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Innovation, regional knowledge spillovers and R&D cooperation☆

Michael Fritsch[a,*], Grit Franke[b]

[a] *Technical University Bergakademie Freiberg, Faculty of Economics and Business Administration, Lessingstr. 45, D-09596 Freiberg, Germany*
[b] *State Street Bank, Frankfurt, Main, Germany*

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Abstract

We investigate the impact of knowledge spillovers and R&D cooperation on innovation activities in three German regions. We begin by estimating the knowledge-production function in order to test for interregional difference with regard to the efficiency of innovation activities. In a second step, we analyze the contribution of spillovers from R&D effort of other private firms and of public research institutions to explain these differences. The inclusion of variables for R&D cooperation in the model indicates that R&D cooperation is only of relatively minor importance as a medium for knowledge spillover.

JEL classification: D21; O3; R30

Keywords: Innovation; Knowledge spillovers; R&D cooperation; Regional innovation systems

1. Introduction: how do knowledge spillovers become effective?

In recent years, it has become increasingly recognized in the literature that ‘spillovers’ of knowledge from external sources may have an important impact on innovation processes and economic development.[1] A number of theoretical arguments as well as some empirical findings suggest that such knowledge spillovers are concentrated in spatial proximity from their respective source.[2] Therefore, it can be assumed that knowledge spillovers constitute an important factor in shaping the regional conditions for innovation activities. Accordingly, the “new” growth theory has devoted considerable attention to the regional dimension of innovation and economic development (cf. Krugman, 1999). The recognition that geographical space is of crucial importance for the spillover of knowledge leads us to the question of how and why such spillovers become effective and what are the primary means for their diffusion.[3] It has become a

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* Corresponding author. Tel.: +49-3731-392439; fax: +49-3731-393690.
E-mail address: fritschm@vwl.tu-freiberg.de (M. Fritsch).

[1] This is a fundamental issue in recent approaches to growth theory (cf. Krugman, 1991; Romer, 1994) or the concept of (national or regional) innovation systems (cf. Edquist, 1997; Lundvall, 1992; Metcalfe, 1995; Nelson, 1993).

[2] Empirical evidence that knowledge spillovers are concentrated in spatial proximity to the respective source is provided in Acs et al. (1992), Audretsch and Feldman (1996), Anselin et al. (1997) and Jaffe et al. (1993). The theoretical explanation is based on the notion that in most cases face-to-face-contacts are necessary for transferring ‘tacid’ knowledge.

[3] See Breschi and Lissoni (2001) and Feldman (1999) for an overview of the evidence.

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popular hypothesis in the literature that cooperative relationships between regional actors may be an important vehicle for such spillovers.[4] Consequently, a number of authors argue that policy could contribute to a wider and faster diffusion of knowledge spillovers by actively stimulating cooperative relationships or at least by not hindering them, motivated, e.g. by the desire to secure a competitive market structure (cf. Jorde and Teece, 1990).

In this paper, we analyze the impact of spillovers on innovation activities in a region and examine the significance of R&D cooperation for these knowledge spillovers. Following a brief introduction to the database (Section 2) and a discussion of the analytical framework (Section 3), we first investigate the impact of location on innovation activities (Section 4). Next, we assess how far knowledge spillovers generated by other economic actors in the region may explain these interregional differences in R&D (Section 5). By introducing variables that describe cooperation with other actors, we finally test for the contribution of R&D cooperation in the diffusion of such spillovers (Section 6). In the last section (Section 7), we draw some conclusions for policy and for further research.

2. Data

The main data source of our analysis is information gathered by postal questionnaires from manufacturing enterprises in three German regions.[5] We expected these regions to be characterized by considerable differences with regard to the local conditions for innovation activities. The regions were:

- Baden, the western part of the state of Baden-Wuerttemberg, a prosperous region characterized by considerably above-average performance with regard to innovation. According to conventional wisdom, transfer institutions and cooperative relationships are well developed in this region (Cooke, 1996; Heidenreich and Krauss, 1998).
- The region Hanover–Brunswick–Goettingen in the state of Lower Saxony. The region has a high share of employment in large-scale manufacturing (e.g. automobiles, steel) and the proportion of employment in new innovative industries is comparatively low. Despite various policy attempts to improve innovation performance in this region, its innovation system is said to have considerable deficiencies (Schasse, 1995).
- Saxony, one of the new German states, until 1990 under a socialist regime. The region has a long tradition in manufacturing, particularly in the mechanical engineering industry. Due to the breakdown of the manufacturing sector after the fall of the Iron Curtain, small establishments predominate. Large establishments are rather rare in this region.

