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Determinants of Firm R&D: The Role of Relationship-specific Interactions for R&D Spillovers

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Abstract

Research and Development (R&D) is a key component behind technological development and economic growth; therefore, understanding the drivers of R&D is crucial. An interesting question is the role of technology spillovers, transferred by trade, and their impact on firm R&D. Here we analyze not only how international and domestic inter- and intra-industry technology spillovers affect firm R&D but also the relatively unexplored issue of how relationship-specific interactions between buyer and seller affect such spillovers. We find international technology spillovers to be larger and more significant than domestic inter- and intra-industry spillovers. Moreover, relationship-specific interactions between seller and buyer enhance technology spillovers in general and international spillovers in particular.

Keywords: R&D; spillovers; imports, relationship-specific investments
JEL classification: L1; L6; O1; O3

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1. Introduction

In 2005, expenditures on research and development (R&D) in Sweden accounted for almost four percent of GDP, making Sweden one of the most R&D-intensive countries in the world. Because R&D is a major factor driving technological development, R&D is associated with economic growth. It is therefore worthwhile to consider how different economic factors affect R&D.

We analyzed the role played by domestic and international trade as a vehicle for technology (R&D) spillovers and their impact on firm R&D. As Nunn (2007) notes, trade does not occur spontaneously; in some cases, relationship-specific investment must precede trade. We argue that such relationship-specific investments not only enhance trade in certain goods but also ease the transmission of technology spillovers (rent spillovers). As some researchers (e.g., Geroski (1990), Cohen and Levinthal (1989)) have noted, spillovers do not comes for free, instead, the absorption of outside technology requires efforts (investments in the absorptive capacity). It is therefore plausible to assume that specific buyer-seller interactions work as oil in the transmission of technology spillovers.

The vast majority of empirical studies on spillovers utilize industry-level data or limited surveys, see, e.g., Stoneman (1995) and Aghion & Howitt (1999). However, as detailed firm-level data have become increasingly available, firm-level studies have also become more common. By using highly detailed firm-level data, we are able to analyze not only trade-related technology spillovers but also the effect of specific buyer-seller interactions on spillovers and firm R&D.

The significant role played by import-driven technology spillovers is highlighted by the fact that at least 90 percent of the technology used by most countries is sourced from abroad (Keller, 2004). Empirical research has established that spillovers are locally bounded and that trade plays an important role in the transmission of technology and spillovers.[1] This research demonstrates that technology spillovers exist, they are non-negligible, they tend to follow trade and input-output linkages and they are to some extent locally bounded. In addition, the diffusion of technology is not inevitable or automatic. Investments or other efforts are needed to absorb outside technology.

[1] Arguments for localized knowledge are characterized as five 'stylised facts' by Dosi (1988) and further developed by Feldman (1994a, 1994b) as well as Baptista and Swann (1998). The spatial dimension of economic growth is highlighted by Amiti (1998) and Hanson (1998). Studies on trade, technology spillovers and R&D include Griliches (1992), Coe & Helpman (1995), Fagerberg (1997), Keller (1997, 2000) and Cohen and Levinthal (1989). For a survey, see Keller (2004).

When analyzing spillovers, the unit of observation is crucial. Keller (2004) concludes that macro-level study cannot control for implicit aggregation biases and that the level of disaggregation affects the results. Thus, we analyzed firms in the Swedish manufacturing sector. Given that R&D is related to decisions made at the firm level, this unit of observation is well chosen.[2] Moreover, although the manufacturing sector only accounts for a limited share of total employment, it has long been considered the key to industrial and economic growth because of its significant positive effect on technical skills, employment, and efficiency. Because the manufacturing sector is a primary tool for modernizing the economy, it is a primary recipient of various types of positive spillovers (Tybout, 2000).

Trade contributes to the diffusion of technology by allowing firms access to global technologies. Firm-level empirical studies show that increased trade often leads to within-firm productivity gains (Fernandes 2007, p. 53). Specifically, Fernandes found that increased exposure to foreign competition generates productivity gains for manufacturing plants in Colombia. Using what the author refers to as the "direct" approach, the production function equation includes trade policy as a regressor. A strong impact of trade liberalization on plant-level productivity is found, and large and less competitive plants reap an even bigger return. Regarding Colombia's export market, Brooks (2006) suggested that foreign experts who train domestic workers in Colombia could have a substantial and persistent positive effect on domestic wages and value-added per worker (Markusen and Trofimenko, 2009).

Lopez (2006) investigated the role of imports on plant survival in Chile. Additionally, using plant-level panel data on Chilean manufacturers, Pavcnik (2002) provided evidence of within-plant productivity improvements that can be attributed to increased trade. On the export side, Alvarez (2006) searched for factors that contribute to transforming Chilean manufacturing plants into permanent exporters. Results suggest that export experience, multinational spillovers, and an increase in productivity positively contribute to the probability of becoming a permanent exporter. Finally, adding to the topic of technology diffusion, Lopez (2008) examined the existence of intra- and inter-industry productivity spillovers from foreign technology licensing by the Chilean manufacturing sector. Because importing a technology rather than developing new technology does not require complete mastery of it, technology licensing by developing economies is common. Lopez found a positive spillover effect from technology licensing in upstream sectors, but a negative effect in downstream sectors.

[2] For example, it may be crucial to control for firm-level heterogeneity, but such a control is difficult when using aggregated data.

Other studies suggest that imported capital and intermediate goods may work as channels through which technological knowledge diffuses. Schiff, Wang, and Olarreaga (2002) were among the first to conduct such an analysis at the industry level for developing countries. They examined the effect of North-South and South-South R&D spillovers on total factor productivity (TFP). Utilizing the Coe and Helpman (1995) approach for measuring spillovers, they found that although North-South spillovers were the largest, North-South and South-South spillovers were still positively correlated with total factor productivity.

