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Andrea Fracasso

and

Giuseppe Vittucci Marzetti

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Trade network and international R&D spillovers

Andrea Fracasso*

Department of Economics, University of Trento, Inama 5, 38122 Trento, Italy

Giuseppe Vittucci Marzetti

Department of Sociology ad Social Research, University of Milano-Bicocca, via Bicocca degli Arcimboldi 8, 20126 Milan, Italy

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Abstract

Following Coe and Helpman (International R&D Spillovers, EER, 39, 859-887, 1995), the literature on the trade-related channels of international knowledge flows has flourished. Departing from Coe and Helpman's tenets on the proportionality of trade and productivity spillovers and thus relaxing the implicit assumption that the knowledge transferred internationally is physically embodied in the exchanged products, we test whether relatively strong bilateral trade relationships are significantly associated with important international R&D spillovers. Notably, we focus on refined measures of bilateral trade that account for country size, time-invariant pair-specific factors and time-varying country-specific factors. By distinguishing closer and more distant trade partners without weighting their R&D stocks for the bilateral trade flows, we show that trade is indeed an international transmission channel of knowledge even when distance and other pair specific time-invariant factors are taken into account.

Key words: International R&D spillovers, Total Factor Productivity, International trade network

JEL Classification: C23, F01, O30, O47

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*Corresponding author: Address: Department of Economics, University of Trento, via Inama 5, 38122 Trento, Italy, Phone: +39 0461 282216, Fax: +39 0461 282222

Email addresses: `andrea.fracasso@unitn.it` (Andrea Fracasso), `giuseppe.vittucci@unimib.it` (Giuseppe Vittucci Marzetti)

1. Introduction

Many theoretical models show why and how knowledge contributes to technological progress and productivity growth. Not only knowledge has positive effects on the productivity of the country in which it is produced and accumulated (see, for instance, Aghion and Howitt, 1992; Romer, 1990); as argued in several theoretical contributions (Grossman and Helpman, 1991; Rivera-Batiz and Romer, 1991; Keller, 2004), in fact, knowledge may also affect foreign productivity to the extent it is directly and indirectly transferred abroad. The process of ever-increasing political and economic integration initiated in the early 1970s led several authors to assess empirically whether productivity does indeed depend both on domestic and on foreign stocks of knowledge.[1]

Coe and Helpman (1995) are pioneers in developing an empirical approach to estimate how domestic and foreign knowledge impact on domestic Total Factor Productivity (TFP). By focusing on a sample of 22 advanced countries over the period 1971-1990, they investigate one of the various channels of international transmission of knowledge, namely trade flows. To account for the trade-related transmission of knowledge, they i) build import-weighted sums of trade partners' cumulative Research & Development (R&D) expenditures as measures of foreign knowledge stocks; and ii) include in their preferred specification an interaction term between the degree of trade openness (i.e., the country's import/GDP ratio) and the stock of trade-weighted foreign R&D. In the following years, several scholars refine the analysis along several directions, ranging from the econometric technique to the level of disaggregation and the composition of the trade flows (e.g. Coe *et al.*, 2009; Engelbrecht, 1997; Lichtenberg and van Pottelsberghe de la Potterie, 1998; Xu and Wang, 1999; Lumenga-Neso *et al.*, 2005).

Keller (1998) takes a critical stance on the issue and points out that Coe and Helpman's (1995) empirical specification implicitly builds on three demanding

[1]Besides the literature on knowledge and aggregate trade flows, a strand of the literature examining firm-level data has progressed, following Griliches (1992), on a separate avenue. Peri (2005) refers to the former as the trade-growth literature and the latter as the micro-productivity literature.

assumptions: i) output and productivity positively depend on the number of differentiated intermediate inputs used in the production of final products; ii) the number of varieties produced in a country depends on the local R&D stock; iii) the larger the aggregate trade flows, the greater the number of imported varieties of intermediate inputs. Even conceding that these conditions materialize, Keller questions the appropriateness of the weighting scheme used by Coe and Helpman in the construction of the foreign stocks of knowledge. According to his own empirical findings, in fact, the unweighted sum of the R&D produced abroad over time does an equivalently good job, especially for large countries, in picking-up the knowledge diffusion process than trade-weighted measures. Keller concludes that, contrary to what suggested by Coe and Helpman, who postulate that knowledge spillovers follow a local diffusion process affected by the size and composition of trade flows, the knowledge diffusion process is global and trade-unrelated.[2]

We concur with Keller in questioning the fact that the empirical studies using trade-weighted foreign R&D stocks and trade-related interacting terms in the specification do implicitly assume that the internationally transferred knowledge is proportional to the size of the trade flows.[3] In fact, as explained by Keller (2004) and recognized in passing also by Coe *et al.* (2009, footnote 12), the channels through which trade influences knowledge transmission and TFP growth are numerous and exchanges of technology embodied in the intermediate goods are only one of them.Thus, while a non-negligible trade relationship most likely is a necessary condition for the international transmission of knowledge, knowledge transfers and trade flows need not be proportional.

Accordingly, in this work we investigate whether international trade enhances knowledge spillovers without assuming the existence of a proportional relationship

[2]This finding is consistent with a model of international technology diffusion without trade in intermediate goods, such as the model built by Keller (2004) on the basis of Eaton and Kortum (1999).

[3]This is in line with those theoretical models (such as Grossman and Helpman, 1991; Rivera-Batiz and Romer, 1991; Eaton and Kortum, 2002) where traded goods are used as productive inputs and differentiated goods embody technological know-how.

between the size of trade and knowledge flows, but simply postulating that knowledge flows materialize conditional on the existence of relevant commercial relationships. In this way, we depart both from Keller (1998), as we take trade patterns into account, and from Coe and Helpman (1995), as we neither calculate a trade-weighted measure of foreign R&D stocks nor impose a proportionality relationship between trade and knowledge flows.

Focusing on actual bilateral trade flows, we distinguish the "close" (more important) and "distant" (less important) trade partners of each country in each year of the sample: we consider a partner as "close" when its bilateral commercial exchange with the importing country overcomes a critical value. Then, we calculate for each country in the sample two simple sums of the foreign R&D stocks: one for the "close" partners and one for the "distant" ones. We test whether the impact of the two R&D stocks on domestic TFP is the same, as suggested by Keller (and implied by a trade-unrelated knowledge transmission process), or not, as postulated by Coe and Helpman. Failing to reject that the impact of the two foreign R&D stocks is the same would provide evidence in favor of Keller's intuition that trade does not impact on the international transmission of knowledge. In fact, we reject this null hypothesis and show that trade patterns affect the international transmission of knowledge (and the impact of the latter on domestic TFP).

