336)
Obs.	720	744
AIC	-1648.260	-1614.276
BIC	-1483.407	-1475.914

Dependent variable: $\log F$. Data 1971–2004 for 24 countries. Regressions include leads and lags of first differenced independent variables. In particular, on the basis of the Akaike Information Criterion, one lead and two lags of first differenced variables are in specification (1), and a lag of order two of first differenced variables in specification (2). Newey–West standard errors (4 lags) in parenthesis. Significance levels: * 10%; ** 5%; *** 1%.

For the sake of brevity and because we use the dataset produced by Coe et al. (2009), we refer to this article for the tests of integration and panel cointegration, as well as for a graphical representation of the individual series.

In line with the original findings, neither model is rejected by the data. The estimates of specification (2) suggest that R&D spillovers appear as global (and trade–unrelated), whereas the estimates of specification (1) indicate that the spillovers are localized and trade–related. As the elasticity of TFP with respect to S^f_{CH} is higher than with respect to S^f_K and the standard error of the former is lower, one would be tempted to conclude about a superior performance of Coe and Helpman's (1995) measure over Keller's (1998). In fact, a direct comparison between the two is prevented by the fact that the models are not nested.

To assess properly the "global pool" hypothesis against the alternative of localized spillovers, one should develop a more general, nonlinear model that nests Equation (2) as a specific case. Notably, notwithstanding a vast literature in this area of research, no previous work, to the best of our knowledge, goes in this direction. Thus, we tackle the issue and propose the following specification to discriminate between the competing hypotheses:

$$\log F_{it} = \alpha_i + \beta^h \log H_{it} + \beta^d \log S^d_{it} + \beta^f \log \left(S^f_{Kit} + \iota S^{fA}_{it}\right) + \epsilon_{it} \tag{3}$$

complete homogeneity of the slope coefficients. In fact, Coe et al. (2009) show that a panel group mean estimation, allowing for complete parameter heterogeneity, leads to similar results. Moreover, while panel DOLS could be sensitive to the time span and the sample–units, Coe et al. (2009) show that the results are robust to restricting the countries from 24 to 22 and/or from reducing the time span to end in 1990. Admittedly, in one section of their article, Coe and co–authors do tackle the issue of parameter heterogeneity by means of interacting terms reflecting cross–country legal and institutional differences: we do not explore the issue further, as this would prevent us from estimating a model nesting the baseline equations (1) and (2). This notwithstanding, the homogeneity of the slope parameters represents an issue of further research, and we thank an anonymous referee for pointing it out.

where $S_{it}^{fA} = \sum_{j \in \mathcal{A}_i \setminus \{i\}} S_{jt}^{d}$ and $\mathcal{A}_i$ is a subset of the set of countries, so that S_{it}^{fA} is the simple sum of the R&D stocks of the foreign countries belonging to a particular subset of the world, which can vary across countries.

Given a set of subsets $\mathcal{A}$, one for each country, one can test the null hypothesis $\mathrm{H}_0 : \iota = 0$, so that model (3) simplifies in (2), against the alternative $\mathrm{H}_1 : \iota \neq 0$. Clearly, the rejection of the null implies the rejection of the "global pool" hypothesis.

Since the model is linear under the null and non–linear under the alternative, the simplest (and least computationally–intensive) way to test the restriction is by means of a LM test, as it uses estimates only under the (linear) null. The test statistic is equal to NT times the (uncentered) R–squared from the regression of the residuals from the restricted model (2) on the gradient of (3) with respect to the parameters evaluated at the restricted estimates (see, for instance, Engle (1984, p. 809–811) or Wooldridge (2002, p. 363 e ss.)). In the present case, it amounts to: i) estimate specification (2) and take the residuals $\tilde{\epsilon}$; ii) regress $\tilde{\epsilon}$ on $(\alpha, \log H, \log S^d, \log S_K^f, S^{fA}/S_K^f)$;[5] iii) multiply the R–squared from the latter regression by $24 \times 34 = 816$. The test statistic has a limiting $\chi^2(1)$ distribution.

