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HETEROGENEITY IN R&D COOPERATION STRATEGIES

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ABSTRACT

Heterogeneity in R&D Cooperation Strategies*

We explore heterogeneities in the determinants of innovating firms' decisions to engage in R&D cooperation, differentiating between three types of cooperation partners: suppliers and customers (vertical cooperation), competitors (horizontal cooperation), and universities and research laboratories (institutional cooperation). We use panel data on innovating firms drawn from two Dutch Community Innovation Surveys in 1996 and 1998. Applying a system method estimator for probit equations shows significantly positive correlations between the different cooperation decisions, suggesting that R&D cooperation strategies are complements rather than substitutes. We find that the determinants of R&D cooperation differ significantly and substantially across cooperation types. As suggested by industrial organization theory of R&D cooperation, the effects of spillovers depend on their source: while horizontal spillovers have ambiguous effects on horizontal cooperation, vertical spillovers positively impact vertical cooperation and institutional spillovers significantly impact all types of cooperation. The results are largely robust to correction for potential simultaneity bias.

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1. Introduction

The growing role of R&D collaboration in firms' innovative activities (Hagedoorn, 2002) has spurned research into the determinants of such R&D cooperation and the performance of cooperative R&D. Two major strands of theoretical literature can be distinguished. The Industrial Organization (IO) literature has extensively examined the incentives and performance effects of R&D cooperation among competing firms focusing on the role of R&D spillovers and appropriability. Theoretical contributions in the management literature have stressed that R&D collaboration stems from the search for complementary know-how between partner firms (e.g. Kogut, 1988; Das and Teng 2000). Empirical work on R&D cooperation has utilized micro-level survey data, such as from the European Community Innovation Surveys (CIS). The main determinant of R&D cooperation considered in these empirical studies are firm size and R&D intensity (Becker and Dietz, 2002; Kleinknecht and Reijnen, 1992; Kaiser, 2002; Veugelers, 1997).

Most of the existing literature does not distinguish R&D cooperation by type of partner (e.g. competing firms, suppliers, clients, universities) but aggregated over R&D cooperation types. Recent exceptions include Kaiser (2002), who distinguished between vertical cooperation and a mix of other R&D partnerships in analyzing cooperative R&D by German service firms. Fritsch and Lukas (2001) differentiate cooperation by type of partner to focus on the impact of firm size and R&D intensity on the propensity to cooperate among German manufacturing firms. Cassiman and Veugelers (2002), using 1994 data on Belgian firms distinguished between university-firm cooperation and cooperation with vertically related partners, but did not consider cooperation with competitors. Related work by Mohnen & Hoareau (2002) and Veugelers and Cassiman (2003) has restricted the analysis to university-firm cooperation in R&D.

In this paper we explicitly consider heterogeneity in R&D cooperation. We explore the differences in the determinants of innovating firms' decisions to establish three types of cooperation: vertical (with suppliers or customers), horizontal (with competitors) and research institutional cooperation (with universities and research institutes). We take into account a broad set of possible explanatory variables and more particularly different types of spillovers, a central focus in the IO literature. Furthermore, while previous studies have investigated the propensity to establish different R&D partnerships in separate models, we allow for possible complementarities between R&D cooperation strategies, by applying a system method of estimation for limited dependent variables. In addition, previous studies only had a cross-section data at their disposal and hence have grappled with the problem of a simultaneous relationship between R&D cooperation and R&D intensity and spillovers. We are able to reduce simultaneity bias by employing lagged explanatory variables utilizing panel data from Dutch CIS surveys in 1996 and 1998. We further check the robustness of the results to potential simultaneity bias by estimating a model limiting the analysis to firms who had no R&D cooperation in 1996, examining the determinants of the propensity to establish new cooperation agreements in 1998.

The remainder of this paper is organized as follows. The next section provides a brief overview of the theoretical and empirical literature on R&D cooperation. Section 3 explains the empirical model used and describes the dataset. Section 4 presents the results and Section 5 concludes.

2. R&D Cooperation: theoretical and empirical models

Theoretical Models

Models that seek to answer the questions of why and what kinds of firms seek to perform joint research activities are grounded in several theoretical approaches. The management literature typically analyzes cooperation from a transaction costs and resource-based framework (Tyler & Steensma, 1995). The transaction cost approach describes alliances as a hybrid form of organization combining aspects of hierarchical transactions within the firm and arm's-length transactions in the market place. Cooperation may reduce transaction costs through a better control and monitoring of technology transfer than on arm's length markets, while the inherent reciprocal relationship and "hostage" exchange between partners with complementary capabilities can minimize opportunism (e.g. Pisano, 1990; Hennart, 1998). The resource-based view of the firm suggests that the rationale for partnerships is the value-creation potential of pooling together firms resource bases. Cooperation is viewed as a mechanism to maximize firm value through effectively combining the resources of the partners by exploiting complementarities (Kogut, 1988; Hagedoorn, 1993; Das and Teng 2000; Hagedoorn, Link and Vonortas 2000).

The Industrial Organization (I.O.) literature has focused on the relationship between spillovers and R&D cooperation between competing firms (horizontal cooperation). When anticipated, voluntary or involuntary transfers of know-how complicate R&D strategies in a non-trivial way. This is the case for non-cooperative R&D[1] and a fortiori for cooperative R&D strategies (e.g. Spence, 1984; Katz, 1986; d'Aspremont & Jacquemin, 1988; De Bondt & Veugelers, 1991; Kamien et al., 1992; Suzumura, 1992; Vonortas, 1994; Leahy & Neary, 1997 and Katsoulacos & Ulph, 1998). A first finding in these models is that investment in R&D when firms cooperate is increasing in the level of the spillover. A second finding across the various models is that when spillovers are high enough, i.e. above a critical level, cooperation in R&D will result in higher R&D investment compared to a

[1] De Bondt (1996) provides an overview of the impact of spillovers on non-cooperative R&D investment levels. Spence (1984) and Kamien et al (1992) model spillovers in R&D inputs where they become substitutes to own R&D. d'Aspremont & Jacquemin (1988) model spillovers on R&D output, where they increase the efficiency of own R&D and hence complement own R&D. See Amir (2000) for a discussion of the two types of models. Although spillovers increase the stock of effective knowledge and hence have a market expansion or cost reduction effect, large spillovers typically have a disincentive effect on the firm's level of non-cooperative R&D. This disincentive effect is demonstrated most clearly in strategic two-stage models where firms take into account that whenever knowledge leaks out to competing firms, this will have a negative impact on their own profitability, thus reducing the attractiveness of investing in R&D. The nature of product market competition critically shapes this disincentive effect, with the critical spillover level depending on whether firms are producing substitutes or complements.

situation of non-cooperating firms. Cooperation allows the firms to overcome the disincentive effect from the positive externality that outgoing spillovers create on rival firms. When goods are substitutes, the level of product differentiation and the number of rivals are important parameters that determine the critical spillover level (De Bondt et al, 1992; Röller et al, 1997) [2]. Similarly, inter-industry cooperation is more likely to boost R&D investments as compared to intra-industry co-operation (Steurs, 1995). Thirdly, these models find that R&D-cooperation always increases the firm profitability. Furthermore, spillovers increase the profitability of R&D cooperation and once spillovers are sufficiently high, further increases in spillovers make R&D cooperation more attractive as compared to non-cooperative R&D (De Bondt & Veugelers, 1991). These models thus predict that spillovers are an important positive driver of R&D cooperation. However, models considering free riding problems in joint ventures have found that higher spillovers also increase the incentives to cheat by partner firms and the profits from free-riding by outsiders to the cooperative agreement (Kesteloot & Veugelers, 1994; Eaton & Eswaran, 1997). R&D cooperation may still be profitable as long as firms are able to restrict outgoing spillovers and selectively share information with cooperation partners. These results emphasize a dual role of spillovers: outgoing spillovers may jeopardize the cooperative agreement while incoming spillovers increase the attractiveness of cooperation.