It is worth pointing out that we do not examine nominal trade flows or import shares, as commonly done in the literature. Since each nominal trade flow reflects the heterogeneous sizes of the trading countries, a unique critical value to distinguish "close" from "distant" foreign partners should not be used for all the countries in the sample: small countries, in fact, would hardly be found "close" partners of other small countries. Instead, as we aim at detecting *relatively* strong bilateral trade relationships, we need to adjust the nominal flows for the economic size of the trading countries. To do so, we estimate a gravity model of trade and, subsequently, we calculate the size-adjusted bilateral trade flows as the differences between the actual bilateral trade flows and those predicted by the model taking into account the GDP of both countries.[4] Then, as it could be argued that the same time-invariant pair-specific factors that affect trade flows also influence R&D spillovers (geographical distance is a case in point), we calculate bilateral trade measures that are adjusted to account for both the size of countries' GDP (as before) and the pair-specific factors (shortly, size- and pair-adjusted trade values). The results indicate that relevant trade relationships matter for the diffusion of knowledge even once distance and other time-invariant pair-specific factors are taken into account.

In this work we contribute to the literature in two main ways. First, by nesting Keller's (1998) specification into a more general model accounting for trade patterns, we contribute to discriminate more clearly between the hypotheses of trade-related and trade-unrelated knowledge flows, which are equally plausible at the theoretical level. Adopting nested models is a step forward with respect to previous works which use non-nested models to test each of the hypotheses in turn. In so doing, we address Keller's (2004) claim that "the extent to which R&D spillovers are related to the patterns of international trade must be estimated in a model which allows simultaneously for trade-unrelated international technology diffusion" (2004, p.1480).

Second, by distinguishing "close" and "distant" trade partners without weighting R&D stocks for the size of the trade flows but on the basis of innovative size- and pair-adjusted bilateral trade measures, we manage to show that trade patterns matter in the transmission of knowledge even relaxing the assumption of a proportional relationship between the sheer size of trade flows and knowledge spillovers. Notably, these adjusted flows are calculated in a way that allows distinguishing "close" and "distant" partners by means of a metric that fits all

[4] Taking stock on the recent advancements in the gravity literature (see Baldwin and Taglioni, 2006, 2007) to ensure that the estimated coefficients are unbiased, we adopt a specification that acknowledges both time-invariant pair-specific and time-varying country-role-specific unobserved factors.

countries independently of their economic size.[5]

The paper proceeds as follows. In Section 2 we present the baseline empirical analysis of Coe and Helpman (1995) and Keller (1998). In Section 3 we illustrate the model and the analytical strategy, while we explain in Section 4 the country-size- and pair-adjusted trade measures adopted to distinguish "close" and "distant" trade partners. The illustration of the data can be found in Section 5. Section 6 presents our main empirical findings, whereas robustness checks are included in Section 7. Section 8 concludes.

2. Trade flows, R&D stocks and international transmission of knowledge

In their seminal paper, Coe and Helpman (1995) estimate an intuitive specification to capture the effect of foreign R&D on domestic TFP:

$$\log F_{it} = \alpha_i + \beta^d \log S^d_{it} + \beta^f \frac{M_{it}}{Y_{it}} \log S^f_{it} \tag{1}$$

where i is a country index, t is the time index, $\log F$ is the log of TFP, S^d the domestically produced R&D stock, S^f_{it} an import-weighted sum of the R&D stock produced outside the country i at time t (i.e. $S^f_{it} = \sum_{j \neq i} \frac{M_{ijt}}{\sum_{j \neq i} M_{ijt}} S^d_{jt}$), and M_{it}/Y_{it} represents the import-GDP ratio of country i at time t.[6,7]

Trade enters this specification in two distinct ways: i) in the trade-weighted construction of the foreign stocks of R&D; ii) in the interaction term which allows for cross-country variation in the elasticity of TFP with respect to foreign R&D (i.e. $\beta^f M_{it}/Y_{it}$).

Coe and Helpman (1995) find significant and relatively large values for β^f and conclude that both domestic and foreign R&D stocks positively impact

[5] In addition, we point out in passing that, using the appropriate specification proposed by Baldwin and Taglioni (2006, 2007), we estimate a gravity model of trade for 24 OECD countries over a very long period (1971-2004), a time span longer than Wang *et al.* (2010).

[6] Coe and Helpman (1995) also add a term obtained by interacting the domestic R&D stock with a dummy variable for the G7 countries to allow their output elasticities to differ from the others.

[7] Lichtenberg and van Pottelsberghe de la Potterie (1998) claim that import shares should not be used to weight foreign R&D and suggest to resort to weights equal to the ratios of bilateral imports over the GDP of exporting country. As shown by Coe *et al.* (2009), this reasonable modification does not invalidate nor weakens what found using specification (1).

on TFP, thus corroborating the theoretical works that postulate the impact of international knowledge flows on productivity. These findings are confirmed by Coe *et al.* (2009), where the analysis is repeated on an extended sample of 24 countries over the period 1971-2004 and human capital stocks are added to the regressors.

Keller (1998) contends that the simple sum of the R&D stocks in the rest of the world performs as well as Coe and Helpman's (1995) trade-weighted measures of foreign R&D. To show this, he estimates

$$\log F_{it} = \alpha_i + \beta^d \log S_{it}^d + \beta^f \log S_{Kit}^f + \epsilon_{it} \tag{2}$$

where $S_{Kit}^f = \sum_{j \neq i} S_{jt}^d$. He finds estimates for β^f close to those obtained by Coe and Helpman (1995), casting some doubts on specification (1).

Although Coe and Helpman's (1995) results have been proved quite solid in the literature, Keller's point opens up a series of questions. The problem in adjudicating among the competing claims about the relevance of trade-related transmission of knowledge is that the models proposed by Coe and Helpman (1995) and Keller (1998) are non-nested: this makes impossible to run direct tests between them and to use measures of their goodness of fit to discern which is the preferable one. In addition, even assuming that Keller's (1998) conclusions on the irrelevance of trade-related local transmission mechanism implied by Coe and Helpman's (1995) estimation form are correct,[8] we cannot exclude the existence of different global and trade-related transmission mechanisms. In fact, trade patterns may be important even excluding the existence of a proportional relationship between trade and knowledge flows.[9]

The question of whether the network of trade flows is informative on R&D spillovers remains to be tackled. In the next sections, we develop a way to nest

[8] Coe and Helpman (1995) estimate a specification form implying that knowledge is transferred abroad only to the extent it is embodied in traded goods. This characterizes a local trade-related diffusion process of knowledge transmission.

[9] Although we do not discuss specific channels here, trade-unrelated knowledge flows may also be relevant. For instance, Peri (2005) considers patent-related knowledge spillovers across regions in developed countries and shows that knowledge flows are highly localized.

Keller's model into a more general one that takes trade and trade patterns into account in a flexible way.

3. Model and analytical strategy

In this section we introduce the technical aspects concerning the model specification, the estimation technique, the classification of trade partners of each importing country, and the strategy adopted to carry out the tests. The method employed to calculate the adjusted bilateral trade measures will be illustrated in Section 3.