To compute the heteroskedasticity–robust version of the test, one needs to i) regress S^{fA}/S_K^f on $(\alpha, \log H, \log S^d, \log S_K^f)$ and collect the residuals $\tilde{r}$; ii) subtract from NT (=816) the sum of squared residuals from the regression of a constant on $\tilde{\epsilon}_{it}\tilde{r}_{it}$ (see Wooldridge (2002, p. 368) and Wooldridge (1991) for details).

The results of the test are clearly dependent on the set of subsets $\mathcal{A}$, but the important point to consider is that, if spillovers were truly global, so that all countries could absorb knowledge from a common and global pool, the coefficient ι would not significantly differ from zero, no matter the partition of countries (i.e., the actual $\mathcal{A}_i$ for each country i). Therefore, instead of relying on a particular $\mathcal{A}$, we draw at random several different $\mathcal{A}$s, and perform a LM test for each of them.

In particular, we perform 1000 different repetitions. In each repetition, we draw 24 random subsets $\mathcal{A}_i$ (one for each of the countries in the sample) out of the 2^{24} possible ones, with each country having probability 1/2 of belonging to the subset of any other country. The expected number of countries belonging to $\mathcal{A}_i \setminus \{i\}$ for each country i is therefore binomially distributed with expected value $23 \times 1/2 = 11.5$. Given $\mathcal{A}$, we can compute S^{fA} and the p–value of the corresponding LM statistic, thus testing the null $\mathrm{H}_0 : \iota = 0$.

Since we are looking at 1000 independent tests, in order to reject the null with a significance level γ for all the randomizations, the significance level for the single test must be lower. In particular, since the probability of Type I error in at least one of the 1000 independent tests is $\gamma = 1-(1-\gamma_0)^{1000}$, where γ_0 is the probability of Type I error in each test, we set a significance level $\gamma_0 = 1-(1-\gamma)^{\frac{1}{1000}}$ for the single test and reject the null when at least one of the 1000 tests rejects it at γ_0. For instance, when γ is set equal to 0.01, the corresponding value of γ_0 is 1.00503×10^{-5}.

Our results, reported in Table 2, show that the global pool hypothesis is strongly rejected by the data. The (heteroskedasticity–robust) LM–tests reject the null 308 times (or more as γ increases), i.e. around 30% of the cases. We recall that, had the global pool hypothesis been correct, we would have rejected the null in none of them.

[5] The derivate of (3) with respect to ι evaluated at $\iota = 0$ is $\tilde{\beta}^f S_{it}^{fA}/S_{Kit}^f$, which is proportional to S_{it}^{fA}/S_{Kit}^f.

Table 2 Results of LM–test ($H_0 : \iota = 0$, 1000 repetitions)

Experiment–wide significance level (γ)	Significance level per comparison (γ_0)	Number of LM–tests with p–value $< \gamma_0$	Number of heteroskedasticity–robust LM–tests with p–value $< \gamma_0$
0.01	0.000010050	421	308
0.05	0.000051292	458	343
0.10	0.000105355	481	364

These results indicate that R&D spillovers are not global because they significantly depend on the exact partition of the foreign countries. This, together with previous findings in the literature mentioned above, strengthens the intuition that spillovers are localized.

Having ascertained this, it remains to be assessed whether geographical distance, with its impact both on international trade flows and the amount of face–to–face interactions/cultural proximity, turns out as the only determinant of knowledge spillovers, or instead there is still room for an additional effect of country openness to trade in such spillovers. The hypothesis that trade is irrelevant once distance is considered has been maintained in the literature. Keller (2002), for instance, argues that spillovers are localized because they decay with geographical distance, and no role is left to trade as an additional source of spillovers: lower spillovers appear empirically associated with lower trade mainly because the geographical distance between two countries negatively affects both international knowledge diffusion and international trade.