The questionnaire was sent to all enterprises with ten or more employees. The resulting data set contains rather detailed information about the innovation input and output of the enterprises. Additional information collected included the number of cooperative relationships with other private sector firms and public research institutions. For the three German regions, our data set comprises more than 1800 cases constituting a quite representative random sample of the entire population of manufacturing enterprises.[6] Analyzing differences between the regions with regard to innovation activities of manufacturing enterprises (Franke, 2002; Fritsch et al., 1999; Fritsch, 2000), we find Baden in first place, Hanover in the second position and Saxony ranked third lagging somewhat

[4] This constitutes a main hypothesis in the literature on "industrial districts" (for an overview, see Porter, 1998 and the contributions in Pyke et al., 1990), "innovation networks" (Camagni, 1991; Grabher, 1993) and "innovative milieu" (Aydalot and Keeble, 1988; Crevoisier and Maillat, 1991; Ratti et al., 1997). The role of R&D cooperation for innovation processes has also been intensively discussed in the competition policy literature (cf. Jorde and Teece, 1990; Katz and Ordover, 1990).

[5] Because the focus of the questions was on innovation, one could expect a relatively low representation by non-innovative enterprises in the data. A non-response analysis for the survey taken in Saxony revealed that there was no such bias with respect to the share of innovative enterprises. However, the innovative enterprises in the sample tended to have a slightly higher share of R&D personnel than the entire population of enterprises. The survey was conducted between September and December of 1995.

[6] The response rate amounted to 17.8% in Baden, 20.6% in the Hanover region and 27.7% in Saxony. The sample is characterized by a relatively high share of small enterprises that do not belong to a larger multi-plant firm. The share of enterprises with less than 20 employees in 1995 amounted to 24% and the share of enterprises with 200 and more employees in 1995 made about 13%.

behind. Other data used in the analysis comes from a complimentary postal inquiry of business oriented services suppliers that was conducted in the same regions at about the same time[7] and from official statistics.[8]

3. Estimation procedure

For an empirical analysis of interregional differences of innovation activities, the estimation of a knowledge-production function appears to be an adequate approach.[9] The knowledge-production function expresses the relationship between R&D input and R&D output within the overall framework of a production function (see Griliches, 1979). The basic assumption is that the output of the innovation process constitutes the result of R&D capital or investment respectively, that is

$$\text{R\&D output} = f(\text{R\&D input}) \tag{1}$$

Adopting the Cobb–Douglas form of a production function, the basic relationship can be written as

$$\text{R\&D output} = a(\text{R\&D input})^{b} \tag{2}$$

where the term a represents a constant factor and b the elasticity by which R&D output varies in relation to the input to the R&D process. If the elasticity equals 1, a 100% increase in R&D expenditure would lead to a doubling of innovative output. An elasticity value lower than 1 indicates that innovative output does not increase in proportion to rising R&D input. Taking the natural logarithms of both sides, we get

$$\ln(\text{R\&D output}) = \ln a + b(\ln(\text{R\&D input})) \tag{3}$$

This equation can be estimated by applying standard regression methods. We choose R&D expenditure here as a measure of innovative input that includes inputs purchased from other firms. The output elasticity of R&D expenditure can be interpreted as an indicator for the productivity of the input to the innovation process and, hence, for the efficiency of the innovation system in a certain region. In particular, this elasticity should be relatively high if a location is characterized by good availability of inputs to the R&D process, an intense division of innovative labor and pronounced knowledge spillovers between the actors in the region, whether they are public research institutions or private sector firms.[10]

Much less clear is the interpretation of the resulting constant term. If the number of innovations is used as an indicator for the success of R&D activities, the constant term denotes how many innovations have been generated without a corresponding R&D input on behalf of the enterprise during the period for which R&D input was measured. Assuming that the generation of innovations necessitates some R&D input, there are two possible explanations for the existence of a positive constant term. One explanation would be that the innovation is not based on current input but on an existing stock of 'old knowledge,' i.e. that the respective input had been spent in earlier periods. The second possible explanation could be that the innovation was completely the result of knowledge spillovers from other sources without any R&D effort on the part of the firm that claimed to have generated it. In the latter case, the constant term of the knowledge-production function describes innovations that is 'falling from heaven' on a particular economic sector or region.