More recent IO models take into account that firms can attempt to manage spillovers, trying to minimize outgoing spillovers while at the same time maximizing the incoming spillovers (Cassiman et al. 2002; Martin 1999, Amir et al 2003). Minimizing outgoing spillovers can be accomplished through the use of effective legal and strategic protection measures. Firms can maximize incoming spillovers by voluntarily increasing the spillovers among cooperating partners, as in the research joint venture scenario of Kamien et al (1992) and Katsoulacos and Ulph (1998). In addition, firms can increase the effectiveness of incoming spillovers by investing in "absorptive capacity". Cohen and Levinthal (1989) argue that external knowledge is more effective for the innovation process when the firm engages in own R&D. The direct effect of higher absorptive capacity is thus to increase the effectiveness of incoming information. Finally, the choice of research approach by the firm influences the appropriability conditions it faces and the extent of incoming spillovers it enjoys. Kamien and Zang (2000) show that firms that cooperatively choose their R&D expenditures seek to maximize information flows (their incoming spillovers) by choosing broader research directions for the research joint venture.

IO theory has not paid much attention to R&D cooperation between non-competing firms (e.g. vertical cooperation) or R&D cooperation with public institutes (e.g. universities), but nevertheless stresses the importance of strength of competitive forces in horizontal cooperation. Different types of R&D cooperation partners, reflecting different regimes of competitive impact, are likely to be associated with a differential role of spillovers. One would expect that outgoing spillovers and appropriability concerns do not play a major role for cooperation with universities and public research

[2] When firms are marketing complementary goods, cooperation always results in higher R&D investment levels than non-cooperation, independent of the level of spillovers.

institutes. In contrast, appropriation is a key issue when dealing with more commercially sensitive information in horizontal cooperative agreements. In vertical cooperative agreements, commercially sensitive information may also leaks out indirectly to competitors through common suppliers or customers. Hence, only firms that can sufficiently protect their own proprietary information are expected to engage in this type of cooperation.

Summarizing the theoretical literature on spillovers and R&D cooperation, higher incoming spillovers increase the profitability and probability of cooperative R&D. The literature does not provide clear-cut predictions concerning the effect of outgoing spillovers. On the one hand, lower appropriability increases the scope for the internalization of information flows between firms through cooperation in R&D. On the other hand, lower appropriability increases free rider problems related to R&D investments, which reduce profitability and threaten the stability of cooperative agreements in R&D. Hence, when firms can control outgoing knowledge flows to competing firms, they are more likely to enter into R&D cooperation agreements. Important to note here is that the role of spillovers differs across type of cooperation partner, with appropriability concerns less important in vertical partnerships and university-firm cooperation than in horizontal R&D cooperation. Recent contributions further show that cooperation is not only influenced by exogenous spillovers but that cooperation at the same time improves knowledge transfers, leading to a simultaneous relationship between cooperation and incoming spillovers. A similar simultaneous relationship holds between cooperation and own R&D: while incoming knowledge through R&D partnerships impacts R&D investments, own R&D at the same time enhances the efficiency of cooperation through an enhanced absorptive capacity.

Empirical Research

There is an expanding empirical literature on the determinants of R&D cooperation. Given the difficulties to empirically assess the profitability of R&D cooperation, most studies indirectly use the frequency of occurrence of R&D cooperation to assess which characteristics are more beneficial to R&D cooperation. Product complementarities among partners are found to positively affect the likelihood of R&D cooperation (Röller et al., 1997). Sakakibara (1997) finds that access to complementary knowledge is one of the most important objectives of establishing government sponsored research cooperations in Japan. Tether (2000) seeks to identify key experiential features that characterize cooperating innovators based on the UK CIS survey. These features include R&D continuity and focus on higher-level innovations, which may suggest that growing complexity of technologies is a major driving force behind increased levels of cooperation. Tyler & Steensma (1995) find that the ability to share cost and risks is important for the success of R&D cooperation. Röller et al (1997) and Colombo and Garrone (1996) show a positive impact of firm size and R&D intensity of firms on R&D cooperation. This is reminiscent of the absorptive capacity idea that stresses the need to have in-house (technological) knowledge to optimally benefit from R&D cooperation. Fritsch and

Lukas (2001) confirm that firm size and R&D increase the propensity to cooperate among German manufacturing firms but find that the assignment within the firm of ‘gatekeepers’ monitoring and transmitting external information to relevant internal departments has an additional positive impact. This parallels the argument in Veugelers (1997) for including a permanent R&D variable as facilitator of appropriation of external knowledge. Similarly, Kleinknecht & van Reijnen (1992) find that having an own R&D department increases the probability of co-operation.

Another line of empirical research has focused on the taking into account this simultaneous relationship between R&D cooperation and in-house R&D activities. Colombo and Garrone (1996) test for Granger causality between a firm’s R&D intensity and its technology cooperative agreements and conclude that a simultaneous treatment of in house R&D intensity and technological co-operation indeed is the appropriate framework. Veugelers (1997), using a simultaneous equations framework, finds that Belgian firms spending more on internal R&D have a significantly higher probability of co-operation in R&D. Kaiser (2002) uses a similar framework and finds a positive but only weakly significant effect of cooperation on own R&D expenditures. Cassiman and Veugelers (2002) provide evidence of a strongly positive effect of internal R&D activities on cooperation in R&D, but after controlling for endogeneity through a two-step procedure, this effect became less significant. Becker and Dietz (2002) using a sample of German firms find that an aggregate count of R&D cooperation partnerships has a positive impact on R&D intensity and vice versa.

The relationship between R&D spillovers and R&D cooperation, although relatively well developed in theoretical models, has remained largely unexplored in empirical work. Cassiman & Veugelers (2002), study the relationship between R&D cooperation and the importance of public information sources (public spillovers) for firms’ innovation process. They find that incoming public spillovers as well as outgoing spillovers (lack of appropriability of internally generated knowledge) have important and separately identifiable effects on R&D cooperation. Firms with higher incoming public spillovers have a higher probability of cooperating in R&D, while high outgoing spillovers, i.e. low appropriability of the results of R&D, affect the decision to cooperate negatively.

Empirical work on R&D cooperation distinguishing between the type of cooperation partner has been limited and has singled out specific types of partnerships. Cassiman and Veugelers (2002), when analyzing the impact of spillovers on cooperation could only distinguish between research institutes and vertically related partners. They find that higher incoming public spillovers positively affect the probability of cooperating with research institutes and universities, but have no effect on cooperation with customers or suppliers. Increased appropriability of results of the innovation process (lower outgoing spillovers), however, increases the probability of cooperating with customers or suppliers, but is unrelated to cooperative agreements with research institutes. Furthermore, taking into account the simultaneous relationship between spillovers and R&D cooperation, they find evidence for a feedback effect of cooperation in R&D on incoming spillovers and appropriability. This effect, again, only becomes apparent when distinguishing between different types of cooperative R&D agreements. Cooperative agreements with universities increase the usefulness of the publicly available pool of public knowledge and the effectiveness of appropriation mechanisms for the firm's innovation process. Cooperative agreements with suppliers or customers, however, reduce the effectiveness of appropriability measures. Kaiser (2002) applies a nested logit framework to analyze firms' R&D cooperation in the German service sector. As a first step the model considers the decision whether or not to cooperate as a function of horizontal and vertical spillover pools, a size measure, and R&D intensity while also controlling for diversification of research, ownership and location of the firm. The second step choice concerns the type of cooperation, but here only a distinction could be made between vertical cooperation and a mixed category of university and competitor (horizontal) cooperation. The cooperation type model had weak explanatory power and measures of spillovers nor variables proxying the research base of the firm were found to have a significant impact.