Although this conjecture regarding the spurious nature of the positive empirical relationship between trade and spillover localization is plausible, Keller (2002) does not encompass both trade and distance in the estimated specification. In the next section, we shall analyze the impact of trade and geographical proximity on R&D spillovers. Contrary to previous studies encompassing either trade or geographical distance in the estimated functional form, in what follows we will assess whether international trade remains positively related to R&D spillovers even once geographical proximity is already accounted for in the specification.[6]

3 Is trade proxying for geographical proximity?

To consider both distance and trade in the international diffusion of knowledge and test for the relevance of trade openness once accounting for geographical proximity, we introduce international trade in a modified version of the nonlinear specification proposed in Keller (2002), where spillovers simply decay with distance, that is:

$$\log F_{it} = \alpha_i + \beta^h \log H_{it} + \beta^d \log S^d_{it} + \beta^f \log \left(\sum_{j \neq i} S^d_{jt} \mathrm{e}^{-\delta D_{ij}} \right) + \epsilon_{it} \qquad (4)$$

where D_{ij} is the geodesic distance between the capital cities of country i and country j,[7] normalized so that the minimum smallest bilateral distance in the sample (that

[6] We explore the role of bilateral trade relationships once bilateral distances are accounted for in a companion paper, to which we refer the interested reader for details and results.

[7] Data on distances borrowed from The CEPII Gravity Dataset.

between Belgium and the Netherlands in our sample—173.03 kilometers) is equal to one.[8]

More precisely, to detect the impact of foreign knowledge on domestic TFP, we adopt a more general model that accounts for a distance–related decay of the spillovers and also allows for a distance–unrelated role played by trade openness:

$$\log F_{it} = \alpha_i + \beta^h \log H_{it} + \beta^d \log S^d_{it} + \beta^f \log \left(\sum_{j \neq i} S^d_{jt} \mathrm{e}^{-\delta D_{ij}} \right) + \\ + \beta^{fm} m_{it} \log \left(\sum_{j \neq i} S^d_{jt} \mathrm{e}^{-\delta D_{ij}} \right) + \beta^m m_{it} + \epsilon_{it} \tag{5}$$

where m_{it} is the share of imports on GDP in country i at time t.

In Equation (5), the sum of the elasticities of TFP with respect to the foreign R&D stocks is not constant as in Equation (4), but it is an increasing function of the share of imports in the domestic economy. Indeed, the TFP elasticity of country i with respect to the R&D stock of country j is

$$\frac{\partial \log F_{it}}{\partial \log S^d_{jt}} = \frac{\partial \log F_{it}}{\partial S^d_{jt}} \left(\frac{\mathrm{d} \log S^d_{jt}}{\mathrm{d} S^d_{jt}} \right)^{-1} = (\beta^f + \beta^{fm} m_{it}) \frac{S^d_{jt} \mathrm{e}^{-\delta D_{ij}}}{\sum_{c \neq i} S^d_{ct} \mathrm{e}^{-\delta D_{ic}}}$$

Hence, their sum is:

$$\sum_{j \neq i} \frac{\partial \log F_{it}}{\partial \log S^d_{jt}} = \beta^f + \beta^{fm} m_{it} \tag{6}$$

In turn, the semielasticity of TFP to the import share is an increasing function of the distance–weighted foreign R&D stock:

$$\frac{\partial \log F_{it}}{\partial m_{it}} = \beta^m + \beta^{fm} \log \left(\sum_{j \neq i} S^d_{jt} \mathrm{e}^{-\delta D_{ij}} \right) \tag{7}$$

If R&D spillovers were mainly trade–unrelated and driven by geographical distance, Equation (5) would simplify to Equation (4). On the contrary, if also international trade were affecting the way foreign knowledge influences domestic TFP, then the marginal impact of trade on productivity—Equation (7)—and the effect of trade on the TFP elasticity to the distance–weighted foreign R&D stocks—β^{fm} in Equation (6)—would be positive.

Since both the import share (m_{it}) and the foreign R&D capital stock enter Equation (5), no cross restriction is imposed on the estimated elasticity of TFP with respect to each of these variables. This makes this functional form preferable to the specifications that include the interacting term $m_{it} \log \left(\sum_{j \neq i} S^d_{jt} \mathrm{e}^{-\delta D_{ij}} \right)$, but do not include m_{it}. However, there are also good reasons not to include m_{it} in the specification: panel unit root tests, as shown by Coe et al. (2009) to which we refer

[8] This normalization amounts to a change in the measurement unit of distance and it does not affect elasticities. However, contrary to what stated by Keller (2002), it does affect the size of δ. Therefore, because of the different minimum distance in the sample (that in Keller (2002) is the distance between Germany and the Netherlands, which is 3.34 times the distance between the Netherlands and Belgium), our estimates of δ cannot be directly compared with his. To do so, one would need to divide (multiply) his (our) value by 3.34.