We use two forms of indicators for the output of R&D activities. Both are based on the information about an enterprise's patenting activity. The first indicator is whether or not an enterprise had registered an innovation for patenting in the preceding three years. Logit analysis was applied to estimate the models for this dichotomous variable.[11] A second type of model uses information about the number of innovations registered for patenting as a dependent variable. Assuming that a Poisson-like process generates the number of patents, Poisson-regression analysis may be applied as the estimation method. However, we used negative-binomial (negbin) regression because it

[7] The data have been raised in the first stage of the European Regional Innovation Survey (ERIS) project. For an overview of the project design, the different inquiries carried out as well as the main aims and hypotheses, see Sternberg (2000).

[8] For a more detailed description of the data, see Franke (2002).

[9] For some other approaches to analyzing interregional differences of R&D activities, see Fritsch (2000).

[10] See Fritsch (2002) for a more detailed treatment of this issue.

[11] The variable assumes the value "1" if the enterprise has registered at least one innovation for patenting and it is ''0" if no innovation has been registered for patenting.

is based on somewhat more general assumptions than Poisson regression.[12] The estimations, which included the number of patents as an explanatory variable, were restricted to those enterprises that had registered at least one innovation for patenting during the preceding 3 years. This avoids the problem of having 'too many' zero-values in the model, which would imply a violation of the distribution assumptions of the estimation procedure. Taken together, both models constitute a count-data-hurdle model of patenting behavior. The logit estimation analyzes the impact of diverse factors to overcome the 'hurdle' to participate in the patenting process. Based on that, the negbin-regression model investigates the factors that determine the number of patents applied for.

4. Regional differences in the production of knowledge

In the empirical analysis, we investigated first if any differences exist with regard to the efficiency of innovation activities between the three regions under inspection. Among the explanatory variables that were included in the model (model I in Table 1), an enterprise's R&D expenditure can be expected to have a relatively strong impact on innovation output.[13] In the negbin-part of the model, we also included the logarithm of a firm's own R&D expenditure in its squared form, which proved to have a statistically significant influence. The significant impact of the squared R&D expenditure indicates that output elasticity with regard to R&D input is not constant but rises slightly with increased R&D activity. No such significant impact could be found in the logit part of the model, so the squared variable was omitted here. An index for the degree of agglomeration in the region where the enterprise is located was supposed to control for all kinds of regional factors that are associated with population density and the rank in the spatial hierarchy (e.g. price levels, agglomeration economies and diseconomies).[14] The agglomeration index is included on the level of the 13 planning regions that make up the three regions under analysis.[15] The Herfindahl index measures the degree of market concentration in the respective industry and controls for industry-specific effects.[16] We attempt to measure two kinds of differences in the knowledge-production functions in the regions under inspection. Dichotomous dummy variables for a location in the West German regions of Baden or Hanover[17] indicate differences with regard to the constant term of the knowledge-production function. Estimates of the impact of R&D expenditure interacting with the regional dummies are supposed to reflect distinctive slopes of the function and, therefore, to show differences with regard to the efficiency of R&D activities.

Looking at the coefficients for the regional dummy variables, which are meant to indicate differences in the constant term of the knowledge-production function, we find significant positive signs for the two West German regions Baden and Hanover. There are at least two interpretations for this result. One interpretation is that there are higher levels of spillover in these regions than in Saxony. Another explanation

[12] Negative binomial regression allows for a greater variance of observations than is assumed for a Poisson process. For a more detailed description of these estimation methods, see Greene (1997, pp. 931–939).

[13] The data on R&D expenditure and the patents generated relate to the 1992–1995 period.