3.1. Model specification and estimation technique

While Keller builds a measure of foreign knowledge as the simple sum of all foreign R&D stock, we suggest to distinguish the R&D stock of the "close" trading partners from that of the "distant" partners. We shall come back in the next sub-section on how to identify these partners.

We estimate a more general specification of Keller's (1998) model by means of Nonlinear Least Squares (NLS):

$$\log F_{it} = \alpha_i + \beta^h \log H_{it} + \beta^d \log S^d_{it} + \beta^f \log\left(S^{fc}_{it} + \delta(S^f_{Kit} - S^{fc}_{it})\right) + \epsilon_{it} \quad (3)$$

with F, S^d and S^f_K as before, H_{it} staying for the human capital stock of country i at time t, and S^{fc}_{it} staying for the sum of the R&D stock of its "close" partners. With respect to Keller's specification, model (3) includes human capital among the regressors, in line with what usually done in the most recent works.

Model (3) nests (2) as the former becomes the latter when $\delta = 1$. Accordingly, we propose to test the null hypothesis H_0: $\delta = 1$ on the basis of a trade-related division of foreign countries into "close" and "distant" partners. If the null is rejected, there is evidence that trade patterns matter in determining the international transmission of knowledge.

3.2. Trade patterns

To implement our method, we first need to identify each country's "close" and "distant" trading partners, so that for each country and period in the sample we can calculate the two unweighted R&D stocks of their partners (respectively, S_{it}^{fc} and $S_{Kit}^{f} - S_{it}^{fc}$).

To do so, we are not interested in the aggregate values of the imports entering any given country, but we aim to classify each annual bilateral flow as either more relevant (linking the importing country to a "close" partner) or less relevant (vice versa). The relevance of bilateral trade flows is assessed on the basis of adjusted trade measures with respect to a certain threshold. We shall come back on adjusted trade measures and threshold below.

For the sake of simplicity, consider annual bilateral imports as the trade flows under scrutiny. For a given threshold (say φ), the network Γ^{φ} ($= (\mathcal{N}^{\varphi}, \mathcal{G}^{\varphi})$, with $\mathcal{G}^{\varphi}$ the set of trade links and $\mathcal{N}^{\varphi}$ the set of country-nodes) is dichotomized and a binary directed network is calculated. In practice, the value of any bilateral trade flow larger than φ is substituted with a 1, whereas the value of any bilateral trade flow smaller than or equal to φ is substituted with a 0. Thus, for each country in each year, the rest of the world is divided into two groups of countries according to the underlying binary directed network: a) "close" partners, and b) "distant" partners.

For each country-year, we then calculate the simple sum of the R&D stocks of the country's "close" partners $S_{it}^{fc} = \sum_{j \in \mathcal{N}_i^{\varphi}} S_{jt}^{d}$ and of the other foreign countries $S_{Kit}^{f} - S_{it}^{fc}$.

Given the threshold φ and the corresponding identification of "close" countries, we estimate the model (3) with NLS, and then test the null H_0: $\delta = 1$.

3.3. Threshold values and testing strategy

It is apparent that the choice of the threshold φ is a key determinant of the results. This is all the most important as, following what mentioned in the Introduction, it is not fully clear at the theoretical level what determines the relative importance of a bilateral trade relationship in terms of knowledge transmission. To overcome such issue, we adopt a strategy that does not revolve around an arbitrarily chosen value of the threshold.

We start by noticing that if trade patterns did not matter and knowledge flows were not stronger where trading links are tighter, then the null hypothesis $H_0 : \delta = 1$ should never be rejected for any value of φ. Instead, if there exist at least some threshold values for which the null hypothesis can be rejected, then it can be concluded that trade patterns (identified on the basis of the dichotomized trade networks associated with such thresholds) do affect the international transmission of knowledge.

On these grounds, we apply the method described in the previous subsections over a very fine grid of threshold values. If we could never reject the null hypothesis that $\delta = 1$ for any of the thresholds belonging to the range of the grid search, we would conclude that Keller's model is not rejected by the data. On the contrary, if we could reject the null for some values, we would conclude that, once properly identified, trade-patterns affect the way knowledge is transferred abroad. It is worth stressing once again that this approach takes bilateral trade patterns into account, but it does not impose a proportional relationship between trade and knowledge flows as in Coe and Helpman (1995).

Clearly, only a limited range of threshold values identifies reasonable trade networks, in turn conducive to meaningful estimates of model (3). Too high a value of the threshold, for instance, entails that S_{it}^{fc} is almost empty, as no country ever qualifies as "close" partner of country i: an almost-empty series S_{it}^{fc}, in turn, negatively affects the estimation and also the goodness of fit worsens.[10] Similar problems occur when an excessively low value of the threshold is chosen. For this reason, we run the grid search over ranges of values ensuring that the average density of the binarized network of "close" partners falls between 0.3 and 0.7. This conservative choice makes easier to compare the results found with the adoption of different bilateral trade measures, which we discuss in the next section.

[10] It should be noted that while an estimated δ equal to 0 implies that the R&D stocks in "distant" partners are irrelevant to domestic TFP, that is clearly a situation we cannot rule out in principle, an almost-empty S_{it}^{fc} makes pointless the introduction of the series in the estimation and complicates the estimation of our nonlinear specification.

4. Gravity model and adjusted trade measures

For the sake of simplicity, in the previous subsections we followed the literature and assumed in the exposition of our approach that nominal bilateral imports (M_{ijt}) were the measures of trade flows to consider. Using nominal bilateral trade flows is indeed the most direct and intuitive way to distinguish and rank trade relationships. However, as each bilateral trade flow reflects the heterogeneous sizes of the countries involved in the exchange, it is difficult to find a unique threshold able to identify properly the close and the distant partners of each importing country in the sample. For any given value of M_{ijt}, in fact, larger (smaller) countries more (less) easily result to be close partners of any importing or exporting country. As discussed at length in the Introduction, moreover, the importance of a trade relationship for knowledge transmission depends more on its features than on the absolute dimensions of the flow. On this basis, it seems warranted to adjust the trade measures for the sizes of the countries as this correction most likely helps to know special partners from less important ones.

It could be argued that several works resort to import-GDP ratio (M_{ijt}/Y_{it}), rather than to nominal flows M_{ijt}, and that this partially adjusts for the heterogeneous size of the importers. Although this is true, the size of the exporter is in fact not taken into account: the largest exporting nations tend to be more easily included in the group of "close" partners and the smallest countries in the group of "distant" countries. Moreover, failing to normalize for the size of both trading partners prevents from determining which exchanges are relatively more important on the basis of information regarding the whole trade network.

Intuitively, to detect relatively strong bilateral trade flows in terms of a unique critical value, we need to adjust trade flows for the size of both trading countries. A straightforward measure, clearly, would be $M_{ijt}/(Y_{it}Y_{jt})$. However, this metric implicitly assumes a unitary elasticity of demand for imports with respect to GDP and also accounts neither for different patterns in import and GDP price deflators, nor for trends common to the entire panel of countries.