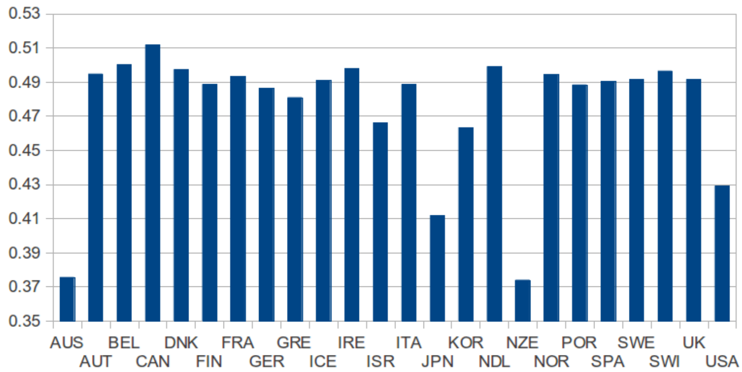

Fig. 1 Point estimates of the semielasticity of TFP to the import share by country

for details, reject the null of unit root for m in all groups. Moreover, Edmond (2001) shows that, in all the linear specifications where m is included as an independent regressor, Pedroni's (2004) test retains the null of no cointegration. Therefore, with a view at reducing the risk of spurious regressions due to the improper inclusion of a stationary m, but at the cost of implicitly imposing some cross restrictions on the estimated elasticity of TFP (Lichtenberg and van Pottelsberghe de la Potterie 1998; Coe and Hoffmaister 1999), we estimate the alternative specification below:

$$\log F_{it} = \alpha_i + \beta^h \log H_{it} + \beta^d \log S^d_{it} + (\beta^f + \beta^{fm} m_{it}) \log \left(\sum_{j \neq i} S^d_{jt} \mathrm{e}^{-\delta D_{ij}} \right) + \epsilon_{it} \quad (8)$$

where m_{it} does not appear as an independent regressor.

The results of the Nonlinear Least Squares (NLS) estimations are reported in Table 3.[9] The estimation confirms that R&D spillovers decline with the geographic distance between the sender and the recipient country, in support of the idea that R&D spillovers are geographically localized. Given the estimates of δ, the implied "half–life distance of technology", i.e., the distance at which only half of the foreign country's R&D stock is domestically available, ranges roughly from 10 to 15 times the distance between Belgium and the Netherlands (1,750 to 2,600 kilometers).[10] In the models specified by Equations (5) and (8), the estimated decay rate increases, pointing to a possible underestimation in the baseline specification—Equation (4)—because of the omission of trade among the regressors, which is positively correlated with TFP and negatively correlated with distance. Our estimates are lower than those reported in Keller (2002), where the half–life of technology ranges from 162 to about 1,200 kilometers in his preferred specification, and thus appear more in line with the model of Klenow and Rodriguez-Clare (2005).

[9] Computations done using gretl 1.9.5 (`gretl.sourceforge.net`): Levenberg–Marquardt algorithm with supplied analytical derivatives. Code available at request.
[10] Because of the exponential specification, this distance is assumed to be constant and equal to $\ln 2/\delta$.

Table 3 Estimation results (NLS with country dummies. Data for 24 countries over 1971–2004: 816 observations)

	Eq. (4)	Eq. (5)	Eq. (8)
β^h	0.527***	0.515***	0.490***
	(0.0516)	(0.0466)	(0.0483)
β^d	0.038***	0.029***	0.044***
	(0.0068)	(0.0067)	(0.0071)
β^f	0.168***	0.057**	0.128***
	(0.0153)	(0.0147)	(0.0167)
δ	0.046***	0.069***	0.064***
	(0.0114)	(0.0089)	(0.0085)
β^{fm}		0.358***	0.036***
		(0.0468)	(0.0079)
β^m		-4.370***	
		(0.6304)	
$\beta^f + \beta^{fm}\bar{m}$ [a]		0.171***	0.140***
		(0.0156)	(0.0154)
$\beta^m + \beta^{fm}\log\bar{S}^f$ [b]		0.409***	
		(0.1182)	
$\beta^{fm}\log\bar{S}^f$			0.486***
			(0.1055)
AIC	-1624.8	-1766.1	-1681.9
BIC	-1493.1	-1624.9	-1545.5