3. Empirical model, data, and estimation method

We contribute to the growing empirical literature on R&D cooperation by estimating an multivariate probit model that jointly determines the decision to engage in all three types of R&D cooperation: horizontal, vertical and (research) institutional R&D partnerships. While the nested logit approach used in previous work (Kaiser, 2002) fails to account for the fact that firms can engage simultaneously in multiple cooperation agreements, the multivariate probit specification allows for systematic correlations between choices for the different cooperation types. Such correlations may be due to complementarities (positive correlation) or substitutability (negative correlation) between different cooperation types, e.g. the benefit of horizontal cooperation may be viewed to be larger if the firm also cooperates with universities or research institutes. Positive correlation also arises if there are unobservable firm-specific characteristics that affect several cooperation decisions but that are not easily captured by measurable proxies, such as the stock of tacit knowledge. The multivariate probit model takes these correlations into account, although it is not able to distinguish between the two sources of correlation. If correlation exists, the estimates of separate (probit) equations of the cooperation decisions are inefficient.

Our panel dataset is constructed from two consecutive CIS surveys performed by Statistics Netherlands in 1996 and 1998, which allows us to take past values of independent variables (in 1996) to explain the existence of R&D cooperation in 1998. This setup reduces simultaneity bias inherent to cross section analysis in a single year. The two main explanatory variables that are most likely to be simultaneously determined with the cooperation decision are incoming spillovers and R&D intensity: R&D investments may increase if cooperation makes own R&D activities more effective, and incoming spillovers should increase through cooperation in particular if disaggregated by source (vertical, horizontal or institutional), if only because of information sharing among partners. In our model setup using two year lagged variables such bias will be reduced, but it may not be completely neutralized. In case R&D partnerships last longer than 2-3 years, the R&D intensity and the importance of incoming spillovers in 1996 may still be partly impacted by possible R&D partnerships formed in or before 1996 that are still in existence in 1998. In order to further eliminate potential simultaneity bias, we will also look at a sub-sample of firms lacking any cooperative agreements in 1996. This allows us to test for the robustness of the impact of 1996 R&D intensity and incoming spillovers on the possible establishment of new R&D partnerships in the 1997-1998 period. Although this approach eliminates any potential feedback effect of cooperation on R&D and spillovers, its results need to be interpreted with care. Restricting the sample to firms without any type of R&D cooperation in 1996 among the set of innovating firms in 1996, excludes persistently cooperating firms –those firms that are most likely to engage in R&D partnerships. This selection itself creates a sample selection bias and reduces the number of observations substantially, which is likely to bias standard errors upwards. However, if tests on the lower tail of firms inclined to cooperate, replicate the results from the complete sample, we take this as a strong indication of the robustness of the results.

Data

The dataset used in this paper concerns data at the establishment level (in this paper referred to as 'firms') from the CIS surveys in the Netherlands in 1996 and 1998. The CIS survey in 1998 includes 6327 innovating Dutch establishments. A total of 1575 (24.9%) establishments have at least one R&D cooperation link. The partnerships are relatively well distributed among the different cooperation types: 908 (14.4%) of the establishments cooperate with customers/clients, 943 (14.9%) with suppliers, 686 (10.8%) with competitors, 574 (9.1%) with research institutes, and 510 (8.1%) with universities.[3] About 4.1% of the firms in the sample have 5 or 6 different types of cooperation partners, while 13.7% of the firms have 1 or 2 types of partners.

To create a panel data set, the 6327 innovating firms in 1998 are matched with the information on these firms in the 1996 survey: 2353 firms could be linked to the 1996 survey and were classified as innovating firms in that survey.[4] Due to missing values for some of the 1996 explanatory variables the number of observations used in the complete sample is 2156. The distribution of cases for the three equations by the dependent variable is presented in Tables 1 and 2. There were 609 firms with R&D cooperation of any type among the 2156 innovating firms in 1998. Vertical cooperation is most prominent, independent (204) or in combination with institutional cooperation (136). A total of 109 firms have cooperative agreements of all three types. The model testing the robustness of determinants or R&D cooperation by restricting the sample to firms with newly formed cooperative agreements or no R&D cooperation at all uses a smaller sample of 1488 firms, in which and the number of firms with cooperation in 1998 is substantially reduced to 269.

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[3] In addition, 577 (9.1%) cooperate with consultants. We ignore this type of cooperation in the empirical analysis because of its heterogeneous character and doubts whether linkages with consultants are genuine R&D efforts.

[4] Information on explanatory variables is only available in the survey if firms are classified as innovating firms. Since we did not correct for a possible sample selection bias on innovating firms, the results need to be interpreted as applicable to innovation active firms only.

Dependent and Independent Variables

The dependent variables of the model are three dummy variables: whether the firm was engaged in 1998 in an active R&D partnership with competitors (horizontal cooperation), suppliers and/or clients (vertical cooperation), or research institutes and/or universities (institutional cooperation). The model includes a range of explanatory variables based on our review of theoretical work and previous empirical models. Given our interest to explore the varying determinants of R&D cooperation between the types, we include each explanatory variable in all three equations to test whether some variable impacts cooperation of one type but not another. The descriptive statistics for the samples are presented in Table 1. A detailed description of the variables is provided in Appendix A and a correlation table in Appendix D.

We include firm-specific and type-specific direct measures of the importance of *incoming spillovers*.[5] The firms are asked in the CIS survey to rate the importance of various external sources of information for the firm's innovation activities. We include the average of scores of importance of information from suppliers and customers (*vertical incoming spillovers*), the score for information from competitors (*horizontal incoming spillovers*) and the average of scores of information from universities and research institutions (*institutional incoming spillovers*). We expect that R&D cooperation of a type is more likely if the information coming from the potential partners is more important[6].

An important shortcoming of the Dutch version of the CIS questionnaire is the lack of a question to construct a measure of firm-specific outgoing spillovers or appropriability. Instead we proxy outgoing spillovers at the industry level, by taking the average of horizontal spillovers of firms in the same industry. The variable *Industry outgoing spillovers* is constructed at the 2-digit industry level and measures the mean of average scores of information obtained from competitors and patents reported by all competing firms in the industry. If competitors in the industry report that they obtain important information from competitors and through published patents (filed among others by competitors), appropriability conditions in the industry are weak and this may negatively affect the propensity to cooperate. *Industry outgoing spillovers* is only expected to impact horizontal cooperation negatively since it only measures spillovers to same-industry competitors.

We include *R&D intensity*, and *R&D intensity squared*, allowing for a non-linear impact of R&D (measured as the number of R&D personnel over total personnel). Increasing levels of R&D intensity up to a point will be closely correlated with absorptive capacity. Further increases no longer capture absorptive capacity but are more associated with the conduct of more basic research or

[5] Several alternative indirect measures of spillovers have been used in previous empirical work, e.g., based on uncentered correlation (Jaffe 1988, Adams 1990), Euclidean distance (Inkmann and Pohlmeier 1995), and geographic distance. According to a comparative study of various spillover measures by Kaiser (2002) both uncentered correlation and direct measures (used in our model) appear to capture spillovers quite accurately.

[6] Other types of incoming spillovers such public spillovers and spillovers from patent information had no significant additional impact. Several other types of spillovers are likely to be captured by the source specific spillovers measures (i.e. information from patents applied for by suppliers, clients or competitors), while institutional spillovers are for a large part public spillovers.

perhaps idiosyncratic in-house R&D efforts. Hence, we expect a concave relationship with the marginal effect of R&D intensity declining. Following previous theoretical and empirical work, we also expect the relationship between R&D intensity and R&D cooperation to differ depending on the type of cooperation partner. In case of horizontal cooperation, the products are substitutes and the positive relationship is predicted to be weaker than in case of vertical or institutional cooperation. A large R&D base is likely to be associated with stronger proprietary knowledge and greater risks for the firm of leakage of information in cooperation with competitors. This risk is less important in case of cooperation with research institutes and suppliers and customers.