To build comparable, country size-adjusted measures of bilateral trade flows, we estimate a gravity model for the countries in our sample over the entire period 1971-2004. Then, we calculate the size-adjusted flows as the differences between the actual bilateral trade flows and the amounts of trade due, according to the estimated coefficients, to the GDP of the countries. The gravity model of trade is widely used in international economics to detect the relationship linking actual trade flows and the GDP of the pair of trading countries, while taking into account other observable determinants of trade and also some unobserved pair-, country- and time-specific factors.[11]

For our exercise to be correct the gravity model must be specified in a way that removes, or at least reduces, the estimation biases for the coefficients. Baldwin and Taglioni (2006, 2007) discuss the biases arising from measurement errors and from the failure of accounting for the effects of the *multilateral trade resistance* (Anderson and van Wincoop, 2003), i.e. the factors (such as income and trade barriers) that characterize all the countries.

In the case of directional trade flows, each observation in the panel has three dimensions: a time dimension and two country dimensions, as countries appear either as importers or as exporters. As shown by Baldwin and Taglioni (2006), to avoid biased estimates in this context it is not sufficient to include in the specification of the gravity model either time-invariant pair-specific effects or time-invariant country-role-specific effects: they are all time-invariant factors which fail to pick the time-varying nature of multilateral resistance factors and, thus, do not remove much of the correlation between the residuals and the regressors.

Taking stock on the recent advancements in the literature on gravity models in panel data, we adopt a specification that relates the imports of country i from country j at time t (M_{ijt}) as a function of the product of importer's and exporter's GDP ($Y_{it}Y_{jt}$), a constant (θ_0), time-invariant pair-specific factors

[11] An analysis of the topological properties of the network derived from the residuals of an estimated gravity model is in Fagiolo (2010), who shows that, far from being random, such network actually displays complex trade-interaction patterns, with many small-sized but trade-oriented countries that, independently of their geographical position, play the role of local hubs or attract large and rich countries.

($\upsilon_{ij.}$), and time-variant country-role factors ($\eta_{i.t}$, $\eta_{.jt}$, respectively capturing any importer-specific time-variant effect and exporter-specific time-variant effect).[12]

Accordingly, the specification of the gravity equation, where the nominal bilateral trade flows and the GDP are in logs ($m_{ijt} = \ln M_{ijt}$, $y_{it} = \ln Y_{it}$, $y_{jt} = \ln Y_{jt}$) reads as follows:

$$m_{ijt} = \theta_0 + \theta_1(y_{it} + y_{jt}) + \upsilon_{ij.} + \eta_{i.t} + \eta_{.jt} + \varepsilon_{ijt} \tag{4}$$

where ε_{ijt} is the error component. The GDP and the trade series are taken in nominal terms because, as observed by Baldwin and Taglioni (2006), the gravity equation reflects a modified expenditure function. In fact, the introduction of the dummies that pick-up the (time-variant and invariant) unobserved effects makes the choice of the denomination of the series almost immaterial.[13]

The measures we are interested in, that is the size-adjusted bilateral trade flows (m_{ijt}^{sa}), can be calculated on the basis of the estimates of Equation (4). More precisely, the size-adjusted bilateral trade flows are:

$$m_{ijt}^{sa} = m_{ijt} - \hat{\theta}_0 - \hat{\theta}_1(y_{it} + y_{jt}) \tag{5}$$

It could be argued that the same pair-specific factors that affect the bilateral trade flows also impact on the R&D spillovers: was this the case, trade could appear as a significant channel of transmission of knowledge while, in fact, it acts as a proxy of some pair-specific factors. We then use the previous unbiased estimates of the coefficients of the gravity model to calculate the size- and pair-adjusted measures of bilateral trade flows m_{ijt}^{spa}, whereby the (otherwise unobservable) pair-specific component of trade is dropped:

$$m_{ijt}^{spa} = m_{ijt} - \hat{\theta}_0 - \hat{\theta}_1(y_{it} + y_{jt}) - \hat{\upsilon}_{ij.} \tag{6}$$

[12] When we use . in place of i or j or t, we intend that the unobserved factor is common to, respectively, all the importers from j at time t, all the exports to i at time t, and all the periods for the pair (i, j).

[13] As we deal with aggregate import flows for OECD countries, our sample is almost fully balanced and less than 0.1% of the bilateral trade flows are equal to zero. Hence, we do not face the problems that emerge in the presence of many zeros when the series in logs and the heteroskedasticity of the residuals is not duly accounted for. This issue is cleverly addressed in the case of large cross-sections of data by Santos Silva and Tenreyro (2006) and Baier and Bergstrand (2009).

If knowledge spillovers were unrelated to trade, then the null H_0: $\delta = 1$ would not be rejected when either of these adjusted trade measures is used because no trade-related partition would result as significantly associated with knowledge spillovers. If knowledge spillovers were related to trade patterns only to the extent that close trading partners are more in general well connected countries, then the null $H_0 : \delta = 1$ would be more difficultly rejected using m_{ijt}^{spa} than using m_{ijt}^{sa}, as the former is adjusted for the pair-specific effects.

It should be noted that this measure is very conservative: when we subtract the pair-specific factors from m_{ijt}^{sa} we get rid of parts of the bilateral exchanges which might be really important in the transmission of knowledge and, in fact, do not proxy for any common factors. For this reason, we do not claim that m_{ijt}^{spa} is preferable to m_{ijt}^{sa}, but rather that it is more conservative.

5. Data

To maintain the comparability with the work of Coe and Helpman, we focus on the sample of 24 OECD countries over the period 1971-2004 analyzed by Coe *et al.* (2009). R&D stocks, human capital and TFP indexes are taken from Coe *et al.* (2009); bilateral trade imports (in current dollars) come from the historical archive of the IMF Direction of Trade Statistics; GDP (in current dollars) from IMF IFS and UN Statistics Division.

6. Results

Armed with the size-adjusted and size- and pair-adjusted trade measures described in Section 4, we apply the method illustrated in Section 3.1 and run the estimations for the threshold φ in the range of admissible values ensuring that the average density of the binary network of "close" partners remains between 0.3 and 0.7 (see Section 3.3).

On a year-by-year basis and for each threshold in the range of admissible values, we i) identify the pairs of partners characterized by a relevant trade relationship (when the trade measure overcomes the threshold); ii) dichotomize the bilateral trade network accordingly (see Section 2); iii) build the series S_{it}^{fc} corresponding to the threshold. Finally, we estimate Equation (3) and test the null H_0: $\delta = 1$.