[a] $\bar{m} = 0.319$ is the mean import share in the sample.
[b] $\bar{S}^f = \sum_{i,t,j\neq i} S^d_{jt}\mathrm{e}^{-\hat{\delta}D_{ij}}/NT$ is the sample mean of the distance–weighted R&D stock.
Unreported country dummies. Heteroskedasticity–robust standard errors in parentheses. Significance levels: * 10%; ** 5%; *** 1%.

What is more important is that, even when distance is accounted for, trade continues to affect significantly how R&D spillovers impact on TFP.[11] In particular, the marginal impact of the countries' import share on productivity calculated at the sample mean of the distance–weighted R&D stock—respectively, $\beta^m + \beta^{fm}\log\bar{S}^f$ in Equation (5) and $\beta^{fm}\log\bar{S}^f$ in Equation (8)—is positive and significant. Clearly, the estimates of the coefficient β^{fm} differ notably in the specifications because of the omission of one interacting term in the latter: once such "structural" difference is accounted for, the marginal impact of the countries' import share appears to be very similar (and strongly significant).

Figure 1 shows the point estimates of the semielasticity of TFP to the import share by country for Equation (8), i.e. $\hat{\beta}^{fm}\log\left(\sum_{t,j\neq i} S^d_{jt}\mathrm{e}^{-\hat{\delta}D_{ij}}/T\right)$. The mean marginal impact of the import share on the percentage increase of the country's TFP positively depends on its average distance–weighted foreign R&D stock: it ranges from a minimum of 0.374 for the New Zealand to a maximum of 0.512 for Canada.

[11] As a robustness check, we allow time–specific effects and re-estimate all the models with the inclusion of time dummies. The estimates are fairly similar to those reported in the main text and the information criteria are always lower. Results available upon request.

4 Conclusions

Despite the rich literature on international R&D spillovers, whether the effects on productivity of R&D are global or localized (and, in the latter case, trade–related or trade–unrelated) is still an open empirical issue, because evidence has been provided in support of both hypotheses. Different works offer contrasting results on this, but they can hardly be compared because of the different and nonnested empirical specifications they adopt.

By using the enlarged sample of countries employed by Coe et al. (2009) and adopting two new empirical specifications that nest models proposed in the literature, we test the hypothesis that spillovers are global rather than localized. In particular, we carry out an exercise based on a randomization of the original model in Keller (1998) to test the hypothesis of a "global pool" of technology. Data strongly reject this hypothesis.

On this basis, we adopt a modified version of the model proposed by Keller (2002) so as to allow both international trade and geographical distance to affect the impact of foreign knowledge on domestic TFP. We reject the hypothesis that international trade plays no role once geographical distance is accounted for. In fact, trade openness considerably increases the elasticity of TFP with respect to the distance–weighted foreign R&D stock.

Despite the presence of nonlinear coefficients and interacting terms, the estimated marginal impact on productivity of the countries' import share and of their foreign R&D stocks are robust across specifications.

The impact of domestic and foreign knowledge on domestic productivity is an important economic issue which bears on the patterns of aggregate growth and on the features of the catching–up process of developing countries. For instance, as argued in Klenow and Rodriguez-Clare (2005), lack of international spillovers would be incompatible with the observed catching–up process. Although we do not offer a fully–fledged discussion of the implications of our findings for R&D policy, some suggestions can be drawn from the results. In particular, the existence of localized and trade–related spillovers entails that, in pursuing greater domestic TFP, policy–makers should both support domestic expenditures in R&D and facilitate trade integration with countries well endowed of technology. Once trade–related spillovers are taken into account, an inward oriented policy (such as import substitution) might be dynamically inefficient.

Acknowledgements The authors are grateful to the Department of Economics of the University of Trento and the OPENLOC project (sponsored by the Autonomous Province of Trento) for financial support. They also thank Roberto Golinelli, Stefano Schiavo, Maria Luigia Segnana and two anonymous referees for valuable comments and suggestions on previous versions of this work. Usual disclaimers apply.

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