[14] This index is a classification of German regions into seven categories according to their degree of congestion and their position in the spatial hierarchy. A relatively high value of this index indicates a correspondingly high degree of agglomeration. For a detailed description of this index, see Bundesamt für Bauwesen und Raumordnung (1998).

[15] Planning regions ("Raumordnungsregionen") are widely used for regional analyses in Germany. They are functional regions that consist of at least one center and the respective periphery. Planning regions are somewhat larger than labor market regions. According to the current definition, there are 94 such planning regions in Germany. Baden consists of three planning regions while the Hanover region and Saxony both comprise five planning regions.

[16] The higher the value of the Herfindahl index, the more concentrated the supply side in the respective industry. The data were taken from Monopolkommission (1996). Including industry dummies together with the Herfindahl index reveals a high degree of multicollinearity between these variables, so that only one type of industry-specific variable should be incorporated in the model. We choose the Herfindahl index here because estimations based on this variable led to better results than models with dummy variables for the different industries.

[17] The regional dummy variables assume the value "1" if an enterprise is located in the respective region and are otherwise "0." The enterprises located in Saxony constituted the reference group here.

Table 1
Models with regional dummies and spillover variables

	Model I		Model II	
	Logit	Negbin	Logit	Negbin
Constant	−0.79[a] (4.03)	1.43[a] (11.03)	−10.87[a] (3.20)	−3.71 (1.63)
ln R&D expenditure	0.42[a] (5.43)	0.49[a] (8.18)	0.49[a] (5.03)	0.47[a] (7.82)
(ln R&D expenditure)^2	–	0.06[a] (3.63)	–	0.06[a] (3.57)
Regional spillovers				
ln R&D expenditure in the same industry	–	–	0.19[a] (2.66)	0.08 (1.52)
ln R&D expenditure in business related services	–	–	0.28[c] (1.66)	0.19[c] (1.68)
ln external funds attracted by public research institutions	–	–	0.03[b] (1.96)	0.002 (0.12)
Regional dummies				
Baden	0.82[a] (3.89)	0.25[b] (2.05)	0.52[b] (2.16)	0.09 (0.67)
Hanover	0.61[a] (3.25)	0.21[c] (1.76)	0.11 (0.42)	−0.004 (0.02)
Dummy Baden[c] × log R&D expenditure	0.27[c] (1.95)	−0.01 (0.14)	0.27[c] (1.89)	−0.01 (0.14)
Dummy Hanover[c] × log R&D expenditure	−0.05 (0.42)	−0.12 (1.60)	−0.03 (0.22)	−0.13[c] (1.71)
Agglomeration index	−0.03 (0.58)	0.02 (0.68)	−0.25[a] (2.63)	−0.02 (0.31)
Herfindahl index	0.002 (1.63)	−0.001[b] (2.42)	0.001 (1.27)	−0.002[a] (2.74)
Alpha	–	0.53[a] (10.37)	–	0.52[a] (10.29)
Number of cases	961	349	961	349
Pseudo R^2	0.12	0.11	0.13	0.11
χ^2	151	224	166	230

Asymptotic *t*-values of the coefficients in parentheses.
[a] Statistically significant at the 1% level.
[b] Statistically significant at the 5% level.
[c] Statistically significant at the 10% level.

could be that firms in Hanover and Baden are better able to exploit their longer existing knowledge stock. Both interpretations are quite plausible. Given that the innovation system in the East German region of Saxony had to be more or less completely reorganized during the last ten years, one may expect the level of spillovers to be significantly lower there. Even more important, a considerable part of the knowledge stock generated under the socialist regime had to be depreciated because it was no longer useful under the conditions of a market system (cf. Fritsch and Werker, 1999). The coefficients of the regional dummy variables interacting with R&D expenditure in model I indicate a statistically significant steeper slope of the knowledge-production function and, therefore, of the efficiency of innovation activities in Baden as compared to Saxony. In model II, the coefficient for R&D expenditure interacting with the regional dummy variable for location in Hanover also proves to be statistically significant with a negative sign, thus indicating a lower productivity of R&D activities when compared to Saxony. While the agglomeration index does not have a statistically significant influence in model I, we find that a high degree of market concentration as measured by the Herfindahl index tends to have a negative impact on the number of patents generated. Because firms in concentrated industries tend to be large, this negative relationship of market concentration on patenting could be a result of the relatively low ratio of innovation output to input in large firms that has been found in many empirical studies.[18]