6.1. Size-adjusted trade flows

When we consider the size-adjusted trade flows m_{ijt}^{sa} and run a regression for each value of the threshold within the range $[-0.7, 0.7]$, the data suggest to reject the null hypothesis for all the values of the threshold between -0.4 and 0.2.[14]

Figure 1 shows the p-values of the F-test of the null hypothesis H_0: $\delta = 1$ and the average density of the network of "close" partners. It can be easily seen that the null can be rejected at very low level of significance for several different values of the threshold φ. Notably, Figure 2 shows that the fit of the model – evaluated in terms of the log-likelihood – is relatively higher for the range of values of the threshold which reject the null.[15,16]

In a nutshell, Figures 1 and 2 suggest that trade patterns significantly affect the international transmission of knowledge. A failure to reject the null for all the possible values of the threshold φ would have instead suggested that no trade-related partition of "close" and "distant" partners is significantly associated with R&D spillovers.

As can be seen in Figure 2, the best fitting model is found in correspondence of a threshold equal to -0.172: a size-adjusted import flow above -0.172 identifies a more relevant trade relationship (for the importer i, the exporter j is a classified as a "close" partner) and one equal or below -0.172 identifies a less relevant

[14]The interval over which the grid search is conducted ensures non-empty S_{it}^{fc} and $S_{Kit}^{f} - S_{it}^{fc}$; more precisely, in line with what explained in Section 3.3, this interval ensures an average density of the binary network of "close" partners between 0.3 and 0.7.

[15]The models do not differ in the number of coefficients but only in terms of the series S_{it}^{f1}, which in turn affect the estimated coefficient δ. Accordingly, there is no need to use information criteria, which attach a penalization for the number of estimated coefficients.

[16]It could be argued that it is not surprising that the p-value of the F-test falls when the log-likelihood rises (and vice versa) as the former falls and the latter increases when the sum of squares residuals of the unrestricted model – i.e. Equation (3) – falls. However, while the p-value has a floor at 0, the log-likelihood has no ceiling: thus, these two statistics convey coherent, but different messages.

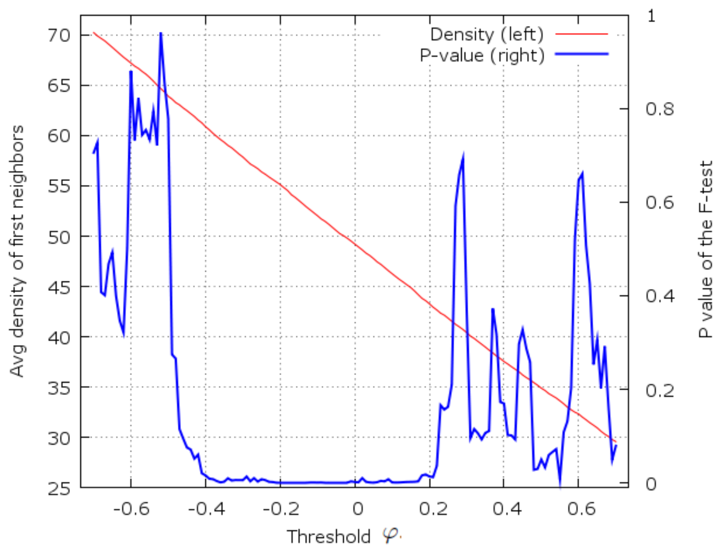


Figure 1: F-test p-value and density of the "close" partners network. Trade measure: size-adjusted flows m^{sa}

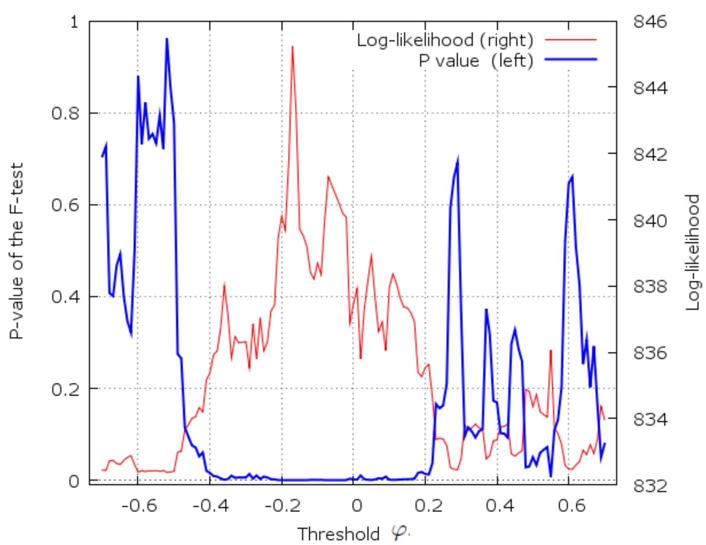


Figure 2: F-test p-value and log-likelihood. Trade measure: size-adjusted flows m^{sa}

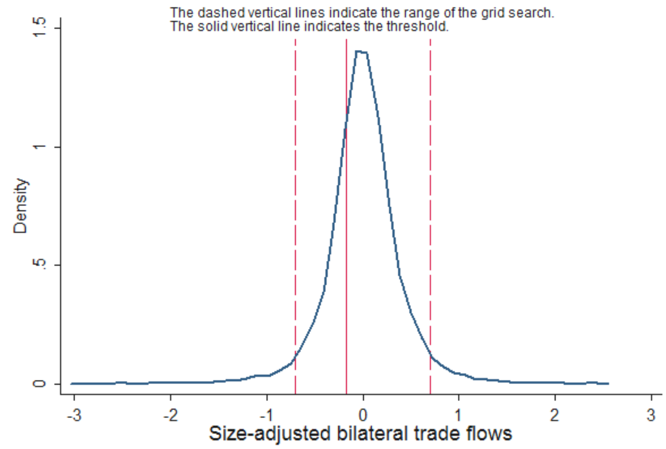


Figure 3: Distribution of size-adjusted trade flows, grid-search range and best-fitting threshold

relationship (for the importer i, the exporter j is classified as a "distant" partner).

In Figure 3, we plot the distribution of the size-adjusted flows, the range of the admissible values of φ and the best-fitting threshold. This fit-maximizing value of φ will turn out to be useful in Section 7, where we calculate the point estimates and the bootstrapped standard errors of the coefficients associated with specific values of φ.

6.2. Size- and pair-adjusted trade flows

There could be pair-specific factors affecting both bilateral trade and R&D flows. These factors could be mistakenly picked up by the size-adjusted trade measures which would then act as proxies of the former. To take it into account, we calculate more conservative adjusted trade flows: size- and pair-adjusted measure of bilateral exchanges (m^{spa}_{ijt}).