In line with the existing literature, we also include *firm size* (the logarithm of the number of the firm's employees). We expect that the larger the firm, ceteris paribus, the more likely it is that it engages in R&D cooperation. For any given level of R&D intensity, larger firms perform more R&D and are more likely to possess the necessary absorptive capacity to benefit from R&D cooperation. Larger firms are also more likely to be engaged in multiple technologies that may require various R&D partnerships. The propensity to engage in cooperation is also affected by the presence or absence of partner firms with complementary resources in R&D, and the ease with which suitable partners can be located. Both are likely to be related to the presence of large innovating firms. We can control for this influence in case of horizontal cooperation by including the variable *industry average firm size* (mean of turnover of all innovating firms in the 2-digit industry). We expect a positive impact, but only on horizontal cooperation.

We include three firm-specific measures that aim to capture factors hampering the innovation process of the firm, potentially pushing the firm to search for cooperation partners. This follows the perspective of the management literature on R&D alliances on the various motivations for partnerships. *Cost constraint* captures bottlenecks caused by lack of financial resources or high costs of new innovation projects. *Risk constraint* captures bottlenecks caused by financial uncertainty (profitability) or uncertain market conditions. *Organizational capability constraint* is an average of ranked scores of the bottlenecks that relate to the firm's shortage of (R&D) personnel, lack of knowledge, and organizational rigidity that cause the delay or abandonment of new innovation projects or the failure to start these. These constraints are expected to provide an incentive for firms to cooperate to reduce reduce costs, risks, and organizational constraints.

The management literature on R&D cooperation and alliances also stresses the importance of alliances in R&D when there are rapid technological developments, short product life cycles, and uncertainty concerning the technology that will be prevailing in the future (e.g. Tyler and Steensma, 1995; Hagedoorn, 1993). If technological developments are rapid and different technology strategies are followed it is likely that firms want to be active in multiple technological trajectories which buys them options to expand in the technology directions that eventually prevails. This consideration may explain the preponderance of R&D alliances in industries such as biotechnology and electronics. To proxy for *the speed of technological change* we take the ratio of the number of firms in the 2-digit industry that reported that they had introduced products new to the industry to the number of firms that did not introduce new products, weighted by firm size. We expect that firms operating in industries characterized by rapid introduction of completely new products have a higher incentive to engage in cooperation. In particular institutional cooperation in research and cooperation with competitors are expected to be affected. One problem with this measure is that the question on new products may not adequately pick up technological change in the services sector. To get an unbiased impact of speed of technological change we include a *service dummy*. If service sectors are more technologically active than the speed of technological change proxy suggests, the service dummy will have a positive sign correcting for this bias in the variable. Naturally, the service dummy in addition will pick up any systematic differences in cooperation between manufacturing and service sectors beyond this bias.[7]

We also control for the relative importance of information used in the innovation process coming from other establishments that are part of the same firm group. *Internal knowledge flows* is the ratio of the score on the importance of information from other firms within the group to the importance of external spillovers (sum of scores of all external sources of information). We expect a negative impact on cooperation, as firms that rely more on internally generated know-how, perhaps because of unique innovation processes or technologies, are less likely to see benefit in cooperation with external partners. Table 1 indeed shows that the mean of the internal knowledge flow variable is lower for cooperating firms than for non-cooperating firms, while the means for the incoming spillover variables are higher for cooperating firms.

We include a dummy for firms that are *part of a group*. It takes the value 1 if an establishment is part of a larger firm group. Independent business units are less likely to engage in cooperation because they face higher transaction costs. Firms that are part of a larger group may draw on group financial and technological resources that make them more attractive as cooperation partners.[8] In addition, we include a dummy variable for *multinational firm*, taking the value 1 if the headquarters of the group to which the firm belongs is located outside the Netherlands. To the extent that domestically owned firms are more embedded in local research networks whereas affiliates of multinational firms may rely on technology transfers from the parent, multinational firms' affiliates may be less likely to engage in R&D cooperation.[9]

Finally, we control for the possible role of R&D subsidies, by including a dummy taking the value one if the firm stated that it received an *R&D subsidy*. On the one hand, R&D subsidies can moderate financial bottlenecks for the firm's R&D activities and hence reduce the need to cooperate to share costs. On the other hand, given that a variety of R&D national and European subsidy schemes

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[7] We ran separate models for manufacturing and services firms only but found remarkably little differences in explanatory factors. Furthermore, a specification with a full set of industry dummies did not improve the statistical results. The LR-test Chi-square statistic of 43.43 (with 42 degrees of freedom) indicated that the constrained specification of only incorporating the service dummy could not be rejected.

[8] Note that the internal spillover variable already corrects for a potential greater inclination towards intra-group rather than external R&D cooperation for firms.

[9] A sizeable proportion (26.95%) of the establishments are owned by foreign multinationals. The dependent variable includes a limited number of international R&D partnerships. We also ran the models limiting the analysis of R&D cooperation to domestic cooperation. As expected, we found a stronger negative impact of the multinational firm dummy, but no major changes in the overall results.

are aimed at promoting R&D cooperation, the availability of R&D subsidies may make the difference in motivating firms to establish R&D partnerships. These schemes particularly target pre-competitive and basic R&D cooperation (e.g. with universities) but are less often aimed at R&D partnerships with competing firms, hence a positive effect in particular on vertical and institutional cooperation is expected. However, we cannot measure the availability of subsidies schemes but only the actual receipt of subsidies by the firms. If indeed R&D subsidies are conditional on cooperation, there will be a strong positive correlation between subsidies and cooperation but this is due to a simultaneous relationship between the two rather than a causal effect of subsidies. By comparing results of the full model with results of the new cooperation model we will be able to further examine the different effects of subsidies.[10]

Model and estimation method

Our model consists of three binary choice equations. These choices are for vertical, horizontal and institutional cooperation, respectively. We have three binary dependent variables y_1, y_2 and y_3 where

$$y_1 = \begin{cases} 1 \text{ if } x_1\beta_1 + \omega_1 > 0 \\ 0 \quad \text{otherwise} \end{cases}$$

$$y_2 = \begin{cases} 1 \text{ if } x_2\beta_2 + \omega_2 > 0 \\ 0 \quad \text{otherwise} \end{cases}$$

$$y_3 = \begin{cases} 1 \text{ if } x_3\beta_3 + \omega_3 > 0 \\ 0 \quad \text{otherwise} \end{cases}$$

and $(?_1 \, ?_2 \, ?_3) \sim N(0, S)$ where Σ is the covariance matrix of the error terms. The error terms are likely to be correlated if only because of omitted variables in these choice processes. In case one does not take this into account, for example with three separate probit equations, inefficient estimators result. To capture the possible interdependence of yes-or-no decisions we employ a multivariate limited dependent variable (multivariate probit) model. The computation of the maximum likelihood function based on T-variate normal distribution requires multidimensional integration. Simulation methods have been proposed (see Train, 2002, chapter 5) to approximate such a function. The GHK (Geweke et al. 1997; Hajivassiliou et al. 1996) simulator has been a particularly popular choice. Another possibility is to apply a GMM along the lines of the estimator proposed by Bertschek and

[10] A number of other control variables among which a self-reported measure of the firm's market position, a dummy whether the firm applied for patents in 1996, whether the focus of innovative activities is on process or product innovation, and the age of the firm, were included in the model but appeared irrelevant to the cooperation decision.