5. Regional spillovers and innovation activities

In the second step of the analysis, we investigated to what degree the differences of the efficiency of innovation activities between regions may be explained by knowledge spillovers from other sources located

[18] For an overview of the evidence and an explanation of this phenomenon see Cohen and Klepper (1996).

in the respective region. For that reason, variables for the amount of R&D expenditures of other actors located in the region were added to the set of explanatory variables (model II in Table 1). As in the agglomeration index, we use the 13 planning regions of our sample as a spatial framework for calculating the spillover variables. Because we have only information about innovation activities in some of those surrounding regions that are included in our sample, analysis had to be restricted to spillovers from R&D within the same planning region.[19] The fact that our data does not allow us to account for possible knowledge spillovers from adjacent regions need not be regarded as a very serious deficiency. The existent empirical evidence clearly shows that R&D spillovers tend to be limited to areas in close vicinity to the respective source.[20] Accordingly, our results indicate that intra-regional spillovers are sufficient to explain differences in local conditions for R&D activities (see below).

With regard to the R&D expenditures of other manufacturing firms in the region, we found a statistically significant impact only for the resources spent by firms in the same industry. Innovation activities in other manufacturing industries seemed to be unimportant as a source of knowledge spillovers.[21] This could explain the results of numerous empirical analyses which identified a tendency for innovative activity in the same technological field or industry to be clustered in space (e.g. Audretsch and Feldman, 1996; Baptista and Swann, 1999; Porter, 1998). Obviously, spatial clustering is mainly a result of localization economies, i.e. spatial concentration of similar activities, while spatial proximity to firms in other manufacturing industries turns out to be less important. Because R&D activities in other industries proved to be insignificant, the respective variables were not included in the model. The coefficient for the impact of R&D expenditure in the business-related service sector[22] on the innovation output of the manufacturing firms has the expected positive sign but is not statistically significant in model II. It proves, however, to have a significant impact in those models in which the regional dummy variables were omitted (models III and IV in Table 2).

In measuring knowledge spillovers generated by public research institutions,[23] it would be plausible to assume that their entire budget is in some sense related to R&D. However, we found a statistically significant impact for R&D activities in public research institutions only when the outside funding they had attracted was taken as the measure. Because outside funding is in most cases allocated by some kind of competitive process, obtaining such funding indicates a certain minimum quality of the respective research. The finding of a significant knowledge spillover effect for public research institutions as measured by the outside funding which they managed to attract suggests that it is not the mere amount of resources spent, but the quality of this R&D activity that is of crucial importance for its relevance as a source of spillovers. For these reasons, we selected this outside funding as

[19] However, if we include the information that we have about R&D activities in some of the adjacent planning regions into the model, the respective coefficients are in no way statistically significant.

[20] C.f. Acs et al. (1992), Audretsch and Feldman (1996), Jaffe et al. (1993) and Anselin et al. (1997).

[21] The amount of resources devoted to innovation activities in a manufacturing industry per planning region was estimated on the basis of the data on R&D expenditure raised by our questionnaire and information about the total number of enterprises belonging to the respective industry in the region. Data on the total population of enterprises of different industries in the regions was taken from the German Social Insurance Statistics. This estimation was carried out for seven groups of manufacturing industries. These industry groups were "food, beverages and tobacco," "textile, clothing and leather," "wood, paper, printing, furniture," "mineral oil, chemicals, rubber, plastics, ceramics and glass," "metal products and recycling," "vehicles and mechanical engineering" and "data processing, electrical and electronic equipment, optical instruments." Case numbers of firms in our sample did not allow for a more disaggregated industry classification.