Portugal-Perez and Wilson (2009) analyzed the role of trade costs for developing countries. In their work, they considered import costs, but they primarily focused on high trade costs associated with exports. They concluded that high trade costs limited the full realization of gains from trade in many nations. Anderson and Wincoop (2004) contend that there is a significant relationship between trade costs and market structure. Both of these variables suggest a limiting rate up to which a country or firm can either absorb technological information or exploit external knowledge.

Coe and Helpman (1995) have also found significant productivity spillovers driven by imports. Their study examined bilateral import-share-weighted R&D stocks in a sample of 22 OECD countries and concluded that spillovers increase with the degree of openness. Similar effects are found for technology diffusion running from industrialized to less developed countries (Coe, Helpman and Hoffmaister 1997). Xu and Wang (1999) adapted a related but slightly different approach to analyze R&D spillovers embodied in the imports of differentiated capital goods.

Typically, the measurement of R&D spillovers makes use of current trade only. Lumega-Neso and Olarreaga (2005) studied 22 OECD countries for the period 1971-1990 and found evidence that R&D spillovers exist without direct trade flows. In many ways, indirect trade links through trade partners are more important than direct imports. These results are consistent with the importance of dynamic effects from imports, where the potential technology spillovers stemming from import from country B also depend on technology spillovers from country C to other countries (including country B).

Using data spanning 30 years from a relatively large number of countries, Archarya and Keller (2007) have also found evidence of substantial productivity spillovers related to import of foreign R&D stocks. Their results indicate that import spillovers are asymmetrically distributed among receiving countries within the G6 group. The hypothesis widely tested in a number of papers (see Helpman (1995), Keller 2005)) is that foreign R&D elasticities are the same in all countries. Archarya and Keller (2007) clearly reject this hypothesis.

Further, previous studies have mainly focused on productivity effects. However, Mancusi (2008) and Malerba et al. (2007) analyze import-driven R&D spillovers using a knowledge-production framework. Mancusi (2008) examines patent applications to measure innovation. R&D spillovers are computed by comparing the relative shares of patent citations within a given industry with patents in other domestic industries and patents in foreign industries. The hypothesis is that more patent citations increase the firms' ability to benefit from R&D activities performed elsewhere. As Mancusi (2008) concludes, international spillovers are more important in laggard countries than in the technology leaders. The analysis in Malerba (2007) is based on innovation activity in 135 technological fields, classified as chemical-, electronics- and machinery-intensive sectors, and covers six countries (France, Germany Italy, Japan, UK and US). In line with Mancusi (2008), they found both international spillovers and intra-sectoral spillovers to be important determinants of innovation.

Additionally, as Nunn (2007) and others have reported, personal interaction between the buyer and the seller may act as a mechanism that enhances trade of certain (non-standard) types of goods. More specifically, Nunn shows that countries with well-functioning institutions have a comparative advantage in the exports of goods that are intensive in seller-buyer interactions.[3] The relationship-specificity (RS) index used by Nunn (2007) stems from Rauch (1999), and it examines how product differentiation affects the need for interaction between the buyer and the seller. The question of how relationship-specific interactions and investments affect various decisions of a firm has attracted a series of papers. Examples include the following studies: Altomonte and Békés (2010), analyzing trade and productivity; Casaburi and Gattai (2009), examining intangible assets; Ferguson and Formai (2011), analyzing trade, firm choice and contractual institutions; Bartel, Lach and Sicherman (2009), analyzing outsourcing and relationship-specific interactions; and Kukenova and Strieborny (2009), analyzing finance and relationship-specific investments. Hence, it seems clear that relationship-specific investments may be related to a wide range of issues. However, given the close relation between trade of intermediate products, technology spillovers and personal interactions, it is surprising that no one has yet analyzed the influence of personal interaction on technological (rent) spillovers; hence, we aim to fill this gap.

The paper is organized as follows: section 2 presents the model and data; section 3 contains the econometric results; and section 4 concludes.

[3] To construct the relation-specificity (RS) index, Nunn (2007) builds on Rauch (1999) by using information regarding whether an input is sold on an organized exchange.

2. The model

For a single firm, outside knowledge may be instrumental in developing the knowledge stock. An important channel in this respect is knowledge spillovers from imports or other domestic firms. In this vein, we analyzed technology spillovers, carried across firms through trade, and how these spillovers in combination with seller-buyer interactions feed into firms' incentives to invest in R&D.

Griliches (1992) points at substantive spillovers associated with trade. Coe and Helpman (1995) apply R&D weighted imports to capture international technology spillovers. Both of these confirm that imports serve as a channel for foreign technology spillovers. In an array of papers (see, e.g., Keller 1997, 2000, 2002a, 2002b, 2004), Keller has studied both national and international technology spillovers. In short, there exists robust evidence for technology spillovers.

We followed the above tradition and assumed that import spillovers follow input and output links. That is, we assumed that spillovers from domestic or foreign industries can be measured as a weighted average of new knowledge produced in these sectors, as measured by the R&D stocks in the sector and weighted by domestic deliveries and imports from the different sectors.