Lechner (1998). This estimator is shown to have good small sample properties and to have limited efficiency loss compared to maximum likelihood. Greene (2002) using the same data as Berschek and Lechner (1998), shows that maximum likelihood estimates using the GHK simulator are very close to GMM estimates. We will follow the GHK simulator approach and choose a simulated maximum likelihood estimator that also offers possibilities of cross-equation tests and restrictions in parameters. The GHK-procedure is briefly presented in Appendix B.[11].

4. Empirical Results

Table 3 reports the results for the trivariate probits using the GHK-procedure for the complete sample of 2156 observations. First of all, we note that the three correlation coefficients of the error terms in the multivariate probit are positive, ranging from 0.622 to 0.779, and highly significant.[12] This supports the notion of interdependence between the different cooperation decisions, and may be due to complementarity in R&D cooperation strategies but also to omitted firm-specific factors affecting all types of cooperation. The positive signs suggest that various modes of cooperation are viewed by the firms as complementary. However, they could also result from an omitted variable bias. A second finding is that the estimated coefficients of several variables, such as the incoming spillovers, have opposite signs in de different equations, while others have substantially different explanatory power across equations. This indicates the appropriateness of disaggregating between cooperation types. In order to formally test this, we estimated a (nested) constrained specification with all slope coefficients forced to be equal. The likelihood ratio test statistic was 411.57 (51 degrees of freedom), decisively rejecting the null hypothesis of equal slope coefficients.[13] This result strongly indicates the heterogeneity in cooperation strategies and, consequently, the unsuitability of aggregating them into one cooperation variable (cf. Fritsch and Lukas, 2001; Janz et al. 2002).

The hypothesis that source-specific incoming spillovers positively affect the probability of cooperation is partly confirmed. *Vertical incoming spillovers* have, as expected, a positive and significant effect in the *vertical* cooperation equation. *Horizontal incoming spillovers* have the expected sign in the *horizontal* cooperation equation, but the coefficient is not significant. A possible explanation is that the model does not sufficiently correct for outgoing spillovers at the firm level, with the outgoing spillovers variable measured at the industry level and hence not fully representative for the specific appropriability conditions for individual firms within the industry.[14] Firms reporting high incoming spillovers may also be more likely to have stronger outgoing spillovers, in which case models of R&D cooperation have suggested an ambiguous relationship between spillover levels and

[11] The results are obtained with a Stata routine due to Lorenzo Cappellari and Stephen P. Jenkins and are based on 200 random draws.
[12] For comparison we also report the results when using three independent univariate probits in Appendix C.1
[13] The results of the restricted model are not reported here but can be obtained from the authors upon request.
[14] An alternative explanation may be that firms rating horizontal incoming spillovers as important are more likely to be technology followers rather than leaders and as such less attractive R&D partners.

the propensity to cooperate. Horizontal incoming spillovers has a negative sign in the institutional and vertical cooperation equations with the latter coefficient significant, suggesting that they do matter in the choice of R&D cooperation type. Firms tend to gravitate here to the cooperation type that has the potentially highest value in terms of incoming knowledge. *Institutional incoming spillovers* have a positive and strongly significant effect in all three cooperation equations, and, as expected, the largest impact on institutional cooperation. The impact on vertical and horizontal cooperation suggest that institutional incoming spillovers are more generic in nature, improving the general effectiveness of the firm's R&D activities and stimulating vertical and horizontal cooperation as well. Also, the importance of this type of incoming spillovers may reflect that the firms are engaged in basic R&D, such that information sharing within R&D cooperation is more effective (Katsoulacos and Ulph, 1998). *Industry outgoing spillovers* has the expected negative impact on horizontal cooperation, but it just fails to reach conventional two-sided significance levels.[15] Firms that operate in industries in which competitors benefit from information received from other market participants may foresee difficulties to restrict outgoing spillovers.

The effect of *R&D intensity* on the probability of cooperation is positive and concave as expected, with the linear term positive and the quadratic term negative, but there are differences between cooperation types. A robust concave relationship is estimated for vertical cooperation with the maximum reached at a rather high level of 0.18 (percentage of R&D employees over total employees). For institutional cooperation the quadratic term fails to reach conventional significance levels. For horizontal cooperation none of the terms are significant with the coefficients substantially smaller than in the vertical and institutional cooperation equations. On the other hand, the F-test on removing both R&D intensity terms from the equation is rejected and a specification in which the quadratic term is dropped give a significantly positive coefficient on the linear term (not reported here). Overall these findings suggest a positive but weaker impact of R&D intensity on horizontal cooperation. This is consistent with the notion that R&D-intensive firms in horizontal partnerships also face greater risks of leakage of their proprietary knowledge, which may outweigh the potential benefits of knowledge in-flows due to cooperation.

Firm size is positive and significant in each of the equations, with the coefficient highest in case of institutional cooperation. Larger firms are more likely to have the critical size and absorptive capacity required to engage in R&D cooperation, while R&D cooperation with universities and institutes requires the largest critical size. The *industry average firm size* variable is positive and significant in the horizontal cooperation equation as hypothesized. The availability of large innovating potential partners stimulates horizontal cooperative R&D.

The *organizational capability constraint* is significantly positive in the vertical and institutional cooperation equations. The commercial *risk constraint* variable is significant and positive for both the horizontal and vertical cooperation decisions, while the *cost constraint* variable does not have any significant impact. Commercial risk sharing and access to complementary knowledge when

[15] The coefficient is significant in the univariate probit model reported in Appendix C.1.

faced with internal resource constraints appear important motivations for firms to seek R&D partners in vertical relationship in particular. The *speed of technological change* variable is positive and significant for the horizontal and institutional cooperation decisions. Firms in industries with shorter product life cycles and rapid technological developments are more inclined to cooperate with rivals or to cooperate in generic technologies with research institutes and universities. The *speed of technological change* variable may have been less adequately measured for the service industries and, therefore, we incorporated a *service dummy* expecting a positive impact if this dummy corrects for under-reported speed of technological change. The service dummy has the expected positive effect in the horizontal and vertical cooperation equations.

The effect of the *internal knowledge flow* variable is negative as expected in each of the three equations but insignificant. Firms that are *part of a group* are more likely to cooperate vertically, but not with competitors or research institutions. The dummy for a *multinational firm* is negative and significant in the horizontal cooperation equation: affiliates of multinationals are less likely to cooperate with local rivals, but are not less inclined to engage in vertical or institutional linkages. Finally, the *R&D subsidy* variable has a positive and significant impact on vertical and research institutional cooperation, which appears to suggest that subsidies promote pre-competitive R&D partnerships.

New R&D Cooperation

The multivariate probit results obtained on the sub-sample of firms not (yet) cooperating in 1996 are presented in Table 4. [16] The results are broadly in line with results for the complete sample. The standard errors are generally larger, which is likely to be due to a smaller sample (1488 observations) and the exclusion of consistently cooperating firms resulting in a much smaller percentage of cooperating firms. However, a number of differences are worth noting, since they may suggest that the full model results are affected by simultaneity bias. *Institutional spillovers* remains significantly positive in both the horizontal and institutional cooperation equations, while the coefficient in the vertical cooperation equation now just falls below conventional significance levels.[17] These findings by and large confirm the robustness of results in the presence of potential simultaneity bias. Similarly, the coefficient for *horizontal incoming spillovers* remains significant and negative in the vertical cooperation equation and insignificant in the other two equations. The main difference in the results on spillovers compared with the full sample is the lack of significance of *vertical incoming spillovers* on vertical cooperation. In this case the significantly positive effect found in the full sample may be sensitive to the simultaneity bias.

The *R&D intensity* results also remain fairly robust. For vertical cooperation, the concave relationship is again confirmed. Similarly, in the institutional cooperation equation the positive effect of R&D intensity is confirmed, be it that now the concavity proves to be significant as well. For

[16] For comparison, the results from the three binary probits on this sample are reported in Appendix C.2.
[17] In the individual probit results reported in Appendix C.2 the coefficient does remain significant.

horizontal cooperation, we again fail to find a significant effect of own R&D. Overall, the comparison of the full sample with the restricted sample confirm that the results of *R&D intensity* are robust to potential simultaneity bias.