[22] R&D expenditure in the business-related service-sector was estimated on the basis of information gathered by a corresponding postal inquiry in this sector using information on the total number of establishments in this sector in the respective region as provided by Social Insurance Statistics. Business related services here comprised tax advisers, lawyers, accountants, data processing services, software developers, business consultants, market research, engineering & planning bureaus, check- and test-labs as well as architects. The inquiry on business service firms was carried out shortly after the inquiry on manufacturing firms. R&D expenditure of business service firms relates to the same time-period (1993–1995) as that for the manufacturing enterprises.

[23] The public research institutions comprise the universities, the *Fachhochschulen* (universities with a particular focus on applied studies in engineering, business and other subject areas) and publicly funded non-university research organizations such as the institutes of the Max-Planck and the Fraunhofer Society.

Table 2
Models with spillover and with cooperation variables

	Model III		Model IV	
	Logit	Negbin	Logit	Negbin
Constant	−12.64[a] (5.06)	−3.56[b] (2.08)	−13.28[a] (5.18)	−4.04[b] (2.33)
ln R&D expenditure	0.44[a] (8.50)	0.41[a] (12.04)	0.38[a] (6.88)	0.39[a] (10.30)
(ln R&D expenditure)^2	–	0.06[a] (3.32)	–	0.06[a] (3.44)
Regional spillovers				
ln R&D expenditures in the same industry	0.22[a] (3.05)	0.09[c] (1.81)	0.19[a] (2.68)	0.08 (1.64)
ln R&D expenditure in business related services	0.36[a] (2.75)	0.17[b] (2.04)	0.38[a] (2.84)	0.20[b] (2.35)
ln external funds attracted by public research institutions	0.03[b] (1.98)	−0.003 (0.34)	0.03[b] (2.15)	−0.004 (0.19)
Number of cooperative relationships with				
Customers	–	–	−0.0003 (0.49)	−0.001[b] (2.33)
Manufacturing suppliers	–	–	−0.001 (0.42)	0.0001 (0.12)
“Other” firms	–	–	0.02[c] (1.94)	−0.004 (0.94)
Cooperation with (yes/no)				
Service firms	–	–	0.35 (1.39)	0.003 (0.02)
Public research institutions	–	–	0.52[a] (3.26)	0.15 (1.38)
Agglomeration index	−0.27[a] (3.51)	−0.01 (0.12)	−0.32[a] (3.95)	−0.01 (0.24)
Herfindahl index	0.001 (1.44)	−0.002[a] (2.85)	0.001 (1.47)	−0.002[a] (2.81)
Alpha	–	0.53[a] (10.29)	–	0.52[a] (10.17)
Number of cases	961	349	955	347
Pseudo R^2	0.13	0.11	0.14	0.12
χ^2	158	225	174	232

Asymptotic *t*-values of the coefficients in parentheses.
[a] Statistically significant at the 1% level.
[b] Statistically significant at the 5% level.
[c] Statistically significant at the 10% level.

a measure of the R&D activities carried out by public research institutions.[24]

When we include these indicators for regional knowledge spillovers in the model (see model II in Table 1), they prove to have some significant impact. In contrast, the values of the coefficients for the regional dummies decrease considerably and become more or less insignificant. This clearly indicates that the spillovers generated by the innovation activities of other firms or by public research institutions in the region may explain a large part of the regional difference in the conditions for R&D that we find in our data. Remarkably, the coefficients of the interaction variables, which supposedly measure interregional differences in the slope of the knowledge-production function, remain largely unaffected by the introduction of the spillover indicators. This suggests that spillovers lead to a higher level of innovation output but do not increase the productivity of R&D activities. Because of the relatively high correlation between the regional dummy variables and the spillover variables, the dummies were omitted in the subsequent analysis in order to avoid multi-collinearity problems. We also excluded the regional dummy variables interacting with a firm’s R&D expenditure due to their low level of significance. If the model is estimated without these regional variables (cf. model III in Table 2), the coefficients for the spillovers from innovation activity in the same industry and in service firms located in the respective planning region prove to have a significant impact in both parts of the model. On the other hand, the spillovers generated by public research institutions seem to affect only the propensity to patent

[24] The data relates to the year 1995 and was provided on the internet by the German Federal Ministry of Education and Research (“Bundesministerium für Bildung und Forschung”) (“Forschungslandkarte Deutschland,” http://www.forschung.bmbf.de).

but not the number of innovations that have been registered for patenting. Comparing the estimates of model I and model III, we find that the share of explained variance as measured by the Pseudo R^2 is more or less identical. This suggests that the regional differences in R&D activities may be almost completely explained by the amount of R&D conducted by actors located in the same region. If R&D activities in adjacent planning regions, which could not be considered here, had made a substantial contribution, the share of explained variance in model III should have been smaller than in model I. That this is not the case indicates that R&D conducted outside the region is largely irrelevant for knowledge spillovers and as an explanation for interregional differences in innovation activities.