The weights b_{jl} are computed from the Swedish input-output tables of 1995. This method can be described in the following manner: the column vector of gross output, x_j, is decomposed according to the formula

$$x_j = \sum m_{jl}^D + \sum m_{jl}^F + \omega_j \quad ,$$

where $m_{jl}^D, m_{jl}^F, \omega_j$ is the cost of the *l*th good (domestic and imported), used in the *j*th sector. A typical element in **M**, m_{jl}, reflects the amount of intermediate goods originating from sector *l* and used by sector *j*. The technical coefficients are computed using the following equation:

$$b_{jl} = m_{jl} / x_j \, .$$

A typical element b_{jl} shows the cost share of commodity *l* used in the unit production of *j*. The potential pool of national and international R&D spillovers can be measured as

$$r_{ijt}^W = b_{jj}^D (R\&D_{jt} - R\&D_{ijt})^D \qquad (2.1)$$

$$r_{jt}^B = \sum_l b_{jl}^D R\&D_{lt}^D \qquad (2.2)$$

$$r^F_{jt} = \sum_l b^F_{jl} R\&D^F_{lt} \qquad (2.3)$$

where r^W, r^B and r^F, indicate within, between and foreign spillovers. The terms $b^D_{jj}, b^D_{jl}, b^F_{jl}$ are respective representations of the percentage of R&D stocks generated in industry *j* and *l* domestically and the percentage of R&D stocks generated in industry *l* abroad that are accessible to industry *j* home.

The firms' R&D investments are explained by the pool of R&D spillovers defined in (2.1) to (2.3). Putting all of these factors together in an econometric setting, we have

$$r^O_{ijt} = g(r^W_{ijt}, r^B_{jt}, r^F_{jt}, \mathbf{X}) \qquad (2.4),$$

where internal R&D expenditures, r^O, is a function of r^W which is R&D spillovers stemming from domestic firms within the same industry as the firm belongs to, r^B is a function of R&D spillovers between domestic industries and r^F is a function of R&D spillovers from abroad.

To analyze the role of interactions between buyers and sellers in the occurrence of spillovers, we use the industry-specific relationship index developed by Nunn (2007). The Nunn data are freely available on the web, and we match the relation-specific index to the (Swedish) 3-digit SNI 92 industry classification. This enables us to analyze spillovers and how they vary with respect to the intensity of buyer-seller interactions.

2.2 Other determinants of firm R&D

In the early literature on R&D, researchers distinguished between three classes of explanatory variables that capture inter-industry variation in R&D: appropriability conditions, opportunity conditions and product demand. Many researchers have acknowledged the importance of these concepts, but we still lack a clear and precise understanding of how to measure them. Technological opportunity refers to the possibility of converting the benefit of an innovation into a new, enhanced product or production process. Geroski (1991b) argues that industries in the early phase of the product cycle are characterized by high rates of innovation, firm turnover and technological opportunity, all of which stimulate R&D. A reasonable measurement of technological opportunity might be the firm turnover rate (*Fto*), measured as the share of firm entry and exit within a given industry. Our *a priori* expectation is that a high firm turnover rate is positively associated with firm R&D.[4]

According to Schumpeter (1942), monopoly rents and profits are instrumental in funding firm R&D, and several studies have stressed the role of monopoly power in innovation activity (see, e.g., Arrow (1962) and Dasgupta and Stiglitz (1980)). To capture the impact of competition on firm R&D, we apply the Herfindahl index *(H)*. The Herfindahl index is bounded in the interval 0-10 000, with a value of 10 000 indicating a monopoly situation.

The perhaps most obvious and well-studied driver of R&D is firm size. Decades of empirical research on the relationship between firm size and R&D have established a consensus view of a R&D elasticity with respect to firm size close to unity. In the empirical literature on the determinants of firm R&D, the capital intensity of the firm is largely ignored. This finding is surprising because technological innovations are typically embodied in new machinery.[5] For example, DeLong and Summers (1991) argue that countries with high capital investment rates tend to be those with high productivity growth, and Aghion and Howitt (1999) demonstrate how a positive correlation between innovation and capital intensity can be established.

Augmenting equation (2.4), a linear semi-log representation of the full model takes the following form (equation 2.5)

$$\ln\left(r_{ijt}^{O}\right) = \propto_0 + \propto_i + \propto_t + \gamma_1 \ln\left(r_{ijt}^{W}\right) + \gamma_2 \ln\left(r_{jt}^{B}\right) + \gamma_3 \ln\left(r_{jt}^{F}\right) + \gamma_4 H_{jt} + \gamma_5 Fto_{jt} + \gamma_6 \ln\left(Size_{ijt}\right) + \gamma_7 \ln\left(k_{ijt}\right) + \varepsilon_{ijt} \quad ; \quad \varepsilon_{ijt} \sim iid(0, \sigma_\varepsilon^2) \quad ,$$

where r^O represents R&D expenditures in firm *i* at industry *j* at time *t*, r^W represents within-industry R&D spillovers, r^B represents domestic between industry R&D spillovers, r^F represents R&D spillovers imported from abroad, *H* represents the Herfindahl index, *Fto* represents firm turnover rate, *Size* represents firm size measured as the firm's turnover, and *k* represents the firm's capital intensity. Finally, ε is the classical error term.

[4] Aghion and Howitt (1999) demonstrate how a positive correlation between productivity growth and entry and exit of firms can be established.

[5] See, e.g., Stoneman (1983).