We run a regression for each of the values of the threshold within the range of admissible values $[-0.15, 0.15]$, i.e. those ensuring non-empty S^{fc}_{it} and $S^{f}_{Kit} - S^{fc}_{it}$, so to maintain the average density of the binary network of "close" partners between 0.3 and 0.7. Figure 4 reproduces the p-values of the F-test of the null H_0: $\delta = 1$ and the average density of the network of "close" countries. The data suggest to reject the null for the values of the threshold between -0.1 and

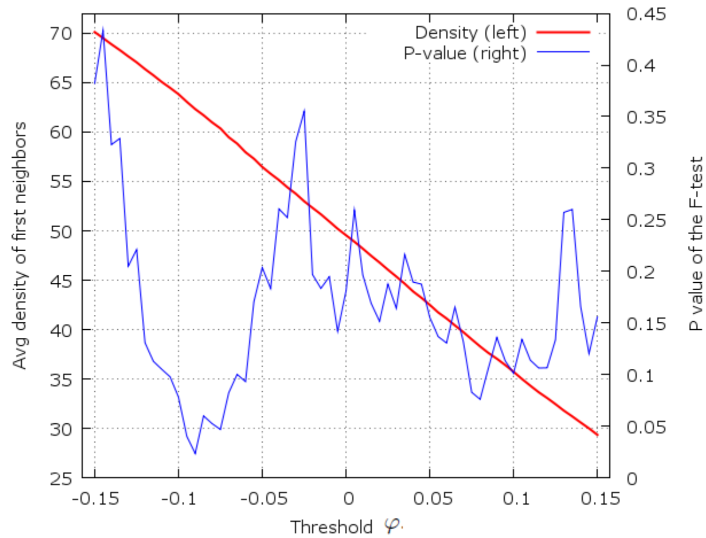


Figure 4: F-test p-value and density of the "close" partners network. Trade measure: size- and pair-adjusted flows m^{spa}

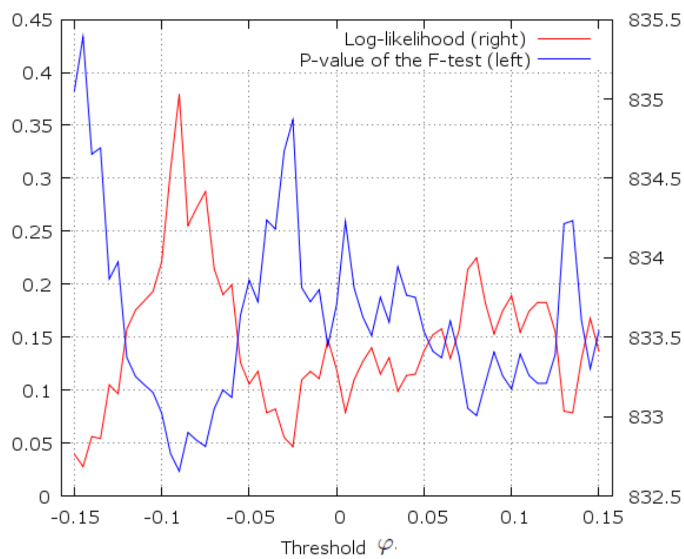


Figure 5: F-test p-value and log-likelihood. Trade measure: size- and pair-adjusted flows m^{spa}

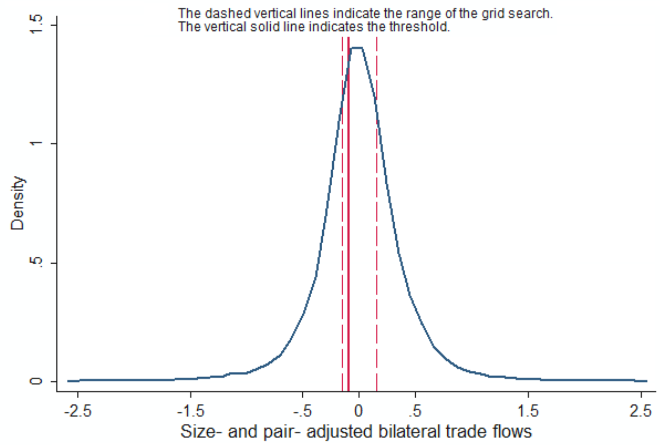


Figure 6: Distribution of size- and pair-adjusted flows m^{spa}, grid-search range and best-fitting threshold φ.

-0.07 at the 10% of significance level (or less). Also in this case, the fit of the model evaluated in terms of the log-likelihood is relatively higher for the range of values of the threshold which reject the null (see Figure 5). Also in this case trade patterns appear significantly associated with R&D spillovers.

The best fitting model is found for the threshold -0.089. In Figure 6, we plot the distribution of the size- and pair-adjusted flows, the range for the grid search and the best-fitting threshold.

7. Point estimates and bootstrapped distributions of the parameters

The analysis carried out in Section 6 shows that the null hypothesis of a global and trade-unrelated transmission of knowledge can be rejected for many partitions of “close” and “distant” countries. The null, moreover, is rejected adopting both the proposed adjusted trade measures. All in all, our analysis corroborates the hypothesis that global knowledge spillovers are indeed related to trade flows and patterns, as suggested by Coe and Helpman (1995) and contrary to Keller (1998).

What remains to be shown, however, are the point estimates (and the standard errors) of the estimated coefficients associated with the most significant partitions of "close" and "distant" partners. Our findings would be strengthened if we could also show that: i) the estimation of our nonlinear specification using trade-related partitions is as good as (or better than) the estimation based on the linear form proposed by Keller (1998); ii) the estimated values of δ are lower than one.

Moreover, focusing on the estimates associated with some specific values of φ (rather than on the series of the F-test run on the whole range of admissible values) allows us to take into consideration some of the peculiar problems connected with the complex estimation procedure adopted in the text. In particular, we are aware that our size- and pair-adjusted trade measures are calculated on the basis of the estimated parameters of the gravity model of trade. The use of estimated series suggests to employ more conservative standard errors that those obtained with asymptotic statistics. To account for these issues, we estimate all the functional forms and calculate confidence intervals and standard errors by means of the panel moving-blocks bootstrap (proposed by Goncalves (2011) in the context of fixed effects linear panel models with large N and large T). We obtain a distribution of the estimated parameters which allows to carry out more robust inference.

The simplest way to distinguish the "close" and "distant" partners of each importing country is to assume an intuitive value for the threshold φ, namely 0. In the case of size-adjusted trade measures, for instance, this implies that when the adjusted trade value is greater (smaller) than zero, the partners trade more (less) than what suggested by the sheer size of their GDP and are "close" ("distant"). In the next subsection we adopt this intuitive critical value of the threshold, while in Section 7.2 we use the values of the threshold maximizing the fit of the model (hereafter, best-fitting thresholds) found in Sections 6.1 and 6.2.