It is quite remarkable that the agglomeration index, which proved to be insignificant in model I, becomes statistically significant with a negative sign for the first part of the model when the spillover variables are included (models II and III). This suggests that, apart from the existence of knowledge spillover generated by other actors in the region, location in a center has a negative impact on the propensity to patent and has no effect on the number of patents. Or to put it differently: what makes the center an attractive place for innovation activities is the knowledge spillovers from other actors located in that region.[25]

6. How important is R&D cooperation as a medium for knowledge spillovers?

The questionnaire that was used for gathering the bulk of our data comprised a number of questions that asked for comprehensive information about the existence of cooperative relationships with different types of partners. These types of cooperation partners were:

- customers;
- manufacturing suppliers;
- suppliers of business services;
- "other" firms (i.e. non-vertically related businesses, particularly including competitors); and
- publicly funded research institutions.

In a first question, respondents were asked whether, in the preceding three years, their enterprise had maintained cooperative relationships with customers, manufacturing suppliers, publicly funded research institutions or with "other" firms. Cooperation with suppliers or customers was defined as a relationship that went beyond "normal" business interaction. With regard to "other" firms, suppliers of business services and publicly funded research institutions, every relationship was assumed to be cooperative. In a subsequent question, four categories of cooperative relationships that are in some way related to innovation activities were defined more concretely.[26] Although we cannot completely rule out that respondents reported cooperative relationships having nothing to do with innovation activities,[27] the dominant share of these relationships represents R&D cooperation. The data set also provides information on the number of cooperative relationships with the different types of partner in certain regional categories ("within the same region," "outside the region," "abroad"). The responses to these questions revealed that R&D cooperation is obviously a widespread phenomenon. A little more than 60% of the enterprises in our sample maintained cooperative relationships with their customers, nearly 49% had cooperative relationships with their manufacturing suppliers, 85% with business

[25] We found no significant impact for interaction between R&D expenditures of other actors in the region and the agglomeration index when such variables were included in the model. This also suggests that the density of actors in a region, as such, has no impact on the intensity of the knowledge spillovers.

[26] For cooperative relationships with customers and manufacturing suppliers these categories were "casual contact for information purposes," "organized exchange of information and experiences," "involvement in planning and operation of projects" and "pilot use of an innovation." For the assessment of cooperative relationships with "other" firms, the final two categories were substituted by "joint use of equipment or laboratories" and "joint R&D projects." With regard to co-operation with publicly funded research institutions, the categories for the type of relationship were "use of equipment or laboratories," "research contracts," "joint R&D projects" and "collaboration with regard to theses." For relationships with suppliers of business related services, no information about the type of relationship was raised by the questionnaire.

[27] This may be particularly the case for relationships with suppliers of business related services where no definitions of certain types of R&D cooperation have been given in the questionnaire. However, to decide how much a certain relationship is in some way concerned with innovation activities may be quite hard or impossible, even for managers of the respective firms.

oriented service firms, 33% with public research institutions and about 31% with "other" enterprises. The cooperating partners tended to be concentrated in the same region, particularly in the case of public research institutions and "other" firms (for a detailed analysis, see Fritsch, 2001; Fritsch and Lukas, 2001).

Based on this data, a range of indicators employing different definitions of what constitutes a "cooperation" can be constructed. In testing numerous versions of the cooperation indicators, we did not find any major discrepancy in our estimation results. The statistical explanation for this result is the high degree of correlation among these alternative indicators, so that the concrete definition of cooperation is of minor importance for the results of the analysis. Therefore, we used the broadest definition, as given in the first question of our questionnaire, in which cooperation with suppliers and customers was defined as a relationship that in character went beyond "normal" business interaction. We also do not restrict our measure of R&D cooperation to relationships among actors in the same region because this has no effect on the results. According to our data, establishments that maintain cooperative relationships with a partner outside their own region tend to have cooperation partners in their own region, so that cooperation nearly always includes relationships with partners within the region.