2.3 Data

Data on inputs and outputs of Swedish firms are obtained from Statistics Sweden. The Financial Statistics (FS) and Regional Labor Statistics (RAMS) contain information on all manufacturing firms with at least 50 employees from 1990 to 2000. Whereas RAMS mainly contain information on employees' education and wages, FS contain information about firms' input and output, such as sales, capital stock, investment, profits, and R&D. R&D data cover all firms with at least 50 employees or, for smaller firms, at least 50% of one full time employee active in R&D. Our analysis was therefore restricted to firms with at least 50 employees. Numbers on R&D were retrieved annually; firms are required to provide this information. [6] Respondents were asked to provide exact figures regarding R&D expenditure or to answer in an interval scale and 52% of our observations consist of firms not performing R&D.[7] Data on the industry intensity of relationship-specific interactions were drawn from Nunn (2007) and are available at
http://www.economics.harvard.edu/faculty/nunn/data_nunn.[8]

From Table A2, we note that the share of foreign-owned firms has increased over time. Considering the debate on ownership and whether foreign owned firms move R&D out of Sweden and concentrate it to the home country, we add two ownership dummy variables to Eq. (2.5): a foreign-domestic dummy and a dummy indicating whether the firm is private or public owned.

3. Results: Trade, relationship-specific interactions and R&D spillovers

R&D is associated with sunk costs, and not all observed firms perform R&D. Given that firms are not randomly drawn into R&D, this issue must be considered. We begin the analysis with OLS estimations and thereafter add control for selection and fixed effects. With this framework, we can transparently observe the impact of various refinements.[9]

[6] The annual response rate for firms with at least 50 employees in the financial statistics is approximately 97 percent.

[7] An alternative to the FS R&D data is the bi-annually collected Research Statistics (RS), based on all firms in the FS with at least 200 employees and on a sample of firms with 50 – 200 employees, and given that these firms report R&D expenditures of at least 200 000 SEK to the FS. Regarding statistical reliability, the bi-annually collected "Research Statistics" is of higher quality but has less coverage. The RS and FS data generate very similar results, but the RS reduces the sample size with more than 50%, and we therefore focus on results from the FS.

[8] Examples of industries not intensive in relationship-specific interactions include poultry processing, flour milling, petroleum refineries and corn milling; conversely, automobile, aircraft and computers are examples of industries intensive in relationship-specific investments.

[9] It might be argued that spillovers are endogenous and/or that spillovers are realized with an impact lag. We therefore follow the assumption of strong exogeniety (Hendry, 1995) and apply the spillover variables with one lag. An alternative is to use external instruments, which was not feasible for our research. In addition, as shown by Bound et al. (1995), using weak instruments may amplify the bias.

Our initial model in Table 1 is a basic OLS regression, and estimation 1 is estimated for firms with positive values of R&D. As pointed out above, if firms are not randomly drawn into R&D, these results may be biased. Therefore, in column 2, we substitute the OLS model for a Heckman selection model.[10] Although tests suggest that selection approaches are appropriate, results from the Heckman model are rather similar to those obtained by OLS.[11] Both the OLS and the Heckman models suggest that foreign spillovers are positive and significant, whereas the results for domestic spillovers are weaker and mostly not significant.

[Table 1 about here]

When working with data where zeros are frequent Poisson or negative binominal models have become increasingly popular. These models possess a number of attractive features. As Westerlund and Wilhelmsson (2009) and Burger *et al*. (2009) have identified, these models are relatively robust to non-homoscedasticity; contrary to the Heckman model, these models do not rely on an exclusion restriction and we by-pass the complication of deciding how to treat the undefined value $ln(0)$.[12] A sensitive assumption of the Poisson model is that the mean and variance of the dependent variable should have the same value. Therefore, the negative binominal is often recommended and also applied here. To test the robustness of the results, we present results from binomial models where the dispersion parameter is treated as a random effect (RE) (the default) and models where the dispersion parameter is specified according to a fixed effect (FE) framework. Negative binomial models presented here are estimated using bootstrapped standard errors.

Results from negative binomial models verify our previous findings: the largest positive and most significant spillovers are found from foreign spillovers. We also find positive and significant within-industry domestic spillovers, though their estimated elasticity is relatively small. Perhaps the largest difference between negative binomial models and the other models is that the estimated elasticity's for the spillover variables are somewhat smaller for the negative binomial models.

[10] The significance of both tests for independent equations and the Mills ratio indicates that a selection procedure is appropriate. We find no contradictions between the selection and target equation, though we notice generally lower significance in the selection.
[11] Note that the Inverse Mills Ratio (IMR) is a nonlinear function of the variables included in the first-stage probit and that the target equation can be identified from this nonlinearity alone. The nonlinearity of IMR arises from the assumption of normality. However, identification is aided by adding a variable to the selection equation that is closely related to the decision to undertake R&D. As discussed above, firms' profit fits these requirements and is therefore applied.
[12] Flowerdew and Aitkin (1982) and Santos and Tenreyro (2006).

As discussed above, results may be affected by unobserved firm- or industry-level heterogeneity. One way to tackle this issue is to control for fixed industry effects. Therefore, in Table A1, as a robustness check, we control for fixed industry effects. The results in Table A1 indicate that including the full set of industry dummies generally decreases the significance of the estimated coefficients. More specifically, considering the full set of industry dummies, foreign spillovers remain positive and significant independent of the estimation technique, with an estimated elasticity between 0.3-0.4; conversely, domestic spillovers are insignificant or barely significant, with relatively small and negative estimates. Hence, including industry fixed effects leads to increased standard errors, and the occasional negative effects of domestic R&D spillovers indicate that domestic spillovers may substitute for in-house R&D.

The results found above indicate that control of fixed effects might influence the results. Moreover, Table A3 indicates that our spillover variables show larger cross sectional variation than variation over time, as do most of the other control variables. As noted by Plümper and Troeger (2007), the inclusion of fixed effects makes the estimation of slowly changing variables cumbersome. Plümper and Troeger (2007) thus propose the Fixed Effect Variance Decomposition (FEVD) method as a way to address this problem. However, several researchers have recently contested the FEVD model (Greene 2010, Breusch et al. 2010), and Greene's is perhaps the severest critique. Plümper and Troeger (2011) comment in some detail on these critiques and argue strongly for the advantages of the FEVD model. Nevertheless, the issue is not yet settled, and we therefore recommend viewing results from FEVD models as complementary. In particular, we use results from the FEVD models to analyze to what extent unobserved heterogeneity and not controlling for firm level fixed effects influences the results. This strategy also enables us to test robustness. Hence, we stress that our results are robust and do not depend upon specific estimation procedures.