A number of other observations can be made from Table 4. Interestingly, firms that rate *internal knowledge flows* as relatively important appear less likely to form new vertical and research institutional links, an effect that was not identified significantly in the full sample model. In addition, group membership as such, not differentiated by the importance of knowledge flows, now has a significantly negative impact on horizontal cooperation. These results suggest that firms that are part of a larger group are more likely do R&D internally in cooperation with other group members, rather than externally. There are also a number of changes in the estimated impacts of the innovation constraint variables. The *organizational capability* variable no longer is significant, while the *risk constraint* variable remains significant in the horizontal cooperation equation. Cost constraints now appear with a counter-intuitive significantly negative impact on vertical cooperation.

The most accentuated change in the results compared with the results for the full sample model occurs for the *R&D subsidy* dummy, as expected. In the new cooperation model containing only firms without cooperative agreement in 1996, the R&D subsidy dummy will only measures the effects of R&D subsidies that are not conditional on R&D cooperation. Hence the results cannot be affected by simultaneity between subsidies and cooperation but reflect the effect of *existing* R&D subsidies on *new* R&D cooperation. While the estimated effect in the full model was significantly positive in vertical and institutional cooperation and insignificantly negative in horizontal cooperation, the effect looses significance in the vertical and institutional new cooperation and is significantly negative in the horizontal new cooperation equation. This confirms the financial constraint alleviation hypothesis: R&D subsidies moderate financial bottlenecks for the firm’s R&D activities and hence reduce the need to cooperate. Non-cooperating firms that have received subsidies are more likely to find it optimal to maintain reliance on internal R&D efforts instead of sharing funds and research results with competitors. The results suggest that the positive impact found for the full sample may indeed be biased upward by simultaneity between cooperation and subsidies.[18]

5. Conclusion.

This paper has explored the heterogeneity in the determinants of firms’ decisions to engage in vertical (suppliers, customers), horizontal (competitors) and research institutional (universities, research labs) R&D cooperation. Unlike previous studies we differentiated between these three different types of cooperation strategies and used a broad set of determinants among which source-specific incoming spillovers. In the empirical model of cooperation decisions we limited potential

[18] In this case, the bias may be caused by a positive impact of R&D subsidies in 1996 effectively allocated to joint R&D projects set up around that time and still in existence in 1998.

problems of simultaneity bias between cooperation and its determinants, in particular R&D intensity and incoming spillovers, by utilizing a two period dataset on innovating firms, which allowed us to employ lagged variables. In addition, as a further robustness check we considered a sample of firms that did not (yet) cooperate in the first period, eliminating potential simultaneity problems. We used a multivariate probit model to reflect that firms consider simultaneously the decisions to cooperate with various partners. We found significantly positive correlations between the equations, which may indicate that the various cooperation decisions tend to be viewed by the firms as complementary rather than substitutes.

Our results confirm that incoming spillovers are an important determinant of R&D cooperation, with vertical spillovers leading to vertical cooperation and institutional spillovers having a large positive impact on institutional cooperation. We found no significant impact of horizontal spillovers on horizontal cooperation, which might be attributed to insufficient controls in the empirical model for firm-specific outgoing spillovers. This result is consistent with stylized results from theoretical industrial organization models of R&D cooperation, where spillover levels (if undifferentiated between outgoing and incoming spillovers) have an ambiguous impact on horizontal R&D cooperation. Another finding was that incoming spillovers from universities and research institutes also stimulate cooperation of the other two types, suggesting that this knowledge is more generic in nature and improves the general effectiveness of the firm's R&D activities and R&D cooperation strategies.

R&D intensity has a positive impact on vertical and institutional cooperation with a decreasing marginal impact for highly R&D intensive firms, while. A weaker positive impact was found for horizontal R&D cooperation, consistent with the notion that firms in horizontal partnerships also face greater risks of leakage of proprietary knowledge due to own R&D. Firm size has a positive impact on all three types of cooperation, as expected: larger firms are more likely to have the critical size and absorptive capacity required to engage in R&D cooperation. The largest firms were more likely to cooperate with universities and research institutes, suggesting that cooperation with universities and research institutes requires the largest critical size. Cost, risk, and organizational constraints in the firm's innovation process generally had a positive impact on R&D cooperation, with the most robust results for the commercial risk factor on horizontal cooperation and organizational constraints on vertical cooperation. R&D cooperation with institutions and competitors were found to be more likely in case of a greater speed of technological change in the industry. The presence of large innovating rivals in an industry made horizontal cooperation more likely, indicating that horizontally cooperating firms are more likely to find attractive R&D partners among larger firms. Foreign multinationals were found to have a lower propensity to engage in horizontal cooperation, but were not less inclined to cooperate vertically or with universities and research institutes. The estimated impact of R&D subsidies is sample sensitive: they had a positive effect on R&D cooperation in the full model, but this impact was likely to be biased by simultaneity bias. In the model for new cooperation, firms that were previously granted R&D subsidies were found to be less inclined to engage in horizontal cooperation.

This suggests that subsidies, if not granted conditional on cooperation, reduce the financial constraints on own R&D and the need to seek R&D partnerships.

The results show that there is substantial merit in disaggregating R&D cooperation by type of partner and that there are substantial differences in the motives and determinants of the different types of cooperation. Further empirical work in this area would greatly benefit from an extension of theoretical models to other types of R&D partnerships than horizontal cooperation. High on the agenda of future empirical work is analysis of potential complementarities between cooperation types, i.e. the choice of multiple R&D partnerships, and the effects of these on innovative performance.

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Table 1. Descriptive statistics

	Sample mean (n=2156)	Mean non-cooperating firms (n=1547)	Mean cooperating firms (n=609)	Sample Mean new cooperation (n=1488)
Horizontal incoming spillovers	1.107	1.070	1.202	1.024
Vertical incoming spillovers	1.268	1.234	1.355	1.191
Institutional incoming spillovers	0.445	0.363	0.656	0.343
Industry outgoing spillovers	0.711	0.703	0.729	0.705
R&D intensity	0.029	0.025	0.039	0.024
R&D intensity squared	0.004	0.003	0.005	0.003
Firm size	4.455	4.303	4.841	4.270
Industry average firm size	0.080	0.077	0.088	0.076
Org. capability constraint	0.042	0.033	0.067	0.034
Cost constraint	0.061	0.054	0.080	0.047
Risk constraint	0.101	0.081	0.151	0.075
Speed of technological change	0.501	0.491	0.526	0.495
Service dummy	0.349	0.357	0.328	0.350
Internal knowledge flows	0.538	0.563	0.474	0.575
Part of a group	0.472	0.446	0.537	0.438
Foreign multinational	0.279	0.273	0.294	0.274
R&D subsidy	0.435	0.378	0.578	0.357

Table 2. Distribution of cooperation cases

	Number of cases	Number of cases for new cooperation	(New) Horizontal cooperation	(New) Vertical cooperation	(New) Institutional cooperation
	1547	1219	0	0	0
	39	19	0	0	1
	204	105	0	1	0
	136	41	0	1	1
	43	26	1	0	0
	31	13	1	0	1
	47	26	1	1	0
	109	39	1	1	1
Total	2156	1488			