7.1. Zero threshold

We start by dichotomizing the trade network (both for size-adjusted and for size- and pair-adjusted trade measures) on the basis of a threshold φ equal to zero. Estimation results for size- and pair-adjusted trade measures are reported

Table 1: Estimation results (Pooled data 1971-2004 for 24 countries: 816 observations)

	(1)	(2)	(3)	(4)	(5)
β^h	0.523***	0.499***	0.530***	0.501***	0.537***
	(0.0494)	(0.0498)	(0.0533)	(0.0513)	(0.0516)
β^d	0.046***	0.050***	0.046***	0.049***	0.047***
	(0.0085)	(0.0063)	(0.0086)	(0.0075)	(0.0079)
β^f	0.158***	0.159***	0.159***	0.161***	0.160***
	(0.0156)	(0.0156)	(0.0161)	(0.0161)	(0.0151)
δ		0.552***	0.912***	0.409***	0.847***
		(0.5254)	(0.0845)	(0.1574)	(0.0966)
Trade measure		m^{sa}	m^{spa}	m^{sa}	m^{spa}
φ		0	0	-0.172	-0.089
Bootstrapped one-tailed p-value H_0: $\delta < 1$		0.135	0.119	0.012	0.052
R^2	0.840	0.842	0.841	0.845	0.841
log-L	832.368	837.456	833.296	844.260	834.936
AIC	-1610.736	-1618.912	-1610.591	-1630.519[a]	-1611.871[a]
BIC	-1483.717	-1487.188	-1478.868	-1494.092[a]	-1475.446[a]

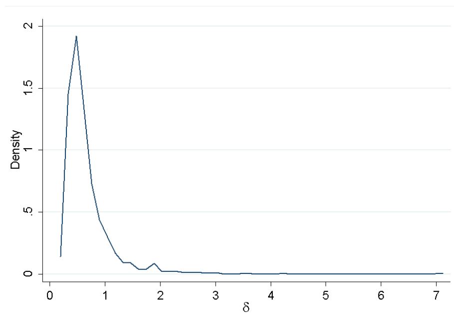
[a]Corrected to account for the fact that the threshold (φ) is estimated.

Unreported country dummies. Bootstrapped standard errors robust to serial and cross sectional dependence in parentheses. Coefficient significance based on bootstrapped two-tailed confidence intervals. Significance levels: * 10%; ** 5%; *** 1%.

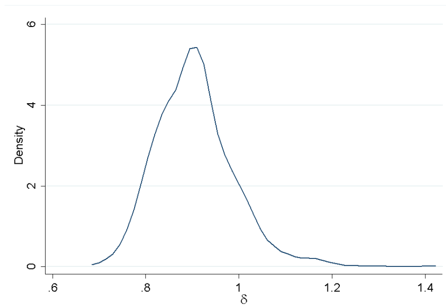
in Table 1 (column (2) and (3) respectively). These can be compared with those obtained by reproducing Keller's (1998) specification (column (1)).

The estimates of the coefficients (β^h and β^d) are very close across the specifications in the first three columns. The same holds true for β^f, but our dichotomization of the trade network allows to appreciate the difference in the relative contribution to R&D spillovers of the knowledge stocks in "close" and "distant" partners. The point estimates of δ take values lower than 1 and this indicates that the stocks of knowledge of "distant" partners contribute less than those of the "close" partners to the domestic TFP of the importing country. All the estimated coefficients are significant although we use bootstrapped standard errors to account for the potential heteroskedasticity, serial correlation and cross sectional correlation in the residuals.[17]

[17]By looking at the distribution of bootstrapped values, we reject that δ is equal to zero. It should be noticed, however, that the bootstrapped distribution cannot contain too negative values of δ because these latter would render negative the argument of the log and would prevent convergence. As we cannot exclude that this causes some of the failures at achieving



(a) Size-adjusted trade flows



(b) Size- and pair-adjusted trade flows

Figure 7: Bootstrapped distribution of δ

Although comforting, these results suffer from two shortcomings. The first is that, in particular when size-adjusted trade flows are used, we cannot exclude at the 10% significance level that δ takes values equal to or above 1. As Figure 7(a) shows, this is due to the presence of a tail of estimated values of δ much larger than 1 even though the bulk of the bootstrapped distribution of δ is clearly concentrated in a limited interval greater than 0 and lower than 1. The second shortcoming is that, when we adopt size- and pair-adjusted trade measures, the overall fit of the model does not improve much (or even worsens) according to all the criteria (i.e., R^2, log-likelihood, AIC and BIC).

One cannot exclude *a priori* that these shortcomings are due to the improper restriction imposed on the value of the threshold φ. Hence, we use a more sophisticated approach to distinguish trade partners and employ the value of the threshold which maximizes the best fit of the model. As said, such value of φ is equal to -0.172 in the case of size-adjusted bilateral trade flows (m^{sa}_{ijt}) and to -0.089 for size- and pair-adjusted flows (m^{spa}_{ijt}).

7.2. Best-fitting thresholds

The estimates of Equation (3) for a threshold $\varphi = -0.172$ appear in column (4) of Table 1. While the coefficients β^d and β^h are not too different from

convergence in almost 8% of the repetitions, the distribution of bootstrapped values for specification (3) may be truncated somewhere below zero. Were this the case, the significance of δ and the value of δ at the 10% one-tailed confidence interval could be overestimated.

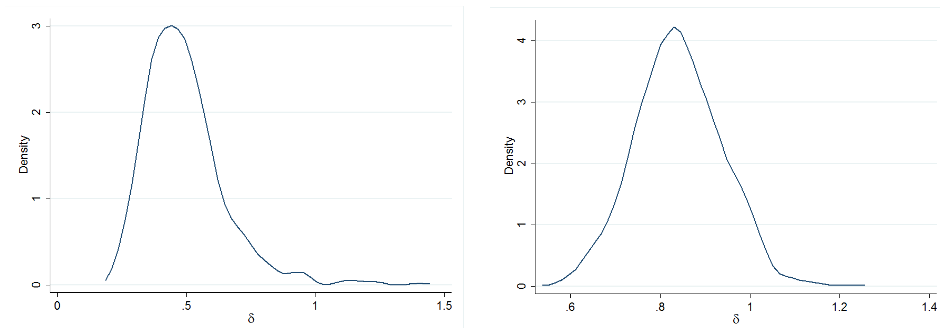
those obtained using the simple sum of all foreign R&D stocks, the coefficient δ is significantly different from 0 and smaller than 1. The increase in the log-likelihood and in the other information criteria (corrected to account for the fact the threshold is estimated) signals that the fit of the model increases considerably passing from the baseline model in column (1) (where all foreign R&D stocks are summed up in S^f_{Kit}) to the model in column (4). This implies that our choice of splitting the stock of R&D of the "distant" partners from that of the "close" countries is warranted.

These findings provide further evidence in favor of the hypothesis that trade patterns matter for the international transmission of knowledge when the trade series are adjusted for the economic size of the countries and when we do not over-impose a proportional relationship between the size of the bilateral trade flows and knowledge flows.

The estimates of Equation 3 for a threshold $\varphi = -0.089$ are reproduced in column (5) of Table 1. The estimates of the coefficients for the domestic stock of R&D, the stock of human capital and the stock of knowledge of the "close" partners are similar to the previous ones. The coefficient δ is significantly different from 0, but closer to 1 than when the size-adjusted trade measures are used (column 4). By the same token, despite the increase in the R^2 and in the log-likelihood with respect to the baseline model in column (1), the fit is inferior to that of the model in column (4). All in all, then, the estimates reveal that the stock of R&D of the "distant" partners has a smaller impact on domestic TFP than the stock cumulated in the "close" partners, although the differentiation of the trading partners is less satisfactory than when m^{sa}_{ijt} is used.