In estimation 5 in Table 1, we estimate a FEVD model applied to a selection-model framework in which Eta (η) is the variance decomposition variable that absorbs non-observed heterogeneity. It is worth to note that the R^2 increases from 56 percent in the OLS model to 91 percent in the FEVD model, suggesting that there is a significant amount of firm-level heterogeneity absorbed by the variance decomposition method. In addition, the fixed effect variance decomposition variable (Eta) is highly significant with the expected point estimate of unity.

Using the FEVD model, we note a general increase in the applied variables' significance regarding positive and significant spillovers from both domestic and foreign sources; further, foreign spillovers are again found to be associated with the largest elasticity. Hence, these results are consistent with research indicating that foreign knowledge may be especially important for small, open economies in which the domestic knowledge stock is small relative to global knowledge stock. These results also indicate that results from other models are not driven by the lacking control of fixed-effects.[13]

Having analyzed the general relationship between foreign and domestic intra- and inter-industry trade spillovers, we next analyze complementariness between relationship-specific investments and spillovers. Is there any evidence that the potential for adapting and learning from outside R&D is particularly high in relationship-specific intensive industries where personal interactions between buyer and seller are likely to precede trade?

[Table 2 about here]

In Table 2, we analyze whether spillovers are related to the intensity of industry relation-specific interactions between seller and buyer. The results presented in Table 2 indicate that R&D spillovers are related to relationship specificity in an interesting way. The clearest results are found for international spillovers. In all estimates, the results indicate that imported international R&D spillovers are important for technology diffusion and that the impact of spillovers increases as the degree of relationship-specificity intensifies; consequently, these results suggest that international knowledge transfers are enhanced by personal interactions.

For domestic spillovers, however, results are less clear. Both domestic intra- and inter-industry spillovers are largely insignificant, except when using the FEVD framework. Regarding domestic inter-industry spillovers, there is a tendency toward positive spillovers in relationship-specificity intensive industry. For intra-industry spillovers, the picture is almost the opposite when compared with inter-industry spillovers. For intra-industry spillovers, our results suggest that positive spillovers are more likely in industries not intensive in industry-specific interactions, whereas intra-industry spillovers substitute for in-house R&D in industries intensive in industry-specific interactions. However, the overall impression is that

[13] The maximum number of observations is 15821, including firms with and without R&D. The selection equation accounts for a slight drop in observations. Results for the OLS model, Heckman target equation and the selection-adjusted FEVD reflects the number of R&D-performers. The Negative binomial model includes firms with zero observations where the fe calculation of the dispersion parameter accounts for loss of observations. See, e.g., Guimarães (2007) and Hilbe (2007).

for domestic spillovers, the estimated coefficients are relatively small with many insignificant or weakly significant results.[14]

[Table 3 about here]

In Table 3, we analyze whether results are robust regarding simultaneous inclusion/exclusion of the spillover variables. The results in Table 3 largely verify previous results. Including one spillover mechanism at a time, our results indicate that foreign spillovers manifest the strongest and most significant impacts. Regarding local spillovers, robust and positive spillovers are only found for between-industry spillovers in industries with intensive relationship-specific interactions, indicating that relationship-specific interactions enhance spillovers. In industries where trade does not require much interaction, we are likely to find negative or complementary spillover impacts on firm R&D. Hence, when including all three variables simultaneously, our results change only slightly for domestic, intra-industry spillovers; however, this link is also where trade-related spillovers appear weakest.[15]

3.1. Results: Other determinants of firm R&D

In line with Schumpeter (1934), we find the Herfindahl index to be positive and significant in all models, which indicates that competition mitigates R&D. Hence, industries with few firms tend, on average, to be relatively R&D-intensive, but the effect is rather small.

Perhaps the most frequently analyzed question addresses the relationship between firm size and R&D. Decades of research have established an elasticity close to unity. For the log-linear models, we find that average R&D elasticity with respect to firm size is slightly larger than unity, with estimates ranging from 1.12 to 1.27 (see Table 1); conversely, the negative binomial models indicate a lower estimate. The lower estimates found in these models might result from the inclusion of all zero R&D observations, and for these observations, firm size may vary despite a zero value for R&D.

In the literature on embodied technological change (Stoneman 1983), technological progress is propelled by investments in new machinery, thus identifying a link between capital and R&D. Surprisingly, the econometric analysis indicates a negative relationship between capital and R&D.

[14] One explanation for the negative results found regarding particular intra-industry spillovers in interaction intensive industries may be the extent that R&D might be outsourced; however, this is likely to be most pronounced in the home industry where personal interactions are common.
[15] The correlation matrix in Table A4 indicates that though there is no severe multicollinearity, though we cannot exclude that multicollinearity might affect results when all spillover variables are considered.

As stressed by the Schumpeterian theory, decisions about whether to undertake risky investments are linked to firm profitability. Profitable firms are considered better R&D candidates than low profitability firms. Hence, the profit ratio may be a good indicator of R&D, whereas factors like firm size are likely to be connected to the volume of R&D. In the Heckman selection equations (see Table 1 and 2) we find that, although theoretically well motivated, the profit ratio did not significantly explain the probability to invest in R&D.