Table 3. Multivariate probit, 3 equations

	(1) Horizontal Cooperation	(2) Vertical Cooperation	(3) Institutional cooperation
Horizontal incoming spillovers	0.018 (0.046)	-0.065 (0.039)*	-0.015 (0.043)
Vertical incoming spillovers	-0.065 (0.057)	0.136 (0.049)***	-0.039 (0.055)
Institutional incoming spillovers	0.322 (0.066)***	0.249 (0.057)***	0.459 (0.062)***
Industry outgoing spillovers	-0.480 (0.306)	0.152 (0.268)	-0.198 (0.297)
R&D Intensity	1.665 (1.634)	3.959 (1.454)***	3.782 (1.541)**
R&D intensity squared	-2.187 (5.092)	-11.301 (4.943)**	-7.752 (4.966)
Firm size	0.144 (0.031)***	0.175 (0.028)***	0.226 (0.031)***
Industry average firm size	0.865 (0.394)**	0.327 (0.377)	0.457 (0.414)
Org. capability constraint	-0.184 (0.258)	0.581 (0.215)***	0.412 (0.227)*
Cost constraint	0.062 (0.342)	-0.291 (0.296)	0.504 (0.317)
Risk constraint	0.382 (0.153)**	0.292 (0.132)**	0.032 (0.146)
Speed of technological change	0.454 (0.240)*	0.321 (0.211)	0.861 (0.243)***
Service dummy	0.224 (0.092)**	0.171 (0.080)**	0.013 (0.091)
Internal knowledge flows	0.007 (0.071)	-0.051 (0.066)	-0.101 (0.077)
Part of a group	-0.055 (0.079)	0.165 (0.067)**	0.033 (0.076)
Foreign multinational	-0.220 (0.092)**	-0.023 (0.074)	-0.069 (0.085)
R&D subsidy	-0.016 (0.089)	0.219 (0.073)***	0.205 (0.083)**
Constant	-2.061 (0.270)***	-2.402 (0.238)***	-2.858 (0.272)***
Rho12	0.631 (0.035)***		
Rho13	0.737 (0.030)***		
Rho23	0.787 (0.024)***		
Observations	2156		
LL	-2135.84		
Wald Chi2(51)	371.69		
LR test of Rho21=Rho31=Rho32=0 Chi2(3)	708.16		
LL_0 (57)	-2341.63		
LR chi2(51)	411.57		

* significant at 10%; ** significant at 5%; *** significant at 1%

Standard errors in parentheses

Table 4. Multivariate probit, 3 equations on new cooperation

	(1) Horizontal Cooperation	(2) Vertical Cooperation	(3) Institutional cooperation
Horizontal incoming spillovers	-0.064	-0.092	-0.047
	(0.061)	(0.051)*	(0.060)
Vertical incoming spillovers	0.008	0.037	-0.061
	(0.076)	(0.064)	(0.076)
Institutional incoming spillovers	0.215	0.126	0.311
	(0.097)**	(0.082)	(0.091)***
Industry outgoing spillovers	-0.066	0.287	-0.088
	(0.431)	(0.385)	(0.429)
R&D Intensity	2.001	4.861	6.662
	(2.726)	(2.170)**	(2.876)**
R&D intensity squared	-7.189	-13.926	-27.320
	(9.949)	(7.917)*	(13.306)**
Firm size	0.118	0.203	0.206
	(0.046)***	(0.040)***	(0.048)***
Industry average firm size	0.835	-0.737	0.399
	(0.549)	(0.629)	(0.631)
Org. capability constraint	-0.696	0.511	0.422
	(0.426)	(0.300)*	(0.333)
Cost constraint	-0.379	-0.989	-0.702
	(0.565)	(0.483)**	(0.562)
Risk constraint	0.441	0.252	0.008
	(0.234)*	(0.198)	(0.239)
Speed of technological change	0.053	0.294	1.110
	(0.334)	(0.284)	(0.348)***
Service dummy	0.146	0.300	0.001
	(0.122)	(0.104)***	(0.126)
Internal knowledge flows	-0.003	-0.168	-0.330
	(0.090)	(0.088)*	(0.132)**
Part of a group	-0.213	0.100	-0.026
	(0.109)**	(0.090)	(0.107)
Foreign multinational	-0.234	-0.029	0.118
	(0.127)*	(0.099)	(0.116)
R&D subsidy	-0.218	0.075	-0.055
	(0.123)*	(0.099)	(0.117)
Constant	-1.939	-2.429	-2.834
	(0.351)***	(0.313)***	(0.370)***
Rho12	0.731		
	(0.040)***		
Rho13	0.839		
	(0.035)***		
Rho23	0.778		
	(0.035)***		
LR test of Rho21=Rho31=Rho32=0 Chi2(3)	408.93		
Observations	1488		
LL	-1085.33		
Wald Chi2 (51)	147.35		

* significant at 10%; ** significant at 5%; *** significant at 1%

Standard errors in parentheses

Appendix A: Description of Variables

#	variable name	Definition
1	Horizontal incoming spillover	Importance of competitors as source of knowledge for the firm's innovation process.
2	Vertical incoming spillover	Average of importance of clients and suppliers as source of knowledge for the firm's innovation process
3	Institutional incoming spillover	Average of importance of universities, innovation centers, and research institutions as source of knowledge for the firm's innovation process.
4	Industry outgoing spillovers	Mean of scores of importance of information received from competitors and patents for all firms operating in the (2-digit) industry.
5	R&D intensity	R&D employees/total employees
6	R& D intensity squared	R&D employees/total employees squared
7	Firm size	Logarithm of number of employees
8	Industry average firm size	Mean of sales by all innovating firms operating in the 2-digit industry.
9	Organizational capability constraint	Average of scores on the following responses: innovation project not started due to short of staff not started due short of knowledge not started due to rigid organization
10	Risk constraint	Average of scores on the following responses: innovation project not started due to economic risks not started due to uncertain markets
11	Cost constraint	Average of scores on the following responses: innovation project not started or delayed or abandoned due to short of financing not started or delayed or abandoned due to high costs
12	Speed of technological change	Sum of sales of firms in the 2-digit industry that stated that they had introduced products new to the industry, divided by sum of sales of all firms in the industry.
13	Service dummy	1 if business unit belongs to the services sector, else 0
14	Internal knowledge flows	Importance of other group firms as source of knowledge for the firm's innovation process, divided by the total of importance scores of all external sources of knowledge
15	Part of a group	1 if the business unit is part of the larger firm, else 0
16	Foreign multinational	1 if headquarters of the firm is located outside the Netherlands, else 0
17	R&D subsidy	1 if firm received subsidy for innovation activities, else 0

Note: all independent variables are derived from the 1996 CIS survey

Appendix B: the GHK estimation procedure

For a trivariate probit the evaluation of the likelihood function requires the computation of a trivariate integral

(1) $\mu(\theta; \mathbf{z}_n) = \iiint g(?_1 ?_2 ?_3; \theta; y_n)\, d?_1 d?_2 d?_3$

where $\mu(\theta; \mathbf{z}_n)$ are probabilities such that for a random sample **y** $\{y_1\ y_2\ y_3\}$ we want to maximize the likelihood of the sample (see Hajivassiliou and Ruud 1994; Train 2002) being:

(2) $$Q_N^{ML}(\theta) = \sum_{n=1}^{N} \log(\mu(\theta; \mathbf{z}_n))$$

The (infeasible) maximum likelihood estimator $\hat{\theta}$ is as follows

(3) $$\hat{\theta} \equiv \arg\max_{\theta} \sum_{n=1}^{N} \log(\mu(\theta; \mathbf{z}_n)$$

The maximum simulated likelihood estimator is now calculated as:

(4) $\hat{\theta}_{MSL} \equiv \arg\max_{\theta} Q_N^{ML}(\theta)$ where

(5) $$Q_N^{ML}(\theta) = \sum_{n=1}^{N} \log\left[\frac{1}{R} \cdot \sum_{i=1}^{R} \mu_i(\theta; \mathbf{z}_n; \phi_{ni})\right]$$

for a sequence $\{\phi_n\}$ n=1 .. N

Hajivassiliou and Ruud (1994) prove that under regularity conditions the MSL estimator θ_{MSL} is consistent if R→ ∞ as N→ ∞ with further result from Gourieroux and Monfort (1996) that if $\sqrt{N}/R \rightarrow 0$ and R→ ∞ as N→ ∞ then $\sqrt{N}(\mathbf{b}_{sml} - \beta)$ has the same limiting normal distribution with zero mean as $\sqrt{N}(\mathbf{b}_{ml} - \beta)$.