This data on R&D cooperation offers the opportunity for testing the role that cooperative relationships play in the diffusion of knowledge spillovers. If R&D cooperation constitutes an important medium of knowledge spillover, then the impact of the spillover variables in our estimation should decline considerably when variables for R&D cooperation are introduced. Accordingly, in model IV (Table 2) we included variables for the existence of R&D cooperation with a certain type of partner or—if this information was available—for the number of such relationships.[28] The results for these variables and the changes in the spillover variables reveal the importance of cooperation with different types of partners in enabling knowledge spillovers to come about.[29]

Comparing the results of models III and IV in Table 2, we find that the coefficients of the spillover variable remain largely unaffected when the variables for R&D cooperation are added. Remarkably, some of these spillover variables even increase in value and significance. The cooperation variables prove to be largely insignificant. One exception is the indicator for cooperative relationships with public research institutions, which is statistically significant with the expected sign in the logit estimation for the propensity to register at least one innovation for patenting. This may be interpreted as indicating that a relationship with public research institutions is conducive to R&D activities, enabling enterprises to achieve a level of innovation sufficient to qualify for patenting. For cooperative relationships with all other types of actors, the estimates provide no indication for a significant impact on the amount of R&D spillovers received. Because the spillover variables and the indicators for R&D cooperation are largely unrelated statistically, the limited impact of the cooperation variables does not increase noticeably if the spillover variables are omitted.

7. Interpretation and conclusion

From our analysis, we arrived at three main conclusions. First, we could demonstrate that significant differences between regions exist with regard to the productivity of R&D activities. Second, we found that these interregional differences can be more or less completely explained by R&D spillovers from other R&D activities by actors located in the same region. And third, our assessment of the importance of R&D cooperation for the spread of such spillovers clearly suggests that R&D cooperation plays only a minor role as a medium for knowledge spillovers. This conclusion is consistent with other analyses of the underlying data set which show that regions where private

[28] With regard to R&D cooperation with suppliers of business-oriented services, we only know if such a relationship exists by how these relationships have been assessed in the questionnaire. Because we also have no information on the number of cooperative relationships with public research institutions in Hanover, the respective variable only indicates if at least one such relationship existed (value = "1") or not (value = "0").

[29] The data set provides some information on the location of co-operation partners. A closer inspection of this data shows that in almost all cases at least some of the co-operation partners are located in the same region. There is virtually no case of a cooperative relationship, where not at least one local partner is involved (cf. Fritsch, 2001).

establishments had a relatively high propensity to cooperate on R&D tended not to have a correspondingly high efficiency in their innovation processes (Fritsch, 2001, 2004). Apparently, cooperative relationships, as such, do not lead to those kinds of knowledge spillovers that are important for the efficiency of innovation activities. As to the question of whether only certain types of cooperative relationships act as a medium for relevant spillovers, we must admit that we have failed to identify the characteristics of such relationships in the various approaches we took in analyzing the data. We can also not completely rule out that the modes of information exchange that are relevant for the spread of spillovers are rather 'loose' or informal in character, below the level of a cooperative relationship as defined in the questionnaire used in our investigation (cf. Fritsch and Lukas, 2001). However, since the definition of a cooperative relationship used in the inquiry was already rather broad, such low-level forms of cooperation may be very hard to assess empirically. If there are so-called soft factors at work here, they may be so soft that they are 'atmospheric' in nature and, therefore, perhaps beyond the scope of the type of analysis that has been reported here.

Yet, if we have concluded correctly that R&D cooperation is a relatively unimportant medium for knowledge spillover, the question of how spillovers come about remains unanswered. This is obviously a very important issue since we were able to show that the knowledge spillovers stemming from other actors in the respective region can largely explain the interregional differences in R&D activities. However, we have to conclude that we still cannot explain how the majority of innovation-relevant knowledge spillover occurs within a region.

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