Firm ownership may affect the possibility of funding R&D. In a policy sense, it is important to analyze whether publicly owned firms *ceteris paribus* spend more on research than privately owned firms. Our results indicate that public firms spend slightly more on R&D. Finally, studies of multinational and foreign owned firms indicate that, for many firms, most innovative activity is performed in the home country. However, our results indicate that foreign-owned firms spend more on R&D than domestic ones. This finding might indicate that Sweden possesses a comparative advantage in R&D.[16]

4. Concluding remarks

R&D is known as a key component behind technological development and economic growth, and thus it is crucial to understand the drivers of firm R&D. An important question assesses how technology spillovers, transferred through trade, affect innovation and R&D. Knowledge spillovers provide firms with information that may induce new ideas and/or reduce the uncertainty associated with R&D projects. We capture such spillovers by estimating R&D stocks domestically in the own- and other industries as well as abroad. Combining this information with data on trade allows us to analyze spillovers.

To further analyze factors that enhance the transmission of technology and spillovers, we extend the analysis of trade-related spillovers by investigating how relationship-specific interactions between buyer and seller affect such spillovers. As pointed out by Nunn (2007), it is sometimes necessary that buyers and sellers interact for trade to occur. Industries intensive in such interactions are therefore labeled “intensive in relationship-specific interactions.” Considering that technology spillovers to a large extent are related to the understanding of a technology, it is plausible to assume that such interactions not only enhance trade in certain industries but also enhance spillovers.

In our analysis of the effects of R&D spillovers, we found that international R&D spillovers have a positive and significant impact on firm R&D. Using a wide range of estimators and model specifications, we found that the elasticity of international R&D

[16] Similar results are obtained in the research of Gustavsson and Kokko (2003) and ITPS (2004).

spillovers with respect to firm R&D are approximately between 0.2-0.7. The fact that Sweden is a small, open economy might explain why the dissemination of technology from imports of intermediate products has such a strong impact on firms' R&D activities. For domestic intra- and inter-industry spillovers results were less clear with some positive and significant results, but the impact of domestic spillovers was often insignificant.

When addressing the question of complementarities between inflow of R&D technology and relationship-specific investments, some interesting results appear. Our analysis indicates that international R&D spillovers are important for technology diffusion and that the impact of international spillovers increases with the degree of relationship-specific interactions, which suggests that international knowledge transfers are enhanced by personal interactions.

However, analyzing the interplay between domestic spillovers and relationship-specific interactions, results are less clear. For domestic inter-industry spillovers, we found a tendency for positive spillovers in industries intensive in relationship-specific interactions, whereas domestic spillovers substitute their own R&D when there is less of a need for relationship-specific interactions. That is, the overall conclusion is that international spillovers are positive and significant and that such spillovers are enhanced by relationship-specific interactions between the seller and the buyer. The weaker results found for domestic spillovers may be explained by closeness factors. As noted in the introduction, spillovers are to some extent locally bounded, and for domestic spillovers to occur, channels other than trade may be available. For example, within domestic borders, psychic, cultural and geographic distance is small and labor mobility is frequent, all of which promote domestic spillovers and reduce the role of domestic trade as a carrier of spillovers.

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Appendix

Table 1. The effect of R&D spillovers (within, between and imported).
Dependent variable: natural log of firms' R&D expenditures

	OLS [(a)]	**HECKMAN** [(a)]		**Neg** [(b) (c)] **Binom., re**	**Neg** [(b)] **Binom., fe**	**FEVD** [(a)] **selection adj.**
		(Select)	(Target)			
$\ln(R^W)_{t-1}$	0.1012	0.0317	0.1110	0.0299	0.0308	0.1024
	(0.060)	(0.035)	(0.068)	(0.013)**	(0.014)**	(0.001)***
$\ln(R^B)_{t-1}$	0.3668	-0.0763	0.3550	0.0285	0.0539	0 .1996
	(0.200)*	(0.141)	(0.226)	(0.054)	(0.0604)	(0.005)***
$\ln(R^F)_{t-1}$	0.6138	0.339	0.6854	0.2191	0.1731	0.7505
	(0.110)***	(0.095)***	(0.125)***	(0.042)***	(0.040)***	(0.003)***
$\ln(\text{Firm size})_t$	1.1227	0.3982	1.203	0.3691	0.3451	1.2660
	(0.048)***	(0.027)***	(0.034)***	(0.029)***	(0.0312)***	(0.002)***
$\ln(K/L)_t$	-0.1664	0.0085	-0.1621	-0.0241	-0.0309	-0.19745
	(0.075)**	(0.037)	(0.081)**	(0.028)	(0.023)	(0.004)***
$(\text{Profit/sales})_{t-1}$	-	0.1028	-			-
	-	(0.083)	-			-
$(\text{Firm turnover})_t$	0.0060	-0.0006	0.0051	0.0021	0.0027	0.0005
	(0.004)	(0.004)	(0.004)	(0.003)	(0.002)	(0.0006)***
$(\text{Herfindahl})_t$	0.0002	4.9e-05	0.0002	2.7e-05	2.4e-05	0.0002
	(0.000)***	(0.000)*	(0.000)***	(1.6e-05)*	(1.4e-05)	(0.000)***
$(\text{Private})_t$	0.1301	-0.1011	0.0714	0.1374	0.1326	0.0869
	(0.183)	(0.154)	(0.214)	(0.114)	(0.152)	(0.0162)***
$(\text{Foreign})_t$	0.1061	0.1404	0.1425	0.224	0.2025	0 .1648
	(0.067)	(0.057)**	(0.082)*	(0.053)***	(0.043)***	(0.0060)***
Mills ratio	-	-	0.4248			0 .8045
	-	-	(0.125)***			(0.1682)***
Eta, FEVD	-	-	-			1(0.002)***
Industry dum.	no	no	no	no	no	no
Period dum.	yes	yes	yes	yes	yes	yes
R-squared	0.56	-	-	-	-	0.91
Observations	7 625	14231	7625	15 821	10 548	6 978

Note: * p<0.10, ** p<0.05, **, *** p<0.01. [(a)] OLS, Heckman and Heckman-FEVD estimations based on robust standard errors clustered by industry. [(b)] Negative binomial models estimated using bootstrapped standard errors. [(c)] LR test pooled. p-val = 0.000.