In practice the probability Pr(**e<b**) = $\Pr(e_1 < b_1, e_2 < b_2, e_3 < b_3)$ is estimated as

(6) $$\Pr(\mathbf{e}<\mathbf{b}) = ?(b_1) \cdot\left(\left(1/R \cdot \sum_{i=1}^{R} ?(b_1 - s_{21} \cdot \mu_1 / s_{22}\right) \cdot \left(1/R \cdot \sum_{i=1}^{R} ?(b_3 - s_{31}\mu_1 - s_{32}\mu_2)/s_{33}\right)\right.$$

where s_{ij} are the elements of Choleski-decomposed matrix of the error terms and m, m x 1 vector of i.i.d. normal density draws such that $\mathbf{e} = \lambda \cdot (\Sigma) \cdot m$ (detailed exposition can be found in Hajivassilou et al. 1996; Train 2002).

Appendix C. 1 Individual probit results for the full sample

	(1) Horizontal Cooperation	(2) Vertical Cooperation	(3) Institutional cooperation
Horizontal incoming spillovers	0.030	-0.059	-0.013
	(0.046)	(0.039)	(0.045)
Vertical incoming spillovers	-0.069	0.139	-0.036
	(0.058)	(0.049)***	(0.057)
Institutional incoming spillovers	0.329	0.249	0.474
	(0.066)***	(0.057)***	(0.063)***
Industry outgoing spillovers	-0.536	0.180	-0.230
	(0.311)*	(0.270)	(0.302)
R&D Intensity	1.870	4.054	4.062
	(1.656)	(1.487)***	(1.576)***
R&D intensity squared	-2.814	-11.988	-8.946
	(5.239)	(5.269)**	(5.157)*
Firm size	0.143	0.176	0.243
	(0.031)***	(0.028)***	(0.032)***
Industry average firm size	0.846	0.295	0.469
	(0.395)**	(0.375)	(0.410)
Org. capability constraint	-0.173	0.561	0.400
	(0.269)	(0.216)***	(0.236)*
Cost constraint	0.036	-0.271	0.540
	(0.349)	(0.296)	(0.324)*
Risk constraint	0.390	0.304	0.030
	(0.155)**	(0.133)**	(0.153)
Speed of technological change	0.496	0.293	0.923
	(0.243)**	(0.211)	(0.255)***
Service dummy	0.213	0.161	-0.035
	(0.093)**	(0.080)**	(0.094)
Internal knowledge flows	0.018	-0.044	-0.085
	(0.070)	(0.065)	(0.079)
Part of a group	-0.080	0.163	0.035
	(0.081)	(0.067)**	(0.078)
Foreign multinational	-0.225	0.031	-0.111
	(0.094)***	(0.074)	(0.087)
R&D subsidy	-0.033	0.209	0.187
	(0.090)	(0.073)***	(0.085)**
Constant	-2.031	-2.412	-2.941
	(0.277)***	(0.238)***	(0.285)***
Observations	2156	2156	2156
LL	-680.58	-1058.77	-750.57
Chi2	102.83	208.11	292.18

* significant at 10%; ** significant at 5%; *** significant at 1%
Standard errors in parentheses

Appendix C. 2 Individual probit results for the new cooperation sample

	(4)	(5)	(6)
	hcopnew	vcopnew	gcopnew
Horizontal incoming spillovers	-0.054	-0.088	-0.033
	(0.062)	(0.051)*	(0.063)
Vertical incoming spillovers	0.000	0.046	-0.069
	(0.078)	(0.065)	(0.081)
Institutional incoming spillovers	0.215	0.136	0.309
	(0.101)**	(0.082)*	(0.095)***
Industry outgoing spillovers	-0.109	0.274	-0.112
	(0.439)	(0.387)	(0.443)
R&D Intensity	3.017	4.597	7.431
	(2.778)	(2.175)**	(3.119)**
R&D intensity squared	-9.616	-13.434	-31.528
	(10.545)	(8.020)*	(15.410)**
Firm size	0.128	0.207	0.237
	(0.047)***	(0.040)***	(0.050)***
Industry average firm size	0.737	-0.566	0.525
	(0.550)	(0.607)	(0.625)
Org. capability constraint	-0.740	0.506	0.457
	(0.492)	(0.298)*	(0.358)
Cost constraint	-0.380	-0.867	-0.573
	(0.580)	(0.476)*	(0.591)
Risk constraint	0.461	0.239	-0.111
	(0.246)*	(0.200)	(0.264)
Speed of technological change	0.050	0.284	1.225
	(0.344)	(0.285)	(0.375)***
Service dummy	0.112	0.284	-0.041
	(0.127)	(0.105)***	(0.133)
Internal knowledge flows	-0.002	-0.150	-0.341
	(0.089)	(0.088)*	(0.158)**
Part of a group	-0.216	0.090	0.022
	(0.112)*	(0.090)	(0.113)
Foreign multinational	-0.186	-0.045	0.075
	(0.130)	(0.100)	(0.121)
R&D subsidy	-0.269	0.064	-0.122
	(0.129)**	(0.100)	(0.122)
Constant	-1.936	-2.448	-3.016
	(0.362)***	(0.316)***	(0.403)***
Observations	1488	1488	1488
LL	-360.54	-573.09	-356.16
Chi2	32.91	68.67	82.45

* significant at 10%; ** significant at 5%; *** significant at 1%
Standard errors in parentheses

Appendix D. Correlations

(obs=2156)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
(2)	0.3272													
(3)	0.3682	0.4624												
(4)	0.0516	0.0690	0.0898											
(5)	0.0421	0.0934	0.0955	0.3638										
(6)	0.1169	0.1639	0.1458	0.2167	0.2255									
(7)	-0.0284	-0.0043	-0.0472	-0.2930	-0.4156	-0.2619								
(8)	-0.0035	0.0218	0.0092	0.0808	-0.0259	-0.0038	0.0927							
(9)	0.1043	0.1852	0.1760	0.1387	0.0759	0.3246	-0.0709	0.0195						
(10)	0.0531	0.0958	0.1002	0.1634	0.0766	0.1155	-0.0445	0.1511	0.2851					
(11)	0.0695	0.1729	0.1379	0.0970	0.0534	0.2227	-0.0237	0.0418	0.3275	0.2617				
(12)	0.0369	0.1059	0.0801	0.0338	0.0198	0.1432	-0.0095	0.0110	0.1829	0.1369	0.8870			
(13)	0.0327	0.0337	0.0899	0.1483	0.0173	0.1407	0.0501	0.1639	0.1699	0.0275	-0.0044	-0.0151		
(14)	0.0446	0.0747	0.0829	0.0727	0.0481	0.1151	-0.0883	0.0117	0.2334	0.4875	0.2109	0.1343	-0.0039	
(15)	0.0087	0.0170	0.0266	-0.0126	-0.0229	0.0505	0.0128	0.0499	0.0306	0.0888	-0.0116	-0.0184	0.1605	-0.2456

(1) Org. capability constraint
(2) Cost constraint
(3) Risk constraint
(4) Incoming Horizontal spillovers
(5) Incoming Vertical spillovers
(6) Incoming institutional spillovers
(7) Internal knowledge flows
(8) Foreign multinational
(9) R&D subsidy
(10) Industry outgoing spillovers
(11) R&D Intensity
(12 R&D intensity squared
(13) Firm Size
(14) Industry speed of technological change
(15) Industry average firm size