It is worth noticing that the estimated values of δ are significantly smaller than 1: the bootstrapped p-value of the one-tail test of $\mathrm{H}_0 : \delta < 1$ are 1.2% and 5.2% in the case of, respectively, m^{sa}_{ijt} and m^{spa}_{ijt}. This confirms that imposing a value of 0 to the threshold φ was causing excessive noise in the estimates of the coefficient δ. The distributions of the bootstrapped values of δ for m^{sa}_{ijt} (with $\varphi = -0.172$) and m^{spa}_{ijt} (with $\varphi = -0.089$) are plotted in Figure 8.

As claimed above, the lower estimated coefficient δ obtained adopting the



(a) Size-adjusted trade flows (b) Size- and pair-adjusted trade flows

Figure 8: Bootstrapped distribution of δ with best-fitting threshold

size-adjusted (rather than the size- and pair-adjusted) trade measure suggests that relatively more important trade relationships are indeed associated with stronger knowledge spillovers also because of time-invariant pair-specific factors, such as distance. This would suggest that some of those factors that make two countries commercially "close" also strengthen the transmission of knowledge between them. This does not imply that the trade channel is not relevant. First, although we cannot exclude that pair-specific factors affect both trade and knowledge flows, it is equally plausible that these factors indeed affect the trade relationship and this latter then influences the extent knowledge is transmitted abroad. Second, as discussed above, the null hypothesis that knowledge spillovers are trade-unrelated is rejected using both the adjusted trade measures and the estimated δ are significantly lower than 1. All in all, thus, we conclude that trade patterns do have a significant impact on international knowledge spillovers even once distance and other time-invariant bilateral factors are taken into account.

7.3. Robustness check

For the various reasons discussed in the Introduction, we have so far presented the results of our analysis against the baseline specification proposed by Keller (1998), which corresponds to column (1) in Table 1. Besides being linear, Keller's model implicitly assumes no partition between "close" and "distant" partners. To better appreciate these results, however, we believe it is worth showing that they

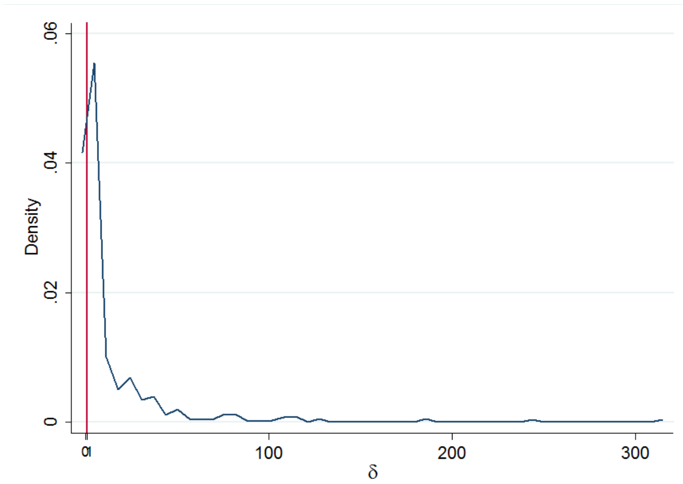


Figure 9: Distribution of δ for 432 random partitions of partners.

also differ from another stylized model, that is one in which an equiproportional partition of countries in "close" and "distant" is randomly drawn from all the possible combinations of the 23 partners or each of the 24 countries. Were most of these random (hence, trade-unrelated) partitions associated with values of δ lower than 1 and with good measures of fit, we could not claim that our trade-related partitions are related with knowledge spillovers. In fact, this is not the case. As can be seen in Figure 9, which plots the estimated δ for more than 400 equiproportional random partitions of the countries, the values of δ are very volatile, often insignificantly different from zero because of large standard errors, and in several cases they make little economic sense. These findings strengthen our previous results and conclusions.

8. Closing remarks

The relationship between international trade and knowledge diffusion has been the object of intense research and debate. Starting with Coe and Helpman (1995), most empirical studies have used trade-weighted foreign R&D stocks to measure foreign knowledge and assumed that the internationally transferred knowledge is proportional to the size of the trade flows, in line with the theoretical models (e.g. Grossman and Helpman, 1991; Rivera-Batiz and Romer, 1991; Eaton and Kortum, 2002) where imported intermediate goods embody foreign technological know-how.

In this work we also investigate whether international trade enhances knowledge spillovers but introduce some novelties in the analysis. First, we do not assume the existence of a proportional relationship between the size of trade and knowledge flows (as in Coe and Helpman, 1995): rather, we more simply assume that more relevant commercial relationships (relatively strong trading ties) are a favorable precondition for knowledge flows to materialize. Second, we develop and estimate a nonlinear model which allows to detect such trade-related transmission of knowledge and which also nests Keller's (1998) model, according to which knowledge transfers are trade-unrelated. Third, we do not calculate trade-weighted measures of foreign R&D stocks: i) we first distinguish, on the basis of adjusted measures of bilateral trade flows, the "close" and "distant" trading partners of each country in each year of our sample; ii) then, we calculate the unweighted sums of the foreign R&D stocks for the "close" partners and the "distant" ones (for each importing country of the sample); iii) finally, we test whether the impact of the two R&D stocks on domestic TFP is the same, as implied by a trade-unrelated knowledge transmission process as in Keller (1998), or not, as postulated by Coe and Helpman (1995). By nesting Keller's (1998) specification into a more general model accounting for trade patterns, we contribute to discriminate between the hypotheses of trade-related and trade-unrelated knowledge flows.

We do not consider nominal trade flows or import shares, as commonly done in the literature, because the latter reflect the heterogeneous sizes of the trading countries and reduce the probability of a small exporting country to count as a "close" partner of other small countries. Instead, on the basis of the estimates of a gravity model of trade for the countries in the sample and over the entire period, we produce adjusted measures of trade, which account for the economic sizes of the trading countries. We also calculate bilateral trade measures that are adjusted to account for both the size of countries' GDP and the pair-specific factors that might affect trade flows as well as directly influence R&D spillovers.

We reject the null hypothesis that the impact of the stocks of knowledge of both "close" and "distant" partners on domestic productivity is the same and we conclude that trade patterns affect the international transmission of knowledge (and the impact of the latter on domestic TFP). The contribution of foreign R&D on domestic TFP is greater for the "close" than for "distant" trading partners, but both stocks play a statistically significant role in the international transmission of knowledge.

Besides their intrinsic empirical relevance, our findings bear on the theoretical analysis on the international transmission of knowledge and help discriminate between the theoretical models that, equally plausibly, support the hypotheses of trade-related and trade-unrelated knowledge flows. Our empirical findings suggest that it is not the absolute size of the trade flows that matters the most, but rather the existence of a special relationship between the countries that exhibit relatively strong commercial connections. This is all the most useful to account for those theoretical models where trade patterns matter in the transmission of knowledge even though intermediate traded goods do not physically embody the knowledge produced abroad.

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