Table 2. The effects of R&D spillovers divided into low- respectively high values of relationship-specificity. Dependent variable: natural log of firms' R&D expenditures

	OLS [(a)]	HECKMAN [(a)]		Neg [(b) (c)] Binom., re	Neg [(b)] Binom., fe	FEVD [(a)] selection adj.
		(Select)	(Target)			
$\ln(R^W\text{-}RS_{Low})_{t-1}$	0.0223	0.0108	0.0239	0.0171	0.0178	0.0159
	(0.045)	(0.017)	(0.049)	(0.010)*	(0.009)**	(0.001)***
$\ln(R^W\text{-}RS_{High})_{t-1}$	-0.0322	-0.0604	-0.0487	-0.0623	-0.0433	-0.0646
	(0.026)	(0.011)***	(0.029)*	(0.010)***	(0.008) ***	(0.000)***
$\ln(R^B\text{-}RS_{Low})_{t-1}$	-0.1383	-0.0946	-0.1685	-0.0594	-0.0257	-0.2585
	(0.173)	(0.053)*	(0.186)	(0.051)	(0.047)	(0.004)***
$\ln(R^B\text{-}RS_{High})_{t-1}$	0.1345	-0.0318	0.1168	0.0487	0.0960	0 .0710
	(0.120)	(0.049)	(0.126)	(0.037)	(0.036)***	(0.003)***
$\ln(R^F\text{-}RS_{Low})_{t-1}$	0.1636	0.1129	0.1807	0.0703	0.0321	0.2239
	(0.104)	(0.056)***	(0.116)	(0.037)*	(0.039)	(0.003)***
$\ln(R^F\text{-}RS_{High})_{t-1}$	0.4347	0.3056	0.5143	0.2317	0.1373	0.5848
	(0.137)***	(0.039)***	(0.152)***	(0.0416)***	(0.046)***	(0.003)***
$\ln(\text{Firm Size})_t$	1.1288	0.4162	1.2047	0.4135	0.3847	1.2731
	(0.052)***	(0.031)***	(0.038)***	(0.027)***	(0.024)***	(0.001)***
$\ln(K/L)_t$	-0.0405	0.0222	-0.0297	0.0054	-0.0016	-0.0425
	(0.052)	(0.032)	(0.055)	(0.026)	(0.031)	(0.004)***
$(\text{Profit/sales})_{t-1}$		0.0964				
		(0.079)				
$(\text{Firm turnover})_t$	0.0012	-0.0028	-3.9e-05	0.0013	0.0022	-0.001
	(0.004)	(0.004)	(0.005)	(0.002)	(0.002)	(0.001)
$(\text{Herfindahl})_t$	0.0002	4.7e-05	0.0002	3.8e-05	3.3e-05	0.0002
	(0.000)***	(0.000)**	(0.000)***	(0.000)**	(0.000)**	(0.000)***
$(\text{Private})_t$	0.2082	-0.0880	0.1496	0.1432	0.1450	0.1574
	(0.178)	(0.148)	(0.208)	(0.122)	(0.113)	(0.016)***
$(\text{Foreign})_t$	0.1155	0.1460	0.1510	0.1920	0.1732	0.1816
	(0.075)	(0.047)***	(0.084)*	(0.047)***	(0.056)***	(0.007)***
Mills ratio	-	-	0.3895			0.7591
	-	-	(0.111)***			(0.149)***
Eta, FEVD	-	-	-			1 (0.001)***
Industry dum.	no	No	No	no	no	no
Period dum.	yes	Yes	Yes	yes	yes	yes
R-squared	0.58	-	-	-	-	0.91
Observations	7655	14262	7655	15 853	10 578	7007

Note: * p<0.10, ** p<0.05, **, *** p<0.01. [(a)] OLS, Heckman and Heckman-FEVD estimations based on robust standard errors clustered by industry. [(b)] Negative binomial models estimated using bootstrapped standard errors. [(c)] LR test pooled. p-val = 0.000

Table 3. Sensitivity analysis. Dependent variable: natural log of firms' R&D expenditures

	Neg [b] [c] Binom., re	FEVD [a]	Neg [b] [c] Binom., re	FEVD [a]	Neg [b] [c] Binom., re	FEVD [a] selection adj.
$ln(R^W\text{-}RS_{Low})_{t-1}$	-0.0166	-0.0562		-		-
	(0.005)***	(0.000)***		-		-
$ln(R^W\text{-}RS_{High})_{t-1}$	-0.0146	0.0361		-		-
	(0.007)**	(0.000)***		-		-
$ln(R^B\text{-}RS_{Low})_{t-1}$		-	-0.0659	-0.3040		-
		-	(0.036)*	(0.004)***		-
$ln(R^B\text{-}RS_{High})_{t-1}$		-	0.1430	0.4581		-
		-	(0.016)***	(0.001)***		-
$ln(R^F\text{-}RS_{Low})_{t-1}$		-		-	0.1107	0.2505
		-		-	(0.034)***	(0.002)***
$ln(R^F\text{-}RS_{High})_{t-1}$		-		-	0.1173	0.5162
		-		-	(0.018)***	(0.001)***
Full set of control variables included, see Table 2						
Industry dum.	no	no	no	no	no	no
Period dum.	yes	yes	yes	yes	yes	yes

Note: * p<0.10, ** p<0.05, **, *** p<0.01. [a] Heckman-FEVD estimations based on robust standard errors clustered by industry. [b] Negative binomial models estimated using bootstrapped standard errors.
[c] LR test pooled. p-val = 0.000

Table A1. The effect of R&D spillovers.
Estimations with full set of industry dummies at the 2-digit level included.
Dependent variable: natural log of firms' R&D expenditures.

Estimator	**OLS** [a]	**HECKMAN** [a]		**Neg** [b] [c] **Binom., re**
		(Select)	(Target)	
$ln(R^W)_{t-1}$	-0.0553	-0.0854	-0.0769	-0.0666
	(0.03)	(0.03)***	(0.04)*	(0.034)*
$ln(R^B)_{t-1}$	-0.107	-0.0547	-0.201	-0.1240
	(0.10)	(0.11)	(0.11)*	(0.112)
$ln(R^F)_{t-1}$	0.283	0.269	0.377	0.3296
	(0.14)*	(0.09)***	(0.16)**	(0.117)***
Full set of control variables included, see Table 1				
Industry dum.	yes	yes	yes	yes
Period dum.	yes	yes	yes	yes
R-squared	0.56	-	-	-

Note: * p<0.10, ** p<0.05, **, *** p<0.01. [a] OLS, Heckman and Heckman-FEVD estimations based on robust standard errors clustered by industry. [b] Negative binomial models estimated using bootstrapped standard errors. **[c]** LR test pooled. p-val = 0.000.

Table A2 Summary statistics

Year	No of firms [a]	No. of foreign firms (employment share)	No. of public firms (employment share)	R&D share performed by the top ten R&D firms
1990	2018	346 (18.9%)	77 (4.6%)	59%
1991	1940	367 (21.0%)	83 (6.9%)	60%
1992	1758	363 (21.4%)	90 (8.1%)	58%
1993	1610	320 (19.2%)	55 (4.0%)	58%
1994	1652	339 (19.8%)	63 (10.7%)	61%
1995	1751	408 (24.0%)	45 (7.6%)	65%
1996	1801	416 (23.9%)	53 (8.8%)	63%
1997	1840	446 (25.7%)	66 (8.0%)	67%
1998	1924	485 (27.6%)	63 (7.6%)	67%
1999	1887	492 (32.1%)	59 (7.4%)	72%
2000	1932	527 (36.7%)	49 (6.9%)	74%

Note: [a] 3 632 unique firms.

Table A3 Variance decomposition and correlation between RS-index and spillover variables

Variable	Within stdv.	Between stdv.		Correlation spillover variables and RS-index	
ln(R&D)	0.70	1.94		Variable	Correlation with RS-index
ln(R^W)	0.54	2.01		*ln*($(R^W)_{LOW}$)	-0.70
ln(R^B)	0.24	0.56		*ln*($(R^W)_{HIGH}$)	0.73
ln(R^F)	0.19	0.85		*ln*($(R^W)_{LOW}$)	-0.06
ln(Firm size)	0.28	1.15		*ln*($(R^W)_{HIGH}$)	0.66
ln(K/L)	0.39	1.07		*ln*($(R^W)_{LOW}$)	-0.58
Profit/sales	0.30	0.84		*ln*($(R^W)_{HIGH}$)	0.85
Fto3	6.91	6.89			
H	575	1254			

Table A4 Correlation matrix, variables

1. ln(R&D)	**1.**	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**	**8.**	**9.**	**10.**
2. ln((R^W)	.26	1								
3. ln((R^B)	.06	-.16	1							
4. ln(R^F)	.30	.35	.42	1						
5. ln(Size)	.65	.16	-.17	-.02	1					
6. (Fto)	.03	.01	.12	.09	-.03	1				
7. (Private)	.04	.03	-.04	-.02	.06	.02	1			
8. (Foreign)	.16	.08	.04	.15	.14	-.00	-.10	1		
9. ln(k)	.09	.03	-.22	-.12	.32	-.06	.02	.07	1	
10. ln(profit)	.03	-.00	.04	.01	.08	.03	-.01	.02	-.02	1
11.Herfindahl	.21	.01	-.10	.05	.13	.08	.03	.04	-.02	.02

Table A5 Summary statistics, variables

Variable	Obs	Mean	Std. Dev.	Min	Max
ln(R&D)	9262	7.7	2.1	1.2	16.7
ln(R^W-RS_{Low})	20113	2.5	4.7	0.0	13.3
ln(R^W-RS_{High})	20113	2.8	4.7	-0.4	14.1
ln(R^W)	20074	10.3	2.0	-0.4	14.1
ln(R^B-RS_{Low})	20113	10.9	0.8	9.1	13.1
ln(R^B-RS_{High})	20113	9.4	1.7	3.9	12.4
ln(R^B)	20113	11.7	0.6	10.2	13.3
ln(R^F-RS_{Low})	20113	13.5	0.9	12.2	15.8
ln(R^F-RS_{High})	20113	12.4	1.6	9.7	16.1
ln(R^F)	20113	14.4	0.9	12.7	16.2
ln(Firm Size)	19931	11.9	1.2	6.4	18.9
ln(K/L)	19919	5.0	1.0	-4.1	10.7
Fto3	20018	9.8	8.4	0.0	100.0
H	20113	1250.7	1300.6	0.0	10000.0
Private	20113	0.0	0.2	0	1
Foreign	20113	0.2	0.4	0	1